

Integrated Late Santonian-Early Campanian sequence stratigraphy, New Jersey Coastal Plain: Implications for global sea-level studies

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ABSTRACT: Recent studies of the Santonian-lower Campanian section (Merchantville Formation) in two coreholes (Ancora and Bass River) from the New Jersey coastal plain postulated the existence of concatenated sequences in glauconitic facies (Miller et al. 2004). The lithologic expression of unconformities within the Merchantville glauconitic sediments is obscure and their resolution requires an integrated stratigraphic approach. Here, we present detailed litho- and biostratigraphic analyses of the Merchantville Formation sequences in four New Jersey coastal plain coreholes (Sea Girt, Ancora, Millville, and Bass River). Biofacies analysis reveals four benthic foraminiferal assemblages from inner to middle neritic environments. Correlation of benthic foraminiferal biofacies, percentage of planktonic foraminifera, and lithologic data indicates that paleowater depths varied between 30 and 75m. The correlation of biostratigraphy, benthic foraminiferal biofacies, lithology, and gamma logs delineates unconformities, and identifies three sequences within the Merchantville Formation (MeI, MeII, MeIII). The ages of these sequences have been constrained by calcareous nannoplankton biostratigraphy (MeI: CC16; MeII: CC17-18; MeIII: CC18-19) from 78.8 to 84.5 Ma. The Merchantville I sequence is observed in the Sea Girt and Bass River coreholes. The Merchantville II and III sequences are present throughout the New Jersey coastal plain, and the ages of the Merchantville II and III sequences boundaries are similar to those of North Carolina, and North-Western Europe suggesting an interregional cause of sequences boundaries. Comparison of the New Jersey shallow marine sequences with the deep-sea record from DSDP Site 511 (Falkland Plateau) show that the episodes of sea-level fall in New Jersey are synchronous with $\delta^{18}\text{O}$ increases. Our data imply that the Merchantville sequence boundaries may be attributed to ice volume increases and support the contention that global sea-level changes were controlled by ice-volume variations even during the peak warmth of the Cretaceous.

INTRODUCTION

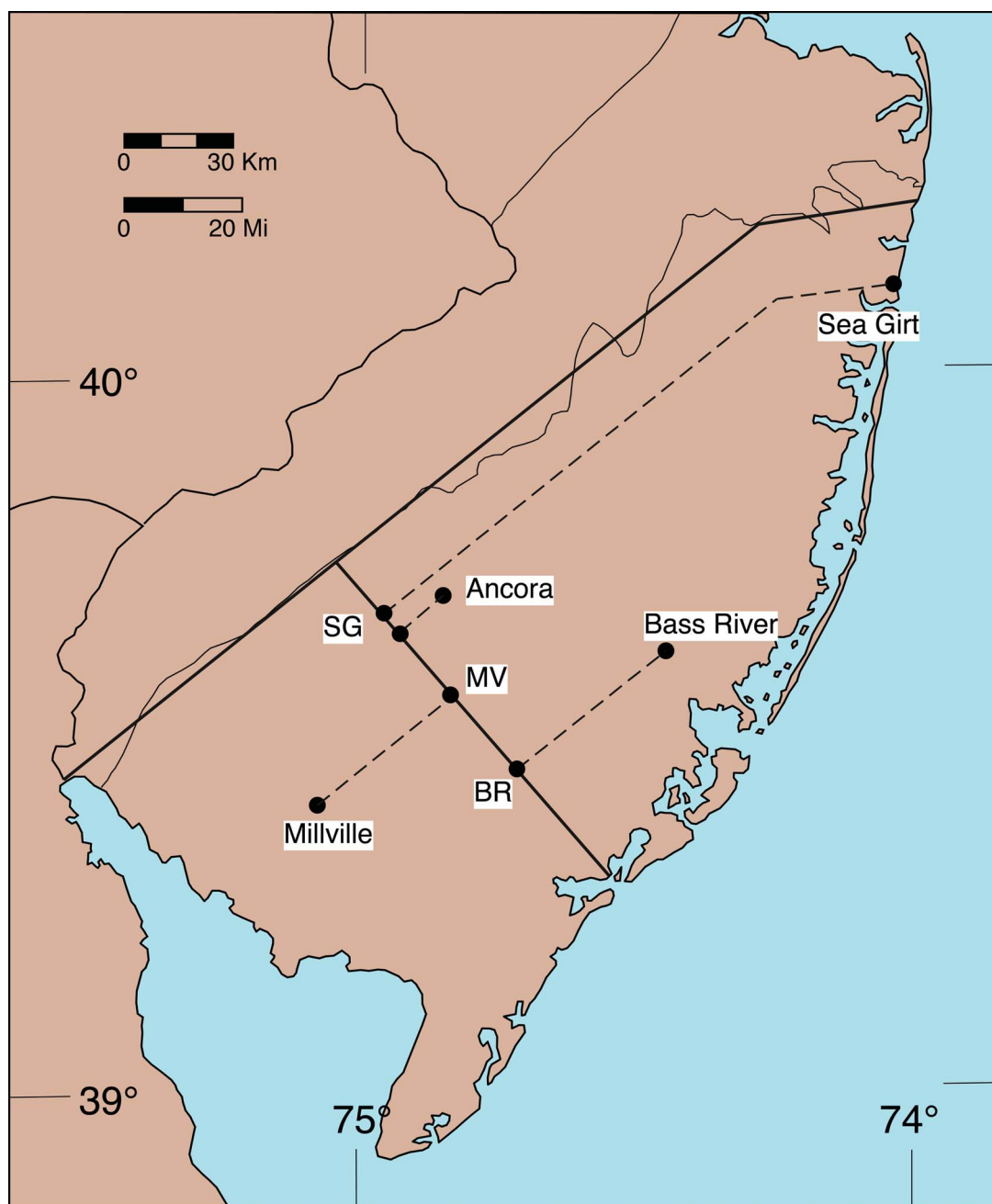
The Late Cretaceous has been reconstructed as a Greenhouse world with warm polar climates and high CO_2 levels (e.g., Bice et al. 2006). Most studies have assumed a total absence of polar ice sheets during the Late Cretaceous (e.g., Huber et al. 1995). Beginning with the work of Exxon Production Research Company (Vail et al. 1977; Haq et al. 1987) and continuing with more recent publications (Van Sickel et al. 2004; Miller et al. 2003, 2004, 2005a,b; Kominz et al. 2008), sea-level studies have indicated large (tens of meters), rapid (<1 myr) Late Cretaceous global sea-level (eustatic) variations. Such large and rapid eustatic changes can only be explained by glacioeustasy (Pitman and Golovchenko 1983). Matthews (1984) realized this enigma, and, based on sea-level records and his reinterpretation of the $\delta^{18}\text{O}$ record, postulated the presence of intermittent ice sheets in the Cretaceous. Stoll and Schrag (2000) interpreted Cretaceous isotopic fluctuations as reflecting growth and decay of ice sheets. Miller et al. (2003, 2004, 2005a,b) interpreted Late Cretaceous sea-level variations as reflecting the growth and decay of small to medium ice sheets ($10\text{--}15 \times 10^6 \text{ km}^3$).

The paleoceanographic community has remained skeptical of the Matthews-Stoll-Miller hypothesis (see Moryia et al. 2007 for a rejection and Miller et al. 2008 for a reply) and assumed the absence of polar ice sheets. This assumption may not be warranted for two reasons. First, there is no direct evidence (e.g., IRD, tills) of glaciation near Antarctica older than 33 Ma, but indirect evidence suggests glaciers formed in Antarctica

prior to that time (Browning et al. 1996; Tripathi et al. 2005). In fact, it took many years of drilling to find direct evidence of Antarctic glaciation in the Oligocene (see summaries in Zachos et al. 1992; Miller et al. 1991). Second, Late Cretaceous climate studies have only provided a broad scale (essentially million years) view of high latitude climate. Short cool intervals are likely to be missed (Royer et al. 2004).

Parts of the Late Cretaceous provide an opportunity to recover the short-term eustatic pulses (<1 myr) and evaluate their triggering mechanisms. The evidence of short glacial intervals can be inferred by synchronous changes in sea-level and global $\delta^{18}\text{O}$ records. The late Santonian-early Campanian is a particularly critical interval for evaluating possible links between sea-level and global $\delta^{18}\text{O}$ changes because this was one of the two warmest intervals of the Late Cretaceous (Huber et al. 1995).

The New Jersey passive continental margin provides an excellent location to reconstruct short-term Cretaceous sea-level changes. There are minimal regional tectonic influences (Kominz et al. 1998), well-developed Upper Cretaceous sequences (unconformity-bounded units) (Miller et al. 1998, 2004), and excellent preservation of calcareous nannofossils for age control (Sugarman et al. 1995; Miller et al. 2004). The New Jersey coastal plain Drilling Program (part of the Mid-Atlantic Transect, Ocean Drilling Program [ODP] 174AX) launched in 1993 has established a high-resolution sequence stratigraphy of the New Jersey coastal plain for the last 100 myr. Continuous



TEXT-FIGURE 1

Location map of New Jersey coastal plain and coreholes: Ancora, Bass River, Millville, and Sea Girt. Heavy lines show strike and dip of the Cretaceous strata. Dashed lines show position of coreholes projected onto the dip line.

coastal plain coring by ODP Leg 174AX yielded well-preserved Upper Cretaceous deposits with prominent upper Santonian-lower Campanian sections. Integrated lithostratigraphic and biostratigraphic analyses of the Ancora and Bass River coreholes (Miller et al. 2004) revealed very low sedimentation rates, assuming continuous sedimentation, in late Santonian-early Campanian glauconitic facies. The low sedimentation rates are suggestive of hiatuses and the presence of multiple cryptic unconformities. Miller et al. (2004) tentatively recognized and named three sequences in this interval: Merchantville I (MeI), Merchantville II (MeII), and Merchant-

ville III (MeIII; Miller et al. 2004, 2005a). The MeII and MeI sequences are comprised of the Merchantville Formation deposits and the MeIII sequence is comprised of the upper section of the Merchantville Formation along with the Woodbury and lower Englishtown formations.

