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3. BETHANY BEACH SITE[1]

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SECTION AUTHORSHIP

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Biostratigraphy:
Spores, pollen, and dinocysts: McLaughlin
Planktonic foraminifers: Benson, Browning, McLaughlin
Benthic foraminifers: Benson, Browning, Hernandez, McLaughlin
Calcareous nannofossils: Aubry
Radiolarians: Benson
Diatoms: Benson
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SITE SUMMARY

The Bethany Beach borehole was drilled in May and June 2000 as the seventh onshore site of the Coastal Plain Drilling Project and fourth site of Ocean Drilling Program (ODP) Leg 174AX, complementing shelf

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drilling during Leg 174A. Drilling at Bethany Beach targeted Miocene sequences at a point where they reach their maximum regional thickness onshore (i.e., the depocenter of the Salisbury Embayment). Recovery was very good (mean recovery = 80%), and a full suite of slimline logs was obtained from the surface to 205 ft and from the surface to total depth of 1470 ft (448.06 m) in mid-Oligocene sediments. A team of scientists from the Delaware Geological Survey (DGS), Rutgers University, the New Jersey Geological Survey (NJGS), and the U.S. Geological Survey (USGS) collaborated in drilling and stratigraphic studies of the borehole, which was funded by the National Science Foundation (NSF, Earth Science Division, Continental Dynamics Program), DGS, and USGS.

Sequence-bounding unconformities were identified on the basis of physical stratigraphy, including irregular contacts, reworking, bioturbation, major facies changes, gamma ray peaks, and paraconformities inferred from biostratigraphic and Sr isotopic breaks. Miocene sections in Delaware lack the clear deltaic influence seen in coeval sections in New Jersey; however, they still comprise generally thin transgressive systems tracts (TSTs) and thick highstand systems tracts (HSTs), with lowstand systems tracts (LSTs) generally absent. The overall association of facies suggests that most of the Bethany Beach Miocene section fits a wave-dominated shoreline model, with fluvial to upper estuarine, lower estuarine, upper shoreface/foreshore, distal upper shoreface, lower shoreface, and offshore (including inner and middle neritic) environments represented.

The Pleistocene (5–52.9 ft; 1.52–16.12 m) Omar Formation is interpreted to include two marginal-marine sequences. The upper sequence comprises a transgressive succession composed of marsh-lagoon-tidal delta sediments that probably correlates with marine isotopic Stage 5 (5.0–50.65 ft; 1.52–15.44 m). The lower sequence is a thin estuarine clay of uncertain age (50.65–52.9 ft; 15.44–16.12 m). The underlying Beaverdam Formation (52.9–117.5 ft; 16.12–35.81 m) consists of quartz sand, some gravelly sand, and subordinate silty clay, deposited primarily in fluvial and estuarine environments; the base of this formation at Bethany Beach represents estuarine(?) environments. The Beaverdam Formation contains two surfaces that may represent sequence-bounding unconformities or facies shifts in fluvial environments. The unit is poorly dated but apparently is Pliocene (possibly upper Miocene) as suggested by the presence of exotic pollen.

The informal Bethany formation (117.5–197.4 ft; 35.81–60.17 m) is characterized by interbedded sands and clays deposited in lower shoreface to estuarine environments. Pollen studies place this unit in the upper Miocene or Pliocene. Whereas the Bethany formation comprises one definite sequence at Bethany Beach, it can be subdivided by two additional surfaces (150.6 and 185.6 ft; 45.90 and 56.57 m), though the significance of these surfaces as unconformities vs. autocyclical facies shifts is unclear.

The informal Manokin formation is primarily an upper Miocene sand that can be divided into three sequences: (1) the upper sequence (197.4–294.1 ft; 60.17–89.64 m) is fine to medium sand deposited in lower shoreface or estuarine environments; (2) the medial sequence (294.1–374 ft; 89.64–114.0 m [N1]) coarsens upward from fine to medium sands, comprising a thick succession of regressive distal upper shoreface deposits; and (3) the lower sequence (374–452.45 ft; 114.0–137.91 m), which extends into the top of the underlying St. Marys Formation, coarsens upsection from offshore silty sands to lower shoreface sands. Transgressive systems tracts are very thin in these sequences.

The St. Marys Formation (449.4–575.2 ft; 136.98–175.32 m) is a silty clay to clayey silt deposited in offshore inner to middle neritic (25–75 m) paleodepths. In addition to the sequence spanning the St. Marys and Manokin Formations, it can be broken into two distinct sequences (452.45–523.05 and 523.05–575.2 ft; 137.91–159.43 and 159.43–175.32 m) that were starved of sand input; lithostratigraphic successions show minimal changes, but benthic foraminiferal biofacies show evidence of moderate shallowing upsection.

The Choptank Formation (575.2–819.9 ft; 175.32–249.91 m) is a sandier unit than the immediately overlying and underlying formations and is characterized as interbedded fine to coarse sand, shell, silt, and some clay. At Bethany Beach, it can be divided into four sequences: (1) the upper sequence (575.2–649 ft; 137.91–197.82 m) is comprised of a regressive fine to coarse sand deposited in lower shoreface to upper shoreface environments; (2) the medial sequence (649–698.5 ft; 197.82–212.90 m) grades down from a granuliferous sand to a silt, representing a regression from lower shoreface to upper shoreface/estuarine environments; (3) the lower sequence (698.5–787.1 ft; 212.90–239.91 m) consists of a thick regressive HST in lower shoreface environments, a zone of maximum flooding in offshore environments, and a thick TST in upper to lower shoreface environments; and (4) the basal Choptank Formation (787.1–819.9 ft; 239.91–249.91 m) comprises the upper HST of a sequence spanning the Choptank/Calvert Formation boundary and includes sands of the locally important Milford aquifer. This uppermost Calvert–lowermost Choptank sequence shows a classic pattern of thin basal TST, thick medial lower HST silts, and upper HST sands at the top.

The Calvert Formation (819.9–1420 ft; 249.91–732.82 m) comprises interbedded silt, sand, and clay with common shells that can be broken into distinct sequences: (1) the lower part (819.9–897.7 ft; 249.91–273.62 m) of the sequence spanning the Choptank/Calvert Formation boundary includes the lower HST (819.9–887.7 ft; 249.91–270.57 m) and a thin TST (887.7–897.7 ft; 270.57–273.62 m); (2) the sequence from 897.7 to 981.3 ft (273.62 to 299.10 m) is composed of at least three shallowing-upward parasequences in offshore to upper shoreface environments; (3) the sequence from 981.3 to 1057.95 ft (299.10–322.46 m) comprises a classic thin lower shoreface-offshore TST and thick coarsening-upward HST representing deposition in lower to upper shoreface environments; (4) the sequence from 1057.95 to 1153 ft (322.46–351.43 m) sequence is predominantly a lower HST silt with a fine sand upper HST deposited in lower shoreface environments; and (5) a very thick sequence from 1153 to 1421.1 ft (351.43 to 433.15 m) is composed of thick coarse sands deposited in upper shoreface environments (upper HST), a medial silty sand to silt (lower HST) deposited primarily in offshore to lower shoreface environments, a very thin basal TST; the sandy upper HST portion of the sequence correlates to the Cheswold sand aquifer updip.

An unnamed lowermost Miocene glauconitic clay comprises the base of the sequence down to 1421.1 ft (433.15 m); below this, it may be divided into three thin sequences: an upper sequence from 1421.1 to 1430.5 ft (433.15 to 436.02 m), a middle sequence from 1430.5 to 1454.5 ft (436.02 to 443.33 m), and a lower sequence from 1454.5 to 1465.7 ft (443.33 to 446.75 m). An unnamed Oligocene foraminiferal clay was penetrated in the base of the borehole (1465.7–1467.95 ft; 446.75–447.43 m).

Our initial studies of the Bethany Beach borehole provide important findings in three areas of study:

1. Sequence Ages. One of the primary goals of the study was to date sequences identified in the borehole. Sequences above 375 ft (114.3 m) are poorly dated because of the general absence of carbonate fossils. Abundant shell material below 375 ft (114.3 m) provided Sr isotopic age estimates for 11 or 12 Miocene sequences. Especially important are the dates on upper middle Miocene and younger sequences. Based on Sr isotopes and sedimentation rate estimates, the lower Manokin sequence is estimated as 8.8–10.2 Ma and two St. Marys Formation sequences are dated as 10.2–10.6 and 11.6–11.9 Ma. The latter correlates with the Kw-Cohansey sequence in New Jersey; the former provides the first firm dates on onshore sequences straddling the middle/upper Miocene boundary.

   The Sr isotopic ages in the older Miocene sequences allow us to evaluate regional differences in sedimentation and possible tectonic controls. The middle to lower Miocene section is very thick at Bethany Beach and provides an excellent comparison to the more upbasin locations drilled during Legs 150X and 174AX in New Jersey. Equivalents of the Kw3, Kw2c, Kw2b, Kw2a, Kw1c, and Kw1a sequences are represented at Bethany Beach, although the sequences are generally thicker and sedimentation rates are higher in Delaware. Sedimentation rates were 37–59 m/m.y. (mean = 53 m/m.y.) at Bethany Beach from 9.8 to 18.8 Ma and 136 m/m.y. from 20.2 to 20.8 Ma. In contrast, sedimentation rates at the thickest Miocene section in New Jersey, Cape May, were 29–47 m/m.y. (mean = 40 m/m.y.) from 11.5 to 20.2 Ma and 91 m/m.y. from 20.2 to 20.6 Ma. Nevertheless, thickness does not equate with stratigraphic continuity; the New Jersey record is much more complete in the early part of the early Miocene (19–23.8 Ma) with the Kw1b and Kw0 sequence apparently missing in Delaware. The Delaware section is more complete in the late part of the early Miocene (~19–16.2 Ma), with one sequence (18.0–18.4 Ma) not represented in New Jersey. The upper part of the upper Oligocene and the lowermost Miocene (~27–21 Ma) are also absent at Bethany Beach, due to truncation.
2. Sediment Supply. Facies recovered from the thick Miocene section at Bethany Beach are noticeably different in many aspects than coeval sections in New Jersey, in part reflecting differences in sediment supply and/or tectonics. For example, silts are predominant in the medial parts of the Delaware sequences and there is a paucity of clays; in contrast, thick silty clays predominate in the medial parts of Miocene sequences in New Jersey. The strong deltaic influence noted in New Jersey is largely absent in Delaware, where wave-dominated shoreline facies models are applicable.
3. Sequence Expression. Despite fundamentally different sedimentary regimes (wave-dominated shorelines in Delaware vs. deltaic systems in New Jersey), both regions share a similar sequence stratigraphic signature for the Miocene. LSTs are largely absent, and thus transgressive surfaces are usually merged with sequence boundaries. TSTs are present at the base of some sequences but

> are thin. HSTs can generally be broken into a lower fine-grained unit (silty clay in New Jersey, generally silts in Delaware) and an upper sandy unit. The upper HST sands comprise important aquifers in both regions that are generally confined by the overlying lower HST. Aside from these similarities, there are important sequence stratigraphic differences between regions. Maximum flooding surfaces (MFSs) identified in the Bethany Beach borehole show much greater evidence for erosion than MFSs in New Jersey, whereas sequence boundaries are often more subtle in Delaware, due to juxtaposition of similar facies.

The Bethany Beach borehole thus provides (1) excellent recovery, delineation, and dating of 11 or 12 lowermost upper Miocene to lower Miocene sequences; (2) constraints on the differential development of sequences during the Icehouse (glacioeustatic) world of the Miocene, due to processes of tectonics and sedimentation; and (3) new information on the hydrostratigraphy of important aquifers and confining units in southern Delaware.

BACKGROUND AND OBJECTIVES

The Bethany Beach borehole was the seventh continuously cored and logged onshore hole drilled as part of the Middle Atlantic Coastal Plain Drilling Project and the fourth drilled as part of ODP Leg 174AX. Drilling began in 1993 with ODP Leg 150 on the New Jersey (NJ) continental slope (Mountain, Miller, Blum, et al., 1994) as part of the New Jersey/Mid-Atlantic Sea-Level Transect (Miller and Mountain, 1994). The primary goal of the transect was 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 (Miller and Mountain, 1994). During Leg 150, four sites were drilled on the NJ continental slope, providing a preliminary framework of sequence chronology for the Oligocene–Miocene of the region (Mountain, Miller, Blum, et al., 1994).

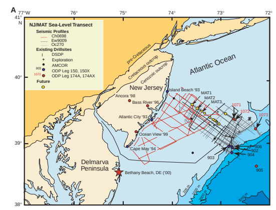
Concurrent with and subsequent to Leg 150, a complementary drilling program designated Leg 150X was undertaken to core coeval strata onshore in NJ. This drilling was designed not only to provide additional constraints on Oligocene–Holocene sequences but also to address an important goal not resolvable by shelf and slope drilling: to document the ages and nature of middle Eocene and older "Greenhouse" sequences, a time when mechanisms for sea level change are poorly understood (Miller et al., 1991). Sites were drilled at Island Beach (March–April 1993), Atlantic City (June–August 1993), and Cape May (March–April 1994) (Miller et al., 1994a, 1994b, 1996a; Miller, Newell, and Snyder, 1997). Together, Legs 150 and 150X were extremely successful in dating Eocene–Miocene sequences, correlating them to the $\delta^{18}O$ proxy for glacioeustasy, and causally relating sequence boundaries to glacioeustatic falls (Miller et al., 1996b, 1998a).

During Leg 174A, the Mid-Atlantic Transect was continued by drilling between previous slope and onshore sites, targeting the NJ continental shelf (Austin, Christie-Blick, Malone, et al., 1998). The Joint Oceanographic Institutes (JOI) planning committee endorsed a subsequent phase of onshore drilling as an ODP-related activity and designated the program ODP Leg 174AX. As part of this leg, sites were drilled at

1. Bass River, NJ (October–November 1996) (Miller et al., 1998b), targeting Upper Cretaceous to Paleocene strata poorly sampled during Leg 150X;
2. Ancora, NJ (July–August 1998) (Miller et al., **Chap. 1,** this volume), an updip, less deeply buried Cretaceous–Paleocene section complimentary to Bass River;
3. Ocean View, NJ (September–October 1999) (Miller et al., **Chap. 2,** this volume), targeting upper Miocene–middle Eocene sequences; and
4. Bethany Beach, Delaware (DE).

The Bethany Beach borehole extended the drilling transect along strike and down dip into the depocenter of the Salisbury Embayment (Fig. **F1**), with the goals of verifying the ages and regional significance of sequences, evaluating tectonic and sediment supply effects on sedimentation patterns, and testing models of sedimentation within sequences. The depocenter of the Salisbury Embayment extends into the central part of the Delmarva Peninsula, making Bethany Beach an ideal site to drill Miocene sequences where they reach their maximum regional thickness onshore and where the marine influence is greatest. The Bethany Beach borehole provides a more down-dip location for defining and dating sequences in the very thick Miocene section of the Salisbury Embayment. We were able to date 11–12 Miocene sequences at Bethany Beach ranging from 20.8 to 9.8 Ma. The well-dated sequence stratigraphic record from Bethany Beach provides material needed for future studies addressing the control of sea level, tectonics, and sediment supply on sequence stratigraphic architecture, in addition to local aquifer potential.

F1. Location maps, p. 55.



1. Sea Level. Previous drilling onshore in NJ has not provided a readily datable record of the late Miocene to Pliocene; hence, all attempts at reconstructing a sea level record younger than 12 Ma in NJ have been limited. The Delmarva region contains thicker, more marine, and more fossiliferous upper Miocene–Pliocene sections (e.g., Ward and Blackwelder, 1980; Olsson et al., 1987) than coeval estuarine to marginal marine strata in NJ. In addition, lower to middle Miocene sequences in near Bethany Beach are thicker than previously drilled sections in NJ and should represent deeper marine facies than the coeval NJ sections.

   Recovery of a thick, well-dated Miocene section at Bethany Beach provides material needed to derive a sea level estimate via backstripping that can be compared with backstripped records from other areas. Backstripping is a proven method for extracting amplitudes of global sea level from passive margin records (e.g., Steckler and Watts, 1978). One-dimensional backstripping progressively removes the effects of sediment loading (including the effects of compaction), eustasy, and paleowater depth from basin subsidence to obtain tectonic subsidence. By modeling thermal subsidence on a passive margin, the tectonic portion of subsidence can be assessed and a eustatic estimate obtained (Kominz et al., 1998). Backstripping requires relatively precise ages, paleodepths, and porosities of sediments, and these data are being collected from Bethany Beach. Backstripped estimates from Bethany Beach will be compared with eustatic estimates derived from NJ backstripped records (Kominz et al., 1998) and global $\delta^{18}O$ records (Miller et al., 1998a).

2. Tectonics. Understanding stratigraphic contrasts between Bethany Beach and the areas previously drilled in NJ is critical for assessing tectonic effects. The thickest Cenozoic section in the region is present in the Salisbury Embayment just south of Bethany Beach near the Delaware/Maryland border (Fig. **F1B**) (Olsson et al., 1988). Whereas NJ is technically part of the same basin as the Salisbury Embayment, some differential movement between the two regions is required to explain the stratigraphic contrasts (Benson, 1994). For example, the differences between thick marine upper Neogene sequences in Delmarva and coeval thin nonmarine sequences in NJ require excess accommodation space in the Delmarva region (Owens and Gohn, 1985). Backstripping of records from New Jersey well sites and Bethany Beach will provide a baseline for comparison of sections between the two regions and evaluation of tectonic influences vs. sea level changes on sequence expression.
3. Sequence Architecture and Sediment Supply. Comparison of Miocene sequences from Bethany Beach with those in NJ will allow evaluation of facies models and the effects of differences in sediment supply and sedimentary environment on sequence architecture. Miocene sequences of New Jersey reflect a strong deltaic influence on sedimentation that is lacking at Bethany Beach, and Miocene sedimentation rates are higher than those sampled in NJ. Despite these differences, drilling at Bethany Beach demonstrates that both areas display similar sequence architecture. Sequence boundaries are typically coincident with transgressive surfaces and are expressed as the flooding of marine clays over deltaic sands. As a result, LSTs are largely absent and TSTs are present at the base of nearly all sequences but are thin. Sequences are predominantly regressive HST successions. Nevertheless, this study has revealed important differences in sequence stratigraphic architecture between these two areas. For example, in NJ HSTs consist of a lower prodelta silty clay and an upper delta front/nearshore sandy unit vs. typical medial offshore silts and upper shoreface sands in Delaware. An understanding of similarities and differences in the expression of sequences between NJ and Bethany Beach will help differentiate the influences of sediment supply and tectonics on sequence stratigraphy.

Comparison of NJ boreholes and the Bethany Beach site will also provide a north-south transect that will allow an evaluation of the effects of regional vs. local sediment supply and regional climate change on sedimentation in this region. Poag and Sevon (1989) documented that offshore depocenters have remained near their present locations during the Cenozoic, implying that there was no major shift in the number of major riverine systems; however, stream capture and avulsion have strongly influenced the local position of fluvial systems. Poag and Sevon (1989) and Pazzaglia (1993) ascribed the Oligocene to Miocene margin transformation to changes in sediment supply linked to hinterland uplift (central Appalachian). They emphasized that the largest increase in sedimentation from the continental shelf to the rise occurred in the middle Miocene, although it is clear that sediment supply increased in the NJ region by the Oligocene (Miller et al., 1997) or even the late

Eocene (Pekar et al., 2000). The ascription of progradation to hinterland tectonics requires that sediment input increased overall across the region at about the same time. Drilling at Bethany Beach will determine if the timing of increased sediment supply in this region was the same as in NJ.

4. Local Lithostratigraphy and Aquifer Stratigraphy. Drilling at Bethany Beach was impelled by another major objective: to provide a more complete understanding of the geological history of the sediments underlying southern Delaware, with a special attention to the aquifers of this rapidly growing area. The Delaware Geological Survey partially funded direct drilling costs for the Bethany Beach borehole with these goals in mind. The lithostratigraphy of the near-surface units of coastal Sussex County, Delaware, is complicated by significant lateral facies changes. Because previous studies have been based principally on geophysical log data, the Bethany Beach hole will provide valuable core data to better understand the depositional history of the area. The site will provide a valuable stratigraphic reference section for the Neogene of the Delaware Coastal Plain and help formalize the stratigraphic nomenclature of the shallow section. In addition, it will allow us to establish a sequence stratigraphic framework that can be compared with that of adjacent states. In particular, the findings should improve our understanding of the hydrogeology of the locally important Pocomoke and Manokin aquifers, especially in delineating the distribution of fresh- and saline-water zones deeper in the subsurface.

Summary

Comparison of the Bethany Beach borehole with previous drilling results from ODP Legs 150, 150X, 174A, and 174AX provides a means of evaluating global, regional, and local controls on the stratigraphic record. Cognizant of this, 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, the New Jersey Geological Survey, and the Delaware Geological Survey.

OPERATIONS

Drilling at Bethany Beach, DE (38°32′53″N, 75°03′45″W; elevation = 4.6 ft [1.4 m]; Bethany Beach quadrangle, Sussex County) began in May 2000. Drilling operations were superintended by Gene Cobbs, USGS Eastern Earth Surface Processes Team (EESPT; Don Queen, Head Driller; Jean Self-Trail, Drilling Coordinator); Gene Cobbs III was the driller and Manuel Canabal and Matthew Smith were the assistant drillers. The Delaware National Guard (DNG) provided space, water, and electricity at the Bethany Beach Training Site (Lt. Colonel Rhoads, DNG Commander, CWO4 Perry, Post Administrator). On 12 May 2000, the EESPT drillers arrived onsite and began rigging up, testing the water well onsite, and connecting electrical and water hookups. On 12 May, B. Cramer (Rutgers) and P. McLaughlin (DGS) moved equipment onsite and set up a field laboratory in an Allied trailer. A Kodak DC260 digital zoom camera (38.4–115.2 mm lens; 1536 × 1024 megapixel resolution), Macintosh Power 7200, and photography stand were set up to photograph 2-ft (0.61 m) core segments. Camera default settings (including flash) with wide-angle lens (38.4 mm) were used, following procedures established at Ocean View, NJ (Miller et al., **Chap. 2,** this volume).

All core measurements are given in feet, and depths refer to feet below land. We follow the ODP convention of top justifying depths for intervals with incomplete core recovery, with core depths assigned based on the depth of the top of the coring run plus distance below the top of the core.

The first core was obtained on 12 May using a Christensen 94-mm (HQ) system with a Christensen 4.25-in. bit. For unconsolidated sands, an extended ("snout") shoe was used to contact the sample 1.5–2.5 in (3.8–6.4 cm) ahead of the bit; core diameter is 2.4 in (6.1 cm) with a rock shoe and 2.1 in (5.3 cm) with the snout shoe. Approximately 2 ft (0.61 m) of large-diameter (12 in) surface casing was set; the large diameter was designed to catch cuttings from reaming a 5-in (12.7 cm) hole for casing targeted at 200 ft (61 m). The top 5 ft (1.52 m) was drilled but not cored; coring commenced with rapid recovery of six cores (28.6 ft [8.72 m] recovered between 5 and 50 ft [1.52 and 15.24 m]; recovery = 63.5%).

On 13 May, coring runs were shortened and the mud was thickened from 8.5 to 9 lb to try to improve recovery. Recovery was fair (~50%) on runs 7 through 11 (50–75 ft; 15.24–22.86 m). No core was recovered on run 12 (75–80 ft; 22.86–24.38 m), and run 13 (80–85 ft; 24.38–25.91 m) only recovered 1 ft (0.30 m) after penetrating a layer that turned the mud yellow green. Run 13A redrilled this section, recovering 1 ft (0.30 m) of sand and clay that was left in the outer barrel (logged as 81–82 ft; 24.69–24.99 m). The day ended by pulling the rods and unplugging the inner core barrel, with 14.05 ft (4.28 m) recovered from 35 ft (10.67 m) drilled (recovery = 40.1%).

On 14 May, the drillers circulated between runs to clear caving sands and extended the shoe farther out of the barrel. Run 16 recovered 2 ft between 90 and 91 ft (27.43 and 27.74 m). The bottom of the hole (BOH) collapsed on the next run. Run 17 (91–94 ft; 27.74–28.65 m) recovered 2 ft (0.61 m). The BOH collapsed again. The rods were pulled, the core barrel was rinsed, the water swivel was replaced, and the section was cored to 105 ft (32.00 m) on runs 18–20. Despite these setbacks, recovery was much improved for the day (15.9 ft [4.85 m] recovered between 85 and 105 ft [25.91 and 32.00 m]; recovery = 79.5%).

Coring recovery and rate improved on 15 May as we penetrated more consolidated sands on runs 21–30 (105–155 ft; 32.00–47.24). Much of run 24 (120–125 ft; 36.58–38.10 m) slipped out of the barrel, and run 25 (125–130 ft; 38.10–39.62 m) recovered 5.9 ft (1.80 m), including some from the previous run. Only 1.4 ft (0.43 m) was recovered on run 30 (150–155 ft; 45.72–47.24 m), but recovery was otherwise good for the day (34.65 ft [10.56 m] recovered between 105 and 155 ft [32.00 and 47.24 m]; recovery = 69.3%).

Coring proceeded smoothly on 16 May on runs 31–39 with good recovery (41.42 ft [12.93 m] recovered between 155 and 205 ft [47.24–62.48 m]; recovery = 82%). We penetrated a silty clay (193.5–197.55 ft; 58.98–60.21 m) suitable for setting polyvinyl chloride (PVC) casing.

On 17 May run 40 (205–210 ft; 62.48–64.01 m) was obtained to finish the rod, and the hole was prepped for logging. Nine logging runs were done from surface to 205 ft (62.48 m) with no operational problems. All logging was performed using Century Geophysical Corporation tools. The natural gamma ray tool was run downhole and uphole in the rods. The following tools were then run up- and downhole on formation: multitool (electric logs including spontaneous potential [SP], short normal resistivity [16N], long normal resistivity [64N], point resistivity, and lateral), sonic, and induction (conductivity, calculated resistivity). A caliper log was obtained uphole. The drillers reamed the hole to 43 ft (13.11 m) using an 8-in (20.3 cm) drag bit. On 18 May, the BOH collapsed and the hole was reamed from 23 to 193 ft (7.01 to 58.83 m); 5 in (12.7 cm) PVC (schedule 4) casing was run to 192.5 ft (58.67 m) to be removed on completion. The casing became stuck at ~25 ft (~7.62 m) in the first Omar Formation clay and had to be worked hard to penetrate; the bottom 20 ft (6.10 m) of casing was pushed in with considerable effort.

Coring resumed on 19 May (runs 41–45). Coring was delayed because sand inside the casing made it difficult to equalize mud pressure. On run 41 (210–215 ft; 64.01–65.53 m), the inner core barrel was difficult to extrude from the outer barrel because the shoe came unscrewed; no core was recovered. The casing was pushed to 194 ft (59.13 m) to make sure the sands were cased off. Coring continued to 240 ft (73.15 m), recovering 17.75 ft (5.41 m; recovery = 59.2% for the day).

On 20 May, drillers again had problems with equalizing mud pressure; the mud was thickened to ~9 lb. The drillers were concerned that sands were getting by the casing, with hydraulic pressure from the Ocean City aquifer (part of the Bethany formation) either forcing the casing off bottom or blowing out the confining bed. Recovery was poor for the day (runs 46–52), due to caving sands (9.15 ft [2.79 m] recovered from 240 to 270 ft [73.15 to 82.30 m]; recovery = 30.5%).

On 21 May, we had better recovery in the sand by making shorter runs on runs 53–60 (i.e., 2–3 ft vs. 5–7 ft; 0.6–0.9 vs. 1.5–2.1 m). Drilling pressure was better; the hole stayed open below the casing, and caving sands were no longer a problem. The caving sands apparently were making their way around the casing; these sands apparently had bridged off at the casing point. A clay layer was anticipated at 265 ft (80.77 m) where the casing could be reset, but it was never encountered. The drillers penetrated a gravelly sand at the bottom of Core 58 (292–294 ft; 89.00–89.61 m) that caused chattering; Core 59 (294–297 ft; 89.61–90.53 m) recovered 0.7 ft (0.21 m) of gravel at the top that was caved from 293.8 to 294 ft (89.55 to 89.61 m). In general, recovery was improved for the short runs, but the loss of run 53 (270–275 ft; 82.30–83.82 m) and most of run 60 (297–300 ft; 90.53–91.44 m) resulted in poor recovery for the day (10.45 ft [3.19 m] recovered between 270 and 300 ft [82.30 and 91.44 m]; recovery = 34.8%).

On 22 May, heavy rains slowed drilling, but recovery dramatically improved with penetration of uniform fine-medium sands on runs 61–67. Anticipating a fining of the section downhole, we extended run 67 (330–340 ft; 100.58–103.63 m) to 10 ft (3.05 m), recovering 4.75 ft (1.45 m) of sands that represent at least 6 to 7 ft (1.83 to 2.13 m) of recovery. Not accounting for this compression, we ended the day with 27.82 ft (8.48 m) recovered between 300 and 340 ft (91.44 and 103.63 m; recovery = 69.6%).

On 23 May, the hole was open and clear in the morning, caving had ceased, and the drillers went for 10 ft (3.05 m) on run 68 (340–350 ft; 103.63–106.68 m). Caved pebbles jammed the ball on the quad latch, allowing drilling mud to wash through the inner core barrel; no core was recovered. Recovery was good on run 69 (350–355 ft; 106.68–108.20 m) with 3.55 ft (1.08 m) of soupy aquifer sands probably representing nearly full recovery. Good recovery of sands continued on runs 70 through 75 (355–380 ft; 108.20–115.82 m), including excellent recovery of a thick shelly interval (380–400 ft; 115.82–121.92 m). At the end of the day, 40 ft (12.19 m) of rods were pulled and the hole was conditioned with 300 gallons of mud. A total of 42.35 ft (12.91 m) was recovered between 340 and 400 ft (103.63 and 121.92 m; recovery = 70.6%) for runs 68–78.

The weather on 24 May was beautiful, providing excellent coring conditions. Recovery was good on 5-ft (1.52 m) runs 79 through 84 (400–430 ft; 121.92–131.06 m), and we decided to switch to the 10-ft (3.05 m) barrel in the afternoon beginning at 430 ft (131.06 m). Excellent recovery continued in the fine-grained sediments below 450 ft (137.16 m). Run 88 (460–470 ft; 140.21–143.26 m) had 67% recovery because the soft clays stopped moving into the barrel, resulting in 3.5 ft (1.07 m) of liquefied core and drilling mud on top of the core. The day ended on run 89 with 70.45 ft (21.47 m) recovered between 400 and 480 ft (121.92 and 146.30 m; recovery = 88.6%).

Coring operations on 25 May yielded excellent recovery in silty clay on runs 90 and 91 (480–485 and 485–490 ft [146.30–147.83 and 147.83–149.35 m], respectively). On runs 92 through 94 (490–516 ft; 149.35–157.28 m), a switch was made to 10-ft (3.05 m) runs, with excellent recovery. Run 95 (516–520 ft; 157.28–158.50 m) recovered only 0.2 ft (0.06 m) of an indurated zone that blocked the barrel. In the afternoon, drilling was briefly suspended for logging. A gamma log was obtained from within the rods to 505 ft (153.92 m). When drilling resumed, run 96 (520–523 ft; 158.50–159.41 m) was stopped after 3 ft (0.91 m) by a lithified zone. The lithified zone and 6 ft (1.83 m) of underlying clay were recovered on run 97 (523–530 ft; 159.41–161.54 m). The day ended with 46.72 ft (14.24 m) recovered between 480 and 530 ft (146.30 and 161.54 m; recovery = 93.44%).

Coring started on 26 May with excellent weather conditions and outstanding recovery on runs 98 and 99 (530–550 ft; 161.54–167.64 m). Run 100 (550–558.5 ft; 167.64–170.23 m) was cut short. In the afternoon, shell beds began to slow drilling because the shells would not allow core to fill the barrel. Runs 101 through 106 (558.5–588 ft; 170.23–179.22 m) could not penetrate the full 10 ft (3.05 m) and had to be shortened. The day ended with 53.7 ft (16.37 m) recovered between 530 and 588 ft (161.54 and 179.22 m; recovery = 92.6%).

On 27 May, drilling on runs 107–115 mainly encountered soft sands with a few large shells and some thin cemented zones. These cemented zones blocked the barrel, and soft sands could not push through. Most core runs had to be stopped short of the full 10 ft (3.05 m) to prevent blowing away the sands; full penetration was only achieved on runs 109 (600–610 ft; 182.88–185.93 m) and 113 (620–630 ft; 188.98–192.02 m). Recovery was excellent despite the alternations of hard cemented and soft sand zones. The soft nature of these sediments made it difficult to wash off drilling mud without destroying sedimentary structures. Loose drilling mud was gently washed away using a hose with a misting spray head. The remaining "rind" of smeared sand and mud was removed by shaving a thin layer off of the outside of the core using a sharp kitchen knife (for the clays) or a putty knife (for the sands) and rinsing away any remaining rind with a mist. This not only left the cores free of drilling mud, but also helped accentuate clay laminae and other physical structures, clay-filled burrows, and general bioturbation in what may originally appeared to be featureless sands. The day ended on run 115 with the bottom of the hole at 645 ft (196.60 m). We recovered 50.11 ft (15.27 m) between 588 and 645 ft (179.22 and 196.60 m; recovery = 88.9%).

On 28 May, we once again drilled through soft sands and silts with occasional indurated layers (runs 116–125). These indurated layers blocked run 119 (660–670 ft; 201.17–204.22 m), preventing the sands below from entering the inner core barrel. The sands and silts were quickly cored, and no mechanical problems were encountered with the rig. Run 122 (690–692 ft; 210.31–210.92 m) recovered 4.75 ft (1.45 m) from a 2-ft (0.61 m) run. The drillers believe that the upper 3 ft (0.91 m) recovered was core that had been left in the hole from the bottom of the previous run and that the lower 1.75 ft (0.53 m) represented the cored interval. Run 123 recovered only 2.1 ft (0.64 m) from an 8-ft (2.44 m) run (692–700 ft; 210.92–213.36 m), due to blockage by indurated layers. The day ended with recovery of 57.95 ft (17.66 m) between 645 and 720 ft (196.60 and 219.46 m; recovery = 77.3%).

We drilled runs 126–133 without major problems on 29 May. As has been the case every day since we penetrated the Choptank Formation at 575.2 ft (175.32 m), occasional indurated layers blocked the barrel and either cut runs short (run 126 [720–726 ft; 219.46–221.28 m] and run 132 [770–776.5 ft; 234.70–236.67 m]) or caused loss of the lower part of a run (run 128 [734–740 ft; 223.72–225.55 m] and run 133 [776.5–780; 236.68–237.74 m]). The day ended with the bottom of the hole at 780 ft (237.74 m). We recovered 56.35 ft (17.18 m) between 720 and 780 ft (219.46 and 237.74 m; recovery = 93.9%).

Indurated layers slowed coring on 30 May. Run 134 (780–790 ft; 237.74–240.79 m) recovered several thin (~0.1–0.2 ft; 3–6 cm), hard layers, but run 135 (790–792 ft; 240.79–241.40 m) was stopped by an indurated layer. Run 136 (792–792.5 ft; 241.40–241.55 m) was stopped 0.5 ft (0.15 m) into the run, recovering an indurated shelly interval. Run 137 (792.5–800 ft; 241.55–243.84 m) recovered 1.0 ft (0.30 m) of indurated material and 2.6 ft (0.79 m) of underlying soft sand. Recovery of these soft sands below the hard rock was made feasible by modification of the Christensen rock shoe, cutting uphole-directed teeth into the shoe. Run 138 (800–805 ft; 243.84–245.36 m) was shortened to 5 ft (1.52 m), attaining nearly full recovery in sands. Run 139 (805–807 ft; 245.36–245.97 m) was stopped short by an indurated layer that damaged the shoe. Run 140 (807–810 ft; 245.97–246.89 m) recovered indurated zones at the top and base, with soft sand in between; recovery was still only 1.1 ft (0.33 m), presumably losing sands from the lower part of the interval. Slow drilling of hard rock and interbedded sand on run 141 was stopped at 819 ft (249.63 m). The day ended with 26.95 ft (8.21 m) recovered between 780 and 819 ft (237.74 and 249.63 m; recovery = 69.1%).

On 31 May, runs 142 (819–829.25 ft; 249.63–252.76 m), 143 (829.25–839.5 ft; 252.76–255.88 m), and 144 (839.5–849.75 ft; 255.88–259.00 m) were drilled an extra 0.25 ft (0.08 m) to force the core into the barrel; recovery was 6.1, 8.7, and 10.35 ft (1.86, 2.65, and 3.15 m), respectively on these runs. Run 145 (849.75–851.75 ft; 259.00–259.61 m) was stopped short by an indurated layer. Run 146 (851.75–860 ft; 259.61–262.13 m) drilled easily and had >9 ft (2.74 m) of recovery; the driller pulled up 2 ft (0.61 m) from the BOH and recored the bottom 2 ft (0.61 m). About 1 ft (0.30 m) of chewed-up core was discarded below 6 ft (1.83 m) into the run; most of the remaining core from 6 to 8.4 ft (1.83 to 2.56 m) in the run is solid, though a few layers are probably a mixture of chewed-up core and drilling mud. Run 147 (860–870 ft; 262.13–265.18) recovered 10 ft (3.05 m) of core, with brecciation due to drilling disturbance at 7.3–8.6 ft (2.23–2.62 m). Run 148 (870–880 ft; 265.18–268.22 m) recovered 10.17 ft (3.10 m). The day ended with 55.73 ft

(16.99 m) recovered between 819 and 880 ft (249.63 and 268.22 m; recovery = 91.36%).

