Quantification of the effects of eustasy, subsidence, and sediment supply on Miocene sequences, mid-Atlantic margin of the United States

James V. Browning†
Kenneth G. Miller
Department of Geological Sciences, Rutgers University, Piscataway, New Jersey 08854, USA

Peter P. McLaughlin
Delaware Geological Survey, DGS Building, University of Delaware, Newark, Delaware 19716, USA

Michelle A. Kominz
Department of Geosciences, Western Michigan University, Kalamazoo, Michigan 49008-5150, USA

Peter J. Sugarman
Donald Monteverde
New Jersey Geological Survey, P.O. Box 427, Trenton, New Jersey 08625, USA

Mark D. Feigenson
John C. Hernández
Department of Geological Sciences, Rutgers University, Piscataway, New Jersey 08854, USA

ABSTRACT

We use backstripping to quantify the roles of variations in global sea level (eustasy), subsidence, and sediment supply on the development of the Miocene stratigraphic record of the mid-Atlantic continental margin of the United States (New Jersey, Delaware, and Maryland). Eustasy is a primary influence on sequence patterns, determining the global template of sequences (i.e., times when sequences can be preserved) and explaining similarities in Miocene sequence architecture on margins throughout the world. Sequences can be correlated throughout the mid-Atlantic region with Sr-isotopic chronology (±0.6 m.y. to ±1.2 m.y.). Eight Miocene sequences correlate regionally and can be correlated to global $\delta^{18}O$ increases, indicating glacioeustatic control. This margin is dominated by passive subsidence with little evidence for active tectonic overprints, except possibly in Maryland during the early Miocene. However, early Miocene sequences in New Jersey and Delaware display a patchwork distribution that is attributable to minor (tens of meters) intervals of excess subsidence. Backstripping quantifies that excess subsidence began in Delaware at ca. 21 Ma and continued until 12 Ma, with maximum rates from ca. 21–16 Ma. We attribute this enhanced subsidence to local flexural response to the progradation of thick sequences offshore and adjacent to this area. Removing this excess subsidence in Delaware yields a record that is remarkably similar to New Jersey eustatic estimates. We conclude that sea-level rise and fall is a first-order control on accommodation providing similar timing on all margins to the sequence record. Tectonic changes due to movement of the crust can overprint the record, resulting in large gaps in the stratigraphic record. Smaller differences in sequences can be attributed to local flexural loading effects, particularly in regions experiencing large-scale progradation.

Keywords: Miocene, sequence stratigraphy, Delaware, New Jersey, eustasy.

INTRODUCTION

Over the past 30 yr, sequence stratigraphy has provided an important approach for evaluating the role of global sea level (eustasy), tectonic subsidence and uplift, and sediment supply processes on the deposition of continental margin strata (e.g., Vail et al., 1977; Posamentier et al., 1988). Sequences are genetically related packages of sediment separated by unconformities or their correlative conformities (Mitchum et al., 1977) and comprise the fundamental building blocks of the stratigraphic record (e.g., Christie-Blick, 1991). Vail et al. (1977) and Haq et al. (1987) suggested that global sea-level (eustatic) change is the dominant process controlling sequences, though tectonic changes in base level also create sequence boundaries (e.g., Christie-Blick and Driscoll, 1995). The effects of eustasy and tectonics (including thermal subsidence, loading, flexure, and compaction) control accommodation, the space available for sediment to accumulate. Sediment supply controls how that space is filled. The interplay of accommodation and sediment supply control the formation of stratal surfaces, stratal geometries, and facies distributions as demonstrated by forward modeling (Reynolds et al., 1991).

Previous studies of the New Jersey margin have examined Oligocene-Miocene sequences onshore and offshore and their relationship to global sea level changes due to the growth and decay of continental ice sheets (glacioeustasy) inferred from global $\delta^{18}O$ variations. New Jersey sequence boundaries (Ocean Drilling Program [ODP] Legs 150X and 174AX) correlate with sequence boundaries identified beneath the continental shelf and slope (ODP Legs 150 and 174A), implying at least a regional cause (Miller and Mountain, 1996; Miller et al., 1998a). The number and timing of onshore and offshore

†E-mail: jvb@rci.rutgers.edu.

GSA Bulletin; May/June 2006; v. 118; no. 5/6; p. 567–588; doi: 10.1130/B25551.1; 13 figures; Data Repository item 2006064.

sequence boundaries are similar to those identified by Haq et al. (1987), implying a global cause. Sequence boundaries both onshore and offshore correlate with global $\delta^{18}O$ increases, causally linking them with glacioeustatic falls (Miller and Mountain, 1996; Miller et al., 1998a, 2002a). Sequence boundaries have been directly tied to $\delta^{18}O$ increases at slope Site 904, providing prima facie evidence for a causal link (Miller et al., 1998a). Thus, the formation of Oligocene-Miocene sequence boundaries was controlled by glacioeustasy, which determines those times when sequences can be preserved (i.e., the template of sequences).

Theoretical models of sequences are well established, particularly as dip cross sections (e.g., the "slug model" of Posamentier et al., 1988; Van Wagoner et al., 1988). These models have been evaluated from detailed outcrop studies (e.g., Book Cliffs, Utah: Van Wagoner and Bertram, 1995; New Zealand: Abbott and Carter, 1994), subsurface strata in cratonic basins (e.g., Cardium Formation, Canada; Plint, 1988), and the modern Gulf of Mexico (Rodriguez et al., 2001), providing information on contrasting stratal architecture in widely different settings. However, these models are generalizations that are complicated by variations in subsidence and sediment supply, particularly along strike (Posamentier and Allen, 1993). Along-strike variations are potentially associated with differences in sequence thickness and preservation such as observed on the mid-Atlantic margin (Brown et al., 1972; Owens et al., 1997). Few studies have quantified the relative effects of eustasy, tectonics, and sediment supply and the resultant variation in thickness and preservation. Drilling in New Jersey and Delaware (Fig. 1) was designed to help evaluate the cause of these along-strike variations.

Tectonics (including faulting/folding, thermal subsidence, and flexural and Airy loading) potentially overprints the eustatic signal recorded by sedimentary strata even on a passive margin such as the middle Atlantic margin of the United States. Such tectonic variations cause lateral variations in the thickness and preservability of sequences. Brown et al. (1972) and Owens et al. (1988, 1997) ascribed shifting depositional patterns in the Salisbury Embayment, a broad structural low on the middle Atlantic margin

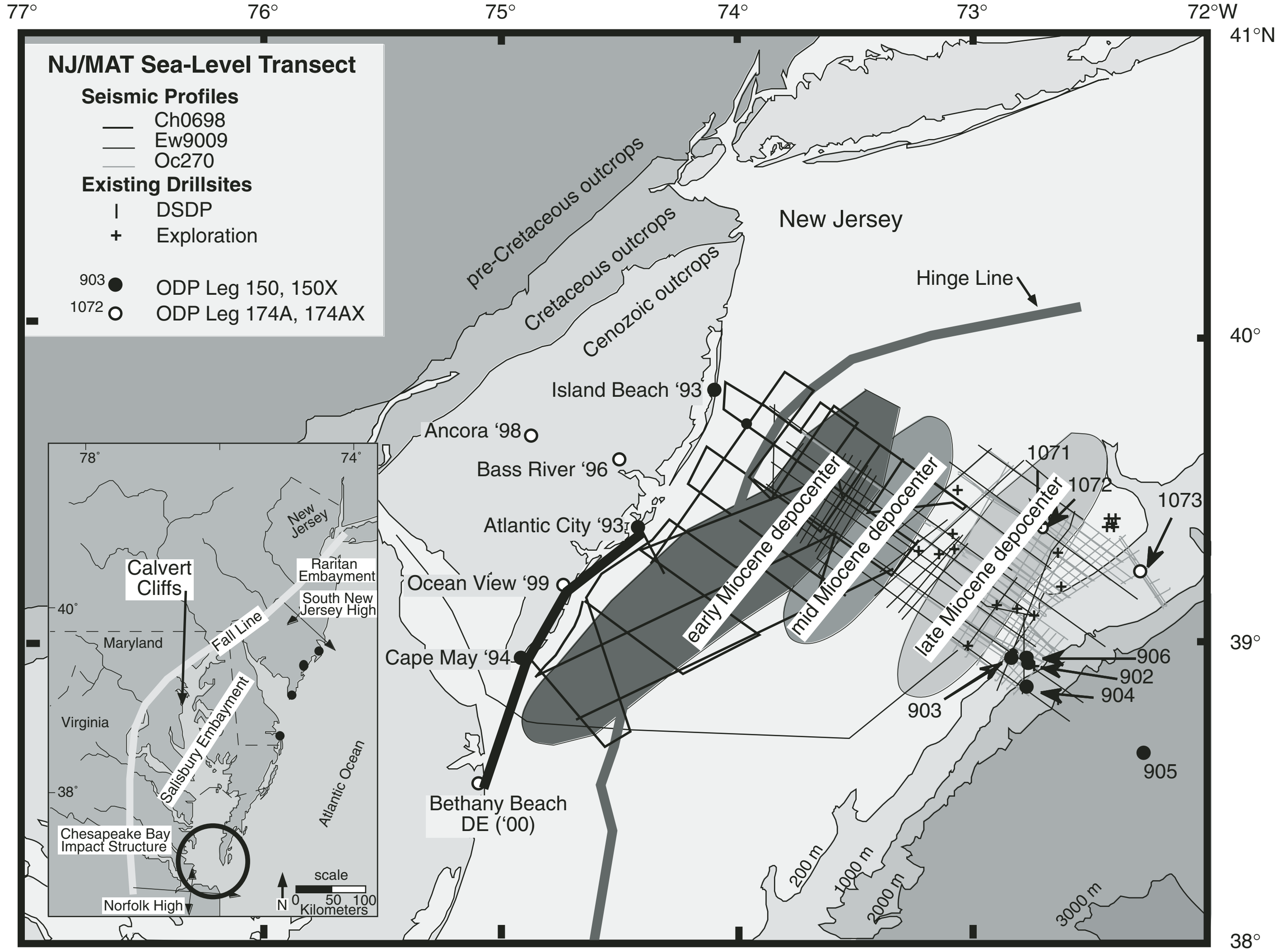

Figure 1. Location map showing the coreholes studied here and other holes drilled as a part of the New Jersey/Mid-Atlantic (NJ/MAT) Sea Level Transect. Inset map shows the position of the Salisbury Embayment. ODP—Ocean Drilling Program; DE—Delaware.

(Fig. 1), to active intrabasinal tectonics (e.g., wrench faulting). Active faulting has occurred in the Atlantic coastal plain south of the Salisbury Embayment (e.g., near Charleston, South Carolina; Weems and Lewis, 2002), and active faults may be present on the south side of the Salisbury Embayment as an aftermath of the Chesapeake Bay impact structure (Johnson et al., 1998; Poag et al., 2004). However, other evidence for major Miocene faulting in the Salisbury Embayment is equivocal; this region lacks evidence for the large number or magnitude of earthquakes found in areas of active faulting elsewhere in the Atlantic Coastal Plain (Seeber and Armbruster, 1988). Studies in New Jersey have shown that the tectonic component of accommodation in this part of the Salisbury Embayment has been dominated by passive tectonic effects, including simple thermoflexural subsidence and Airy loading (Kominz et al., 1998, 2002). Thus, comparison of Miocene sequences in New Jersey and elsewhere in the Salisbury Embayment provides a means of evaluating the effects of thermal subsidence, loading, and eustasy in different parts of the basin.

Changes in sediment supply also influence the development of sequences. Christie-Blick et al. (1990) quantitatively demonstrated that formation of sequence boundaries is not caused by changes in sediment supply. However, sediment supply can profoundly influence the character of sequences by affecting the location of the strand line, the shape and thickness of sequences, intrasequence stratal surfaces, and lithofacies variations within sequences (Reynolds et al., 1991). Though no major shift in the number of large riverine systems occurred on the Atlantic margin during the Cenozoic, regional changes in sediment input, stream capture, and avulsion have strongly influenced the position of fluvial systems (Poag and Sevon, 1989). New Jersey was influenced by a large delta system throughout the Miocene (Fig. 2; Sugarman et al., 1993), but the deltaic influence is not observed in outcrops in the southern part of the Salisbury Embayment (Kidwell, 1984). These areal and temporal variations in sediment supply and distribution on the mid-Atlantic margin provide a natural experiment for evaluating the effects of local and regional sedimentation changes on sequences.

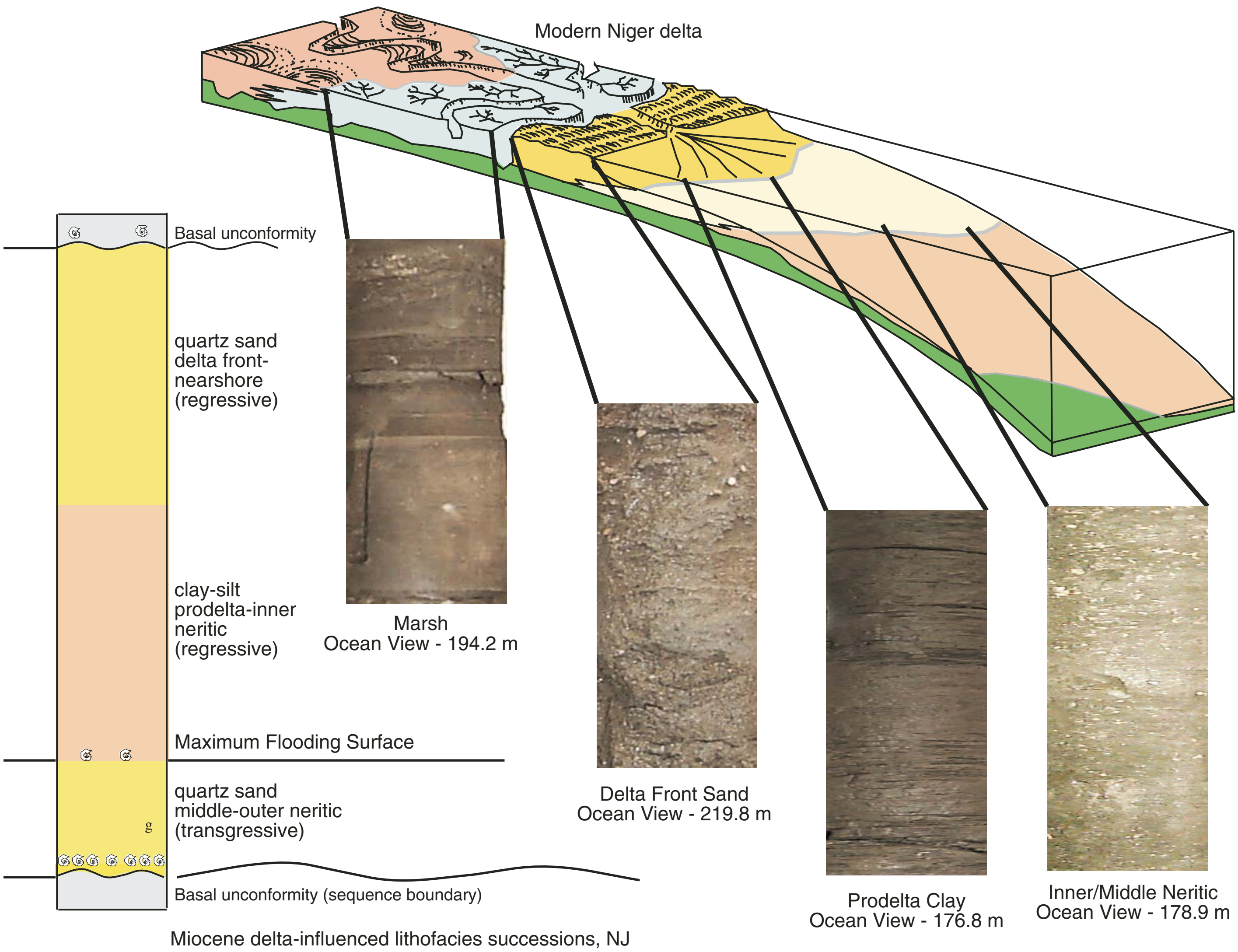

Figure 2. General lithofacies model applicable to the New Jersey (NJ) Miocene sediments. Core photographs are from the Ocean View core hole at the indicated depths.

The objective of this paper is to quantitatively evaluate the effects of eustasy, tectonics, and sediment supply variations on Miocene sequences in the middle Atlantic margin. This paper compares Miocene sequences from a recent corehole at Bethany Beach, Delaware (ODP Leg 174AX; Miller et al., 2002b and this study) with previously published studies of Miocene sections from Island Beach, Atlantic City, Cape May, Bass River, and Ocean View, New Jersey (Fig. 1; Miller et al., 1997b, 1998b, 2001), and with Maryland outcrops. Bethany Beach is located near the depocenter of the Salisbury Embayment where the Miocene is thicker than sites in New Jersey (Fig. 1; Miller, et al., 2002b). This paper examines the sequence stratigraphy of the Bethany Beach site in detail, quantitatively evaluates subsidence history using one-dimensional backstripping, and contrasts the stratigraphy and subsidence history of this site with coeval New Jersey and Maryland sections. The lessons provided by these comparisons are exportable to studies of passive margins of any age throughout the world: though eustasy determines the global record of preservable sequences, regional tectonics and localized flexural subsidence determine the preservation potential of these sequences.

