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7. Cape May Zoo Site[1]

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INTRODUCTION

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CAPE MAY ZOO SITE SUMMARY

The Cape May Zoo site (September and October 2004) was the eleventh continuously cored borehole drilled as part of the New Jersey Coastal Plain Drilling Project (NJCPDP) and the eighth site drilled as part of Ocean Drilling Program (ODP) Leg 174AX. Located between the Leg 174AX Ocean View and Leg 150X Cape May sites, drilling at Cape May Zoo (39°06′16.9″N, 74°48′52.6″W; elevation = 19.4 ft; Stone Harbor

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Quad, USGS 7.5 minute quadrangle; Middle Township, Cape May County, New Jersey) targeted lower Miocene through Pleistocene sequences. Recovery was good (mean recovery = 70.3%) and ended at a total depth (TD) of 720 ft (219.46 m) in lower Miocene sediments. A full suite of slim-line logs was obtained to 708.3 ft (215.89 m), and a gamma log was obtained to 711.3 ft (216.8 m). A team of scientists from the New Jersey Geological Survey (NJGS), Rutgers University, the Delaware Geological Survey (DGS), and the U.S. Geological Survey (USGS) collaborated in drilling and stratigraphic studies of this corehole that was funded by the NJGS. The scientific team provided descriptions of sedimentary textures, structures, colors, and fossil content and identified lithostratigraphic units, lithologic contacts, and sequences (unconformity-bounded units). On-site and postdrilling studies of lithology, sequence stratigraphy, biostratigraphy, Sr isotopes, and aminostratigraphy comprise the basic data sets on which this site report is based.

The Cape May Formation (?Holocene–Pleistocene) is 93.6 ft (28.53 m) thick and can be divided into at least two sequences. Nearshore sand and thin gravel beds (0–20.5 ft; 0–6.25 m) form the upper part of Sequence Cm2, whereas tidal channel and foreshore sand and gravel with clay laminae form the lower part from 20.5 to 37 ft (6.25 to 11.28 m). The lower and older Sequence Cm1 (37–93.6 ft; 11.28–28.53 m) is a slightly deeper water deposit (estuary/bay/inner shelf) consisting of varying size sand with occasional shell beds above to finer grained very fine sand and sandy silty clay to clayey silt to clay below. Amino acid racemization (AAR) age estimates for this interval are middle Pleistocene (300–400 ka), suggesting correlation with marine isotope Chron (MIC) 9e or 11.

The ?upper Miocene sequence from 93.6 to 180.4 ft (28.53 to 54.99 m) is tentatively assigned to Sequence Ch4 of de Verteuil (1997) and placed in the newly named Stone Harbor Formation. The age and sequence assignment are provisional, as no datable material was obtained between 93.6 and 180.4 ft (28.53 and 54.99 m). The upper part from 93.6 to 113 ft (28.53 to 34.44 m) is fluvial coarse to very coarse pebbly sand. Below this are barrier beach deposits with generally finer grained sand, silty sand, sandy silt, and organic-rich clay and occasional lignite.

An upper Miocene sequence (180.4–231.4 ft; 54.99–70.53 m) contains mostly lower and some upper estuarine deposits and is tentatively correlated to Sequence Ch3 of de Verteuil (1997). Variegated lignitic sandy clay and poorly sorted sand with lignite and pebbles dominate this sequence, which is also placed in the Stone Harbor Formation.

A middle Miocene (~12 Ma) Kirkwood-Cohansey sequence (Kw-Ch2), from 231.4 to 293.3 ft (70.53 to 89.40 m), is a classic "New Jersey" coarsening-upward sequence with deeper water (shelf and prodelta) facies at the base of the sequence and shallow-water (shoreface) facies toward the top. Laminated to interbedded shelly sand and clayey silt (shelf deposits) from 283.5 to 293.3 ft (86.41 to 89.40 m) grade upward into laminated, slightly micaceous, slightly silty clay (prodelta deposits) from 261.2 to 283.5 ft (79.61 to 86.41 m). Interbedded silty fine to medium sand with thin clay beds (250–261.2 ft; 76.20–79.61 m) were deposited as lower shoreface deposits, coarsening upward to upper shoreface medium to coarse sand (231.4–248.7 ft; 70.53–75.80 m). We correlate this sequence with Sequence Ch2 of de Verteuil (1997).

An upper middle Miocene sequence (Sr isotope ages of 12.7 and 13.1 Ma; East Coast Diatom Zone [ECDZ] 7) is also a classic New Jersey coarsening-upward sequence at Cape May Zoo. The sequence was poorly recovered from 293.3 to 325 ft (89.40 to 99.06 m). This sequence is ~0.7

m.y. older than the overlying Kirkwood-Cohansey sequence and has a thinner upper highstand systems tract (HST). This sequence correlates in age with the lower Kirkwood-Cohansey sequence (Kw-Ch1; Miller et al., 1997, 1998) and is equivalent to Sequence Ch1 of de Verteuil (1997). Offshore deposits from 323.7 to 324.6 ft (98.66 to 98.94 m) contain very shelly, silty clayey sand with medium to fine sand laminae. These deposits grade into slightly micaceous sandy silty clay with rare shells, representing prodelta and distal delta front environments. The thin upper HST (293.3–304 ft; 89.40–92.66 m) contains delta front deposits consisting of cross-bedded to laminated, fine to very fine, silty, slightly micaceous quartz sand with silt and clay laminae and beds, and slightly micaceous, slightly silty, clay with thin sand and organic-rich laminae from 302 to 304 ft (92.05 to 92.66 m).

Sequence Kw3 (325–415.7 ft; 99.06–126.71 m) is thick with two flooding surfaces in the HST. This sequence contains diatoms assigned to ECDZ 6 and has Sr isotope age estimates between 14 and 13 Ma. The base of this sequence (406–415.7 ft; 123.75–126.71 m) contains bioturbated, slightly silty fine to medium sand with scattered shell fragments and numerous granules deposited in lower shoreface environments representing the transgressive systems tract (TST). Above this, the offshore facies from 368.5 to 406 ft (112.32 to 123.75 m) is gray clayey silt (369–370.2 ft; 112.47–112.84 m) with common sulfur, tight clay (370.2–371.1 ft; 112.84–113.11 m), and bioturbated, shelly, slightly silty clay (371.1–400 ft; 113.11–121.92 m) that contains the maximum flooding surface (MFS) (395 ft; 120.40 m). The HST occurs from 325 to 395 ft (99.06 to 120.4 m) and is punctuated by two flooding surfaces (FS) at 352.8 and 368.5 ft (107.53 and 112.32 m). It is dominated by shoreface environments and shallows from a finer grained lower shoreface environment in the lower part to a coarser grained upper shoreface environment above. Bioturbated, slightly shelly sandy silt (360–368.6 ft; 109.73–112.35 m) coarsens upward to bioturbated silty, slightly shelly fine sand (355–360 ft; 108.20–109.73 m) deposited in the upper shoreface. The HST from 325 to 352.8 ft (99.06 to 107.53 m) is also composed of sediments deposited in dominantly lower shoreface environments. From 351.7 to 352.8 ft (107.20 to 107.53 m) is shelly clayey silt. Clayey silt grades to sandy silt from 332.7 to 351.7 ft (101.41 to 107.20 m). An abrupt facies change occurs at 332.7 ft (101.41 m), with the section coarsening upward to burrowed, silty fine sand with traces of mica, wood, and shell from 325.5 ft (99.21 m). This distal upper to lower shoreface deposit represents the upper part of an HST.

Sequence Kw2b (16.7 Ma based on Sr isotope age estimates; ECDZ 3–4) is a coarsening-upward New Jersey sequence (415.7 5–15.7 ft; 126.71–157.19 m), which may have a thin lowstand systems tract (LST) at its base. This potential LST (510.4–515.7 ft; 155.57–157.19 m) is a medium–coarse, bioturbated, granuliferous shelly muddy sand deposited in a proximal upper shoreface environment. Above the LST is the lower part of the TST, comprised of slightly clayey silt (500–510.4 ft; 152.40–155.57 m) with shell fragments deposited in offshore environments. The lower HST deposited in prodelta environments consists of predominantly laminated organic-rich clay with thin sand laminae and sand beds from 483.7 to 493.7 ft (147.43 to 150.48 m). There is a transition to upper HST muddy cross-bedded sand with interbedded clean sand, lignite clay, and silty brown organic-rich clay (479.2–483.7 ft; 146.06–147.43 m) deposited in delta front environments. Above a flooding surface or autocyclical change, thick upper shoreface, bioturbated, muddy, very shelly fine–medium sand is found from 442.9 to

479.2 ft (135.00 to 146.06 m). Above this is heavily bioturbated, shelly, fine–medium sand (430.0–438.5 ft; 131.06–133.65 m) that is interpreted as part of a general stillstand from 424 to 442 ft (129.24 to 134.72 m). The upper part of the Kw2b sequence (415.7–424 ft; 126.71–129.24 m) consists of slightly shelly, silty fine–medium sand deposited in wave-dominated shoreface environments.

The early Miocene Kw2a sequences (Kw2a1, Kw2a2, and Kw2a3) are assigned to ECDZ 2 and have Sr isotope age estimates from 17.8 to 17.0 Ma. These Kw2a sequences, from 515.7 to 630.7 ft (157.19 to 192.24 m), are dominated by offshore and prodelta clay and silt, except for the coarser grained Sequence Kw2a2 (529–549.5 ft; 161.24–167.49 m).

Sequence Kw2a1 is the thickest (81.2 ft; 24.75 m) of the Kw2a sequences (549.5–630.7 ft; 167.49–192.24 m). We interpret a thin LST from 625 to 630.7 ft (190.50 to 192.24 m). Above this is a thin TST (620.1–625 ft; 189.01–190.50 m) composed of interbedded very fine sand and silty clay deposited in prodelta environments. The unit from 549.5 to 620.1 ft (167.49 to 189.01 m), a thick HST, is generally fine-grained, laminated clayey silt with very fine sand laminae (549.5–558.5 ft; 167.49–170.23 m), silty very fine sand (558.5–561.7 ft; 170.23–171.21 m), laminated silty clay with very fine sand laminae (561.7–586 ft; 171.21–178.61 m), and shelly laminated silty clay with very fine sand laminae (586–620.1 ft; 178.61–189.01 m) deposited in offshore (probably inner neritic), prodelta, and lower shoreface environments. The thin Kw2a2 sequence, from 529 to 549.5 ft (161.24 to 167.49 m), is a slightly clayey, shelly medium sand with a trace of mica and glauconite deposited in lower shoreface to offshore environments. The thinnest of the Kw2a sequences, Sequence Kw2a3 (13.3 ft [4.05 m]; 515.7–529 ft [157.19–161.24 m]), is a micaceous, organic-rich laminated clay to thin bedded silty clay with occasional fine sand beds and shell fragments, interpreted as a prodelta deposit.

The lower Miocene Kw1c sequence (Sr isotope age estimates of 18.8–19.2 Ma) is much thinner at this site (25.8 ft [7.86 m]; 630.7–656.5 ft [192.24–200.10 m]) than at the Leg 150X Cape May site to the south. Sequence Kw1c at Cape May Zoo consists of slightly muddy, fine–medium sand with shell fragments toward the base deposited in distal upper and lower shoreface environments. A thin, indurated, medium-grained sandstone (643.0–643.5 ft; 195.99–196.14 m) with pebbles and large shells (including oysters) marks either a flooding surface or an autocyclical change. Above the surface the sequence is laminated silty clay with thin, interbedded, fine, organic-rich, slightly shelly sand (prodelta environments) grading upward to black, organic-rich, shelly, silty, fine–medium sand interbedded with organic-rich sandy clayey silt deposited in delta front environments. Based on Sr isotope age estimates, its age ranges from 18.8 to 19.2 Ma, though reworking in the lower part of the section yields older ages.

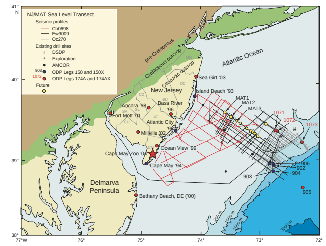
The hole bottomed in the HST of the lower Miocene (Sr isotope age estimates of 19.2–20.0 Ma) Kw1b sequence. Sequence Kw1b is dominated by lower and distal upper shoreface deposits characterized by bioturbated, shelly, slightly silty, fine–medium sand with occasional coarser sand beds.

The Miocene sequences recovered at the Cape May Zoo site not only verify sequences found at the Cape May site (especially Sequence Kw1c), they also compliment sequences that will be divided by Integrated Ocean Drilling Program Expedition 313 in summer 2007. The section also provides insights to the hydrostratigraphy of the Cape May peninsula and aquifer distribution.

BACKGROUND AND OBJECTIVES

This chapter is the site report for Cape May Zoo corehole (Fig. F1), the eleventh continuously cored and logged onshore site drilled as part of the NJCPDP. The NJCPDP began with drilling at Island Beach (March–April 1993), Atlantic City (June–August 1993), and Cape May (March–April 1994) as part of Leg 150X (Miller et al., 1994a, 1994b, 1996a; Miller and Snyder, 1997). Drilling at these three sites targeted Oligocene–Miocene sequences in an attempt to unravel Icehouse sea level changes tied to continental slope drilling by the *JOIDES Resolution* during ODP Leg 150 (Miller and Mountain, 1994; Miller et al., 1996b, 1998a).

F1. Drillsite locations, p. 38.



Operations during Leg 174AX continued onshore drilling at the following locations:

- Bass River, New Jersey (October–November 1996) (Miller et al., 1998b), targeting Upper Cretaceous to Paleocene strata poorly sampled during Leg 150X.
- Ancora, New Jersey (July–August 1998) (**Miller et al.,** this volume), an updipping, less deeply buried Cretaceous–Paleocene section complimentary to the Bass River Formation.
- Ocean View, New Jersey (September–October 1999) (**Miller et al.,** this volume), focusing on upper Miocene–middle Eocene sequences.
- Bethany Beach, Delaware (May–June 2000) (**Miller et al.,** this volume), concentrating on the thick Miocene sequences in the depocenter of the Salisbury Embayment.
- Fort Mott, New Jersey (October 2001) (**Sugarman et al.,** this volume), targeting the largely nonmarine mid- Cretaceous Potomac Group.
- Millville, New Jersey (May–June 2002) (**Sugarman et al.,** this volume), drilled to further our understanding of Upper Cretaceous "greenhouse" sequences.
- Sea Girt, New Jersey (September–November 2003) (**Miller et al.,** this volume), drilled to tie Upper Cretaceous sequences to an offshore seismic grid.

These sites provide a chronology of sequences over the past 100 m.y. (e.g., Miller et al., 2005). The Joint Oceanographic Institutions for Deep Earth Sampling Planning Committee and Science Planning Committee designated drilling at these sites as ODP Leg 174AX. In total, these previous coreholes recovered 11,685 ft (3,561 m) from 14,266.5 ft (4,348 m) drilled (recovery = 82%).

The Cape May Zoo corehole, the final Leg 174AX corehole, was selected between the Ocean View (Leg 174AX) and Cape May (Leg 150X) sites to provide insights into lower Miocene to Holocene sequences and hydrostratigraphy and to complement offshore drilling during Expedition 313. One surprise in drilling to date was the relative completeness of the lower to middle Miocene section of the Leg 150X Cape May site compared to other onshore coreholes, with at least nine sequences represented. Even the more basinal Bethany Beach site (Leg 174AX) was less complete in the early Miocene than Cape May (see Browning et al., 2006, for detailed comparison). Several of these sequences pinch out upbasin toward the Ocean View site (Leg 174AX), and it was hoped that drilling at Cape May Zoo would capture these sequences.

The Kirkwood Formation consists of sand and silty clay usually influenced by a delta. The formation has been dated as lower to middle Miocene and divided into nine sequences at the Cape May borehole (Miller et al., 1996a). Two of these sequences, Kw1c and Kw2c, have only been recognized at Cape May, and one major unfulfilled objective of drilling at the Ocean View site (**Miller et al.,** this volume) was to validate these two sequences. Drilling at Ocean View did sample higher order sequences within the Kw1 and Kw2 sequences, but Sr isotopic studies make it clear that Sequence Kw1c pinches out in the 17 mi from Cape May to Ocean View. It also appears that Sequence Kw2c is not present at Ocean View, though this needs to be reexamined.

Drilling at Cape May Zoo targeted Kirkwood sequences, particularly Sequence Kw1c, which was estimated to lie at ~650–700 ft at this site. Because the Kw1c sequence contains a potentially useful aquifer, the NJGS funded drilling of the Cape May Zoo corehole.

An unnamed estuarine gray sand and clay unit was sampled at the Cape May corehole and dated with dinocysts as upper Miocene (de Verteuil, 1997). Coeval yellow Cohansey Formation was sampled in the Ocean View corehole and dated with dinocysts as upper Miocene Zone DN8 (**Miller et al.,** this volume). Drilling at Cape May Zoo recovered a thick gray estuarine gray sand and clay unit that appears to correlate with the Cape May corehole.

The Kirkwood sequences at the Cape May Zoo site are well characterized lithologically and with downhole logs and contain enough shells throughout that we were able to construct a detailed Sr isotope chronology for the Miocene. Numerous Kirkwood sequences can be recognized by comparison of the preliminary descriptions with the downhole gamma ray and resistivity logs. We conducted a preliminary correlation of the Cape May Zoo Kirkwood sequences with Cape May and Ocean View boreholes and believe we have at least nine Kirkwood sequences: Kw-Ch2, Kw-Ch1, Kw3, Kw2c, Kw2b, Kw2a3, Kw2a2, Kw2a1, and Kw1c. Preliminary correlations suggest that each of these sequences is represented at two of the three coreholes, extending the validated number of lower–middle Miocene sequences to 11 (i.e., including the Kw1b, Kw1c, and Kw0 sequences). Preliminary correlations suggest that the Kw-Ch, Kw3, and Kw1c sequences may be divided into higher order sequences, further suggesting the presence of from 14 to 16 lower to middle Miocene sequences.

The following lithologic and sequence stratigraphy of the Kirkwood Formation is a preliminary interpretation based on core-log correlations between the Ocean View, Cape May Zoo, and Cape May coreholes.

The Cape May Zoo site is critical for understanding the hydrogeology of the rapidly developing Cape May Peninsula. The Atlantic City "800-foot" sand aquifer is a critical aquifer in the New Jersey coastal plain, yet its distribution is complicated in the Cape May Peninsula. At the Cape May site, three sand bodies can be mapped within the Atlantic City 800-foot sand vs. two outside of the peninsula (e.g., Atlantic City). The highest of these aquifer sands is associated with the HST of Sequence Kw1c, whereas the medial and lower aquifers are associated with the HST of Sequences Kw1b and Kw1a as they are at Atlantic City and Ocean View (Sugarman et al., 2005). The Kw1c sequence and associated aquifer sand clearly pinches out 15 km (9 mi) to the north at Ocean View (Sugarman et al., 2005). Drilling at Cape May Zoo targeted these aquifers in an effort to resolve their relative continuity and interconnectedness. Because this corehole is critical to the citizens of this region, the NJGS paid for all drilling costs for the Cape May Zoo corehole.

The National Science Foundation (Earth Science Division, Continental Dynamics Program) provided support for field and subsequent analyses and ODP provided all publication support.

OPERATIONS

Drilling at the Cape May Zoo (39°06′16.9″N, 74°48′52.6″W; elevation = 19.4 ft; Stone Harbor Quad, USGS 7.5 minute quadrangle; Middle Township, Cape May County, New Jersey) began in late September 2004. Drilling operations were superintended by Gene Cobbs III, Head Driller, USGS Eastern Earth Surface Processes Team. Casey McKinney was the drilling assistant. The Cape May County Park and Zoo provided space, water, and electricity for the site (Dominic Rosselli, Park Director). The drillers arrived late in the day on 27 September. On 28 September they began rigging up behind the park maintenance building and ran a water line from the park maintenance yard. On 29 September a field trailer was set up as a portable laboratory and electric hookups made to the yard. An Olympus C70 Ultra Zoom digital zoom camera (6.3–63 mm lens; 4 megapixel resolution), Macintosh G4, and the DGS photography stand were set up to photograph 2-ft (0.61 m) core segments. The camera's default settings with fill-in flash were used.

All cores were measured in feet (all depths are given in feet below land surface with metric conversions provided). We continued to adopt ODP convention of top-justifying depths for intervals with incomplete recovery for all field notes and photos.

The first core was obtained on 29 September using a Christensen 94-mm (HQ) system, 4.5-in Longyear bit, and a 2.5-in (6.4 cm) core diameter. For unconsolidated sand, 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. The first core was obtained at 0900 hr, with coring proceeding with moderate recovery (average = 45%) in sand and gravel on Runs 1 (0–3 ft; 0–0.91 m), 2 (3–7 ft; 0.91–2.13 m), and 3 (7–11 ft; 2.13–3.35 m), stopping at 1100 hr to rig up electrical supply. Coring continued in the afternoon in soft sand, with very good recovery on Run 4 (11–15 ft [3.35–4.57 m]; recovery = 88%), but moderate recovery on Run 5 (15–20 ft [4.57–6.10 m]; recovery = 50%) as we blew away sand. Run 6 (20–21 ft; 6.10–6.40 m) was blocked by sand inside the barrel at 1 ft (0.30 m) into the run. Run 7 (21–27 ft; 6.40–8.23 m) recovered 3.3 ft (1.01 m) of core. Run 8 (27–35 ft; 8.23–10.67 m) had poor recovery of 2.05 ft (0.62 m). Run 9 (35–40 ft; 10.67–12.19 m) only had 40% recovery. The core was compressed when pushed out, so recovery probably was a little better. Run 10 (41–48 ft [12.50–14.63 m]; 4 ft [1.22 m] of recovery) was the final run of the day. We lost 40–41 ft (12.19–12.50 m) as the barrel was sand locked. Drilling was slow at the end of the day, as caving sand required extra mud pumping to clear the hole. The day ended at 48 ft (14.63 m) with 22.82 ft (6.96 m) recovered from 48 ft (14.63 m) drilled (recovery = 47.5%).

On 30 September, 6.2 ft (1.89 m; recovery = 89%) was recovered from the first run (48–55 ft; 14.63–16.76 m). On Run 12, we recovered only 1 ft (0.30 m) between 55 and 60 ft (16.76 and 18.29 m). Run 13 (60–70 ft; 18.29–21.34 m) initially recovered 2.9 ft (0.88 m); however, on the next run (Run 14: 70–75 ft; 21.34–22.86 m) we recovered 8.45 ft (2.58 m). We placed the top 3.75 ft (1.14 m) at the bottom of the previous 10-ft (3.05 m) run (62.9–66.5 ft; 19.17–20.27 m), and placed 4.7 ft (1.43 m) in the run from 70 to 75 ft (21.34 to 22.86 m) and labeled it 70–74.7 ft (21.34–22.77 m). On Run 15 we had perfect recovery from 75–80 ft (22.86–24.38 m). On the next run from 80 to 90 ft (24.38 to 27.43 m), we recovered 5.5 ft (1.68 m). Run 17, from 90 to 97 ft (27.43 to 29.57 m), recovered 3 ft (0.91 m) and a contact between clay above and sand below. The next few runs generally had poor recovery resulting from the coarse nature of the material. On Run 18 (97–100 ft; 29.57–30.48 m), we had 1.1 ft (0.34 m) of coarse sand and gravel. Run 19 (100–105 ft; 30.48–32.00 m) was similar, with 1.9 ft (0.58 m) of sand recovered. Recovery improved on Run 20, with 3.5 ft (1.07 m) recovered between 105 and 110 ft (32.00 and 33.53 m). Run 21 (110–117 ft; 33.53–35.66 m) recovered 3.2 ft (0.98 m). On the final run of the day from 117 to 125 ft (35.66 to 38.10 m) there was no recovery because the core barrel was sand locked. Recovery for the day was 41.75 ft (12.73 m) from 77 ft (23.47 m) drilled (recovery = 54.2%).

On 1 October, 4.4 ft (1.34 m; recovery = 88%) was recovered on Run 23 (125–130 ft; 38.10–39.62 m). The last run of the day (Run 24: 130–138 ft [39.62–42.06 m]), collected 7.1 ft (2.16 m) of core. Recovery for the day was 11.5 ft (3.51 m) from 13 ft (3.96 m) drilled (recovery = 88.5%). The rods were then pulled. Just after 1200 hr, two wireline logging runs (downhole and uphole) were conducted from surface to 98.6 ft (30.05 m). Although the hole depth was 138 ft (42.06 m), an obstruction (likely running sand) prevented passage of the logging tool below 100 ft (30.48 m). Logging was performed by DGS personnel (P.P. McLaughlin and K.W. Ramsey) using the Rutgers University Department of Geological Science's Century Geophysical Corporation drawworks and the USGS Annapolis Office's Century Gamma-Electric Multitool (Model 8043A). This logging tool simultaneously records a gamma ray log and a suite of electric logs, including spontaneous potential (SP), short normal resistivity (16N), long normal resistivity (64N), point resistance, and lateral resistivity.

On 2 October the hole was cased 78 ft (23.77 m) into clay with 5-in polyvinyl chloride (PVC) casing to be removed on completion. The rods were run to the bottom of hole (BOH) at 138 ft (42.06 m) and the hole flushed. Runs 25 (138–140 ft; 42.06–42.67 m) and 26 (140–150 ft; 42.67–45.72 m) recovered 1.38 and 3.05 ft (0.42 and 0.93 m), respectively. Recovery for the day was 4.6 ft (1.40 m) from 12 ft (3.66 m) drilled (recovery = 38.3%).

On 3 October, 64.7 ft (19.72 m) of core was recovered from 150 to 240 ft (45.72 to 73.15 m; recovery = 72%). Recovery in the morning was moderate (recovery = 60%), but improved in the afternoon (recovery = 79%). Mud pressures were high at the end of core runs, suggesting that the inner barrel was running too low on the bit. We pulled the rods and replaced a bad landing ring.

On 4 October the rods were run from surface to BOH and coring began at 240 ft (73.15 m). Runs 39 (240–245 ft; 73.15–74.68 m) and 40 (245–250 ft; 74.68–76.20 m) recovered 2.2 ft and 3.65 ft (0.67 and 1.11 m), respectively, in sand. Compression of the sand probably caused underestimated recovery. We switched to a 10-ft (3.05 m) barrel on Runs 41 (250–260 ft; 76.20–79.25 m) and 42 (260–270 ft; 79.25–82.30 m) and recovered 8.75 ft (2.67 m) and 10.0 ft (3.05 m), respectively. Recovery improved as we penetrated the clay of the Kirkwood Formation. Run 43 recovered 4.45 ft (1.36 m) from 270 to 280 ft (82.30 to 85.34 m), with ~2 ft (0.61 m) of slurry discarded. Run 44 recovered 5.65 ft (1.72 m) from 280 to 290 ft (85.34 to 88.39 m). Recovery from the interbedded sand and clay was difficult. Run 45 (290–300 ft; 88.39–91.44 m) had 5.8 ft

(1.77 m) of recovery. Run 46, from 300 to 310 ft (91.44 to 94.49 m), had 3.8 ft (1.16 m) of recovery. The final run of the day (Run 47: 310–320 ft; 94.49–97.54 m) had 4.5 ft (1.37 m) of recovery. Recovery for the day was 49.8 ft (15.18 m) from 80 ft (24.38 m) drilled (recovery = 62.3%).

On 5 October, Run 48 (320–325.5 ft; 97.54–99.21 m) was cut short by hard material (shell), with 4.6 ft (1.40 m) recovered. Run 49 (325.5–327.5 ft; 99.21–99.82 m) was also cut short as the barrel was sand locked; 1.3 ft (0.40 m) was recovered. Run 50, from 327.5 to 330 ft (99.82 to 100.58 m) recovered 1.5 ft (0.46 m). Run 51, from 330 to 332 ft (100.58 to 101.19 m) recovered 1.8 ft (0.55 m). Using a long shoe resulted in slower drilling. Drilling recovery improved for Run 52 (332–340 ft; 101.19–103.63 m) to 7.6 ft (2.32 m), as the smaller shoe cut faster. Runs 53 and 54 (340–350 ft [103.63–106.68 m] and 350–355 ft [106.68–108.20 m]) recovered 2.5 and 3.4 ft (0.76 and 1.04 m), respectively. The final two runs of the day (Runs 55 and 56), which were described on the morning of 6 October, came up without incident (355–360 ft [108.20–109.73 m], 4.8 ft [1.46 m] recovered; 360–370 ft [109.73–112.78 m], 10.0 ft [3.05 m] recovered). Recovery for the day was 37.5 ft (11.43 m) from 50 ft (15.24 m) drilled (recovery = 75.0%).

