

## THE CENOMANIAN/TURONIAN CARBON BURIAL EVENT, BASS RIVER, NJ, USA: GEOCHEMICAL, PALEOECOLOGICAL, AND SEA-LEVEL CHANGES

P. J. SUGARMAN<sup>1</sup>, K. G. MILLER<sup>2</sup>, R. K. OLSSON<sup>2</sup>, J. V. BROWNING<sup>2</sup>, J. D. WRIGHT<sup>2</sup>, L. M. DE ROMERO<sup>3</sup>, T. S. WHITE<sup>4</sup>, F. L. MULLER<sup>1</sup>, AND J. UPTEGROVE<sup>1</sup>

### ABSTRACT

The Bass River borehole (ODP Leg 174AX) recovered approximately 200 ft (61 m) of upper Cenomanian to lower Turonian strata from the New Jersey Coastal Plain, USA, including the expression of a global carbon burial event. The Cenomanian/Turonian (C/T) boundary is recognized at Bass River at ~1935.5 ft (589.9 m) based on the contact of nannofossil *Microstaurus chias-tius* and *Eiffellithus eximius* Subzones of the *Parhabdolithus asper* Zone. Carbon isotopic records of both *Gavelinella* and *Epistomina* show a large (>2‰) increase immediately below the C/T boundary, with maximum values of 6‰ in *Epistomina* and 4.3‰ in *Gavelinella*. The  $\delta^{13}\text{C}$  offset between these taxa is constant and we conclude that *Epistomina*, like *Gavelinella*, faithfully records seawater  $\delta^{13}\text{C}$  changes. Above the sharp  $\delta^{13}\text{C}$  increase, elevated  $\delta^{13}\text{C}$  and sedimentary organic carbon (>0.9%) values continue into the lower Turonian, culminating in a sharp  $\delta^{13}\text{C}$  decrease. High  $\delta^{13}\text{C}$  values in the uppermost Cenomanian-lower Turonian at Bass River correlate with a global carbon burial event recorded in Europe and the U.S. Western Interior; we estimate the duration of this event at Bass River as 400–500 k.y.

Although the carbon burial event occurred during a long-term eustatic rise (10 m.y. scale), it occurs within a 1–2 m.y. long sequence at Bass River that indicates no relationship with sea-level lowering on the m.y. scale. The carbon burial event does not appear to be associated with maximum flooding either, indicating little correlation with sea-level rise on a m.y. scale. Within the sequence spanning the carbon event, there are at least 4 shallowing-upward parasequences (durations ~350–460 k.y.) indicated by changes in abundance and type of *Epistomina* species,  $\delta^{18}\text{O}$  variations, and minor lithologic variations. The highest occurrences of 6 *Epistomina* species and the origination of *Epistomina sliteri* Olsson n. sp. are associated with the parasequences and possibly with higher  $\delta^{18}\text{O}$  values. There is no clear association of parasequence boundaries inferred at Bass River with the carbon burial event; thus, there does not appear to be a relationship of the event with sea-level change on the 100 k.y. scale. We conclude that while the organic carbon burial event was associated with a general long-term (10 m.y. scale) eustatic rise, the initiation and termination of the peak organic burial event itself were unrelated to sea-level change.

### INTRODUCTION

The New Jersey Coastal Plain Drilling Project (Ocean Drilling Program Legs 150X and 174AX) was designed to evaluate global sea-level change and its influence on the timing and characteristics of sequences, stratigraphic units bounded by unconformities and correlative surfaces that are associated at least locally with the lowering of base level (definition of Mitchum et al., 1977 modified by Miller et al., 1998). Eocene-Miocene sequences recovered by Leg 150X demonstrated synchrony between sequence boundaries and  $\delta^{18}\text{O}$  increases for the past 42 million years, implying a primary control by ice sheet growth and decay (Miller and others, 1998). Leg 174AX drilling at Bass River, NJ, USA (Fig. 1) targeted Upper Cretaceous (Cenomanian-Maastrichtian) sequences and evaluated the relationship between sea-level change and several critical events in Earth History, including the Cretaceous/Tertiary boundary (Olsson and others, 1997) and the global peak in organic carbon extraction/burial associated with the Cenomanian/Turonian boundary.

Cenomanian to Turonian strata are characterized by organic-rich deposits resulting from an increase in burial of organic carbon (Arthur and others, 1985, 1987). This organic burial event (Ocean Anoxic Event 2 [OAE2]; Arthur and others, 1985) is reflected in a pronounced positive excursion of  $\delta^{13}\text{C}$  in the Cenomanian/Turonian boundary interval (e.g. Schlanger and others, 1987; Jenkyns and others, 1994). Long-term sea-level was near its highest levels ( $180 \pm 40$  m above the present level) during the mid-Cretaceous, although the precise timing of the long-term record is not well constrained: Revelle and others (1990) placed the highest point in the Albian, while Haq and others (1987) placed it in the early-mid Turonian. Million-year scale eustatic changes were superimposed on this long-term rise, preserving discrete m.y.-scale unconformity-bounded stratigraphic sequences (Haq, 1987; Olsson, 1991; Gale, 1995, 1996; Mitchell and others, 1996). Rising  $\delta^{13}\text{C}$  values throughout the early Turonian mimic the long-term eustatic curve, and the carbon burial event is generally associated with a long-term sea-level maximum (Jenkyns and others, 1994; Arthur and others, 1987). Thus, carbon isotopic and organic carbon burial events appear to be associated with long-term (10-m.y. scale) sea-level rise. Relationships been

→

FIGURE 1. Cenomanian/Turonian stratigraphic section from the Bass River borehole (see inset map for location). From left to right: depth in ft, a generalized lithologic column, downhole gamma ray log, cumulative percentages of the coarse fraction, sequences and lithologic units,  $\delta^{13}\text{C}$  values, and the percentage of total organic carbon. Wavy line at 1806.4 ft indicates unconformity. FS = flooding surfaces defining the bases of parasequences. MFS = maximum flooding surface. x = highest occurrence of the genus *Rotalipora*.