METHODS

A 448.06 m continuous core hole was drilled in May and June 2000 at the Bethany Beach National Guard base (Fig. 1) as a cooperative venture among Rutgers University, the Delaware Geological Survey (DGS), the New Jersey Geological Survey (NJGS), and the U.S. Geological Survey (USGS). The Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) planning committee endorsed drilling at Bethany Beach as an ODP-related activity and designated drilling there and at Bass River, Ancora, and Ocean View, New Jersey as ODP Leg 174AX (Miller et al., 2002b).

The Bethany Beach cores were photographed (Fig. 3) and analyzed for lithology (including sedimentary textures, structures, colors, and fossil content), lithologic contacts, biostratigraphy, benthic foraminiferal biofacies, and isotopic stratigraphy. Semiquantitative grain-size studies were conducted on samples taken at ~1.5 m intervals and displayed on cumulative percent plots of the sediments (Figs. 4–7). Each sample was dried, weighed, and washed through a 63 μm sieve, yielding the percentage of sand versus silt and clay. The sand fraction was dry-sieved through a 250 μm sieve, and the fractions were weighed to obtain the percent of very fine and fine sand versus coarser material. The relative percentages of quartz, glauconite, carbonate (foraminifers and other shells), mica, and other materials contained in the sand fraction were estimated visually using a binocular microscope. Lithostratigraphic nomenclature uses the units of Andres (1986) and Benson (1990).

We recognized sequence boundaries in cores on the basis of physical stratigraphy and age breaks. Criteria for recognizing sequence-bounding unconformities include: (1) irregular contacts, with up to 5 cm of relief on a 6.4-cm-diameter core; (2) reworking, including rip-up clasts found 0.3–0.6 m above the contact; (3) heavy bioturbation, including burrows filled with overlying material as much as 0.3–0.6 m below the contact; (4) major lithofacies shifts, typically from shallow- to deeper-water environments above the contact; (5) gamma ray increases associated with changes from low-radioactivity sands below to hotter clays above (e.g., Fig. 5), glauconite immediately above sequence boundaries (e.g., Fig. 7), and/or marine omission surfaces (e.g., with high U/Th scavenging); (6) shell lags above the contact; and (7) age breaks evinced by Sr-isotopic stratigraphy or biostratigraphy. In general, there were few sharp lithologic contacts at Bethany Beach, and most sharp contacts proved to be either sequence boundaries or maximum flooding surfaces (MFS). MFS may be differentiated from sequence boundaries by the lack of an age break at an MFS, upward-deepening paleobathymetric successions below MFS versus shallowing upward below sequence boundaries, and changes in benthic foraminiferal biofacies. Though MFS at Bethany Beach are heavily burrowed and might be omission surfaces, they generally lack rip-up clasts and age breaks and are associated with the tops of distinct retrogradational lithofacies successions. Not all potential sequence boundaries display all of the criteria listed above, though the minimal evidence for a sequence boundary requires a lithologic contact, a facies shift, and evidence of erosion (rip-up clasts and lags) and/or age breaks. The 14 Miocene sequence boundaries identified in the Bethany Beach core hole are supported by lateral correlations among water wells and downhole logs in Delaware (Miller et al., 2002b), indicating that they can be correlated regionally.

Age control for Miocene strata at Bethany Beach is derived primarily from Sr-isotopic stratigraphy because biochronology is limited due to the relatively shallow water paleoenvironments represented. We obtained 68 Sr-isotope age estimates (tabulated in Miller et al., 2002b) from mollusk shells following standard procedures (Oslick et al., 1994) on a VG Sector Mass Spectrometer at Rutgers University. Strontium isotopic standard NBS 987 is measured on the Rutgers Sector as 0.710255 normalized to $^{86}Sr/^{88}Sr$ of 0.1194. Internal precision on the sector for the data set averaged 0.000008; external precision is approximately ±0.000020 (Oslick et al., 1994). Most of the Sr-isotopic analyses yielded monotonically increasing values upsection, which reflect decreasing age (Fig. 8). At least seven data points are interpreted as statistical outliers (open circles on Fig. 8) due to stratigraphic reworking from older strata (e.g., 185.01, 189.68, 216.56 m) and minor alteration of some of the shells (e.g., in indurated zones at 174.59, 174.96 m).

We assigned ages using the Berggren et al. (1995) time scale; we used the Miocene Sr-isotopic regressions of Oslick et al. (1994). Age errors for 15.5–22.8 Ma are ±0.61 m.y. and 9.7–15.5 Ma are ±1.17 m.y. at the 95% confidence interval for a single analysis (Miller et al., 1991). The regression for the late Oligocene–earliest Miocene (22.8–27.5 Ma) has an age error of ±1 m.y. for 1 analysis at the 95% confidence interval (Reilly et al., 2002).

We reconstructed a subsidence history for Bethany Beach using one-dimensional inverse models termed backstripping (Watts and Steckler, 1979; Bond and Kominz, 1984; Bond et al., 1989). The first step in backstripping is to remove the effect of compaction and sediment loading (assuming Airy isostasy in one-dimensional backstripping) from observed basin subsidence (termed R1 for first reduction). By assuming thermal subsidence on a passive margin, a portion of tectonic subsidence can be removed. The difference between observed subsidence and a best-fit theoretical thermal curve (termed R2 for second reduction; Bond and Kominz, 1984) is the result of either eustatic change or any subsidence unrelated to two-dimensional passive margin subsidence (e.g., flexural loading; Kominz et al., 1998). Using forward modeling, Steckler (1981) showed that coastal plain subsidence is primarily a flexural response to sediment loading of the stretched crust seaward of the basement hinge zone (Fig. 1), but that coastal plain subsidence is exponential in form beginning 15–20 m.y. after rifting. Kominz et al. (1998, 2002) termed this thermo-flexural subsidence and documented that thermo-flexural subsidence, sediment loading, and compaction are the dominant causes of subsidence in the New Jersey coastal plain since 100 Ma. Our data set from Bethany Beach begins at 24 Ma, ~100–120 m.y. after subsidence began beneath the coastal plain (Olsson et al., 1988); therefore, the subsidence generated by flexure in the coastal plain is expected to be thermal in form (Kominz et al., 1998, 2002).

The greatest uncertainty in backstripping is from water depth estimates. Benthic

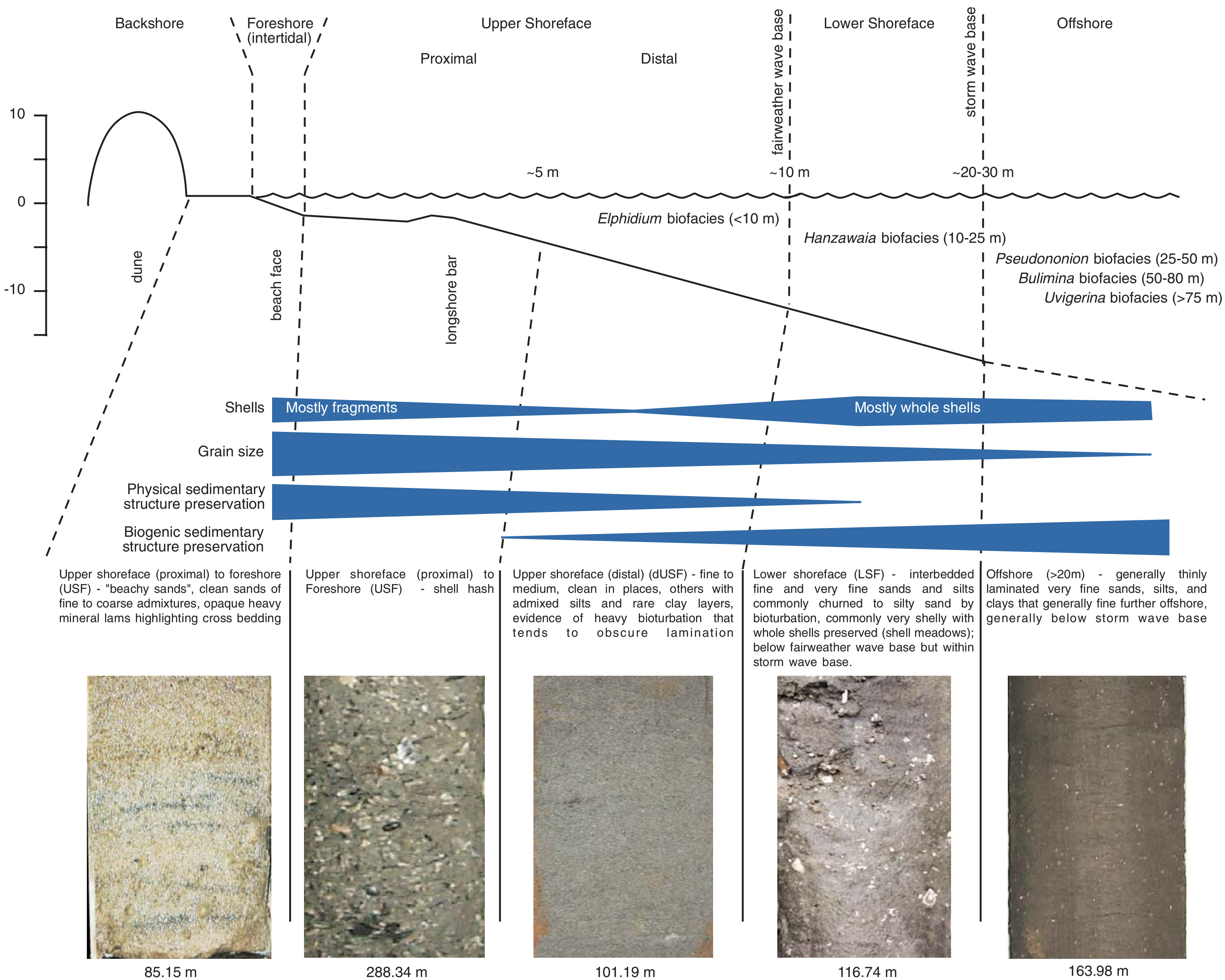

Figure 3. General lithofacies and biofacies model used to interpret the sediments found in the Bethany Beach core hole. *Elphidium, Hanzawaia, Pseudononion, Bulimina,* and *Uvigerina* biofacies are defined by Miller et al. (1997b). Core photographs are from the Bethany Beach core hole at the depths indicated below the photographs.

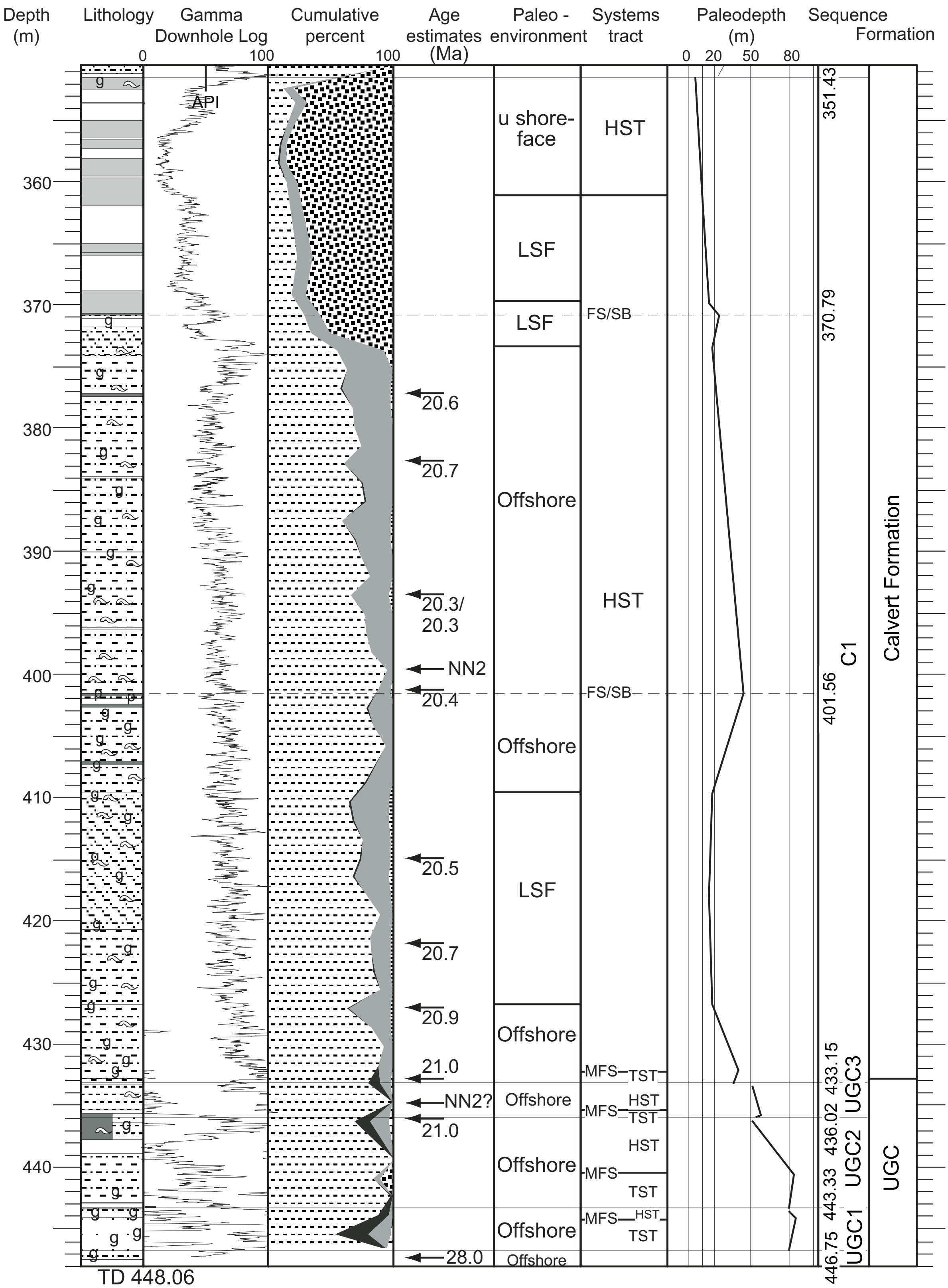

Figure 4. Lithology, gamma-ray log, sediments, age estimates, environment of deposition, systems tracts, and inferred paleodepths for the lowermost Miocene UGC1–3 and C1 sequences, Bethany Beach core hole. See Figure 7 for key to lithology symbols. UGC—unnamed glauconitic clays and clayey glauconite sand sequences discussed in the text; MFS—maximum flooding surface; TST—transgressive systems tract; HST—high-stand systems tract; FS—flooding surface; SB—sequence boundary; LSF—lower shoreface; API—American Petroleum Institute gamma ray unit; TD—total depth.

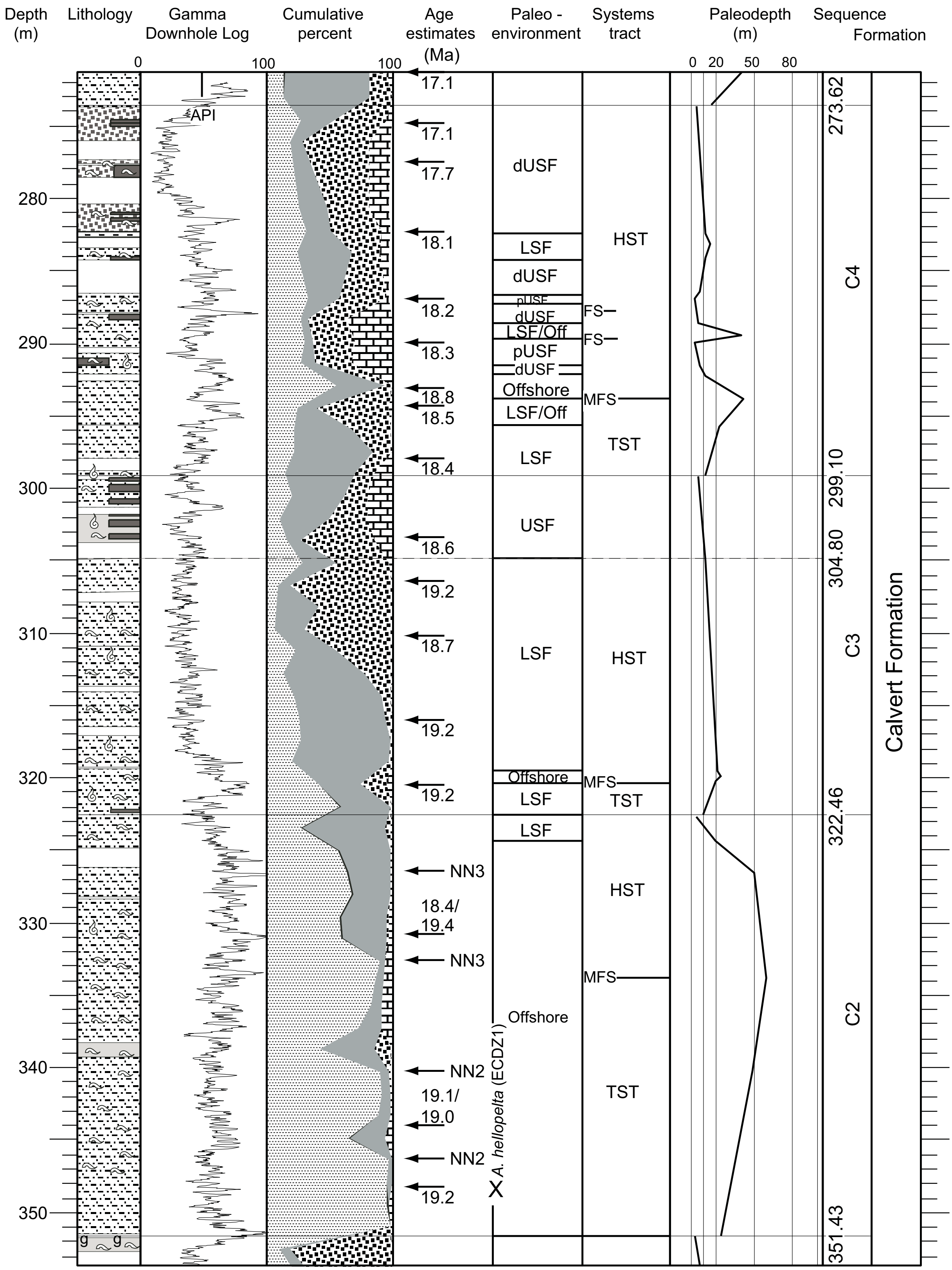

Figure 5. Lithology, gamma log, sediments, age estimates, environment of deposition, systems tracts, inferred water depths for the lower Miocene C2–4 sequences, Bethany Beach core hole. Abbreviations are the same as for Figure 4. See Figure 7 for key to lithology symbols. dUSF—distal upper shoreface; pUSF—proximal upper shoreface; LSF—lower shoreface; USF—upper shoreface; ECDZ1—East Coastal Diatom Zone 1.

