Miller, K.G., Sugarman, P.J., Browning, J.V., et al.
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5. Millville Site[1]

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INTRODUCTION

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

Operations: Browning, Cobbs, Cobbs III, Huffman, Miller, Sugarman
Lithostratigraphy: Browning, Buttari, Cramer, Hernandez, Katz, Lettini, McLaughlin, Miller, Misintseva, Monteverde, Patrick, Roman, Sugarman, Wojtko
Biostratigraphy:
Spores, pollen, and dinocysts: Brenner
Planktonic foraminifers: Browning, Miller, Misintseva, Olsson
Benthic foraminifers: Browning, Harris, Olsson
Calcareous nannofossils: Aubry (Cenozoic), Bukry (Mesozoic)
Diatoms: Barron
Logging: Curtin, McLaughlin
Sr isotopic stratigraphy: Browning, Feigenson, Monteverde

MILLVILLE SITE SUMMARY

Millville was the ninth site drilled as part of the Coastal Plain Drilling Project (CPDP) and the fifth site drilled as part of Leg 174AX. Drilling at the Bridgeton Pike Well Complex, Millville, New Jersey (39°24′16.67″N,

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75°05′19.99″W; elevation = 89.7 ft [27.16 m]; Millville quadrangle, Cumberland County), targeted Upper Cretaceous sequences and aquifers with a 1500-ft (457.20 m) corehole drilled from 4 May to 24 June 2002. At Millville, we recovered 1254.85 ft (382.48 m); mean recovery was 83.7% for the 1500 ft (457.20 m) cored. Gamma ray, conductivity, spontaneous potential, and resistivity downhole geophysical logs were collected from the borehole. A team of scientists from the New Jersey Geological Survey (NJGS), Rutgers University, the Delaware Geological Survey (DGS), and the U.S. Geological Survey (USGS) collaborated in the drilling and stratigraphic studies of the borehole, which were funded by the NJGS (direct drilling costs) and the National Science Foundation (NSF; Earth Science Division, Continental Dynamics Program).

Surficial sand and gravel (0–37.4 ft; 0–11.40 m) assigned to the Bridgeton Formation are interpreted as fluvial deposits. The Cohansey Formation (37.4–157.8/160 ft; 11.40–48.10/48.77 m) consists of fine to coarse sands deposited in a variety of laterally contiguous nearshore and marginal marine environments including shoreface, lagoon, and back barrier. The overall facies association within the Cohansey Formation suggests regression followed by a stillstand. The sands assigned to the Bridgeton and Cohansey Formations are not dateable at the Millville site but probably represent middle–upper Miocene deposits.

The lower–middle Miocene Kirkwood Formation can be divided into at least three sequences at Millville:

1. The upper sequence (157.8/160–223.6 ft; 48.10/48.77–68.15 m) consists of slightly lignitic, bioturbated, interbedded clays and silts. It is assigned to the Wildwood Member and was probably deposited in lagoonal or estuarine environments; it is tentatively correlated with sequence Kw2a.
2. The middle sequence (223.6–255.3 ft; 68.15–77.82 m) consists primarily of medium to coarse sands with interbeds of lignite and silty clay deposited in neritic and delta-front environments and is tentatively correlated to the Shiloh Member and sequence Kw1b.
3. The basal sequence (255.3–410 ft; 77.82–124.97 m) consists of upper fine to medium lignitic sands deposited in delta-front environments and interbedded muddy medium to fine sand deposited in shoreface environments and lower laminated silty clays deposited in prodelta and lower shoreface environments; numerous Sr isotopic age estimates correlate this sequence with sequence Kw1a (~20.2–20.5 Ma).

No Oligocene sediments occur in the Millville corehole. The middle–upper Eocene is thick at Millville (321.9 ft; 97.47 m). Thick, glauconitic, shelly, slightly muddy quartz sands (410–605 ft; 124.97–184.4 m) are assigned to the upper Shark River Formation, Toms River Member. Biostratigraphy correlates these sands to upper Eocene Zones NP19–NP20 (P16–P17); thus, they are equivalent in age to downdip clays assigned to the Absecon Inlet Formation and are younger than previously dated sections of the Toms River Member. These sands are very porous and friable and comprise an aquifer. The sands can be divided into two sequences: one correlated with sequence E10 and the other comprising the highstand systems tract (HST) of sequence E9. They were deposited in inner neritic, predominantly lower shoreface (5–20 m) environments. The lower part of the upper Shark River Formation (605–640.35 ft; 184.4–

223.74 m) consists of glauconitic sandy, shelly clays to clayey glauconite sands deposited in offshore, inner neritic environments; they span the middle/late Eocene boundary (Zones NP18–?NP17; P14–P16) and comprise the lower part of sequence E9 (Zone NP18) and sequence E8 (Zones NP18 to ?NP17). The lower Shark River Formation consists of silty clays to clays with varying glauconite, sporadic quartz sand, and shell content; the lower part is porcellanitic (= Horizon A^c cherts). This unit is primarily lower middle Eocene Zones NP14b–N15 and P8–P10 undifferentiated through P12, though the basal part is uppermost lower Eocene (Zone NP13; P8). It was deposited in middle neritic environments and comprises three sequences that correlate with sequences E7 (Zones NP15–NP16; P11–P12), E6 (Zones NP14b–NP14 undifferentiated), and E4 (Zone NP13).

The lower Eocene at Millville is comprised primarily of carbonate-rich clays of the Manasquan Formation (731.9–847 ft; 223.08–258.17 m). Sequence boundaries are subtle in these deeper-water (middle–outer neritic) environments and are recognized by gamma log kicks and biostratigraphy. Sequence E3 (Zone NP12; P7) is 24.5 ft (7.48 m) thick, sequence E2 (Zone NP11) is 80 ft (23.38 m) thick, and glauconite-rich sequence E1 (Subzone NP10d; P6a) is thin (11 ft; 3.35 m).

Basal Eocene (Subzone NP9b) clays (847–899.4 ft; 258.17–274.14 m) comprise an unusual lithologic unit previously identified at the Ancora, Bass River, and Clayton sites. At these latter sites, the clays contain the global Paleocene/Eocene carbon isotopic excursion, kaolinitic clays, and magnetic nanoparticles at their base (e.g., Kent et al., 2003). At these other sites, the carbon isotope excursion (CIE) is found a few meters above an unconformity. Preliminary nannofossil studies suggest that the CIE may not be complete at Millville, and the CIE is predicted at a disconformity. The clay unit at Millville (here, designated sequence Pa4) was deposited in middle–outer neritic environments; it is tentatively assigned to the Vincentown Formation, though a new name is probably warranted for these subsurface clays.

The Paleocene sequence at Millville consists of occasionally sandy and micaceous clays and slightly glauconitic clays of the Vincentown Formation (847–970.2 ft; 258.17–295.72 m) and clayey glauconite sands of the Hornerstown Formation (970.2–983.3 ft; 295.72–299.71 m). Sequence Pa3 comprises most of the Vincentown Formation, consisting of upper prodelta and lower middle neritic clays assigned to Zones NP8–NP9a (P4c). Sequence Pa2 spans the formational boundary and is assigned to Zones NP6–NP8 (P4a). The Hornerstown Formation also contains sequences Pa1 (Zoned NP3–NP4; P3b) and a very thin Zone P1a sequence at its base (982.0–982.95 ft; 299.39–299.69 m).

The Cretaceous/Paleogene (K/P) boundary at Millville does not appear to contain a complete record of the latest Cretaceous impact. The K/P boundary at Millville is placed between samples at 983.0 ft (299.62 m) and 983.05 ft (299.63 m). The presence of *Parvularugoglobigerina eugubina* in the sample at 983.0 ft (299.62 m) identifies lower Danian Zone Pα. The basal Danian Zone P0 may lie just below this. Samples at 983.05–983.5 ft (299.63–299.77 m) are placed in the uppermost Maastrichtian. Although biostratigraphically nearly complete, the Millville K/P boundary lacks the impact spherules and shocked minerals that were found in situ in the Bass River corehole (Olsson et al., 1997) and reworked in the Ancora corehole. This reflects the heterogeneity of preservation of this event on the New Jersey coastal plain.

The Maastrichtian section at Millville is relatively thick (53.7 ft; 16.37 m), and the lithologic units differ from coreholes and outcrops to the north. This may reflect a higher Maastrichtian sedimentation rate (13 m/m.y.) at Millville than previously encountered in New Jersey. Maastrichtian lithologic units at Millville consist of an upper carbonate-rich glauconitic clay (New Egypt equivalent) and a lower carbonate-rich glauconitic clay to clayey glauconite sand (Navesink equivalent). Two contacts in the Maastrichtian may be sequence boundaries, though the significance of these contacts requires further study:

1. The upper contact (988.1 ft; 301.17 m) may be the lower sequence boundary of a latest Maastrichtian to early Danian sequence (~65.5–64.5 Ma); the contact correlates with a global warming at ~65.5 Ma.
2. The lower contact at 1014.5 ft (309.22 m) occurs in the lower part of Zone CC26c (~66 Ma) and may represent a mid-Maastrichtian sequence boundary.

The entire Maastrichtian section was deposited in relatively deep water (middle–outer neritic environments). In other New Jersey boreholes, the contact and sequence boundary at the base of the Maastrichtian Navesink sequence consists of glauconite sand above quartz sand containing phosphate and is associated with a large gamma ray peak. The contact at Millville has been obscured by extensive bioturbation and reworking. It is recognized at a rubbly contact at 1032.9 ft (314.83 m) just below a phosphate lag deposit and the largest gamma ray peak found in this borehole.

Campanian–Santonian sequences are marine and well represented at Millville, though age control is coarser than at Ancora or Bass River because of diagenetic effects on Sr isotopes. Nannofossil zones and limited Sr isotopic data provide age control that is consistent with the ages of Campanian–Santonian sequences found at Ancora and Bass River (Miller et al., 2004). Four definite and two possible Campanian–Santonian sequences are found at Millville:

1. The Marshalltown sequence (1032.9–1059.5 ft; 314.83–322.94 m) consists of an upper carbonate-rich quartzose and glauconitic sandy clay (undifferentiated Mount Laurel and Wenonah equivalents) and a lower shelly fine to very fine glauconite sand (Marshalltown Formation). This sequence is late Campanian (Zones CC21 partim to CC23a). The absence at Millville of quartz sand (Mount Laurel Formation) and sandy silt (Wenonah Formation) beneath the distinctive Navesink glauconite sand as found in other New Jersey coreholes and outcrops to the north, indicates that the Maastrichtian delta had less of an influence on sedimentation along strike to the south.
2. The upper Englishtown sequence (1059.5–1086.85 ft; 322.94–331.27 m) consists of a silty very fine to fine sand and a thin basal glauconite. The sand was deposited in lower shoreface environments influenced by a delta. The sequence is middle Campanian (Zones CC19/CC21–CC21). The sands of the upper and lower Englishtown might have potential for limited water supply and aquifer recharge, though they are dominantly fine grained and silty.
3. The Merchantville sequence (1086.85–1246.25 ft; 331.27–379.86 m) is a thick succession consisting of an upper medium to very fine quartz sand and micaceous, silty fine sand (lower Englishtown Formation), a medial thick clay (Woodbury Forma-

tion), and a basal clayey glauconite sand (Merchantville Formation). The sediments were deposited on a generally transgressing shelf; the sands represent lower shoreface environments, the clays represent prodelta environments, and the glauconites represent middle to outer neritic environments. The sequence is dated as late to middle Campanian (Zones CC17, CC18, CC19, and ?CC20). Two contacts within the Merchantville Formation (1225.7 ft [373.59 m] and 1239.2 ft [377.71 m]) may be sequence boundaries for thin late Santonian to early Campanian (Zones CC17–CC18) sequences.

4. The Cheesequake Formation and sequence (1246.25–1254.4 ft; 379.86–382.34 m) is a cross-bedded to homogeneous lignitic, glauconitic, fine- to medium-grained quartz sand, with thin interbedded clays deposited on a delta front. It is dated as early Santonian (Zone CC15).

The Magothy Formation (1254.4–1300.5 ft; 382.34–396.39 m) consists of variable sediments including fine to very fine sands with sphaerosiderite, lignitic pyritic silt, white clay, and mottled red and white clays and silty clays with red root zones. These sediments represent a complex of alluvial plain environments including levee, crevasse splay, fluvial overbank, soils, and subaqueous alluvial plain. The formation consists of one sequence at Millville dated as pollen Zone V (late Turonian to early Coniacian).

The Bass River Formation (1300.6–1422.1 ft; 396.42–433.46 m) at Millville consists primarily of silty, shelly, micaceous (including chlorite) clay deposited in lower shoreface to middle neritic environments. Sequence boundaries at 1342.55 and 1374.4 ft (409.21 and 418.92 m) divide the Bass River Formation into three sequences dated as late Cenomanian–early Turonian (limited Sr isotopic ages; pollen Zone IV), middle Cenomanian (Zone CC10 and pollen Zone IV), and early Cenomanian (Zone CC9 and pollen Zone III).

The Potomac Formation (1421.9–1495.5 ft; 433.4–455.83 m total depth [TD]) is dominated by paleosols consisting of mottled clays and silts, some with sphaerosiderite, and lignitic very fine sands all deposited in alluvial plain environments. Pollen dates this formation as late Albian to early Cenomanian (Zones III and ?IIc).

As an updip site, the Millville corehole provided little new information on Miocene sequences. Upper Eocene sequences (E8–E10) are well expressed at this site and should provide new insights into the distribution, facies, and aquifer potential of sequences of this age. Middle (E4, E6, and E7) and lower (E1–E4) Eocene sequences are consistent with results from other New Jersey coreholes. The Paleocene/Eocene Thermal Maximum sequence and the K/P boundary do not appear as complete as in other boreholes. Maastrichtian sequences at Millville appear to be thick and to provide evidence for two middle–late Maastrichtian sequences. Campanian–Santonian sequences (Marshalltown, Merchantville, and Cheesequake) are well represented, and the Millville borehole may provide new insights into late Santonian–early Campanian sequences contained within the Merchantville Formation. The Magothy and Potomac Formations at this site seem to provide little new sequence information, but the intervening Bass River Formation can be unequivocally divided into three sequences (late Cenomanian–early Turonian, middle Cenomanian, and early Cenomanian).

The Millville corehole has greater similarities to Cretaceous and Paleogene sections in Delaware than those to the north (e.g., generally thinner sequences, especially Magothy, with the exception of the upper Eocene, Maastrichtian, and Cenomanian sections). This reflects the South Jersey High as a tectonic feature that influenced the sedimentation patterns, separating north and southernmost New Jersey sedimentation patterns.

BACKGROUND AND OBJECTIVES

This chapter is the site report for the Millville corehole (Fig. F1), the ninth continuously cored and logged onshore site drilled as part of the CPDP. The CPDP began with drilling at Island Beach (March–April 1993), Atlantic City (June–August 1993), and Cape May (March–April 1994) as part of Ocean Drilling Program (ODP) Leg 150X (Miller et al., 1994a, 1994b, 1996a; Miller, Newell, and Snyder, 1997) (Fig. F1). These three sites targeted Oligocene–Miocene sequences, trying to unravel Icehouse sea level changes (Miller and Mountain, 1994; Miller et al., 1996b, 1998a). Onshore drilling continued as part of Leg 174AX at

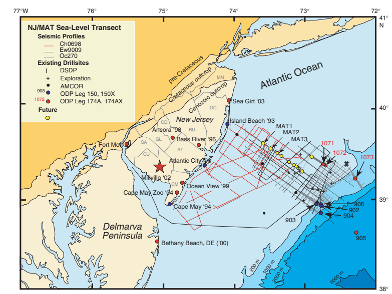
1. Bass River, New Jersey (October–November 1996; Miller, et al., 1998b), targeting Upper Cretaceous to Paleocene strata poorly sampled during Leg 150X;
2. Ancora, New Jersey (July–August, 1998; Chap. 1, this volume), an updip, less deeply buried Cretaceous–Paleocene section complimentary to Bass River;
3. Ocean View, New Jersey, (September–October, 1999; Chap. 2, this volume), targeting upper Miocene–middle Eocene sequences;
4. Bethany Beach, Delaware, targeting the thick Miocene sequences in the depocenter of the Salisbury Embayment (Chap. 3, this volume); and
5. Fort Mott, New Jersey (October, 2001; Chap. 4, this volume), targeting the largely nonmarine Potomac Formation (Fig. F1).

In total, these previous boreholes recovered 9,313.65 ft (2838.8 m) from 11,382.5 ft (3469.4 m) drilled (recovery = 81%).

Despite the logistic and scientific success in onshore coring to date, there is a significant gap in our understanding of Upper Cretaceous "greenhouse" sequences. Drilling at Bass River provided thick Upper Cretaceous sequences (696.1 ft; 212.17 m), but the section suffered from diagenetic overprinting because of its deep burial (1956.5 ft; 596.34 m TD). Drilling updip at Ancora, New Jersey, recovered unaltered Upper Cretaceous sections that were dated using Sr isotopic stratigraphy (Miller et al., 2003, 2004). However, because of its updip location, the section at Ancora was deposited in paleodepths too shallow for sampling a few critical sections (e.g., the Cenomanian/Turonian boundary). In addition, Ancora provides our only well-dated Upper Cretaceous section and one or more additional sections are needed to verify the regional significance and global ages of these greenhouse sequences and attendant sea level changes.

We targeted two new sites located on a projected dip profile between Ancora and Bass River that should provide ideal settings for sampling Upper Cretaceous sequences. The first site is the subject of this report, Millville, New Jersey, where the top of the Potomac Group was estimated to be within the drilling capabilities of the USGS Eastern Earth Surface Processes Team (EESPT) Mobile B51 truck-mounted drill rig

F1. Location map, p. 56.



(1500–1600 ft; 457.20–487.68 m). This site was also chosen because of its critical location for sampling important aquifers and the absence of continuous core data from Cumberland County (Figs. F2, F3, F4, F5, F6, F7). To address these hydrogeologic objectives, NJGS paid for all drilling costs for the Millville borehole. The second site is located adjacent to the coastline at Sea Girt, New Jersey, along strike of Millville (Fig. F1). This site will be tied into a nearshore multichannel seismic grid collected in May 2003 by G.S. Mountain, N. Christie-Blick, S. Pekar, and others, allowing us to evaluate the geometry of Upper Cretaceous sequences. The Upper Cretaceous sections at Bass River, Ancora, Millville, and Sea Girt and their integration with seismic control should provide an unparalleled opportunity to evaluate and date Upper Cretaceous greenhouse sequences. The JOIDES Planning Committee (PCOM) and Science Committee (SCICOM) designated drilling at Bass River, Ancora, Ocean View, Bethany Beach, Fort Mott, Millville, and Sea Girt as ODP Leg 174AX.

Drilling at Millville will also provide needed constraints for confined aquifers and groundwater potential for the southernmost part of the state of New Jersey (Fig. F8), particularly Cumberland County. Groundwater is the primary means of water supply for Cumberland County (Cauller et al., 1999). The Kirkwood-Cohansey aquifer system, an unconfined aquifer, is the main source of water in Cumberland County. This aquifer is susceptible to water-quality problems including nitrate, radium, mercury, organic chemicals, and pesticides. As populations grow in the county, the need to understand the thickness, properties, and extent of deeper confined aquifers is essential for water resource planners. The Millville corehole was intended to target these deeper aquifers in Cumberland County.

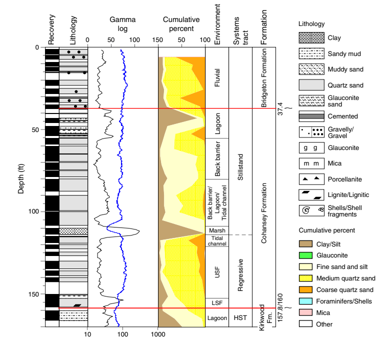
OPERATIONS

Drilling at Millville, New Jersey, at the Bridgeton Pike Well Complex (39°24′16.67″N, 75°05′19.99″W; elevation = 89.7 ft [27.16 m]; Millville quadrangle, Cumberland County) (Fig. F1) began in May 2002. Drilling operations were superintended by Gene Cobbs, USGS EESPT (Don Queen, Drilling Coordinator); Gene Cobbs III was the driller, and Brad A. Huffman was the assistant driller. On 2 May, the EESPT drillers arrived on site and began rigging up and connecting electrical and water hookups. On 2 May, James Browning and Peter Sugarman moved equipment on site and set up a field laboratory in a trailer. A Kodak DC260 digital zoom camera (38.4–115.2 mm lens; 1536 × 1024 megapixel resolution), Macintosh G4, and photography stand were set up to photograph 2-ft (0.61 m) core segments. Camera default settings (including flash) with wide angle (38.4 mm) were used, following procedures established at the Ocean View, New Jersey, drill site (Chap. 2, this volume).

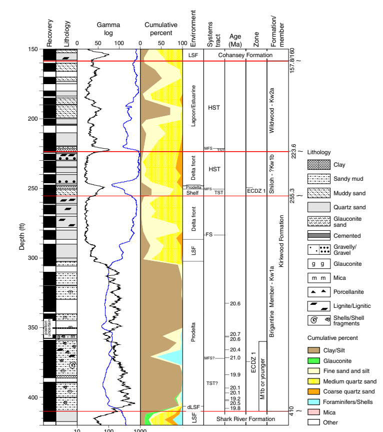
All cores were measured in feet (all depths are given in feet below land surface), and all operations are described in feet only. We continued to adopt ODP convention of top-justifying depths for intervals with incomplete recovery for all field notes and photographs.

The first core was obtained on 4 May 2002 using a Christensen 94-mm (HQ) system. We initially used a CME 4.5-in bit but switched on the second day of drilling to a Christensen 4.25-in bit. For unconsolidated sands, an extended ("snout") shoe was used to contact the sample 1.5–2.5 in ahead of the bit; core diameter was 2.4 in with a rock shoe

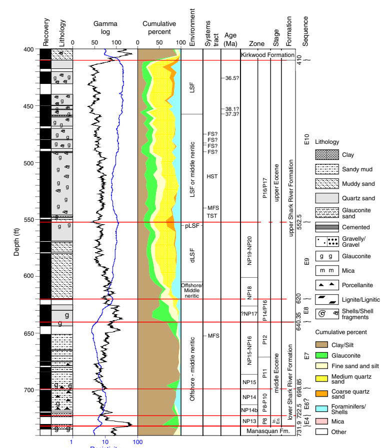
F2. Bridgeton and Cohansey stratigraphic section, p. 57.



F3. Wildwood, Brigantine, and Shiloh Marl stratigraphic section, p. 58.



F4. Shark River stratigraphic section, p. 59.



and 2.1 in with the snout shoe. Approximately 1.5 ft (0.46 m) of large-diameter (10 in) surface casing was set; the large diameter was designed to catch cuttings from reaming a 5-in hole for casing.

Coring commenced on 4 May; the top 1.5 ft (0.46 m) was drilled but not cored. The first four cores (13.5 ft; 4.11 m) between 1.5 and 15 ft (0.46 and 4.57 m; recovery = 76%) were rapidly recovered. The first three cores penetrated sand and gravel from the Bridgeton Formation; from 7.4 to 15.5 ft (2.26 to 4.72 m) the core was mostly coarse to very coarse sand and gravel. At 15 ft (4.57 m), run 5 was cut short (15–15.5 ft; 4.57–4.72 m) because the outer core barrel was clogged with sand. Run 6 was drilled to 20 ft (6.10 m), but only 0.4 ft (1.12 m) was recovered (15.5–15.9 ft; 4.72–4.85 m); the remaining material was washed away. The drillers had trouble with the new experimental (CME 4.5 in) drill bit. The water grooves on the inside of the bit are not deep enough to allow sand to wash through it easily. The bit becomes clogged in the coarse sands encountered at the top of the hole, preventing good recovery. The landing ring wore out, allowing the quad latch to slip through. The drillers halted for the day after run 9 (30–31 ft; 9.14–9.45 m) to replace the landing ring. The day ended with 18.4 ft (5.61 m) recovered from a 29.5-ft run (8.99 m; recovery = 62.4%).

On 5 May, we drilled to 100 ft (30.48 m); 54.85 ft (16.72 m) of core was obtained from 69 ft (21.03 m; recovery = 79.5%) and drilled under ideal weather conditions. We used the new drill bit in the morning, but it continued to block up. At noon, we switched to a 4.25-in Christensen bit and the footage drilled and recovery dramatically improved.

On 6 May, smooth coring continued on run 23 (100–110 ft; 30.48–33.53 m) in interbedded sands and clays. A clay bed was penetrated at 110–113.9 ft (33.53–34.72 m), though sands reappeared at 115.3 ft (35.14 m). We decided not to set casing in this clay but to wait for clays predicted in the lower part of the Wildwood Member of the Kirkwood Formation. Runs were shortened on runs 24–29 (110–140 ft; 33.53–42.67 m) because the core barrel was filled with sand, preventing advancement. Recovery on these runs is greater than computed because the loose sands compress easily. The section became siltier at 150.8 ft (45.96 m), allowing 10-ft (3.05 m) runs with good recovery (runs 31–32, 150–170 ft; 45.72–51.82 m). Recovery was moderate on run 33 (170–180 ft; 51.82–54.86 m) because clay plugged the barrel and the soft sands below were washed away. The day ended at 180 ft (54.86 m), with 50.55 ft recovered (15.41 m; recovery = 63.2%).

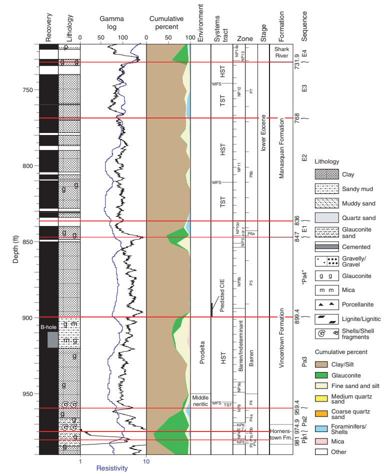
On 7 May, no problems were encountered on runs 34–37 (180–204 ft; 54.86–62.18 m). During run 38 (204–210 ft; 62.18–64.01 m), we encountered a lithified zone 0.8 ft (0.24 m) into the run and the rest of the run (204.8–210 ft; 62.42–64.01 m) was lost. Smooth drilling was encountered the rest of the day. We ended at 240 ft (73.15 m) in a coarse sand (upper Atlantic City 800-foot sand aquifer). Recovery for the day was 48.15 ft (14.68 m) from 60 ft drilled (18.29 m; recovery = 80.25%).

On Wednesday, 8 May, we cored 70 ft (21.34 m) with very good recovery (56.85 ft; 17.33 m; recovery = 81.21%) through fine to coarse sands and silty very fine sands. We ended at 310 ft (94.49 m) in clay; the contact of the sand above with the stiff clay below was well preserved at 302.4–303.7 ft (92.17–92.57 m).

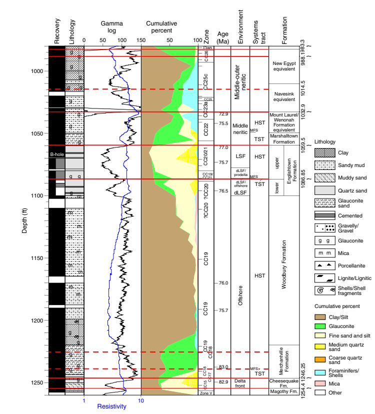
On Thursday, 9 May, run 52 (310–320 ft; 94.49–97.54 m) was drilled into clay (9.5 ft [2.90 m] recovered) to check its continuity for casing. The rods were pulled in anticipation of logging and casing.

P. McLaughlin (DGS) obtained downhole and uphole logs to 315 ft (96.01 m) using the DGS Century Geophysical Corporation drawworks

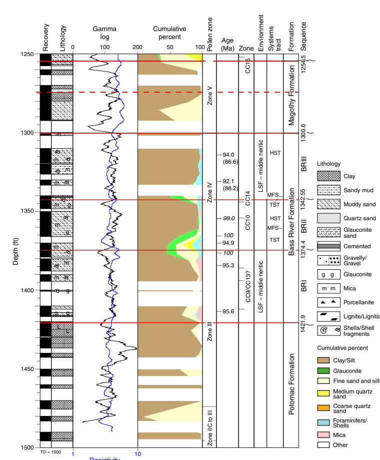
F5. Manasquan, Vincentown, and Hornerstown stratigraphic section, p. 60.



F6. New Egypt, Navesink, Mount Laurel, etc. stratigraphic section, p. 61.



F7. Magothy, Bass River, and Potomac stratigraphic section, p. 62.



and gamma-multipoint electric logging tool (model 8044A). The tool records a gamma log and suite of electric logs, including spontaneous potential (SP), short normal resistivity (16N), long normal resistivity (64N), point resistivity, and lateral resistivity. The downhole log was not useful because of electrical noise from the adjacent pump house and aerator unit. For the uphole log, electrical noise was significantly reduced by using a generator instead of the local electric and by having the drillers fill the hole all the way to the top with water/mud and placing the ground electrode at the mouth of the hole. The only evidence of electrical noise on the up-run log is a resistivity spike around 50 ft (15.24 m); it is possible that the spike around 90 ft (27.43 m) is also noise.

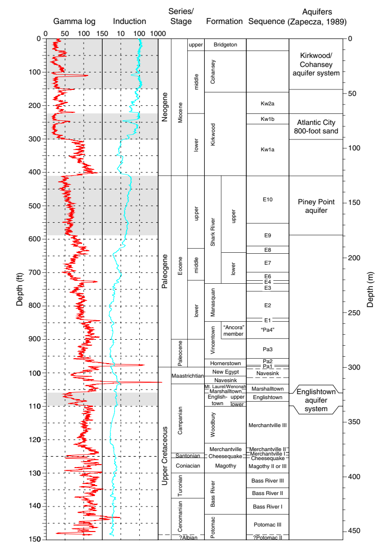
From 10 to 12 May, the hole was reamed twice with a $7\frac{7}{8}$-in tricone bit, and 5-in (12.7 cm) polyvinyl chloride (PVC) (schedule 80) casing was set to 308 ft (93.88 m) to be removed upon completion. No problems were encountered in setting casing.

Coring resumed on 13 May. Runs 53 and 54 (320–340 ft; 97.54–103.63 m) recovered 9.95 and 8.5 ft (3.03 and 2.59 m), respectively. No core was initially recovered on run 55 (340–350 ft; 103.63–106.68 m). We went down two more times to recover the lost core; only 0.4 ft (0.12 m) was recovered. During run 56 (350–355 ft; 106.68–108.20 m), we drilled 5 ft (1.52 m), again with poor recovery (0.4 ft; 0.12 m). We pulled the rods. With core recovered the next day from 340 to 350 ft (103.63–106.68 m), we recovered 19.25 ft (5.87 m) from 35 ft drilled (10.67 m; recovery = 55%).

On 14 May, the drillers recovered 3.3 ft (1.01 m) that had lodged itself in the outer core barrel. This solid core probably came from 340–350 ft (103.63–106.68 m) and is designated Core 56A. The 0.5-ft (0.15 m) core from 340.0–340.5 ft (103.63–103.78 m) may have blocked the barrel; the core was left sticking out of the bottom of hole (BOH) and was pushed aside during run 56 (350–355 ft; 106.68–108.20 m). Alternatively, the core may have come from 350.5–355 ft (106.68–108.20 m). The next run (run 57: 355–359 ft; 108.20–109.42 m) on 14 May recovered 3.1 ft (0.94 m) of core; the very top to 0.2 ft (0.06 m) is a solid glauconitic clay that may be out of place (?overturned), whereas the subsequent 0.2–0.7 ft (6–21 cm) is slurry underlain by a slightly micaceous shelly silty clay (355.7–358.1 ft; 108.42–109.15 m). This suggests that we missed a sequence boundary between the glauconitic clay and the silty clay. Smooth coring with over 100% recovery in expanding silty clays continued during runs 58–59 (359–379 ft; 109.42–115.52 m). Only 7 ft (2.13 m) was recovered during run 60 (379–389 ft; 115.52–118.57 m) as a tight, waxy clay hindered recovery. The lost clay was chewed up and injected into the top 0.3 ft (0.09 m) of the next core (389–400 ft; 118.57–121.92 m). During this run, clays interbedded with silty clays resulted in changes from high (400 lb) to moderate (200 lb) mud pressures during the first 7–8 ft (2.13–2.44 m) of the run, which caused a thick rind; the bottom 3–4 ft (0.91–1.22 m) had uniform pressures (200 lb) and no rinds as we penetrated silty clays. Smooth coring continued during the last two runs (runs 62–63: 400–420 ft; 121.92–128.02 m), even though we penetrated various clay and sand lithologies. Recovery for the day was 59 ft (17.98 m) from 65 ft drilled (19.81 m; recovery = 91%).

On 15 May, 10.1 ft (3.08 m) was recovered during run 64 (420–430 ft; 128.02–131.06 m). During run 65 (430–440 ft; 131.06–134.11 m), the core barrel came up empty and the drillers found the teeth had broken off the shoe. The drillers went back down to try and catch the core

F8. Lithologic units and aquifers correlation, p. 63.



again; they recovered only 0.6 ft (0.18 m). Good recovery resumed between 440 and 490 ft (134.11 and 149.35 m) during runs 66–70. Drilling ended for the day at 490 ft (149.35 m) with 55.25 ft (16.84 m) recovered from 70 ft drilled (21.34 m; recovery = 79%).

On 16 May, smooth coring continued in clayey glauconitic quartz sands, with full recovery during runs 71–75 (490–540 ft; 149.35–164.59 m). During run 76 (540–550 ft; 164.59–167.64 m), we chewed up the bottom 1.5 ft (0.46 m) and discarded 0.3 ft (0.09 m) of chewed core from the top of this run, yielding 8.3 ft (2.53 m) of recovery. The next core was stopped 5 ft (1.52 m) into the run, as the lithology appeared to change to coarser sands that we wanted to avoid blowing away; 4.9 ft (1.49 m) was recovered. Run 78 (555–556 ft; 169.16–169.47 m) recovered 5.8 ft (1.77 m) of solid core; we have no explanation for this over-recovery in the sands except expansion. The last run (run 79: 560–570 ft; 170.69–173.74 m) recovered 8.9 ft (2.71 m). The day ended with 81.2 ft (24.75 m) recovered from 80 ft drilled (24.38 m; recovery = 101.5%).

During the morning of 17 May, drilling continued smoothly through glauconitic quartz sand (runs 80–82: 570–600 ft; 173.74–182.88 m). Mud pressures increased in the lower 3 ft (0.91 m) of run 83 (600–610 ft; 182.88–185.93 m). Gravel or hard material was encountered but not recovered in the bottom part of run 84 (610–620 ft; 185.93–188.98 m). During Run 85, the driller sensed recovery problems and stopped after 5 ft (1.52 m [620–625 ft; 188.98–190.50 m]). Only 0.5 ft (0.15 m) was recovered. The hard silty sand lithology caused the end of the shoe to flare out. Run 86 drilled the next 5 ft (1.52 m [625–630 ft; 190.50–192.02 m]) with excellent recovery, and two subsequent core runs (87 and 88: 630–640 and 640–650 ft; 192.02–195.07 and 195.07–198.12 m, respectively) went smoothly overall, with the exception of high (700 psi) mud pressure in the upper part of run 87. Out of 80 ft (24.38 m) drilled for the day, 69.8 ft was recovered (21.28 m; recovery = 87%).

On 18 May, rainy and very windy weather hindered operations. The rain cleared by noon, though cold and windy conditions prevailed. The drill crew began by running back 40 ft (12.12 m) of rods they pulled the previous day. This shaved the hole and helped prevent the inner core barrel from sticking in the hole. An empty core barrel was retrieved on the third try; effectively 1 ft (0.30 m) was drilled from 650 to 651 ft (198.12 to 198.42 m). Runs 90 (651–657.5 ft; 198.42–200.41 m) and 91 (657.5–665 ft; 200.41–202.69 m) recovered 6.5 and 7.2 ft (1.98 and 2.19 m), respectively. The day ended with 5.45 ft (1.66 m) recovered from a 5-ft run (1.52 m [665–670 ft; 202.69–204.22 m]), yielding 19.15 ft (5.84 m) recovered from 20 ft (6.10 m) drilled for the day (recovery = 96%).

On 19 May, drilling slowed because of the semilithified nature of the Shark River Formation. Recovery was good between 670 and 675 ft (204.22 and 205.74 m) during run 93, although drilling was slow. From 675 to 680 ft (205.74 to 207.26 m), drilling was still slow; 3.3 ft (1.01 m) was recovered; and the lower part of the core was lithified (porcellanite?). There was excellent recovery during run 95 (680–684 ft; 207.26–208.48 m; 3.7 ft [1.13 m] recovered), although drilling was difficult because of changing lithologies from silt to clay and variable degrees of consolidation of the sediment. The core was chewed between 684 and 694 ft (208.48 and 211.53 m), although recovery was 10.1 ft (3.08 m). Runs 97–99 (694–720 ft; 211.53–219.46 m) recovered 5.0, 10.7, and 9.85 ft (1.52, 3.26, and 3.00 m), respectively. The day ended with 47.35 ft (14.43 m) recovered from 50 ft drilled (15.24 m; recovery = 94.7%).

On 20 May, run 100 (720–730 ft; 219.46 m) had poor recovery because of porcellanite beds; 3.4 ft (1.04 m) was recovered. Run 101 (730–

740 ft; 222.50–225.55 m) recovered 4.25 ft (1.30 m); the lower part of the core apparently slipped out of the core catcher. Run 102 was a 5-ft (1.52 m) run from 740 to 745 ft (225.55 to 227.08 m), with 5.8 ft (1.77 m) recovered; the extra 0.8 ft (0.24 m) recovered was placed between 739.2 and 740 ft (225.31 and 225.55 m). Run 103 (745–754 ft; 227.08–229.82 m) was stopped at 9 ft (2.74 m). Run 104 (754–760 ft; 229.82–231.65 m) was 6 ft (1.83 m) to even out the run depths, recovering 5.4 ft (1.65 m). Run 105 (760–770 ft; 231.65–234.70 m) recovered 9.8 ft (2.99 m) of core. For the day, 37.95 ft (11.57 m) was recovered from 50 ft drilled (15.24 m; recovery = 76%).

On the morning of 21 May, the rods were stuck in the hole and it took the drillers 3 hr to loosen them. Coring the Manasquan Formation was slow. The first core (run 106) was up at 1130 hr. During run 107 (780–790 ft; 237.74–240.79 m), the core slipped out of the inner core barrel while it was being pulled. The drillers went back down after the core and were able to retrieve 6.95 ft (2.12 m). Runs 108 (790–797.5 ft; 240.79–243.08 m) and 109 (797.5–803 ft; 243.08–244.75 m) recovered 8 and 4.5 ft (2.44 and 1.37 m), respectively; the former probably includes ~0.5 ft (0.15 m) from the previous run. Out of 33 ft (10.06 m) drilled, 27.1 ft (8.26 m) was recovered (recovery = 82%). The drillers pulled 160 ft (48.77 m) of rods for the night.

One 22 May, the rods barely turned; we ran the inner core barrel and lowered 160 ft (48.77 m) to prepare for coring. Run 110 (803–806 ft; 244.75–24.38 m) recovered 7 ft (2.13 m) of slurry, 2 ft (0.61 m) of mixed core and slurry that was discarded, and 1.25 ft (0.38 m) of apparently solid core. We discussed whether the top 1.0 ft (0.30 m) of this 1.25-ft (0.38 m) segment was solid or intruded by mud because it appeared different from the tight clays at the base (bottom 0.25 ft; 8 cm) of the run. Careful slicing of the core shows it to be a solid core. During run 111 (806–810 ft; 245.67–246.89 m), we left 3 ft (0.91 m) of core in the hole. During run 112 (810–816 ft; 246.89–248.72 m), the barrel filled 6 ft (1.83 m) into the run; the core contained 7.2 ft (2.19 m) of solid core and 3 ft (0.91 m) of ground-up core that was discarded. There was a natural break in the core at 1.8 ft (0.55 m); this was added to run 111 and the rest (5.4 ft; 1.65 m) to run 112. The heavy rind washed easily off of the core, revealing a laminated to massive foraminiferal clay. Personnel from the USGS Water Resources Division sampled from 810.0 to 811.0 ft (246.89 to 247.19 m) (two samples, 0.7 ft [0.21 m] for pore squeezing and 0.3 ft [0.09 m] for microbiology). During run 113 (816–820 ft; 248.72–249.94 m), we recovered 5.2 ft (1.58 m) of core. The total recovery from runs 111–113 (806–820 ft; 245.67–249.94 m) was thus 13 ft (3.96 m), and the core depths should probably be recomputed for high-resolution studies assuming near total recovery for this interval. Run 114 (820–830 ft; 249.94–252.98 m) recovered 8.15 ft (2.48 m), but run 115 (830–840 ft; 252.98–256.03 m) only recovered 0.5 ft (0.15 m), ending the day with 23.30 ft (7.10 m) recovered from 37 ft drilled (11.28 m; recovery = 62.97%). We lost circulation at the end of run 115. The drillers swabbed the hole at the end of the run by pulling up and lowering the rods 5 ft (1.52 m); on the first swab, pressure ran very high, suggesting that we recut/blew away the core that had either slipped out or not broken off. The drillers pulled 200 ft (60.96 m) off the bottom for the night to avoid getting stuck in the swelling Manasquan clays.

On 23 May, we recovered 3.9 ft (1.19 m) of core from the previous day; it was chewed up in sections. We placed this core in the interval from 831 to 834.9 ft (253.29 to 254.48 m), although we are unsure of its precise location. Drilling became easier during the next few runs with excellent recovery as we penetrated the Vincentown Formation clays. The day ended at 890 ft (271.27 m), with 50.1 ft (15.27 m) recovered (recovery = 100%). The drillers pulled up 160 ft (48.77 m) overnight to avoid being trapped by the swelling Manasquan clays.

On 24 May, the drillers had great difficulty getting to the BOH. Swelling clay in the upper part of the Vincentown Formation equivalent prevented hole entry beginning at 847 ft (258.17 m); we recut the hole with difficulty, particularly near 870 ft (265.18 m). This is this same lithologic interval that caused diversion of the rods at Ancora, New Jersey, at 543 ft (165.51 m) causing us to start coring Hole B there. We were concerned that we had to penetrate below these clays into the glauconitic quartzose sandy clays of the lower part of the Vincentown equivalent before reaming the hole. We reached the BOH at 1130 hr and pulled the inner core barrel. It was filled with slurry and 3.95 ft (1.20 m) of solid core obtained somewhere between 847 and 890 ft (258.17 and 271.27 m). This was saved for demonstration/classroom studies. The bottom 0.2 ft (0.06 m) probably came from the BOH; it contained a solid clay similar to the lithology from the last run. Drilling was faster (20 min) during run 121 (890–900 ft; 271.27–274.32 m) and we had full recovery (10.65 ft; 3.25 m), though we had to remove a thick rind from clays above 899.25 ft (274.09 m). We penetrated glauconitic clays at the base of the run that lacked the rind. Smooth, moderately slow drilling during runs 122 (900–910 ft; 274.32–277.37 m) and 123 (910–920 ft; 277.37–280.42 m) recovered 10.5 and 10.3 ft (3.20 and 3.14 m), respectively, in glauconitic clays, yielding 31.45 ft (9.59 m) recovered from 30 ft (9.14 m) drilled for the day (recovery = 105%).

The drillers went to Reston, Virginia, on Saturday and returned on Sunday. They reamed the hole using a $4^3/_4$-in diameter tricone roller bit to alleviate swelling of the clays in the lower Shark River, Manasquan, and Vincentown Formations. At ~880 ft (268.22 m), we started drilling a new hole as the swelling clays diverted the rods as they did at Ancora. The hole was drilled without coring down to 908 ft (276.76 m). Runs 124 (908–910 ft; 276.76–277.37 m) and 125 (910–920 ft; 277.37–280.42 m) contained 2.6 and 10.25 ft (0.79 and 3.12 m) of solid core, respectively. Therefore, we double-cored the interval from 908 to 920 ft (276.76 to 280.42 m). The second cores from this interval were marked with "B" to distinguish them from the original 908–920 ft (276.76–280.42 m). Coring was excellent for the day. We ended at 937.7 ft (285.81 m). For the day, 30.95 ft (9.43 m) was recovered from 29.5 ft drilled (8.99 m; recovery = 105%).

On 30 May, we cored 2.5 ft (0.76 m) during run 128 (937.5–940 ft; 285.75–286.51 m), resuming 10-ft (3.05 m) cores during run 129 with full recovery. Run 130 (950–957.5 ft; 289.56–291.85 m) was pulled up short because slurry filled the top 2.5 ft (0.76 m) of the barrel. Run 131 finished the rod to 960 ft (292.61 m) with full recovery. Run 132 (960–970 ft; 292.61–295.66 m) also had full recovery. We ended at 980 ft (298.70 m) with 42.5 ft (12.95 m) recovered from 42.5 ft drilled (12.95 m; recovery = 100%).

On 31 May, run 134 (980–985 ft; 298.70–300.23 m) recovered 5.2 ft (1.58 m) that includes the K/P boundary. Run 135 (985–995 ft; 300.23–303.28 m) recovered 10.4 ft (3.17 m). A 5-ft (1.52 m) run finished the rod from 995 to 1000 ft (303.28 to 304.80 m), with 4.7 ft (1.43 m) of recovery. The next run from 1000 to 1010 ft (304.80 to 307.85 m) had excellent recovery of 10.2 ft (3.11 m). On the final run of the day, from 1010 to 1020 ft (307.85 to 310.90 m), 5.1 ft (1.55 m) was recovered. We recovered 36.9 ft (11.25 m) from 40 ft drilled (12.19 m; recovery = 92.3%) for the day.

On 1 June, the drillers recored the bottom of the last run from the previous day and recovered an additional 1.3 ft (run 138A; 0.40 m). This makes a total recovery of 36.9 ft (11.25 m) for the 40-ft (12.19 m) interval between 980 and 1020 (298.70 and 310.90 m), or 92.25% recovery. The five subsequent runs made on 1 June all went smoothly and had excellent recovery. Run 139 recovered 9.1 ft (2.77 m) from the 1020 to 1030 ft (310.90 to 313.94 m) interval. Run 140 encountered harder drilling during the run and recovered 10.2 ft (3.11 m) from 1030 to 1040 ft (313.94 to 316.99 m). Runs 141 (1040–1050 ft; 316.99–320.04 m) and 142 (1050–1060 ft; 320.04–323.09 m) recovered 9.9 ft and 10.1 ft (3.02 m and 3.08 m), respectively. Run 143, the final run of the day, from 1060 to 1070 ft (323.09 to 326.14 m) was drilled quickly. The day ended with 48.9 ft (14.90 m) recovered of 50.0 ft drilled (15.24 m; recovery = 97.8%).

No problems were encountered on 2 June, the last day of drilling with HQ core. The day ended with 29.05 ft (8.85 m) recovered of 30 ft (9.14 m) drilled (recovery = 97%). Of 1100 ft (335.28 m) of HQ cored, we recovered 951.35 ft (289.97 m; recovery = 86%). The rods were pulled in anticipation of logging on 4 June.

On 4 June, P. McLaughlin (DGS) obtained a series of open-hole geophysical logs using the DGS Century Geophysical Corporation drawworks and logging tools. The gamma-multipoint electric logging tool (model 8044A) was run seven times in attempts to reduce major problems with electrical interference on the electric logs related to power lines and equipment at the water treatment facility; none of the runs were entirely satisfactory. The deepest of the runs reached 928 ft (282.85 m) depth. The electric logging was followed by two runs (down and up) of the gamma-induction tool to 925 ft (281.94 m) depth. The magnetic-induction sensors allowed calculation of a resistivity log that was not affected by electrical interference as were the logs obtained with the electrical resistivity tool.

The drillers returned to Reston, Virginia, loaded pipe onto the trailer, and returned to New Jersey on Saturday, 8 June. Coring resumed using a Christensen CNWL (NQ) system that produces a 3.162 in (8.03 cm) hole diameter and cuts 1.875-in (4.76 cm) diameter cores with a rock shoe and 1.67-in in (4.24 cm) diameter cores with an extended shoe. The hole was blocked by swelling clays of the Manasquan and Vincentown Formations beginning at 800 ft (243.84 m). We pulled the rods and rereamed the hole with a 4$^3/_4$-in diameter tricone roller bit. The drillers began to rerun the rods on 12 June. On 13 June, we began to recore the bottom 50 ft (15.24 m) of the hole into which material had caved. At 1070 ft (326.14 m), the drillers realized that the bit had started a new hole. The three runs from 1070 to 1100 ft (326.14 to 335.28 m) cored in this new hole are referred to Hole B. Heavy rains started at 1515 hr, and the drillers decided to quit for the day because we were to 1100 ft (335.28 m), the equivalent of the base of the HQ hole. We ended with 18.6 ft (5.67 m) recovered from the 30 ft (9.14 m) cored again (recovery = 62%).

Swelling kaolinitic clays in the Paleocene/Eocene (P/E) boundary interval at 880 ft (268.22 m) proved to be the bane of maintaining a stable, open hole. Despite having reamed these clays with a 4$^3/_4$-in diameter tricone roller bit over the Memorial Day weekend, by 12 June the diameter of the hole had become narrower than the NQ rods (2.875 in). These clays may have been responsible for problems at Bass River and not the caving sands. We discussed two options for future drilling through the P/E boundary: (1) using larger casing at the top so we could use a larger reaming bit and (2) casing off the clays.

Normal coring operations in a stable hole continued in the NQ hole on 14 June. Run 150 (1100–1110 ft; 335.28–338.33 m) only recovered 2.1 ft (0.64 m), as a pyrite nodule blocked the shoe, and soft silty clays below were blown away. Smooth coring on runs 151 and 152 (1110–1130 ft; 338.33–344.42 m) provided full recovery. Heavy rain delayed operations 1 hr. On the next run, the core barrel would not go down the hole; we suspected that one rod may have been bent. We switched core barrels and got the inner barrel to latch in. As we were preparing to add rod to resume drilling, we found that the rods would not turn. We circulated mud and freed the rods and had full recovery on run 153 (1130–1140 ft; 344.42–347.47 m). We ended the day with 32.5 ft (9.91 m) recovered from 40 ft drilled (12.19 m; recovery = 81%).

On 15 June, 102% was recovered on run 154 (1140–1150 ft; 347.47–350.52 m). Run 155 (1150–1160 ft; 350.52–353.57 m) also had perfect recovery of 104%. Run 156 (1160–1170 ft; 353.57–356.62 m) recovered 4.7 ft (1.43 m). The core dropped out of the inner barrel, and we were unable to recover it. On runs 157 (1170–1180 ft; 356.62–359.66 m) and 158 (1180–1190 ft; 359.66–362.71 m), 10.25 and 7.6 ft (3.12 and 2.32 m) of core was recovered, respectively. Recovery for the day was 43.15 ft (13.15 m) from 50 ft drilled (15.24 m; recovery = 86%).

The first two cores on 16 June (1190–1210 ft; 362.71–368.81 m) came up without incident. After drilling run 161 (1210–1220 ft; 368.81–371.86 m), clays behind the quad latch prevented the drillers from retrieving the inner core barrel. Additional mud circulation eventually cleaned the quad latch, allowing drilling to continue. No further difficulties were encountered. The day ended with 51.9 ft (15.82 m) recovered from 50 ft drilled (15.24 m; recovery = 104%).

On 17 June, we began with a 5-ft (1.52 m) run from 1240 to 1245 ft (377.95 to 379.48 m), of which 4.6 ft (1.40 m) was recovered. During run 165 (1245–1250 ft; 379.48–381.00 m), we recovered 5.9 ft (1.80 m); some of this interval is probably material missed above. Run 166 (1250–1260 ft; 381.00–384.05 m) had 7.9 ft (2.41 m) of recovery and ended in clay. Run 167 (1260–1270 ft; 384.05–387.10 m) recovered 3.2 ft (0.98 m) of core. There was a problem dropping the core barrel down on the next run. Run 168 (1270–1280 ft; 387.10–390.14 m) recovered 10.4 ft (3.17 m). The day ended with 32 ft (9.75 m) recovered from 40 ft drilled (12.19 m; recovery = 80%).

On 18 June, runs 169 and 170 (1280–1292 ft; 390.14–393.80 m) had to be cut short because of hard layers. Run 171 (1292–1300 ft; 393.80–396.24 m) recovered only 0.2 ft (0.06 m) of indurated sand because the hard layer broke the shoe. The drillers believe the material that was not recovered under the indurated layer was sand. Run 172 recovered only 1.7 ft (0.52 m) from a 10-ft (3.05 m) run (1300–1310 ft; 396.24–399.29 m). The drillers were not sure that the inner core barrel latched in properly. The drillers had to cut off ~300 ft (91.44 m) of frayed cable before starting the next run. Run 173 (1310–1318.5 ft; 399.29–401.88 m) was cut short at a shell layer. The day ended with 22.65 ft (6.90 m) recovered from 38.5 ft drilled (11.73 m; recovery = 58.8%).

On 19 June, run 174 finished the rod with 1.2 ft (0.37 m) recovered from 1.5 ft (0.46 m) drilled. Run 175 (1320–1330 ft; 402.34–405.38 m) recovered 6.15 ft (1.87 m) with high, variable mud pressures (up to 1000 psi); the core cleaned well, though some interbeds still had minor intrusions of drilling mud. Shells hindered recovery during run 176

(1330–1340 ft; 405.38–408.43 m), with high, variable pressures, blowing away the bottom 6.7 ft (2.04 m). Hard drilling during run 177 (1340–1350 ft; 408.43–411.48 m) yielded 8.1 ft (2.47 m) of recovery. Run 178 (1350–1360 ft; 411.48–414.53 m) yielded 10.55 ft (3.22 m), for a total recovery for the day of 29.25 ft (8.92 m) from 41.5 ft drilled (12.65 m; recovery = 70%).

On 20 June, run 179 (1360–1365 ft; 414.53–416.05 m) slipped out of the inner core barrel as the drillers were retrieving it. They drilled 5 more ft (1.52 m; 1365–1370 ft; 416.05–417.58 m) and brought up both cores together. This is logged as a single run (run 179; 1360–1370 ft; 414.53–417.58 m). Runs 180 (1370–1380 ft; 417.58–420.62 m) and 181 (1380–1390 ft; 420.62–423.67 m) recovered 9 ft and 7.75 ft (2.74 and 2.36 m), respectively. Run 182 (1390–1400 ft; 423.67–426.72 m) recovered 4.4 ft (1.34 m) after hitting a siltstone. The day ended with 27.1 ft (8.26 m) recovered from 40 ft drilled (12.19 m; recovery = 67.8%).

On 21 June, the rods were stuck and several hours were spent freeing them. During run 183 (1400–1410 ft; 426.72–429.77 m), only 0.65 ft (0.20 m) of 10 ft (3.05 m) was recovered; the recovered lithology was a sandstone that clogged the core barrel. During run 184 (1410–1420 ft; 429.77–432.82 m), 6.8 ft (2.07 m) was recovered. There was a thin siltstone at the bottom of the core that probably clogged the barrel, limiting complete recovery. Run 185 (1420–1430 ft; 432.82–435.86 m) recovered 9.2 ft (2.80 m). Recovery during run 186 (1430–1435 ft; 435.86–437.39 m) was 100%. After the final run, the drillers did not have enough cable on the winch for the overshot device to reach the inner barrel, so they raised the drill bit to ~1400 ft (426.72 m) before sending the overshot down. The day ended with a recovery rate of 54%. The drillers raised the rods 220 ft (67.06 m) at the end of the day in the hope of reducing problems with stuck rods in the morning.

On 22 June, the rods again stuck briefly at the beginning of the day. The drilling was again modified to accommodate the short cable on the winch for the overshot. At the end of each run, the bottom of the drill string was raised to between 1400 and 1420 ft (426.72 and 432.82 m) before sending down the overshot device to retrieve the inner barrel. After retrieving the core, the inner barrel was sent back down, latched in place, and the string lowered from ~1400 to 1420 ft (426.72 to 432.82 m) to BOH to resume drilling. Run 187 (1435–1440 ft; 437.39–438.91 m) started the day with a recovery of 1.65 ft (0.50 m). This set the tone for a day where hard zones in the section created coring problems. Core recovery was often incomplete, and cores were often worn down to a thin, twisted remnant. Run 188 (1440–1450 ft; 438.91–441.96 m) recovered 2.65 ft (0.81 m). Run 189 only ran 2 ft (0.61 m), stopping at 1452 ft (442.57 m) where a hard zone was encountered; it recovered 2.15 ft (0.66 m). Run 190 (1452–1460 ft; 442.57–445.01 m) finished off the rod begun on the previous run, recovering 2.3 ft (0.70 m). The final run of the day, run 191 (1460–1470 ft; 445.01–448.06 m), recovered 2.1 ft (0.64 m) due to the problems created by hard concretions. Total recovery for the day was 10.85 ft (3.31 m) of 30 ft (9.14 m) drilled, for 31% recovery. At the end of the day, 260 ft (79.25 m) of drill string was removed to raise the bottom of the string above sticky clays.

On the morning of 23 June, the drill string was again stuck in the hole. The cuttings indicated that the rods were sticking in the Manasquan Formation. The drillers regained circulation at 0855 hr and got the rods back to the BOH by 1015 hr. The first run came up at 1130 hr. No complications were experienced the rest of the day. The day ended with 14 ft (4.27 m) recovered from 30 ft drilled (9.14 m; recovery =

46.2%), leaving the BOH at the target depth of 1500 ft (457.20 m). The drillers pulled 400 ft (121.92 m) from the BOH overnight.

On 24 June, the rods were run back to 1500 ft (457.20 m); we pumped and rotated, thinning the mud to 8.5 lb for logging. S. Curtin (USGS) and P. McLaughlin (DGS) obtained a series of geophysical logs from the hole using the USGS Annapolis, Maryland, Water Resources Division Century Geophysical Corporation drawworks with USGS and DGS Century Geophysical Corporation logging tools. Gamma logs were obtained to 1491 ft (454.46 m) from inside the drill rods for both downhole and uphole runs using the DGS Century slim-line gamma tool (model 9012A). Following logging, the rods were pulled. When all rods were out of the hole, open-hole logging was conducted using the USGS Geophysical Corporation gamma-multipoint electric logging tool (model 8043A); downhole and uphole runs were made to 1496 ft (455.98 m) depth. The resistivity logs obtained were affected by electrical noise related to power lines and equipment at the water treatment facility, especially on the downhole run (shifts at 410–420 ft [124.94–128.02 m] and 820–840 ft [249.94–256.03 m]). A second suite of openhole logs was obtained with the DGS Century Geophysical Corporation gamma-induction tool; downhole and uphole runs reached 1497 ft (456.29 m) depth. The magnetic-induction sensors allowed calculation of a resistivity log that was not affected by electrical interference as were the logs obtained with the electrical resistivity tool.

On 25 June, the PVC casing was removed and the hole grouted with 22 bags of concrete, plugged, and abandoned. The USGS drillers returned to Reston, Virginia and we bid Gene Cobbs a fond retirement.

Careful comparison among logging runs and matching logging signature to core lithology indicated that there are offsets due to registry problems on the USGS winch. We constructed a composite log consisting of (1) the HQ log taken with the DGS winch shifted down 1 ft (0.30 m) for 0–90 ft (0–27.43 m) and (2) the induction tool log shifted up 4 ft (1.22 m) for 905 ft (275.84 m) to BOH. The logs were spliced just below an increase in the HQ log at ~905 ft (275.84 m).

At Millville, we recovered 1254.85 ft (382.48 m) from a total depth of 1500 ft (457.2 m) drilled and had a recovery of 83.7% for the 1495 ft (455.68 m) cored; median recovery was 90%. Lithologies were described on site and subsequently at the Rutgers University core facility; these descriptions form the basis for the preliminary lithologic descriptions. Cores were cut into 2-ft (0.61 m) sections, labeled at top and bottom of each section, placed into split PVC pipe (3 in diameter), wrapped in plastic sheeting, and stored in 2-ft (0.61 m) NQ wax boxes. A total of 176 core boxes were moved to permanent storage at the Rutgers University core library for further study. Cores were sampled at ~5 ft (1.52 m) intervals for planktonic foraminiferal, calcareous nannofossil, palynology, dinocyst, and diatom biostratigraphy and coarse-fraction lithologic studies at the Rutgers University core library.

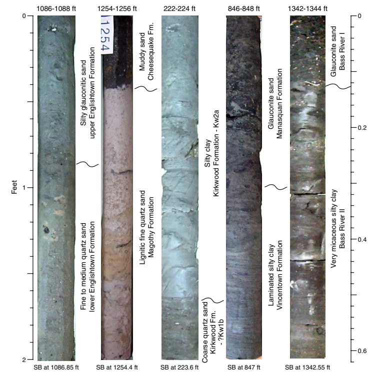
LITHOSTRATIGRAPHY, SEQUENCE STRATIGRAPHY, AND HYDROSTRATIGRAPHY

Summary

The on-site scientific team provided preliminary descriptions of sedimentary textures, structures, colors, fossil content, identification of lithostratigraphic units (NJGS Information Circular 1, 1990), and lithologic contacts (Table T1; Figs. F2, F3, F4, F5, F6, F7). Subsequent studies integrated preliminary descriptions with additional descriptions, biostratigraphy, biofacies studies, isotopic stratigraphy, and geophysical well logs. Unconformities were identified on the basis of physical stratigraphy, including irregular contacts, reworking, bioturbation, major facies changes, gamma ray peaks, and paraconformities inferred from biostratigraphic breaks (Fig. F9). For the nonmarine and nearshore sections (primarily the Miocene and younger section and the Magothy and Potomac Formations), lithofacies interpretations provide the primary means of recognizing unconformities and interpreting paleoenvironments. For the neritic sections (primarily the Paleogene, Santonian–Maastrichtian, and mid-Cenomanian to Turonian sections), biostratigraphic and biofacies studies provide an additional means of recognizing unconformities and the primary means of interpreting paleoenvironments. Recognition of these surfaces allows identification of sequences at the Millville borehole. Benthic foraminiferal biofacies were used to recognize inner (0–30 m), middle (30–100 m), and outer (100–200 m) neritic and upper bathyal (200–600 m) paleodepths.

T1. Core descriptions, p. 68.

F9. Representative sequence boundaries, p. 64.



Cumulative percent plots of the sediments in the cores were computed from samples washed for paleontological analysis (Table T2). Each sample was dried and weighed before washing, and the dry weight was used to compute the percentage of sand. This differs from the method used in previous New Jersey coastal plain cores (Bass River, Island Beach, Atlantic City, and Cape May) in which the samples were not dried before washing.

T2. Data used to construct cumulative percent logs, p. 72.

Bridgeton Formation

Age: ?late Miocene
Interval: top–37.4 ft (11.40 m)

The hole spudded into the top of a plateau that is mapped as a fluvial channel bar in the Bridgeton Formation by Newell et al. (2000), which is assumed to be upper Miocene (Fig. F2). The top 7.4 ft (2.26 m) contained reddish yellow and yellowish brown coarse to very coarse sand with gravel layers. From 7.4 to 15.5 ft (2.26 to 4.72 m), the lithology is a coarse to very coarse sand with occasional granules. The interval from 15.5 to 15.9 ft (4.72 to 4.85 m) is a poorly sorted granuliferous sand, with no recovery from 15.9 to 20 ft (4.85 to 6.10 m). From 20 to 26.8 ft (6.10 to 8.17 m) is thinly interbedded sand and granuliferous sand with feldspar grains that weather to kaolinite; beds are 15–45 mm thick, with alternating yellow silty fine to medium sand and pale brown medium to coarse sand. The section fines slightly downsection. There is a gravel bed from 26.8 to 27.2 ft (8.18 to 8.29 m), and washed residues (Fig. F2) show an increase upsection in coarse sand from this level to the top of the borehole. The interbedded sands and granuliferous sands continue down to 36.7 ft (11.19 m), though the color changes to light gray at 30 ft (9.14 m); the beds are ~1 ft thick. A sandy clay (36.7–37.1 ft; 11.19–11.31 m) overlies a gravelly, clayey sand with weathered feldspar that marks the contact of the Bridgeton Formation with the underlying Cohansey Formation. The environment of deposition of the Bridgeton Formation at Millville is fluvial.

Cohansey Formation

Age: ?late and/or ?middle Miocene

Interval: 37.4–157.8/160.0 ft (11.40–48.10/48.77 m)

The upper part of the Cohansey Formation (Fig. F2) consists of an interlaminated silty clay and clayey sand (37.4–37.65 ft; 11.40–11.48 m), a poorly recovered medium to very coarse sand (40–40.4 ft; 12.19–12.31 m), and a limonitic yellow-brown, thinly interlaminated (1–3 mm) silty fine sand and silty clay (43–55.15 ft; 13.11–16.81 m) with dominant flaser and subordinate lenticular structures. Coring gaps at 37.65–40 and 40.4–43 ft (11.48–12.19 and 12.31–13.11 m) separate these lithologies. The succession from 37.4 to 55.15 ft (11.40 to 16.81 m) was deposited in lagoonal environments. A facies shift at 55.15 ft (16.81 m) to primarily "beachy" sands deposited in back barrier environments is associated with a gamma log kick. From 55.15 to ~80 ft (16.81 to ~24.40 m), the section consists primarily of silty fine to medium sand with scattered mica throughout, scattered reddish (hematitic) clay laminae, silty clay interbeds (66.8–69.0 ft; 20.36–21.03 m), iron staining (75–76.7 and 77.7–78.95 ft; 22.86–23.38 and 23.68–24.06 m), and a gray, slightly more micaceous sand (76.6–77.7 ft; 23.35–23.68 m). The section from 55.15 to ~80 ft (16.81 to ~24.40 m) was deposited in back barrier environments as evidenced by common clay drapes within otherwise clean fine–medium sands, the lack of obvious placers of opaque heavy minerals that are typically found on the shoreface (though opaque heavy minerals are scattered throughout), and poorly preserved root traces.

Below 80 ft (24.4 m), the clay-silt fraction increases slightly as exemplified by higher gamma log values and more poorly sorted and "soupy" sands (Fig. F2). Medium sands increase below 90 ft (27.43 m), with a trace of coarse sand; the facies appear as clayey silty fine–coarse sand that probably reflects disrupted thinly interlaminated sand and clay beds. These more poorly sorted facies are probably also back barrier environments, though they could be lagoonal.

Interbedded clay-sand (100–101.75 ft; 30.48–31.01 m) probably represent tidal channel sands with clay drapes. From 101.75 to 108 ft (31.01 to 32.92 m), the fine–medium sand with scattered clay drapes again represent a back barrier beach. Clay rip-up clasts of the laminae, possible burrows, and circular brown root casts occur from 107 to 108.5 ft (32.61 to 33.07 m). From 108.5 to 110 ft (33.07 to 33.53 m) is a coring gap.

Laminated yellow-brown clays with thin (1–3 mm) silty sand laminae appear at 110 ft (33.53 m); the clays become browner downsection to a sharp contact at 111.35 ft (33.94 m) with very dark gray-black, slightly sandy, organic-rich clay below; the dark clays have fine dispersed plant debris and are interpreted at a marsh deposit.

Yellow-brown clays (114.5–115.3 ft; 34.87–35.14 m) reappear immediately above an indurated zone (Fig. F2). Pebbly granuliferous very coarse sand interpreted as tidal channel deposit grades down by 121 ft (36.88 m) to medium–coarse sand with opaque heavy mineral laminae. Though associated with a distinct gamma log kick and interpreted in the field as a sequence boundary, we interpret the 115.3-ft (35.14 m) surface as a facies change from tidal channel sands below to marsh above. From 121 to 150.7 ft (36.88 to 45.93 m), the section consists of medium-grained, slightly micaceous, distinctly cross bedded sands (with opaque heavy mineral laminae and cross beds up to 20°), with occasional clay rip-up clasts and scattered granules; these sands clearly fit the upper shoreface model of Miller, McLaughlin, Browning, et al. (Chap. 3, this volume). Facies variations within the upper shoreface setting are reflected by the following: 130–130.2 ft (39.62–39.68 m) is slightly clayey sand, 130.2–130.7 ft (39.68–39.84 m) is granule-rich sand with an ironstone cemented base, 136.9 ft (41.73 m) is a granule layer, and 150.7 ft (45.93 m) is a zone of iron-cemented concretions. This surface at 150.7 ft (45.93 m) could be a sequence boundary, although it most likely reflects a facies shift in nearshore environments. Silty, clayey, heavily bioturbated, homogeneous, fine–medium sand with carbonaceous debris from 150.7 to 157.8 ft (45.93 to 48.10 m) represents deposition in lower shoreface environments (deposited below wave base, as evidenced by common fines); the lack of shells is attributed to postdepositional dissolution. These sands develop an oxidized brownish yellow stain reflecting Fe-rich groundwater. A lithology shift across a coring gap (157.8–160 ft; 48.1–48.77 m) to grayer interbedded sand, silt, and clay is associated with a sharp upsection increase in gamma log radiation beginning at 157 ft (47.85 m). We tentatively place a sequence boundary at 157.8 ft (48.10 m) at the contact of the Cohansey Formation above with the interbedded sands and clays of the Kirkwood Formation (Fig. F2). Sediments from 157.6 to 157.8 ft (48.04 to 48.10 m) contain clay blebs and darker organic material that may reflect ripping up of the underlying clays. In summary, the Cohansey Formation at Millville appears to comprise one sequence (37.4–157.8 ft; 11.40–48.10 m) with a regressive lower section (111.35–157.8 ft; 33.94–48.10 m) and a general stillstand upper section (37.4–111.35 ft; 11.40–33.94 m).

The Cohansey Formation forms the upper part of the Kirkwood-Cohansey aquifer system (Zapecza, 1989) (Fig. F2). The lower part of the Cohansey Formation is an excellent aquifer, with medium to very coarse sand concentrated in tidal channels and the upper shoreface from ~100 to 150 ft (30.48 to 45.72 m). Wells screened in this interval have reported yields of up to 1000 gpm (Rooney, 1971).

Kirkwood Formation

Age: early middle to middle Miocene
Interval: 157.8/160.0–407.95 ft (48.01/48.77–124.34 m)

?Kw2a Sequence/Wildwood Member

Age: early to middle Miocene
Interval: 157.8/160.0–223.6 ft (48.01/48.77–68.15 m)

Interbedded sand and clay (160–185.7 ft; 48.77–56.60 m) at the top of the Kirkwood Formation (Fig. F3) consists of

1. Thicker, fine–medium (0.3–1.0 ft [9–30 cm] thick), cross-bedded sand with scattered lignite fragments;
2. Thinner (0.05–0.3 ft; 1.5–9 cm), fine–very fine sands; and
3. Laminated, slightly sandy, silty clay (0.05–0.3 ft; 1.5–9 cm) with scattered lignite.

Subsequent to drilling, the cores developed a thin yellow (sulfur-rich?) and orange (?limonitic) coating, suggesting Fe- and S-rich groundwater (Fig. F3). The section appears to fine downsection to ~170 ft (51.82 m) and then coarsen to 185.7 ft (56.60 m). The environment of deposition is possibly lagoonal, though it could be estuarine.

From 185.7 to 190 ft (56.60 to 57.91 m) is very dark grayish brown, heavily bioturbated, slightly micaceous clayey silty sand to clayey sandy silt with scattered granules and lignite; the environment was probably lagoonal, although mica and carbonaceous material suggest a probable deltaic/riverine influence (in a lower delta plain).

Clayey, sandy, heavily bioturbated silts with thin, lenticular cross-sand laminae (190–200 ft; 57.91–60.96 m) represent a finer-grained lagoonal facies (Fig. F3). A silica-cemented sandstone lens (204–204.1 ft; 62.18–62.21 m) overlies a coarser grained, burrowed, silty clayey sand with scattered granules (204.1–217 ft; 62.21–66.14 m). Gypsum crystals and a brownish coating develop on the core surfaces, indicating the presence of Fe- and Ca-rich (dissolved shells?) groundwater. The section fines down from 217 to 219.6 ft (66.14 to 66.93 m) and returns to silty very fine sand with scattered granules and dispersed plant debris from 220 to 221.4 ft (67.06 to 67.48 m). Possible environments of deposition include lower shoreface or lagoonal; we favor the latter interpretation in view of facies successions. Blue-gray silty clays (221.4–223.6 ft; 67.48–68.15 m) are slightly micaceous and weather with a thick brown rind; these are interpreted as lagoonal, although the low organic content is not consistent with this interpretation. The top of the clay (221.4 ft; 67.48 m) is interpreted as a maximum flooding surface (MFS), and we place a sequence boundary at the base of the clay (223.6 ft; 68.15 m) in association with a distinct gamma ray kick and a facies shift from the clay to delta-front sands below. Below the clay is a varied, 0.5-ft (0.15 m) lithologic interval containing a thin-bedded succession of silty sands, lignite, and clay rip ups similar to the clay above. The sequence from 157.8/160.0 to 223.6 ft (48.10/48.77 to 68.15 m) probably correlates with the Kw2a sequence of Miller et al. (1997). The Kw2a sequence at Millville appears to have been deposited on a delta plain in contrast to the prodelta clays that dominate the Kw2a sequence to the north.

If our correlation of this sequence with the Kw2a is correct, then the Wildwood Member at Millville is a very leaky confining unit separating coarse sands in the overlying Cohansey Formation from coarse sands in the underlying Shiloh Member (the "Atlantic City 800-foot sand" aquifer of Zapecza, 1989) (Fig. F3). This contrasts with the Ocean View corehole (Chap. 2, this volume), where the Wildwood Member is thick clay–silt that comprises an effective confining bed (Wildwood-Belleplain confining unit of Sugarman, 2001). The Rio Grande water-bearing zone is not found at Millville.

Kw1b Sequence/Shiloh Member

Age: early Miocene
Interval: 223.6–255.3 ft (68.15–77.82 m)

The interval from 223.6 to 224.0 ft (68.15 to 68.28 m) is a thin-bedded to cross-bedded clayey silty coarse to very coarse sand. From 224.0 to 230 ft (68.28 to 70.10 m) the section is slightly finer, with medium–coarse sand with lignite beds (225.2–225.3, 228.1–228.2 ft; 68.64–68.71, 69.52–69.56 m) and scattered granules (Fig. F3). The section becomes slightly coarser again from 230 to 248 ft (70.10 to 75.59 m), consisting of homogeneous coarse to very coarse sands. There are some thin (3–30 mm) laminae of peaty silty clay between 243 and 247.9 ft (74.07 and 75.56 m). These organic-rich homogeneous sands develop a yellow-brown limonitic rind indicative of Fe-rich groundwater. The sands from 223.6 to 247.9 ft (68.15 to 75.56 m) were deposited in delta-front environments. A burrowed surface at 247.9 ft (75.56 m) separates medium–coarse sand above from laminated, slightly micaceous, slightly lignitic silty clay below. These silty clays develop gypsum and sulfur overgrowths. This surface (247.9 ft; 75.56 m) is a facies change from delta-front sands above (upper highstand systems track [HST]) to prodelta silts and clays (lower HST) below. The laminated prodelta silty clays continue to 250.2 ft (76.26 m). From 250.2 to 250.6 ft (76.26 to 76.38 m), a clay with sandy laminae and sand blebs that appear to be burrows is present; this clay was also deposited in a prodelta environment. There is a facies shift at 250.6 ft (76.38 m) to heavily burrowed silty, clayey fine sands below, deposited in a shelf environment. The sands continue to 255.3 ft (77.82 m) where there is a gamma log increase and a subtle burrowed contact overlying muddy delta-front sands. This contact is a sequence boundary. Identification of *Actinoptychus heliopelta* (East Coast Diatom Zone 1; R. Benson, pers. comm., 2003) at 249.4 ft (76.17 m) suggests correlation of the 223–255.3 ft (67.97–77.82 m) sequence with the Kw1a/b sequence and probably the Kw1b sequence (Fig. F3). These sediments represent a generally shallowing upward succession within a deltaic setting. The sands at the base of the sequence (250.6–255.3 ft; 76.38–77.82 m) are interpreted to be the transgressive systems track (TST) of the sequence. The facies shift at 250.6 ft (76.38 m) represents the MFS, and the prodelta clays and delta-front sands are the HST.

The coarse nature of the sands from 224 to 248 ft (68.28 to 75.59 m) in the Shiloh Member (Kw1b sequence) form a confined aquifer equivalent to the upper sand of the Atlantic City 800-foot sand aquifer (Zapecza, 1989) (Fig. F8). At this site, the leaky confining unit that typically separates the upper and lower sands in the Atlantic City 800-foot sand is ~8 ft (2.44 m) thick (247–255 ft; 75.29–77.724 m) and consists of silty clay, clayey silt, and silty very fine sand.

Kw1a Sequence/Brigantine Member

Age: early Miocene
Interval: 255.3–410 ft (77.82–124.97 m)

Sands from 255.3 to 286.6 ft (77.82 to 87.36 m) can be divided into several distinct delta-front facies:

1. Muddy fine–medium lignitic sands (255.2–258.6 ft; 77.78–78.82 m), showing decreasing mud and gamma log values downsection;
2. Fine–medium lignitic sands (258.6–275 ft; 78.82–83.82 m) that further fine downsection with low gamma log values;
3. Silty lignitic fine sand (275–284 ft; 83.82–86.56 m) with very low gamma log values and small-scale cross bedding highlighted by muddy sand laminae;
4. Micaceous, clayey medium to fine lignitic sand (284–284.4 ft; 86.56–86.69 m); and
5. Coarse sand with scattered granules (284.4–286.6 ft; 86.69–87.36 m).

From 285.7 to 286.6 ft (87.08 to 87.36 m), there are muddy coarse-grained sand beds separated from clean coarse-grained sands. There appears to be a flooding surface at 284.4 ft (86.69 m), with some burrowing and a trace of phosphatic granules present around this surface (Fig. F3).

Below a coring gap (286.6–290 ft; 87.36–88.39 m) the facies change to an interbedded muddy, slightly micaceous medium to fine sand, with silty clay to clayey silt laminae to beds (290–302.4 ft; 88.39–92.17 m). The sand becomes slightly coarser with less mud downsection. We interpret these sediments as lower shoreface deposits, based on heavy bioturbation and the paucity of lignite.

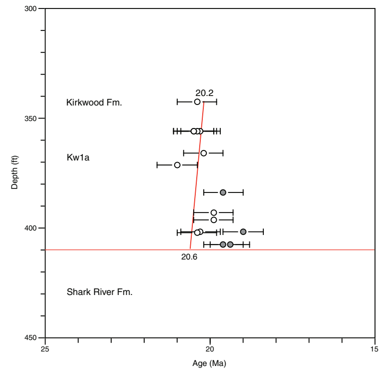
The sand (255.3–290.0 ft; 77.82–88.39 m) at the top of the Brigantine Member (Kw1a sequence) at Millville is equivalent to the lower Atlantic City 800-foot sand aquifer (Zapecza, 1989) (Fig. **F8**). The sand within this aquifer is coarser (medium sands) both in the upper part (255–270 ft; 77.72–82.30 m) and near its base (281.6–290 ft; 85.83–88.39 m). The two upward-fining successions defined by these coarser beds may reflect subaqueous channel deposition.

A granule laminae (2 mm thick) caps a prodelta silty clay succession (302.4–340 ft; 92.17–103.63 m). The top of this succession (302.4–303.3 ft; 92.17–92.45 m) consists of organic-rich interlaminated silty clay to clayey silt with sandy silt and interspersed 0.1–0.5 ft (3–15 cm) thick granule laminae. Sand decreases downsection to 310 ft (94.49 m) as shown by increasing gamma log values; sands are very fine grained and found in lenticular beds with wispy cross-laminations that decrease downsection. Although deposited in prodelta environments, these coarser-grained sediments at the top reflect interfingering with prodelta/nearshore environments. Interlaminated, dark, “chocolate” brown organic-rich silty clays to clayey silts continue down to 340.6 ft (103.81 m). Laminations are generally well preserved, though a moderate number of small burrows are present, especially small vertical burrows (?*Planolites*) from 324.5 to 325.0 ft (98.91 to 99.06 m). Crystals of gypsum are noted on the core, suggesting that carbonate was present but has dissolved. The gamma log suggests several cycles containing coarser-grained sediments at 313, 317, 324, and 335 ft (95.40, 96.62, 98.76, and 102.11 m); these intervals are generally slightly lighter gray and appear to be siltier. Very fine sand to silt laminae occur throughout the section (Fig. **F3**).

A lithologic change occurs at 340.6 ft (103.81 m) from silty clay above to lighter-colored, less distinctly laminated (fewer partings), slightly clayey silt that continues to ~350.4 ft (106.80 m; position uncertain). Burrowed clayey shelly silt appears at 355 ft (108.20 m) below a coring gap and continues down to a contact at 372.1 ft (113.42 m). Below this contact is a facies change to a slightly silty clay with sand laminae. Sr isotopic age estimates between 355 and 410 ft (108.20 and 124.97 m) ranging from 19.2 to 21.0 Ma indicate correlation to the Kw1a sequence of Miller et al. (1997). The top of the shelly zone (372.1 ft; 113.42 m) may mark an MFS or a sequence boundary. We interpret it as an MFS based on the lack of a Sr isotopic break and ages that correlate to the Kw1a sequence above and below (Fig. **F3**). The facies above and below the contact were deposited in a prodelta environment; the sediments below the contact are clayier with more common shells and more bioturbation, suggesting slower sedimentation rates.

Uniform slightly silty to silty, micaceous, laminated dark clay with sparse shells continues below the contact at 372.1 ft (113.42 m) to a sequence boundary at 410 ft (124.97 m), with shells increasing below 400 ft (121.92 m). From 372.1 to 374 ft (113.42 to 114.00 m), the silty clay contains burrows filled with the lighter shelly clayey silt from above. The section is fairly uniform down to 406 ft (123.75 m), where coarse to very coarse quartz sand with reworked, scattered glauconite that increases downsection in these silty clays to a contact at 410 ft (124.97 m) (10% at the top grading down to ~50%) with common granules. Variations in sand content from 408 to 410 ft (124.36 to 124.97 m) yield clear laminae, some of which appear to be inclined (408–410 ft; 124.36–124.97 m). Shell concentrations occur in this section (407.9, 408.15, 408.9, and 409.2 ft; 124.33, 124.40, 124.63, and 124.72 m). The environment from 406 to 410 ft (123.75 to 124.97 m) appears to be distal lower shoreface on a storm-dominated shelf. The section from 372.1 to 410 ft (113.42 to 124.97 m) is interpreted as the TST of the Kw1a sequence (Figs. F3, F10).

F10. Miocene age depth plot, p. 65.



Upper Shark River Formation

Age: late middle to late Eocene
Interval: 410–640.35 ft (124.97–195.18 m)

A distinct sequence boundary at 410 ft (124.97 m) associated with a large gamma log kick separates granuliferous, silty clayey sand above from a shelly, slightly muddy, glauconitic sand below (Fig. F4). This is the contact between the Miocene Kirkwood Formation clays and sands (particularly glauconitic sands) of the upper Shark River Formation. Onsite studies considered that the glauconitic sands might be assigned to the Oligocene Atlantic City or Sewell Point Formations. However, our studies show that these sands are upper Eocene:

1. A Sr isotopic age at 451 ft (137.46 m) is not Oligocene but essentially "dead" (>39 Ma).
2. Nannofossils constrain the section above 626 ft (189.55 m) to upper Eocene Zone NP18 or younger and those above 595.9 ft (180.44 m) to Zones NP19–NP20.
3. The identification of planktonic foraminifer *Turborotalia cerroazulensis* at 451 ft (137.46 m) indicates that the section at this level is upper Eocene to uppermost middle Eocene and not Oligocene (Table T3).

T3. Cenozoic planktonic foraminiferal occurrences, p. 77.

At Millville, upper Eocene glauconitic quartz sands are lithologically similar to the sandy upper Shark River Formation (= Toms River Member of Enright, 1969), which is correlated to Zones NP18 and NP19–NP20 at Millville (Fig. F4). In other New Jersey coreholes, the Shark River Formation is restricted to Zone NP18 and older (i.e., this formation just breaks into the upper Eocene; Browning et al., 1997b). Zone NP19/NP20 sediments at Atlantic City and ACGS#4 (Mays Landing) are clays that stratotypify the upper Eocene Absecon Inlet Formation and comprise sequences E10 and E11 (Browning et al., 1997a). At Millville, however, the NP19–NP20 sands (= sequence E10) are assigned to the upper Shark River Formation (= Toms River Member of Enright, 1969) (Fig. F4). Thus, this formation must be time transgressive.

Below the 410-ft (124.97 m) contact, shells increase in the heavily bioturbated glauconitic shelly silty sands from 410 to 412 ft (124.97 to 125.58 m), with alternating concentrations of shellier and less shelly zones. Shells (mostly fragments <3 mm) compose a significant portion (typically 20%) of the sediments down to 620 ft (188.98 m); there are a few concentrated shell zones (e.g., 447.8 ft; 136.49 m). Glauconite increases downsection from ~10% at ~410 ft (124.97 m) to ~30% below 414 ft (126.19 m); alternations of glauconite-rich and less glauconitic beds continue to 620 ft (188.98 m), varying by ~10%–25%. The sand fraction is dominated by fine- to medium-grained quartz, with scattered coarse and very coarse grains and fine- to very fine grained glauconite varying by ~20%. Rare pyrite is present, and scattered, thin, rusty brown clayey sand laminae are present through the interval. The sediments appear similar to the reworked glauconite sands that comprise the Oligocene in New Jersey, although biostratigraphy clearly indicates that they are older (Fig. **F4**). Zones with less mud (cleaner sands) and concentrations of shell material (447.8–447.9, 448.6–448.7, 450.7–450.9, 451.7–452.8, 453.3–453.7, and 454.6–454.8 ft; 136.49–136.52, 136.73–136.76, 137.37–137.43, 137.68–138.01, 138.17–138.29, and 138.56–138.62 m) become increasingly common down to 457.5 ft (139.45 m). The sands from 407.95 to 457.5 ft (124.34 to 139.45 m) are very porous and friable and comprise the upper part of an aquifer (the term "Piney Point" has been applied to this aquifer by Nemickas and Carswell [1976], although it is best termed the Shark River aquifer). The sands were deposited in an inner neritic environment and probably represent lower shoreface deposits.

Shelly, clayey to slightly clayey, heavily burrowed glauconitic (15%–30%) quartz sands with clayier interbeds are present from 457.5 to 543.9 ft (139.45 to 165.78 m). This section has slightly less shell material, slightly more clay, and slightly more glauconite (typically 25%–30%) than the section above. The lower amounts of shell and higher amounts of clay are expressed by higher gamma log values below 457.5 ft (139.45 m). The section becomes generally clayier downsection, and there are alternations between sandier and clayier zones. Contacts in which the clays overlie the sands are sharp and may be minor flooding surfaces (e.g., 475.1, ~482.7, 484.75 [heavily burrowed], and 490.35 ft [burrowed]; 144.81, ~147.13, 147.75, and 149.46 m) (Fig. **F4**), whereas the shifts back to sands are gradual. Sandier intervals are present from 500 to 505.3 ft (152.4 to 154.02 m), as shown by slightly lower gamma logging values. The section from 510 to 540 ft (155.45 to 164.59 m) is slightly sandier, with clay burrows decreasing, shell increasing, and sand increasing downsection. Below ~540 ft (164.59 m), the section shifts to muddier sand that fines down to a sequence boundary at 552.5 ft (168.40 m; see below). This change from fining to coarsening upsection is interpreted as an MFS at ~540 ft (164.59 m), although there is no distinct kick on the gamma log or obvious surface in the core (Fig. **F4**).

The environment of deposition for the muddy sands from 457.5 to 547.0 ft (139.45 to 166.73 m) is middle neritic (suggested by the heavy bioturbation, predominance of clay, and benthic foraminifers). Benthic foraminifers from 440 to 541 ft (134.11 to 164.90 m) are a moderately diverse assemblage of guttulinids, dentilinids, *Cibicides*, and *Cibicidoides*; the paleodepths are middle neritic (Table **T4**).

T4. Cenozoic benthic foraminiferal occurrences, p. 81.

A very clayey medium glauconitic quartz sand (547.0–547.15 ft; 166.73–166.77 m) fines downsection to interlaminated, bioturbated slightly clayey to very clayey sand (547.15–548.3 ft; 166.77–167.12 m). Medium-grained, very glauconitic (25%–30%), shelly (with abundant weathered fragments), slightly muddy sand with scattered coarse sand to granules (550–552.5 ft; 167.64–168.40 m) overlies a granuliferous unit, and we place a sequence boundary at this facies change (552.3–552.5 ft; 168.34–168.40). The sequence boundary is obscured by extensive bioturbation, though it is apparent on the gamma log (Fig. **F4**). We correlate the sequence from 410 to 552.5 ft (124.97 to 168.40 m) with sequence E10 of Browning et al. (1997a) based on assignment to biozones P16–P17 (see **"Biostratigraphy,"** p. 42).

Coarser-grained, poorly sorted, slightly muddy glauconitic shelly granuliferous medium–very coarse sand (552.5–555.1 ft; 168.40–169.19 m) appears below the sequence boundary. This granuliferous unit was deposited in proximal lower shoreface environments. It fines downsection to muddy, tighter, medium-grained glauconitic quartz sand with scattered chalky shelly fragments and coarse grains (555.1–608 ft; 169.19–185.32 m). This unit contains a few less muddy granuliferous sand beds in the upper part (555.7–556.2, 556.8–557.1, 557.4–557.9, and 558.0–558.1 ft; 169.38–169.53, 169.71–169.80, 169.90–170.05, and 170.08–170.11 m). Shell material increases downsection from ~12% at 570–605 ft (173.74–184.40 m) to >20% at 605 ft (184.40 m). This sandy unit was deposited in distal lower shoreface environments. Clay content increases downsection from 596 to 611 ft (181.66 to 186.23 m). Predominantly sandy clay occurs below ~608 ft (185.32 m), with homogeneous sandy glauconitic shelly silty clay (608–616 ft; 185.32–187.76 m) to very clayey sand (616–620 ft; 187.76–188.98 m) with abundant shell fragments and shells. The section is slightly less silty, more glauconitic, and has slightly larger shell fragments below 619.45 ft (188.81 m). These sandy clays and clayey sands were deposited in offshore environments (middle neritic based on foraminifers, dentilinids, and *Cibicides*). A hard (but not cemented) zone of muddy, glauconitic, shelly fine–medium quartz sand was encountered between 620 and 620.5 ft (188.98 and 189.13 m). A sequence boundary is placed at 619.5 ft (188.82 m) in a minor coring gap (619.45–620 ft; 188.81–188.98 m) above the hard zone with sequence E9 (Zone NP18/NP19–NP20) above and E8 (Zone ?NP17/NP18) below (Fig. **F4**). The sequence boundary is interpreted from the gamma log, which shows an increase from 619.5 to 615 ft (188.82 to 187.45 m).

Below a coring gap (620.5–625 ft; 189.13–190.50 m), a facies change occurs with darker, more glauconitic sandy clays with whole shells below (Fig. **F4**). From 625 to 640.35 ft (190.50 to 195.18 m), the section is a heavily bioturbated clayey sand that becomes increasingly glauconitic downward, from more quartz than glauconite above ~623 ft (189.89 m) to more glauconite than quartz below 623 ft (189.89 m). The increase in quartz suggests shallowing in the HST. The section below 623 ft (189.89 m) has more prominent burrows. The burrows have a thick lining of silty clay and become more common downsection and larger below 635.3 ft (193.70 m). A contact at 640.35 (195.18 m) marks the base of the sequence.

Aquifer sands within the 230-ft-thick (70.10 m) upper Shark River Formation are present from 410 to 590 ft (124.97 to 179.83 m). The upper part of the aquifer sands (407.95–457.5 ft; 124.34–139.45 m) contain the coarser, cleaner sands and should have the highest permeability (Fig. **F8**). Higher percentages of clay and glauconite and thin clay interbeds probably decrease permeability lower in the aquifer.

Lower Shark River Formation

Age: middle to latest early Eocene
Interval: 640.35–732.4 ft (195.18–223.24 m)

A significant contact was encountered at 640.35 ft (195.18 m) with burrowed glauconitic sand resting on a heavily burrowed, dark greenish silty clay with abundant glauconite sand stringers modified by burrows (Fig. **F4**). A pyritic silt-filled burrow lies just under the contact (640.45 ft; 195.21 m). The amount of glauconite ranges from 15% to 75% (average = ~20%) and decreases downsection to 643.75 ft (196.22 m). We place the clays in the lower part of the Shark River Formation vs. the coarser, more glauconitic upper Shark River Formation. The lower part of the Shark River Formation at Millville is greenish gray, bioturbated, and laminated to thin-bedded silty clay and clay with some very fine sand and 1%–2% very fine grained glauconite (Fig. **F4**).

A coring gap from 643.75 to 651 ft (196.22 to 198.42 m) separates more glauconitic clays from slightly glauconitic clays (651–652.2 ft; 198.42–198.79 m). A subtle surface at 652.2 ft (198.79 m) separates dark greenish gray, slightly glauconitic silty clays from grayish green clays ("ash colored marls") below (Fig. **F4**). This surface is most likely an MFS. There is a gamma log kick at 649 ft (197.82 m) that implies a ~4 ft (1.22 m) offset in the cores vs. logs.

Uniform grayish green foraminiferal-rich clays with scattered shell and lignite debris continue to 670 ft (204.22 m). Burrows are present but are mostly small scale (few millimeter). Subtle color bands are preserved (1 cm scale), reflecting lighter, more microfossil rich zones and darker, more clay rich zones (Fig. **F4**). The clay becomes slightly silty (670 ft; 204.22 m) with very minor amounts of very fine sand and very fine glauconite sand (1%–2%). From 675 to 682 ft (205.74 to 207.87 m), the lithology is similar to above, although it is harder and contains more foraminifers and a thin porcellanite zone (677.3–678.3 ft; 206.44–206.75 m). From 682 to 684.6 ft (207.87 to 208.67 m), the section is clayier, consisting of slightly silty clay with distinct color banding and wormy bioturbation (1- to 2-mm burrows filled with lighter material). Silty clay returns from 684.6 to 685.6 ft (207.87 to 208.97 m) and returns to slightly silty clay similar to that above from 685.6 to 690.7 ft (208.97 to 210.53 m). The gamma log suggests a cyclicity with hotter zones at 643–649, 651–653, 657.5–659.5, 663.5–665, 669–672, 674–676, 681–684, and 686–698 ft (195.99–197.82, 198.42–199.03, 200.41–201.02, 202.23–202.69, 203.91–204.83, 205.44–206.04, 207.57–208.48, and 209.09–212.75 m); these zones may reflect a higher clay content (Fig. **F4**).

A lithologic change to glauconitic sandy silty clay with common mud-lined burrows is present at 690.7 ft (210.53 m). Glauconite increases downsection from ~10% to 15%–20% in the interval 694–699 ft (211.53–213.06 m). A porcellanite nodule occurs at 694.9–695.05 ft (211.81– 211.85 m). Glauconite is high (20%–50%) in the interval from 695 to 698.85 ft (211.84 to 213.01 m), marking the lower part of the sequence (TST?). A sequence boundary at 698.85 ft (213.01 m) consists of a heavily burrowed contact zone (698.5–699 ft; 212.90–213.06), with glauconitic sandy clay above and brownish clay below. Glauconite filled, mud-lined burrows extend down to 699 ft (213.06 m). This sequence is assigned to Zones NP15 and NP15–NP16 (P11 and P12) (see **"Biostratigraphy,"** p. 42) (Fig. **F4**) and correlates with sequence E7 of Browning et al. (1997b).

Brown, burrowed, slightly glauconitic, slightly silty clay with scattered fine to very fine glauconite sand extends to 712.9 ft (217.29 m). Wormy burrows (similar to those between 682 and 684.6 ft; 207.87 and 208.67 m) are common. Porcellanite zones are found at 704–704.9, 706.8–707.2, 708.8–709.2, and 709.8–709.9 ft (214.58–214.85, 215.43–215.55, 216.04–216.16, and 216.35–216.38 m) (Fig. **F4**). These porcellanites are lower middle to upper lower Eocene and thus correlate with the "Horizon A cherts."

Between 712.9 and 720.6 ft (217.29 and 219.64 m) the section becomes more glauconitic (15%–20%), harder, and siltier clay with abundant *Planolites*-type burrows. There is a porcellanite bed from 713 to 713.1 ft (217.32 to 217.35 m). From 720.6 to 721.55 ft (219.64 to 219.93 m), a porcellanitic carbonate claystone with 3%–5% glauconite sand and abundant small burrows is present. From 721.55 to 722.5 ft

(219.93 to 220.22 m), a slightly glauconitic silty clay is present. There is a faint surface at 722.5 ft (220.22 m) that may be a sequence boundary separating sequence E4 from E6. Although the lithologic evidence for this as a sequence boundary is weak, calcareous nannoplankton Subzone NP14a is cut out and indicates a hiatus. There is a gamma log kick at 719.5 ft (219.30 m), again suggesting a 3-ft (0.91 m) core-log offset (Fig. F4).

From 722.5 to 723.5 ft (220.22 to 220.52 m), a more glauconitic silty clay with glauconite increasing downsection to 10% (Fig. F4) is present. An extensively burrowed (with clay lined burrows from 1-cm to millimeter) very glauconite-rich (20%–25%) silty clay (730–731.9 ft; 222.50–223.08 m) appears below a coring gap (723.5–730 ft; 220.52–222.50 m). A distinct sequence boundary occurs at 731.8–731.9 ft (223.05–223.08 m) with an irregular surface that includes a nodule that may be an ash bed; the sequence boundary separates very glauconitic silty clay from a slightly glauconitic silty clay below (Fig. F4). This sequence is assigned to Zone NP13 (P8) and thus correlates with lower Eocene sequence E4 of Browning et al. (1997b).

Manasquan Formation

Age: early Eocene
Interval: 731.9–847 ft (223.08–258.17 m)

The Manasquan Formation at Millville (731.9–847 ft; 223.08–258.17 m) is a dark greenish gray carbonate-rich clay with sparse glauconite ("Ash Marl" of Cook, 1868). The section from 731.9 to 732.75 ft (223.08 to 223.34 m) is more glauconitic than below because of bioturbation from above (Fig. F5). Below this, much less glauconitic (generally <5%) soft dark greenish gray clay with abundant foraminifers is found from 732.75 to 746 ft (223.34 to 227.38 m). Glauconite decreases from 3%–5% to <1% and becomes finer grained at 746 ft (227.38 m); there is a gamma log kick here that may indicate the MFS (Fig. F5). Glauconite decreases from 746 ft (227.38 m) to trace amounts at 756 ft (230.43 m) and increases slightly at 767–768 ft (233.78–234.09 m) from trace to 1%–2%. The clays are slightly stiffer from 756 to 770 ft (230.43 to 234.70 m), and there are porcellanite zones: 758–759.4, 763.6–764.0, and 764.8–765.0 ft (231.04–231.47, 232.75–232.87, and 233.11–233.17 m). No obvious surface was noted in the section. The sequence from 731.9 to 768 ft (223.08 to 234.09 m) is assigned to Zones NP12 and P7 (see "Biostratigraphy," p. 42). This section correlates with sequence E3 of Browning et al. (1997b). We tentatively place a sequence boundary at ~768 ft (234.09 m) at an upsection gamma radiation and glauconite increase.

Sequence E2 is thick at Millville (~69 ft; 21.03 m) and comprises a uniform dark greenish gray carbonate-rich clay with sparse glauconite (Fig. F5). The clays continue below the inferred sequence boundary, with glauconite dropping again to trace amounts at 772 ft (235.31 m), and varying between trace and 1% down to 799 ft (243.54 m). Heavy bioturbation typifies the section from 760 to 791 ft (231.65 to 241.10 m) with silty, very fine to fine sand occasionally infilling the burrows. Below a coring gap (778.2–780 ft; 237.20–237.74 m), the section from 780 to 786 ft (237.74 to 239.57 m) is sandiest, with sand concentrated in the burrows and decreasing downsection. Laminations of clay and slightly silty clay occur from 791 to 798 ft (241.10 to 243.23 m). From 798 to 804 ft (243.23 to 245.06 m), slightly darker green foraminiferal clay with small shell fragments is present; laminations are not obvious, with only small (2–5 mm) burrows. The interval 791–804 ft (241.10–245.06 m) appears to be of deeper water than above or below based on greater amounts of clay and foraminifers. These clays were deposited in offshore environments (middle–outer neritic).

Surfaces and lithologic variations are faint in the Manasquan Formation, particularly sequence E2, making sequence stratigraphic subdivisions vague. There is a faint, slightly irregular contact at 804.0 ft (246.06 m) with a dark gray clay above burrowed down into a foraminifer-rich silty clay. This surface may mark a flooding sequence (FS) (Fig. F5). There is a coring gap from 804.25 to 806.0 ft (245.14 to 245.67 m). More common to pervasive burrowing with scattered sand-filled wispy burrows returns from 806 to 811.3 ft (245.67 to 247.28 m). Foraminifers decrease in abundance slightly downsection from 807 to 811.3 ft (245.97 to 247.28 m). A contact at 811.3 ft (247.28 m) separates the burrowed clays above from slightly bioturbated, slightly glauconitic (<1%) laminated slightly silty clay to slightly sandy clay that continues downsection to 814.9 ft (248.38 m). This contact is a facies change with no evidence for erosion and probably marks the MFS. The sandier clays above the surface are interpreted as the HST. The clay below 814.9 ft (248.38 m) is less sandy, has fewer foraminifers, and is less laminated than the clays above; these clays continue down to 832 ft (253.59 m). There is a gradual downsection transition to a slightly glauconitic, foraminiferal-bearing clay (832–844.6 ft; 253.59–257.43 m); foraminifers increase downsection at 831 ft (253.29 m), whereas glauconite increases downsection at 832 ft (253.59 m). Based on biostratigraphy, we tentatively place a sequence boundary in a coring gap (834.5–840 ft; 254.36–256.03 m) at a gamma ray kick at 836 ft (254.81 m), with sequences E2 (Zone NP11 (P6b) above and E1 (Zone NP10) below (Fig. F5).

Sequence E1 is thin (<10 ft; 3.05 m) at Millville (Fig. F5), as it is at most New Jersey sites where it comprises a glauconite clay to clayey glauconite sand (Farmingdale Member). Below 840 ft (256.03 m), there is a gradual downsection increase in glauconite from trace amounts to as much as 50% between 846 and 847 ft (257.86 and 258.17 m). A contact separating glauconitic sandy clay above from laminated clay with glauconite-filled burrows below at 847 ft (258.17 m) is a sequence boundary separating the lower Eocene (sequence E1) from an unnamed basal Eocene clay found at Bass River and Ancora (Fig. F5).

Vincentown Formation

Age: late Paleocene to basal Eocene
Interval: 847–970.2 ft (258.17–295.72 m)

The upper part of the Vincentown Formation is a slightly micaceous, glauconitic, generally laminated silty clay (Fig. F5). From 847 to 850 ft (258.17 to 259.08 m), the section is a slightly glauconitic laminated clay with the glauconite concentrated in burrows. The coarser glauconite is burrowed down from the sequence boundary; the fine, disseminated glauconite appears in situ. Sandy silty clay from 850 to 852.7 ft (259.08 to 259.90 m) is more glauconitic (>5%) and contains very fine quartz sand (as much as 10%). Between 852.7 and 855.5 ft (259.90 and 260.76 m) a clay with shell and common foraminifers is present. The section gradually fines downsection to a clay at 860.1 ft (262.16 m), where glauconite disappears and a planktonic foraminiferal excursion fauna (e.g., *Acarinina africana*) (Table T3) is found. The clays below 860.1 ft (262.16

m) are presumed to be the equivalent of clays at Ancora, New Jersey, that contain the carbon isotopic excursion fauna (figure F4 in **Chap. 1,** this volume) (Fig. **F5**). From 860.1 to 890 ft (262.16 to 271.27 m), the laminated to thinly bedded clay appears to be rhythmically bedded, with alternating darker, thin (5 mm thick) layers and lighter (15 mm thick) very slightly silty layers. Burrows (some with nodules), shells, and replaced shells are scattered through the section. Foraminiferal clays with a trace of mica and traces of scattered glauconite (890–896.0 ft; 271.27–273.10 m) show increasing burrowed glauconite from 896 to 898.3 ft (273.10 to 273.80 m). There is a transition zone of clay and burrowed glauconite clays from below (898.3–898.8 ft; 273.80–273.95 m) and a contact at 898.8–899.4 ft (273.95–274.14 m) with slightly silty glauconitic clay below (glauconite increasing to 10%). At Bass River and Ancora, a similar change in lithology accompanies a ~5‰ decrease in carbon isotopic values that marks the onset of the CIE and Paleocene/Eocene Thermal Maximum (Cramer et al., 1999; Cramer, 2002; Kent et al., 2003); the interval from 897 to 898.8 ft (273.41 to 273.95 m) is therefore predicted to mark the Paleocene/Eocene boundary (Fig. **F5**). This is consistent with nannofossil biostratigraphy that assigns the section from 855 to 895 ft (260.60 to 272.80 m) to Subzone NP9b (the section below 895 ft is barren/indeterminate; see **"Biostratigraphy,"** p. 42).

The interval from 898.9 to 899.4 ft (273.98 to 274.14 m) is a transition from the clay to micaceous, glauconitic sandy silty clays below. The contact at 899.4 ft (274.14 m) could either be a classic sequence boundary or the reflection of a bolide impact followed by rapid deposition of impact ejecta. We believe the surface at 898.4 ft (273.83 m) is a sequence boundary separating a previously unnamed sequence (Pa4) (Fig. **F5**) from sequence Pa3. The CIE is probably truncated at this site based on nannofossil studies (see **"Biostratigraphy,"** p. 42).

We assigned the slightly micaceous, glauconitic, generally laminated silty clay from 847 to 899.4 ft (258.17 to 274.14 m) to the Vincentown Formation (Fig. **F5**), although this unit is distinctly finer grained than typical outcrops or other subsurface sections of the Vincentown Formation. A similar fine-grained subsurface unit has been noted at Clayton, Bass River, and Ancora (Kent et al., 2003). We apply the term upper Vincentown Formation to these fine-grained facies, although we recognize that a distinct member or formation name should be sought for this unit (e.g., Ancora Member/Formation) (Fig. **F8**). We interpret that this clay was deposited in middle–outer neritic environments.

Micaceous glauconitic quartzose sandy silty clays below the contact are assigned to the Vincentown Formation (Fig. **F5**). Laminations of sandy silty clay and less sandy silty clay begin at 902 ft (274.93 m), with scatted concretions around burrows. Glauconite, mica, and quartz sand content decrease downsection, as does burrowing (899.4–920 ft; 274.14–280.42 m) (Fig. **F5**). Burrowed, micaceous, slightly sandy silty clay with traces of glauconite and quartz sand restricted to burrows becomes clayier and less sandy down to 930 ft (283.46 m). Fairly uniform burrowed micaceous silty clay continues to 950 ft (289.56 m), with slightly fewer burrows downsection; glauconite occurs in trace quantities. A very fine sand bed is present from 938.7 to 938.9 ft (286.12 to 286.18 m). The lithofacies variations from 899.4 to 950 ft (274.14 to 289.56 m) reflect a shallowing upward HST deposited in prodelta environments.

Glauconite and foraminifers increase downsection in slightly micaceous clays beginning at 950 ft (289.56 m), becoming a increasingly coarser, progressively more burrowed sandy clay from 955.8 to 959.4 ft

(291.33 to 292.43 m), with glauconite up to 5% (Fig. F5). This represents a shift to deposition in middle neritic environments with minimal deltaic influence. A shelly bed with *Gryphaea dissimilis* (959.1–959.3 ft; 292.33–292.39 m) overlies an irregular burrowed erosional surface (959.4 ft; 292.43 m), marking a sequence boundary. An MFS is either at the shell bed or the top of the glauconitic interval (955.8 ft; 291.33 m); in either case, the MFS is only slightly above the sequence boundary (Fig. F5). This correlates the shell bed at 959.1 ft (292.33 m) to an apparently coeval bed at 1230 ft (374.90 m) at Bass River (Miller et al., 1998b). The sequence from 899.4 to 959.9 ft (274.14 to 292.33 m) is assigned to Zones NP8–NP9 and thus correlates with sequence Pa3 of Liu et al. (1997).

The underlying sequence (959.4 ft–974.9 ft; 292.43–297.15 m) is thin, with a truncated TST (i.e., the clays that represent the TST in this setting are very thin). Clays with common pyrite (959.4–960.0 ft; 292.52–292.61 m) underlie the 959.4 ft (292.52 m) sequence boundary (Fig. F5). From 960.0 to 963 ft (292.52 to 293.52 m), the section is lighter-colored glauconitic sandy clayey silt with common foraminifers. Lighter laminations represent more foraminiferal rich intervals. *Gryphaea* shells occur at 961.9 ft (293.19 m), with scattered shells from 961.9 to 964 ft (293.19 to 293.83 m). Foraminifers increase in abundance downsection from 962.5 ft (293.37 m) (Tables T5, T6, T7, T8). Glauconite increases and becomes coarser downsection from 963 to 967.6 ft (293.52 to 294.92 m), reaching 20%. The core progresses from siltier to clayier at 966.9 ft (294.71 m). From 967.6 to 970.2 ft (294.92 to 295.72 m), the core is foraminiferal-rich micaceous sandy clayey silt.

T5. K/P boundary planktonic foraminiferal occurrences, p. 83.

T6. K/P boundary benthic foraminiferal occurrences, p. 85.

T7. Campanian–Santonian foraminiferal occurrences, p. 89.

T8. Cenomanian–Turonian foraminiferal occurrences, p. 90.

Hornerstown Formation

Age: early to earliest late Paleocene
Interval: 970.2–983.3 ft (295.72–299.71 m)

We placed the top of the Hornerstown Formation at a change to glauconite-rich clay at 970.2 ft (295.72 m) (Fig. F5). This places the Vincentown/Hornerstown Formation contact in Zone P4a at Millville, Ancora, and Bass River. From 970.2 to 974 ft (295.72 to 296.88 m), the section is heavily burrowed, very glauconite rich (40%) silty clay with scattered thin shell fragments; glauconite increases downsection to a clayey glauconite sand (977–980.1 ft; 297.79–298.73 m). Shells occur from 974.7 to 974.9 ft (297.09 to 297.15 m; *Oleneothyris harleni*). We place a sequence boundary at this level (Fig. F5). Above the contact is a dark greenish gray very clayey glauconite sand; below the boundary is a micaceous quartzose glauconite sand with weathered glauconite. The sample at 976 ft (297.48 m) is assigned to Subzone P3b, correlating the sequence from 959.4 to 974.9 ft (292.43 to 297.15 m) to sequence Pa2 of Liu et al. (1997).

Quartzose glauconite sand with weathered glauconite continues below the 974.9-ft (297.15 m) sequence boundary. From 980 to 981 ft (298.70 to 299.01 m), the sands contain small clay blebs and hard cemented nodules that are either concretions or rip-up clasts. From 981 to 982.5 ft (299.01 to 299.47 m), the section contains clayier zones. The K/P boundary occurs in a zone from 982.5 to 983.4 ft (299.47 to 299.74 m). At 982.5–983.3 ft (299.47–299.71 m), there is a shift to sandy clay with decreasing sand downsection. We place the base of the Hornerstown Formation at 983.3 ft (299.71 m), although a very similar glauconite sand (987.1–988.1 ft; 300.87–301.17) recurs below an intervening clay (Fig. F5).

Cretaceous/Paleogene Boundary Section

Interval: 983.0–983.05 ft (299.70–299.71 m)

Samples from 981.0 to 983.5 ft (299.08 to 299.85 m) in a glauconitic clay interval were processed for planktonic foraminifers to identify the K/P boundary (Fig. F6; Table T5). Planktonic foraminifers from the lower Danian were sparse and moderately preserved, whereas those from the Cretaceous were more numerous and well preserved. The K/P boundary is placed between the samples at 983.0 ft (299.70 m) and 983.05 ft (299.71 m). The presence of *P. eugubina* in a sample at 983.0 ft (299.70 m) identifies the lower Danian Zone Pα (Fig. F6). The basal Danian Zone P0 may lie just below this. Our experience shows this zone to be a centimeter or so thick in the New Jersey Coastal Plain boreholes. Danian Zone P1a is identified from samples at 982.95–982.0 ft (299.68–299.39 m) and on the occurrence of *Eoglobigerina edita, E, eobulloides, Guembelitria cretacea,* and *Praemurica taurica*. The identification of *Subbotina triloculinoides* in the sample at 981.0 ft (299.08 m) indicates Danian Zone P1b. There is a probable unconformity between 981.0 ft (Zone NP3 [P1b]; younger than ~63.8 Ma) and 983.0 ft (299.62 m) (Zone P1a; older than 64.6 Ma); this is a regional unconformity, with the underlying sequence spanning the K/P boundary (Miller et al., 2004).

The Cretaceous samples 983.05–983.5 ft (299.85–299.85 m) are placed in the uppermost Maastrichtian based on the occurrences of *Hedbergella monmouthensis, Pseudoguembelina hariaensis, Rugoglobigerina macrocephala, R. reicheli,* and *G. cretacea*. The environment of deposition was too shallow to allow a full complement of deeper-dwelling planktonic foraminiferal species to occur. For instance, the genus *Globotruncana* is very rare. The range of *P. hariaensis* falls within the uppermost Maastrichtian *Abathomphalus mayeroensis* Zone.

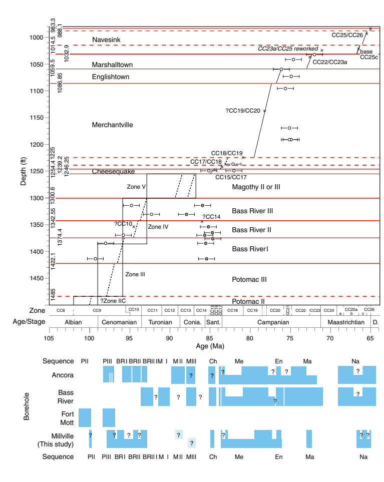
New Egypt Equivalent

Age: late Maastrichtian
Interval: 983.3–1010 ft (299.71–307.85 m)

Sandy silty clay with burrowed glauconite sand occurs from 983.3 to 987.5 ft (299.71 to 300.99 m), with glauconite and burrowing increasing downsection to a clayey glauconite sand from 987.5 to 988.1 ft (300.99 to 301.17 m) (Fig. F6). At the base of the glauconite sand (988.1 ft; 301.17 m), there is a phosphate nodule and a probable sequence boundary. This is a previously poorly recognized uppermost Maastrichtian sequence (983.3–988.1 ft; 299.62–301.17 m) that elsewhere spans the K/P boundary (i.e., it extends into Danian Zone P1a) (Miller et al., 2004); here it assigned to uppermost Maastrichtian Zone CC26 (see "Biostratigraphy," p. 42) (Fig. F11).

Below the sequence boundary, the lithology is a glauconitic (15%–20%) slightly silty clay with finely disseminated mica from 988.1 to 994.7 ft (301.17 to 303.18 m). There are common foraminifers (Table T6) and glauconite-filled burrows. Slight bedding contrasts occur between clay-rich and glauconite-rich beds. At 994.7 ft (303.18 m), there is a shift to a very slightly silty, heavily bioturbated clay with lower (<5%) glauconite and silt content (Fig. F6). The clay is uniform and

F11. Cretaceous age depth plot, p. 66.



heavily bioturbated with a few glauconite-filled burrows. There is a gradational downsection change beginning at 997–997.9 ft (303.89–304.16 m) to more glauconitic, more carbonate/gypsum-rich clays. The increase in carbonate results in a change from dark gray to black to lighter greenish gray clays downsection. From 997.9 to 1010 ft (304.16 to 307.85 m), an intensely bioturbated silty clay with glauconite sand (~5%–10%) is present; burrows are often clay filled, with a few glauconite filled. Lighter gray clay-filled burrows, carbonate, and glauconite increase from 1003 to 1010 ft (305.71 to 307.85 m).

Formational assignment of these glauconitic clays and subordinate clayey glauconite sands is difficult because of facies changes from type sections in Monmouth County, New Jersey, to Millville (Fig. F8). Olsson (1960, 1963) defined clayey glauconite sands and glauconitic clays in Monmouth County as the New Egypt Formation. At Bass River, Miller et al. (1998b, 2004) assigned glauconitic clays with subordinate clayey glauconite sands at the top of the Maastrichtian to the New Egypt Formation. At Millville, the facies from the K/P boundary to ~1010 ft (307.85 m) consist of a clayey glauconite sand at the top to a carbonate-rich glauconitic clay below, with carbonate increasing downsection; although similar to the facies in the Bass River corehole, Millville differs from the sections of the New Egypt Formation by its high carbonate content, and we apply the term New Egypt equivalent to these facies at Millville.

Navesink Equivalent

Age: Maastrichtian
Interval: 1010–1033 ft (307.85–314.86 m)

The transitional contact to the Navesink equivalent is at ~1010 ft (307.85 m) based on the appearance of coarse glauconite, an increase in glauconite to 20%, an increase in carbonate content, and a decrease in clay content to ~50% (Fig. F6). In the downdip Bass River corehole, Miller et al. (1998b, 2004) assigned glauconitic carbonate-rich clays to the Navesink Formation, which is generally a clayey glauconite sand in outcrop and updip boreholes (e.g., Olsson, 1960, 1963). At Millville, the Navesink Formation is very carbonate rich (Fig. F6). The lithology is a hard, foraminifer-rich clay with glauconitic sand and intense bioturbation from 1010 to 1012.4 ft (307.85 to 308.58 m), passing into a heavily burrowed, very dark clayey glauconite (~50%) sand from 1012.5 to 1014.5 ft (308.58 to 309.22 m). A contact at 1014.5–1015.1 ft (309.22–309.40 m) has glauconite sand overlying heavily bioturbated, light gray, microfossil-rich, slightly glauconitic (5%) carbonate-rich clay that continues down to a coring gap at 1016.4 ft (309.80 m). Burrows in the carbonate-rich clay are filled with darker gray silty clay from above. The contact at 1014.5 ft (309.22 m) may be an MFS or a sequence boundary. This contact is present in the lower part of Subzone CC25c (~66–66.5 Ma) (see "Biostratigraphy," p. 42; Fig. F11) and appears to correlate with the poorly documented mid-Maastrichtian Navesink I/Navesink II sequence boundary of Miller et al. (2004). If so, then the Millville borehole has the best characterization and dating of Maastrichtian sequence(s) of any New Jersey CPDP corehole to date.

The section from 1020 to 1033 ft (310.90 to 314.86 m) is an extensively burrowed light gray carbonate-rich glauconitic clay, with glauconite generally increasing downsection. The section from 1020 to 1030 ft (310.90 to 313.94 m) contains fairly abundant small (1–2 mm) carbonate concretions. Glauconite increases downsection from 1020 to 1024.5 ft (310.90 to 312.27 m) from 10% to 50% (Fig. **F6**). Glauconite decreases at 1024.5 ft (312.27 m) 10%–20% and increases downsection to 1027 ft (313.03 m). At 1027 ft (313.03 m), there is a slight decrease in glauconite (20%–30%), with glauconite increasing again downsection. There is a coring gap from 1029.1 to 1030 ft (313.67 to 313.94 m). There is an extensively burrowed, shelly (including corals), glauconite sand-rich chalky light gray clay (1030–1033 ft; 313.94–314.86 m), with glauconite increasing downsection to a rubbly contact at 1032.9 ft (314.83 m). The base of the Navesink and top of the Mount Laurel are difficult to pick lithostratigraphically and biostratigraphically at Millville because of extensive reworking (e.g., Subzone CC23a material extends into the Navesink, whereas elsewhere in the coastal plain this zone is restricted to the underlying Mount Laurel Formation) (Miller et al., 2004) (Fig. **F11**). Just above the contact at 1032.9 ft (314.83 m), there are thick (2 cm) cemented burrows. A dramatic gamma log peak occurs at Millville at 1032 ft (314.55 m); this peak is regionally associated with a phosphorite lag deposit in the top 1–4 ft (0.30–1.22 m) of the Mount Laurel Formation, just below the base of the Navesink Formation (i.e., the sequence boundary actually separates Mount Laurel sands from phosphatic reworked Mount Laurel sands) (Fig. **F6**). We thus place the sequence boundary and the base of the Navesink Formation at 1032.9 ft (314.83 m). These glauconite sands and sandy clays were deposited in middle–outer neritic paleoenvironments.

Mount Laurel-Wenonah Equivalents

Age: late Campanian
Interval: 1032.9–1049.7 ft (314.83–319.95 m)

The clayey glauconite sand of the Navesink Formation rests on a softer, mottled, extensively burrowed, lighter greenish gray glauconitic (20%–30%) chalky clay admixed (~50%) with darker gray clay burrow fill (1032.9–1034 ft; 314.83–315.16 m). Burrow fill decreases downsection (Fig. **F6**). Small dark grains (phosphate) are found in this section, along with small (<10 mm) dark concretions (burrows?); the phosphate yields a high gamma log signature. From 1034 to 1038 ft (315.16 to 316.38 m), a hard, light gray, heavily bioturbated glauconitic (10%–20% with zone up to 40% in burrows) marl (calcareous clay) with scattered dark grains (?phosphate) is present. The section becomes increasingly clayier downsection from 1038 to 1040 ft (316.38 to 316.99 m), with some hard marly burrows extending down from the overlying unit. Shells become increasingly common below 1039 ft (316.69 m). Glauconite sand increases downsection from 20% to 50% in a gray, extensively burrowed silty clay (1040–1047.1 ft; 316.99–319.16 m). Clayey glauconite sand (1047.1–1049.7; 319.16–319.95 m) becomes clayier and more glauconitic downsection. Shell concentrations (1040.6–1040.7, 1041.7–1041.8, 1042.3–1043.0, 1044.5, 1046.7–1046.8, and 1047.6–1048.0 ft; 317.17–317.21, 317.51–317.54, 317.69–317.91, 318.36, 319.03–319.06, and 319.31–319.43 m) may mark flooding surfaces; a gamma log kick at 1049 ft (319.74 m) probably marks the MFS (Fig. **F6**). This clayey lithologic unit underlying the Navesink Formation at Millville differs from outcrop and other borehole sections that have quartz sand (Mount Laurel Formation) and/or sandy silt (Wenonah Formation) beneath the distinctive Navesink greensand. The finer-grained facies expressed at Millville reflect less of a deltaic influence along strike to the south. These shelly glauconite sands and sandy clays are interpreted to have been deposited in middle neritic paleoenvironments.

Marshalltown Formation

Age: late Campanian
Interval: 1049.7–1059.5 ft (319.95–322.94 m)

From 1049.7 to 1058 ft (319.95 to 322.48 m), a very clayey, silty, fine to very fine glauconite sand with thin shell fragments is present; glauconite sand equals or slightly exceeds the amount of clay at 1049.7 ft (319.95 m), marking the top of the Marshalltown Formation (Fig. F6). Glauconite is highest and quartz sand is lowest at ~1055 ft (321.56 m). From 1058 to 1059.5 ft (322.48 to 322.94 m), there is an increasing amount of quartz sand and a color change from darker green above to yellow green below, in part reflecting the higher amounts of quartz sand, reworked glauconite, and weathering by groundwater from the underlying Englishtown Formation. The Marshalltown Formation is interpreted to have been deposited in middle–outer neritic paleoenvironments.

Englishtown Formation

Age: middle–late Campanian
Interval: 1059.5–1100 ft (322.94–335.28 m)

A clear change in lithology occurs at 1059.5 ft (322.94 m) in association with a gamma ray decrease and a sequence boundary separating the Marshalltown Formation above from the upper Englishtown Formation below (Fig. F6). The top of the Englishtown Formation (1059.5–1077.5 ft; 322.94–328.42 m) is a heavily burrowed, very fine to fine-grained quartz sand with scattered shells. Large thick oyster shells are present at 1065.6, 1071.4, 1073.05, and 1076.3 ft (324.79, 326.56, 327.07, and 328.06 m); thinner shells are present from 1080 to 1086 ft (329.18 to 331.01 m). There is an indurated zone from 1065.6 to 1065.7 ft (324.79 to 324.83 m). Clay-lined, sand-filled burrows as thick as 1 cm are most abundant in the upper part of the formation. The sands have a mottled appearance due to bioturbation and patchy distribution of yellow- and orange-stained quartz grains. The sands were deposited in a lower shoreface environment, although common organic material suggests a deltaic influence. The sand becomes silty and slightly micaceous below 1077.5 ft (328.42 m), with abundant silt from 1080 to 1086.5 ft (329.18 to 331.17 m); medium sand decreases at this level. These slightly micaceous silty sands were deposited in distal lower shoreface and/or prodelta environments. Glauconite is largely absent in the upper sands, appears in trace amounts at 1070 ft (326.14 m), and increases to a few percent below 1080 ft (329.18 m). The finer-grained sediments below 1077.5 ft (328.42 m) comprise the lower HST of the upper Englishtown sequence. Glauconite increases at 1086 ft (331.01 m) to 30% in very silty fine sand immediately above a spectacular contact at 1086.85 ft (331.27 m) (Fig. F10); the glauconite-rich sand comprises the TST of the upper Englishtown sequence deposited in distal lower shoreface to offshore environments. The sequence boundary is associated with a minor gamma ray peak (Fig. F6). The contact has rip-up clasts of material from below and material from above burrowed down into the underlying fine to medium sand.

Heavily burrowed, silty, slightly micaceous fine to medium quartz sand with a trace to 1%–2% glauconite and scattered shells appears below the sequence boundary (1086.85 ft; 331.27 m) and continues to 1092.4 ft (332.96 m). The section becomes siltier and more micaceous below an indurated, slightly more glauconitic sand (1092.4–1092.6 ft; 332.96–333.02 m); very silty micaceous sand with thin-walled shells occurs from 1092.6 to 1096.5 ft (333.02 to 334.21 m). We interpret facies from 1086.85 to 1092.6 ft (331.27 to 333.02 m) as the HST of the Englishtown-Woodbury-Merchantville sequence; this section was deposited in a distal lower shoreface environment with a deltaic influence. The section becomes progressively indurated from 1096.5 to 1096.8 ft (334.21 to 334.30 m), becoming an indurated, burrowed, slightly glauconitic, slightly shelly "dirty" sand from 1096.8 to 1097.6 ft (334.30 to 334.55 m). Brown glauconite appears below this indurated zone. A thin, silty, fine sand (1097.6–1100 ft; 334.55–335.28 m) with clayey burrows and scattered shells becomes progressively siltier downsection in a gradual transition to the micaceous silty clays that mark the Woodbury Formation beginning at 1100 ft (335.28 m).

The Englishtown sand is rarely used as a water supply in Cumberland and Salem Counties and is considered a minor aquifer (Fig. F8). The limited supply potential of the Englishtown sands in this area is due to high percentages of clay and the dominance of fine sand. At Millville, the sands are relatively thick (90 ft; 27.43 m) and might have potential for limited water supply and aquifer recharge, although the sands are dominantly fine grained with a silty matrix.

Woodbury Formation

Age: early–middle Campanian
Interval: 1100–1219.9 ft (335.28–371.83 m)

Micaceous, heavily burrowed sandy silty clays appear at 1100 ft (335.28 m). This lithology also appears at 2.5 ft (0.76 m) in Core 149B (1090–1100 ft; 332.23–335.28 m); however, the top 9.8 ft (2.99 m) recovered in Core 146A (1090–1100 ft; 332.23–335.28 m) consists entirely of sands, suggesting that Core 149B is from the lower part of the drilled interval and the lithologic change is at ~1100 ft (335.28 m). A log increase at 1101 ft (335.58 m) also suggests that the transition to the Woodbury Formation is close to 1100 ft (335.28 m) (Fig. F6). The downsection change from the sands of the Englishtown to the clays of the Woodbury Formation is gradational: the section from 1100 to 1126 ft (335.28 to 343.20 m) consists of 60%–70% silty clay that we place in the Woodbury Formation, although consistently high (80%–98%) clay is not attained until 1130 ft (344.42 m).

The Woodbury Formation at Millville consists of dark greenish gray to greenish black burrowed, very micaceous, very sandy silty clay at the top that becomes progressively finer downsection (Fig. F6). The Woodbury Formation represents a classic prodelta deposit. The sand is very fine grained. Dark organic matter, scattered pyrite/marcasite nodules, small (<1 cm), very thin shell fragments, wood fragments, and clay laminae are scattered throughout. Sand decreases from 1110 to 1120 ft (338.33 to 341.38 m) to <20% and further decreases below 1140 ft (347.47 m) to <10%. Clay laminations are progressively preserved from 1128 to 1136 ft (343.81 to 346.25 m) as the unit fines downsection. The section at ~1140 ft (347.47 m) is the finest grained (slightly sandy, slightly silty clay), with silt increasing below this to a slightly sandy silty clay. Scattered very thin laminae of very fine sand appear below 1140 ft (347.47 m). The section from 1154.5 to 1164.7 ft (351.89 to 355.00 m) is finer grained very slightly silty clay. At 1170 ft (356.62 m), the section shifts back to silty clay and becomes clayier from 1180 to 1190 ft (359.66 to 362.71 m). From 1190 to 1192 ft (362.71 to 363.32 m) the core is coated with a dusting of gypsum crystals; foraminifers and shell fragments become common in the washed residues (up to 3.5%) from 1190 to 1221 ft (362.71 to 372.16 m). Slightly silty clays continue to 1210 ft (368.81 m). There is a very subtle change at 1196.9 ft (364.82 m) from very slightly glauconitic carbonate-rich silty clay above to carbonate-bearing, more micaceous silty clay below. At 1210 ft (368.81 m) there is a change from silty clay above to clay below; glauconite sand starts to increase at this level. Between 1210 and 1220 ft (368.81 and 371.86 m), the amount of glauconite in the core increases from 2%–3% at the top to nearly 50% at the bottom. This section is heavily burrowed (5 mm–1 cm diameter), with clay-lined burrows and high amounts of glauconite in sand-filled burrows (e.g., 1216.8 and 1217.7 ft; 370.88 and 371.15 m). Mica occurs in trace quantities throughout. The shift from fine-grained sediments above to glauconite sandy clay/clayey sand below is the contact with the Merchantville Formation, and the formational boundary is placed at 1219.9 ft (371.83 m).

Merchantville Formation

Age: early Campanian to Santonian
Interval: 1219.9–1246.25 (371.83–379.86 m)

The contact between the Woodbury and Merchantville Formations is a gradational one. In this borehole, the contact is identified at the place where the amount of glauconite in the core is ~50% (Fig. F6). The Merchantville Formation is a heavily bioturbated clayey to very clayey (~30%–50% clay) glauconite sand with traces of mica and quartz sand, scattered pyrite nodules, common clay-filled burrows, and rare to scattered shell debris. There are large shells at 1225.9 and 1231.1 ft (373.65 and 375.24 m).

There are subtle facies changes in the Merchantville Formation. Silvery gray glauconitic clay (1220 ft; 371.86 m) grades down to clayey glauconite sand (1222 ft; 372.47 m) to a surface at 1225.7 ft (373.59 m). From this level down to ~1228.4 ft (374.42 m) there is an overall increase in the amount of glauconite; there is a surface at 1228.4 ft (374.42 m) where glauconite decreases and the color changes from silvery gray to blue-gray. Glauconite increases downsection from 1228.4 to 1232 ft (374.42 to 375.51 m); the interval below this (1232.7–1234.3 ft; 375.73–376.21 m) has more clay, but this appears to be a drilling artifact. Glauconite sand (~60%) increases (Fig. F6) from 1234.3 to 1238.2 ft (376.21 to 377.40 m), where it shifts back to a clayey glauconite sand. The section is heavily burrowed. Shells are found at 1236.3, 1237, and 1238.1 ft (376.82, 377.04, and 377.37 m). A glauconite silty clay is present from 1238.2 to 1239.2 ft (377.40 to 377.71 m); there is a possible sequence boundary and facies shift at 1239.2 ft (377.71 m). Below this, the section is a mottled mixture of very muddy glauconite sand with reddish clay-filled burrows; the reddish clay reflects reworked soils. Muddy glauconite sand with reddish clay-lined burrows continues to 1246.25 ft (379.86 m); medium–coarse quartz sand with shell fragments and pyrite nodules is mixed in below 1240 ft (377.95 m). We interpret this lower 6 ft (1.83 m) as a TST; the surface at 1239.2 ft (377.71 m) may be an MFS or the Merchantville I/II sequence boundary of Miller et al. (2004).

Cheesequake Formation

Age: Santonian
Interval: 1246.25–1254.4 ft (379.86–382.34 m)

The contact between the Merchantville and Cheesequake Formations occurs at 1246.25 ft (379.86 m), with fine to very fine silty glauconite sand above to slightly silty, slightly glauconitic (~3%) fine-grained quartz sand below (Fig. F6). The contact zone is burrowed with quartz granules and dark angular cemented fragments (siderite?). From 1245 ft (379.48 m) to the contact, there are scattered granules and shell fragments as large as 2 cm; this section is browner than above and reflects reworking of Cheesequake sediments into the overlying Merchantville Formation. The darker Merchantville lithology is burrowed down to 1247 ft (380.09 m).

The Cheesequake Formation is a cross-bedded to homogeneous lignitic glauconitic (few percent) fine- to medium-grained quartz sand with thin interbedded clays. There are thin shells throughout (Fig. F6). There is a facies shift at 1250–1251.4 ft (381.00–381.43 m) to a shelly, slightly muddy fine quartz sand with traces of mica that grades into a slightly micaceous, finer-grained muddy sand to 1254.4 ft (382.34 m). The environment of deposition of the Cheesequake Formation at Millville is interpreted as delta front.

Magothy Formation

Age: undifferentiated early Turonian–Coniacian
Interval: 1254.4–1300.6 (382.34–396.42 m)

A spectacular contact (Fig. F10) is present at 1254.4 ft (382.34 m), with darker muddy sand above (Cheesequake Formation) and a pinkish gray fine sand with lignite below (Magothy Formation) (Fig. F7). There are rip-up clasts (up to 4 mm) of the Magothy Formation from 1253.0 to 1254.0 ft (381.91 to 382.22 m). The light sand (1254.4–1256.6 ft; 382.34–383.01 m) ranges from very fine sand below the contact to fine and very fine sand at 1255–1256.6 ft (382.52–383.01 m). The sands contain sphaerosiderite nodules (1254.8–1255.2 ft; 382.46–382.52 m) with hematite rinds. A dark clay clast occurs at 1255.3 ft (382.62 m). The sands were deposited in an alluvial plain and may represent crevasse splay or levee subenvironments and incipient soil formation exemplified by sphaerosiderite. The underlying section consists of lignitic, pyritic silt (1256.6–1257.0 ft; 383.01–383.13 m), an irregular contact with rip-up clasts at 1257 ft (383.13 m), and white clay (1257–1257.9 ft; 383.13–383.41 m). The environment of deposition of the silts and clays was a subaqueous alluvial plain with a soil profile at the top.

Below an interval of no recovery (1257.0–1260 ft; 383.13–384.05 m), mottled white and red clays with red root zones were deposited as soils in an interfluvial mudplain environment. The mottled facies are typical of the Potomac Group and have not previously been reported from the Magothy Formation. The shift from the intense alternating wet–dry soil forming white and red clays below 1260 ft (384.05 m) to subaqueous silts and clays above 1257 ft (383.13 m), may reflect a sequence boundary or a shift in depositional systems from marginal to more proximal alluvial plain (Fig. F7).

From 1260 to 1274.3 ft (384.05 to 388.41 m), a mottled red, dusky red, and white silty clay with rootlike traces (up to 2–3 cm) and drab halos is present; these clays are soils deposited in highly weathered, well-drained alluvial plain. An irregular contact at 1274.3 ft (388.41 m) may be a soil surface or a sequence boundary (Fig. F7). Root traces near the bottom of this interval are smaller (a few millimeters). Sphaerosiderite appears at 1272 ft (388.32 m) and becomes common at 1273–1274.3 ft (388.01–391.24 m). Light gray silty clay (1274.3–1283.6 ft; 391.24–391.24 m) changes downsection to a light gray, slightly clayey silty very fine sand and sandy silt (1283.6–1286.25 ft; 391.24–392.05 m) that becomes increasingly coarser with lignite fragments down to 1283.6 ft (391.24 m). Cracks and root traces are more common from 1274.3 to 1276 ft (388.41 to 388.92 m). From 1283.6 to 1286.25 ft (391.24 to 392.05 m), the sand increases to a silty fine- to very fine grained sand with abundant lignite and pyrite nodules; lignite is ~25% of the volume from 1285 to 1286.25 ft (391.67 to 392.05 m). Clay rip-up clasts are found from 1286.1 to 1286.25 ft (392.00 to 392.05 m). Thus, from 1274.3 to 1286.25 ft (388.41 to 392.05 m), a fining upward succession from lignitic silty sand at the base to silty clay at the top represents deposition in an alluvial overbank environment and with a surface of soil formation at the top.

There is a contact at 1286.25 ft (392.05 m) with a light gray clayey silt below (1286.25–1292 ft; 392.05–393.80 m), also deposited in an alluvial overbank environment (Fig. F7). Slightly silty clay to clayey silt below the contact becomes increasingly dark, lignitic, and sandy down to 1292.3 ft (393.89 m). The surface at 1286.25 ft (392.05 m) is marked by some degree of soil formation (gleying) with subtle mottling and cracking down to 1289 ft (392.89 m). Thus, there are two upward-fining packages (1274.3–1285.25 and 1286.25–1292.2 ft; 388.41–391.74 and 392.05–393.86 m), probably with more weathering in the upper part of the cycles. The only sediment recovered from 1292.2 to 1300 ft (393.86 to 396.24 m) was a medium–coarse lignitic sandstone (1292.0–1292.2 ft; 393.80–393.86) that appears to be cemented (?hematite) Magothy lithology. Below the coring gap is another lignitic poorly sorted, poorly cemented fine to medium sandstone containing abundant pyrite and pyrite weathered to hematite between 1300 and 1300.2 ft (396.24 and 396.30 m). From 1300.2 to 1300.6 ft (396.30 to 396.42 m), a mixture of muddy fine-grained sand, silty clay, and lignite fragments is present. The silty clay may be rip-up clasts from below. At 1300.5 ft (396.39 m), a large (up to 3 cm diameter) iron-cemented concretion around a pyrite-cemented sand (2 cm), which might be a rip-up clast or burrow fill, is present. A contact at 1300.6 ft (396.42 m) is very abrupt.

Bass River Formation

Age: Cenomanian to early Turonian
Interval: 1300.6–1421.9 ft (396.42–433.40 m)

Below the 1300.6 ft (396.42 m) contact is silty, shelly, micaceous (including chlorite) clay of the Bass River Formation (Fig. F7). Sandy silt-filled burrows are common at the top of the formation. There is a coring gap from 1301.7 to 1310 ft (396.76 to 399.29 m). Between 1312.5 and 1313 ft (400.05 and 400.20 m), the lithology grades down to slightly silty clay below and sandy filled burrows become less conspicuous. At

1318.4 ft (401.85 m), shells are more common; between 1318.5 and 1318.9 ft (401.88 and 402.00 m), a calcite-cemented shelly, slightly siltier and sandier interval is present. A whole ammonite shell occurs at 1319.4 ft (402.15 m). Below the sandier interval, the sediments return to shelly clay, slightly siltier than above with slight shell concentrations at 1320, 1320.7, 1320.9, 1323.1, 1323.7, and 1324.2 ft (402.34, 402.55, 402.61, 403.28, 403.46, and 403.62 m). This unit represents storm-dominated shallow shelf deposition (outer inner to middle neritic, near storm-wave base). A dark greenish black clay (1324.95–1325.25 ft; 403.84–403.94 m) may be more organic rich. From 1331.7 to 1332.4 ft (405.90–406.12 m), a shell hash in a slightly sandy (very fine), slightly clayey silt matrix is present.

Shelly, slightly silty to silty clay with traces of glauconite continues to 1340.4 ft (408.55 m). From 1340.4 to 1340.9 ft (408.55 to 408.71 m), a slightly indurated shell concentration/bed (including corals) is sandier and has less clay than above. There is a contact at 1340.9 ft (408.71 m) with shelly, slightly clayey silty glauconitic fine-grained sand below that fines downsection to a slightly clayey sandy silt with common small shells and shell fragments (1340.9–1342.55 ft; 408.71–409.21 m). The contact at 1340.9 ft (408.71 m) may mark a sequence boundary, with an admixture of quartz and glauconite sand (1340.9–1342.55 ft; 408.71–409.21 m) in the HST below. Alternatively (and preferred), this surface is a MFS and there is a sequence boundary at an irregular contact at 1342.55 ft (409.21 m) (Fig. **F10**). The 1342.55-ft (409.21 m) contact has micaceous slightly glauconitic muddy sand above and very micaceous silty clay below (Fig. **F7**). Shelly sands are burrowed down from 1342.55 to 1343.1 ft (409.21 to 409.38 m), consistent with 1342.55 ft (409.21 m) as a sequence boundary. The sequence boundary separates the Bass River III sequence above from the Bass River II sequence below (Miller et al., 2004).

Very micaceous silty clay is found from 1342.55 to 1344 ft (409.21 to 409.65 m), with thin wispy micaceous silty sands to sandy silts (Fig. **F7**). The interval 1344–1348.1 ft (409.65–410.90 m) is very micaceous and alternates between very micaceous clay and subordinate wispy beds of very micaceous slightly sandy silt and shell concentrations. Scattered burrows are present at 1346.5, 1346.7, and 1347.2 ft (410.41, 410.47, and 410.63 m). There is a coring gap (1348.1–1350 ft; 410.90–411.48 m) with silty micaceous clay (1350–1351 ft; 411.48–411.78 m) below with less mica and sand. From 1351 to 1360 ft (411.78 to 414.53 m), the section consists of micaceous very silty clay with pyritic burrows and scattered small shells and small shell debris. The section becomes sandier at 1360–1360.3 ft (414.53–414.62 m) with a clayey sandy silt with fine glauconite sand, mica, and shell debris. From 1360.3 to 1360.75 ft (414.62 to 414.76 m), the section becomes more indurated micaceous glauconitic sandy silt with carbonate fossils. There is a contact at 1360.75 ft (414.76 m) where the lithology changes below to slightly micaceous silty clay. There is little irregularity across the contact and little evidence of reworking, and we interpret it as a flooding (probably MFS) surface (Fig. **F7**).

From 1360.75 to 1365.95 ft (414.76 to 416.34 m), slightly micaceous silty clay contains subordinate wispy silty laminated beds (1–2 cm), small shell fragments, and sulfur-rich burrows altered from pyrite. From 1365.5 to 1365.95 ft (416.20 to 416.34 m), the lithology becomes sandier, shellier, and more glauconitic. Below a coring gap (1365.95–1370 ft; 416.34–417.58 m), a micaceous shelly sandy slightly clayey silt (1370–1371.7 ft; 417.58–418.09 m) with glauconite dominating the sand fraction (~25% of total) is present (Fig. F7). From 1371.7 to 1372.9 ft (418.09 to 418.46 m), a more indurated (calcite cemented) silty glauconite-quartz sand with fewer shell fragments, more whole shells, and thin clay laminae is present. From 1372.9 to 1373.4 ft (418.46 to 418.61 m), the shelly silty glauconite-quartz sand continues, although it is not as indurated and clayier and contains clay laminae. From 1373.4 to 1373.7 ft (418.61 to 418.70 m), the section returns to an indurated dirty quartz-glauconite sand with abundant shells. From 1373.7 to 1374.4 ft (418.70 to 418.92 m), a slightly clayey, shelly, glauconite-quartz sand with decreasing shell debris downsection and scattered pyrite is present; this is a lag deposit. There is a sequence boundary at 1374.4 ft (418.92 m) associated with a facies shift from glauconite-quartz sand above to a very sandy silty clay below and a major gamma log increase. The contact is irregular with the lag deposit above and heavy burrows continuing down to 1375.0 ft (419.10 m). The sequence boundary separates the Bass River II sequence above from the Bass River I sequence below (Miller et al., 2004).

The lower part of the Bass River Formation (1374.4–1422 ft; 418.92–433.43 m) is generally sandier than above (Fig. F7). Sandier intervals alternate with finer-grained intervals, perhaps reflecting thin parasequences that are also visible on the gamma log (Fig. F7). Most of the section was deposited in inner–middle neritic environments near or just below storm-wave base, although some of the sandier units may have been deposited in a lower shoreface environment. The interval 1374.4–1376.1 ft (418.92–419.44 m) consists of a slightly micaceous, very sandy silty clay with abundant glauconite-quartz sand and shell debris. An indurated shelly glauconite-quartz sand (1376.1–1376.9 ft; 419.44–419.68 m) contains mainly whole and some articulated bivalve shells (to 2 cm diameter). A shelly very sandy clay to clayey silty glauconitic quartz sand (1376.9–1377.4 ft; 419.68–419.83 m) with common shell fragments overlies a very micaceous clayey slightly glauconitic sandy silt (1377.4–1379 ft; 419.83–420.32 m) with very fine sand and shell fragments. Very micaceous silty very fine to fine quartz sand (1380–1380.5 ft; 420.62–420.78 m) is muddy at the top and clean at the bottom. Very sandy micaceous silty clay (1380.5–1387.75 ft; 420.78–422.99 m) with scattered shells, pyrite/sulfur-filled burrows, and small shell fragments become slightly less micaceous below a coring gap (1387.75–1390 ft; 422.99–423.67 m). The interval 1390–1394 ft (423.67–424.89 m) is a sandy slightly micaceous silty clay. From 1394 to 1394.4 ft (424.89 to 425.01 m), there is a micaceous glauconitic siltstone with abundant sand-sized shell debris. This lithology is present from 1400 to 1400.65 ft (426.72 to 426.92 m), sandwiched between coring gaps (1394.4–1400 and 1400.65–1410 ft; 425.01–426.72 and 426.92–429.77 m). From 1410 to 1412.3 ft (429.77 to 430.47 m), a micaceous silt with some very fine sand and thin shells is underlain by an intensely bioturbated silty glauconite sand (1412.3–1414.2 ft; 430.47–431.05 m) that contains large shells and a concretion. Burrowed to laminated very micaceous, slightly clayey silty very fine sand is found from 1414.2 to 1416.35 ft (431.05 to 431.70 m), with common small shell fragments and burrows disrupting laminae. There is a pyritic burrow at 1416 ft (431.60 m) and a shell concentration at 1416.15–1416.35 ft (431.64–431.70 m). The facies from 1414.2 to 1416.35 ft (431.05 to 431.70 m) was probably deposited in a lower shoreface environment, although a lower estuarine environment cannot be excluded. The facies shift at 1414.2 ft (431.05 m) could be a sequence boundary, and there is a minor gamma kick at this level. There is a facies shift at 1416.35 ft

(431.70 m) to a slightly silty, slightly micaceous dense clay (1416.35–1416.8 ft; 431.70–431.84) with common small shell fragments. There is a coring gap (1416.8–1420 ft; 431.84–432.82 m) and an interesting interval from 1420 to 1422.1 ft (432.82 to 433.46 m). From 1420 to 1420.5 ft (432.82 to 432.97 m) a lignitic silty clay is present. From 1420.5 to 1421.9 ft (432.97 to 433.40 m) is silty clay with scattered shell fragments. Glauconite appears at 1420.5 ft (432.97 m) and increases downsection to a few percent at 1421.9 ft (433.40 m). Lignite is common at 1421.8 ft (433.36 m). The section from 1421 to 1421.9 ft (433.12 to 433.40 m) is burrowed with reddish clay in the burrows. The environment of deposition of the section from 1420 to 1421.9 ft (432.82 to 433.40 m) is probably shallow marine influenced by a terrestrial source of lignite (delta?). From 1421.9 to 1422.1 ft (433.40 to 433.16 m) is a thin iron-cemented dirty sand with lignite fragments. A sequence boundary marking the contact with the Potomac Formation is present at 1421.9 ft (433.40 m), separating the indurated sand below from the shelly glauconitic silty clay above.

Potomac Formation

Age: Albian/?earliest Cenomanian (Zones III–IIC?)
Interval: 1421.9–TD ft (433.40–TD m)

The nonmarine Potomac Formation was encountered at 1421.9 ft (433.40 m) (Fig. **F7**). The top of the formation (1421.9–1450.2 ft; 433.40–442.02 m) is mostly gray clay with minor mottling, some lamination/banding and scattered pyrite, occasional microsphaerosiderite, and plant debris/charcoal. There are alternations between darker gray silty clays and lighter gray silty clays and very fine sands, reflecting changes between unaltered alluvial plain/swamp deposits and immature (gleyed) paleosols.

A slightly lignitic gray silty clay (1422.0–1422.2 ft; 433.43–433.49 m) is sulfur rich in the lower part and overlies a lignite bed (1422.2–1422.25 ft; 433.49–433.50 m). From 1422.2 to 1423.0 ft (433.49 to 433.73 m) is a very stiff, very silty, very fine sand with abundant lignite fragments and small holes (?root casts) filled with clean quartz sand. This upper interval was deposited in a swamp. From 1423 to 1425.6 ft (433.73 to 434.52 m) is a succession of silty, slightly sandy clay that transitions from very sandy at the top to silty clay to a thin (0.1 ft; 3 cm) lignite bed at the base; the color changes from medium light gray to dark gray at the bottom with a corresponding increase in lignite. This succession was deposited in an overbank/swamp environment with an incipient soil at the top. The next succession (1425.6–1426.6 ft; 434.52–434.83 m) ranges from a light gray silty clay at the top to a slightly silty light gray sand at the bottom, yielding a typical upward-fining overbank succession. From 1426.6 to 1427.6 ft (434.83 to 435.13 m), the core consists of dark gray sandy silty clay with small root fills and sandy cross lamination. From 1427.6 to 1433.5 ft (435.16 to 436.93 m), the core consists of slightly sandy light gray clay that darkens downsection with remnants of plant debris. Sphaerosiderite is found from 1430.4 to 1431.2 ft (435.99 to 436.23 m). The section from 1433.5 to 1435 ft (436.93 to 437.39 m) is similar in lithology although darker in color.

A more significant paleosol from 1435 to 1442.6 ft (437.39 to 439.72 m) consists of a hard light gray to medium gray to olive-colored silt with some banding, mottling, and soil cracks; this section has been subjected to significant soil formation, mostly through gleying. Sphaerosiderite is found from 1442.0 to 1442.5 ft (439.52 to 439.67 m). Below a coring gap (1442.6–1450 ft; 439.72–441.96 m), there is a dark gray laminated slightly silty clay (1450.0–1450.25 ft; 441.96–442.04 m). A silty, very fine sand (1450.25–1451.3 ft; 442.04–442.36 m) has a pockmocked appearance due to rooting on the upper surface; the upper part of this interval has sphaerosiderite that decreases downsection. From 1451.3 to 1454.3 ft (442.36 to 443.27 m) is an interval of clayey silt/silty clay that changes from light gray at the top to medium gray, more carbonaceous, and sulfur bearing at the bottom. The intervals 1452.0–1452.15 ft (442.57–442.62 m) and 1452.7–1452.9 ft (442.78–442.84 m) contain sphaerosiderite. From 1460 to 1462.2 ft (445.01 to 445.68 m), a dark gray clay with scattered sulfur blooms and iron concretions is present; there is a concretion at 1462.1–1462.2 ft (445.65–445.68 m). Below a coring gap (1462.2–1470 ft; 445.68–448.06 m), the section from 1470 to 1475 ft (448.06 to 449.58 m) consists of a dark gray slightly sandy clayey silt at the top that transitions to a dark gray silty clay at the bottom. The upper 1 ft (1470–1471 ft; 449.58–448.36 m) includes mica, small lignite fragments, pyrite, and sand-filled root holes. From 1475.0 to 1481.05 ft (449.58 to 451.42 m) is a micaceous fine to very fine sand; the grains have a rusty coating and there is scattered lignitic debris in the sand. The interval 1481.05 to 1481.5 ft (451.42 to 451.56 m) is dark gray sandy lignitic clay with iron concretions. From 1481.5 to 1482.9 ft (451.56 to 451.99 m) is a slightly sandy, slightly clayey silt with microsphaerosiderite. From 1482.9 to 1483.0 ft (451.99 to 452.02 m) is a sliver of clay. Below a coring gap (1483.0–1490.0 ft; 452.02–454.15 m), the section from 1490 to 1491.2 ft (454.15 to 454.52 m) is a silty, very fine sand with pockmarks suggesting rooting. It is possible that this sand correlates with the sand at the base of Potomac sequence III at Fort Mott (**Chapter 4,** this volume) (Fig. F7).

The interval 1491.2 to 1492.35 ft (454.52 to 454.87 m) is light medium gray, slightly clayey, slightly sandy silt with scattered lignite fragments and pyrite. A lignitic sandy silt (1492.35–1493.1 ft; 454.87–454.10 m) overlies a large lignite chunk at the base. From 1493.1 to 1495.5 ft (454.10 to 455.83 m; TD), the core consists of a mottled dark gray to reddish gray silty clay with scattered lignite.

Pollen from the very bottom of the core (1495.5 ft; 455.83 m) was assigned to the Zone III/IIC boundary (Table T9). In the Fort Mott borehole, Potomac Unit 3 is 222.5 ft (68.58 m) thick (**Chap. 4,** this volume). The Potomac Unit 3 should be thicker in the downdip Millville borehole than at Fort Mott. We thus favor the Zone III assignment and interpret the entire Potomac Formation in this borehole as Unit 3.

T9. Pollen and dinocyst occurrences, p. 91.

BIOSTRATIGRAPHY

Planktonic Foraminifers

Cenozoic

Planktonic foraminifers were only locally abundant through most of the Cenozoic section at Millville (Table T3). For the most part, the shallow-water sections here did not preserve important index species. Where found, planktonic foraminferal assemblages are dominated by morphologically simple and long-ranging forms. Age determinations can only be reliably assigned in part of the lower middle and upper lower Eocene and in the lower Paleocene.

The Miocene section at the Millville borehole was only fossiliferous in the lowermost section (360–406 ft; 109.73–123.75 m) and yielded a sparse planktonic fauna including *Globoquadrina dehiscens* and large *Globigerinoides trilobus* with well-developed supplementary apertures. This indicates an assignment to Subzone M1b (= upper N4b).

The highest occurrence (HO) of *Turborotalia cerroazulensis* at 451 ft (137.46 m) marks the top of the known Eocene sediments. The section above 451 ft (137.467 m) to the sequence boundary at 407.95 ft (124.34 m) is barren of planktonic foraminifers and cannot be zoned. The section between 451 and 620 ft (137.46 and 188.98 m) is mostly barren of plankton. Where plankton are present, members of the genera *Acarinina*, *Morozovella*, and *Truncorotaloides* are absent, indicating assignment to undifferentiated Zones P15–P17. These zones cannot be differentiated in the Millville borehole because of the absence of the marker species *Cribrohantkenina inflata* and *Porticulasphaera semiinvoluta*.

The HO of *Morozovella spinulosa* and the absence of *Morozovella aragonensis* at 626 ft (190.80 m) indicates that the sequence between 620 and 640.35 ft (188.98 and 195.18 m) is assigned to undifferentiated Zones P12–P14. The boundary between Zones P11 and P12 is placed at the highest occurrence in the corehole of *M. aragonensis* between 666 and 676 ft (203.00 and 206.04 m), and the section between 640.35 ft (195.18 m) and the sequence boundary at 666 ft (203.00 m) is assigned to Zone P12. The base of Zone P11 is approximated between 691 and 701 ft (210.62 and 213.66 m) by the lowest occurrence (LO) of *Turborotalia pomeroli* because *Globigerapsis* is not found in the borehole. The base of *Acarinina bullbrooki* approximates the base of Zone P9, and the section between 701 and 722.5 ft (213.66 and 220.22 m) is assigned to undifferentiated Zones P9 and P10. Samples 731 to 761 ft (222.81 to 231.95 m) are assigned to Zone P8 based on the presence of *M. aragonensis* and the absence of *A. bullbrooki* and *Morozovella formosa*. Samples between 771 and 741 ft (235.00 and 225.86 m) are assigned to Subzone P6b based on the presence of *M. formosa* and the absence of *M. aragonensis*. Note that Zone P7 is apparently absent in the core; however, *M. formosa* is very rare and may range higher. The sample at 846 ft (257.86 m) is assigned to Subzone P6a based on the absence of *M. formosa*.

Samples at 866 and 891 ft (263.96 and 271.58 m) are assigned to Zone P5. A sample from 866 ft (263.96 m) contains members of the Paleocene/Eocene Thermal Maximum "excursion fauna." Samples between 899 and 956 ft (274.02 and 291.39 m) are either barren or unzoned because of very poor preservation. Samples at 961 ft (292.91 m) contain *Globanomalina pseudomenardii* and *Morozovella angulata* and are assigned to Subzone P4a. Samples from 970–976 ft (295.66–297.48 m) may be assigned to Subzone P3b based on the presence of *Acarinina strabocella* and *Igorina tadjikistanensis*.

Cretaceous/Paleogene Boundary

Samples from 981.0 to 983.5 ft (299.08 to 299.85 m) in a glauconitic clay interval were processed for planktonic foraminifers to identify the Cretaceous/Paleogene boundary (Table T5). Planktonic foraminifers from the lower Danian were sparse and moderately preserved, whereas those from the Cretaceous were more numerous and better preserved. The Cretaceous/Paleogene boundary is placed between samples from 983.0 ft (299.70 m) and 983.05 ft (299.71 m). The presence of *P. eugubina* in the sample at 983.0 ft (299.07 m) identifies lower Danian Zone Pα. Basal Danian Zone P0 may lie just below this. Our experience shows this zone to be a centimeter or so in the New Jersey Coastal Plain boreholes. Danian Subzone P1a is identified from samples at 982.95–982.0 ft (299.68–299.39 m) and on the occurrence of *E. edita, E. eobulloides, G. cretacea,* and *P. taurica*. The identification of *S. triloculinoides* in the sample at 981.0 ft (299.08 m) indicates Danian Subzone P1b.

The Cretaceous samples at 983.05–983.5 ft (299.85–299.85 m) are placed in the uppermost Maastrichtian on the occurrences of *H. monmouthensis, P. hariaensis, R. macrocephala, R. reicheli,* and *G. cretacea*. The environment of deposition was too shallow to allow a full complement of deeper-dwelling planktonic foraminiferal species to occur. For instance, the genus *Globotruncana* is very rare. The range of *P. hariaensis* falls within the uppermost Maastrichtian *A. mayeroensis* Zone.

Maastrichtian

The Maastrichtian occurs from samples at 1032.9–983.05 ft (299.85–314.91 m) that include the Navesink and New Egypt equivalents (Table T5). The HO of *Gansserina gansseri* is in the sample at 996.0 ft (303.66 m) and may indicate the top of the *G. gansseri* Zone, although the top occurrence may have been depressed due to shallow-water environments of deposition. The HOs of *Globotruncana linneiana* and *Rosita fornicata* identify the top of the lower Maastrichtian *Globotruncana aegyptiaca* Zone.

Campanian

Low diversity and a scarcity of marker taxa characterize the Campanian formations in the Millville borehole. The occurrence of *Globotruncana ventricosa* in a sample at 1036 ft (315.77 m) indicates the section above 1036 ft (315.77 m) is middle or upper Campanian. Samples at 1036 and 1041 ft (315.77 and 317.30 m) from the Mount Laurel/ Wenonah Formations contain *Marginotruncana marginata,* which is typically confined to the Santonian. R. Olsson has observed such occurrences in other wells on the New Jersey coastal plain. We interpret the *M. marginata* to be reworked into these samples. A specimen of *Ventilabrella browni* at 1220 ft (371.86 m) indicates the section below to be lower Campanian or older. No Santonian marker species were found.

Cenomanian–Turonian

The Bass River Formation contained a sparse planktonic foraminiferal fauna. The HO of *Rotaliapora cushmani*, a marker for the top of the Cenomanian, was found in a sample at 1371 ft (417.88 m). Calcareous nannofossils indicate that the Cenomanian section continues to 1354 ft (412.7 m), and we believe the HO of *R. cushmani* is premature.

Benthic Foraminifers

Benthic foraminifers were locally abundant in the Miocene–Eocene section (Table T4). Most samples had five to ten species of benthic foraminifers that allowed preliminary paleodepth estimates. Specimens were picked from the >63-µm size fraction that was also used for sedimentological analysis.

The Miocene Kirkwood Formation contains sparse benthic foraminiferal assemblages. The average sample contained five species. The two most common species are *Nonionellina pizarrensis* and *Caucasina elon-*

gata. *N. pizarrensis* dominates samples at 356 ft (108.51 m) and from 406 to 381 ft (123.75 to 116.13 m). *C. elongata* is approximately equally present in samples at 361 and 366 ft (110.03 and 111.56 m). *N. pizarrensis* characterizes the *N. pizarrensis* biofacies of Miller et al. (1997). This biofacies is interpreted to represent 25–50 m paleowater depths (Miller et al., 1997). *C. elongata* characterizes the *Bulimina gracilis* biofacies of Miller et al. (1997). This biofacies is interpreted by Miller et al. (1997) to represent 50–80 m paleowater depths. The biofacies are interpreted to represent paleowater depths of 25–50 m at the base of the sequence. The section deepens to 50–80 m between 361 and 366 ft (110.03 and 111.56 m) and shallows to 25–30 m above 356 ft (108.51 m). This is in agreement with lithofacies analysis that places the maximum flooding surface at 372 ft (113.39 m).

The Eocene benthic foraminifers are generally well preserved, although there is some overprinting of the biofacies by dissolution. Paleowater depths were assigned using the benthic foraminiferal biofacies defined by Browning et al. (1997b). Three sequences between 640.35 and 410 ft (195.18 and 124.97 m) contain a middle neritic fauna dominated by *Cibicidoides* cf. *pseudoungerianus* and were deposited at paleowater depths of ~100 m. Sequence E7 (698.85–640.35 ft; 213.01–195.18 m; lower Shark River Formation) contains abundant *Cibicidoides subspiratus* and was deposited at paleowater depths of ~135 m. Sequence E6 (722.5–698.85 ft; 220.22–213.01 m) is dominated by *Cibicidoides* aff. *subspiratus* and was deposited in ~155 m paleowater depth. Sequence E4 (731.9–722.5 ft; 223.08–220.22 m) is dominated by *C.* cf. *pseudoungerianus* and was deposited in ~100 m paleowater depth. Sequence E3 (756–731.9 ft; 230.43–223.08 m) from the Manasquan Formation is dominated by *C.* aff. *subspiratus* at the base and *Siphonina claibornensis* on top. This represents paleowater depths of ~155 m at the base shallowing to paleowater depths of ~125 m on top. Sequence E2 (836–756 ft; 254.81–230.43 m), though affected by dissolution through the middle part of the sequence, is dominated by *Cibicidoides eocena* and *Eponides jacksonensis* and was deposited in paleowater depths of ~185 m. Sequence E1 (847–836 ft; 258.17–254.81 m) is dominated by *Cibicidoides mimulus* and was deposited in paleowater depths of ~135 m.

Cretaceous benthic foraminifers are only locally abundant, probably because of dissolution and shallow paleowater depths. Maastrichtian samples are dominated by *Buliminella carseyae*, *Coryphostoma plaitum*, *Pseudouvigerina seligi*, and *Gavelinella*. This indicates outer inner to inner middle neritic paleowater depths. The dominance of species of *Gavelinella* in Campanian samples indicates mostly inner neritic paleowater depths. Bass River Formation samples are dominated by species of *Epistomina,* indicating inner neritic paleowater depths. A sample at 1371 ft (417.88 m) contains a much more abundant and diverse fauna and was likely deposited in middle neritic paleowater depths.

Calcareous Nannoplankton

Cenozoic

The calcareous nannoplankton biozonal subdivision of the Cenozoic section in the Millville corehole is difficult because of pervasive dissolution throughout the middle Eocene–Paleocene interval. Assemblages are thus impoverished, discoasters are few to extremely rare, and markers may be absent. The zonal scheme used below is that of Martini (1971) and Martini and Müller (1986).

The section from 572 to 595.9 ft (174.35 to181.63 m) is assigned to Zones NP19–NP20a based on the occurrence of *Isthmolithus recurvus*, *Discoaster saipanensis*, *Discoaster barbadiensis*, and *Reticulofenestra reticulata*. The section from 601.0 to 626.0 ft (183.18 to 190.80 m) contains *Chiasmolithus oamaruensis* without *I. recurvus* and is assigned to Zone NP18. A sample at 631.0 ft (192.33 m) is tentatively assigned to Zone NP17 based on the HO of *Chiasmolithus grandis*.

Samples through most of the middle Eocene are poorly preserved and are only provisionally zoned at this time. Samples at 636.0–641.0 ft (193.85–195.38 m) contain a mixture of fossils and cannot be zoned. Samples at 656.0 and 656.5 ft (199.95 and 200.10 m) yield *Chiasmolithus solitus*, *R. reticulata,* and *Reticulofenestra floridana* and belong to the upper part of Zone NP16 (Subzone NP16b). The HO of *Discoaster distinctus* in the sample at 661.5 ft (201.63 m) indicates mid-Zone NP16. Samples at 691.0 and 696.0 ft (210.62 and 212.14 m) are assigned to Zone NP15 based on the occurrence of *Nannotetrina quadrata*. The interval between the samples at 706.0 and 711.0 ft (215.19 and 216.71 m) may belong to Zone NP14 or NP15. *Discoaster sublodoensis* is rare in this interval with poor preservation, which is further characterized by the occurrence of *Nannotetrina cristata*.

The lowermost middle Eocene and lower Eocene has a better preserved flora and biozonal interpretations are more confident. Samples between 717.0 and 722.5 ft (218.54 and 220.22 m) contain *D. sublodoensis* and *Blackites inflatus* (717.0 ft; 218.54 m) and lack *Discoaster lodoensis* and *Discoaster kuepperi,* indicating assignment to Subzone NP14b. A sample at 731.0 ft (222.81 m) is assigned to Zone NP13 based on the occurrence of *D. lodoensis* and a diverse, well-preserved, typical lower Eocene assemblage. Samples between 734.0 and 767.0 ft (223.72 and 233.67 m) are assigned to Zone NP12 based on the co-occurrence of *D. lodoensis* and *Tribrachiatus orthostylus*. Samples between 771.0 and 831.1 ft (235.00 and 253.29 m) are assigned to Zone NP11 based on the occurrence of *T. orthostylus*. Dissolution in this interval is pervasive, and the nannofossil assemblages are considerably impoverished. Location of the NP11/NP12 zonal boundary is provisional because dissolution is strong throughout the Zone NP11–NP12 interval and *D. lodoensis* is fragmented to completely dissolved. A sample at 841.0 ft (256.34 m) containing *Tribrachiatus contortus* is assigned to Subzone NP10d, and samples at 846.0–851.0 ft (257.86–259.38 m) are provisionally assigned to either Subzone NP10a or NP10c.

Heavy dissolution in much of the Paleocene section makes it difficult to zone. Samples between 856.0 and 891.0 ft (260.91 and 271.58 m) are assigned to Subzone NP9b. Assemblages in this interval are characterized by *Fasciculithus tympaniformis*, *Discoaster multiradiatus*, *Discoaster araneus*, *Discoaster anartios* (891.0 ft; 271.58 m), *Rhomboaster spineus*, and *Rhomboaster cuspis* (the latter four taxa representing the *Rhomboaster* spp.-*D. araneus* [or RD] assemblage). *D. araneus* is rare in this interval, and there is no clear acme of *Rhomboaster* spp. The sample at 891.0 ft (271.58 m) is younger than the acme of the *Rhomboaster-Discoaster* assemblage. The HO of *Fasciculithus alanii* in a sample at 896.0 ft (273.10 m) and the LO of the RD in a sample at 891.0 ft (271.58 m) marks the NP9a/NP9b subzonal boundary. Subzone NP9a extends down to 946.0 ft (288.34 m). The interval between 921.0 and 941.0 ft (280.72 and 286.82 m) is barren. Samples between 951.0 and 966.0 ft (289.86 and 294.44 m) are assigned to Zone NP8 based on the abundant occurrence of *Heliolithus riedelii*; however, there are almost no discoasters preserved to either refine the position within the biozone or exclude the occurrence of the Zone NP9 marker *D. multiradiatus*. A sample at 971.0 ft (295.96 m) with *Heliolithus cantabriae* is assigned to either Zone NP6 or NP7. A sample at 976.0 ft (297.48 m) with *Ellipsolithus distichus*, *Sphenolithus primus*, *Fasciculithus janii*, and without *F. tympaniformis* is assigned to upper Zone NP4. A sample at 981.0 ft (299.01 m) just above the K/P boundary contains *Cruciplacolithus tenuis* and *Chiasmolithus danicus* and is assigned to Zone NP3.

Cretaceous

Cretaceous coccolith slides from the Millville corehole reflect a coccolith-rich environment with only one barren sample. Maastrichtian floras at 986 and 991 ft (300.53 and 302.06 m) are similar, but the floras at 986 ft (300.53 m) are more abundant. These samples are assigned to Zone CC26 based on the presence of *Micula prinsii* and *Nephrolithus frequens*. Samples from 996 to 1020.1 ft (303.58 to 310.93 m) are assigned to Subzone CC25c, based on the occurrence of *Arkhangelskiella cymbiformis*, *Lithraphidites grossopectinatus*, *Lithraphidites quadratus*, *Micula murus*, and *Micula praemura*. The sample at 1021.9 ft (311.48 m) contains *A. cymbiformis* and no other marker species and is assigned to Zone CC25.

The Campanian is identified in the corehole between 1026 and 1086 ft (312.72 and 331.01 m). Samples between 1026 and 1036 ft (312.72 and 315.77 m) are assigned to Subzone CC23a based on the presence of *Broinsonia parca*, *Reinhardtites levis*, and *Tranolithus phacelosus* and the absence of *Reinhardtites anthophorus*. Coccoliths show no age difference across the Navesink/Mount Laurel contact at 1032.9 ft (314.83 m) based on the floral similarities in samples at 1031 and 1036 ft (314.25 and 315.77 m). This reflects extensive reworking of the Campanian Mount Laurel Formation lithology in the Maastrichtian Navesink Formation lithology. The higher sample at 1031 ft (314.25 m) has much more abundant coccoliths. Both contain *B. parca* and *R. levis*, typical of late Campanian to early Maastrichtian floras. The sample at 1041 ft (317.30 m) contains *B. parca* and *R. anthophorus* and is assigned to Zone CC22. The sample at 1041 ft (317.30 m) has a distinctive shallow-water flora with *Braarudosphaera* and abundant *Lucianorhabdus*. The presence of *R. anthophorus* between 1071 and 1086 ft (326.44 and 331.01 m) suggests this section is Campanian. Samples from 1071 to 1075.9 ft (326.44 to 218.54 m) are assigned to Zone CC20–CC21 undifferentiated based on the presence of *B. parca* and *Calculites obscurus* and the absence of *R. levis*. A sample at 1086 ft (331.01 m) lacks *C. obscurus* and is assigned to CC19–CC21.

A sample at 1251.9 ft (381.589 m) is assigned to Santonian Zone CC15 based on the occurrence of *Calculites ovalis*, *Lithastrinus septenarius*, and *R. anthophorus*. A sample at 1344 ft (409.65 m) is assigned to lower Santonian/upper Coniacian Zone CC14 based on the occurrence of *L. septenarius* and *Micula decussata*. This is different from the Turonian age assigned using Sr isotopes and regional correlations of the Bass River Formation to the Cenomanian–lower Turonian and must reflect either downhole or laboratory contamination.

The sample at 1354 ft (412.70 m) is surprising for the abundant and well-preserved coccoliths. The sample contains *Gartnerago obliquum* and *Lithraphidites acutus* and is assigned to Zone CC10. Samples from 1386 to 1412 ft (422.45 to 430.38 m) are etched and have low diversity, making zonal determination difficult. These samples contain *Eiffellithus tur-*

riseiffelii and are assigned to Zone CC9–CC10 undifferentiated. The sample at 1416.7 ft (431.81 m) is barren.

Diatoms

Fourteen Miocene samples were processed for diatoms from the Millville borehole. Diatoms were generally rare to absent in these samples. A sample at 374.4 ft (114.15 m) contains common diatoms assignable to East Coast Diatom Zone 1 (ECDZ 1) of Andrews (1988). Two samples at 249.9 and 250.0 ft (76.17 and 76.20 m) contain a fragmented, poorly preserved diatom assemblage. Diatoms include *Paralia sulcata*, *Biddulphia tuomeyi*, *Melosira westii*, *Coscinodiscus* sp., and *Goniothecium rogersii*. The assemblage is similar to that of the ECDZ 1 diatom assemblage at 374.7 ft (114.15 m) but it lacks marker species *A. heliopelta*. *A. heliopelta* is reported at 249.5 ft (76.05 m) by R. Benson (pers. comm., 2003) of the Delaware Geological Survey. Therefore, the section between 249.5 and 374.4 ft (76.05 and 114.15 m) is assigned to ECDZ 1.

Pollen

Thirteen samples were analyzed from the Millville corehole for palynomorphs, pollen, and spores (Table **T9**). All but one sample contained biostratigraphically useful specimens, although specimen recovery was generally poor to very poor (Table **T9**). Preservation in the Potomac Formation was generally better than samples higher upsection. Samples are assigned ages using the zonations of Brenner (1967) and Doyle and Robbins (1977).

Four samples taken from the Magothy Formation (between 1249.4 and 1291.8 ft; 380.82 and 393.74 m) contain several species of triporates of the genera *Complexipollis* and *Porocolpopollenites* and lack triporates typical of the middle and upper Magothy Formation. This strongly suggests Zone V (late Turonian) for the Magothy Formation at Millville, which is stratigraphically equivalent to the South Amboy Fire Clay. Samples in the Bass River Formation between 1320.0 and 1354.0 ft (402.40 and 412.70 m) contain either the *Atlantpollis* complex or *Complexipollis* sp. A, a triporate-*Normapolle* type very similar to similar to the *Atlantpollis* complex, and are assigned to Zone IV (late Cenomanian). This is stratigraphically equivalent to the Raritan Formation. A sample at 1384.0 (421.84 m) contains *Ajatipollis* sp. A, which is common in Zone III. The stratigraphic range of *Ajatipollis* sp. A is not well known, and it may extend into Zone IV. If *Ajatipollis* sp. A does extend into Zone IV, then, given the paucity of palynomorphs in this sample, dating is uncertain and the boundary between Zones IV and III is approximate. Three samples between 1411.2 and 1473.7 ft (430.13 and 449.18 m) contain several species of *Tricolporopollenites* that are indicative of Zone III (early Cenomanian). A sample at 1495.5 ft (455.83 m) contains both Subzone IIC and Zone III forms. The abundance of bisaccate coniferous pollen is a very common aspect of the upper Patapsco. This most likely reflects cooler paleoclimatic conditions at this time. The boundary between Subzone IIC and Zone III have not been well defined; this, together with the mixture of taxa, results in an uncertain assignment of the base of the borehole.

STRONTIUM ISOTOPE CHRONOSTRATIGRAPHY

Sr isotopic age estimates were obtained from mollusk shells. Approximately 4–6 mg of shells were cleaned in HCl, ultrasonically cleaned, and dissolved in 1.5-N HCl. Sr was separated using standard ion exchange techniques (Hart and Brooks, 1974). The samples were analyzed on two different machines at Rutgers University; a VG Sector mass spectrometer (Table T10) and an Isoprobe T Multicollector thermal ionization mass spectrometer (TIMS) (Table T2). Internal precision on the Sector for the data set averaged 0.000012, and the external precision is approximately ±0.000020 (Oslick et al., 1994). Internal precision on the Isoprobe for the data set averaged 0.000007, and the external precision is approximately ±0.000010 (replicate analyses of standards). National Bureau of Standards (NBS) reference material 987 is measured for these analyses at 0.710255 (2σ standard deviation = 0.000008, N = 22) normalized to $^{86}Sr/^{88}Sr$ of 0.1194 for the Sector and 0.710241 for the Isoprobe.

Miocene Sr isotopic ages were assigned using the Cande and Kent (1995) timescale (Table T2) and the early and middle Miocene regressions of Oslick et al. (1994), with age errors of ±0.61 and ±1.17 m.y. at the 95% confidence interval for one analysis, respectively. The Oligocene–Miocene portion of the Cande and Kent (1995) timescale is identical to the Berggren et al. (1995) timescale that is used to assign calcareous and planktonic foraminiferal ages.

Strontium ages were obtained on 22 samples from the Kirkwood and upper Shark River Formations (Table T10; Figs. F10, F11). No shells were found above 342.5 ft (104.39 m). Samples at 365.9 and 402.3 ft (111.53 and 122.62 m) yielded ages of 8.5 and 0.9 Ma, respectively. These ages are very different from other Miocene samples at this stratigraphic level and are assumed to represent either contamination or diagenesis of these samples. These data points are not plotted on Figure F10. The remaining samples between 342.5 and 407.9 ft (104.39 and 124.35 m) yielded ages ranging in age from 19.0 Ma at 402 ft (122.53 m) to 21.0 Ma at 371.65 ft (113.28 m) (Fig. F10). The heavy line on Figure F10 represents our preferred age interpretations for these sediments. Neglecting 3 samples that fall off the line (stippled circles), the mean age for 11 samples is 20.4 Ma, with a preferred age estimate of 20.2–20.6 Ma. This correlates these sediments to the Kw1a sequence of Sugarman et al. (1993). The sedimentation rate for the Kw1a sequence at Millville is 51.8 m/m.y., which is comparable to the 40 m/m.y. sedimentation rate found by Miller et al. (1997) for this sequence at Cape May and Atlantic City.

Five samples between 425.5 and 457 ft (129.69 and 139.29 m) yielded Eocene ages that are outside of the useful range for Sr isotopic analysis.

Cretaceous ages were assigned using linear regressions developed for upper Coniacian through Maastrichtian sections by Miller et al. (2004). Using a similar late Campanian–Maastrichtian regression, Sugarman et al. (1995) conservatively estimated age errors of ±1.9 m.y. at the 95% confidence interval for one Sr isotopic analysis; age errors for the coeval and older sections are purportedly one order of magnitude better according to Howarth and McArthur (1997). We estimate that the maximum Sr isotopic age resolution for this interval is ±0.5 to ±1.0 m.y. (i.e., the external precision of 0.000010 [Isoprobe] to 0.000020 [Sector] divided by the slopes of the regressions of ~0.000020/m.y.). For Ceno-

T10. Sr isotopic data, p. 94.

manian through Turonian sections, ages were assigned using the look-up tables of Howarth and McArthur (1997), who measure NBS 987 at 0.710248. Thick mollusk shells were not common in the Millville borehole, and thin shells gave ages that were not in agreement with the calcareous nannofossil biostratigraphy.

Sr isotopic ages were obtained from five samples in the Navesink Formation. These samples yielded ages ranging from 28.4 to 0.4 Ma and therefore they must be altered by diagenesis. These samples are not plotted on Figure **F11.** Age relations for the Maastrichtian are based upon calcareous nannofossil biochronology.

Thirteen Sr isotopic ages were obtained from Campanian through Santonian sediments. Two samples in the Marshalltown sequence (1033 and 1042 ft; 314.86 and 317.6 m) yielded ages of 72.1 and 74.7 Ma, respectively. (A third age of 0.6 Ma at 1045 ft [318.52 m] reflects diagenesis and is not included on Fig. **F10**.) If both of these ages are correct, the sedimentation rate would be no higher than 3.1 m/m.y. In the Ancora borehole, the Marshalltown sequence had a sedimentation rate between 7.7 and 16.2 m/m.y. We assumed that there was some postdepositional mixing of sediments in the Marshalltown sequence at Millville. We prefer the younger age (72.1 Ma) because it is in agreement with the age assigned using calcareous nannofossils. Age data are too sparse to allow a confident interpretation of this sequence's sedimentation rate.

Two Sr isotopic ages, 76.2 Ma at 1060 ft (323.09 m) and 75.0 Ma at 1073 ft (327.05 m), were obtained from the upper Englishtown sequence in the Millville borehole (an age of 55.9 Ma from a sample at 1084.2 ft [330.46 m] is assumed to have been altered by diagenesis). These ages are compatible with the age of the upper Englishtown obtained in the Ancora and Bass River boreholes. The sedimentation rate of the Englishtown sequence in the Millville borehole is 12.6 m/m.y. based on the age relationships shown in Figure **F11.** This is comparable to the 15.2 m/m.y. sedimentation rate found at Ancora and the 10.9 m/m.y. sedimentation rate found at Bass River (Miller et al., 2004).

Four strontium ages were obtained on thin-walled bivalve shells from the Woodbury Formation (Merchantville III sequence) at Millville. These provided ages of 75.7–75.0 Ma, which are younger than the Merchantville III sequence at either Ancora or Bass River (Miller et al., 2004). The Millville Sr isotopic ages from the Woodbury Formation do not agree with calcareous nannofossil biostratigraphy. The thin shells found in the Woodbury Formation do not provide reliable ages, most likely because of diagenesis. An age of 82.2 Ma was obtained from a shell at 1237 ft (377.04 m) in the Merchantville I sequence. This is comparable with the age of this sequence found at Ancora and Bass River (Miller et al., 2004).

The Cheesequake sequence at Millville is dated with Sr isotopic ages of 82.1 and 85.2 Ma at 1249 and 1249.5 ft (380.70 and 380.85 m), respectively. The age of 85.2 Ma is in agreement with the assignment to nannofossil Zone CC15.

The Bass River sequences are difficult to date because the Sr isotopic record has minima and maxima in the Coniacian through Cenomanian (Howarth and McArthur, 1997). Two potential ages for most isotopic values are plotted on Figure **F11.** We prefer the older ages for each sample because they are required by the pollen biostratigraphy and sparse calcareous nannofossil biostratigraphy. A few samples have only one age plotted because values above the maxima in the Sr isotopic curve are undefined. The sample at 1340 ft (408.43 m) yielded an age of 62.6 Ma and is not plotted on Figure **F11.** The Bass River III sequence had ages of 94.8 and 92.3 Ma at 1314 and 1331 ft (400.51 and 405.69 m), respectively. The Bass River II sequence had an age of 95.8 Ma at 1370 ft (417.58 m). The Bass River I sequence had ages of 98.0 and 99.3 Ma at 1384 and 1413 ft (421.84 and 430.68 m), respectively.

The ages of sequences at Millville are consistent with those at Bass River and Ancora (Fig. F9), although the chronology of the Millville corehole is not as firm. Less of the late Campanian–early Maastrichtian sediments appear to be represented at Millville, although the middle–late Maastrichtian appears to record and date two sequences that were poorly recognized previously (Fig. F9). Similarly, although the Turonian–Coniacian section is less complete at Millville, the Santonian–lower Campanian Merchantville sequences and the Cenomanian–Turonian Bass River sequences are well represented at Millville (Fig. F9).

SUMMARY AND FUTURE WORK

Drilling at Millville was successful in providing the first continuous corehole data from southernmost central New Jersey coastal plain (Cumberland County) (1) to evaluate local and regional aquifers and (2) to document the regional and global significance of Upper Cretaceous sequences (<100 Ma). Groundwater availability is limited mainly to Tertiary aquifers. Our examination of the hydrostratigraphy at Millville yields the following observations:

1. The top 150 ft (45.72 m) of the Cohansey and Bridgeton Formations forms a very productive unconfined aquifer. It is the best aquifer sampled at this site. However, because of its shallow nature, it is highly vulnerable to surface pollutants.
2. A leaky confining bed separates the Cohansey aquifer from the Atlantic City 800-foot sand. The confining bed is correlative with the Wildwood member of the Kirkwood Formation and the Kw2a sequence. This updip equivalent of the Wildwood-Belleplain confining bed is coarser grained than typical sections along the coast. The confined Kirkwood aquifer at this site (Atlantic City 800-foot sand) is predominantly composed of the upper sand from the Brigantine Member, or Kw1a sequence, and some sand from the Shiloh Member (Kw1b sequence). The thin "confining bed" that separates the upper and lower 800-foot sand is <10 ft (3.05 m) thick at Millville and probably doesn't function as a confining bed.
3. The "Piney Point aquifer" is in the upper part of the Shark River Formation. It is thick (~180 ft; 54.86 m), although thin clay beds and clay-silt in the matrix limit its productivity. Its assignment to Zones NP19–NP20 (upper Eocene) differs from other locations in New Jersey where the aquifer has been dated as middle Eocene and late Oligocene. Further study of this interval will be required to better resolve the relationship of these upper Eocene sands to other aquifers.
4. The Englishtown aquifer system (lower and upper Englishtown Formations) is a potential aquifer and 80 ft (24.38 m) thick, although it is predominantly silty fine sands and finer grained in the lower part. The quality of water in this aquifer is unknown.
5. The Magothy Formation is thin and a poor aquifer at this location vs. a major aquifer in sections to the north (e.g., Ancora, Bass River, and Sea Girt).

We previously evaluated the timing of Upper Cretaceous sequence boundaries at Bass River and Ancora with global records and noted the similarity of these records, suggesting that glacio-eustasy was responsible for sea level changes in the Late Cretaceous greenhouse world. Drilling at Millville and Sea Girt provides additional sites to evaluate Upper Cretaceous sequences and sea level history. Subsequent studies of the Millville Maastrichtian and upper Santonian–lower Campanian sequences may provide clues about the number and ages of sequences in these enigmatic intervals. The Millville Cretaceous and Paleogene sections are similar to those to the south in Delaware and differ from sections to the north; in particular, the Magothy is thin, the K/P and P/E boundaries may be truncated (although further studies of these sections are needed), and the Santonian to Maastrichtian sections have much less of a deltaic influence, with much of the section truncated. We suggest that the South Jersey High acted as feature that influenced sedimentation patterns, separating north and southernmost New Jersey/Delaware provinces.

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Figure F1. Location map showing existing ODP boreholes analyzed as a part of the New Jersey (NJ)/Mid Atlantic (MAT) sea level transect. Also shown are multichannel seismic data (MCS) from *Ewing* Cruise 9009 (Ew9009), *Oceanus* Cruise (Oc270), and *Cape Hatteras* cruise (CH0698). Millville borehole location is shown as a star. MN = Monmouth County, OC = Ocean County, BU = Burlington County, CD = Camden County, GL = Gloucester County, AT = Atlantic County, SA= Salem County, CU = Cumberland County, CM = Cape May County. AMCOR = Atlantic Margin Coring Project.

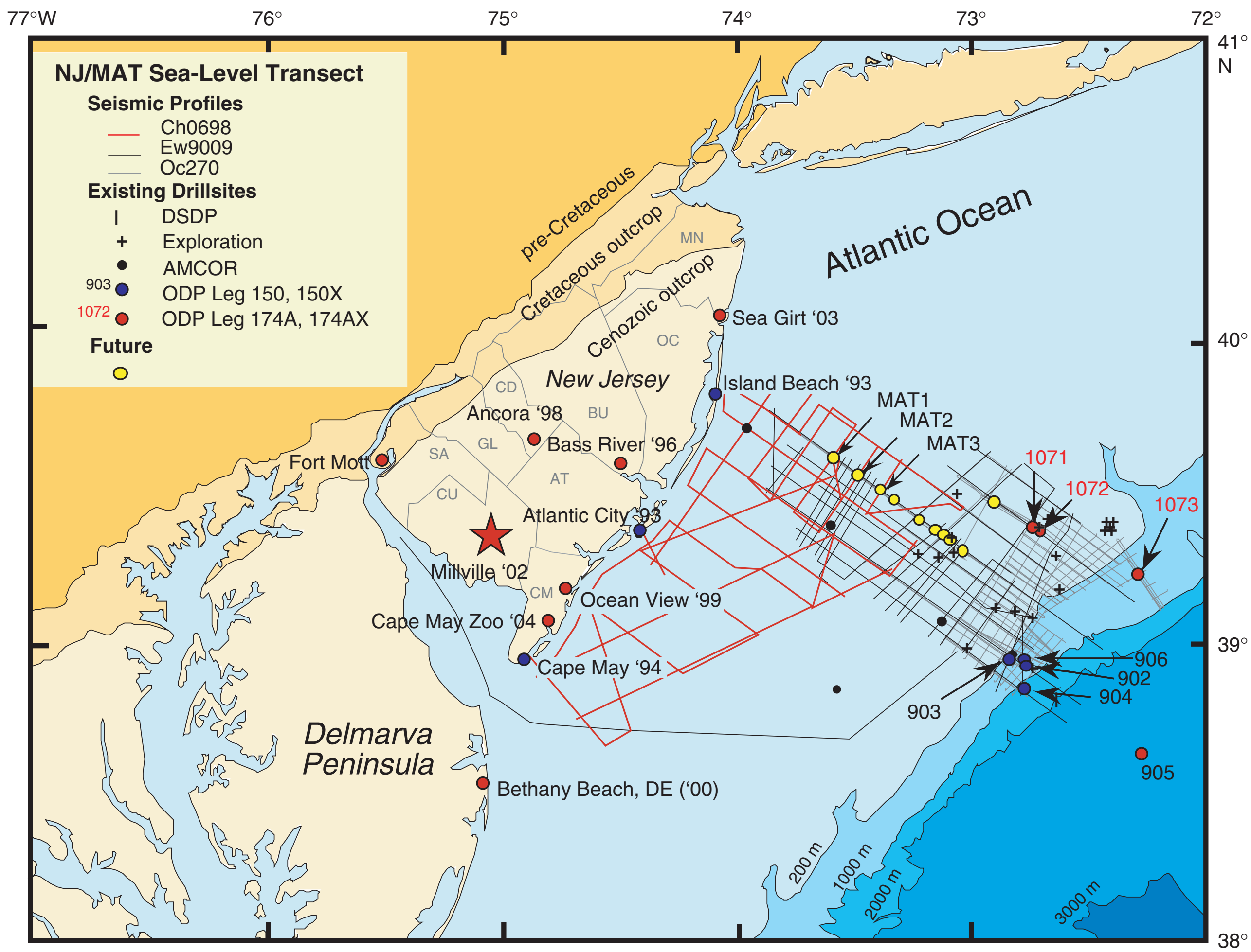

Figure F2. Summary stratigraphic section for Bridgeton Formation (?late Miocene) and Cohansey Formation (?upper and/or ?middle Miocene) from the Millville borehole. This and subsequent similar figures summarize core recovery, lithology, gamma ray logging signature, age, environments, and sequence stratigraphic interpretations. Fm. = formation. HST = highstand systems tract. LST = lowstand shoreface, USF = upper shoreface.

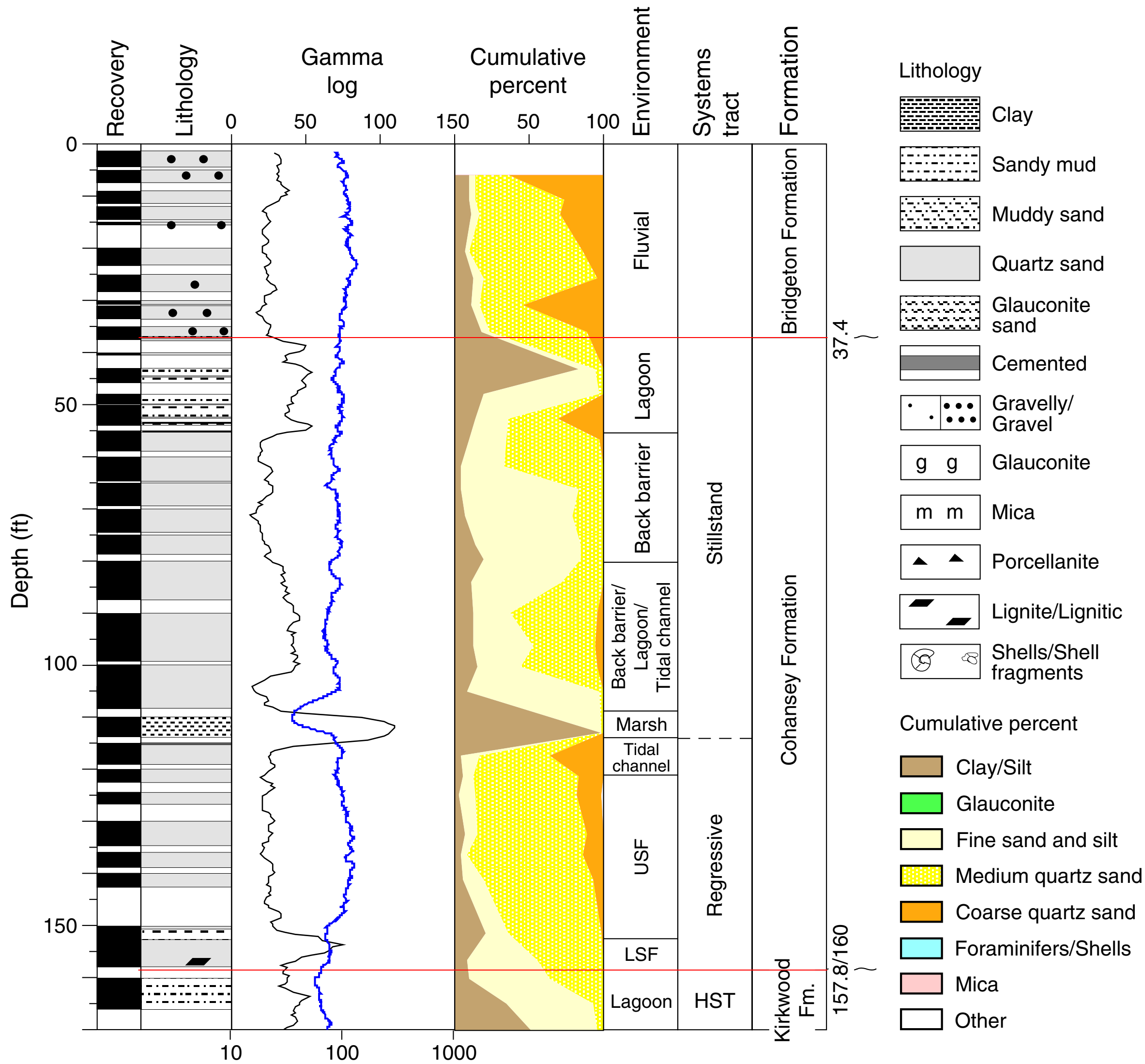

Figure F3. Summary stratigraphic section for Wildwood (lower to middle Miocene), Brigantine, and Shiloh Marl Members (lower Miocene) of the Kirkwood Formation from the Millville borehole. The symbol key is given in Figure F2, p.57. Kw1a and Kw2a are sequences defined by Sugarman et al. (1993). LSF = lowstand shoreface, dLSF = distal lower shoreface. HST = highstand systems tract, MFS = maximum flooding surface, TST = transgressive systems track, FS = flooding surface. ECDZ 1 = East Coast Diatom Zone 1 of Andrews (1988).

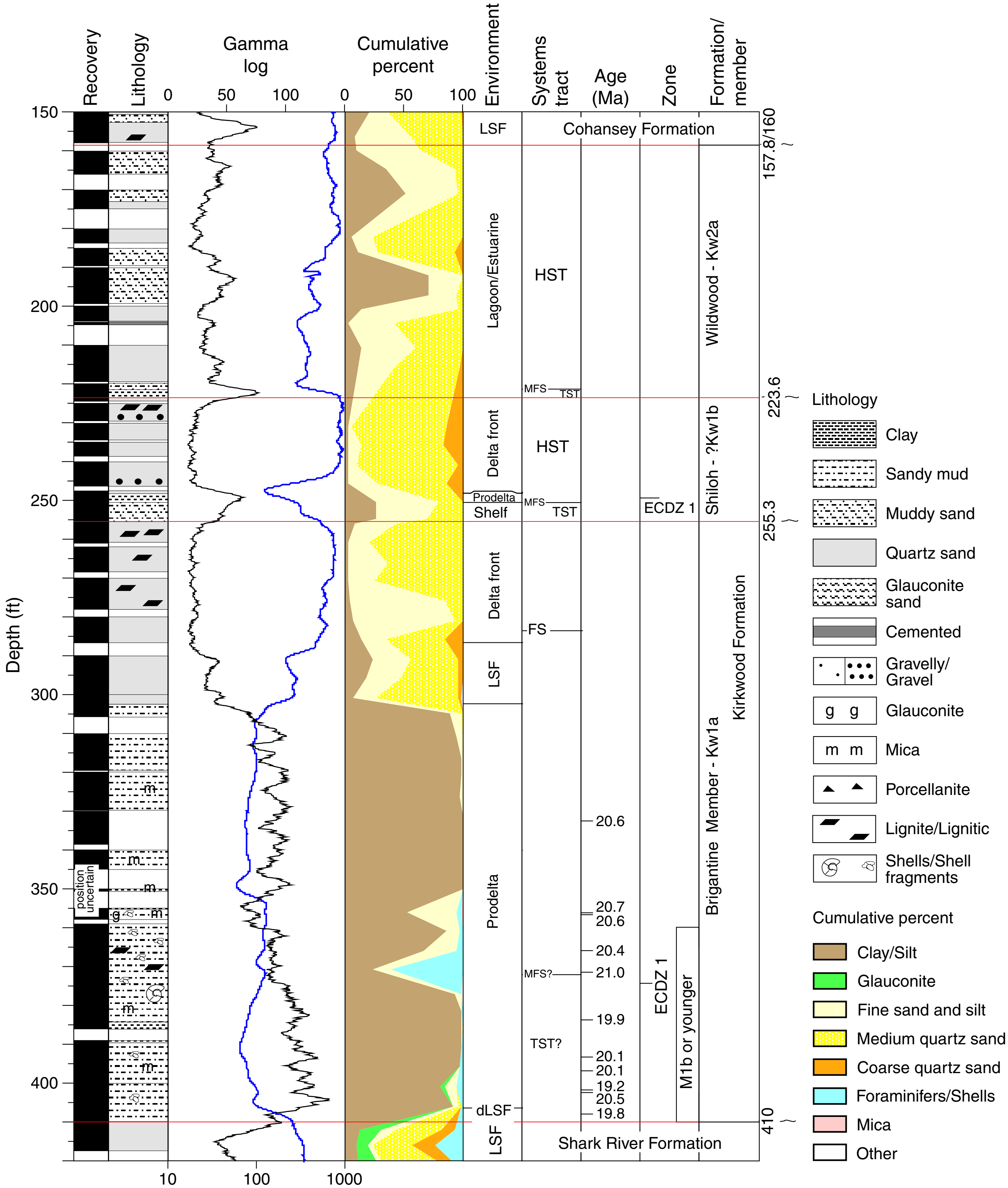

Figure F4. Summary stratigraphic section for the Shark River Formation (middle to uppermost lower Eocene) from the Millville borehole. E4–E10 are sequences defined by Browning et al. (1997a, 1997b). LSF = lowstand shoreface, dLSF = distal lower shoreface, pLSF = proximal lower shoreface. HST = highstand systems tract, MFS = maximum flooding surface, TST = transgressive systems track, FS = flooding surface.

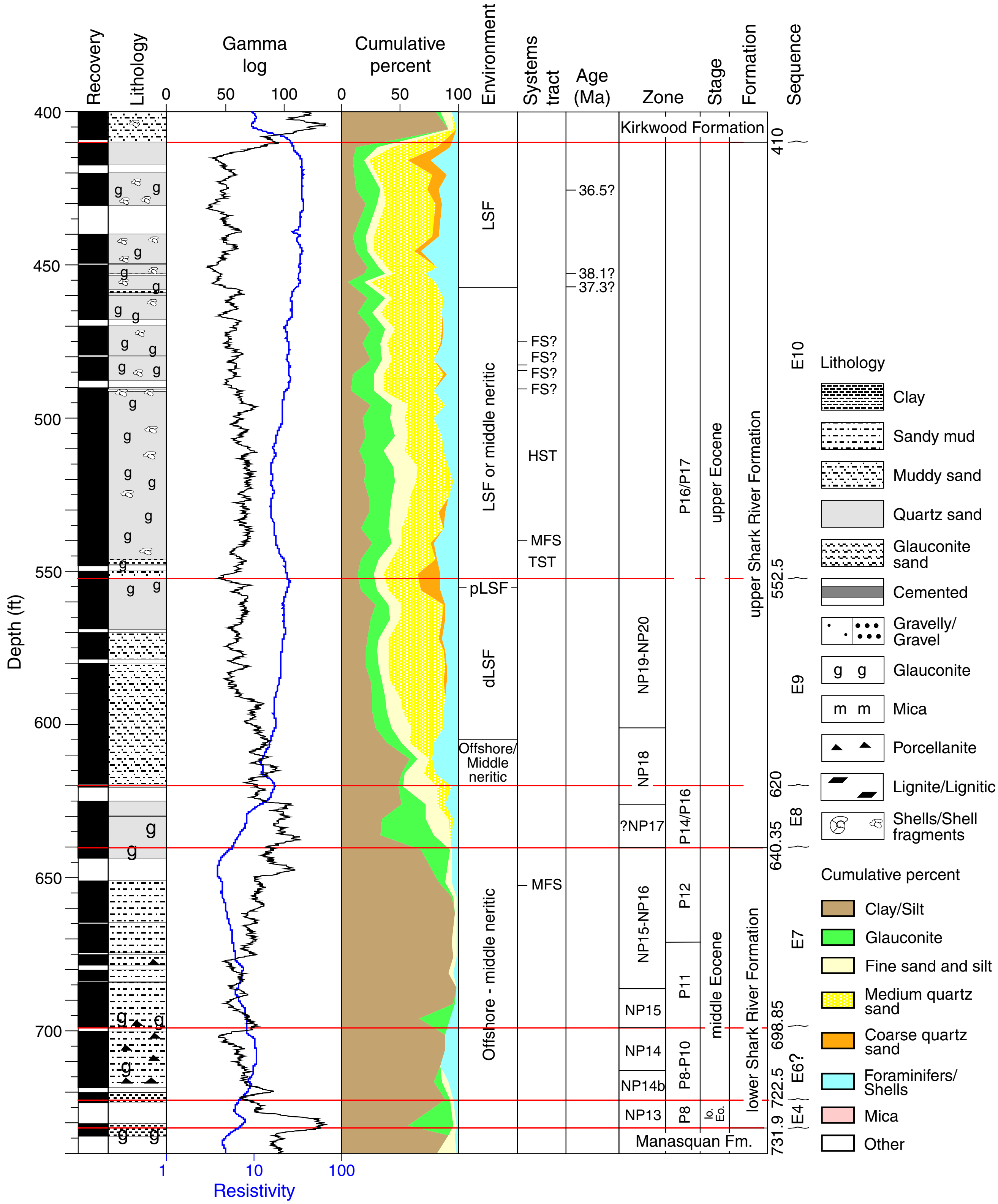

Figure F5. Summary stratigraphic section for the Manasquan Formation (lower Eocene), Vincentown Formation (upper Paleocene), and Hornerstown Formation (lower to lowermost upper Paleocene) from the Millville borehole. E1–E3 are sequences defined by Browning et al. (1997b). Pa1–Pa3 are sequences defined by Liu et al. (1997). Pa4 is defined herein. HST = highstand systems tract, MFS = maximum flooding surface, TST = transgressive systems track, FS = flooding surface, CIE = carbon isotope excursion. Fm. = formation

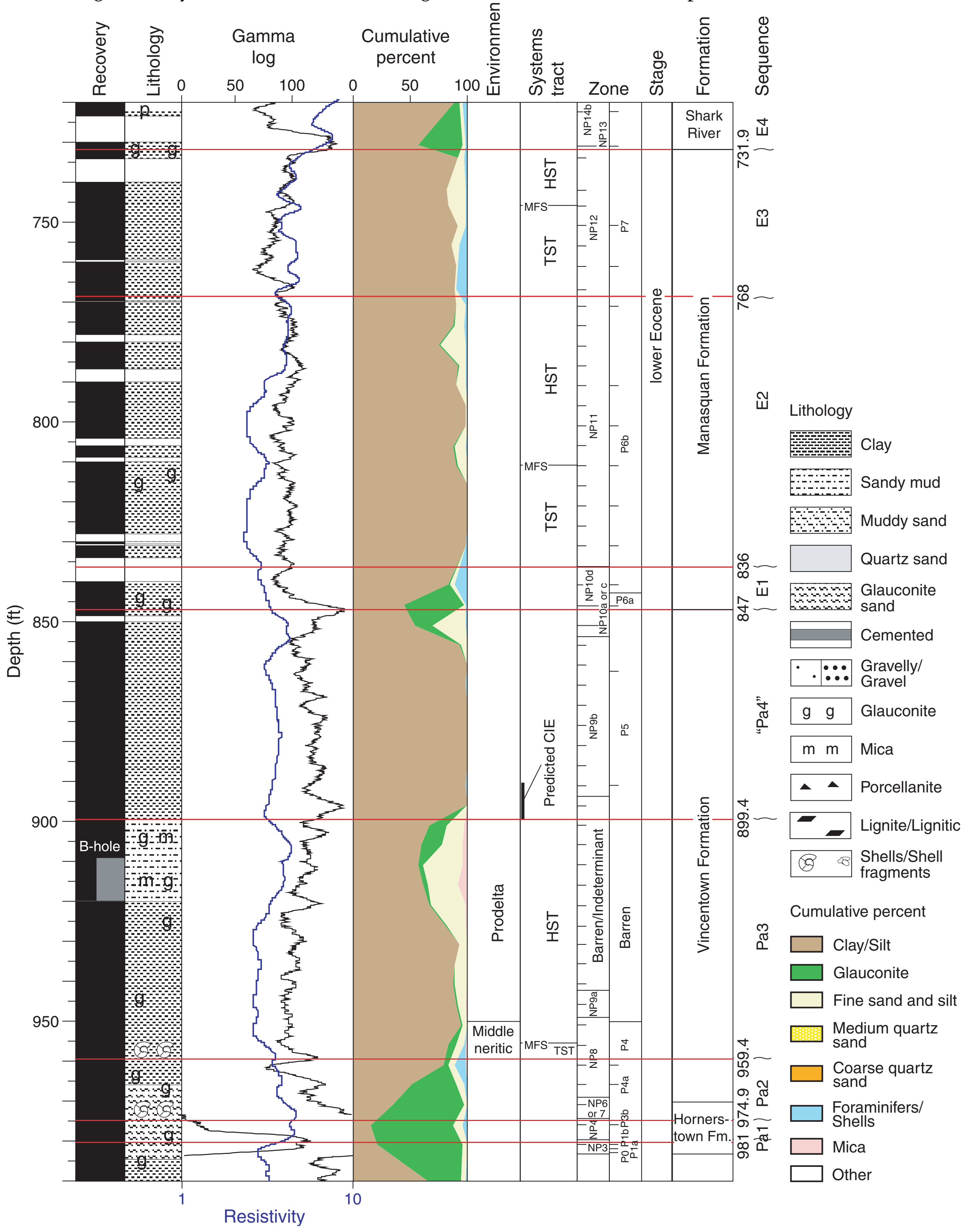

Figure F6. Summary stratigraphic section for the New Egypt equivalent (Maastrichtian), Navesink equivalent (Maastrichtian), Mount Laurel equivalent (late Campanian), Wenonah equivalent (late Campanian), Marshalltown Formation (late Campanian), Englishtown Formation (middle to late Campanian), Woodbury Formation (early to middle Campanian), Merchantville Formation (Santonian to earliest Campanian) and Cheesequake Formation (Santonian) from the Millville borehole. LSF = lowstand shoreface, dLSF = distal lower shoreface. HST = highstand systems tract, MFS = maximum flooding surface, TST = transgressive systems track, FS = flooding surface, CIE = carbon isotope excursion. Fm. = formation.

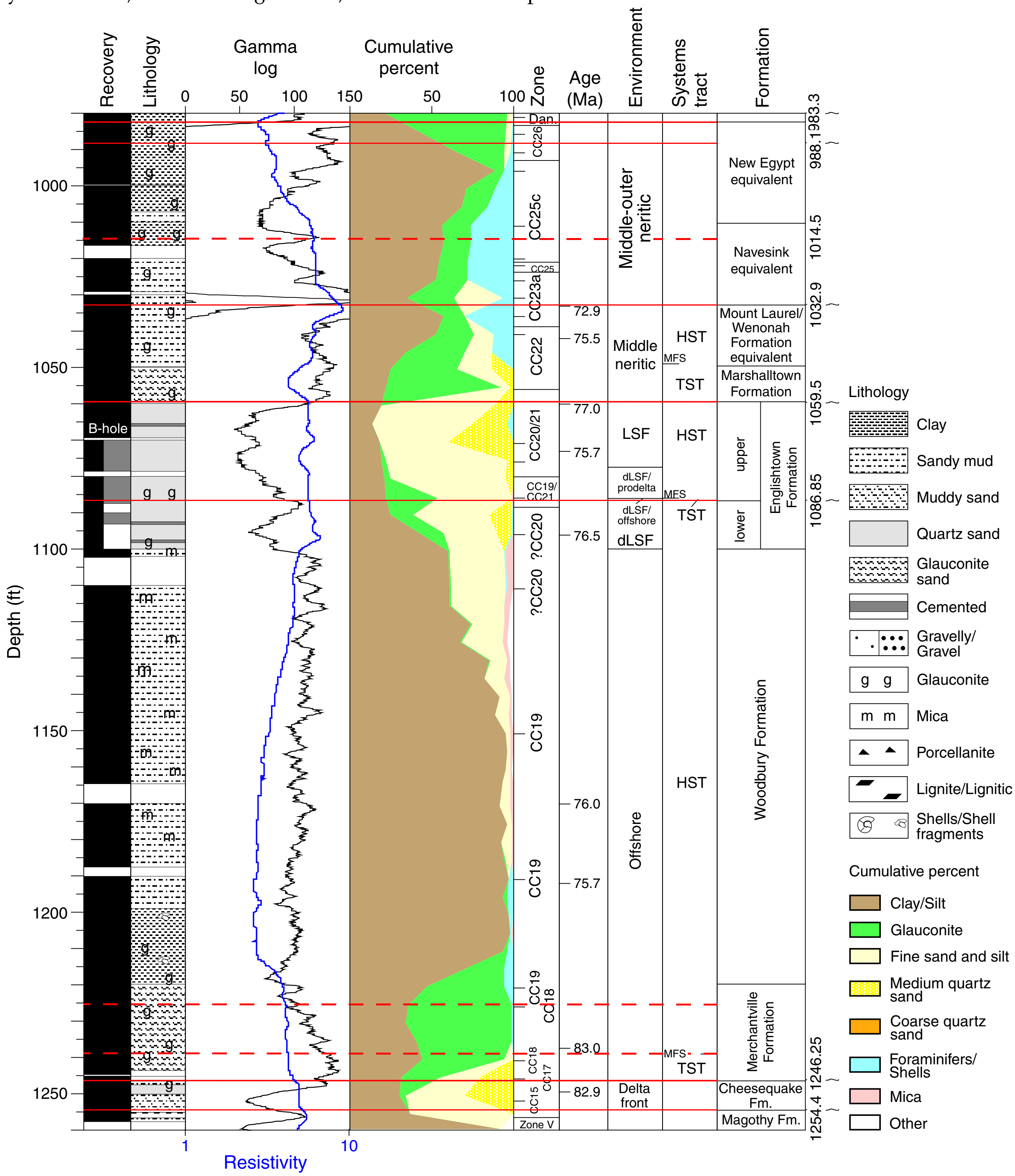

Figure F7. Summary stratigraphic section for the Magothy (Turonian or Coniacian), Bass River (Cenomanian to Turonian), and Potomac Formations (Cenomanian to ?Albian) from the Millville borehole. BRI = Bass River I sequence, BRII = Bass River II sequence, BRIII = Bass River III sequence. LSF = lowstand shoreface. HST = highstand systems tract, MFS = maximum flooding surface, TST = transgressive systems track, FS = flooding surface.

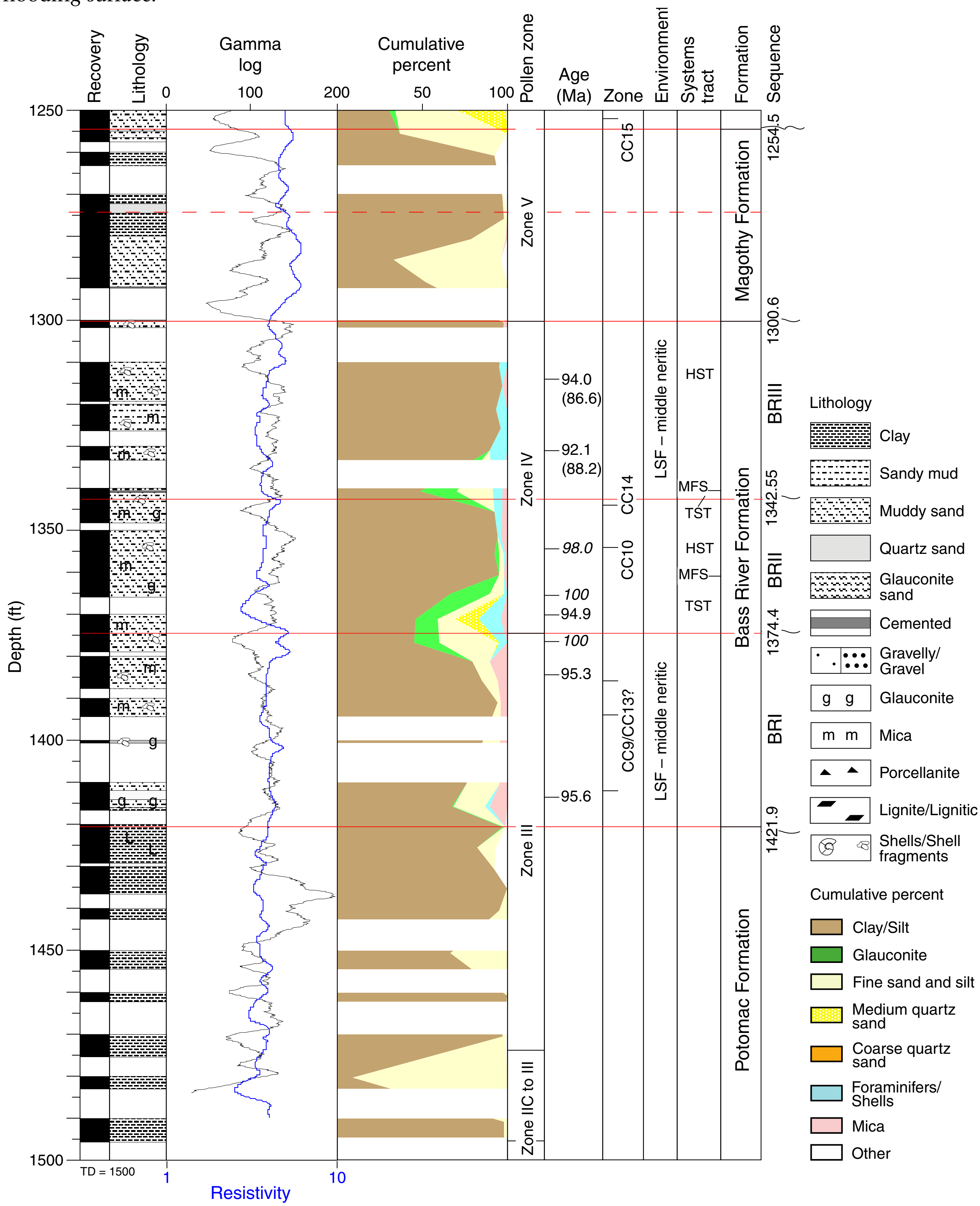

Figure F8. Correlation of lithologic units and aquifers for units recovered from the Millville borehole. Gray areas in the gamma and resistivity log columns indicate aquifers.

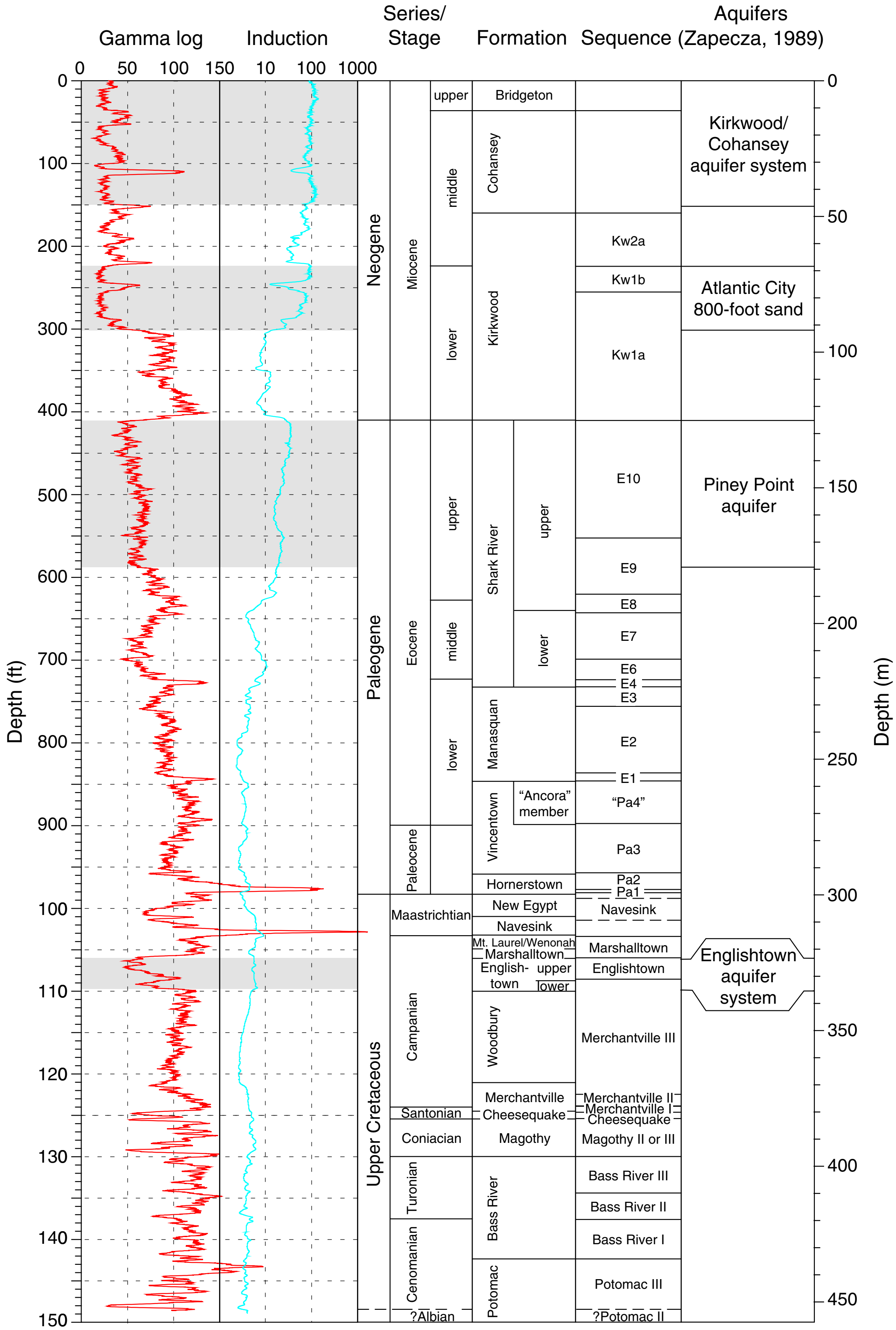

Figure F9. Representative sequence boundaries from the Millville borehole. Sequence boundary in the Englishtown Formation (1086.85 ft; 331.27 m) separates glauconite-rich sands above from fine–medium quartz sand below. Sequence boundary between the Cheesequake and Magothy Formations (1254.4 ft; 382.34 m) separates darker muddy sand above from pinkish gray fine sand with lignite below. Sequence boundary between the Brigantine and Shiloh Members of the Kirkwood Formation (223.6 ft; 68.15 m) separates blue-gray silty clays above from lignitic silty sands below. Sequence boundary between the Vincentown and Manasquan Formations (847 ft; 258.17 m) separates glauconitic sandy clay above from laminated clay with glauconite in burrows below. Sequence boundary between Bass River sequences II and III (1342.55 ft; 409.21 m) separates micaceous, slightly glauconitic muddy sand above from very micaceous silty clay below.

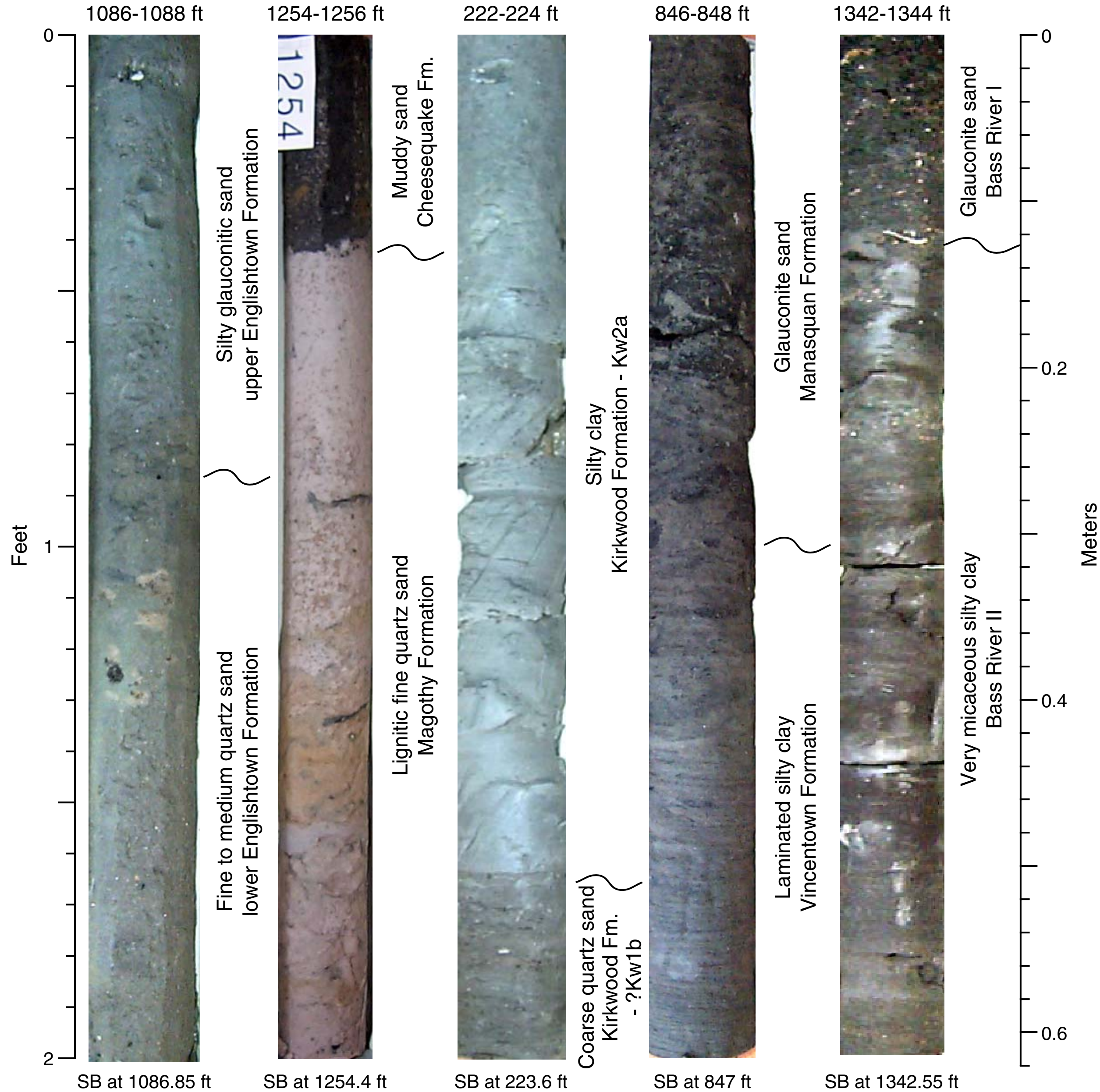

Figure F10. Age depth plot for the Miocene from the Millville borehole. Error bars are two standard deviations for one analysis (Oslick et al., 1994). Solid points are interpreted as diagenetically altered or stratigraphically reworked (see text). Thin horizontal lines indicate sequence boundaries. Timescale after Berggren et al. (1995). Fm. = formation.

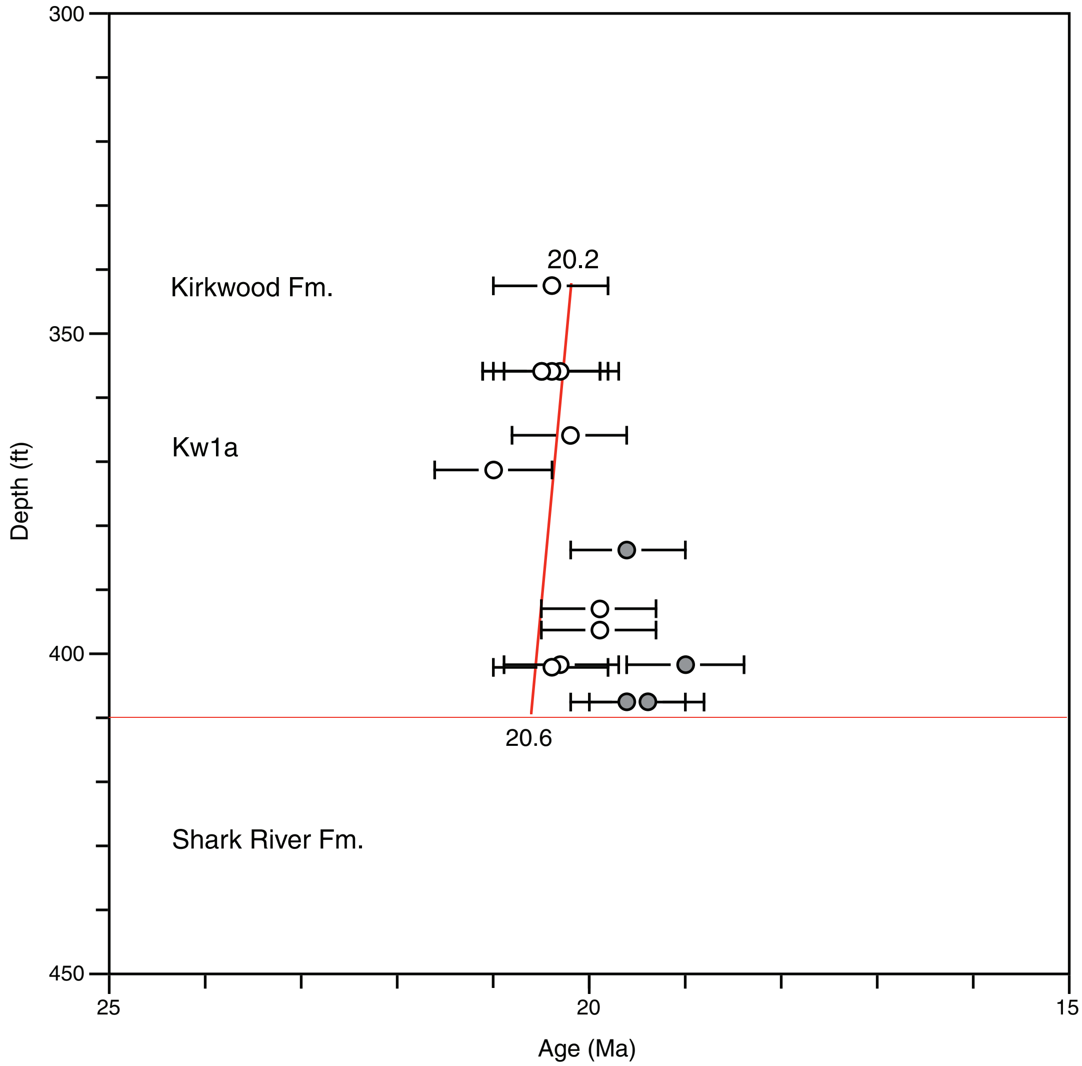

Figure F11. Age depth plot for the Cretaceous from the Millville borehole. Error bars are two standard deviations for one analysis (Oslick et al., 1994). Solid points are interpreted as diagenetically altered, stratigraphically reworked, or alternate age interpretations (see text). Thin black boxes represent pollen zones. Thin, red, horizontal lines indicate sequence boundaries. Blue boxes at bottom compare the ages of Cretaceous sequences in the Ancora, Bass River, Fort Mott, and Millville boreholes. Cross-hatches indicate uncertain ages. Sequence nomenclature of Miller et al. (2004). Biostratigraphic timescale correlations of Bralower et al. (1995) and Erba et al. (1995) are tied to the Gradstein et al. (1994) timescale. P = Potomac, BR = Bass River, M = Magothy, Ch = Cheesequake, ME = Merchantville, En = Englishtown, Ma = Marshalltown, Na = Navesink. (**Figure shown on next page.**)

Figure F11 (continued). (Caption shown on previous page.)

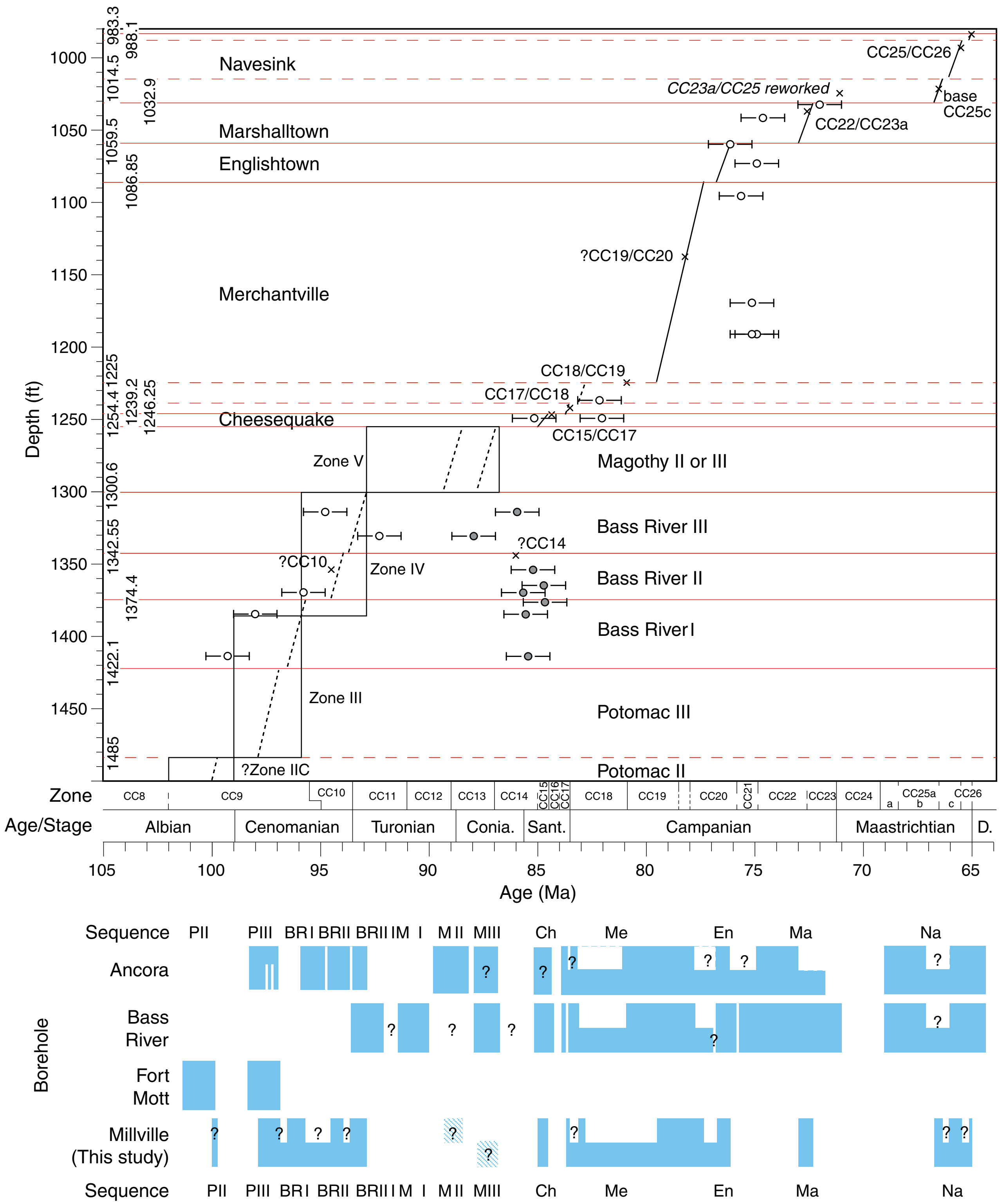

Table T1. Core descriptions, Millville borehole, Leg 174AX. (Continued on next 3 pages.)

Run number	Date (2002)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Lithology	Formation
1	4 May	1.5–5	3.5	2.90	83	Coarse to very coarse sand	Bridgeton
2	4 May	5–9	4.0	2.40	60	Slightly silty sandy gravel	Bridgeton
3	4 May	9–12	3.0	2.40	80	Silty sand; medium to coarse gravely sand	Bridgeton
4	4 May	12–15	3.0	2.50	83	Coarse to very coarse sand	Bridgeton
5	4 May	15–15.5	0.5	0.50	100	Very coarse sand	Bridgeton
6	4 May	15.5–20	4.5	0.40	9	Slightly silty sandy gravel	Bridgeton
7	4 May	20–25	5.0	3.20	64	Silty medium to very coarse sand	Bridgeton
8	4 May	25–30	5.0	3.20	64	Fine to medium sand; gravel layer	Bridgeton
9	4 May	30–31	1.0	0.90	90	Gravelly medium to coarse sand; medium to coarse sand	Bridgeton
10	5 May	31–35	4.0	2.65	66	Gravelly medium to coarse sand; medium to coarse sand	Bridgeton
11	5 May	35–40	5.0	2.65	53	Medium to coarse sand; clay; gravel; 37.4 ft contact	Bridgeton/Cohansey
12	5 May	40–43	3.0	0.40	13	Medium to very coarse sand	Cohansey
13	5 May	43–48	5.0	3.90	78	Laminated silty clay with sand interbeds	Cohansey
14	5 May	48–50	2.0	1.85	93	Silty clay??	Cohansey
15	5 May	50–55	5.0	4.00	80	Interbedded silty fine to very coarse sand and silty clay	Cohansey
16	5 May	55–60	5.0	4.15	83	Silty fine to medium sand	Cohansey
17	5 May	60–65	5.0	4.80	96	Silty fine to medium sand	Cohansey
18	5 May	65–70	5.0	4.50	90	Fine to medium sand w/clay laminae	Cohansey
19	5 May	70–75	5.0	4.40	88	Fine to medium sand	Cohansey
20	5 May	75–80	5.0	3.95	79	Fe-stained clayey sand	Cohansey
21	5 May	80–90	10.0	7.45	75	Silty fine to medium sand	Cohansey
22	5 May	90–100	10.0	9.25	93	Silty fine to medium sand	Cohansey
23	6 May	100–110	10.0	8.15	82	Alternating sand and clay; fine sand	Cohansey
24	6 May	110–114.5	4.5	3.90	87	Yellow clay; 111.4 ft contact; gray clay	Cohansey
25	6 May	114.5–120	5.5	4.70	85	Very dark gray clay; 115.3 ft contact; weathered clay; indurated zone; medium to coarse sand	Cohansey
26	6 May	120–124.5	4.5	2.60	58	Fine to coarse sand	Cohansey
27	6 May	124.5–130	5.5	2.25	41	Medium to very coarse sand; cyclic coarsening down	Cohansey
28	6 May	130–136	6.0	4.60	77	Medium to coarse sand; cyclic, coarsening down	Cohansey
29	6 May	136–140	4.0	2.90	73	Medium to coarse sand; cyclic, fining upward?	Cohansey
30	6 May	140–150	10.0	2.75	28	Medium to coarse sand	Cohansey
31	6 May	150–160	10.0	7.80	78	Medium sand; very fine sand; silty very fine sand with lignite	Cohansey
32	6 May	160–170	10.0	6.00	60	Interbedded clay, sand and silt	Kirkwood
33	6 May	170–180	10.0	4.90	49	Interbedded silty sand and sandy clay; mostly sand below 173 ft	Kirkwood
34	7 May	180–185	5.0	3.70	74	Interbedded silty sand and sandy clay	Kirkwood
35	7 May	185–190	5.0	4.30	86	Interbedded silty sand and sandy clay; burrowed contact at 185.7 ft	Kirkwood
36	7 May	190–200	10.0	9.20	92	Interbedded silty sand and sandy clay	Kirkwood
37	7 May	200–204	4.0	3.80	95	Silty sand	Kirkwood
38	7 May	204–210	6.0	0.80	13	Sand	Kirkwood
39	7 May	210–220	10.0	9.60	96	Silty sand	Kirkwood
40	7 May	220–225	5.0	4.65	93	Sand/clay contact	Kirkwood
41	7 May	225–230	5.0	4.40	88	Coarse to very coarse sand	Kirkwood
42	7 May	230–235	5.0	4.10	82	Coarse to very coarse sand	Kirkwood
43	7 May	235–240	5.0	3.60	72	Coarse to very coarse sand	Kirkwood
44	8 May	240–247.5	7.5	6.70	89	Coarse to very coarse sand	Kirkwood
45	8 May	247.5–255	7.5	7.50	100	Sand over laminated clay–silt/silty very fine sand	Kirkwood
46	8 May	255–262	7.0	6.00	86	Clay over sand	Kirkwood
47	8 May	262–270	8.0	6.40	80	Medium sand	Kirkwood
48	8 May	270–280	10.0	8.00	80	Interbedded sand	Kirkwood
49	8 May	280–290	10.0	6.30	63	Interbedded sand	Kirkwood
50	8 May	290–300	10.0	10.10	101	Sand	Kirkwood
51	8 May	300–310	10.0	5.85	59	Sand/clay contact	Kirkwood
52	9 May	310–320	10.0	9.50	95	Laminated clay/silt	Kirkwood
53	13 May	320–330	10.0	9.95	100	Laminated clay/silt	Kirkwood
54	13 May	330–340	10.0	8.50	85	Laminated clay/silt	Kirkwood
55	13 May	340–350	10.0	0.40	4	Clay	Kirkwood
56	13 May	350–355	5.0	0.40	8	Clay	Kirkwood
56A	13 May–14 May	?340.5–345?	0.0	3.30	34	Silty clay	Kirkwood
57	14 May	355–359	4.0	3.10	78	Slightly glauconitic clay contact slightly micaceous silty clay	Kirkwood
58	14 May	359–369	10.0	10.60	106	Slightly shelly to shelly silty clay	Kirkwood
59	14 May	369–379	10.0	10.50	105	Shelly silty clay; shell bed; 372.1 ft contact; uniform silty clay	Kirkwood

Table T1 (continued).

Run number	Date (2002)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Lithology	Formation
60	14 May	379–389	10.0	7.00	70	Uniform silty clay grading down to clay	Kirkwood
61	14 May	389–400	11.0	10.40	95	Clay; interbedded clay and silty clay; silty clay	Kirkwood
62	14 May	400–410	10.0	9.95	100	Slightly silty, slightly shelly clay; granuliferous silty, shelly, fine quartz sand	Kirkwood
63	14 May	410–420	10.0	7.45	75	Granuliuferous quartz sand/quartz–glauconite sand	upper Shark River
64	15 May	420–430	10.0	10.10	101	Shelly glauconitic medium sand	upper Shark River
65	15 May	430–440	10.0	0.60	6	Shelly glauconitic medium sand	upper Shark River
66	15 May	440–450	10.0	9.40	94	Shelly glauconite sand/thin clay beds	upper Shark River
67	15 May	450–460	10.0	10.00	100	Shelly glauconite sand and sandy clay	upper Shark River
68	15 May	460–470	10.0	7.90	79	Shelly glauconite sand and sandy clay	upper Shark River
69	15 May	470–480	10.0	9.50	95	Shelly glauconite sand and sandy clay	upper Shark River
70	15 May	480–490	10.0	7.75	78	Shelly glauconite sand and sandy clay	upper Shark River
71	16 May	490–500	10.0	9.95	100	Slightly shelly clayey glauconite–quartz sand with quartz glauconite sand interbeds	upper Shark River
72	16 May	500–510	10.0	10.20	102	Shelly clayey glauconite–quartz sand, claying down	upper Shark River
73	16 May	510–520	10.0	10.40	104	Clayey glauconite quartz sand with increasing clay	upper Shark River
74	16 May	520–530	10.0	10.00	100	Interbedded clayey glauconite quartz sand and glauconitic clay	upper Shark River
75	16 May	530–540	10.0	10.20	102	Shelly slightly clayey to clayey glauconitic quartz sand	upper Shark River
76	16 May	540–550	10.0	8.30	83	Shelly clayey glauconitic quartz sand; clay beds at 556.9–7.1 and 557.6–7.9 ft	upper Shark River
77	16 May	550–555	5.0	4.90	98	Shelly clayey glauconitic medium quartz sand grading down to glauconitic granuliferous medium to very coarse quartz sand	upper Shark River
78	16 May	555–560	5.0	5.80	116	Interbedded sandy clay and clayey medium to coarse sand	upper Shark River
79	16 May	560–570	10.0	8.90	89	Interbedded sandy clay and clayey medium to coarse sand	upper Shark River
80	17 May	570–580	10.0	9.70	97	Interbedded sandy clay and clayey medium to coarse sand	upper Shark River
81	17 May	580–590	10.0	10.30	103	Interbedded sandy clay and clayey medium to coarse sand	upper Shark River
82	17 May	590–600	10.0	10.50	105	Interbedded sandy clay and clayey medium to coarse sand	upper Shark River
83	17 May	600–610	10.0	10.40	104	Interbedded sandy clay and clayey medium to coarse sand	upper Shark River
84	17 May	610–620	10.0	9.45	95	Interbedded sandy clay and clayey medium to coarse sand	upper Shark River
85	17 May	620–625	5.0	0.50	10	Interbedded sandy clay and clayey medium to coarse sand	upper Shark River
86	17 May	625–630	5.0	4.90	98	Burrowed fine to medium glauconitic sand	upper Shark River
87	17 May	630–640	10.0	10.30	103	Medium glauconite sand; abundant mud–lined burrows	upper Shark River
88	17 May	640–650	10.0	3.75	38	Medium glauconite sand; abundant mud–lined burrows; 640.35 ft contact; underlain by silty clay with glauconite–filled burrows	upper Shark River/lower Shark River
89	18 May	650–651	1.0	0.00	0		lower Shark River
90	18 May	651–657.5	6.5	6.50	100	Silty clay	lower Shark River
91	18 May	657.5–665	7.5	7.20	96	Clay	lower Shark River
92	18 May	665–670	5.0	5.45	109	Clay	lower Shark River
93	19 May	670–675	5.0	4.70	94	Silt	lower Shark River
94	19 May	675–680	5.0	3.30	66	Silt with thin clay interbeds	lower Shark River
95	19 May	680–684	4.0	3.70	93	Silt with thin clay interbeds	lower Shark River
96	19 May	684–694	10.0	10.10	101	Interbedded silt/clay with glauconite at base	lower Shark River
97	19 May	694–700	6.0	5.00	83	Clayey silt with increasing glauconite	lower Shark River
98	19 May	700–710	10.0	10.70	107	Laminated clayey silt and clay	lower Shark River
99	19 May	710–720	10.0	9.85	99	Silty clay with porcellanite	lower Shark River
100	20 May	720–730	10.0	3.40	34	Clay	lower Shark River
101	20 May	730–740	10.0	4.25	43	Clay; 731.9 ft contact	lower Shark River/ Manasquan
102	20 May	740–745	5.0	5.80	116	Foraminiferal rich clay	Manasquan
103	20 May	745–754	9.0	9.30	103	Foraminiferal rich clay	Manasquan
104	20 May	754–760	6.0	5.40	90	Foraminiferal rich clay and minor claystone	Manasquan
105	20 May	760–770	10.0	9.80	98	Foraminiferal rich clay and minor claystone	Manasquan
106	21 May	770–780	10.0	8.20	82	Foraminiferal rich clay and minor claystone	Manasquan
107	21 May	780–790	10.0	6.40	64	Foraminiferal rich clay and minor claystone	Manasquan
108	21 May	790–797.5	7.5	8.00	107	Foraminiferal rich clay and minor claystone	Manasquan
109	21 May	797.5–803	5.5	4.50	82	Foraminiferal rich clay and minor claystone	Manasquan
110	22 May	803–806	3.0	1.25	42	Foraminiferal rich clay	Manasquan
111	22 May	806–810	4.0	2.80	70	Foraminiferal rich clay, slightly glauconitic	Manasquan

Table T1 (continued).