On the New Jersey coastal plain, Olsson (1960) pioneered the benthic foraminiferal studies that is one of the analytical keys for recognizing sequence boundaries and making paleowater depth estimates. Since unconformities are developed during sea-level falls (Posamentier et al. 1988), continental margins

contain the stratigraphic signal of sea-level lowering either in the physical evidence of an unconformity or by paleontological evidence that indicates a hiatus or biofacies shift (Olsson 1988). The paleontological evidence may be biostratigraphic or paleoecologic (abrupt changes in biofacies and inferred paleobathymetry). Paleoecologic studies of unconformities have focused attention on resolution of sequence boundaries within lithologically similar successions, because physical features of unconformities produced during sea-level falls are not always preserved (Olsson 1988). The detailed analysis of the benthic foraminiferal biofacies for the Merchantville Formation potentially can detect short-term (<1 myr) hiatuses and provide water-depth estimates.

In this paper, we revisit Santonian-early Campanian Merchantville sequences in New Jersey using recently drilled coreholes and more detailed analyses than were available in previous studies. The Millville and Sea Girt coreholes (Miller et al. 2006; Sugarman et al. 2005) were drilled to provide a more regional perspective on the New Jersey Cretaceous sequences described at Ancora and Bass River. We identify the MeI, II, and III sequences in these 4 coreholes, estimate paleowater depths, and provide biostratigraphic age control on the sequences. The Merchantville sequence-stratigraphic framework can be used to compare with sequences in other regions and global $\delta^{18}\text{O}$ records, and to evaluate possible controlling mechanisms for the Santonian-lower Campanian sea-level changes.

METHODS

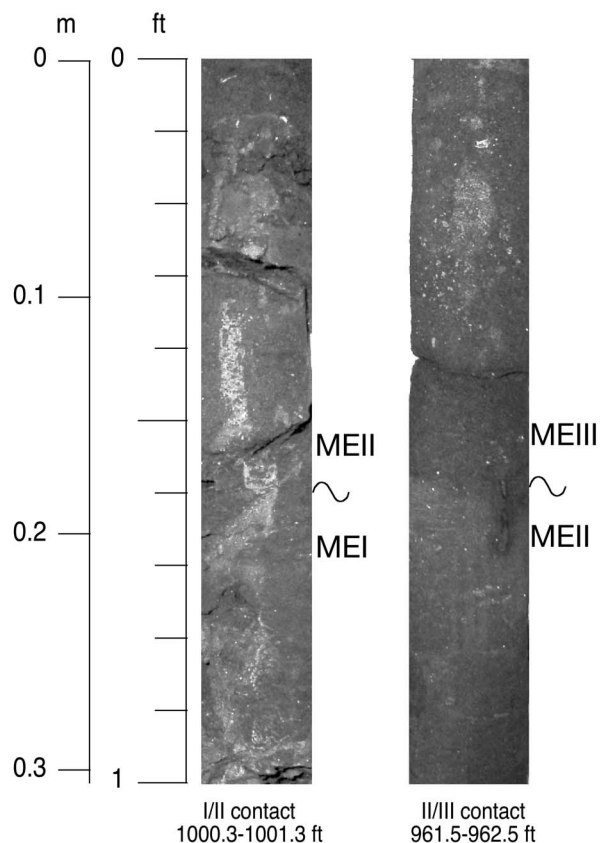
The Merchantville Formation was studied in four ODP (174AX) New Jersey coastal plain coreholes (Bass River, Millville, Sea Girt, and Ancora; text-fig. 1). Sequence boundaries are recognized on the basis of physical stratigraphy (including irregular contacts, with reworking and heavy bioturbation, major lithofacies shifts, and gamma ray increases) and benthic foraminiferal biofacies analysis. Age control for the Merchantville sequences relies primarily on calcareous nannofossil biostratigraphy. Paleodepths and paleoenvironments are interpreted using biofacies analysis, foraminiferal metrics and paleoslope modeling (e.g., Nyong and Olsson 1984).

Lithofacies

Lithofacies were recognized on the basis of grain size, general lithology, bedding, and sedimentary structures. The cumulative-percent plots of the sediment fractions were taken from site reports (Miller et al. 1998, 1999, 2006; Sugarman et al. 2005;). The samples taken at ~2ft (~0.6m) interval, were dried and weighed before washing; the dry weight was used to compute the percentage of sand versus silt and clay. Samples were washed through a 63- μm sieve to eliminate the silt and clay fractions; more indurated samples were soaked in a sodium metaphosphate solution to deflocculate the clays. The sand fraction was dried and sieved through a 250- μm screen to separate very fine and fine sand, from the medium and coarse fractions. The fractions were weighed to obtain the percent of very fine and fine versus medium and coarser sand. The sand fractions were examined and visual estimates were made using a binocular microscope to compute the percentages of quartz, glauconite, carbonate (foraminifers and other shells), mica, and other materials contained in the samples.

Biofacies analysis and foraminiferal metrics

Samples from the Bass River, Millville, Ancora, and Sea Girt coreholes were analyzed for foraminiferal content in this study.



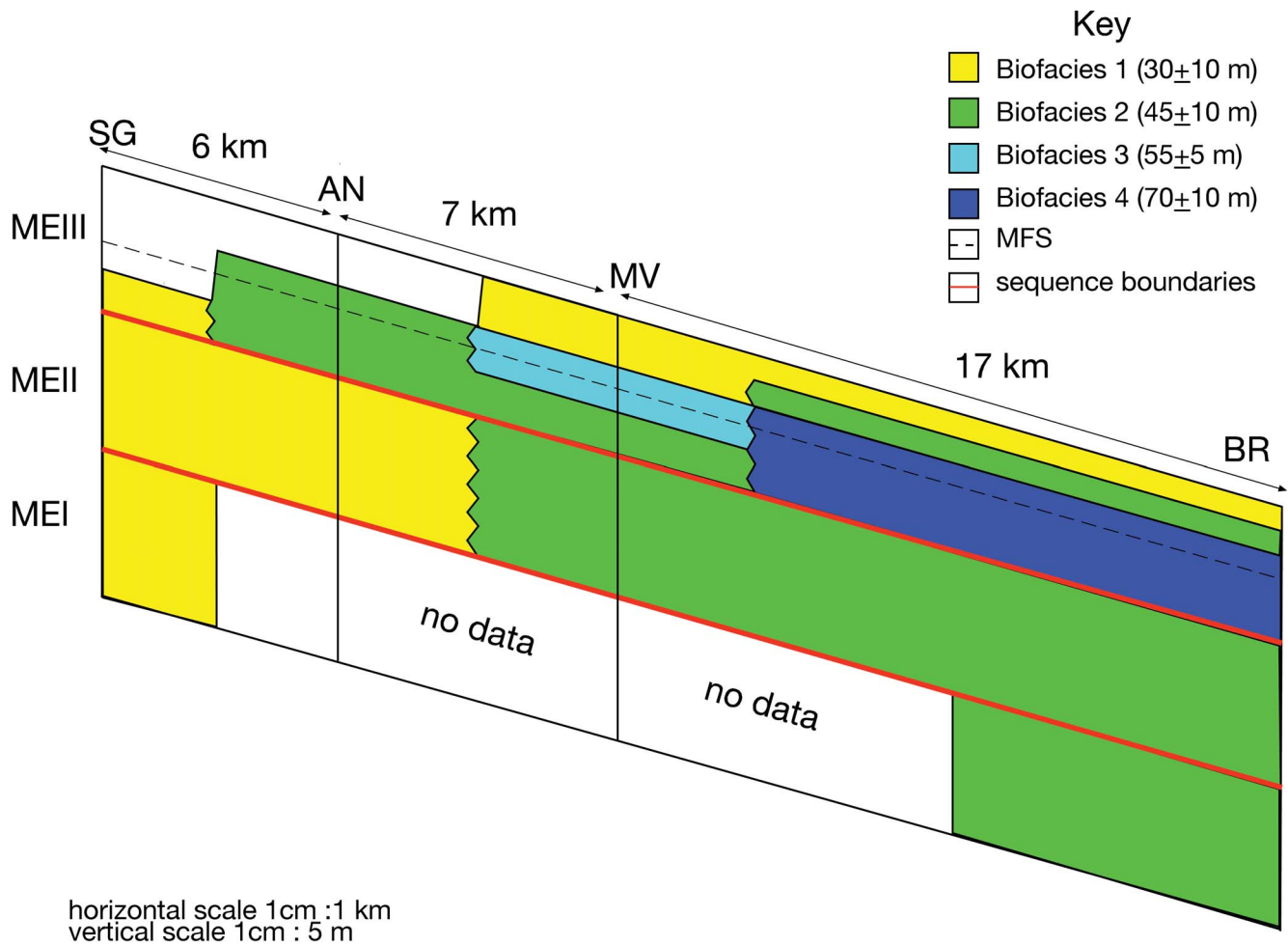
TEXT-FIGURE 2

Photographs of Sea Girt core, intervals of 1000.3-1001.3ft and 961.5-962.5ft. Red wavy lines represent the sequence boundaries of Merchantville I and II (MeI/MeII) (1000.9ft, 305.1m) and Merchantville II and III (MeII/MeIII) (962.1ft, 293.2m).

Approximately ~300 benthic specimens were picked from each sample. Very rich samples were split before picking. Some samples poor in foraminifers from Sea Girt corehole were floated in perchloroethylene to concentrate the specimens. Samples that contained fewer than 50 specimens total were eliminated from the statistical analysis of biofacies.