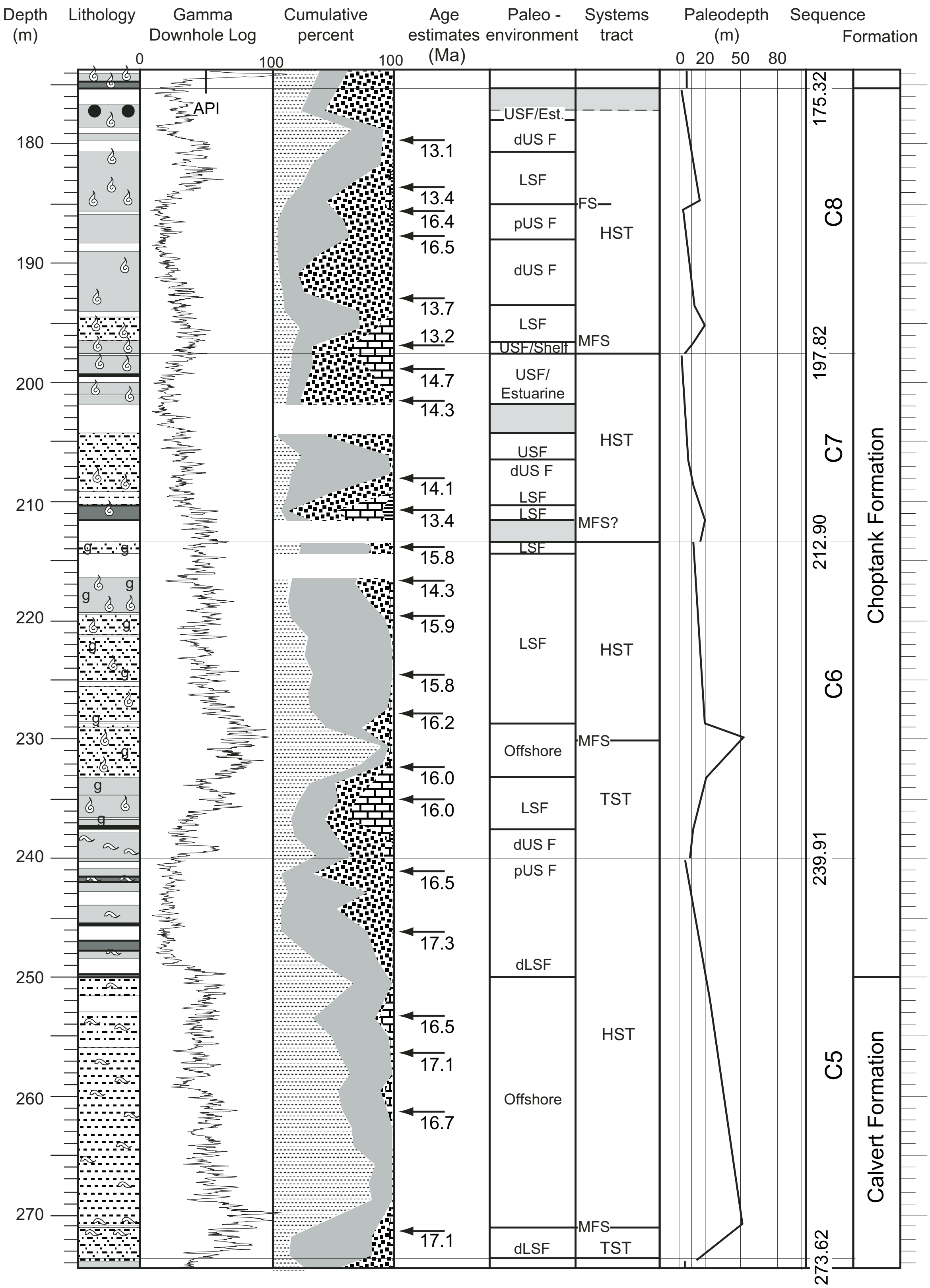

Figure 6. Lithology, gamma log, sediments, age estimates, environment of deposition, systems tracts, inferred water depths for the uppermost lower to middle Miocene C5–8 sequences, Bethany Beach core hole. Abbreviations are the same as for Figure 4. See Figure 7 for key to lithology symbols.

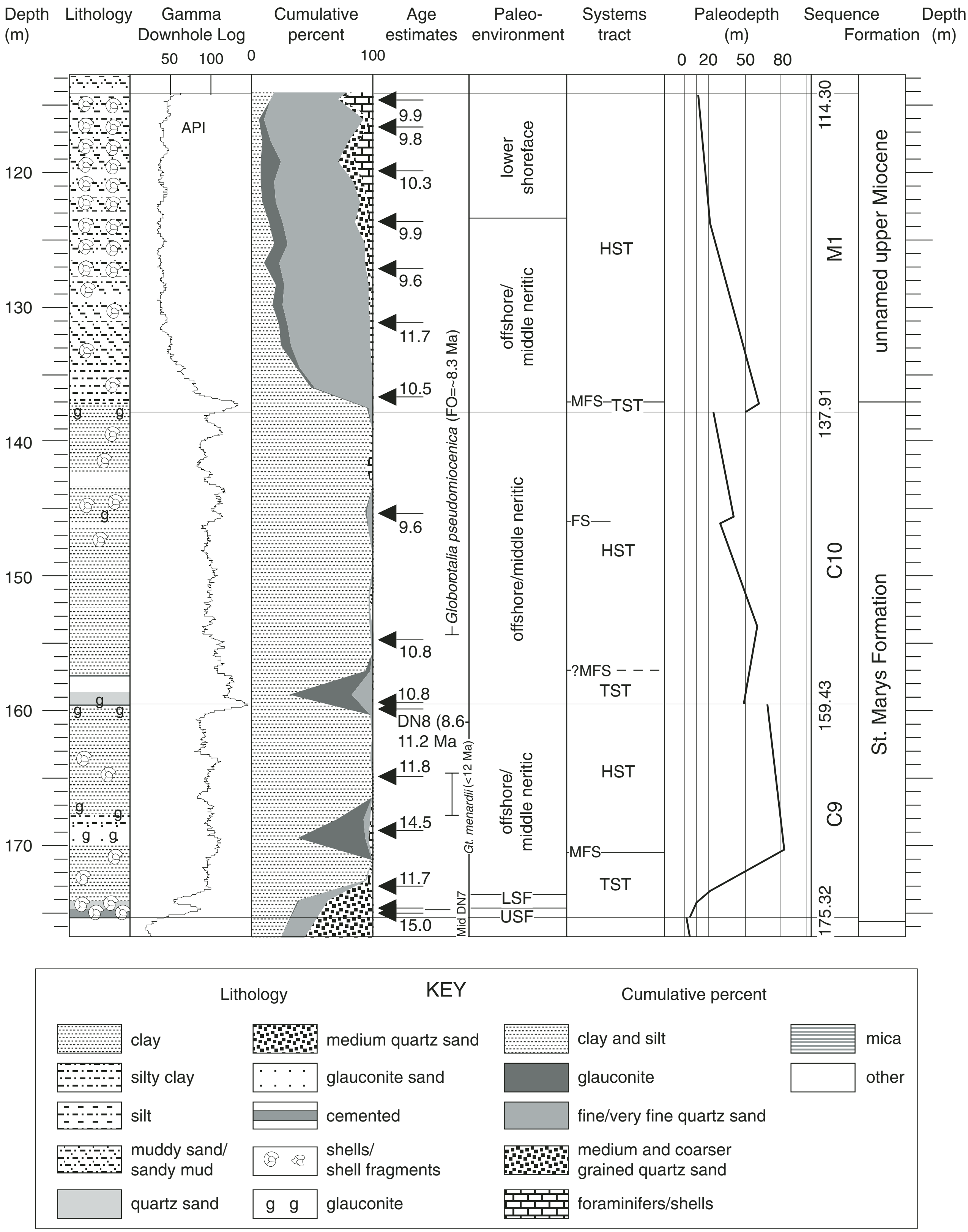

Figure 7. Lithology, gamma log, sediments, age estimates, environment of deposition, systems tracts, inferred water depths for the uppermost middle and upper Miocene C9–10 and M1 sequences, Bethany Beach core hole. Abbreviations are the same as for Figure 4. FO—first occurrence.

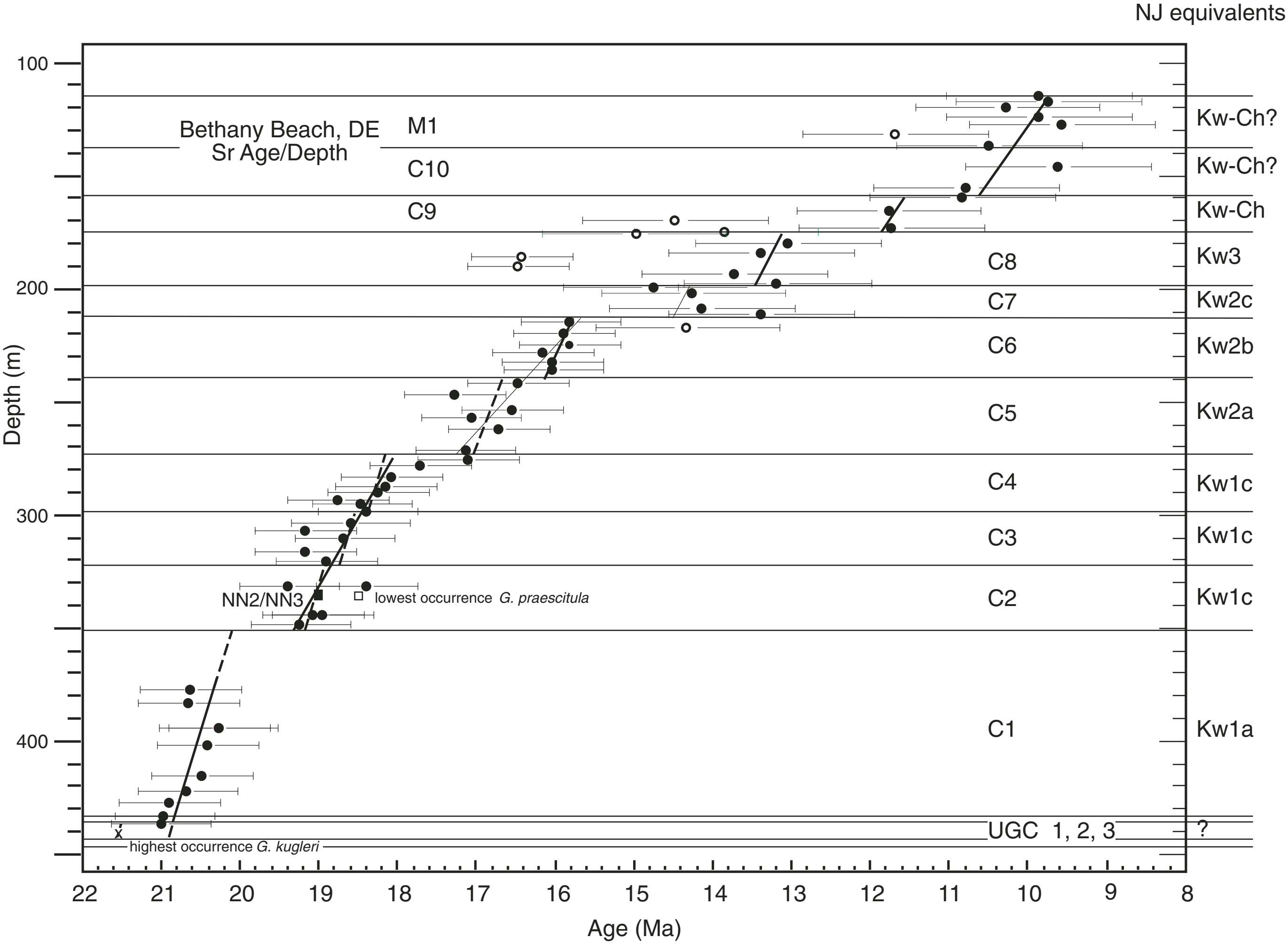

Figure 8. Age-depth plot showing the temporal distribution of the Miocene sequences in the Bethany Beach, Delaware (DE) core hole. UGC1–3, C1–10, and M1—sequences defined in the text; Kw notation—sequences defined in New Jersey (NJ) by Miller et al. (1997b); open circles—altered strontium samples; closed circles—strontium isotopic ages; NN2/NN3—boundary between calcareous nannoplankton zones.

foraminiferal biofacies and lithofacies provide paleobathymetric control for our interpretations and backstripping. In shallow-water sections (i.e., <30 m), including much of the Delaware and New Jersey Miocene strata, we estimate that lithofacies and lithofacies successions within sequences provide water-depth histories with better than ±10 m accuracy (Figs. 2 and 3). Resolution is coarser for middle neritic (we estimate approximately ±20 m for 30–100 m) and outer neritic (approximately ±50 m for 100–200 m) paleodepths based primarily on benthic foraminiferal biofacies.

We discuss lithologic (descriptive and semi-quantitative), downhole gamma log, Sr-isotopic ages, biostratigraphic control, paleoenvironment, paleodepth interpretations, and systems tracts interpretations (Figs. 4–7) from the oldest to youngest.

RESULTS

Integrated Lithofacies and Biofacies Model

Drilling at Bethany Beach revealed a striking difference from the Miocene sedimentary regime in New Jersey. Wave-dominated nearshore environments in Delaware contrast with delta-influenced facies successions within New Jersey Miocene sequences (Fig. 2). We developed a facies model for Miocene strata at Bethany Beach (Fig. 3) based on a wave-dominated shoreline model devised by Bernard et al. (1962) on Galveston Island and further developed by Harms et al. (1975, 1982) and McCubbin (1982). Sediments in Delaware were deposited in typical marine environments ranging from beach to outer neritic. We recognize five different paleoenvironments in the Miocene strata at Bethany Beach (Fig. 3).

1. Foreshore: The shallowest paleodepth lithofacies was deposited in foreshore to proximal upper shoreface paleoenvironments (Fig. 3). It consists of well-sorted, fine to coarse sand; occasional laminations of opaque heavy minerals highlight cross-bedding. This lithofacies probably represents deposition in the intertidal zone (~0–2 m).

2. Proximal upper shoreface: Deposits consist of fine to medium sand with abundant molluscan shell fragments (~2–5 m paleodepth).

3. Distal upper shoreface: Deposits contain fine to medium sand. The sand is generally well sorted, but in places there are admixed silt and clay layers. Physical structures are not often preserved and are difficult to interpret in boreholes. Laminae and rare cross-beds are preserved, but physical structures tend to be obscured by moderate-to-heavy bioturbation. Individual burrows are often impossible to discern; rather,

the sediments have been homogenized, leaving a vague bioturbate texture. Distal upper shoreface deposits were probably deposited in water depths down to fair-weather wave base (~5–10 m paleodepth based on modern facies observations; e.g., McCubbin, 1982).

4. Lower shoreface: Deposits consist of fossiliferous, interbedded, fine and very fine sand and silt. These sediments are often heavily bioturbated. and the sediments are mixed to form silty sand. Shells consist of thin-walled, generally small, whole shells, probably in life position. Sediments of the lower shoreface were deposited below fair-weather wave base but above storm wave base (~10–20 m paleodepth based on modern facies observations; e.g., McCubbin, 1982).

5. Offshore: Deposits accumulated in paleodepths greater than 20 m paleodepth based on modern facies observations (e.g., McCubbin, 1982). They consist of thinly laminated, very fine sand, silt, and clay and generally contain foraminifers.

Benthic foraminifers provide additional constraints on paleodepth variations, though benthic foraminifers are only locally abundant in the Bethany Beach core hole. Miller et al. (1997b) used benthic foraminifers to determine water depth changes in the New Jersey lower to middle Miocene sediments. Five benthic biofacies established by Miller et al. (1997b) in New Jersey are used to interpret paleodepths in the Bethany Beach core hole (Fig. 3).

1. The *Elphidium* biofacies is an indicator of near-shore paleoenvironments (<10 m paleodepth), including lower estuarine, bay, and innermost neritic environments. This biofacies overlaps with the upper shoreface and foreshore paleoenvironments (Fig. 3).

2. The *Hanzawaia* biofacies (*Hanzawaia* cf. *H. hughesi* and *H. concentrica*) is an indicator of inner neritic paleodepths (from 10 to 25 m; ~lower shoreface paleoenvironment).

3. The *Pseudononion* biofacies is dominated by *Pseudononion pizarrensis* and commonly includes *Nonionella miocenica* and *Hanzawaia.* We interpret it to reflect paleodepths of 25–50 m (offshore; outer-inner to inner-middle neritic).

4. The *Bulimina* biofacies characterizes offshore middle neritic (50–80 m).

5. The *Uvigerina* biofacies characterizes offshore middle neritic paleodepths (>75 m).

Lithostratigraphy and Sequence Stratigraphy

Miocene lithostratigraphic units in the Bethany Beach core hole include (from oldest to youngest) an unnamed glauconitic clay and clayey glauconite sand, the Calvert Formation, the Choptank Formation, the St. Marys Formation, and an unnamed upper Miocene unit (Figs. 4–7; details in the Data Repository).[1] Fourteen Miocene sequences are discussed here: three thin, poorly fossiliferous lowermost Miocene sequences (UGC1–3); ten lower-middle Miocene Chesapeake Group sequences (Calvert, Choptank, and St. Marys Formations; C1–C10); and one sequence (M1) from the unnamed upper Miocene beds. Five sequences overlying M1 are not discussed because they lack age control. Sequences UGC1 through lower C4 are lower Miocene, upper C4–C9 are middle Miocene, and C10–M1 are upper Miocene.

Miocene sequences at Bethany Beach have a basal unconformity overlain by an occasionally glauconitic shell bed or a shelly quartz sand, deposited in a neritic paleoenvironment. Thin Transgressive Systems Tracts (TST) are overlain by regressive Highstand Systems Tracts (HST). Lowstand Systems Tracts (LST) generally are not preserved in the coastal plain. Because LST are generally absent, transgressive surfaces are merged with the sequence boundaries.

Sequence UGC1 (446.75–443.33 m; Fig. 4)

UGC1 has a prominent basal erosional surface that separates underlying Oligocene dark, olive-gray, foraminiferal clay from clayey glauconite sand. The clayey glauconite sand grades up to an MFS (444.09 m) with rare middle neritic foraminifers and an overlying glauconitic clay (444.09–443.33 m) that was deposited in offshore (>20 m paleodepths) paleoenvironments. The sequence is dated with Sr-isotopic ages of 21.0 Ma and 28.0 Ma in the overlying and underlying sequences, respectively.

Sequence UGC2 (443.33–436.02 m; Fig. 4)

The basal UGC2 sequence boundary is a heavily burrowed surface associated with a major gamma log peak. Clayey glauconitic sand above the sequence boundary grades upward to laminated, clayey silt (442.87–441.15 m) and shelly silty clay (441.15–436.25 m; offshore paleoenvironments). Benthic foraminifers indicate middle to outer neritic depths (80–100 m) in the lower part, shallowing to middle neritic (50–75 m; *Bulimina* biofacies) near the top. The MFS is associated with this biofacies shift and gamma log peak at 440.43 m. The sequence is dated with Sr-isotopes as ca. 21.0 Ma.

Sequence UGC3 (436.02–433.15 m; Fig. 4)

The basal UGC3 sequence boundary consists of a glauconite sand overlying and burrowed into a clay. Clayey, glauconitic sand (436.02–435.56 m) is overlain by clay that extends to the top of the sequence. These offshore lithofacies were deposited in ~50 m paleodepth (*Pseudononion* biofacies with some of the *Bulimina* biofacies). As in UGC1 and UGC2, HST sands typical of Miocene sequences are truncated/absent. The sequence is tentatively assigned to Zone NN2.

Sequence C1 (433.15–351.43 m; Fig. 4)

The thick lower Miocene C1 sequence consists of a heavily burrowed, irregular sequence boundary (433.15 m), a very thin TST, and a very thick HST (Fig. 4). The MFS (432.21 m) is associated with a minor gamma-log peak separating glauconitic silt below from sandier silt. Surfaces at 401.56 m and 370.79 m appear to represent flooding surfaces (= parasequence boundaries) within the overall thick C1 sequence (Fig. 4).

Homogeneous, slightly sandy silt above the MFS (Fig. 3; offshore paleoenvironments) becomes progressively sandier upsection (426.72–409.58 m; distal lower shoreface). Sandy silts (409.58–373.59 m) represent a return to deeper water offshore deposition (~20–30 m; Fig. 3). Coarsening upward, muddy sands (373.59–368.81 m; distal lower shoreface) are overlain by silty, medium sands (368.81–361.16 m; proximal lower shoreface) and poorly sorted, coarse quartz sands (361.16–351.59 m; upper shoreface).

Paleodepths of the offshore deposits were 25–50 m (*Pseudononion* biofacies). Sr-isotope ages range from 20.3 Ma at the top to 21.0 Ma at the base, with a best estimate of 20.8–20.2 Ma obtained from a linear fit (Fig. 8).

Sequence C2 (351.43–322.46 m)

Sequence C2 consists of a very thick TST and a thinner, coarsening-upward HST that coarsens and shallows upsection (Fig. 5). The basal sequence boundary is inferred by a sharp lithofacies shift in a minor coring gap, from coarse quartz sand below to glauconitic sand above, and a large gamma-ray log kick. Overlying laminated, clayey silt with scattered shell fragments (351.13–348.60 m) grades up to slightly sandy silt (348.60–338.94 m) representing shallowing within offshore environments. We place the MFS at 334 m where benthic foraminifers indicate maximum paleodepths. Overlying burrowed, very fine sands were deposited in lower shoreface paleoenvironments.

Benthic foraminifera indicate changes in paleodepth from 25 to 50 m at the base, 50–80 m in the middle, and 25–50 m at the top. *Pseudononion* biofacies are found at the base of the sequence (351.43–340.16 m). Benthic foraminiferal diversity increases from 340.16 to 326.44 m, and the sequence is dominated by the *Bulimina* biofacies. The *Pseudononion* biofacies

[1]GSA Data Repository item 2006064, additional material, is available on the Web at http://www.geosociety.org/pubs/ft2006.htm. Requests may also be sent to editing@geosociety.org.

returns above 326.44 m. Sequence C2 has Sr-isotopic ages ranging from 19.2 to 18.9 Ma (Figs. 5 and 8), with a best estimate of 19.3–18.8 Ma obtained assuming constant sedimentation rates (Fig. 8). Though sedimentation rates varied between systems tracts, this assumption provides first-order estimate of ages given the scatter amongst the Sr-isotopic data (Fig. 8). The highest occurrence of *Triquetrorhabdulus carinatus* at 332.54 m (ca. 19 Ma [Berggren et al., 1995]; = base of Zone NN3) is consistent with the constant sedimentation rate model (Fig. 8).

Sequence C3 (322.46–299.10 m)

This sequence contains a thin TST and a thick, coarsening upward HST (Fig. 5). A heavily bioturbated sequence boundary (322.46 m) separates an indurated sandstone above from a burrowed fine sand below. The TST consists of slightly shelly, fine sand and silt (lower shoreface). The MFS (320.22 m) separates sand below from clayey silt above deposited in offshore paleoenvironments. The section coarsens in the HST to heavily bioturbated fine sand with numerous clay/silt laminae (319.43–304.80 m; lower shoreface). Shell fragments become more common between 304.80 and 299.10 m, where the sediments are well-sorted, medium-fine sand (upper shoreface).

Benthic foraminifers are not common in this sequence. *P. pizarrensis* is the most consistent species, indicating paleodepths of 25–50 m. Sequence C3 (299.10–322.46 m) has Sr-isotopic ages from 19.2 to 18.6 Ma, with a best estimate of 18.8–18.4 Ma (Fig. 8).

Sequence C4 (299.10–273.62 m)

This sequence has a moderately thick TST and HST, but the facies pattern is complex, with abrupt lithofacies changes and at least two flooding surfaces (289.71 and 286.79 m; Fig. 5). The basal sequence boundary is a shelly, calcite-cemented sandstone (299.10 m) separating sand below from silt. Above this, bioturbated fine and medium sand with shells and shell fragments (299.10–295.66 m; lower shoreface) fines upsection to silty sand (295.66–292.61 m; offshore/distal lower shoreface) representing deepening in the TST. The MFS is associated with a minor gamma-log peak at 293.83 m.

The HST generally shallows upsection, although it is punctuated by flooding surfaces (Fig. 5). Offshore/distal lower shoreface deposits (293.83–292.61 m) are replaced by silty sand (292.14–291.47 m) deposited in distal upper shoreface paleoenvironments. From 291.47 to 289.71 m, the section includes muddy sand and sandy shell hash, with granule-sized shell fragments (proximal upper shoreface deposits). A contact at 289.71 m, interpreted as a flooding surface (FS), separates this sand from overlying lower shoreface/offshore silt. Silt interbedded with shelly sand (289.71–288.65 m; distal lower shoreface to offshore) changes upsection to a shelly sand (288.65–287.27 m; distal upper shoreface) and silty sand with abundant shell debris (287.27–286.79 m; proximal upper shoreface). A contact (286.79 m) between shelly sand and clayey sand above is interpreted as a second flooding surface. Clayey sand above the flooding surface (286.79–286.66 m; distal upper shoreface) is replaced by shelly, muddy sand, (284.20–282.43 m; lower shoreface). We tentatively place an FS at this level. At the top of the sequence, shelly sand (282.43–273.62 m) was deposited in distal upper shoreface paleoenvironments. Overall, the HST of sequence C4 shallows upward from offshore deposits to distal upper shoreface deposits.

Rare benthic foraminifers (*Pseudononion* biofacies) are similar to those in the underlying sequence, suggesting deposition in paleodepths of 25–50 m. The sequence is dated with Sr-isotopic ages between 18.8 and 17.1 Ma (Figs. 6 and 8), with a best-age estimate of 18.4–18.0 Ma.

Sequence C5 (273.62–239.91 m)

This sequence also consists of a thin TST and a thick HST (Fig. 6). The basal sequence boundary (273.62 m) is a heavily burrowed contact separating medium sand below from silty fine sand and is coincident with a sharp gamma-ray increase. Silty fine sand above the sequence boundary fines upward to slightly sandy silt (lower shoreface). The MFS is a burrowed contact at 270.57 m, coincident with a minor gamma-log peak.

The HST regresses from inner neritic to upper shoreface environments (Fig. 6). Laminated to bioturbated silt with scattered shells (270.57–249.91 m; inner neritic) are overlain by shelly, fine, and medium quartz sand (249.91–245.23 m; lower shoreface and distal upper shoreface). From 245.23 m to the top of the sequence (239.91 m), well-sorted, fine-medium sand with scattered heavy mineral laminae represents upper shoreface environments.

Benthic foraminifers indicate shallowing upsection through the HST with the most diverse assemblages at the MFS (*Pseudononion* assemblage, ~50 m paleodepth) passing upsection to assemblages containing rare *Hanzawaia* (~10 m paleodepth) at the top. Sr-isotopic ages range from 17.3 to 16.5 Ma (Figs. 6 and 8). Several ages in this sequence are inverted, possibly indicating reworking of younger shells within the sequence. Assuming constant sedimentation rates through this sequence (Fig. 8) yields an age estimate of 17.3–16.4 Ma.

Sequence C6 (239.91–212.90 m)

This middle Miocene sequence contains the thickest TST and a relatively thin HST (Fig. 6). We place a sequence boundary at 239.91 m, where the lithofacies stacking pattern changes from regressive below to transgressive above, coincident with a sharp gamma-log increase. The sequence boundary is poorly expressed because upper shoreface/foreshore sands above and below the sequence boundary are burrowed together.

The TST (239.91–229.79 m) consists of a well-developed deepening-upward succession (Fig. 6). A shelly, silty sand (239.91–239.36 m; upper shoreface paleoenvironments) is overlain by interbedded sand, shell hash, and silty sand (239.36–237.74 m; distal upper shoreface). Deepening continues as shelly, bioturbated, fine sand (237.47–233.45 m; lower shoreface) is overlain by heavily burrowed, slightly shelly silt (233.17–229.79 m; offshore). The MFS (229.79 m) is represented by an especially diverse benthic foraminiferal assemblage (~50 m paleodepth) and a gamma-log peak. The HST (Fig. 6) consists of heavily burrowed silt (229.79–228.69 m; offshore paleoenvironments) overlain by heavily bioturbated, medium to fine sand (228.69–213.36 m; lower shoreface).

Sporadic foraminifers indicate shallowing upsection within the HST. A low-diversity *Pseudononion* assemblage (inner neritic ~30 m paleodepths) dominates the TST. A more diverse assemblage associated with the MFS (including abundant *P. pizarrensis* and *B. paula*) represents the deep end of the *Pseudononion* biofacies or shallow end of the *Bulimina* biofacies (~50 m paleodepth). The HST contains a low-diversity *Pseudononion* biofacies interpreted to represent inner neritic (~30 m) paleodepths. Sr-isotopic ages from this sequence range from 16.2 to 15.8 Ma.

Sequence C7 (212.90–197.82 m)

The sequence boundary and very thin TST are inferred from a lithofacies change, minor gamma-log increase, and a major break in Sr-isotopic ages across an unrecovered interval (213.36–211.56 m). The thin HST exhibits excellent lithofacies changes reflecting deposition on a shallowing shelf (Fig. 6). Shelly, medium sand with shell layers (211.56–210.31 m; lower shoreface paleoenvironments) shallows up to laminated sand and silt (210.31–204.22 m; upper shoreface paleoenvironments). Upper shoreface to estuarine deposits (201.93–197.82 m) consist of poorly sorted, granule-bearing, silty sand, with common shell fragments.

The presence of rare to common *Hanzawaia* (207.57–204.52 m) suggests maximum paleodepths of 10–25 m. Sr-isotopic ages range from 14.7 to 13.4 Ma (Figs. 5 and 8). Some Sr-ages are inverted in this sequence, although these inversions are within the external precision. The age of sequence C7 is the most poorly constrained of the Miocene sequences at Bethany Beach and could date from 14.7 to 13.4 Ma. Assuming similar sedimentation rates as found in other sequences (Fig. 8) yields an age estimate of 14.5–14.2 Ma for this sequence.

Sequence C8 (197.82–175.32 m)

This sequence consists of a thin TST and an HST with at least one flooding surface (Fig. 6). The sequence boundary is inferred by a sharp facies change across an interval of no recovery (197.82–197.60 m), a minor gamma-log peak, and a Sr-isotopic break (Fig. 6). A shell bed (197.60–197.36 m) and a shelly, silty, phosphatic sand (197.36–196.60 m) marking the MFS overlie the sequence boundary.

Paleoenvironments in the HST shallow upward to a parasequence boundary at 184.94 m (Fig. 5). Interbedded silt and sand with scattered shells (196.60 and 193.70 m) were deposited in lower shoreface paleoenvironments. Medium and coarse sand (193.70–187.80 m) was deposited in distal upper shoreface paleoenvironments. Less silty, medium sand (187.80–185.14 m) and a shell bed (185.14–184.94 m) represent proximal upper shoreface deposits. The deepening of paleoenvironments across the shell bed indicates there is a flooding surface at 184.94 m.

The HST shallows upward between 184.94 and 175.32 m. Heavily bioturbated sand with scattered clay laminae and shell fragments (184.94–180.75 m; lower shoreface paleoenvironments) are replaced by laminated sand and silt (180.75–178.00 m; distal upper shoreface paleoenvironments). Gravelly, silty sand (178.00–177.09 m) and overlying fine to medium sand (177.09–176.78 m) were deposited in upper shoreface to lower estuarine paleoenvironments.

Benthic foraminifers generally are rare in this sequence. An assemblage immediately above the sequence boundary is suggestive of the inner neritic *Hanzawaia* biofacies (10–25 m paleodepth). Abundant *Hanzawaia* and less numerous *P. pizarrensis* (~25 m paleowater depth) are found at the MFS. Sr-isotopic ages range from 13.7 to 13.1 Ma (Figs. 6 and 8), with a best estimate of 13.5–13.1 Ma and an average sedimentation rate of 56 m/m.y.

Sequence C9 (175.32–159.43 m; Fig. 7)

This sequence (lower St. Marys Formation) represents paleoenvironments deeper than sequences C6–C8. The sequence boundary (175.32 m) occurs at the base of a cemented, quartz sandstone (175.32–174.89 m) associated with a sharp gamma-ray peak. The cemented bed and an overlying shell bed with a quartz sand matrix (174.89–174.53 m) were deposited in upper shoreface paleoenvironments. Shells are less common in a faintly laminated, homogeneous sand, with increasing bioturbation upsection (174.53–173.80 m; lower shoreface paleoenvironment). Above this is a burrowed, micaceous clay (173.83–169.93 m; inner neritic or middle neritic offshore paleoenvironment). An extensively burrowed surface at 169.93 m separates the clay from a glauconite sand (169.93–168.71 m). Although this surface looks typical of many sequence boundaries, the facies stacking pattern under it (173.81–169.93 m) is clearly transgressive from upper shoreface to inner/middle neritic offshore environments. Thus, we interpret the surface at 169.93 m as the MFS.

The HST represents a middle neritic paleoenvironment. Glauconite sand (169.93–168.71 m; Fig. 7) is overlain by silty clay and clayey silt (168.71–166.27 m) that grades to a foraminiferal-rich, laminated, silty offshore clay (166.27–159.65 m). Unlike older sequences in the Bethany Beach core hole, there are no sandy lithofacies at the top of sequence C9.

Benthic foraminifers indicate that the section shallows upward. Benthic foraminiferal assemblages from 174.35 to 164.59 m represent the *Uvigerina* biofacies (~75 m or greater paleodepths). Above 164.59 m the presence of *Pseudononion* and *Hanzawaia* with abundant *Bulimina* (Hernandez, 2002) indicates deposition in the shallow end of the *Bulimina* biofacies paleodepth range (~50 m). The dominance of gastropods, numerous concretions, and common laminations suggest deposition in an oxygen-deficient benthic paleoenvironment.

The tentative identification of *Trinovantedinium glorianum* at 174.35 m indicates sequence C9 may not be older than dinocyst Zone DN7 (<12.4 Ma; late middle Miocene; Miller et al., 2002b). A more precise date is difficult to confirm because of wide-ranging Sr-isotopic ages of 15.0–11.7 Ma (Figs. 7 and 8). The older ages obtained from the sequence probably result from either diagenesis or reworking of older material. Age estimates of 11.7 and 11.8 Ma were obtained from shells taken from fine-grained silts and clays in which diagenesis or reworking is less likely; thus we prefer an age assignment of ca. 11.8 Ma for this sequence. Assuming similar sedimentation rates as found in the overlying C10 sequence (56 m/m.y.; see below; Fig. 8) as a rough estimate yields an age of 11.9–11.6 Ma for this sequence.

Sequence C10 (159.43–137.91 m)

A sequence boundary occurs at 159.43 m at the top of an indurated zone (159.65–159.43 m; Fig. 7), coincident with a gamma-ray maximum. Glauconite sand-filled burrows from above the boundary extend down through the indurated zone into the underlying clay, obscuring the contact. Paleodepths shallow upward across this sequence boundary, contrasting with other sequences that deepen across their basal boundaries.

This upper Miocene sequence (upper St. Marys Formation) consists of a thin TST and a thick HST (Fig. 7). Silty glauconite sand (159.43–158.50 m; middle neritic paleoenvironment) representing the TST is overlain by a poorly recovered indurated interval (157.34–157.12 m) with scattered phosphate grains that marks the MFS. The HST (157.12–137.91 m) is a generally laminated, clay to silty clay, with scattered shells (mostly gastropods) and numerous concretions. The absence of evidence for a major erosional truncation at the top (e.g., rip-up clasts, hardgrounds) indicates that the lack of sand in the HST may be due to sediment starvation.

Benthic foraminiferal biofacies indicates deposition in inner to middle neritic paleoenvironments. The base of the sequence contains the *Pseudononion* biofacies (25–50 m paleodepth). The sequence attained maximum paleodepths of 50–80 m (*Bulimina* biofacies) from 155.45 to 152.40 m. Paleodepths returned to 25–50 m in the upper part. As in sequence C9, sequence C10 was likely deposited in an oxygen-deficient benthic environment. The C10 sequence has three Sr-isotopic ages of 10.0, 10.8, and 9.6 Ma (Figs. 4 and 8). Linear regression through the data in this and the overlying sequence yields a best-age estimate of 10.2–10.6 Ma (Fig. 8), with a mean sedimentation rate of ~56 m/m.y.

Sequence M1 (137.94–114.30 m)

This sequence consists of a very thin TST and a thick HST (Fig. 7). A sequence boundary associated with a gamma-log peak (137.94 m) separates slightly glauconitic shelly clay above from laminated brown clay below. Above this, slightly glauconitic clay transitions up to slightly silty clay. This burrowed (but not erosional) MFS (136.98 m) separates clay below from very fine sandy silt above. The HST (Fig. 7) consists of sandy silt with thin-walled mollusk shells (136.98–135.64 m), heavily bioturbated, silty sand (135.64–123.44 m; offshore/middle neritic paleoenvironments), and granule-bearing sand, with abundant mollusk shells and shell hash (123.44–114.30 m; lower shoreface paleoenvironments). We place a sequence boundary in an interval of no recovery between 113.78 and 114.30 m because of a major lithologic shift and a gamma-log peak at 114.00 m.

The *Bulimina* biofacies (50–80 m) dominates the bottom of the sequence (137.91–133.20 m). A sparse shallow-water assemblage, characterized by *Quinqueloculina* and *Pseudononion,* dominates the sequence above 133.20 m. Sr-isotopic age estimates range from 11.7 to 9.6 Ma, though they cluster from 10.5 to 9.6 Ma (the 11.7 Ma estimate is interpreted to be an outlier). Linear regression through the data in this and the overlying sequence yields a best-age estimate of 10.2–9.8 Ma for the M1 sequence (Fig. 8), with a mean sedimentation rate of ~56 m/m.y.

Comparison Between New Jersey Coreholes and Bethany Beach, Delaware

Miller et al. (1997b) identified nine lower and middle Miocene sequences in the New Jersey Coastal Plain (Figs. 9 and 10). The number of Miocene sequences preserved in New Jersey increases downdip from three at Island Beach to six at Atlantic City and Ocean View to nine at Cape May. This simple pattern of increasing preservation downdip becomes more complex and patchwork when comparing with sequences in Delaware and Maryland.

Sequences in New Jersey and Delaware compare well in age (Figs. 9 and 10), although there are some differences. The precise correlation of the lowermost Miocene UGC sequences with the higher-order New Jersey Kw1 sequences is uncertain. In New Jersey, sediments between 21 and 20.1 Ma are assigned to sequence Kw1a. In the Ocean View, Cape May, and Atlantic City coreholes, the sequence Kw1 was further divided into three subsequences: Kw1a1 (21.5–20.4 Ma), Kw1a2 (20.4–20.3 Ma), and Kw1a3 (20.3–20.2 Ma), from oldest to youngest. Sequence C1, deposited between 20.8 and 20.2 Ma (Fig. 8), appears to correlate with the New Jersey Kw1a sequence (Miller et al., 1997b), though it is not clear how sequence C1 is related to the higher-order Kw1a1–1a3 sequences. UGC1 and UGC3 sequences were not dated. UGC2 yielded an Sr-isotopic age of 21.0 ± 0.6 Ma at 436.11 m and the HO of *Globorotalia kugleri* at 349.48 m (21.5–23.8 Ma; Figs. 4 and 8). Foraminifera thus indicate that UGC2 is equivalent to the Kw0 sequence in New Jersey (ca. 22–23.5 Ma; Miller et al., 1998a), though Sr-isotopes are more compatible with a Kw1a1 correlation, UGC1 equivalent to the Kw0 sequence of New Jersey and UGC3 with the Kw1ab sequence. For backstripping we assigned an age of 21.7–21.6 Ma to UGC3, an age of 21.6–21.5 Ma to sequence UGC2, and an age of 21.5–21.4 Ma to sequence UGC1. Additional study is needed to define the age of these thin, basal Miocene sequences in Delaware.

The Bethany Beach section from 351.43 to 273.62 m (C2, C3, and C4) contains three sequences, but the hiatuses between them are too short to firmly resolve them using Sr-isotopic stratigraphy (Figs. 5 and 8). We present two age models (Fig. 8): the first represents continuous sedimentation (mean sedimentation rate = 57 m/m.y.); the second model assumes short hiatuses, with a mean sedimentation rate similar to that found in sequence C1 (136 m/m.y.). Sequence C2 (19.2–18.9 Ma assuming short hiatuses) is equivalent in age to sequence Kw1c in New Jersey (Miller et al., 1997b), and sequence Kw1b is missing in Delaware. Sequence C3 (18.75–18.55 Ma assuming short hiatuses) is equivalent in age to sequence Kw1c in New Jersey (Miller et al., 1997b). Sequence C4 (18.4–18.15 Ma assuming short hiatuses) does not appear to have a sequence of equivalent age in New Jersey.

Sequences C5 and C6 are difficult to date precisely. Sequence C5 ranges from 17.3 to 16.4 Ma (assuming continuous sedimentation) to 17.0–16.7 Ma (assuming best fits to Sr; dashed line, Fig. 8). Sequence C6 ranges in age from 16.4 to 15.7 Ma (assuming continuous sedimentation) to 16.2–15.8 Ma (assuming best fits to Sr; dashed line, Fig. 8). Thus, sequences C5 and C6 correlate with the Kw2a and Kw2b sequences, respectively, in New Jersey (Miller et al., 1997b).

Sequence C7 and C8 have linear regression best-age estimates of 14.5–14.2 Ma and 13.5–13.1 Ma (Figs. 6 and 8), correlating with the Kw2c and Kw3 sequences, respectively, in New Jersey (Miller et al., 1997b). Sequence C9 is ca. 11.8 Ma, equivalent to the Kirkwood-Cohansey (Kw-Ch) sequence in New Jersey.

Early late Miocene sequences are well expressed in Delaware and better dated than in New Jersey. Sequence C10 has Sr-ages of 10.8 and 9.6 Ma (Figs. 7 and 8). Sr-isotopic age estimates for the M1 sequence range from 11.7 to 9.6 Ma, though they cluster from 10.5 to 9.6 Ma (Figs. 7 and 8). Linear regressions through the data yield a best-age estimate of 10.6–10.2 Ma for sequence C10 and 10.2–9.8 Ma for the M1 sequence (Figs. 7 and 8). Sequences equivalent in age to the C10 and M1 sequences have not been firmly dated in New Jersey, though they may correlate with the Ch3 and Ch4 sequences of De Verteuil (1997; Fig. 10), respectively, which have been dated only with dinocysts.

Reevaluation of Maryland Outcrop Ages

Subsurface sections in Maryland have generally not been continuously cored (Olsson et al., 1987), but classic outcrops along Chesapeake Bay (the Calvert Cliffs of Maryland and Virginia; Calvert and Choptank Formations; Fig. 1) provide information on Miocene sequences from the southern Salisbury Embayment. Kidwell (1984) identified four sequence boundaries in outcrops of the Plum Point Member (sequence boundaries PP0 through PP3) and two in the Choptank Formation (CT0, CT1). Biostratigraphic correlations of these outcrops are uncertain because they are shallow-marine sediments. Miller and Sugarman (1995) measured Sr-isotopic ratios in mollusk shells from Maryland and Virginia outcrops and noted that diagenetic overprints and intense bioturbation complicate correlation.

We reevaluated the Maryland Sr-isotopic ages of Miller and Sugarman (1995) using the new Sr-isotopic calibration (see Methods, above) and plotted the revised age estimates on an age-depth diagram (Fig. 11). Though the sequence ages in Maryland are uncertain, we provide the following correlations.

1. The ages of strata older than the PP0 sequence boundary (Fairhaven Member) are >17.8 ± 0.6 Ma, correlating with sequences C4 in Delaware and Kw1c in New Jersey (Fig. 12). Miocene strata older than ca. 18 Ma appear to be absent in the Maryland-Virginia outcrops, where upper lower Miocene strata rest unconformably on Eocene strata. Olsson et al. (1987) reported one older sequence (ca. 22–22.5 Ma, mid-Zone N5) in the Maryland subsurface that may correlate with Kw0.
2. A short hiatus is associated with the PP0 sequence boundary (ca. 17.9–17.7 Ma). The age of the PP0 sequence is ca. 17.7–17.1 Ma, correlating with sequences C5 and Kw2a (Fig. 12).
3. There is significant hiatus associated with the PP1 sequence boundary (17.1–16.2 Ma); the PP1 sequence (ca. 16.2–15.7 Ma) correlates with sequences C6 and Kw2b (Fig. 12).
4. Age control on the PP2 and PP3 sequences is moderately poor (±1.2 m.y.), in part due to the lower rate of change of $^{87}Sr/^{86}Sr$. A visual best fit through the data (dashed line in Fig. 11) yields no discernable hiatus. We prefer an age model (solid line Fig. 11) in which the PP2 sequence correlates with sequence C7 and the Kw2c and PP3 with C8 and Kw3.
5. Ages in the CT0 and CT1 sequences are 11.8–14.0 Ma (mean of CT0, 12.7 Ma; mean of CT1, 13.1 Ma). Olsson et al. (1987) reported that the Choptank Formation is Tortonian (early late Miocene; ca. 8.5–9.0 Ma), in sharp contrast with our Sr-isotopic ages. We suspect diagenetic alteration and believe that redating these strata is necessary.

DISCUSSION

Influence of Sediment Supply and Stratal Architecture

Although coastal plain strata in both Delaware and New Jersey are derived primarily from siliciclastic systems, our data indicate that depositional systems were fundamentally different between these two areas. Wave-dominated

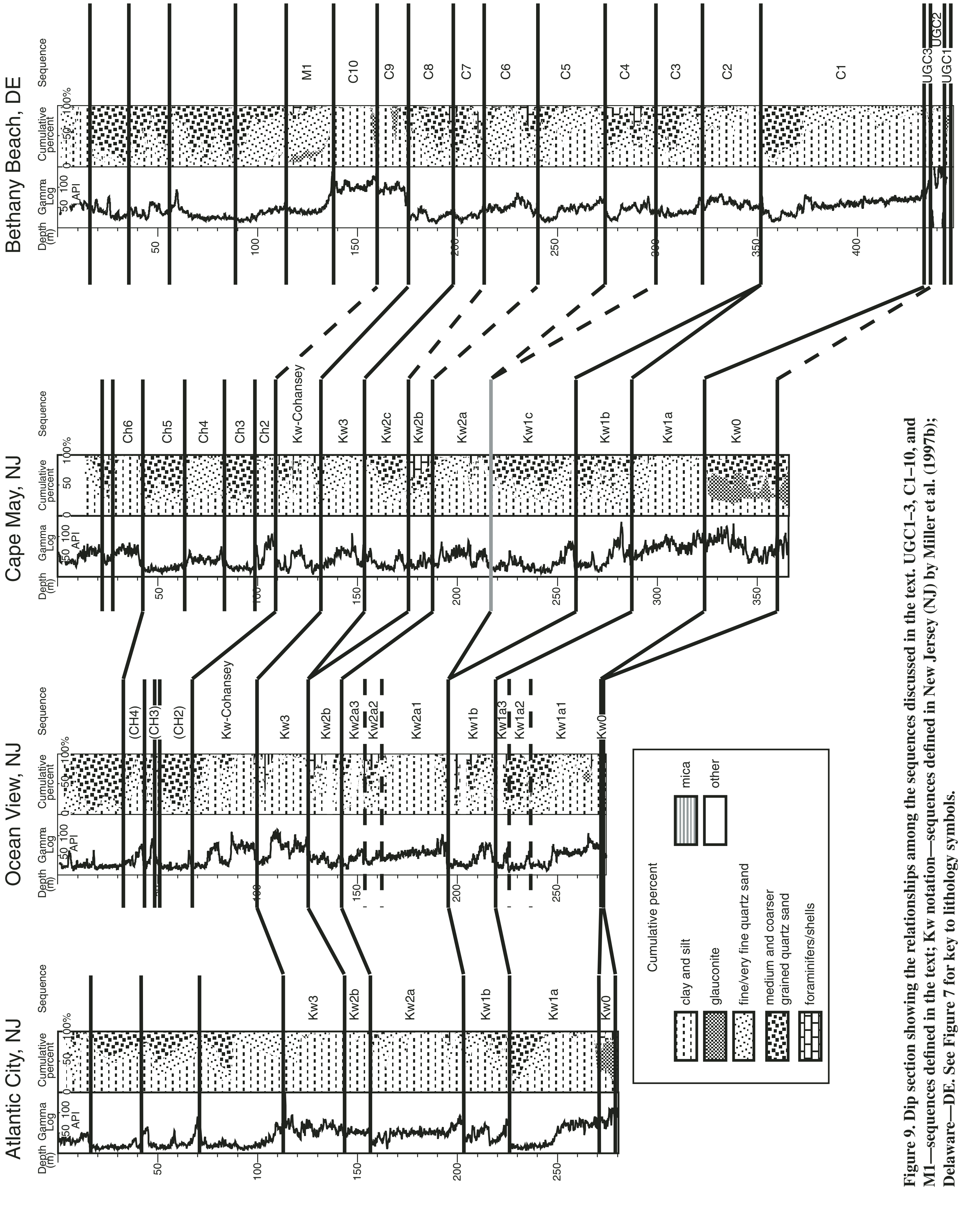

Figure 9. Dip section showing the relationships among the sequences discussed in the text. UGC1–3, C1–10, and M1—sequences defined in the text; Kw notation—sequences defined in New Jersey (NJ) by Miller et al. (1997b); Delaware—DE. See Figure 7 for key to lithology symbols.

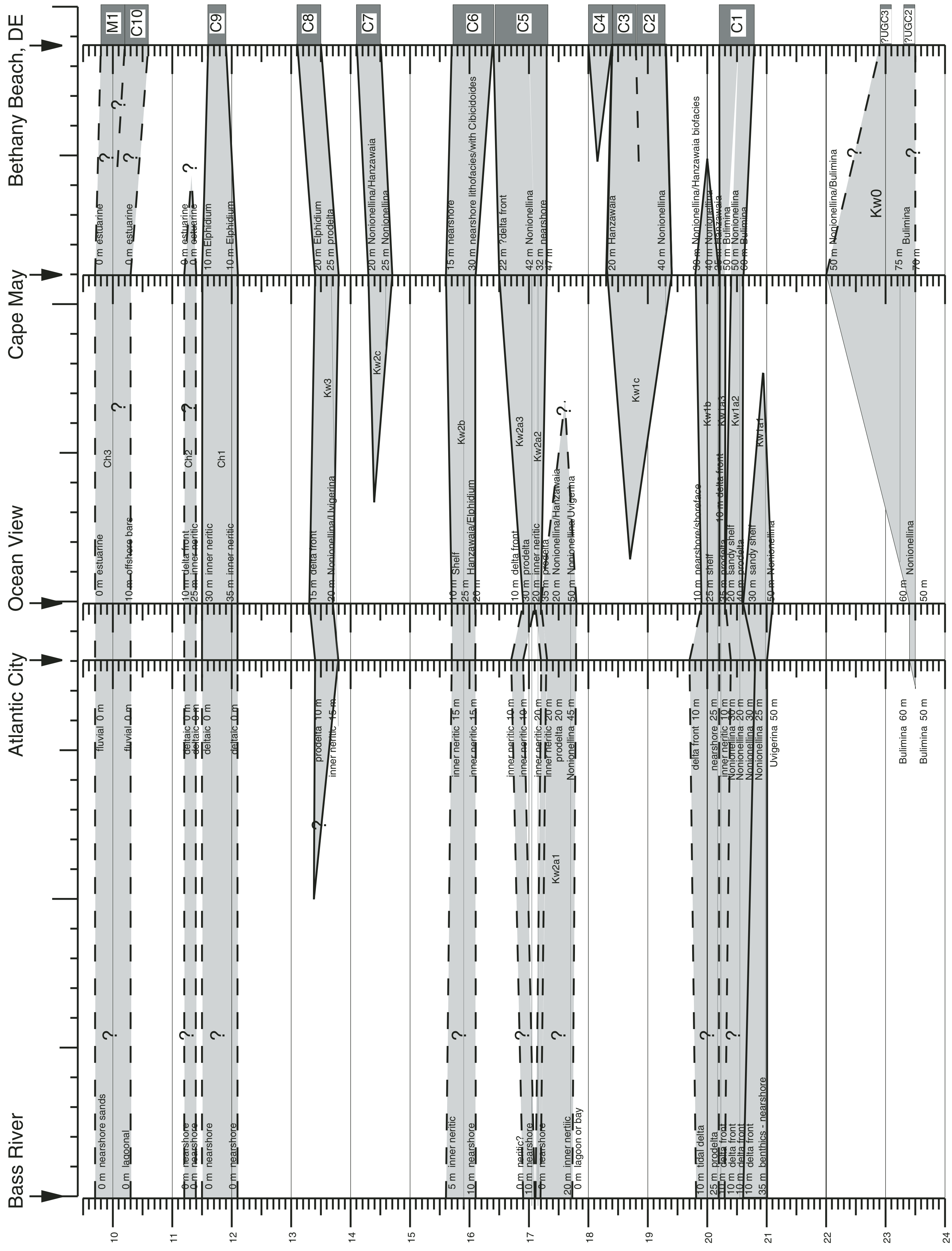

Figure 10. Diagram showing the distribution of the New Jersey and Delaware Miocene sequences in time. UGC1–3, C1–10, and M1—sequences defined in the text; Kw notation—sequences defined in New Jersey (NJ) by Miller et al. (1997b). Ch notation refers to sequences within the Cohansey Formation.

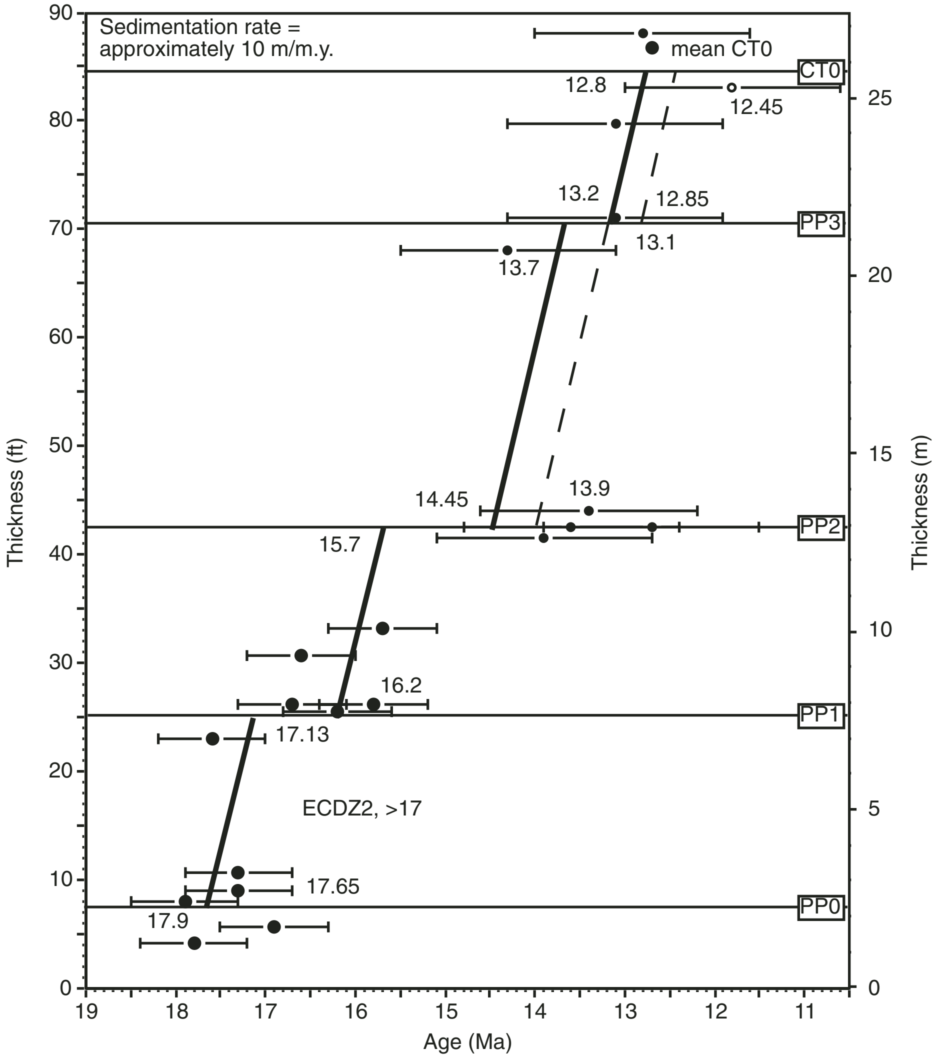

Figure 11. Age-depth plot showing the distribution through time of the outcropping Miocene sequences from Maryland. Dashed line—an alternate age interpretation; ECDZ2—East Coast Diatom Zone 2. CT0 and PP notation refers to sequence boundaries defined by Kidwell (1984).

shoreline deposits are characteristic at Bethany Beach (Fig. 3), whereas deltaic systems dominate in New Jersey (Fig. 2). Nevertheless, both regions share a similar sequence stratigraphic succession for the Miocene. LST are largely absent in the seven coreholes drilled in New Jersey and Delaware, and transgressive surfaces are usually merged with sequence boundaries. TST occur at the bases of some sequences but are thin. In Delaware, the thickest Miocene sequences generally have the thinnest TST. In general, HST are divided into a lower fine-grained unit (prodelta silty clays in New Jersey, generally silts in Delaware) and an upper sandy unit. The HST sand comprises important aquifers in both regions and are generally confined by fine-grained units of the overlying TST and lower part of the HST. Aside from these similarities, there are important sequence stratigraphic differences between the Delaware and New Jersey regions. For example, MFS and other flooding surfaces identified in the Bethany Beach core hole (in particular those in sequences C1, C3, C5, and C9) are associated with more evidence of burrowing and erosion than MFS in New Jersey, whereas sequence boundaries commonly are more subtle in Delaware due to juxtaposition of similar facies.

Sedimentation rates were high in the Miocene at Bethany Beach compared to coeval sections in New Jersey. Sedimentation rates were 37–59 m/m.y. (mean 53 m/m.y.) in Delaware from 9.8 to 18.8 Ma and 136 m/m.y. from 20.2 to 20.8 Ma. In contrast, sedimentation rates at the thickest Miocene section in New Jersey (Cape May) were 29–47 m/m.y. (mean 40 m/m.y.) from 11.5 to 20.2 Ma and 91 m/m.y. from 20.2 to 20.6 Ma. Nevertheless, in this case thickness does not scale into stratigraphic continuity. The New Jersey record is much more complete in the earliest Miocene (22–23.8 Ma). In contrast, the Delaware section is more complete in the late early Miocene (ca. 19–16.2 Ma; Fig. 10).

Eustatic versus Tectonic Effects

Comparison of sequences from different parts of the Salisbury Embayment (New Jersey, Delaware, and Maryland-Virginia; Fig. 12) shows similarities testifying to a global control but also significant differences testifying to tectonic overprints. In general, Miocene sequences deposited between 17.5 and 12 Ma correlate well across the basin from New Jersey to Delaware (Figs. 9 and 10). The chronology of sequences in the Maryland outcrops is consistent with the New Jersey and Delaware records from the late early to middle Miocene (ca. 17.5–12 Ma; Fig. 12). The stratigraphic correlation of sequence boundaries with global $\delta^{18}O$ increases (Fig. 12) suggests control by glacioeustasy, as previously concluded by Miller et al. (1996, 1998a). However, the early Miocene distribution of sequences (Fig. 12) and backstripping at Bethany Beach shows a more complicated pattern than would be expected from glacioeustasy alone. The distribution of sequences in the early Miocene (24–17.5 Ma; Figs. 9, 10, and 12) reveals a patchwork distribution of sequences in the mid-Atlantic region. Distributional differences include the following.

1. Lower Miocene strata older than ca. 18 Ma are very thin or absent in Maryland outcrops and subsurface (this study and Olsson et al., 1987).
2. Lowermost Miocene (UGC) sequences are very thin in Delaware versus New Jersey.
3. Lower Miocene Kw1b does not appear to have an equivalent in Delaware.
4. Lower Miocene sequence C4 at Bethany Beach does not appear to have an equivalent in New Jersey (Figs. 9, 10, and 12).

These distributional differences suggest a noneustatic overprint to the stratigraphic record. Active tectonics may explain some distributional differences. The lower Miocene of Maryland (Olsson et al., 1987) and Virginia (Edwards et al., 2004, 2006) appears to be thin throughout as compared to Delaware and New Jersey. The thinness of the lower lower Miocene in this area may be ascribed to crustal movements as suggested by Brown et al. (1972), though further coring of Maryland and Virginia sections is warranted to

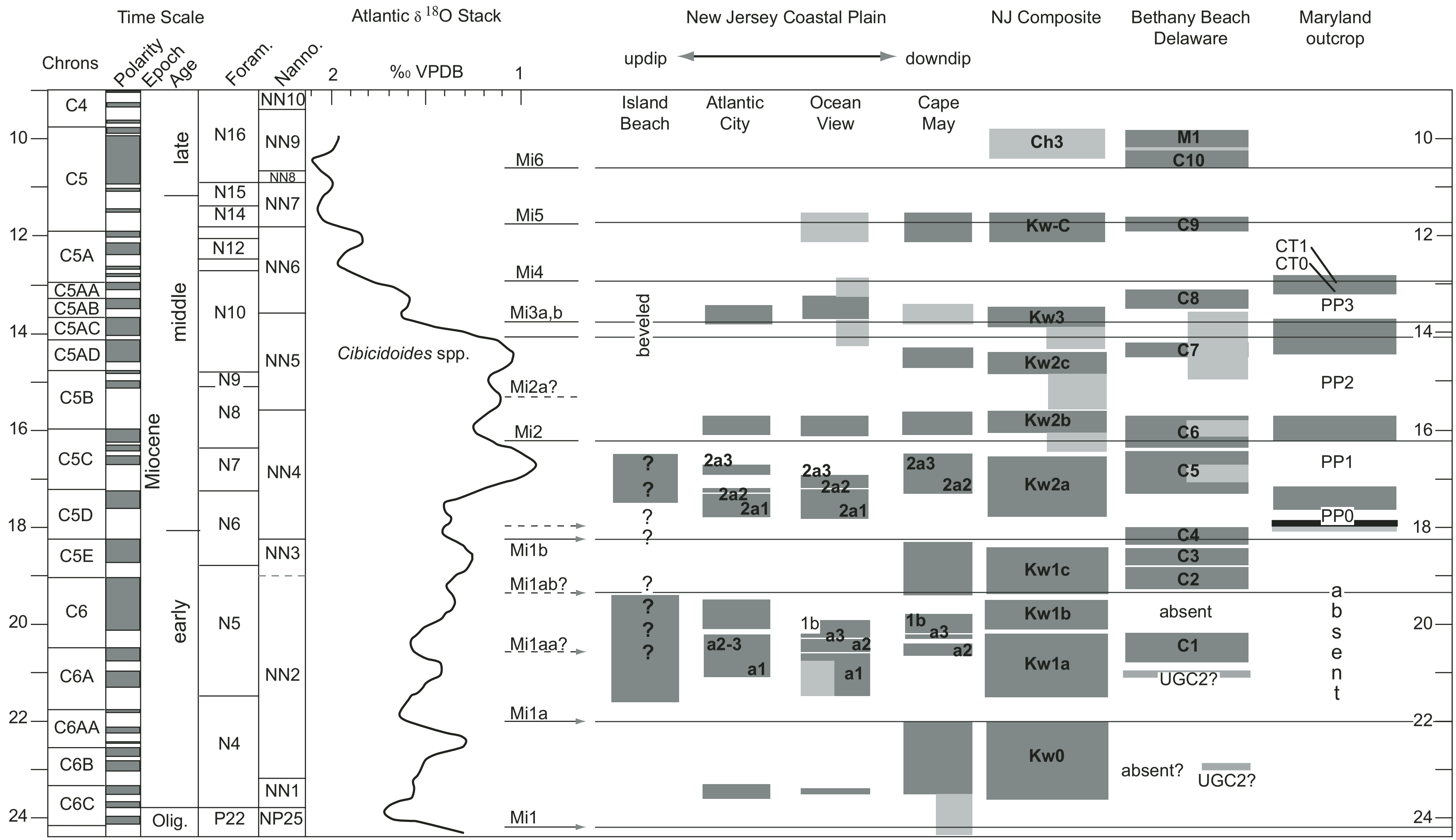

Figure 12. Summary diagram for the sequences from New Jersey, Delaware, and Maryland. Time scale is from Berggren et al. (1995). Foram.—planktonic foraminiferal biozone; Nanno.—calcareous nannoplankton biozone. Also shown is the benthic foraminiferal oxygen isotopic record for Atlantic deep-sea sites (modified after Miller et al., 1987). Mi events are major isotopic increases that are inferred to correlate with ice-growth events on Antarctica; arrows are placed at inflection points. UGC1–3, C1–10, and M1—sequences defined in the text; Kw notation—sequences defined in New Jersey (NJ) by Miller et al. (1997b); blue boxes—time represented; cross-hatched boxes—uncertain ages. CT0 and PP notations refer to sequence boundaries defined by Kidwell (1984). VPDB—Vienna Peedee belemnite.

determine the exact preservation of sequences and the cause of these differences. Stratigraphic differences between New Jersey and Delaware Miocene require only moderate (tens of meters) variations in accommodations that can be explained by local loading effects rather than active tectonics. For example, the 21–11 Ma section at Bethany Beach is substantially thicker (~320 m) than coeval sections in New Jersey (e.g., ~250 m at Cape May and ~220 m at Ocean View), requiring ~30–50 m in excess accommodation as estimated by backstripping.

Backstripping provides a quantitative estimate of accommodation caused by eustasy and tectonics. The subsidence of the basement beneath the coastal plain is a flexural response to offshore sedimentation on the stretched, thermally subsiding margin (Kominz et al., 1998). As long as sedimentation keeps up with subsidence, coastal plain subsidence should be exponential in form, mimicking the tectonic subsidence of the thermally cooling passive margin ("thermoflexural subsidence"). Backstripping shows that accommodation for New Jersey Miocene sequences can be explained by thermoflexural subsidence, with no evidence for active tectonics (e.g., faulting or basin inversion; Kominz et al., 1998; Van Sickel et al., 2004). Subsidence at Bethany Beach also followed a predictable thermoflexural curve (e.g., thermal subsidence lines, Fig. 13) from inception of subsidence at ca. 140 Ma until the earliest Miocene (ca. 21 Ma). At that time, a period of anomalous subsidence began at Bethany Beach and continued until 12 Ma, with peak subsidence being from 21 to 16 Ma (Fig. 13), as shown by a rising R2 (second reduction, accounting for the effects of compaction, Airy loading, and thermoflexural subsidence) curve from ca. 22–12 Ma, which is indicative of increasing accommodation space (Fig. 13B). The R2 curve (Fig. 13) illustrates that total excess accommodation (i.e., not accounted for by eustasy, compaction, and Airy loading) was ~30 m from 21 to 12 Ma. Removing a linear, 30 m rise from the Bethany R2 curves (Fig. 13) yields a curve remarkably similar to the R2 curves from New Jersey, implicating eustasy as the dominant effect and quantifying the "tectonic" response at Bethany Beach. In fact, we suggest that the cause was not tectonic in the sense of active or thermal subsidence but is attributable to a local flexural response to sediment loading, as explained below.

The flexural response of an elastic plate to a load results in subsidence near the load and a slight uplift (flexural bulge). The amplitudes are characteristic of the magnitude of the load, and distances are characteristic of the plate rigidity (Turcotte and Schubert, 1982). The main load is the large (~16 km thick) offshore sediment package comprising the Baltimore Canyon Trough (Grow and Sheridan, 1988). However, Miocene sequences show a prograding clinoform geometry with over 100 m of sediment in the thickest parts of the clinoforms (Fig. 1). The loads of these clinoforms would have created excess adjacent flexural subsidence. We suggest that a flexural response associated with the deposition of the thickest part of the clinoform rollovers of sequences led to excess accommodation and enhanced sequence preservation near the clinoform. The R2 curve (Fig. 13) shows that the greatest increase in excess accommodation in Delaware (~20–25 m; Fig. 13) occurred at C1 time (ca. 21 Ma) when the prograding clinoforms were centered near Bethany Beach (at this site, immediately offshore, and along strike toward Cape May; Fig. 1). This implies that the anomalous early Miocene subsidence at Bethany Beach was caused by local flexural loading of a thick (i.e., 100 m or so) lower Miocene clinoform near this site and that the equivalent accumulations are also anomalously thick at Cape May.

Sequence progradation, coupled with a flexural response to the prograding load, can partially explain thickness and preservation of sequences (Fig. 1; e.g., Pekar et al., 2000). Seismic data from offshore New Jersey show that the thickest lower Miocene clinoforms are located offshore of Cape May ("early Miocene depocenter," Fig. 1). Though no detailed seismic profiles are available in the vicinity of Bethany Beach, this depocenter trends into Bethany Beach (Fig. 1). Sequences were generally thin in New Jersey and Delaware through the Oligocene (Pekar et al., 2000). Sediment supply increased progressively beginning in the late Oligocene (27 Ma) and continuing through the early and middle Miocene (e.g., Miller et al., 1997a; Steckler et al., 1999). Uppermost Oligocene sequences reach their maximum thickness immediately landward/updip of Cape May (Pekar, et al., 2000). We suggest this caused excess subsidence in the earliest Miocene at Cape May. A 35-m-thick lowermost Miocene sequence at Cape May was preserved as a result (24 Ma, Kw0, Fig. 10). Thick Miocene sequences are next found at Bethany Beach beginning at 21 Ma (sequence C1, 80 m), suggesting the sequences were thickest immediately offshore at this time. By C2–C5 time (19–17 Ma), sequences had prograded 10–30 km offshore (Fig. 1) resulting in thinner deposits at Bethany Beach (30 m each). By C6–M1 time (ca. 16–10 Ma), sequences were 30–40 km away (Fig. 1) and were thinner yet, onshore at Bethany Beach (20 m). The strike of these sequences is oblique to the trend of the modern coastline. Older depocenters are first found along the modern coastline to the north. Younger sequences prograded over the older sequences and are found progressively to the south. This gives the impression of basin rolling to the south but is in fact an artifact of progradation oblique to the coastline.

Global Implications

Our comparisons of Miocene sections at Bethany Beach, Delaware, with well-studied sections to the north in New Jersey and more poorly sampled sections to the south in Maryland clearly demonstrate the roles played by eustasy and by local subsidence in generating the architecture of sequences. Eustasy provides the common element among different parts of the basin, whereas variations in subsidence determine the local preservation and the stratigraphic expression of the sequences. The global commonality of Miocene sequences in many settings (Bartek et al., 1991) testifies that eustasy is a dominant variable.

Previous studies have invoked active tectonics (Brown et al., 1972) or a warping of basins ("rolling basins" of Owens et al., 1997) to explain differential preservation of sequences on the Atlantic margin of the United States. Our mechanism ascribes most of the differences to prograding sequences that affected accommodation through flexural loading. This observation is applicable not only to this margin but also margins throughout the world.

Prograding Miocene sequences are observed not only on passive margins (e.g., New Jersey, offshore Alabama, Canterbury Basin, New Zealand; Lu and Fulthorpe, 2004) but also on active margins (e.g., Indonesia; see Bartek et al., 1991 for examples). This increase in progradation has been attributed to an increase in global weathering rates in the Miocene (Richter and DePaolo, 1988). Our studies predict that such prograding sequences on other margins will also cause differential preservation of coastal plain sequences. Preservation of sequences will be optimal near the depocenter (e.g., the lowermost Miocene of southern New Jersey or the lower Miocene of Delaware) and will be spottier near the margins of the depocenter.

We cannot explain all aspects of sequence stratigraphy by eustasy, thermal subsidence, and flexural loading, because active basin movements can remove whole series. For example, Upper Cretaceous sequences in the Carolinas (Self-Trail et al., 2002) are remarkably similar to New Jersey (Miller et al., 2004), testifying to the importance of eustasy; however, the Paleogene series is thin and absent in southern North Carolina due to movement on the Cape Fear Arch (Self-Trail et al., 2004). A similar

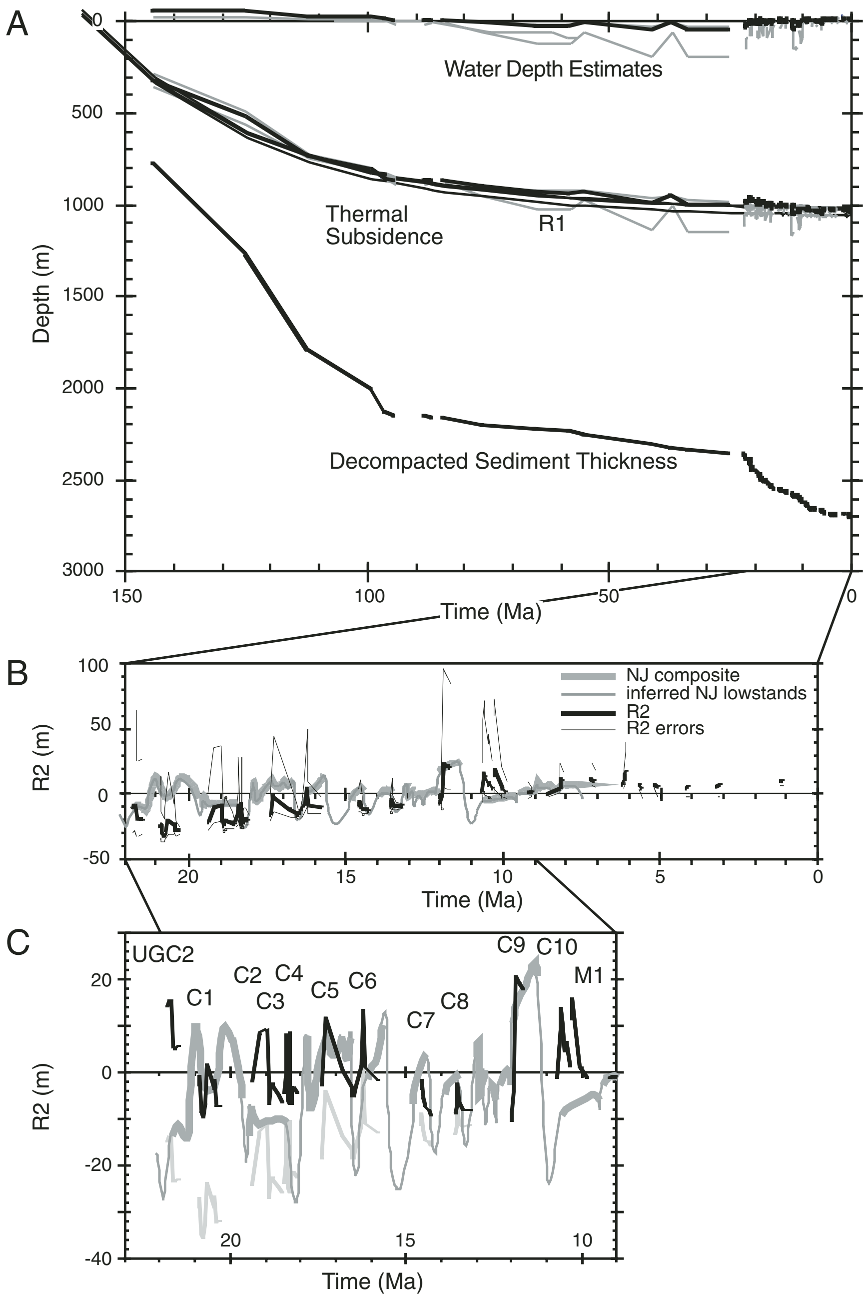

Figure 13. Backstripping results from Bethany Beach borehole. (A) R1 results. R1 is accommodation space or the subsidence of the basement in the absence of a sediment load. The "thermal subsidence curves" are estimates of the tectonic portion of subsidence. The decompacted sediment thickness curve shows the thickness of the compacting sediment column from the basement. The water depths and uncertainties are shown at the top of the plot. Pre-Miocene thicknesses, lithologies, and environments were estimated from Doyle (1982), Hansen (1982, 1984), and Doyle and Robbins (1977). (B) R2 results. The difference between the thermal subsidence curves and the R1 subsidence curves are termed "R2." The gaps between plotted data indicate the presence of hiatuses. The thick gray lines—average results from earlier New Jersey coastal plain R2 analyses (Van Sickel et al., 2004); thin gray lines connecting thick gray line segments—postulated lowstands; thin black lines—errors on the thick black R2 estimates. (C) Enlargement of Figure 13B. Gray stippled line is the R2 estimate from Bethany Beach, Delaware. The third reduction, R2, was computed by linearly removing 30 m of apparent sea-level rise progressively from the Bethany Beach R2 curve from 21 to 12 Ma. Recalling the uncertainty in dating of the sequences of ±1–2 m.y., there is an excellent correspondence of R3 (black) and the R2 of New Jersey (gray).

active mechanism may explain the thinness of the lower Miocene in Maryland and Virginia (Edwards et al., 2003, 2006). Regional differences between the southern (Maryland-Virginia) and northern (New Jersey–Delaware) parts of the Salisbury Embayment could be explained by differences in sediment supply and/or structural differences (e.g., more active wrench tectonic [Brown et al., 1972] or upper/lower plate motions [Lister, 1986]). However, the often puzzling differences in preservation of sequences on passive continental margins on the tens of meters scale do not require large-scale crustal movements and can be better explained by a flexural response due to sediment loading. We conclude that: (1) sea-level rise and fall is a first-order control on accommodation and provides a globally similar record; (2) large-scale tectonic changes due to crustal movement can overprint the record resulting in large gaps (e.g., whole series/stages); (3) smaller differences in sequences can be attributed to local flexural loading effects, particularly in regions experiencing large-scale progradation.

CONCLUSIONS

1. We identified and dated twelve major early-middle Miocene (UGC1–3 and C1–9) and two late Miocene (Sequences C10, M1) sequences in the Bethany Beach, Delaware, corehole. Age control is provided primarily by Sr-isotopes (resolution of ±0.6 to ±1.2 m.y.) and limited biochronology.

2. In contrast to Miocene sequences in New Jersey that were dominated by deltaic sedimentation, Delaware sequences represent nearshore and shelf paleoenvironments. We developed wave-dominated shoreline lithofacies and biofacies models and applied them to Miocene sequences in Delaware for paleodepth control.

3. Miocene sequence stratigraphic architecture is similar in Delaware and New Jersey despite the fundamentally different depositional regimes. Lowstand deposits are largely absent, transgressive systems tracts are thin, and highstand systems tracts are thick. The lower, fine-grained, highstand deposits (prodelta silty clays in New Jersey, silts in Delaware) contrast with sandier upper highstand deposits (delta-front sands in New Jersey, upper shoreface sands in Delaware). There are also important sequence stratigraphic differences between Delaware and New Jersey. MFSs identified in the Bethany Beach corehole, for example, show greater evidence of erosion than MFSs in New Jersey, whereas sequence boundaries are often more subtle in Delaware due to juxtaposition of similar facies.

4. We reevaluated Miocene sequences in Maryland outcrops and compared sequences

throughout the Salisbury Embayment from central New Jersey to Maryland. Eight sequences are common to Delaware and New Jersey, and four of these can be correlated to sequences in Maryland outcrops. The sequence boundaries correspond with nine global $\delta^{18}O$ increases. This indicates that glacioeustasy provides the template sequence deposition.

5. Though there are similarities in the ages of sequences, significant differences occur, particularly within the lower Miocene (ca. 24–17.5 Ma) deposits. Lower Miocene strata are absent in Maryland outcrops and the subsurface. The lowermost Miocene sequences in Delaware are very thin, and the lower Miocene Kw1b equivalent is missing in Delaware. Finally, two lower Miocene sequences are only found at Bethany Beach. This indicates that differential subsidence determines the preservation of sequences in the study area.

6. Backstripping quantifies the eustatic and tectonic components of accommodation. It shows that anomalously high subsidence occurred from ca. 21–16 Ma at Bethany Beach at the same time that the depocenter was located just seaward of this site. We suggest that Miocene subsidence differences on this passive continental margin are primarily caused by variations in sediment supply associated with prograding sequences that affect accommodation through flexural loading.

ACKNOWLEDGMENTS

We thank J. Friedmann, W. Galloway, M.E. Katz, C.W. Poag, and E. Rankey for reviews and the members of the Coastal Plain Drilling Project, who are too numerous to list here, for their time, expertise, and abundant energy. The Delaware Geological Survey supplied materials, personnel, and logging support. The U.S. Geological Survey Eastern Regional Mapping Team drillers (Gene Cobbs and Gene Cobbs III) did a superb job coring at Bethany Beach and the New Jersey sites. Supported by National Science Foundation grants EAR97-08664 (Miller), EAR99-09179 (Miller), EAR02-24767 (Miller and Kominz), EAR98-14025 (Kominz), EAR03-7101 (Kominz), and the Ocean Drilling Program.

REFERENCES CITED

Abbott, S.T., and Carter, R.M., 1994, The sequence architecture of mid-Pleistocene (ca. 1.1–0.4 Ma) cyclothems from New Zealand: Facies development during a period of orbital control on sea-level cyclicity: International Association of Sedimentologists Special Publication 19, p. 367–394.

Andres, A.S., 1986, Stratigraphy and depositional history of the Post-Choptank Chesapeake Group: Delaware Geological Survey Report of Investigations 42, 39 p.

Bartek, L.R., Vail, P.R., Ross, M.R., Emmet, P.A., Liu, C., and Wu, S., 1991, Effect of Cenozoic ice sheet fluctuations in Antarctica on the stratigraphic signature of the Neogene: Journal of Geophysical Research, v. 96, no. B4, p. 6753–6778.

Benson, R.N., 1990, Geologic and hydrologic studies of the Oligocene-Pleistocene section near Lewes, Delaware: Delaware Geological Survey Report of Investigations 48, 34 p.

Berggren, W.A., Kent, D.V., Swisher, C.C., 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: Society of Economic Paleontologists and Mineralogists Special Publication 54, p. 129–212.

Bernard, H.A., Le Blanc, R.J., Jr., and Major, C.F., 1962, Recent and Pleistocene geology of southeast Texas, *in* Rainwater, E.H., and Zingula, R.P., eds., Geology of the Gulf Coast and Central Texas and Guidebook of Excursions: Houston, Texas, Houston Geological Society, p. 175–224.

Bond, G.C., and Kominz, M.A., 1984, Construction of tectonic subsidence curves for the early Paleozoic miogeocline, southern Canadian Rocky Mountains: Implications for the subsidence mechanisms, age of breakup, and crustal thinning: Geological Society of America Bulletin, v. 95, p. 155–173, doi: 10.1130/0016-7606(1984)95<155:COTSCF>2.0.CO;2.

Bond, G.C., Kominz, M.A., Steckler, M.S., and Grotzinger, J.P., 1989, Role of thermal subsidence, flexure and eustasy in the evolution of early Paleozoic passive-margin carbonate platforms, *in* Crevello, P.D., Wilson, J.L, Sarg, J.F., and Read, J.F., eds., Controls on Carbonate Platform and Basin Development: Society of Sedimentary Geologists Special Publication 44, p. 39–61.

Brown, P.M., Miller, J.A., and Swain, F.M., 1972, Structural and stratigraphic framework, and spatial distribution of permeability of the Atlantic Coastal Plain, North Carolina to New York: U.S. Geological Society Professional Paper 796, 79 p.

Christie-Blick, N., 1991, Onlap, offlap, and the origin of unconformity-bounded depositional sequences: Marine Geology, v. 97, p. 35–56, doi: 10.1016/0025-3227(91)90018-Y.

Christie-Blick, N., and Driscoll, N.W., 1995, Sequence stratigraphy: Annual Review of Earth and Planetary Sciences, v. 23, p. 451–478, doi: 10.1146/annurev.ea.23.050195.002315.

Christie-Blick, N., Mountain, G.S., and Miller, K.G., 1990, Seismic stratigraphic record of sea level change, *in* Sea-Level change, National Academy of Sciences studies in geophysics: Washington, D.C., National Academy Press, p. 116–140.

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: Proceedings of the Ocean Drilling Program, Scientific Results, v. 150X, p. 129–145.

Doyle, J.A., 1982, Palynology of continental Cretaceous sediments, Crisfield geothermal test well, eastern Maryland, pt. 2, *in* Hansen, H.J., and Doyle, J.A., eds., Waste Gate Formation: Maryland Department of Natural Resources, Geological Survey Open-File Report 82-02-01, 37 p.

Doyle, J.A., and Robbins, E.I., 1977, Angiosperm pollen zonation of the continental Cretaceous of the Atlantic Coastal Plain and its application to deep wells in the Salisbury Embayment: Palynology, v. 1, p. 43–78.