Run number	Date (2002)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Lithology	Formation
112	22 May	810–816	6.0	5.40	90	Foraminiferal rich clay, slightly glauconitic	Manasquan
113	22 May	816–820	4.0	5.20	130	Clay	Manasquan
114	22 May	820–830	10.0	8.15	82	Clay	Manasquan
115	22 May	830–840	10.0	4.50	45	Clay, slightly glauconitic	Manasquan
116	23 May	840–850	10.0	8.50	85	Clay, slightly glauconitic; 847 ft contact	Manasquan/Vincentown
117	23 May	850–860	10.0	10.10	101	Silty clay to clay	Vincentown
118	23 May	860–870	10.0	10.50	105	Clay	Vincentown
119	23 May	870–880	10.0	10.45	105	Clay	Vincentown
120	23 May	880–890	10.0	10.55	106	Clay	Vincentown
121	24 May	890–900	10.0	10.65	107	Clay; 899.25 ft contact; glauconitic clay	Vincentown
122	24 May	900–910	10.0	10.50	105	Glauconitic silty clay	Vincentown
123	24 May	910–920	10.0	10.30	103	Glauconitic silty to slightly silty clay	Vincentown
124	29 May	908B–910B	10.0	2.60	26	Glauconitic silty to slightly silty clay	Vincentown
125	29 May	910B–920B	10.0	10.25	103	Slightly glauconitic clayey silt	Vincentown
126	29 May	920–930	10.0	10.40	104	Slightly silty clay	Vincentown
127	29 May	930–937	7.5	7.70	103	Clay and silty clay	Vincentown
128	30 May	937–940	2.5	2.60	104	Micaceous, slightly glauconitic silty clay	Vincentown
129	30 May	940–950	10.0	9.70	97	Micaceous, slightly glauconitic silty clay	Vincentown
130	30 May	950–957.5	7.5	7.60	101	Micaceous, slightly glauconitic silty clay	Vincentown
131	30 May	957.5–960	2.5	2.33	93	Micaceous, slightly glauconitic silty clay; shell concentration at 959.1 ft	Vincentown
132	30 May	960–970	10.0	10.12	101	Glauconitic silty clay to very glauconitic clay	Vincentown
133	30 May	970–980	10.0	10.15	102	Glauconite sand; 970.2 ft contact	Vincentown/Hornerstown
134	31 May	980–985	5.0	5.20	104	Glauconite sand; clay with some glauconite sand, contact at 983.3 ft	Hornerstown/New Egypt
135	31 May	985–995	10.0	10.40	104	Clayey glauconite sand; clay with glauconite	New Egypt
136	31 May	995–1000	5.0	4.70	94	Clay with glauconitic sand	New Egypt
137	31 May	1000–1010	10.0	10.20	102	Silty clay with glauconite sand	New Egypt
138	31 May	1010–1020	10.0	6.40	64	Cemented foraminiferal rich clay and clayey glauconite sand	Red Bank/ Navesink
138A	1 Jun					Note: recovered 1.3 ft lost from bottom of Run 38 yesterday; added to 5.1 ft recovered yesterday	
139	1 Jun	1020–1030	10.0	9.10	91	Burrowed clayey silt with glauconitic sand	Navesink
140	1 Jun	1030–1040	10.0	10.20	102	Burrowed clayey silt or silty clay with and glauconite sand and some quartz sand; claystone; 1032.9 ft contact	Navesink/Mount Laurel–Wenonah
141	1 Jun	1040–1050	10.0	9.90	99	Clayey silt with increasing glauconite downward; glauconite sand at base; 1049.7 ft contact	Mount Laurel–Wenonah/ Marshalltown
142	1 Jun	1050–1060	10.0	10.10	101	Very silty sand or sandy silt; glauconite–rich; burrowed; 1059.5 ft contact	Marshalltown/ Englishtown
143	1 Jun	1060–1070	10.0	9.60	96	Very fine to fine, silty sand	Englishtown
144	2 Jun	1070–1080	10.0	8.65	87	Very fine to fine, silty sand	Englishtown
145	2 Jun	1080–1090	10.0	10.30	103	Very fine to fine, silty sand	Englishtown
146	2 Jun	1090–1100	10.0	10.10	101	Very fine to fine, silty sand	Englishtown
147	13 Jun	1070–1080B	10.0	8.50	85	Very fine to fine, silty sand	Englishtown
148	13 Jun	1080–1090B	10.0	7.40	74	Very fine to fine, silty sand; 1086.85 ft contact	Englishtown
149	13 Jun	1090–1100B	10.0	3	27	Very fine to fine, silty sand	Englishtown
150	14 Jun	1100–1110B	10.0	2.10	21	Micaceous, slightly sandy silty clay	Woodbury
151	14 Jun	1110–1120B	10.0	10.00	100	Micaceous, slightly sandy, slightly glauconitic silty clay	Woodbury
152	14 Jun	1120–1130	10.0	9.90	99	Micaceous, slightly sandy, slightly glauconitic silty clay	Woodbury
153	14 Jun	1130–1140	10.0	10.50	105	Slightly micaceous glauconitic silty clay	Woodbury
154	15 Jun	1140–1150	10.0	10.20	102	Slightly micaceous silty clay	Woodbury
155	15 Jun	1150–1160	10.0	10.40	104	Micaceous silty clay	Woodbury
156	15 Jun	1160–1170	10.0	4.70	47	Micaceous silty clay	Woodbury
157	15 Jun	1170–1180	10.0	10.25	103	Micaceous clay	Woodbury
158	15 Jun	1180–1190	10.0	7.60	76	Clayey silt	Woodbury
159	16 Jun	1190–1200	10.0	10.35	104	Silty clay	Woodbury
160	16 Jun	1200–1210	10.0	10.60	106	Silty clay	Woodbury
161	16 Jun	1210–1220	10.0	10.65	107	Clay changing to clayey glauconite sand; 1210.9 ft contact	Woodbury/Merchantville
162	16 Jun	1220–1230	10.0	10.30	103	Clayey glauconite sand	Merchantville
163	16 Jun	1230–1240	10.0	10.00	100	Clayey glauconite sand	Merchantville
164	17 Jun	1240–1245	5.0	4.60	92	Clayey glauconite sand	Merchantville
165	17 Jun	1245–1250	5.0	5.90	118	Clayey glauconite sand; sand and interbedded clay; 1246.25 ft contact	Merchantville/ Cheesequake
166	17 Jun	1250–1260	10.0	7.90	79	Clayey sand over oxidized sand, silt, and clay; 1254.4 ft contact	Cheesequake/Magothy
167	17 Jun	1260–1270	10.0	3.20	32	Mottled clay	Magothy

Table T1 (continued).

Run number	Date (2002)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Lithology	Formation
168	17 Jun	1270–1280	10.0	10.40	104	Mottled clay; gray clay at bottom	Magothy
169	18 Jun	1280–1285	5.0	4.95	99	Gray silty clay	Magothy
170	18 Jun	1285–1292	7.0	7.30	104	Gray silty clay	Magothy
171	18 Jun	1292–1300	8.0	0.20	3	Sandstone	Magothy
172	18 Jun	1300–1310	10.0	1.70	17	Sandstone; 1300.6 ft contact; gray shelly, silty clay	Magothy/Bass River
173	18 Jun	1310–1318.5	8.5	8.50	100	Gray shelly, silty clay	Bass River
174	19 Jun	1318.5–1320	1.5	1.20	80	Shelly micaceous very slightly silty clay	Bass River
175	19 Jun	1320–1330	10.0	6.15	62	Shelly micaceous clay	Bass River
176	19 Jun	1330–1340	10.0	3.25	33	Shelly slightly micaceous very slightly silty clay	Bass River
177	19 Jun	1340–1350	10.0	8.10	81	Shelly slightly micaceous silty clay	Bass River
178	19 Jun	1350–1360	10.0	10.55	106	Shelly slightly micaceous silty clay	Bass River
179	20 Jun	1360–1370	10.0	5.95	60	Shelly slightly micaceous silty clay	Bass River
180	20 Jun	1370–1380	10.0	9.00	90	Shelly slightly micaceous silty clay	Bass River
181	20 Jun	1380–1390	10.0	7.75	78	Shelly slightly micaceous silty clay	Bass River
182	20 Jun	1390–1400	10.0	4.40	44	Shelly slightly micaceous silty clay	Bass River
183	21 Jun	1400–1410	10.0	0.65	7	Slightly glauconitic shelly sandstone	Bass River
184	21 Jun	1410–1420	10.0	6.80	68	Silt; glauconite sand; silt; clay	Bass River
185	21 Jun	1420–1430	10.0	9.20	92	Clay; 1422.1 ft contact?	Bass River/Potomac
186	21 Jun	1430–1435	5.0	5.00	100	Clay	Potomac
187	22 Jun	1425–1440	5.0	1.65	33	Clay	Potomac
188	22 Jun	1440–1450	10.0	2.65	27	Clay	Potomac
189	22 Jun	1450–1452	2.0	2.15	108	Clay	Potomac
190	22 Jun	1452–1460	8.0	2.30	29	Clay	Potomac
191	22 Jun	1460–1470	10.0	2.10	21	Clay	Potomac
192	23 Jun	1470–1480	10.0	5.35	54	Clay	Potomac
193	23 Jun	1480–1490	10.0	3.00	30	Clay	Potomac
194	23 Jun	1490–1500	10.0	5.50	55	Clay	Potomac

Table T2. Data used to construct the cumulative percent logs in Figures F2–F7. (See **table notes.** Continued on next four pages.)

Sample depth (ft)	Clay and silt (%)	Glauconite (%)*	Fine quartz sand (%)*	Medium quartz sand (%)*	Coarse and coarser quartz sand (%)*	Carbonate (%)*	Mica (%)*	Other (%)*
6.0	10.30	0	4	21	64	0	0	0
11.0	9.06	0	4	59	27	0	0	0
13.7	11.51	0	5	54	29	0	0	0
21.0	6.63	0	3	77	13	0	0	0
26.0	11.90	0	7	77	4	0	0	0
31.3	10.89	0	5	29	55	0	0	0
36.5	18.39	0	5	66	11	0	0	0
43.4	83.08	0	11	6	0	0	0	0
48.4	19.15	0	78	3	0	0	0	0
52.8	13.64	0	23	32	31	0	0	0
57.1	9.44	0	25	63	3	0	0	0
62.1	4.30	0	29	66	0	0	0	0
66.4	4.42	0	79	16	0	0	0	0
71.6	7.47	0	72	20	0	0	0	0
77.2	13.79	0	71	15	0	0	0	0
80.1	19.49	0	65	15	0	0	0	0
84.5	11.34	0	60	28	0	0	0	0
90.2	12.40	0	26	57	4	0	0	0
96.2	12.45	0	40	42	5	0	0	0
100.2	15.90	0	28	52	3	0	0	0
105.1	7.89	0	89	3	0	0	0	0
113.0	98.37	0	1	0	0	0	0	0
117.1	3.59	0	13	48	36	0	0	0
121.2	5.38	0	7	70	17	0	0	0
125.0	3.38	0	10	69	17	0	0	1
132.2	6.26	0	9	73	12	0	0	0
136.5	3.94	0	4	79	13	0	0	0
141.0	4.90	0	14	74	6	0	0	0
151.2	21.30	0	15	62	1	0	0	0
156.5	8.49	0	46	45	0	0	0	0
160.2	9.27	0	54	37	0	0	0	0
165.0	34.22	0	59	7	0	0	0	0
171.3	50.82	0	46	4	0	0	0	0
182.2	5.26	0	18	77	0	0	0	0
186.5	11.85	0	15	66	7	0	0	0
192.2	71.49	0	28	0	0	0	0	0
197.5	71.12	0	23	6	0	0	0	0
201.0	13.32	0	82	4	0	0	0	0
204.7	2.68	0	39	58	0	0	0	0
211.0	13.64	0	46	40	0	0	0	0
216.0	11.66	0	30	56	3	0	0	0
231.0	2.13	0	4	80	14	0	0	0
236.0	2.78	0	11	70	16	0	0	0
241.0	2.88	0	7	86	4	0	0	0
246.0	3.37	0	24	59	13	0	0	0
250.7	26.23	0	53	21	0	0	0	0
255.0	26.01	0	43	31	0	0	0	0
256.0	8.87	0	35	57	0	0	0	0
261.0	2.74	0	19	78	0	0	0	0
266.5	2.51	0	34	63	0	0	0	0
271.0	2.07	0	23	75	0	0	0	0
276.0	4.32	0	81	15	0	0	0	0
281.0	7.44	0	85	7	0	0	0	0
286.0	13.66	0	22	50	15	0	0	0
291.0	23.61	0	31	41	4	0	0	0
296.0	18.34	0	29	49	5	0	0	0
301.0	7.03	0	20	70	3	0	0	1
305.0	88.59	0	10	2	0	0	0	0
311.0	94.81	0	5	0	0	0	0	0
316.5	98.70	0	1	0	0	0	0	1
321.0	99.23	0	1	0	0	0	0	0
326.2	97.56	0	2	0	0	0	0	0
331.0	99.56	0	0	0	0	0	0	0

Table T2 (continued).

Sample depth (ft)	Clay and silt (%)	Glauconite (%)*	Fine quartz sand (%)*	Medium quartz sand (%)*	Coarse and coarser quartz sand (%)*	Carbonate (%)*	Mica (%)*	Other (%)*
336.0	99.95	0	0	0	0	0	0	0
341.0	99.38	0	1	0	0	0	0	0
350.3	99.86	0	0	0	0	0	0	0
356.0	52.09	0	43	0	0	4	1	0
361.0	86.08	0	11	0	0	2	0	0
366.0	66.28	0	29	0	0	4	1	0
371.0	23.23	0	15	0	0	61	0	0
377.0	92.46	0	6	0	0	1	0	1
381.5	98.15	0	1	0	0	1	0	0
386.1	99.23	0	0	0	0	0	0	0
391.0	98.12	0	1	0	0	1	0	0
396.0	97.35	0	1	0	0	2	0	0
401.0	80.02	5	10	0	0	5	0	0
406.0	90.97	1	4	3	0	1	0	0
412.0	12.83	17	12	40	10	8	0	0
416.0	9.89	10	4	34	19	23	0	0
421.1	11.55	14	4	47	13	10	0	0
425.9	13.01	21	2	37	10	17	0	0
430.5	20.30	10	7	44	5	14	0	0
441.0	9.22	12	7	50	5	16	0	0
446.0	12.30	10	5	35	6	32	0	0
451.0	21.60	10	7	43	1	18	0	0
453.0	19.48	18	7	28	1	27	0	0
456.0	5.28	15	5	55	1	20	0	0
461.0	22.53	16	5	44	0	13	0	0
466.0	14.21	12	7	53	0	13	0	0
471.0	24.51	13	9	40	0	13	0	0
476.0	17.44	16	5	47	0	15	0	0
481.0	24.36	10	8	37	0	20	0	0
486.0	9.28	19	9	51	2	10	0	0
491.0	8.32	20	7	43	0	21	0	0
496.0	25.56	17	13	33	0	11	0	0
500.0	17.59	24	12	26	0	20	0	0
506.0	21.12	25	11	28	0	14	0	0
511.0	15.48	21	18	33	0	12	0	0
516.0	21.27	24	20	27	0	8	0	0
521.0	20.00	25	19	31	0	4	0	0
526.0	23.17	19	16	34	0	8	0	0
531.0	23.52	19	15	25	6	12	0	0
536.0	16.02	25	10	36	0	12	0	0
541.0	26.09	17	8	26	3	21	0	0
546.0	16.63	15	11	38	2	17	0	0
551.0	13.53	15	9	28	19	16	0	0
556.0	16.01	15	9	29	16	16	0	0
561.0	28.70	11	12	36	1	11	0	0
566.0	25.48	17	7	37	2	11	0	0
572.0	22.07	10	9	43	3	14	0	0
576.0	21.00	10	9	48	1	11	0	0
581.0	20.70	11	8	49	1	10	0	0
586.0	24.68	10	7	46	2	10	0	0
591.0	27.01	11	12	39	0	11	0	0
596.0	27.01	11	14	35	0	12	0	0
601.0	29.65	14	17	26	0	13	0	0
606.0	38.88	12	8	20	0	21	0	0
611.0	58.64	6	10	4	0	22	0	0
616.0	50.93	4	16	9	0	20	0	0
620.3	49.12	4	30	12	0	5	0	0
626.0	51.99	20	10	7	0	11	0	0
631.0	35.20	37	19	5	0	4	0	0
636.0	33.19	46	14	2	0	5	0	0
641.0	67.40	26	1	0	0	6	0	0
651.5	83.54	6	6	0	0	5	0	0
656.0	95.07	0	3	0	0	1	0	0
661.5	96.79	0	2	0	0	1	0	0
666.0	95.55	0	2	0	0	2	0	0
671.0	94.03	0	4	0	0	2	0	0
676.0	96.40	0	3	0	0	1	0	0

Table T2 (continued).

Sample depth (ft)	Clay and silt (%)	Glauconite (%)*	Fine quartz sand (%)*	Medium quartz sand (%)*	Coarse and coarser quartz sand (%)*	Carbonate (%)*	Mica (%)*	Other (%)*
681.0	91.87	0	4	0	0	4	0	0
686.0	98.48	0	1	0	0	1	0	0
691.0	96.15	1	1	0	0	2	0	0
696.0	66.25	27	0	0	0	7	0	0
701.0	89.14	0	0	0	0	11	0	0
706.0	88.32	0	0	0	0	11	0	0
711.0	84.74	0	0	0	0	15	0	0
716.5	79.80	6	6	0	0	8	0	0
722.5	88.32	5	4	0	0	4	0	0
731.0	57.10	39	3	0	0	1	0	0
734.0	91.61	0	5	0	0	3	0	0
742.0	81.59	1	16	0	0	2	0	0
746.0	83.13	1	14	0	0	2	0	0
751.0	91.34	0	7	0	0	1	0	0
756.0	86.30	0	7	0	0	7	0	0
761.0	90.95	0	1	0	0	8	0	0
767.0	88.77	0	1	0	0	10	0	0
771.0	90.04	0	7	0	0	2	0	0
776.0	88.07	1	9	0	0	2	0	0
781.0	75.15	0	22	0	0	2	0	0
786.0	92.17	0	7	0	0	1	0	0
791.0	90.14	0	9	0	0	1	0	0
796.0	98.88	0	1	0	0	0	0	0
801.0	99.33	0	0	0	0	1	0	0
806.2	87.84	1	11	0	0	1	0	0
811.0	90.60	0	8	0	0	0	0	0
816.0	99.79	0	0	0	0	0	0	0
821.0	99.92	0	0	0	0	0	0	0
826.0	99.94	0	0	0	0	0	0	0
831.2	98.74	0	0	0	0	1	0	0
841.0	83.73	1	5	0	0	11	0	0
846.0	44.43	53	2	0	0	1	0	0
851.0	54.80	15	29	0	0	1	0	0
856.0	92.73	2	5	0	0	0	0	0
861.0	99.41	0	0	0	0	1	0	0
866.0	99.24	0	0	0	0	1	0	0
871.0	99.68	0	0	0	0	0	0	0
876.0	99.61	0	0	0	0	0	0	0
881.0	99.49	0	0	0	0	1	0	0
886.0	99.39	0	0	0	0	1	0	0
891.0	98.77	0	0	0	0	1	0	0
896.0	99.35	0	0	0	0	0	0	0
901.0	66.07	15	15	0	0	0	3	0
906.0	59.64	18	18	0	0	0	4	0
911.0	57.10	4	34	0	0	0	4	0
916.0	61.67	4	27	0	0	0	8	0
921.0	66.41	2	30	0	0	0	2	0
926.0	80.28	1	18	0	0	0	1	0
931.0	93.14	0	6	0	0	0	0	0
936.0	88.25	1	11	0	0	0	1	0
941.0	87.89	1	11	0	0	0	1	0
946.0	89.64	2	7	0	0	0	1	0
951.0	94.21	2	3	0	0	0	0	0
956.0	83.59	7	7	0	0	2	1	0
961.0	78.53	4	5	0	0	11	1	0
966.0	51.41	39	7	0	0	2	0	0
971.0	34.51	62	3	0	0	0	0	0
976.0	14.57	73	9	0	0	4	0	0
981.0	21.20	75	4	0	0	0	0	0
991.0	65.30	29	3	0	0	2	0	0
996.0	88.60	6	0	0	0	6	0	0
1001.0	71.17	17	0	0	0	12	0	0
1006.0	68.12	16	0	0	0	16	0	0
1011.0	56.30	17	0	0	0	26	0	0
1016.0	57.63	17	0	0	0	25	0	0
1021.0	54.32	18	0	0	0	27	0	0
1026.0	53.20	19	0	0	0	28	0	0

Table T2 (continued).

Sample depth (ft)	Clay and silt (%)	Glauconite (%)*	Fine quartz sand (%)*	Medium quartz sand (%)*	Coarse and coarser quartz sand (%)*	Carbonate (%)*	Mica (%)*	Other (%)*
1031.0	35.09	29	29	0	0	6	0	0
1036.0	57.75	13	0	0	0	30	0	0
1041.0	52.71	24	12	0	0	12	0	0
1046.0	34.72	36	16	0	0	13	0	0
1051.0	25.02	41	21	13	0	0	0	0
1056.0	21.76	70	6	2	0	0	0	0
1061.0	19.58	0	69	12	0	0	0	0
1066.0	14.07	0	61	21	0	4	0	0
1071.0	18.30	0	42	40	0	0	0	0
1076.0	19.59	2	74	4	0	0	0	0
1081.0	21.30	4	70	4	0	0	0	0
1086.2	22.64	31	45	0	0	0	0	0
1091.0	24.98	14	46	14	0	1	0	0
1096.0	42.68	15	33	9	0	1	0	0
1101.0	60.25	1	33	0	0	0	5	0
1111.0	60.78	1	34	0	0	0	4	0
1116.0	61.54	1	32	0	0	0	4	2
1121.0	74.36	1	20	0	0	0	3	3
1126.0	67.85	1	25	0	0	0	3	3
1131.0	85.50	0	11	0	0	0	2	1
1136.0	82.64	0	12	0	0	0	3	2
1141.0	91.46	0	6	0	0	0	1	1
1146.0	88.72	0	8	0	0	0	2	1
1151.0	95.26	0	2	0	0	0	2	0
1156.0	96.35	0	2	0	0	0	1	0
1161.0	95.51	0	2	0	0	0	2	0
1164.5	93.18	0	5	0	0	0	2	0
1171.0	91.85	0	6	0	0	0	2	0
1176.0	96.64	0	3	0	0	0	1	0
1181.0	92.68	0	6	0	0	0	1	0
1186.0	94.70	0	4	0	0	1	1	0
1191.0	96.92	0	0	0	0	3	0	0
1196.0	93.05	3	0	0	0	3	0	0
1201.0	97.56	0	0	0	0	2	0	0
1206.0	97.90	0	0	0	0	1	1	0
1211.0	93.17	3	0	0	0	4	0	0
1216.0	71.00	23	0	0	0	6	0	0
1221.0	47.51	47	0	0	0	5	0	0
1226.0	36.28	63	0	0	0	1	0	0
1231.0	33.76	65	1	0	0	1	0	0
1236.0	40.63	58	1	0	0	1	0	0
1241.0	44.59	50	6	0	0	0	0	0
1246.0	31.91	24	24	21	0	0	0	0
1251.0	30.61	4	36	29	0	0	0	0
1256.0	37.13	0	63	0	0	0	0	0
1261.0	92.74	0	0	0	0	0	0	7
1271.0	96.76	0	2	0	0	0	0	2
1276.0	98.50	0	2	0	0	0	0	0
1281.0	78.42	0	20	0	0	0	1	0
1286.0	33.33	0	63	0	0	0	0	3
1291.0	51.99	0	48	0	0	0	0	0
1300.8	97.78	0	0	0	0	0	2	0
1311.3	95.14	0	0	0	0	5	0	0
1316.0	97.24	0	0	0	0	0	2	0
1321.5	93.68	0	0	0	0	6	0	0
1326.0	96.62	0	0	0	0	3	0	0
1331.2	89.97	0	0	0	0	10	0	0
1341.2	49.29	21	21	0	0	5	3	0
1346.0	92.60	0	0	0	0	4	3	0
1351.5	94.80	0	0	0	0	2	4	0
1356.0	92.21	3	3	0	0	1	1	0
1361.0	95.32	0	2	0	0	0	2	0
1365.5	66.27	24	8	0	0	2	0	0
1371.3	46.00	13	11	13	0	13	4	0
1377.0	45.28	15	35	1	0	5	0	0
1381.5	79.30	0	10	0	0	0	10	0
1386.0	85.34	0	9	0	0	0	6	0

Table T2 (continued).

Sample depth (ft)	Clay and silt (%)	Glauconite (%)*	Fine quartz sand (%)*	Medium quartz sand (%)*	Coarse and coarser quartz sand (%)*	Carbonate (%)*	Mica (%)*	Other (%)*
1391.5	94.29	0	2	0	0	1	3	0
1411.0	75.61	0	20	0	0	0	5	0
1416.0	67.64	1	19	0	0	3	10	0
1421.0	96.75	1	1	0	0	0	0	1
1426.0	82.84	0	10	0	0	0	0	7
1431.0	92.24	0	0	0	0	0	0	8
1435.8	99.77	0	0	0	0	0	0	0
1441.0	95.45	0	5	0	0	0	0	0
1451.0	66.37	0	34	0	0	0	0	0
1461.0	99.73	0	0	0	0	0	0	0
1471.0	97.45	0	2	0	0	0	0	1
1480.7	9.42	0	91	0	0	0	0	0
1491.0	97.75	0	2	0	0	0	0	0
1495.0	98.04	0	2	0	0	0	0	0

Note: Figure F2, p. 57. Figure F3, p. 58. Figure F4, p. 59. Figure F5, p. 60. Figure F6, p. 61. Figure F7, p. 62.

Table T3. Cenozoic planktonic foraminiferal occurrences. (See **table note.** Continued on next three pages.)

Sample depth (ft):	356.0	360	366	381.5	386.1	396.1	406.1	416	426	441	451	461	471	481	486	496	506	516	526	536	541	551	561	601	611	616	620.3	626	636
Preservation:	B	F	B	B	F	F	F	F	B	B	G	B	B	B	B	B	P	B	B	B	F	F	B	P	F	B	B	G	F
Planktonic foraminiferal zone:		M1b	M1b	M1b	M1b	M1b	M1b	P16	P16	P16	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P14/P16	P14/P16
Acarinina africana																													
Acarinina angulosa																													
Acarinina aspensis																													
Acarinina bullbrooki																													
Acarinina cuneicamerata																													
Acarinina mckannai																													
Acarinina esnaensis																													
Acarinina nitida																													
Acarinina pentacamerata																													
Acarinina primitiva																													
Acarinina pseudotopilensis																													
Acarinina soldadoensis																													
Acarinina spinuloinflata																													
Acarinina strabocella																													
Catapsydrax																					X								
Globanomalina chapmanni																													
Globanomalina pseudomenardii																													
Globanomalina *luxorensis*																													
Globanomalina planoconica																													
Globigerina sp.		X						X																					
Globigerina anguliofficinalis					X																								
Globigerina praebulloides						X					?						X				?								
Globigerina woodi					X																								
Globigerinatheka mexicana																					X								
Globigerinoides trilobus		X					X																						
Globoquadrina dehiscens							X																						
Igorina tadjikistanensis																													
Morozovella acuta																													
Morozovella aequa																													
Morozovella angulata																													
Morozovella apanthesma																													
Morozovella aragonensis																													
Morozovella edgari																													
Morozovella formosa																													
Morozovella gracilis																													
Morozovella lensiformis																													
Morozovella occlusa																													
Morozovella praeangulata																													
Morozovella quetra																													
Morozovella spinulosa																													X
Morozovella subbotinae																													
Morozovella velascoensis																													
Parasubbotina eoclava																													
Parasubbotina griffinae																													
Pseudoglobigerinella bolivariana																													
Pseudohastigerina sharkriverensis																													
Pseudohastigerina wilcoxensis																													
Subbotina eocaena											X						X								X				
Subbotina frontosa																													
Subbotina hornibrooki																													
Subbotina inaequispira																						X							
Subbotina linaperta																						X			X			X	
Subbotina lozanoi																													
Subbotina roegnesensis																													
Subbotina senni																													

Table T3 (continued).

Sample depth (ft):	356.0	360	366	381.5	386.1	396.1	406.1	416	426	441	451	461	471	481	486	496	506	516	526	536	541	551	561	601	611	616	620.3	626	636
Preservation:	B	F	B	B	F	F	F	F	B	B	G	B	B	B	B	B	P	B	B	B	F	F	B	P	F	B	B	G	F
Planktonic foraminiferal zone:		M1b	M1b	M1b	M1b	M1b	M1b	P16	P16	P16	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P16/P17	P14/P16	P14/P16
Subbotina triangularis																													
Subbotina velascoensis																													
Turborotalia cerroazulensis											X																		
Turborotalia pomeroli																												X	X
Turborotalia possagnoensis																													
Truncorotaloides rohri																													
Tenuitella gemma																								X				X	
Total count by zone:	0	2	0	0	2	1	2	1	0	0	3	0	0	0	0	0	2	0	0	0	3	2	0	1	2	0	0	3	2

Note: G = good, F = fair, P = poor, B = barren.

Table T3 (continued).

Sample depth (ft):	656	666	676	686	691	701	711	722.5	731	751	761	771	791	801	811	841	846	866	891	951	956	961	966	970	976	981	
Preservation:	G	F	F	F	F	F	F	F	F	F	F	G	G	F	F	G	G	F	F	F	F	F	F	F	F	P	
Planktonic foraminiferal zone:	P12	P12	P11	P11	P11	P9/P10	P9/P10	P9/P10	P8	P8	P8	P6b	P6b	P6b	P6b	P6b	P6a	P5	P5			P4a	P4a	P3b			Total count by species
Acarinina africana																		X									1
Acarinina angulosa							X	X	X	X	X	X	X	X	X	X	X										11
Acarinina aspensis						X																					1
Acarinina bullbrooki	X	X			X	X		X																			6
Acarinina cuneicamerata						X	X	X			X		X														5
Acarinina mckannai																							X				1
Acarinina esnaensis																			X			X					2
Acarinina nitida										X	X																2
Acarinina pentacamerata		X				X	X	X	X			X	X			X											9
Acarinina primitiva			X										X		X			X									4
Acarinina pseudotopilensis		X		X	X			X	X	X	X	X	X														9
Acarinina soldadoensis													X	X	X	X	X										5
Acarinina spinuloinflata		X		X				X	X																		4
Acarinina strabocella																								X			1
Catapsydrax																											1
Globanomalina chapmanni																							X				1
Globanomalina pseudomenardii																						X	X				2
Globanomalina luxorensis																		X									1
Globanomalina planoconica																		X									1
Globigerina sp.																											2
Globigerina angulioffic inalis																											1
Globigerina praebulloides																											4
Globigerina woodi																											1
Globigerinatheka mexicana																											1
Globigerinoides trilobus																											2
Globoquadrina dehiscens																											1
Igorina tadjikistanensis																								X			1
Morozovella acuta																						X					1
Morozovella aequa												X	X		X	X	X	X									6
Morozovella angulata																						X	X		X		3
Morozovella apanthesma																	X					X	X				3
Morozovella aragonensis			X		X					X	X																4
Morozovella edgari												X															1
Morozovella formosa												X	?			?											3
Morozovella gracilis														X	X	X											3
Morozovella lensiformis													X			?											2
Morozovella occlusa																					X						1
Morozovella praeangulata																								X			1
Morozovella quetra	X										X	X															3
Morozovella spinulosa																											2
Morozovella subbotinae												X	X	X	X	X		X									6
Morozovella velascoensis																		X									1
Parasubbotina eoclava						X																					1
Parasubbotina griffinae									X		X	X			X	X											5
Pseudoglobigerinella bolivariana								X																			1
Pseudohastigerina sharkriverensis							X		X																		2
Pseudohastigerina wilcoxensis		X		X						X	X	X															6
Subbotina eocaena	X	X	X	X	X	X	X			X																	12
Subbotina frontosa	X	X	X	X			X	X																			7
Subbotina hornibrooki									X	X									X								3
Subbotina inaequispira												X			X												3
Subbotina linaperta				X	X	X	X	X	X	X		X	X	X	X												14
Subbotina lozanoi			X	X	X	X			X	X																	6
Subbotina roegnesensis																X		X									2
Subbotina senni					X	X	X																				3

Table T3 (continued).

Sample depth (ft):	656	666	676	686	691	701	711	722.5	731	751	761	771	791	801	811	841	846	866	891	951	956	961	966	970	976	981	
Preservation:	G	F	F	F	F	F	F	F	F	F	F	G	G	F	F	G	G	F	F	F	F	F	F	F	F	P	
Planktonic foraminiferal zone:	P12	P12	P11	P11	P11	P9/P10	P9/P10	P9/P10	P8	P8	P8	P6b	P6b	P6b	P6b	P6b	P6a	P5	P5			P4a	P4a	P3b			Total count by species
Subbotina triangularis																X		X			X	X			X		5
Subbotina velascoensis																X	X	X	X	X	X	X			X		8
Turborotalia cerroazulensis																											1
Turborotalia pomeroli																											2
Turborotalia possagnoensis				X	X																						3
Truncorotaloides rohri	X	X		X																							3
Tenuitella gemma																											2
Total count by zone:	5	8	5	9	8	9	8	9	9	9	8	12	11	5	9	12	5	10	3	1	3	7	5	3	3	0	

Table T4. Cenozoic benthic foraminiferal occurrences. (Continued on next page.)

Sample depth (ft):	356.0	361.0	366.0	381.5	386.1	396.1	406.1	416.0	426.0	441.0	451.0	461.0	471.0	481.0	486.0	496.0	506.0	516.0	526.0	536.0	541.0	551.0	561.0	601.0	611.0	616.0	620.3	626.0	636.0	651.5	656.0	666.0	676.0
Agglutinated spp.																																	
Alabamina											X		X	X				X		X	X		X		X	X	X	X		X			
Allomorphina																																	
Anomalinoides acuta																																	
Bolivina				X																								X		X			
Bulimina																														X		X	
Bulimina macilenta																																	
Caucasina elongata	X	X	X		X	X	X																										
Cibicidina																		X			X								X			X	
Cibicidoides		X								X	X	X	X	X				X	X		X	X	X	X	X	X	X	X		X			
Cibicidoides aff. *subspiratus*																														X	X	X	X
Cibicidoides beckmanni																																X	X
Cibicidoides cf. *pseudoungerianus*								X	X	X	X	X	X	X	X	X	X	X	X		X	X		X	X	X	X	X	X	X	X		
Cibicidoides eocaena																																	
Cibicidoides mimulus																																	
Cibicidoides subspiratus																															X		X
Clavulina																																	
Dentalina																																	
Discorbis									X		X			X		X	X			X		X	X	X	X			X					
Ellipsonodosaria paleocenica																																	
Eponides																																	
Falsoplanulina ammophila																																	
Fursenkoina																																	
Gavelinella																																	
Globobulimina																		X	X	X	X							X					
Globocassidulina											X																						
Guttulina			X			X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Gyroidina obesa																																	
Gyroidina subangulata																																	
Gyroidinoides											X	X	X	X			X	X	X		X		X		X	X	X	X	X	X	X	X	X
Hanzawaia		X					X			X											X	X	X	X					X	X			
Lagaena			X				X														X												
Lenticulina							X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X		X	X	X	X	X	X
Marginulinopsis																																	
Massalina decorata																																	
Melonis																												X	X	X		X	
Nodosarids								X	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X
Nonionellina pizarensis	X	X		X	X	X	X																						X				
Oridorsalis																																	
Osangularia																												X					
Pararotalia stellata											X																						
Parella																																	
Percultazonaria																															X		X
Pleurostomella																																	
Polymorphina						X	X	X			X						X			X													
Pullenia																																	
Pulsiphonina prima																																	
Quinqueloculina											X		X															X					
Ramulina globulifera																																	
Sigmoidella		X				X				X	X																						
Sigmomorphina							X						X	X		X	X					X	X	X						X		X	
Siphonina							X																					X	X	X			
Spiroplectammina mississippiensis	X						X	X					X	X		X					X				X		X						
Spiroplectammina spectabilis																																	
Stilostomella																														X			X
Textularia		X	X				X																							X			X
Trifarina																																	
Triloculina											X			X			X			X	X												
Turrilina robertsi																																	
Uvigerina	X			X		X	X				X			X			X											X	X	X			
Vaginulinopsis midwayensis																																	

Table T4 (continued).

Sample depth (ft):	686.0	691.0	701.0	711.0	722.5	731.0	734.0	742.0	746.0	751.0	761.0	771.0	791.0	801.0	811.0	816.0	826.0	831.0	841.0	846.0	866.0	891.0	951.0	956.0	961.0	966.0	976.0
Agglutinated spp.	x	x	x	X		X				X		X	X		X	X						X					
Alabamina		X		X		X			X																		
Allomorphina																									X		
Anomalinoides acuta		X		X	X	X			X		X		X	X	X	X	X	X	X		X	X	X	X	X	X	X
Bolivina																											
Bulimina		X																				X					
Bulimina macilenta																							X				
Caucasina elongata																											
Cibicidina	X																										
Cibicidoides																			X	X	X	X		X	X		X
Cibicidoides aff. *subspiratus*						X		X																			
Cibicidoides beckmanni	X		X	X	X	X				X			X	X													
Cibicidoides cf. *pseudoungerianus*		X	X		X	X	X		X	X	X		X														
Cibicidoides eocaena					X	X				X	X	X	X		X			X	X		X						
Cibicidoides mimulus										X	X	X							X	X							
Cibicidoides subspiratus	X	X	X	X	X		X	X	X																		
Clavulina																							X	X			
Dentalina																					X				X	X	
Discorbis																											
Ellipsonodosaria paleocenica																									X		
Eponides								X					X						X								
Falsoplanulina ammophila			X		X				X	X	X	X															
Fursenkoina												X															
Gavelinella													X		X				X	X		X	X	X	X	X	
Globobulimina				X	X								X							X	X		X	X			
Globocassidulina																											
Guttulina	X	X	X	X	X	X					X								X					X			
Gyroidina obesa																					X						
Gyroidina subangulata																					X						
Gyroidinoides	X	X	X	X	X	X									X						X	X					X
Hanzawaia			X			X			X										X								
Lagaena																			X								
Lenticulina	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X			X	X	X			X			X
Marginulinopsis																					X			X			
Massalina decorata			X																								
Melonis	X											X						X		X							
Nodosarids	X	X	X	X	X		X	X	X	X	X		X		X	X	X	X	X	X	X	X	X		X		
Nonionellina pizarensis																											
Oridorsalis								X		X	X							X									
Osangularia															X							X	X				
Pararotalia stellata																											
Parella										X			X	X	X				X								
Percultazonaria	X	X	X	X		X		X		X	X	X			X			X	X	X							
Pleurostomella																				X	X		X				
Polymorphina																											
Pullenia												X	X					X						X			
Pulsiphonina prima															X												
Quinqueloculina																											
Ramulina globulifera											X																
Sigmoidella																											
Sigmomorphina		X	X	X																							
Siphonina						X	X							X													
Spiroplectammina mississippiensis			X					X													X		X				
Spiroplectammina spectabilis								X		X	X																
Stilostomella		X	X			X		X			X				X	X		X	X	X	X	X			X	X	
Textularia	X				X														X	X					X		
Trifarina										X	X						X				X						
Triloculina																											
Turrilina robertsi								X			X					X	X		X								
Uvigerina															X												
Vaginulinopsis midwayensis																								X		X	

Table T5. K/P boundary planktonic foraminiferal occurrences. (Continued on next page.)

Period/Epoch:	Cretaceous																				
Sample depth (ft):	1026.0	1021.0	1016.0	1011.0	1006.0	1000.0	996.0	991.0	990.1	990.0	989.0	988.0	987.0	986.0	985.0B	985.0A	984.0	983.9	983.8	983.7	983.6	983.5
Chiloguembelina midwayensis																						
Chiloguembelina morsei																						
Eoglobigerina edita																						
Eoglobigerina eobulloides																						
Globanomalina archeocompressa																						
Globanomalina planocompressa																						
Globoconusa daubjergensis																						
Guembelitria cretacea	X		X	X	X	X	X	X						X		X	X					X
Parasubbotina aff. *pseudobulloides*																						
Parasubbotina pseudobulloides																						
Parasubbotina varianta																						
Parvularugoglobigerina cf. *eugubina*																						
Parvularugoglobigerina eugubina																						
Praemurica cf. *taurica*																						
Praemurica pseudoinconstans																						
Praemurica taurica																						
Subbotina triloculinoides																						
Subbotina trivialis																						
Woodringina cf. *hornerstownensis*																						
Woodringina claytonensis																						
Woodringina hornerstownensis																						
Archeoglobigerina blowi	X	X	X		X	X	X															
Archeoglobigerina cretacea	X	X	X	X		X	X	X														
Contusatruncana contusa					X																	
Gansserina gansseri				X		X	X															
Globigerinelloides escheri						X	X	X			F	X	X									
Globigerinelloides multispina	X	X	X	X	X	X	X	X		X	X	X	X			X	X					X
Globigerinelloides prairiehillensis	X	X	X	X	X	X	X															
Globigerinelloides subcarinata	X			X						X	X		X	X			X					
Globotruncana aegyptiaca				X		X					X	X		X		X	X					X
Globotruncana arca		X	X	X	X		X	X				X		X		X	X					X
Globotruncana bulloides	X	X	X		X	X	X															
Globotruncana deuplesi							X															
Globotruncana lapparenti	X		X	X	X																	
Globotruncana linneiana	X		X																			
Globotruncana rosetta	X		X																			
Globotruncana tricarinata																	X					
Globotruncana ventricosa	X						cf.															
Globotruncana weidermeyeri						X																
Globotruncanita angulata			X								X											
Globotruncanita stuartiformis				X																		
Globotruncanella petaloidea		X	X	X	X	X	X					X										
Heterohelix globulosa	X	X	X	X	X	X	X	A		X	A	A	A	A		A	A					A
Heterohelix punctulata				X	X	X	X	X				X		X		X	X					
Hedbergella holmdelensis			X	X																		
Hedbergella monmouthensis																						X
Hedbergella sliteri																	cf.					
Laeviheterohelix dentata				X	X	X		X		X	F	X	X	X		X	X					
Laeviheterohelix glabrata	X	X	X	X	X	X																
Planoglobulina acervulinoides					X			X														
Planoglobulina carseyae													X			X	X					
Pseudoguembelina costulata		X		X	X	X	X	X				X	X			X	X					X
Pseudoguembelina hariaensis						X	X	cf.			X	X	X	X		X						X
Pseudotextularia elegans		X		X	X	X	X					1	2	4		3						
Pseudotextularia nuttalli													X									
Racemiguembelina powelli														X			X					
Rosita fornicata		X	X																			
Rugoglobigerina																						
Rugoglobigerina hexacamerata				X	X	X	X				X		X	X			X					
Rugoglobigerina macrocephala			X	X			X	X				X	X			X	X					
Rugoglobigerina reicheli				X						X		X				X	X					X
Rugoglobigerina rotundata													X			X						
Rugoglobigerina rugosa	X	X	X	X			X	X		X	X	X	X	X			X					X
Rugoglobigerina scotti												X	X				X					
Rugotruncana subcircumnodifer			?			X																

Table T5 (continued).

Sample depth (ft):	983.45	983.4	983.31	983.3	983.25	983.2	983.15	983.1	983.05	983.0	982.95	982.9	982.85	982.8	982.7	982.6	982.5	982.4	982.3	982.2	982.1	982.0	981.0
Period/Epoch:	Cretaceous									Danian													
Chiloguembelina midwayensis														X	X	X	X	X			X		
Chiloguembelina morsei																	X					X	
Eoglobigerina edita															X		X	X	X			X	X
Eoglobigerina eobulloides										X	X	X	X	X	X	X	X	X	X		X	X	X
Globanomalina archeocompressa																	X						
Globanomalina planocompressa																							X
Globoconusa daubjergensis										X	X		X	X	X	X	X	X	X	X	X	X	X
Guembelitria cretacea					X	X	X	X	X	X	X	X	X	X	X	X	X	X					
Parasubbotina aff. *pseudobulloides*																							
Parasubbotina pseudobulloides																		X	X	X			X
Parasubbotina varianta																					X	X	X
Parvularugoglobigerina cf. *eugubina*																							
Parvularugoglobigerina eugubina										X													
Praemurica cf. *taurica*																							
Praemurica pseudoinconstans																X	X	X	X			X	X
Praemurica taurica										X			X	X	X	X		X	X		X	X	X
Subbotina triloculinoides																							X
Subbotina trivialis																					X	X	X
Woodringina cf. *hornerstownensis*												X											
Woodringina claytonensis										X		X				X	X		X				
Woodringina hornerstownensis																							
Archeoglobigerina blowi																							
Archeoglobigerina cretacea																							
Contusatruncana contusa																							
Gansserina gansseri																							
Globigerinelloides escheri																							
Globigerinelloides multispina	X				X	X	X	X	X	X	X	X	X										
Globigerinelloides prairiehillensis																							
Globigerinelloides subcarinata					X																		
Globotruncana aegyptiaca								X															
Globotruncana arca																							
Globotruncana bulloides																							
Globotruncana deuplesi																							
Globotruncana lapparenti																							
Globotruncana linneiana																							
Globotruncana rosetta																							
Globotruncana tricarinata																							
Globotruncana ventricosa																							
Globotruncana weidermeyeri																							
Globotruncanita angulata																							
Globotruncanita stuartiformis																							
Globotruncanella petaloidea								X															
Heterohelix globulosa	X				A	A	A	A	A	C	F	X	X	X	X		X						
Heterohelix punctulata																							
Hedbergella holmdelensis							X																
Hedbergella monmouthensis						X	X		X	X						?							
Hedbergella sliteri																							
Laeviheterohelix dentata																							
Laeviheterohelix glabrata																							
Planoglobulina acervulinoides																							
Planoglobulina carseyae					X	X																	
Pseudoguembelina costulata						X			X	X													
Pseudoguembelina hariaensis																							
Pseudotextularia elegans						X			X														
Pseudotextularia nuttalli																							
Racemiguembelina powelli									X														
Rosita fornicata																							
Rugoglobigerina										X													
Rugoglobigerina hexacamerata																							
Rugoglobigerina macrocephala									X														
Rugoglobigerina reicheli							X	X	X														
Rugoglobigerina rotundata																							
Rugoglobigerina rugosa					X	X		X	X														
Rugoglobigerina scotti																							
Rugotruncana subcircumnodifer																							

Table T6. K/P boundary benthic foraminiferal occurences. (See table note. Continued on next three pages.)

Biofacies:	Biofacies 1																								
Sample depth (ft):	1030.0	1029.0	1028.0	1027.0	1026.0	1025.0	1024.0	1023.0	1022.0	1021.0	1020.0	1016.0	1015.0	1014.0	1013.0	1012.0	1011.0	1010.0	1009.0	1007.0	1006.0	1005.0	1004.0	1003.0	1002.0
Agglutinate small																									
Alabamina midwayensis																									
Angulogerina																									
Angulogerina naheolensis																									
Anomalinoides acuta																									
Anomalinoides cf. *welleri*																									
Anomalinoides midwayensis	VR	VR	VR	R	VR	VR	VR	VR	VR	VR	VR	R	F	F	R	R	R	VR	R	F	R	C	R	R	F
Anomalinoides nobilis																			R	R	R	F	F	R	R
Arenobulimina subsphaerica								VR	R	VR	VR	VR		VR						VR	VR	VR		VR	
Bolivina incrassata	VR	F	C	A	F	F	F	F	F																
Bolivina sp.																									
Bolivinoides draco													VR						VR	F	R	VR			
Bolivinoides giganteus	VR	VR	VR							VR		VR								VR					
Bulimina arkadelphiana																									
Bulimina quadrata	VR	VR	VR	R	R	R	R	VR	VR	VR	VR	VR	R							VR	VR	VR	R	VR	F
Bulimina referata type																			VR	VR					
Bulimina sp.																									
Bulimina virginiana																									
Buliminella carseyae			R	F		F	F		F	F	F	F	F	F	R	F	F	VR	F	C	C	C	A	A	A
Chilostomella trinidadensis													VR												
Cibicides harperi			VR	VR		F	F	F	F	F	R	F	F	C	VR	VR	VR		R	F	F	F	F	F	C
Cibicidoides large																									
Citharina sp.																									
Clavulinoides trilatera	R	VR	R	F	R	R	R	R	C	C	C	cf	R	VR			VR	VR		R	VR	R	F	R	F
Coryphostoma plaitum	R		F	F	R		VR	VR	VR	VR	R	F	C	F	F	C	C	R	C	C	A	C	A	A	A
Dentalina alternata												X													
Dentalina colei	VR		VR	VR	VR		VR	VR		VR	VR	VR	R	VR	VR		R			VR	R	R	R	R	VR
Dentalina pseudoaculeata												VR	VR				R		VR				VR	VR	VR
Dentalina sp.																									
Dorothea bulleta		VR		R	VR	VR	VR	VR	R	VR	VR	VR	R												
Dorothea conica					VR					VR		cf					VR			VR					
Dorothea monmouthensis												VR		VR		VR	VR			VR	VR	VR	R	VR	R
Eggerella trochoides							VR				VR		R	VR			VR			VR		VR	VR		VR
Eouvigerina gracilis			VR	F		VR																			
Epistominella sp.																				VR					
Eponides sp.										lg		X					VR				VR				
Frondicularia sp.	VR		VR				VR		VR		VR		VR										VR		VR
Fursenkoina sp.?																									
Gaudryina laevigata			R	F	F	F	C	C	C	C	VR	VR	VR	VR	VR		VR			VR	VR	VR	R	R	R
Gaudryina navarroana			VR	F				VR	VR				VR								VR	VR	VR	VR	
Gavelinella compressa morph																									
Gavelinella cf. *marylandicus*		VR	VR	VR																					
Gavelinella cf. *neelyi*																									
Gavelinella pinguis	VR	R		F	F	R	C	R	R	R	R	R	R	R	R	VR	R		VR	R	R		R	R	F
Gavelinella monterelensis	R	F	R	F	F	F	R	F	F	F	R	F	A												
Gavelinella sp.		VR	R	VR	VR																				
Gavelinella spissocostata	R	F	C	A	F	VR	VR	VR	VR	VR	VR	VR	R	R		VR			VR	R		F	VR	VR	VR
Globulina gibba			VR	VR									VR	VR						VR			VR	VR	VR
Globorotaloides sp.					X																				
Gyroidinoides globosa				VR	VR		VR		VR	VR	VR	VR	VR				R		VR	VR	F		R	VR	F
Gyroidinoides imitata	VR	VR	R	R	R	F			VR	F	F	F	F	F	F	F	F			R	F	VR	R	R	
Heterostomella americana			VR					VR	VR	VR	VR														
Kyphopxya sp.																									
Lagena sulcata		VR	VR							VR				VR		VR				VR		VR		VR	
Lenticulina		VR	VR	VR	VR	R	R	R	R	R	F	F	R	VR			R			VR	R	R	R	R	F
Lenticulina discus Brotzen																									
Marginulina sp.																								VR	VR
Neoflabellina reticulata					VR					VR	VR										VR	VR	VR	VR	VR
Nodosarella sp.												VR					VR								
Nodosaria latejugata	VR			VR		VR	VR	VR	VR		VR										VR	VR		VR	VR
Nodosaria longiscata				VR		VR	VR	VR	VR		VR									VR		VR			VR
Nodosaria obscura																							VR	VR	VR
Nonionella sp.	VR		VR							VR		VR		VR											
Oolina hispida			VR	VR		VR			VR		VR		VR		VR				VR	VR			VR	VR	VR
Orodorsalis sp.				VR		VR	VR	VR		VR				VR								VR			

Table T6 (continued).

Biofacies:	Biofacies 1																								
Sample depth (ft):	1030.0	1029.0	1028.0	1027.0	1026.0	1025.0	1024.0	1023.0	1022.0	1021.0	1020.0	1016.0	1015.0	1014.0	1013.0	1012.0	1011.0	1010.0	1009.0	1007.0	1006.0	1005.0	1004.0	1003.0	1002.0
Osangularia plummerae									R	R	R	R	F	F	F		C		R	F	A	F	C	F	F
Pleurostomella sp.			VR																				VR		
Pseudoclavulina clavata																									
Pseudouvigerina seligi			VR	R	R	R	R	F	R		A	F	F	VR	VR		R	R	R	F	A	F	C	A	A
Pullenia americana		VR	VR					R	VR		VR	VR			R		R		R	F	F	VR	VR	F	F
Pullenia cretacea											VR		VR												F
Pullenia coryelli		VR	VR	R	R						VR														
Pulsiphonina prima				VR			VR	VR	VR		VR	VR	VR	VR			VR	VR	R	F	VR	C	R	R	VR
Quadrimorphina allomorphinoides									VR		VR		R			F	R	VR		F	F	R	R	R	R
Rectonodosaria sp.	VR		VR			VR	VR	VR	VR	VR	VR	VR	VR	VR		VR				VR	VR	VR		VR	VR
Reophax sp.																		VR							
Saracenaria	VR									X				VR											
Siphogeneroides plummerae																									
Spirobolivina	VR		VR		VR	VR			VR	VR	R	VR					VR			VR	VR	VR	VR	VR	VR
Spiroplectammina laevis																					VR				
Spiroplectammina sp.																									
Stensioina exculpta			VR	VR	VR	VR		VR	VR	VR	VR														
Stilostomella alexanderi				VR	VR	VR					VR	VR					VR				VR	VR	VR	VR	
Stilostomella paleocenica																									
Stilostomella pseudoscripta										VR	R	VR					VR		VR	VR	R		F	F	C
Tappanina selmensis									R	VR	VR	VR	VR	VR	VR	VR				VR		VR	VR	VR	VR
Vaginulina cretacea	VR		VR	R		R		VR	VR	VR	VR	VR					VR					VR	VR	VR	
Valvulineria depressa		VR	VR				VR	VR	VR		VR	VR	R	R	VR	VR	R		R	F	C	C	C	F	F
Valvulineria sp.																									
Verneulina sp.																									

Note: A = abundant, C = common, F = few, R = rare, VR = very rare. lg = larger than typically seen.

Table T6 (continued).

Biofacies:				Biofacies 4								Biofacies 3					Biofacies 2							
Sample depth (ft):	1001.0	1000.0	996.0	995.0	994.0	993.0	992.0	991.0	990.0	989.0	988.0	987.0	986.0	985.0A	984.0	983.5	983.25	983.2	983.15	983.1	983.05	983.0	982.95	982.9
Agglutinate small																								
Alabamina midwayensis																	F	R	VR	R	R	F	R	R
Angulogerina																								
Angulogerina naheolensis																	F	F	F	F	VR	VR	VR	
Anomalinoides acuta																	F	F-C	R	F	F	R	R	R
Anomalinoides cf. *welleri*																								
Anomalinoides midwayensis	C	F	F	C	C	C	C	F-C	F	F	F	F	F	F	F	R	C	F	F	F	C	F		
Anomalinoides nobilis		VR																						
Arenobulimina subsphaerica		VR																						
Bolivina incrassata																								
Bolivina sp.																								
Bolivinoides draco																								
Bolivinoides giganteus																								
Bulimina arkadelphiana						VR	VR	R-F	F		R													
Bulimina quadrata	VR	VR	F	R		VR	VR	R		VR	VR	VR	VR		VR	VR		VR	VR					
Bulimina referata type		VR				VR												VR		VR		VR		
Bulimina sp.																								
Bulimina virginiana																								
Buliminella carseyae	A	C	C	C	A	A	A	A	C	F	F	F	F	F	F	R	F	F	R	F	F	F	F	R
Chilostomella trinidadensis																								
Cibicides harperi	C	F	F	VR	R	VR	VR	VR	VR		VR	F	R	R		VR								
Cibicidoides large																								
Citharina sp.																								
Clavulinoides trilatera	F	F	F	VR	VR	VR	VR	VR	VR		VR	VR	VR	VR	R	VR	VR	R		VR	VR	VR		
Coryphostoma plaitum	A	C	C	C	A	A	C	F	F	F	F	R	C	C	F	F	F	F	R	R	R	R		
Dentalina alternata	VR																							
Dentalina colei	VR	VR	R		VR	VR	VR	VR		VR	VR	VR	VR				VR		VR	VR	VR	VR	R	VR
Dentalina pseudoaculeata			VR	VR																				
Dentalina sp.																								
Dorothea bulleta																								
Dorothea conica																								
Dorothea monmouthensis	VR		VR	VR	VR	VR	VR	R		VR	VR		VR											
Eggerella trochoides																								
Eouvigerina gracilis																								
Epistominella sp.																								
Eponides sp.		VR					VR			VR			VR	R	VR	VR	R	VR						VR
Frondicularia sp.																								
Fursenkoina sp.?																	VR			VR		VR		
Gaudryina laevigata	R	R	VR	R	F	F	R	R	VR	VR	VR	VR	VR	VR	R		VR	VR	VR	VR	R		VR	
Gaudryina navarroana						R		R		VR	VR	VR	VR											
Gavelinella compressa morph	R															VR								
Gavelinella cf. *marylandicus*																								
Gavelinella cf. *neelyi*													VR					VR	VR	VR	VR	VR	VR	
Gavelinella pinguis		R	R	R	R	F	R	R	F	R	F			VR	VR									
Gavelinella monterelensis																								
Gavelinella sp.				VR		VR	VR			VR		VR		VR										
Gavelinella spissocostata	R																							
Globulina gibba	VR	VR	VR		VR	VR	VR	VR	VR	VR	VR		VR		VR	VR	R	VR	VR	VR	VR	VR	VR	VR
Globorotaloides sp.																								
Gyroidinoides globosa	R	F	C				VR																	
Gyroidinoides imitata	C	F	A	F	C	C	R	VR	C	C	F	R	F	F	R	VR	R	R		R	F	R		
Heterostomella americana																								
Kyphopxya sp.																					VR			
Lagena sulcata	VR		VR		VR	VR	VR																	
Lenticulina	R	R	R		VR	VR	VR	R		VR	VR	VR	VR	VR	R	R	R	R	R	R	R	VR	VR	VR
Lenticulina discus Brotzen																			VR	VR				
Marginulina sp.																								
Neoflabellina reticulata	VR		VR					VR						VR										
Nodosarella sp.													VR	VR										
Nodosaria latejugata		VR										VR								VR		VR	VR	
Nodosaria longiscata	VR		VR	VR		VR	VR							VR			VR	VR		VR	VR	VR	VR	VR
Nodosaria obscura	VR		VR	VR	VR	R	VR																	
Nonionella sp.										VR	VR		VR											
Oolina hispida	VR	VR			VR					VR					VR					VR				
Orodorsalis sp.	VR				VR	VR																		

Table T6 (continued).

Biofacies:				Biofacies 4								Biofacies 3					Biofacies 2							
Sample depth (ft):	1001.0	1000.0	996.0	995.0	994.0	993.0	992.0	991.0	990.0	989.0	988.0	987.0	986.0	985.0A	984.0	983.5	983.25	983.2	983.15	983.1	983.05	983.0	982.95	982.9
Osangularia plummerae	A	A	C	C	C	C	F	VR	VR	R		F	F	F	R	R	F	R	R	R	R	R	R	R
Pleurostomella sp.																								
Pseudoclavulina clavata													VR	VR	VR	VR								
Pseudouvigerina seligi	C	A	C	VR	R	F	VR	F	C	F	VR	F	F	VR	VR	VR	R	F	VR	VR	R	VR		
Pullenia americana	F	F	C	R	R	R	F	R	R	R	VR	VR	VR	F	R	R	R	VR	VR	VR	VR	VR		VR
Pullenia cretacea																VR		VR						
Pullenia coryelli			VR																					
Pulsiphonina prima	VR	R	R	VR	R	F	VR	R	R	R	VR	F	R	C	C	F	F	F	R	F	F	R	VR	
Quadrimorphina allomorphinoides	F	F	F	R	F	C	R	F	F	F	R													
Rectonodosaria sp.	VR									VR			VR	VR		VR								
Reophax sp.																								
Saracenaria																								
Siphogeneroides plummerae												VR	VR	VR	VR	VR								
Spirobolivina	VR	VR		VR						VR					VR									
Spiroplectammina laevis			VR								VR													
Spiroplectammina sp.																								
Stensioina exculpta																								
Stilostomella alexanderi	VR	VR	VR			VR	VR			VR	VR							VR						
Stilostomella paleocenica																								VR
Stilostomella pseudoscripta		R	R						VR			VR	VR		R	R	R	R	VR		R	R	R	R
Tappanina selmensis	VR				VR								VR	VR	VR	VR	R	R	VR	F	R	VR	VR	
Vaginulina cretacea						VR					VR		VR	VR	VR									
Valvulineria depressa	F	F	R	VR	VR	F	VR	R	R	R	VR	VR	R	R	R	VR	VR	VR	VR	VR	R	VR	VR	VR
Valvulineria sp.																								
Verneulina sp.																								

Table T7. Campanian–Santonian planktonic and benthic foraminiferal occurences.

Sample depth (ft):	1031.0	1036.0	1041.0	1046.0	1066.0	1091.0	1101.0	1131.0	1141.0	1151.0	1161.0	1171.0	1181.0	1191.0	1201.0	1211.0	1220.0	1221.0	1231.0	1251.0
Planktonic species																				
Archeoglobigerina blowi	X	X		X				X	X	X	X									
Archeoglobigerina cretacea	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X			X	
Globigerinelloides multispina	X	X	X																	
Globigerinelloides prairiehillensis		X	X																	
Globotruncana arca			X																	
Globotruncana bulloides				X		X								X	X	X	X	X	X	
Globotruncana lapparenti				X		X							X		X	X				
Globotruncana linneiana	X	X	X	X		X								X	X		X		X	
Globotruncana rosetta		X																		
Globotruncana ventricosa		X																		
Globotruncanita stuartiformis				X																
Heterohelix globulosa	X	X	X	X					X		X	X			X				X	
Marginotruncana marginata		X?	X?																	
Rosita fornicata	X	X	X	X		X							X	X	X	X		X	X	
Rugoglobigerina rugosa	X	X	X																	
Ventilabrella browni																	X			
Benthic species																				
Arenobulimina subsphaerica				X																
Bolivina incrassata	X	X																		
Bolivinoides decoratus		X	X																	
Bulimina quadrata			X	X																
Buliminella carseyae	X		X	X																
Citharina sp.			X									X								
Clavulinoides trilatera			X	X																
Coryphostoma plaitum	X																			
Dentalina colei		X	X	X																
Dorothea bulleta		X	X																	
Dorothea conica	X	X	X																	
Epistomina supracretacea												X	X	X	X					
Frondicularia sp.		X	X										X							
Gaudryina laevigata	X	X																		
Gaudryina rudita							X													
Gavelinella cf. *marylandicus*			X	X																
Gavelinella compressa morph	X																			
Gavelinella dumblei				X																
Gavelinella infrequens							X					X	X	X	X					
Gavelinella monterelensis	X	X	X																	
Gavelinella pinguis	X	X		X																
Gavelinella nelsoni			X	X																
Gavelinella spissocostata		X	X																	
Gavelinella texana							X		X	X				X	X	X		X	X	X
Globorotalites michelinianus		X	X	X																
Globulina gibba						X														
Gyroidinoides globosa		X	X				sm.					sm.								
Gyroidinoides imitata			cf.																	
Heterostomella faveolata																			X	
Lenticulina				X		X	X	X	X	X	X		X	X	X	X		X	X	
Pullenia cretacea																				
Nodosaria latejugata			X					X						X	X	X			X	
Nodosaria longiscata																				
Nodosaria sp.							X													
Oolina hispida												X								
Pamula sp.							X													
Praebulimina cf. *cushmani*							X													
Pseudogaudrinella capitosa						X						X			X	X		X	X	
Pullenia americana		X		X																
Rectonodosaria sp.	X		X	X								X								
Spiroplectammina laevis		X	X	X																
Stensioina exculpta		X																		
Vaginulina cretacea						X														
Vaginulina large								X												X
Valvulineria depressa			X																	

Note: sm. = small.

Table T8. Cenomanian–Turonian planktonic and benthic foraminiferal occurences.

Sample depth (ft):	1311.30	1321.50	1331.20	1341.20	1351.50	1361.00	1371.30	1381.50	1386.60	1391.00	1411.00	1416.00
Planktonic species												
Hedbergella delrioensis							X				X	
Hedbergella planispira					X	X	X	X	X	X	X	X
Hedbergella simplex								X	X		X	
Heterohelix moremani						X	X					
Heterohelix reussi		X										
Praeglobotruncana stephani		X					X	X				
Rotalipora cushmani							X					X
Whiteinella archeocretacea	X	X	X	X	X	X	X		X	X		
Whiteinella baltica			X	X	X	X	X		X	X		X
Whiteinella inornata											X	X
Benthic species												
Citharina kochii							X					
Citharina sp.			X									
Epistomina lenticularia	X	X	X	X	X	X						
Epistomina stelligera			X	X	X	X						
Epistomina suturalis							X		X	X	X	
Frondicularia sp.								X				
Gavelinella cenomana							X					
Gavelinella dakotensis									X			
Gavelinella sp.											X	
Gavelinella sp. 2				X								
Globulina gibba										X		X
Lenticulina spp.					X	X			X	X		
Marginulina siliquina									X	X	X	X
Nodosaria sp.								X				
Quinqueloculina sp.								X	X		X	
Spiroloculina sp.						X			X			

Table T9. Pollen and dinocyst occurences. (Continued on next two pages.)

Sample information	Biozone	Discussion
Sample: 1249.4–1249.5 ft (380.82–380.85 m) Palynological zone: Zone V Stage determination: late Turonian Stratigraphic correlation: South Amboy Fire Clay (lower Magothy Formation) Paleoecology: nonmarine Palynological recovery: very poor Diagnostic taxa: Pollen *Heidelbergipollis* sp. A Christopher *Osculapollis* sp. C Christopher *Tricolporate* type 6 Doyle 1969	 Amboy Stoneware Clay Oldbridge–Cliffwood Magothy	
Sample: 1256.4–1256.6 ft (382.95–383.01 m) Palynological zone: Zone V (dating based on sample at 1285.3 ft [391.76 m]) Stage determination: late Turonian Stratigraphic correlation: South Amboy Fire Clay (lower Magothy Formation) Paleoecology: nonmarine Palynological recovery: very poor Diagnostic taxa: Pollen *Tricolporites distinctus* *Tricolporate* type 2 Doyle 69 Fig. F3 *Triatriopollenites* sp. Spores *Rugubivesiculites reductus* *Araucariacites australis*	 II–V Raritan (Zone IV) Raritan–Magothy upper Patapsco–Maastrichtian Jurassic–Cretaceous	
Sample: 1257.7–1257.9 ft (383.35–383.41 m) Barren		
Sample: 1285.3–1285.5 ft (391.76–391.82 m) Palynological zone: Zone V Stage determination: late Turonian Stratigraphic correlation: South Amboy Fire Clay (lower Magothy Formation) Paleoecology: nonmarine Palynological recovery: poor Diagnostic taxa: Pollen *Complexipollis* sp. Type 1 *Complexipollis* sp. Type 2 *Complexipollis* sp. D Christopher 1979 *Tricolporites distinctus*	 V (SAFC) V (SAFC) V (SAFC)–upper Magothy II–V	The appearance of several species of triporates of the genera *Complexipollis* and *Porocolpopollenites* and the absence of triporates, typical of the middle and upper Magothy in both this sample and at 1291.8–1291.95 ft (393.74–393.79 m) strongly suggests Zone V (SAFC) for this sample.
Sample: 1291.8–1291.95 ft (393.74–393.79 m) Palynological zone: Zone V Stage determination: late Turonian Stratigraphic correlation: South Amboy Fire Clay (lower Magothy Formation) Paleoecology: nonmarine Palynological recovery: poor Diagnostic taxa: *Complexipollis* sp. D Christopher 1979 *Complexipollis* sp. Type 2 Bebout *Porocolpopollenites* sp. Doyle 1969 *Complexipollis* sp. B Doyle	 V (SAFC)–upper Magothy V (SAFC) V V (SAFC)	No Raritan or upper Magothy triporates are found in this sample. The presence of several species of *Complexipollis* common to the SAFC places it at this horizon.
Sample: 1320.2–1320.3 ft (402.40–402.43 m) Palynological zone: Zone IV Stage determination: late Cenomanian Stratigraphic correlation: Raritan (Woodbridge member) Paleoecology: marine shelf Palynological recovery: poor Diagnostic taxa: Pollen *Complexipollis* sp. A Doyle *Tricoporoidites* sp. A Doyle Dinoflagellates	 IV (Raritan) III–IV	Although there are few palynomorphs in this sample, *Complexipollis* sp. A is one of the oldest triporate-Normapolle types that are found in the Woodbridge Clay member of the Raritan Formation. It is very similar to the *Atlantpollis* complex of the Woodbridge Clay.

Table T9 (continued).

Sample information	Biozone	Discussion
Epelidosphaerida spinosa Davey	Cenomanian of the Scotia Shelf	
Sample: 1341–1342 ft (408.74–409.04 m) Palynological zone: Zone IV Stage determination: late Cenomanian Stratigraphic correlation: Raritan (Woodbridge member) Paleoecology: marine shelf Palynological recovery: very poor Diagnostic taxa:		
Pollen and Spores		
Piceapollenites alatus	I–IV	
Araucariacites australis	II–IV	
Cicatricosisporites spp.	Long ranging	
Gleicheniidites senonicus	Cretaceous	
Dinoflagellates		
Hystrichosphaeridium (fragment)		
Callaiosphaeridium asymmetricus	Hauterivian–Coniacian on the Scotian shelf	
Sample: 1353.8–1354.0 ft (412.64–412.70 m) Palynological zone: Zone IV Stage determination: late Cenomanian Stratigraphic correlation: Raritan (Woodbridge member) Paleoecology: brackish Palynological recovery: very poor Diagnostic taxa:		The diversity of palynomorphs is very low in this sample. The organic matter is dominated by vitrain and fusain, which is common for marsh conditions in the Bass River–Raritan horizons. *Atlantapollis verrucosa* is a key species only found in Zone IV. It is easy to identify and is one of the earliest Normapolles to appear in the Cretaceous section. The appearance of numerous tiny, spherical acritarchs (10–12 µm), and the absence of the larger Spiniferites types (dinoflagellates) suggests brackish water conditions.
Dinoflagellates		
Cleistosphaeridium sp.	Similar to those found in the Woodbridge Clay	
Exochosphaeridium bifidum	upper Albian–Campanian	
Micrhystridium spp.	When dominant, indicates brackish conditions	
Pollen		
Atlantapollis verrucosa	IV (Raritan)	
Sample: 1383.8–1384.0 ft (421.78–421.84 m) Palynological zone: Zone III? Stage determination: lower Cenomanian Stratigraphic correlation: subsurface Raritan of Delaware, Raritan of Maryland Paleoecology: brackish–marine Palynological recovery: very poor Diagnostic taxa:		It is possible that *Ajatipollis* sp. A extends into Zone IV, although it has not been studied. If it does, then given the paucity of palynomorphs in this sample, dating is uncertain. The sample contains mostly vitrain and fusain.
Pollen		
Ajatipollis sp. A Doyle	IIB–III, rare in I, common in III	
Spores		
Camarozonosporites rudus	Found commonly in Zone III	
Acritarchs and dinoflagellates		
Micrhystridium spp.	When dominant indicates brackish conditions	
Cyclonephelium sp.		
Sample: 1411.2–1411.4 ft (430.13–430.19 m) Palynological zone: Zone III Stage determination: early Cenomanian Stratigraphic correlation: uppermost Patapsco: subsurface Raritan of Delaware, Raritan of Maryland Paleoecology: nonmarine Palynological recovery: very poor Diagnostic taxa:		
Pollen and spores		
Rugubivesiculites sp.	II–Maastrichtian	
Appendicisporites potomacensis	I–III	
Brenneropollis peroreticulatus	I–III	
Stephanocolpites tectorius	III	
Tricolporopollenites sp. A Doyle	III	
Sample: 1434.2–1434.3 ft (437.14–437.17 m) Palynological zone: Zone III Stage determination: early Cenomanian Stratigraphic correlation: uppermost Patapsco: subsurface Raritan of Delaware, Raritan of Maryland Paleoecology: nonmarine Palynological recovery: poor		

Table T9 (continued).

Sample information	Biozone	Discussion
Diagnostic palynomorphs:		
Appendicisporites potomacensis	I–III	
Cingulatisporites eukirchensoides	Albian of eastern Austrlia	
Tricolporopollenites triangulus	IIC–III	
Tricolporopollenites sp. B Doyle	III	
Sample: 1473.5–1473.7 ft (449.12–449.18 m)		
Palynological zone: Zone III		
Stage determination: early Cenomanian		
Stratigraphic correlation: uppermost Patapsco: subsurface Raritan of Delaware, Raritan of Maryland		
Paleoecology: nonmarine		
Palynological recovery: fair		
Diagnostic taxa:		
Pollen		
Ajatipollis sp. A Doyle	IIB–III, rare in I, common in III	
Tricolpites nemejci Pacltova	III	
Tricolporoidites sp. A Doyle	III	
Spores		
Camarozonosporites rudus	Found commonly in Zone III	
Gleicheniidites circinidites	Potomac Group	
Appendicisporites tricornatatus	Potomac Group	
Sample: 1495.3–1495.5 ft (455.77–455.83 m)		Both Subzone IIC and Zone III forms are found in this sample. The abundance of bisaccate coniferous pollen is a very common aspect of the upper Patapsco. This most likely reflects cooler paleoclimatic conditions at this time. The boundaries between Subzone IIC and Zone III have never been defined in the literature so a mixed assemblage creates a dating problem.
Palynological zone: Zone IIC to lower III		
Stage determination: early Cenomanian		
Stratigraphic correlation: uppermost Patapsco: Elkneck Beds of Maryland to subsurface Delaware and Raritan of New Jersey		
Paleoecology: brackish		
Palynological recovery: good		
Diagnostic taxa:		
Angiosperm Pollen		
Peromonolites allenensis Brenner	I–II	
Tricolpies nemejci Pacltova	III	
Tricolpites triangularus Groot, Penney & Penney	IIC–III	
Spores		
Appendicisporites tricornatus	Potomac Group	
Gleicheniidites circiidites	Potomac Group	
Lycopodiacidites triangularis Brenner	Potomac Group	
Taurocosporites spackmani Brenner	IIB–IIC	
Gymnosprem Pollen		
Alisporites bilateris	Potomac Group	
Abietineaepollenites spp.	Potomac Group	
Rugubivesiculites rugosus IIC type	IIC–lower III	
Abietineaepollenites microviculatus	Potomac Group	
Acritarchs		
Micrhystridium spp.	When dominant indicates brackish conditions	

Table T10. Sr isotopic data.

Strontium laboratory number	Run date	Depth (ft)	Depth (m)	Material	Sr Value	Corrected Sr value	Error	Age (Ma)	Age (Ma)*	Machine
9	16-Jun-2004	342.5	104.39	Shell	0.708448	0.708462	0.000007	20.4		Isoprobe
6	16-Jun-2004	356	108.51	Shell	0.708440	0.708454	0.000011	20.5		Isoprobe
10	16-Jun-2004	356.2	108.57	Shell	0.708447	0.708461	0.000008	20.4		Isoprobe
23	20-Jun-2004	356.2	108.57	Shell	0.708455	0.708469	0.000007	20.3		Isoprobe
26	20-Jun-2004	356.2	108.57	Shell	0.708440	0.708454	0.000005	20.5		Isoprobe
11	16-Jun-2004	365.9	111.53	Shell	0.708459	0.708473	0.000010	20.2		Isoprobe
27	20-Jun-2004	365.9	111.53	Shell	0.708954	0.708968	0.000007	8.5		Isoprobe
3330	13-Jun-2002	371.65	113.28	Shell	0.708423		0.000014	21.0		VG
159	24-Sep-2004	384	117.04	Shell	0.708499	0.708513	0.000006	19.6		Isoprobe
160	24-Sep-2004	393.3	119.88	Shell	0.708480	0.708494	0.000005	19.9		Isoprobe
161	24-Sep-2004	396.6	120.88	Shell	0.708480	0.708494	0.000005	19.9		Isoprobe
7	16-Jun-2004	402	122.53	Shell	0.708454	0.708468	0.000008	20.3		Isoprobe
162	24-Sep-2004	402	122.53	Shell	0.708543	0.708557	0.000005	19.0		Isoprobe
12	16-Jun-2004	402.3	122.62	Shell	0.708446	0.708460	0.000009	20.4		Isoprobe
28	20-Jun-2004	402.3	122.62	Shell	0.709155	0.709169	0.000004	0.9		Isoprobe
163	24-Sep-2004	407.9	124.33	Shell	0.708504	0.708518	0.000006	19.6		Isoprobe
170	10-Oct-2004	407.9	124.33	Shell	0.708516	0.708530	0.000005	19.4		Isoprobe
13	16-Jun-2004	425.5	129.69	Shell	0.707765	0.707779	0.000011	35.8		Isoprobe
25	20-Jun-2004	425.5	129.69	Shell	0.707777	0.707791	0.000005	35.4		Isoprobe
3331	13-Jun-2002	452.7	137.98	Shell	0.707731	0.707745	0.000006	36.7		VG
8	16-Jun-2004	457	139.29	Shell	0.707731	0.707745	0.000009	36.7		Isoprobe
14	16-Jun-2004	457	139.29	Shell	0.707752	0.707766	0.000009	36.1		Isoprobe
172	10-Oct-2004	1000	304.80	Shell	0.708043	0.708057	0.000004	28.4		Isoprobe
173	10-Oct-2004	1011	308.15	Shell	0.709158	0.709172	0.000004	0.8		Isoprobe
174	10-Oct-2004	1016	309.68	Shell	0.708163	0.708177	0.000004	25.7		Isoprobe
175	10-Oct-2004	1026	312.72	Shell	0.709170	0.709184	0.000004	0.4		Isoprobe
176	10-Oct-2004	1031	314.25	Shell	0.708186	0.708200	0.000005	25.3		Isoprobe
15	16-Jun-2004	1033	314.86	Shell	0.707671	0.707685	0.000008	72.1		Isoprobe
16	16-Jun-2004	1042	317.60	Shell	0.707623	0.707637	0.000013	74.7		Isoprobe
195	18-Oct-2004	1045	318.52	Shell	0.709163	0.709177	0.000008	0.6		Isoprobe
17	16-Jun-2004	1060	323.09	Shell	0.707596	0.707610	0.000007	76.2		Isoprobe
67	2-Jul-2004	1073	327.05	Shell	0.707619	0.707633	0.000006	75.0		Isoprobe
3360	5-Nov-2002	1084.2	330.46	Shell	0.707978		0.000010	55.9		VG
68	2-Jul-2004	1096	334.06	Shell	0.707605	0.707619	0.000005	75.7		Isoprobe
69	2-Jul-2004	1170	356.62	Shell	0.707615	0.707629	0.000006	75.2		Isoprobe
70	2-Jul-2004	1191	363.02	Shell	0.707619	0.707633	0.000024	75.0		Isoprobe
131	28-Aug-2004	1191	363.02	Shell	0.707614	0.707628	0.000018	75.2		Isoprobe
65	2-Jul-2004	1237	377.04	Shell	0.707488	0.707502	0.000004	82.2		Isoprobe
66	2-Jul-2004	1249	380.70	Shell	0.707489	0.707503	0.000004	82.1		Isoprobe
3361	5-Nov-2002	1249.5	380.85	Shell	0.707447		0.000018	85.2		VG
74	9-Jul-2004	1314	400.51	Shell	0.707405	0.707419	0.000004	86.0	94.8	Isoprobe
75	9-Jul-2004	1331	405.69	Shell	0.707341	0.707355	0.000005	88.0	92.3	Isoprobe
76	9-Jul-2004	1340	408.43	Shell	0.707844	0.707858	0.000004	62.6		Isoprobe
117	18-Aug-2004	1354	412.70	Shell	0.707424	0.707438	0.000005	85.3		Isoprobe
118	18-Aug-2004	1365	416.05	Shell	0.707435	0.707449	0.000004	84.8		Isoprobe
119	18-Aug-2004	1370	417.58	Shell	0.707413	0.707427	0.000004	85.7	95.8	Isoprobe
120	18-Aug-2004	1376	419.40	Shell	0.707437	0.707451	0.000005	84.7		Isoprobe
121	18-Aug-2004	1384.7	422.06	Shell	0.707417	0.707431	0.000006	85.6	98.0	Isoprobe
122	18-Aug-2004	1413.5	430.83	Shell	0.707419	0.707433	0.000005	85.5	99.3	Isoprobe

Note: VG = VG Sector Mass Spectrometer. * = from Howarth and McArthur.