Species identification relied upon Olsson (1977, 1988), Olsson and Usmani (1992), Cushman (1946), and Loeblich and Tappan (1988). Benthic foraminiferal counts were converted into percentages and Q-mode factor analysis with varimax rotation was performed using Systat computer program to compare variation among the samples. The resulting loadings of ~1.0 or greater were considered suitable for interpretation. Four factors were extracted and identified as biofacies 1-4. Three to six dominant benthic foraminiferal species with factor scores greater than 0.5 were recognized for each assemblage. The dominant species were used to identify paleoenvironments inhabited by the assemblages (Olsson 1988; Olsson and Usmani 1992; Sugarman et al. 1999).

The number of foraminiferal specimens divided by the total weight of a sample in grams (foraminiferal number) is a characteristic of depositional paleowater depth (Bandy and Arnal 1957). The number of foraminiferal specimens increases as wa-



TEXT-FIGURE 3

The paleoslope model: the distribution of biofacies (1-4) along the dip slope of the New Jersey Coastal Plain; SG -Sea Girt, MV -Millville and BR -Bass River Coreholes, MeI -Merchantville I, MeII -Merchantville II, MeIII -Merchantville III.

ter depth increases across the shelf. Paleobathymetric changes may reflect variations in the foraminiferal number.

The percentage of planktonic foraminifers in a sample provides an approximate measure of the paleowater depth (Grimsdale and Van Morkhoven 1955). Planktonic foraminifera are generally excluded from shallow water environments. A comparison with a standard depth distribution constructed by Grimsdale and Van Morkhoven (1955) provides water depth estimates. However, for shallow neritic sediments, the abundance of planktonic foraminifers is not always sufficient for water depth estimates. In our studies, the percentage of planktonic foraminifers from the Millville, Ancora, and Sea Girt coreholes are used only to estimate relative water depth changes. At Bass River the abundance of planktonic foraminifera is high enough for water-depth estimates.

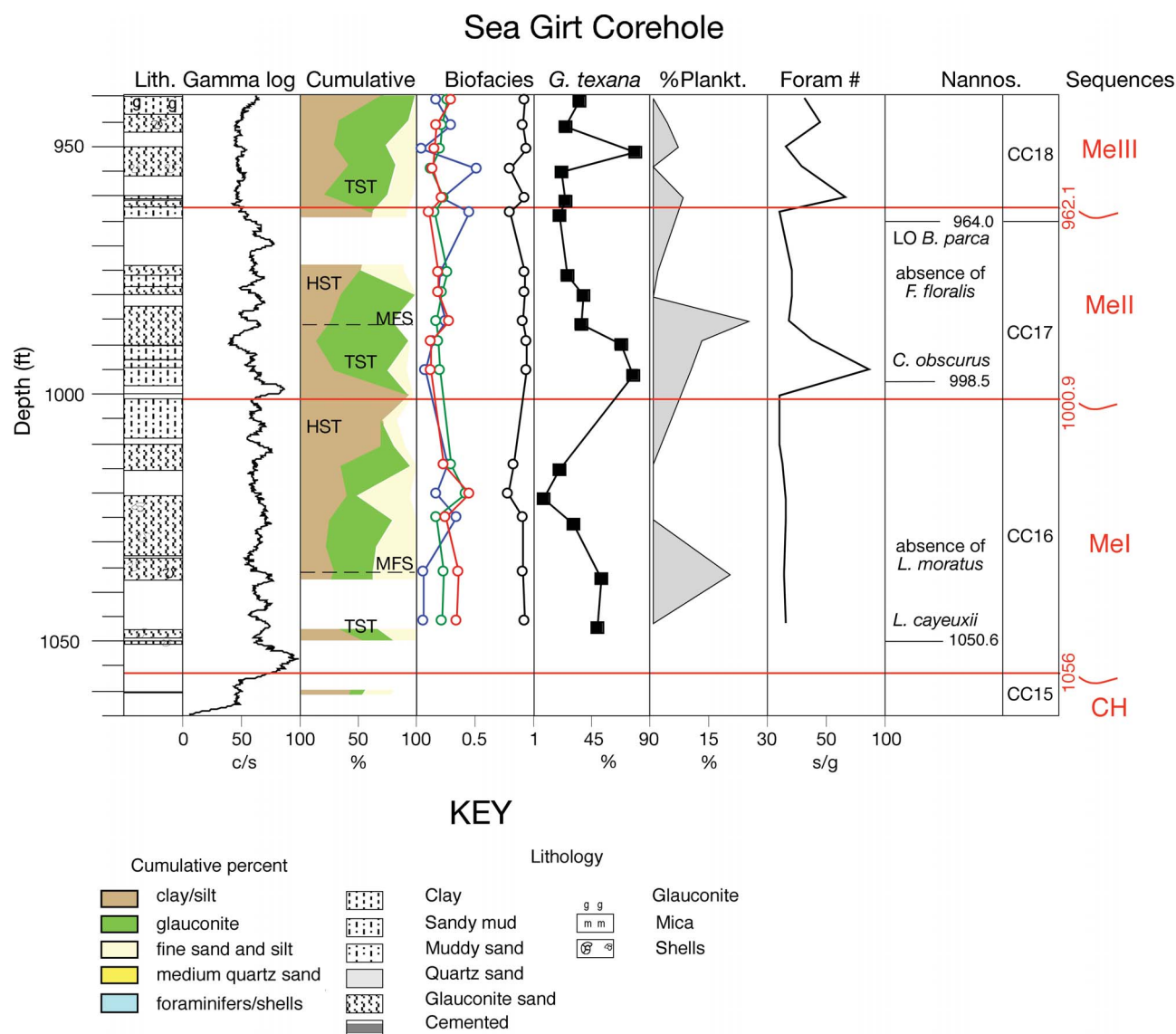
The abundance distribution of *Gavelinella texana* was calculated at Sea Girt, the most updip site. In the Sea Girt corehole, relatively low numbers of benthic and planktonic foraminifers limited paleobathymetric estimates. The percentages of the most abundant benthic foraminiferal species, *Gavelinella*

texana, were used as paleowater depth indicator. An increase in the abundance distribution of *Gavelinella texana* was considered as relative increase in paleowater depth.

Age Estimates: Calcareous Nannofossil Biostratigraphy

Age estimates for the Merchantville sequences are based on calcareous nannofossil biostratigraphy. For nannofossil analysis, sediments were smeared with distilled water on the glass slide, and mounted with Ayac. The slides were examined under a Zeiss photo-microscope in 1250X magnification. Identification of nannofossils was based on Bown (1999).

The nannofossil biostratigraphy was used to date the Merchantville sequences (nannofossil Zones CC16-19) of Sissingh (1978) and Perch-Nielsen (1985). Zonation relied upon the following markers: the lowest occurrence (LO) of *Lucianorhabdus cayeuxii* identifies the base of Zone CC16, the LO of *Calculites obscurus* and the presence of *Calculites ovalis* identifies the base Zone CC17, the LO of *Broinsonia parca parca* identifies the base Zone CC18, and the highest occurrence (HO) of *Marthasterites furcatus* identifies the base Zones CC19. The timescale of Gradstein et al. (1994) is used throughout (text-fig. 9).



TEXT-FIGURE 4

Sea Girt borehole: lithology (white space are unrecovered); gamma log; percent composition; benthic foraminiferal biofacies where black is factor 1, red is factor 2, green is factor 3, blue is factor 4; abundance distribution of *Gavelinella texana*; percent of planktonic foraminifera; foraminiferal number (number of foraminifera specimens per gram), nannofossil zones and their markers; red lines are the sequence boundaries of Merchantville II (MeII) and Merchantville III (MeIII).

RESULTS PALEOBATHYMETRY

Benthic Foraminiferal Biofacies

Factor analysis recognized four stratigraphically significant assemblages interpreted as biofacies 1-4. Each biofacies is interpreted to have inhabited a specific environment of deposition and thus provides a paleowater depth estimate. Here, the biofacies are discussed from shallowest to deepest.

Biofacies 1

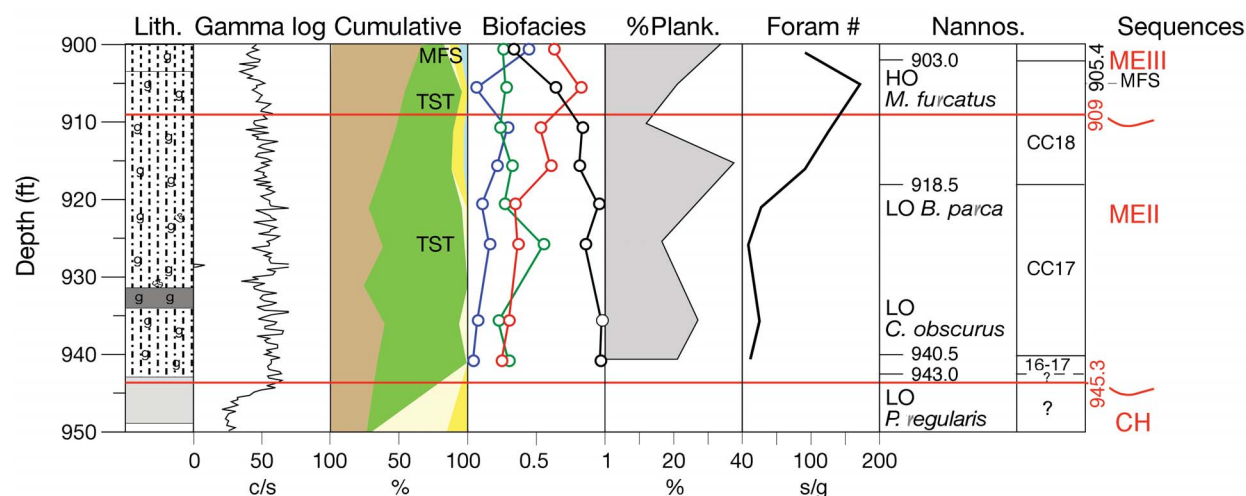
Gavelinella texana (score = 8.5), *Gavelinella infrequens* (score = 1.0), and *Buliminella* sp. (score = 1.1) are the dominant taxa in this biofacies. *Gavelinella texana* ranged from inner and middle shelf to upper slope environments, *Gavelinella infrequens* occupied inner and middle shelf environments and *Buliminella* sp. occupied inner shelf to upper slope environ-

ments (Olsson 1988). These species coexisted in the inner and middle shelf environments. The presence of *in situ* glauconite sand suggests the water depth was not shallower than ~30m. We assign biofacies 1 to the outer part of the inner neritic environment.