Run 57 (370–380 ft; 112.78–115.82 m) came up empty originally, but 3.8 ft (1.16 m) of core was recovered when the drillers went back down with the inner core barrel to recover it. Drilling was slowed because acorns kept falling in the mud pan, clogging the mud pump. Core recovery improved markedly for Runs 58–61 (380–414.5 ft [115.82–126.34 m]; 33.6 ft [10.24 m] recovered) in clay and silty sand. At 414.5 ft (126.34 m) the drillers encountered a coarse or cemented zone requiring them to switch to the rock bit. The indurated layer destroyed a shoe and blocked the core barrel on the next run, limiting recovery for Run 62 (414.5–420 ft; 126.34–128.02 m) to 1.2 ft (0.37 m). For the final run of the day (Run 63: 420–430 ft; 128.02–131.06 m), the drillers went back to the short snout shoe and recovered 4.3 ft (1.31 m). Recovery for the day was 42.9 ft (13.08 m) from 60 ft (18.29 m) drilled (recovery = 71.5%).

On 7 October, Run 64 recovered 100% from 430 to 438.5 ft (131.06 to 133.65 m). The next run (Run 65) was very short resulting from refusal from a cemented sandstone. We recovered 1 ft (0.30 m) from 438.5 to 439.7 ft (133.65 to 134.02 m). Run 66 was an unusual length (439.7–450 ft; 134.02–137.16 m), and 5.45 ft (1.66 m) was recovered. In Run 67 (450–460 ft; 137.16–140.21 m), 5.2 ft (1.58 m) was recovered. Run 68 (460–470 ft; 140.21–143.26 m) had perfect recovery. Run 69 (470–480 ft; 143.26–146.30 m) had 10.35 ft (3.15 m) of recovery. The day ended at 510 ft (155.45 m) with 64.85 ft (19.77 m) recovered from 80 ft (24.38 m) drilled (recovery = 81.1%).

On 8 October, drilling through clay and shelly sand on Run 73 (510–520 ft; 155.45–158.50 m) recovered 6.2 ft (1.89 m). The Rutgers Marine Geology class visited the drill site. The top 1.5 ft (0.45 m) of Run 74 (520–530 ft; 158.50–161.54 m) had 1 ft (0.30 m) of solid core over 0.5 ft (0.15 m) of slurry that was discarded. This top 1 ft (0.30 m) was apparently from the previous run. The core from the inner barrel could only be extruded with high pressures. Recovery was 7.2 ft (2.19 m), and the core was somewhat "chewed." Run 75 (530–533.5 ft; 161.54–162.61 m) was cut short when the bit would not penetrate; recovery was 3.85 ft (1.17 m). Runs 76 (533.5–540 ft; 162.61–164.59 m) and 77 (540–550 ft; 164.59–167.64 m) recovered 5.9 and 10.4 ft (1.80 and 3.17 m), respectively. A hard clay layer stopped Run 78 (550–558.5 ft; 167.64–170.23 m), although 7.1 ft (2.16 m) was recovered. Run 79 (558.5–567 ft;

170.23–172.82 m) had full recovery, whereas Run 80 (567–575 ft; 172.82–175.26 m) only recovered 4.6 ft (1.40 m). The day ended at 575 ft (175.26 m) with 54.15 ft (16.50 m) recovered from 65 ft (19.81 m) drilled (recovery = 83.3%).

On 9 October, smooth coring in consistent clay occurred from 575 to 625 ft (175.26 to 190.50 m) on Runs 81–87, with 48.35 ft (14.74 m) recovered (recovery = 96.7%). Recovery suffered on 10 October as we penetrated a sand with indurated zones. We shortened the runs and obtained 27.9 ft (8.5 m) on Runs 88–94 from 625 to 670 ft (190.50 to 204.22 m; recovery = 62%).

The last day of coring was 11 October. We maintained short runs in shelly sand with moderate recovery. Acorns falling into the mud pans continued to block the lines; the pans were cleaned for the seventh time. Run 98 (690–697 ft; 210.31–212.45 m) was stopped when it felt like the section was being blown away (5.5 ft [1.68 m] recovered). The day ended at 720 ft (219.46 m) with 28.55 ft (8.70 m) recovered from 50 ft (15.24 m) drilled (recovery = 57.1%).

On 12 October, P. McLaughlin and the DGS team arrived on site and obtained gamma logs through the rods. The rods were pulled, and two logging runs were made on formation. Logging was performed by personnel of the DGS using the same equipment used on 1 October. Logging went relatively smoothly. The multitool hung a few times on the way down but was worked past bridges and a good uplog was obtained. For some undetermined reason not related to any tool malfunction, the electric logs provided geologically dubious readings shallower than 280 ft (85.34 m) on both up and down runs.

On 12 and 13 October, the hole was grouted with cement, plugged, and abandoned. At Cape May Zoo, we recovered 499.35 (152.20 m) from a TD of 720 ft (219.46 m; mean recovery = 70.3%). Lithologies were described on site and subsequently at the Rutgers core facility. These descriptions form the basis for the preliminary lithologic descriptions. Samples were obtained at ~5-ft (1.52 m) intervals for planktonic foraminiferal, calcareous nannofossil, and diatom biostratigraphy and coarse-fraction lithologic studies. Cores were cut into 2-ft (0.61 m) sections, labeled at the top and bottom of each section, placed into split PVC pipe (3-in diameter), wrapped in plastic sheeting, and stored in 2-ft (0.61 m) wax boxes. Seventy-two core boxes were moved to permanent storage at the Rutgers University core library for further study.

LITHOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY

The on-site scientific team provided preliminary descriptions of sedimentary textures, structures, colors, fossil content, identification of lithostratigraphic units (NJGS Information Circular 1, 1990), and lithologic contacts (Table T1). Subsequent studies integrated preliminary descriptions with additional descriptions, biostratigraphy, biofacies studies, isotopic stratigraphy, and the downhole gamma log. Unconformities were identified on the basis of physical stratigraphy, including irregular contacts, reworking, bioturbation, major facies changes, and gamma ray peaks. Paraconformities were inferred from biostratigraphic breaks. Core photographs (see the **"Appendix,"** p. 35) illustrate sequence bounding unconformities and facies variations within sequences.

T1. Core descriptions, p. 57

For the nonmarine and nearshore sections, lithofacies interpretations provide the primary means of recognizing unconformities and interpreting paleoenvironments and systems tracts. For the neritic sections, biostratigraphic studies and Sr isotopes provide an additional means of recognizing unconformities and interpreting paleoenvironments and systems tracts.

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

Facies changes within onshore sequences generally follow repetitive transgressive–regressive patterns (Sugarman et al., 1993, 1995) that consist of

1. A basal transgressive glauconite (particularly Paleogene–Upper Cretaceous sections) or quartz sand (particularly Miocene sections) equivalent to the TST of Posamentier et al. (1988), and
2. A coarsening-upward succession of regressive medial silt and upper quartz sand equivalent to the HSTs of Posamentier et al. (1988).

LSTs are usually absent in the coastal plain and the TSTs are generally thin. Because the TSTs are thin, MFSs are difficult to differentiate from unconformities. Shell beds and gamma ray peaks can mark both TSTs and MFSs. Flooding surfaces, particularly MFSs, may be differentiated from sequence boundaries by the association of erosion and rip-up clasts at the latter, lithofacies successions, and benthic foraminiferal changes. The transgressive surface, marking the top of the LST, represents a change from regressive to transgressive facies. Because LSTs are generally absent, these surfaces are generally merged with the sequence boundaries. Where present, LSTs are recognized as thin, regressive, fluvial-estuarine sediments underlying TSTs and overlying sequence-bounding unconformities.

Cape May Formation

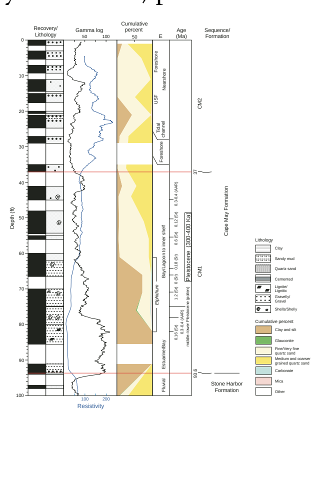
Age: Pleistocene
Interval: 0–93.6 ft (0–28.53 m)

Sequence Cm2

Age: late Pleistocene
Interval: 0–37 ft (0–11.3 m)

The gravel and sand of the Cape May Formation at Cape May Zoo (Fig. F2) form a modern terrace that has been correlated with MIC 5 (Ashley et al., 1991). Our preliminary interpretation is consistent with an upper sequence correlated with the Cape May Formation Unit II of Newell et al. (2000) and a lower sequence correlated with the Cape May Formation Unit III of Newell et al. (2000). Alternatively, it is possible that there are three Cape May sequences at Cape May Zoo and that the uppermost sequence is the Cape May Formation Unit I sequence of Newell et al. (2000) and not the Cape May Formation Unit II.

F2. Stratigraphic section, Cape May Formation, p. 39.



The upper 20.5 ft (6.3 m) at Cape May Zoo consists of sand and thinner beds (<0.7 ft; 0.2 m) of well-rounded pebbly gravel (Fig. F2). The sand is mostly yellowish and grayish brown well-sorted quartz with occasional very dark opaque heavy mineral (OHM) laminae (1–3 mm), though there are also faintly bioturbated intervals within the laminated beds. OHM concentrations are 3%–5%. The sand is medium to coarse to 11 ft and predominantly fine–very fine from 11 to 20.5 ft (3.4 to 6.2 m). Gravel layers occur at 0–1.2, 4.0–4.3, 4.6–4.7, 7.0–7.7, 8.1–8.3, and 15.6–16.1 ft (0–0.4, 1.2–1.3, 1.4–1.43, 2.1–2.3, 2.47–2.53, and 4.75–4.91 m). The gravel beds consist primarily of rounded to subrounded quartz pebbles (typically 3 mm, but up to 13 mm) in a coarse sand matrix. At Ocean View, Miller et al. (this volume) interpreted similar facies as reworked fluvial sediments deposited in a nearshore environment (foreshore at top, upper shoreface below 11 ft [93.35 m]), an interpretation followed here.

A facies change occurs in an unrecovered interval between 20.5 and 21 ft (6.25 and 6.40 m), associated with a gamma log increase, and an iron-stained interval of brown clay and sandy pebbles below. The clay is weathered, possibly because of subaerial exposure. A gamma log kick occurs at this level in the nearby Cape May Court House New Jersey Water Company Well 8, though the kick is less pronounced on the Cape May Zoo gamma log (Fig. F2).

Yellow-brown sand and gravel are found from 21 to 24.3 ft (6.40 to 7.41 m) with clay rip-up clasts and clay laminae. The succession from 21 to 24.3 ft (6.40 to 7.41 m) shows abrupt changes from clay to gravel, suggesting rapid changes in flow regime, and we interpret them as deposition in a tidal channel (Carter, 1978). There is a coring gap from 24.3 to 27 ft (7.41 to 8.23 m). From 27 to 29 ft (8.23 to 8.84 m), the gravel is finer grained, with opaque heavy mineral laminations and hints of bioturbation; these are nearshore (probably shoreface) sediments. A coring gap from 29 to 35 ft (8.84 to 10.67 m) is underlain by coarse to very coarse sand with some granules and pebbles (35–36.8 ft; 10.67–11.22 m) and very fine silty sand with opaque heavy minerals (36.8–37 ft; 11.22–11.28 m), which are interpreted as foreshore deposits (Fig. F2). We term this sequence the Cm2. No datable material was found in Sequence Cm2 at this site, though it is constrained as younger than the underlying sequence (300–400 k.y.).

Sequence Cm1

Age: middle Pleistocene
Interval: 37–93.6 ft (11.28–28.53 m)

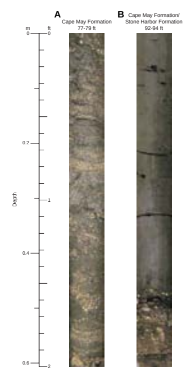
We tentatively place a sequence boundary between Sequences Cm2 and Cm1 at 37 ft (11.28 m), although the interval between 37 and 41 ft (11.28 and 12.50 m) was not recovered (Fig. F2). The contact is placed primarily to reflect the transition from barrier beach–type facies above (Sequence Cm2) to nearshore facies below (Sequence Cm1). Slightly micaceous fine sand (41–41.6 ft; 12.50–12.68 m), medium sand (41.6–42.6 ft; 12.68–12.98 m), fining-upward shelly sand (42.6–45 ft; 12.98–13.72 m), and slightly bioturbated micaceous fine–medium shelly quartz sand (48–52.6 ft; 14.63–16.03 m) occur in this unit. The sediments become bioturbated below 36 ft (10.97 m), and shell fragments appear below 44 ft (13.41 m). We interpret that these sediments were deposited in nearshore environments. A gamma log kick at 42.5 ft (12.95 m) is associated with a minor change to siltier sand below 42.7 ft (13.01 m). There is no major facies change in the core at this level.

There is a contact at 52.6 ft (16.03 m) with yellow micaceous laminated shelly sand above and gray clayey silty fine to very fine micaceous sand with common shell fragments below (Fig. F2). This contact could be interpreted as a sequence boundary and the sequence from 37 to 52.6 ft (11.28 to 16.03 m) could be correlated to the Cape May Formation Unit II of Newell et al. (2000). It is more likely, however, that the section from 37 to 93.8 ft (11.28 to 28.59 m) represents one sequence, as indicated by the general coarsening upward from ~63 to 37 ft (19.2 to 11.3 m), the lack of a major log kick associated with the surface, and the relative uniformity of facies.

Medium cross-laminated sand with wood and shell fragments (55–62.6 ft; 16.76–19.08 m) overlies micaceous woody silty clay to silt with clay and sand laminae (62.6–66.5 ft; 19.08–20.27 m). Very fine shelly sand, micaceous silty clay, and sandy silty clay are interbedded to ~78 ft (23.77 m), where the section becomes predominantly clay (Fig. F2). The presence of shells throughout this interval indicates that it is shallow marine. The presence of an *Elphidium* biofacies (61–81.9 ft; 18.59–24.96 m) indicates bay/lagoon to inner shelf environments. The interval from 77 to 79 ft (23.47 to 24.08 m) is very shelly (Fig. F3). The section from 78 to 92.6 ft (23.77 to 28.22 m) is clay, the upper part of which is laminated and contains lignite. The clay becomes massive and blue from 85 to 92.6 ft (25.91 to 28.22 m) and contains common disseminated lignite. This is probably an estuarine or bay deposit.

A dramatic pebble contact (Fig. F3) with an abrupt change back to sand below at 93.6 ft (28.53 m) is associated with a gamma log increase at 94 ft (28.65 m). We place the base of the Cape May Formation at 93.6 ft (28.53 m). Six Sr isotopic ages averaging 0.4 Ma favor an age correlation of this sequence with MIC 9 or 11. This is also supported by amino acid racemization analyses of shells at 44.8 and 77.0 ft (13.66 and 23.47 m) that yield ages of 300–400 ka (middle Pleistocene; see "Amino Acid Racemization Stratigraphy," p. 27).

F3. Representative lithofacies, Cape May Formation, p. 40.



Stone Harbor Formation (New)

Age: ?late Miocene
Interval: 93.6–231.4 ft (28.53–70.53 m)

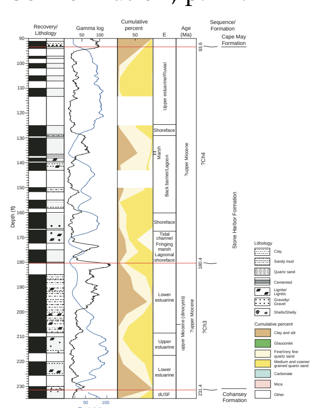
Sequence ?Ch4

Age: ?late Miocene
Interval: 93.6–180.5 ft (28.53–55.02 m)

Beneath the 93.6-ft (28.53 m) pebble contact, greenish gray, coarse to very coarse, poorly sorted pebbly sand generally coarsens downsection to 113.2 ft (34.50 m) (Fig. F4). There are several fining-upward channels with bases at 105.8, 106.6, and 107.5 ft (32.25, 32.49, and 32.77 m). Pebbles are as large as 1.5 cm in diameter and OHM and rock fragments are common (to 5%). The section was deposited in fluvial environments, probably in upper estuarine subenvironments (e.g., paleo-Delaware Bay) (Fig. F4).

A large coring gap (113.2–125 ft; 34.50–38.10 m) apparently missed coarser grained sediment (e.g., sand and gravel), as interpreted from gamma and resistivity logs. There is a facies shift below the gap (125–129.4 ft; 38.10–39.44 m) to yellow to gray medium–coarse silty quartz

F4. Stratigraphic section, Stone Harbor Formation, p. 41.



sand with clay drapes (noted at 126.2–126.3; 127.5–127.7; 128.6–128.7, and 129.0–129.4 ft [38.47–38.50, 38.86–38.92, 39.20–39.23, and 39.32–39.44 m]). Compared to the sand above, this sand is better sorted, has fewer OHM (1%–2%), no lithic fragments, and is bioturbated. These facies probably represent beach environments and are similar in aspect to the Cohansey Formation, although fluvial-dominated upper estuarine facies are also possible.

From 130.0 to 133.0 ft (39.62 to 40.54 m) is a generally fining-downward succession from bioturbated, silty, slightly micaceous fine–medium sand to clayey silty sand. Interbedded sandy silt and organic-rich brown clay are common from 133.0 to 136.0 ft (40.54 to 41.45 m). The section is bioturbated with sand-filled burrows as large as 8 mm in diameter. These facies were deposited in back-barrier lagoonal environments. A micaceous, organic-rich clay occurs at 136.0–136.8 ft (41.45–41.70 m), with a lignite bed from 136.8 to 139.2 ft (41.70 to 42.43 m). This may be a fringing marsh deposit.

From 139.2 to 143 ft (42.43 to 43.59 m), the sequence is homogenized, fine–medium quartz sand with scattered common chunks of lignite as large as 2 cm in diameter. Below a coring gap, (143.0–150.0 ft; 43.59–45.72 m) there is an interbedded fine–medium slightly silty sand (with beds ~13 mm thick) and a bioturbated clayey medium sand (beds of 34 mm). Clayey sand (150.95–151.4 ft; 46.01–46.15 m) overlies clay (151.4–151.5 ft; 46.15–46.18 m) with lignite laminae. Lignitic sand returns from 151.5 to 157.4 ft (46.18 to 47.98 m) and 158.0 to 160 ft (48.16 to 48.77 m), and interbedded, highly bioturbated sand and clayey sand return from 157.4 to 158.0 ft (47.98 to 48.16 m). A sticky, greenish gray sandy clay occurs from 160.0 to 160.6 ft (48.77 to 48.95 m). These facies represent a continuation of lagoonal back-barrier environments.

There is a facies change to a foreshore environment from 160.6 to 168.0 ft (48.95 to 51.21 m). There is cross-laminated, medium–coarse quartz sand with OHM and scattered granules and pebbles from 160.6 to 166.6 ft (48.95 to 50.78 m). Sand from 168.0 to 170.0 ft (51.21 to 51.82 m) is coarser, consisting of coarse sand with abundant granules and small pebbles. From 170 to 171.3 ft (51.82 to 52.21 m) is granuliferous coarse sand with abundant lignite in layers (e.g., 171.1–171.3 ft; 52.15–52.21 m) and scattered chunks. These deposits might represent tidal channel and fringing marsh environments.

There is a change in compaction and core competence at 175 ft (53.34 m) and 185 ft (56.39 m) between two coring gaps (171.4–175 and 180.4–185 ft; 52.24–53.34 and 54.99–56.39 m), both associated with large gamma log increases. The core from 175.0 to 176.5 ft (53.34 to 53.80 m) is interbedded medium sand and clayey sand deposited in upper to lower shoreface environments, whereas 176.5–180.4 ft (53.80–54.99 m) consists of medium–coarse quartz sand with rare OHM laminations deposited in foreshore environments. A sequence boundary is tentatively placed at 180.4 ft (54.99 m) at the top of the coring gap (180.4–185 ft; 54.99–56.39 m) and the top of the large gamma ray increase. It is possible that the sequence boundary could also be placed in the interval of no core recovery at the base of the gamma log increase at ~183 ft (55.78 m). The sequence boundary is also inferred from the transition from shoreface-dominated deposits above to lower estuarine deposits below.

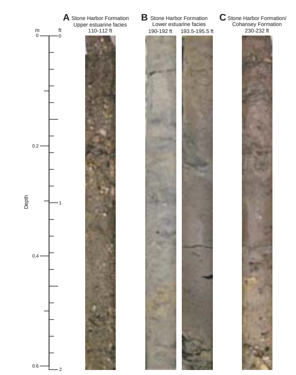
The formational assignment of lignitic, occasionally pebbly, primarily gray sand found from 93.6 to 180.4 ft (28.53 to 54.99 m) at the Cape May Zoo corehole is uncertain (Fig. F4). It might be the equivalent to the ?Cohansey (107.5–166.7 ft; 32.77–50.81 m) and Cohansey Formation (166.7–220.55 ft; 50.81–67.22 m) at Ocean View, the unnamed estuarine clay unit at Cape May (140–357 ft; 42.67–108.81 m), or the "unnamed unit beneath Cape May Peninsula" of Newell et al. (2000). The sand lacks the distinct yellow color, except for an interval at 125 ft (38.10 m), of the Cohansey Formation, though it may be an equivalent, as shown by Newell et al. (2000). The unnamed estuarine clay unit at the Cape May borehole contained dinocysts assigned to lower upper Miocene Zone DN8? (de Verteuil, 1997). We name this unit the Stone Harbor Formation (see the **"Appendix,"** p. 35) and assign it to Sequence Ch4 of de Verteuil (1997).

Sequence Ch3

Age: ?late Miocene
Interval: 180.4–231.4 ft (54.99–70.53 m)

Below an interval of no recovery (180.4–185 ft; 54.99–56.39 m), uniform, heavily bioturbated, lignitic sandy clay occurs from 185 to 201.3 ft (56.39 to 61.36 m) (Fig. **F4**). The clay is blue to greenish gray on fresh exposure and weathers to grayish white. The clay from 187 to 188 ft (57.00 to 57.30 m) is oxidized red. Sands are generally fine grained and restricted to the burrows except for beds at 198.6–198.7, 198.9–199.0, and 200.6–200.7 ft (60.53–60.56, 60.62–60.66, and 61.14–61.17 m), the latter with a sharp base. Lignite is particularly common from 200.0 to 200.6 ft (60.96 to 61.14 m). There is a change to coarse, poorly sorted, granuliferous sand with clay rip-up clasts (200.6–205.75 ft; 61.14–62.71 m). A lignitic, burrowed, fine–medium quartz sand occurs from 205.75 to 210.4 ft (62.72 to 64.13 m), with an interbed of lignitic, slightly sandy clay (208–208.5 ft; 63.40–63.55 m). The juxtaposition of high- and low-energy environments suggests that this section was deposited in lower estuarine environments (Fig. **F5**).

F5. Representative lithofacies, Stone Harbor Formation, p. 42.



Sand from 210.4 to 220.9 ft (64.13 to 67.33 m) is coarse to very coarse, with beds of granules and fine pebbles. The sand is arranged in distinct fining-upward channel deposits with bases at 215.2 and 220.9 ft (65.59 and 67.33 m). These facies appear to be more fluvially influenced and are interpreted as upper estuarine. From 220.9 to 230.2 ft (67.33 to 70.16 m) is lignitic medium–coarse sand that is highly bioturbated and interpreted as lower estuarine. A woody, interbedded fine–medium quartz sand and clay (230.2–230.8 ft; 70.16–70.35 m) with a thin gravel laminae (230.2 ft; 70.16 m) overlies a sandy, slightly micaceous laminated clay (230.8–231.4 ft; 70.35–70.53). This section was deposited in a lower estuarine environment. The base of the clay is irregular and associated with a sharp gamma log increase (Figs. **F4, F5**), interpreted as a sequence boundary between Sequence ?Ch3 above and the Kirkwood-Cohansey sequence (Ch2) below. We also place this sequence in the Stone Harbor Formation. There were no definitive dates derived from material contained within this sequence. At 205 ft (62.48 m), abundant nonmarine palynomorphs are dominated by oak and are clearly pre-Quaternary based on the presence of *Pterocarya*. The sample from 205 ft (62.48 m) is similar to upper Miocene samples from the Scotian Shelf (see **"Palynomorphs and Dinocysts,"** p. 23).

Cohansey Formation

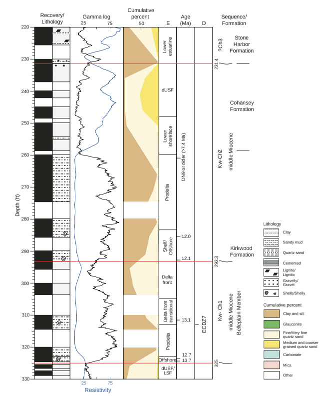
Age: ?late Miocene
Interval: 231.4–261.2 ft (70.53–79.61 m)

Sequence Kw-Ch2

Age: late middle Miocene
Interval: 231.4–293.3 ft (70.53–89.40 m)

Below the sequence boundary (Fig. F6), clean medium–coarse sand (231.4–248.7 ft; 70.53–75.80 m) is heavily bioturbated, has few opaque minerals, and is interpreted as a distal upper shoreface deposit influenced by a delta. A gravel layer (with pebbles as large as 1.5 cm) is present at 231.8 ft (70.65 m). Dark laminations appear at 241.5 ft (73.61 m), with the section fining and becoming progressively more organic rich to 248.6 ft (75.77 m). Interbedded silty fine to medium sand with thin clay beds (250–261.2 ft; 76.20–79.61 m) was deposited as a lower shoreface deposit influenced by a delta. A sample from 261 ft (79.55 m) is assigned at a minimum to Zone DN9 (>7.4 Ma) of de Verteuil (1997) and could be older.

F6. Stratigraphic section, Cohansey and Kirkwood Formations, p. 43.



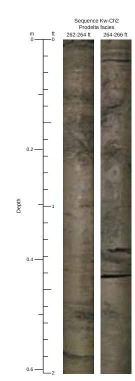
The base of the Cohansey Formation is defined here at the base of the sand that dominates the corehole above 261.2 ft (89.40 m). The laminated prodelta clay below 261.2 ft (89.40 m) is more typical of the Kirkwood Formation. The formational boundary is uncertain here and at the nearby Ocean View corehole because it is often difficult to place (see the "Appendix," p. 35). The sand from 231.4 to 261.2 ft (70.53 to 79.61 m) at Cape May Zoo could be placed in the Kirkwood Formation based on color (gray-green vs. yellow typical of the Cohansey); however, the sand is relatively coarse grained and more typical of the Cohansey Formation. Correlations with Ocean View (Miller et al., this volume) suggest that the equivalent unit at ~220–245 ft (67.06–74.68 m) correlates lithologically and in sequences with this unit at Cape May Zoo. This sequence spans the Cohansey/Kirkwood Formation contact.

Kirkwood Formation

Age: late middle Miocene
Interval: 261.2–713 ft (TD; 89.40–217.32 m)

Sequence Kw-Ch2 spans the Cohansey/Kirkwood Formational boundary at the Cape May Zoo corehole. Laminated, slightly micaceous, slightly silty clay with common sulfur is present from 261.2 to 283.5 ft (79.61 to 86.41 m). Cross laminations are present from 271.1 to 272 ft (82.63 to 82.91 m). These sediments were deposited in prodelta environments (Fig. F7). Laminated to interbedded shelly sand and clayey silt is found from 283.5 to 293.3 ft (86.41 to 89.09 m). The sand is cross-bedded to highly bioturbated. Shells first appear at 285.5 ft (87.02 m). The section from 283.5 to 293.3 ft (86.41 to 89.09 m) appears to be an offshore shelf deposit with intermittent prodelta influences. Sr isotope age estimates of 12.0 and 12.1 Ma were obtained from shell fragments at 285.5 and 292.9 ft (87.02 and 89.28 m). A contact at 293.3 ft (89.40 m) is a sequence boundary separating Sequence Kw-Ch2 (~12 Ma) above from Sequence Kw-Ch1 (13.1–13.7 Ma) below. The Kw-Ch2 sequence is a classic transgressive-regressive coarsening-upward sequence at this site. It is unclear how the Kirkwood-Cohansey sequences relate to the Ch sequences of de

F7. Prodelta facies, p. 44.



Verteuil (1997), though age relationships suggests that Sequence Kw-Ch2 is equivalent to Sequence Ch2 and Sequence Kw-Ch1 is equivalent to Sequence Ch1.

Sequence Kw-Ch1

Age: late middle Miocene
Interval: 293.3–325 ft (89.40–99.06 m)

A sharp facies contact at 293.3 ft (89.40 m) is associated with a gamma log kick that is a sequence boundary (Fig. F6). From 293.3 to 304.0 ft (89.40 to 92.66 m), the section is cross-bedded to laminated, fine–very fine, silty, slightly micaceous quartz sand with silt and clay laminae and beds. Bedding in this section is highly variable:

- 293.3–296 ft (89.40–90.22 m): heavily bioturbated,
- 296–300 ft (90.22–91.44 m): mixture of laminated and cross-bedded intervals,
- 300–301.2 ft (91.44–91.81 m): laminated to cross-laminated,
- 301.2–302.0 ft (91.81–92.05 m): heavily bioturbated, and
- 302–304 ft (92.05–92.66 m): slightly micaceous, slightly silty clay with thin sand and organic-rich laminae.

The section appears to be distinctly shallower and with higher energy than the shelf-prodelta sections above, and we interpret it as delta front.

Below a coring gap (304–310 ft; 92.66–94.49 m), slightly micaceous sandy silty clay with rare shells continues across a coring gap (314.5–320.0 ft; 95.86–97.54 m) to 323.7 ft (98.66 m). The section from 310 to 314 ft (94.49 to 95.71 m) represents a downhole transition from delta front (interbedded and highly variable, as shown on logs) to prodelta (more laminated and more consistent lithology) environments that continue to 323.7 ft (98.66 m). From 323.7 to 324.6 ft (98.66 to 98.94 m) is a very shelly, slightly micaceous, silty clayey sand with medium to fine sand laminae deposited in offshore environments. A contact associated with a gamma log kick was lost between shelly sandy clayey silt at 324.6 ft (98.94 m) and medium sand at 325.5 ft (99.21 m) deposited in proximal lower shoreface environments.

Sequence Kw-Ch1 at Cape May Zoo (293.3–325 ft; 89.40–99.06 m) has Sr isotope age estimates of 13.1 (311.7 ft; 95.01 m), 12.7 (323.7 ft, 98.66 m), and 13.7 Ma (324.4 ft [98.88 m]; just above the sequence boundary) and diatoms assigned to ECDZ 7 of Andrews (1988). These indicate a middle Miocene age for Sequence Kw-Ch1 with a best estimate of 13.2–13.6 Ma. This is comparable in age to the Ch1 sequence of de Verteuil (1997).

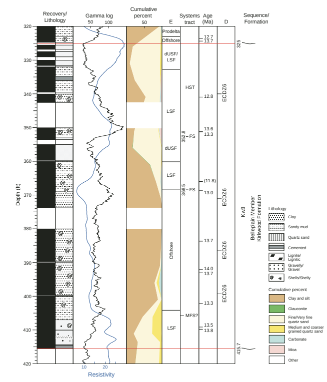
Sequence Kw3

Age: late middle Miocene
Interval: 325–415.7 ft (99.06–126.71 m)

Sequence Kw3 has a moderately thick TST (9.7 ft; 2.96 m) and a very thick HST (72 ft; 24.69 m) punctuated by at least two FSs at 352.8 and 368.5 ft (107.53 and 112.32 m). Sr isotope ages and diatom zonations both suggest that the thick succession from 325 to 415.7 ft (99.06 to 126.71 m) is one sequence. Gamma log kicks and surfaces at 352.8 and 368.5 ft (107.53 and 112.32 m) are quite dramatic, and we initially interpreted them as sequence boundaries; however, further examination of facies successions, Sr isotopes, and diatoms suggest that these surfaces are FSs.

Below the contact at 324.6/325.5 ft (98.94/99.21 m), burrowed, silty fine sand with traces of mica, wood, and shell was recovered from 325.5 to 332.7 ft (99.21 to 101.41 m) (Fig. F8). Faint bedding laminae are preserved despite the extensive bioturbation. This sand is a distal upper to lower shoreface deposit and represents the upper part of an HST.

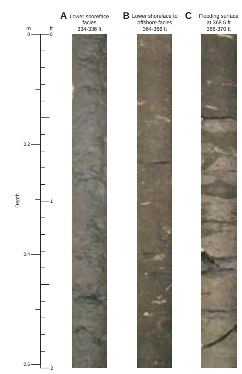
F8. Stratigraphic section, Belleplain Member, p. 45.



An abrupt facies change occurs at 332.7 ft (101.41 m), with the section fining downward to sandy silt to 334 ft (101.80 m) and clayey silt to 352.8 ft (107.53 m). Common shells appear at 340 ft (103.63 m) with a very abundant shell layer at 351–351.7 ft (106.98–107.20 m). From 351.7 to 352.8 ft (107.20 to 107.53 m) is shelly clayey silt deposited in a lower shoreface environment (Fig. F9). A FS is placed at 352.8 ft (107.53 m), marked by a sharp contact between shelly clayey silt above to sand below (Fig. F8). Silt is burrowed to ~0.5 ft (0.15 m) below the contact.

Below a coring gap (353.4–355 ft; 107.72–108.20 m), the section is bioturbated silty, very slightly micaceous, slightly shelly fine sand (355–360 ft; 108.20–109.73 m) with 2%–3% glauconite that weathers with a yellow sulfur-rich rind. This is a distal upper shoreface deposit. The section fines downward to bioturbated, very slightly micaceous, slightly shelly sandy silt (360–368.6 ft; 109.73–112.35 m) deposited in lower shoreface environments (Fig. F9). Large, whole shells occur at 363.1 and 364.0 ft (110.67 and 110.95 m). A contact at 368.5 ft (112.35 m) has blebs of darker brown sandy silt from above with gray clayey silt below (Fig. F9). The two lithologies are burrowed and ripped into each other over 0.5 ft (0.15 m). This contact (368.5 ft; 112.35 m) is also interpreted as an FS.

F9. Representative lithofacies, Sequence Kw3, p. 46.



Below the contact, gray clayey silt (369–370.2 ft; 112.47–112.84 m) with common sulfur was deposited in an offshore environment. Tight clay from 370.2 to 371.1 ft (112.84 to 113.11 m) yields a distinct gamma log kick. This clay overlies a bioturbated, shelly, slightly silty clay (371.1–400 ft; 113.11–121.92 m) also deposited in offshore environments. Shells become more common toward the bottom of this section. The section from 369 to 404 ft (112.84 to 123.14 m) is an excellent confining bed. From 404 to 406 ft (123.14 to 123.75 m) is fine–medium sand deposited in lower shoreface environments. From 406 to 412 ft (123.75 to 125.58 m) is a heavily bioturbated, slightly silty fine–medium sand with scattered shell fragments and numerous granules deposited in lower shoreface environments, which fines upward, suggesting transgression. Phosphate pellets from 408.6 to 412 ft (124.54 to 125.58 m) yield a hot zone on the gamma ray log for the sand and may be reworked from the sequence boundary (Fig. F8). Muddy fine–medium sand (412–414.5 ft; 125.58–126.34 m) is also a lower shoreface deposit, though mud in this section may be intruded drilling mud. An indurated calcite-cemented sandstone (414.5–415.7 ft; 126.34–126.71 m) marks a sequence boundary that separates Sequences Kw3 and Kw2b (Fig. F8). The sand at the base of the sequence (406–414.5 ft; 123.75–126.34) represents the TST, though it may be possible to place the sequence boundary at 412 ft (125.58 m) at the base of the phosphate pebbles, with the section from 412 to 414.5 ft (125.58 to 126.34 m) obscured by drilling slurry.

Sequence Kw2b

Age: middle Miocene
Interval: 415.7–515.7 ft (126.71–157.19 m)

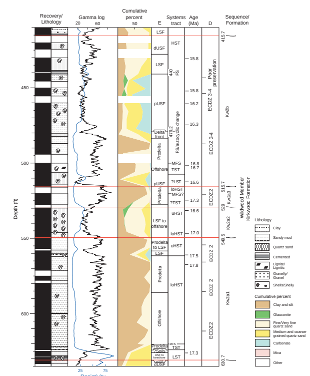
Drilling the thick (100 ft; 30.48 m) Kw2b sequence recovered a thin LST, a thin TST, and a thick HST punctuated by at least one FS (438.5 ft; 133.65 m). Facies within this sequence are more complex than typical New Jersey sequences, though both Sr isotopes and diatoms indicate that the succession is one sequence.

Below a coring gap (415.7–420 ft; 126.71–128.02 m), silty fine–medium sand (420.0–438.5 ft; 128.02–133.65 m) was deposited in wave-dominated shoreface environments (Fig. F10). From 420.0 to 422.2 ft (128.02 to 128.68 m) is a massive, slightly micaceous, silty fine–medium sand that weathers brown as a result of iron staining, particularly within burrows. A surface at 422.2 ft (128.69 m) separates laminated to thin bedded slightly micaceous fine sand (422.2–424.0 ft; 128.69–129.24 m) with silty interbeds that yields a distinct gamma log high. We interpret both sections as distal upper shoreface deposits. Below a coring gap (424.0–430.0 ft; 129.24–131.06 m) is heavily bioturbated, shelly, slightly micaceous, slightly silty fine–medium sand (430.0–438.5 ft; 131.06–133.65 m) that coarsens downward to medium sand. These sands were deposited in lower shoreface environments and are probably equivalent to the Rio Grande water-bearing zone at the Cape May corehole based on Sr isotope age correlations.

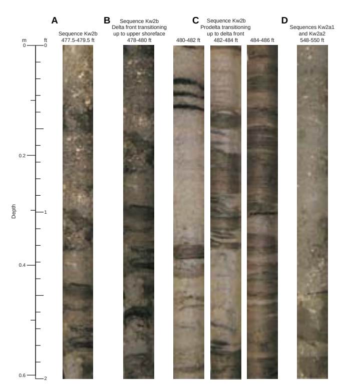
A calcareous, clayey, slightly glauconitic, fine–medium sandstone with less indurated zones is present from 438.5 to 442.9 ft (133.65 to 135.00 m). This indurated interval is a similar facies to the lower shoreface sand above and is interpreted as an FS (Fig. F10). It lies atop a bioturbated, muddy, very shelly fine–medium sand (442.9–474.9 ft; 135.00–144.75 m) that shows a slight fining at the top. Phosphorites, glauconite sand, and lithic fragments, including a glauconitic clay ~1 cm thick, are present. There is a shell hash from 474.9 to 476.0 ft (144.75 to 145.08 m). This sand from 442.9 to 476.0 ft (135.00 to 145.08 m) is interpreted as upper shoreface with slight deepening at the top. The interval from 476.0 to 479.2 ft (145.08 to 146.06 m) is an interval of reworking, with organic-rich clays at 476.0–476.4, 476.8–477.0, 477.9–478.0, 478.5–478.7, and 478.9–479.05 ft (145.08–145.21, 145.33–145.39, 145.66–145.69, 145.85–145.91, and 145.97–146.01 m). Only the top and bottom clays cut across the core, whereas the other clays are clearly ripped up from below.

A distinct contact at 479.2 ft (146.06 m) (Fig. F11) separating the shelly muddy sand above from organic-rich laminated mud below is interpreted as an FS or autocyclic change in depositional environments from delta front to upper shoreface sand. Below this FS is muddy cross-bedded sand with interbedded clean sand, lignite clay, and silty brown organic-rich clay (479.2–483.7 ft; 146.06–147.43 m). These sediments become progressively finer from 483.7 to 493.7 ft (147.43 to 150.48 m), with predominantly laminated organic-rich clay with thin sand laminae and scattered thin (0.1–0.4 ft; 3–12 cm) sand beds. The section from 479.2 to 483.7 ft (146.06 to 147.43 m) represents delta-front deposition in one of several subenvironments (distributary channels, bays/lagoons, and marshes). The sediments from 483.7 to 493.7 ft (147.43 to 150.48 m) were deposited in prodelta environments (Fig. F11). There is a facies shift at 493.7 ft (150.48 m) to burrowed sand without shells deposited in indeterminate shoreface environments. A coring gap from

F10. Stratigraphic section, Wildwood Member, p. 47.



F11. Representative lithofacies, Sequences Kw2a and Kw2b, p. 48.



494.0 to 500.0 ft (150.57 to 152.40 m) is associated with another facies shift.

Thin transgressive and ?lowstand systems tracts are present below the coring gap. Slightly clayey silt (500–510.4 ft; 152.40–155.57 m) with shell fragments are present below the gap and continues to a sequence boundary at 515.7 ft (157.19 m). The silt from 500 to 510.4 ft (152.40 to 155.57 m) represents offshore environments (Fig. **F10**). Within this fairly uniform facies is slightly clayey silt (506.0–506.6 ft; 154.23–154.41 m) and an irregular contact (506.6 ft; 154.41 m). It might be possible to place a sequence boundary at the irregular contact in association with a major gamma ray log increase. Facies successions are not consistent with this placement as a sequence boundary but are consistent as a transgressive surface. Below the contact is a fine to very fine, laminated to bioturbated fine–very fine sand (506.6–507.0 ft; 154.41–154.53 m), a clay bed (506.9–506.95 ft; 154.50–154.52 m), and a clayey, sandy silt (507.0–507.35 ft; 154.53–154.64 m) that weathers to brownish gray. Medium–coarse, bioturbated, granuliferous shelly muddy sand is present from 510.4 to 515.7 ft (155.57 to 157.19 m), deposited in proximal upper shoreface environments. The section may, therefore, be a regressive lowstand deposit from 510.4 to 515.7 ft (155.57 to 1557.19 m). The interval from 515.1 to 515.7 ft (157.00 to 157.19 m) has sand and laminated clay that have been ripped up from below. This contact is interpreted as a sequence boundary separating Sequences Kw2b and Kw2a. The Kw2b sequence is correlative with ECDZ 3–4 at this site and has Sr isotope age estimates between 16.2 and 15.6 Ma.

Sequence Kw2a

Age: early middle Miocene
Interval: 515.7–630.7 ft (157.19–192.24 m)

The thick (115 ft; 35.05 m) Sequence Kw2a may be divided into three higher order sequences (Kw2a1, Kw2a2, and Kw2a3) as noted at Ocean View (**Miller et al.,** this volume). Both Sr isotopes and diatoms indicate a break between Sequence Kw2b (ECDZ 3–4) above and Sequence Kw2a below (ECDZ 2; 17.8–16.9 Ma).

A change from silt and sand above to micaceous, organic-rich laminated clay to thin bedded silty clay with occasional fine sand beds and shell fragments (515.7–527.2 ft; 157.19–160.69 m) (Fig. **F10**) is interpreted as a prodelta deposit that is the lower HST of Sequence Kw2a3.

Below a coring gap (527.2–530 ft; 160.69–161.54 m), there is a change to a slightly clayey, shelly medium sand with a trace of mica and glauconite (530–549.5 ft; 161.54–167.49 m) deposited in lower shoreface (Fig. **F11**) to offshore environments. We interpret this facies shift from sand below to silt above in the coring gap as a sequence boundary (529 ft; 161 m) associated with a minor gamma ray increase. This sequence boundary separates Sequence Kw2a3 above and Sequence Kw2a2 below. The section fines slightly downward and shells become less common. This sandy unit represents the upper HST that may be the equivalent of the Rio Grande water-bearing unit as defined by Sugarman (2001).

A dramatic contact at 549.5 ft (167.49 m) (Fig. **F11**) separates intensively burrowed sand from an underlying laminated clay to laminated clayey silt deposited in prodelta environments. This is a sequence boundary separating Sequence Kw2a2 from Sequence Kw2a1 below. The clay and silt are equivalent to the great diatom bed (Woolman, 1895; Palmer, 1986). The unit from 549.5 to 620 ft (167.49 to 188.98 m) is generally fine grained and monotonous, with the following lithologies:

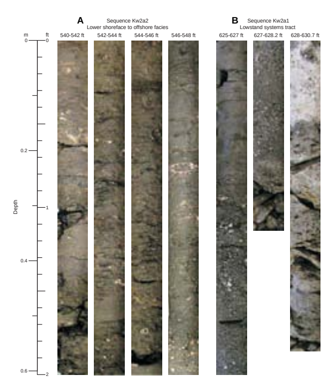
1. Laminated clayey silt with very fine sand laminae (549.5–558.5 ft; 167.19–170.23 m) deposited in prodelta to lower shoreface environments,
2. Silty very fine sand (558.5–561.7 ft; 170.23–171.21 m) deposited in lower shoreface environments,
3. A laminated silty clay with very fine sand laminae (561.7–586 ft; 171.21–178.61 m) deposited in prodelta environments, and
4. Shelly laminated silty clay with very fine sand laminae from 586 to 620.1 ft (178.61 to 189.01 m) deposited in offshore (probably inner neritic) environments.

It might be possible to place a sequence boundary at the top of the sand at 558.5 ft (170.23 m) associated with a gamma log kick, even as the overlying sequence boundary was placed at 510.4 ft (155.57 m), though a good physical break is associated with the facies shift at 515.7 ft (157.19 m) (Fig. **F11**); however, the major physical break appears not at 556 ft (169.47 m) but at 549.5 ft (167.49 m), and we place the sequence boundary here. The section from 620.1 to 625 ft (189.01 to 190.50 m) is interbedded very fine sand and slightly sandy silty clay that comprises a TST deposited in prodelta environments. A contact in a coring gap (624.0–625.0 ft; 190.20–190.50 m) with weathered brown clay and sulfur blooms (625.0–625.4 ft; 190.50–190.62 m), a very fine sand bed (625.4–625.6 ft; 190.62–190.68 m), and a hard brown clay (625.6–626.0 ft; 190.68–190.80 m) is below. The environment of deposition of these clays and sands is uncertain. A contact is present at 626.0 ft (190.80 m) with a granuliferous medium–coarse sand with phosphate pebbles below; therefore a major facies shift is present between 624 and 625.6 ft (190.20 and 190.68 m). The section from 625.0 to 625.6 ft (190.50 to 190.68 m) shows evidence of exposure (weathering, including kaolinization), with a gray clay from 625.6 to 626.0 ft (190.68 to 190.80 m). It is possible to interpret this contact (626 ft; 190.80 m) as a sequence boundary; however, we prefer to interpret it as a transgressive surface and the interval from 625 to 630.7 ft (190.50 to 192.24 m) as an LST (Fig. **F12**) based on the following points:

1. An Sr isotopic age estimate of 17.3 Ma at 626.0 ft (190.80 m) is consistent with Sequence Kw2a (see **"Strontium Isotopic Stratigraphy,"** p. 24); and
2. The facies succession from 625.0 to 630.7 ft (190.50 to 192.24 m) coarsens upward, consistent with regression in an HST, with evidence of exposure from 625.0 to 626.0 ft (190.50 to 190.80 m).

The uniform sequence from 549.5 to 630.7 ft (167.49 to 192.24 m) is correlated with Sequence Kw2a1. With the exception of the sand from 558.5 to 561.7 ft (170.23 to 171.21 m), HST sand is mostly lacking from this sequence. The Kw2a sequences have been correlated with ECDZ 2 and have Sr isotope age estimates ranging from 16.9 to 17.8 Ma.

F12. Representative lithofacies, Sequence Kw2a, p. 49.

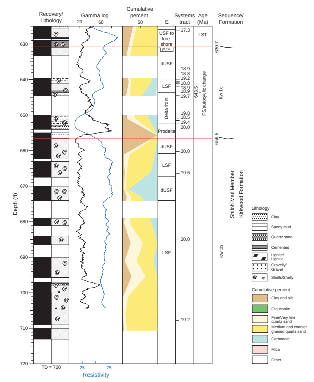


Sequence Kw1c

Age: early middle Miocene
Interval: 630.7–656.5 ft (192.24–200.10 m)

A major drilling objective was attained by the recovery of sequence Kw1c. The sequence is dated as 19.0–18.8 Ma. A major indurated zone (628.0–631.7 ft; 191.41–192.54 m) marks a sequence boundary (Fig. F13). The sandstone from 628.0 to 630.7 ft (191.41 to 192.24 m) is poorly sorted, granuliferous, phosphatic, dominantly medium grained, and shelly deposited in proximal upper shoreface to foreshore environments. We place a sequence boundary at 630.7 ft (192.24 m) at the base of the shelly section above a well-sorted, clean, cross-bedded sandstone below deposited in a proximal upper shoreface environment. There is a minor gamma ray log increase ~2 ft (0.61 m) above the sequence boundary.

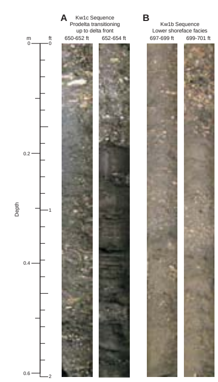
F13. Stratigraphic section, Shiloh Marl Member, p. 50.



Below the indurated zone around the sequence boundary (631.7–633.05 ft; 192.54–192.05 m) is moderately sorted, slightly muddy, fine–medium sand. This sand was deposited in distal upper shoreface environments. The interval from 639.5 to 643.45 ft (194.92 to 196.12 m) is silty medium sand with shell fragments and sand-sized lignite deposited in lower shoreface environments. A thin, indurated, medium-grained sandstone (643.0–643.5 ft; 195.99–196.14 m) with pebbles and large shells (including oysters) that marks either an FS or an autocyclical change is a depositional facies from delta front to lower shoreface deposits.

Below the FS at 643.5 ft (196.14 m) is black, organic-rich, shelly silty fine–medium sand interbedded with organic-rich sandy clayey silt (643.45–652.5 ft; 196.12–198.88 m). These beds are associated with moderate and variable gamma ray log values. We interpret this depositional environment as a delta front. A shift to laminated silty clay from 652.5 to 656.5 ft (198.88 to 200.10 m) (Fig. F14) with thinly interbedded, fine, organic-rich, slightly shelly sand (~0.1 ft; 3 cm) represents prodelta environments, whereas the sand may represent storm events.

F14. Representative lithofacies, Sequences Kw1c and Kw1b, p. 51.



We place a sequence boundary at 656.6 ft (200.13 m) associated with a dramatic gamma ray log kick and a facies shift from the organic-rich silty clay to massive, well-sorted, medium sand below. Sr isotope age estimates for Sequence Kw1c at this site are ~19 Ma. The Kw1c sequence is much thicker (140 ft; 42.67 m) at the Cape May site (Miller et al., 1996a) to the south vs. this site (25.8 ft [7.86 m] thick). This is consistent with the pinching out of Sequence Kw1c 5 km to the north before the Ocean View site (**Miller et al.,** this volume).

Sequence Kw1b

Age: early middle Miocene
Interval: 656.5–713 ft (TD; 200.10–217.32 m)

Slightly silty, slightly coarse, medium sand (656.5–665.0 ft; 211.10–202.69 m) with scattered shells that becomes more common downsection and a thin clay (660.8–660.9 ft; 201.41–201.44 m) represent distal upper shoreface environments. Heavy bioturbation obscures bedding. A very shelly, very fine sand bed (665.0–666.5 ft; 202.69–203.15 m) was deposited in lower shoreface environments. Silty fine–medium sand (666.5–667.2 ft; 203.15–203.67 m) was also deposited in lower shoreface environments, with a coring gap from 667.2 to 670.0 ft (203.67 to 204.22 m). Very shelly fine–medium sand from 670.0 to 674.0 ft (204.22 to 205.44 m) with large shell fragments and whole clam shells has decreasing amounts of shell downsection and appears to be an upper shoreface deposit (probably proximal). The section from 670.0 to 713 ft (204.22 to 217.32 m) consists of bioturbated fine–medium sand deposited in lower shoreface environments (Fig. F14), with alternating amounts of shells, silt, coarser beds, and organic-rich beds, as follows:

1. The interval from 697.0 to 699.0 ft (212.45 to 213.06 m) is more shelly,
2. The interval from 698.0 to 701.0 ft (212.75 to 213.66 m) has interbeds of silty fine sand and shows two gamma log peaks at 698 and 701 ft (212.75 and 213.66 m),
3. The interval from 701.0 to 703.0 ft (213.66 to 214.27 m) is a granuliferous coarse to very coarse shelly sand associated with low gamma log values, and
4. The interval from 703.0 to 713.0 ft (214.27 to 217.32 m) is an organic-rich, silty medium–coarse sand with few shells.

The section from 656.5 to 713 ft (200.10 to 217.32 m) is potentially an excellent aquifer that correlates to the upper sand of the Atlantic City 800-foot sand aquifer of Zapecza (1989).

BIOSTRATIGRAPHY

Palynomorphs and Dinocysts

The samples from the Cape May Zoo corehole are reasonably fossiliferous but largely lacking in age-diagnostic dinocysts. The samples are very hard to process.

The sample from 75 ft (22.86 m) is rich in pollen and contains several dinocysts. The upland flora is typical of the modern oak-pine-hickory forest farther south of modern New Jersey. The age is interpreted to be middle–late Pleistocene. A quantitative analysis of the pollen in the sample reveals the following:

- 60% *Pinus*;
- 18% *Quercus*;
- 4% *Tsuga*;
- 3% *Carya*;
- 2% *Ulmus*;
- 1% *Picea*, *Taxodiaceae*-type, *Fraxinus*, *Ostrya,* and *Chenopodiacea*; and
- <1% *Betula*, *Alnus*, *Corylus*, *Acer*, *Salix*, *Juglans*, *Nyssa*, and *Compositae*.

Fourteen cysts were seen at 75 ft (22.86 m), which include *Bitectatodinium tepikiense* (six), *Spiniferites mirabilis* (two), *Operculodinium centrocarpum* (two), *Operculodinium israelianum* (one), *Spiniferites ramosus* (one), *Brigantedinium simplex* (one), and *Selenopemphix quanta* (one).

The sample at 190 ft (57.91 m) contains sparse but well-preserved palynomorphs revealing an oak-dominated assemblage. A few long-ranging dinocysts (e.g., *B. simplex* and *S. ramosus*) are also found. There is abundant highly oxidized “charcoal”-like material in the sample. Age diagnostic material is lacking.

A sample at 205 ft (62.48 m) contains abundant and well-preserved terrestrial palynomorphs. No marine specimens were noted. The terrestrial flora is strongly dominated by oak but is clearly pre-Quaternary based on the presence of *Pterocarya*. It is very similar to upper Miocene samples from the Scotian shelf.

The sample at 261 ft (79.55 m) is Zone DN9 or older of de Verteuil (1997) (i.e., late Tortonian or older), based on a single specimen of *Batiacasphera sphaerica*. The sample contains almost no marine palynomorphs but does contain significant amounts of oak and other temperate deciduous tree pollen (including *Pterocarya*) and pine. These species and the other dinocysts suggest a marginal marine environment (e.g., *Lejeunecysta* and *Brigantedinium*).

The sample at 281 ft (85.65 m) has a typical marine shelf assemblage (e.g., *Spiniferites* spp., *Brigantedinium* sp., *Tectatodinium pellitum*, *Lingulodinium machaerophorum*, and *Habibacysta tectata*) but does not contain age-diagnostic forms. By comparison with the Ocean View corehole (**Miller et al.,** this volume), however, the assemblage resembles the one found between 450 and 362 ft (137.16 and 110.34 m) at that site (i.e., early middle Miocene).

Diatoms

Seventeen samples were examined for diatom biostratigraphy (Table T2). Diatoms were generally common to abundant and moderately to well preserved in the Cape May Zoo corehole. Samples were assigned to zones using the ECDZ biostratigraphy of Andrews (1988).

T2. Diatom occurrences, p. 60.

Samples above the sequence boundary at 293.3 ft (89.40 m) could not be zoned. Samples at 194.5 and 231.15 ft (598.28 and 70.45 m) were barren of diatoms. A sample at 282.1 ft (85.98 m) contained rare, poorly preserved diatoms that were not age diagnostic (Table T2).

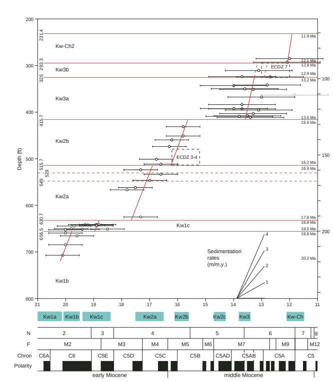
Middle Miocene ECDZ 6 and ECDZ 7 are well represented in the Cape May Zoo corehole (Table T2). A sample at 313.1 ft (95.43 m) is assigned to ECDZ 7 (middle middle Miocene) in agreement with the age assigned using Sr isotopes. ECDZ 6 is found from 340 to 399.1 ft (103.63 to 121.65 m). This encompasses all of Sequence Kw3 in the corehole. These samples include assemblages estimated by Barron (2003) to be ~13–12 Ma. This is younger than previous estimates of the age of Sequence Kw3 (13.8–13.4 Ma) (Miller et al., 1997) and is not in agreement with Sr isotope estimates in the corehole that also indicate an age of 13.8–13.0 Ma.

ECDZ 3–4 of Andrews (1988) is identified in two samples in the Cape May Zoo corehole (Table T2). The samples at 453.9 and 487.2 ft (138.35 and 148.50 m) contain an assemblage equivalent to the lower part of ECDZ 3–4 from the lower middle Miocene. The sample at 453.9 ft (138.35 m) is found in sediments assigned to Sequence Kw2b in agreement with the lower middle Miocene assignment. The sample at 487.2 ft (148.50 m) is in sediments with Sr ages equivalent to Sequence Kw2a from the lower Miocene. This difference cannot be reconciled at this time.

T3. Sr isotope data, p. 63.

ECDZ 2 is found in samples from 521.1 to 611.7 ft (158.83 to 186.45 m) in sediments assigned to Sequence Kw2a (Table T2). This agrees with the Sr isotope stratigraphy that places these sediments in the uppermost lower Miocene. Sediments from Sequence Kw1 are generally medium to coarse sand and were not sampled for diatoms.

F15. Age-depth plot, p. 52.



STRONTIUM ISOTOPIC STRATIGRAPHY

Sr isotope age estimates were obtained from mollusk shells (~4–6 mg) at the Cape May Zoo borehole (Table T3; Figs. F2, F4, F6, F8, F10, F13, F15). Shells were cleaned ultrasonically and dissolved in 1.5-N HCl. Sr was separated using standard ion exchange techniques (Hart and Brooks, 1974). The samples were analyzed on an Isoprobe T Multicollector thermal isotope mass spectrometer. Internal precision on the Isoprobe for the data set averaged 0.000007 and the external precision is approximately ±0.000008 based on replicate analyses of standards. National Bureau of Standards (NBS) 987 is measured for these analysis at 0.710241 normalized to a $^{86}Sr/^{88}Sr$ ratio of 0.1194. Ages were assigned using the Berggren et al. (1995) timescale (Table T3), and 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 the Pleistocene analysis, we derived a linear regression using the data of Farrell et al. (1995), correcting their data to NBS 987 of 0.710255 and fitting linear segments to the data between 0 and 2.5 Ma:

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

Miller et al. (1991) and Oslick et al. (1994) estimate age errors derived from linear regressions of Sr isotopic records. Age errors are ±0.61 m.y. for 15.5–22.8 Ma and ±1.17 m.y. for 9.7–15.5 Ma 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 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) (K.G. Miller, unpubl. analysis of data of Farrell et al., 1996).

The upper 280 ft (85.34 m) of the borehole was only locally fossiliferous for carbonate, and age estimates rely primarily on pollen and dinocyst data. Shells were numerous between 50 and 82 ft (15.24 and 24.99 m) in the corehole (Unit 1 of the Cape May Formation) (Fig. F2). Six ratios were obtained from shells in this interval, providing ages ranging from 0 to 1.23 Ma and an average age of 0.4 Ma; however, there is substantial scatter to the data and the average age is in agreement with ages provided by amino acid racemization (~0.3–0.4 Ma).

The Kirkwood Formation was generally fossiliferous for mollusks, and an excellent chronology was obtained using Sr isotopes. Sequence Kw-Ch2 only contained shells in the lower 9.4 ft (2.87 m; between 283.9 and 293.3 ft [86.53 and 89.40 m]). Two isotopic ages were obtained on shells at 285.5 and 292.9 ft (87.02 and 89.28 m) yielding ages of 12.0 and 12.1 Ma, respectively (latest middle Miocene) (Figs. F6, F15) consistent with previously assigned ages of 12.1–11.5 Ma for the Kw-Ch sequence (Miller et al., 1997; 1998a).

Sequence Kw-Ch1 yielded three ages of 13.1 (311.7 ft; 95.01 m), 12.7 (323.7 ft; 98.66 m), and 13.7 Ma (324.4 ft; 98.88 m), with an average age of 13.1 Ma. The oldest age estimate comes from a sample taken very close to the sequence boundary, yielding an age similar to those from samples below the unconformity. The sample may be reworked. The age-depth plot provides a rough estimate of 12.8–12.9 Ma for Sequence Kw-Ch1.

Fourteen age estimates obtained from Sequence Kw3 yielded ages ranging from 11.8 to 14.0 Ma (Figs. F8, F15). There is considerable scatter to the data, and the ages do not monotonically decrease upsection. The average age for these samples is 13.4 Ma, which is in agreement with previous estimates for Sequence Kw3 (Miller et al., 1997, 1998a).

The age-depth plot provides a rough estimate of 13.2–13.6 Ma for Sequence Kw3.

Sequence Kw2b (Wildwood Member) is well represented in the Cape May Zoo corehole. Four age estimates were obtained on samples between 415.7 and 479.2 ft (126.71 and 146.06 m), ranging from 16.3 to 15.8 Ma (Figs. F10, F15). These ages are consistent with ages previously assigned to Sequence Kw2b (16.1–15.6 Ma) (Miller et al., 1997, 1998a). No ages consistent with Sequence Kw2c (14.7–14.3 Ma) were encountered in the corehole, suggesting that Sequence Kw2c is not present.

The age of the sediments between 479.2 and 515.7 ft (146.06 and 157.19 m) is difficult to interpret, though we tentatively assign them to Sequence Kw2b. Two Sr ages were obtained (Figs. F10, F15). The sample at 501.9 ft (152.98 m) was run twice, giving ages of 16.7 and 16.8 Ma, and a sample at 512.0 ft (156.06 m) gave an age of 16.6 Ma. These are consistent with previous estimates for Sequence Kw2a (17.8–16.5 Ma; Miller et al., 1997; 1998a), not Sequence Kw2b. Diatoms at 487.2 ft (148.50 m) are assigned to the lower part of ECDZ 3–4, consistent with assignment to Sequence Kw2b. Diatom zones are not well calibrated to the Berggren et al. (1995) timescale, and it may be that the lower part of ECDZ 3–4 is found in the upper part of Sequence Kw2a. There is also the possibility that an irregular contact at 506.6 ft (154.41 m) is a sequence boundary, which would explain the 16.6 Ma age at 512.0 ft (156.06 m). This still fails to explain the 16.75-Ma age at 501.9 ft (152.98 m), though it is possible that this sample could be reworked. We retain the sections from 479.2 to 515.7 ft (146.06 to 157.19 m) in Sequence Kw2b, which has an age of 16.1–15.6 Ma elsewhere (Miller et al., 1997; 1998a). We acknowledge, however, that the sequence boundary could be 506.6 ft (154.41 m) and the one sample is reworked.

Sequence Kw2a (515.7 and 630.7 ft; 157.19 and 192.24 m) is well defined using Sr isotopes. Six isotopic ratios were obtained with ages ranging from 17.8 to 16.6 Ma with an average age of 17.3 Ma (Figs. F10, F15). The ages do not regularly decrease in age upsection, and all of the ages except the oldest age estimate (17.8 Ma at 567.3 ft [172.91 m]) cluster within the previously defined age range for Sequence Kw2a of 17.8–16.5 Ma (Miller et al., 1997; 1998a).

Sediments between 630.7 and 643.5 ft (192.24 and 196.14 m) are assigned to Sequence Kw1c. Seven age estimates were obtained ranging from 18.8 to 19.2 Ma, which is within the ages previously given (18.4–19.4 Ma) (Miller et al., 1997, 1998a) for Sequence Kw1c (Figs. F13, F15). Sediments of this age were previously only known from the Cape May corehole (Miller et al., 1996a).

Sediments between 643.5 and 656.5 ft (196.14 and 200.10 m) are difficult to interpret. Five age estimates obtained range in age from 18.5 to 20 Ma (Figs. F13, F15). Four of the five samples are consistent with an assignment to Sequence Kw1b. A single sample at 651 ft (198.42 m) gave an age of 18.5 Ma, consistent with Sequence Kw1c. The section appears continuous with the section assigned to Sequence Kw1c above. It may be that these are Sequence Kw1b sediments reworked during the deposition of Sequence Kw1c.

The section from 656.5 to 713 ft (200.10 to 217.32 m) is assigned to Sequence Kw1b. Four age estimates were obtained with ages ranging from 20.1 to 19.2 Ma (Figs. F13, F15). All of these ages are consistent with Sequence Kw1b elsewhere (19.5–20.1 Ma) (Miller et al., 1997; 1998a).

AMINO ACID RACEMIZATION STRATIGRAPHY

This report summarizes the use of AAR for the purpose of estimating the ages of macrofossils. Samples for AAR were collected from depths of ~40 to ~80 ft (12.2 to 24.4 m) in the Cape May Zoo corehole. AAR is a qualitative method of estimating ages for samples from the last 1.0 to 1.5 m.y., as reviewed in numerous publications (e.g., Wehmiller and Miller, 2000, and references therein).

Racemization geochronology depends on the phenomenon that amino acids in fossil skeletal material convert from their original 100% "left-handed" configuration to an equal mixture of right- and left-handed amino acids. The rate of this racemization reaction is a function of many variables; therefore, the method is rather qualitative, but with suitable calibration it can be used to estimate ages up to ~1.5 m.y. in the mid-Atlantic region of the United States. A useful example of the use of AAR methods for comparison with the results presented here is the work of O'Neal et al. (2000), who studied the Quaternary stratigraphy of estuarine units along the New Jersey shore of Delaware Bay between the Cohansey and Maurice Rivers.

Samples and Methods

Samples were obtained from the Cape May Zoo corehole by J.F. Wehmiller. They were prepared and analyzed using standard gas chromatographic methods as reviewed in Wehmiller and Miller (2000). Samples of *Mulinia, Ensis,* and *Mercenaria* were obtained from several depths in the core, and after washing and visual examination the best-preserved samples were selected for analysis. The methods employed yield D/L (right/left) values, which increase from 0.0 in living samples to 1.0 in "infinitely old" samples, for up to seven amino acids. The internal consistency of the D/L values for multiple amino acids serves as a qualitative check on the reliability of the results. Samples from ~44.6 ft (13.6 m) were from a sandy and gravelly unit with shell hash. Samples from the greater depths were in a compact mud.

Results

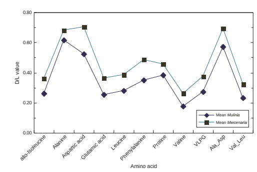
Analytical results (Table **T4**) show the mean D/L value for each amino acid in each sample analyzed. Data in Table **T4** represent modified output from the University of Delaware Aminostratigraphy Lab database. In this table, "Sample" refers to a specific shell, and "Subsample" uniquely identifies any fragment taken from that shell for analysis. In many cases, although not in this study, more than one subsample might be taken from a single shell. Samples are organized by genus and depth in the hole. The amino acids for which values are reported are alloisoleucine (the ratio of D-alloisoleucine to L-isoleucine), alanine, aspartic acid, glutamic acid, leucine, phenylalanine, proline, and valine. "VLPG" is the average of valine, leucine, phenylalanine, and glutamic acid; "Val_Leu" is the average of valine and leucine; "Ala_Asp" is the average of alanine and aspartic acid. In some cases, these averages are a useful way to minimize the "noise" that might arise from the measurements of individual amino acids.

T4. Amino acid analyses data, p. 64.

Reported D/L values are mean values from at least two chromatograms for each sample. D/L values are reported by both peak area and peak height. Peak areas are the ratios computed from the measured areas of both the D and L peaks. Peak heights are the ratios computed from the heights of these peaks. Differences between area and height ratios are usually <3%. If the differences are >3%, then an analytical issue (usually an interfering peak on the chromatogram) is identified and the ratios are considered less reliable. Coefficients of variation (CV) are also given in Table **T4.** The CVs are computed for each genus, combining both area and height values. CVs for *Mulinia* are usually greater than those for *Mercenaria* and are usually interpreted to be the result of the fragile nature of *Mulinia* and the large ratio of surface area to shell mass, which enhances the possibility of open-system diagenesis.

Figure **F16** shows the mean D/L values for the *Mercenaria* and *Mulinia* results given in Table **T4**. Because it is known that *Mercenaria* is a "faster racemizer" than *Mulinia* (York et al., 1989), we use the relation seen in Figure **F16** to conclude that both taxa show internally consistent D/L values (e.g., the "pattern" of D/L among the different amino acids is similar) and that the two groups of D/L values (*Mercenaria* and *Mulinia*) represent material of approximately the same geological age. In other words, the spacing of D/L values seen in Figure **F16** is consistent with the conclusion that the two groups of samples are equal in age. *Ensis* is considered to be a "slow racemizer," so the results for the analysis of this single *Ensis* specimen are consistent with this conclusion.

F16. Mean D/L values, *Mulinia* and *Mercenaria*, p. 53.



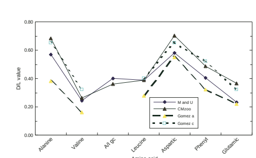
Discussion

Because *Mercenaria* is a much more robust sample than *Mulinia*, and therefore more geochemically reliable (as often seen by comparing the CV values for the two taxa), we usually focus on *Mercenaria* results for chronological interpretations. Nevertheless, the *Mulinia* can be used as a test of the reliability of any conclusions based on *Mercenaria.*

The robustness of *Mercenaria*, however, makes it more likely that fragments of this genus will survive reworking and transport (Wehmiller et al., 1995), particularly compared with *Mulinia.* In the case of the Cape May Zoo corehole results, we use the combination of these characteristics to infer an age for the *Mulinia*-bearing unit (depth = ~23 m) using not only the results for shells at this depth but also the results for apparently reworked/transported *Mercenaria* shells at ~44.8 ft (13.66 m) depth. Because the *Mercenaria* shells are rounded fragments found at the contact between an overlying sandy unit and the underlying mud unit, we conclude that the *Mercenaria* are found as part of a lag deposit and that they represent the same age as the underlying *Mulinia*-bearing muddy unit.

The proposed age estimate for the *Mercenaria* and the "age equivalent" *Mulinia* is based on a direct comparison with the *Mercenaria* results presented by O'Neal et al. (2000). Figure **F17** shows this comparison by plotting mean D/L values for the Cape May Zoo *Mercenaria* along with results from the Morie and Unimin Pits (Mauricetown, New Jersey) and two aminozones at Gomez Pit, Virginia that serve as qualitative calibrations. Following the approach of O'Neal et al. (2000), we conclude that the Cape May Zoo shells are roughly equivalent in age to those from Morie and Unimin Pits and that these shells all represent a "pre-last interglacial" age, probably correlative with either MIC 9 or 11 of the marine isotope record, or roughly 300 to 400 ka This conclusion is based on the fact that the D/L values in the New Jersey samples are all greater than those seen in calibration samples (MIC 5; 80 ka) at Gomez Pit (Gomez a in Fig. **F17**) and quite similar to the D/L values seen in samples from an older unit at Gomez (Gomez c in Fig. **F17**). Using kinetic mod-

F17. Mean D/L values, *Mercenaria*, p. 54.



els of racemization and the Gomez a calibration point, Gomez c has been estimated to be at least 250 ka in age (Mirecki et al., 1995); correcting for temperature differences between southern New Jersey and southeastern Virginia leads to the conclusion that the New Jersey samples are at least 15% older than those from Gomez c.

Summary and Conclusions

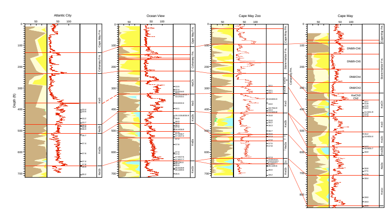
Mercenaria and *Mulinia* were sampled from depths of ~44.6 and 77.1 ft (13.6 and 23.5 m), respectively, in the Cape May Zoo corehole. Although the *Mercenaria* samples are clearly transported and probably reworked, the combined analysis of all D/L results suggests that *Mercenaria* and *Mulinia* can both be used to estimate the age of the *Mulinia*-bearing unit at ~77.1 ft (23.5 m). Based on comparisons with other AAR data from the United States Atlantic coastal plain, the *Mulinia*-bearing unit is ~300–400 ka in age. The age of the shallower, sandy unit is not well constrained by the results presented here, as the only samples from this unit (*Mercenaria*) were taken right at its base and are almost definitely transported or reworked.

SUMMARY AND CONCLUSIONS

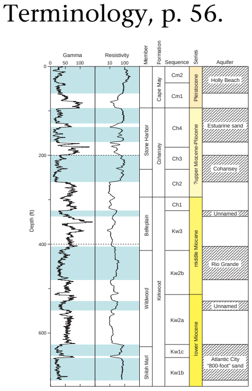
The Cape May Zoo corehole recovered Miocene–?Pliocene Kirkwood and Cohansey sequences and Pleistocene Cape May sequences allowing for:

- Better resolution and dating of sequences, which provides a test of the age and regional significance of sequences cored at Cape May and Ocean View (Fig. **F18**);
- Development of a more precise geologic history of the Cape May peninsula, including improved correlations with Delaware; and
- Development of a more precise and detailed hydrostratigraphic framework for the Cape May Peninsula (Fig. **F19**).

F18. Dip section, p. 55.



F19. Terminology, p. 56.



Resolution of Neogene Sequences

Drilling at Cape May Zoo confirmed the regional significance of the following:

- The Cape May Formation Unit 1 (Unit 3 of Newell et al., 2000) is 300,000–400,000 years old and is correlative with MIC 9e or 11.
- The Miocene–?upper Pliocene section thickens from Ocean View to Cape May Zoo to Cape May (Fig. **F18**).
- Potential Cohansey (Ch) sequences were identified and mapped. The Ch4 and Ch3 sequences were named the Stone Harbor Formation, although their ages are still poorly resolved. The Ch1–Ch2 sequence is middle Miocene (~12 Ma) and is a classic coarsening-upward New Jersey sequence.
- The middle Miocene Kw3 sequence can be divided into two units, providing a higher resolution sequence stratigraphy from this site to test global sea level correlations (Fig. **F18**);
- The lower middle Miocene Kw2a1, Kw2a2, and Kw2a3 sequences occur at this site, verifying that these sequences, first recognized at Ocean View (Fig. **F18**), are regional.

- The lower Miocene Kw1c sequence thins rapidly to the north from Cape May to the Cape May Zoo (Fig. F18).

Hydrostratigraphic Framework

A major objective of the Cape May Zoo corehole was to improve the resolution of Miocene sequences between Ocean View and Cape May and the hydrogeologic framework on the Cape May Peninsula (Fig. F19). Aquifer terminology follows the usage of Lacombe and Carleton (2002). The Holly Beach water-bearing zone, an unconfined aquifer, correlates with the Cape May Formation Unit II (and possibly Unit I) (Fig. F19). Sandy sections assigned to this unit are ~60 ft (18.3 m) thick at this site (0–60 ft; 0–18.3 m), although the resistivity log suggests it might be only 35 ft (10.67 m) thick (0–35 ft; 0–18.3 m). A 34- to 57-ft-thick (10.36–17.37 m) confining bed contained within Cape May Formation Unit 1 separates the Holly Beach zone above from the Estuarine Sand aquifer below. The Estuarine Sand aquifer (Fig. F19) is ~90 ft (27.43 m) thick (93.6–180.4 ft; 28.53–54.99 m) and correlates with Sequence Ch4 and the upper part of the newly named Stone Harbor Formation. Gill (1962) incorrectly correlated this aquifer with the estuarine sand facies of the Cape May Formation; consequently, a new aquifer name might be given to this dominantly sandy interval that does not correlate with the Cape May Formation. A ~20-ft-thick (6.1 m) confining bed (180.4–200 ft; 55–61 m) in the upper part of Sequence Ch3 (and lower part of the newly named Stone Harbor Formation) separates the confined Estuarine Sand aquifer above from the confined Cohansey aquifer below (Fig. F19). The Cohansey aquifer is 60 ft (18.3 m) thick at this site. The Cohansey aquifer is separated from the Rio Grande aquifer (405–480 ft; 123.4–146.3 m) by a thick (150 ft; 45.7 m) confining bed (upper part of Wildwood-Belleplain confining unit of Sugarman, 2001) correlative with the Kirkwood-Cohansey and Kw3 sequences (Fig. F19). Within this confining bed (250–405 ft; 76.2–137.6 m) is potentially a thin unnamed aquifer from 325 to 345 ft (99 to 105 m). The Rio Grande aquifer is separated from the upper part of the Atlantic City 800-foot sand by a thick (150 ft; 45.72 m) confining unit (lower part of Wildwood-Belleplain confining unit from 480 to 630 ft (146.3 to 192 m). A thin (20 ft; 6 m) unnamed aquifer is also present within this confining unit from 530 to 550 ft (161.5 to 167.6 m). The corehole terminated in the Atlantic City 800-foot sand aquifer. At this site, the upper sand is composed of sand from Sequences Kw1b and Kw1c. The relatively thin clay from 650 to 661 ft (198.1 to 201.5 m) probably has limited capabilities as a confining bed separating the two sands within the Shiloh Marl Member of the Kirkwood Formation (Fig. F19).

Future Work

The Cape May Zoo corehole focused on early–middle Miocene sequences, recovering nine dateable sequences of this age (Sequences Kw-Ch2, Kw-Ch1, Kw3, Kw2b, Kw2a3, Kw2a2, Kw2a1, Kw1c, and Kw1b) and two poorly dated upper Miocene sequences (?Ch3 and ?Ch4). Though operations during Legs 150X and 174AX drilled 11 onshore coreholes, Miocene sections progressively thin dramatically and are temporally much less complete updip. Along a projected dip profile, the most downdipping sites are Bethany Beach, Cape May, and Cape May Zoo, with ~12, ~13, and 11 Miocene sequences, respectively. Despite the success of sampling numerous sequences at the Cape May Zoo corehole, including the first verification of Sequence Kw1c, which is really quite limited, hiatuses limit our understanding of Miocene sequences onshore. For example, numerous penetrations of the Miocene section during Legs 150X and 174AX have provided a sampling of a maximum of 50% of the early to middle Miocene (~11.2–23.8 Ma). At Cape May Zoo, our age estimates suggest that as little as 2.5 m.y. of this 12.6-m.y. interval is represented (Fig. **F15**). There is simply more gap than record onshore. We did manage to capture one or two possible LSTs at Cape May Zoo, but LSTs are generally lacking and the sections onshore only represent a small portion of the record.

The Cape May Zoo corehole complements offshore drilling during IODP Expedition 313 (summer 2007) that will also target thick lower–middle Miocene sequences. Seismic evidence shows that the offshore sections beneath the inner continental shelf are more complete and reflect a full range of systems tracts. Though several discontinuous holes have sampled Miocene sequences beneath the inner shelf (AMCOR, ACOW), there has been no continuous sampling of these sequences where they are their thickest, the imprint of sea level change is most clearly recorded, and the ties between facies distribution and sequence architecture can be firmly established. Expedition 313 will sample these critical facies and bring the New Jersey Sea Level/Mid-Atlantic Transect to its conclusion.

REFERENCES

Andrews, G.W., 1988. A revised marine diatom zonation for Miocene strata of the southeastern United States. *Geol. Surv. Prof. Pap. U.S.,* 1481:1–29.

Ashley, G.M., Wellner, R.W., Esker, D., and Sheridan, R.E., 1991. Depositional model for valley fills on a passive continental margin. *Spec. Publ.—SEPM (Soc. Sediment. Geol.),* 51:285–301.

Barron, J.A., 2003. Planktonic marine diatom record of the past 18 m.y.: appearances and extinctions in the Pacific and Southern Oceans. *Diatom Res.,* 18:203–224.

Berggren, W.A., Kent, D.V., Swisher, C.C., III, and Aubry, M.-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. *In* Berggren, W.A., Kent, D.V., Aubry, M.-P., and Hardenbol, J. (Eds.), *Geochronology, Time Scales and Global Stratigraphic Correlation.* Spec. Publ.—SEPM (Soc. Sediment. Geol.), 54:129–212.

Browning, J.V., Miller, K.G., McLaughlin, P.P., Kominz, M.A., Sugarman, P.J., Monteverde, D., Feigenson, M.D., and Hernández, J.C., 2006. Quantification of the effects of eustasy, subsidence, and sediment supply on Miocene sequences, mid-Atlantic margin of the United States. *Geol. Soc. Am. Bull.,* 118(5):567–588. **doi:10.1130/B25551.1**

Carter, C.H., 1978. A regressive barrier and barrier-protected deposits: depositional environments and geographic setting of the Tertiary Cohansey sand. *J. Sediment. Petrol.,* 48:933–950.

de Verteuil, L., 1997. Palynological delineation and regional correlation of lower through upper Miocene sequences in the Cape May and Atlantic City boreholes, New Jersey coastal plain. *In* Miller, K.G., and Snyder, S.W. (Eds.), *Proc. ODP, Sci. Results,* 150X: College Station, TX (Ocean Drilling Program), 129–145. **doi:10.2973/odp.proc.sr.150X.310.1997**

Farrell, J.W., Clemens, S.C., and Gromet, L.P., 1995. Improved chronostratigraphic reference curve of late Neogene seawater $^{87}Sr/^{86}Sr$. *Geology,* 23:403–406.

Gill, H.E., 1962. Groundwater resources of Cape May County, N.J., saltwater invasion of principal aquifers. *Spec. Rep.—State New Jersey, Dep. Conserv. Econ. Dev., Div. Water Policy Supply,* 18.

Hart, S.E., and Brooks, C., 1974. Clinopyroxene-matrix partitioning of K, Rb, Cs, Sr and Ba. *Geochim. Cosmochim. Acta,* 38(12):1799–1806. **doi:10.1016/0016-7037(74)90163-X**

Isphording, W.C., and Lodding, W., 1969. Facies changes in the New Jersey Miocene. *In* Subitsky, S. (Ed.), *Geology of Selected Areas in New Jersey and Eastern Pennsylvania and Guidebook of Excursions:* New Brunswick (Rutgers University Press), 7–13.

Lacombe, P.J., and Carleton, G.B., 2002. Hydrogeologic framework, availability of water supplies, and saltwater intrusion, Cape May County, New Jersey. *Water-Resour. Invest. Rep. (U. S. Geol. Surv.),* 01–4246.

Miller, K.G., Browning, J.V., Liu, C., Sugarman, P., Kent, D.V., Van Fossen, M., Queen, D., Goss, M., Gwynn, D., Mullikin, L., Feigenson, M.D., Aubry, M.-P., and Burckle, L.D., 1994a. Atlantic City site report. *In* Miller, K.G., et al., *Proc. ODP, Init. Repts.,* 150X: College Station, TX (Ocean Drilling Program), 35–55. **doi:10.2973/odp.proc.ir.150X.112.1994**

Miller, K.G., Kominz, M.A., Browning, J.V., Wright, J.D., Mountain, G.S., Katz, M.E., Sugarman, P.J., Cramer, B.S., Christie-Blick, N., and Pekar, S.F., 2005. The Phanerozoic record of global sea-level change. *Science,* 310(5752):1293–1298. **doi:10.1126/science.1116412**

Miller, K.G., Liu, C., Browning, J.V., Pekar, S.F., Sugarman, P.J., Van Fossen, M.C., Mullikin, L., Queen, D., Feigenson, M.D., Aubry, M.-P., Burckle, L.D., Powars, D., and Heibel, T., 1996a. Cape May site report. *Proc. ODP, Init. Repts.,* 150X (Suppl.): College Station TX (Ocean Drilling Program), 5–28. **doi:10.2973/odp.proc.ir.150XS.014.1996**

Miller, K.G., and Mountain, G.S., 1994. Global sea-level change and the New Jersey margin. *In* Mountain, G.S., Miller, K.G., Blum, P., et al., *Proc. ODP, Init.*

Repts., 150: College Station, TX (Ocean Drilling Program), 11–20. doi:10.2973/odp.proc.ir.150.102.1994

Miller, K.G., Mountain, G.S., Browning, J.V., Kominz, M., Sugarman, P.J., Christie-Blick, N., Katz, M.E., and Wright, J.D., 1998a. Cenozoic global sea level, sequences, and the New Jersey transect: results from coastal plain and continental slope drilling. *Rev. Geophys.,* 36:569–601.

Miller, K.G., Mountain, G.S., and Leg 150 Shipboard Party and Members of the New Jersey Coastal Plain Drilling Project, 1996b. Drilling and dating New Jersey Oligocene–Miocene sequences: ice volume, global sea level and Exxon records. *Science,* 271:1092–1095. doi:10.1126/science.271.5252.1092

Miller, K.G., Rufolo, S., Sugarman, P.J., Pekar, S.F., Browning, J.V., and Gwynn, D.W., 1997. Early to middle Miocene sequences, systems tracts, and benthic foraminiferal biofacies, New Jersey coastal plain. *In* Miller, K.G., Newell, W., and Snyder, S.W. (Eds.), *Proc. ODP, Sci. Results,* 150X: College Station, TX (Ocean Drilling Program), 361–373. doi:10.2973/odp.proc.sr.150X.313.1997

Miller, K.G., and Snyder, S.W., (Eds.), 1997. *Proc. ODP, Sci. Results,* 150X: College Station, TX (Ocean Drilling Program). doi:10.2973/odp.proc.sr.150X.1997

Miller, K.G., Sugarman, P.J., Browning, J.V., Olsson, R.K., Pekar, S.F., Reilly, T.J., Cramer, B.S., Aubry, M.-P., Lawrence, R.P., Curran, J., Stewart, M., Metzger, J.M., Uptegrove, J., Bukry, D., Burckle, L.H., Wright, J.D., Feigenson, M.D., Brenner, G.J., and Dalton, R.F., 1998b. Bass River site. *In* Miller, K.G., Sugarman, P.J., Browning, J.V., et al., *Proc. ODP, Init. Repts.,* 174AX: College Station, TX (Ocean Drilling Program), 5–43. doi:10.2973/odp.proc.ir.174AX.101.1998

Miller, K.G., Sugarman, P., Van Fossen, M., Liu, C., Browning, J.V., Queen, D., Aubry, M.-P., Burckle, L.D., Goss, M., and Bukry, D., 1994b. Island Beach site report. *In* Miller, K.G., et al., *Proc. ODP, Init. Repts.,* 150X: College Station, TX (Ocean Drilling Program), 5–33. doi:10.2973/odp.proc.ir.150X.111.1994

Miller, K.G., Wright, J.D., and Fairbanks, R.G., 1991. Unlocking the ice house: Oligocene–Miocene oxygen isotopes, eustasy, and margin erosion. *J. Geophys. Res.,* 96:6829–6848.