<sup>1</sup> NJ Geological Survey, PO Box 427, Trenton, NJ 08625, USA.

<sup>2</sup> Dept. Geol. Sciences, Rutgers University, Piscataway, NJ 08854, USA.

<sup>3</sup> Dept. Geol. Sciences, Univ. of North Carolina, Chapel Hill, NC 27599, USA.

<sup>4</sup> Dept. Geol., 3 Trowbridge Hall, Univ. of Iowa, Iowa City, IA 52240, USA.

Bass River Borehole, Cenomanian-Turonian

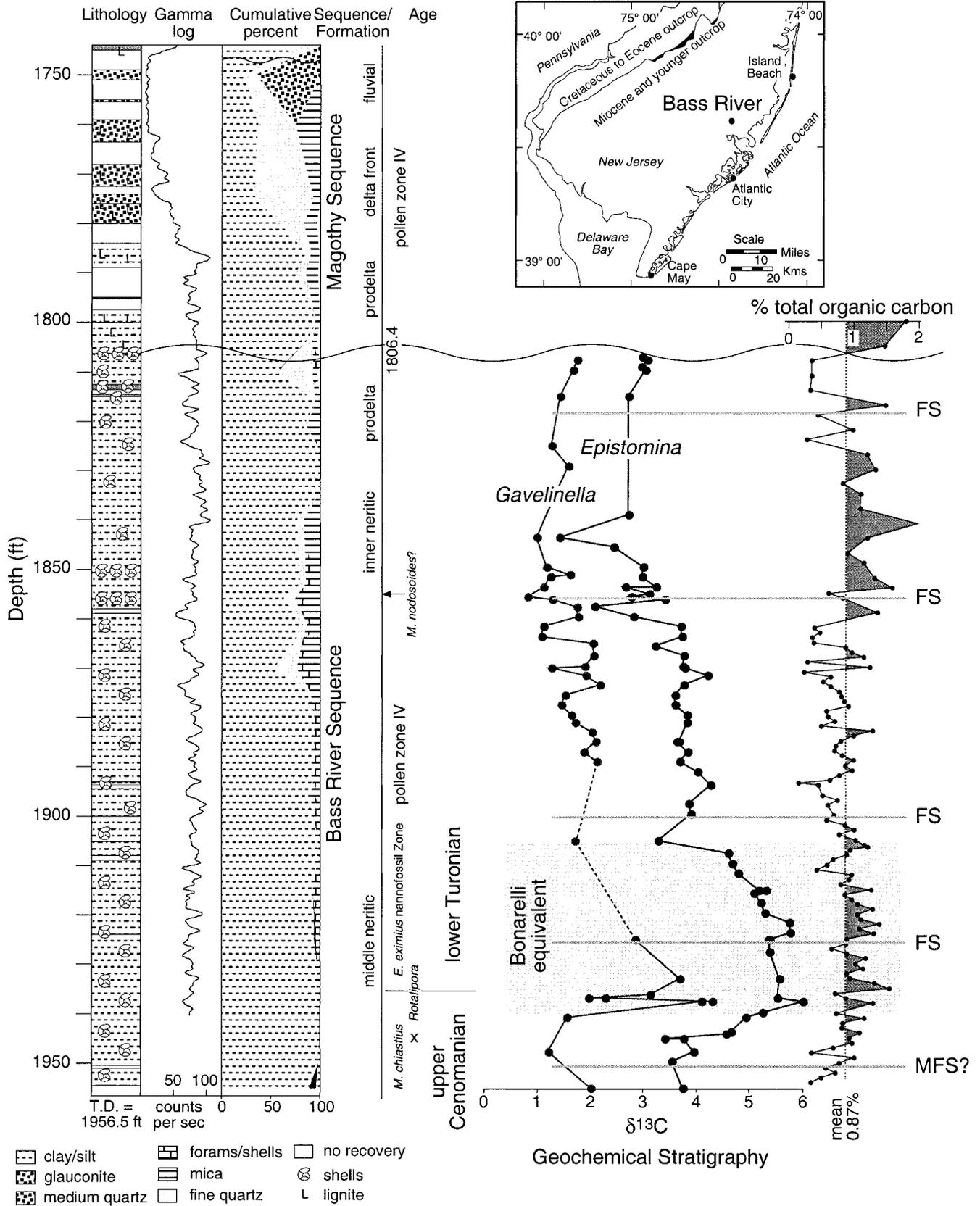


TABLE 1. Carbon and oxygen isotopic data for the late Cenomanian/early Turonian, