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1. Ancora Site[1]

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SECTION AUTHORSHIP

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

Operations: Miller, Queen
Lithostratigraphy: Browning, Cramer, Metzger, Miller, Monteverde, Muller, Mullikin, Pekar, Reilly, Skinner, Sugarman, Uptegrove
Biostratigraphy:
Foraminifers: Browning (Eocene), Georgescu (Cretaceous), Olsson (Cretaceous–Tertiary)
Calcareous nannofossils: de Romero (Cretaceous), Aubry (Tertiary)
Cretaceous pollen: Brenner
Isotopic Stratigraphy: Browning, Feigenson

SITE SUMMARY

The Ancora borehole was the fifth site drilled as part of the New Jersey Coastal Plain Drilling Project and the second site drilled as part of Ocean Drilling Program (ODP) Leg 174AX, which complements shelf drilling conducted during Leg 174A. Drilling at Ancora, New Jersey (location = 39°41′31.975″N, 74°50′56.459″W; elevation = 103.9 ft [31.65 m]; Hammonton 7.5-min quadrangle), targeted middle Miocene and older sequences, with the primary focus on Upper Cretaceous (Cenoma-

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nian–Maastrichtian) to Paleocene strata. Between 2 July and 11 August 1998, the United States Geological Survey (USGS) Eastern Earth Surface Processes Team (EESPT) drilled two holes at Ancora.

At Hole A, we recovered 693.82 ft (211.48 m) between the surface and 759 ft (231.34 m; 91.4% recovery), whereas at Hole B we recovered 591.48 ft (180.28 m) between 543 ft (165.55 m) and a total depth of 1170 ft (356.71 m; 94.3% recovery). Total recovery (92.7%) was remarkable and a gamma-ray log was obtained to total depth. The on-site scientific team provided descriptions of sedimentary textures, structures, colors, fossil content, identification of lithostratigraphic units, lithologic contacts, and sequences (unconformity-bounded units) that were integrated with subsequent biostratigraphic, Sr isotopic, and gamma ray–log studies.

Neogene sequences at Ancora are largely unfossiliferous except for the lowermost Miocene. The ?upper–middle Miocene Cohansey Formation consists of two sequences deposited in nearshore (beach, shoreface, and offshore sand ridge) environments. The Kirkwood Formation consists of two shallowing-upward lower Miocene sequences (Kw1a and ?Kw1b) deposited in neritic to prodelta to delta-front environments. Lowermost Miocene (Sequence Kw0) through uppermost Eocene strata are not represented at Ancora.

The upper to middle Eocene Shark River Formation consists of a very sandy upper Toms River Member, a sandy upper Shark River unit, and a clayier lower Shark River unit. The Toms River Member is potentially an important aquifer that comprises the highstand systems tract (HST) of a thick Sequence E9, spanning the middle/late Eocene boundary (Zones NP16 partim to NP18). A sequence that comprises most of the upper Shark River unit is assigned to Zone NP16 partim and correlates with Sequence E8, whereas most of the lower Shark River unit correlates with Sequences E7 and E6. Three thin sequences (E3–E6) span the middle/lower Eocene boundary and the Shark River/Manasquan Formation contact.

The lower Eocene Manasquan Formation at Ancora displays larger lithologic variations than previously drilled locations further downdip. The Manasquan Formation is dominated by calcareous silty clays ("marls") as at other locations, but fine quartz sand and reworked glauconite comprise highstand deposits within Manasquan sequences. Three sequences comprise the Manasquan Formation (E1–E3), with the bulk of the formation represented by Sequence E2 (Zones NP11–NP12 partim and P6b partim to P7).

Silty clays (equivalent in part to the Vincentown Formation) comprise an exceptionally thick (75 ft, 22.87 m) uppermost Paleocene section (Zone NP9). This section encompasses the late Paleocene thermal maximum (LPTM) and is associated with an intriguing interval of cross-bedded clay and silty clay, interrupted by two sections exhibiting convoluted bedding (543.5–545.5 and 559.2–560.0 ft; 165.66–166.27 and 170.44–170.69 m) with mini-flame and mini-ball structures. Both planktonic foraminifer and nannofossil "excursion taxa" occur in this interval and indicate that the carbon isotope excursion (CIE) associated with the LPTM occurs at or just below the base of the lower interval of convoluted bedding. The LPTM section at Ancora potentially represents one of the most expanded records of this global event. The CIE apparently overlies a possible sequence boundary at 562.1 ft (171.33 m). A glauconitic transgressive–regressive sequence occurs below this level in the "Vincentown equivalent."

Sequence boundaries are not readily observable in the lowermost Vincentown equivalent and the Hornerstown Formation because the entire lower part of the Paleocene section is uniform clayey glauconite sands. Three sequence boundaries were inferred in the lowermost Vincentown equivalent and the Hornerstown Formation based on biostratigraphic evidence, gamma ray–log kicks, and regional sequence stratigraphic relationships. The presence of Zones P1b and P2 indicates that the lower Paleocene section at Ancora is expanded relative to other coastal plain sites.

The Cretaceous/Tertiary (K/T) boundary in Hole A contains clay clasts above the uppermost Maastrichtian Navesink Formation; a spherule layer is absent. By contrast, Hole B contains a spherule layer at 617.1 ft (188.09 m). The presence of glauconite grains and foraminifers indicates that the original tektites were redeposited from deeper water. The K/T boundary is tentatively placed at an indistinct surface at 618.3 ft (188.50 m). Below this level, Cretaceous planktonic foraminifers and nannofossils are abundant. Both holes provide an excellent opportunity to assess the recovery of marine microorganisms from the terminal Cretaceous extinction event and the relationship of global sea-level change to the extinctions and recovery.

Cretaceous sequences are thick and well expressed lithologically. The Santonian–Maastrichtian section is dated by calcareous nannofossil biostratigraphy, limited planktonic foraminifer biostratigraphy, and Sr isotopic stratigraphy. The Santonian–Maastrichtian section consists of five sequences deposited in neritic paleoenvironments:

1. The Navesink Formation comprises an upper (<68.3 Ma) to uppermost (Zone CC26) Maastrichtian sequence. The Red Bank Formation is not found in this area; reworking of glauconite sands in the HST yields a Navesink lithology that is partly coeval with the Red Bank Formation found elsewhere in New Jersey. The base of the sequence at Ancora (68.3 Ma) may be slightly younger than at other boreholes (~69 Ma).
2. The Mount Laurel Formation sand (upper HST) along with the Wenonah Formation silt (lower HST) and the Marshalltown Formation comprise a middle–upper Campanian sequence that can be dated well with Sr isotopes (73.4–71.1 Ma) and nannofossils (Zones ?CC20, CC21–CC23). The Marshalltown Formation glauconite sand is tentatively interpreted as recording a lowstand, a transgressive interval, and part of a HST.
3. The upper Englishtown Formation comprises a sequence assigned to middle Campanian Zones CC19 to ?CC20.
4. The lower Englishtown Formation sands are the highstand deposit of a sequence spanning the Santonian/Campanian boundary. The underlying Woodbury Formation is a thick clay (lower HST) that is dated as lower to middle Campanian Zone CC19 with an age of ~77.4 Ma. The basal part of the sequence consists of the transgressive Merchantville Formation and is dated as Zones CC17–CC18 with an age of ~79 Ma.
5. The Cheesequake Formation is a thin ?Santonian sequence.

Recovery of the nonmarine ?Turonian–?Santonian Magothy Formation was excellent. The unit appears to consists of two sequences as it does at Bass River. The upper sequence consists of an upper very coarse sand to sandy gravel deposited in a delta plain and a lower slightly sandy silty clay and lignitic sand deposited in a delta-front or estuarine setting.

The lower Magothy sequence is a thick unit of predominantly medium to coarse sand; its age and depositional setting are enigmatic, although it may have been deposited in a nearshore marine setting. It is unique in that it lacks the typical stratal succession found in other New Jersey sequences, perhaps reflecting unusually low sea level. The upper and lower sands of the Magothy Formation are both excellent aquifers.

The neritic Bass River Formation consists of fossiliferous, micaceous (chloritic), clayey silts and silty clays with occasional sandy silts. The Bass River Formation consists of three sequences at Ancora. Facies within these units are much more variable and vertical variations are more dramatic than at Bass River, reflecting not only the more updip location but also the preservation of two Cenomanian sequences not found at Bass River. Nannofossils indicate that the Bass River Formation at Ancora is Cenomanian below 1074.5 ft (327.51 m); the section above is barren of nannofossils. Planktonic foraminifers suggest that the upper part may be Turonian. The section from 1064 to 1066 ft (324.31–324.92 m) is darker with a faint petroleum scent; we speculate that this interval correlates with the lowermost Turonian Bonarelli bed equivalent observed at Bass River.

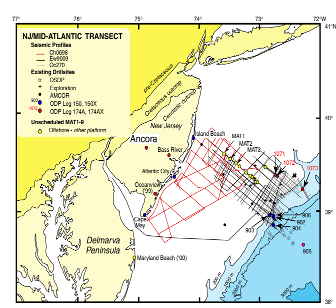
Abrupt facies variations occur within the Potomac Group that is dated as lower to middle Cenomanian by pollen, and as upper Albian to lower Cenomanian Zone CC9 by nannofossils. The section contains marginal neritic clays, marine to estuarine shelly clayey very fine sands and clays, and ?nonmarine kaolinitic clays. Several sequences may occur within the Potomac Group, although age and facies variations are not sufficient for unambiguous recognition of sequences and their global correlations.

The Ancora borehole has provided cores that address various aspects of global sea-level change, sequence stratigraphic development, and local hydrogeology. The Upper Cretaceous (Cenomanian–Maastrichtian) section complements the downdip Bass River borehole in New Jersey; this should allow reconstruction of sea-level variations for this interval and evaluation of sequence stratigraphic succession and facies models. The Ancora borehole also provides material needed to evaluate aquifer-confining unit relationships and local hydrogeology, especially major aquifer units within the Magothy, Englishtown, Mount Laurel, and Kirkwood–Cohansey Formations.

BACKGROUND AND OBJECTIVES

This chapter is the site report for the fifth continuously cored and logged borehole drilled onshore as part of the New Jersey Sea Level Transect. The first three sites (Fig. F1) were drilled at Island Beach (March–April 1993), Atlantic City (June–August 1993), and Cape May (March–April 1994) as part of ODP Leg 150X (Miller et al., 1994a, 1994b, 1996), the landward continuation of slope drilling by ODP Leg 150 (Mountain, Miller, Blum, et al., 1994). ODP Leg 174A continued the transect by drilling on the shelf (Austin, Christie-Blick, Malone, et al., 1998), whereas drilling at Bass River (ODP Leg 174AX; Miller, Sugarman, Browning, et al., 1998) continued the onshore transect by drilling deeper into Upper Cretaceous strata. The Ancora borehole was designed to sample updip equivalents of Upper Cretaceous strata sampled at Bass River and to push further into the middle Cretaceous section. The Planning Committee endorsed onshore drilling as an ODP-related activity and designated drilling at Bass River, Ancora, and Ocean View (Fig. F1)

F1. Location map showing ODP coastal plain and nearshore sites, p. 51.



as ODP Leg 174AX. Onshore drilling of the Leg 150X and 174AX boreholes was sponsored by the National Science Foundation, Earth Science Division, Continental Dynamics and Ocean Drilling Programs, and the New Jersey Geological Survey (NJGS).

The geologic background and scientific justification for the New Jersey Sea Level Transect are provided by Miller and Mountain (1994). The Transect is intended to document the response of passive continental margin sedimentation to glacioeustatic changes during the Oligocene to Holocene "Icehouse World," a time when glacioeustasy was clearly operating, and to document the ages and nature of Eocene and older "Greenhouse" sequences, a time when mechanisms for sea-level change are poorly understood (Miller et al., 1991). The Ancora borehole sampled Upper Cretaceous to lower Eocene "Greenhouse" sequences, an interval thought to have been ice free. Our objective was to date these sequences and compare them with other proxies of global sea-level change (e.g., $\delta^{18}O$ changes and Haq et al.'s record [1987]; see Browning et al. [1997b]). This is a particularly intriguing task, because onshore sequence stratigraphic studies in New Jersey and elsewhere provide evidence for large, rapid sea-level changes in this supposedly ice-free world, although the only known mechanism for such large, rapid sea-level variations is glacioeustasy (Pitman and Golovchenko, 1983).

The Ancora borehole was specifically located to sample critical events in Earth history, specifically the LPTM, the K/T boundary, and the Cenomanian/Turonian (C/T) boundary. Based on updip drilling at Clayton, New Jersey (Gibson et al., 1993), and downdip sections at Bass River (Cramer et al., in press), we expected that the section representing the LPTM at Ancora would be one of the most complete representations of this abrupt climatic event. Drilling at Ancora recovered two penetrations of a thick LPTM section.

The Ancora site was also selected to optimize recovery of the K/T boundary section. This section at Bass River provided an unprecedented coastal plain view of K/T boundary events, establishing that ballistic ejecta from the Chicxulub impact was associated with the marine mass extinction event (Olsson et al., 1997). Although drilling at Bass River recovered an excellent K/T boundary succession, there are several issues that required recovery of an additional New Jersey section, where we predicted that the boundary would be continuous, including:

1. What paleobathymetric changes were associated with the impact, and what is the relationship (if any) of the impact to sea-level changes and sequences?
2. What was the response of marine organisms to the impact? Various studies show a global pattern of planktonic response (e.g., Smit, 1982). In contrast, studies show benthic foraminifers experienced few extinctions (e.g., Beckmann, 1960). At Bass River, we failed to recover Subzone P1b, hindering our evaluation of the recovery of marine plankton to the extinction event. We initially planned to drill an updip section at Parvin, New Jersey, to address these issues. We had the opportunity to take a 2-ft core spanning the K/T boundary at Parvin in 1997 and determined that the spherule bed was missing, although a clay clast bed was present as it was at Bass River. We, thus, shifted our proposed drilling from Parvin along strike to Ancora where we managed two penetrations of the K/T boundary, one of which included spherules (see below). In addition, the Ancora borehole recovered two samplings of a thick, relatively complete lower Pale-

ocene section that will allow evaluation of the response and recovery of marine organisms to the K/T event.

The Ancora, Bass River, and planned Ocean View boreholes had another major objective: to evaluate the stratigraphic continuity and hydrogeological potential of aquifers and confining units, particularly those of Cretaceous age. The NJGS funded direct drilling costs for Bass River and partially funded Ancora and Ocean View, targeting Cretaceous aquifers in the Mount Laurel, Englishtown, and Potomac-Raritan-Magothy (PRM) Formations (see Zapecza [1989] for discussion of these aquifers). Continuous coring in the New Jersey Coastal Plain has shown that aquifer-confining couplets are sequences bounded by unconformities (Sugarman and Miller, 1997). Thus, sequence stratigraphy provides a means to predict the continuity and regional distribution of aquifer-confining units (Sugarman and Miller, 1997). However, the updip-downdip relationships of aquifer-confining units is not clear in many cases. For example, the Magothy aquifer displays complex updip-downdip relationships (Miller, Sugarman, Browning, et al., 1998). The Ancora borehole was specifically located to sample these Cretaceous aquifers and to answer outstanding questions about Cenozoic aquifers. In the latter case, the sequence stratigraphy and hydrostratigraphic distribution of the units confining the “Atlantic City 800-ft Sand” aquifer and the regional distribution and significance of the “Piney Point” aquifer are very poorly known in the vicinity of Ancora.

Drilling at Ancora, New Jersey, met “Greenhouse,” global event, and aquifer objectives by obtaining remarkable recovery of mid-Cretaceous to Holocene sediments.

OPERATIONS

Drilling at Ancora, New Jersey, began in early July 1998. Drilling operations were superintended by Don Queen, head driller for the USGS EESPT; drillers were Gene Cobbs and Gene Cobbs III. On 2 July, the USGS team arrived on site, began rigging up, and tested the water well. J. Browning (staff scientist) moved equipment on site and tested electrical outlets installed by Esposito Electric and the Ancora maintenance engineers (J. Sargent, chief engineer). Hydrocarbons in the well prompted removal of a gasoline storage tank from the site and delayed setup until 7 July when 12-in surface casing was set to 2 ft (0.61 m). Water was provided by a NJGS 1500-gal water truck. On 8 July, heavy morning rains delayed setup; the science team found that the building originally designated for use as a field lab was unacceptable because of the presence of pesticides and a leaking roof. A field lab was set up in a barn on site. A digital Olympus D-320L camera and a Power Macintosh 7200 were set up to photograph 2-ft (0.61 m) core segments; we evaluated the photographs for lighting artifacts on hand auger cores, white polyvinyl chloride (PVC) liner, and black background using National Institutes of Health (NIH) Imaging 1.61 software. Background levels on blanks were typically 15–45 over 256 grayscale units.

All cores were measured in feet, and all depths are given in feet below land surface. In this report, measurements are also reported in meters for the convenience of the reader. We adopted the ODP convention of top, justifying depths for intervals with incomplete recovery, for all field notes and photos.

The first core from Hole A was obtained on 8 July, making 5-ft runs to recover the sands expected in the upper 200 ft (60.96 m). The inner core barrel could not be extracted from the first run; the 8.5-ft rod was pulled to show that the 1-in extended shoe had flared while penetrating gravels. As a result, 2 ft (0.61 m) was recovered on a 5-ft (1.52 m) run. The second run recovered 2.1 ft (0.64 m) of gravel from a 2.5-ft (0.76 m) run; recovery was close to 100% when accounting for the volume of the expanded gravels. Gravels at the top of the next run (9.5–12.0 ft [2.90–3.66 m]) were probably caved in, with 1 ft (0.3 m) of in situ core. The day ended at 15 ft (4.57 m), having recovered 7.3 ft (2.23 m) out of 13 ft (3.96 m) cored (56% recovery).

On July 9, D. Queen left for Reston, Virginia, to pick up casing. Coring proceeded smoothly through unconsolidated and semiconsolidated sands. We opted for short (1.0–2.5 ft [0.30–0.76 m]) runs for good recovery between 15 and 30 ft (4.57–9.14 m). Several consolidated layers slowed coring, but recovery was excellent. We switched back to 5-ft (1.52 m) runs at 30 ft (9.14 m) and had excellent recovery in the Cohansey sands; recovery was higher than that shown in Table T1 as a result of the "squashing" of the sands (i.e., 4.3–4.6 ft [1.31–1.40 m] recovered on a 5-ft [1.52 m] run represents virtually 100% recovery). The day ended with 43.3 ft (13.20 m) recovered out of 50 ft (15.24 m) cored (87% recovery). The hole was purged with 150 gal of mud (8.75-lb mud weight), and 20 ft (6.10 m) of rods was hung in the hole.

T1. Ancora site summary, p. 59.

Smooth coring continued on the morning of 10 July, with excellent recovery throughout the morning to 95 ft (28.96 m). At 1100 hr, the hydraulic motor seized. The drillers returned to Reston to get a new pump. On 11 July, the pump was repaired.

Coring resumed on 12 July from 95 to 145 ft (28.96–44.20 m), with 42.7 ft [13.01 m] recovered. The computed recovery of 85.4% actually exceeds 90% after accounting for "squashing" of the sands. The hole consumed water throughout the morning. The bottom of the hole (BOH) collapsed after recovery of Core 33 (135–140 ft [41.15–42.67 m]) as a result of a change in lithology from clayey sands to more porous clean quartz sands at ~138.5 ft (42.21 m). Core 35 (140–145 ft [42.67–44.2 m]) contained "dry sands" that proved difficult to extract from the core barrel. The rods were pulled 10 ft (3.05 m) from the BOH and hung overnight to hinder collapse of the porous clean sands.

Smooth coring continued on 13 July at 10 ft/hr, penetrating the top of the Kirkwood Formation at 167.9 ft (51.18 m). Core 40 (170–175 ft [51.82–53.34 m]) had only 0.6 ft (0.18 m) of recovery. As the inner barrel was pulled, the core slipped out and lodged in the bit. During the following run (175–180 ft [53.34–54.86 m]), the inner core barrel lodged behind the core without locking into the outer core barrel, resulting in no recovery for Core 41. We pulled the inner core barrel and cleared the obstruction. The top 0.8 ft (0.24 m) of Cores 42–44 (180–195 ft [54.86–59.44 m]) apparently contained cavings from the previous two cores. By Core 45 (195–200 ft [59.44–60.96 m]), there was minimal caving, penetrating clays suitable for casing off the sands in the top 199 ft (60.66 m). The day ended at 205 ft (62.48 m), with 48.5 ft (14.78 m) recovered out of 60 ft (18.29 m) cored (80.8% recovery).

On 14 July, 5 ft (1.52 m) of core (5.3 ft recovery [1.62 m]) was pulled. The drillers reamed the hole on 14–15 July, and 210 ft (64.01 m) of 5-in (12.7 cm) flush PVC casing was set into firm clays at 208.5 ft (63.55 m), leaving 1.5 ft (0.46 m) out of the ground. The hole was grouted with bentonite (Benseal) on 15 July, and the top of the hole was sealed with one 5-gal can of ⅜-in (1 cm) bentonite pellets and two bags of Goldbond medium seal. This grouting and sealing allows either removal of casing at completion or further grouting of the top of the hole. J. Curran of the NJGS was contacted about logging the upper 200 ft (60.96 m); it was decided to log the entire hole at total depth because his logging computer was not operating.

On 16 July, we switched to 10-ft (3.05 m) runs in tight clays and enjoyed perfect recovery. The USGS Water Resources Division (WRD) sampled three clay intervals (212.0–212.8 ft [64.62–64.86 m], 224.1–224.9 ft [68.31–68.55 m], and 251.0–251.7 ft [76.5–76.72 m]). We continued with 10-ft (3.05 m) runs and near-perfect recovery as we penetrated unconsolidated sands of the “Piney Point aquifer.” The day ended with 69.5 ft (21.18 m) recovered out of 70 ft (21.34 m) cored (99.25% recovery).

On 17 July, smooth coring continued with 10-ft (3.05 m) runs. Core 58 was cut short at 6 ft (1.83 m) with no core loss as marls were penetrated. Coring continued through slightly clayey medium-grained quartz sands. The day ended at 360 ft (109.73 m), with 79.5 ft [24.26 m] recovered out of 80 ft (24.34 m) cored (99.4% recovery).

On 18 July, we continued with 10-ft (3.05 m) core runs, enjoying full recovery in the morning in clay and glauconitic clay. In the afternoon, drilling slowed because the dry, fine-grained Manasquan Formation clays between 390 and 405 ft (118.87–123.44 m) began to cake up on the outside of the core barrel, forcing the drilling fluid into the aquifers, and causing the loss of circulation. The USGS WRD took sediment samples for pore squeezing at 362.0–362.5 (110.34–110.49 m) and 393.0–393.5 ft (119.79–119.94 m). The day ended at 410 ft (124.97 m), with 50.7 ft recovered (15.45 m) out of 50 ft (15.24 m) cored (101% recovery); only one run had less than full recovery (Core 68 had a 5-ft run with 4.4 ft recovered [1.34 m recovered out of 1.52 m]).

On 19 July, we continued with 5-ft (1.52 m) runs into the glauconitic clays of the Manasquan Formation. Recovery was excellent from 410 to 427 ft (124.97–130.15 m; 110% recovery). The USGS WRD took samples at 421.5–422.0 ft (128.47–128.63 m). At 427 ft (130.15 m), indurated porcellanitic clays mangled the drill shoe; the section from 427 to 430 ft (130.15–131.06 m) was drilled and recovered using a core catcher designed for hard rock. Carbonate cemented sediment continued to make drilling difficult and resulted in mangled drilling shoes and moderate–poor recovery for Cores 73 (83%; 427–430 ft; 130.15–131.06 m) and 74 (40%; 430–440 ft; 131.06–134.11 m). The day ended at 443 ft (135.03 m), with 28.6 ft (8.72 m) recovered out of 33 ft (10.06 m) drilled (86.5% recovery).

Smooth coring resumed on 20 July despite penetrating interbeds of hard and very hard clays. We ran the snout shoe, cored from 443 to 450 ft (135.03–137.16 m) with 93% recovery, and resumed 10-ft (3.05 m) runs with excellent recovery. The USGS WRD took samples at 458.5–459.0 ft (139.75–139.9 m). Coring slowed and the next run (Core 78; 460–470 ft [140.21–143.26 m]) only recovered 1.05 ft (0.32 m) of core. This core had apparently lodged and pushed the inner core barrel up, leaving the rest of the core in the barrel. We unsuccessfully attempted to retrieve it by running the inner core barrel with a large shoe. The rods were pulled during the afternoon and 0.9 ft (0.27 m) of core was retrieved in the lowermost rod. Although the 1.05-ft (0.32 m) section retrieved in the core barrel is likely from the top of the 10-ft (3.05 m) run and the 0.9-ft (0.27 m) section retrieved in the lowermost rod is likely from the base of the 10-ft (3.05 m) run, the two sections were top justified and logged as a single run with recovery from 460 to 462 ft

(140.21–140.82 m). The section from 461 to 462 ft (140.51–140.82 m) may be significantly disturbed by the process of redrilling and pulling the rods; the section from 461.8 to 462.0 ft (140.76–140.82 m) is especially suspect. The rods were replaced and the section from 400 to 470 ft (121.92–143.26 m) was redrilled to try to clear the clays which had been interrupting circulation.

Coring resumed on 21 July with 10-ft (3.05 m) runs. Circulation was still intermittent throughout the morning. USGS WRD took samples at 476.4–477.0 ft (145.21–145.39 m). The run for Core 81 (490–498 ft [149.35–151.79 m]) had 2 ft of drill mud stuck in the top of the barrel, which prevented drilling a full 10-ft (3.05 m) run. This run was packed in the barrel and may have been fractured during drilling. The next run (498–500 ft [151.79–152.4 m]) retrieved no core. The run for Core 83 (500–508 ft [152.4–154.84 m]) recovered 7.3 ft (2.23 m) of solid core; the top 2 ft (0.61 m) was severely disturbed and was discarded.

On 22 July, most of the first core (Core 84; 508–515 ft [154.84–156.97 m]) was chewed up and mixed with drilling mud; 3.65 ft (1.11 m) was archived, 1.25 ft (0.38 m) was logged, and 0.7 ft (0.21 m) was solid core. Drilling stopped in late morning for filming by the Discovery Channel on deep bacteria. We switched to a 5-ft (1.52 m) run, a short (vs. snub) shoe, and cored to 520 ft (158.5 m) with 102% recovery. We returned to 10-ft (3.05 m) runs from 520 to 540 ft (158.50–164.59 m) and obtained full recovery in uniform silty clays. The day ended at 540 ft (164.59 m), with 26.6 ft (8.11 m) recovered out of 32 ft (9.75 m) cored (83% recovery). The USGS WRD took samples at 515.5–516.3 and 530.2–531.2 ft (157.12–157.37 and 161.6–161.91 m).

On 23 July, the top of the first core (Core 88; 540–550 ft [164.59–167.64 m]) was partly chewed up and mixed with drilling mud; although the barrel came up full, the top 6.4 ft (1.95 m) contained a mixture of solid core and drilling mud, whereas the base of the core contained 3.6 ft (1.10 m) of solid core. After extensive washing, 1.9 ft (0.58 m) of the top 6.4 ft (1.95 m) was saved. We top justified the bottom 3.6 ft (1.10 m) for a total recovery of 5.5 ft (1.68 m); all field notes, photos, and samples reflect a depth of 545.5 ft (166.27 m) for the base of this core. However, it is clear that the bottom 3.6 ft (1.10 m) came from the BOH, and we may need to recalibrate the depths accordingly. This is critical because this section appears to record part of the late Paleocene CIE. The next two cores required extensive circulation after drilling to equalize pressure on the system; both yielded excellent recovery. The USGS WRD took samples at 566.5–567.0 and 575.5–576.0 ft (172.67–172.82 and 175.41–175.56 m). The day ended at 580 ft (176.78 m), with 36.4 ft (11.09 m) recovered out of 40 ft (12.19 m) cored (90.9% recovery).

On 24 July, we switched to 5-ft (1.52 m) runs to minimize core loss near important contacts and enjoyed >100% recovery down to 610 ft (185.93 m). The USGS WRD took samples at 592.5–593.0 ft (180.59–180.75 m). Runs 94 and 95 spanned 590–600 ft (179.83–182.88 m) and are reported as 590–595.0 and 590.5–600.0 ft (179.83–181.36 and 179.98–182.88 m). Based on recovery and the fact that the first run was judged to be slightly <5.5 ft long, (1.68 m), the actual depths of these cores should be 590.0–595.3 and 595.3–600.0 ft (179.83–181.45 and 181.45–182.88 m). Similarly, Cores 95 and 96 spanned 600–610 ft (182.88–185.93 m) and are reported as 600.0–605.5 and 605.5–610.0 ft (182.88–184.56 and 184.56–185.93 m), respectively, although the actual depths are probably 600.0–605.3 and 605.3–610.0 ft (182.88–184.50 and 184.50–185.93 m). The USGS WRD took samples at 606.0–

606.5 ft (184.71–184.86 m). We judged that the K/T boundary would be at ~615 ft (187.45 m) and decided to run a 10-ft (3.05 m) core. We obtained a full-recovery core spanning the K/T boundary. The next 10-ft (3.05 m) run also obtained full recovery. The day ended at 630 ft (192.02 m), with 51.8 ft (15.79 m) recovered out of 50 ft (15.24 m) cored (103.6% recovery including core expansion).

On 25 July, we began with two 5-ft (1.52 m) runs but switched over to 10-ft (3.05 m) runs; recovery remained near perfect. Run 104 was ended short when the core became firmer and the drillers feared they would lose the bottom portion. The day ended at 690 ft (210.31 m), with 60.05 ft [18.30 m] recovered out of 60 ft [18.29 m] cored (100% recovery).

On 26 July, operations continued with 10-ft (3.05 m) runs and excellent core recovery (100.02%) to 750 ft (228.60 m). During drilling from 750 to 760 ft (228.60–231.65 m), the drillers reported hitting a lithified interval that mushroomed the shoe. The core barrel was wedged in the drill string and the rods were pulled to 315 ft (96.01 m) in the afternoon.

On 27 July, the remaining rods were pulled and 8.5 ft (2.59 m) of solid core was removed from the stuck core barrel. While reentering the hole, the rods would not advance below ~543 ft (165.51 m), encountering a bridge, perhaps caused by the swelling of clays. After coring a few feet of caving at 543 ft (165.51 m), the rods were deflected and we began to core fresh sediment in a new hole that subparalleled the first hole. We needed to redrill and recore the entire section from 543 to 759 ft (165.51 to 231.34 m). We designated the second hole as Hole B. Hole A ended with 693.8 ft (211.47 m) recovered out of 759 ft (231.34 m) cored (91.4% recovery). The first run in the new hole (Core 1) recovered mostly caved glauconitic clays, except for the bottom 1.05 ft (0.32 m) of solid core. The next core (Core 2) recovered 6.3 ft (1.92 m) of solid core; the BOH was measured at 550 ft (167.64 m). This 7.35-ft (2.24 m) interval represents the interval 543–550 ft (165.51–167.64 m) in Hole A. Thus, we drilled and recovered the section containing the latest Paleocene event in the second hole. The section from 559.1 to 559.4 ft (170.41–170.51 m) in Hole B contains convoluted bedding, corresponding to the interval from 559.2 to 560.0 ft (170.44–170.69 m) in Hole A. The day ended at 560 ft (170.69 m), with 16.8 ft (5.12 m) recovered out of 17 ft (5.18 m) cored in Hole B (99% recovery).

On 28 July, smooth coring yielded 69.95 ft (21.21 m) out of 70.0 ft drilled (21.34 m; 99.9% recovery), with the BOH at 630 ft (192.02 m). Of particular note is the second recovery of the K/T boundary within a single core barrel.

Overnight, the driller hung the rods 20 ft (6.10 m) from the BOH, as they had on previous days. On the morning of 29 July, the rods were difficult to turn at first. G. Cobbs concluded that the hole was grabbing the drill rods because of its deviation from vertical. If the hole had continued to grab, the target depth of 1200 ft (365.76 m) might not have been reached, so we decided to raise the rods back to 540 ft (164.59 m) and to try to re-enter Hole A. After successfully raising and lowering the rods, we reached the BOH at 630 ft (192.02 m), indicating that we had re-entered Hole B. While lowering the rods, we trimmed sticky clay between 550 and 630 ft (167.64 and 192.02 m), improving circulation, straightening the hole, and attaining zero mud pressure.

Coring resumed on 30 July in Hole B, with nearly complete recovery to 700 ft (213.36 m; 69.16 ft [21.08 m] was recovered out of 70.0 ft [21.34 m] cored [98.8% recovery]). The Navesink/Mount Laurel contact occurred at virtually the same depth in Hole B (651.2–651.3 ft [198.49–198.52 m]) as it did in Hole A (651.3 ft [198.52 m]). This suggests that the two holes are very close to each other (i.e., within a few feet) and that their deviation from vertical is minimal.

Coring was slower than usual in the morning of 31 July because of rain. After the rain stopped, we resumed bringing up approximately one core every hour. During run 21 (730–740 ft [222.5–225.55 m]), a hardground was encountered at 732 ft (223.11 m) that bent the shoe inward and gouged a groove in the lower portion (732–740 ft [223.11–225.55 m]) of that run. On the last run of the day a hardground was encountered at 761 ft (231.95 m). The drillers decided to stop and drill it in the morning.

No problems were encountered drilling to 830 ft (252.98 m) on 1 August, and 69.7 ft (21.24 m) was recovered out of 68.5 ft (20.88 m) cored (102% recovery).

On 2 August, the first run slipped out of the catcher and was lost (0.2-ft [0.06 m] recovery). Excellent recovery was obtained for the next three runs (840–870 ft [256.03–265.18 m]). At the end of run 35 (860–870 ft [262.13–265.18 m]), a water swivel blew, suspending operations for the rest of the day. The rods were hung 60 ft (18.29 m) from the BOH (810 ft [246.89 m]) to prevent swelling and sticking in the Woodbury Formation clays.

On 3 August, despite our best efforts, the rods remained stuck in the hole throughout the morning. We thinned the drilling mud with water to try to loosen the clays binding the drilling string. The drill rods were freed by 1430 and pulled to 650 ft (198.12 m) by the end of the day.

On 4 August, we pulled the rods to 540 ft (164.59 m) and re-reamed the section to the BOH, leaving the rods 30 ft (9.14 m) off the bottom overnight.

The rods had been tight every morning since we penetrated the Manasquan Formation and were tight again on 5 August when we resumed smooth coring in clays of the Woodbury Formation. The USGS WRD took samples at 881.0–881.6, 890.5–891.1, and 900.3–900.8 ft (268.53–268.71, 271.42–271.61, and 274.41–274.56 m). Core runs 36–39 attained >100% recovery. The inner core barrel failed to latch on core run 40, leaving 10 ft (3.05 m) of core in the hole. We ran the inner core barrel with a larger shoe, overrunning the core, jammed the core catcher to block the core from slipping, and attained 104% recovery. The day ended at 920 ft (280.42 m), with 52.0 ft (15.85 m) recovered out of 50 ft (15.24 m) cored (104% recovery).

Smooth coring continued on 6 August with full recovery on the first run. The second run (Core 42; 930.0–931.2 ft [283.46–283.83 m]) encountered a hard clay at the base and drilling stopped 1.2 ft (0.37 m) into the run. We ran a shorter shoe and drilled 2.7 ft (0.82 m) on the next run (Core 43; 931.2–933.9 ft [283.83–284.65 m]), recovering an indurated glauconite sand. We finished the 10-ft (3.05 m) interval with run 44B (933.9–940.0 ft [284.65–286.51 m]), with 10.47 ft (3.19 m) of recovery (105%). The next two runs (940–960 ft [286.51–292.61 m]) attained nearly 100% recovery even though we penetrated a wide range of sands, silts, and clays. The last run penetrated only 4.5 ft (1.37 m) through coarse sands. The day ended at 964.5 ft (293.98 m), with 43.17 ft (13.16 m) recovered out of 44.5 ft (13.56 m) cored (97.0% recovery).

On 7 August, we recovered 35.5 ft (10.82 m) out of 45 ft (13.72 m) cored (78% recovery). Actual recovery is somewhat higher because the sands were compacted. On the third run of the day (Core 50; 980–990 ft [298.70–301.75 m]), the shoe was bent when it penetrated a pyrite nodule that became lodged in the outer core barrel. The inner barrel was eventually freed by pulling up on the wireline, preventing having to pull the drill string.

Coring on 8 August was slow as a result of the presence of numerous gravel beds. These forced us to make runs shorter than the full 10 ft (3.05 m), because it was feared that the gravels might damage the shoe. As a result, only 40 ft (12.19 m) was cored to 1050 ft (320.04 m), with 24 ft (7.32 m) recovered (60% recovery).

On 9 August, we penetrated through the variable lithologies of the Magothy Formation into the more monotonous clays of the Bass River Formation. This enabled the drillers to take complete 10-ft (3.05 m) runs with good recovery. As a result, 45 ft (13.72 m) was cored with 41 ft (12.50 m) of recovery (91.1%). At 1082.5 ft (329.95 m), a hardground was encountered, forcing us to break the interval from 1080 to 1090 ft (329.18–332.23 m) into two runs. On the next run, another indurated zone was encountered at 1095 ft (333.76 m), terminating drilling for the day.

On 10 August, we changed to a short shoe and cored 0.3 ft (0.09 m) of siltstone and 4.7 ft (1.43 m) of silty clay on run 65 (1095–1100 ft [333.76–335.28 m]). Run 66 (1100.0–1107.5 ft [335.28–337.57 m]) was terminated 7.5 ft (2.29 m) into the run by another hard layer. We recovered 8.85 ft (2.70 m) from the next run (1107.5–1117.5 ft [33.57–340.61 m]), leaving 1.6 ft (0.49 m) in the hole. On the next run (1117.5–1120.0 ft [340.61–341.38 m]), we recovered 4.2 ft (1.28 m), picking up the 1.6 ft (0.49 m) previously left in the hole. This 1.6 ft (0.49 m) has a narrower diameter as a result of recoring. The section was top justified at 1116 ft (340.16 m), yielding full recovery (104%) for both runs. Smooth coring continued until a hardground was encountered at 1132 ft (345.03 m). Run 70 recovered 1.8 ft (0.55 m), whereas run 71 recovered 9 ft (2.74 m) for a total of 10.8 ft (3.29 m) from the interval 1130–1140 ft (344.42–347.47 m); the depth of run 71 should be adjusted to a top of 1131.8 ft (344.97 m). The day ended at 1140 ft (347.47 m), with 47.25 ft (14.40 m) recovered out of 45 ft (13.72 m) cored (105% recovery).

On 11 August, the first run (72) stopped at a hard layer at 1146 ft (349.30 m). The next run recovered 4 ft (1.22 m) and lost 0.8 ft (0.24 m) from the bottom. Run 74 also stopped at a hard layer at 1157 ft (352.65 m). The next run (1157–1161 ft [352.65–353.87 m]) lost 0.7 ft (0.21 m) from the bottom as the sands were washed away. Our plan was to drill 20–30 ft (6.10–9.14 m) into the Potomac Group sands so that we could log the contact with the overlying Bass River Formation; this objective was attained on run 76 (1161–1170 ft [353.87–356.62 m]) and Hole B was terminated. The NJGS logger, J. Curran, arrived and obtained a gamma-ray log through the rods. The gamma-ray log obtained was checked and calibrated to depth on site. Log quality was excellent, with major deflections at contacts where previous studies had shown gamma-ray increases (e.g., the Navesink/Mount Laurel contact). Therefore, it was decided not to log directly on formation.

The rods were pulled on 12 August and scientific operations ceased. The drillers returned on 17 August, removed the casing, grouted the hole with Benseal, and finished clean-up operations.

The Ancora borehole was the highest recovery borehole drilled to date in the New Jersey Coastal Plain. Hole A recovered 693.82 ft (211.48 m) out of 759 ft (231.34 m) cored (91.4% recovery), whereas Hole B recovered 591.48 ft (180.28 m) out of 627 ft (191.11 m) cored (94.3% recovery). The total recovery (1285.31 ft [391.76 m] recovered out of 1386 ft [422.45 m] cored) of 92.7% is remarkable.

Lithologies were described on site and subsequently at the Rutgers University core facility. These descriptions formed the basis for the preliminary lithologic descriptions. Samples were obtained at ~5-ft (1.52 m) intervals for planktonic foraminifer and calcareous nannofossil biostratigraphy and coarse-fraction lithologic studies. Cores were cut into 2-ft sections, labeled at the top and bottom of each section, placed into split PVC pipe (3-in [7.6 cm] diameter), wrapped in plastic sheeting, and stored in 2-ft (0.61 m) wax boxes. Seventy-nine Hole A and 72 Hole B boxes were moved to permanent storage at the Rutgers University core library for further studies.

LITHOSTRATIGRAPHY

Summary

The on-site scientific team provided preliminary descriptions of sedimentary textures, structures, colors, fossil content, identification of lithostratigraphic units (NJGS Information Circular 1, 1990), and lithologic contacts (see **"Visual Core Descriptions"** for core images; Table **T1**; Figs. **F2**, **F3**, **F4**, **F5**, **F6**, **F7**, **F8**). Subsequent studies integrated preliminary descriptions with additional descriptions, biostratigraphy, biofacies studies, isotopic stratigraphy, and the gamma-ray log. 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. For the nonmarine and nearshore sections (primarily the Miocene and younger section), lithofacies interpretations provide the primary means of recognizing unconformities and interpreting paleoenvironments. For the neritic sections (primarily the Paleogene and Upper Cretaceous), 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 Ancora borehole.

Lithofacies changes within onshore sequences, particularly Upper Cretaceous sections, generally follow repetitive transgressive–regressive patterns (Sugarman et al., 1993, 1995) that consist of (1) a basal transgressive glauconite sand equivalent to the transgressive systems tract (TST) of Posamentier et al. (1988) and (2) a coarsening-upward succession of regressive medial silts and upper quartz sands equivalent to the HST of Posamentier et al. (1988). Lowstand systems tracts (LSTs) are usually absent in the coastal plain and the TSTs are generally thin. Because the TSTs are thin, maximum flooding surfaces (MFSs) are difficult to differentiate from unconformities. Both can be marked by shell beds and gamma-ray peaks. Flooding surfaces, particularly MFSs, may be differentiated from sequence boundaries by the association of erosion and rip-up clasts at the latter, lithofacies successions, and benthic foraminifer changes. The transgressive surface (TS) marking the top of a LST represents a change from generally regressive to transgressive facies; because LSTs are generally absent, these surfaces are generally merged with the sequence boundaries. Notable exceptions include the base of the Navesink Formation at outcrop (Miller et al., 1999) and the lower Marshalltown sequence described here.

Benthic foraminifer biofacies were used to recognize inner neritic (0–30 m), middle neritic (30–100 m), outer neritic (100–200 m), and upper bathyal (200–600 m) paleodepths. Cumulative percent plots of the sediments in the cores were computed from samples washed for paleontological analysis. 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 Sites), in which the samples were not dried before washing.

Surficial Deposits

Age: ?Pleistocene
Interval: 0.5–9.0 ft (0.15–2.74 m)

Gravels and sands were encountered from just below the soil horizon (0.5 ft [0.15 m] in a hand auger sample) to 9.0 ft (2.74 m), below which is a red clayey quartz sand. The gravels typically consist of rounded quartz pebbles up to 2 cm long. Sporadic chert fragments were noted. The age and lithologic assignment of this surficial unit are uncertain. Field studies of outcrops ~1 mi (1.61 km) north of the drill site (W. Newell, pers. comm., 1998) suggest that these surficial sediments are Bridgeton Formation (upper Miocene) gravels that were reworked by glacial Pleistocene streams.

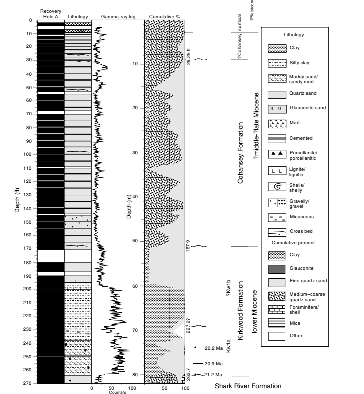
Cohansey Formation

Age: ?early–?middle Miocene
Interval: 9.0–167.9 ft (2.74–51.18 m)

Red, yellow red, and yellowish to reddish brown quartz sands containing indurated zones up to 0.5 ft (0.15 m) thick occur between 9 and 29.25 ft (2.74–8.92 m). These variegated sands vary from fine- to very coarse–grained and have few opaque minerals. Obvious cross-bedding begins at 26 ft (7.92 m). Possible burrowing begins at 27 ft (8.23 m). The lithologic assignment of this variegated unit is uncertain; we tentatively place it in the Cohansey Formation. The environment of deposition is also unclear, and the upper part of the section may be fluvial. Bioturbation below 27 ft (8.23 m) may indicate shallow marine/nearshore deposition. The contact between indurated reddish gravelly sands above 29.25 ft (8.92 m) and yellow gravelly quartz sands below may merely reflect a diagenetic horizon.

Definite Cohansey Formation quartz sands appear at 29.25 ft (8.92 m) and continue to 167.9 ft (51.18 m). The lithology varies from fine to very coarse sand, with laminae of kaolinitic clays. Bedding is predominantly massive with occasional clay drapes; drapes are more common from ~38 to 90 ft (11.6–27.4 m). Coarsening-upward cycles are observed in the intervals 29.25–37, ~37–50, 50–70, 70–90, and 90–112 ft (8.92–11.28, 11.3–15.24, 15.24–21.34, 21.34–27.43, and 27.43–34.14 m). These cycles are also seen on the gamma-ray log (Fig. F2), although the coarse-fraction data show a generally fining-upward pattern from ~50 to 110 ft (15.24–33.53 m; Fig. F2). Medium–coarse sands predominate from ~112 to 145 ft (34.14–44.2 m), with interfingering organic-rich silts and sands at 138.0–138.5 ft (42.06–42.21 m). At 145.35 ft (44.3 m) there is a shift from fine and medium sands above to gravelly coarse sands below. Below this interval and down to 150.2 ft (45.78 m) are red to brownish yellow fine to coarse quartz sands with occasional pebbles; intercalations of medium and medium–coarse sands with clay laminations continue to the base of the Cohansey Formation (167.9 ft [51.18

F2. Surficial deposits, Cohansey and Kirkwood Formations, p. 52.



m]). Cross-beds occur in the basal 3 ft (0.91 m). The quartz sands from 29.25 to 167.9 ft (8.92–51.18 m) were deposited in nearshore (beach, shoreface, and offshore sand ridge) environments. The absence of shell and calcareous plankton precludes the use of Sr isotopic or biostratigraphic ages for this unit.

Kirkwood Formation

Age: early middle to middle Miocene
Interval: 167.90–263.65 ft (51.18–80.36 m)

The Kirkwood Formation is distinguished from the Cohansey Formation at Ancora by its generally finer grain size, color (gray vs. yellow and variegated), and bedding (massive vs. massive and cross-bedded). It was deposited in (inner–middle?) neritic, prodelta, and delta-front environments. We tentatively recognize two Kirkwood sequences at Ancora (167.90–227.27 and 227.27–263.70 ft [51.18–69.27 and 69.27–80.38 m]). Based on Sr isotopic age estimates, the lower sequence correlates with the Kw1a sequence of Sugarman et al. (1993); based on superposition, the upper sequence may correlate with the Kw1b Sequence of Sugarman et al. (1993).

The top of the Kirkwood Formation (167.9–199.1 ft [51.18–60.69 m]) consists of a gray, massive, slightly micaceous, peaty, fine- to medium-grained quartz sand that fines downsection to a silty, very fine to fine sand. The coarsening reflects a shallowing upsection. We tentatively interpret these bioturbated, peaty sands as delta-front deposits. Kirkwood Formation silty clays begin at 199.1 ft (60.69 m) with a gradational contact. Laminated, occasionally lignitic, silty clays to clays containing shell impressions and shell debris were probably deposited in a prodelta environment (199.1–217.4 ft [60.69–66.26 m]). More massive (?burrowed) silty clays alternate with laminated silty clays between 220 and 226.2 ft (67.06 and 68.95 m). There is a probable sequence boundary at 227.2 ft (69.25 m), at the base of a prodelta clay that is associated with a sharp increase in gamma ray–log values (Fig. F2).

The section below the possible sequence boundary at 227.2 ft (69.25 m) shows a distinct shallowing-upward succession from neritic to delta-front environments:

1. Intensely micaceous, woody, cross-bedded silts (227.2–232.0 ft [69.25–70.71 m]) may indicate delta-front environments; on fresh exposure these sediments are dark gray, but they weather to yellowish brown.
2. Grayish brown ("milk chocolate") micaceous, laminated, woody clayey silts (232–238 ft [70.71–72.54 m]) are typical of a prodelta environment.
3. Silty, shelly, massive, slightly micaceous, very fine-grained quartz sands (238.0–262.7 ft [72.54–80.07 m]) were deposited in shelfal (probably inner neritic) environments. Benthic foraminifers indicate inner neritic paleodepths at 246 ft (74.98 m; *Nonionellina pizzarensis* fauna), and possibly middle neritic paleodepths at 261 ft (79.55 m; *Buliminella* fauna; see **"Biostratigraphy,"** p. 29). The upsection facies shift is typical of Kirkwood sequences (Sugarman et al., 1993; Miller et al., 1997), reflecting a shallowing-upward succession from shelf to deep prodelta clay to delta front.

The base of the Kirkwood Formation at Ancora is a spectacular sequence boundary with a reworked lag zone (262.7–263.7 ft [80.07–80.38 m]), sharp gamma ray–log increase, and a basal phosphorite bed (263.7 ft [80.38 m]) overlying poorly sorted quartz sands of the Eocene Shark River Formation. Lowermost Miocene (Sequence Kw0) through uppermost Eocene strata are not represented at Ancora.

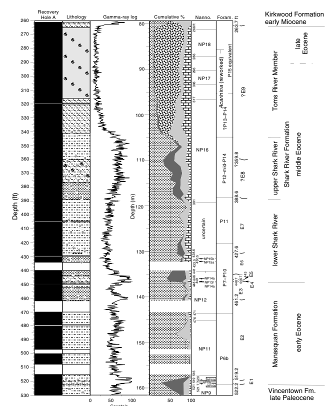
Shark River Formation

Age: middle Eocene, possibly early late Eocene at top
Interval: 263.7–448.7 ft (80.38–136.76 m)

Middle to upper Eocene sands and clays (263.7–388.6 ft [80.38–118.45 m]) are assigned to the Shark River Formation. This formation is subdivided into an very sandy upper Toms River Member (Enright, 1969), an informal sandy upper Shark River Member, and a clayier lower Shark River Member (Miller et al., 1990).

Slightly shelly to shelly medium-grained quartz sands of the Toms River Member of the Shark River Formation appear below the unconformity at 263.7 ft (80.38 m; Fig. F3); this sandy unit is the HST of a sequence (263.7–359.8 ft [80.38–109.67 m]) that includes the upper Shark River Formation (Fig. F2). The dark greenish gray sands are massive with some evidence of burrowing, traces (<2%) of glauconite and brownish clay, occasional pebbles, shells, and rare to common foraminifers. The fairly uniform sands continue to 315.8 ft (96.26 m), thus providing a 50-ft (15.24 m) aquifer used by the Ancora hospital as a water supply. The section from 315.8 to 355.0 ft (96.26 to 108.20 m) generally coarsens upward (Fig. F3), with clayey medium-grained quartz sand (315.8–345.0 ft [96.26–105.16 m]) grading down to glauconitic clay at 345.0–359.8 ft (105.16–109.67 m).

F3. Shark River and Manasquan Formations, p. 53.



Clays (345.0–359.8 ft [105.16 and 109.67 m]) comprise the lower part of the sequence between 263.7 and 359.8 ft (80.38–109.67 m). We interpret a lithologic contact at 359.8 ft (109.67 m) separating glauconitic clays above from glauconitic sandy clays below as a sequence boundary. The sequence from 263.7 to 359.8 ft (80.38–109.67 m) is probably equivalent to Sequence E9 of Browning et al. (1997a, 1997b), containing reworked middle Eocene foraminifers and in situ upper Eocene foraminifers (e.g., *Globigerina praebulloides*) and nannofossils.

A sequence between 359.8 and 388.6 ft (109.67–118.45 m) comprises most of the upper Shark River Formation. The upper part of this sequence is a HST (359.8–371.2 ft [109.67–110.64 m]) containing an admixture of glauconite and quartz sand, typical of HSTs of this age in New Jersey (Browning et al., 1997a, 1997b). Megafossils are common between 363.0 and 371.2 ft (110.64–113.14 m). The lower part of the sequence consists of glauconitic clay (371.2–388.6 ft [110.64 –118.45 m]). A distinct sequence boundary at 388.6 ft (118.45 m) separates glauconitic clay from the much brighter green clays of the underlying sequence. This sequence (359.8–388.6 ft [109.62–118.45 m]) is assigned to Zone NP16 (see **"Biostratigraphy,"** p. 29) and is, thus, equivalent to Sequence E8 of Browning et al. (1997a).

The top of the underlying sequence (388.6–427.6 ft [118.45–130.33 m]) consists of bioturbated, pale green, slightly sandy silty clay (lower Shark River Formation) that grades downsection to pale olive green clay (below ~410 ft [124.97 m]). Between 400 and 417 ft (121.92–127.10 m), the clay is slightly glauconitic, with glauconite increasing below 417 ft to a contact at 427.6 ft (130.33 m). Several 0.1- to 0.2-ft-thick (3–6 cm) indurated zones (porcellanites) occur from 427.0 to 427.9 ft (130.15–130.42 m). The bioturbated contact at 427.6 ft (130.33 m) separates very glauconitic porcellanitic clays from very slightly silty clays and is interpreted as a sequence boundary (E7/E6 of Browning et al., 1997a, 1997b).

Three thin cycles span the middle/lower Eocene boundary. These cycles consist of silty, pale olive clays grading down to glauconite-rich layers associated with gamma-ray peaks; the cycles are interpreted as sequences with sequence boundaries at the bases of the glauconite-rich layers:

1. A sequence from 427.6 to 443.0 ft (130.33–135.03 m) is assigned to Subzones NP15b–NP15a? and is, thus, correlative to Sequence E6 of Browning et al. (1997a, 1997b).
2. A sequence from 443.0 to 446.7 ft (135.03 –136.15m) is assigned to Subzone NP14a and is, thus, correlative to Sequence E5 of Browning et al. (1997a, 1997b).
3. A sequence from 446.7 to 448.7 ft (136.15–136.76 m) is assigned to Zone NP13 and Subzone NP14a and is, thus, correlative to Sequence E4 of Browning et al. (1997a, 1997b).

The contact at 448.7 ft (136.76 m) is a sequence boundary separating Sequence E4 from E3 of Browning et al. (1997a, 1997b).

The section from 388.6 to 448.7 ft (118.45–136.76 m) is assigned to the lower Shark River Formation (Fig. F3). In general, the Shark River Formation can be differentiated in fresh cores from the underlying Manasquan Formation by being less clay rich and darker green. However, grain size and color are not sufficient for differentiating these two formations in the field because both weather to "ash-colored marls" (Cook, 1868). We adopt the criteria of Enright (1969) and Owens et al. (1988) by placing the base of the Shark River Formation at a distinct glauconite bed (Browning et al., 1997a). This maintains the Manasquan Formation as primarily lower Eocene and the Shark River Formation as primarily middle Eocene.

Manasquan Formation

Age: early Eocene
Interval: 448.7–522.2 ft (136.76–159.17 m)

Immediately below the sequence boundary at 448.5 ft (136.70 m), there is a yellowish, weathered, ?kaolinitic clay (448.5–448.7 ft [136.7–136.76 m]). From 448.7 to 449.5 ft (136.76–137.01 m), glauconite is burrowed down from the sequence boundary above. Bioturbated, slightly glauconitic, fossiliferous, interbedded clays and silty clays extend to 451.6 ft (137.65 m); below this level, glauconite is less common and burrows are less visible. We interpret the glauconite as having been reworked into upper HST sands. Interbedded fossiliferous clay and silty clay grade downsection to clay at 458 ft (139.60 m). Glauconite and burrowing appear again at 459.8 ft (140.15 m) with increasing glauconite downsection to 461.2 ft (140.57 m), where there is an abrupt shift to very slightly glauconitic silty clay and a sharp gamma ray–log increase. This level is probably a sequence boundary separating Sequence E3 of Browning et al. (1997a) above from Sequence E2 below. However, there is ambiguity in the placement of the lower sequence boundary as a result of a coring gap between 462 and 470 ft (140.82–143.26 m). Nannofossils indicate that the section from 449 to 471 ft (136.86–143.56 m) is assigned to Zone NP12; Sequence E3 is contained entirely within this zone elsewhere in New Jersey (Browning et al., 1997a). This suggests either that there is contamination immediately below the coring gap or that the sequence boundary lies in, or just below, the coring gap.

Greenish gray silty clays extend from 461.2 ft to 517.4 ft (140.57–157.70 m). From 461.4 to 480.0 ft (140.63–146.30 m), these silty clays are slightly glauconitic. Below 480 ft (146.30 m) there are some finely laminated sections. The clay darkens and glauconite begins to increase below 496 ft (151.18 m). Glauconite increases in the silty clays from 517.4 to 519.2 ft (157.70–158.25 m). The sequence between 461.2 ft and 519.2 ft (140.57–158.25 m) correlates with Sequence E2 of Browning et al. (1997a).

A subtle sequence boundary is indicated by nannofossil biostratigraphy and a minor lithologic change at 519.2 ft (158.25 m). This level separates Subzone NP10d above (519 ft [158.25 m]) from NP10b below (519.9 ft [158.25 m]), with a glauconitic (~10%–20%) clay above and a very slightly glauconitic clay below that is associated with a gamma ray–log kick at about 518–519 ft (158.19–157.89 m). Clayey glauconite sand marks most of the sequence from 520.0 to 522.2 ft (158.50–159.17 m). Phosphorite pellets at 520.7 ft (158.71 m) probably mark the MFS and yield a sharp gamma-ray peak. A lithologic change associated with a sequence boundary occurs at 522.2 ft (159.17 m) from clayey glauconite sand above to a micaceous, very slightly glauconitic silty clay below. The sequence boundary shows a distinct irregular contact, with clay bioturbated ~0.5 ft (0.15 m) above and glauconite burrowed 0.5 ft (0.15 m) below. The sequence between 519.2 and 522.2 ft (158.25–159.17 m) correlates with Sequence E1 of Browning et al. (1997a).

The Manasquan Formation at Ancora displays larger lithologic variations than it does at Island Beach or Bass River, in part as a result from its more updip location. These lithologic and presumably attendant faunal variations should allow a finer evaluation of water depth and eustatic changes for this early Eocene "Greenhouse World."

Vincentown Formation

Age: late Paleocene
Interval: 522.2–604.5 ft (159.17–184.25 m)

The lithologic unit below the sequence boundary at 522.2 ft (159.17 m) is a dark greenish gray silty clay characterized by traces of mica and rare (<1%) to common (~5%) glauconite that continues to 543.4 ft (165.63 m). This unit is massive to laminated (laminae are alternating silt and clay) and contains sporadic shell material. Cross beds and possible lenticular beds are present. This lithologic unit is similar to the Vincentown equivalent at Island Beach (Miller et al., 1994b). At Island Beach, the Vincentown equivalent is sandy near the top, whereas at Bass River the unit is sandier below the CIE (Miller, Sugarman, Browning, et al., 1998). Although it is similar in color and grain size to the overlying Manasquan Formation, the Vincentown equivalent is differentiated at Ancora by its mica and cross-beds.

It appears that the Paleocene/Eocene contact is associated with the sequence boundary at 522.2 ft (159.17 m). Lower Eocene Subzone NP10a is extremely thin and found immediately above the 522.2 ft (159.17 m) disconformity (Sample 521.7 ft [159.01 m]), whereas the section immediately below (522.5 ft [159.26 m]) is assigned to upper Paleocene Subzone NP9b (see **"Biostratigraphy,"** p. 29).

We may have recovered the LPTM in an intriguing interval. Below slightly glauconitic, slightly micaceous laminated silty clay of the Vincentown equivalent (to 543.4 ft [165.63 m]), there is a section of clay that exhibits convoluted bedding, with mini-flame and mini-ball structures (543.5–545.5 ft [165.66–166.27 m]). Interbeds of clay and silty clay (550–560 ft [167.64–170.69 m]) have little mica, trace to 3% glauconite, abundant foraminifers (approaching a foraminifer clay), and unusual bedding; silty clay laminations in the clays show evidence of cross-bedding and possible rip-up clasts. Convoluted bedding (including flame structures) occurs again from 559.2 to 560.0 ft (170.44–170.69 m). Samples 545.5 and "560.15" ft (166.27 and "170.73" m; base of Core 89) contain *Acarinina africana,* a CIE species.[3] This indicates that we have at least part of the LPTM represented at Ancora. There is a return to very slightly micaceous laminated silty clay (560–562 ft [170.69–171.30 m]). Based on lithologic correlations with Bass River and Clayton, it is likely that the CIE marking the LPTM occurs within the interval 561.5–562.5 ft (171.15–171.45 m), where there is an increase in glauconite and a decline in foraminifer preservation.

Glauconite increases downsection (562.1–570.0 ft [171.33–173.74 m]), bioturbation increases, bedding becomes more massive, and the lithology coarsens to glauconitic (up to 20%), micaceous, sandy, clayey silts. Benthic and planktonic foraminifers are rare. Covariance of quartz and glauconite sands indicates that the glauconite is reworked (Miller, Sugarman, Browning et al., 1998). The lithologic change from silty clay above to glauconitic clay below is associated with a sharp lithologic contact in Hole B at 562.1 ft (171.33 m); the contact is less distinct in Hole A at 563.7 ft (171.82 m), with glauconite burrowed up into the clays to 562.8 ft (171.54 m). Based on the sharp surface in Hole B, we tentatively identify the contact at 562.1 ft (171.33 m) as a sequence boundary (Fig. **F4**).

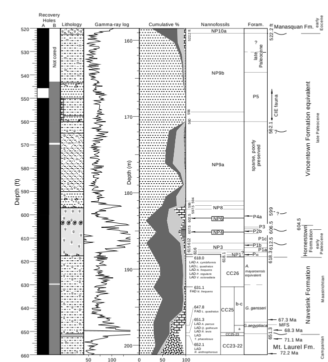
A classic transgressive–regressive sequence occurs between 562.1 and ~599 ft (171.33–182.58 m). Glauconitic, quartzose clays (562.1–566.0 ft [171.33–172.52 m]) with reworked glauconite constitute the upper HST; they grade downhole to micaceous silty clays (566–580 ft [172.52–176.78 m]). Slightly micaceous, silty clay comprises the lower HST. Glauconite increases in glauconitic clays from 589.0 to 595.5 ft (179.53–181.36 m), with an interval of nodules (?replaced shell) at 593.2 ft (180.81 m).

A clay interval at 596.8 ft (181.9 m) in Hole A appears to consist of replaced shell material (?siderite). In Hole B, shells of *Gryphaea dissimilis* are found with replaced shell material at 597.6 ft (182.15 m), suggesting either a 1-ft (0.30 m) offset or some relief on this shell bed.

Sequence boundaries are not readily observable in the lowermost Vincentown and Hornerstown Formations because the entire lower part of the Paleocene section is uniform clayey glauconite sands. Three tentative sequence boundaries (?599, ~606.5, and ~612.5 ft [?182.58, ~184.86, and ~186.69 m]) were inferred in the lowermost Vincentown and Hornerstown Formations based on biostratigraphic evidence (e.g., nannofossil Zones NP7 and NP2 and foraminifer Subzone P3a are missing, and Subzone P1b is less than 1 ft [0.30 m] thick), gamma ray–log kicks, and regional sequence stratigraphic relationships (e.g., the Zone NP7 hiatus is associated with a distinct sequence boundary at Island Beach; Miller et al., 1994b).

[3]Quotation marks indicate that the interval in question is from a core with >100% recovery. For example, "560.15" ft is from run 89 (550–560 ft) that had 102% recovery. Because run 90 also has an interval from 560.15 ft, we use the quotation marks to indicate that interval "560.15" ft is from run 89 and not run 90.

F4. Vincentown, Hornerstown, and Navesink Formations, p. 54.



A sequence boundary is inferred between 597.5 ft (182.12 m; Zone NP8, with NP7 missing) and 600.0 ft (182.88 m; Subzone P4a), near a prominent gamma-ray peak/trough (596.5–600.0 ft [181.81–182.88 m]). This sequence boundary (?599 ft [?182.58 m] in Fig. **F4**) is indicated by regional relationships (i.e., Zone NP7 is missing in association with a clear erosional boundary; fig. 10D in Miller et al., 1994b), although lithologic evidence for a sequence boundary at Ancora is lacking. This sequence boundary separates Sequence Pa3 above from Pa2 of Liu et al. (1997a).

We use the criteria of Owens and Minard (1964) to place the contact between the Vincentown and Hornerstown Formations at the base of an *Oleneothyris harleni* shell bed (600.0–604.5 ft [182.88–184.25 m] in Hole A, 602.7–604.5 ft [183.70–184.25 m] in Hole B), where glauconite becomes subdominant. Alternatively, the formation boundary could be placed at a sequence boundary immediately below the *O. harleni* shell bed (Owens et al., 1997; see Liu et al. [1997a] for a discussion of the formation placement of similar green sands at Island Beach).

Hornerstown Formation

Age: early to earliest late Paleocene
Interval: 604.5–618.5 ft (184.25–188.52 m)

As noted above, the top of the Hornerstown Formation could be placed at 604.5 or 606.0 ft (184.25 or 184.71 m). Glauconite sands with clay burrows (600–610 ft [182.88–185.93 m] in Hole A) contain a shell bed (602.7–604.5 ft [183.7–184.25 m] in Hole A) including *O. harleni*. In Hole B, the shell bed occurs at 606.0–606.8 ft (184.71–184.95 m), thinner and ~2–3 ft (~0.60–0.91 m) lower than in Hole A, perhaps reflecting depositional relief. The shell beds appear to correlate with a gamma ray–log peak (604.5 ft [184.25 m] in Hole B; Fig. **F4**). Planktonic foraminifer biostratigraphy indicates that 600.4, 605.2–606.0, and 607.0 ft [183.00, 184.46–184.71, and 185.01 m] in Hole A correspond to Zones P4a, P3b, and P2 (see **"Biostratigraphy,"** p. 29). The absence of Subzone P3a indicates a probable unconformity between 606 and 607 ft (184.71–185.01 m) in Hole A. There is no obvious physical break in either hole within the clayey sands.

Clayey glauconite sand continues below the inferred unconformity at ~606.5 ft (184.86 m) to another inferred unconformity at ~612.5 ft (~186.69 m). Subzone P1c (608.0–612.0 ft [185.32–186.54 m]) overlies a very thin Subzone P1b (Sample 613.0 ft [186.84 m]) that in turn overlies Subzone P1a (614.0–616.0 ft [187.15–187.76 m]; see **"Biostratigraphy,"** p. 29). The thinness of Subzone P1b (which is absent at Bass River because of an unconformity; Miller, Sugarman, Browning, et al., 1998) indicates a break between either 612 and 613 ft or 613 and 614 ft (186.54–186.84 m or 186.84–187.15 m). A very subtle lithologic change at 612.5 ft (186.69 m) from slightly clayier glauconite sand above to slightly sandier glauconite sand below is 0.5 ft (0.15 m) below a major gamma ray–log kick (Fig. **F4**). The inferred sequence (606.5–612.5 ft [184.86–186.69 m]) is, thus, restricted to Subzone P1c. It shows an upsection increase of quartz sand in the coarse fraction (Fig. **F4**), consistent with an upsection change to a HST. In contrast, nannofossil studies indicate a hiatus between 617 and 615 ft (188.06–187.45 m), between Zones NP1 and NP3. Closer spaced samples are needed to verify the biostratigraphically inferred sequence boundaries and to resolve this discrepancy between foraminifer and nannofossil zonations in the lowermost Paleocene section.

Core 98 contains a change from glauconite sand (with occasional pyrite concretions) of the Hornerstown Formation (to 615.6 ft [187.63 m]) to clayey glauconite sand of the Navesink Formation (618.1 ft [188.40 m] and below). The intervening zone (615.6–618.1 ft [187.63–188.40 m]) is a bioturbated mixture of the two lithologies and is placed in the Hornerstown Formation. Sample 615.4 ft (187.57 m) is assigned to Subzone P1a.

Cretaceous/Tertiary Boundary in Hole A

Level: 618.5 ft (188.52 m)

Within Core 98, clay clasts are present at the top of the Navesink Formation at 618.1 ft (188.44 m), at the base of a bioturbated zone separating the Navesink from the Hornerstown Formation. A spherule layer is absent from Hole A. The clay clasts contain Cretaceous foraminifers; *Heterohelix globulosa* was observed protruding from the clay clasts. A similar clay-clast zone occurs at the K/T boundary at Parvin, New Jersey, and above the spherule layer at Bass River, New Jersey (Olsson et al., 1997). The clay clasts at the Bass River and Parvin boreholes yield numerous Cretaceous foraminifers, as is probably the case at Ancora judging by the readily observable foraminifers in the clasts. The origin of the clay clasts is probably from a deeper water bathymetric setting, judging from the clay lithology, which is not present at any of these boreholes in the underlying Cretaceous section, but is present in the more downdip Anchor Dickinson Gas #1 Well at Cape May (Petters, 1976). Cretaceous planktonic foraminifers are common to abundant and generally well preserved in the uppermost Maastrichtian interval from 618.10 to 618.95 ft (188.44–188.70 m).

Cretaceous/Tertiary Boundary in Hole B

Interval: 617.1–619.1 ft (188.09–188.70 m)

Two thin (2.6 cm total) layers occur toward the base of Core 9 at 617.1 ft (188.14 m) in Hole B. The upper layer is light gray, 1.1 cm thick, and consists of spherules (100–175 µm in diameter as well as some spherules up to 425 µm in diameter), grains of glauconite, and intermixed gray clay. Pyrite is present. The upper layer has a sharp upper boundary with the overlying sediments. The lower layer is 1.5 cm thick and is composed of fine-grained, rounded spherules. It has a sharp lower boundary. The spherule layer consists of a grayish tan interval comprised mostly of spherules (100–175 µm in diameter) with occasional glauconite grains and foraminifers (*H. globulosa* and *Gavelinella*). The presence of glauconite grains and foraminifers in both layers indicates that the original tektites were redeposited. The spherule layer is not continuous in the core as a result of its partial destruction by burrowing organisms. The interval below the spherule layer is intensely burrowed for at least 1 ft (0.30 m) and consists of a clayey glauconite sand. Hornerstown glauconite is seen in burrows for approximately another 0.7 ft (0.21 m) below this surface, before consistent Navesink lithology is encountered, thus blurring a definitive contact between the two formations. The contact is tentatively placed at an indistinct surface at 618.3 ft (188.51 m). Below 618.3 ft (188.51 m), Cretaceous planktonic foraminifers are abundant. The burrowed interval immediately above this level at 618.25 ft (188.49 m) contains numerous Cretaceous planktonic foraminifers that sharply diminish in number upward to 617.15 ft (188.16 m), where they become rare. Rarer Danian planktonic foraminifers are intermixed with the Cretaceous foraminifers. The Subzone Pα index species, *Parvularugoglobigerina eugubina,* occurs from 618.25 to 617.15 ft (188.49–188.16 m) below the spherule layer. The fragmentary occurrence of spherules between Subzones Pα and P1a in Hole B and their absence in Hole A are difficult to explain. The fact that they are redeposited suggests that they were derived from the K/T boundary tektite layer that was encountered in the Bass River borehole. Nearby exposure of the K/T tektite layer after deposition of Subzone Pα sediments at Ancora could have been facilitated by the relatively thin cover (~1.0 ft [0.30 m]) of sediments. Redeposition might indicate a hiatus between Subzones Pα and P1a.

Navesink Formation

Age: Maastrichtian
Interval: 618.3–651.3 ft (188.51–198.52 m)

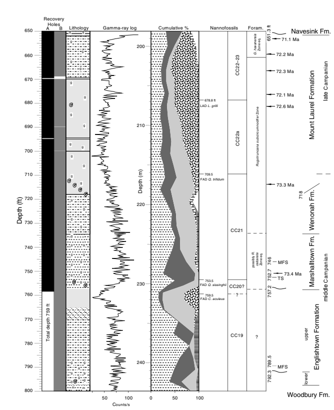
Clayey glauconite sands to glauconitic clays of the Navesink Formation (Fig. F4) are found from 618.3 to 651.3 ft (188.51–198.52 m). The Red Bank Formation is not found in this area; the Navesink Formation represents the latest Cretaceous Period at Ancora. The lithology between 618.3 and 646.0 ft (188.51–196.9 m) consists of massive, clayey, burrowed glauconite sand to massive, glauconitic clays. This interval is slightly micaceous with shell fragments observed throughout. The carbonate content of the sand-sized fraction increases downsection below ~641 ft (~195.38 m), and the section below 647 ft (197.21 m) is light gray foraminifer glauconitic clay. We place the MFS at 646–647 ft (196.90–197.21 m), at the top of the carbonate-rich interval. Quartz sand is present in trace amounts above 646 ft (196.90 m), becomes common below 646 ft (196.90 m), and increases downsection to the Navesink/Mount Laurel contact at 651.3 ft (198.52 m). The increase in quartz sand below ~646 (~196.90 m) ft is consistent with deepening upsection in the TST. Sr isotopic analyses indicate that the Navesink Formation at Ancora is upper Maastrichtian (67.3 and 68.3 Ma at 645.0 and 649.2 ft [196.60 and 197.88 m], respectively).

Mount Laurel Formation

Age: late Campanian
Interval: 651.3–718.0 ft (198.52–218.85 m)

The Mount Laurel Formation (Fig. F5) extends from 651.3 to 714.9 ft (198.52–217.90 m). There is a burrowed contact between the Navesink and the Mount Laurel Formation. A bed of phosphate pebbles occurs between 650.7 and 650.9 ft (198.33–198.39 m) with phosphate pebbles up to 2 cm in diameter. Between 650.9 and 651.7 ft (198.39–198.64 m), there is a contact zone containing both Mount Laurel and Navesink Formation lithology. The sandier Mount Laurel lithology becomes dominant below 651.3 ft (198.52 m), where the lithology consists of pale olive, slightly clayey, glauconitic (~20%) fine- to medium-grained quartz sand, with ovoid phosphate grains throughout. A shell bed occurs at 681.0–682.0 ft (207.57–207.87 m). The Mount Laurel Formation generally fines downsection. From 690 to 695 ft (210.31–211.84 m), the quartz

F5. Mount Laurel, Wenonah, Marshalltown, and Englishtown Formations, p. 55.



sand gradually becomes fine to very fine grained, and by 718 ft (218.85 m) the lithology consists mainly of dark greenish gray, (very fine) sandy, slightly micaceous, glauconitic (10%–15%) silts. Large shell fragments are observed at 712.4, 713.4, 715.1, 716.0, and 718.2 ft (217.14, 217.44, 217.96, 218.24, and 218.91 m). Sr isotopic analyses indicate that the Mount Laurel Formation is upper Campanian, with age estimates generally ranging from ~71 to 73.3 Ma (Fig. F5; Table T2). Age estimates for this unit correlate well with those from other boreholes and outcrops (Sugarman et al., 1995). Using an age of 71.3 Ma for the Campanian/Maastrichtian boundary (Gradstein et al., 1995), the uppermost Mount Laurel age estimate of 71.1 ± 1 Ma could be either earliest Maastrichtian or latest Campanian.

T2. Sr isotopic data, Ancora Site, p. 64.

Wenonah Formation

Age: late Campanian
Interval: 718–742 ft (218.85–226.16 m)

The contact between the Mount Laurel and the Wenonah Formations (Fig. F5) is gradational, extending from 714.1 to 718.0 ft (217.66–218.85 m), with silty clay and mica increasing downsection in the transitional interval. The base of the Mount Laurel Formation is arbitrarily placed at the base of the transitional interval. Below the transition, the lithology consists of slightly glauconitic, micaceous, woody, clayey silty sand to sandy clayey silts. Shell fragments are observed throughout the formation. Glauconite increases downsection to >20% below ~735 ft (224.03 m).

Marshalltown Formation

Age: late Campanian
Interval: 742.0–757.2 ft (226.16–230.79 m)

The contact between the Wenonah and the Marshalltown Formations (Fig. F5) is gradational, occurring within the interval 730–742 ft (222.50–226.16 m). The lithology consists of very dark gray to very dark olive-gray, micaceous, glauconitic (<20%) clays. Glauconite increases downsection, becoming a shelly, pyritic glauconite sand (750–752 ft [228.60–229.21 m]). A peak in carbonate at 746 ft (227.38 m) may represent the MFS (Fig. F5). There is a sharp facies contact at 752 ft (229.21 m) in Hole A, with a shelly, micaceous glauconitic clay below that continuing down to the contact with the Englishtown Formation at 757.2 ft (230.79 m). Inoceramids and oyster shells occur in the basal Marshalltown Formation.

Burrowed clayey glauconite sand typical of the Marshalltown Formation is found down to 752.7 ft (229.42 m) in Hole B. At 752.7 ft (229.42 m), there is sharp facies change equivalent to that at 752 ft (229.21 m) in Hole A. This contact of glauconite sand above and glauconitic clay below could be interpreted as the MFS or TS. This occasionally lignitic lithology continues to 756.9 ft (230.70 m). Between 756.9 and 758.4 ft (230.79–231.16 m) the glauconitic clay lithology is reworked into the glauconitic micaceous, slightly lignitic quartz sand of the Englishtown Formation. We place the Marshalltown/Englishtown contact at 757.4 ft (230.86 m). Based on the overall lithologic change to glauconite above that is typical of TSTs, we interpret the 752.7-ft (229.42 m) surface as reflecting a TS and the basal 4.7 ft (1.43 m) as the LST. This is supported by the presence of common quartz and three-colored reworked glauconite (dark green, light green, and tan) in this lower unit. Alternatively, this basal unit may represent a thin sequence that was not previously recognized.

Upper Englishtown Formation

Age: Campanian
Interval: 757.2–792.3 ft (230.79–241.49 m)

Slightly clayey quartz sands assigned to the Englishtown Formation (Fig. F5) appear at 757.2 ft (230.79 m). The sands are greenish gray, fine–medium grained, and grains are subangular to rounded. The Marshalltown/Englishtown contact is similar in Hole B. The difference in the depth of the sequence boundary contact in the A and B holes is less than 2 ft (0.61 m), suggesting that the vertical deviation is <0.5° and the offset is <10 ft (30.5 m) at this depth.

The upper Englishtown Formation at Ancora is a sequence recording a coarsening- and shallowing-upward succession. Unconsolidated, poorly sorted, lignitic, fine- to medium-grained quartz sand with reworked glauconite sand at the top (758.1–765.2 ft [231.07–233.23 m]) grades downward to shelly, slightly sandy, micaceous silts (770.0–780.0 ft [234.70–237.74 m]). These sands comprise an aquifer. Heavy minerals are conspicuous in washed residues of the sand: Sample 760.5 ft (231.80 m) contains zircon, rutile, garnet, tourmaline, in addition to quartz, ironstone fragments (iron-cemented silt and very fine-grained sand), lignite, and traces of mica. The micaceous silts contain shell material (including corals) and are generally laminated below 777 ft (236.83 m) (often with thin micaceous sand cross-laminae). Between 780.0 and 788.3 ft (237.74–240.27 m), mica and lignite become especially abundant. The lignitic sands were deposited on a shallow shelf (probably nearshore bars), whereas the silts represent deeper water deposition (probably inner–middle neritic or prodelta).

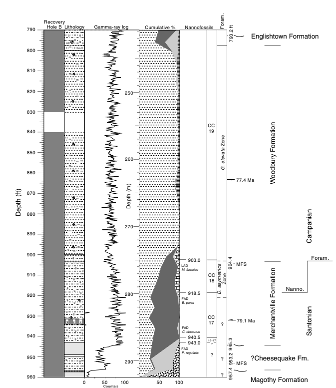
At 788.3 ft (240.27 m), there is an abrupt facies change to a burrowed glauconite-rich silty clay, with a less glauconite-rich silty clay below 789.5 ft (240.64 m). This interval (788.3–789.5 ft [240.27–240.64 m]) is interpreted as the condensed section, with a MFS at 789.5 ft (240.65 m). Glauconitic silty clay continues down to 792.3 ft (241.49 m). A probable sequence boundary occurs at 792.3 ft (241.49 m), separating glauconitic silty clay above from shelly, micaceous, glauconitic, quartzose silty sand below. The sequence boundary is associated with a clear lithologic change and a minor gamma ray–log kick (Fig. F5), although the contact is not as obvious as others at Ancora (note that the coeval sequence boundary at Bass River has a distinct cemented zone). Thus, the upper Englishtown Formation represents a relatively complete sequence of lower glauconite sands/glauconitic clays, medial silts, and upper sands.

Lower Englishtown Formation

Age: Campanian
Interval: 792.3–797.6 ft (241.49–243.11 m)

Shelly, micaceous, glauconitic quartzose silty sands continue down to 797 ft (242.93 m), with several large clay nodules that react slightly with HCl (?replaced shell). We assign these sands to the lower Englishtown Formation (Fig. F6). Below 797 ft (242.93 m), the amount of glauconite

F6. Woodbury, Merchantville, and Cheesequake Formations, p. 56.



in the core decreases down to the contact with the Woodbury Formation at 797.6 ft (243.11 m). The lower Englishtown Formation represents the HST of the Merchantville–Woodbury–lower Englishtown sequence at Ancora as it does at Bass River (Miller, Sugarman, Browning, et al., 1998).

Woodbury Formation

Age: early Campanian
Interval: 797.6–904.4 ft (243.11–275.66 m)

An indurated zone between 797.6 and 797.7 ft (243.11–243.14 m) marks the contact between the Woodbury and upper Englishtown Formations (Fig. F6). The Woodbury Formation consists of laminated to slightly burrowed, very micaceous, lignitic, slightly shelly very dark gray clay with occasional pyrite and pyrite nodules of replaced shell. The clays become glauconitic and more burrowed below 897 ft (273.41 m), with glauconite content reaching ~20% at 900 ft (274.32 m). Glauconite is common by 904.4 ft (275.66 m; >30%) and 40%–50% by 909 ft (277.06 m). Thus, the contact between the glauconitic clays of the lowermost Woodbury and the clayey glauconite sands of the Merchantville Formation is gradational; we place it at a visible increase in glauconite on the outside of the core at 904.4 ft (275.66 m).

Merchantville Formation

Age: early Campanian to Santonian
Interval: 904.4–945.3 ft (275.66–288.13 m)

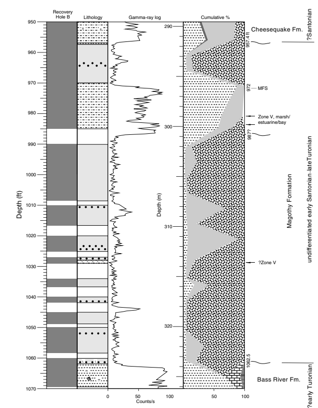
Slightly lighter colored, more carbonate-rich glauconitic clays near the top of the Merchantville Formation (Fig. F6; 905–906 ft [275.84–276.15 m]) may represent a MFS of a sequence, similar to the MFS near the top of this formation at Bass River (Miller, Sugarman, Browning, et al., 1998). Below this, glauconite is typically 40%–60% in clayey glauconite sands to sandy glauconitic clays. Mica is less common (<1%) than in the overlying Woodbury Formation, there is extensive burrowing, and there are several intervals with shell concentrations. An indurated clayey glauconite sand (931.2–933.9 ft [283.83–284.65 m]) is cemented by a carbonate cement (?siderite); intervals of strong cementation in this interval contain bi-color "glauconite" pellets that are probably goethite. Clayey glauconite sand with clay burrows, clay laminae, and thin (1.5 cm thick) clay beds continues down to 944.5 ft (287.88 m), where there is a burrowed mixed interval with increasing quartz sand downsection.

Cheesequake Formation

Age: ?Santonian
Interval: 945.3–957.4 ft (288.13–291.82 m)

Silty, fine- to medium-grained, slightly pebbly quartz sand (Fig. F6) occurs below a distinct, irregular sequence boundary at 945.3 ft (288.13 m). Quartz sand is burrowed above the sequence boundary into the overlying clayey glauconitic sands. The quartz sands below the sequence boundary are lignitic, generally heavily bioturbated with large sand-filled burrows (up to 9 cm long), and contain shark teeth. They are marine (they also contain benthic foraminifers) and were deposited on a shallow (inner neritic?) shelf. These HST sands grade down to a distinct surface at 953.2 ft (290.54 m), which overlies slightly micaceous, slightly glauconitic, bioturbated, clayey, silty quartz sand (953.2–957.0 ft [290.54–291.69 m]). The surface is associated with a gamma ray–log peak and is tentatively interpreted as a MFS. The clayey, silty sands are marine, as indicated by the presence of echinoid spines and intense bioturbation. The interval from 956.9 to 957.4 ft (291.66–291.82 m) is a reworked zone with coarse clasts, phosphates, and lignite. A thin, discontinuous clay layer (957.0–957.2 ft [291.69–291.75 m]) within this reworked zone sits on top of a sequence boundary (957.4 ft [291.82 m]) separating marine sediments above from coarse- to very coarse–grained quartz sands of the Magothy Formation below. The sequence boundary is associated with a distinct gamma ray–log increase (Fig. F6). Thus, the gamma-ray log reflects an increase at the sequence boundary, maximum values at the MFS, and lower values in the sandy HST (Fig. F7). The low amounts of glauconite at the base of the sequence are attributed to the relatively shallow-water depositional environment. We tentatively assign the quartz sands and silts between 945.3 and 957.4 ft (288.13–291.82 m) to the Cheesequake Formation of Litwin et al. (1993).

F7. Magothy Formation, p. 57.

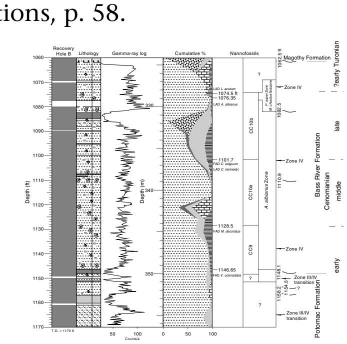


Magothy Formation

Age: undifferentiated Santonian to late Turonian (?Coniacian)
Interval: 957.4–1062.5 ft (291.82–323.85 m)

Poorly sorted coarse- to very coarse–grained quartz sands of the Magothy Formation (Fig. F7) appear below a sequence boundary at 957.4 ft (291.82 m) and continue to 970 ft (295.66 m). A sequence is tentatively identified between 957.4 and 987.0 ft (291.82–300.84 m). Gravelly very coarse–grained sands to sandy gravels and interbedded well-sorted, medium- to coarse-grained quartz sand bracket a lignitic silty clay (962.6–962.7 ft [293.40–293.43 m]). The gravels and sands appear to be channel deposits of a delta plain; they represent the HST of a sequence. A major lithologic change occurs at 970 ft (295.66 m), with interbedded slightly sandy silty clay and lignitic sand below (970.0–984.9 ft [295.66–300.20 m]). These sandy clays appear to have been deposited in a delta-front or estuarine setting; pollen indicates a swamp/marsh, nonmarine environment (see "**Biostratigraphy**," p. 29). We tentatively place a MFS at a gamma ray–log peak at ~972 ft (~296.27 m), overlying an upsection increase in gamma ray–log values (Fig. F8), although this is speculative owing to the marginal to nonmarine environments represented by the sandy clays. We tentatively place a sequence boundary at a major gamma ray–log increase at 987 ft (300.84 m) in a coring gap (984.9–900.0 ft [300.20–274.32 m]) that encompasses a major facies change from sand below to sandy clay above.

F8. Bass River and Potomac Formations, p. 58.



Predominantly medium- to coarse-grained sand returns below a coring gap at 990 ft (301.75 m) and continues down to a sequence boundary at 1062.5 ft (323.85 m). The sand is massive, has occasional silty clay interbeds, and contains common interspersed lignite. The interval between 990 and 1010 ft (301.75–307.85 m) is generally coarser and more lignitic than below and is reminiscent of the delta-front sands at Bass River (1760–1780 ft [536.45–542.54 m]). At Ancora, between 990.0 and 1062.5 ft (301.75–323.85 m), there are several fining-upward successions consisting of a basal coarse to very coarse pebbly to gravely quartz sand (basal contacts at 1010.0, 1025.0, 1043.7, 1051.8, and 1062.4 ft [307.85, 312.42, 318.12, 320.59, and 323.82 m]), fining up to medium- to coarse-grained quartz sand, capped with a thin, sandy kaolinitic silty clay. Directly above the contact at the base of the Magothy Formation (1062.5 ft [323.85 m]), there is a 0.1-ft-thick (3 cm) lignite bed, overlain by a thin gravel bed (0.1 ft [3 cm]) that fines upsection to medium- to coarse-grained quartz sand. The environment of deposition between 1010.0 and 1062.5 ft (307.85–323.85 m) could be fluvial or marine channel (e.g., tidal delta). The paucity of fine sediments suggests that these fining-upward successions were deposited in a nearshore marine setting.

The section from 957.4 to 1062.5 ft (291.82–323.85 m) is assigned to the Magothy Formation. In outcrop, the Magothy Formation consists of sands and silty clays deposited in complex nonmarine to marginal marine environments (Owens and Gohn, 1985), similar to those observed at Ancora.

Bass River Formation

Age: Cenomanian to Turonian
Interval: 1062.5–1148.1 ft (323.85–349.94 m)

A spectacular contact occurs between the Magothy and Bass River Formations (Fig. F8) at 1062.5 ft (323.85 m), separating finer grained sediments below from coarser grained sediments above. Micaceous (including chlorite) silty clay of the Bass River Formation occurs below the contact. The clay has sandy silt laminae, is heavily bioturbated, and continues downsection to 1082.5 ft (329.95 m). The section from 1064 to 1066 ft (324.31–324.92 m) is darker (?higher organic-matter content) with a faint petroleum scent. We speculate that this interval correlates with the lowermost Turonian Bonarelli bed equivalent observed at Bass River (Sugarman et al., 1999). Glauconite is found in trace abundance from 1081.0 to 1082.5 ft (329.49–329.95 m). Common shells occur from 1062.5 to 1082.5 ft (323.85–329.95 m), indicating deposition on a marine shelf.

There is another spectacular contact at 1082.5 ft (329.95 m) that is interpreted as a sequence boundary. Below the contact is a 2.3-ft-thick (0.70 m) indurated shelly (including scaphopods) fine quartz sand. The indurated section overlies a fine quartz sand that fines downward, first to a clayey sand and then to a sandy clay by 1089 ft (331.93 m). The sands are interpreted as an upper HST. The sandy, micaceous clays continue to 1095.3–1095.4 ft (333.85–333.88 m), where another indurated zone (siltstone) was encountered. This zone overlies an irregular contact with rip-up clasts below. Another indurated zone with rip-up clasts below occurs at 1107.5–1107.8 ft (337.57–337.66 m), whereas the interval 1108.8–1108.9 ft (337.96–337.99 m) is partially indurated. The lithologies above and below these indurated zones are the same micaceous silty clays. Although the rip-up clasts may mark sequence boundaries, other evidence for interpreting these contacts as sequence bounding unconformities is lacking. The section from 1095.4 to 1107.5 ft (333.88–337.57 m) is a heavily bioturbated very micaceous (chloritic), slightly glauconitic silty clay with lignite, pyrite, and interspersed shells. Glauconitic clay to clayey glauconite sand (1107.50–1110.88 ft [333.88–338.60 m]) comprise the basal TST. An irregular, sharp contact (1110.9 ft [338.60 m]) that separates a pebbly shell bed above from a laminated shelly clay below is interpreted as a sequence boundary. The entire sequence from 1082.5 to 1110.9 ft (329.95–338.60 m) was deposited on a shallow shelf.

A shelly clay and silt unit (1110.9–1127.0 ft [338.60–343.51 m]) is characterized by laminations of slightly silty clays/clays and thin sand. Silt becomes dominant downsection (1120–1130 ft [341.38–344.42 m]), and the unit becomes more micaceous, glauconitic, bioturbated, less laminated, and shellier, with thin channels interpreted as storm beds. Lignite is common at 1123–1124 ft (342.29–342.60 m). A silty clay (1130.0–1144.6 ft [341.38–348.87 m]) contains varying amounts of glauconite. A nested shell bed (1144.6–1145.0 ft [348.87–349.00 m]) overlies a shelly glauconitic sandstone (1146.0–1148.0 ft [349.30–349.91 m]) with a basal shell bed (1147.7–1148.0 ft [349.82–349.91 m]). This overlies a distinct sequence boundary with slightly shelly clayey very fine sand below. We interpret the succession within the sequence as (1) a basal interfingering between middle shelf neritic glauconite and shell facies, (2) a medial prodelta silt and clay, and (3) an upper interfingering between storm-dominated shelly facies and prodelta sediments.

Pollen indicates that this section is primarily upper Cenomanian to ?lower Turonian Zone IV (1072, 1102, and 1138 ft [326.75, 335.89, and 346.86 m]; see **"Biostratigraphy,"** p. 29). Planktonic foraminifers indicate that the early Turonian is represented at least at the top of the Bass River Formation at Ancora (see **"Biostratigraphy,"** p. 29).

Potomac Group

Age: ?Aptian to Cenomanian
Interval: 1148.1–1170.0 ft (total depth [TD]; 349.94–356.62 m)

Slightly shelly clayey very fine sands and clays encountered below the sequence boundary at 1148.1 ft (349.94 m) are probably the marine equivalent of the generally fluvial–deltaic Potomac Group (Fig. **F8**). Shelly clayey very fine sand at the top of the Potomac Group overlies a very lignitic clay (1150.0–1151.1 ft [350.52–350.86 m]), a poorly sorted medium- to very coarse–grained sand with rock fragments (1151.10–1151.55 ft [350.86–350.99 m]), and a mottled clay (1151.55–1154.50 ft [350.99–351.89 m]) with iron sand (1152.5–1152.9 ft [351.28–351.40 m]) and several very large pyritized burrows (1153.3–1153.8 ft [351.53–351.68 m]). This section is interpreted as marginal marine to estuarine. A sharp surface at 1154.5 ft (351.89 m) may be a sequence boundary with very shelly laminated brown clays below that grade down to a slightly glauconitic clay. The section below the sequence boundary was deposited in an inner–middle neritic setting.

A sharp facies change from neritic clays above to estuarine sands occurs at 1157 ft (352.65 m). The sands from 1157.0 to 1158.2 ft (352.65–353.02 m) are indurated to sandstone, very lignitic, clayey and faintly cross-bedded. A pebbly contact at 1158.2 ft (353.02 m) overlies a kaolinitic silty clay. This surface is probably a sequence boundary. Interbeds of sandy very lignitic, kaolinitic clay and clayey fine sand continue to 1163.5 ft (354.63 m), where there is a 1-ft (0.30 m) bed of lignitic, slightly glauconitic clay with large, reddish burrows (0.2 ft [5 cm] long). These clays are enigmatic because they occur sandwiched within estuarine sediments; they may represent a marine component within an estuary or marine interfingering. The base of the cored section (1164.5–1170.0 ft [354.94–356.62 m]) consists of highly bioturbated clayey silt, convoluted laminated lignitic silty sand, laminated silty clay, and flaser bedded silty clay and fine sand. The section from 1157 ft (352.65 m) to TD represents classic interbedded sand/clay facies deposited in an estuarine environment.

Pollen indicates that this section (samples at 1150 and 1165 ft [350.52 and 355.09 m]) is transitional between lower Cenomanian Zone III and upper Cenomanian to ?lower Turonian Zone IV (see "Biostratigraphy," p. 29). Nannofossils indicate that this section is upper Albian–lower Cenomanian Zone CC9 (see "Biostratigraphy," p. 29). Integration of pollen and nannofossil zonations indicates that the Potomac Group at Ancora is lower Cenomanian.

BIOSTRATIGRAPHY

Planktonic Foraminifers

Summary

Samples were examined qualitatively for planktonic foraminifer biostratigraphy at ~5-ft (1.52 m) intervals. Cenozoic and Maastrichtian samples were also examined for benthic foraminifers. Based on this qualitative examination, preliminary paleodepth estimates were made for Eocene (Browning) and Maastrichtian (Olsson) samples. The presence of ostracod taxa was noted for Upper Cretaceous samples from the Cheesequake to Mount Laurel Formations (Georgescu). Cenozoic foraminifer biostratigraphic resolution is generally limited at this updip location: only the Eocene (Zones P12–P14 undifferentiated, P11, P7–P10 undifferentiated, and P6b) and Paleocene (Zones P5, P4a, P3b, P2, P1c, P1b, P1a, and Pα) epochs could be subdivided. Three Maastrichtian planktonic foraminifer zones (*Abathomphalus mayaroensis* equivalent, *Gansserina gansseri,* and *Globotruncana aegyptiaca*) could be tentatively identified, although the shallow-water setting precludes most primary zonal markers. Biostratigraphic resolution is also limited by the shallow-water nature of the Santonian–Campanian section, although the *Globotruncanella havanensis* Zone (uppermost Mount Laurel Formation), *Rugotruncana subcircumnodifer* Zone (Mount Laurel and Wenonah Formations), *Globotruncanita elevata* Zone (Woodbury Formation), and the Santonian *Dicarinella asymetrica* Zone (Merchantville Formation) could be identified. Planktonic foraminifers were not found in the Cheesequake and Magothy Formations. Planktonic foraminifers are rare to common in the Bass River Formation; the presence of *Rotalipora cushmani* indicates definite Cenomanian strata below 1101.0 ft (335.67 m). Planktonic foraminifers were not found in the Potomac Group.

Miocene

There are no planktonic foraminifers in the Miocene samples examined. Two samples from the lower part of the Kw1a sequence contain inner neritic benthic foraminifers. At 246 ft (74.98 m), benthic foraminifers are common and include *Nonionellina pizarensis, Buliminella elongata, Glandulina, Lenticulina, Guttulina,* and *Cibicidina*. A sample at 261 ft (79.55 m) contains rare specimens of *Buliminella elongata.*

Eocene

Biostratigraphy in the Toms River Member of the Shark River Formation is difficult because of widespread mixing of middle and upper Eocene microfossils (Liu et al., 1997b; Poore and Bybell, 1988). In the Ancora borehole (263.7–359.8 ft [72.15–109.67 m]), planktonic foraminifers are rare, especially at the top of the unit, and are not age diagnostic to the zonal level. All samples in this unit up to 281 ft (85.65 m) contain *Acarinina,* equivalent to middle Eocene Zone P14 or older. However, these samples also contain *Globigerina praebulloides* that has been used to infer a late Eocene age and that the middle Eocene fossils are reworked. Nannofossils indicate that the section from 306 to 266 ft (93.29–81.10 m) is equivalent to upper Eocene Zone P15.

Benthic foraminifers are generally common and well preserved in the Toms River Member. Common taxa include *Cibicidina, Gyroidinoides octocamerata, Epistominella minuta, Pararotalia stellata, Uvigerina elongata, Cibicidoides pippeni, Hanzawaia mauricensis,* and *Valvulineria texana*. In other boreholes on the New Jersey Coastal Plain, these taxa have been interpreted to have inhabited water depths of ~50 m (Olsson and Wise, 1987; Browning et al., 1997a).

The upper Shark River Formation (359.8–388.6 ft [109.67–118.45 m]) contains rare but well-preserved planktonic foraminifers. The samples within this unit contain *Morozovella lehneri, Subbotina frontosa,* and abundant small acarininas and pseudohastigerinids. The co-occurrence of *M. lehneri* and *S. frontosa* places this unit within Zones P12 to mid-P14.

Benthic foraminifers are abundant and show a shallowing-upward trend within the upper Shark River Formation. Samples from the base of the section contain common *Cibicidoides pippeni, C.* cf. *pseudoungerianus, Kolesnikovella elongata, Trifarina wilcoxensis, Discorbis huneri,* and *Alabamina,* indicative of water depths of 75 to 100 m. Samples at the top of the unit contain common *Cibicidina, Epistominella minuta, Pararotalia stellata,* indicative of water depths of 50 to 75 m (Browning et al., 1997a; Olsson and Wise, 1987).

Planktonic foraminifers from the lower Shark River and Manasquan Formations are common, but age-diagnostic taxa are restricted in these shallow-water environments and highest and lowest occurrences are not reliable. In addition, many samples in these units were difficult to disaggregate. The lowest occurrence of *Morozovella lehneri* at 387.5 ft (118.11 m) is interpreted to mark the boundary between Zones P11 and P12. The lowest occurrence of *Globigerinitheka subconglobata* at 420.5 ft (128.17 m) is interpreted to mark the boundary between Zones P10 and P11. Zones P7 through P10 cannot be readily distinguished because (1) *Hantkenina* (zonal criterion for the base of Zone P10) is absent from the borehole, (2) *Planorotalites palmerae* (zonal criterion for the base of Zone P9) is absent from the borehole, and (3) *Morozovella formosa* is only found in two samples (471 and 476 ft [143.56 and 145.08 m]), and it is not clear that these samples represent either its correct highest or lowest occurrence. The top of Subzone P6b is at 471 ft (143.56 m), a level containing *M. formosa* before the first occurrence of *M. aragonensis* at 460.4 (140.33 m). Planktonic assemblages between 471 ft (143.56 m) and the base of the Manasquan Formation are similar; therefore, the base of the formation is interpreted to be Subzone P6b.

Benthic foraminifers in the lower Shark River and Manasquan Formations indicate deposition in middle to outer neritic paleodepths. The lower part of the Manasquan Formation (Sequence E2; 506–471 ft [154.23–143.56 m]) was deposited in the deepest water, as indicated by diverse and abundant planktonic foraminifers as well as benthic biofacies dominated by *Gavelinella capitatus, Eponides,* and *Cibicidoides eocenus* (Browning et al., 1997a). Samples at the top of Sequence E2 are dominated by *C. eocenus, Anomalinoides acuta,* and *Cibicidoides* cf. *pseudoungerianus* that may indicate a shallowing of 30–50 m through this sequence. Benthic foraminifers between 461.2 and 448.0 ft indicate a shallowing from biofacies dominated by *Cibicidoides* aff. *subspiratus* and *Anomalinoides acuta* (~155 m) to one dominated by *Siphonina claibornenesis* (~125 m). Samples in the sequence between 443.0 and 427.6 ft did not disaggregate well enough to recognize trends but benthic foraminifers indicate deposition in >100 m paleodepth. Samples at the bottom of the sequence between 427.6 and 388.6 ft (E6 of Browning et al., 1997a) are dominated by the benthic foraminifers *Cibicidoides subspiratus, Gyroidinoides,* and *Melonis*. Those at the top contain relatively higher percentages of *Cibicidoides pippeni* and *C.* cf. *pseudoungerianus*. This change in dominance may reflect a shallowing upward from ~140 to 110 m paleodepth.

Paleocene

Ancora Hole A

The top of the Paleocene is at 522.2 ft (159.17 m) in Hole A, at the contact between the glauconitic clays of the Manasquan Formation and the green clays of the Vincentown Formation (Fig. F4). Foraminifers are poorly preserved in the uppermost part of this unit. Sample 530.3 ft (161.64 m; base of Core 86) contains *Morozovella occlusa* (a late Paleocene species), *M. aequa, M. gracilis, M. subbotinae, Acarinina soldadoensis, Subbotina patagonica,* and *S. velascoensis*. From 539.60 to 560.15 ft (164.47–170.73 m), abundant well-preserved foraminifers are present. This interval is placed in the *Morozovella velascoensis* Zone (P5) and contains *M. occlusa, M. aequa, M. subbotinae, M. acuta, M. gracilis, Globanomalina chapmani, G. elongata, G. ovalis, Parasubbotina varianta, Subbotina patagonica, S. triangularis,* and *Acarinina soldadoensis*. *Acarinina africana,* a LPTM species, occurs in Samples 545.50 and 560.15 ft (166.27 and 170.73 m). Zone P5 also contains middle neritic benthic foraminifers similar to those encountered in the Bass River borehole (e.g., *Bolivina, Bulimina, Cibicides, Gyroidinoides, Pulsiphonina,* and *Gyroidinoides*).

The interval from 560.15 to 595.40 ft (170.73–181.48 m) contains sparse, poorly preserved foraminifers. Rare occurrences of *Morozovella aequa* and *Parasubbotina varianta* are noted at 570.3 ft (173.87 m), and of *Igorina tadjikistanensis* at 595.4 ft (170.73 m). Benthic foraminifers are sparse throughout the interval, and at the base of the interval only small specimens are noted.

Globanomalina pseudomenardii was found only in Sample 600.4 ft (183.00 m). The association of *Acarinina subsphaerica, A. mckannai, G. chapmani, G. imitata, M. angulata, Subbotina triangularis, S. velascoensis,* and *I. tadjikistanensis* places this sample in Subzone P4a. The interval from 600.4 to 606.0 ft (183.00–184.76 m) is placed in Subzone P3b based on the occurrence of *Acarinina strabocella, Globanomalina ehrenbergi, G. imitata, Igorina pusilla, Morozovella acutispira, M. angulata, M. apanthesma, M. conicotruncana, Parasubbotina varianta,* and *Subbotina triloculinoides*. Sample 607.0 ft (185.06 m) is placed in Zone P2 based on the occurrence of *Eoglobigerina spiralis, Morozovella praeangulata, Parasubbotina pseudobulloides, Praemurica inconstans,* and *Subbotina triloculinoides.*

Foraminifers are abundant, diverse, and generally well preserved in the section from 607.0 to 612.0 ft (185.06–186.58 m). This section is placed in Subzone P1c based on the occurrence of *Eoglobigerina edita, Globanomalina compressa, G. planocompressa, Globoconusa daubjergensis, Parasubbotina pseudobulloides, Praemurica inconstans, Subbotina triloculinoides,* and *S. trivialis.* Sample 613.0 ft (186.89 m) is assigned to Subzone P1b. Characteristic taxa that occur in Subzone P1b include *Eoglobigerina* *edita, E. eobulloides, Globoconusa daubjergensis, Praemurica pseudoinconstans, P. taurica,* and *Subbotina triloculinoides*.

The section from 613.0 to 616.0 ft (186.89–187.80 m) is assigned to Subzone P1a based on the occurrence of *Eoglobigerina eobulloides, Globoconusa daubjergensis, Guembelitria cretacea, Parasubbotina pseudobulloides, Praemurica pseudoinconstans, P. taurica,* and *Woodringina hornerstownensis*. *Parvularugoglobigerina eugubina,* the index species for Subzone Pα, occurs in Sample 617.0 ft (188.11 m) along with *E. eobulloides, G. cretacea, P. taurica, Woodringina claytonensis,* and *W. hornerstownensis*. Because Danian planktonic foraminifers are relatively rare in the basal Hornerstown interval, Sample 617.5 ft (188.26 m) may also belong in Subzone Pα, although *P. eugubina* was not identified. Species identified in this sample include *E. eobulloides, G. cretacea, Parvularugoglobigerina extensa,* and *Praemurica taurica*. Alternatively, this sample could be regarded as upper Zone P0. Sample 617.9 ft (188.38 m) is assigned to Zone P0 based on the range of *Guembelitria cretacea* above the K/T boundary, which is placed at the top of the Navesink Formation at 618.1 ft (188.44 m), and the first occurrence (FO) of *P. eugubina*. Cretaceous planktonic foraminifers are intermixed in the Danian section through Subzone P1a, but are less abundant, rapidly decrease in numbers upsection, and are represented almost entirely by the species *Heterohelix globulosa*.

Ancora Hole B

Only samples from the Hornerstown Formation were examined in Hole B. Sample 608.0 ft (185.36 m) at the top of the Hornerstown Formation is assigned to Subzone P4a based on the occurrence of *Acarinina mckannai, Globanomalina pseudomenardii, Morozovella angulata, Subbotina triangularis, S. triloculinoides,* and *S. velascoensis*. Sample 609.5 ft (185.82 m) contains a mixed assemblage. Subzone P3b species include *Acarinina strabocella, Globanomalina ehrenbergi,* and *Morozovella angulata*. *Morozovella praeangulata* and *Praemurica uncinata* are species indicative either of Zone P2 or lowermost Subzone P3a, suggesting that this sample is close to an unconformity. In contrast, at Ancora Hole A, Subzone P3b lies above Zone P2.

The section from 609.5 to 612.5 ft (185.82–186.74 m) is placed in Subzone P1c based on the occurrence of *Eoglobigerina edita, Globanomalina compressa, Globoconusa daubjergensis, Parasubbotina pseudobulloides, Praemurica inconstans, P. pseudoinconstans, Subbotina triloculinoides,* and *S. trivialis*. Sample 613.0 ft (186.89 m) is assigned to Subzone P1b based on the occurrence of *Eoglobigerina edita, Globoconusa daubjergensis, P. pseudobulloides, Praemurica taurica,* and *S. triloculinoides*. The interval from 613.0 to 616.4 ft (186.89–187.93 m) contains *E. edita, G. daubjergensis, Guembelitria cretacea, P. pseudobulloides,* and *P. taurica* and is assigned to Subzone P1a.

Cretaceous/Tertiary Boundary

Planktonic foraminifer biostratigraphic results from the K/T boundary in both Ancora holes are integrated into **"Lithostratigraphy,"** p. 13.

Upper Cretaceous Section

Navesink Formation

Interval: 618.1–651.3 ft (188.40–198.52 m)

Age: Maastrichtian

The Navesink Formation (618.3–651.3 ft [188.51–198.52 m]) contains common to abundant foraminifers, but planktonic foraminifers are less abundant and diverse and, in general, smaller in size than at the Bass River borehole, reflecting the shallower paleodepths updip at Ancora. Because of the scattered occurrences of planktonic species, the highest occurrences (HOs) and lowest occurrences (LOs) of marker species should be considered tentative. The HO of *Globotruncana linneiana,* which occurs at the base of the *Gansserina gansseri* Zone, is at 646 ft (196.95 m), indicating that the base of the Navesink Formation lies within the *Globotruncana aegyptiaca* Zone as is the case at the Bass River borehole. The HO of *G. gansseri* is at 630.5 ft (192.22 m), which is probably too low in comparison to its HO at the downdip Bass River borehole. Nevertheless, it suggests that the upper part of the Navesink Formation at Ancora lies within the *Abathomphalus mayaroensis* Zone (see Miller, Sugarman, Browning, et al., 1998, for comments on the paleoecology of *A. mayaroensis*). Species typical of the *A. mayaroensis* Zone at Bass River that occur at Ancora include *Globotruncana aegyptiaca, Hedbergella monmouthensis, Laeviheterohelix dentata, Planoglobulina acervulinoides, Racemiguembelina powelli,* and *Rugoglobigerina scotti.*

Except for its more glauconitic facies, the Navesink section at Ancora is identical to the Navesink–New Egypt sequence at Bass River. The two sections are nearly identical in thickness (33.00 and 34.25 ft [10.06 and 10.44 m] at Ancora and Bass River, respectively). As at Bass River, the Navesink sequence at Ancora was deposited in a gradually shallowing sea-level cycle from middle to inner neritic paleodepths. Some deeper water benthic foraminifer taxa that occur in the basal part of the Navesink section include *Arenobulimina subsphaerica, Bolivinoides giganteus, Eggerella trochoides,* and *Gavelinella spissocostata*. Species typical of the shallowing trend include *Anomalinoides midwayensis, Globulina gibba, Gyroidinoides imitata, Pseudoclavulina clavata, Pullenia americana, Pulsiphonina prima, Stilostomella pseudoscripta, Tappanina selmensis,* and *Valvulineria depressa*. As at Bass River, an abrupt shallowing is evident just before the K/T boundary in the appearance of a typical Danian assemblage, characterized by *Alabamina midwayensis, Angulogerina naheolensis, Anomalinoides acuta,* and *Gavelinella neelyi*. This assemblage continues into the Danian section above.

Mount Laurel Formation

Interval: 651.3–715.0 ft (198.52–217.93 m)
Age: late Campanian

Planktonic foraminifers are generally present throughout the Mount Laurel Formation (666.0–711.0 ft [203.00–216.71 m]) and the assemblages resemble those in the underlying Wenonah Formation. Planktonic foraminifer specimens increase in abundance in the uppermost part of the Mount Laurel section (656.0–661.0 ft [199.95–201.47 m]), where some specialized taxa are recognized: *Pseudoguembelina excolata* and *Rugotruncana subcircumnodifer*. According to Nederbragt (1991), the FO of *P. excolata* is placed at the top of the *Globotruncanella havanensis* Zone (late Campanian according to the Gradstein et al. [1995] time scale). The Mount Laurel Formation is assigned to the Campanian (defined using the Gradstein et al. [1995] time scale as older than 71.3 Ma) based on these taxa and the persistent presence of *Globigerinelloides volutus*. Ostracods are numerous and species of the genera *Asciocythere, Cytherella* and *Escharacytheridea* are common, in particular.

Wenonah Formation

Interval: 715.0–735.0 ft (217.93–224.03 m)
Age: late Campanian

Planktonic foraminifers are not common in the Wenonah Formation. Most species are typical constituents of epicontinental sea and shallow-water faunas belonging to *Heterohelix, Globigerinelloides,* and *Hedbergella*. The presence of *Globigerinelloides volutus* indicates that these are upper Campanian sediments (probably belonging in the *Rugotruncana subcircumnodifer* Zone). Keeled taxa, present mostly as fragmentary shells, are small in size and rare.

Large-sized oyster fragments, persistent in the interval 721.0–731.0 ft (219.76–222.81 m) suggests shallower water depositional environments.

Marshalltown Formation

Interval: 735.0–797.2 ft (224.03–242.99 m)
Age: Campanian

Planktonic foraminifers are absent in the lower part of the interval (below 754.0–756.0 ft [229.82–230.43 m]). Specimens above this level belong to the globular morphotypes, such as *Heterohelix globulosa, Globigerinelloides prairiehillensis,* and *Hedbergella*. *Archaeoglobigerina cretacea* is present, although specimens are generally small. Keeled species are rare and specimens are generally broken; most belong to the genus *Globotruncana* (i.e., *G. arca, G. bulloides,* and *G. linneiana*). The scarcity of highly specialized taxa was previously noted in the sediments of the Marshalltown Formation in the Bass River borehole (Miller, Sugarman, Browning, et al., 1998). The age of the Marshalltown Formation is Campanian based on superposition, consistent with the results from other boreholes and outcrops (Olsson, 1964; Petters, 1977; Miller, Sugarman, Browning, et al., 1998).

Englishtown Formation

Interval: 757.2–797.2 ft (230.79–242.99 m)
Age: Campanian

Planktonic foraminifers are very rare in the Englishtown Formation, consisting of fragmentary tests and abraded surfaces. This may be the result of dissolution and/or transport. Ostracods are rare but, when present, show larger shells with smooth, polished surfaces (e.g., *Asciocythere*).

Woodbury Formation

Interval: 797.2–903.0 ft (242.99–275.23 m)
Age: Campanian

At the top of this unit (801.0–861.0 ft [244.14–262.43 m]), all morphologically advanced taxa are absent and only taxa with simple test morphology (e.g., *Heterohelix globulosa* [smooth to fine striated tests], *Globigerinelloides,* and *Hedbergella*) are present. The presence of *Globigerinelloides bollii* indicates a late Santonian–early Campanian age. At the base of the unit (881.0–901.0 ft [268.53–274.62 m]), planktonic foraminifer assemblages are rather rich. The dominant taxa are primitive, globular chambered species of the genera *Heterohelix, Globigerinelloides,* and

Hedbergella. In contrast with the Merchantville Formation, double-keeled species (belonging to the genera *Globotruncana* [i.e., *G. arca* and *G. bulloides*], *Marginotruncana* [i.e., *M. marginata* and *M. pseudolinneiana*], and *Contusotruncana* [i.e., *C. fornicata* and *C. plummerae*]) are numerous. The complete absence of *Marginotruncana sinuosa* suggests that the sediments are younger than Santonian (i.e., the *G. elevata* Zone).

The ostracod assemblages change through the Woodbury Formation. Towards the top (816.0–826.0 ft [248.72–251.76 m]) they are rare and assemblages are dominated by smooth shelled forms (e.g., *Cythereis, Cytherella,* and *Cytheropteron*). At the base, they are numerous, locally abundant (891.3–891.4 ft [271.67–271.70 m]), and dominated by ornamented forms. This suggests a shallowing upsection that is also indicated by an upsection decrease in marine microfossils.

Merchantville Formation

Interval: 903.0–944.5 ft (275.23–287.88 m)
Age: late Santonian to earliest Campanian

Planktonic foraminifer assemblages become more abundant and diverse upsection in the Merchantville Formation, indicating transgression. Planktonic foraminifers are absent at the base of the Merchantville Formation (926.0–941.0 ft [282.24–286.82 m]). The first planktonic foraminifers are recorded beginning with Sample 921.0 ft (280.72 m), with mostly single-specimen occurrences of the primitive species *Heterohelix globulosa, Hedbergella bassriverensis,* and *H.* sp. They become more numerous upsection, with a peak in abundance at the top of the Merchantville Formation, supporting the placement of the MFS at this level (Fig. **F6**). Most of the specimens belong to the globular chambered *Heterohelix globulosa, Globigerinelloides prairiehillensis, Hedbergella div. sp., Archaeoglobigerina blowi, A. cretacea,* and *Rugoglobigerina rugosa*. Morphologically advanced species belonging to the genera *Globotruncana* (i.e., *G. arca, G. bulloides,* and *G. linneiana*), *Marginotruncana* (i.e., *M. marginata, M. pseudobulloides,* and *M. sinuosa*), and *Contusotruncana* (i.e., *C. fornicata*) are rarely seen in the samples collected from the top part of the formation. The FO of *Globotruncana arca* typically occurs in the upper Santonian section; however, a latest Santonian age is suggested by the dominance of specimens of *Marginotruncana* over those of *Globotruncana*.

Ostracods are present in varying numbers at the top of the Merchantville Formation. Spinose valved types are dominant over smooth valved types. Ostracod genera include *Bythocypris, Cytherella, Veenia,* and *Xestoleberis* (906.0–916.0 ft [276.15–279.20 m]).

Cheesequake Formation

Interval: 944.5–957.2 ft (287.88–291.75 m)
Age: ?Santonian

No planktonic foraminifers were found in these sediments. The only fossil material found belongs to small-sized benthic foraminifers and indeterminate mollusks. All the microfossils present are fragmentary, suggesting transportation.

Magothy Formation

Interval: 957.4–1062.5 ft (291.82–323.85 m)
Age: Undetermined

The Magothy Formation consists of fine-, medium-, and coarse-grained sands and some gravel. Lignitic intervals were noted in Samples 961.0 ft (292.99 m), 971.0–981.0 ft (296.04–299.08 m), 1006.0 ft (306.71 m), 1021.0 ft (311.28 m), 1046.0 ft (318.90 m), and 1056.0 ft (321.95 m). Occasional glauconite grains were noted in Samples 961.0 ft (292.99 m), 996.0 ft (303.66 m), and 1041.0 ft (317.38 m). The entire formation is barren of foraminifers, other calcareous microfossils, and shell material.

Bass River Formation

Interval: 1062.5–1148.1 ft (323.85–349.94 m)
Age: Cenomanian to Turonian

Foraminifers are less abundant and diversified in the Bass River Formation (1062.5–1148.1 ft [323.85–349.94 m]) at Ancora than in the Bass River borehole. Planktonic foraminifers are very rare to common and are absent in some intervals as a result of the shallow paleodepth updip position of Ancora. Foraminifers are in general well preserved. A single occurrence of *Rotalipora cushmani,* an upper Cenomanian index species, is noted in Sample 1101.0 ft (335.67 m). Above this level, from 1076.0 to 1075.2 ft (328.05–327.80 m), common occurrences of *Hedbergella delrioensis, H. planispira, H. simplex, Whiteinella archeocretacea, W. baltica,* and *W. inornata* are probably indicative of the *Whiteinella archeocretacea* Zone.

The shallow inner neritic benthic foraminifer assemblages are low in diversity and are dominated in several intervals by species of the genus *Epistomina* that are also common to abundant in the downdip Bass River borehole. *Epistomina stelligera* ranges to the top of the Bass River Formation at Ancora; this, together with the absence of *E. lenticularia* and *E. sliteri,* suggests that the upper part of the Bass River Formation at the Bass River borehole is either missing or is replaced by a nonmarine facies at Ancora. *Gavelinella cenomana,* a diagnostic Cenomanian benthic species, is frequent in the interval from 1096.0 to 1101.0 ft (334.15–335.67 m).

Potomac Group

Interval: 1148.1–1170.0 ft (TD; 349.94–356.62 m)
Age: ?Aptian to Cenomanian

The Potomac Group (1148.1–1170.0 ft [TD; 349.94–356.62 m]) consists of alternating beds of very fine– to fine-grained sand with intervals of lignite and pelecypod shell material. Sample 1156.0 ft (352.44 m) consists almost entirely of micropelecypod shell fragments, whereas Sample 1161.0 ft (353.96 m) is dominated by lignite. Other intervals consist of very fine– to fine-grained sand with varying amounts of lignite and occasional shell fragments. Foraminifers and ostracods are absent.

Cenozoic Calcareous Nannofossils

Summary

Except for a thick stratigraphic interval (575.0–589.0 ft [175.26–179.53 m]) that is barren as a result of secondary silicification, the Paleogene formations recovered from the Ancora borehole yield abundant, generally well-preserved calcareous nannofossils with a high diversity. There are floods of tiny coccoliths at most levels, indicating good preservation and a quiet depositional environment. The biozonal scheme used below is that of Martini (1971) and the subzones are those defined by Bukry (1973, 1975), as codified by Okada and Bukry (1980) and Berggren et al. (1995).

The youngest calcareous nannofossil-bearing beds in the Ancora borehole are at 266.0 ft (81.08 m), 3 ft (0.91 m) below the Shark River/Kirkwood Formation contact, and belong to the lower upper Eocene Zone NP18. This firmly establishes the age of the uppermost levels of the Shark River Formation. The oldest Cenozoic calcareous nannofossil-bearing beds occur at 617.5 ft (188.21 m), and possibly belong to Zone NP1. In the intervening interval (between 266.0 and 617.5 ft [81.08–188.21 m]), almost all calcareous nannofossil biozones have been identified, although many are extremely thin. The only zones that are absent are the Paleocene Zones NP2, NP5, and NP7.

The Ancora borehole provides two exceptionally thick and interesting stratigraphic intervals. The NP15–NP16 zonal interval is 125 ft (38.10 m) thick; this greatly contrasts with the thin Zones NP14 and NP17 (~5 ft [1.52 m] or less, and ~10 ft [3.05 m] or less, respectively). However, as is often the case, it is difficult to delineate zonal/subzonal boundaries within Zones NP15–NP16 because of the scarcity or inconsistent occurrences of the marker species. A thick (77 ft [23.47 m]) NP9–NP10 zonal interval provides a remarkable record of the LPTM that is partly complementary of the Bass River record.

Shark River Formation

Interval: 263.7–448.5 ft (80.38–136.70 m)

The Shark River Formation extends from Zone NP18 to ?Subzone NP14a (lower upper Eocene to lower middle Eocene). Zone NP18 extends from 266.0 to 286.0 ft (81.08–87.17 m). Discoasters are rare in this interval, and preservation is poor as a result of secondary silicification. Zone NP17 is characterized well in Sample 296 ft (90.22 m) and, possibly, Sample 306 ft (93.27 m). The interval between 316.8 and 391.0 ft (96.56–119.18 m) is confidently assigned to Zone NP16. *Reticulofenestra reticulata* and *R. floridana* co-occur at 391.0 ft (119.18 m), which indicates a level in approximately mid-Zone NP16. *Reticulofenestra reticulata,* a species that is usually common in upper middle and upper Eocene assemblages, is very rare in the Ancora borehole. There is a sharp change in species dominance in the lower part of this interval. At 385.0 ft (117.35 m) and above, representatives of *Reticulofenestra* are dominant. At 387.5 ft (118.11 m), representatives of *Reticulofenestra* and *Chiasmolithus* are equally abundant. At 391 ft (119.18 m), representatives of *Chiasmolithus* are dominant and those of *Reticulofenestra* are much fewer.

Biozonal determination in the interval between 391.0 and 428.6 ft (119.18–130.64 m) is uncertain because of poor preservation and lack of biozonal markers. Sample 430.5 ft (131.22 m) belongs to Subzone NP15b, characterized by *Nannotetrina fulgens* and *Chiasmolithus gigas,* whereas Sample 433.5 ft (132.13 m), which yields *N. fulgens* and *Cruciplacolithus staurion* but no *C. gigas,* probably belongs to Subzone NP15a. The zonal assignment of level 441.0 ft (134.42 m) is uncertain. Sample 446.0 (135.94 m) belongs to Subzone NP14a, as indicated by the co-occurrence of *Discoaster sublodoensis* and *Discoaster lodoensis* and the absence of *Blackites inflatus*. Sample 447.9 ft (136.52 m) yields one of the richest and best preserved assemblage of the Paleogene section recovered from the Ancora borehole. However, its zonal position is difficult to determine; *Discoaster lodoensis* (five- and six-rayed) is common as is

Discoaster kuepperi. A few characteristic *Discoaster cruciformis* as well as very rare *Tribrachiatus orthostylus* that are probably reworked are present. The co-occurrence of *D. lodoensis, D. kuepperi,* and *D. cruciformis* would be indicative of lower Zone NP13. However, a couple of poorly preserved discoasters may be assignable to *D. sublodoensis,* and an NP14a zonal assignment (with *D. cruciformis* reworked) cannot be excluded.

The rapid zonal succession NP15b–NP15a–NP14a (or –NP13) is suggestive of a succession of unconformable surfaces and dates successive sequences. Unconformable units of these ages have been recognized on the New Jersey margin and are discussed in Aubry (1991, 1995).

Manasquan Formation

Interval: 448.5–522.2 ft (136.70–159.17 m)

The Manasquan Formation comprises Zones NP12, NP11, and NP10. Zone NP12 extends from 448.8 to 471.0 ft (136.79–143.56 m). *Tribrachiatus orthostylus* is very common at 476 ft (145.08 m), together with *Imperiaster obscurus*. With the exception of *Discoaster binodosus,* discoasters are very rare at this level. It is possible that the absence of *D. lodoensis* reflects the paucity in discoasters. However, *D. lodoensis* was not encountered at any level below 471 ft (143.56 m). Thus, the NP11/NP12 zonal boundary is located between 471 and 476 ft (143.56–145.08 m). Assemblages are very diverse and well preserved throughout this NP12–NP11 zonal interval; *Rhomboaster bitrifida* and *Rhomboaster intermedia* occur at several levels (e.g., at 496.0 and 501.0 ft [151.18 and 152.70 m]). The HO of *Tribrachiatus contortus* at 519 ft (158.19 m) places the NP11/NP10 zonal boundary between 516.3 and 519.0 ft (157.37–158.19 m).

The subzonal zonation of Aubry (1996) is easily applied to the NP10 interval in the Ancora borehole. Subzone NP10d is identified at 519 ft (158.19 m). Unless reworked, very rare specimens of *T. bramlettei* at this level may indicate the lower part of the subzone (Aubry, 1996). Based on the occurrence of *Tribrachiatus digitalis,* Subzone NP10b is identified between 519.9 and 521.0 ft (158.47–158.80 m). The occurrence of *Tribrachiatus bramlettei* and the absence of *T. digitalis* at 521.7 ft (159.01 m) indicate Subzone NP10a.

There is no record of Subzone NP10c, and the NP10b/NP10d subzonal contact between 519.0 and 519.9 ft (158.19–158.47 m) is unconformable.

Calcareous nannofossil assemblages are very diverse in the NP10 zonal interval. *Hornibrookina australis* occurs in the lower part of the zone.

Vincentown Formation

Interval: 522.2–596.6 ft (159.17–181.84 m)

The Vincentown Formation essentially belongs to Zone NP9, except for its lowermost part which belongs to Zone NP8. The boundary between the two zones is located between 594.0 and 596.2 ft (181.05–181.72 m).

The unconformable Vincentown/Manasquan contact at 522.2 ft (159.17 m) coincides with the NP9b/NP10a subzonal contact. Subzone NP10a is extremely thin in the Ancora borehole, suggesting a stratigraphic gap corresponding to most of the subzone. The gap is also indicated by the simultaneous HOs of *F. tympaniformis* and *Discoaster mahmoudii* at 522.6 ft (159.29 m) and the LO of *T. bramlettei* at 521.7 ft (159.01 m).

It appears possible to subdivide Zone NP9 into two subzones, with the younger subzone distinguished by the occurrence of *Rhomboaster* (*R. bitrifida* and *R. calcitrapa*) and *Tribrachiatus spineus* in the upper part of the zone. However, it remains unclear which criteria would constitute the best means for global correlation of the NP9a/NP9b subzonal boundary. Several criteria are possible: the HO of *Fasciculithus alanii* and the LOs of *Rhomboaster calcitrapa, Discoaster anartios,* and *Discoaster araneus.* In several sections, Aubry et al. (M. Aubry, pers. comm., 1999) have observed that these events are stratigraphically coincident. This is not the case at Ancora, suggesting that this section is more complete across the NP9a/NP9b subzonal boundary. In the Ancora borehole, the boundary would be placed between 559.75 and 555.90 ft (170.61–169.44 m) depending on which criterion is selected. As indicated by Cramer et al. (in press) and Aubry et al. (M. Aubry, pers. comm., 1999), the NP9a/NP9b subzonal boundary is associated with the LPTM. Thus, the LO of these taxa in the Ancora section allows us to predict the location of the CIE in the interval 563.00–559.75 ft (171.60–170.61 m).

Calcareous nannofossil assemblages are poorly preserved in Samples 561 and 562 ft (170.99 and 171.30 m) as a result of secondary silicification, and discoasters are rare. The occurrence of *Discoaster* sp. aff. *D. mediosus* at 559.75 ft (170.61 m) is the lowest indication in the Ancora borehole of the proximity of the LPTM. *Discoaster* sp. aff. *D. mediosus* differs from *D. mediosus* by its long slender arm tips, which in some specimens are irregularly spaced (but located in the same plane, unlike the arms of *D. araneus*). *Discoaster* sp. aff. *D. mediosus* is a form reminiscent of the late Eocene *Discoaster levini* (Hay, 1967). This is followed by the LO of *D. anartios* at 557.0 ft (169.77 m) and the LOs of *D. araneus, Tribrachiatus spineus, Rhomboaster bitrifida,* and *R. calcitrapa* at 556.0 ft (169.47 m).

A thick interval (575–589 ft [175.26–179.53) in Subzone NP9a is barren, as a result of secondary silicification.

Diversity increases progressively through Subzone NP9a (perhaps as a result of increasingly better preservation), and is very high in Subzone NP9b. The "LPTM calcareous nannofossil taxa" do not range throughout Subzone NP9b but are most abundant in its lower part between 539.6 and 556.0 ft (164.47–169.47 m). *Discoaster anartios* and *Rhomboaster calcitrapa* were not encountered above this level, whereas *T. spineus* is rare, and *D. araneus* is occasional up to 522.6 ft (159.29 m). A marked decrease in diversity among fasciculiths occurs at 542.5 ft (165.35 m), but the genus is represented (common) up to the top of the Vincentown Formation. The bulk of the assemblage in Subzone NP9b consists of *Toweius pertusus* and *Hornibrookina australis* (=*Hornibrookina arca*).

Sample 596.2 ft (181.72 m) belongs to Zone NP8. Sample 594.0 ft (181.05 m) yields few multi-rayed rosette-shaped discoaster that are early morphotypes of *D. multiradiatus.* In both samples, *Heliolithus riedelii* is common and characteristic.

Hornerstown Formation

Interval: 596.6–618.5 ft (181.84–188.52 m)

The Hornerstown Formation extends from Zone NP8 to ?Zone NP1, and includes several large stratigraphic gaps with Zones NP7, NP5, and NP2 absent.

Sample 597.5 ft (182.12 m) belongs to Zone NP8. Sample 602.5 ft (183.64 m) belongs to Zone NP6, characterized by *Heliolithus kleinpelli* (rare) and *H. cantabriae* (common). Sample 607.5 ft (185.17 m) belongs to Zone NP4, characterized by the presence of *Ellipsolithus macellus* and the absence of *Sphenolithus primus*. Samples 612.0 and 614.9 ft (186.54 and 187.42 m) belong to Zone NP3, with *Chiasmolithus danicus* very common, but this species was not observed in Sample 614.0 ft (187.15 m). Sample 616.0 ft (187.76 m) is essentially barren. Cretaceous taxa are abundant in Samples 617.0 and 617.5 ft (188.06 and 188.21 m). The scarcity of small coccoliths (genus *Prinsius* in particular) is surprising and may reflect poor preservation. These levels are tentatively assigned to Zone NP1.

The rapid succession of biozones in the Hornerstown Formation is strongly suggestive of successive unconformities (sequence boundaries) between 597.5 and 602.5 ft (182.12–183.64 m), 602.5 and 607.5 ft (183.64–185.17 m), 607.5 and 612.0 ft (185.17–186.54 m), and possibly 615 and 616 ft (187.45–187.76 m), some of which intervals are delineated on the basis of lithologic changes (see **"Lithostratigraphy,"** p. 13).

Cretaceous Calcareous Nannofossils

Summary

Samples were taken at 2-ft (0.61 m) intervals except near the K/T boundary where sampling density was increased. Smear slides were prepared using standard techniques and examined under the light microscope at a magnification of 1250×.

Calcareous nannofossil abundance and diversity are high and preservation is generally good to excellent in samples from the Navesink, Mount Laurel, and Wenonah Formations, and from most of the Marshalltown Formation. Below 753.5 ft (229.67 m), near the base of the Marshalltown Formation and continuing through the Englishtown and upper Woodbury Formations down to 851.5 ft (259.54 m), nannofossils are less abundant with poor to fair preservation. Barren intervals are common in the Englishtown Formation. In the lower Englishtown Formation (851.5–943.0 ft [259.54–287.43 m]), nannofossil abundance increases and preservation improves. Below this, the Cheesequake, Magothy and uppermost Bass River Formations are barren of nannofossils. The Bass River Formation nannofossils are mostly well preserved with low abundance and high diversity. Throughout the core, nannofossil assemblages include both high- and low-latitude species. Holococcoliths are generally common to abundant.

The nannofossil zonation and CC terminology of Sissingh (1977) were used to subdivide the section. Several of the Sissingh (1977) zones have been modified by Perch-Nielsen (1985) based largely on reclassification of the names of original species and genera. Perch-Nielsen (1985) also defined several subzonal units, and these are also applied here. Zones defined by Bralower (1988) have been applied to the Cenomanian/Turonian boundary interval. All zones are correlated to stages according to the scheme of Gradstein et al. (1995). Table T3 lists the zonal definitions and assigned intervals in the Ancora borehole.

T3. Cretaceous nannofossil zones, Ancora Site, p. 65.

Cretaceous/Tertiary Boundary

The precise position of the K/T boundary is difficult to determine using nannofossil stratigraphy because of substantial mixing of Upper Cretaceous and lower Paleocene assemblages between 617.1 and 618.0 ft (188.09–188.37 m). Nannofossil assemblages in this interval are rare, poorly preserved, and dominated by Cretaceous taxa and the disaster genus *Throracosphaera*. Paleocene taxa, including *Cruciplacolithus primus*, extend down into the upper Maastrichtian section. Other taxa diagnostic of lower Paleocene Zone NP1, including *Biantholithus sparsus* and *Neobiscutum romeinii,* are rare. The boundary interval appears to be complicated by slumping. For example, a sample that belongs to Zone NP2 (617.7 ft [188.27 m]) appears to lie below a sample that belongs to Zone NP1 (617.4 ft [188.18 m]). Reworking of Cretaceous nannofossils into the Tertiary section is pervasive as in many other sections (e.g., Pospichal, 1996). Our tentative placement of the K/T boundary at 618.0 ft (188.37 m) is based on a dramatic increase in the relative proportion of Cretaceous nannofossils below this level. Clearly, more detailed investigations of the boundary interval, including sampling at the centimeter scale, are warranted.

Navesink Formation

Interval: 618.1–651.3 ft (188.40–198.52 m)

The Navesink Formation is assigned to upper Maastrichtian Zones CC26 to CC25. Calcareous nannofossils are abundant. Preservation is excellent in the upper part of the formation and decreases to good in the lower part of the formation because of overgrowth.

The upper and lower boundaries of Zone CC26 are precisely identified by the HO and LO of *Nephrolithus frequens* (618.1 and 631.1 ft [188.40 and 192.36 m]), respectively. Subzones CC26a and CC26b cannot be identified because of the absence of *Micula prinsii*.

The interval between 631.1 and 651.3 ft (192.36–198.52 m) is assigned to Zone CC25. Evidence of mixing between Zone CC25 and the zone that lies unconformably below it (CC23 or possibly CC22) in the interval 650.7–651.6 ft (198.33–198.61 m) makes it difficult to determine the lower boundary of Zone CC25. This interval includes the base of the Navesink Formation and the top of the Mount Laurel Formation.

The only specimen of *Micula murus* observed in the Ancora borehole was found at 618.83 ft (188.62 m) in Zone CC26. Thus, it is not possible to determine the boundary between Subzones CC25b and CC25c (Table T3). The top of Subzone CC25a is precisely identified by the LO of *Lithraphidites quadratus* at 647.8 ft (197.45 m).

Mount Laurel Formation

Interval: 651.3–715.0 ft (198.52–217.93 m)

The Mount Laurel Formation is assigned to upper–middle Campanian Zones CC22–CC21, and possibly Zone CC23. It may extend into the lower Maastrichtian, as Zone CC23 spans the Campanian/Maastrichtian boundary (Gradstein et al., 1995). Nannofossil preservation is good to fair. Species identification is occasionally difficult because of overgrowth. Abundance and diversity are high, particularly among the holococcoliths.