Mirecki, J.E., Wehmiller, J.F., and Skinner, A.F., 1995. Geochronology of Quaternary coastal deposits, southeastern Virginia, USA. *J. Coastal Res.,* 11:1135–1144.

Newell, W.L., Powars, D.S., Owens, J.P., Stanford, S.D., and Stone, B.D., 2000. Surficial geologic map of central and southern New Jersey, 1:100,000. *U.S. Geol. Surv. Map Ser.*, I-2540-D.

NJGS Information Circular 1, 1990. Generalized stratigraphic table for New Jersey. *N. J. Geol. Surv.*

O'Neal, M.L., Wehmiller, J.F., and Newell, W.L., 2000. Amino acid geochronology of Quaternary coastal terraces on the northern margin of Delaware Bay, southern New Jersey, USA. *In* Goodfriend, G.A., Collins, M.J., Fogel, M.L., Macko, S.A., and Wehmiller, J.F. (Eds.), *Perspectives in Amino Acid and Protein Geochemistry:* New York (Oxford Univ. Press), 301–319.

Oslick, J.S., Miller, K.G., Feigenson, M.D., and Wright, J.D., 1994. Oligocene–Miocene strontium isotopes: stratigraphic revisions and correlation to an inferred glacioeustatic record. *Paleoceanography,* 9(3):427–443. doi:10.1029/94PA00249

Owens, J.P., Sugarman, P.J., Sohl, N.F., Parker, R.A., Houghton, H.F., Volkert, R.A., Drake, A.A., Jr., and Orndorff, R.C., 1998. *Bedrock Geologic Map of Central and Southern New Jersey,* 1:100,000. Misc. Invest. Ser. Map, I-2540-B.

Palmer, A.A., 1986. Miocene radiolarian biostratigraphy, U.S. mid-Atlantic coastal plain. *Micropaleontology,* 32(1):19–31. doi:10.2307/1485697

Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988. Eustatic controls on clastic deposition, I. Conceptual framework. *In* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H.W., Van Wagoner, J., and Kendall, C.G.St.C. (Eds.), *Sea-Level Changes: An Integrated Approach.* Spec. Publ.—Soc. Econ. Paleontol. Mineral., 42:109–124.

Sugarman, P.J., 2001. Hydrostratigraphy of the Kirkwood and Cohansey Formations of Miocene age in Atlantic County and vicinity, New Jersey. *Bull.—N. J. Geol. Surv.,* 40.

Sugarman, P.J., Miller, K.G., Browning, J.V., Kulpecz., A.A., McLaughlin, P.P., Jr., and Monteverde, D.H., 2005. Hydrostratigraphy of the New Jersey coastal plain: sequences and facies predict the continuity of aquifers and confining units. *Stratigraphy*, 2(3):259–275.

Sugarman, P.J., Miller, K.G., Bukry, D., and Feigenson, M.D., 1995. Uppermost Campanian–Maestrichtian strontium isotopic, biostratigraphic, and sequence stratigraphic framework of the New Jersey Coastal Plain. *Geol. Soc. Am. Bull.,* 107:19–37. **doi:10.1130/0016-7606(1995)107<0019:UCMSIB>2.3.CO;2**

Sugarman, P.J., Miller, K.G., Owens, J.P., and Feigenson, M.D., 1993. Strontium isotope and sequence stratigraphy of the Miocene Kirkwood Formation, southern New Jersey. *Geol. Soc. Am. Bull.,* 105:423–436. **doi:10.1130/0016-7606(1993)105<0423:SIASSO>2.3.CO;2**

Wehmiller, J.F., and Miller, G.H., 2000. Aminostratigraphic dating methods in Quaternary geology. *In* Noller, J.S., Sowers, J.M., and Lettis, W.R. (Eds.), *Quaternary Geochronology: Methods and Applications*. AGU Ref. Shelf, 4:187–222.

Wehmiller, J.F., York, L.L., and Bart, M.L., 1995. Amino acid racemization geochronology of reworked Quaternary mollusks on US Atlantic coast beaches: implications for chronostratigraphy, taphonomy, and coastal sediment transport: *Mar. Geol.,* 124(1–4):303–337. **doi:10.1016/0025-3227(95)00047-3**

Woolman, L., 1895. Artesian wells in southern New Jersey. *Annu. Rep. State Geol. 1894, Geol. Surv. New Jersey,* 153–189.

York, L.L., Wehmiller, J.F., Cronin, T.M., and Ager, T.A., 1989. Stetson Pit, Dare County, North Carolina: an integrated chronologic, faunal, and floral record of subsurface coastal sediments. *Palaeogeogr., Palaeoclimatol., Palaeoecol.,* 72:115–132. **doi:10.1016/0031-0182(89)90136-3**

Zapecza, O.S., 1989. Hydrogeologic framework of the New Jersey coastal plain. *Geol. Surv. Prof. Pap. (U.S.),* 1404-B.

APPENDIX

Definition of Middle to Upper Miocene Stone Harbor Formation, New Jersey Coastal Plain

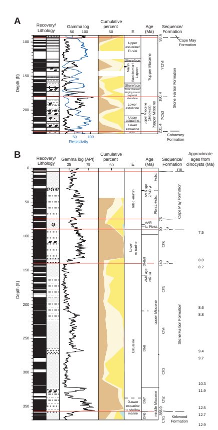
In outcrop and in the subsurface, the unconsolidated sands, silts, and clays of the middle to upper Miocene Cohansey Formation are unconformably overlain by surficial units (Pleistocene Cape May, ?upper Miocene–Pliocene Pennsauken, ?upper Miocene Bridgeton, and ?upper Miocene Beacon Hill Formations) (Newell et al., 2000), and unconformably overlie the middle to lower Miocene Kirkwood Formation. Differentiation of Kirkwood and Cohansey Formation sands can be particularly difficult since both are nearshore deposits, though the latter generally consists of coarser grained, yellow sand vs. finer grained gray sand (Isphording and Lodding, 1969). In the deeper subsurface penetrated by Legs 150X and 174AX (e.g., Atlantic City and Ocean View) (Fig. **F16**), the first definite Kirkwood Formation is identified on the first downhole occurrence of brownish silty clay or silty micaceous gray sand. The upper limit of the Cohansey Formation and its lateral equivalents is even more enigmatic, particularly in the Cape May Peninsula. At the Cape May site, an estuarine unit of sand and sandy clay from 90 to 356.9 ft (27.43 to 108.78 m) was first thought to be ?Pleistocene and Pliocene age (Miller et al., 1994), though subsequent dinocyst studies show the entire unit is middle to upper Miocene (Zones DN7–DN9; >7.5 Ma) (de Verteuil, 1997). Owens et al. (1998) mapped this unit as a sand with woody clays in the Cape May Peninsula (his Tu unnamed unit) that may be laterally equivalent to the Cohansey Formation updip and along strike. This same unit of gray to black pebbly, clayey sand and woody clayey silt was mapped in the Cape May Peninsula by Newell et al. (2000) as an unnamed Tertiary unit (Tu); his sections indicate that the Tu is either laterally equivalent to or cuts into and removes the Cohansey Formation. We recognize this lignitic sand as a distinct formation and here designate these lithologically variable, dominantly estuarine sediments in the Cape May Peninsula as the Stone Harbor Formation.

Stone Harbor Formation

We formally designate middle–upper Miocene sand and clay between 93.6 and 231.4 ft (28.53 and 70.53 m) at the Cape May Zoo corehole as the Stone Harbor Formation stratotype (Fig. **AF1**). Because the primary stratotype has relatively poor age control, a costratotype is designated at the Leg 150X Cape May site from 90 to 356.9 ft (27.43 to 108.78 m) because of its relatively precise dinocyst stratigraphy (de Vertueil, 1997). The name is derived from the Stone Harbor Country Club that is adjacent to the stratotype corehole, which is 7 km from the town of Stone Harbor, New Jersey. The name Cape May Formation is preempted by its use for the overlying Pleistocene–Holocene sands, whereas the use of other nearby towns for the name of the unit are either similarly preempted (e.g., Wildwood and Rio Grande) or would cause confusion (e.g., Cape May Zoo Formation, Cape May Courthouse Formation, and Middle Township Formation).

The Stone Harbor Formation at the Cape May Zoo corehole is 137.8 ft (42.0 m) thick and is primarily a sand, with the following facies:

AF1. Cape May Zoo, Cape May, and Ocean View coreholes, p. 65.



1. Medium- to coarse-grained quartz sand with very coarse, granuliferous, and pebbly beds;
2. Lignitic sandy clay; and
3. Organic-rich sandy silt with organic brown clay.

Lignite is generally common throughout the formation, OHMs are present but not common, organic-rich beds are common, and mica is scarce. Sandier units are typically 30–40 ft thick (9.14–12.19 m) and alternate with the finer grained units that are typically 10–20 ft (3.05–6.10 m) thick. Environments of deposition are generally estuarine in the lower part and nearshore (including shoreface, lagoon, marsh, tidal channel, and backbarrier) to fluvial/estuarine in the upper part.

The Stone Harbor Formation in the Cape May corehole is 266.9 ft (81.35 m) thick and consists predominantly of sand, with the following facies in order of thickness:

1. Medium to coarse sand (e.g., 140–210 and 270–320 ft; 42.67–64.10 and 82.30–97.54 m) that is locally organic rich;
2. Fine, very micaceous sand (210–270 ft; 64.10–82.30 m);
3. Thinly laminated clay to sandy clay (90–140 ft [27.43–42.67 m]; originally placed in the Cape May Formation); and
4. Silty sandy clay, clayey silt, and clay (320–356.9 ft; 97.54–108.78 m).

Lignite is generally common and there are scattered granuliferous and pebbly beds. The environment of deposition is primarily estuarine.

The age of the Stone Harbor Formation is constrained primarily at the Cape May site, where it is assigned to Zones DN7 (322–357 ft; 98.15–108.81 m; ~12–12.5 Ma), DN8 (Sequences Ch3 [274–322 ft; 83.52–98.15 m] and Ch4 [210–274 ft; 64.01–83.52 m]; ~9–10.5 Ma), and DN8/9 (Sequences Ch5 [140–210 ft; 42.67–64.01 m] and Ch6 [90–140 ft; 27.43–42.67 m]; ~7.5–8.5 Ma). At the Cape May Zoo site, dinocysts constrain the lower sequence as upper Miocene.

Based on lithologic criteria the Stone Harbor Formation is readily differentiated from the Cohansey Formation by its more variable grain size (ranging from pebbles to clay) and facies, a greater abundance of lignite and organic-rich beds, and generally estuarine depositional environment. It is similar to the Cohansey Formation in containing some barrier and back-barrier environments and generally lacking calcareous fossils, but locally containing dinoflagellate cysts. It is differentiated from the overlying Cape May Formation by its generally coarser, more variable, and more lignitic facies. As noted, it is possible that the Stone Harbor Formation is laterally equivalent to the Cohansey Formation, though the Stone Harbor Formation may in fact be cut into the Cohansey Formation (Newell et al., 2000). It appears that the Stone Harbor Formation is in part the same age as the Cohansey Formation (10–12.5 Ma), though it may be younger in the upper part (e.g., 7.7–8.0 Ma) than the Cohansey Formation.

There are possibly five sequences in the Stone Harbor Formation at the Cape May site (Sequences Ch2–Ch6) (de Verteuil, 1997), though the regional extent of these possible sequences has not been established. At Cape May Zoo, we identify two distinct sequences within the Stone Harbor Formation (93.6–180.4 and 180.4–231.4 ft [28.53–54.99 and 54.99–54.99 m]) and tentatively correlate them with de Verteuil's Sequences Ch3 and Ch4.

In the subsurface, the unit has been mapped across the Cape May Peninsula (Owens et al., 1998; Newell et al., 2000) and can be extended to at least the Leg 174AX Ocean View site (Fig. **AF1**). In the stratotype and Ocean View coreholes, the Stone Harbor Formation is overlain by the Cape May Formation and overlies nearshore sands assigned to the Cohansey Formation. The unit does not appear to outcrop.

Figure F1. Location map showing existing Deep Sea Drilling Project (DSDP), Atlantic Margin Coring Project (AMCOR), and Ocean Drilling Program (ODP) coreholes analyzed as a part of the New Jersey (NJ)/Mid-Atlantic (MAT) sea level transect. Also shown are multichannel seismic data from the *Ewing* (Ew9009), *Oceanus* (Oc270), and *Cape Hatteras* (Ch0698) cruises. MN = Monmouth County, OC = Ocean County, BU = Burlington County, CD = Camden County, GL = Gloucester County, AT = Atlantic County, SA = Salem County, CU = Cumberland County, CM = Cape May County.

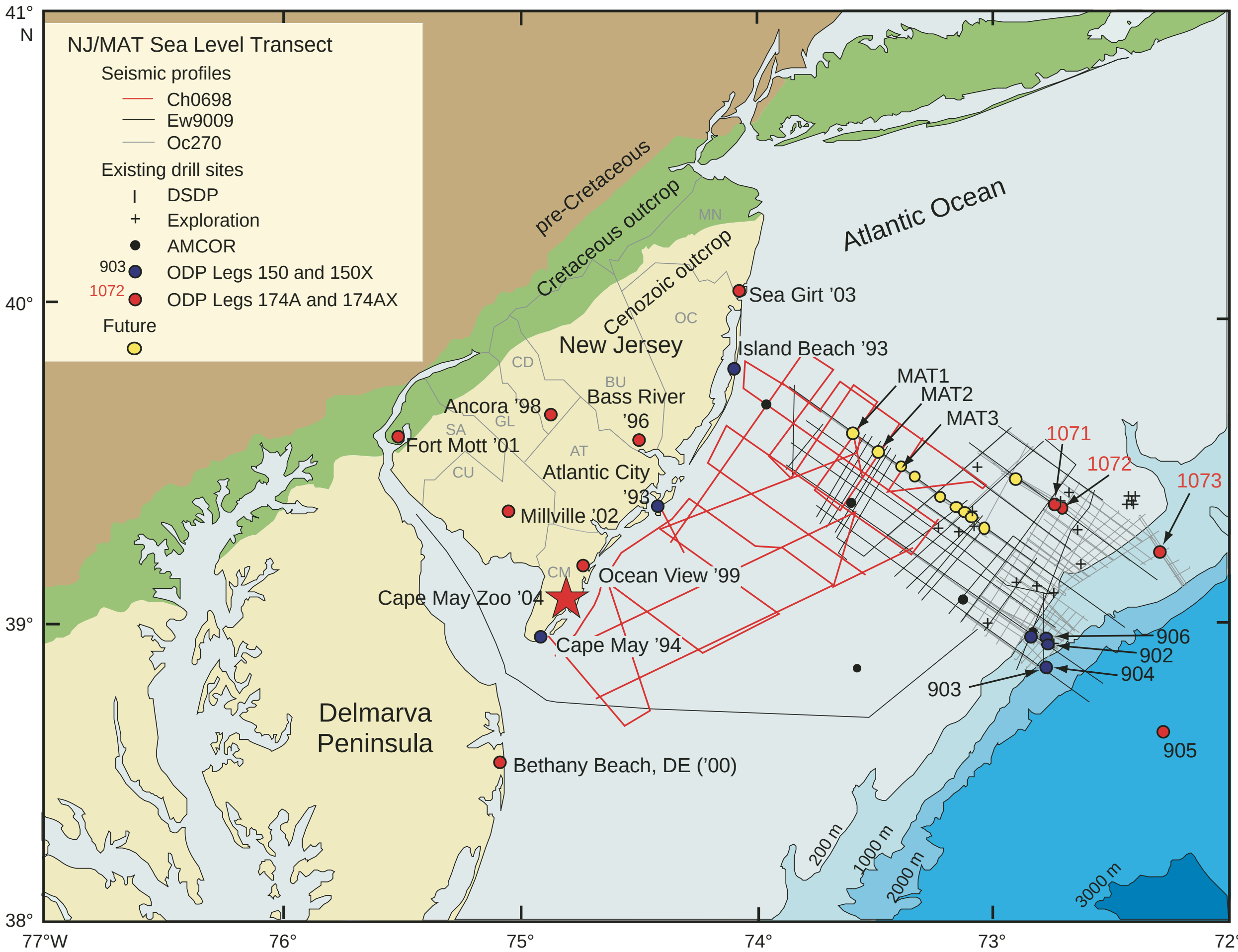


Figure F2. Stratigraphic section summarizing core recovery, lithology, gamma ray and resistivity log signatures, age, and environments for the Cape May Formation (Pleistocene) from the Cape May Zoo corehole. Sequences defined by Miller et al. (1997) and Sugarman et al. (1993). USF = upper shoreface, AAR = amino acid racemization, E = environment.

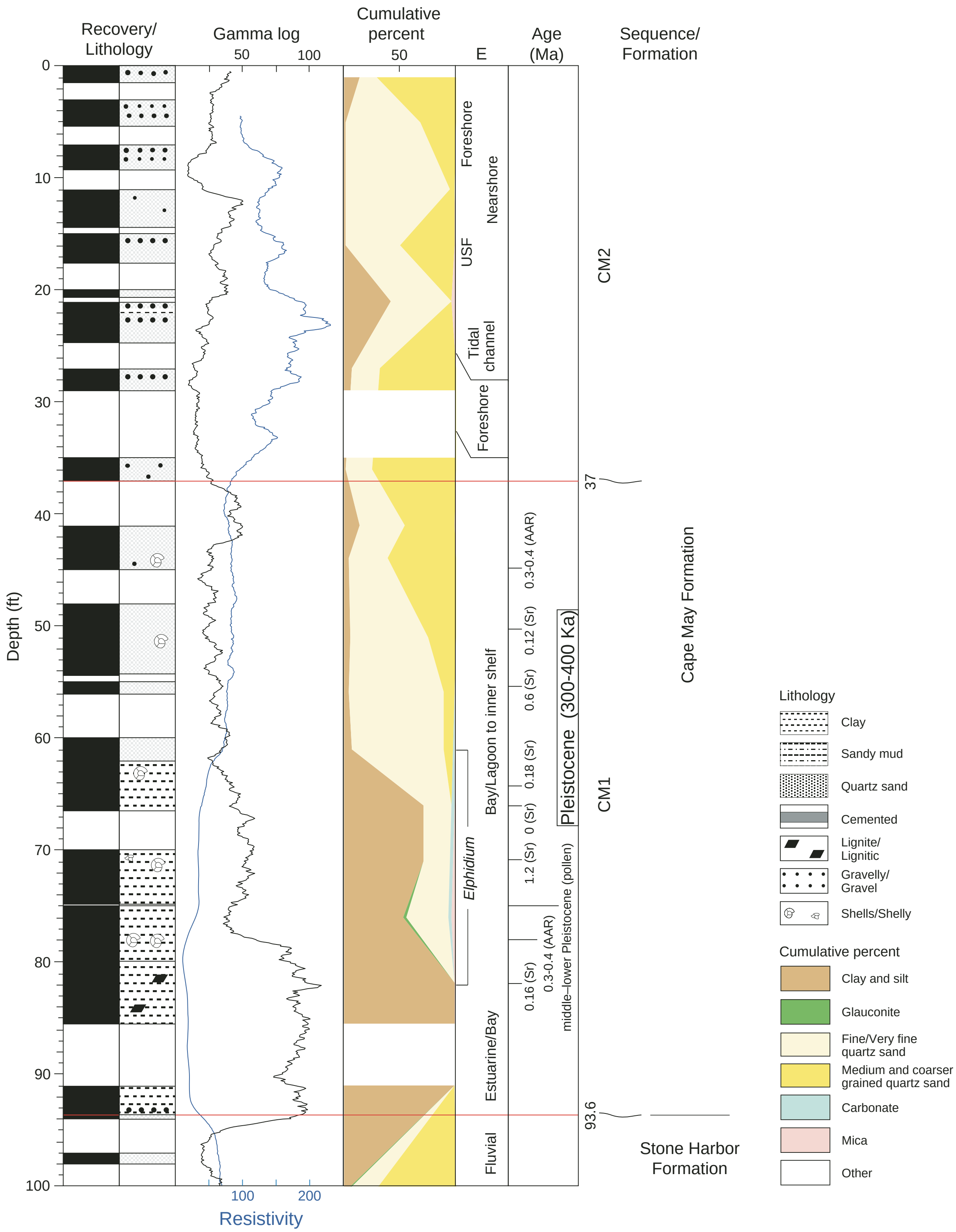


Figure F3. Representative lithofacies from the Cape May Formation in Cape May Zoo corehole. **A.** Shell beds (77–79 ft; 23.5–24.1 m). **B.** Cape May Formation/Stone Harbor Formation (92–94 ft; 28.0–28.7 m) contact at 93.6 ft (28.5 m).

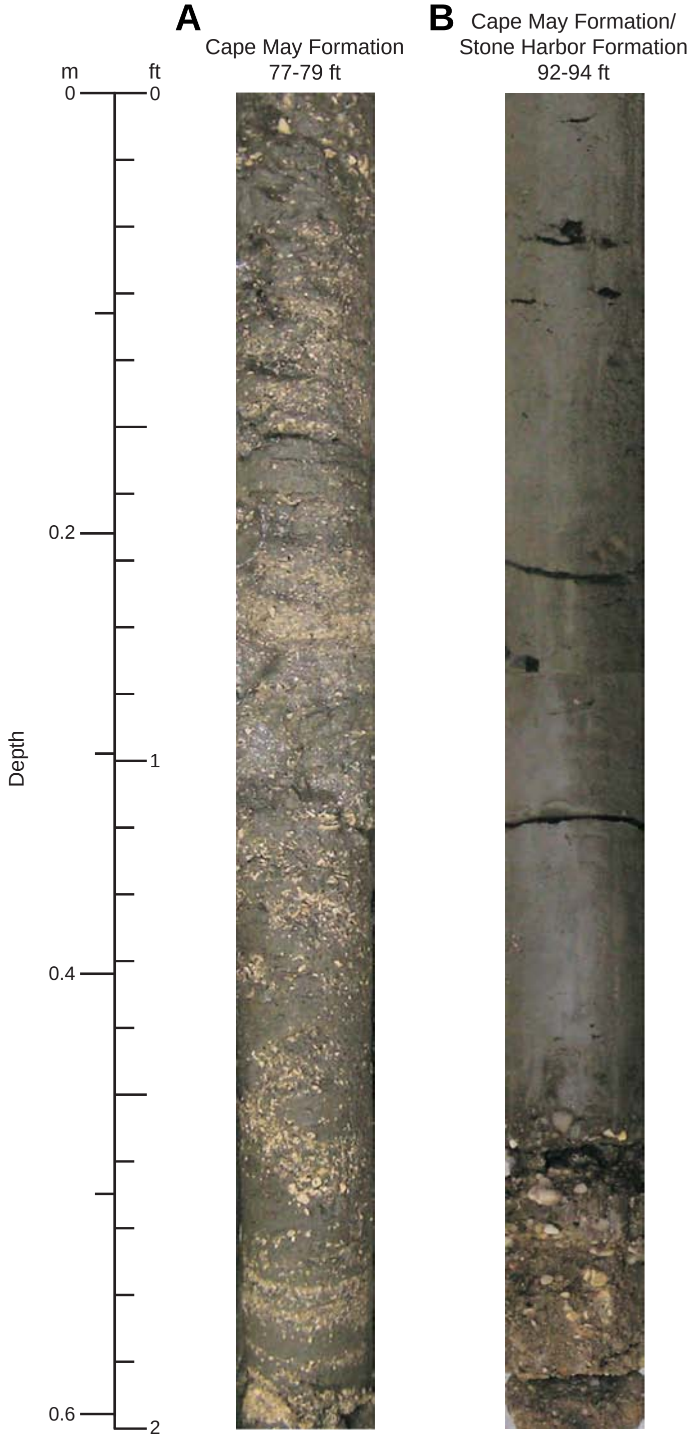


Figure F4. Stratigraphic section summarizing core recovery, lithology, gamma ray and resistivity log signatures, age, and environments for the Stone Harbor Formation (proposed; ?upper Miocene) in Cape May Zoo corehole. Sequences defined by de Verteuil (1997). dUSF = distal upper shoreface, E = environment.

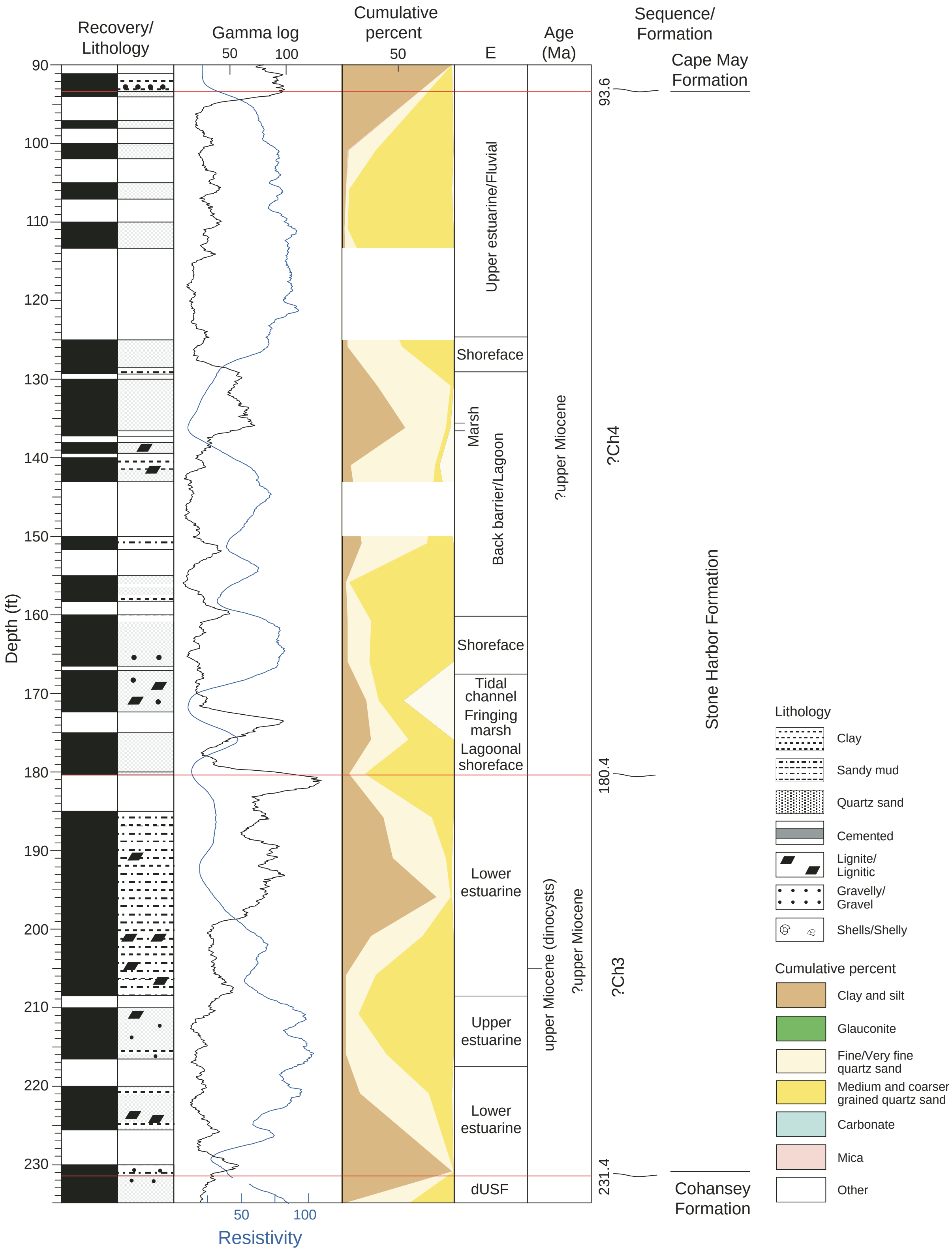


Figure F5. Representative lithofacies from the Stone Harbor Formation (proposed) in Cape May Zoo corehole. **A.** Upper estuarine facies (110–112 ft; 33.5–34.1 m). **B.** Lower estuarine facies (190–192 ft [57.9–58.5 m] and 193.5–195.5 ft [59.0–59.6 m]). **C.** Stone Harbor Formation/Cohansey Formation (230–232 ft; 70.1–70.7 m) contact at 231.4 ft (70.5 m).

Figure F6. Stratigraphic section summarizing core recovery, lithology, gamma ray and resistivity log signatures, age, and environments for the Cohansey Formation partim (middle Miocene) and the Belleplain Member partim of the Kirkwood Formation (Sequences Ch1 and Ch2) from the Cape May Zoo corehole. Sequences Kw-Ch1, Kw-Ch2, and Kw3 defined by Miller et al. (1997) and Sugarman et al. (1993). Sequences Ch1 and Ch2 defined by de Verteuil (1997). D = diatom zone, ECDZ = East Coast Diatom Zone, dUSF = distal upper shoreface, LSF = lower shoreface, E = environment.

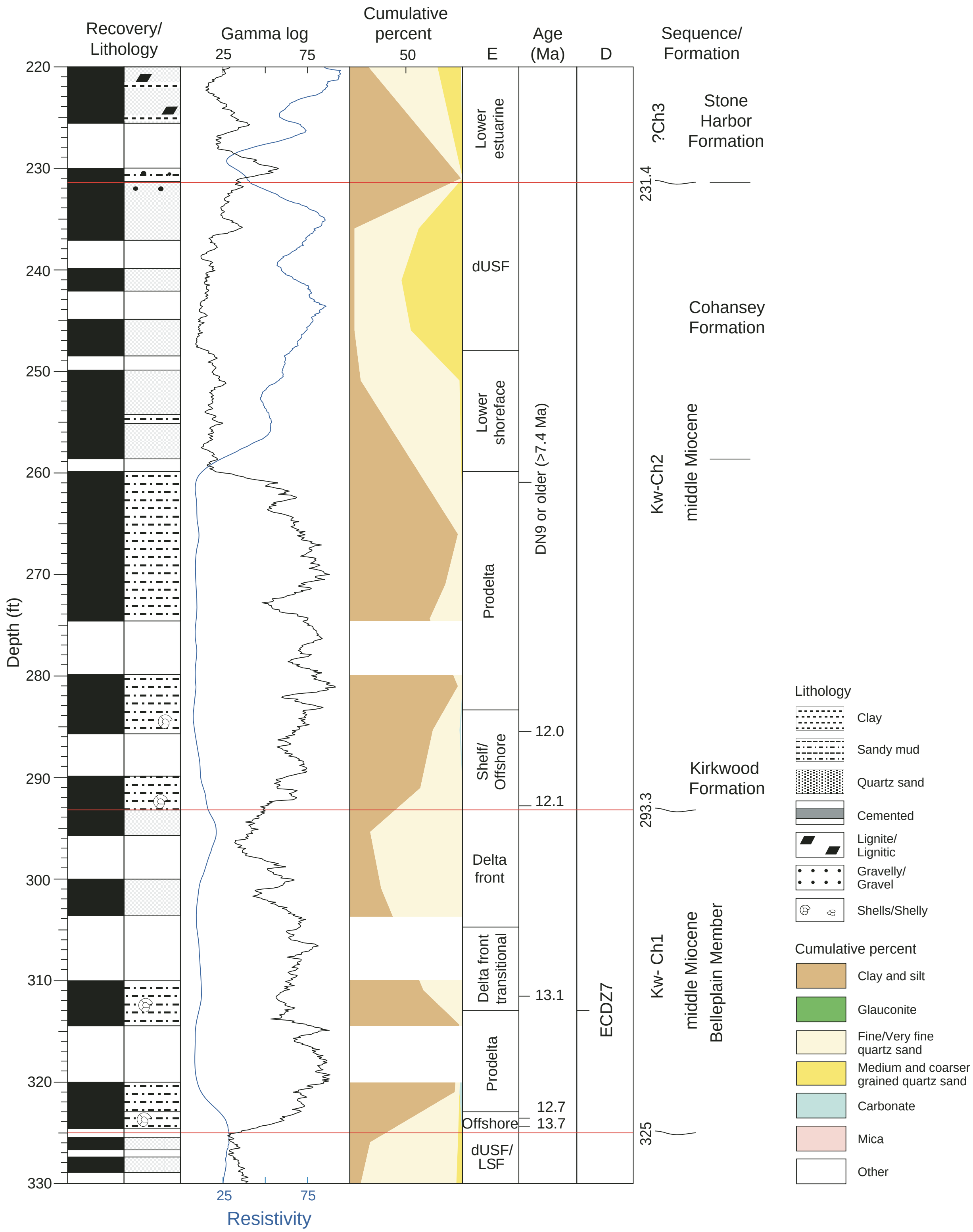


Figure F7. Prodelta facies (262–266 ft; 79.9–81.1 m) from the Kirkwood-Cohansey sequence in Cape May Zoo corehole.

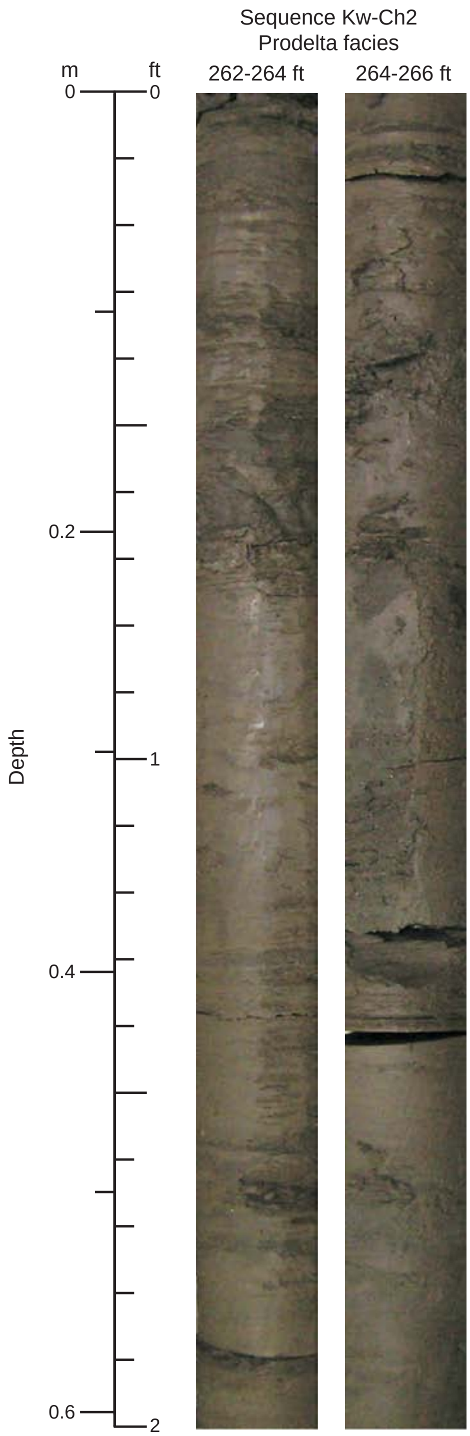


Figure F8. Stratigraphic section summarizing core recovery, lithology, gamma ray and resistivity log signatures, age, and environments for the Belleplain Member of the Kirkwood Formation partim, (middle Miocene; Sequence Kw3) in Cape May Zoo corehole. Sequence defined by Miller et al. (1997) and Sugarman et al. (1993). dUSF = distal upper shoreface, LSF = lower shoreface. HST = highstand systems tract, FS = flooding surface, MFS = maximum flooding surface. D = diatom zone, ECDZ = East Coast Diatom Zone, E = environment.

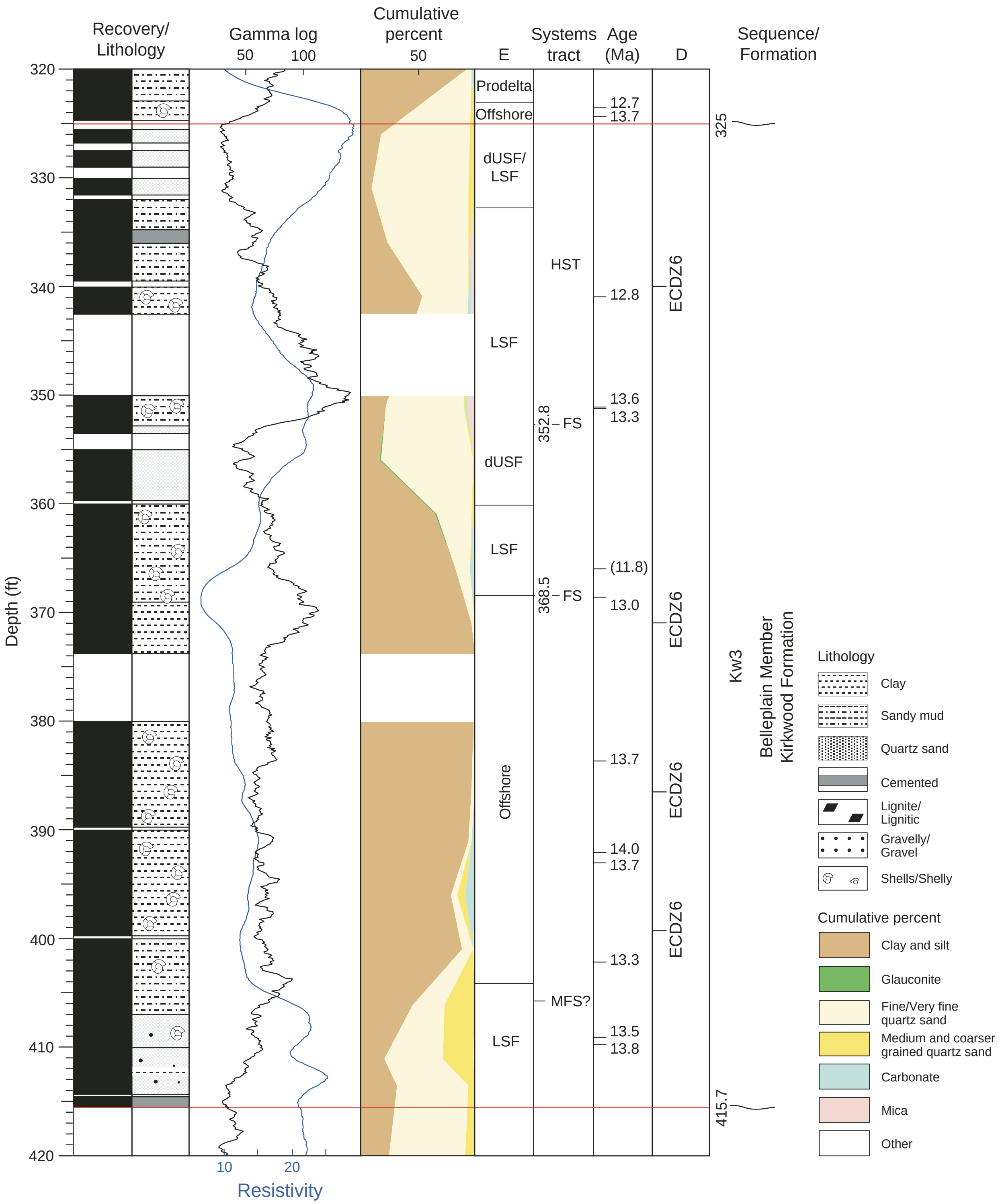


Figure F9. Representative lithofacies from Sequence Kw3 in Cape May Zoo corehole. **A.** Lower shoreface facies (334–336 ft; 101.8–102.4 m). **B.** Lower shoreface to offshore facies (364–366 ft; 110.9–111.6 m). **C.** 368–370 ft (112.2–112.8 m) with flooding surface at 368.5 ft (112.3 m).

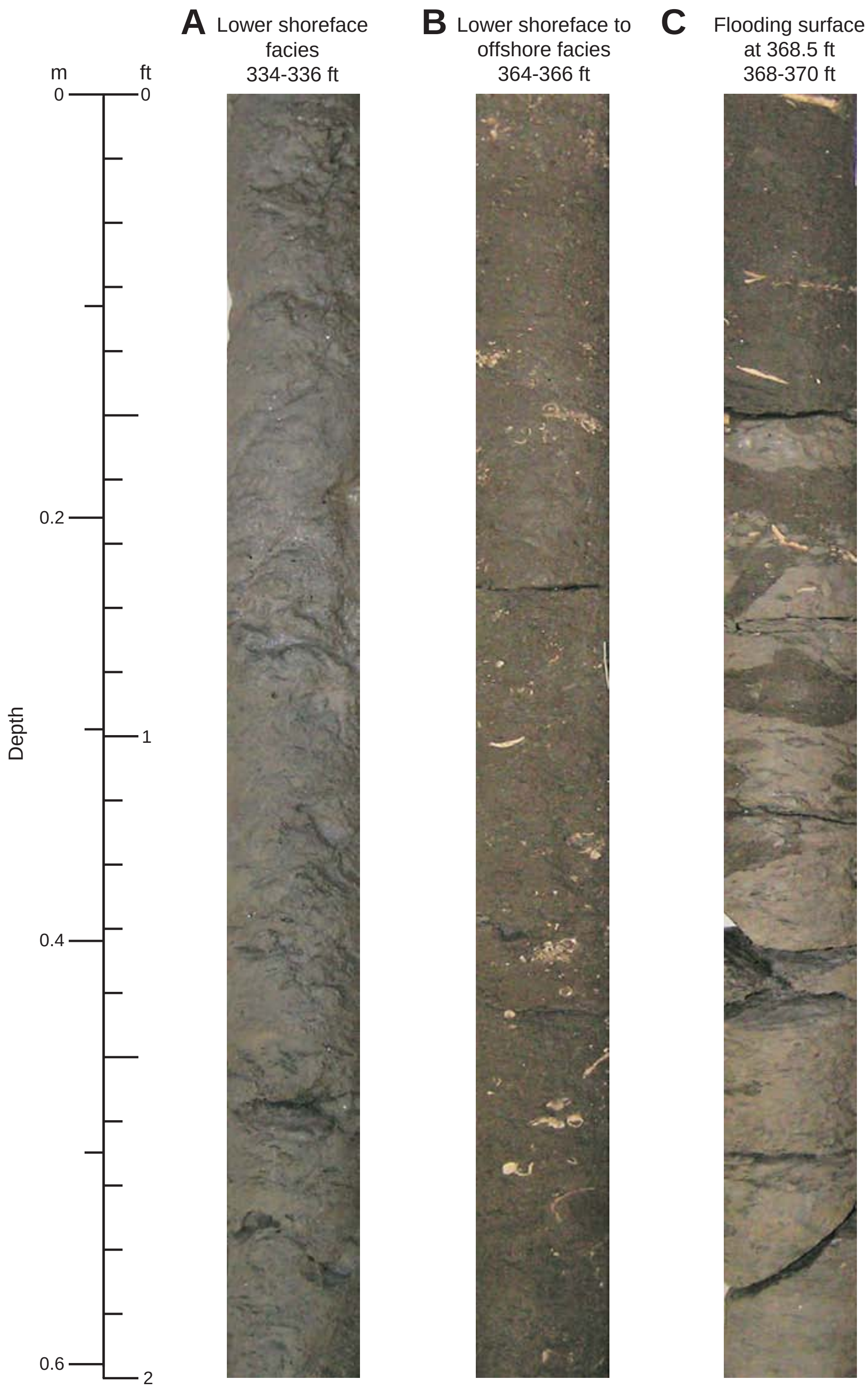


Figure F10. Stratigraphic section summarizing core recovery, lithology, gamma ray and resistivity log signatures, age, and environments for the Wildwood Member of the Kirkwood Formation (lower–middle Miocene; Sequences Kw2a and Kw2b in Cape May Zoo corehole). Sequences Kw2a and Kw2b defined by Miller et al. (1997) and Sugarman et al. (1993). Division of Sequence Kw2a into the Kw2a1, Kw2a2, and Kw2a3 subsequences follows Miller et al. (this volume). LSF = lower shoreface, dUSF = distal upper shoreface, pUSF = proximal upper shoreface. HST = highstand systems tract, FS = flooding surface, MFS = maximum flooding surface, TST = transgressive systems tract, LST = lowstand systems tract, loHST = lower highstand systems tract, uHST = upper highstand systems tract, D = diatom zone, ECDZ = East Coast Diatom Zone, E = environment.

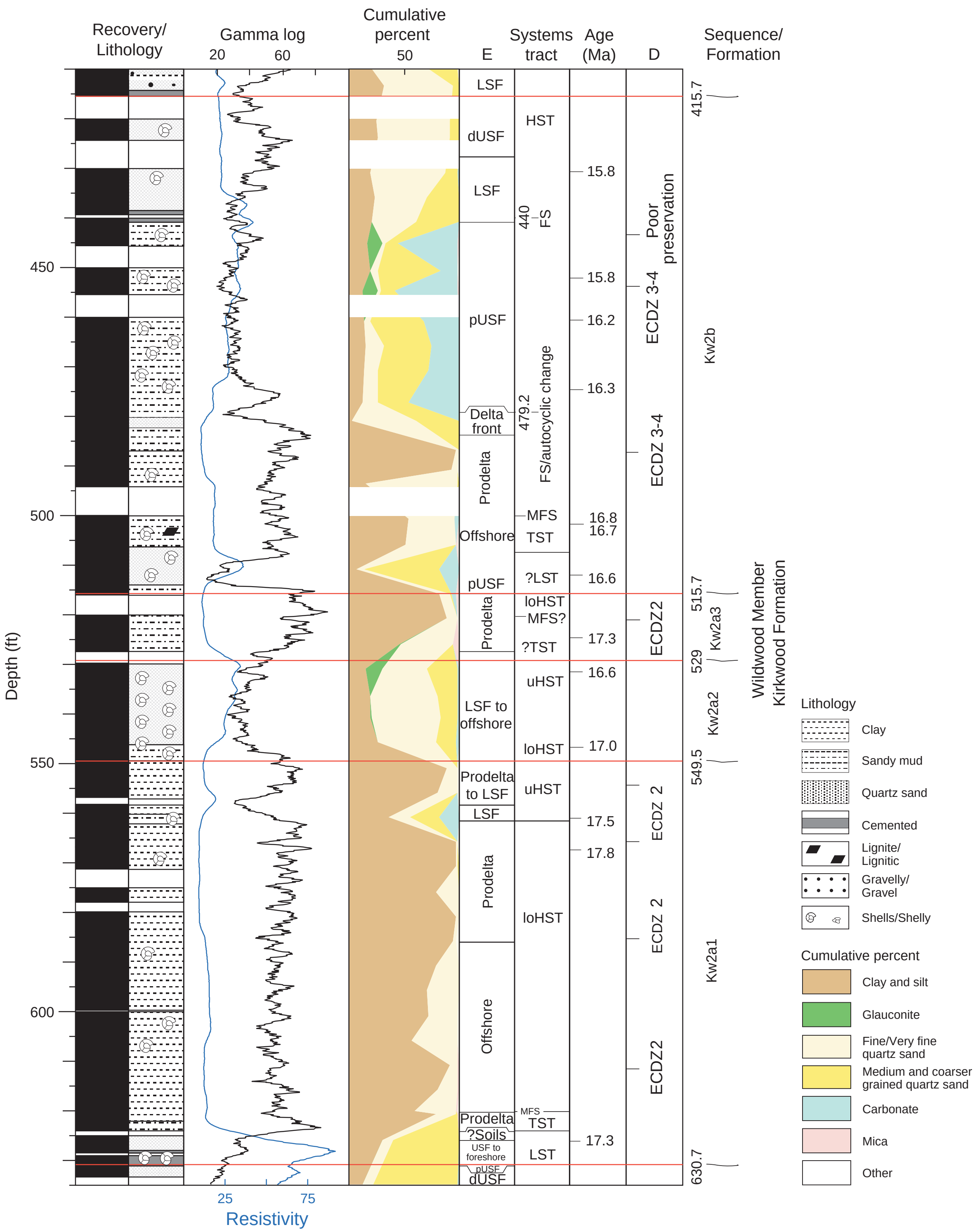


Figure F11. Representative lithofacies from Sequences Kw2a and Kw2b in Cape May Zoo corehole. **A.** 477.5–479.5 ft (145.5–146.2 m) with flooding surface at 479.2 ft (146.1 m). **B.** Delta front transitioning up to upper shoreface (478–480 ft; 145.7–146.3 m). **C.** Prodelta transitioning up to delta front (480–486 ft; 146.3–148.1 m). **D.** 548–550 ft (167.0–167.6 m) with contact at 549.5 ft (167.5 m).

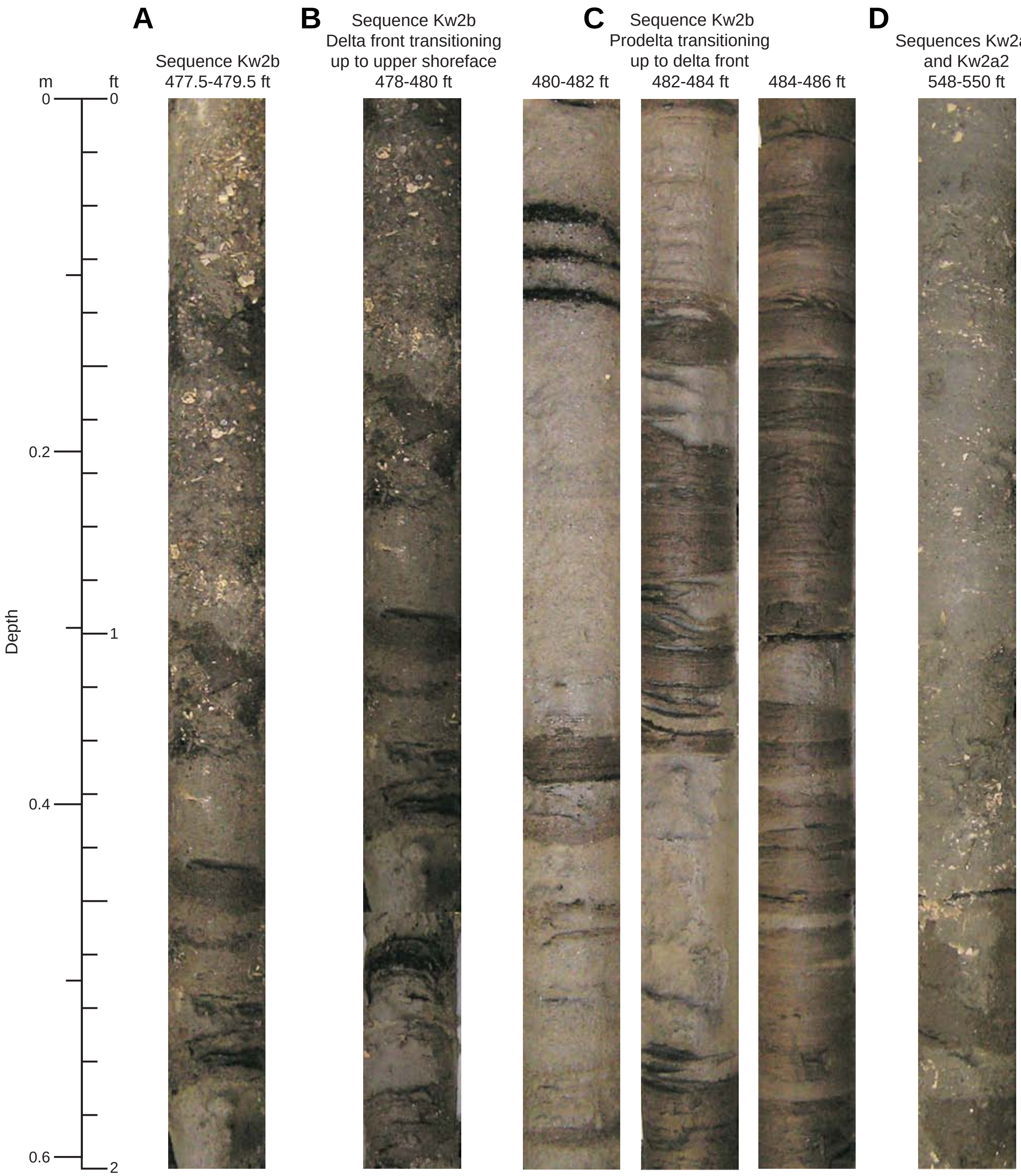


Figure F12. Representative lithofacies from Sequence Kw2a in Cape May Zoo corehole. **A.** Lower shoreface to offshore facies (540–548 ft; 164.6–167.0 m). **B.** Lowstand systems tract (625–630.7 ft; 190.5–192.2 m).

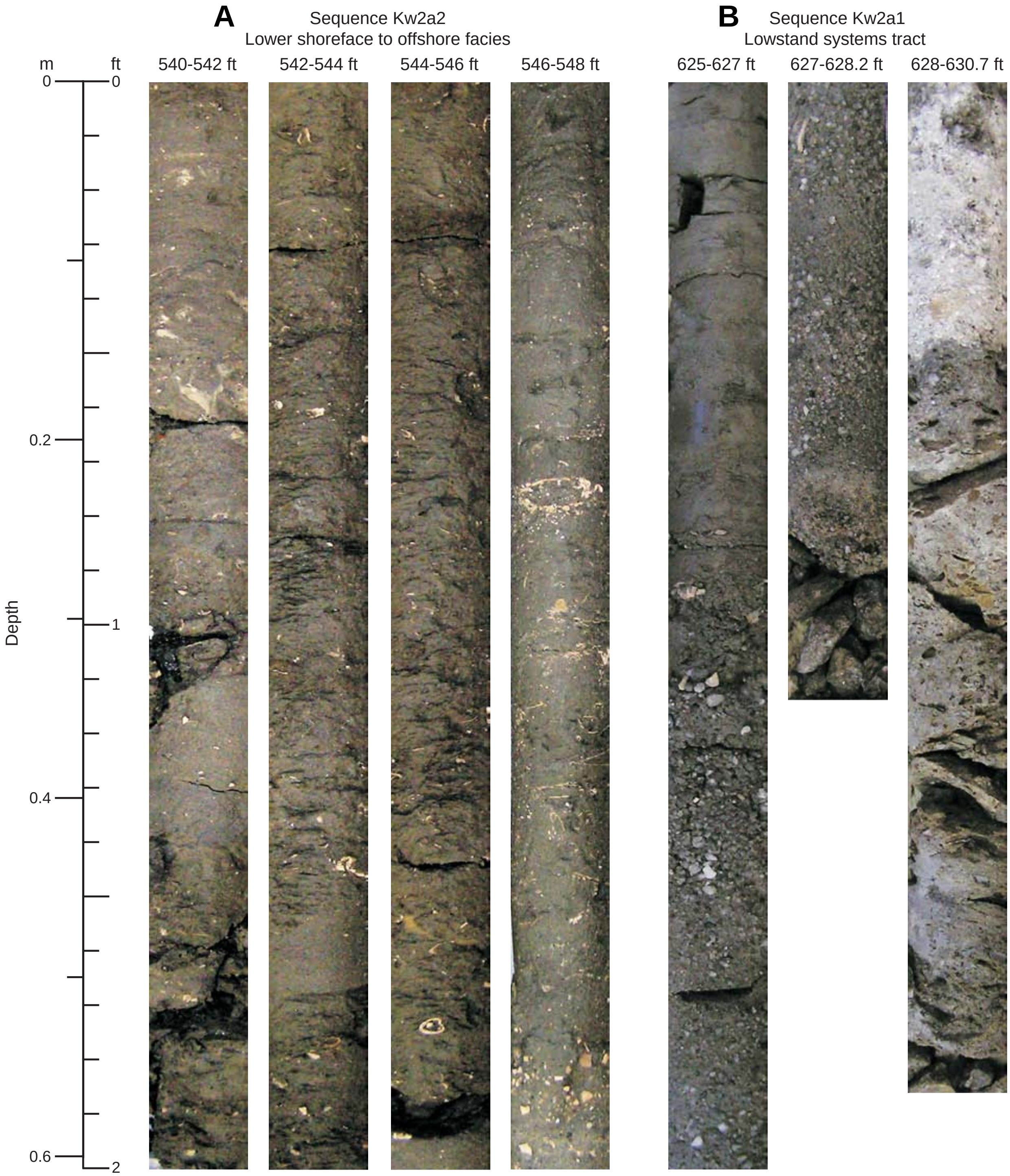


Figure F13. Stratigraphic section summarizing core recovery, lithology, gamma ray and resistivity log signatures, age, and environments for the Shiloh Marl Member of the Kirkwood Formation (lower Miocene; Sequences Kw1b partim and Kw1c) in Cape May Zoo corehole. Sequences defined by Miller et al. (1997) and Sugarman et al. (1993). USF = upper shoreface, pUSF = proximal upper shoreface, dUSF = distal upper shoreface, LSF = lower shoreface, LST = lowstand systems tract, FS = flooding surface, E = environment, TD = total depth.

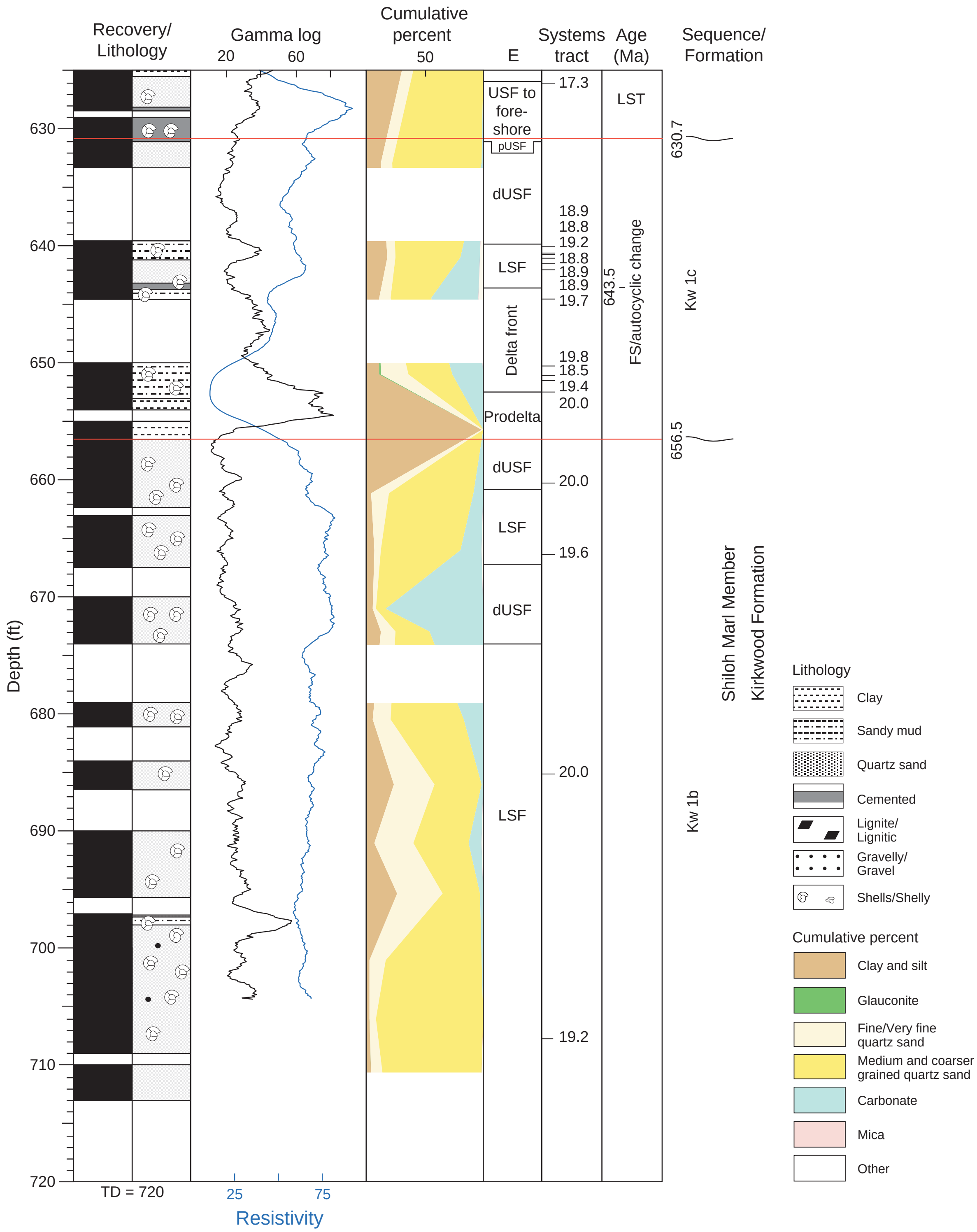


Figure F14. Representative lithofacies from Sequences Kw1c and Kw1b, Cape May Zoo corehole. **A.** Prodelta transitioning up to delta front (650–654 ft; 198.1–199.3 m). **B.** Lower shoreface facies (697–701 ft; 212.4–213.7 m).

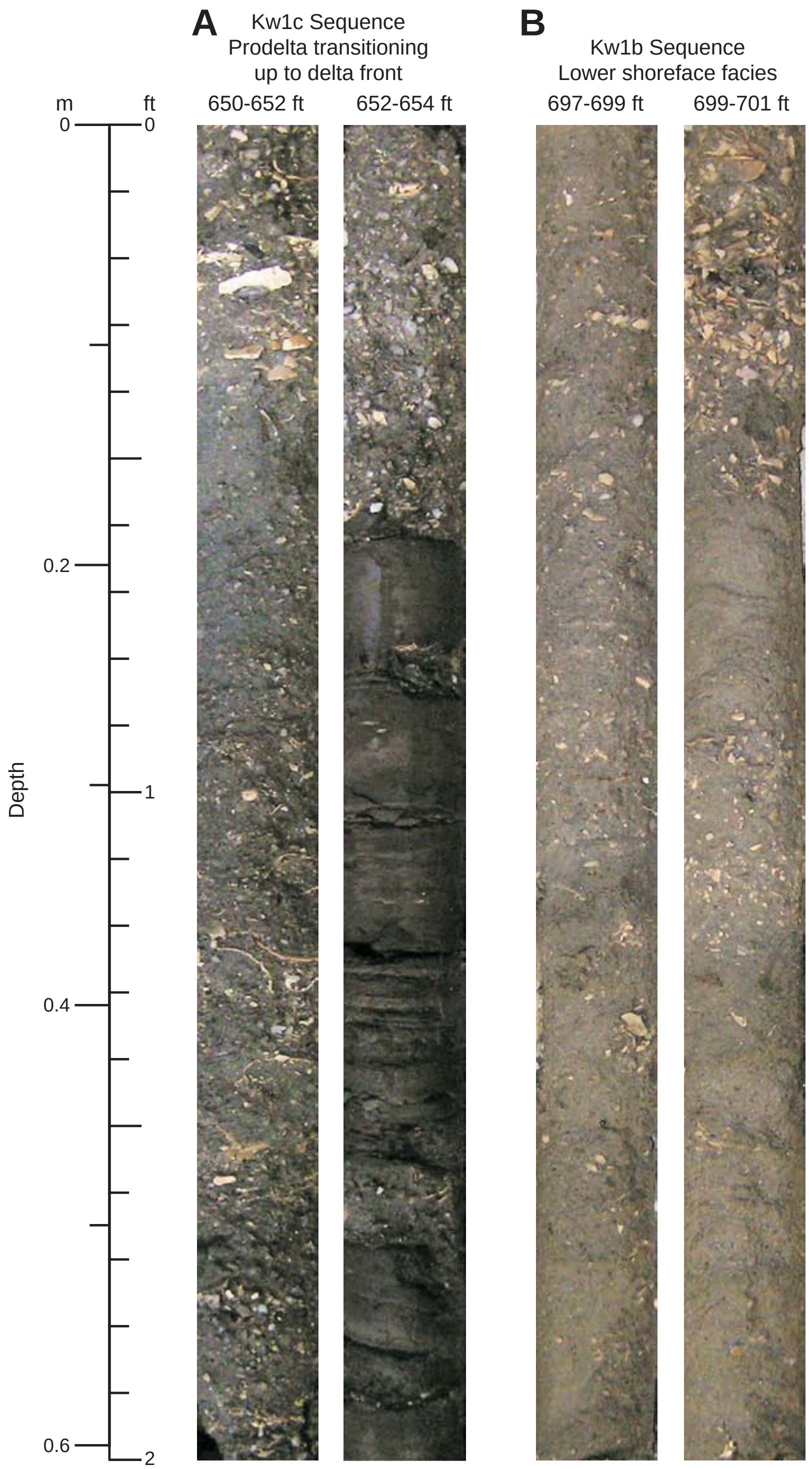


Figure F15. Age-depth plot for the early–middle Miocene in the Cape May Zoo corehole. Circles = Sr isotopic age estimates. Error bars are two standard deviations for one analysis (Oslick et al., 1994). Heavy red line = preferred chronology. ECDZ = East Coast Diatom Zone (after Andrews, 1988). Thin horizontal lines = sequence boundaries. Blue boxes along the bottom indicate time represented. Timescale after Berggren et al. (1995). N = nannofossil zone, F = planktonic foraminiferal zone.

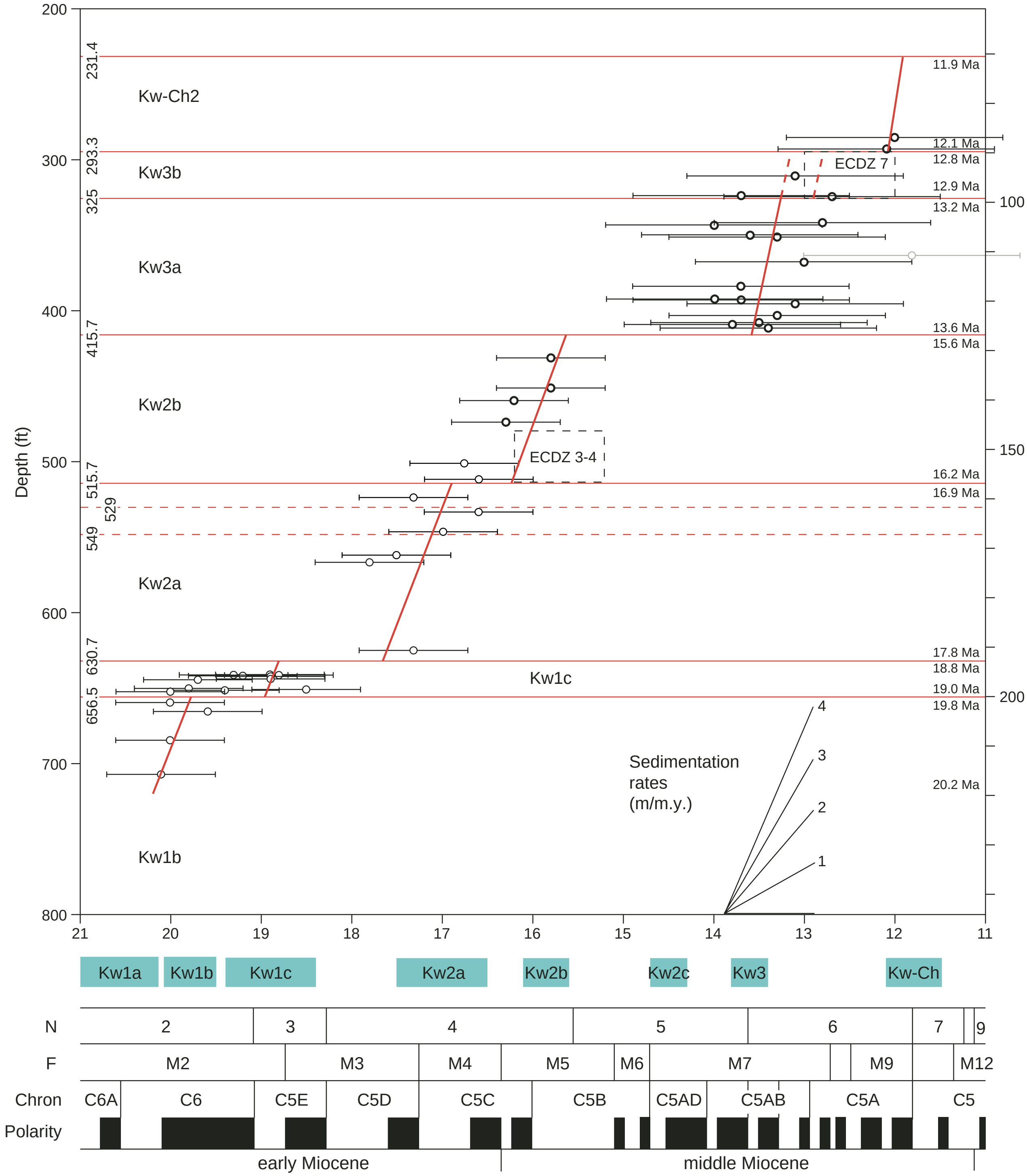


Figure F16. Mean D/L values of *Mulinia* and *Mercenaria* from the Cape May Zoo corehole. See Table T4, p. 64, for depth information and raw data. The similar pattern of the extent of racemization in the two genera indicates a general consistency of results. Each amino acid racemizes at its own characteristic rate, so patterns such as these are expected if samples are "reliable." If lines cross in a plot like this, then results are contradictory. VLPG = average of valine, leucine, phenylalanine, and glutamic; Ala_Asp = average of alanine and aspartic; Val_Leu = average of valine and leucine.

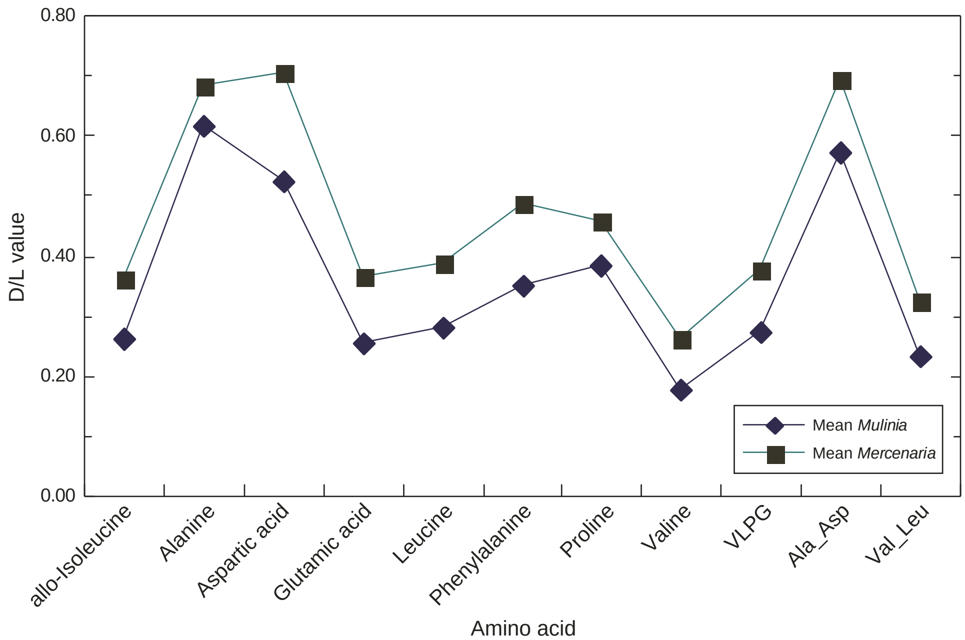


Figure F17. Mean D/L values of *Mercenaria* results for the Cape May Zoo (CMzoo) corehole compared with mean values from Morie (M) and Unimin (U) Pits (Mauricetown, New Jersey), and the two superposed aminozones at Gomez Pit, Virginia (Gomez a and Gomez c) (Mirecki et al., 1995). See O'Neal et al. (2000) for detailed discussion of the original presentation of the Morie and Unimin results.

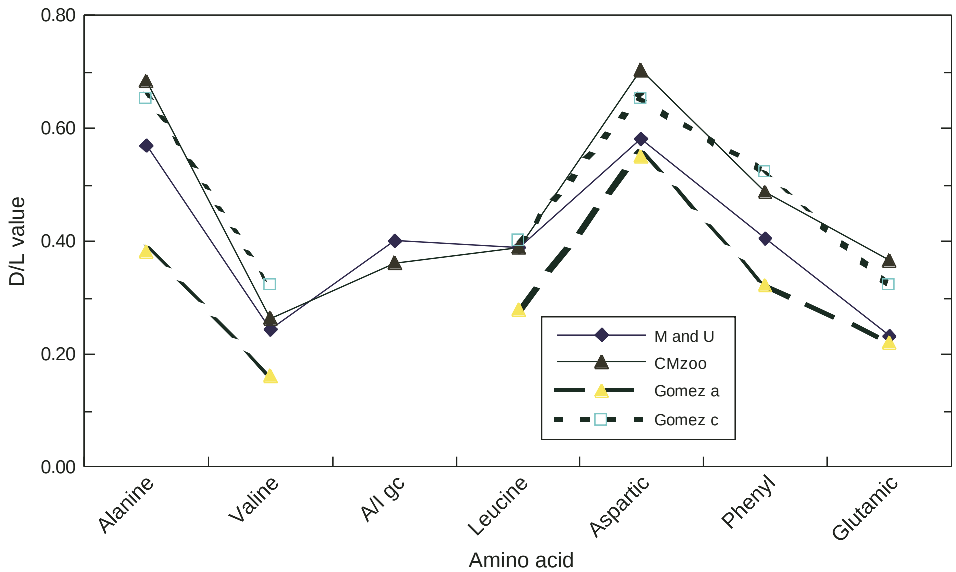


Figure F18. Dip section showing the relationships among the sequences discussed in the text. Sequences defined by Miller et al. (1997) and Sugarman et al. (1993). Corehole locations shown in Figure **F1**, p. 38.

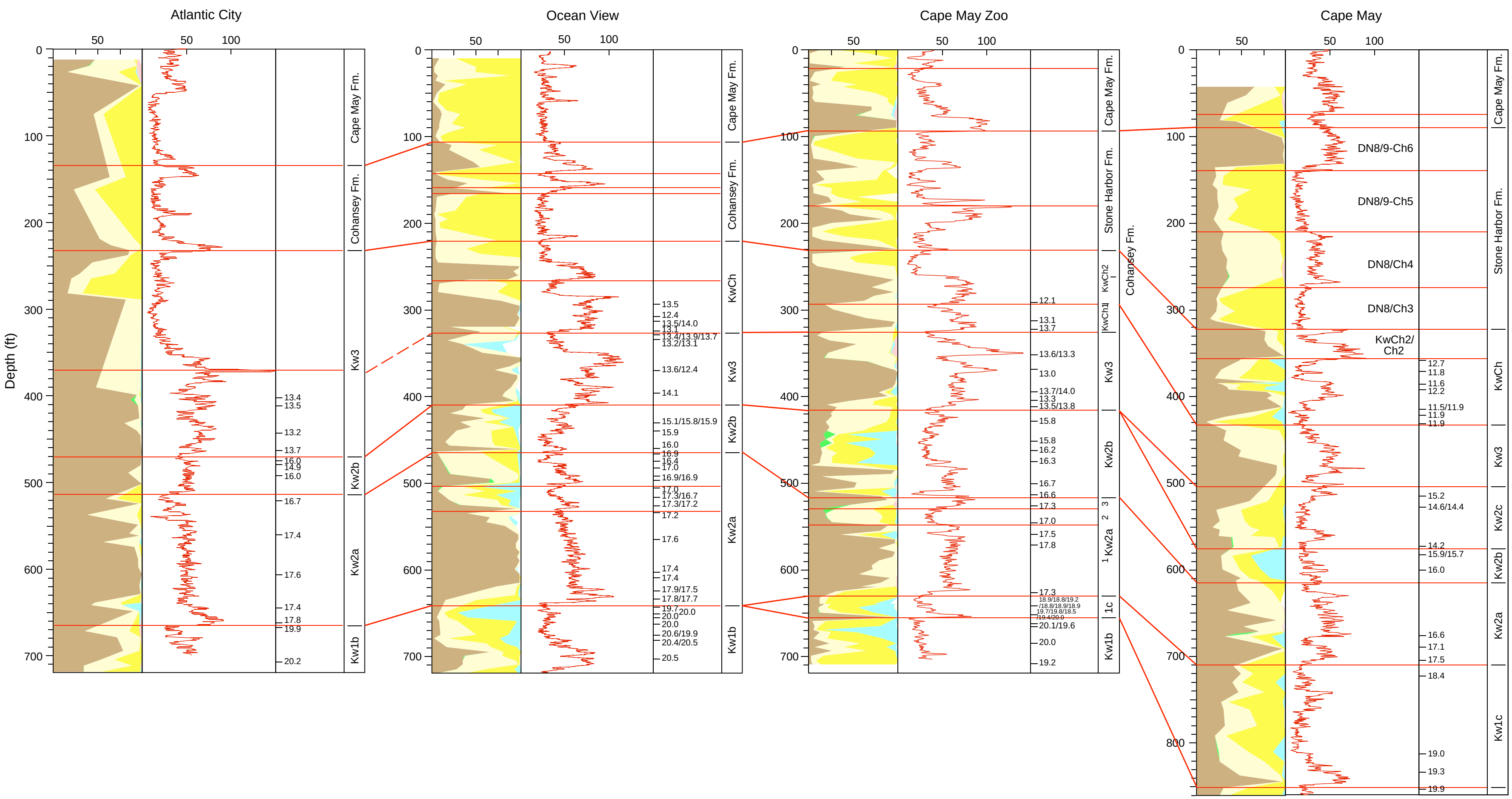


Figure F19. Lithologic and hydrostratigraphic terminology for units recovered from the Cape May Zoo corehole. Gray areas in the gamma and resistivity log columns indicate aquifers.

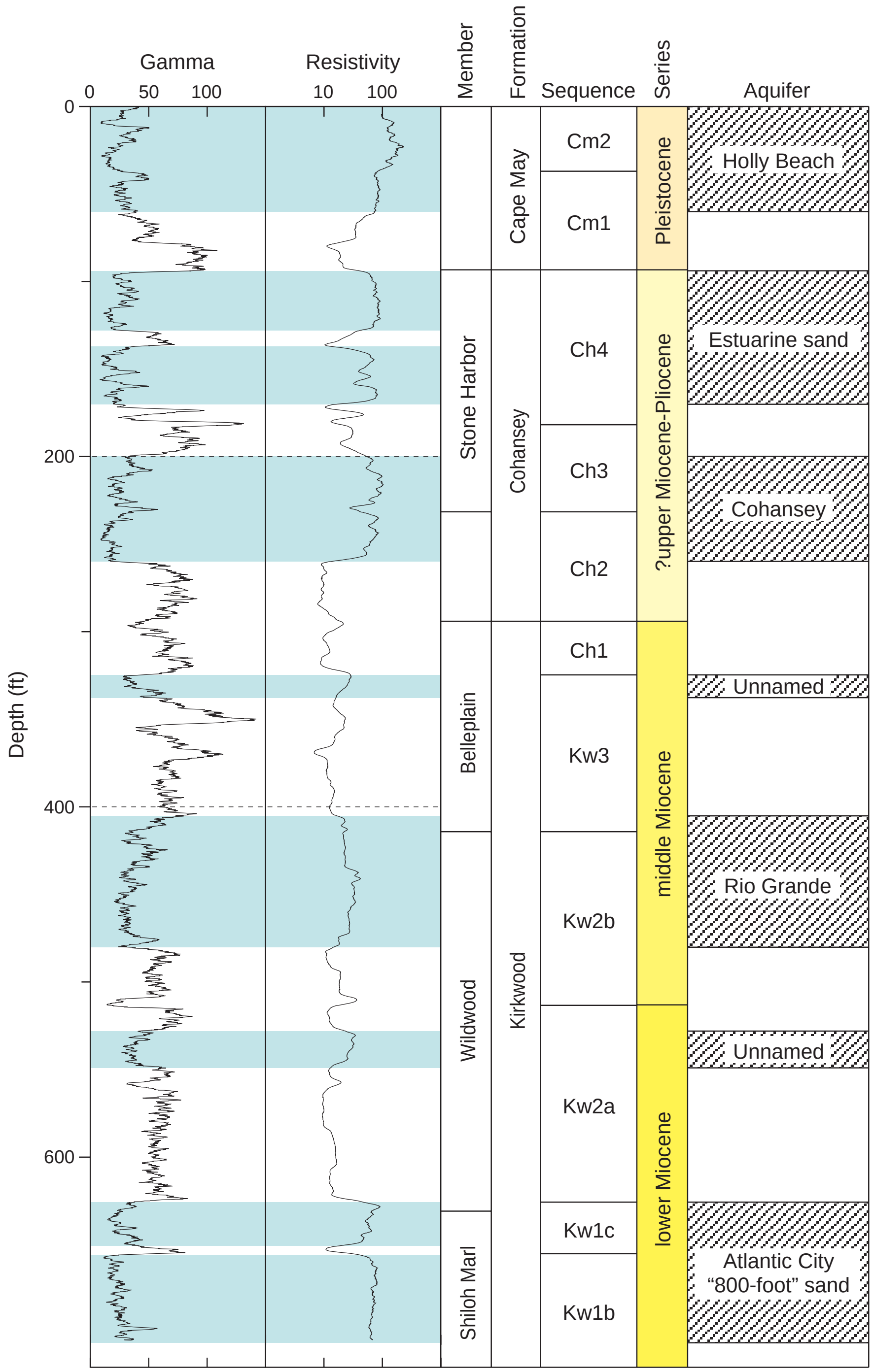


Table T1. Core descriptions.

Run number	Date (2004)	Cored interval (ft)	Run length (ft)	Recovery (ft)	Recovery (%)	Lithology	Formation	Sequence	Dominant color
1	29 Sep	0–3	3.0	1.47	49	Medium–coarse granuliferous sand			Olive yellow (2.5Y 6/6)
2	29 Sep	3–7	4.0	1.25	31	Medium sand and gravel beds			Olive yellow (2.5Y 6/6)
3	29 Sep	7–11	4.0	2.25	56	Medium sand and gravel beds			Gray (10YR 6/1) and light yellowish brown (2.5Y 6/3)
4	29 Sep	11–15	4.0	3.5	88	Fine–very fine sand	Cape May Formation Unit II		Light brownish gray and grayish brown (2.5Y 6/2-5/2)
5	29 Sep	15–20	5.0	2.5	50	Fine–medium sand			Light brownish gray (2.5Y 6/2)
6	29 Sep	20–21	1.0	0.5	50	very fine to fine sand			Light yellowish brown (2.5Y 6/3)
7	29 Sep	21–27	6.0	3.3	55	Interbedded gravels, sands, and clays			Yellowish brown (10YR 5/4)
8	29 Sep	27–35	8.0	2.05	26	Sand and gravel			Light yellowish brown (2.5Y 6/4)
9	29 Sep	35–40	6.0	2	33	Coarse to very fine sand	Cape May Formation Unit II/I		Pale yellow (2.5Y 7/4)
10	29 Sep	40–48	7.0	4	57	Sand			Light yellowish brown (2.5Y 6/4)
11	30 Sep	48–55	7.0	6.2	89	Shelly sand and woody shelly sand			Brown (10YR 5/3) and greenish gray (Gley 1 5GY 5/1)
12	30 Sep	55–60	5.0	1	20	Fine to medium woody sand			Greenish gray (Gley 1 5GY 5/1)
13	30 Sep	60–70	10.0	6.65	67	Sand over clay–silt	Cape May Formation Unit I		Greenish gray (Gley 2 5BG 5/1) and dark greenish gray (Gley 2 5BG 4/1)
14	30 Sep	70–75	5.0	4.7	94	Silty clay and very fine sandy silt			Dark greenish gray (Gley 2 5BG 4/1)
15	30 Sep	75–80	5.0	5	100	Shelly clay with interbedded sand			
16	30 Sep	80–90	10.0	5.5	55	Clay			Dark greenish gray (Gley 1 10GY 4/1)
17	30 Sep	90–97	7.0	3	43	Clay over gravelly sand; recovered interval is 91–94 ft; contact at 93.6 ft	Cape May Formation Unit I/ Stone Harbor Formation		Dark bluish gray (Gley 2 10B 4/1) and greenish gray (Gley 1 10Y 5/1)
18	30 Sep	97–100	3.0	1.1	37	Coarse to very coarse sand			Greenish gray (Gley 1 10Y 5/1)
19	30 Sep	100–105	5.0	1.9	38	Sand and gravel			Greenish gray (Gley 1 10Y 5/1)
20	30 Sep	105–110	5.0	3.5	70	Sand and gravel			Greenish gray (Gley 1 10Y 5/1)
21	30 Sep	110–117	7.0	3.2	46	Sand and gravel			Gray (5YR 5/1) and light gray (5YR 7/1)
22	30 Sep	117–125	8.0	0	0	No recovery			
23	1 Oct	125–130	5.0	4.4	88	Coarse and medium sands			Reddish yellow (5YR 6/6) and gray (5YR 6/1)
24	1 Oct	130–138	8.0	7.1	89	Very fine silty sand to mud			Gray (Gley 1 N 5/)
25	2 Oct	138–140	2.0	1.55	78	Silty clay			Very dark gray (Gley 1 N 3/)
26	2 Oct	140–150	10.0	3.05	31	Medium to fine sand			Greenish gray (Gley 1 5/1)
27	3 Oct	150–155	5.0	1.51	30	Fine sandy clay			Very dark gray (Gley 1 N 3/)
28	3 Oct	155–160	5.0	3.25	65	Medium sand with sandy clay	Stone Harbor Formation		Dark gray (Gley 1 N 4/)
29	3 Oct	160–167	7.0	6.62	95	Medium to coarse sand			Greenish gray (Gley 1 5/1)
30	3 Oct	167–175	8.0	4.3	54	Coarse sand over very coarse sand, gravel and lignite beds			Dark gray (Gley 1 N 4/)
31	3 Oct	175–180	5.0	5	100	Clayey sand over coarse sand fining to fine sand			Gray (Gley 1 N 5/)
32	3 Oct	180–185	5.0	0.4	8	Coarse sand			Very dark gray (Gley 1 N 3/)
33	3 Oct	185–190	5.0	5.4	108	Very clayey sand to clayey sand with pockets of sandy silty clay			Light greenish gray (Gley 1 7/1)
34	3 Oct	190–200	10.0	10.15	102	Silty clay over slightly micaceous clay			Greenish gray (Gley 1 10Y 5/1)
35	3 Oct	200–210	10.0	8.5	85	Coarse sand with clay interbeds			Light gray (Gley 1 N 7/)
36	3 Oct	210–220	10.0	6.8	68	Coarse sand with abundant gravels			Dark greenish gray (Gley 1 10Y 4/1)
37	3 Oct	220–230	10.0	5.55	56	Medium to coarse sand with clay lenses	Stone Harbor Formation /Cohansey Formation		Gray (Gley 1 N 5/)
38	3 Oct	230–240	10.0	7.2	72	Medium to coarse sand with clay lenses; contact at 231.4 ft			Olive gray (5Y 5/2)
39	4 Oct	240–245	5.0	2.2	44	Medium to coarse sand	Cohansey Formation		Dark brown (7.5YR 3/2)
40	4 Oct	245–250	5.0	3.65	73	Medium sand			Very dark gray (5Y 3/1)
41	4 Oct	250–260	10.0	8.75	88	Medium sand			Very dark greenish gray (Gley 1 10Y 3/1)

Table T1. (continued)

Run number	Date (2004)	Cored interval (ft)	Run length (ft)	Recovery (ft)	Recovery (%)	Lithology	Formation	Sequence	Dominant color
42	4 Oct	260–270	10.0	10	100	Interbedded clay and sand			Very dark gray (5Y 3/1)
43	4 Oct	270–280	10.0	4.45	45	Interbedded clay and sand	Cohansey Formation		Very dark greenish gray (Gley 1 10Y 3/1)
44	4 Oct	280–290	10.0	5.65	57	Interbedded clay and sand			Light greenish gray (Gley 1 5GY 7/1)
45	4 Oct	290–300	10.0	5.8	58	Interbedded clay and sand; contact at 293.3 ft	Cohansey Formation/ Kirkwood Formation		Greenish black (Gley 1 5G 2.5/1)
46	4 Oct	300–310	10.0	4.8	48	Interbedded clay and sand			Greenish gray (Gley 1 10GY 5/1)
47	4 Oct	310–320	10.0	4.5	45	Laminated to interbedded clay and silt		Ch1	Greenish gray (Gley 1 5GY 5/1)
48	5 Oct	320–325.5	5.5	4.6	84	Silty clays over shelly sandy clayey silt			Dark greenish gray (Gley 1 5GY 4/1)
49	5 Oct	325.5–327.5	2.0	1.3	65	Medium sand			Greenish gray (Gley 1 5GY 5/1)
50	5 Oct	327.5–330	2.5	1.5	60	Sand and interbedded silty sand			Dark greenish gray (Gley 1 5GY 4/1)
51	5 Oct	330–332	2.0	1.8	90	Fine to medium sand			Dark greenish gray (Gley 1 5GY 4/1)
52	5 Oct	332–340	8.0	7.6	95	Interbedded sand and silty sand over clay			Dark greenish gray (Gley 1 5GY 4/1)
53	5 Oct	340–350	10.0	2.5	25	Silty clay			Very dark greenish gray (Gley 1 5GY 3/1)
54	5 Oct	350–355	5.0	3.4	68	Silty clay with shells			Dark greenish gray (10GY 4/1)
55	5 Oct	355–360	5.0	4.8	96	Silty sand		Kw3	Greenish gray (Gley 1 10Y 5/1)
56	5 Oct	360–370	10.0	10	100	Silty sand			Dark greenish gray (Gley 1 5GY 4/1)
57	6 Oct	370–380	10.0	3.8	38	Clay			Dark greenish gray (Gley 1 5GY 4/1)
58	6 Oct	380–390	10.0	9.7	97	Clay			Dark greenish gray (Gley 1 5GY 4/1)
59	6 Oct	390–400	10.0	9.6	96	Silty clay to clayey silt			Dark greenish gray (Gley 1 5GY 4/1)
60	6 Oct	400–410	10.0	10	100	Silt to silty sand			Dark greenish gray (Gley 1 5GY 4/1)
61	6 Oct	410–414.5	4.5	4.3	96	Medium sand			Dark greenish gray (Gley 1 10GY 4/1)
62	6 Oct	414.5–420	5.5	1.2	22	Sandstone; contact at 415.7 ft		Kw3/Kw2b	Light bluish gray (Gley 2 10B 7/1)
63	6 Oct	420–430	10.0	4.3	43	Fine sand			Very dark greenish gray (Gley 2 10BG 3/1)
64	7 Oct	430–438.5	8.5	8.5	100	Shelly fine sand			Greenish black (Gley 1 10GY 2.5/1)
65	7 Oct	438.5–439.7	1.2	1	83	Dolomitic(?) sandstone			Very dark greenish gray (Gley 1 10Y 3/1)
66	7 Oct	439.7–450	10.3	5.45	53	Sand and sandy mud with shells			Very dark greenish gray (Gley 1 5GY 3/1)
67	7 Oct	450–460	10.0	5.2	52	Muddy sand		Kw2b	Dark greenish gray (Gley 1 5GY 4/1)
68	7 Oct	460–470	10.0	10.1	101	Muddy sand with shells	Kirkwood Formation		Very dark greenish gray (Gley 1 5GY 3/1)
69	7 Oct	470–480	10.0	10.35	104	Muddy sand with shells			Greenish gray (Gley 1 10GY 5/1)
70	7 Oct	480–490	10.0	10.05	101	Interbedded clays and silts, organic rich			Grey (Gley 1 N 5/)
71	7 Oct	490–500	10.0	3.9	39	Laminated clay with interbedded sands			Dark gray (5Y 4/1)
72	7 Oct	500–510	10.0	10.3	103	Slightly clayey silt with very fine sand			Dark greenish gray (Gley 1 5GY 4/1)
73	8 Oct	510–520	10.0	6.2	62	Medium to coarse sand with abundant shell fragments; contact at 515.7 ft		Kw2b/Kw2a	Gray (10YR 6/1)
74	8 Oct	520–530	10.0	7.2	72	Slightly shelly micaceous silty clays			
75	8 Oct	530–533.5	3.5	3.85	110	Clayey shelly medium sand			Dark greenish gray (Gley 1 10Y 4/1)
76	8 Oct	533.5–540	6.5	5.9	91	Medium to coarse sand over muddy fine sand			Dark greenish gray (Gley 1 10Y 4/1)
77	8 Oct	540–550	10.0	10.4	104	Shelly clayey medium sand; contact at 549.3			Very dark greenish gray (Gley 1 10Y 3/1)
78	8 Oct	550–558.5	8.5	7.1	84	Laminated silty clay			
79	8 Oct	558.5–567	8.5	8.9	105	Silty very fine sand over laminated clays and silts with shells			Very dark greenish gray (Gley 1 10Y 3/1)
80	8 Oct	567–575	8.0	4.6	58	Laminated clay		Kw2a	Very dark greenish gray (Gley 1 10Y 3/1)
81	9 Oct	575–580	5.0	2.95	59	Laminated clay with interbedded very fine sand			Very dark greenish gray (Gley 1 10Y 3/1)
82	9 Oct	580–584	4.0	4	100	Laminated clay with interbedded very fine sand			Greenish black (Gley 1 10Y 2.5/1)
83	9 Oct	584–590	6.0	6.15	103	Silty clay			Very dark greenish gray (Gley 1 10Y 3/1)
84	9 Oct	590–600	10.0	10.3	103	Laminated silty clay			Very dark greenish gray (Gley 1 10Y 3/1)
85	9 Oct	600–610	10.0	10.5	105	Laminated silty clay			Very dark greenish gray (Gley 1 10Y 3/1)
86	9 Oct	610–620	10.0	10.4	104	Laminated silty clay			Dark greenish gray (Gley 1 10Y 4/1)
87	9 Oct	620–625	5.0	4.05	81	Finely laminated silty clay			Dark greenish gray (Gley 1 10Y 4/1)
88	10 Oct	625–629	4.0	3.2	80	Granuliferous sand			Greenish gray (10Y 5/1)

Table T1. (continued)

Run number	Date (2004)	Cored interval (ft)	Run length (ft)	Recovery (ft)	Recovery (%)	Lithology	Formation	Sequence	Dominant color
89	10 Oct	629–639.5	10.5	4.05	39	Sandstone, dolomite cement(?); contact at 630.7 ft		Kw2a/Kw1c	Gray (5Y 5/1)
90	10 Oct	639.5–650	10.5	5.05	48	Poorly sorted sand; contact at 643.5 ft			Greenish gray (Gley 1 10Y 5/1)
91	10 Oct	650–655	5.0	4.15	83	Poorly sorted muddy sand		Kw1c or Kw1b	Very dark greenish gray (10Y 3/1) and greenish black (10Y 2.5/1)
92	10 Oct	655–656.5	1.5	1.5	100	Slightly silty, very finely laminated clay			Very dark gray (10YR 3/1)
93	10 Oct	656.5–663	6.5	5.75	88	Medium sand			Very dark greenish gray (Gley 1 10Y 3/1)
94	10 Oct	663–670	7.0	4.2	60	Very shelly medium sand			Dark gray (5Y 4/1)
95	11 Oct	670–679	9.0	4	44	Shell bed to medium sand	Kirkwood Formation		Dark greenish gray (Gley 2 5BG 4/1)
96	11 Oct	679–684	5.0	1.90	38	Shelly medium sand			Dark greenish gray (Gley 1 10/Y 4/1)
97	11 Oct	684–690	6.0	2.3	38	Shelly medium sand		Kw1b	Very dark greenish gray (Gley 1 10Y 3/1)
98	11 Oct	690–697	7.0	5.5	79	Shelly medium sand			Bluish gray (Gley 2 10B 5/1)
99	11 Oct	697–703	6.0	5.75	96	Shelly medium sand			Dark gray (2.5Y 4/1)
100	11 Oct	703–710	7.0	6.1	87	Shelly medium sand			Very dark greenish gray (Gley 1 10Y 3/1)
101	11 Oct	710–720	10.0	3	30	Shelly medium sand			Very dark gray (2.5Y 3/1)

Note: Total depth = 720.0 ft, total core recovered = 499.35 ft, total recovery = 70.3%.

Table T2. Diatom occurrences.

Sample depth (ft)	(m)	Comment	Observed diatoms	Interval	Age (Ma)	ECDZ
194.5	59.28	Poorly sorted silt with organic material	Barren			
231.15	70.45	Silt and clay	Barren			
265.45	80.91	Mostly clastic quartz grains	Few *Coscinodiscus* fragments			
282.1	85.98	Rare, poorly preserved diatoms, mostly fragments and sponge spicules	*Coscinodiscus* spp.	Unknown		
			Melosira westii			
			Paralia sulcata			
313.1	95.43	Common, moderately preserved diatoms	*Actinocyclus octonarius*	middle middle Miocene		7
			Actinocyclus cf. *divisus*			
			Cymatogonia amblyoceras, triangular form			
			Delphinei biseriata			
			Delphinei novaecaesareae			
			Paralia sulcata			
			Raphoneis diamantella			
			Raphoneis paralis			
340	103.63	Abundant, well-preserved diatoms	*Actinocyclus elipticus*	middle middle Miocene	~12.6–12	6
			Actinocyclus octonarius			
			Actinoptychus marylandicus			
			Azpeitia vetustissimus			
			Bogorovia lancettula			
			Cavitatus jouseanus			
			Coscinodiscus gigas var. *diorama*			
			Cymatosira cf. *lorenziana*			
			Delphineis biseriata			
			Delphineis novaecaesareae			
			Denticulopsis simonsenii			
			Paralia sulcata			
			Thalassiosira grunowii			
			Thalassiosira leptopus			
370.9	113.05	Abundant, moderately well preserved diatoms	*Actinocyclus ellipticus*	middle middle Miocene	~12.6–12.3	6
			Actinocyclus octonarius			
			Bogorovia lancettula			
			Coscinodiscus gigas var. *diorama*			
			Crucidenticula nicobarica			
			Cymatosira cf. lorenziana			
			Delphineis angusata			
			Denticulopsis simonsenii			
			Paralia sulcata			
			Rhaphoneis paralis			
386.4	117.77	Abundant, well-preserved diatoms	*Actinocyclus octonarius*	middle middle Miocene	~13.0–12.3	6
			Azpeitia vetustissimus			
			Cavitatus jouseanus			
			Coscinodiscus gigas var. *diorama*			
			Crucidenticula nicobarica			
			Cymatosira cf. *lorenziana*			
			Delphineis angusata			
			Delphineis novaecaesareae			
			Denticulopsis simonsenii			
			Paralia sulcata			

Table T2. (continued)

Sample depth (ft)	Sample depth (m)	Comment	Observed diatoms	Interval	Age (Ma)	ECDZ
			Rhaphoneis paralis			
			Thalassiosira grunowii			
399.1	121.65	Abundant, well-preserved diatoms	*Actinocyclus ellipticus*	middle middle Miocene	~13.0–12.3	Lower 6
			Coscinodiscus gigas var. *diorama*			
			Crucidenticula nicobarica			
			Cymatosira cf. *lorenziana*			
			Delphineis cf. *angusata*			
			D. novaecaesareae			
			D. penelliptica			
			Denticulopsis simonsenii			
			Paralia sulcata			
			Rhaphoneis paralis			
443.1	135.06	Few, poorly preserved diatoms; many clastic grains (sand?)	*Coscinodiscus fragments*	middle Miocene or younger, based on sample below		
			Parlia sulcata			
			Sceptroneis fragments			
			Thalassionema nitzschioides			
453.9	138.25	Abundant, moderately well preserved diatoms	*Craspedodiscus coscinodiscus*	early middle Miocene		Lower 3–4
			Delphineis cf. *angustata*			
			Delphineis ovata			
			Delphineis penelliptica			
			Paralia sulcata			
			Rhaphoneis fusiformis			
			Rhaphoneis cf. magaritata			
			Sceptoneis grandis			
			Rhaphoneis hungarica			
487.2	148.5	Abundant, moderately well preserved diatoms	*Cavitatus jouseanus*	early middle Miocene		Lower 3–4
			Coscinodiscus lewisianus			
			Cymatogonia amblyoceras			
			Delphineis lineata			
			Delphineis ovata			
			Delphineis penelliptica			
			Paralia sulcata			
			Rhaphoneis fusiformis			
			Sceptoneis hungarica			
521.1	158.83	Common, moderately well preserved diatoms	*Actinocyclus octonarius* (undulated form)	earliest middle Miocene		Upper 2
			Delphineis ovata			
			Paralia sulcata			
			Rhaphoneis margaritata			
			Sceptroneis grandis			
			Sceptroneis hungarica			
554.3	168.95	Abundant, moderately well preserved diatoms	*Actinocyclus octonarius* (undulated form)	latest early to earliest middle Miocene		Middle 2
			Azpeitia vetustissimus			
			Craspedodiscus coscinodiscus			
			Delphineis ovata			
			Paralia sulcata			
			Rhaphoneis fusiformis			
			Rhaphoneis margaritata			
			Rhaphoneis scaralis			

Table T2. (continued)

Sample depth (ft)	(m)	Comment	Observed diatoms	Interval	Age (Ma)	ECDZ
			Sceptoneis caduceus			
585.2	178.37	Abundant, well-preserved diatoms	*Actinocyclus octonarius* (undulated form)	latest early to earliest middle Miocene		Middle 2
			Craspedodiscus coscinodiscus			
			Delphineis cf. *angustata*			
			Delphineis lineata			
			Delphineis ovata			
			Paralia sulcata			
			Rhaphoneis margaritata			
			Rhaphoneis scaralis			
			Sceptoneis sp.			
			Thalassiosira eccentrica			
611.7	186.45	Abundant, well-preserved diatoms	*Actinocyclus octonarius* Ehrenberg (undulated form)	latest early to earliest middle Miocene		Middle 2
			Cavitatus jouseanus			
			Cymatogonia amblyoceras			
			Delphineis cf. *angustata*			
			Delphineis lineata			
			Delphineis ovata			
			Paralia sulcata			
			Rhaphoneis margaritata			
			Rhaphoneis scaralis			
			Thalassiosira eccentrica			

Notes: ECDZ = East Coast Diatom Zone of Andrews (1988). Age estimates based on Barron (2003).

Table T3. Sr isotope data.

Sr lab number	Run date	Depth (ft)	Depth (m)	Sr value	Corrected Sr value	Error	Age (Ma)
806	21 Jun 2006	50.3	15.33	0.709171	0.709188	0.000008	0.12
511	4 Aug 2005	55.3	16.86	0.709147	0.709164	0.000004	0.63
393	13 May 2005	64.1	19.54	0.709168	0.709185	0.000004	0.18
804	21 Jun 2006	66	20.12	0.709179	0.709196	0.000008	–0.05
807	21 Jun 2006	70.9	21.61	0.709119	0.709136	0.000012	1.23
805	21 Jun 2006	81.9	24.96	0.709169	0.709186	0.000009	0.16
885	8 Sep 2006	285.5	87.02	0.708866	0.708876	0.000008	12.0
395	13 May 2005	292.9	89.28	0.708862	0.708872	0.000008	12.1
506	4 Aug 2005	311.7	95.01	0.708837	0.708847	0.000011	13.1
889	8 Sep 2006	323.7	98.66	0.708846	0.708856	0.000013	12.7
508	4 Aug 2005	324.4	98.88	0.708821	0.708831	0.000004	13.7
888	8 Sep 2006	341.0	103.94	0.708844	0.708854	0.000007	12.8
754	11 May 2006	342.1	104.27	0.708813	0.708823	0.000009	14.0
381	4 May 2005	351.1	107.02	0.708823	0.708833	0.000004	13.6
501	4 Aug 2005	351.3	107.08	0.708831	0.708841	0.000004	13.3
890	8 Sep 2006	366.0	111.56	0.708871	0.708881	0.000006	11.8
390	13 May 2005	368.5	112.32	0.708838	0.708848	0.000004	13.0
886	8 Sep 2006	383.8	116.98	0.708820	0.708830	0.000009	13.7
632	30 Sep 2005	392.1	119.51	0.708812	0.708822	0.000006	14.0
505	4 Aug 2005	393.0	119.79	0.708821	0.708831	0.000005	13.7
751	11 May 2006	398.6	121.49	0.708837	0.708847	0.000011	13.1
627	30 Sep 2005	402.2	122.59	0.708830	0.708840	0.000005	13.3
624	30 Sep 2005	409.3	124.75	0.708824	0.708834	0.000006	13.5
628	30 Jun 2005	409.9	124.94	0.708816	0.708826	0.000005	13.8
752	11 May 2006	410.9	125.24	0.708829	0.708839	0.000013	13.4
630	30 Sep 2005	430.7	131.28	0.708764	0.708774	0.000005	15.8
382	4 May 2005	452.0	137.77	0.708768	0.708778	0.000004	15.8
512	4 Aug 2005	460.6	140.39	0.708741	0.708751	0.000004	16.2
394	13 May 2005	474.8	144.72	0.708734	0.708744	0.000004	16.3
510	4 Aug 2005	501.9	152.98	0.708705	0.708715	0.000004	16.7
887	8 Sep 2006	501.9	152.98	0.708698	0.708708	0.000008	16.8
383	4 May 2005	512.0	156.06	0.708712	0.708722	0.000005	16.6
509	4 Aug 2005	524.8	159.96	0.708664	0.708674	0.000007	17.3
631	30 Sep 2005	531.8	162.09	0.708708	0.708718	0.000006	16.6
392	13 May 2005	546.8	166.66	0.708682	0.708692	0.000008	17.0
384	4 May 2005	561.0	170.99	0.708649	0.708659	0.000004	17.5
502	4 Aug 2005	567.3	172.91	0.708632	0.708642	0.000006	17.8
507	4 Aug 2005	626.0	190.80	0.708663	0.708673	0.000015	17.3
750	11 May 2006	640.3	195.16	0.708553	0.708563	0.000009	18.9
686	14 Dec 2005	640.7	195.29	0.708563	0.708573	0.000005	18.8
753	11 May 2006	640.7b	195.29b	0.708502	0.708512	0.000031	19.7
783	12 Jun 2006	640.8	195.32	0.708534	0.708544	0.000028	19.2
784	12 Jun 2006	641.0	195.38	0.708563	0.708573	0.000007	18.8
786	12 Jun 2006	641.4	195.50	0.708552	0.708562	0.000008	18.9
782	12 Jun 2006	642.0	195.68	0.708554	0.708564	0.000008	18.9
787	12 Jun 2006	644.5	196.43	0.708500	0.708510	0.000006	19.7
633	30 Sep 2005	650.2	198.18	0.708494	0.708504	0.000011	19.8
785	12 Jun 2006	651.0	198.42	0.708581	0.708591	0.000008	18.5
683	14 Dec 2005	651.3	198.52	0.708519	0.708529	0.000005	19.4
693	20 Dec 2005	652.4	198.85	0.708482	0.708492	0.000018	20.0
385	4 May 2005	660.3	201.26	0.708479	0.708489	0.000018	20.0
503	4 Aug 2004	666.4	203.12	0.708503	0.708513	0.000004	19.6
504	4 Aug 2005	685.1	208.82	0.708480	0.708490	0.000004	20.0
391	13 May 2005	707.8	215.74	0.708471	0.708481	0.000008	20.1

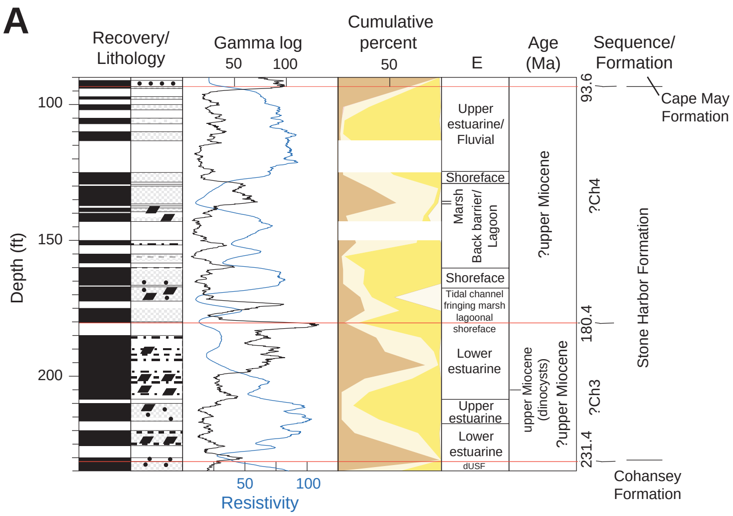
Notes: Analyses made on shell material. Sr values and ages of samples from above 81.9 ft (24.96 m) are corrected for 758 regression.

Table T4. Amino acid analyses data.

Sample depth (ft)	Sample depth (m)	Sample	Sample type	Subsample	Ratio type	allo-Isoleucine	Alanine	Aspartic acid	Glutamic acid	Leucine	Phenylalanine	Proline	Valine	VLPG	Ala_Asp	Val_Leu
78.1	23.8	jw2006-010-001	Mulinia	2006128	Area	0.281	0.723	0.524	0.269	0.311	0.347	0.399	0.181	0.277	0.623	0.246
		jw2006-010-001		2006128	Height	0.282	0.699	0.522	0.265	0.312	0.349	0.411	0.187	0.278	0.611	0.250
		jw2006-010-002		2006129	Area	0.242	0.500	0.507	0.232		0.340	0.375	0.168		0.503	
		jw2006-010-002		2006129	Height	0.242	0.520	0.512	0.238		0.347	0.388	0.176		0.516	
		jw2006-010-003		2006130	Area	0.251	0.516	0.544	0.291	0.276		0.404	0.186		0.530	0.231
		jw2006-010-003		2006130	Height	0.253	0.541	0.544	0.288	0.295	0.362	0.411	0.192	0.284	0.543	0.243
		jw2006-010-006		2006133	Area		0.411	0.522		0.215					0.466	
		jw2006-010-006		2006133	Height			0.507								
77.0	23.5	jw2006-009-002		2006127	Area	0.236	0.543	0.538	0.273	0.291	0.367	0.368	0.175	0.276	0.540	0.233
		jw2006-009-002		2006127	Height	0.252	0.548	0.538	0.265	0.289	0.337	0.373	0.177	0.267	0.543	0.233
		jw2006-009-003		2006121	Area	0.287	0.777	0.517	0.199	0.276		0.353	0.153		0.647	0.215
		jw2006-009-003		2006121	Height	0.269	0.714	0.520	0.230	0.285		0.360	0.167		0.617	0.226
		jw2006-009-004		2006122	Area	0.273	0.821	0.511	0.246	0.267		0.387	0.171		0.666	0.219
		jw2006-009-004		2006122	Height	0.262	0.699	0.534	0.241	0.271	0.350	0.376	0.169	0.258	0.617	0.220
					Mean Mulinia	0.261	0.616	0.524	0.253	0.281	0.350	0.384	0.175	0.273	0.571	0.232
					Standard deviation	0.017	0.127	0.013	0.027	0.026	0.010	0.019	0.011	0.009	0.062	0.012
					CV	6.6%	20.6%	2.5%	10.6%	9.4%	2.9%	5.1%	6.0%	3.5%	10.9%	5.1%
77.0	23.5	jw2006-009-001	Ensis	2006126	Area	0.202	0.475	0.516	0.239	0.230	0.369	0.250	0.135	0.243	0.495	0.182
		jw2006-009-001		2006126	Height	0.186	0.460	0.534	0.240	0.254	0.330	0.242	0.130	0.238	0.497	0.192
44.8	13.66	jw2006-001-001	Mercenaria	2006125	Area	0.407	0.598	0.758	0.394	0.398	0.512	0.501	0.264	0.392	0.678	0.331
		Jw2006-001-001		2006125	Height	0.382	0.637	0.733	0.388	0.423	0.504	0.515	0.282	0.399	0.685	0.352
		jw2006-001-002		2006120	Area	0.331	0.740	0.652	0.335	0.364	0.482	0.424	0.255	0.359	0.696	0.310
		jw2006-001-002		2006120	Height	0.325	0.755	0.672	0.344	0.370	0.442	0.395	0.252	0.352	0.713	0.311
					Mean Mercenaria	0.361	0.682	0.704	0.365	0.389	0.485	0.459	0.263	0.376	0.693	0.326
					Standard deviation	0.034	0.067	0.043	0.026	0.024	0.027	0.050	0.012	0.020	0.013	0.017
					CV	9.5%	9.8%	6.2%	7.1%	6.1%	5.5%	11.0%	4.4%	5.4%	1.9%	5.4%

Notes: CV = coefficient of variation. VLPG = average of valine, leucine, phenylalanine, and glutamic; Val_Leu = average of valine and leucine; Ala_Asp = average of alanine and aspartic.

Figure AF1. Summary stratigraphic sections for the Stone Harbor Formation. Sequences defined by de Verteuil (1997). **A.** Cape May Zoo (ODP Leg 174AX; stratotype), dUSF = distal upper shoreface. **B.** Cape May (ODP Leg 150X; costratotype), AMS = accelerator mass spectrometer radiocarbon date, AAR = amino acid racemization. (Continued on next page.)



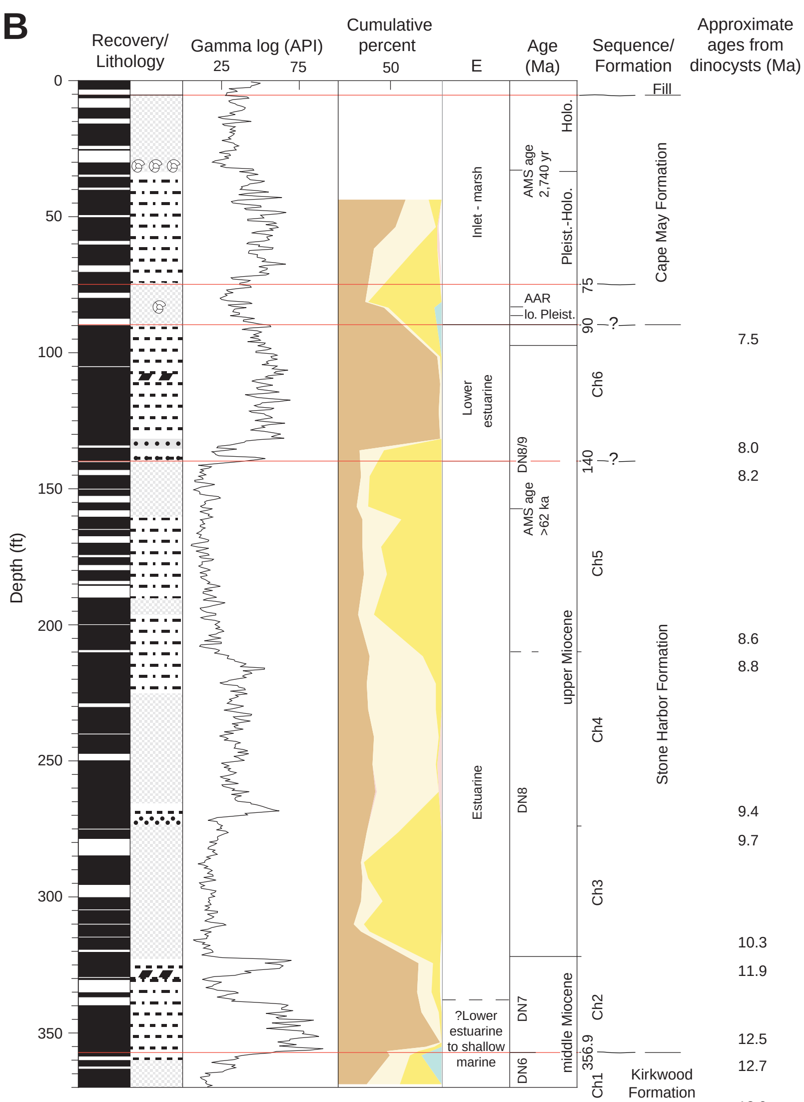


Figure AF1 (continued). C. Ocean View coreholes.