On 1 June, the drillers repaired a pump, delaying the first run of the day. Runs 149 (880–889 ft; 268.22–270.97 m) and 150 (889–899 ft; 270.97–274.02 m) recovered 8.7 and 9.85 ft (2.65 and 3.00 m), respectively. Run 151 recovered 1.2 ft (0.37 m) of core from a 1-ft interval (899–900 ft; 274.02–274.32 m), returning core runs to 10-ft (3.05 m) depth intervals. Run 152 (900–910 ft; 274.32–277.37 m) hit indurated layers and difficult drilling at 902.5 ft (275.08 m); 5.85 ft (1.78 m) of core was recovered. The core had a moderate odor of kerosene. Run 153 (910–911.35; 277.37–277.78 m) hit a hard layer that stopped drilling at 911.35 ft (277.78 m) and ripped up the cutting shoe. Run 154 (911.35–920 ft; 277.78–280.42 m) recovered 2.65 ft (0.81 m). The day ended with 29.0 ft (8.84 m) recovered between 880 and 920 ft (268.22 and 280.42 m; recovery = 72.5%).

On 2 June, runs 155 (920–930 ft; 280.42–283.46 m), 156 (930–940 ft; 283.46–286.51 m), 157 (940–945 ft; 286.51–288.04 m), and 158 (945–953.5 ft; 288.04–290.63 m) recovered 7.5, 2.4, 4.5, and 7.6 ft (2.29, 0.73, 1.37, and 2.32 m), respectively. Run 159 (953.5–960 ft; 290.63–292.61 m) recovered 4.95 ft (1.51 m); a stick clogged the pump for the water hose, delaying core extrusion from the core barrel. Runs 160 (960–970 ft; 292.61–295.66 m) and 161 (970–980 ft; 295.66–298.70 m) recovered 9.8 and 7.4 ft (2.99 and 2.56 m), respectively. The day ended with 44.15 ft (13.46 m) recovered between 920 and 980 ft (280.42 and 298.70 m; recovery = 73.6% recovery).

On 3 June, run 162 (980–982 ft; 298.70–299.31 m) was stopped by a cemented layer at 2 ft (0.61 m) and recovered 1.5 ft (0.46 m). Runs 163 (982–990 ft; 299.31–301.75 m), 164 (990–1000 ft; 301.75–304.80 m), 165 (1000–1010 ft; 304.80–307.85 m), 166 (1010–1020 ft; 307.85–310.90 m), 167 (1020–1030 ft; 310.90–313.94 m), and 168 (1030–1040 ft; 313.94–316.99 m) recovered 6.4, 6.55, 7.4, 9.8, 9.05, and 8.1 ft (1.95, 2.00, 2.56, 2.99, 2.76, and 2.47 m), respectively. Run 168 became stuck in the core barrel; the pump malfunctioned, causing the core to overrun the tray. Pieces of core fell on the ground but were reconstructed. A cup in the mud pump cylinder wore out and was replaced at the end of the day. Total core recovered for the day was 48.8 ft (14.87 m) between 980 and 1040 ft (298.70 and 316.99 m; recovery = 81.33%).

On 4 June, run 169 (1040–1047.5 ft; 316.99–319.28 m) recovered 7.2 ft (2.19 m); drillers stopped at 1047.5 ft (319.28 m) because drilling was "acting strange." Run 170 (1047.5–1055 ft; 319.28–321.64 m) recovered 7.95 ft (2.42 m); mud pressure picked up in the last 2–3 ft (0.61–0.91 m). Run 171 (1055–1057 ft; 321.56–322.17 m) hit a rock at 1057 ft (322.17 m) and recovered 1.35 ft (0.41 m) of core. Run 172 (1057–1060 ft; 322.17–323.09 m) recovered 3.7 ft (1.13 m) of core. The drillers noted that the top of the core had a wear ring on it from the drilling of the previous run. The extra 0.7 ft (0.21 m) recovered on run 172 is most likely from the bottom of run 171 and should be placed with core from run 171. Run 173 (1060–1070 ft; 323.09–326.14 m) recovered 5.2 ft (1.58 m). Run 174 (1070–1077 ft; 326.14–328.27 m) recovered 6.7 ft (2.04 m) and stopped when the shoe became plugged. Total core recovered for the day was 32.15 ft (9.80 m) between 1040 and 1077 ft (316.99 and 328.27 m; recovery = 87%).

At the end of 4 June, the drillers pulled the rods; the rods were difficult to pull, possibly because of an uncentered, irregular hole. The HQ drilling was completed with 811.75 ft (247.42 m) recovered from 1072 ft (326.75 m) cored (recovery = 75.7%); 670.43 ft (204.35 m) was recovered in the 872 ft (265.79 m) cored below casing (recovery = 76.9%). The drillers returned to Reston, VA, on 5 June to pick up NQ rods, returning on the evening of 9 June.

After a 5-day pause to switch from HQ to NQ rods, drilling resumed on 10 June as the drillers began to run NQ rods. Beginning at 208 ft (63.40 m; at the base of casing), numerous sand bridges slowed reentry of the hole, requiring extensive flushing. One zone from 540 to 555 ft (164.59 to 169.16 m) required redrilling. The next 200 ft (60.96 m) was reentered more easily, and 780 ft (237.74 m) had been reentered by the end of 11 June. On 12 June, with the uneventful addition of the bottom 300 ft (91.44 m) of rod, coring resumed using a Christensen CNWL (NQ) system. The NQ system produces a 3.162-in (8.03 cm) hole diameter, cutting cores of 1.875-in (4.76 cm) diameter core with a rock shoe and 1.67-in (4.24 cm) diameter with extended shoes. Smooth coring and excellent recovery occurred on runs 175 (1077–1080 ft; 328.27–329.18 m), 176 (1080–1090 ft; 329.18–332.23 m), 177 (1090–1100 ft; 332.23–335.28 m), and 178 (1100–1110 ft; 335.28–338.33 m), recovering 2.9 ft (0.88 m), 9.95 ft (3.03 m), 10.3 ft (3.14 m), and 10.5 ft (3.20 m), respectively. Total recovery for the day was 33.7 ft (10.27 m) from 33 ft drilled (10.06 m; recovery = 102.1%).

On June 13, smooth coring proceeded on runs 179–182 (1110–1150 ft; 338.33–350.52 m) with slightly >100% recovery due to core expansion. Run 183 (1150–1153.5 ft; 350.52–351.59 m) was stopped short by a large shell that bent the shoe, recovering 2.55 ft (0.78 m). The next run (run 184; 1153.5–1160 ft; 351.59–353.57 m) used the rock shoe, recovering 2.85 ft (0.87 m) from the top part of the run. Total recovery for the day was 47.3 ft (14.42 m) from 50 ft (15.24 m) drilled (recovery = 94.6%).

Sands slowed drilling and hindered recovery on 14 June. Run 185 (1160–1165 ft; 353.57–355.09 m) stopped 5 ft (1.52 m) into the run when the drillers noted that the bit was grinding; the barrel had not latched in and only 0.15 ft (0.06 m) was recovered. The core slipped out and blocked the outer core barrel. After washing the blockage from the outer core barrel, run 186 (1165–1170 ft; 355.09–356.62 m) had nearly full recovery. Run 187 (1170–1175 ft; 356.62–358.14 m) was pulled up short as sands clogged the barrel; run 188 (1175–1180 ft; 358.14–359.66 m) finished the rod. The lower 2.5 ft (0.76 m) of run 189 (1180–1190 ft; 359.66–362.71 m) was ground up during drilling. Total recovery for the day was 19.05 ft (5.81 m) between 1160 and 1190 ft (353.57 and 362.71 m; recovery = 63.5%).

On 15 June, poor recovery on runs 190 (1190–1200 ft [362.71–365.76 m]; 0 ft [0 m] recovery), 191 (1200–1201 ft [365.76–366.06 m]; 4.3 ft [1.31 m] recovery) and 192 (1201–1210 ft [366.06–368.81 m]; 0 ft [0 m] recovery) was probably due to grinding of coarse-grained sand beds containing thin beds and burrows of silt and clay. Recovery was excellent on runs 193, 194, and 195 (1210–1220, 1220–1230, and 1230–1237.5 ft [368.81–371.86, 371.86–374.90, 374.90–377.19 m]; recovery = 94% for these three runs) because the sand fraction disappeared. Run 195 was cut short at the top of an indurated interval. Total recovery for the day was 30.25 ft (9.22 m) between 1190 and 1237.5 ft (362.71–377.19 m; recovery = 63.7%).

On 16 June drillers switched to a rock shoe for run 196 (1237.5–1240; 377.19–377.95 m) and finished the rod with full recovery of 0.7 ft (0.21 m) of indurated silt and 1.8 ft (0.55 m) of silt. Recovery was excellent all day drilling through sandy silts. Drillers reported high mud pressures during runs 197–201 (1240–1290 ft; 377.95–393.19 m). High mud pressures likely caused extensive drilling disturbance in runs 197 and 199; the core was infiltrated by the drilling mud, creating a thick rind of core material mixed with mud. This soft core material was easily split off the inner hard core, and the core was wrapped and photographed with the softer material pushed to the side. Total recovery for the day was 52.6 ft (16.03 m) between 1237.5 and 1290 ft (377.19–393.19 m; recovery = 100.2%).

On 17 June, the first run (run 202; 1290–1300 ft; 393.19–396.24 m) had no recovery; the drillers redrilled the same interval and retrieved 10.4 ft (3.17 m) of core. Although the run was drilled past 1300 ft (396.24 m) in order to retrieve the core, the run was logged as 1290–1300 ft (393.19–396.24 m) with 104% recovery. Complete recovery was obtained for run 203 (1300–1310 ft [396.24–399.29 m]; 10.55 ft [3.22 m] recovery). Run 204 (1310–1320; 399.29–402.34 m) recovered 8.9 ft (2.71 m), including a cemented zone at the base. Run 205 (1320–1320.3 ft; 402.34–402.43 m) was stopped after only 0.3 ft (0.09 m) when rock was encountered. Drillers switched to a rock shoe for run 206 and completed the 10-ft rod (1320.3–1330 ft; 402.43–405.38 m) with 5.6 ft (1.71 m) recovered. The day ended with 35.75 ft (10.90 m) recovered between 1290 and 1330 ft (393.19–405.38 m; recovery = 89.4%).

On 18 June, the drillers achieved high recovery rates on runs 207–212, recovering 61.75 ft (18.82 m) between 1330 and 1390 ft (405.38–423.67 m; recovery = 102.9%). Excellent recovery continued on the first three runs on 19 June, runs 213–215 (1390–1420 ft; 423.67–432.82 m). On run 216 (1420–1429 ft; 432.82–435.56 m), drilling was stopped short at 9 ft (2.74 m). Slow drilling continued during run 217 (1429–1437 ft; 435.56–438.00 m), with high mud pressures. The run was stopped because the mud pump blew; one rod was pulled to prevent sticking the rods in the clay penetrated during run 216. The day ended with 46.50 ft (14.17 m) recovered between 1390 and 1437 ft (423.67–438.00 m; recovery = 98.94%).

On 20 June, the first run, run 218 (1437–1440 ft; 438.00–438.91 m), had no recovery; the core had apparently slipped out of the core catcher. The drillers ran 5 ft (1.52 m) on run 219 (1440–1445 ft; 438.91–440.44 m), hoping to catch the lost core, but only recovered 3.75 ft (1.14 m). Run 220 (1445–1450 ft; 440.44–441.96 m) recovered 6.5 ft (1.98 m); the top 1.3 ft (0.40 m) appeared recored, indicating it was from the previous run. Thus, 10.25 ft (3.12 m) was recovered from a cored interval of 1440–1450 ft (438.91–441.96 m; recovery = 103%); we presume that the entire section from 1437 to 1440 ft (438.00 to 438.91 m) was lost. Field notes describe core from the interval 1445–1450 ft (440.44–441.96 m) as recovering 6.5 ft (1.98 m), though the top 1.3 ft (0.40 m) should be 1443.7–1450 ft (440.04–441.96 m). Run 221 (1450–1454 ft; 441.96–443.18 m) was stopped when the rate of penetration dropped significantly, due to a hard layer or spalling of glauconite sands on the bit. Run 222 (1454–1460 ft; 443.18–445.01 m) encountered hard drilling at the top and easier drilling in the lower part, with 6.2 ft (1.89 m) recovered. The last run (run 223; 1460–1470 ft; 445.01–448.06 m) recovered 7.95 ft (2.42 m), yielding 27.85 ft (8.49 m) recovered between 1437 and 1470 ft (438.00–448.06 m; recovery = 84.4%).

Logging was conducted on 20 and 21 June by P. McLaughlin and S. Baxter of the DGS and S. Curtin of the USGS WRD Annapolis using the DGS's Century logging tools and the USGS's logging truck and winch. On June 20 after the drillers reached the 1470-ft (448.06 m) total depth of the hole, the drill string was pulled up off the BOH and gamma logs were recorded from within the drill rods. Logs were obtained in both the up and down travel directions to the bottom of the drill string (1458 ft; 444.40 m). On 21 June, open-hole logging was conducted after the drill string was pulled from the hole. The multitool was run to the BOH (1470 ft; 448.06 m) in both the up and down directions, collecting gamma, spontaneous potential, long-normal resistivity, short-normal resistivity, and point resistivity logs. The induction tool was also run to the BOH, providing gamma and conductivity logs to the bottom of the hole. An attempt to run a full-wave sonic log was unsuccessful, due to malfunctions in the tool. The hole was grouted with cement, plugged, and abandoned on 22 and 23 June.

Total recovery at Bethany Beach was 1166.5 ft (355.55 m) from a total depth of 1470 ft (448.06 m) drilled and 1465 ft (446.53 m) cored, for an overall recovery of 79.62%; median recovery of the drilling runs was 86%. Lithologies were described onsite and later reexamined in more detail at the Rutgers core facility; these descriptions form the basis for the preliminary lithologic descriptions. Cores were cut into 2-ft (0.61 m) sections, labeled at top and bottom of each section, placed into split PVC pipe (3 in [7.62 cm] diameter), wrapped in plastic sheeting, and stored in 2-ft (0.61 m) NQ wax boxes. One hundred and sixty four core boxes were moved to permanent storage at the Rutgers University core library for further study. Cores were sampled at ~5-ft (1.52 m) intervals for planktonic foraminiferal, calcareous nannofossil, palynology, dinocyst, and diatom biostratigraphy and coarse-fraction lithologic studies at the Rutgers core library.

LITHOSTRATIGRAPHY

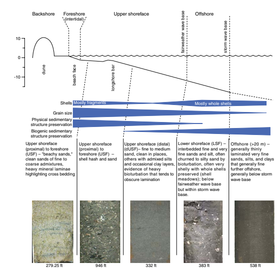
Summary

The on-site scientific team provided preliminary descriptions of sedimentary textures, structures, colors, fossil content, identification of lithostratigraphic units (Andres, 1986; Benson, 1990), and lithologic contacts (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 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 and Sr isotopic breaks. For the nonmarine and nearshore sections (primarily the upper Miocene and younger section), lithofacies interpretations provide the primary means of recognizing unconformities and interpreting paleoenvironments.

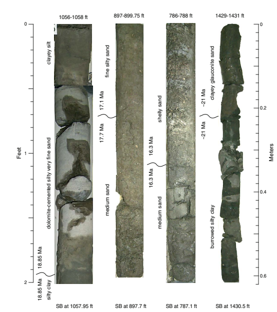
Facies changes within onshore New Jersey Miocene sequences generally follow repetitive transgressive–regressive patterns (Owens and Sohl, 1969; Sugarman et al., 1993, 1995) that consist of (1) a basal, generally thin, transgressive quartz sand equivalent to the TST of Posamentier et al. (1988) and (2) a coarsening-upward succession of regressive medial silts and upper quartz sands equivalent to the HST of Posamentier et al. (1988). Miocene sections in Delaware lack the clear deltaic influence seen in coeval sections in New Jersey; however, they still comprise generally thin TSTs and thick HSTs. LSTs are usually absent in both coastal plains. Because the TSTs are thin, MFS are difficult to differentiate from unconformities. Both can be marked by shell beds and gamma ray peaks. Flooding surfaces (FSs), particularly MFSs, may be differentiated from sequence boundaries by the association of erosion and rip-up

T1. Core descriptions, p. 68.

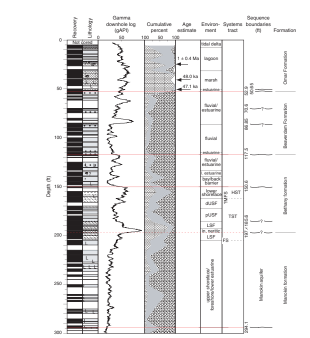
F2. Nearshore sedimentation model, p. 57.



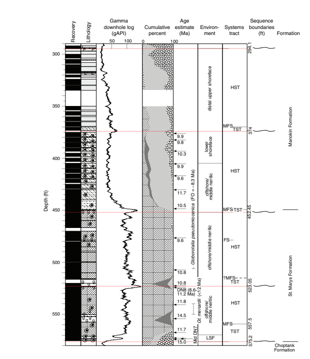
F3. Sequence boundaries, p. 58.



F4. Stratigraphic summary, Omar Formation, p. 59.



F5. Stratigraphic summary, lower Manokin formation, p. 61.



clasts at the latter, lithofacies successions, and benthic foraminiferal changes. The transgressive surface (TS), marking the top of the LST, represents a change from generally regressive to transgressive facies; because LSTs are generally absent, these surfaces are generally merged with the sequence boundaries (Fig. F3).

The overall association of facies suggests that most of the Bethany Beach section fits a wave-dominated shoreline model devised by Bernard et al. (1962) on Galveston Island and further developed by Harms et al. (1975, 1982), and McCubbin (1981). Whereas the New Jersey Miocene sections generally contain significant amounts of clay, plant debris, and micaceous sands consistent with a deltaic influence, the Bethany Beach section overall has less lignite, less mica in the sands, and fine-grained sediments dominated by silt rather than clay, reflecting movement of sediments by wave energy. The facies model used in this study recognizes the following environments (Fig. F2):

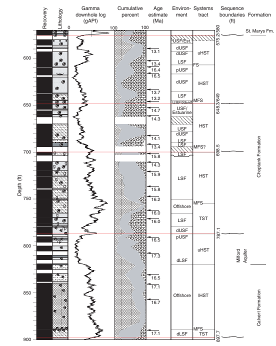
1. Fluvial to upper estuarine: dominantly sand, including likely cut-and-fill channels lined with gravels and mostly composed of clean sands with little clay; sands commonly poorly sorted; commonly lignitic;
2. Lower estuarine: poorly sorted sands admixed with interlaminated thin sands and clays; commonly lignitic; commonly associated with "beachy" sands;
3. Upper shoreface/foreshore: clean "beachy" sands of fine to coarse admixtures, with opaque heavy mineral laminae highlighting cross bedding; mostly representing upper shoreface, due to poor preservation of foreshore deposits;
4. Distal upper shoreface: fine to medium sands, clean in places, others with admixed silts and less common clay layers; commonly shows evidence of heavy bioturbation that tends to obscure lamination;
5. Lower shoreface: interbedded fine and very fine sands, commonly silty due to mixing, and commonly very shelly with whole shells preserved; deposited below fair-weather wave base but within storm wave base; and
6. Offshore: thinly laminated very fine sands, silts, and clays; deposited below storm wave base, with finer sediments representing deposition farther offshore.

In these environments, small changes in sea level can produce dramatic shifts in sedimentary facies.

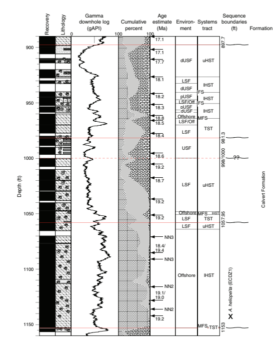
Benthic foraminiferal biofacies were used to recognize inner (0–30 m), middle (30–100 m), outer (100–200 m) neritic, and upper (200–600 m) bathyal paleodepths. The upper shoreface/foreshore, distal upper shoreface, and lower shoreface environments all lie within inner neritic depth ranges. The offshore environment encompasses middle neritic and deeper paleodepths.

Cumulative percent plots of the sediments in the cores were computed from samples washed for paleontological analysis (Table T2). Each sample was dried and weighed before washing, and the dry weight was used to compute the percentage of sand vs. silt and clay (Table T2). This differs from the method used in previous New Jersey Coastal Plain cores (Bass River, Island Beach, Atlantic City, and Cape May) in which the samples were not dried before washing. The sand fraction was dry sieved through a 250-µm sieve, and the fractions were weighed to obtain the percent of very fine and fine vs. medium and coarser sand. The

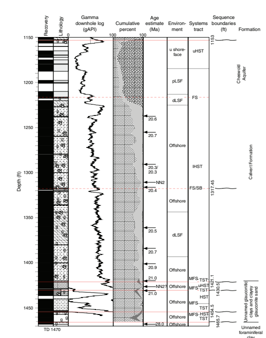
F6. Stratigraphic summary, Choptank Formation, p. 62.



F7. Stratigraphic summary, middle Calvert Formation, p. 63.



F8. Stratigraphic summary, lower Calvert Formation, p. 64.



T2. Data used to construct the cumulative percent lots, p. 73.

sand fractions were examined using a microscope and a visual estimate was made of the relative percentages of quartz, glauconite, carbonate (foraminifers and other shells), mica, and other materials contained in the sample. The values for these sand components given in Table T2 are derived by dividing the visual estimate (a whole number percentage) by the weight percent sand and thus may not add up to 100%, due to rounding error.

Omar Formation

Age: Pleistocene
Interval: 5.0–52.9 ft (1.52–16.12 m)

The Omar Formation was erected by Jordan (1962) as a heterogeneous unit of gray quartz sands interbedded with clayey silts and silty clays that commonly contain abundant plant debris. At Bethany Beach (Fig. F4), sands and clays of the Omar Formation comprise the upper part of the section cored (5.0–52.9 ft; 1.52–16.12 m). We interpret these sands and clays as representing deposition in a complex of nearshore, lagoonal, and marsh environments.

Cross-bedded, fine to very coarse, moderate to poorly sorted sands at the top (5.0–5.35 and 5.7–7.2 ft; 1.52–1.63 and 1.74–2.19 m) and interbedded greenish gray, slightly sandy clays (5.35–5.7 ft; 1.76–1.87 m) are interpreted as back barrier tidal delta deposits. Interbedded sands and clays (7.2–31.5 ft; 2.19–9.61 m) are interpreted as lagoonal deposits, whereas organic-rich, in some cases peaty, clays (31.5–50.65 ft, 9.60–15.44 m) are interpreted as retrograding marsh deposits. The sands are generally fine- to very fine grained, silty in places, and moderately sorted, with scattered plant debris and some shells (including *Mulina* sp.); the interbedded clays are sticky, silty in places, and contain thin sand stringers with shell concentrations. The organic-rich clays are generally laminated (1- to 2-mm laminations). A sharp contact at 50.65 ft (15.44 m) is abrupt and irregular, with a weathering horizon at the top. This is interpreted as a sequence boundary, and thus the interval from 5.0–50.65 ft (1.52–15.44 m) comprises a single sequence tracing a transgression from estuarine to bay marsh to lagoonal to tidal delta environments (Fig. F4).

Radiocarbon accelerator mass spectrometer dates of >48.0 ± 10.5 ka at 40.9–40.95 ft (12.47–12.48 m) and 47.1 ± 1.2 ka at 50.4–50.5 ft (15.36–15.39 m) were measured at the Woods Hole Oceanographic NOAMS facility. These dates would reflect late Pleistocene (marine isotope Stage 3) deposition, if valid, but could also be "dead" radiocarbon ages. Samples examined for palynology between 8.0 and 24.5 ft (2.44 and 7.47 m) have a cool-climate assemblage, indicating a Pleistocene age. Pollen analysis of samples from lower in the Omar Formation, near the radiocarbon-dating samples (34.4, 40.9, and 45.8 ft; 10.49, 12.47, and 13.96 m), indicate a warmer climate. A sample from the Omar Formation near Bethany Beach was assigned to amino acid Zone IIa (75–130 ka) (Wehmiller in Groot et al., 1990), suggesting equivalence to marine isotope Stages (MISs) 5a–5e. Studies elsewhere in southern Delaware assign the Omar to amino acid Zones IIb (age undefined, somewhere between 130 and 200 ka) and IId (400–600 ka) (Wehmiller in Groot et al., 1990). Based on the Pleistocene pollen assemblages and the nearby aminostratigraphy, we interpret these as samples as beyond the range of radiocarbon dating and derived from radioactively "dead" carbon. Thus, we interpret the transgressive sequence from 5.0 to 50.65 ft (1.52 to 15.44 m) as late Pleistocene.

A strontium value of 0.709147 was obtained from a shell at 24.6 ft (7.50 m) (Table T3); this corresponds to an age of isotopic age of 1 ± 0.35 Ma (see **"Strontium Isotope Chronostratigraphy,"** p. 44). Thus, Sr results suggest a middle–early Pleistocene age for this section. Further studies are needed to evaluate the validity of this measurement and the possibility that the shell was reworked from older strata.

T3. Sr isotopic data, p. 77.

A dark greenish gray (kaolinitic?) clay (50.65–51.6 ft; 15.44–15.73 m) becomes slightly sandy at its base (51.6–52.9 ft; 15.73–16.12 m). This interval appears to be bracketed by stratal surfaces interpreted tentatively as sequence boundaries (Fig. F4). The lower contact (52.9 ft; 16.12 m) is marked by a sharp change to laminated coarse sands. We tentatively interpret the environment of deposition as estuarine.

Beaverdam Formation

Age: Pliocene?
Interval: 52.9–117.5 ft (16.12–35.81 m)

The Beaverdam Formation consists primarily of white to buff to greenish gray quartz sand, some gravelly sand, and lesser light gray to greenish gray silty clay, deposited in fluvial and estuarine environments (Groot et al., 1990). It was originally described in Maryland (Rasmussen and Slaughter, 1955) and later recognized in Sussex County, DE, by Rasmussen at al. (1960) and Jordan (1962). Palynological studies place this unit in the Pliocene (Groot and Jordan, 1999).

The contact between the Omar and Beaverdam Formations was placed tentatively at 52.9 ft (16.12 m) at a change from clay above to coarse, poorly sorted sands below (Fig. F4). Sands from 52.9 to 70.0 ft (16.12 to 21.34 m) are generally homogenous, coarse to very coarse, and poorly sorted, with orange-tinted possible feldspar grains typical of the Beaverdam Formation (Ramsey, 1990), scattered cross laminae of organic-rich material, and scattered clay blebs. A laminated clay layer at 70.0–70.6 ft (21.34–21.52 m) overlies a slightly irregular contact at 70.6 ft (indicated with a ? unconformity on Fig. F4); however, there is little evidence of reworking other than clay blebs burrowed into the fine-medium sands below, and the significance of this contact is uncertain. Poorly sorted sands, including a bed of granular very coarse sands (73.4–73.5 ft; 22.37–22.40 m), continue down to a contact with a clay layer (86.3–86.85 ft; 26.30–26.47 m) that overlies gravelly coarse sand. The contact at 86.85 ft is associated with a large shift on the geophysical logs, suggesting that it may be a sequence-bounding unconformity; however, like the contact at 70.6 ft, this contact may reflect a change from sand to a clay layer in a fluvial system (Fig. F4). Sands above 86.3 ft (26.30 m) are cleaner/better sorted than below and may represent either fluvial or upper estuarine deposition; sands below 86.85 ft (26.47 m) are generally more poorly sorted, fine to coarse granular sands with scattered pebbles and appear to be fluvial in origin. Sands between 110.0 and 114.3 ft (33.53 and 34.84 m) are yellow (iron) stained. From 115 to 117.5 ft (35.05 to 35.81 m), the sands are fine to medium grained and better sorted than above, with ~3% opaque heavy mineral concentrated in cross laminae. The base of the sand contains granules and pebbles up to 15 mm diameter. These are tentatively interpreted as estuarine or possibly upper shoreface deposits. The boundary between the Beaverdam and Bethany Formations is placed at 117.5 ft at the contact between the gravelly sand and an underlying thin clay; a sequence boundary is also tentatively placed at that level. Thus, the sequence(s) from 52.9 to 117.5 ft (16.12 to 35.81 m) represent fluctuations between upper estuarine and fluvial conditions.

The Beaverdam Formation and the two underlying stratigraphic units, the Bethany formation and the Manokin formation, are all predominantly medium to very coarse sand. Because few clear lithologic breaks are present between 54.5 and 317 ft (16.61 and 96.62 m), lithostratigraphic subdivision of this section is uncertain, particularly the contact between the Beaverdam Formation and the Bethany formation. Stratigraphic subdivision is further complicated by the significant facies changes observed in these units based on comparison to geophysical logs of nearby wells; as little as 2 mi (3.2 km) away, an apparently equivalent section includes notably thicker fine-grained intervals. Sequence stratigraphic concepts are difficult to apply in this section, though several clay layers associated with erosional contacts serve as the basis for the preliminary sequence framework discussed herein. An additional complication for sequence definition and correlation of surfaces within the Beaverdam Formation is their common truncation by the erosional surface at the base of the overlying Pleistocene Omar Formation.

Bethany Formation

Age: late? Miocene to Pliocene?
Interval: 117.5–197.4 ft (35.81–60.17 m)

The Bethany formation is an informal local unit characterized by Andres (1986) as a lithologically complex unit of gray sand, interlayered gray, olive-gray, and blue-gray clay, and silt with common lignite, shells, and a "sawtooth" gamma log pattern. It includes two important local aquifers, the Pocomoke and Ocean City aquifers. The top of the Bethany formation is placed at 117.5 ft (35.81 m) where a gravelly sand interpreted as the basal Beaverdam Formation rests upon a thin clay placed in the Bethany formation (Fig. **F4**). The clay is 0.35 ft (0.11 m) thick, finely laminated, olive gray, and contains plant debris and lignite fragments. It is underlain by an interval of generally poorly sorted, granule- and pebble-bearing sands from 117.85 to 133.3 ft (35.92 to 40.63 m). These vary from lignitic silty, clayey fine sand to very poorly sorted, coarse, pebbly, silty, clayey sands. They represent deposition in an estuarine environment (probably fluvial-estuarine). Below this, sands generally fine downsection, with medium to coarse sands with abundant granules (135.0–139.1 ft; 41.15–42.40 m) passing into to moderately well sorted medium-coarse sand with less common granule zones and a few clay-filled burrows (140.0–150.6 ft; 42.67–45.90 m). We interpret this section as representing a downsection transition from lower estuarine to bay/back barrier, with the sequence shallowing upsection from 150.6 to 117.5 ft (45.90 to 35.81 m). A sharp burrowed contact at 150.6 ft (45.90 m) separates gray, fine, moderately well-sorted sands above from iron-stained, oxidized, heavily bioturbated, silty fine sands below. The contact is irregular, has burrowed clay blebs extending 0.2 ft (0.06 m) above the contract, and cemented burrows. It is interpreted as a sequence boundary and a subaerial surface of erosion separating shelf sands below from bay/back-barrier sands above.

Below this sequence boundary, from 150.6 to 162.25 ft (45.90 to 49.45 m), are bioturbated to very heavily bioturbated, silty, clayey, fine to medium sands with scattered clayey laminations broken by burrows (Fig. **F4**). These sands rapidly develop a 2- to 3-mm-thick rind of iron oxide when exposed to air. An irregular contact at 162.25–163.35 ft (49.45–49.79 m) separates these heavily bioturbated lower shoreface sands above from upper shoreface sands below. Although this could be a sequence boundary, it is more likely a facies change reflecting a flooding surface/parasequence boundary (Fig. **F4**). Below the contact, fine to medium sands are somewhat bioturbated, with hints of cross lamination interpreted as distal upper shoreface. Cross laminations with concentrations of opaque heavy minerals become more prominent below 173.0 ft (52.73 m); these sands also develop a thin limonitic coating after scraping. The clean, generally well-sorted, cross-laminated sands from 173.0 to 185.6 ft (52.73 to 56.57 m) are interpreted as deposits from foreshore/upper shoreface environments. Thus, the section from 150.6 to 185.6 ft (45.90 to 56.57 m) overall deepens upsection from foreshore/upper shoreface to lower shoreface. However, maximum bioturbation occurs around 163 ft (49.68 m); this may reflect a zone of maximum flooding, with TST below and a thin, clayey lower HST above.

A sharp lithologic contact at 185.6 ft (56.57 m) is tentatively interpreted as a sequence boundary. The contact consists of a thin gravel layer (185.59 ft; 56.57 m) underlying the foreshore sands, with a return to bioturbated, very fine to medium lower shoreface sands below. The contact may be unconformable or merely reflect an overstepping facies shift from lower shoreface to foreshore. This section grades downsection to a sandy clayey silt (190–195 ft; 57.91–59.44 m) to a sandy silty clay (195–197.4 ft; 59.44–60.17 m); we interpret this as a shallowing-upward trend within the inner neritic zone. Another possible sequence boundary at 197.4 ft (60.17 m) is associated with a sharp gamma log peak; this irregular surface overlies a white, possibly kaolinitic weathered clay zone (197.4–197.6 ft; 60.17–60.23 m) that is reworked as clay blebs (197.3 ft; 60.14 m) above. Very fine to fine silty sand underlies the clay (Fig. **F4**).

Because of the significant facies changes in the Beaverdam–Bethany–Manokin interval, the upper and lower boundaries of the Bethany formation are considered time-transgressive, occurring at significantly different levels in nearby wells. Where prominent stratigraphic surfaces are present in the upper part of the Bethany Beach borehole, it is not always clear whether they should be interpreted as regional unconformities or as local cut-and-fill structures related to facies changes. Considering the estuarine to nearshore environment in this interval and difficulty in correlating to nearby wells, many of these surfaces (e.g., 185.6 and 197.4 ft; 56.57 and 60.17 m) may simply be normal erosional surfaces that reflect facies changes. Nevertheless, the stacking pattern associated with the 197.4-ft (60.17 m) surface, from progradational below to retrogradational above, suggests that this surface may be a regional unconformity. The surface at 150.6 ft (45.90 m) appears to be consistently recognizable in the area and thus is interpreted as a sequence boundary.

Manokin Formation

Age: late Miocene
Interval: 197.4–449.4 ft (60.17–136.98 m)

The transition from the Bethany formation to the upper part of the informal Manokin formation is picked at 197.4 ft (60.17 m) where the section changes from interbedded sands and silts/clays above to an overall sand section below (Fig. F4). Andres (1986) established the Manokin formation as an informal local stratigraphic unit characterized predominately by gray sand, with some beds of gravel, and local clayey/silty, lignitic, and shelly beds. The Manokin formation is sandier than the Bethany formation and generally consists of a lower, upward-coarsening progradational section and an upper aggradational or mixed section with facies indicative of higher-energy depositional environments (Andres, 1986). We found that the progradational and aggradational sections comprise distinct sequences.

The boundary between the Bethany formation and the Manokin formation coincides with a tentative sequence boundary at 197.4 ft (60.17 m) (Fig. F4). The section immediately under this boundary, from 197.4 to 205.1 ft (60.17 to 62.51 m), is enigmatic. This section consists of heavily bioturbated silty fine sand, similar to that noted between 185.6 and 190 ft (56.57 and 57.91 m), that is interpreted as a lower shoreface deposit. Within this unit, a lignitic sand (203.0–203.25 ft; 61.87–61.95 m) is stained brown throughout and shows aspects of a weathered soil, though there are not obvious roots. At 205.1 ft (62.51 m), the section changes to lignitic, bioturbated nearshore sand. We interpret this as a minor flooding surface; alternatively, we could have placed a sequence boundary at this level rather than at 197.4 ft (60.17 m).

The section from 205.1 to 294.1 ft (62.51 to 89.64 m) consists of bioturbated, cross-laminated, silty fine to medium sands with laminations of lignite and opaque heavy minerals (Fig. F4). This interval is interpreted as representing upper shoreface/foreshore to lower estuarine environments. Burrows are up to 0.2 ft (6 cm) long. The amount of lignitic material and plant fragments is greater above 232 ft (70.71 m). The sands display several fining-upward successions (e.g., 223–225, 229–231.5, and 292–294 ft; 67.97–68.58, 69.80–70.56, and 89.00–89.61 m); poor recovery precludes further details. The lowermost succession grades down to a gravelly sand (293.8–294.0 ft; 89.55–89.61 m) that overlies a thin clay (294.0–294.1 ft; 89.61–89.64 m) and a medium sand below 294.1 ft (89.64 m). A sequence boundary is placed at 294.1 ft (89.64 m) at the contact between the clay and the sand.

Beneath the 294.1 ft (89.64 m) sequence boundary, the Manokin formation consists of predominantly medium sand to 318 ft (96.93 m) (Fig. F5). These sands are homogenous because of heavy bioturbation but are laminated in places. They include trace amounts of opaque heavy minerals and lignite and thin interbeds of silty organic-rich clays (305.5–305.65, 317.25–317.55, and 318.0–318.5 ft; 93.12–93.16, 96.70–96.79, and 96.93–97.08 m). The sands between 318.35 and 369.3 ft (97.03 and 112.56 m) are generally well-sorted fine to medium sand without obvious shell fragments. The section thus coarsens upsection and is interpreted as the HST. These sands are considered to reflect distal upper shoreface environments rather than upper shoreface based on the infrequent cross beds and concentrations of opaque heavy minerals. In places they develop limonitic rinds when exposed to air. The mud fraction increases slightly beginning at 370 ft (112.78 m), and the formation is slightly silty sand to 373.3 ft (113.78 m).

There is a major lithologic change in an interval of no recovery between 373.3 and 375.0 ft (113.78 and 114.30 m). The section changes from a silty sand above this surface to a shelly, glauconitic, granule-bearing sand below that continues to 403.3 ft (122.93 m). We tentatively place a sequence boundary at a gamma log kick at 374.0 ft (114.00 m) in the interval of no recovery and interpret the silty sands from 370 to 373.3 ft (112.78 to 113.78 m) as the TST of the overlying sequence (Fig. **F5**). Alternatively, the succession from 294.1 to 373.3 ft (89.64 to 113.78 m) could represent a very thick HST. Local well log correlations indicate that the 374.0-ft (114.00 m) surface is correlatable, supporting its interpretation as a sequence boundary. However, the facies shift from lower shoreface below to distal upper shoreface above could be explained simply as a facies shift due to shallowing upsection.

Mollusk shells become very common under this tentative sequence boundary. The shells range from large whole clams *(Mercenaria)* to coarse shell hash. Though glauconite appears in trace amounts in washed residues above this point (such as at 350 ft; 106.68 m), only below this level is it clearly present in visual inspection of the core. Phosphate also appears at this level and continues to 390 ft (118.87 m). The interval from the 374-ft (114.00 m) sequence boundary to 403.3 ft (122.93 m) is interpreted as representing deposition in lower shoreface environments.

The section from 405 to 449.4 ft (123.44 to 136.98 m) is composed of silty, shelly, homogeneous, heavily bioturbated sands with traces of glauconite (Fig. **F5**). The section becomes increasingly finer grained downward, with thinner shells and fewer quartz granules than in the overlying shelly sand. The abundance of shells further decreases below 415 ft (126.49 m), and the shells become thinner-walled and smaller. Lignite and mica are present in trace amounts in this interval, and the lignite becomes more common and coarser (up to 1.5 cm) downsection. At 438 ft (133.50 m) the amount of silt in the core increases, and below 445 ft (135.67 m) the sediments are dominantly silt. The base of this interval from 449.1 ft to 449.4 ft (136.89 to 136.98 m) includes clays burrowed up from the underlying interval. Overall, the sediments from 405.0 to 449.4 ft (123.44 to 136.98 m) indicate quiet offshore/middle neritic environments that reflect deeper paleodepths than the overlying interval. Thus, the section from 449.4 to 374.0 ft (136.98 to 114.00 m) is interpreted as an upward-shoaling HST succession.

St. Marys Formation

Age: late Miocene
Interval: 449.4–575.2 ft (136.98–175.32 m)

The St. Marys Formation was established in Maryland by Shattuck (1902) and first recognized in Delaware by Rasmussen et al. (1960) as an important Miocene aquitard in Sussex County. It is characterized by glauconitic laminated to burrowed sandy and silty clays (Andres, 1986; Ramsey, 1997) and is an overall finer-grained unit than the Manokin. In many places, it appears to gradually coarsen upward into the Manokin formation (Andres, 1986). In this borehole (Fig. **F5**), the formation boundary is a distinct contact at 449.4 ft (136.98 m) where a bioturbated surface separates very fine sandy silt of the basal Manokin formation from the slightly silty clay of the St. Marys Formation. Burrows are up to 1 cm (0.03 ft) wide and extend down from the contact to 450.25 ft (137.24 m) and up to 449.1 ft (136.89 m) in the overlying sequence. This contact could be interpreted as a sequence boundary or MFS. We favor the latter because there is an erosional surface slightly lower in the section, at 452.45 ft (137.91 m), associated with a distinct gamma log kick that appears to be the sequence boundary. This possible sequence boundary at 452.45 ft (187.91 m) separates slightly glauconitic (with medium-coarse glauconite) shelly clay above from laminated brown clay below. From the contact at 452.45 ft (137.91 m), brown clays are burrowed up to 451 ft (137.46 m) and glauconitic clays are burrowed down to 454 ft (138.38 m).

The section below the sequence boundary, from 452.45 to 515.6 ft (137.91 to 157.15 m), is a uniform, generally laminated clay to silty clay with scattered shells (mostly gastropods) and numerous shell concretions developed around burrows. Concretions are Fe and S rich, weathering to Fe- and S-stained rinds on the core near the concretions. Scattered very fine glauconite and traces of mica are present in the clay to silty clay. Burrows break up the laminations, especially between 452.45 and 454.0 ft (137.91 and 138.38 m); below this laminations are better preserved. The depositional environment of this section is not clear; the dominance of *Pseudononion pizarrensis* in the foraminiferal fauna (paleodepth = 25–50 m; see **"Biostratigraphy,"** p. 35) favors a starved outer inner to inner middle neritic environment. The dominance of gastropods, the numerous concretions, and the laminations suggest a low-oxygen benthic environment. The absence of sands could be attributed either to erosional truncation of the sandy part of an upper HST or to sediment starvation. We favor the latter interpretation based on the upsection decrease in gamma log values, suggesting shallowing upsection, and on the lack of evidence for a major erosional truncation (e.g., rip-up clasts and hardgrounds).

A minor concentration of glauconite and shells at 479.15 ft (146.04 m) is associated with a minor gamma ray log peak. We do not interpret this as a sequence boundary but instead as a parasequence boundary associated with a minor flooding surface. A similar gamma log peak at 457–458 ft (139.29–139.60 m) could be interpreted as another flooding surface; it is expressed as a minor increase in glauconite in the core. Uniform, generally laminated clay continues to 515.5 ft (157.12 m). A poorly recovered indurated interval (515.5–516.2 ft; 157.12–157.34 m) with carbonate cement and scattered phosphate? grains may mark the MFS within this sequence. Below this, a silty glauconite sand (520.0–523.05 ft; 158.50–159.43 m) represents a TST deposited in middle neritic environments. Large shells are present at 522–522.7 ft (159.11–159.32 m).

A distinct sequence boundary is placed at 523.05 ft (159.43 m) (Fig. F5) at the top of an indurated zone (523.05–523.8 ft; 159.43–159.65 m). Glauconite sand is extensively burrowed down into underlying clays to 524.2 ft (159.78 m), obscuring the contact. Glauconite sand-filled burrows extend down to 524.6 ft (159.90 m), with a few glauconite blebs burrowed down to 526 ft (160.32 m). The lithology below the contact is laminated, slightly silty clay with a few nodules and is slightly lighter gray (and probably less organic rich) than the clays in the overlying sequence. This is similarly interpreted as representing a starved low-oxygen middle neritic offshore environment.

Laminated clays continue down to 545.5 ft (166.27 m), with an increasingly silty section of silty clays and clayey silts down to 553.5 ft

(168.71 m). Glauconite content increases from ~1%–2% at the top of the silty interval to 2%–3% at the bottom (Fig. F5). The silts are underlain by a glauconite sand from 553.5 to 557.5 ft (168.71 to 169.93 m), which is in turn underlain by a stiff slightly silty micaceous clay that continues downward to 570.23 ft (173.81 m). The contact between the sand and the clay at 557.5 ft (169.93 m) is extensively burrowed, with large burrows extending 1.35 ft (0.41 m) down into the clay. Burrows are present throughout the underlying clay and generally increase in abundance downward. It is shelly and laminated in places and becomes harder downward. We interpret this clay interval as an offshore deposit representing outer inner to middle neritic paleodepths.

The nature of the surface at 557.5 ft (169.93 m) is not clear. Although it looks typical of many sequence boundaries in the coastal plain with a basal glauconite bed, the facies stacking pattern under it from 557.5 to 570.23 ft (169.83 to 173.81 m) is clearly transgressive, deepening upsection from upper shoreface to distal? upper shoreface to outer inner neritic or middle neritic offshore environments (Fig. F5). Thus, we interpret the surface at 557.5 ft (169.93 m) as a MFS, with the TST below. The MFSs identified thus far in the Bethany Beach borehole show much greater evidence for erosion than MFSs in New Jersey.

At 570.23 ft (173.81 m), the clays grade abruptly down to a muddy homogeneous sand with faint laminations and scattered chalky shell fragments with increasing bioturbation toward the top (Fig. F5). The sand is interpreted as a lower shoreface deposit. From 572.6 to 573.8 ft (174.53 to 174.89 m), the lithology changes to a shell bed with a poorly sorted quartz sand matrix. From 573.8 to 575.2 ft (174.89 to 175.32 m) is a cemented mollusk-rich sandstone with large shells (including *Pecten*) and a poorly sorted quartz sand matrix deposited in upper shoreface environments overlying a fine-medium slightly clayey sand (580–581 ft; 176.78–177.09 m) with common shell fragments deposited in upper shoreface environments. We interpret a sequence boundary below the sandstone at 575.2 ft (175.32 m), associated with a sharp gamma ray peak in an unrecovered interval (575.2–580 ft; 175.32–176.78 m).

Choptank Formation

Age: middle–late Miocene
Interval: 575.2–819.9 ft (175.32–249.91 m)

The Choptank Formation was defined by Shattuck (1902) in Maryland as a division of the Chesapeake Group based on lithology and fossil content. Rasmussen et al. (1960) first applied the name Choptank Formation in Delaware to the part of the Miocene that includes important aquifers near the town of Milford. It is a sandier unit than either the overlying St. Marys Formation or the underlying Calvert Formation (Ramsey, 1997) and is characterized as interbedded fine to coarse sand, shell, silt, and some clay (Benson, 1990).

The contact between the St. Marys and Choptank Formations is placed at 575.2 ft (175.32 m) at the top of an unrecovered interval (575.2–580 ft; 175.32–176.78 m) across which the section changes from predominantly silty to significantly sandy (Fig. F6). From 580 to 581 ft (176.78 to 177.09 m) is a thin bed of fine to medium sand. This is underlain by a gravelly silty sand from 581 to 584 ft (177.09 to 178.00 m) that was deposited in upper shoreface to lower estuarine environments.

Sediments from 584 to 593 ft (178.00 to 180.75 m) are laminated sand and sandy clayey silt with common shells and bioturbation disrupting laminae. These are interpreted as distal upper shoreface deposits, from a slightly deeper environment than the overlying gravelly sand. This is underlain by an interval of heavily bioturbated sands from 593 to 606.75 ft (180.75 to 184.94 m) that contains scattered clay laminae, discrete clay-lined burrows, rare cross laminae, and shell fragments. These sands reflect further deepening downsection from distal upper shoreface to lower shoreface. Overall, the entire interval from 581 to 606.75 ft (177.09 to 184.94 m) appears to comprise a shallowing-upward succession. This succession is underlain by a shell bed at 606.75 ft (184.94 m). The gamma log kick evident at this contact can be traced in southern Delaware, suggesting that it may be a sequence boundary (Fig. F6). However, there is little evidence in the Bethany Beach borehole for erosion at this level, and thus this surface may instead represent a flooding surface at the top of a parasequence that can be traced regionally.

The shell bed at the top of this succession (606.75–607.4 ft; 184.94–185.14 m) has abundant fragments of thick shells in a medium sand matrix and is underlain by medium sands down to 620 ft (188.98 m). Fine to very coarse sands predominate from 620 to 630 ft (188.98 to 192.02 m), passing back to medium sands from 630 to 635.5 ft (192.02 to 193.70 m). Shells are less common below the shell bed at the top, but fragments become more common toward the bottom of this interval. The sands from 606.75 to 616.15 ft (184.94 to 187.80 m) are clean and interpreted as upper shoreface deposits; sands below, from 616.15 to 635.5 ft (187.80 to 193.70 m), contain thin silt laminae and were deposited in slightly deeper distal upper shoreface environments (Fig. F6).

Between 635.5 and 645 ft (193.70 and 196.60 m), the section is silt interbedded with sand and scattered shells and becomes progressively silty downsection (Fig. F6). These deposits represent lower shoreface environments that progressively shallow upsection. Below the silt is shelly, silty, phosphatic sand (645–647.5 ft; 196.60–197.36 m) with a shell bed between 647.5 ft and 648.3 ft (197.36 and 197.60 m). The environment of deposition of the shell bed is uncertain; it could be an upper shoreface environment, implying deepening above it, or a mid-shelf condensed section (Kidwell, 1984), implying shallowing upsection. We consider it likely that a sequence boundary is present in the interval of no recovery between 648.3 and 649 ft (197.51 and 197.82 m); we place the boundary at 649 ft (197.82 m) associated with a minor gamma log peak. This placement implies that the shell bed represents part of the transgression above the sequence boundary.

Granuliferous silty sand with common phosphate and shell fragments is present from 649 to 662.5 ft (197.82 to 201.93 m) below the sequence boundary. These sands differ those above by the presence of shell fragments instead of whole shells and by their poorly sorted rather than moderately sorted character. An irregularly cemented zone is present from 656 to 661.5 ft (199.95 to 201.63 m), and a hard indurated layer is present from 661.5 to 662.5 ft (201.63 to 201.93 m). This interval represents deposition in upper shoreface to estuarine environments, reflecting shallower depths and higher energy than above.

Below a coring gap from 662.5 to 670 ft (201.93 to 204.22 m), the core is composed of finer sediments than above, with laminated sands and silts (670–686 ft; 204.22–209.09 m) fining downward to silt (686.3–687.0 ft; 209.18–209.40 m). Drilling disturbance obscures the section from 687.0 to 690 ft (209.40 to 210.31 m). The interval from 670 to 677.5 ft (204.22 to 206.50 m) reflects deposition in the upper shoreface

(Fig. F6). From 677.5 to 690 ft (206.50 to 210.31 m), the section is interpreted as distal upper shoreface transitioning downsection to lower shoreface silts. Below that, the section is again sandy and consists of shelly medium sands to sandy shell layers that contain abundant phosphatized shell fragments between 690 and 694.1 ft (210.31 and 211.56 m) and are hard to weakly cemented in places. They represent deposition in lower shoreface environments.

Below these cemented sands, a facies change occurs in an unrecovered interval (694.1–700 ft; 211.56–213.36 m) associated with a minor gamma log increase and a major break in Sr isotopic ages (see **"Strontium Isotope Chronostratigraphy,"** p. 44). A sequence boundary is placed at 698.5 ft (212.90 m). The section immediately under this inferred sequence boundary (700–703.2 ft; 213.36–214.34 m) is composed of shelly, heavily bioturbated, medium to fine silty sands. The environments above and below this inferred sequence boundary are interpreted as lower shoreface, but the facies under it differ in the greater degree of burrowing, the less cohesive texture, and the more common occurrence of glauconite and shells. The glauconite grains are generally the same size as or smaller than the quartz grains, possibly indicating that the glauconite grains are reworked. The sediments contain abundant sulfur, and many grains have a limonitic coating that may reflect subaerial exposure.

Under the burrowed bed at the top of the sequence the sands fine slightly to fine-grained and burrowing is less common (710–719.45 ft; 216.41–219.29 m). Indistinct silt laminae are present, but the finer material is mostly mixed with the sand by bioturbation. Between 720 and 750.3 ft (219.46 and 228.69 m) the lithology becomes finer, changing to fine to very fine slightly shelly burrowed sands interlaminated with silts (Fig. F6). This fining downsection represents a deepening downsection within lower shoreface (700–750.3 ft; 213.36–228.69 m) environments. Heavily burrowed, slightly clayey, less shelly silt predominates from 750.3 to 765 ft (228.69 to 233.17 m). The shift to silts at 750.3 ft (228.69 m) is abrupt and represents a change to offshore environments. Sands are burrowed down in the silt to 751.5 ft (229.06 m). *Pseudononion pizarrensis* dominates a generally low-diversity biofacies in most of this interval (721, 726, 751, 756, and 766 ft; 219.76, 221.28, 228.90, 230.43, and 233.48 m), indicating inner neritic (~30 m) paleodepths. A gamma log peak between 753 and 755 ft (229.51 and 230.12 m) is inferred as the MFS. The identification of the MFS is supported by recovery of an especially diverse foraminiferal fauna at 753.9 ft (229.79 m), suggestive of outer inner neritic to inner middle neritic paleodepths (~50 m).

Fine to very fine sands are interlaminated with silts from 765 to 765.9 ft (233.17 to 233.45 m). Shelly, extensively bioturbated fine to very fine sands predominate from 765.9 to 779.1 ft (233.45 to 237.50 m), becoming increasing shelly and sandy downsection. The section from 765 to 779.1 ft (233.17 to 237.50 m) was deposited in lower shoreface environments that shallow downsection. Interbedded cemented sands, sandy shell hash, and silty sands with scattered shells from 780 to 785.3 ft (237.74 to 239.36 m) were deposited in distal upper shoreface environments. Shells are concentrated in layers, and below 766 ft (233.48 m) some are dark and possibly phosphatized. Thin (0.2 ft; 6 cm) indurated zones are found between 776.5 and 792 ft (236.68 and 241.40 m). The section from 776.5 to 785.3 ft (236.68 to 239.36 m) is silty vs. cleaner sand below. From 785.3 to 787.1 ft (239.36 to 239.91 m), a silty, rubbly, shelly sand with fragments of cemented sandstone and sand steinkerns was deposited in upper shoreface environments. Thus, the section from 755 to 787.1 ft (230.12 to 239.91 m) deepens upsection, comprising the TST.

Clean, proximal upper shoreface/foreshore sands underlie a surface at 787.1 ft (239.91 m). We place a sequence boundary at 787.1 ft (239.91 m) based on (1) a change in stacking pattern from progradation/aggradational below to retrogradational above and (2) a sharp gamma log kick. The physical expression of the sequence boundary in the core is poorly expressed because the upper shoreface/foreshore sands are reworked/ripped up into upper shoreface environments (Fig. F3).

Clean, well sorted fine-medium sands with scattered silt and heavy mineral laminae (some cross laminae) continue from the sequence boundary at 787.1 to 804.55 ft (239.91 to 245.23 m), with interbedded indurated zones including a sandy molluscan limestone (792–793.5 ft; 241.40–241.86 m) (Fig. F6). A calcite-cemented shelly sandstone and interbedded fine sands was poorly recovered (805–812.5 ft; 245.36–247.65 m). It overlies a fine to medium quartz sand with shell debris (812.5–814.9 ft; 247.65–248.38 m). Below a coring gap (814.9–819 ft; 248.38–249.63 m), a calcareous sandstone (819–819.9 ft; 249.63–249.91 m) overlays a sandy, clayey silt (819.9–888.7 ft; 249.91–270.88 m). Silty sands above 819.9 ft (249.91 m) were deposited in lower shoreface environments as part of the upper HST; the silts below represent offshore environments and comprise the lower HST. The sands from 787.5 to 819.9 ft (240.03 to 249.91 m) correlate updip with the local Milford aquifer. The base of this sandy interval marks the base of the Choptank Formation and is underlain by siltier facies of the Calvert Formation.

Calvert Formation

Age: early–middle Miocene
Interval: 819.9–1420 ft (249.91–732.82 m)

The Calvert Formation was defined by Shattuck (1902) in Maryland as a division of the Chesapeake Group based on lithology and fossil content and was first recognized in Delaware by Rasmussen et al. (1960). It is characterized by interbedded silt, sand, and clay with common shells (Benson, 1990; Ramsey, 1997) and is overall finer grained than the overlying Choptank Formation. The Choptank/Calvert boundary is picked in the borehole at 819.9 ft (249.91 m) at the change from the predominantly sandy section to predominantly silt (Fig. F6).

Sandy, clayey, laminated (including cross laminations) to bioturbated silt with scattered to rare shells characterizes the upper Calvert Formation from 819.9 to 887.7 ft (249.91 to 270.57 m). This interval was deposited in inner neritic environments and comprises the lower part of the sequence identified in the lower part of the Choptank Formation. The section becomes finer downward in this interval, with sand decreasing from ~40% of the section to ~10% at 880 ft (268.22 m). The silts are indurated from 851.65 to 853.75 ft (259.58 to 260.22 m). The MFS is interpreted at 887.7 ft (270.57 m) at a burrowed contact. Below the MFS from 887.7 to 888.7 ft (270.57 to 270.88 m) and coring gap, 889–889.45 ft (270.97–271.10 m), the amount of shell and sand increases as the section becomes a darker, sandier shelly silt. Heavily bioturbated fine silty sand with rare to scattered shells is present from 889.45 to 897.7 ft (271.10 to 273.62 m). A heavily burrowed contact

(897.7–898.0 ft; 273.67–273.71 m) separates silty fine sand above from medium sand below, with silty fine sand burrowed down to 899.2 ft (274.08 m). The contact is interpreted as a sequence boundary and is tentatively placed at 897.7 ft (273.62 m) at the level of a sharp gamma ray peak (Figs. F3, F6).

Cemented and unconsolidated sands characterize the upper HST of the underlying sequence (897.7–926.6 ft; 273.62–282.43 m) (Fig. F7). A number of calcite-cemented layers were encountered below 900 ft (274.32 m): 901.5–902.8, 911.35–914, 922.2–923.05, 924.1–926 (irregular), and 931.9–932.4 ft (274.78–275.17, 277.78–278.59, 281.09–281.35, and 281.67–282.24 m). The sands contain shells and shell fragments, with the indurated zones containing the most shell material. The sands were deposited in distal upper shoreface environments.

Clayey silty sands from 926.6 to 932.4 ft (282.43 to 284.20 m) contain thin-walled shells deposited in lower shoreface environments. Below a coring gap (932.4–940 ft; 284.07–286.51 m) is an interval of clayey sand representing distal upper shoreface environments (940.5–940.9 ft; 286.66–286.79 m). This is underlain by more proximal upper shoreface deposits that include silty sand with abundant shell debris (940.9–942.5 ft; 286.79–287.27 m) and granuliferous silty shelly sand (942.5–947 ft; 287.27–288.65 m), both of which include barnacles and bone phosphate. A large clay-infilled burrow is present at the contact between clayey sand and the shelly sand (940.9 ft; 286.79 m); the contact is interpreted as a flooding surface.

Another calcite-cemented sandstone was encountered from 945 to 945.3 ft (288.04 to 288.13 m), with partly cemented sand continuing to 947 ft (288.65 m). These are interpreted as upper shoreface deposits (Fig. F7). They are underlain from 947 to 950.5 ft (288.65 to 289.71 m) by silt with common interbedded shelly sands that represent distal lower shoreface to offshore environments. A contact at 950.5 ft (289.71 m) marks another FS where these lower shoreface silts overlie upper shoreface sands. From 950.5 to 953.5 (289.71 to 290.63 m), the section is silty sand with granule-sized fragments of thick shells and phosphate. This is underlain by clayey sand (953.5–954.9 ft; 290.63–291.05 m), with a thin interbedded shell hash (954–954.15; 290.78–290.82 m), and a cemented shell hash with sand (954.9–956.25 ft; 291.05–291.47 m), also interpreted as promixal upper shoreface deposits. The section fines downward. Silty sand from 956.25 to 958.45 ft (291.47 to 292.14 m) represents distal upper shoreface environments. From 960 to 964 ft (292.61 to 293.83 m), the section is laminated to slightly cross laminated sandy silt deposited in inner neritic/offshore/distal lower shoreface environments (*Pseudononion pizarrensis* biofacies; ~25–50 m paleodepth). Below 964 ft (293.83 m), the section becomes sandier and a secondary gamma log peak at 964 ft (293.83 m) is interpreted as an MFS. The underlying sediments are silty sands (964–967 ft; 293.83–294.74 m), passing to mottled tan and blue-gray clayey silts (967 ft; 294.74 m), and then to a sulfur-bearing silty interval (968–970 ft; 295.05–295.66 m). The environment of this section is enigmatic. It could be interpreted as representing lagoonal environments, based on the presence of sulfur, or as lower shoreface to offshore, based on stratigraphic succession and the interbedding of sand and silts. The presence of marine to marginal marine dinoflagellates supports an interpretation of lower shoreface to offshore environments (see "Biostratigraphy," p. 35).

Very fine to fine sands dominate from 970 to 977.4 ft (295.66 to 297.91 m), with clayey and silty sand in the upper part (970–971.1 ft;

295.66–295.99 m) and silty sand below (Fig. F7). There are a few laminations in this generally well-bioturbated interval. These sands represent lower shoreface environments. They are underlain by slightly silty fine to medium sands with shells and shell fragments (980–981.3 ft; 298.70–299.10 m) that also represent lower shoreface environments. These silty sands pass downward into a calcite-cemented sand layer with shells (981.3–981.5 ft; 299.10–299.16 m) and a sandy shell hash (981.5–983.8; 299.16–299.86 m) deposited in upper shoreface environments. Between 983.8 and 995.1 ft (299.86 and 303.31 m), cemented shelly sands (983.8–985.0, 986.7–988.0, 991.65–992.3, and 994.0–995.1 ft; 299.86–300.23, 300.75–301.14, 302.25–302.45, and 302.97–303.31 m) alternate with shell hash facies (985–986.7, 988.0–991.65, and 992.3–994 ft; 300.23–300.75, 301.14–302.25, and 302.45–302.97 m). A shelly, slightly silty sand from 995.1 to 996.5 ft (303.31 to 303.73 m) has clay laminations. We interpret the facies from 996.5 to 981.3 ft (303.73 to 299.10 m) to represent upper shoreface environments, with a clear overstepping to distal lower shoreface environments at 981.3 ft (299.10 m).

It is clear that a sequence boundary should be picked somewhere in the turnaround of stacking patterns between the progradational section below 1000 ft (304.80 m) and the clear deepening above 970 ft (295.66 m). Based on deepening of paleoenvironments, a slight increase in gamma log values, and a clear decrease in resistivity values, we prefer to place a sequence boundary at 981.3 ft (299.10 m). The overlying section from 981.3 to 964 ft (299.10 to 293.83 m) would represent a TST succession deepening from lower shoreface to offshore environments. The section under the sequence boundary from 981.3 to 1000 ft (299.10 to 304.8 m) was deposited in upper shoreface environments as part of the HST of the underlying sequence.

The section from 1000 to 1050.85 ft (304.8 to 320.30 m) generally shows a fining and deepening trend downsection (Fig. F7). Well-sorted, clean medium-fine sand with scattered coarse shell fragments and interspersed clayey silt laminae (1000–1007 ft; 304.8–306.93 m) grades down to relatively homogeneous, predominantly fine silty sand with shell fragments and common thin clayey silt laminae (1007–1021 ft; 306.93–311.20 m). Heavily bioturbated, predominantly fine sands with numerous clay/silt laminations (1021–1046 ft; 311.20–318.82 m) are more heavily bioturbated in the upper part and more laminated in the lower, with a general increase in grain size upsection. These silty sands represent proximal lower shoreface environments. Under this, a shelly fine to very fine lower shoreface silty sand (1046–1048 ft; 318.82–319.43 m) overlies clayey silt with scattered sand laminae, scattered thin shell laminae, and scattered bioturbation (1048.0–1050.6 ft; 319.43–320.22 m) deposited in offshore environments.

A contact at 1050.6 ft (320.22 m) separates silts with sand laminae above from very fine to fine sand with scattered shell debris below (1050.6–1050.8 ft; 320.22–320.28 m). The surface at 1050.6 ft (320.22 m) is a FS, perhaps the MFS, and thus the overlying silts (1048–1050.6 ft; 319.43–320.22 m) would represent the lower HST and the sands above 1048 ft (319.43 m) the upper HST. Below the FS is a hard, slightly glauconitic, slightly shelly, silty fine sand (1050.8–1052.6 ft; 320.28–320.83 m). The sand grades to a hard, mottled, burrowed silt with scattered shells (1052.6–1054.5 ft; 320.83–321.41 m), a hard clayey silt with faint laminae (1054.5–"1055.45" ft; 321.41–"321.70" m), and a silty sand (1055–1056.35 ft; 321.56–321.98 m). This is underlain by a dolomite-cemented, silty, very fine sand (1057–1057.8 ft; 322.17–322.42 m) and a light-colored slightly sandy silt (1057.8–1057.95 ft; 322.42–322.46 m). The interval from 1050.8 to 1057.95 ft (320.28 to 322.46 m) appears to represent deposition in a distal lower shoreface setting. This interval comprises the TST of the sequence.

A distinct contact at 1057.95 ft (322.46 m) is heavily bioturbated and separates the indurated sands above from distinctly different mottled burrowed facies below (Fig. F7). A silty clay bed just below this surface (1057.95–1058.05 ft; 322.46–322.49 m) grades down to an underlying mottled yellow and gray clayey silty very fine sand with burrows surrounded by iron staining (1058.05–1058.2 ft; 322.49–322.54 m). This is underlain by a mottled silty very fine sand with 2%–3% glauconite (1058.2–1058.75 ft; 322.54–322.71 m) that weathers to a mottled rusty brown with gypsum crystals on the surface, followed by more mottled yellow and gray clayey silty very fine sand (1058.75–1059 ft; 322.71–322.78 m). Together, these features suggest that this interval (1057.95–1059 ft; 322.46–322.78 m) was deposited in distal lower shoreface environments, with the mottled appearance between 1058.05 and 1059.0 ft (322.49 and 322.78 m) as evidence for extended submarine or subaerial exposure.

We interpret the surface at 1057.95 ft (322.46 m) as a sequence boundary (Fig. F3). The sharp contact marks a stacking pattern change from regressive distal lower shoreface below to transgressive lower shoreface sands and offshore silts above. This is supported by the evidence of extended exposure just under this surface from 1057.95 and 1059 ft (322.46 and 322.78 m).

Burrowed silty very fine sand with scattered shell fragments (1059–1064 ft; 322.78–324.31 m) grades down to a sandy silt (1065–1109 ft; 324.61–338.02 m) (Fig. F7). These sands comprise the upper HST of the sequence. The section from 1077 to 1109 ft (328.27 to 338.02 m) consists of a laminated dark gray very fine sandy clayey silt. The fine sand decreases downsection, with small shell fragments increasing below 1086 ft (331.01 m) from rare to somewhat common. The section from 1109 to 1112.45 ft (338.02 to 339.07 m) becomes slightly sandy and shelly. Laminated silts with very fine sand containing scattered shell fragments and some foraminifers continue from 1112.45 to 1143.7 ft (339.07 to 348.60 m). Shells become rare toward the base of this section. Clay content increases downsection, becoming laminated clayey silt from 1143.7 to 1152 ft (348.60 to 351.13 m). At 1152 ft (351.13 m), there is a gradational change to a glauconitic, shelly, silty sand down to 1152.55 ft (351.30 m). Below an unrecovered interval (1152.55–1153.5 ft; 351.30–351.59 m) is a medium to coarse quartz sand with some granules that contains large broken shell fragments in the upper 0.5 ft (0.15 m) (1153.5–1154 ft; 351.58–351.74 m). The major shift in lithofacies between cores from silty glauconitic sand above to coarse quartz sand below associated with a large gamma ray log kick suggests that the contact was not gradational but abrupt and in the unrecovered interval (1152.55–1153.5 ft; 351.30–351.58 m). We interpret this shift as a sequence boundary (1153 ft; 351.43 m) separating TST silts above from HST sands below (Fig. F7).

A thick sand interval from 1153.5 to 1227 ft (351.58 to 373.99 m) is interpreted as a HST succession (Fig. F8). The uppermost part (1153.5–1170.4 ft; 351.58–356.74 m) consists of clayey, silty, coarse, heavily bioturbated quartz sands. Below this (1170.4–1184.9 ft; 356.74–361.16 m), clayey, silty sands are interbedded with cleaner, though poorly sorted, heavily bioturbated dry sands. These upper HST sands (1153–1184.9; 351.43–361.16 m) were deposited in upper shoreface environments. Silt increases from 1184.9 to 1187.5 ft (361.16 to 361.95 m), reflecting a slightly deeper water environment (proximal lower shoreface). Below an interval of no recovery (1187.5–1196.7 ft; 361.95–364.75 m), silty mottled medium sands with scattered flat to inclined silty clay laminae (1196.7–1201 ft; 364.75–366.06 m) also represent proximal lower shoreface environments.

Mottled, heavily bioturbated olive-gray very silty/clayey sands between 1210 and 1213.4 ft (368.81 and 369.84 m) contain thin (~0.2 ft; 6 cm) silt interbeds (Fig. F8). The section is siltier and somewhat clayey from 1213.4 to 1216.5 ft (369.84 to 370.79 m). The sands from 1210 to 1213.4 ft (368.81 to 369.84 m) were deposited in proximal lower shoreface environments, whereas the siltier section from 1213.4 to 1216.5 ft (369.84 to 370.79 m) was deposited in distal lower shoreface environments. The sands above 1216.5 ft (370.79 m) comprise the Cheswold aquifer farther north in Delaware. An interesting interval is present between 1216.5 and 1217.0 ft (370.79 and 370.94 m), where there is mixture of light-colored silts from above the contact (1216.5 ft; 370.79 m) and darker silts from below the contact. Clasts in this interval could be either indurated rip-up clasts or burrows. In either case, it is clear that this surface is one of marine omission and heavy bioturbation. We interpret this surface as a FS (parasequence boundary), though not the MFS of the sequence between 1153 and 1421.14 ft (351.43 and 401.56 m).

Homogenous olive-gray very muddy sands extend from 1217 to 1225.7 ft (370.94 to 373.59 m) and were deposited in distal lower shoreface environments (Fig. F8). Grain size gradually decreases in this interval, with scattered shells in the lower part. Heavily bioturbated, sparsely shelly sandy silts with traces of glauconite throughout predominate from 1225.7 to 1343.7 ft (373.59 to 409.56 m), marking the top of offshore deposits representing the lower HST. The silt is sandier near the top (up to ~40% sand), with fine sand generally decreasing downsection to ~1315 ft (400.81 m), reflecting shallowing upsection in offshore environments. The silt is broken by a number of interesting horizons. A ~1-ft-thick (0.30 m thick) calcite-cemented indurated zone (1237.2–1238.15 ft; 377.10–377.39 m) is composed of sandy silt similar to the unconsolidated material above and below. A 0.1-ft (3 cm) sand bed was recovered from 1272.25 to 1272.35 ft (387.78 to 387.81 m), and very thin sand stringers are present below 1280 ft (390.14 m). An interval of very abundant shells is present between 1291 and 1293.7 ft (393.50 and 394.32 m), with the main clayey shell bed present between 1292 and 1293.2 ft (393.80 and 394.17 m). A surface at 1317.45 ft (401.56 m) is present just below a 0.15-ft-thick (4.5 cm thick) cemented sand layer that is overlain by a condensed interval between 1315.8 and 1317.3 ft (401.06 and 401.51 m). The condensed interval is marked by abundant shells and phosphatized burrows. Dark olive-gray silts return below the sharp contact at 1317.45 ft (401.56 m). This contact may be either a FS of a thick sequence between 1153 and 1421.3 ft (351.43 and 433.21 m) or a higher-order sequence boundary.

Below the surface at 1317.45 ft (401.56 m), sandy silts predominate and the section shoals downward from offshore to distal lower shoreface. The section from 1317.45 to 1320.3 ft (401.56 to 402.43 m) is heavily bioturbated, irregularly indurated silt with thin interlaminated sand. Dolomite-cemented, slightly shelly siltstone is present between 1320.3 and 1320.8 ft (402.43 and 402.58 m). Laminated sandy silts (1320.8–1322.9 ft; 402.58–403.22 m) overlie heavily bioturbated, slightly micaceous sandy silts with a few thin sand laminae and rare shell fragments (1322.9–1343.75 ft; 402.95–409.58 m). Burrows in this section tend to have sandy fill. Silts below ~1320 ft (402.34 m) appear to be slightly richer in fine-grained glauconite (Fig. F8). The interval from 1343.75 to 1355 ft (409.58 to 413.00 m) consists of bioturbated homogeneous sandy silt to silty sand. From 1355 to 1400 ft (413.00 to 426.72 m), laminae are better preserved in silts with interlaminated very fine sands that display low-angle cross laminations and truncated lamination. We interpret the section from 1317.45 to 1343 ft (401.56 to 409.35 m) as representing offshore environments and the section from 1343 to 1393 ft (409.35 to 424.59 m) as distal lower shoreface environments, though the transition between the two is gradual. The section from 1393 to 1400 ft (409.35 to 426.72 m) is interpreted as offshore.