Biofacies 2

This biofacies is dominated by *Gavelinella tennesseensis* (score = 8.5), *Verneuilina limbata* (score = 1.3), and *Gavelinella ammonoides* (score = 0.9). *G. tennesseensis* inhabited inner to middle shelf environments, *G. ammonoides* inhabited middle shelf to outer slope environments and *Verneuilina limbata* inhabited middle shelf environments (Olsson and Usmani 1992). Thus, the biofacies 2 characterizes shallow-middle neritic environments.

Ancora Corehole



TEXT-FIGURE 5

Ancora borehole: lithology, gamma log, cumulative composition, benthic foraminiferal biofacies where black is factor 1, red is factor 2, green is factor 3, blue is factor 4; percent of planktonic foraminifera; foraminiferal number (number of foraminifera specimens per gram); nannofossil zones and their markers; red lines are the sequence boundaries of Merchantville II (MeII) and Merchantville III (MeIII). See text-figure 4 for symbol key.

Biofacies 3

This biofacies is dominated by *Epistomina* sp. (score = 8.5), *Gavelinella ammonoides* (score = 0.8), and *G. tennesseensis* (score = 0.5). *Epistomina* sp. characterized inner to middle shelf environments (Sugarman et al. 1999), *Gavelinella ammonoides* characterized middle shelf to outer slope environments (Olsson and Usmani 1992), and *Gavelinella tennesseensis* characterized inner to middle neritic environments (Olsson 1988, Olsson and Usmani 1992). Thus, biofacies 3 is an indicator of middle neritic environments.

Biofacies 4

This biofacies is dominated by *Buliminella* sp. (score = 5.9), *Gavelinella ammonoides* (score = 4.8), *Gyroidinoides depressa* (score = 2.2), *Planulina* sp. (score = 1.1) and *Valvulineria* (score = 1.0). *Buliminella* sp. inhabited inner shelf to upper slope environments, and *Gavelinella ammonoides* ranged from middle shelf to upper slope (Olsson and Usmani 1992; Olsson 1988). Paleoenvironments for the other three dominant species range from middle to outer neritic. Thus, biofacies 4 is an indicator of deep-middle shelf environments.

Paleobathymetry Estimates

Paleobathymetry is inferred from biofacies analysis, a paleoslope model, the foraminiferal number, the percent planktonic foraminifera, and the abundance distribution of *Gavelinella texana* at Sea Girt. As noted above, biofacies 1 is assigned to inner neritic paleoenvironments and biofacies 2, 3 and 4 are assigned to progressively deeper middle neritic environments. Distance downdip is used as the measure of increasing paleodepth using a paleoslope gradient of 1:1000 obtained from 2-dimensional backstripping (Steckler et al. 1999), a gradient similar to the modern continental shelf gradient (Heezen and Tharp 1965). Overall our dip line profile is 30 km long yielding

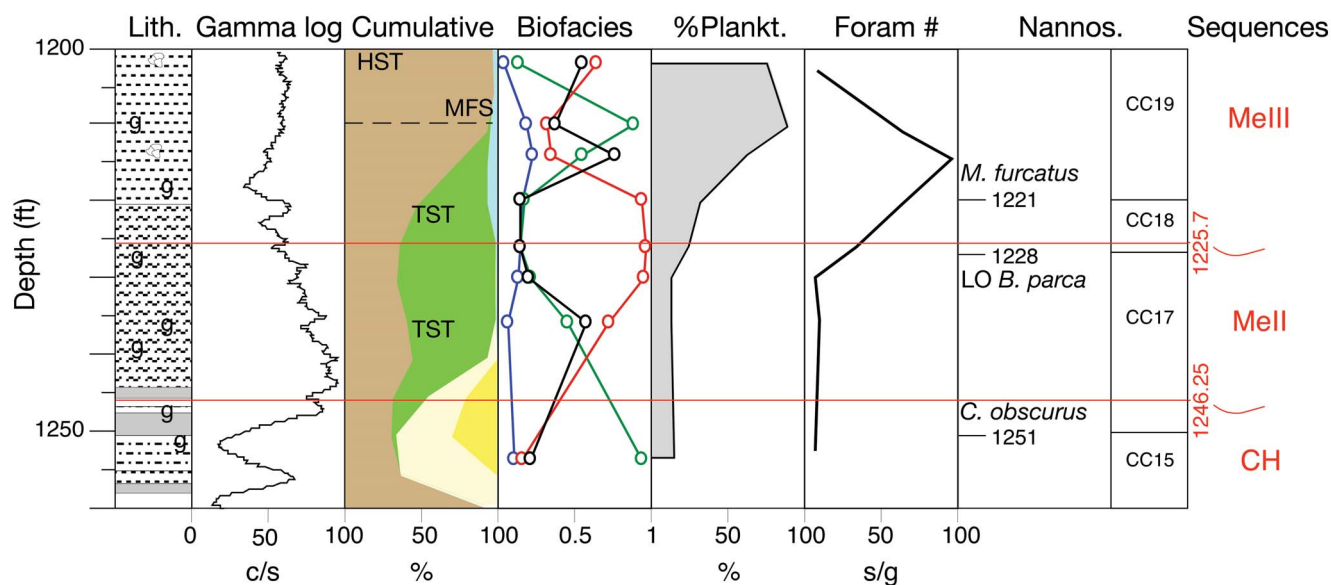
us 30m of water depth increase from the updip (Sea Girt) and downdip (Bass River) locations; Ancora and Millville are 6 and 13m deeper, respectively, than Sea Girt (text-fig. 3).

Inner neritic biofacies 1 is found at the Sea Girt and Ancora coreholes in the MeII sequence and it is replaced downdip by biofacies 2 in the MeII sequence at the Millville and Bass River coreholes. Using the paleoslope gradient, the paleowater depth difference between biofacies 1 and 2 is ~15m maximum (text-fig. 3).

The correlation of benthic foraminiferal biofacies, percent of planktonic foraminifera, and foraminiferal number indicate water depth maxima and minima. Correlation of water depth peaks with lithologic and gamma log data allowed us to recognize the maximum flooding surface (MFS) of the MeIII sequence at the Bass River, Ancora, and Millville coreholes. The MFS of MeIII sequence is used as a time horizon to compare the distribution of temporally equivalent biofacies on the paleoslope model. At Sea Girt, no significant water depth changes were identified in the lower MeIII sequence; we assume that the MFS of the MeIII sequence appears above the examined interval. The MFS of the MeIII sequence is identified by biofacies 2 at Ancora and by biofacies 3 and 4 at Millville and Bass River, respectively. The distribution of biofacies along the MFS indicates the paleodepth differences between the biofacies 2 and 3 was ~10m and between biofacies 3 and 4 was ~15m also (text-fig. 3).

Based on the depth zonation inferred from benthic foraminiferal studies, lithological analysis and paleoslope modeling, we derived depth estimates for each of the biofacies identified in this study. The shallowest, inner neritic biofacies 1 indicates water depths of ~30m. On the paleoslope model, the difference in water depth between biofacies 1 and 2 is about 15m, which indicate a paleodepth of ~45 for biofacies 2. A similar approach has

Millville Corehole



TEXT-FIGURE 6

Millville borehole: lithology; gamma log, percent composition; benthic foraminiferal biofacies where black is factor 1, red is factor 2, green is factor 3, blue is factor 4; percent of planktonic foraminifera, foraminiferal number (number of foraminifera specimens per gram); nannofossil zones and their markers; red lines are the sequence boundaries of Merchantville II (MeII) and Merchantville III (MeIII). See text-figure 4 for symbol key.

been taken to identify water depth on the paleoslope model for biofacies 3 and 4 that gives us estimates of ~55m for biofacies 3 and ~70m for biofacies 4.

These depth estimates for the biofacies are compared with the water depths estimated by the percentage of planktonic foraminifera analysis at Bass River corehole. At Bass River, independent water depth estimates are derived from the comparison of percentage of planktonic foraminifera with a standard depth distribution of Grimsdale and Van Morkhoven (1955). The water depths range from 40-80m. This depth estimates for the biofacies match closely with water-depth estimates derived from the percentage of planktonic foraminifera analysis.

LITHOSTRATIGRAPHY AND SEQUENCE STRATIGRAPHY

MeI

The MeI sequence is identified in the Sea Girt and Bass River coreholes. The sequence boundary with the underlying Cheesequake Formation is identified as a prominent lithological unconformity associated with a gamma log sharp peak at 1056ft (321.9m) at Sea Girt (text-fig. 4) and at 1683ft (513m) at Bass River (text-fig.7).

At Sea Girt, the MeI sequence (1056-1000.9ft [321.8-305.07 m]) is a succession of muddy, burrowed glauconite and quartz sand that is overlain by micaceous silty clay and silt. Biofacies 1 indicates that the MeI sequence was deposited in an inner neritic paleoenvironment with paleodepth of 30m. At Sea Girt, the foraminiferal number is low (~30 s/g) through the entire MeI sequence, and planktonic foraminifera are present only at

1037ft (316.0m), suggesting that the 1037ft (316.0m) represents maximum water depth and possibly the MFS. Lithology and foraminiferal analyses suggest that the glauconite and quartz sands (1056-1037ft [321.8 -316.0]) comprise the transgressive system tract (TST) of the MeI sequence, the water depth peak at 1037ft (316.0m) may mark the maximum flooding surface (MFS), and the micaceous silty clay and silt comprise the highstand system tract (HST).

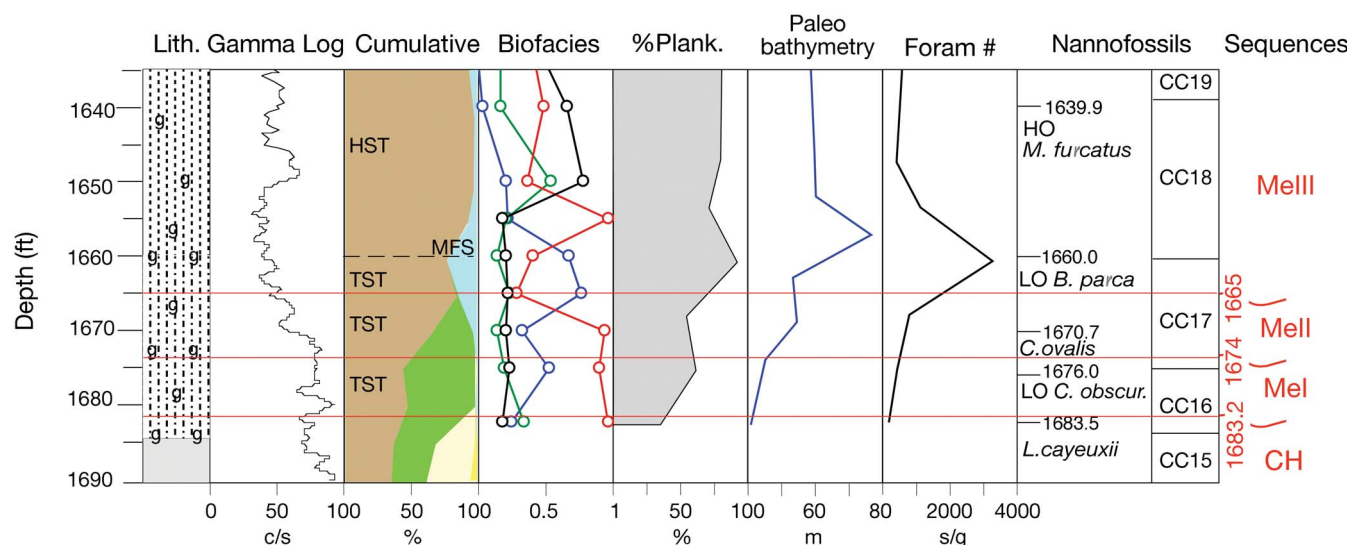
The presence of calcareous nannofossils *Lucianorhabdus cayeuxii* at 1050.6ft (320.2m) indicates the base of nannofossil Zone CC16. At Sea Girt, the MeI sequence is assigned to Zone CC16 (84.5-84 Ma; Gradstein et al. 1995).

At Bass River, the MeI sequence (1683-1674ft; 513.0-507.5m) consists of clayey glauconite sand (up to 70% glauconite) and glauconite clays (text-fig. 7). Biofacies 2 indicates deposition in a middle neritic environment with a paleowater depth of ~45m. The foraminiferal number and the percent of planktonic foraminifera indicates gradual water depth increase toward the top of the MeI sequence. Lithologic and foraminiferal analyses suggest that the glauconite sands and clays comprise thin a TST and HST respectively.

The presence of the calcareous nannofossil *Lucianorhabdus cayeuxii* at 1683.5ft (513.1m) identifies the base of Zone CC16 and the MeI sequence is assigned to Zone CC16 at Bass River (84.5-84 Ma; Gradstein et al. 1995).

MeII

The MeII sequence appears above a prominent sequence boundary associated with a burrowed contact and large gamma ray in-



TEXT-FIGURE 7

Bass River borehole: lithology; gamma log; percent composition; benthic foraminiferal biofacies where black is factor 1, red is factor 2, green is factor 3, blue is factor 4; percent of planktonic foraminifera; foraminiferal number (number of foraminifera specimens per gram), nannofossil zones and their markers; red lines are the sequence boundaries of Merchantville II (MeII) and Merchantville III (MeIII). See text-figure 4 for symbol key.

crease at Sea Girt (1000.9ft; 305.1m), Ancora (945.3ft; 288.13m), Millville (1246.2; 379.8m), and Bass River (1674ft; 510.2m).

At Sea Girt, the MeII sequence (1000.9–962.1ft; 305.1–293.2m) consists of clayey slightly quartzose glauconite sand at the base, glauconite sand in the middle, and glauconite clay at the top (text-fig. 4). Biofacies 1 indicated deposition of the MeII sequence in an inner neritic environment (paleodepth of ~30m). Peaks in glauconite sand content and the percent of planktonic foraminifera mark a possible MFS at 986ft (300.5m). Peaks in foraminiferal number and in abundance of *Gavelinella texana* (998ft (304.1m) appear just above the sequence boundary (1000.9ft; 305.1m). We assume that concentration of foraminifera in quartzose glauconite sand is a result of re-worked material accumulating at the sequence boundary and do not consider these foraminiferal data an indicator of water depth. At Sea Girt, glauconite sands deposited during rapid increase in water depth comprise the TST between the sequence boundary (1000.9ft [305.1m]) and the MFS (986ft [300.5 m]), and glauconite clays associated with gradational shallowing comprise the HST from 986ft (300.5m) to 962.1ft (293.2m).

The LO of *Calculites obscurus* at 998.5ft (304.3m) assigns the interval from 998.5–964.0ft (304.3–293.8m) interval to Zone CC17. The LO of *Broinsonia parca parca* at 964.0ft (293.8m) identifies the base of Zone CC18 and assigns the 964.0ft–962.1ft (293.8–293.2m) to Zone CC18. At Sea Girt, the MeII sequence is assigned to Zone CC17–18 indicating an age of 84–83 Ma (Gradstein et al. 1995).

At Ancora, the MeII sequence (945.3–909.0ft; 288.1–277.0m) is recognized as a succession of slightly quartzose glauconite sand at the base, glauconite sand in the middle, and glauconite silty clay at the top (text-fig. 5). Biofacies 1 assigns the MeII sequence to an inner neritic environment with an estimated paleowater depths of ~30m. Variations in the percent of the planktonic foraminifera and the foraminiferal number indicate a

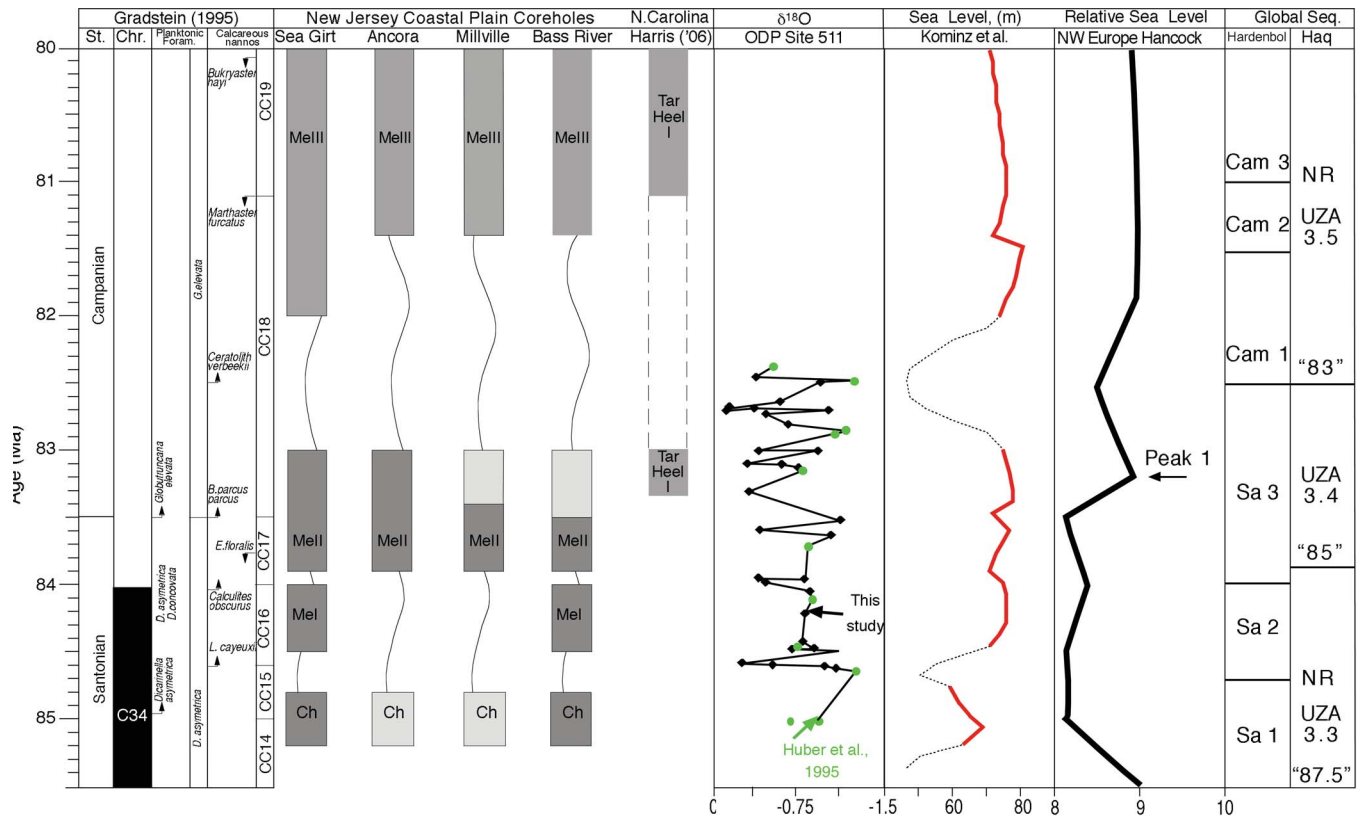
gradual increase in water depth toward the top of the sequence. We interpret that the glauconite sands comprise the TST, and glauconite clays comprise the HST. The MFS of the MeII sequence is placed at 930ft (283.4m) where a gamma log peak associated with an indurated zone.