Coincidence of the HOs of *Reinhardtites levis, Aspidolithus parcus, Calculites obscurus, Quadrum gothicum,* and *Tranolithus phacelosus* in the transition between the Navesink and Mount Laurel Formations suggests the presence of an unconformity that spans Zone CC24 and maybe the lower part of Zone CC25 and upper part or all of Zone CC23. The presence of Zone CC23 is questionable because of a lack of consensus on making a diagnosis between *Reinhardtites levis* and *R. anthophorus* (Bralower and Siesser, 1992; J. Bergen, pers. comm., 1999; J. Self-Trail, pers. comm., 1999). The interval 678.8–709.5 ft (206.90–216.26 m) belongs to Subzone CC22a based on the HO of *Lithastrinus grillii* and the LO of *Quadrum trifidum*. It is difficult to determine the top of the subzone with certainty because of the sporadic occurrence of *Lithastrinus grillii.* The interval 709.5–714.9 ft (216.26–217.90 m) is assigned to the top of Zone CC21 based on the absence of *Quadrum trifidum* and the presence of *Quadrum sissinghii.*

Wenonah Formation

Interval: 715.0–735.0 ft (217.93–224.03 m)

The Wenonah Formation is assigned to middle Campanian Zone CC21. Nannofossils are abundant with high diversity, although the abundance of holococcoliths is lower than in overlying units. Preservation is good to excellent. *Quadrum sissinghii* continues to be present throughout the Wenonah Formation, indicating that it belongs to Zone CC21.

Marshalltown Formation

Interval: 735.0–757.2 ft (224.03–230.79 m)

The Marshalltown Formation is assigned to middle Campanian Zone CC21 and possibly the upper part of Zone CC20. From 735.0 to 753.5 ft (224.03–229.67 m), nannofossil abundance is high and preservation good to excellent, with dissolution increasing downhole. Samples in the interval from 753.5 to 757.5 ft (229.67–230.79 m) are barren.

Based on the continued presence of *Quadrum sissinghii* throughout the fossiliferous part of the formation, the interval 735.0–753.5 ft (224.03–229.67 m) is assigned to Zone CC21. The base of the Marshalltown Formation (753.5–756.5 ft [229.67–230.79 m]) is assigned with some uncertainty to Zone CC20 based on the LO of *Q. sissinghii* at 753.5 ft (229.67 m); however, it is plausible that Zone CC21 continues through this barren interval.

Englishtown Formation

Interval: 757.2–797.2 ft (230.79–242.99 m)

The Englishtown Formation is assigned to middle Campanian Zone CC19 and possibly part of Zone CC20. Much of the formation is barren of nannofossils. In fossiliferous samples, nannofossils are scarce and poorly preserved. Dissolution is common and many specimens are broken.

Identification of Zone CC20 is uncertain. The uppermost sample in the Englishtown Formation at 758.5 ft (231.19 m) is tentatively assigned to Zone CC20 based on the occurrence of *Ceratolithoides aculeus.*

However, preservation is poor and diversity low and only one specimen of this species was found in the sample. A 4-ft (1.23 m) barren interval lies below this sample (759.5–763.5 ft [231.5–232.72 m]). Part or all of the barren interval may also belong to Zone CC20. On the other hand, given the poor preservation, it is also possible that specimens of *Q. sissinghii* have been dissolved and Zone CC21 extends down to 763.5 ft (232.71 m). If so, an unconformity must lie at the base of Zone CC21. If not, Zone CC20 probably represents a condensed section or deposition at a diminished sedimentation rate.

On the basis of the absence of *Ceratolithoides aculeus,* the interval between 763.5 ft (232.71 m) and the base of the formation (792.2 ft [242.99 m]) is assigned to Zone CC19. The barren interval above, from 759.5 to 763.5 ft (231.50–232.71 m), may also belong to this zone.

Woodbury Formation

Interval: 797.2–903.0 ft (242.99–275.23 m)

The Woodbury Formation is assigned to lower–middle Campanian Zone CC18. Nannofossils are rare and their preservation poor to fair to a depth of 851.5 ft (259.54 m) in the upper Woodbury Formation. Preservation improves to good below this level. The entire Woodbury Formation is assigned to Zone CC19 based on the absence of *Ceratolithoides aculeus* and *Marthasterites furcatus*.

Merchantville Formation

Interval: 903.0–944.5 ft (275.23–287.88 m)

The Merchantville Formation is assigned to upper Santonian to lower Campanian Zones CC18–CC17. Calcareous nannofossil abundance is high and preservation good to very good in most of the formation. Preservation diminishes to fair because of dissolution in samples from 939.5 and 941.5 ft (286.36 and 286.97 m). Below this level, sediments are barren of nannofossils.

The top of Zone CC18 is precisely defined at 903.0 (275.23 m) by the HO of *Marthasterites furcatus*. The LO of *Aspidolithus parcus* defines the top of Zone CC17 at 918.5 ft (279.96 m), indicating that strata below this level can be dated as Santonian based on nannofossil correlations. Zonal assignment of the interval 940.5–943.0 ft (286.70–287.43 m) is uncertain as the holococcolith *C. obscurus,* the major marker species for the base of Zone CC17, is absent. However, holococcoliths are rare in Zone CC17 and none are found in the Merchantville Formation below the LO of *C. obscurus*. The lack of holococcoliths in the interval 940.5–943.0 ft (286.70–287.43 m) is possibly a result of changing environmental conditions. *Parhabdolithus regularis,* the LO of which lies in the middle of combined Zones CC16 and CC17 (Bralower and Siesser, 1992), is found throughout this interval. Thus, this interval belongs to either Zone CC17 or CC16. The zonal correlation of the barren section from 943.0 to 944.5 ft (287.43–244.5 m) is uncertain.

Cheesequake and Magothy Formations

Interval: 944.5–1062.5 ft (287.88–323.85 m)

All samples examined from these formations are barren of calcareous nannofossils. The Cheesequake and Magothy Formations lie somewhere in the interval comprising middle Santonian Zone CC16 to lower Turonian Zone CC11.

Bass River Formation

Interval: 1062.5–1148.1 ft (323.85–349.94 m)

The interval from 1061.9 to 1074.5 ft (323.67–327.51 m) is barren of nannofossils. Abundance varies from low to high and preservation from poor to good in the interval below, which ranges from the upper Cenomanian *Parhabdolithus asper* Zone (*Microstaurus chiastius* Subzone) to the lower Cenomanian *Axopodorhabdus albianus* Zone (Zones CC10–CC9 of Sissingh [1977]).

The interval between 1074.5 and 1076.4 ft (327.51–328.09 m) is assigned to the *Parhabdolithus asper* Zone, *Microstaurus chiastius* Subzone. *Microstaurus chiastius* is not found in this interval. However, we have identified this subzone using the HO of the secondary marker, *Lithraphidites acutum,* which lies near the base of the *Microstaurus chiastius* Subzone in several sections (Bralower, 1988). The *Axopodorhabdus albianus* Zone is precisely identified from 1076.4 to 1146.7 ft (328.09–349.51 m), between the HO of *Axopodorhabdus albianus* and the FO of *Vagalapilla octoradiata*.

Although the Sissingh (1977) zonation scheme has been shown to be inapplicable in the Cenomanian/Turonian boundary interval (Bralower, 1988), we show the CC zonation in the Bass River Formation for reference. The coexistence of *M. decoratus* and *Lithraphidites acutum,* whose range is restricted to the Cenomanian (Perch-Nielsen, 1985), indicates that the interval between 1074.5 and 1128.5 ft (327.51–343.97 m) lies in Zone CC10. *Quadrum gartneri,* the principal marker for the top of Zone CC10, is not present in the Ancora borehole. Subzone CC10b is considered to extend to 1101.7 ft (335.80 m). As *Microstaurus chiastius* is not present, the LO of *Corollithion exiguum* was used as a secondary marker for the base of this subzone (Self-Trail and Bybell, 1995). The interval between 1101.7 and 1128.5 ft (335.80–343.97 m) belongs to Subzone CC10a, with the LO of *Microrhabdulus decoratus* at 1128.5 ft (343.97 m) marking the base of the subzone and the top of Zone CC9.

Potomac Group

Interval: 1148.1–1170.0 ft (TD; 349.94–356.62 m)

The top of the Potomac Group is assigned to Zone CC9 (upper Albian to lower Cenomanian). Nannofossil preservation is fair and abundance is scarce in the uppermost sample at 1149.0 ft (350.22 m). Below this, all samples are barren and no zonal correlation is possible. The uppermost sample is assigned to Zone CC9 based on the co-occurrence of *Lithraphidites alatus* and *Eiffellithus turriseiffelii*.

Pollen

The upper part of the Magothy Formation at Ancora is assigned to pollen Zone V (samples at 980.9 and 983.6 ft [299.05 and 299.88 m]) of Christopher (1982), which is generally correlated to the upper Turonian–Santonian (Fig. F7). The lower part of the Magothy Formation at

Ancora (1028.9 ft [313.7 m]) is tentatively assigned to pollen Zone V (Fig. F7), consistent with previous studies (Christopher, 1982). Three Bass River Formation samples (1072.0, 1102.0, and 1138.0 ft [326.82, 335.98, and 246.95 m]; Fig. F8) are assigned to upper Cenomanian to lowermost Turonian pollen Zone IV of Christopher (1982). Two Potomac Group samples (1150.5 and 1165.0 ft [350.76 and 355.18 m]) are assigned to the pollen Zone III/IV transition; this interval is lower–middle Cenomanian.

STRONTIUM ISOTOPIC STRATIGRAPHY

Nineteen Sr isotopic age estimates were obtained from mollusk and foraminifer shells (~4–6 mg) at the Ancora borehole (Table T1; Figs. F2, F4, F5, F6). Shells and foraminifer tests were cleaned ultrasonically and dissolved in 1.5 N HCl. Sr was separated using standard ion exchange techniques (Hart and Brooks, 1974), and analyzed on a VG Sector Mass Spectrometer at Rutgers University. Internal precision on the sector for the data set averaged 0.000025, and the external precision was approximately ±0.000020 (Oslick et al., 1994). NBS 987 was measured for these analyses at 0.710255 (2σ standard deviation = 0.000008, N = 22), normalized to a $^{87}Sr/^{86}Sr$ of 0.1194. Cenozoic ages were assigned using the Berggren et al. (1995) time scale (Table T2), using the early Miocene regression of Oslick et al. (1994) with age errors of ±0.61 at the 95% confidence interval for one analysis. Cretaceous ages (Table T2) were assigned using the regressions of Sugarman et al. (1995) and Howarth and McArthur (1997); Sugarman et al. (1995) conservatively estimated Campanian–Maastrichtian errors of ±1.9 at the 95% confidence interval for one analysis (Table T2). Age errors for the coeval and older sections are purportedly one order of magnitude better according to Howarth and McArthur (1997). Recent evaluation of Campanian–Maastrichtian Sr isotopic correlations suggests that ±1 m.y. is a reasonable estimate of the error (Miller et al., 1999).

Because of the poorly fossiliferous nature of the Miocene and younger sediments of the borehole, the first Sr isotopic ratio was obtained from 243 ft (74.07 m). Marine Cretaceous sediments generally contained sufficient fossils for Sr isotopic analysis.

Three Sr isotopic age estimates from shells at the base of the Kirkwood Formation (243, 255, and 263 ft [74.07, 77.72, and 80.16 m]) ranged from 20.2 to 21.2 Ma and are correlated to the lower Miocene Kw1a sequence (Fig. F2; Sugarman et al., 1993; Miller et al., 1997).

Eleven Cretaceous samples yield ages similar to those based on biostratigraphy. Samples from the Navesink through Wenonah Formations (645.0–713.8 ft [196.60–217.57 m]) gave reliable ages. One reliable age estimate was obtained from each of the Marshalltown (750.8 ft [228.84 m]), Woodbury (863.5 ft [263.19 m]), and Merchantville (932.1 ft [284.10 m]) Formations.

Five samples yielded ages younger than predicted by biostratigraphy; these samples are listed in Table T1, although the ages are not plotted. Three samples have ages that are significantly younger than other Sr isotopic ages bracketing them (740.5, 776.7, and 892.1 ft [225.70, 236.74, and 271.91 m] from the Marshalltown, Englishtown, and Woodbury Formations, respectively). Previous studies of the New Jersey Coastal Plain samples have shown that diagenesis is a potential problem for some Upper Cretaceous samples (Sugarman et al., 1995), particularly for aragonitic shells that have a vesicular wall structure (e.g., *Pycnodonte*). Two samples from the Cenomanian portion of the Bass River Formation yield one age (82.2 Ma) that is younger than the actual age of >91.3 Ma and one age that could either be younger (85.0 Ma) or older (96.7–101.0 Ma) than its actual age; it is not clear if this is a diagenetic problem or if this results from problems in the Sr isotopic age calibration.

SUMMARY AND CONCLUSIONS

The Leg 174AX Ancora borehole continuously cored 693.82 ft (211.48 m) in Hole A between the surface and 759 ft (231.34 m; 91.4% recovery), and 591.48 ft (180.28 m) in Hole B between 543 ft (165.55 m) and a TD of 1170 ft (356.71 m) with remarkable recovery (92.7% total). At the Ancora Site, we recovered the oldest sediments cored by the New Jersey Coastal Plain Drilling Project, including several Cenomanian sequences for the first time. Otherwise, Cenomanian through Eocene strata record sequences similar to those in the Bass River borehole (Miller, Sugarman, Browning, et al., 1998). These two sites together, thus, provide an updip (Ancora) to downdip (Bass River) transect designed to recover, identify, and date Upper Cretaceous sequences, to obtain eustatic estimates from these sequences, and to evaluate facies relationships within sequences. This updip–downdip pair also addresses important issues in local hydrogeology by recovering major aquifer units within the Magothy, Englishtown, Mount Laurel, and Kirkwood–Cohansey Formations. In addition, the Ancora borehole recovered several critical events in Earth history: (1) a remarkably thick section representing the LPTM contains an intriguing interval of convoluted bedding; (2) the lowermost Paleocene section is the thickest found to date in New Jersey, providing an excellent opportunity to assess the recovery of marine microorganisms from the terminal Cretaceous extinction event and its relationship with global sea-level change; (3) the Cenomanian–Turonian section recovered the equivalent to the lowermost Turonian Bonarelli bed that is complimentary to the coeval section at Bass River. Thus, the Ancora section provides an excellent record of global changes in sea level, climate, and the carbon system during the “Greenhouse World” of the Late Cretaceous to Eocene.

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Figure F1. Location map showing existing ODP boreholes analyzed as a part of the New Jersey transect, proposed sites for boreholes at Ocean View and Maryland Beach, and proposed nearshore Sites MAT1–3. Also shown are multichannel seismic profiles Ew9009, Oc270, and Ch0698.

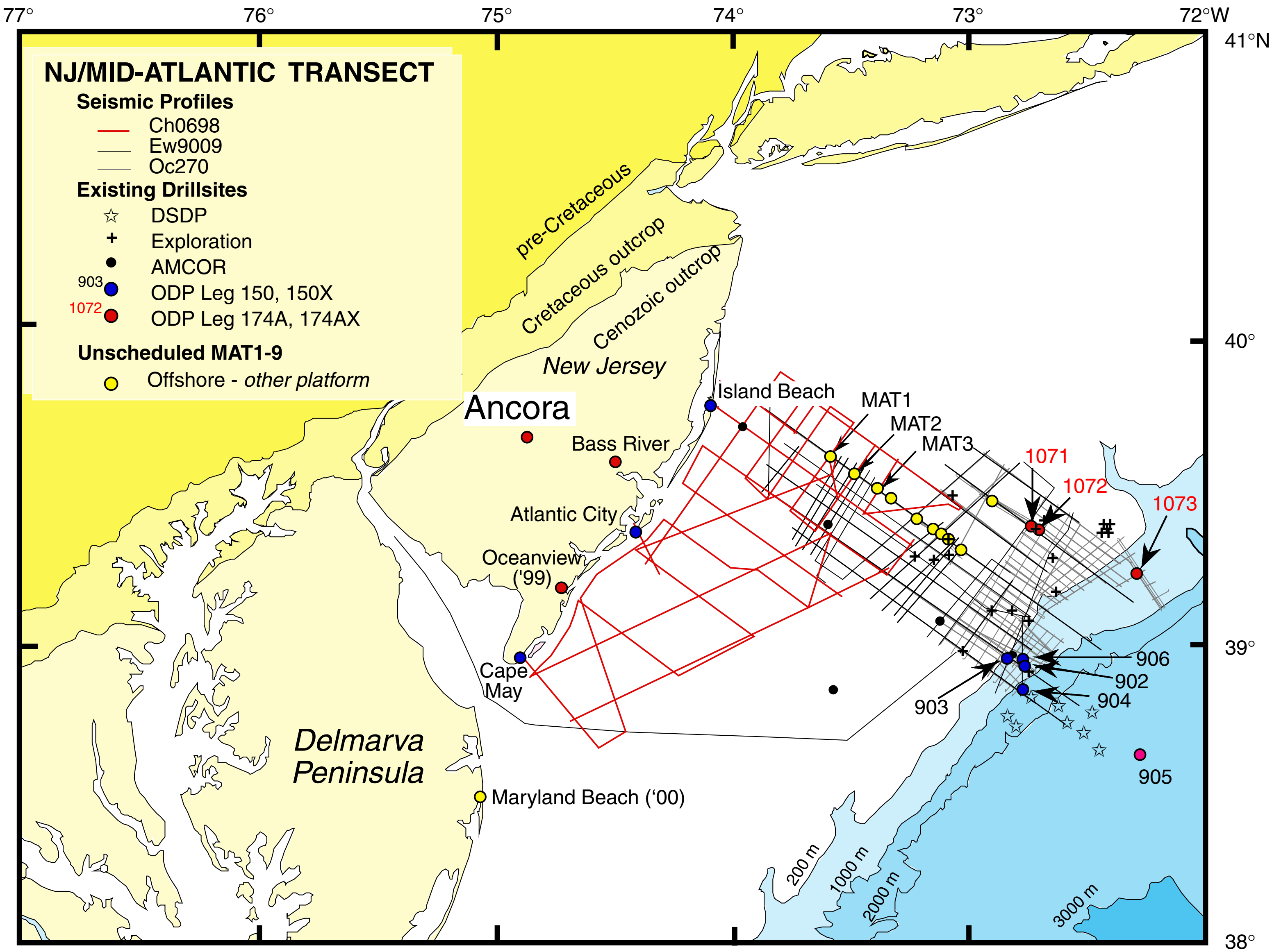

Figure F2. Surficial deposits (?Pleistocene–Holocene), Cohansey Formation (?upper and/or ?middle Miocene), and Kirkwood Formation (lower to ?middle Miocene), Ancora Site. Numbers in Ma are Sr isotopic age estimates (Table T2, p. 64). Kw1 and ?Kw1a are sequences correlated to those of Sugarman et al. (1993).

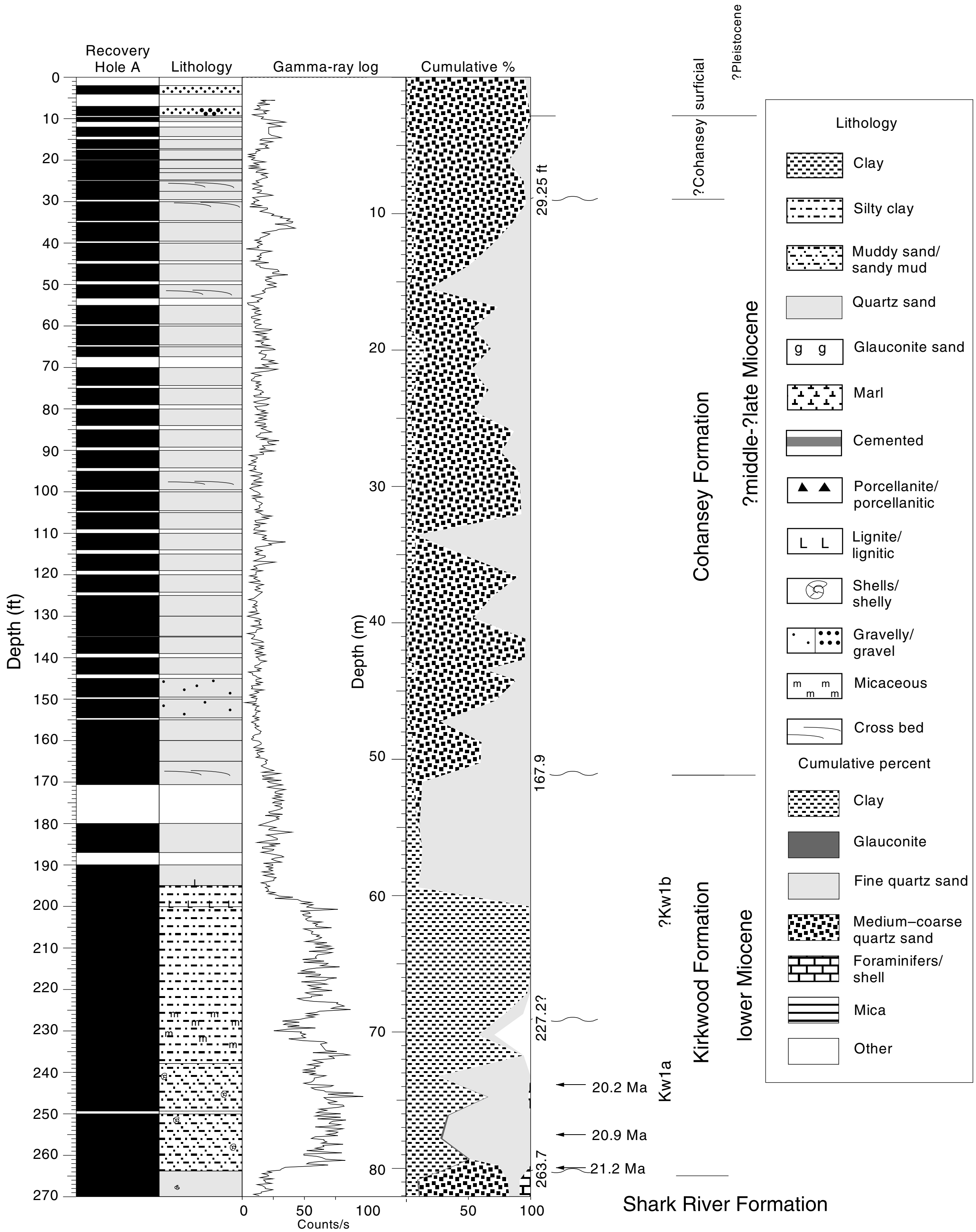

Figure F3. Shark River (middle Eocene) and Manasquan (lower Eocene) Formations, Ancora Site. The key for symbols is given in Figure F2, p. 52. E1–E8 are sequences defined by Browning et al. (1997b). Foram. = planktonic foraminifer biostratigraphy; Nanno. = calcareous nannoplankton biostratigraphy; Fm. = Formation.

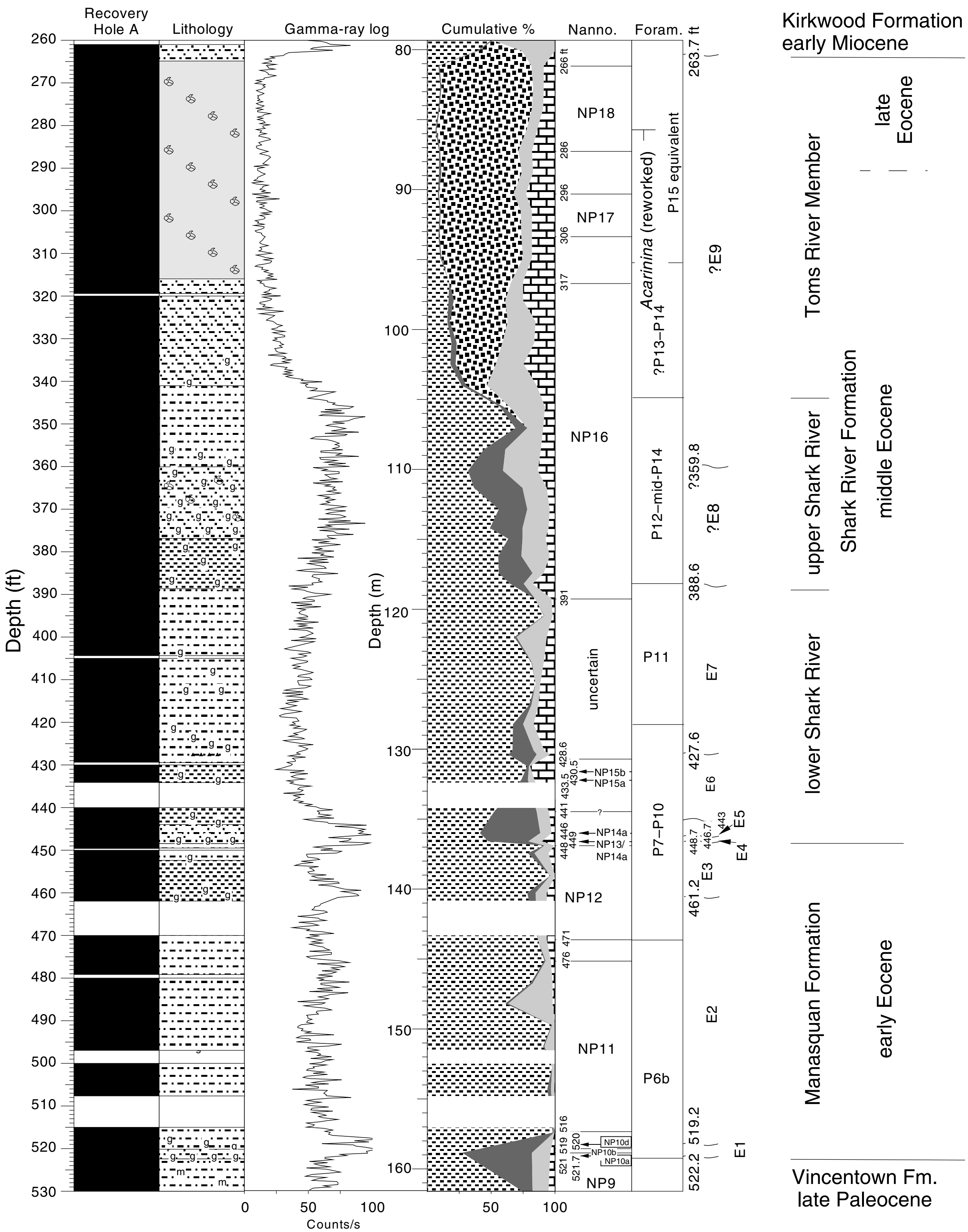

Figure F4. Vincentown (upper Paleocene), Hornerstown (lower to lowermost upper Paleocene), and Navesink (Maastrichtian) Formations, Ancora Site. Numbers in Ma are Sr isotopic age estimates (Table T2, p. 64). The key for symbols is given in Figure F2, p. 52. Foram. = planktonic foraminifer biostratigraphy; Nannofossils = calcareous nannoplankton biostratigraphy; FAD = first appearance datum; LAD = last appearance datum; Fm. = Formation; MFS = maximum flooding surface; CIE = correlative to the carbon isotopic excursion.

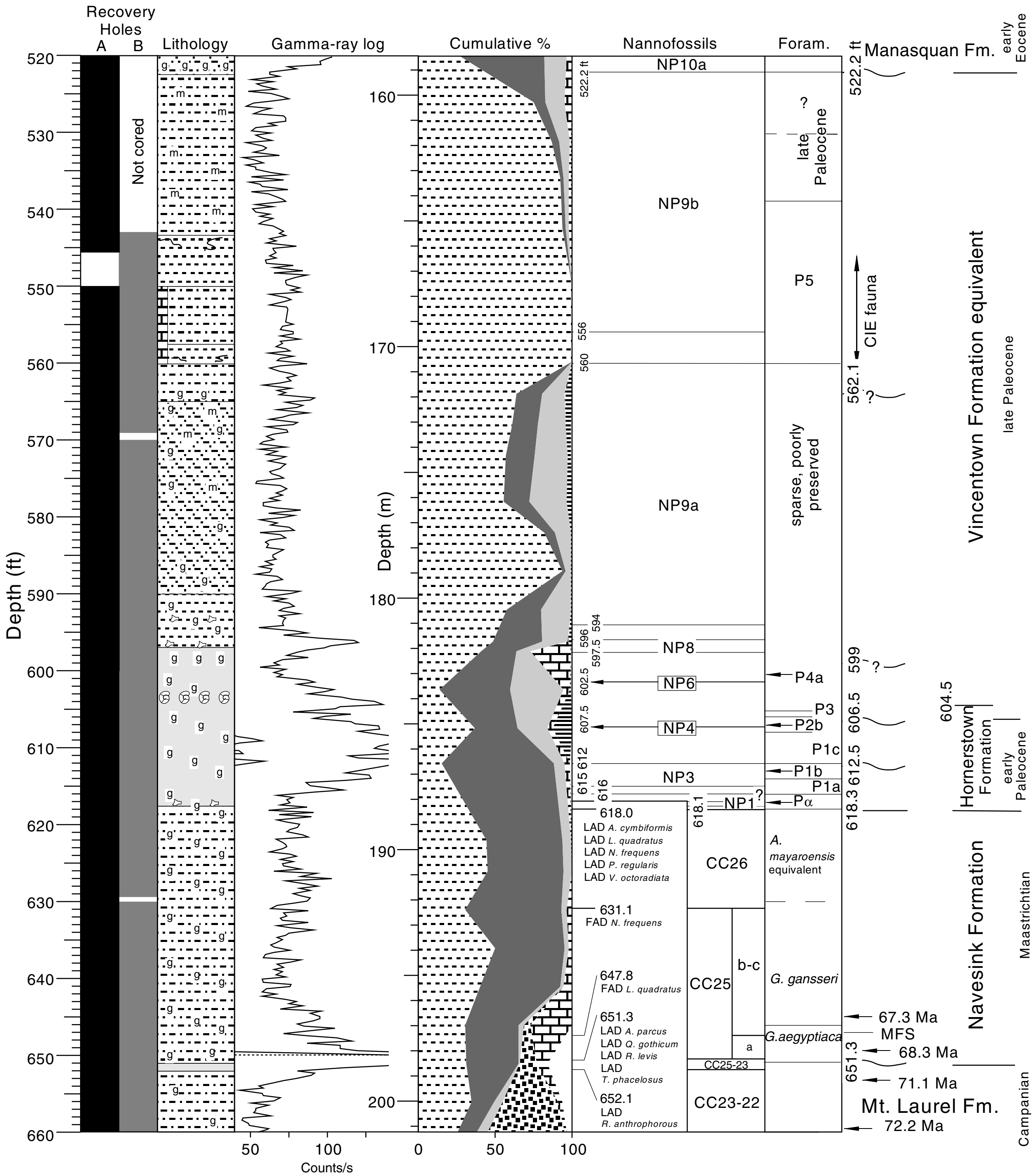

Figure F5. Campanian Mount Laurel, Wenonah, Marshalltown, and Englishtown Formations, Ancora Site. Numbers in Ma are Sr isotopic age estimates (Table T2, p. 64). The key for symbols is given in Figure F2, p. 52. Foram. = planktonic foraminifer biostratigraphy; Nannofossils = calcareous nannoplankton biostratigraphy; FAD = first appearance datum; LAD = last appearance datum; Fm. = Formation; MFS = maximum flooding surface; TS = transgressive surface; eq. = equivalent.

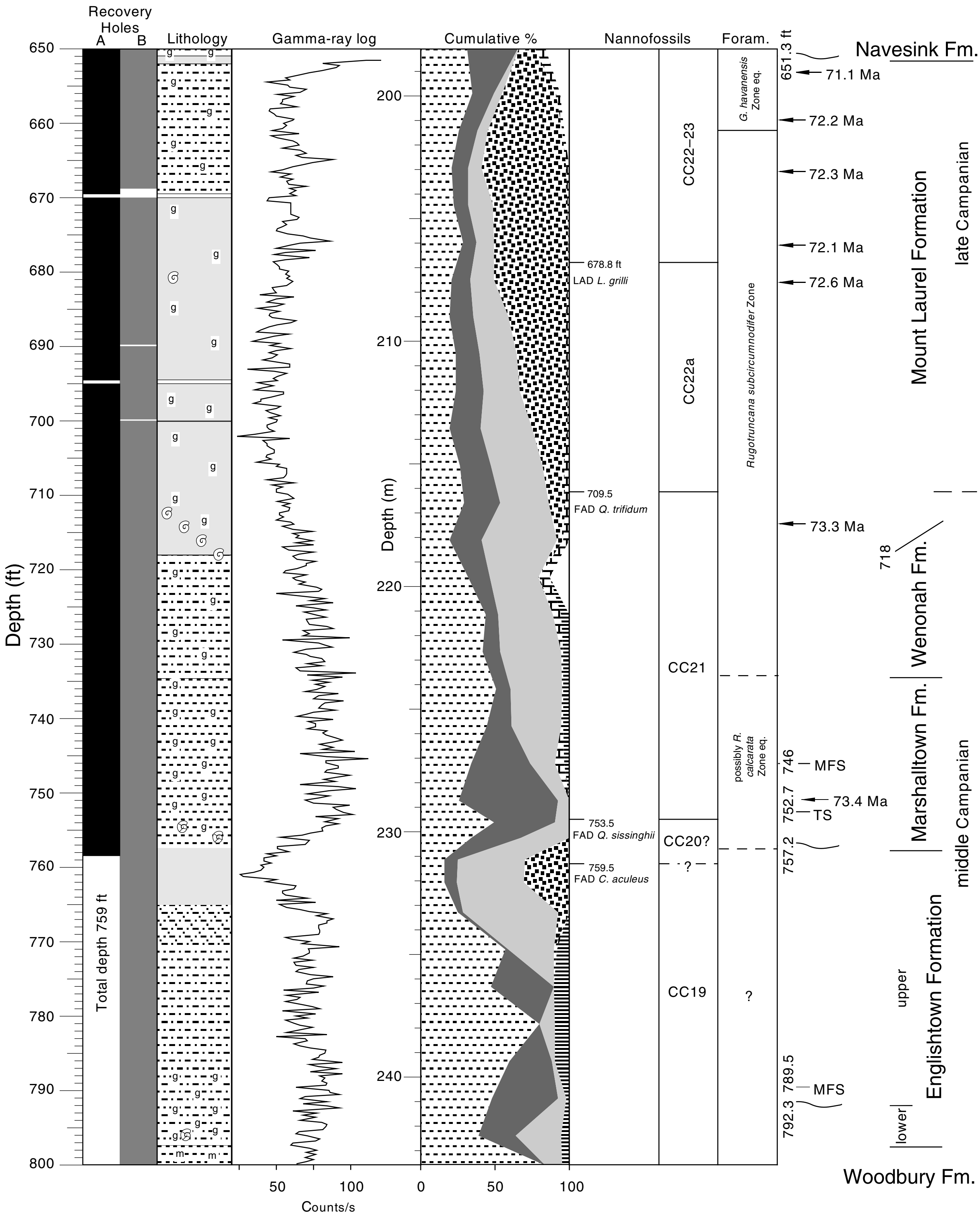

Figure F6. Woodbury (?lower Campanian), Merchantville (Santonian to lowermost Campanian), and Cheesequake (Santonian) Formations, Ancora Site. Numbers in Ma are Sr isotopic age estimates (Table T2, p. 64). The key for symbols is given in Figure F2, p. 52. Foram. = planktonic foraminifer biostratigraphy; Nannofossils (Nanno.) = calcareous nannoplankton biostratigraphy; FAD = first appearance datum; LAD = last appearance datum; Fm. = Formation; MFS = maximum flooding surface.

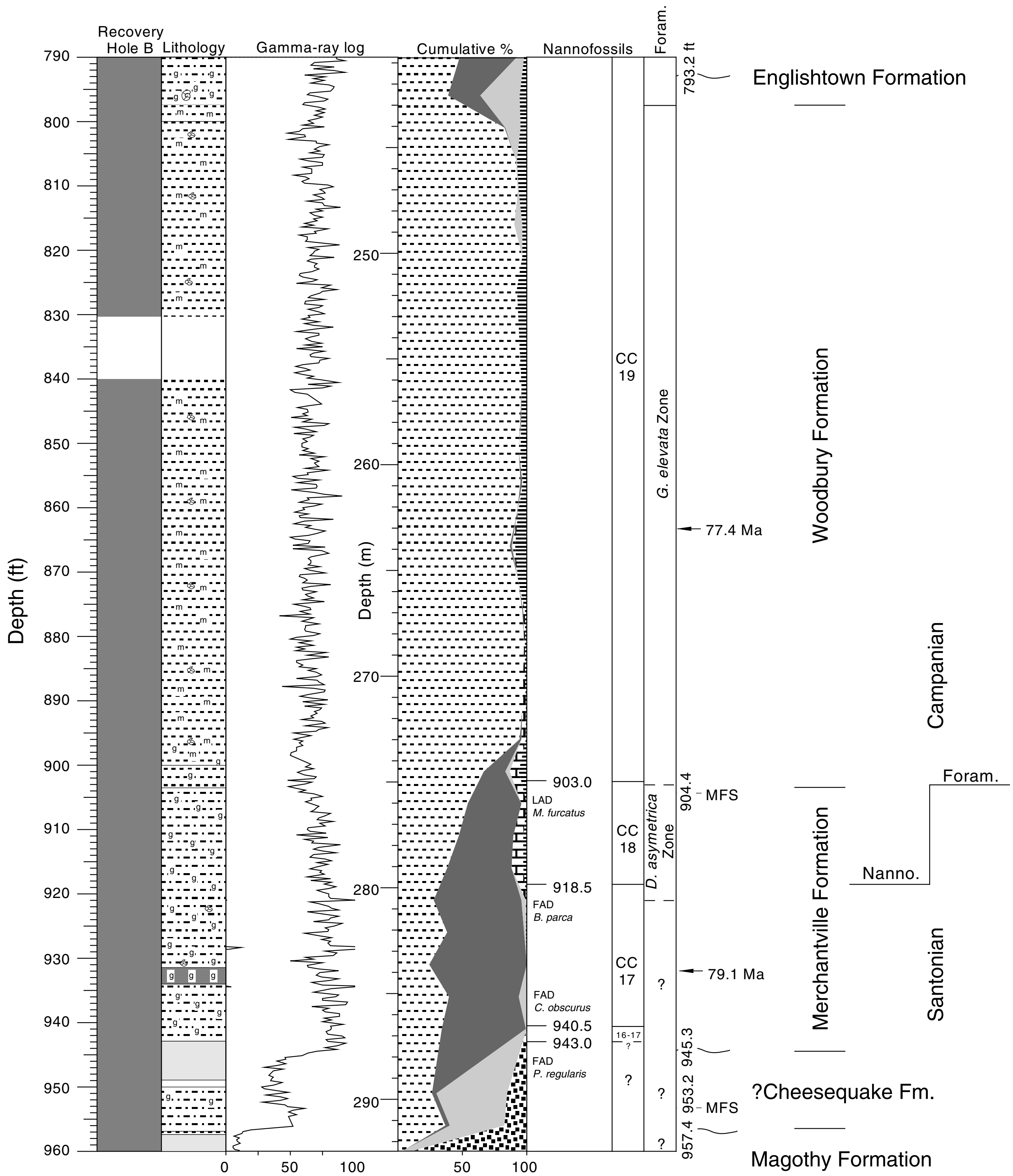

Figure F7. Magothy Formation (undifferentiated lower Turonian–Santonian [?Coniacian]), Ancora Site. Zone V is a pollen zone. The key for symbols is given in Figure F2, p. 52. Fm. = Formation; MFS = maximum flooding surface.

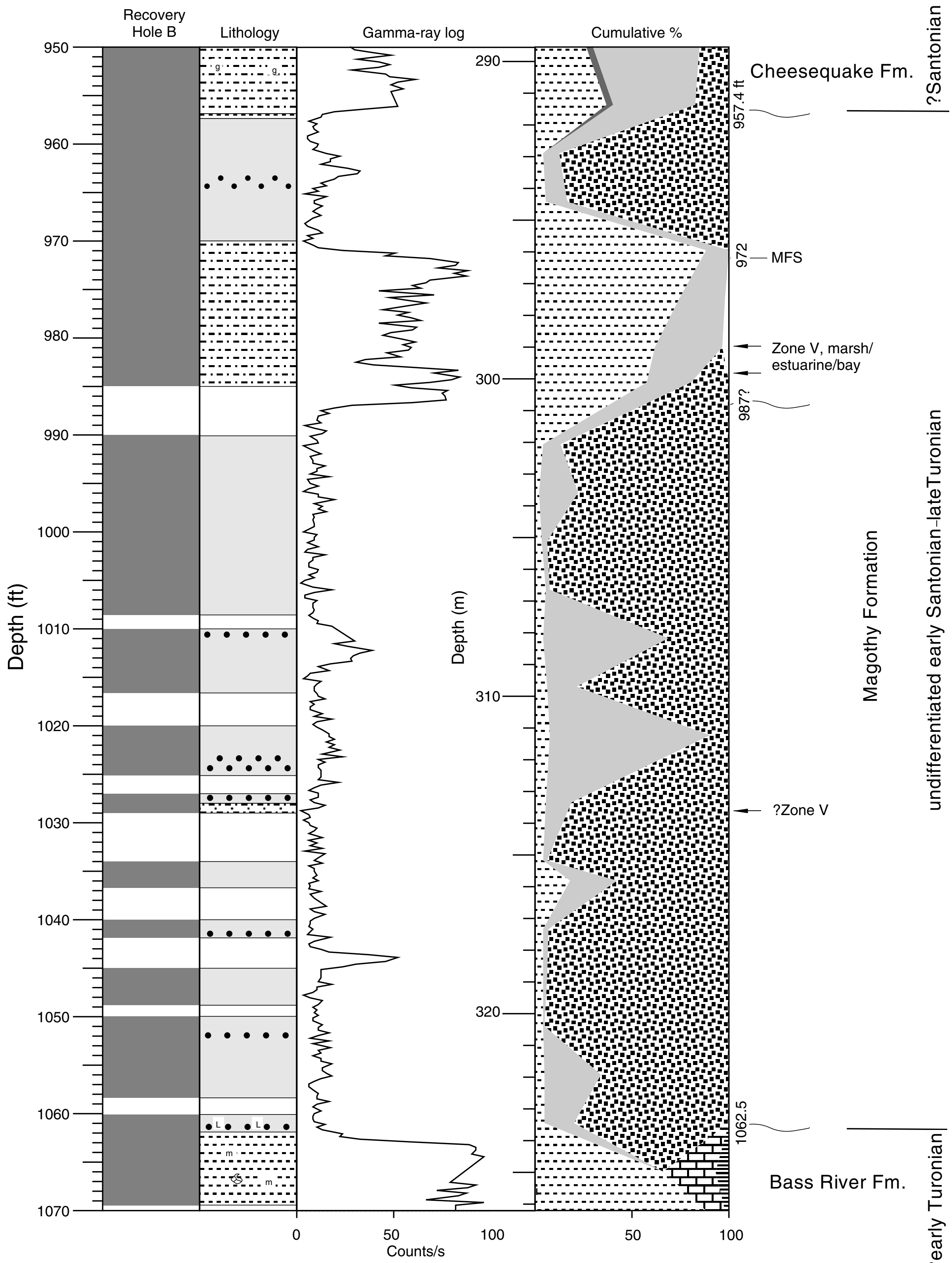

Figure F8. Bass River (Cenomanian to Turonian) and Potomac (Cenomanian) Formations, Ancora Site. Zones III and IV are pollen zones. The key for symbols is given in Figure F2, p. 52. Nannofossils = calcareous nannoplankton biostratigraphy; FAD = first appearance datum; LAD = last appearance datum; T.D. = total depth.

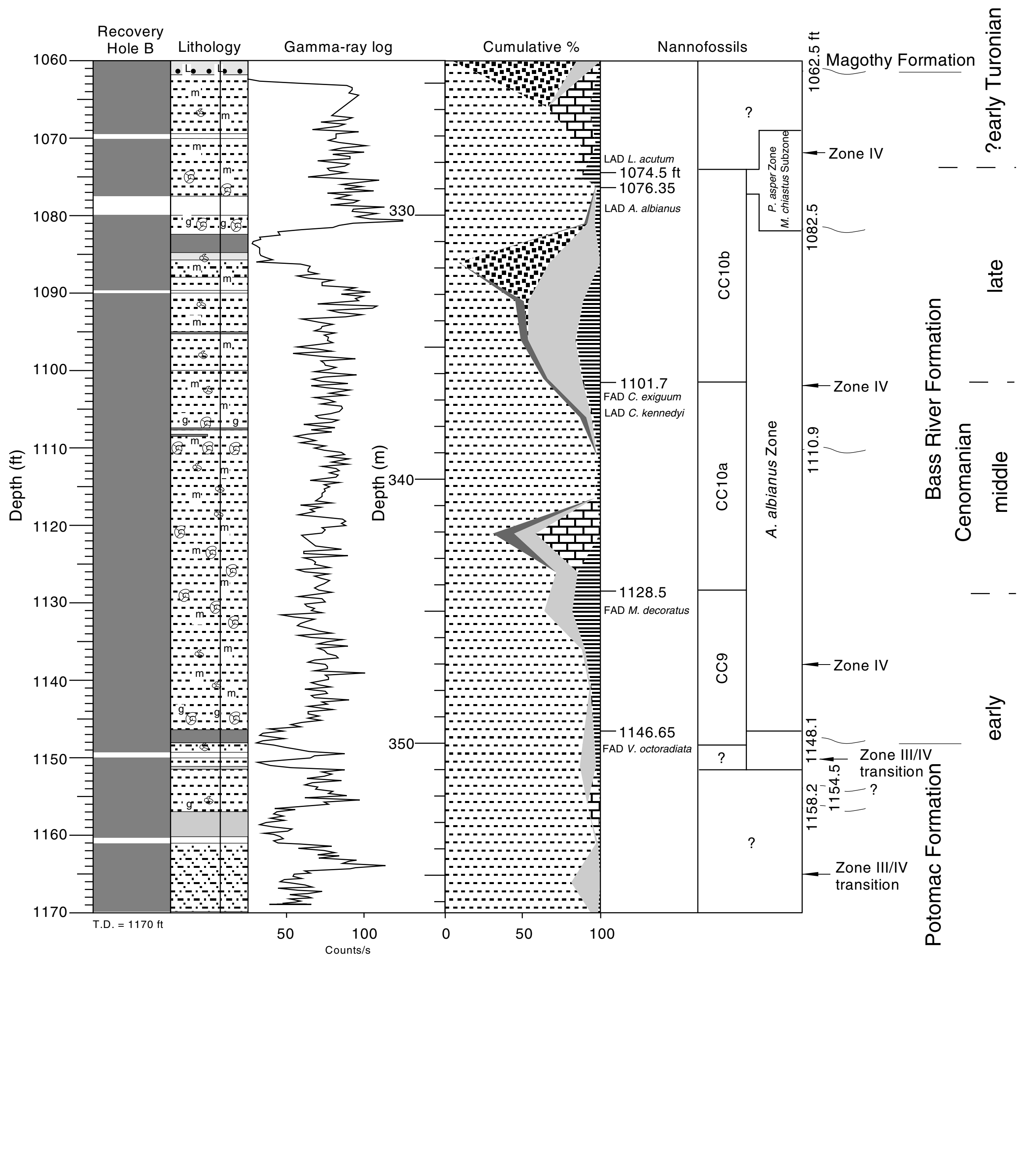

Table T1. Coring summary, Ancora Site. (Continued on next four pages.)

Run number	Date (1998)	Cored interval (ft)	Run length (ft)	Recovery (ft)	Recovery (%)	Primary lithology	Formation	Color
Hole A								
1	8 July	2-7	5.0	2	40	Gravel	Surficial	12.5Y7/6-7/8 yellow
2	8 July	7-9.5	2.5	2.1	84	Red gravel	Surficial	2.5Y7/6 light red
3	8 July	9.5-12	2.5	1	40	Red clayey sand	?Cohansey	5YR5/8 yellowish red
4	8 July	12-15	3.0	2.2	73	Medium to fine sand	?Cohansey	10YR5/4 yellowish brown
5	9 July	15-17.5	2.5	2.1	84	Medium to coarse quartz sand	?Cohansey	5YR4/6 yellowish red
6	9 July	17.5-20	2.5	2.3	92	Medium to coarse quartz sand	?Cohansey	5YR4/4 yellowish red
7	9 July	20-22	2.0	2	100	Pebbly variegated coarse quartz sand	?Cohansey	2.5YR4/4 dusky red
8	9 July	22-23	1.0	1	100	Semi-indurated variegated coarse quartz sand	?Cohansey	2.5YR2.5/4 very dusky red
9	9 July	23-25	2.0	1.8	90	Indurated and semi-indurated very coarse quartz sand	?Cohansey	5YR3/2 dark red brown
10	9 July	25-27.5	2.5	2.6	104	Cross-bedded medium to very coarse quartz sand	?Cohansey	5YR4/6 yellowish red
11	9 July	27.5-30	2.5	1.9	76	Indurated very coarse sand; fine to medium sand; contact at 29.25 ft; definite Cohansey Formation	Cohansey	10YR8/8 yellow + red + gray
12	9 July	30-35	5.0	4.45	89	Cross-bedded, burrowed medium to coarse quartz sand	Cohansey	10YR7/6 yellow
13	9 July	35-40	5.0	4.6	92	Cross-bedded, burrowed medium to coarse quartz sand	Cohansey	10YR7/8 yellow
14	9 July	40-45	5.0	4.3	86	Massive fine to medium quartz sand	Cohansey	10YR7/6 yellow
15	9 July	45-50	5.0	4.1	82	Massive fine quartz sand	Cohansey	10YR7/6 yellow
16	9 July	50-55	5.0	3.2	64	Massive and cross-bedded fine to medium quartz sand	Cohansey	10YR7/8 yellow
17	9 July	55-60	5.0	4.5	90	Massive medium to coarse quartz sand	Cohansey	10YR7/8 yellow
18	9 July	60-65	5.0	4.4	88	Medium sand with interbedded clay	Cohansey	10YR8/6 yellow
19	10 July	65-70	5.0	2.2	44	Medium sand with interbedded clay	Cohansey	10YR8/6 yellow
20	10 July	70-75	5.0	4.2	84	Medium sand with interbedded clay	Cohansey	10YR8/7 yellow
21	10 July	75-80	5.0	4	80	Medium sand with interbedded clay	Cohansey	10YR8/6 yellow
22	10 July	80-85	5.0	4	80	Medium sand with interbedded clay	Cohansey	10YR6/6 yellow
23	10 July	85-90	5.0	4.1	82	Coarse sand with interbedded clay	Cohansey	10YR8/6 yellow
24	10 July	90-95	5.0	4.1	82	Medium sand with interbedded clay	Cohansey	10YR7/6 yellow
25	12 July	95-100	5.0	4.4	88	Medium sand with interbedded silt	Cohansey	10YR6/6 yellow
26	12 July	100-105	5.0	4.3	86	Medium to coarse sand, variegated	Cohansey	7.5YR6/6 reddish yellow
27	12 July	105-110	5.0	4	80	Medium sand, silty clay lenses, fining up	Cohansey	7.5YR6/4, 10YR6/4 light brown, light yellowish brown
28	12 July	110-115	5.0	4	80	Fine sand, two thin silty clay lenses	Cohansey	10YR7/8-7/4 yellow-very pale brown
29	12 July	115-120	5.0	4	80	Fine to coarse sand, variegated	Cohansey	10YR7/6, 5YR6/6 yellow, reddish yellow
30	12 July	120-125	5.0	4.1	82	Medium to coarse sand, pebbles up to 4 mm	Cohansey	2.5YR4/8, 7.5YR7/4 dark red, pink
31	12 July	125-130	5.0	5	100	Fine to medium sand grading to coarse	Cohansey	2.5YR4/8 dark red
32	12 July	130-135	5.0	4.9	98	Medium to coarse sand	Cohansey	5YR5/8 yellowish red
33	12 July	135-140	5.0	4	80	Medium to coarse sand, two silty sand lenses	Cohansey	5YR5/8, 7.5YR7/1 yellowish red, light gray
34	12 July	140-145	5.0	4	80	Medium to coarse sand	Cohansey	10YR7/4 very pale brown
35	13 July	145-150	5.0	4.5	90	Pebbly fine to very coarse quartz sand	Cohansey	10YR5/8 yellowish brown
36	13 July	150-155	5.0	4.6	92	Pebbly medium to coarse quartz sand	Cohansey	2.5Y8/6 yellow
37	13 July	155-160	5.0	5.3	106	Medium sand	Cohansey	10YR7/8-6/6 yellow-brown yellow
38	13 July	160-165	5.0	5.1	102	Slightly silty medium sand	Cohansey	2.5Y7/4 pale yellow
39	13 July	165-170	5.0	5.1	102	Cross-bedded medium sand; massive fine to medium sand; sequence boundary at 167.9 ft	Cohansey/Kirkwood	2.5Y7/6, 5GY4/1 yellow, dark greenish gray
40	13 July	170-175	5.0	0.6	12	Cross-bedded medium sand; massive fine to medium sand	Kirkwood	2.5Y7/6, 5GY4/1 yellow, dark greenish gray
41	13 July	175-180	5.0	0	0			
42	13 July	180-185	5.0	5.6	112	Silty very fine to fine quartz sand	Kirkwood	N5 gray
43	13 July	185-190	5.0	2	40	Silty very fine to fine quartz sand	Kirkwood	N5 gray

Table T1 (continued).

Run number	Date (1998)	Cored interval (ft)	Run length (ft)	Recovery (ft)	Recovery (%)	Primary lithology	Formation	Color
44	13 July	190-195	5.0	5.4	108	Silty very fine to fine quartz sand	Kirkwood	N5 gray
45	13 July	195-200	5.0	5	100	Silty very fine to fine sand; silty clay	Kirkwood	N5 gray
46	13 July	200-205	5.0	5.3	106	Silty clay to clay	Kirkwood	N3 very dark gray
47	14 July	205-210	5.0	5.35	107	Silty clay to clay	Kirkwood	N5 gray
48	16 July	210-220	10.0	10.325	103	Thinly bed and mass clay and silty clay	Kirkwood	10YR31/1-2, 5Y3/2 very dark gray, dark olive gray
49	16 July	220-230	10.0	10.3	103	Thinly bed and mass clay and silty clay; sequence boundary at 227.2 ft	Kirkwood	10YR3/1-2, 2.5Y4/1 very dark gray, dark gray
50	16 July	230-240	10.0	10.2	102	Sandy silt; clayey silt; silty fine sand	Kirkwood	7.5YR4/1, 10YR5/2, 2.5Y3/2 dusky red
51	16 July	240-250	10.0	9.1	91	Silty very fine quartz sand	Kirkwood	10YR3/1 very dark gray
52	16 July	250-260	10.0	10.3	103	Silty very fine to fine quartz sand	Kirkwood	10YR3/1 very dark gray
53	16 July	260-270	10.0	9.65	97	Shelly silty very fine sand; lag; medium to coarse glauconitic quartz sand; contact at 263.7 ft	Kirkwood/Shark River	5GY5/1-4/1 greenish gray to dark greenish gray
54	16 July	270-280	10.0	9.6	96	Shelly silty very fine sand; lag; medium to coarse glauconitic quartz sand	Shark River	5GY4/1 dark greenish gray
55	17 July	280-290	10.0	10	100	Medium to coarse quartz sand	Shark River	5GY5/1-4/1 dark greenish gray
56	17 July	290-300	10.0	10.2	102	Medium to coarse quartz sand	Shark River	5GY5/1-4/1 dark greenish gray
57	17 July	300-310	10.0	10	100	Medium to coarse quartz sand	Shark River	5GY5/1-4/1 dark greenish gray
58	17 July	310-316	6.0	6	100	Medium to coarse quartz sand; clayier medium to coarse quartz sand	Shark River	5GY5/1 greenish gray
59	17 July	316-320	4.0	3.3	83	Medium to coarse quartz sand; clayier medium to coarse quartz sand	Shark River	5GY6/1 greenish gray
60	17 July	320-330	10.0	10	100	Medium to coarse quartz sand; clayier medium to coarse quartz sand	Shark River	5GY6/1 greenish gray
61	17 July	330-340	10.0	9.7	97	Medium to coarse quartz sand; clayier medium to coarse quartz sand	Shark River	5GY5/1 greenish gray
62	17 July	340-350	10.0	10.3	103	Medium to coarse quartz sand; clayier medium to coarse quartz sand	Shark River	5GY5/1 greenish gray
63	17 July	350-360	10.0	10	100	Glauconitic clay and glauconite sand; sequence boundary at 359.8 ft	Shark River	5GY5/1 greenish gray
64	18 July	360-370	10.0	10.4	104	Glauconitic clay	Shark River	5G4/1 dark greenish gray
65	18 July	370-380	10.0	10.2	102	Glauconitic clay	Shark River	5GY5/1 greenish gray
66	18 July	380-390	10.0	10.2	102	Glauconitic clay; silty clay; sequence boundary at 388.6 ft	Shark River	5GY4/1,5G6/2 dark grayish gray, pale green
67	18 July	390-400	10.0	10.35	104	Silty clay	Shark River	5G6/2 pale green
68	18 July	400-405	5.0	4.4	88	Silty clay with glauconite	Shark River	5G5/2 grayish green
69	18 July	405-410	5.0	5.1	102	Silty clay with glauconite	Shark River	5G5/2 grayish green
70	19 July	410-415	5.0	5.2	104	Silty clay with glauconite; glauconitic clay	Shark River	10GY5/2, 10Y6/2 greenish green, pale olive
71	19 July	415-420	5.0	5.7	114	Silty clay; glauconitic slightly sandy clay	Shark River	10Y6/2 pale olive
72	19 July	420-427	7.0	7.8	111	Glauconitic clay	Shark River	10Y6/2 pale olive
73	19 July	427-430	3.0	2.5	83	Indurated, heavily glauconitic clay; silty clay with glauconite; sequence boundary at 427.6 ft	Shark River	10Y6/2, 5Y6/3 pale olive
74	19 July	430-440	10.0	4	40	Clay with glauconite; glauconitic clay	Shark River	5Y6/2 light olive gray
75	19 July	440-443	3.0	3.35	112	Glauconitic clay grading to clayey glauconite sand	Shark River	5Y6/3 pale olive
76	20 July	443-450	7.0	6.5	93	Glauconitic clay and clayey glauconite sand; sequence boundaries at 443 and 446.7 ft; contact at 448.7 ft	Shark River/Manasquan	5GY4/1 dark greenish gray
77	20 July	450-460	10.0	10.4	104	Interbedded clay and silty clay	Manasquan	5G6/2 pale green
78	20 July	460-470	10.0	1.95	20	Slightly glauconitic silty clay; sequence boundary at 461.2 ft	Manasquan	5G5/1 greenish gray
79	21 July	470-480	10.0	9.2	92	Slightly glauconitic interbedded clay and silt	Manasquan	5GY5/1 greenish gray
80	21 July	480-490	10.0	10.2	102	Laminated; rippled silty clay	Manasquan	5GY5/1 greenish gray
81	21 July	490-498	8.0	6.9	86	Slightly glauconitic silty clay with some sand	Manasquan	5GY5/1 greenish gray
82	21 July	498-500	2.0	0	0			
83	21 July	500-508	8.0	7.3	91	Interbedded clay and silty clay	Manasquan	5GY4/1 dark greenish gray
84	22 July	508-515	7.0	1.25	18	Silty clay	Manasquan	5GY4/1 dark greenish gray

Table T1 (continued).

Run number	Date (1998)	Cored interval (ft)	Run length (ft)	Recovery (ft)	Recovery (%)	Primary lithology	Formation	Color
85	22 July	515-520	5.0	5.1	102	Silty clay; glauconitic silty clay; sequence boundary at 519.2 ft	Manasquan	5GY4/1 dark greenish gray
86	22 July	520-530	10.0	10.2	102	Clayey glauconite sand; very slightly glauconitic micaceous silty clay; contact at 522.2 ft	Manasquan/ Vincentown equivalent	N2.5, 5GY4/1 black, dark greenish gray
87	22 July	530-540	10.0	10	100	Micaceous silty clay	Vincentown equivalent	5GY4/1 dark greenish gray
88	23 July	540-550	10.0	5.5	55	Silty clay; convoluted clay	Vincentown equivalent	5GY4/1 dark greenish gray
89	23 July	550-560	10.0	10.15	102	Interbedded silty clay and clay	Vincentown equivalent	5GY5/1-6/1 greenish gray
90	23 July	560-570	10.0	10.3	103	Laminated silty clay to massive glauconitic, micaceous, sandy clayey silt	Vincentown equivalent	5GY5/1-6/1, 4GY4/1 greenish gray, dark greenish gray
91	23 July	570-580	10.0	10.4	104	Massive glauconitic, micaceous, sandy clayey silt	Vincentown equivalent	5GY4/1 dark greenish gray
92	24 July	580-585	5.0	5.1	102	Massive glauconitic, micaceous, sandy clayey silt	Vincentown equivalent	5GY4/1 dark greenish gray
93	24 July	585-590	5.0	5.4	108	Massive glauconitic, micaceous, sandy clayey silt	Vincentown equivalent	5GY4/1 dark greenish gray
94	24 July	590-595.5	5.5	5.5	100	Glauconitic clay	Vincentown equivalent	5GY4/1 dark greenish gray
95	24 July	595.5-600	4.5	4.9	109	Glauconitic clay to clayey glauconite sand; sequence boundary at 597.5 ft	Vincentown equivalent	5GY4/1 dark greenish gray
96	24 July	600-605	5.5	5.5	100	Glauconite sand; contact at 604.5 ft	Vincentown equivalent/ Hornerstown	5GY4/1 dark greenish gray
97	24 July	605.6-610	4.5	4.8	107	Glauconite sand	Hornerstown	N3 very dark gray
98	24 July	610-620	10.0	10.2	102	Glauconite sand; clayey glauconite sand; sequence boundary at 612.5 ft; contact at 618.1 ft	Hornerstown/Navesink	N3, 5GY4/1 very dark gray, dark greenish gray
99	24 July	620-630	10.0	10.4	104	Glauconite sand	Navesink	5GY4/1 dark greenish gray
100	25 July	630-635	5.0	5.1	102	Glauconite clay	Navesink	5GY4/1 dark greenish gray
101	25 July	635-640	5.0	5.25	105	Glauconite clay	Navesink	5GY4/1 dark greenish gray
102	25 July	640-650	10.0	10	100	Glauconite clay	Navesink	5GY4/1 dark greenish gray
103	25 July	650-660	10.0	10.1	101	Quartzose and glauconitic clayey sand; contact at 651.3 ft	Navesink/Mt. Laurel	N7 light gray
104	25 July	660-666	6.0	6.4	107	Quartzose and glauconitic clayey sand	Mt. Laurel	5Y6/3 pale olive
105	25 July	666-670	4.0	3.4	85	Quartzose and glauconitic clayey sand	Mt. Laurel	5Y6/3 pale olive
106	25 July	670-680	10.0	10	100	Quartzose sand	Mt. Laurel	5Y5/2 olive gray
107	25 July	680-690	10.0	9.8	98	Quartzose sand	Mt. Laurel	5Y5/2 olive gray
108	26 July	690-700	10.0	9.6	96	Slightly glauconitic clayey fine quartz sand	Mt. Laurel	5GY5/1 greenish gray
109	26 July	700-710	10.0	10.15	102	Slightly glauconitic clayey fine quartz sand	Mt. Laurel	5GY4/1 dark greenish gray
110	26 July	710-720	10.0	9.8	98	Glauconitic clayey fine quartz sand; slightly glauconitic sandy micaceous silt; contact at 718 ft	Mt. Laurel/Wenonah	5GY4/1, 5Y3/2 dark greenish gray, dark olive gray
111	26 July	720-730	10.0	10.5	105	Slightly glauconitic micaceous clay-silt	Wenonah	5Y3/1 very dark gray
112	26 July	730-740	10.0	10	100	Bioturbated, very silty clay	Wenonah	5Y3/1 very dark gray
113	26 July	740-750	10.0	10.2	102	Bioturbated, silty, glauconitic, clay; contact at 742 ft	Wenonah/Marshalltown	5Y3/1 very dark gray
114	27 July	750-759	9.0	8.5	94	Shelly, clayey glauconite sand, glauconitic clay, quartz sand; contact at 757.2 ft	Marshalltown/Englishtown	N3, N4 very dark gray, dark gray
Hole A coring totals:			759.00	693.82	91.4			
Hole B								
1	27 July	543-544	1.0	1.05	105	Micaceous clay, interbedded silty clay	Vincentown equivalent	5GY5/1 greenish gray
2	27 July	544-550	6.0	6.30	105	Laminated clay	Vincentown equivalent	5GY6/1 greenish gray
3	27 July	550-560	10.0	9.45	95	Laminated clay; convoluted bedding	Vincentown equivalent	5GY6/1 greenish gray
4	28 July	560-570	10.0	9.35	94	Laminated glauconitic micaceous silty clay	Vincentown equivalent	5GY5/1 greenish gray
5	28 July	570-580	10.0	10.40	104	Massive micaceous glauconitic silt	Vincentown equivalent	5GY4/1 dark greenish gray
6	28 July	580-590	10.0	10.25	103	Laminated micaceous glauconitic silt	Vincentown equivalent	5GY4/1 dark greenish gray
7	28 July	590-600	10.0	10.15	102	Glauconitic silt to silty glauconitic sand	Vincentown equivalent	5GY4/1, N2.5 dark greenish gray, black

Table T1 (continued).

Run number	Date (1998)	Cored interval (ft)	Run length (ft)	Recovery (ft)	Recovery (%)	Primary lithology	Formation	Color
8	28 July	600-610	10.0	10.40	104	Massive glauconitic sand; shell bed; contact at 604.5 ft	Vincentown equivalent/ Hornerstown	N2.5 black
9	28 July	610-620	10.0	10.10	101	Glauconite sand; contact at 618.1 ft	Hornerstown/Navesink	N2.5 black
10	28 July	620-630	10.0	9.30	93	Silty glauconite sand	Navesink	5GY4/1 dark greenish gray
11	30 July	630-640	10.0	10.30	103	Massive, burrowed glauconitic clay	Navesink	5GY4/1 dark greenish gray
12	30 July	640-650	10.0	10.50	105	Massive, burrowed glauconitic clay	Navesink	5GY4/1 dark greenish gray
13	30 July	650-660	10.0	10.05	101	Glauconitic clay; glauconitic clayey sand; contact at 651.3 ft	Navesink/Mt. Laurel	5GY4/1, 5GY5/1 dark greenish gray, greenish gray
14	30 July	660-670	10.0	8.40	84	Silty glauconitic fine to medium quartz sand	Mt. Laurel	5GY6/1 greenish gray
15	30 July	670-680	10.0	10.40	104	Silty glauconitic fine to medium quartz sand	Mt. Laurel	5GY5/1-6/1 greenish gray
16	30 July	680-690	10.0	9.75	98	Silty glauconitic fine quartz sand	Mt. Laurel	5GY5/1-4/1 greenish gray, dark greenish gray
17	30 July	690-700	10.0	9.76	98	Silty glauconitic fine quartz sand	Mt. Laurel	5GY4/1 dark greenish gray
18	31 July	700-710	10.0	9.90	99	Silty glauconitic fine quartz sand	Mt. Laurel	5GY4/1 dark greenish gray
19	31 July	710-720	10.0	10.60	106	Silty glauconitic fine quartz sand	Mt. Laurel/Wenonah	5GY4/1,10YR3/1 dark greenish gray, very dark gray
20	31 July	720-730	10.0	10.40	104	Silty glauconitic fine quartz sand	Wenonah	5Y3/1 very dark gray
21	31 July	730-740	10.0	9.90	99	Silty glauconitic fine quartz sand	Wenonah	5Y3/1 very dark gray
22	31 July	740-750	10.0	10.50	105	Clayey glauconite sand; contact at 742 ft	Wenonah/Marshalltown	5Y2/1 black
23	31 July	750-760	10.0	10.00	100	Glauconite sand; glauconitic clay; glauconitic quartz sand; contact at 757.2 ft	Marshalltown/upper Englishtown	N2.5, 2.5Y3/1, 2.5Y5/2 black, very dark gray, grayish brown
24	31 July	760-761.5	1.5	1.40	93	Glauconitic quartz sand	upper Englishtown	2.5Y5/2 grayish brown
25	1 Aug	761.5-770	8.5	9.50	112	Quartz sand and sandy silt	upper Englishtown	2.5Y5/2 grayish brown
26	1 Aug	770-780	10.0	10.30	103	Micaceous slightly sandy silt	upper Englishtown	N2.5 black
27	1 Aug	780-790	10.0	9.90	99	Sandy silt and glauconitic clay	upper Englishtown	N2.5 black
28	1 Aug	790-800	10.0	10.40	104	Glauconitic clay and micaceous clay; contact at 792.3 ft (upper/lower Englishtown Formation); contact at 797.6 ft (lower Englishtown/ Woodbury Formation)	upper Englishtown/lower Englishtown/Woodbury	N2.5 black
29	1 Aug	800-810	10.0	10.40	104	Micaceous clay	Woodbury	N3 very dark gray
30	1 Aug	810-820	10.0	9.90	99	Micaceous clay	Woodbury	N3 very dark gray
31	1 Aug	820-830	10.0	9.30	93	Micaceous clay	Woodbury	N3 very dark gray
32	2 Aug	830-840	10.0	0.20	2	Micaceous clay	Woodbury	N3 very dark gray
33	2 Aug	840-850	10.0	10.50	105	Micaceous clay	Woodbury	N3 very dark gray
34	2 Aug	850-860	10.0	10.40	104	Micaceous clay	Woodbury	N3 very dark gray
35	2 Aug	860-870	10.0	10.30	103	Micaceous clay	Woodbury	N3 very dark gray
36	5 Aug	870-880	10.0	10.70	107	Micaceous clay	Woodbury	N4/N3 dark-very dark gray
37	5 Aug	880-890	10.0	10.20	102	Micaceous clay	Woodbury	N3 very dark gray
38	5 Aug	890-900	10.0	10.60	106	Micaceous clay; micaceous glauconitic clay	Woodbury	N3-N2.5 black
39	5 Aug	900-910	10.0	10.20	102	Micaceous glauconitic clay; very glauconitic clay; contact at 904.4 ft	Woodbury/Merchantville	N3-N2.5 black
40	5 Aug	910-920	10.0	10.30	103	Glauconitic clay to clayey glauconite sand	Merchantville	N3 very dark gray
41	6 Aug	920-930	10.0	10.10	101	Glauconitic clay to clayey glauconite sand	Merchantville	N3 very dark gray
42	6 Aug	930-931.2	1.2	1.27	106	Glauconitic clay to clayey glauconite sand	Merchantville	N3 very dark gray
43	6 Aug	931.2-933.9	2.7	2.90	109	Indurated clayey glauconite sand	Merchantville	5Y3/2 dark olive gray
44	6 Aug	933.9-940	6.1	6.30	103	Clayey glauconite sand	Merchantville	5Y3/2 dark olive gray
45	6 Aug	940-950	10.0	10.00	100	Clayey glauconite sand; silty medium to fine quartz sand; contact at 945.3 ft	Merchantville/ Cheesequake	5Y3/1, 5Y3/2 very dark gray, dark olive gray
46	6 Aug	950-960	10.0	9.60	96	Clayey quartz sand; glauconitic quartz sand; silt; coarse to very coarse quartz sand; contact at 957.4	Cheesequake/Magothy	5Y3/1, 5Y6/1 very dark gray, gray
47	6 Aug	960-964.5	4.5	3.00	67	Very coarse gravelly sands	Magothy	5Y6/1 gray

Table T1 (continued).

Run number	Date (1998)	Cored interval (ft)	Run length (ft)	Recovery (ft)	Recovery (%)	Primary lithology	Formation	Color
48	7 Aug	964.5-970	5.5	5.10	93	Very coarse gravelly sands	Magothy	5Y6/1 gray
49	7 Aug	970-980	10.0	7.70	77	Laminated silty clay	Magothy	10YR4/1 dark gray
50	7 Aug	980-990	10.0	4.90	49	Laminated silty clay	Magothy	10YR5/1 gray
51	7 Aug	990-1000	10.0	9.45	95	Medium to coarse sand	Magothy	10YR7/1 light gray
52	7 Aug	1000-1010	10.0	8.40	84	Medium to coarse sand	Magothy	10YR7/1 light gray
53	8 Aug	1010-1020	10.0	6.60	66	Medium to coarse sand	Magothy	10YR7/1 light gray
54	8 Aug	1020-1027	7.0	5.10	73	Medium sand and coarse gravelly sand	Magothy	10YR7/1 light gray
55	8 Aug	1027-1034	7.0	2.00	29	Medium sand and coarse gravelly sand	Magothy	2.5Y7/1 light gray
56	8 Aug	1034-1040	6.0	2.70	45	Medium sand and coarse gravelly sand	Magothy	2.5Y5/1 gray
57	8 Aug	1040-1045	5.0	3.90	78	Medium sand and coarse gravelly sand	Magothy	2.5Y7/1 light gray
58	8 Aug	1045-1050	5.0	3.70	74	Medium sand and coarse gravelly sand	Magothy	2.5Y5/1 gray
59	9 Aug	1050-1060	10.0	8.60	86	Pebbly coarse quartz sand; fine to medium quartz sand	Magothy	2.5Y7/1 light gray
60	9 Aug	1060-1070	10.0	9.50	95	Micaceous chloritic clays with pebbles at top; contact at 1062.5 ft	Magothy/Bass River	2.5Y2.5/1 black
61	9 Aug	1070-1080	10.0	7.30	73	Micaceous chloritic clays, abundant shells	Bass River	2.5Y2.5/1 black
62	9 Aug	1080-1082.5	2.5	2.60	104	Micaceous chloritic clays, abundant shells; sequence boundary at 1082.5 ft	Bass River	2.5Y2.5/1 black
63	9 Aug	1082.5-1090	7.5	7.40	99	Indurated sand, clayey sand; clay	Bass River	2.5Y3/1 very dark gray
64	9 Aug	1090-1095	5.0	5.60	112	Sandy micaceous clay	Bass River	2.5Y2.5/1 black
65	10 Aug	1095-1100	5.0	5.25	105	Siltstone; very micaceous silty clay	Bass River	N4 dark gray
66	10 Aug	1100-1107.5	7.5	7.75	103	Micaceous silty clay; glauconitic at base	Bass River	N4 dark gray
67	10 Aug	1107.5-1116	8.5	8.85	104	Indurated siltstone; shelly glauconitic sand; laminated shelly clay; sequence boundary at 1110.9 ft	Bass River	N4, 5GY4/1, 10YR3/1 dark gray, dark greenish gray, very dark gray
68	10 Aug	1116-1120	4.0	4.20	105	Laminated shelly clay	Bass River	2.5Y3/1 very dark gray
69	10 Aug	1120-1130	10.0	10.40	104	Shelly, laminated to cross-bedded glauconitic silt to silty clay	Bass River	2.5Y3/1 very dark gray
70	10 Aug	1130-1132	2.0	1.80	90	Shelly, laminated to cross-bedded glauconitic silt to silty clay	Bass River	N4/ dark gray
71	10 Aug	1132-1140	8.0	9.00	113	Shelly micaceous clayey silt to silty clay	Bass River	5GY4/1, 2.5Y4/1 dark greenish gray, dark gray
72	11 Aug	1140-1146	6.0	6.10	102	Micaceous silty clay; shelly clayey glauconite sand	Bass River	N3, 5GY4/1 very dark gray, dark greenish gray
73	11 Aug	1146-1150	4.0	3.20	80	Indurated glauconite sandstone; shelly quartz sand; contact at 1148.1 ft	Bass River/Potomac	N3, 5GY4/1 with 10YR3/2 very dark gray, dark greenish gray with very dark grayish brown
74	11 Aug	1150-1157	7.0	7.30	104	Variegated clays, sands, and glauconitic clay; ?sequence boundary at 1154.5 ft	Potomac	Various greenish, brownish, dark, light grays
75	11 Aug	1157-1161	4.0	3.30	83	Indurated clayey sand, kaolinitic clay, cross-bedded clayey sand; sequence boundary at 1158.2 ft	Potomac	10YR4/3, 10YR5/1 brown, gray
76	11 Aug	1161-1170	9.0	8.90	99	Lignitic cross-bedded sand, laminated clay	Potomac	Various; mostly brownish gray
Hole B coring totals:			627.00	591.48	94.3			
Ancora Site coring totals:			1386.00	1285.30	92.7			

Table T2. Sr isotopic data, Ancora Site.

Sample depth (ft)	Sample depth (m)	$^{87}Sr/^{86}Sr$ ratio	Analytical error (2σ)	Age (Ma)	Age* (Ma)
243.0	74.07	0.708475	0.000027	20.2	
255.0	77.72	0.708425	0.000008	20.9	
263.0	80.16	0.708407	0.000006	21.2	
645.0	196.60	0.707820	0.000010	67.3	66.2
649.2	197.88	0.707802	0.000004	68.3	67.4
653.1	199.06	0.707749	0.000005	71.1	70.8
659.5	201.02	0.707728	0.000005	72.2	71.6
666.5	203.15	0.707726	0.000013	72.3	71.7
676.4	206.17	0.707713	0.000005		72.1
681.5	207.72	0.707698	0.000006		72.6
713.8	217.57	0.707676	0.000005		73.3
740.5	225.70	0.707792	0.000007		(68.2)
750.8	228.84	0.707674	0.000022		73.4
776.7	236.74	0.707753	0.000004		(70.6)
863.5	263.19	0.707584	0.000005		77.4
892.1	271.91	0.707657	0.000004		(74.0)
932.1	284.10	0.707554	0.000022		79.1
1104.9	336.77	0.707507	0.000005		(82.2)
1144.2	348.75	0.707444	0.000008		(85.0)

Note: * = Howarth and McArthur (1997).

Table T3. Cretaceous nannofossil zones, Ancora Site.

Zone/Subzone	Age (Gradstein et al., 1995)	Base definition	Top definition	Interval (ft [m])
CC26 *Nephrolithus frequens*[1]	latest Maastrichtian	LO *Nephrolithus frequens*	HO *Nephrolithus frequens*	618.1–631.1 (188.40–192.36)
CC26b[5]		LO *Micula prinsii*	HO *Nephrolithus frequens*	
CC26a[5]		LO *Nephrolithus frequens*	LO *Micula prinsii*	
CC25 *Arkhangelskiella cymbiformis*[2]	late Maastrichtian	HO *Reinhardtites levis*	LO *Nephrolithus frequens*	631.1–651.3 (192.36–198.52)
CC25c[5]		LO *Micula murus*	LO *Nephrolithus frequens*	631.1–indet. (192.36–indet.)
CC25b[5]		LO *Lithraphidites quadratus*	LO *Micula murus*	indet.–647.8 (indet.–197.45)
CC25a[5]		HO *Reinhardtites levis*	LO *Lithraphidites quadratus*	647.8–651.3 (197.45–198.52)
CC24 *Reinhardtites levis*[3]	late Maastrichtian	HO *Tranolithus phacelosus*	HO *Reinhardtites levis*	not present
CC23 *Tranolithus phacelosus*[2]	late Campanian to early Maastrichtian	HO *Reinhardtites anthophorus*	HO *Tranolithus phacelosus*	651.3–indet. (198.52–indet.)
CC22 *Quadrum trifidum*[2]	late Campanian	LO *Quadrum trifidum*	HO *Reinhardtites anthophorus*	indet.–709.5 (indet.–216.26)
CC22a[5]		LO *Quadrum trifidum*	HO *Lithastrinus grillii*	678.8–709.5 (206.90–216.26)
CC21 *Quadrum sissinghii*[3]	middle to late Campanian	LO *Quadrum sissinghii*	LO *Quadrum trifidum*	709.5–753.5 (216.26–229.67)
CC20 *Ceratolithoides aculeus*[3]	middle Campanian	LO *Ceratolithoides aculeus*	LO *Quadrum sissinghii*	753.5–759.5 (229.67–231.50)
CC19 *Calculites ovalis*[2]	early to middle Campanian	HO *Marthasterites furcatus*	LO *Ceratolithoides aculeus*	759.5–903.0 (231.50–275.23)
CC18 *Aspidolithus parcus*[2]	early Campanian	LO *Aspidolithus parcus*	HO *Marthasterites furcatus*	903.0–918.5 (275.23–279.96)
CC17 *Calculites obscurus*[2]	latest Santonian	LO *Calculites obscurus*	LO *Aspidolithus parcus*	918.5–940.5 (279.96–286.66)
CC16 *Lucianorhabdus cayeuxii*[2]	middle to late Santonian	LO *Lucianorhabdus cayeuxii*	LO *Calculites obscurus*	not identified
CC15 *Reinhardtites anthophorus*[2]	early Santonian	LO *Reinhardtites anthophorus*	LO *Lucianorhabdus cayeuxii*	not identified
CC14 *Micula staurophora*[2]	late Coniacian	LO *Micula staurophora*	LO *Reinhardtites anthophorus*	not identified
CC13 *Marthasterites furcatus*[2]	latest Turonian to late Coniacian	LO *Marthasterites furcatus*	LO *Micula staurophora*	not identified
CC12 *Lucianorhabdus maleformis*[2]	middle to late Turonian	LO *Lucianorhabdus maleformis*	LO *Marthasterites furcatus*	not identified
CC11 *Tetralithus pyramidus*[2]	early to middle Turonian	LO *Quadrum gartneri*	LO *Lucianorhabdus maleformis*	not identified
Parhabdolithus asper[4]	late Cenomanian to early Turonian	HO *Axopodorhabdus albianus*	HO *Parhabdolithus asper*	1074.5–1076.4 (327.51–328.09)
Eiffellithus eximius Subzone[4]	early Turonian	HO *Microstaurus chiastius*	HO *Parhabdolithus asper*	not identified
Microstaurus chiastius Subzone[4]	late Cenomanian	HO *Axopodorhabdus albianus*	HO *Microstaurus chiastius*	1074.5–1076.4 (327.51–328.09)
Axopodorhabdus albianus[4]	late Cenomanian	LO *Vagalapilla octoradiata*	HO *Axopodorhabdus albianus*	1076.4–1146.7 (328.09–349.51)
CC10 *Microrhabdulus decoratus*[2]	early to late Cenomanian	LO *Microrhabdulus decoratus*	LO *Quadrum gartneri*	1074.5–1128.5 (327.51–343.97)
CC10b[5]		HO *Microstaurus chiastius*	LO *Quadrum gartneri*	1074.5–1101.7 (327.51–335.80)
CC10a[5]		LO *Microrhabdulus decoratus*	HO *Microstaurus chiastius*	1101.7–1128.5 (335.80–343.97)
CC9 *Eiffellithus turriseiffelii*[2]	late Albian to early Cenomanian	LO *Eiffellithus turriseiffelii*	LO *Microrhabdulus decoratus*	1128.5–1150.3 (343.97–350.61)

Notes: 1 = Cepek and Hay (1969), 2 = Sissingh (1977), 3 = Sissingh (1977) modified by Perch-Nielsen (1985), 4 = Bralower (1988), 5 = Perch-Nielsen (1985); LO = lowest occurrence, HO = highest occurence; indet. = indeterminate.