Edwards, L.E., Powars, D.S., and Self-Trail, J.M., 2004, Post-impact dinoflagellate and calcareous nannofossil biostratigraphy, lithology, sedimentation accumulation rates, and patterns in the filling and refilling of the Chesapeake Bay Impact Crater, *in* Edwards, L.E., Horton, J.W., Jr., and Gohn. G.S., compil., ICDP-USGS Workshop on Deep Drilling in the Central Crater of the Chesapeake Bay Impact Structure, Virginia, USA: Herndon, Virginia, Proceedings Volume, September 22–24: U.S. Geological Survey Open-File Report 2004-1016, p. 51–52.

Edwards, L.E., Barron, J.A., Brewster-Wingard, G.L., Bukry, D., Bybell, L.M., Cronin, T.M., Poag, C.W., and Weems, R.E., 2006, Paleontology of the upper Eocene to Quaternary stratigraphic section in the USGS-NASA Langley core, Hampton, Virginia, *in* Horton, J.W., Jr., Powars, D.S., and Gohn, G.S., eds., Studies of the Chesapeake Bay impact structure—The USGS-NASA Langley corehole, Hampton, Virginia, and related coreholes and geophysical surveys: U.S. Geological Survey Professional Paper, chapter H (in press).

Grow, J.A., and Sheridan, R.E., 1988, U.S. Atlantic continental margin; a typical Atlantic-type or passive continental margin, *in* Sheridan, R.E., and Grow, J.A., eds., The Atlantic Continental Margin, U.S.: Geological Society of America, Decade of North American Geology, v. I-2, p. 1–8.

Hansen, H.J., 1982, Hydrogeologic framework and potential utilization of the brine aquifers of the Waste Gate Formation, a new unit of the Potomac Group underlying the Delmarva Peninsula, pt. 1, *in* Hansen, H.J., and Doyle, J.A., eds., Waste Gate Formation: Maryland Department of Natural Resources, Geological Survey Open-File Report 82-02-01, p. 1–50.

Hansen, H.J., 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1987, Chronology of fluctuating sea levels since the Triassic (250 million years ago to present): Science, v. 235, p. 1156–1167.

Harms, J.C., Southard, J.B., Spearing, D.R., and Walker, R.G., 1975, Depositional environments as interpreted from primary sedimentary structures and stratification sequences: Society of Economic Paleontologists and Mineralogists, Notes for a Short Course 2, 161 p.

Harms, J.C., Southard, J.B., and Walker, R.G., 1982, Structure and sequence in clastic rocks: Society of Economic Paleontologists and Mineralogists, Notes for a Short Course 9, 249 p.

Hernandez, J.C., 2002, Sequence stratigraphy spanning the middle/late Miocene boundary at Bethany Beach, DE: Isotopic and benthic foraminiferal evidence [M.S. thesis]: New Brunswick, New Jersey, Rutgers University, 79 p.

Johnson, G.H., Kruse, S.E., Vaughn, A.W., Lucey, J.K., Hobbs, C.H., III, and Powars, D.S., 1998, Post-impact deformation associated with the late Eocene Chesapeake Bay impact structure in southeastern Virginia: Geology, v. 26, p. 507–510, doi: 10.1130/0091-7613(1998)026<0507:PDAWTL>2.3.CO;2.

Kidwell, S.M., 1984, Outcrop features and origin of basin margin unconformities in the Lower Chesapeake Group (Miocene), Atlantic Coastal Plain, *in* Schlee, J.S., ed., Interregional Unconformities and Hydrocarbon Accumulation: American Association of Petroleum Geologists Memoir 36, p. 37–58.

Kominz, M.A., Miller, K.G., and Browning, J.V., 1998, Long-term and short-term global Cenozoic sea-level estimates: Geology, v. 26, p. 311–314, doi: 10.1130/0091-7613(1998)026<0311:LTASTG>2.3.CO;2.

Kominz, M.A., Van Sickel, W.A., Miller, K.G., and Browning, J.V., 2002, Sea-level estimates for the latest 100 million years: One-dimensional backstripping of onshore New Jersey Boreholes, *in* Armentrout, J., ed., Sequence Stratigraphic Models for Exploration and Production: Evolving Methodology, Emerging Models and Application Case Histories: Houston, Texas, Proceeding of the 22nd Annual Bob F. Perkins Research Conference 2002, Gulf Coast Section SEPM, CD-ROM publication only, p. 303–315.

Lu, H., and Fulthorpe, C.S., 2004, Controls on sequence stratigraphy of a middle Miocene–Holocene, current-swept, passive margin; offshore Canterbury Basin, New Zealand: Geological Society of America Bulletin, v. 116, p. 1345–1366, doi: 10.1130/B2525401.1.

McCubbin, D.G., 1982, Barrier-island and strand plain facies, *in* Scholle, P.A., and Spearing, D., eds., Sandstone depositional environments: American Association of Petroleum Geologists Memoir 31, p. 247–279.

Miller, K.G., and Mountain, G.S., 1996, The Leg 150 shipboard party, and members of the New Jersey Coastal Plain Drilling Project, Drilling and dating New Jersey Oligocene-Miocene sequences: Ice volume, global sea level, and Exxon record: Science, v. 271, p. 1092–1094.

Miller, K.G., and Sugarman, P.J., 1995, Correlating Miocene sequences in onshore New Jersey boreholes (ODP Leg 150X) with global $\delta^{18}O$ and Maryland outcrops: Geology, v. 23, p. 747–750, doi: 10.1130/0091-7613(1995)023<0747:CMSION>2.3.CO;2.

Miller, K.G., Fairbanks, R.G., and Mountain, G.S., 1987, Tertiary oxygen isotope synthesis, sea-level history, and continental margin erosion: Paleoceanography, v. 2, p. 1–19.

Miller, K.G., Wright, J.D., and Fairbanks, R.G., 1991, Unlocking the Ice House: Oligocene-Miocene oxygen isotopes, eustasy, and margin erosion: Journal of Geophysical Research, v. 96, p. 6829–6848.

Miller, K.G., Browning, J.V., Pekar, S.F., and Sugarman, P.J., 1997a, Cenozoic evolution of the New Jersey Coastal Plain: Changes in sea level, tectonics, and sediment supply, *in* Miller, K.G., and Snyder, S.W., eds., Proceedings of the Ocean Drilling Program, Scientific results, Volume 150X: College Station, Texas, Ocean Drilling Program, p. 361–373.

Miller, K.G., Rufolo, S., Sugarman, P.J., Pekar, S.F., Browning, J.V., and Gwynn, D.W., 1997b, Early to middle Miocene sequences, systems tracts, and benthic foraminiferal biofacies, New Jersey coastal plain, *in* Miller, K.G., and Snyder, S.W., eds., Proceedings of the Ocean Drilling Program, Scientific results, Volume 150X: College Station, Texas, Ocean Drilling Program, p. 169–186.

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 slope drilling: Reviews of Geophysics, v. 36, p. 569–601, doi: 10.1029/98RG01624.

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., eds., Proceedings of the Ocean Drilling Program, Initial Reports, Volume 174AX: College Station, Texas, Ocean Drilling Program, p. 5–43.

Miller, K.G., Sugarman, P.J., Browning, J.V., Pekar, S.F., Katz, M.E., Cramer, B.S., Monteverde, D., Uptegrove, J., McLaughlin, P.P., Jr., Baxter, S.J., Aubry, M.-P., Olsson, R.K., Van Sickel, B., Metzger, K., Feigenson, M.D., Tiffen, S., McCarthy, F., and Mullikin, L., 2001, Ocean View Site Report, Proceedings of the Ocean Drilling Program, Initial Reports, 174AX (supplement): College Station, Texas, Ocean Drilling Program, 72 p.

Miller, K.G., Browning, J.V., Sugarman, P.J., McLaughlin, P.P., Jr., Kominz, M.A., Olsson, R.K., Wright, J.D., Cramer, B.S., Pekar, S.F., and Van Sickel, W., 2002a, 174AX Leg summary: Sequences, sea level, tectonics, and aquifer resources: Coastal plain drilling, *in* Miller, K.G., Sugarman, P.J., Browning, J.V., et al., eds., Proceedings of the Ocean Drilling Program, Leg 174AX (supplement): College Station, Texas, Ocean Drilling Program, p. 1–40.

Miller, K.G., McLaughlin, P.P., Jr., Browning, J.V., Benson, R.N., Sugarman, P.J., Hernandez, J., Ramsey, K.W., Baxter, S.J., Feigenson, M.D., Aubry, M.-P., Monteverde, D., Cramer, B.S., Katz, M.E., McKenna, T.E., Strohmeier, S.A., Pekar, S.F., Uptegrove, J., Cobbs, G., Cobbs, G., III, and Curtain, S.E., 2002b, Bethany Beach Site Report, Proceedings of the Ocean Drilling Program, Initial Reports, Leg 174AX (supplement): College Station, Texas, Ocean Drilling Program, p. 1–85.

Miller, K.G., Sugarman, P.J., Browning, J.V., Kominz, M.A., Olsson, R.K., Feigenson, M.D., and Hernandez, J.C., 2004, Upper Cretaceous sequences and sea-level history, New Jersey Coastal Plain: Geological Society of America Bulletin, v. 116, p. 368–393, doi: 10.1130/B25279.1.

Mitchum, R.M., Vail, P.R., and Thompson, S., 1977, The depositional sequence as a basic unit for stratigraphic analysis, *in* Payton, C.E., ed., Seismic Stratigraphy—Applications to Hydrocarbon Exploration: American Association of Petroleum Geologists Memoir 26, p. 53–62.

Olsson, R.K., Melillo, A.J., and Schreiber, B.L., 1987, Miocene sea level events in the Maryland coastal plain and the offshore Baltimore canyon trough, *in* Ross, C.A., and Haman, D., eds., Timing and depositional history of eustatic sequences: Constraints on seismic stratigraphy: Cushman Foundation for Foraminiferal Research Special Publication 24, p. 85–97.

Olsson, R.K., Gibson, T.G., Hansen, H.J., and Owens, J.P., 1988, Geology of the northern Atlantic coastal plain: Long Island to Virginia, *in* Sheridan, R.E., and Grow, J.A., eds., The Atlantic Continental Margin, U.S.: Geological Society of America, Decade of North American Geology, v. I-2, p. 87–105.

Oslick, J.S., Miller, K.G., and Feigenson, M.D., 1994, Oligocene-Miocene strontium isotopes: Stratigraphic revisions and correlation to a glacioeustatic record: Paleoceanography, v. 9, p. 427–443, doi: 10.1029/94PA00249.

Owens, J.P., Bybell, L.M., Paulachok, G., Ager, T.A., Gonzalez, V.M., and Sugarman, P.J., 1988, Stratigraphy of the Tertiary sediments in a 945-foot-deep core hole near Mays Landing in the southeastern New Jersey coastal plain: U.S. Geological Survey Professional Paper 1484, 39 p.

Owens, J.P., Miller, K.G., and Sugarman, P.J., 1997, Lithostratigraphy and paleoenvironments of the Island Beach borehole, New Jersey coastal plain, *in* Miller, K.G., and Snyder, S.W., eds., Proceedings of the Ocean Drilling Program, Scientific Results, Leg 150X: College Station, Texas, Ocean Drilling Program, p. 15–24.

Pekar, S.F., Miller, K.G., and Kominz, M.A., 2000, Reconstructing the stratal geometry of latest Eocene to Oligocene sequences in New Jersey: Resolving a patchwork distribution into a clear pattern of progradation: Sedimentary Geology, v. 134, p. 93–109, doi: 10.1016/S0037-0738(00)00015-4.

Plint, A.G., 1988, Sharp-based shoreface sequences and "offshore bars" in the Cardium Formation of Alberta: Their relationship to relative changes in sea level, *in* Wilgus, C.K., Hastings, B.S., Ross, C.A., Posamentier, H.W., Van Wagoner, J.C., and Kendall, C.G.St.C., eds., Sea level changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 357–370.

Poag, C.W., and Sevon, W.D., 1989, A record of Appalachian denudation in postrift Mesozoic and Cenozoic sedimentary deposits of the U.S. middle Atlantic margin: Geomorphology, v. 2, p. 119–157, doi: 10.1016/0169-555X(89)90009-3.

Poag, C.W., Koeberl, C., and Reimhold, W.U., 2004, The Chesapeake Bay Crater: New York, Springer, 522 p. and CD-ROM.

Posamentier, H.W., and Allen, G.P., 1993, Variability of the sequence stratigraphic model: Effects of local basin factors: Journal of Sedimentary Petrology, v. 86, p. 91–109, doi: 10.1016/0037-0738(93)90135-R.

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.C., and Kendall, C.G.St.C., eds., Sea level changes: An Integrated Approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 109–124.

Reilly, T.J., Miller, K.G., and Feigenson, M.D., 2002, Late Eocene to Oligocene Sr-isotopic reference section, Site 522, eastern South Atlantic: Paleoceanography, v. 18, p. 1–9.

Reynolds, D.J., Steckler, M.S., and Coakley, B.J., 1991, The role of the sediment load in sequence stratigraphy: The influence of flexural isostasy and compaction: Journal of Geophysical Research, v. 96, p. 6931–6949.

Richter, F.M., and DePaolo, D.J., 1988, Diagenesis and Sr isotopic evolution of seawater using data from DSDP 590B and 575: Earth and Planetary Science Letters, v. 90, p. 382–384, doi: 10.1016/0012-821X(88)90137-9.

Rodriguez, A.B., Fassell, M.L., and Anderson, J.B., 2001, Variations in shoreface progradation and ravinement along the Texas coast, Gulf of Mexico: Sedimentology, v. 48, p. 837–853, doi: 10.1046/j.1365-3091.2001.00390.x.

Seeber, L., and Armbruster, J.G., 1988, Seismicity along the Atlantic seaboard of the U.S.: Intraplate neotectonics and earthquake, *in* Sheridan, R., and Grow, J., eds., The Atlantic continental margin, U.S.: Geological Society of America, Decade of North American Geology, v. I-2, p. 437–444.

Self-Trail, J.M., Prowell, D.C., Christopher, R.A., and Weems, R.E., 2002, Stratigraphic correlation of Turonian through Santonian sediments from three cores across the Cape Fear Arch: Abstract Volume of the Bald Head Island Conference on Coastal Plains, *in* Harris, W.B., Farrell, K.M., and Weems, R.E., eds., The Cape Fear Arch, Transition between the northern and southern Atlantic Coastal Plain: Fourth Bald Head Island Conference, November 16–19, 2002, FT. Fisher, North Carolina, Abstract Volume, p. 42.

Self-Trail, J.M., Prowell, D.C., and Christopher, R.A., 2004, The Collins Creek and Pleasant Creek Formations: Two new Upper Cretaceous subsurface units in the Carolina/Georgia Coastal Plain: Southeastern Geology, v. 42, p. 237–252.

Steckler, M.S., 1981, Thermal and mechanical evolution of Atlantic-type continental margins [Ph.D. thesis]: Palisades, New York, Columbia University, 261 p.

Steckler, M.S., Mountain, G.S., Miller, K.G., and Christie-Blick, N., 1999, Reconstruction of Tertiary progradation and clinoform development on the New Jersey passive margin by 2-D backstripping: Marine Geology, v. 154, p. 399–420, doi: 10.1016/S0025-3227(98)00126-1.

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: Geological Society of America Bulletin, v. 105, p. 423–436, doi: 10.1130/0016-7606(1993)105<0423:SIASSO>2.3.CO;2.

Turcotte, D.L., and Schubert, G., 1982, Geodynamics: Application of continuum physics to geological problems: New York, John Wiley, 450 p.

Vail, P.R., Mitchum, R.M., Jr., Todd, R.G., Widmier, J.M., Thompson, S., III, Sangree, J.B., Bubb, J.N., and Hatlelid, W.G., 1977, Seismic stratigraphy and global changes of sea level: American Association of Petroleum Geologists Memoir 26, p. 49–212.

Van Sickel, W.A., Kominz, M.A., Miller, K.G., and Browning, J.V., 2004, Late Cretaceous and Cenozoic sea-level estimates: Backstripping analysis of borehole data, onshore New Jersey: Basin Research, v. 16, p. 451–465, doi: 10.1111/j.1365-2117.2004.00242.x.

Van Wagoner, J.C., and Bertram, G.T., 1995, Sequence stratigraphy and marine to nonmarine facies architecture of foreland basin strata, Book Cliffs, Utah, USA: American Association of Petroleum Geologists Memoir 64, p. 137–223.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J., 1988, An overview of the fundamentals of sequence stratigraphy and key definitions, *in* Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., and Van Wagoner, J.C., eds., Sea level changes—An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication 42, p. 39–45.

Watts, A.B., and Steckler, M.S., 1979, Subsidence and eustasy at the continental margin of eastern North America, *in* Talwani, M., Hay, W.W., and Ryan, W.B.F., eds., Deep Drilling Results in the Atlantic Ocean: Continental Margins and Paleoenvironment, American Geophysical Union Maurice Ewing series 3, p. 218–234.

Weems, R.E., and Lewis, W.C., 2002, Structural and tectonic setting of the Charleston, South Carolina region: Evidence from the Tertiary stratigraphic record: Geological Society of America Bulletin, v. 114, p. 24–42, doi: 10.1130/0016-7606(2002)114<0024:SATSOT>2.0.CO;2.

Manuscript Received by the Society 19 December 2003
Revised Manuscript Received 7 March 2005
Manuscript Accepted 10 April 2005

Printed in the USA