The LO of *Calculites obscurus* is identified at 940.5ft (286.5m) marking the base of Zone CC17. The LO of *Broinsonia parca parca* is found at 918.5ft (279.9m), indicating the base of Zone CC18. Thus, at Ancora, the MeII sequence is assigned to Zone CC17–18 (83.9–83.5 Ma; Gradstein et al. 1995) (text-fig. 5).

At Millville, the MeII sequence (1246.2–1225.7ft; 379.8–373.6m) consists of slightly quartzose glauconite sand overlain by glauconite sand and glauconite silty clay at the top (text-fig. 6). Biofacies 2 indicates a middle neritic paleoenvironment for the MeII sequence with paleowater depths of about 45m. Variations in the percent of planktonic foraminifera and the foraminiferal number indicate a gradual increase in water depth toward the top of the sequence. The glauconite sand comprises the TST of the MeII sequence, and silty clay comprises the HST of MeII sequence. The MFS is placed at 1239ft.

The LO of *Calculites obscurus* at 1251ft (381.3m) indicates Zone CC17 from 1251–1228ft (374.2m), and the LO of *Broinsonia parca parca* at 1228ft (374.2m) indicates Zone CC18 from 1228–1221ft (374.2–372.1m). Thus, at Millville, the MeII sequence is assigned to Zones CC 17–18 (83.9–83.5 Ma; Gradstein et al. 1995) (text-fig. 6).

At Bass River, the MeII sequence is identified from 1674–1665ft (510.2–507.5m) and consists of 1) clayey glauconite sand at the base and 2) fossiliferous, bioturbated, lignitic silty clay at the top. The section was deposited in a middle neritic environment (biofacies 2). The absence of quartzose sand in the basal section, and generally high carbonate content suggest deeper paleodepths at Bass River than at Sea Girt, Ancora, or Millville. Water depths are estimated as 50–60m



TEXT-FIGURE 8

Comparison of New Jersey coastal plain Merchantville sequences (Merchantville I = MeI, Merchantville II = MeII, Merchantville III = MeIII) with Tar Heel I sequence of southern North Carolina (Harris et al. 2006), deep-sea benthic foraminiferal $\delta^{18}\text{O}$ from ODP Site 511 (Huber et al. 2002-circles, current studies-diamonds); sea-level estimate of Kominz et al. (2008); from backstripping of New Jersey coastal plain paleobathymetry estimates, relative sea-level estimates of Hancock et al. 1993 (Northwestern Europe), and global sequence boundaries of Hardenbol et al. (1998) and Haq et al. (1987; ages in quotes). Time scale of Gradstein (1995). (Con. – Coniacian, Broin.-Broinsonia, *E. floralis* – *Eprolithus floralis*, *L. cayeuxi* – *Lucianorhabdus cayeuxi*).

(text-fig. 7). The percent of planktonic foraminiferal and foraminiferal number both indicate a gradual increase in water depth toward the top of the MeII sequence.

The LO of *Calculites obscurus* is identified at 1676.0ft (510.8m), and the presence of *Calculites ovalis* is noted at 1670.7ft (509.2m). The LO of *Broinsonia parca parca* is identified at 1660.0ft (505.9m). At Bass River, the MeII sequence is assigned to Zone CC1718 (83.9–83.5 Ma; Gradstein et al. 1995) (text-fig. 7).

MeIII

Detailed analysis is provided only for the lower MeIII sequence found in the Merchantville Formation. Data for upper MeIII (Woodbury and Upper Englishtown formations) are derived from the site reports of ODP Leg174AX coreholes Bass River, Millville, Sea Girt, and Ancora.

The MeIII sequence at Sea Girt occurs from 962.1–837.6ft (293.2–255.3m) (Miller et al. 2006). The lower MeIII sequence (962.1–941ft [293.2–286.8m]) consists of quartzose glauconite sand, burrowed glauconite sand, and slightly shelly micaceous clay. In the lower MeIII sequence, biofacies 1 indicates a paleodepth of ~30m. Foraminiferal analyses detected no signif-

icant changes in paleodepth within the lower MeIII sequence: 1) the abundance of *Gavelinella texana* is about 45–50% with ~5% variation; 2) the percentage of planktonic foraminifers is ~10% and variations do not exceed several percent; and 3) the foraminiferal number is generally low (less than 50 specimens/gm). A peak in foraminiferal number at 961ft (292.9m) appears just above the sequence boundary at 962.1ft (255.3m) and associated with reworked sediments. The MFS of the sequence is assumed to appear above the interval of study. The lower MeIII glauconites comprise the TST of the MeIII sequence.

The LO of *Broinsonia parca parca* at 964.4ft (293.9m) identifies the base of Zone CC18 and we assign the interval of 964.0ft–901.0ft (293.9–274.6m) to Zone CC18. The HO of *Marthasterites furcatus* is identified above the interval of study at 901.0ft, and we assign 901.0–891.0ft (274.6–271.5m) to Zone CC19 (Miller et al. 2006) (text-fig. 4). Thus, at Sea Girt, the MeIII sequence is assigned to Zone CC18–19 (82–78.8 Ma; Gradstein et al. 1995).

At Ancora, the MeIII sequence is identified from 909–793.2ft (277.1–241.8m) (Miller et al. 1999). The lower section of the MeIII sequence (909–901.0ft [277.1–274.6 m]) consists of black

glaucinite (>50%) sand from 909-906ft (277.1-276.1m) and carbonate-rich clay from 906-905ft (276.1-275.8m) (text-fig. 5). The lower MeIII sequence contains biofacies 2, indicating paleodepths of about 45m. The percent of planktonic foraminifers gradually increases from the base to the top of the MeIII sequence. The foraminiferal number increases from the base at 909ft (276.1m), peaks at 906ft (276.1m), and decreases from 906 (276.1m) to 901ft (274.6m). A peak in foraminiferal number is associated with a lithofacies change from glauconite sand to carbonate clay at 906ft (276.1m). The MFS of the lower MeIII sequence is thus placed at 906ft (276.1m). The glauconite sand below the MFS comprises the TST of the MeIII sequence, and the carbonate clay above the MFS is the lower part of the thick HST of the MeIII sequence.

The LO of *Broinsonia parca parca* at 918.5ft (279.9m) indicates Zone CC18 and the HO of *Marthasterites furcatus* at 903.0ft (275.2m) designates Zone CC19. Thus, at Ancora, the MeIII sequence is assigned to Zone CC18-19 (81.4–78.8 Ma; Gradstein et al. 1995) (text-fig. 5).

At Millville, the MeIII sequence is identified from 1225.7-1086.85ft (373.6-331.3m) (Sugarman et al. 2005). The lower section of the MeIII sequence (1225.7-1201.0ft (373.6-366.0m) contains glauconite sand that grades upward into a silvery gray carbonate-rich clay and glauconite clay (text-fig. 6). The glauconite sand is associated with biofacies 2 (paleodepth ~ 45m). The carbonate-rich clay contains biofacies 3, and the glauconite clay contains biofacies 1. In the clay deposits, the environment of deposition changes from middle to inner neritic, and paleowater depth changes from 60 to 30m. The foraminiferal number and the percentage of planktonic foraminifers indicate a water depth increase within the glauconite sands (a peak in organic rich clay, and a decrease in glauconite clay). The peak in the percent planktonic foraminifers and typical MFS lithofacies (organic rich clay) indicate a possible MFS at 1210ft (368.8m). The basal glauconite sand comprises the TST of the lower MeIII sequence and the HST consists of the overlying glauconite clay.

The LO of *Broinsonia parca parca* at 1228ft (374.2m) indicates Zone CC18 from 1228-1221ft (374.2-372.1m). The HO of *Marthasterites furcatus* at 1221ft (372.1m) indicates Zone CC19. Thus, at Millville, the MeIII sequence is assigned to Zone CC18-19 (81.4–78.8 Ma; Gradstein et al. 1995) (text-fig. 6).

At Bass River, the MeIII sequence is identified from 1665-1472.6ft (507.5-448.8m) (Miller et al. 1998). The lower section of the MeIII sequence (1665-1630.0ft [507.5-496.8 m]) consists of bioturbated glauconite clay, overlying glauconite foraminiferal clay, and micaceous, fossiliferous, bioturbated, lignitic silty clay. Peaks in the foraminiferal number and the percent planktonic foraminifers mark the MFS at 1660ft (505.97m) (text-fig. 7). The basal glauconite clay and the foraminiferal clays are associated with biofacies 4, and the overlying silty clay is associated with biofacies 2. Paleobathymetric estimates indicate that paleodepths ranged from 40-80m (text-fig. 7).

At Bass River, the MeIII sequence is assigned to Zone CC17-19. The base of Zone CC17 is identified by the LO of *Calculites obscurus* at 1676.0ft (510.8m) and the presence of *Calculites ovalis* at 1670.7ft (509.2m). The base of Zone CC18 is identified by the LO of *Broinsonia parca parca* at 1660.0ft (505.9m) and the base of Zone CC19 are identified by the HO

of *Marthasterites furcatus* at 1639.9ft (499.8m). Thus, the ages of MeIII sequence at Bass River is 81.4–78.8 Ma (Gradstein et al. 1995) (text-fig. 7).

DISCUSSION

Sequences: lithostratigraphy and biostratigraphy

Our lithologic analysis of the Merchantville Formation reveals cyclical alternation of lithofacies driven by water-depth fluctuations. Unconformities define the bases of the MeI, MeII, and MeIII sequences. Lithofacies changes and gamma log peaks defining the MeI, II, and III sequence boundaries, which are best developed at Sea Girt (text-figs. 2, 3). Biofacies showed only small variations at the sequence boundaries at Sea Girt. The MeII/MeIII sequence boundaries at Ancora, Millville, and Bass River are associated with biofacies changes, but not at Sea Girt.