The section from 1400 to 1420 ft (426.72 to 432.82 m) deepens downsection (Fig. F8). Homogeneous, faintly laminated, micaceous, slightly sandy silt (1400–1410 ft; 426.72–429.77 m) overlies silts with common (every 0.5–1.5 ft; 0.15–0.45 m) clay laminae, some sandy laminae, and more abundant glauconitic burrows (1410–1420 ft; 429.77–432.82 m). These sediments represent offshore environments. Foraminifers in a sample at 1411.0 ft (430.07 m) suggest depths from deep inner neritic to middle neritic (~30–50 m). High values are evident on the gamma log at the base of this unit between 1418 and 1420 ft (432.21 and 432.82 m), reflecting the increasing clay and glauconite comment. The MFS is interpreted to be somewhere in this interval, probably associated with a secondary gamma log peak at 1418 ft (432.21 m), supporting the interpretation of the surface at 1317.45 ft (401.56 m) as a FS rather than a MFS.

We place the base of the Calvert Formation at the top of the glauconitic sandy silt at 1420 ft (432.82 m) (Fig. F8). As recognized in Delaware, the Calvert Formation is a unit of silts and sands that is finer grained and less shelly than the overlying Choptank Formation. Generally, the Calvert Formation has no more than trace glauconite. Where more abundant glauconite is found in the lower Miocene section, it has been separated as different units, such as the "Unnamed Glauconitic Sand" and "Unnamed Glauconitic Silt" of Benson (1990). The glauconitic sandy silt at 1420 ft (432.82 m) at Bethany Beach provides a distinct lithologic and gamma log break and thus a reasonable place to locate the formational boundary. It is also worth noting that the lower part of the Calvert Formation at this site (from ~1290 to 1420 ft; 393.19 to 432.82 m) appears to correlate to the significantly more glauconitic facies of the "Unnamed Glauconitic Sand" of Benson (1990) in the Oh25-02 well, which is ~10 mi north near Lewes, DE.

Unnamed Glauconitic Clays and Clayey Glauconite Sands

Age: early Miocene
Interval: 1420.0–1465.7 ft (432.82–446.75 m)

This unnamed lithologic unit consists of clayey glauconitic sands, clayey glauconitic silts, clay, and glauconitic clay (Fig. F8). The top of this unit is a thin, glauconitic, heavily bioturbated silt from 1420 ft (432.82 m) to a sequence boundary at 1421.1 ft (433.15 m). Burrows containing glauconitic clay extend ~1 ft (0.30 m) below the boundary. Below the sequence boundary at 1421.1 ft (433.15 m) is an olive, faintly laminated clay unit that extends to 1428.3 ft (435.35 m). These are offshore deposits; foraminifers at 1422.0 ft (433.54 m) suggest water depths of ~50 m. A contact zone between 1429.0 and 1431.25 ft (435.56 and 436.25 m) is disturbed by drilling in the upper 0.7 ft (0.21 m); the lithology of the zone is indurated clayey glauconitic sand. The glauconite sand appears in situ down to 1430.5 ft (436.02 m), with reworked clay above and piped-down glauconite sand below. We interpret the contact at 1430.5 ft (436.02 m) as a lower Miocene sequence boundary (Fig. F3). The thin sequence from 1421.1 to 1430.5 ft (433.15 to 436.02 m) thus consists of a thin glauconite TST and a silty lower HST; the upper HST sands appear to be truncated/absent.

The sequence boundary at 1430.5 ft (436.02 m) and underlying reworked contact zone (down to 1431.25 ft; 436.25 m) overlie a hard burrowed silty clay with disseminated shells and shell debris (1431.25–1447.35 ft; 436.25–441.15 m). This also represents offshore deposition, with foraminifers suggesting deepening downward from middle neritic depths (50–75 m) near the top of the sequence to deeper middle neritic or even outer neritic depths (80–100 m) in the lower part. Glauconite is burrowed down into this unit to 1432.4 ft (436.60 m) and reappears in trace abundances in laminated clayey silts (1432.4–1453 ft; 436.60–442.87 m), increasing downsection as the section changes to clayey glauconitic sands (1453–1454.5 ft; 442.87–443.33 m). The clayey glauconitic sands contain weathered brown glauconite/goethite, typical of Oligocene sediments in New Jersey (e.g., Miller et al., Chap. 2, this volume) and may represent part of a thin TST. We tentatively place a MFS at a secondary gamma log peak at 1445 ft (440.43 m).

A burrowed contact associated with a major gamma log peak is interpreted as a sequence boundary at 1454.5 ft (443.33 m) (Fig. F8). Clayey glauconite sand overlies glauconitic clay (1454.9–1457 ft; 443.45–444.09 m) at this surface, with large burrows of glauconite sand continuing down into the clay. The clay grades down into a clayey glauconite sand at 1457.0 ft (444.09 m) with "tricolored" (green, black, and brown) glauconite grains. Brown glauconite grains become less prominent or disappear and the glauconite becomes fine to medium grained below 1461.8 ft (445.56 m). The clays at the top of the sequence are interpreted as the HST and the underlying clayey glauconitic sand as the TST, making the contact at 1457.0 ft (444.09 m) the MFS. The base of the sequence is marked by a prominent sequence boundary at 1465.7 ft (446.75 m) that separates black glauconite sand above from a dark olive-gray foraminiferal clay below.

Unnamed Foraminiferal Clay

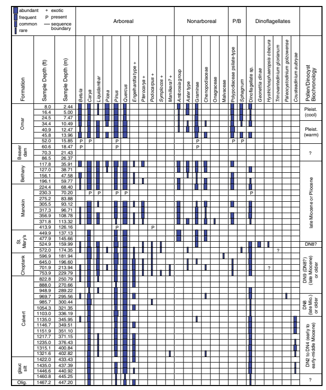
Age: Oligocene
Interval: 1465.7–1467.95 ft (446.75–447.43 m)

The section at the bottom of the hole (1465.7–1467.95 ft; 446.75–447.43 m) consists of a thinly laminated dark olive-gray foraminiferal clay (Fig. F8). The clay was deposited in an offshore setting, with foraminifers suggestive of an outer neritic paleoenvironment. It is lithologically similar to the Absecon Inlet Formation in New Jersey (upper Eocene) (Browning et al., 1997). Foraminiferal and Sr isotopic results indicate it is lower upper Oligocene.

BIOSTRATIGRAPHY

Palynomorphs

Samples were selected from the Bethany Beach corehole for palynological analysis based on lithologies that were most likely to yield spores, pollen, or dinocysts. Samples were subjected to standard processing methods, similar to those described in Traverse (1988). Dilute nitric acid was used for oxidation, which removes excess organic debris, but oxidation can lower the recovery of some protoperidinacean dinoflagellates, especially *Brigantedinium* (Hopkins and McCarthy, 2001; F.M.G. McCarthy, pers. comm., 2002). Relative abundances were determined for most samples between 8.0 and 753.9 ft (2.44 and 229.79 m) based on counts of ~300 specimens (Fig. F9). Relative abundances for samples at 449.9 and 477.9 ft (137.13 and 145.66 m) and from 822.8 to 1467.2 ft (250.79 to 447.20 m) are estimates based on thorough scans of the samples (counts not yet completed). Only the most abundant, clearly identifiable, and stratigraphically important forms are included in Figure F9. Less abundant taxa are not included on the figure because of difficulty in estimating their abundances in the samples that were not counted; however, most are noted in the text.



F9. Pollen and dinocysts, p. 65.

The pollen assemblages of the Omar Formation reflect a distinct change in climate through the deposition of the unit. Samples from the upper part of the Omar (8.0, 16.4, and 24.5, ft; 2.44, 5.00, and 7.47 m) contain a cool-climate assemblage dominated by *Pinus* (pine) and *Picea* (spruce). Other common constituents include *Betula* (birch), *Carya* (hickory), *Quercus* (oak), *Sphagnum* (moss), *Lycopodium* (clubmoss), Polypodiaceae (polypod fern family), Gramineae (grass family), and Cyperaceae (sedge family). In contrast, the pollen assemblages in the lower samples (34.4, 40.9, and 45.8 ft; 10.49, 12.47, and 13.96 m) reflect warmer conditions. *Pinus* and *Quercus* are the most abundant, with *Pinus* decreasing downward somewhat as *Fagus* (beech) becomes more abundant; *Picea, Sphagnum,* and *Betula* are absent or uncommon. Dinoflagellates are present in most of the samples from the Omar Formation, indicating estuarine or shallow-marine conditions. Other taxa present include *Abies* (fir), *Alnus* (alder), *Carpinus* (American hornbeam), *Castanea* (chestnut), *Liquidambar* (sweetgum), *Salix* (willow), *Tilia* (linden), *Tsuga* (hemlock), *Ulmus* (elm), TCT (Taxodiaceae-Cupressaceae-Taxaceae, or the bald cypress-cypress-yew families), Ericaceae (heath family), Caryophyllaceae (pink and chickweed family), Cheno-Ams (goosefoot and amaranth families), *Ambrosia*-group composites (ragweeds), and *Aster*-type composites (sunflowers and daisies).

All samples examined for palynomorphs in the Beaverdam Formation had very poor recovery or were barren.

Samples from the Bethany formation (117.8, 127.0, 156.1, and 196.1 ft; 35.91, 38.71, 47.58, and 59.77 m) have assemblages dominated by *Carya* and *Quercus,* with *Quercus* most abundant in the upper part of the unit and *Carya* most abundant in the lower part. *Liquidambar* (sweet gum) and *Pinus* are common, but the latter is less abundant than in the Omar Formation. The Bethany formation also includes several stratigraphically significant "exotic" taxa, plants that are extinct in eastern North America. Rare grains of *Pterocarya* (wing nut) and *Engelhardia*-type pollen have their highest occurrences at 117.8 ft (35.91 m) in the Bethany formation and are present in all Bethany samples studied. Groot (in Groot et al., 1990) considered the presence of such "exotic" taxa to be indicative of a pre-Pleistocene age. In addition, a single specimen of cf. *Dacrydium* (Huon Pine) was noted at 156.1 ft (47.58 m); this conifer is currently restricted to Asia, Australasia, and western South America but was recently noted in the Pliocene of Florida by Hansen et al. (2001). A variety of other palynomorphs are present in the Bethany formation: *Alnus, Betula, Carpinus, Castanea, Ilex, Salix,* TCT, *Tilia, Tsuga, Ulmus, Fagus, Juglans, Nyssa,* Gramineae, Caryophyllaceae, Cheno-Ams, *Ambrosia*-group composites, *Aster*-type composites, and Polypodiaceae. Rare dinoflagellates are present in most samples. Together these occurrences indicate that the Bethany formation is upper Miocene or Pliocene and was deposited under warm temperate conditions in an estuarine or shallow-marine environment.

The Manokin formation samples (224.4, 230.3, 305.5, 317.3, 356.9, 371.8, and 413.9 ft; 68.40, 70.20, 93.12, 96.71, 108.78, 113.33, and 126.16 m) have similar assemblages as the Bethany formation. *Quercus* and *Carya* are dominant and *Pinus* is common. *Liquidambar* is most abundant in the uppermost sample in the formation and *Carya* decreases in the lowermost sample (413.9 ft; 126.16 m). Rare exotics are present in most of the samples, with *Pterocarya* in most of the samples, *Engelhardia*-type pollen present at 356.9 ft (108.78 m), and *Podocarpus* (yew pine) pollen at 413.9 ft (126.16 m). *Epilobium* (willow herb and fireweed) and other Onagraceae are also present. Umbelliferae (carrot family) become a common component of the flora, and *Ambrosia*-group composites are more abundant than in the overlying formations. Many of the same less common constituents are present as in the Bethany formation, including *Alnus, Betula, Carpinus, Castanea, Salix,* TCT, *Tilia Ulmus, Fagus, Juglans,* Gramineae, Caryophyllaceae, Cheno-Ams, *Ambrosia*-group composites, and Polypodiaceae. Dinoflagellates are rare but present in these samples. Like the Bethany formation, these palynomorphs indicate that the Manokin formation is upper Miocene or Pliocene and was deposited under warm temperate conditions in an estuarine or shallow-marine environment.

Two samples in the upper part of the St. Marys Formation (449.9 and 477.9 ft; 137.13 and 145.66 m) have notably more abundant non-arboreal pollen than is present in the Manokin and Bethany samples. Although *Quercus* is the most abundant pollen in these samples, pollen from the family Compositae (sunflower family) are also very common. Other non-arboreal types are present, including family Gramineae (grasses) and Umbelliferae (carrot family), along with arboreal types *Pinus* and *Carya*.

In the lower sample (524.9 ft; 160.0 m) from the St. Marys Formation, *Quercus* becomes the dominant form and the abundance of non-arboreal pollen is reduced. *Carya* and *Pinus* are present, but the abundance of *Carya* is lower than in the section above. Exotic taxa present are rare and include *Pterocarya, Podocarpus, Symplocos* (sweet-leaf), and possible *Eucommia* (hardy rubber tree). Other pollen in the St. Marys Formation include *Alnus, Ilex, Salix, Tilia, Ulmus, Fagus,* and *Juglans*. The pollen assemblage appears to represent a warm-temperate climate based on comparison to previous work by Groot (1997). This sample also contains the highest stratigraphically significant dinoflagellates identified in the cores. The presence of *Hystrichosphaeropsis obscura* restricts this sample to no higher than the top of upper Miocene dinoflagellate Zone DN9 of de Verteuil and Norris (1996a). *Geonettia clinae* is common, a form that is restricted to Zone DN8 in the Cape May corehole (de Verteuil, 1997), although it has a longer known stratigraphic range (upper middle Miocene to upper upper Miocene) (de Verteuil and Norris, 1996b). These criteria, although not definitive, suggest that this sample should be placed in Zone DN8, with an age estimate of 8.6 to 11.2 Ma.

Similar pollen assemblages were identified from the uppermost sample from the Choptank Formation (572.0 ft; 174.35 m). *Quercus* dominates and *Carya* and *Pinus* are important components. Exotics are present but rare, including *Pterocarya, Podocarpus, Engelhardtia*-type, and *Symplocos*. Dinoflagellates are common, with *Polysphaeridium zoharyi* the most common. De Verteuil (1997) noted a similar change in dinoflagellate assemblages in the Cape May borehole, with common *Geonettia clinae* in upper Zone DN8 changing downward to predominantly *Polysphaeridium zoharyi* in lower Zone DN8. A poor specimen resembling *Trinovantedinium glorianum* was noted, which, if accurate, would place the sample no lower than mid-Zone DN7 and thus no older than ~12.4 Ma.

Below this, the upper two samples in the Choptank Formation (596.9 and 645 ft; 181.94 and 196.60 m) are dominated by *Pinus,* with abundant *Quercus* and common *Carya*. The assemblage changes in the lower two Choptank samples (701.9 and 753.9 ft; 213.94 and 229.79 m) to dominance by *Quercus,* with common *Pinus* and *Carya*. Of the exotic taxa, *Engelhardtia*-type pollen becomes significantly more abundant in this interval (notably at 645.0 ft; 196.60 m) than in the samples uphole. *Pterocarya* and *Podocarpus* are also present in most of these samples, and *Symplocos* and possible *Manilkara* pollen are present in a few samples. Other pollen noted in the Choptank Formation include *Alnus, Ilex, Liquidambar,* TCT, *Tilia, Tsuga, Ulmus, Fagus,* and *Nyssa*. Scattered dinoflagellate occurrences were noted, including a partial form probably attributable to *Hystrichosphaeropsis obscura* (last abundance datum [LAD] at top of Zone DN9) (de Verteuil and Norris, 1996a).

The assemblages in the Calvert Formation samples studied between 822.8 and 1321.6 ft (250.79 and 402.82 m) are dominated by arboreal forms and are similar to those in the Choptank Formation. *Quercus* is the most abundant pollen in the Calvert samples studied, with *Pinus* and *Carya* generally important in varying proportions downcore. *Carya* is notably abundant at 985.7 ft (300.44 m), and *Pinus* is abundant at 1103.0 ft (336.19 m). Exotic taxa are present and tend to be more common than in the overlying formations. *Engelhardia* is common in most samples, with scattered occurrences of *Podocarpus* and possible *Manilkara*. *Alnus, Ilex, Liquidambar,* TCT, *Tilia,* and *Ulmus* are also present, with some Cheno-Ams and Gramineae. These pollen findings are consistent with those reported from the Calvert Formation in central Delaware by Groot (1992), who concluded that these assemblages are dominantly temperate and warm-temperate types but with the consistent presence of subtropical or tropical taxa, reflecting a setting similar to the modern Atlantic coastal plain of Georgia or Florida.

Several stratigraphically significant dinoflagellate occurrences were also noted in the Calvert Formation. *Paleocystodinium golzowense* is present at 969.7 ft (295.57 m); this species has its LAD at the top of dinoflagellate Zone DN8 (~8.6 Ma) (de Verteuil and Norris, 1996a). *Cousteadinium aubryae* is present in a number of samples in the Calvert Formation and is common in many. De Verteuil and Norris (1996a) report a range from the base of dinoflagellate Zone DN2 (22.2 Ma) to the top of Zone DN4 (15.2 Ma). Its highest occurrence at 1135.0 ft (345.95 m) and presence through the base of the formation place the lower Calvert (below 1135.0 ft; 345.95 m) in the interval from Zones DN2 to DN4 (22.4–15.2 Ma) (de Verteuil and Norris, 1996a). *Polysphaeridium zoharyi* is also common in most Calvert samples and is considered to reach its maximum development in warm-water, neritic, or estuarine environments (Wall et al., 1977).

Pollen assemblages in the unnamed glauconitic sediments that underlie the Calvert Formation (samples from 1422.0–1460.8 ft; 433.23–445.25 m) are generally characterized by abundant *Quercus,* frequent *Carya,* and common *Pinus. Alnus, Tilia,* TCT, and *Ulmus* are also present in this interval. The samples are characterized by abundant clumpy algal amorphous matter that obscures many of the pollen grains. The sample at 1460.8 ft (445.25 m) has many broken, poorly preserved pollen grains and appears to have suffered significant environmental oxidation. The dinoflagellate *Cousteadinium aubryae* is present at 1435.0 and 1446.6 ft (437.39 and 440.92 m), limiting this interval to a position between the base of Zone DN2 (22.2 Ma) and the top Zone DN4 (15.2 Ma) (de Verteuil and Norris, 1996a).

One sample was analyzed from the lowest unit in the corehole at 1467.2 ft (447.20 m). Like the above sample, abundant algal amorphous matter obscures many of the palynomorphs and many grains are broken. *Quercus* is the most common, and *Carya, Pinus,* and *Engelhardia*-type pollen were also noted. Dinoflagellates are present but not common.

Planktonic Foraminifers

Planktonic foraminifers are generally rare in the Miocene section of the Bethany Beach borehole and are of limited stratigraphic utility. However, they are significantly more abundant in the Oligocene section encountered at the bottom of the hole. The results of the foraminiferal analyses in Table **T4** are based on analyses of the >250-µm fraction studied by J.V. Browning from samples taken at 5-ft intervals through the core. The planktonic foraminifers listed in Table **T5** were identified by R.N. Benson and P.P. McLaughlin in the >63-µm fraction of samples taken where lithologies appeared most likely to yield good foraminiferal faunas.

T4. Foraminiferal occurrences, p. 78.

T5. Fossil occurrences, p. 80.

The greatest abundances of planktonic foraminifers in the Miocene section are in the St. Marys Formation and indicate a probable late Miocene age. A single specimen of a menardiform globorotalid resembling *Globorotalia pseudomiocenica* was identified in the sample at 506 ft (152 m). The first-appearance datum (FAD) of *G. pseudomiocenica* is placed in the *Neogloboquadrina humerosa* Zone by Bolli and Saunders, suggesting an age younger than the 8.3-Ma FAD of *N. humerosa* reported by Berggren et al. (1995). Although the FAD of *G. pseudomiocenica* is not well calibrated, we note that this age is slightly younger than that suggested by the Sr isotopes. *Orbulina suturalis* was found in samples at 501 and 536 ft (152.70 and 163.37 m). The FAD of *O. suturalis* defines the base of Zone M6 (Berggren et al., 1995), indicating an age younger than 15.1 Ma. A short section of re-cored material from somewhere between 540 and 550 ft (164.59 and 167.64 m) yielded one juvenile specimen of *Globorotalia menardii* as well as very rare *Globoquadrina dehiscens.* The FAD of *G. menardii* indicates an age no older than its FAD in the middle part of the middle Miocene (~12 Ma). The last appearance datum (LAD) of *G. dehiscens* is near the top of the Miocene in Zone M14 at 5.8 Ma (Berggren et al., 1995), which provides a youngest possible age for this sample. This recored sample also includes two other forms that have LADs in the Pliocene (based on Bolli and Saunders, 1985), *Globigerinoides obliquus obliquus* and *Globoquadrina altispira.*

One of the few stratigraphically significant planktonic foraminifers noted in the Calvert Formation was *Globorotalia praescitula* at 1103 ft (336.19 m). The FAD of this species is within the lower part of Zone M3 at 18.5 Ma (Berggren et al., 1995), indicating that the section above is no older than 18.5 Ma.

Planktonic foraminifers were recovered in two samples from the sequence between 1430.5 and 1454.5 ft (436.02 and 443.33 m) in the interval referred to as "unnamed glauconitic silt." A sample at 1436.4 ft (437.81 m) contains the planktonic foraminifers *Paragloborotalia mayeri, Globigerina ciperoensis* ssp., and *Globigerina* sp., which indicate a lowermost Miocene or upper Oligocene position. The very rare occurrence of *Globorotalia kugleri* at 1446.6 ft (430.07 m) indicates that this interval is Miocene, with this sample in basal Miocene Zone M1, indicating an age between 21.5 and 23.8 Ma (Berggren et al., 1995). Specimens of *Globigerinoides trilobus* are found sporadically in samples down to 1446.6 ft (430.07 m), also supporting the placement in the Miocene. No foraminifers were recovered in the one sample examined (1460.9 ft) in the sequence between 1454.5 and 1465.7 ft (443.45 and 446.77 m).

Oligocene planktonic foraminifers are present below the dramatic sequence boundary at 1465.7 ft (446.77 m). The presence at 1467.2 ft (447.20 m) of a *Globorotalia opima* form transitional between *Globorotalia opima opima* and *Globorotalia opima nana* (five chambers, intermediate size), as well as *G. opima opima* and *P. mayeri,* suggest this sample lies in Zone P22 based on the ranges defined by Bolli and Saunders (1985). Berggren et al. (1995) provide an estimated age of 23.8 to 27.1 Ma for this zone.

Benthic Foraminifers

Benthic foraminifers are generally present to common in samples below 376 ft (114.60 m) and were examined to determine approximate water depths. The benthic foraminifers in Table **T4** are based on analyses of the >250-µm fraction studied by J.V. Browning from samples taken at 5-ft (1.52 m) intervals through the core. In the 5-ft samples below 1200 ft (365.76 m), specimens were concentrated by floating in tetrachloroethylene. Table **T5** includes the benthic foraminifers identified by R.N. Benson in the >63-µm fraction of samples taken where lithologies appeared most likely to yield good foraminiferal faunas. Some of these samples were studied in detail, with relative abundances based on estimated percentages of each species; others (denoted by # above the sample depth) are general estimates based on quick scans of samples during and shortly after drilling.

The benthic biofacies established by Miller et al. (1997) in New Jersey are used to interpret paleodepths:

Elphidium biofacies: the *Elphidium*-dominated biofacies was defined by Miller et al. (1997) as an indicator of nearshore paleoenvironments with 10 m or less water depth, including lower estuarine, bay, and innermost neritic environments.

Hanzawaia biofacies: the *Hanzawaia* biofacies was defined by Miller et al. (1997) as the *Hanzawaia* cf. *Hanzawaia hughesi* biofacies; this (or a similar) form is also referred to as *Hanzawaia concentrica* in this study. This biofacies is characterized by the presence of the nominate taxon, the common occurrences of *Elphidium,* and the absence of *Pseudononion pizarrensis*. It is associated with inner neritic paleodepths from 10 to 25 m (inner neritic).

Pseudononion biofacies: the *Pseudononion* biofacies is the same as the *Nonionellina* biofacies described by Miller et al. (1997). Here it is dominated by *Pseudononion pizarrensis* and commonly includes *Nonionella miocenica* and *Hanzawaia*. It is interpreted as reflecting paleodepths of 25–50 m (outer inner to inner middle neritic).

Bulimina biofacies: the *Bulimina* biofacies was defined by Miller at al. (1997) as the *Bulimina gracilis* biofacies. *Bulimina elongata* is the same form, or similar, and here is included in this biofacies. It characterizes middle neritic (50–80 m) paleodepths.

Uvigerina biofacies: the *Uvigerina* biofacies characterizes middle neritic paleodepths (>75 m) and has been associated with MFSs by Miller at el. (1997). As defined, it included *Uvigerina modeloensis* and *Uvigerina juncea,* and in this study includes forms identified as *Uvigerina subperegrina/auberiana* and *Uvigerina calvertensis*.

The highest stratigraphic occurrences of foraminifers noted in the Bethany Beach borehole are in the Manokin formation at 376 ft (114.60 m), where rare *P. pizarrensis* were noted. Abundant to common *P. pizarrensis* at the base of the formation (441–451 ft; 134.42–137.46 m) indicates water depths of 25–50 m (Miller et al., 1997). The presence of *Buliminella* in samples at the base of the formation (446.0–451.0 ft; 135.94–137.46 m) indicates that the bottom of the formation was deposited in deeper water and that environments shallow upward.

Foraminifers are generally abundant in the St. Marys Formation. The upper sequence in the St. Marys Formation (down to 452.45 ft; 137.91 m) is dominated by *P. pizarrensis,* indicating water depths between 25 and 50 m. The composition of the fauna changes little through the sequence, although an increase in the number of species downsection may indicate a small amount of deepening. The lower sequence in the St. Marys Formation (523.05–575.2 ft; 159.43–175.32 m) shows deepening downward, with the richest foraminiferal assemblage present near its base. The fauna in the upper part of this sequence is dominated by *P. pizarrensis* and *H. concentrica,* indicating water depths of ~25 m on the shallow end of the *Pseudononion* biofacies. Samples from the lower part (540–555 and 572.0 ft; 164.6–169.2 and 174.35 m) have abundant *U. calvertensis, B. elongata, Cassidulina laevigata, Buccella mansfieldi,* and *Cibicides cravenensis,* with *Transversigerina lamellata* in one sample. These represent a *Uvigerina* biofacies assemblage indicating water depths reached 75 m or more.

Foraminifers are generally rare in the underlying Choptank Formation. Specimens are found in samples at 596, 596.9, and 601 ft (181.66, 181.97, and 183.18 m), just above a flooding surface at ~607 ft (185.01 m). The sparse fauna contains abundant *Hanzawaia* in places and less numerous *P. pizarrensis,* indicating ~25 m paleowater depth.

Immediately above a sequence boundary at ~649.0 ft (197.82 m), a sample from 645.0 ft (196.60 m) yielded *Bolivina paula, Buliminella elegantissima,* and *H. concentrica*. This assemblage is suggestive of the inner neritic *Hanzawaia* biofacies (10–25 m paleodepth). In the underlying sequence (649.0–698.5 ft; 197.81–212.90 m), rare to common *Hanzawaia* are noted in samples between 671 and 681 ft (204.52 and 207.57 m), also suggesting water depths of 10–25 m. This interval corresponds to the lower HST of the sequence.

Foraminifers are also sporadically present in the sequence between 698.5 ft and 787.1 ft (212.90 and 239.91 m). The uppermost fossiliferous samples (721 and 726 ft; 219.76 and 221.28 m) contain a low diversity *Pseudononion* biofacies at the shallow end of its depth range, at inner neritic (~30 m?) paleodepths. Just above the maximum flooding surface at 755 ft (230.12 m), a sample at 753.9 ft (229.79 m) contains a more diverse fauna including abundant *P. pizarrensis, B. paula,* and other small *Bolivina* species, with common *H. concentrica, B. elongata,* and *B. elegantissima* and rare *Spiroplectammina mississippiensis* and *Textularia* spp. These taxa likely represent the deep end of the *Pseudononion* biofacies or shallow end of the *Bulimina* biofacies, at ~50 m paleodepth. A low diversity *Pseudononion* biofacies was noted below this (756 and 766 ft; 230.43 and 233.48 m), again indicating inner neritic (~30 m?) paleodepths. The lowermost fossiliferous sample of this formation (771 ft; 235.00 m) contains *Hanzawaia* without *Pseudononion.* This indicates shallower water at top and at bottom and deeper water in the middle of the sequence, in agreement with the facies analysis.

The Calvert Formation (819.9–1420.0 ft; 249.91–732.82 m) contains locally abundant foraminifers. *P. pizarrensis* is the most common foraminifer in this formation, indicating prevailing water depths were generally 25–50 m (Miller et al., 1997). In some places, *P. pizarrensis* is absent or rare and *Hanzawaia* is present, suggesting shallower water environments. In other places, *P. pizarrensis* is commonly present with *Lenticulina* and *Cibicides/Cibicidoides,* likely representing slightly deeper environments.

In the uppermost sequence in the Calvert Formation (which extends from 787.1 ft [239.91 m] in the Choptank Formation to 897.7 ft [273.62 m] in the Calvert), the benthic foraminifers generally record deepening downsection, with assemblages of rare *Hanzawaia* passing downward into more consistently fossiliferous samples with more diverse assemblages that include common to abundant *Lenticulina* and *P. pizarrensis.* At 822.8 ft (250.83 m), the assemblage includes *B. paula,* small *Bolivina* spp., *H. concentrica, Cibicides americanus,* and *Nonion advenum pustulosum.* The richest samples are present near the maximum flooding surface identified at 887.7 ft. At 888.0 ft (270.66 m), the fauna is composed of *P. pizarrensis, B. paula, Bolivina* spp. (small), *Lenticulina americana, H. concentrica, B. elongata, B. elegantissima, S. mississippiensis,* and *Textularia* sp.

Samples from the underlying sequence, from 897.7 to 981.3 ft (273.62 to 299.10 m) and from 981.3 to 1057.95 ft (299.10 to 322.46 m), yielded foraminifers less consistently. Samples from the lower part of each sequence are generally the most diverse and thus represent the deepest water. *P. pizarrensis* is the most consistently occurring species, and *Hanzawaia* and *Cibicides/Cibicidoides* have scattered occurrences, together indicative of the *Pseudononion* biofacies. The sample at 948.9 ft (289.22 m) also includes frequent *B. elegantissima,* common *B. paula,* and very rare *Transversigerina transversa.* Other forms present with this assemblage include *B. elegantissima, Rotorbinella bassleri,* and *Textularia* spp. at 985.7 ft (300.44 m) and *Textularia* spp. and *S. mississippiensis* at 1054.3 ft (321.35 m).

Immediately under the sequence boundary at 1057.95 ft (322.46 m), foraminifers are sparse. However, other than in the upper 10–15 ft of this sequence, foraminifers are more common and diverse than in the overlying two sequences. A sample just below the top of the sequence at 1059 ft (322.78 m) yielded fine sand and very rare foraminifers. A sample at 1064 ft (324.31 m) yielded very fine sand, glauconite (<1%), and sparse benthic foraminifers that include striate *Uvigerina, H. concentrica,* and *Bulimina.* At 1071 ft (326.44 m), abundance and diversity increase and generally persist through the bottom of the sequence at

1153.0 ft (351.43 m). *P. pizarrensis* and *Lenticulina* spp. are abundant to common through this interval. The greatest diversity was noted between 1071 and 1116 ft (326.44 and 340.16 m), with regular occurrences of *S. mississippiensis, B. paula, H. concentrica, Cibicides/Cibicidoides* sp., *Textularia* spp., *U. subperegrina/auberiana, B. marginata multicostata,* and *B. elegantissima.* Scattered occurrences of *B. paula, Gyroidina scalata, B. elongata,* and *B. curta* were also noted with the common *P. pizarrensis* and *Lenticulina* in the lower part of the sequence. These assemblages are probably overall referable to the *Pseudononion* biofacies, but with some aspects of the *Bulimina* and *Uvigerina* biofacies. These suggest that most of this part of the Calvert Formation was deposited at middle neritic depths (50–80 m), with the upper part of this sequence representing the shallowest water depths.

Foraminifers are less common in the very thick sequence from 1153.0 to 1421.1 ft (351.43 to 433.15 m). *P. pizarrensis* is present in most of the samples, but is abundant in only one sample (1217.7 ft; 371.15 m) and rare in most others. Scattered occurrences of *H. concentrica, B. elegantissima, Cibicides/Cibicidoides* sp., *U. subperegrina/auberiana, B. paula, B. marginata multicostata,* and *Elphidium* spp. were also noted, with *B. elegantissima* common to abundant in several samples. Paleowater depths were probably mostly 25–50 m (*Pseudononion* biofacies).

In the next sequence down, from 1421.1 to 1430.5 ft (433.15 to 436.02 m), the facies become more glauconitic. *P. pizarrensis* is abundant in the uppermost sample at 1422.0 ft (433.43 m), and *B. elongata, B. curta,* and *U. subperegrina/auberiana* are abundant to frequent. *Transversigerina transversa* also is in this sample, but it is very rare. This assemblage, like that in the sequence above, is probably best referred to the *Pseudononion* biofacies, but with some deeper neritic aspects of the *B. gracilis* and *Uvigerina* biofacies, suggesting middle neritic depths (~50 m).

A similar fauna, but with some slightly deeper water aspects, characterizes the sequence between 1430.5 and 1454.5 ft (436.02 and 443.33 m) in the interval referred to as "unnamed glauconitic clays and sands." Samples in the upper part of the sequence (1435.0 to 1436.4 ft; 437.39 to 437.81 m) contains common to abundant *B. elongata,* as well as *P. pizarrensis* and *B. curta.* A sample from the middle of the sequence (1443.5 ft; 439.98 m) contains similar benthic foraminifers in addition to common *Siphonina* cf. *tenuicarinata, Lenticulina* spp., polymorphinids *(Guttulina, Globulina,* and *Pseudopolymorphina)* and assorted lagenids *(Marginulinopsis* sp., *Fissurina* sp., *Oolina* sp., and others). *P. pizarrensis* and *Buliminella curta* are also present in the lower part of the sequence (1446.0–1451.0 ft; 440.74–442.26 m) along with *T. transversa, Gyroidinoides* sp., *Rotorbinella bassleri,* and *B. paula.* The overall increase of diversity downward in this sequence suggests deepening from middle neritic depths characteristic of the *Bulimina* biofacies to deeper middle neritic or even outer neritic depths.

Very rare foraminifers, exclusively *B. elongata* and *Cassidulinoides* sp., were recovered in the one sample examined (1460.8 ft; 445.25 m) in the sequence between 1454.5 and 1465.7 ft (443.33 and 446.77 m).

A significant change in foraminiferal faunas takes place across the dramatic sequence boundary at 1465.7 ft (446.75 m). Several uvigerinids are present in this interval that are not present above, including *Tiptonina nodifera, Uvigerina tumeyensis,* and *U.? glabrans.* Other forms present include *Frondicularia, Guttulina, Gyroidina scalata, Lenticulina* spp., *B. paula, B. elongata,* and *Eponides*? *cocoaensis.* Together these taxa suggest an outer neritic paleoenvironment.

Calcareous Nannofossils

The calcareous nannofossil assemblages, although diverse, are extremely difficult to interpret because of the absence or extreme scarcity of markers.

The upper part of the hole does not yield calcareous nannofossils. Samples of the Omar Formation from 36 and 51 ft (10.97 and 15.54 m) are barren, as is the sample from the Bethany formation at 192 ft (58.52 m).

Of the five samples examined from the St. Marys Formation, only one contains nannofossils. The sample at 486 ft (148.13 m) yields long-ranging taxa, but the sample is remarkable because of the presence of reworked Paleogene taxa (Paleocene in particular). Samples from 451, 506, 531, and 561 ft (137.46, 154.23, 161.85, and 170.99 m) are barren.

Stratigraphically useful nannofossils are present in scattered samples from the Calvert Formation. A sample from 876 ft (267.00 m) contains reworked Paleogene coccoliths. The sample from 1071.0 ft (326.44 m) is probably assignable to Zone NN3 and contains rare *Sphenolithus belemnos*. The sample at 1091 ft (332.54 m) is assigned to Zone NN3 (between the highest occurrence (HO) of *Triquetrorhabdulus carinatus* and the HO of *S. belemnos*) based on the absence of *T. carinatus*. *T. carinatus* is present in levels below but is very rare. The sample at 1116.0 ft (340.16 m) is placed in the upper part of Zone NN2, 1136 ft (346.25 m) in Zone NN2, and 1311 ft (399.59 m) in the lower part of Zone NN2. Samples from 1286 and 1331 ft (391.97 and 405.69 m) cannot be assigned to a zone, and the sample at 1396 ft (425.50 m) is barren.

One sample from the unnamed glauconitic clays and sands in the lower part of the hole yields nannofossils. The sample at 1426 ft (434.64 m) is possibly assignable to the lowermost Zone NN2.

A completely different assemblage is present in the sample at 1466 ft (446.84 m) than those above. It is most probably uppermost Oligocene, in younger Chron C6Cr (~24.2–24.7 Ma).

Radiolarians

Radiolarians are present in nearly all samples between 572.0 and 1446.6 ft (174.35 and 440.92 m), inclusive. Their abundances range from very rare (<100 count) to nearly 5% of the sand fraction (Table T5). Assemblages are dominated by spumelline taxa, mainly actinommids, spongodiscids, coccodiscids, and lithelids. Members of these groups persist in neritic paleoenvironments in the Miocene of the middle Atlantic Coastal Plain (Palmer, 1984, 1986a; Benson, 1998) where oceanic taxa are rare or absent. All identifications were made under low-power and reflected light.

The highest occurrence of biostratigraphically significant radiolarians is the isolated occurrence of *Calocycletta costata* at 822.8 ft (250.79 m). This species ranges from the base of the *Calocycletta costata* Zone (RN4) into the lower part of the *Dorcadospyris alata* Zone (RN5), indicating that the sample should be between 17.03 and ~14 Ma based on the estimated ages of these zones (see Sanfilippo and Nigrini, 1998).

Didymocyrtis mammifera is a stratigraphically useful form that ranges from 822.8 to 948.9 ft (250.79 to 289.22 m). This species is generally considered to appear within the lower Miocene *Stichocorys wolffi* Zone (RN3) and ranges up into the middle Miocene *Dorcadospyris alata* Zone (RN5) (Nigrini and Sanfilippo, 2001). The presence of this species below the lowest occurrence of *C. costata* suggests the samples at 888.0 and 948.9 ft (270.66 and 289.22 m) can be assigned to Zone RN3.

The highest occurrence of the stratigraphically significant radiolarian *Spongasteriscus marylandicus* is at 1103.0 ft. Palmer (1986b) indicated that *Spongasteriscus marylandicus* is a useful stratigraphic indicator of the *S. wolffi* Zone (RN3). Nigrini (1996) identified this species from the uppermost Oligocene Zone RP22 to within lower Miocene Zone RN3 at Ocean Drilling Program (ODP) Sites 902, 903, and 904 on the New Jersey continental slope. Thus, the presence of *S. marylandicus* suggests that this sample is no younger than somewhere within the *Stichocorys wolffi* Zone (RN3).

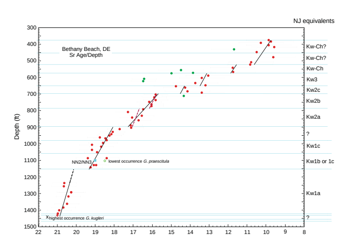
Radiolarians indicative of the lowermost Miocene *Cyrtocapsella tetrapera* Zone (RN1) are present at 1446.6 ft (440.92 m) with the planktonic foraminifer *G. kugleri,* which is restricted to the earliest Miocene Zone M1 (23.8–21.5 Ma) (Berggren et al., 1995). The *C. tetrapera* Zone is defined between the first occurrence (FO) of the nominate taxon (23.62 Ma) and the last occurrence (LO) of *Theocyrtis annosa* (20.53 Ma) (Sanfilippo and Nigrini, 1998). The former is present in the Bethany Beach borehole in the 1446.6-ft (440.92 m) sample (Table T5); the latter taxon was not found in this preliminary study. The radiolarians at 1446.6 ft (440.92 m), therefore, represent the *Cyrtocapsella tetrapera* Zone.

Other species found in the sample 1446.6 ft (440.92 m) (Table T5) support this interpretation: (1) the FO of *Calocycletta virginis* is approximately synchronous with the base of Zone RN1 (Sanfilippo and Nigrini, 1998); (2) the FO of *Cyrtocapsella cornuta* is present within the zone (Sanfilippo and Nigrini, 1998); (3) *Lychnocanoma elongata* (the FO defines the base of the latest Oligocene Zone, RP22, named for the taxon) ranges from late Oligocene to late early Miocene (Sanfilippo and Nigrini, 1998); (4) *Didymocyrtis prismatica* ranges from late Oligocene to late early Miocene (Nigrini and Sanfilippo, 2001); (5) *Spongasteriscus marylandicus* ranges from the latest Oligocene Zone RP22 to within early Miocene Zone RN3 (Nigrini, 1996); and (6) the FOs of *Didymocyrtis violina* and *D. tubaria* are approximately synchronous with the base of the *Stichocorys delmontensis* Zone, RN2 (Sanfilippo and Nigrini, 1998; Nigrini and Sanfilippo, 2001); their FOs in the Bethany Beach borehole suggest that they are older than the base of Zone RN2.

Diatoms

Diatom frustules from the >63-µm size fraction are present in nearly all samples examined, and in several they reach >5% of the sand fraction (Table T5). The only readily identifiable taxon in this size range under low magnification and reflected light is *Actinoptychus heliopelta.* Its LO at 985.7 ft (300.44 m) is within the *Stichocorys wolffi* Zone. Its FO is at 1446.6 ft (440.92 m) in the *G. kugleri* and *Cyrtocapsella tetrapera* zones. Its total range defines East Coast Diatom Zone (ECDZ) 1 (Abbott, 1978; Andrews,1988), which encompasses nearly the entire lower Miocene of the middle Atlantic Coastal Plain.

F10. Age-depth plot, p. 66.



STRONTIUM ISOTOPE CHRONOSTRATIGRAPHY

Sixty-eight Sr isotope age estimates were obtained from mollusk shells (~4–6 mg) from the Bethany Beach borehole (Table T3; Fig. F10). Shells were cleaned ultrasonically, powdered, and dissolved in 1.5-N HCl. Samples were centrifuged and introduced into ion-exchange columns. Standard ion-exchange techniques were used to separate the strontium (Hart and Brooks, 1974), and samples were analyzed on a VG Sector mass spectrometer at Rutgers University. NBS 987 is measured on the Rutgers Sector as 0.710255 (2-σ standard deviation [SD] = 0.000008; n = 22) normalized to $^{86}Sr/^{88}Sr$ = 0.1194. Internal precision on the sector for the data set averaged 0.000008; external precision for the Sector has been reported as approximately ±0.000020 (Oslick et al., 1994). Though most of the Sr isotopic analyses yield monotonically increasing values upsection (decreasing age) (Fig. F10), there are several age inversions, even in the lower lower middle Miocene section; the latter is unexpected because the rate of Sr isotopic increase was high in the early early middle Miocene and previous data sets (e.g., Cape May) (Miller et al., 1996a) generally show monotonically increasing values upsection. In addition, at least seven data points are interpreted as statistical outliers (green dots on Fig. F10). The cause of this may be partly due to stratigraphic reworking (e.g., 607, 622.3, and 710.5 ft; 185.01, 189.68, and 216.56 m) but also may be partially attributed to minor alteration of some of the shells (e.g., in indurated zones at 572.8 and 574 ft; 174.59 and 174.96 m). Additional Sr isotopic studies of foraminifers are warranted to test the fidelity of the measurement made on shell material, particularly for the middle–upper Miocene section.

Ages were assigned using the Berggren et al. (1995) timescale (Table T3); the Miocene regressions of Oslick et al. (1994) were used where possible. The Oslick et al. (1994) regressions are only valid to sections older than 9.9 Ma (Sr isotopic values = <0.708930). For younger Miocene sediments, we used a modification of the regressions of Martin et al. (1999). Martin et al. (1999) noted a uniform offset between their middle–late Miocene regression and that of Oslick et al. (1994) of ~0.000050 after correcting for differences between standards (fig. 7 in Martin et al., 1999). This difference could be attributed to interlaboratory calibration problems (i.e., a 0.000020 difference has been reported between University of Florida and other laboratories after correcting for differences in the NBS987 standard; see Oslick et al. [1994] and Howarth and MacArthur [1997] for discussion). Thus, we subtracted 0.000050 from our data and applied the Martin et al. (1999) regressions for isotopic values 0.709050 and 0.708930 (i.e., the Miocene section younger than 9.2 Ma). We note that following this procedure (i.e., adding 0.00050 to our data and using the Martin et al. [1999] regression) for values between 0.708930 and 0.708850 (i.e., the Miocene section older than 9.2 Ma) yields very similar ages to those obtained using the uncorrected data and the Oslick et al. (1994) regression. The sole Oligocene age was estimated using the age regression of Reilly et al. (in press). For the sole Pleistocene analysis (24.6 ft; 7.50 m), we derived a linear regression using the data of Farrell et al. (1995), correcting their data to NBS987 of 0.710255 and fitting linear segments to the data between 0 and 2.5 Ma:

$$\text{Age} = 15235.08636 - 21482.27712 \times (^{86}\text{Sr}/^{87}\text{Sr}).$$

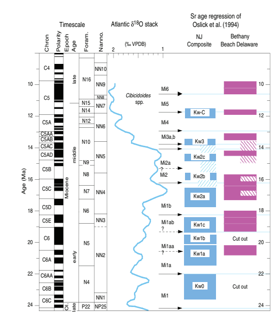
Miller et al. (1991) and Oslick et al. (1994) estimate age errors derived from linear regressions of Sr isotopic records. Age errors for 15.5–22.8 Ma are ±0.61 m.y. and for 9.7–15.5 Ma are ±1.17 m.y. at the 95% confidence interval for a single analysis. Increasing the number of analyses at a given level improves the age estimate (±0.40 and ±0.76 m.y. for three analyses each in the two intervals) (Oslick et al., 1994). The regression for the later Oligocene (23.8–27.5 Ma) has an age error ±1 m.y. (for one analysis at the 95% confidence interval) to ±0.6 m.y. (for three analyses at the 95% confidence interval) (Reilly et al., in press). The regression for the late Pliocene–Pleistocene (0–2.5 Ma) has an age error of ±0.35 m.y. (for one analysis at the 95% confidence interval) to ±0.2 m.y. (for three analyses at the 95% confidence interval) (Miller, unpubl. analysis of the data of Farrell et al., 1995).

A strontium value of 0.709147 obtained from a shell at 24.6 ft (7.50 m) corresponds to an isotopic age of 1 ± 0.35 Ma (Fig. F10). This appears to contradict correlations, that suggest a younger Pleistocene age for this section (see **"Omar Formation,"** p. 18).

The poorly fossiliferous nature of the upper 375 ft (114.3 m) of the borehole otherwise precludes Sr isotopic study. From 375 to 1400 ft (114.3 to 426.72 m), the core contained ample calcareous material for Sr isotopic analysis. Sr isotopes allowed us to provide age estimates for 11–12 Miocene sequences. Samples taken above the sequence boundary at 698.5 ft (212.90 m) have age estimates that vary more than the section below the sequence boundary at 698.5 ft (212.90 m). Age inversions are common above this level, in part reflecting the lower global rate of Sr isotopic change in the younger section.

Sr isotopic age estimates for a sequence from 374 to 452.45 ft (114.0 to 137.91 m; a sequence comprising the lower Manokin formation) range from 9.6 to 11.7 Ma, though they cluster from 9.6 to 10.5 Ma (the 11.7-Ma estimate is an outlier) (Fig. F10). A sequence between 452.45 and 523.05 ft (137.91 and 159.43 m; upper St. Marys Formation) has Sr ages of 9.6 and 10.8 Ma. A linear regression through the data in this and the overlying sequence yields our best age estimate of 9.8–10.2 Ma for the 375- to 452.45-ft (114.3–137.91 m) sequence and 10.2–10.6 Ma for the 452.45- to 523.05-ft (137.91–159.43 m) sequence (Figs. F10, F11) and mean sedimentation rate of ~56 m/m.y. The presence of *Globorotalia pseudomiocenica* at 506 ft (154.23 m) (FO = 8.3 Ma?) may indicate that the lower sequence is slightly younger than indicated by Sr, though this is based on a sole specimen of uncertain taxonomic assignment.

F11. Age comparison, p. 67.



The sequence from 523.05 to 575.2 ft (159.43 to 175.32 m; lower St. Marys Formation) has wide-ranging ages of 11.7–15.0 Ma. We believe the older ages represent either diagenesis or reworking of older material (Fig. F10). The samples at 541.25 and 567.5 ft (164.97 and 172.97 m) with age estimates of 11.8 and 11.7 Ma are fine-grained silts and clays, making diagenesis or reworking less likely, and we prefer an age assignment of ~11.8 Ma for this sequence. Assuming similar sedimentation rates as found in the two sequences above (56 m/m.y.) yields our best age estimate of 11.6–11.9 Ma for this sequence (Figs. F10, F11), though we admit that the age of this sequence is still poorly constrained. Nevertheless, this sequence is clearly late middle Miocene as supported by the identification of dinocyst Zone DN7 (<12.4 Ma) (see **"Biostratigraphy,"** p. 35).

The sequence found from 575.2 to 649 ft (175.32 to 197.82 m; uppermost Choptank Formation) yields ages ranging from 13.1 to 13.7 Ma, except for two analyses of 16.4 and 16.5 Ma at 607 and 622.3 ft (185.01 and 189.68 m), respectively. We consider these two analyses to be from reworked or diagenetically altered shells (Fig. F10). A linear regression through the four reliable points yields an age for the best estimate of this sequence of 13.1–13.5 Ma (Figs. F10, F11) and a sedimentation rate of 56 m/m.y., remarkably similar to the sedimentation rates above. This sequence appears to correlate with the Kw3 sequence in New Jersey (Sugarman et al., 1993; Miller et al., 1997).

The sequence from 649 to 698.5 ft (197.82 to 212.90 m; middle Choptank Formation) has Sr ages ranging from 13.4 to 14.7 Ma. The ages are actually inverted in this sequence, although these inversions are within the external precision (error bars, Fig. F10). Assuming similar sedimentation rates as found in the sequence above (56 m/m.y.) yields our best age estimate of 14.2–14.5 Ma for this sequence (Figs. F10, F11), though the age of this sequence is least well constrained of the Miocene sequences at Bethany Beach (i.e., this sequence could be anywhere in the interval 13.4–14.7 Ma). This sequence appears to correlate with the Kw2c sequence in New Jersey (Miller et al., 1997) (Figs. F10, F11; Table T6).

T6. Sedimentation rates, p. 84.

Sr isotopic ages from the section below 698.5 ft (212.90 m) constrain the ages well. A sequence from 698.5 to 787.1 ft (212.90 to 239.91 m; lower Choptank Formation) has Sr ages ranging from 15.8 to 16.2 Ma. A sample at 710.5 ft (216.45 m; 14.3 Ma) is believed to be burrowed down. This sequence appears to correlate with the Kw2b sequence in New Jersey (Miller et al., 1997) (Figs. F10, F11; Table T6).

The sequence from 787.1 to 897.7 ft (239.91 to 273.62 m; lowermost Choptank–uppermost Calvert Formation) ranges in age from 16.5 to 17.3 Ma. Several ages in this sequence are inverted, possibly indicating reworking of younger shells within the sequence. This sequence appears to correlate with the Kw2a sequence in New Jersey (Miller et al., 1997) (Figs. F10, F11). There is no discernable hiatus between this and the overlying sequence. Assuming constant sedimentation rates through both sequences (38 m/m.y.) yields our best age estimate of 15.7–16.4 and 16.4–17.3 Ma for the 698.5- to 787.1- and 787.1- to 897.7-ft (212.75–239.91 and 239.91–273.62 m) sequences, respectively (Fig. F10; Table T6). Alternatively, assuming best fits to the Sr ages within each sequences yields age estimate of 15.8–16.2 Ma (68 m/m.y. sedimentation rate) and 16.7–17.0 Ma (96 m/m.y. sedimentation rate), respectively (dashed lines, Fig. F10; Table T6).

The section from 897.7 to 1153 ft (273.62 to 351.43 m; Calvert Formation, partim) contains three sequences, but the hiatuses between them are too short to resolve using Sr isotopic stratigraphy. The mean sedimentation rate for these three sequences is 57 m/m.y., again remarkably similar to those above. The sequence from 897.7 to 981.3 ft (273.62 to 299.10 m) yields Sr ages between 17.1 and 18.8 Ma. Assuming constant sedimentation rates for the entire interval from 897.7 to 1153 ft (273.62 to 351.43 m) yields a best age estimate of 18.0 to 18.4 Ma for the 897.7- to 981.3-ft (273.62–299.10 m) sequence. There does not appear to be a sequence of equivalent age in New Jersey. The sequence from 981.3 to 1057.95 ft (299.10 to 322.46 m) has Sr ages between 18.6 and 19.2 Ma. Our best age estimate assuming constant sedimentation rates is 18.4–18.8 Ma. This sequence is equivalent in age to sequence Kw1c in New Jersey (Miller et al., 1997). The sequence from 1057.95 to 1153 ft (322.46 to 351.43 m) has ages ranging between 18.4 and 19.4 Ma (note that the age range is between 18.9 and 19.2 Ma if duplicates are averaged). Our best age estimate assuming constant sedimentation rates is 18.8–19.3 Ma. The estimated age of 19.3 Ma for the base of Zone NN3 at 1091 ft (332.54 m) is remarkably consistent with the sedimentation rate model derived from Sr isotopes (Fig. F10). The presence of *G. praescitula* at 1103 ft (336.19 m) (FO = ~18.5 Ma [Berggren et al., 1995]) does not appear to be consistent with the age model. One possible explanation is that forms assigned to *G.* cf. *praescitula* appeared in strata older than 19 Ma at Site 608 (Miller et al., 1991). This sequence from 1057.95 to 1153 ft (322.46 to 351.43 m) is equivalent in age either to sequence Kw1b or Kw1c in New Jersey (Miller et al., 1997); strict interpretation of the ages suggests that it is equivalent to the Kw1c and that the Kw1b is cut out in Delaware (Fig. F11; Table T6).

The sequence(s) between 1153 and 1421.1 ft (351.43 and 433.15 m) range in age from 20.3 Ma at the top to 21.0 Ma at the base. Fitting a linear regression to the data yields a best age estimate of 20.2–20.8 Ma. The sedimentation rate in this sequence is very high (136 m/m.y.). This sequence correlates to the sequence Kw1a in New Jersey (Miller et al., 1997).

Only one age was obtained on the three sequences between 1421.1 and 1465.7 ft (433.15 and 466.75 m). There are no Sr isotopic ages in the upper or lower sequences (1421.1–1430.5 and 1454.5–1465.7 ft; 433.15–436.02 and 443.33–466.75 m). A sample at 1430.8 ft (436.02 m) yields an age of 21.0 Ma, perhaps indicating that this sequence is equivalent to the Kw1a1 subsequence, the lowermost of three subsequences that comprise the Kw1a sequence in New Jersey (Miller et al., Chap. 2, this volume). This suggests correlation of the 1421.1- to 1430.5-ft (433.15–436.02 m) sequence to the Kw1a2 and the 1153- to 1421.1-ft (351.52–433.15 m) sequence to the Kw1a3 sequence. No Sr results from the Bethany Beach borehole yielded ages equivalent to the Kw0 sequence in New Jersey (~22–23.5 Ma) (Miller et al., 1998a). However, the HO of *G. kugleri* at 1446.6 ft (430.07 m) suggests that these strata are 21.5–23.8 Ma and thus equivalent to Kw0, not Kw1a1.

A Sr age of 29.0 Ma was obtained from a shell at 1467.8 ft (447.39 m), indicating that the base of the borehole is in the Oligocene and that there is a substantial hiatus associated with the Oligocene/Miocene boundary at Bethany Beach. Planktonic foraminifers at 1467.2 ft (447.20 m) are assigned to Zone P22 (23.8–27.1 Ma); the one Sr isotope analysis adjacent to this level is not consistent with this identification but suggests correlation to Biochron P21b.

Sedimentation rates are high in the Miocene at Bethany Beach compared to the coeval sections in New Jersey. Sedimentation rates were 37–59 m/m.y. (mean = 53 m/m.y.) in Delaware from 9.8 to 18.8 Ma and 136 m/m.y. from 20.2 to 20.8 Ma. In contrast, sedimentation rates at the thickest Miocene section in New Jersey, Cape May, were 29–47 m/m.y. (mean = 40 m/m.y.) from 11.5 to 20.2 Ma and 91 m/m.y. from 20.2 to 20.6 Ma. Nevertheless, thickness does not scale into stratigraphic continuity; the New Jersey record is much more complete in the early early Miocene (19–23.8 Ma) with the Kw1b and Kw0 sequence apparently missing in Delaware, though the Delaware section is more complete in the late early Miocene (~19–16.2 Ma) (Fig. F11).

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APPENDIX

Shore-Based Log Processing

Composite Log from Two Runs of the Multi-Parameter Gamma-Electric Log Tool (Century Geophysical Company Tool Model 8044a)

The composite log was constructed from data obtained from two separate open-hole logging operations: a first uprun of the tool in the upper ~200 ft (60.96 m) of the hole before it was cased off for the deeper drilling phase, and a later uprun after completion of drilling, which comprises the data below ~200 ft (60.96 m). The following logs are shown for this well: in the left track, gamma and spontaneous potential (SP), in the right track, point resistance (RES), short-normal (16-in) resistivity (RES(16N)), and long-normal (64-in) resistivity (RES(64N)). The gamma and SP logs are shown on a linear scale, and the resistivity logs are shown on a logarithmic scale. Measurements were recorded every 0.10 ft (0.03 m) and displayed using an 11 point/ft running average (the data point plus 5 points above and 5 points below) for all curves. Data from the first logging operation were rescaled to match the scale of those from the later logging operation to provide an approximation of log values for the cased interval for this run. The following corrections were made for this rescaling: gamma, no correction; SP, subtracted 40 from all values from first run for depths from 202.8 ft (61.81 m) and above; RES, multiplied all values by 0.6592 from 208.1 ft (63.43 m) and above; RES(16N), multiplied all values by 1.481 from 207.4 ft (63.22 m) and above; RES(64N), multiplied all values by 5.198 from 205.4 ft (62.61 m) and above.

Logs Obtained from the Gamma-Induction Log Tool (Century Geophysical Company Tool Model 9512a)

The following logs are shown for this well: gamma; conductivity (COND), corrected for skin effect and temperature; apparent conductivity (AP-COND), a simple temperature-corrected conductivity; and calculated resistivity (RES) derived from the conductivity log as RES = 1000/COND. All logs are shown on linear scales, with the scale reversed on the conductivity logs to show response in the same direction as resistivity. Measurements were recorded every 0.10 ft (0.03 m) and displayed using an 11 point/ft running average (the data point plus 5 points above and 5 points below) for all curves.

Figure F1. A. Location map showing existing ODP boreholes analyzed as a part of the NJ/Mid-Atlantic (MAT) Sea-Level Transect. Also shown are multichannel seismic track lines (MCS) from *Ewing* cruise 9009 (Ew9009), *Oceanus* cruise (Oc270), and *Cape Hatteras* cruise (CH0698). (Continued on next page.)

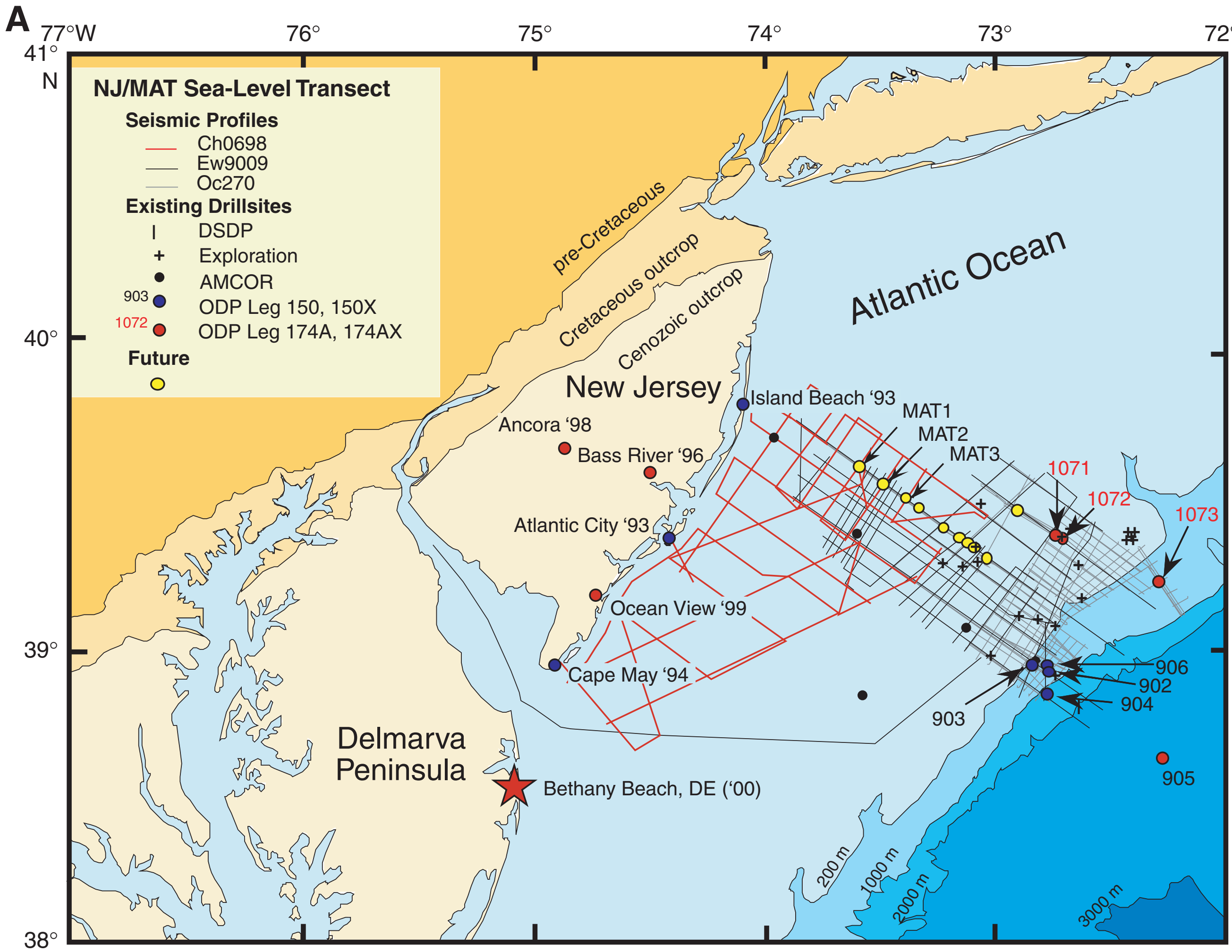

Figure F1 (continued). B. Location map for the Mid-Atlantic region. The fall line is the edge of the coastal plain. The strike of coastal plain sedimentary formations generally parallels the fall line (modified after Owens and Gohn, 1985)

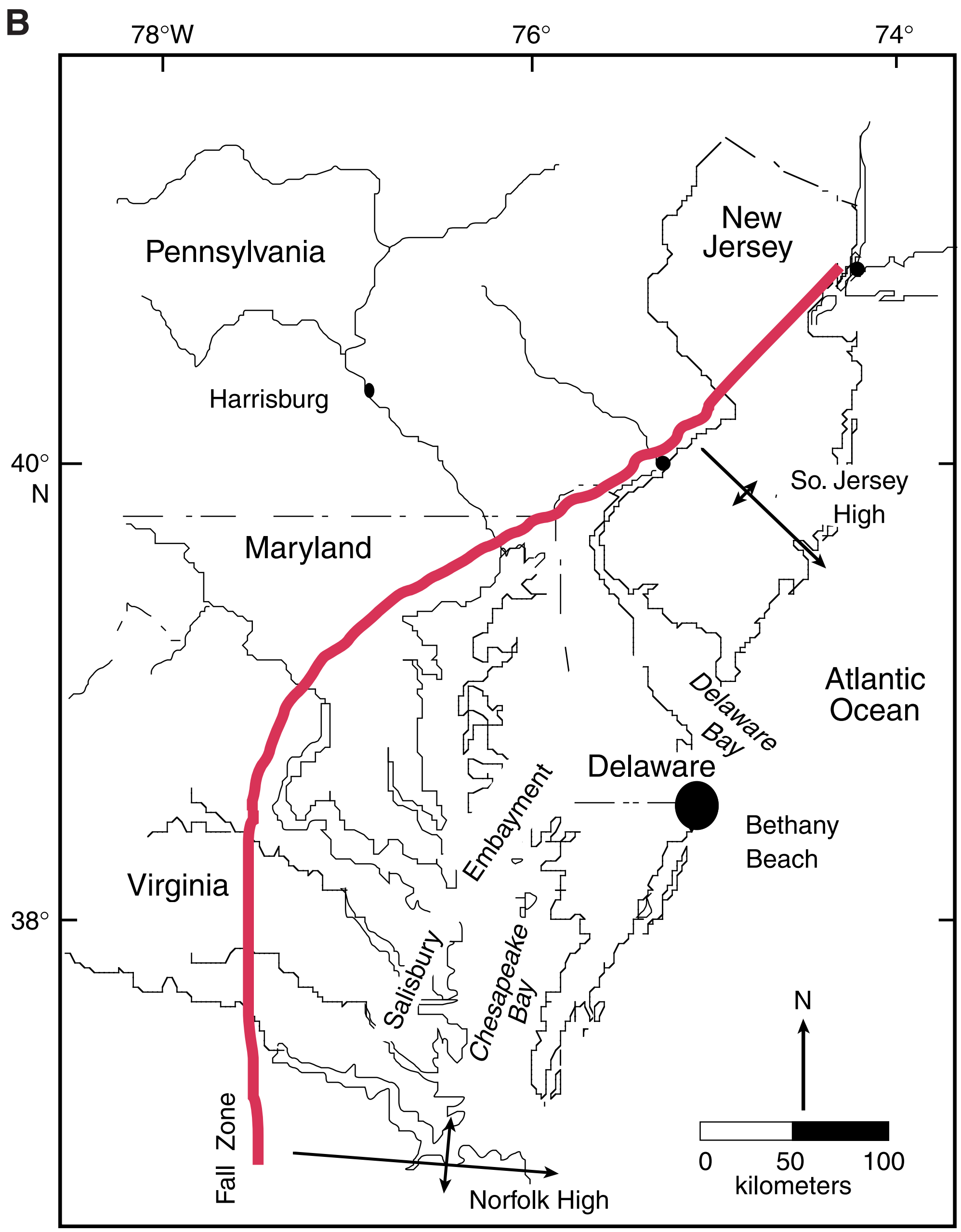

Figure F2. Facies model for nearshore sedimentation, Miocene of Delaware. Trends in textural characteristics shown by bars of varying widths are generalized; see "Lithostratigraphy," p. 16, for explanation. Photographs are examples of each facies in core from given levels in the Bethany Beach borehole.

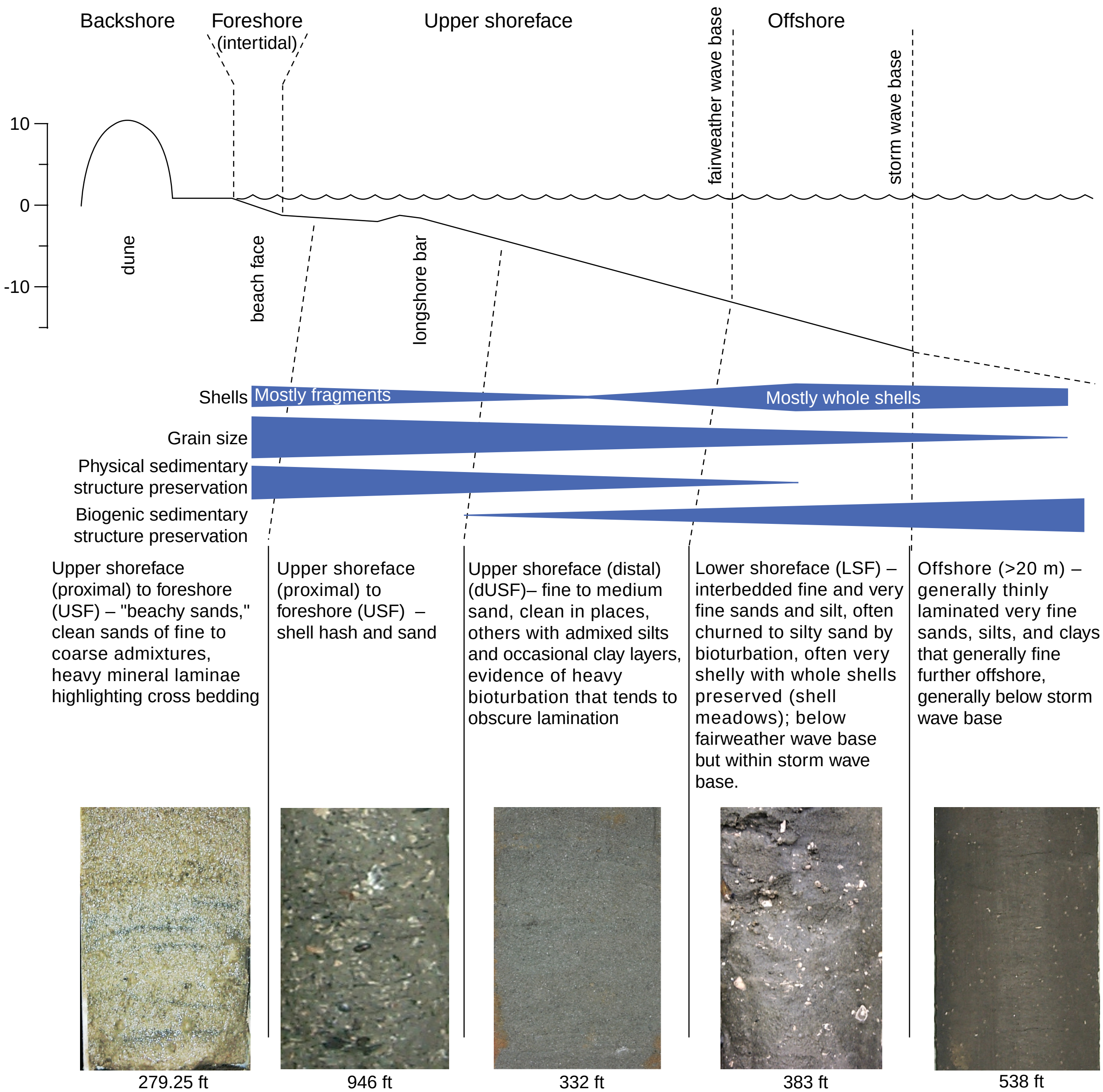

Figure F3. Representative sequence boundaries from the Bethany Beach borehole. Sequence boundary (SB) within the Calvert Formation (1057.95 ft; 322.46 m) separates dolomite cemented silty very fine sand above (lower shoreface) from silty clay (offshore) below. Sequence boundary within the Calvert Formation (897.7 ft; 273.62 m) separates fine silty sand (distal lower shoreface) above which has been burrowed down into medium sand (upper shoreface) below. Sequence boundary within the Choptank Formation (787.1 ft; 239.88 m) separates shelly sand (distal upper shoreface) above from medium sand (proximal upper shoreface) below. Sequence boundary within the unnamed glauconitic clays and clayey glauconite sands (1430.5 ft; 436.02 m) separates clayey glauconite sand above from silty clay below.

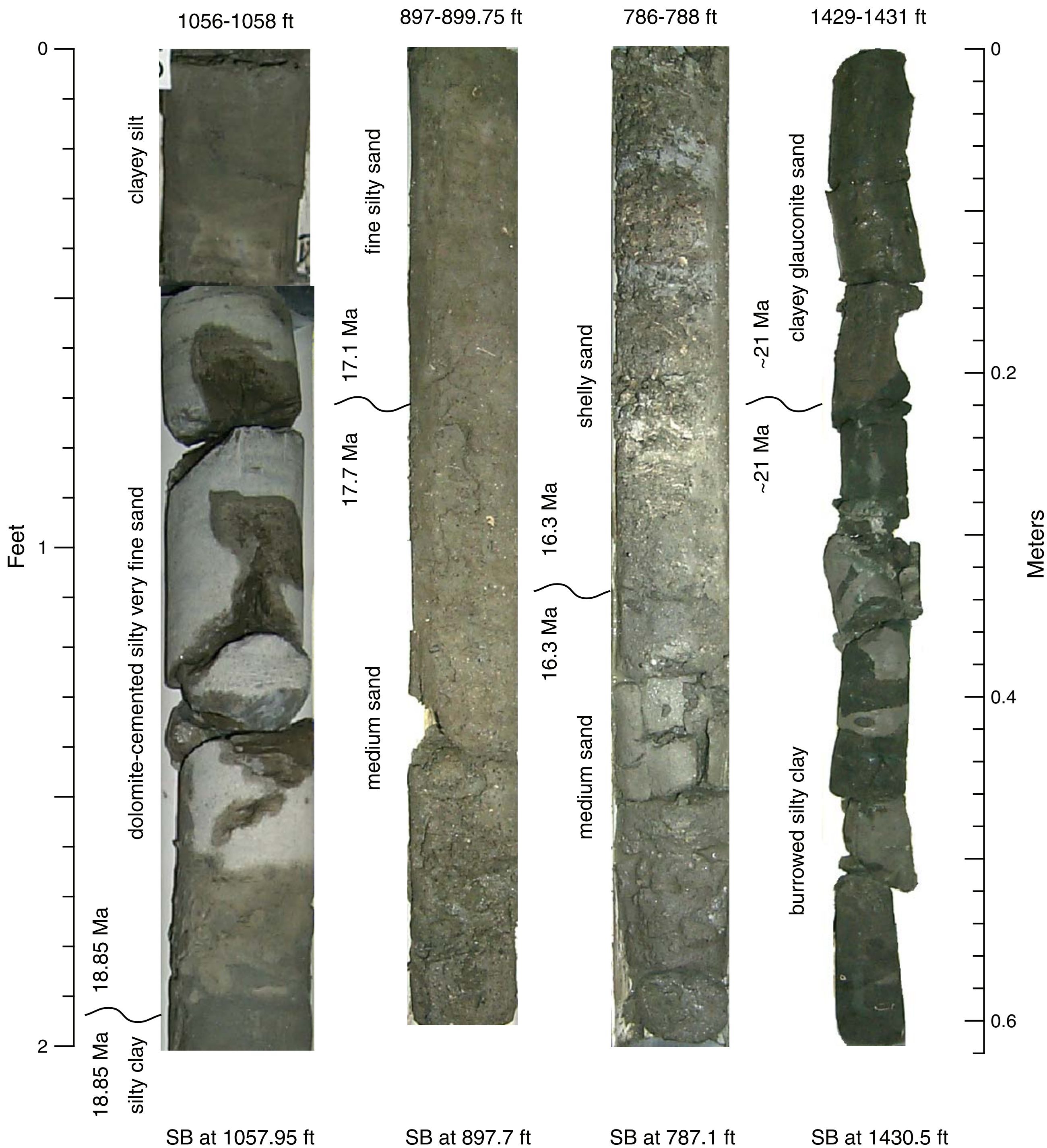

Figure F4. Summary stratigraphic section for Omar Formation (Pleistocene), Beaverdam Formation (upper? Miocene to Pliocene?), Bethany formation (upper? Miocene to Pliocene?), and upper Manokin formation (upper Miocene) from the Bethany Beach borehole. This, and subsequent similar figures, summarizes core recovery, lithology, gamma ray log signature, age, environments, and sequence stratigraphic interpretations. (Continued on next page.)

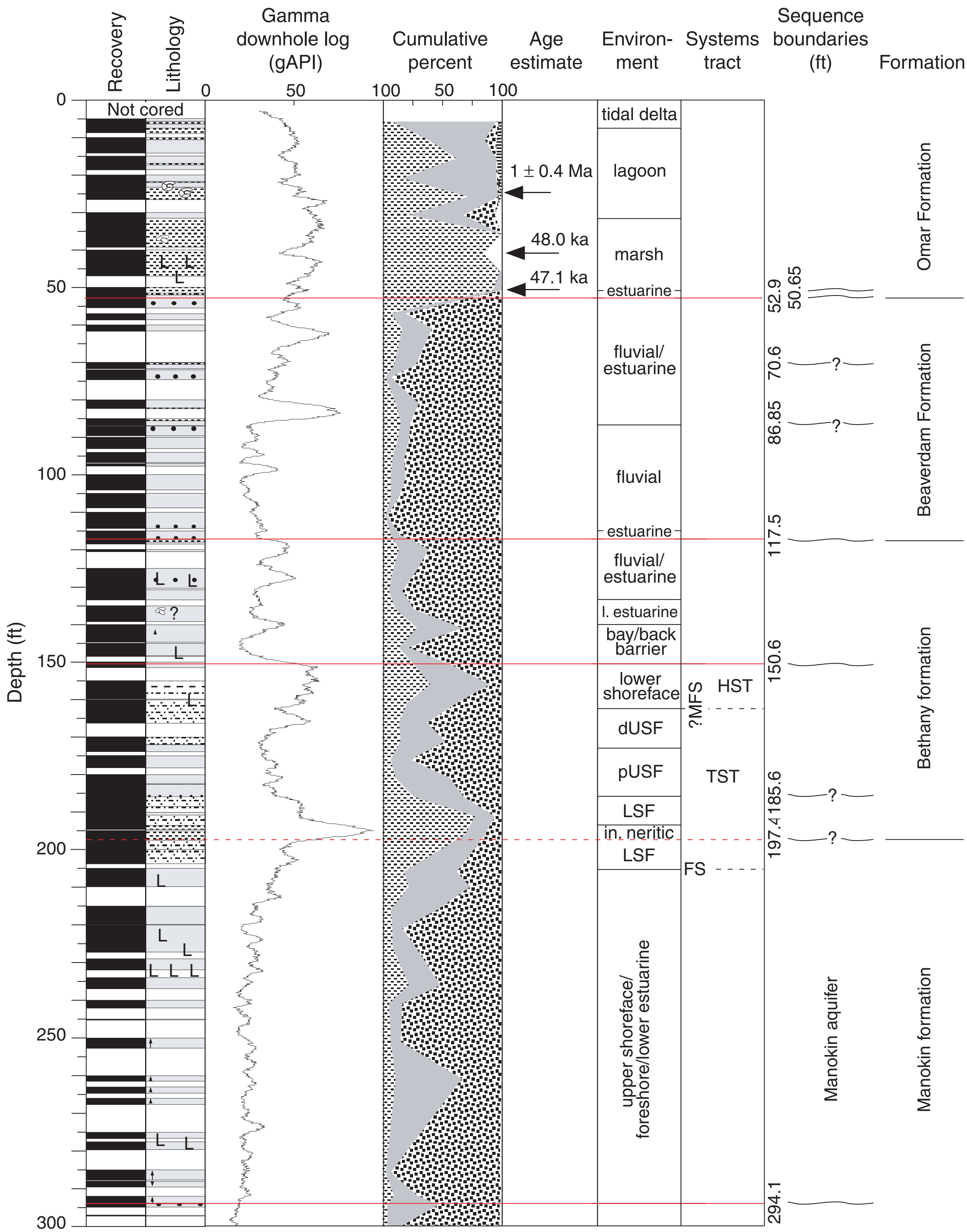

Figure F4 (continued). Key to symbols used on summary stratigraphic figures.

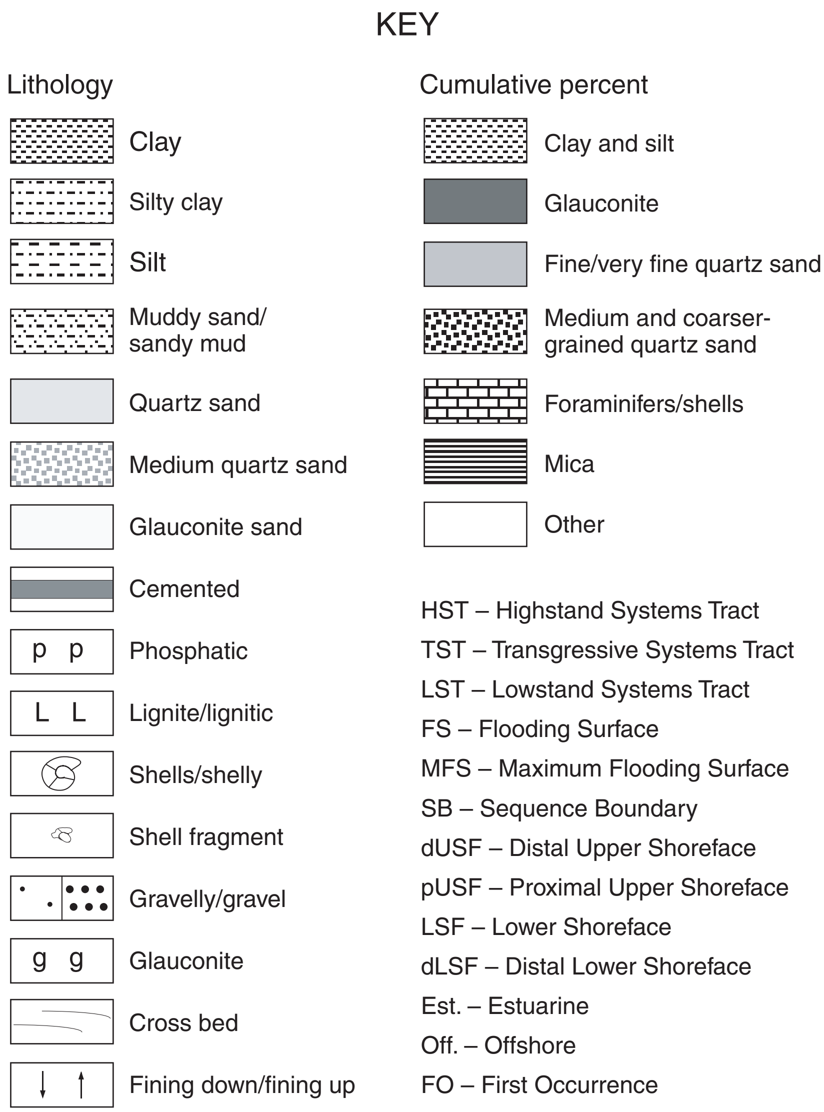

Figure F5. Summary stratigraphic section for lower Manokin formation (upper Miocene) and St. Marys Formation (upper Miocene) from the Bethany Beach borehole. See Figure **F4**, p. 59, for key.

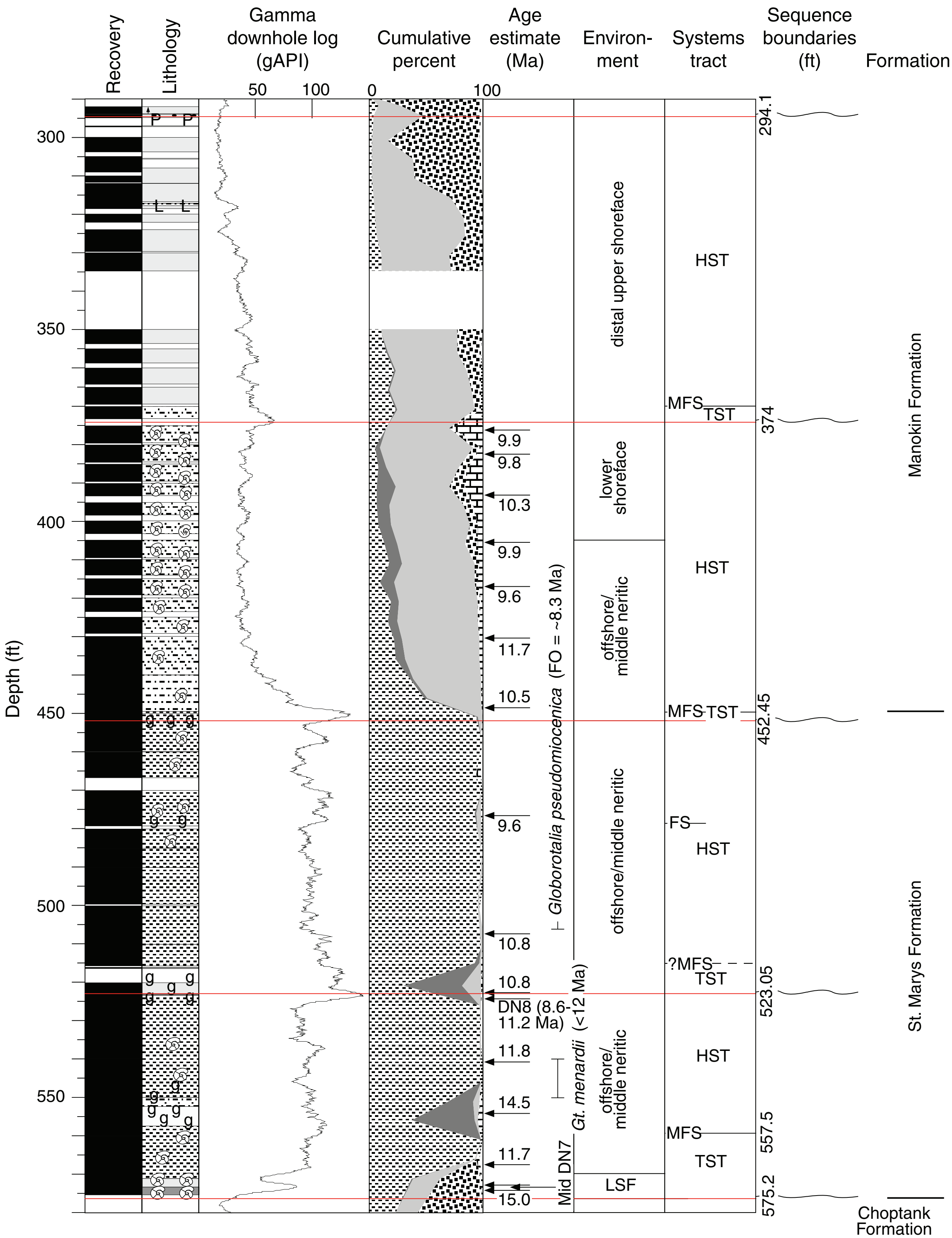

Figure F6. Summary stratigraphic section for the Choptank Formation (middle–upper Miocene), and upper Calvert Formation (lower–middle Miocene) from the Bethany Beach borehole. See Figure F4, p. 59, for key.

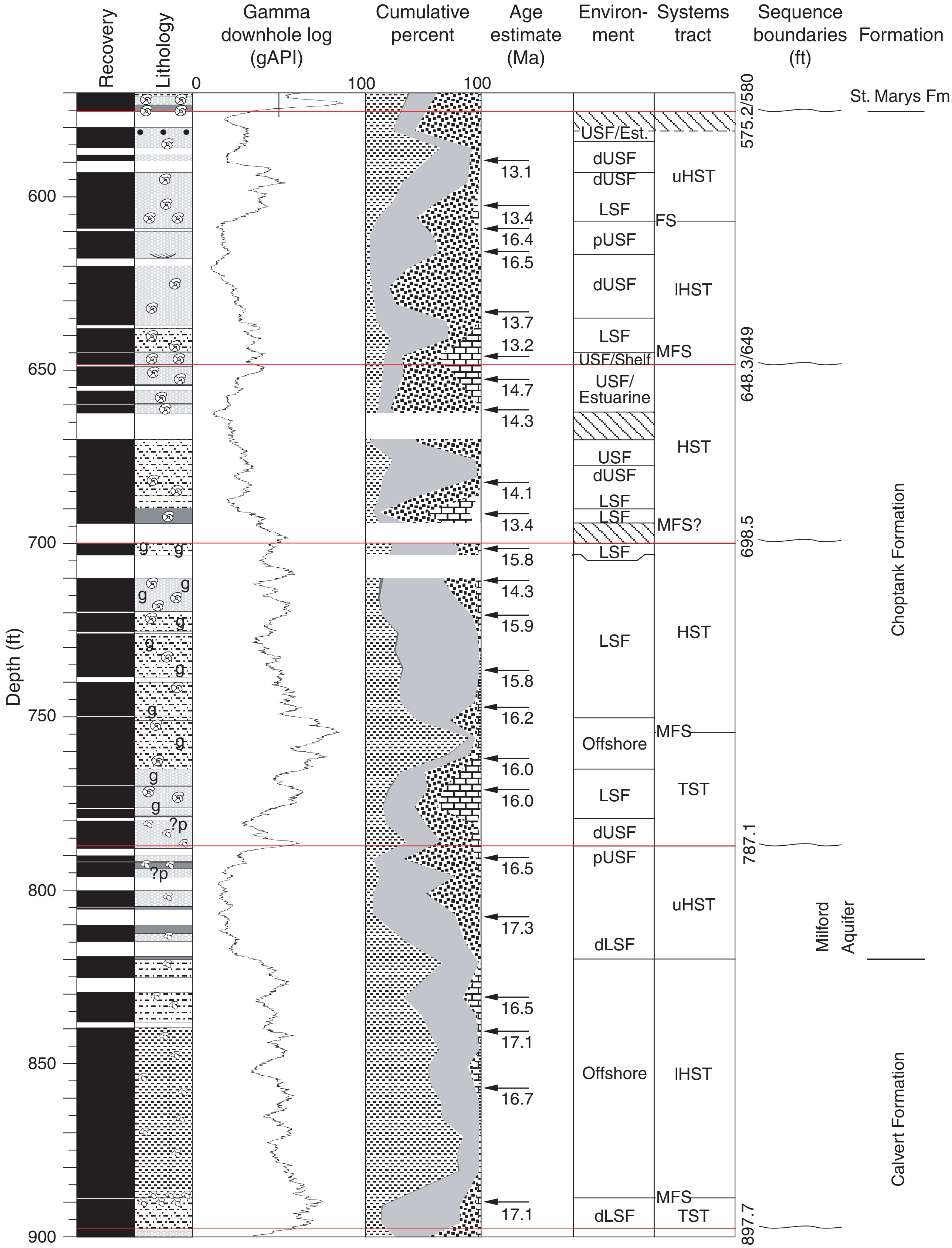

Figure F7. Summary stratigraphic section for the middle Calvert Formation (lower–middle Miocene) from the Bethany Beach borehole. See Figure F4, p. 59, for key.

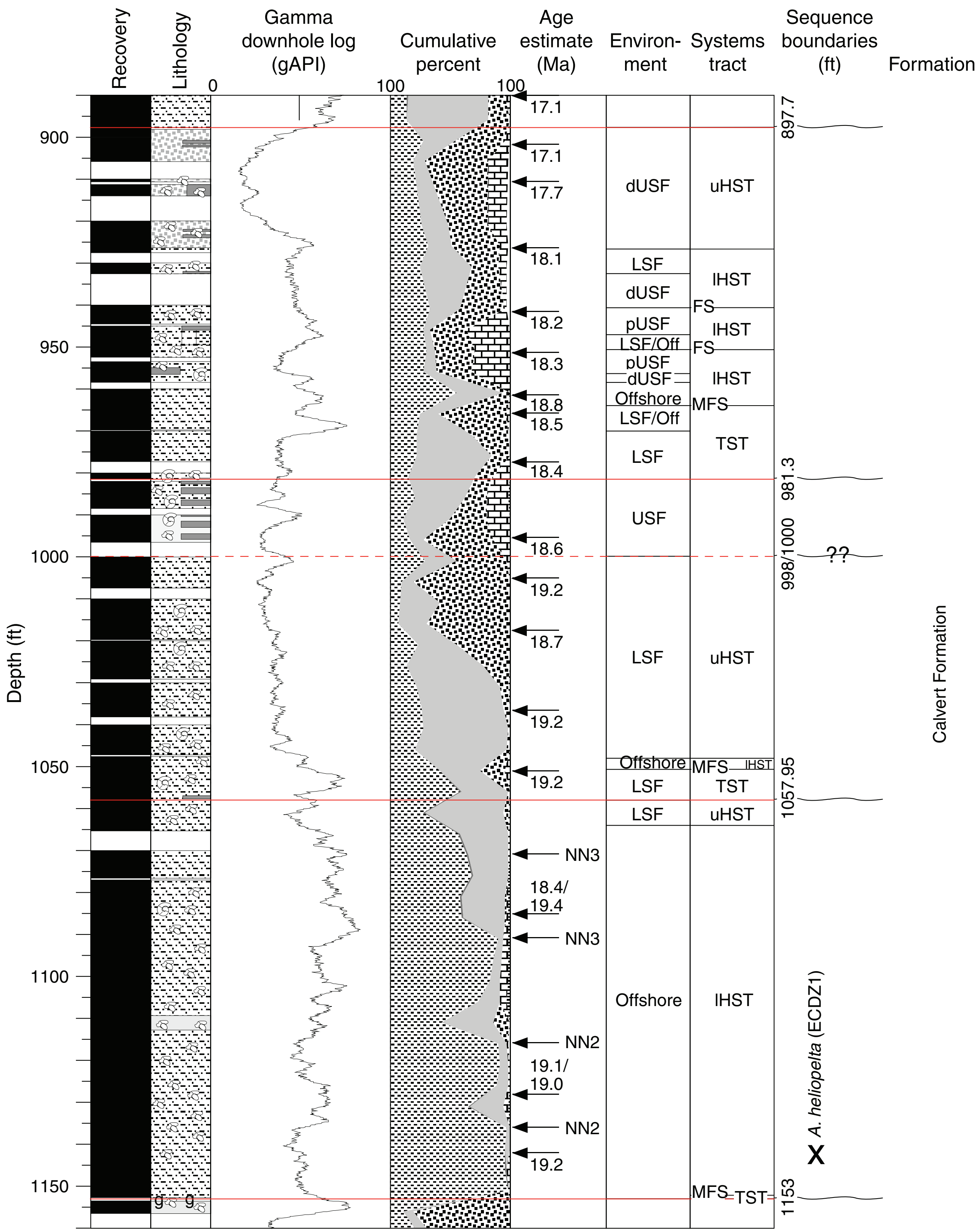

Figure F8. Summary stratigraphic section for the lower Calvert Formation (lower–middle Miocene), unnamed glauconitic clays and clayey glauconite sands (lower Miocene), unnamed foraminiferal clay (Oligocene) from the Bethany Beach borehole. TD = total depth. See Figure **F4,** p. 59, for key.

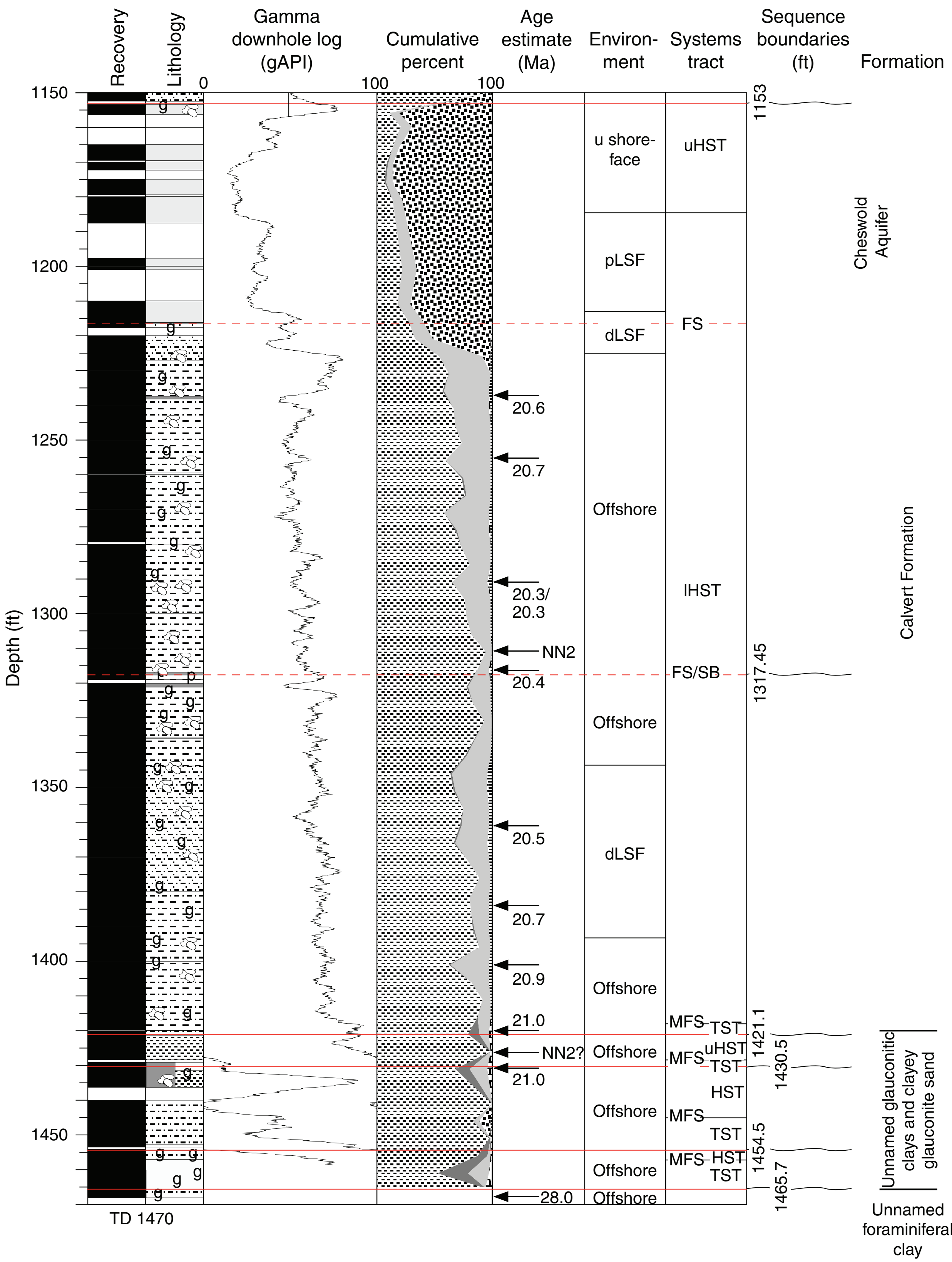

Figure F9. Pollen and dinocyst occurrences in the Bethany Beach borehole, Leg 174AXS.

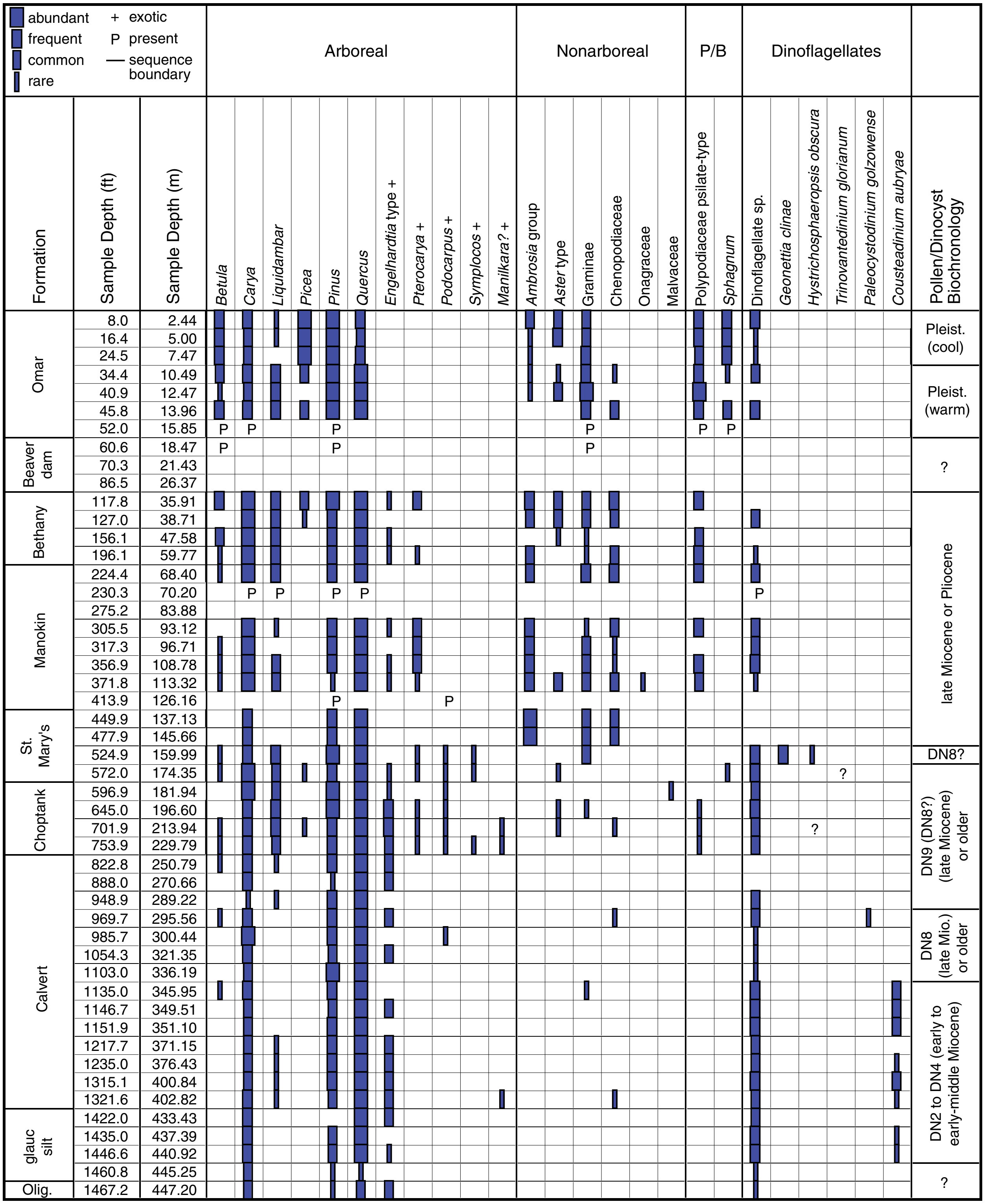

Figure F10. Age-depth plot for the Miocene sequences from the Bethany Beach borehole. Error bars = 2 σ for one analyses (Oslick et al., 1994). Points plotted in green are interpreted as diagenetically altered or stratigraphically reworked (see **"Strontium Isotope Chronostratigraphy,"** p. 44). Dashed lines = uncertain or alternate age model, thin horizontal lines = sequence boundaries. Right column indicates probable correlations to New Jersey sequences using the Kw (Kirkwood) sequence nomenclature of Miller et al. (1997). Timescale after Berggren et al. (1995).

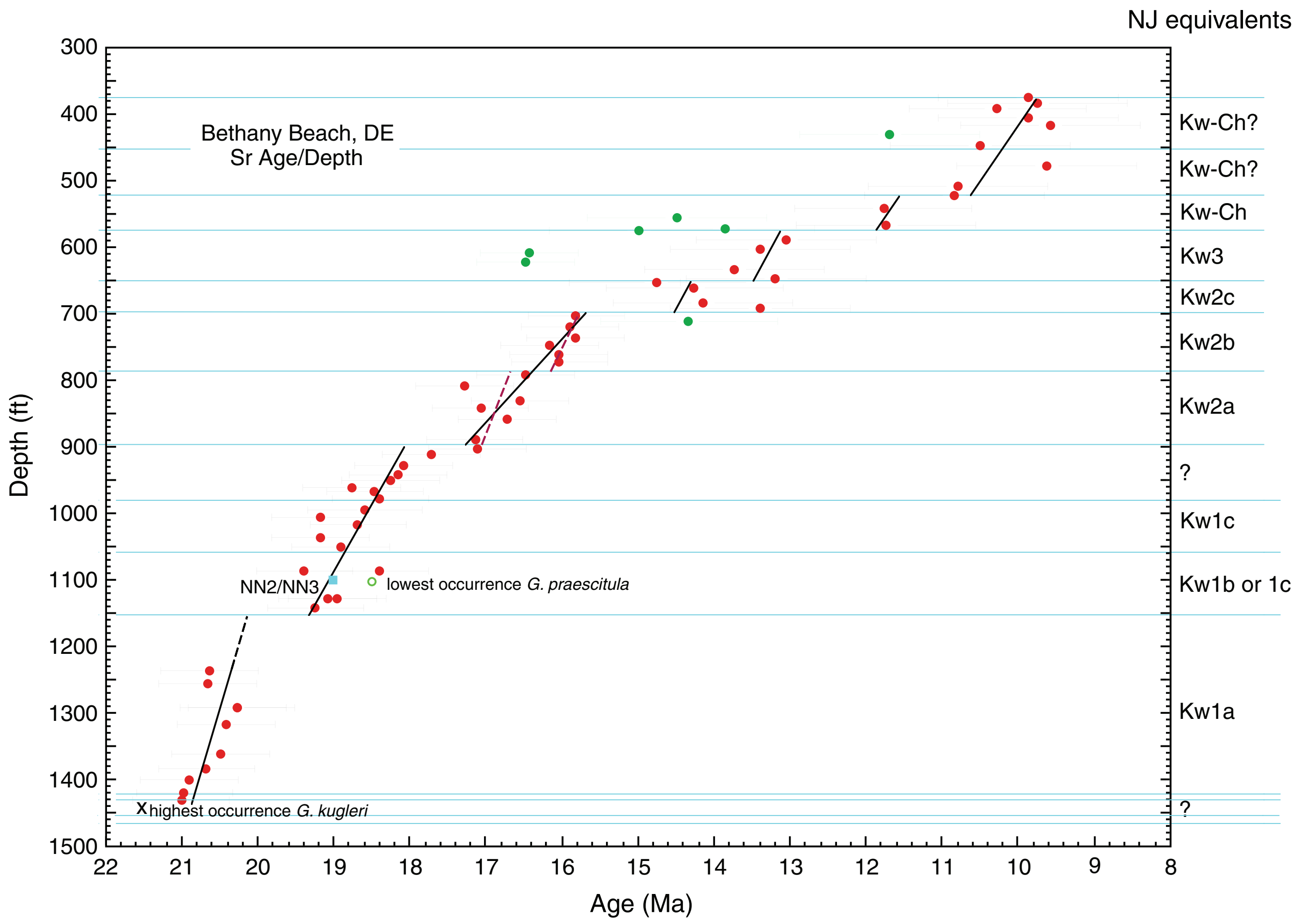

Figure F11. Comparison of the ages of Miocene sequences from the Bethany Beach borehole with the ages of sequences identified in New Jersey. Cross-hatched = uncertain ages. Also shown is the benthic foraminifer oxygen isotopic record for Atlantic deep-sea sites (modified after Miller et al., 1997). Mi events are major isotopic increases that are inferred to correlate with ice-growth events on Antarctica; arrows are placed at inflection points. Timescale after Berggren et al. (1995). VPDB = Vienna Pedee Belmenite.

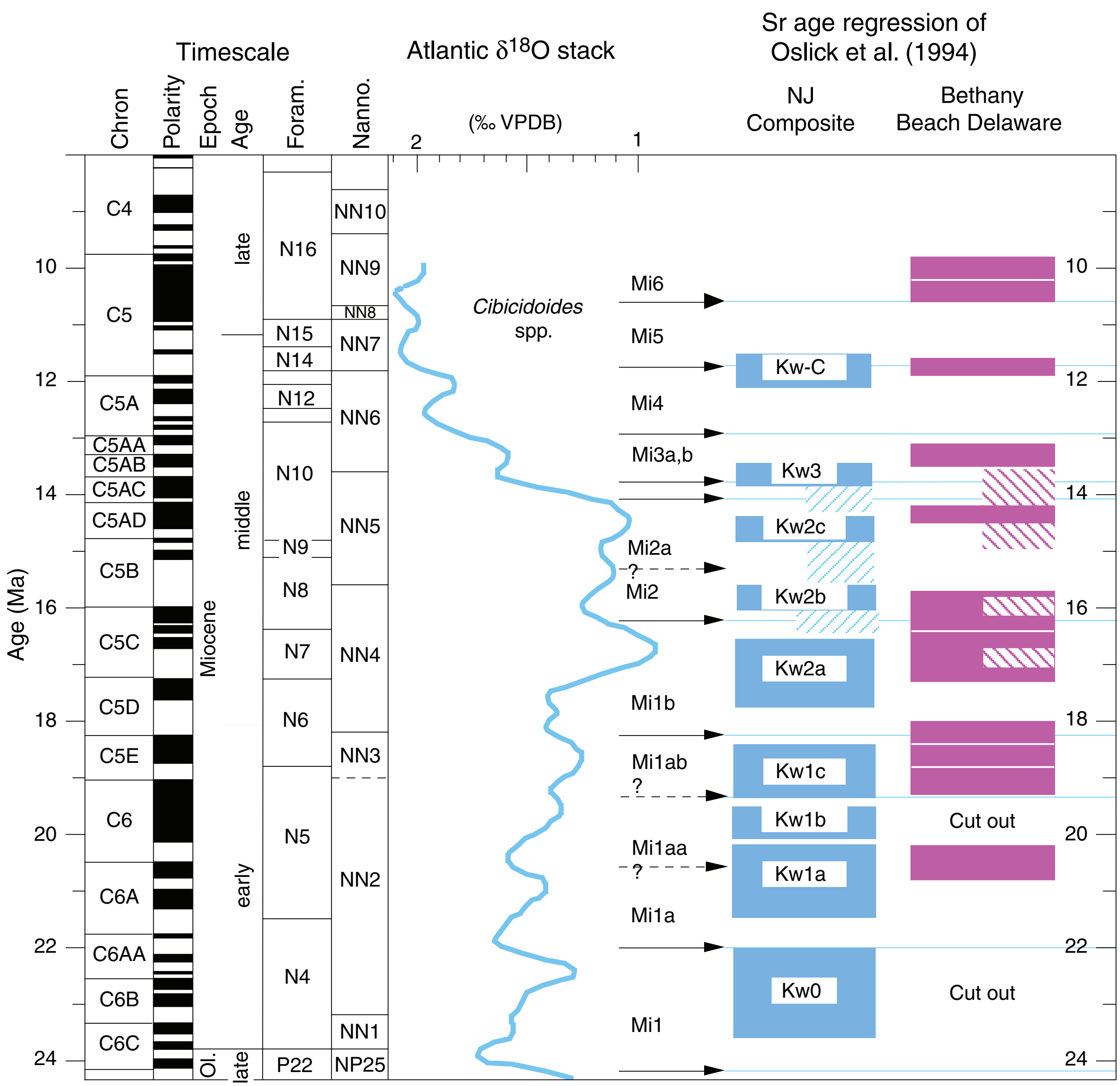

Table T1. Core descriptions, Bethany Beach borehole, Leg 174AXS. (Continued on next four pages.)

Run	Date (2000)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Primary lithology	Formation
1	12 May	5–10	5.0	3.65	73	Sand; 2.2-ft contact, sandy silty clay	Omar
2	12 May	10–15	5.0	4.20	84	Fine–very fine sand and clay	Omar
3	12 May	15–20	5.0	3.60	72	Fine–very fine sand and clay	Omar
4	12 May	20–30	10.0	6.30	63	Very fine sand and silty clay; shell layer	Omar
5	12 May	30–40	10.0	9.20	92	Peaty clay; very fine–coarse sand at top	Omar
6	12 May	40–50	10.0	1.65	17	Peaty clay	Omar
7	13 May	50–57	7.0	5.40	77	Clay grading down to sand; 52.9-ft contact; very coarse sand below	Omar/ Beaverdam
8	13 May	57–60	3.0	1.60	53	Coarse–very coarse sand	Beaverdam
9	13 May	60–70	10.0	1.65	17	Fine–coarse sand	Beaverdam
10	13 May	70–72	2.0	1.65	83	Fine–coarse sand with clay interbeds	Beaverdam
11	13 May	72–75	3.0	2.50	83	Medium sand; very coarse sand	Beaverdam
12	13 May	75–80	5.0	0.00	0	?	Beaverdam
13	13 May	80–85	5.0	1.25	25	Coarse–very coarse sand with clay interbeds	Beaverdam
14	14 May	85–87	2.0	1.85	93	Coarse sand with clay interbeds	Beaverdam
15	14 May	87–90	3.0	2.60	87	Medium–very coarse sand	Beaverdam
16	14 May	90–91	1.0	2.00	200	Fine–very coarse poorly sorted sand	Beaverdam
17	14 May	91–94	3.0	2.00	67	Coarse sand; fine–medium sand	Beaverdam
18	14 May	94–97	3.0	2.75	92	Medium–coarse sand	Beaverdam
19	14 May	97–100	3.0	0.70	23	Coarse sand	Beaverdam
20	14 May	100–105	5.0	4.00	80	Fine–medium sand	Beaverdam
21	15 May	105–110	5.0	3.70	74	Coarse–very coarse sand; medium–fine sand	Beaverdam
22	15 May	110–115	5.0	4.30	86	Medium–coarse sand	Beaverdam
23	15 May	115–120	5.0	3.40	68	Medium sand; 117.5-ft contact; laminated clay and sand	Beaverdam/ Bethany
24	15 May	120–125	5.0	0.40	8	Fine–medium sand	Bethany
25	15 May	125–130	5.0	5.90	118	Medium–coarse silty sand	Bethany
26	15 May	130–135	5.0	3.30	66	Medium, poorly sorted sand	Bethany
27	15 May	135–140	5.0	4.10	82	Medium–coarse sand	Bethany
28	15 May	140–145	5.0	4.70	94	Medium–coarse sand	Bethany
29	15 May	145–150	5.0	3.45	69	Fine–coarse sand, clay interbeds	Bethany
30	15 May	150–155	5.0	1.40	28	Fine–medium silty sand	Bethany
31	16 May	155–160	5.0	4.80	96	Clayey silty fine sand	Bethany
32	16 May	160–170	10.0	6.22	62	Very fine–fine sand, clayey silt laminae	Bethany
33	16 May	170–175	5.0	3.80	76	Very fine–coarse sand	Bethany
34	16 May	175–176.5	1.5	1.50	100	Fine–coarse sands	Bethany
35	16 May	176.5–180	3.5	1.60	46	Very fine–fine well-sorted sand	Bethany
36	16 May	180–185	5.0	5.00	100	Very fine–fine sand; contact at 180.85 ft; silty clay, sand, and silt	Bethany
37	16 May	185–190	5.0	5.30	106	Very fine–fine sand	Bethany
38	16 May	190–195	5.0	4.50	90	Very fine and to silt; silty clay	Bethany
39	16 May	195–205	10.0	8.70	87	Very fine–fine sand; clay lens; 197.4-ft contact	Bethany/ Manokin
40	17 May	205–210	5.0	4.90	98	Very fine–fine silty lignitic sand	Manokin
41	19 May	210–215	5.0	0.00	0		Manokin
42	19 May	215–220	5.0	4.90	98	Indurated sandstone; very fine–fine sand; clay stringers	Manokin
43	19 May	220–229	9.0	7.15	79	Interbedded poorly sorted medium–very fine, fine–very fine, fine–coarse, fine–medium, coarse–fine sand; occasionally lignitic	Manokin
44	19 May	229–234	5.0	2.90	58	Fine–very coarse lignitic sand	Manokin
45	19 May	234–240	6.0	2.80	47	Fine–very coarse sand	Manokin
46	20 May	240–245	5.0	2.00	40	Medium–coarse sand	Manokin
47	20 May	245–250	5.0	0.10	2	Medium–coarse sand	Manokin
48	20 May	250–253.5	3.5	2.60	74	Fine–medium sand	Manokin
49	20 May	253.5–260	6.5	0.00	0		Manokin
50	20 May	260–263	3.0	1.30	43	Fine–medium sand	Manokin
51	20 May	263–266	3.0	1.55	52	Very fine–fine sand	Manokin
52	20 May	266–270	4.0	1.60	40	Fine–very coarse sand	Manokin
53	21 May	270–275	5.0	0.00	0		Manokin
54	21 May	275–277.5	2.5	1.65	66	Medium–coarse sand	Manokin
55	21 May	277.5–285	7.5	2.15	29	Fine–medium sand	Manokin
56	21 May	285–288	3.0	2.45	82	Fine grading down to fine–medium to medium sand	Manokin
57	21 May	288–292	4.0	1.45	36	Medium grading to fine sand	Manokin
58	21 May	292–294	2.0	1.85	93	Medium–coarse sand; very coarse pebbly sand	Manokin
59	21 May	294–297	3.0	0.80	27	Pebbles (caved) over clay contact (294.1 ft) sand	Manokin
60	21 May	297–300	3.0	0.10	3	Fine? sand	Manokin
61	22 May	300–305	5.0	3.70	74	Medium grading to fine well-sorted sand	Manokin
62	22 May	305–310	5.0	4.00	80	Fine–medium well-sorted sand	Manokin
63	22 May	310–312.5	2.5	1.55	62	Fine–medium well-sorted sand	Manokin
64	22 May	312.5–320	7.5	6.37	85	Fine–medium well-sorted sand; lignitic clay	Manokin
65	22 May	320–324	4.0	2.00	50	Fine–medium to fine sand	Manokin
66	22 May	324–330	6.0	5.45	91	Fine–medium sand	Manokin

Table T1 (continued).

Run	Date (2000)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Primary lithology	Formation
67	22 May	330–340	10.0	4.75	48	Fine–medium sand	Manokin
68	23 May	340–350	10.0	0.00	0		Manokin
69	23 May	350–355	5.0	3.55	71	Fine–medium sand	Manokin
70	23 May	355–360	5.0	2.90	58	Fine–medium sand	Manokin
71	23 May	360–365	5.0	4.10	82	Fine–medium sand	Manokin
72	23 May	365–370	5.0	4.30	86	Fine–medium sand	Manokin
73	23 May	370–375	5.0	3.15	63	Clayey fine–medium sand	Manokin
74	23 May	375–380	5.0	4.55	91	Shelly clayey fine–medium sand	Manokin
75	23 May	380–385	5.0	4.40	88	Shelly clayey fine–medium sand	Manokin
76	23 May	385–390	5.0	4.45	89	Shelly clayey fine–medium sand	Manokin
77	23 May	390–395	5.0	3.10	62	Shelly clayey fine–medium sand	Manokin
78	23 May	395–400	5.0	3.10	62	Shelly clayey fine–medium sand	Manokin
79	24 May	400–405	5.0	3.30	66	Shelly clayey fine–medium sand	Manokin
80	24 May	405–410	5.0	4.65	93	Shelly clayey fine–medium sand	Manokin
81	24 May	410–415	5.0	4.05	81	Shelly clayey fine sand	Manokin
82	24 May	415–420	5.0	4.20	84	Shelly clayey fine sand	Manokin
83	24 May	420–425	5.0	3.55	71	Shelly clayey fine sand	Manokin
84	24 May	425–430	5.0	4.25	85	Shelly clayey fine sand	Manokin
85	24 May	430–440	10.0	10.40	104	Shelly clayey fine sand	Manokin
86	24 May	440–450	10.0	10.25	103	Very fine sandy silt/clay; 449.4-ft contact	Manokin/ St. Marys
87	24 May	450–460	10.0	9.95	100	Slightly silty clay	St. Marys
88	24 May	460–470	10.0	6.70	67	Slightly silty clay	St. Marys
89	24 May	470–480	10.0	9.15	92	Slightly silty clay	St. Marys
90	25 May	480–485	5.0	5.10	102	Slightly silty clay	St. Marys
91	25 May	485–490	5.0	5.22	104	Slightly silty clay	St. Marys
92	25 May	490–500	10.0	9.50	95	Slightly silty clay	St. Marys
93	25 May	500–510	10.0	10.15	102	Slightly silty clay	St. Marys
94	25 May	510–516	6.0	5.65	94	Slightly silty clay	St. Marys
95	25 May	516–520	4.0	0.20	5	Indurated layer	St. Marys
96	25 May	520–523	3.0	3.60	120	Glauconite sandy clay	St. Marys
97	25 May	523–530	7.0	7.30	104	Indurated layer with silty clay below	St. Marys
98	26 May	530–540	10.0	10.35	104	Slightly silty laminated clay	St. Marys
99	26 May	540–550	10.0	10.45	105	Slightly silty laminated clay/glauconite at base	St. Marys
100	26 May	550–558.5	8.5	8.85	104	Glauconite sandy clay/clay; contact at 557.7 ft	St. Marys
101	26 May	558.5–560	1.5	1.20	80	Slightly silty clay	St. Marys
102	26 May	560–570	10.0	10.05	101	Slightly silty clay	St. Marys
103	26 May	570–573.5	3.5	3.40	97	Medium sand and shell bed	St. Marys
104	26 May	573.5–580	6.5	1.70	26	Indurated sandy shell bed; 575.2-ft contact	St. Marys/ Choptank
105	26 May	580–581	1.0	1.00	100	Fine to medium sand	Choptank
106	26 May	581–588	7.0	6.70	96	Conglomerate and muddy sand	Choptank
107	27 May	588–593	5.0	1.85	37	Interbedded sand and clay	Choptank
108	27 May	593–600	7.0	7.15	102	Medium sand	Choptank
109	27 May	600–610	10.0	9.15	92	Medium sand	Choptank
110	27 May	610–615	5.0	6.05	121	Medium sand	Choptank
111	27 May	615–616.7	1.7	1.15	68	Medium sand	Choptank
112	27 May	616.7–620	3.3	1.11	34	Medium sand	Choptank
113	27 May	620–630	10.0	9.95	100	Medium sand	Choptank
114	27 May	630–638	8.0	6.95	87	Medium sand	Choptank
115	27 May	638–645	7.0	6.75	96	Medium sand	Choptank
116	28 May	645–649	4.0	3.30	83	Shelly sand/shell bed	Choptank
117	28 May	649–656	7.0	5.35	76	Medium sand/cemented at base	Choptank
118	28 May	656–660	4.0	3.80	95	Medium sand	Choptank
119	28 May	660–670	10.0	2.30	23	Medium sand/cemented	Choptank
120	28 May	670–680	10.0	10.30	103	Laminated sand and silt	Choptank
121	28 May	680–690	10.0	7.15	72	Laminated sand and silt	Choptank
122	28 May	690–692	2.0	4.75	238	Laminated sand and silt/cemented at base	Choptank
123	28 May	692–700	8.0	2.10	26	Medium sand/cemented at top	Choptank
124	28 May	700–710	10.0	9.45	95	Laminated sand and silt	Choptank
125	28 May	710–720	10.0	9.45	95	Laminated sand and silt	Choptank
126	29 May	720–726	6.0	5.05	84	Laminated sand and silt	Choptank
127	29 May	726–730	4.0	4.30	108	Laminated sand and silt	Choptank
128	29 May	730–740	10.0	8.25	83	Laminated sand and silt	Choptank
129	29 May	740–750	10.0	9.90	99	Laminated sand and silt	Choptank
130	29 May	750–760	10.0	10.20	102	Laminated sand and silt	Choptank
131	29 May	760–770	10.0	9.75	98	Laminated sand and silt/very fine sand	Choptank

Table T1 (continued).

Run	Date (2000)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Primary lithology	Formation
132	29 May	770–776.5	6.5	6.30	97	Shelly sand	Choptank
133	29 May	776.5–780	3.5	2.60	74	Shelly sand with hard zones	Choptank
134	30 May	780–790	10.0	7.90	79	Medium–fine sand; hard zone; gravelly, slightly shelly sand	Choptank
135	30 May	790–792	2.0	1.70	85	Medium–fine sand; hard zone	Choptank
136	30 May	792–792.5	0.5	0.50	100	Indurated; sandy molluscan packstone	Choptank
137	30 May	792.5–800	7.5	3.60	48	Sandy molluscan packstone/fine sand	Choptank
138	30 May	800–805	5.0	4.55	91	Fine–medium well-sorted sand	Choptank
139	30 May	805–807	2.0	0.20	10	Sandstone	Choptank
140	30 May	807–810	3.0	1.10	37	Sandstone and fine sands	Choptank
141	30 May	810–819	9.0	4.80	53	Sandstone and fine sands	Choptank
142	31 May	819–829.3	10.3	6.10	60	Sandstone and clayey sandy silt; 819.9-ft contact	Choptank/ Calvert
143	31 May	829.25–839.5	10.3	8.70	85	Sandy silt scattered shell fragments	Calvert
144	31 May	839.5–849.75	10.3	10.36	101	Clayey sandy silt	Calvert
145	31 May	849.75–851.75	2.0	2.00	100	Sandy silt; indurated zone at base	Calvert
146	31 May	851.75–860	8.3	8.40	102	Sandy clayey silt; indurated at top	Calvert
147	31 May	860–870	10.0	10.00	100	Very fine sandy silt; slightly micaceous; rare shell fragments and foraminifers	Calvert
148	31 May	870–880	10.0	10.17	102	Very slightly sandy silt; bioturbated; rare shell fragments; faint layering	Calvert
149	1 Jun	880–889	9.0	8.70	97	Silt to sandy silt; rare shells; shell concentration at base; bioturbated throughout	Calvert
150	1 Jun	889–899	10.0	9.75	98	Shelly fine to medium sand	Calvert
151	1 Jun	899–900	1.0	1.20	120	Medium to coarse massive quartz sand, shell fragments	Calvert
152	1 Jun	900–910	10.0	5.85	59	0–0.8 ft = medium quartz sand; 0.8–2.45 ft = interlayered sand and calcite-cemented sand; 2.45–5.85 ft = medium quartz sand	Calvert
153	1 Jun	910–911.35	1.4	0.85	63	Medium quartz sand with shell fragments; calcite-cemented sand at base	Calvert
154	1 Jun	911.35–920	8.6	2.65	31	Calcite-cemented medium quartz sand with shell fragments	Calvert
155	2 Jun	920–930	10.0	7.50	75	0–6.6 ft = medium quartz sand with abundant shells and fragments with calcite-cemented intervals (2.2, 2.4–3, and parts of 4.1–6.6 ft); 6.6–7.5 ft = laminated clay/silt with sand and clay burrows	Calvert
156	2 Jun	930–940	10.0	2.40	24	0–1.65 ft = silty sand with shells; 1.65–1.9 ft = silty sand; 1.9–2.4 ft = calcite–cemented sand	Calvert
157	2 Jun	940–945	5.0	4.50	90	0–0.65 ft = clayey medium quartz sand; 0.5–0.9 ft = clay-infilled burrow (20 mm wide); 0.65–3.3 ft = clayey to silty shelly quartz sand with phosphate; 3.3-ft contact; 3.3–4.5 ft = clayey to silty quartz sand with shell horizons	Calvert
158	2 Jun	945–953.5	8.5	7.60	89	0–0.3 ft = calcite-cement SS; 0.3–0.6 ft = silty clayey sand; 0.6–1.9 ft = fine–medium sand with shells, etc.; 1.9–5.53 ft = interbedded laminated silt, sandy silt, cross-laminated silt, sand; 5.53–7.6 ft = silty sand, coarsening upward, no bedding, shelly intervals	Calvert
159	2 Jun	953.5–960	6.5	4.95	76	0–1.4 ft = sand to clayey sand with shell hash at 0.5–0.65 ft; 1.4–2.75 ft = cemented shell hash/sandstone; 2.75–4.95 ft = calcareous silty sand with shell fragments at 3.7–3.9 ft	Calvert
160	2 Jun	960–970	10.0	9.80	98	0–4.4 ft = very sandy clayey silt, cross-laminated to 2.3 ft; 4.4–4.7 ft = silt; 5.5–5.7 ft grades to sand silt; 5.7–9.8 ft = bioturbated silt and sandy silt	Calvert
161	2 Jun	970–980	10.0	7.40	74	0–7.4 ft = very fine to fine sand, clayey and silty to 1.1 ft, silty below; a few laminations	Calvert
162	3 Jun	980–982	2.0	1.50	75	0–1.3 ft = slightly silty fine to medium sand with shells; 1.3–1.5 ft = calcite-cemented sandstone with shells	Calvert
163	3 Jun	982–990	8.0	6.40	80	0–0.5, 1.6–3, and 4.6–5.85 ft = calcite-cemented sandstone with shells; 0.5–1.6 and 5.85–6.4 ft = silty sand with shells and fragments; 3–4.6 ft = shelly sand with interbedded silt	Calvert
164	3 Jun	990–1000	10.0	6.55	66	0–1.55, 2.5–3.9, 4.8–6.2, and 6.2–6.55 ft = shelly silty sand; 1.55–2.5 and 3.9–4.8 ft = calcite-cemented sand with shell layers	Calvert
165	3 Jun	1000–1010	10.0	7.40	74	0–1.2 ft = interbedded silt sand and laminated silt; 1.2–7.4 ft = silty sand with zones of increased silt contact and faint laminae	Calvert
166	3 Jun	1010–1020	10.0	9.80	98	0–2.4 and 7–9.8 ft = sand, occasionally silty, scattered shells; 2.4–7 ft = siltier sands in places, laminae more pronounced; 7.9–8 ft = shell hash laminae	Calvert
167	3 Jun	1020–1030	10.0	9.05	91	Fine well-sorted sand, slightly silty, scattered shell fragments, siltier intervals show laminae, a few burrows	Calvert
168	3 Jun	1030–1040	10.0	8.10	81	0–5.1 ft = fine quartz sand, slightly silty, rare shell fragments, scattered laminae/cross-laminae; 5.1–8.5 ft = sand interlaminated with silt and very fine sand, cross-laminations and ripples, sand content increases downcore	Calvert

Table T1 (continued).

Run	Date (2000)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Primary lithology	Formation
169	4 Jun	1040–1047.5	7.5	7.20	96	Slightly silty well-sorted fine sand, laminated to thinly bedded, scattered shells throughout, shells concentrated and more homogeneous sediment (less laminated) below 6.4 ft	Calvert
170	4 Jun	1047.5–1055	7.5	7.95	106	0–3.35 ft = laminated silt and very fine sand, scattered shells and burrows; 3.35–5.1 ft = very fine/fine silty sand, shells, bioturbated; 5.1–7 ft = burrowed silt, very slightly clayey; 7–7.95 ft = clayey	Calvert
171	4 Jun	1055–1057	2.0	1.35	68	Silty very fine sand, burrows, very fine laminae	Calvert
172	4 Jun	1057–1060	3.0	3.70	123	0–0.8 ft = calcite-cemented sandstone with green conchoidal fracture, very fine, burrowed; 0.8–3.7 ft = sand, interlaminated fine and very fine, both silty, lamination often obscured by bioturbation	Calvert
173	4 Jun	1060–1070	10.0	5.25	53	Silty very fine sand, laminae/cross-laminae, scattered shell fragments, below 2.8 ft laminae are disturbed by burrowing	Calvert
174	4 Jun	1070–1077	7.0	6.70	96	Very silty very fine sand, bioturbated, faint laminae throughout	Calvert
175	12 Jun	1077–1080	3.0	2.90	97	Laminated (fine) sandy clayey silt; occasional rare small (<1 cm) shell fragments	Calvert
176	12 Jun	1080–1090	10.0	10.00	100	Laminated fine sandy clayey silt; small shell fragments increase downsection	Calvert
177	12 Jun	1090–1100	10.0	10.30	103	Laminated fine sandy clayey silt; small shell fragments, sand size shell fragments common	Calvert
178	12 Jun	1100–1110	10.0	10.50	105	Laminated fine sandy clayey silt; becoming silty fine sand in lower foot	Calvert
179	13 Jun	1110–1120	10.0	10.45	105	Silty fine sand fines downcore to a sandy clayey silt by 2.5 ft	Calvert
180	13 Jun	1120–1130	10.0	10.30	103	Sandy silt, rare small thin shell fragments, large foraminifers visible	Calvert
181	13 Jun	1130–1140	10.0	10.55	106	Sandy silt, sandier and shellier in the upper 3.5 ft, clay increases in the lower 2 ft	Calvert
182	13 Jun	1140–1150	10.0	10.60	106	Dark gray laminated silt with clay; trace shell fragments	Calvert
183	13 Jun	1150–1153.5	3.5	2.55	73	Dark gray laminated silt with clay; trace shell fragments; over glauconitic quartz. Sand with silt; sequence boundary at 1154 ft	Calvert
184	13 Jun	1153.5–1160	6.5	2.85	44	Medium to coarse quartz sand with thick shell fragments	Calvert
185	14 Jun	1160–1165	5.0	0.15	3	Medium–coarse quartz sand	Calvert
186	14 Jun	1165–1170	5.0	4.65	93	Coarse quartz sand	Calvert
187	14 Jun	1170–1175	5.0	2.25	45	Fine–coarse quartz silty sand	Calvert
188	14 Jun	1175–1180	5.0	4.50	90	Fine–coarse quartz silty sand	Calvert
189	14 Jun	1180–1190	10.0	7.50	75	Fine–coarse quartz silty sand	Calvert
190	15 Jun	1190–1200	10.0	0.00	0		
191	15 Jun	1200–1201	1.0	4.30	430	Fine–coarse quartz silty sand	Calvert
192	15 Jun	1201–1210	9.0	0.00	0		
193	15 Jun	1210–1220	10.0	7.90	79	Very muddy/silty sand, scattered shells	Calvert
194	15 Jun	1220–1230	10.0	10.45	105	Very muddy/silty sand, shelly; silt	Calvert
195	15 Jun	1230–1237.5	7.5	7.60	101	Slightly sandy silt, shelly	Calvert
196	16 Jun	1237.5–1240	2.5	2.50	100	Indurated, sandy silt; slightly sandy, clayey silt	Calvert
197	16 Jun	1240–1250	10.0	10.20	102	Sandy silt	Calvert
198	16 Jun	1250–1260	10.0	9.70	97	Sandy silt	Calvert
199	16 Jun	1260–1270	10.0	10.30	103	Sandy silt	Calvert
200	16 Jun	1270–1280	10.0	9.40	94	Sandy silt	Calvert
201	16 Jun	1280–1290	10.0	10.50	105	Sandy silt, with few sand stringers	Calvert
202	17 Jun	1290–1300	10.0	10.40	104	Sandy or clayey silt; shell bed	Calvert
203	17 Jun	1300–1310	10.0	10.55	106	Silt, shelly	Calvert
204	17 Jun	1310–1320	10.0	8.90	89	Silt; phosphatic shelly silt; cemented sand; silt	Calvert
205	17 Jun	1320–1320.3	0.3	0.30	100	Sandy silt with glauconite sand-filled burrows	Calvert
206	17 Jun	1320.3–1330	9.7	5.60	58	Siltstone; silt, slightly glauconitic	Calvert
207	18 Jun	1330–1340	10.0	10.05	101	Clayey silt, slightly glauconitic	Calvert
208	18 Jun	1340–1350	10.0	10.25	103	Sandy silt becoming silty sand, slightly glauconitic	Calvert
209	18 Jun	1350–1360	10.0	10.45	105	Silty sand, slightly glauconitic	Calvert
210	18 Jun	1360–1370	10.0	10.10	101	Silty sand/sandy silt, slightly glauconitic, thinly laminated	Calvert
211	18 Jun	1370–1380	10.0	10.50	105	Silty sand/sandy silt, slightly glauconitic, thinly laminated	Calvert
212	18 Jun	1380–1390	10.0	10.40	104	Slightly sandy silt, slightly glauconitic, thinly laminated	Calvert
213	19 Jun	1390–1400	10.0	10.55	106	Slightly sandy silt, slightly glauconitic, thinly laminated	Calvert
214	19 Jun	1400–1410	10.0	10.45	105	Slightly sandy silt, slightly glauconitic, thinly laminated	Calvert
215	19 Jun	1410–1420	10.0	9.90	99	Silt, slightly glauconitic, thinly laminated, burrowed	Calvert
216	19 Jun	1420–1429	9.0	8.30	92	Glauconitic silt; 1420-ft contact; clay	Calvert/ Unnamed
217	19 Jun	1429–1437	8.0	7.30	91	Glauconitic silt; contact zone = 1430.6–1431.35 ft; sequence boundary at 1430.5 ft; silty clay	Unnamed
218	20 Jun	1437–1440	3.0	0.00	0		Unnamed
219	20 Jun	1445–1450	5.0	3.75	75	Silty clay	Unnamed

Table T1 (continued).

Run	Date (2000)	Cored interval (ft)	Run length (ft)	Recovered (ft)	Recovery (%)	Primary lithology	Formation
220	20 Jun	1445–1450	5.0	6.50	130	Silty clay/clayey silt	Unnamed
221	20 Jun	1450–1454	4.0	3.45	86	Glauconitic clay/clayey glauconite sand	Unnamed
222	20 Jun	1454–1460	6.0	6.20	103	Glauconite sand; sequence boundary at 1454.5 ft; glauconitic clay; glauconitic sand	Unnamed
223	20 Jun	1460–1470	10.0	7.95	80	Clay glauconite sand; sequence boundary at 1465.7 ft; foraminiferal clay	Unnamed
	Bethany Beach coring totals:		1465.0	1166.5	79.6		

Table T2. Data used to construct the cumulative percent lots on the figures. (**See table notes.** Continued on next three pages.)

	Constituent in sand fraction (%)					
Depth (ft)	Clay and silt	Fine quartz	Medium and coarser quartz	Glauconite*	Shells and foraminifers*	Mica*	Other*
6.00	7.83	88	3	0	0	1	0
11.00	39.43	46	10	0	0	4	0
16.00	62.40	33	0	0	0	5	0
21.00	16.37	80	1	0	1	2	0
26.00	72.53	25	1	0	1	1	0
31.00	21.73	46	27	0	0	0	5
36.00	99.41	0	0	0	0	0	0
41.00	84.54	0	0	0	0	0	15
46.00	99.22	0	0	0	0	0	0
51.00	93.34	7	0	0	0	0	0
57.00	7.02	13	80	0	0	0	0
61.00	16.98	25	58	0	0	0	0
71.00	9.39	18	72	0	0	0	0
74.00	3.43	4	93	0	0	0	0
81.00	11.36	19	69	0	0	0	0
86.00	15.65	9	76	0	0	0	0
91.00	12.57	9	78	0	0	0	0
96.00	7.89	11	81	0	0	0	0
101.00	7.05	12	81	0	0	0	0
106.00	6.55	8	86	0	0	0	0
111.00	3.44	1	93	0	0	0	2
116.00	6.74	7	87	0	0	0	0
120.00	14.33	24	62	0	0	0	0
126.00	7.91	19	73	0	0	0	0
131.00	5.67	11	84	0	0	0	0
136.00	10.88	16	73	0	0	0	0
141.00	29.49	37	33	0	0	0	0
146.00	13.90	8	78	0	0	0	0
151.00	27.18	32	40	0	0	0	0
156.00	40.48	50	9	0	0	1	0
161.00	21.05	41	38	0	0	0	0
166.00	14.16	24	62	0	0	0	0
171.00	15.09	37	48	0	0	0	0
176.00	7.53	16	77	0	0	0	0
181.00	10.59	47	43	0	0	0	0
186.00	26.14	42	32	0	0	0	0
191.00	77.99	16	5	0	0	0	0
196.00	69.69	16	14	0	0	0	0
206.00	17.42	45	37	0	0	0	0
210.00	21.67	52	26	0	0	0	0
216.00	7.15	38	55	0	0	0	0
221.00	7.80	9	83	0	0	0	0
226.00	7.90	20	72	0	0	0	0
236.00	21.69	26	52	0	0	0	0
241.00	4.92	11	84	0	0	0	0
251.00	6.52	9	84	0	0	0	0
261.00	11.09	55	33	0	0	0	1
286.00	3.42	4	90	0	0	0	2
292.00	9.14	20	71	0	0	0	0
294.70	4.83	43	51	0	0	0	1
301.00	3.75	13	81	0	0	0	2
306.00	3.21	36	59	0	0	0	1
311.00	2.83	38	59	0	0	0	1
316.00	5.19	67	28	0	0	0	0
321.00	5.47	78	16	0	0	0	0
326.00	6.64	78	15	0	0	0	0
331.00	11.17	61	28	0	0	0	0
351.00	11.12	67	21	0	0	0	0
356.00	16.15	61	22	1	0	0	1
361.00	22.96	62	13	1	0	1	0
366.00	17.51	73	8	1	0	1	0
371.00	24.30	68	6	1	0	1	0
376.00	15.14	54	3	1	26	0	0
381.00	5.48	82	6	4	2	0	0
386.00	8.85	64	8	7	12	0	0
391.00	7.79	47	15	16	15	0	0

Table T2 (continued).

Depth (ft)	Clay and silt	Fine quartz	Medium and coarser quartz	Glauconite*	Shells and foraminifers*	Mica*	Other*
	Constituent in sand fraction (%)						
396.00	7.36	65	8	11	8	0	0
401.00	7.99	69	8	12	3	0	0
406.00	14.92	59	11	10	5	0	0
411.00	17.88	64	4	11	3	0	0
416.00	10.00	71	3	12	3	0	0
421.00	19.32	70	2	8	2	0	0
426.00	17.26	72	1	8	3	0	0
431.00	22.09	67	1	7	2	0	0
436.00	24.42	66	1	7	2	0	0
441.00	36.63	59	0	3	1	0	0
446.00	49.25	48	0	3	0	0	0
451.00	95.46	3	0	1	0	0	0
456.00	99.25	0	0	0	0	0	0
461.00	97.34	1	0	0	0	1	1
466.00	94.96	0	0	0	3	0	1
471.00	98.91	0	0	0	0	0	0
476.00	94.09	5	0	0	1	0	0
481.00	96.24	3	0	0	0	0	0
486.00	99.29	0	0	0	0	0	0
491.00	99.65	0	0	0	0	0	0
496.00	96.64	1	0	0	1	1	0
501.00	96.57	1	0	0	0	0	2
506.00	97.81	2	0	0	0	0	0
511.00	98.81	1	0	0	0	0	0
515.00	94.00	1	0	4	1	0	0
521.00	30.27	16	1	52	0	0	0
526.00	97.71	1	0	0	0	0	1
531.00	98.49	1	0	0	0	0	0
536.00	97.88	1	0	0	0	0	0
541.00	99.14	0	0	0	0	0	0
546.00	98.28	1	0	0	0	0	0
551.00	70.11	6	0	22	1	0	0
556.00	38.39	2	1	55	3	0	0
561.00	98.33	1	0	0	0	0	0
566.00	93.54	1	0	0	3	0	3
571.00	38.12	23	37	1	0	0	0
581.00	24.43	18	57	0	0	0	0
586.00	65.69	27	8	0	0	0	0
596.00	32.47	57	10	0	0	0	1
601.00	25.96	40	29	0	4	0	2
606.00	11.77	33	48	0	5	0	2
611.00	4.37	54	39	0	0	0	3
616.00	4.62	59	36	0	0	0	0
621.00	4.10	33	63	0	0	0	0
626.00	6.19	14	80	0	0	0	0
631.00	8.29	18	74	0	0	0	0
636.00	10.05	61	29	0	0	0	0
641.00	22.52	50	14	0	14	0	0
646.00	16.48	15	32	0	36	0	0
651.00	15.93	17	44	0	23	0	0
661.00	10.99	12	77	0	0	0	0
671.00	5.03	41	54	0	0	0	0
676.00	24.29	72	4	0	0	0	0
681.00	16.31	82	2	0	0	0	0
686.00	12.92	36	48	0	3	0	0
691.00	7.50	5	41	0	37	0	9
701.00	23.39	60	15	0	2	0	0
711.00	13.29	54	27	2	4	0	0
716.00	11.18	68	17	1	3	0	0
721.00	15.03	78	4	1	2	0	0
726.00	27.52	69	2	1	0	0	0
731.00	25.28	72	1	1	0	0	0
736.00	32.76	65	0	1	0	1	0
741.00	29.11	68	0	1	1	1	0
746.00	30.28	63	3	1	2	1	0
751.00	44.40	29	22	1	3	1	0
756.00	91.27	5	1	0	2	0	0
761.00	71.79	19	5	0	4	0	0
766.00	30.93	21	30	0	18	0	0
771.00	19.46	34	14	1	32	0	0

Table T2 (continued).

Depth (ft)	Constituent in sand fraction (%)						
	Clay and silt	Fine quartz	Medium and coarser quartz	Glauconite*	Shells and foraminifers*	Mica*	Other*
776.00	15.45	28	20	0	37	0	0
781.00	18.68	35	42	0	2	0	2
786.00	36.20	29	26	0	8	0	0
791.00	7.68	26	63	0	3	0	0
796.00	13.09	65	20	0	1	0	0
801.00	7.51	46	46	0	0	0	0
807.00	6.77	71	22	0	0	0	1
814.80	34.97	51	14	0	0	0	0
821.00	67.01	31	2	0	0	0	0
831.00	33.86	52	2	0	13	0	0
836.00	49.28	47	1	0	2	0	0
841.00	55.68	42	0	0	2	0	0
846.00	63.55	36	0	0	0	0	0
851.00	54.91	34	4	0	6	1	0
856.00	57.56	37	0	0	5	0	0
861.00	65.87	32	0	0	1	0	0
866.00	66.67	31	0	0	1	0	0
871.00	84.81	14	0	0	1	0	0
876.00	79.36	19	0	0	1	0	0
881.00	81.49	17	0	0	1	0	0
891.00	14.35	67	14	2	4	0	0
896.00	14.41	68	18	0	0	0	0
901.00	27.26	27	41	0	5	0	0
905.75	19.28	10	53	0	16	0	1
921.00	26.12	23	33	0	15	0	3
926.00	31.25	19	41	0	7	0	1
931.00	25.32	42	23	0	6	0	3
941.00	33.00	26	37	0	2	0	2
946.00	28.11	6	30	0	36	0	1
951.00	30.92	7	33	0	29	0	0
956.00	28.42	11	29	0	32	0	0
961.00	56.24	38	6	0	0	0	0
966.00	24.50	15	57	0	3	0	0
971.00	22.26	45	31	0	0	0	1
976.00	22.15	63	15	0	0	0	0
981.00	15.61	56	14	0	14	0	0
986.00	21.23	42	18	0	18	1	0
991.00	11.57	38	30	0	20	0	0
996.00	16.12	12	57	0	14	0	0
1001.00	29.78	26	42	0	2	0	0
1006.00	10.22	9	81	0	0	0	0
1011.00	8.52	33	59	0	0	0	0
1016.00	7.55	23	69	0	0	0	0
1021.00	23.45	33	44	0	0	0	0
1026.00	13.67	64	22	0	0	0	0
1031.00	22.87	68	8	0	1	0	0
1036.00	27.01	68	5	0	1	0	0
1041.00	27.89	71	1	0	0	0	0
1046.00	21.17	76	2	0	0	0	0
1051.00	41.37	32	22	1	4	0	0
1056.00	57.79	38	2	2	0	0	0
1061.00	27.51	64	5	2	1	0	0
1066.00	57.14	40	0	1	1	0	0
1071.00	64.00	33	0	1	2	0	0
1076.00	68.48	29	0	1	1	1	0
1081.00	58.30	36	2	2	2	1	0
1086.00	60.29	35	1	1	2	1	0
1091.00	89.77	5	0	0	4	1	0
1096.00	85.65	7	0	0	6	1	0
1101.00	83.95	8	0	0	7	2	0
1106.00	73.21	18	0	0	6	3	0
1111.00	43.73	42	14	0	0	0	0
1116.00	89.74	8	0	0	1	1	2
1121.00	92.25	7	0	0	1	0	0
1126.00	88.96	10	0	0	1	1	0
1131.00	65.84	27	0	1	4	2	0
1136.00	96.73	3	0	0	1	0	0

Table T2 (continued).

Depth (ft)	Clay and silt	Constituent in sand fraction (%)					
		Fine quartz	Medium and coarser quartz	Glauconite*	Shells and foraminifers*	Mica*	Other*
1141.00	95.71	4	0	0	0	0	0
1146.00	96.45	1	0	0	2	0	0
1151.00	98.07	1	0	0	1	0	0
1156.00	11.09	8	80	0	0	0	0
1160.00	21.19	10	69	0	0	0	0
1166.00	13.82	6	80	0	0	0	0
1171.00	8.98	5	86	0	0	0	0
1176.00	7.50	6	86	0	0	0	0
1181.00	13.40	9	78	0	0	0	0
1201.00	21.90	13	65	0	0	0	0
1211.00	17.82	11	70	0	1	0	0
1216.00	28.03	12	59	0	1	0	0
1221.00	33.67	15	51	0	1	0	0
1226.00	54.20	38	6	0	1	1	0
1231.00	62.96	35	0	0	1	1	0
1236.00	56.54	40	0	1	0	2	0
1241.00	66.75	31	0	0	1	2	0
1246.00	68.53	30	0	0	0	2	0
1251.00	73.72	25	0	0	0	1	0
1256.00	59.12	39	0	0	0	2	0
1261.00	73.89	24	0	1	0	1	0
1266.00	76.92	21	0	0	0	1	0
1271.00	58.14	38	0	1	1	2	0
1276.00	68.48	29	0	1	1	2	0
1281.00	72.93	25	0	1	1	1	0
1286.00	80.59	17	0	0	0	2	0
1291.00	65.03	30	0	1	1	3	0
1296.00	76.54	21	0	0	0	2	0
1301.00	77.38	20	0	0	0	2	0
1306.00	81.91	16	0	0	0	1	0
1311.00	94.23	5	0	0	0	0	0
1316.00	87.43	9	0	0	3	1	0
1321.00	78.10	19	0	0	0	2	0
1325.80	83.05	15	0	1	0	1	0
1331.00	93.15	6	0	0	0	1	0
1341.00	76.86	20	0	1	0	2	0
1346.00	63.93	30	0	2	0	4	0
1351.00	67.19	28	0	1	0	3	0
1356.00	74.55	22	0	1	0	3	0
1361.00	72.75	23	0	1	0	3	0
1366.00	67.10	28	0	1	0	3	0
1370.00	76.43	21	0	0	0	2	0
1376.00	89.06	9	0	0	0	1	0
1382.00	80.81	17	0	0	0	2	0
1386.00	81.75	15	0	1	0	2	0
1391.00	83.63	13	0	0	0	2	0
1396.00	88.97	9	0	0	0	1	0
1401.00	62.57	33	0	1	0	3	0
1406.00	81.79	15	0	1	0	2	0
1411.00	91.13	7	0	0	0	1	0
1416.00	86.94	11	0	1	0	2	0
1421.00	79.12	9	0	9	2	0	1
1426.00	99.05	0	0	0	1	0	0
1431.00	68.04	16	0	12	4	0	0
1441.00	99.56	0	0	0	0	0	0
1446.00	82.66	6	10	0	0	1	0
1451.00	97.69	0	0	0	2	0	0
1456.00	87.48	3	0	9	1	0	0
1461.00	52.66	18	0	27	0	0	2
1466.00	89.74	2	0	3	5	0	0

Notes: * = obtained by visual best estimate; see **"Summary,"** p. 16, in "Lithostratigraphy." These data were used to construct cumulative percent lots on Figures **F4,** p. 59; **F5,** p. 61; **F6,** p. 62; **F7,** p. 63; and **F8,** p. 64. Note the percent silt and clay in each sample was quantitatively measured by weighing each sample before and after washing off the clay and silt. The weight of the remaining sand was compared to the weight of the original sample to calculate percent silt and clay. All other percentages were arrived at qualitatively by visually estimating the proportion of each constituent in the sand fraction.

Table T3. Sr isotopic data, Bethany Beach borehole, Leg 174AXS.

Depth					Regression age estimate (Ma)	
(ft)	(m)	Material	Sr value	Precision	Martin et al. (1999)	Oslick et al. (1994)
24.60	7.50	Shell	0.709147	0.000006		
376.25	114.68	Shell	0.708936	0.000004	9.87	
382.50	116.59	Shell	0.708940	0.000006	9.75	
393.00	119.79	Shell	0.708921	0.000006		10.27
405.40	123.57	Shell	0.708936	0.000004	9.87	
416.90	127.07	Shell	0.708946	0.000005	9.57	
430.30	**131.16**	**Shell**	**0.708883**	**0.000016**		**11.70**
448.40	136.67	Shell	0.708915	0.000006		10.49
476.60	145.27	Shell	0.708944	0.000004	9.63	
507.25	154.61	Shell	0.708907	0.000007		10.79
522.60	159.29	Shell	0.708906	0.000006		10.83
541.25	164.97	Shell	0.708881	0.000008		11.77
554.25	**168.94**	**Shell**	**0.708809**	**0.000005**		**14.48**
567.50	172.97	Shell	0.708882	0.000005		11.73
572.80	**174.59**	**Shell**	**0.708826**	**0.000006**		**13.84**
574.00	**174.96**	**Shell**	**0.708795**	**0.000008**		**15.00**
589.45	179.66	Shell	0.708847	0.000006		13.05
602.60	183.67	Shell	0.708838	0.000006		13.39
607.00	**185.01**	**Shell**	**0.708733**	**0.000006**		**16.42**
622.30	**189.68**	**Shell**	**0.708730**	**0.000005**		**16.47**
633.10	192.97	Shell	0.708829	0.000006		13.73
646.00	196.90	Shell	0.708843	0.000006		13.20
652.50	198.88	Shell	0.708802	0.000006		14.74
661.40	201.59	Shell	0.708815	0.000005		14.25
682.30	207.97	Shell	0.708818	0.000006		14.14
691.50	210.77	Shell	0.708838	0.000004		13.39
701.50	213.82	Shell	0.708775	0.000005		15.76
710.50	**216.56**	**Shell**	**0.708813**	**0.000015**		**14.33**
720.60	219.64	Shell	0.708769	0.000005		15.90
736.50	224.49	Shell	0.708774	0.000005		15.82
747.10	227.72	Shell	0.708751	0.000005		16.16
762.00	232.26	Shell	0.708759	0.000006		16.04
771.00	235.00	Shell	0.708760	0.000011		16.03
790.70	241.01	Shell	0.708730	0.000005		16.47
807.80	246.22	Shell	0.708675	0.000013		17.27
830.89	253.26	Shell	0.708725	0.000005		16.54
840.70	256.25	Shell	0.708689	0.000011		17.07
857.00	261.21	Shell	0.708713	0.000016		16.72
889.90	271.24	Shell	0.708684	0.000004		17.14
901.85	274.88	Shell	0.708686	0.000006		17.11
910.50	277.52	Shell	0.708645	0.000010		17.71
926.50	282.40	Shell	0.708620	0.000013		18.08
941.50	286.97	Shell	0.708615	0.000004		18.15
951.30	289.96	Shell	0.708608	0.000010		18.25
961.50	293.07	Shell	0.708573	0.000006		18.77
965.70	294.35	Shell	0.708594	0.000005		18.46
977.30	297.88	Shell	0.708599	0.000006		18.39
995.40	303.40	Shell	0.708585	0.000008		18.59
1005.00	306.32	Shell	0.708545	0.000004		19.18
1017.50	310.13	Shell	0.708579	0.000004		18.68
1036.70	315.99	Shell	0.708545	0.000005		19.18
1051.00	320.34	Shell	0.708564	0.000005		18.90
1085.00	330.71	Shell	0.708598	0.000005		18.40
1085.00	330.71	Shell	0.708531	0.000012		19.38
1128.00	343.81	Shell	0.708552	0.000009		19.07
1128.00	343.81	Shell	0.708560	0.000008		18.96
1142.00	348.08	Shell	0.708541	0.000011		19.24
1237.30	377.13	Shell	0.708445	0.000005		20.64
1256.10	382.86	Shell	0.708444	0.000006		20.66
1291.00	393.50	Shell	0.708471	0.000010		20.26
1291.20	393.56	Shell	0.708471	0.000005		20.26
1316.20	401.18	Shell	0.708461	0.000010		20.41
1362.00	415.14	Shell	0.708456	0.000006		20.48
1384.00	421.84	Shell	0.708443	0.000005		20.67
1401.10	427.06	Shell	0.708427	0.000006		20.96
1420.00	432.82	Shell	0.708423	0.000014		20.96
1430.80	436.11	Shell	0.708420	0.000050		21.01
1467.80	447.39	Shell	0.708060	0.000013		29.03

Table T4. Benthic and planktonic foraminiferal occurrences (>250-µm size fraction only) in the Bethany Beach borehole, Leg 174AX. (See table note. Continued on next page.)

Sample depth (m):	114.60	126.80	128.32	129.84	131.37	132.89	134.42	135.94	137.46	138.99	140.51	142.04	143.56	145.08	146.61	148.13	149.66	151.18	152.70	154.23	155.75	157.12	158.80
Sample depth (ft):	376.0	416.0	421.0	426.0	431.0	436.0	441.0	446.0	451.0	456.0	461.0	466.0	471.0	476.0	481.0	486.0	491.0	496.0	501.0	506.0	511.0	515.5	521.0
Benthic foraminifers:																							
Bolivina																							
Buliminella								R	R		R		R					R		R	C	R	
Cassidulina																R	R	R				R	
Cibicidoides																							
Dentalina																							
Elphidium																							
Eponides	R		R	R	R	R	R	R	R			R	C	C	R				R	C	R	R	
Frondicularia																							
Fursenkoina											R												
Guttulina																		R					R
Gyroidinoides																							
Hanzawaia												R								R			R
Lagena							R											R		R			
Lenticulina														R	R	R			R	R			R
Marginulina																							
Miliolina																							
Nonion																					A	A	
Pseudononion	R	R	R	R	R	R	A	C	C	C	A	C	A	A	A	A	A	A	R	A	A	C	R
Pyrgo																							
Quinqueloculina				R	C	R	R	R	R	R	R	R	R	R	A	C	R	R		R	R	R	
Spiroplectammina																							
Textularia							R						R		R			R	R	C	R	R	R
Transversigerina																							
Uvigerina														R	R	R	R	C	R				R
Planktonic foraminifers:																							
Dentoglobigerina globosa																X							
Globigerina bulloides					X		X	X	X	X	X	X	X	X	X	X	X	X	X		X		
Globigerina ciperoensis																							
Globigerinoides ruber																						X	
Globigerinoides subconglobata								X	X	X	X									X			
Globigerinoides trilobus																X	X						
Globorotalia pseudomiocenica?																				X			
Hastigerina sp.																						X	
Neogloboquadrina acostaensis									X					X	X								
Orbulina suturalis																			X				
Orbulina universa																					X		

Sample depth (m):	160.32	161.85	163.37	164.90	166.42	167.94	169.47	170.99	172.52	174.04	181.66	183.18	204.52	206.04	207.57	219.76	221.28	228.90	230.43	233.48	235.00	244.14	253.29
Sample depth (ft):	526.0	531.0	536.0	541.0	546.0	551.0	556.0	561.0	566.0	571.0	596.0	601.0	671.0	676.0	681.0	721.0	726.0	751.0	756.0	766.0	771.0	801.0	831.0
Benthic foraminifers:																							
Bolivina			R									R											
Buliminella	R	R	R						R														
Cassidulina																							
Cibicidoides								R	R	C	R		R									R	
Dentalina					R		R			R				R									
Elphidium																							
Eponides	R	R	R	C	C	R		R	C		R												
Frondicularia																							
Fursenkoina																							
Guttulina					C	C	R	R			R				R	R							
Gyroidinoides																							
Hanzawaia	R	R	A	A	A	A	A	A	A	R	R	R	R	C	C	R	R				R	R	C
Lagena	R			R																			
Lenticulina		R	R		C	C		R	R	R													
Marginulina			R																				
Miliolina					R			R	R		R												
Nonion	R																						
Pseudononion	R	R	C	A	A	A	R	C	A	R	R	R				R	R	R	R	R			
Pyrgo										R					R								
Quinqueloculina																							
Spiroplectammina					R	C	R	R	C				R	R									
Textularia		R	A	C	R	C	R	C	C						R						R		
Transversigerina																							
Uvigerina	R		R	C	A		A	A	A	C													
Planktonic foraminifers:																							
Dentoglobigerina globosa				X																			
Globigerina bulloides											0												
Globigerina ciperoensis																							
Globigerinoides ruber																							
Globigerinoides subconglobata																							
Globigerinoides trilobus	X		X	X	X			X				X					X						
Globorotalia pseudomiocenica?																							
Hastigerina sp.																							
Neogloboquadrina acostaensis																							
Orbulina suturalis			X																				
Orbulina universa			X																				

Note: A = abundant, C = common, R= rare, X = present.

Table T4 (continued).

Sample depth (m):	257.86	259.38	260.91	262.43	263.96	265.48	267.00	268.53	271.58	273.10	292.91	297.48	299.01	312.72	314.25	326.44	327.96	329.49	331.01	332.54	334.06	335.58	337.11
Sample depth (ft):	846.0	851.0	856.0	861.0	866.0	871.0	876.0	881.0	891.0	896.0	961.0	976.0	981.0	1026.0	1031.0	1071.0	1076.0	1081.0	1086.0	1091.0	1096.0	1101.0	1106.0
Benthic foraminifers:																							
Bolivina											R												
Buliminella																				R	R	R	R
Cassidulina																							
Cibicidoides													C	R	R	R	R	R	R	R	C	C	C
Dentalina																	R	R	R	R			
Elphidium	R										R												
Eponides																							
Frondicularia																							
Fursenkoina																							
Guttulina												R		R							C	C	C
Gyroidinoides																							
Hanzawaia	R	R									C			R	R	R	R	R	R	C	C	C	R
Lagena																R	R				C		
Lenticulina			C	A	A	A	A	A	R							A	A	A	A	A	C	C	C
Marginulina																							
Miliolina																							
Nonion																							
Pseudononion		R	C	C	C	C	C	C	R		A	C	C	R	R	A	A	C	A	A	A	A	A
Pyrgo																							
Quinqueloculina																							
Spiroplectammina																C	C	C	C	C	C	C	C
Textularia						R		R			C		R	R		R	R				C	C	C
Transversigerina																							
Uvigerina																	R	R	R	R			
Planktonic foraminifers:																							
Dentoglobigerina globosa																							
Globigerina bulloides		X	X	X			X	X															
Globigerina ciperoensis																							
Globigerinoides ruber																							
Globigerinoides subconglobata																							
Globigerinoides trilobus			X						X	X	X	X		X	X	X	X	X	X	X	X	X	X
Globorotalia pseudomiocenica?																							
Hastigerina sp.																							
Neogloboquadrina acostaensis																							
Orbulina suturalis																							
Orbulina universa																							

Sample depth (m):	338.63	340.16	343.20	344.73	346.25	347.78	349.30	350.82	356.92	369.11	375.21	381.30	387.40	393.50	399.59	405.69	411.78	417.58	423.98	430.07	436.17	442.26	446.84
Sample depth (ft):	1111.0	1116.0	1126.0	1131.0	1136.0	1141.0	1146.0	1151.0	1171.0	1211.0	1231.0	1251.0	1271.0	1291.0	1311.0	1331.0	1351.0	1370.0	1391.0	1411.0	1431.0	1451.0	1466.0
Benthic foraminifers:																							
Bolivina		R					C	R							R								
Buliminella			R	R	R	C	C																
Cassidulina																							
Cibicidoides	R													R									
Dentalina																							
Elphidium																							
Eponides																	R						
Frondicularia																							R
Fursenkoina																							
Guttulina							R	R															R
Gyroidinoides																							R
Hanzawaia	R									R	R												
Lagena																							
Lenticulina	C	C	C	C	A	C	C	A													R	R	R
Marginulina																							
Miliolina																							
Nonion																						R	
Pseudononion	A	A	A	A	C	A	A	A		R	R	R	R		R	R	R	R	R	R	C	R	
Pyrgo																							
Quinqueloculina																							
Spiroplectammina	C																			R			
Textularia	C		C	C	R		C	R															
Transversigerina																						R	C
Uvigerina					R		R													R	R	R	
Planktonic foraminifers:																							
Dentoglobigerina globosa																							
Globigerina bulloides																							
Globigerina ciperoensis										X													
Globigerinoides ruber																							
Globigerinoides subconglobata																							
Globigerinoides trilobus	X		X	X						X								X		X			
Globorotalia pseudomiocenica?																							
Hastigerina sp.																							
Neogloboquadrina acostaensis																							
Orbulina suturalis																							
Orbulina universa																							

Table T5. Fossil occurrences in the Bethany Beach borehole, Leg 174AX. (**See table note.** Continued on next three pages.)

Sample depth (m):	159.99	160.60	164.6–169.2	174.35	181.94	196.60	213.94	229.79	250.79	268.25	270.66	289.22	300.44	321.35	322.78	324.31	336.19	345.95	347.59	349.51	350.67	351.10	370.94	371.15	373.99	376.43	379.48	388.77	397.76	400.84	402.82	408.43	433.43	437.39	437.81	439.98	440.74	440.92	442.87	445.25	446.99	447.20
Sample depth (ft):	524.9	526.9	540–555	572.0	596.9	645.0	701.9	753.9	822.8	880.1	888.0	948.9	985.7	1054.3	1059.0	1064.0	1103.0	1135.0	1140.4	1146.7	1150.5	1151.9	1217.0	1217.7	1227.0	1235.0	1245.0	1275.5	1305.0	1315.1	1321.6	1340.0	1422.0	1435.0	1436.4	1443.5	1446.0	1446.6	1453.0	1460.8	1466.5	1467.2
Shell fragments:	VR		R	VR	VR	A	R	R	VR		VR				VR		VR	VR		R		R		VR	VR	VR	R	F	P	R		VR		VR	VR	VR	R	R	VR			
Echinoid spines:				VR	VR	R	VR	R	R	VR	R	VR	R	VR	VR	VR	VR		VR							VR		P		VR	VR	VR	C	R	VR	R		R		VR		
Orbulina suturalis:					VR	A	VR						F																									?				
Bone/teeth (phosphatic) fragments:	VR		VR	R	VR	R	VR	VR	VR	VR	VR		VR	VR		VR		VR		VR		VR		VR	VR	VR	VR					VR	R	R	VR	VR		R		F		VR
Scolecodonts:													VR	VR																				VR						R		
Pyrite spheres:	A		A		VR																																					
Benthic foraminifers:	R		C	R	VR	R	VR	R	R	VR	R	R	R	R	VR	R	A	A	A	C	A	C		R	VR	R	VR			R	R	VR	F	R	R			F		VR		F
Agglutinated foraminifers?																										VR																R
Assorted lagenids (SF Nodosariacea)	VR		VR	VR		VR		VR			VR	VR					VR	VR		VR		VR		VR	VR								VR					VR			P	VR
Atwillina nodifera																																									R	A
Bolivina calvertensis			C	R			?VR																																			
Bolivina cf. *floridana*											VR																					VR						C				
Bolivina marginata multicostata	cf.		VR									VR		?VR		VR	C	A	A	A	C	A		VR		VR				R												
Bolivina paula			A			A	VR	A	A	P	A	C	VR		VR	VR	A	A		R		C		C	R	R	P				R	R		VR	VR	VR		F			P	A
Bolivina spp. (small)				C				A	C		A		R	?VR																												
Bucella mansfieldi	VR		A	A	VR	VR																																				
Bulimina aculeata?																																									P	VR
Bulimina curta			R															C												VR			A	VR				F				
Bulimina elongata	R		A	A	VR	VR		C	R	P	C	VR	VR	?VR		VR	R	C	R	R		VR		R						VR	VR	VR	A	F	C		P	F	VR	VR	P	C
Bulimina sp. (smooth basal spines)			VR																																							
Bulimina striata mexicana											VR						VR							VR											P							
Buliminella elegantissima	VR				VR	A	VR	C	VR	P	R	F	A		VR	VR	C	C	R	VR		C		R	R	C		P	P	R	A	A		VR							P	R
Cancris sagra				VR								VR																														
Cassidulina laevigata			A	A																																						
Cassidulinoides sp.																																								VR	P	R
Cibicides americanus						R		VR	C			R	R	?VR																												
Cibicides cravenensis				A																																						
Cibicides lobatulus					VR	VR			VR								VR	VR		VR		VR																				
Cibicides spp.													VR			C	R					VR		R		VR				VR	VR					R		VR				
Ciperozea mayi																																			P	VR	P	C				
Coryphostoma georgiana																																			P							
Elphidium cf. *latispatium*												VR																														
Elphidium spp.								VR	VR																	VR	P				C	VR										
Eponides cocoaensis?																																									P	C
Frondicularia sp.																	VR	VR						VR	VR	VR	P							VR								
Fursenkoina fusiformis											R	VR										VR																			P	VR
Globocassidulina sp.			?VR					VR				VR				VR	VR	R		VR		R													P						P	R
Globulina spp.																	VR																VR			VR		R			P	R
Guttulina elegans																		R	R	R		R																R			P	VR
Guttulina problema?																																									P	R

Table T5 (continued).

Sample depth (m):	159.99	160.60	164.6–169.2	174.35	181.94	196.60	213.94	229.79	250.79	268.25	270.66	289.22	300.44	321.35	322.78	324.31	336.19	345.95	347.59	349.51	350.67
Sample depth (ft):	524.9	526.9	540–555	572.0	596.9	645.0	701.9	753.9	822.8	880.1	888.0	948.9	985.7	1054.3	1059.0	1064.0	1103.0	1135.0	1140.4	1146.7	1150.5
Guttulina pulchella					VR																
Guttulina sp.					VR								VR				VR		R		
Gyroidina scalata and *G.* sp.																		C			
Gyroidinoides sp.				R													VR				
Hanzawaia concentrica	VR		A	A	A	C	VR	C	C	P	C	R	A	?VR	VR	C	C	VR	R	VR	
Lenticulina americana / L. a. spinosa			C								C			VR			R	C	C	C	
Lenticulina spp.	VR			R		VR		VR		P						VR	VR	VR	R	VR	C
Marginulina sp.			VR	VR							VR					VR					
Melonis? sp.																					
Nonion advenum pustulosum									C												
Nonion calvertensis											VR	R									
Nonion marylandicum				cf.		VR					VR	VR	VR		VR		VR				
Nonionella miocenica	R		A	VR								VR	VR								
Nonionellina chesapeakensis			cf.		VR																
Plectofrondicularia cookei																					
Pseudononion pizarrensis	R		C	R	VR	VR	VR	A	R	P	A	R	C	R	R	C	A	A	A	A	C
Pseudopolymorphina striata													VR								
Pullenia sp.																					
Rosalina cavernata						VR															
Rosalina? sp.									VR				VR								
Rotorbinella bassleri							?VR	VR	VR		VR		C			VR	VR	VR			
Siphonina sp.																					
Spirobolivina sp.												VR									
Spiroloculina sp.				VR																	
Spiroplectammina mississippiensis				R				R			R		VR	R		R	A		R		
Spiroplectammina spp.					VR						VR							VR			
Stilostomella sp.																					
Textularia spp.			C	R	VR	VR		R	VR	P	R		C	R			C	R	R	R	C
Transversigerina lamellata				VR																	
Transversigerina transversa												VR						VR			
Uvigerina calvertensis	R		C	A																	
Uvigerina glabrans?																					
Uvigerina subperegrina/auberiana							VR	VR			VR	R	VR		VR	C	C	A	R	C	C
Uvigerina tumeyensis																					
Virgulinella miocenica			R										VR								
Planktonic foraminifers:			R	VR	VR	VR		VR	VR	VR	VR	VR	VR	VR		VR	C	VR	R	R	
Dentoglobigerina altispira s.l.			VR																		
Dentoglobigerina venezuelana									VR					VR							
Globigerina angustiumbilicata				VR				cf. VR				VR	VR			VR	R	VR	VR		
Globigerina bulloides type			R																		
Globigerina ciperoensis																	VR				

Sample depth (m):	351.10	370.94	371.15	373.99	376.43	379.48	388.77	397.76	400.84	402.82	408.43	433.43	437.39	437.81	439.98	440.74	440.92	442.87	445.25	446.99	447.20
Sample depth (ft):	1151.9	1217.0	1217.7	1227.0	1235.0	1245.0	1275.5	1305.0	1315.1	1321.6	1340.0	1422.0	1435.0	1436.4	1443.5	1446.0	1446.6	1453.0	1460.8	1466.5	1467.2
Guttulina pulchella																					
Guttulina sp.			VR										VR	P				VR			
Gyroidina scalata and *G.* sp.												C								P	C
Gyroidinoides sp.														P	R		F				
Hanzawaia concentrica	VR		A	VR	R					VR	VR										
Lenticulina americana / L. a. spinosa	A														VR	P	R				
Lenticulina spp.	R		VR								VR	R	VR	VR	R			VR		P	C
Marginulina sp.																P	R				
Melonis? sp.																				P	VR
Nonion advenum pustulosum																					
Nonion calvertensis																					
Nonion marylandicum																					
Nonionella miocenica											VR										
Nonionellina chesapeakensis																					
Plectofrondicularia cookei										VR		VR	VR	VR	VR		R			P	R
Pseudononion pizarrensis	F		A	C	R	P			VR	VR	VR	A	R	R	R		F	VR		P	C
Pseudopolymorphina striata																					
Pullenia sp.																					R
Rosalina cavernata																					
Rosalina? sp.																					
Rotorbinella bassleri	R		R		VR				VR	VR	VR	VR	VR	VR	R		F				
Siphonina sp.															R						
Spirobolivina sp.			VR						VR												
Spiroloculina sp.																	VR				
Spiroplectammina mississippiensis	VR		R														R				
Spiroplectammina spp.					VR									P	VR	P				P	R
Stilostomella sp.													VR								
Textularia spp.	C		R		VR				VR			R			VR		VR				
Transversigerina lamellata																					
Transversigerina transversa												VR			VR	P	R				
Uvigerina calvertensis																					
Uvigerina glabrans?																				R	A
Uvigerina subperegrina/auberiana	C		VR	VR	VR	P			R	VR		A	VR				VR			P	R
Uvigerina tumeyensis																				R	A
Virgulinella miocenica																					
Planktonic foraminifers:	R		R		VR				VR	VR	VR	VR	VR				F				F
Dentoglobigerina altispira s.l.																					
Dentoglobigerina venezuelana																					
Globigerina angustiumbilicata	VR		R						VR												
Globigerina bulloides type																					
Globigerina ciperoensis			R							VR											

Table T5 (continued).

Sample depth (m):	159.99	160.60	164.6–169.2	174.35	181.94	196.60	213.94	229.79	250.79	268.25	270.66	289.22	300.44	321.35	322.78	324.31	336.19	345.95	347.59	349.51	350.67	351.10	370.94	371.15	373.99	376.43	379.48	388.77	397.76	400.84	402.82	408.43	433.43	437.39	437.81	439.98	440.74	440.92	442.87	445.25	446.99	447.20
Sample depth (ft):	524.9	526.9	540–555	572.0	596.9	645.0	701.9	753.9	822.8	880.1	888.0	948.9	985.7	1054.3	1059.0	1064.0	1103.0	1135.0	1140.4	1146.7	1150.5	1151.9	1217.0	1217.7	1227.0	1235.0	1245.0	1275.5	1305.0	1315.1	1321.6	1340.0	1422.0	1435.0	1436.4	1443.5	1446.0	1446.6	1453.0	1460.8	1466.5	1467.2
Globigerina linaperta group (large)																																									P	A
Globigerina sp. (4–5 ch, umb-extraumb ap)																						R																A			P	A
Globigerina spp.			R	R	VR	VR		R	VR	P	VR	VR	VR	VR		VR	R	VR	R	R		R		R		VR	P	P		VR	R	VR	VR	VR	R	VR		A	VR			
Globigerina woodi			R						VR		VR	VR					R	VR	VR	R		VR		R		VR										VR		R				
Globigerinita naparimaensis			R																																							
Globigerinoides immaturus			R								VR		VR				VR																									
Globigerinoides obliquus			R	VR																																						
Globigerinoides primordius																	VR		VR	VR		VR		VR		VR																
Globigerinoides spp.								?VR						?VR																												
Globigerinoides trilobus			VR		VR									VR																								R				
Globoquadrina dehiscens			VR							?				?VR		VR		VR	VR	VR		R		VR																		
Globorotalia kugleri																																						VR				
Globorotalia menardii			VR																																							
Globorotalia obesa																	VR																									
Globorotalia praescitula																	VR																									
Globorotalia spp.										P						VR		VR		VR		R				VR					VR					VR						
Neogloboquadrina mayeri											VR						R					R		R						VR								C			P	C
Neogloboquadrina? sp.																																										
Orbulina suturalis			VR																																							
Paragloborotalia opima nana																																									?R	R
Paragloborotalia o. nana-o. opima trans.																																										VR
Ostracodes:			R	VR	VR	VR			R		VR	VR	VR	VR	VR		R	VR	VR	VR		VR		VR	VR	VR	VR	P		VR	VR	VR	VR	VR	VR			VR			VR	VR
Radiolarians:	VR			VR		VR		VR	R	VR	R	C	VR	VR	VR		R	C	A	A	C	C		R	VR	VR	VR			R	R	R	A	R	VR			C				
Actinommids	VR			VR		VR		VR	A	P	A	F	R				C	A	F	A	A	F		C	VR	R	P		P	R	R	C	A		VR			C				
Hexacontium sp. (cubo, long spines)											C																															
Heliodiscus sp.								VR	VR		VR	C		VR				R	R	R				VR	R		P	P	P	R	C	R	C					R				
Ommatodiscus sp.								VR			VR	VR					VR	VR				VR								VR			VR	VR				VR				
Spongodiscids						VR		R	A	P	R	C	VR		VR		VR	C	A	C		A		VR		VR	P			R	R	R	C	R				C				
Spongasteriscus marylandicus																	VR	VR		VR	P			VR		VR				VR		VR	R	VR				R				
Spongaster cf. *tetras irregularis*									VR		R																															
Hymeniastrum spp.								?VR				VR		VR			C	R	R	R		R		VR			P											R				
Euchitonia spp.									VR	P	VR	R					VR	VR	R	R		R					P			R	VR	VR	C					R				
Dictyocoryne spp.											VR						VR	VR																								
Didymocyrtis prismatica																														?VR								VR				
Didymocyrtis violiona											VR	R	?VR				VR	R	R	C											VR		C	VR				VR				
Didymocyrtis mammifera									VR		VR	VR																														
Didymocyrtis tubaria											?VR	?VR																										VR				
Didymocyrtis sp. (club-shaped columns)												R																														
Lithelids									VR		R	C	VR	VR			VR	R	C					VR	VR	VR				VR	R	R		R				R				

Table T5 (continued).

Sample depth (m):	159.99	160.60	164.6–169.2	174.35	181.94	196.60	213.94	229.79	250.79	268.25	270.66	289.22	300.44	321.35	322.78	324.31	336.19	345.95	347.59	349.51	350.67	351.10	370.94	371.15	373.99	376.43	379.48	388.77	397.76	400.84	402.82	408.43	433.43	437.39	437.81	439.98	440.74	440.92	442.87	445.25	446.99	447.20
Sample depth (ft):	524.9	526.9	540–555	572.0	596.9	645.0	701.9	753.9	822.8	880.1	888.0	948.9	985.7	1054.3	1059.0	1064.0	1103.0	1135.0	1140.4	1146.7	1150.5	1151.9	1217.0	1217.7	1227.0	1235.0	1245.0	1275.5	1305.0	1315.1	1321.6	1340.0	1422.0	1435.0	1436.4	1443.5	1446.0	1446.6	1453.0	1460.8	1466.5	1467.2
Spyrids									VR		VR							VR																				VR				
Cyrtocapsella tetrapera									R	P	R	R	VR		VR		VR	VR	R	R										VR			R	VR				R				
Cyrtocapsella cornuta										P	VR	R								R													C	VR				R				
Stichocorys sp.									VR		VR	VR	VR					VR	VR	VR										VR				VR				R				
Calocycletta virginis/robusta undiff.									VR			VR							VR	VR												VR	VR	VR				R				
Calocycletta costata									VR																																	
Eucyrtidium calvertense									VR		VR	VR						VR	VR	VR										VR								VR				
Carpocanopsis sp.																																		VR				VR				
Lychnocanoma elongata																																						VR				
Pterocanium sp.									VR		VR																			VR		VR										
Lampromitra? sp.											VR																															
Diatoms:	R		A		VR	R	VR	R	R	VR	C	R	R	VR	R		F	A	A	F	F	C		R		R				A	C	C	A	VR	VR			R				VR
Actinoptychus heliopelta													VR	R	C		F	F	A	F	F	C		C			VR		P	F	A	A	VR	VR				R				
A. senarius						R		VR	C	P	C	C	R	VR					R													VR	VR									
Coscinodiscids. (plain circular diatoms)	A		A		VR	R	VR	R	C	P	A	C	C	R	VR		F	F	C	F	F	C		C				P	P	A	C	A	A	VR				R				
Other	R					R		R						VR																												
Sponge spicules:											VR	VR						VR	VR	VR								P			VR			VR								

Note: A = abundant, F = frequent, C = common, R = rare, VR = very rare, P = present.

Table T6. Sedimentation rates in the Bethany Beach borehole, Leg 174AX.

Bethany Beach (ft)		Age (Ma)		Thickness		Sedimentation	New Jersey		
Sequence top	Sequence base	Top	Base	(ft)	(m)	rate (m/m.y.)	Age (Ma)	Sequence	Sedimentation rate (m/m.y.)
375.00	452.45	9.8	10.2	77.45	23.61	59			
452.45	523.05	10.2	10.6	70.60	21.52	54			
523.05	575.20	11.6	11.9	52.15	15.90	53	11.5	Kw-Co	38
575.20	649.00	13.1	13.5	73.80	22.50	56	13.4	Kw3	43
649.00	698.50	14.2	14.5	49.50	15.09	56	14.7	Kw2c	37
698.50	787.10	15.7	16.4	88.60	27.01	39	15.6	Kw2b	24
787.10	897.70	16.4	17.3	110.60	33.72	37	16.5	Kw2a	29
897.70	981.30	18.0	18.4	83.60	25.49	58		Absent	
981.30	1057.95	18.4	18.8	76.65	23.37	56	18.3	Kw1c	47
1057.95	1153.00	18.8	19.3	95.05	28.98	58	19.2	Kw1b	28
1153.00	1421.10	20.2	20.8	268.10	81.74	136	20.2	Kw1a	91
							22.0	Kw0	24

Bethany Beach alternative age (ft)		Age (Ma)		Thickness		Sedimentation	New Jersey		
Sequence top	Sequence base	Top	Base	(ft)	(m)	rate (m/m.y.)	Age (Ma)	Sequence	Sedimentation rate (m/m.y.)
375.00	452.45	9.8	10.2	77.45	23.61	59			
452.45	523.05	10.2	10.6	70.60	21.52	54			
523.05	575.20	11.6	11.9	52.15	15.90	53	11.5	Kw-Co	38
575.20	649.00	13.1	13.5	73.80	22.50	56	13.4	Kw3	43
649.00	698.50	14.2	14.5	49.50	15.09	56	14.7	Kw2c	37
698.50	787.10	15.8	16.2	88.60	27.01	68	15.6	Kw2b	24
787.10	897.70	16.7	17.0	110.60	33.72	96	16.5	Kw2a	29
897.70	981.30	18.0	18.4	83.60	25.49	58		Absent	
981.30	1057.95	18.4	18.8	76.65	23.37	56	18.3	Kw1c	47
1057.95	1153.00	18.8	19.3	95.05	28.98	58	19.2	Kw1b	28
1153.00	1421.10	20.2	20.8	268.10	81.74	136	20.2	Kw1a	91
						Absent	22.0	Kw0	24

Cape May (ft)		Age (Ma)		Thickness		Sedimentation	
Sequence top	Sequence base	Top	Base	(ft)	(m)	rate (m/m.y.)	New Jersey Sequence
357.00	432.00	11.5	12.1	75.00	22.87	38	Kw-Co
432.00	503.00	13.4	13.9	71.00	21.65	43	Kw3
503.00	576.00	14.7	15.3	73.00	22.26	37	Kw2c
576.00	615.00	15.6	16.1	39.00	11.89	24	Kw2b
615.00	710.00	16.5	17.5	95.00	28.96	29	Kw2a
710.00	850.00	18.3	19.2	140.00	42.68	47	Kw1c
850.00	942.00	19.2	20.2	92.00	28.05	28	Kw1b
942.00	1062.00	20.2	20.6	120.00	36.59	91	Kw1a
1062.00	1180.00	22.0	23.5	118.00	35.98	24	Kw0

CHAPTER NOTE*

N1. 11 March 2003—This depth range (in feet and meters) was changed by the author and appears in this version.

*Dates reflect file corrections or revisions.