Although lithofacies successions (systems tracts) are cryptic in the MeI and MeII sequences, certain patterns are clear once the sequence boundaries are recognized. At Bass River, Ancora, and Millville, the lower units of the MeII sequence are characterized by a TST consisting of glauconite sands deposited in inner-middle shelf environments, which are overlain by the HST consisting of carbonate-rich glauconitic clays of the middle shelf. Quartz sands are lacking in the HSTs at Bass River, Ancora, and Millville due to sediment starvation. At Sea Girt, the Merchantville sequences display a pattern of lithofacies successions that is more typical of other Upper Cretaceous sequences in New Jersey. The presence of quartzose sand in the top section of the MeII sequence is a typical feature of Upper Cretaceous New Jersey sequences; some quartz sand also occurs in the upper HST of the MeI sequence at Sea Girt. The MeIII sequence displays a typical New Jersey sequence pattern with a basal glauconite TST, a medial lower HST prodelta silty clay (the Woodbury Formation), and an upper HST delta front sand (lower Englishtown Formation).

Depositional differences between the MeI-MeII and other Upper Cretaceous New Jersey sequences (including MeIII) can be explained by accommodation and sedimentation factors. The distance from the sediment source during sediment starvation precluded formation of thick MeI and MeII sequences at Sea Girt and resulted in thin and concatenated MeI and MeII sequences at Ancora, Millville and Bass River. The MeIII sequence that consists of the Merchantville, Woodbury, and lower Englishtown formations has thick HST silts and clays at all sites. Two different rates of accommodation for MeI and II sequences versus the MeIII sequences may be assumed.

Global comparison

The ages of the base of the MeII sequence and the top of the MeIII sequence are similar to the ages at the base and top of the Tar Heel I sequence (southern North Carolina) respectively (Harris and Self-Trail 2006). The MeII/MeIII sequence boundary correlates with the possible MFS of the Tar Heel I sequence (Harris and Self-Trail 2006). The correlation between the New Jersey coastal plain and southern North Carolina is based on nannofossil biostratigraphy. High-resolution nannofossil biostratigraphy of the Tar Heel I sequence suggests a hiatus between the FO of *Broinsonia parca constrictus* and the LO of *Marthasterites furcatus* at this inferred MFS (text-fig. 5 (age depth plot) in Harris and Self-Trail (2006), and a dashed-lined segment in the Tar Heel I sequence in our paper, text-fig. 8). Our data suggest that this surface may be an unconformity, not a MFS. Increased resolution of nannofossil biostratigraphy on the

TABLE 1

Oxygen isotope values for benthic foraminifera from deep sea drilling project site 511 current studies and Huber et al. (1995)

Depth	Age	$\delta^{18}\text{O}$	Current studies	Huber et al., 1995
248.62	82.56	-0.56		Osangularia
253.41	82.6544	-0.38	Gavelinella beccariiiformis	
253.62	82.66	-1.26		Gavelinella beccariiiformis
254.92	82.6846	-0.93	Gavelinella beccariiiformis	
256.68	82.72	-0.54		mix. benth
258.15	82.75	-0.88		mix. benth
261.06	82.81	-0.52		mix. benth
261.69	82.82	-0.91		mix. benth
261.77	82.8216	-0.29	Oridorsalis	
262.33	82.8328	-0.14	Gyroidina globosa	
262.79	82.842	-0.18	Gyroidina globosa	
263.30	82.8522	-0.16	Gavelinella stephensoni	
263.80	82.8622	-0.36	Gavelinella stephensoni	
264.30	82.8722	-1.00	Gavelinella beccariiiformis	
265.65	82.8992	-0.46	mix Gavelinella	
268.90	82.9642	-0.65	Nuttallinilla florealis	
270.69	83	-1.15		Gavelinella beccariiiformis
271.2	83.01	-1.07		Gavelinella beccariiiformis
277.28	83.1316	-0.40	Nuttallinilla florealis	
277.28	83.1316	-0.91	Gavelinella stephensoni	
281.91	83.2242	-0.29	Gyroidina globosa	
282.29	83.2318	-0.31	Oridorsalis	
283.28	83.2516	-0.75	Nuttallinilla florealis	
283.7	83.26	-0.77		Gyroidina nitidus
289.7	83.38	-0.79		mix. benth
290.85	83.4032	-0.31	Gyroidina globosa	
299.74	83.57	-0.75		mix. benth
300.30	83.5922	-1.10	Gavelinella beccariiiformis	
301.24	83.6	-1.1		mix. benth
303.30	83.6522	-0.43	Globorotaloides	
305.30	83.6922	-0.86	Nuttallinilla florealis	
305.73	83.69	-0.97		Charltonina
305.73	83.69	-0.3		Globorotaloides
305.73	83.69	-1.02		mix Gavelinella
309.23	83.76	-0.82		
319.30	83.9722	-0.79	Nuttallinilla florealis	
319.30	83.9722	-0.39	Gyroidina globosa	
319.80	83.9822	-0.48	mix Gavelinella	
258.15	82.75	-0.88		mix. benth
343.72	84.45	-1.09		Globorotaloides multisetpta
347.31	84.5324	-0.26	Gavelinella stephensoni	
347.72	84.5406	-0.51	Gavelinella stephensoni	
348.28	84.5518	-0.71	Oridorsalis	
348.88	84.5638	-1.09	Globorotaloides micheliniana	
349.80	84.5822	-1.22	Globorotaloides micheliniana	
350.18	84.57	-1.07		Globorotaloides sp.
366.2	84.89	-0.93		Gyoidinoides sp

New Jersey coastal plain for MeII and MeIII sequences (Zone CC18) and paleobathymetry (biofacies) analysis of the Tar Heel I sequence in southern North Carolina will help to resolve the relationship between the MeII/MeIII sequence boundary in New Jersey and the unconformity of the Tar Heel I sequence in southern North Carolina. We hypothesize the synchronous origin of late Santonian early Campanian sequences of New Jersey and the southern North Carolina is due to global sea-level fluctuations.

We compare the Merchantville sequence boundaries with global sea-level records of Hancock (1993), Haq et al. (1987), and Hardenbol et al. (1998). In northwest Europe, Hancock (1993) recognized two sea-level peaks separated by lower sea-levels in the latest Santonian-early Campanian. Hancock (1993) recognized a sea-level lowering in the latest Santonian, transgression across the Santonian-Campanian boundary, and a sea-level maximum (Peak 1) in the earliest Campanian (Jarvis et al. 2002). The sea-level was very low in the late early

Campanian (*Offaster pinula* Zone) and peaked again in the early late Campanian (Peak 2) (*Belemnitella mucronata* Zone). The MeII and MeIII sequences correlate well with Peak 1 and Peak 2 transgressions of Hancock (1993), respectively. The basal unconformity of the MeII sequence is assigned to the base of nannofossil Zone CC17 (83.9 Ma [the latest Santonian]) and the MeII/MeIII sequence boundary is assigned to nannofossil Zone CC18 (83–82 Ma [the early Campanian]). The MeI transgression is not recognized by Hancock (1993), and the late Santonian is characterized by a sea-level minimum (Jarvis et al. 2002).

Haq et al. (1987) resolved two unconformities and three sequences within the late Santonian-early Campanian interval. The MeI sequence correlates to the upper part of UZA-3.3 sequence, the MeII sequence correlates to the UZA-3.4 sequence, and the MeIII sequence correlates to the UZA-3.5 sequence. The sequence boundary separating MeI and MeII sequences corresponds to the “85” unconformity of Haq et al. (1987), and MeII/MeIII sequence boundary corresponds to the “83” unconformity of Haq et al. (1987).

Hardenbol et al. (1998) recognized six sequences within the late Santonian-early Campanian interval. Hardenbol et al. (1998) biostratigraphy is based on the North American Western Interior ammonite zones and sections from Texas and Arkansas. We correlate the Merchantville and Hardenbol et al. (1998) sequences on the basis of the calcareous nannofossil biostratigraphy. The ages of the Cheesequake and MeI sequences correlate remarkably well with the upper Sa1 and Sa2 sequences of Hardenbol et al. (1998), respectively. The MeII sequence correlates with the Sa3 sequence of Hardenbol et al. (1998), and the Merchantville III sequence with Cam 1–3 sequences of Hardenbol et al. (1998). We considered the existence of a possible unconformity within the MeIII deposits and argue that closer correlation is prevented due to limitations in age control and time scale problems. Nevertheless, the global comparison of late Santonian-early Campanian sea-level records indicates an excellent agreement and suggests the origin of the Merchantville sequence boundaries are due to global eustatic changes.

We also compare the Merchantville sequence boundaries with deep-sea $\delta^{18}\text{O}$ benthic foraminiferal records from the Santonian-Campanian section of the DSDP Site 511 (Falkland Plateau). Planktonic foraminifers and calcareous nannofossils are the primary groups that were used for biostratigraphy of Up-

per Cretaceous deposits from Site 511. Standard low-latitude zones were used for calcareous nannoplankton biozonation, similar to those used here for the New Jersey coastal plain. In fact, the same Campanian nannofossil markers are identified within the New Jersey shelf and deep-sea area of Falkland Plateau. These zonations have a resolution that allows reliable correlation between the high-latitude oxygen isotope record at Site 511 and New Jersey. Whereas, it is possible that the first and last occurrence of the nannofossil taxa is diachronous, between a high- and mid-latitude, we regard the comparison shown (text-fig. 8) as reasonable and testable with other age proxies.

Our comparisons link Ch/MeI, Me I/II, and Me II/III sequence boundaries to $\delta^{18}\text{O}$ increases of $\sim 1\text{‰}$, 0.5‰ , and $\sim 1\text{‰}$, respectively, implying that at least part of the Santonian-Campanian $\delta^{18}\text{O}$ signature was due to development of ice sheets (text-fig. 8). The sea-level falls associated with these three sequence boundaries are 10m, 5m, and $\sim 20\text{m}$ respectively (text-fig. 8, Miller et al. 2005a; Kominz et al. 2008). Assuming a $\delta^{18}\text{O}$ /sea-level calibration factor of $0.1\text{‰}/10\text{m}$ (De Conto and Pollard 2003), then the $\delta^{18}\text{O}$ increases represent $\delta^{18}\text{O}$ seawater changes of 0.1, 0.05, and 0.2‰ , respectively. The remainder of the $\delta^{18}\text{O}$ increases (0.9, 0.45, 0.8‰ , respectively) must be due to coolings of 4, 2, and 3.5°C , respectively. Thus, the sea-level records predict development of ice sheets that were about 11% and 22% the size of the modern Antarctic ice sheet. Miller et al. (2003, 2005b) explained the presence of such ice sheets in the Greenhouse world of the Late Cretaceous by proposing that the ice sheets were restricted to the interior of Antarctica and paced by Milankovitch forcing.

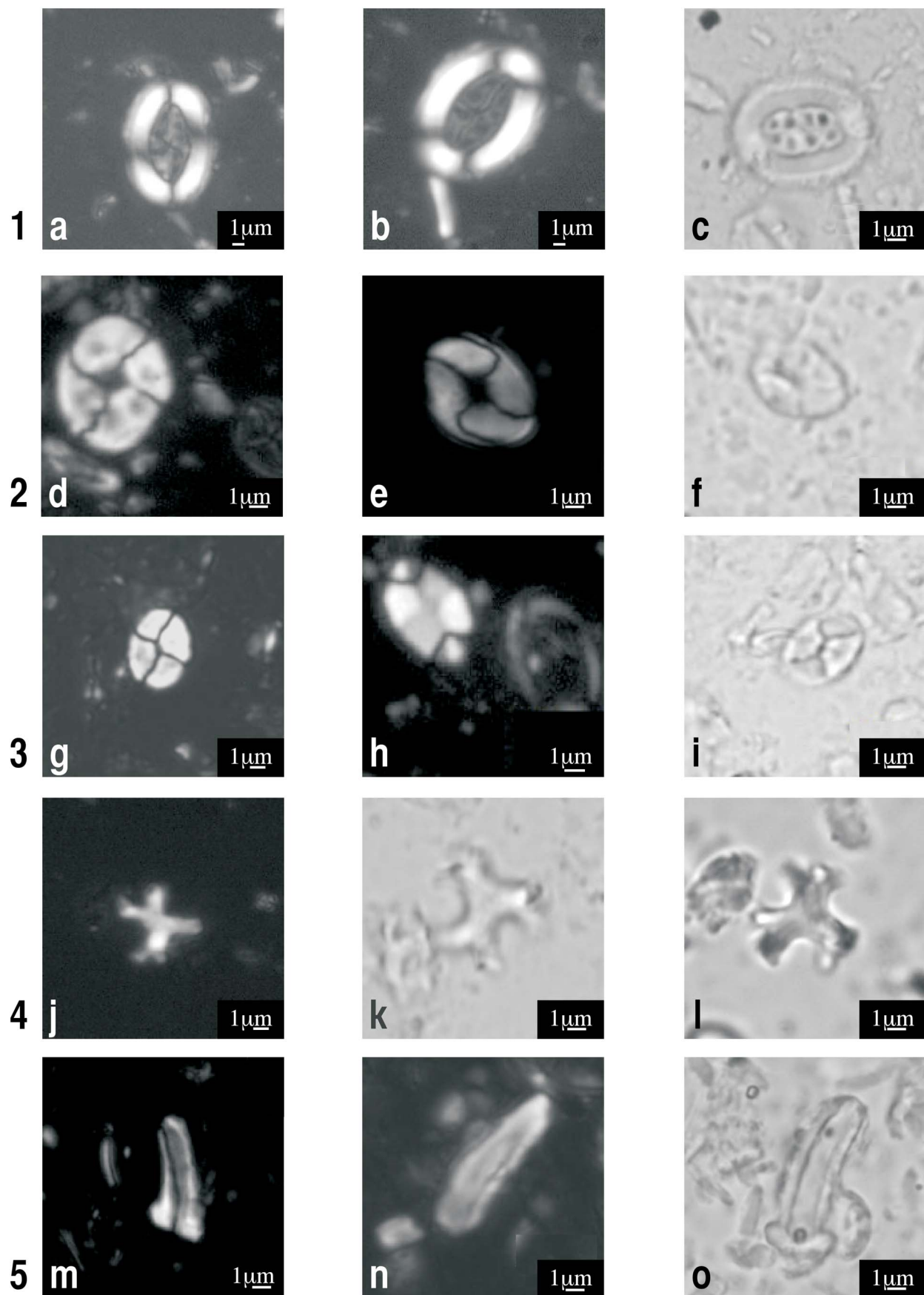
Modeling studies of Milankovitch forcing (Matthews and Frohlich 2002) predict that about 30% of Greenhouse $\delta^{18}\text{O}$ increases should be attributable to $\delta^{18}\text{O}$ seawater changes and the 70% to deep-water coolings. Their model predicts $\delta^{18}\text{O}$ seawater changes of ~ 0.3 , 0.2 , and 0.3‰ across Cheesequake/Merchantville I, Merchantville I/II, and Merchantville II/III sequence boundaries, respectively. Considering limitations of paleobathymetry estimates on the New Jersey margin due to the absence of low stand deposits, and limited resolution of $\delta^{18}\text{O}$ data, we conclude that $\delta^{18}\text{O}_{\text{sea-water}}$ changes predicted from Matthews and Frohlich (2002) modeling solutions are close to those we obtained from sea-level/ $\delta^{18}\text{O}$ estimates.

The eustatic lowerings of approximately 10m, 5m, and $\sim 20\text{m}$ respectively are minimal estimates of the falls and do not account for two effects. First, we do not capture the full sealevel

TEXT-FIGURE 9

All figured specimens are from the Millville corehole of New Jersey coastal plain. The depth refers to the sample from which the figured specimen was taken. All specimen names follow Sissingh (1978) and Perch-Nielsen (1985).

- | | |
|--|---|
| a <i>Lucianorhabdus cayeuxii</i> , 1251 ft (381.3m); | d <i>Broinsonia parca parca</i> , 1228 ft (374.2m); |
| b <i>Marthasterites furcatus</i> , 1221 ft (372.1m); | e <i>Calculites obscurus</i> , 1251 ft (381.3m); |
| c <i>Calculites ovalis</i> , 1236 ft (376.7m); | f <i>Calculites obscurus</i> , 1251 ft (381.3m). |



signal onshore due to missing lowstand deposits. Second, even if our eustatic falls are correct, the actual change in the volume of the oceans could have been greater. It may be more correct to compare apparent sea-level estimates with $\delta^{18}\text{O}$ changes instead of eustatic estimates (Pekar et al. 2002). Backstripping yields eustatic estimates (Van Sickle et al. 2003; Miller et al. 2005; Kominz et al. 2008). Eustasy is the change in sea-level relative to the center of Earth. Apparent sea-level changes are due to eustasy and to subsidence related to changes in water loading of the entire ocean. Apparent sea-level fluctuations exceed the eustatic changes, and to obtain apparent sea-level, eustatic changes need to be divided by 0.68 (Pekar et al. 2002). Thus, eustatic estimates derived from backstripping of the New Jersey margin (Kominz et al. 2008) yield ~15 m, 7 m, and 29 m of apparent sea-level changes at Ch/MeI, MeI/II, and MeII/III sequence boundaries, respectively. This would suggest that the $\delta^{18}\text{O}$ increases represent $\delta^{18}\text{O}_{\text{seawater}}$ changes of 0.15, 0.07, and 0.29‰, respectively (using 0.1‰/10m calibration) and coolings of 3.5, 1.8, and 3°C, respectively. Nevertheless, studies of the last glacial maximum sea-level lowering (Peltier and Fairbanks 2006) show that the whole-ocean loading of water actually results in minimal difference in eustatic loading (e.g., the 120m apparent sea-level change in Barbados is equivalent to a 120m eustatic), and that this difference could be neglected in our calculations. However, this assumes that loading by the change in ocean water volume (hydroeustasy) achieved full isostatic compensation. This exercise of comparing eustatic and apparent sea-level estimates illustrates one further uncertainty in using sea-level records to constrain ice-volume history. Nevertheless, the match of our sea-level estimates with the $\delta^{18}\text{O}$ record suggests that the Merchantville sequences on the New Jersey coastal plain are connected to upper Santonian-lower Campanian global climatic variations and provides evidence for existence of small, ephemeral size ice sheets in Antarctica in the Greenhouse world.

CONCLUSIONS

Integration of biostratigraphy, benthic foraminiferal biofacies, lithology, and gamma logs from the New Jersey coastal plain delineates unconformities, allowing identification of three sequences within the Merchantville Formation (MeI, MeII, MeIII). The ages of these sequences (78.8 to 85.0 Ma) have been constrained by calcareous nannoplankton biostratigraphy (Me I: CC16; MeII: CC17-18; MeIII: CC18-19). The ages of Merchantville sequences boundaries are similar to those reported by Haq (1987), Hardenbol (1998), Harris and Self-Trail (2006), and Hancock (1993), implicating a global cause for their origin. The Merchantville sequences $\delta^{18}\text{O}$ boundaries correlate with deep-sea benthic foraminiferal increases from ODP site 511 (Falkland Plateau), implying that late Santonian-early Campanian sea-level falls can be attributed to the development of ice-sheets. Close correlation in ages of the Merchantville sequences boundaries, global sea-level falls, and $\delta^{18}\text{O}$ increases suggests that the Merchantville sequences on the New Jersey coastal plain are connected to late Santonian-early Campanian glacioeustatic variations and provides possible evidence for the existence of ice sheets in the Greenhouse world.

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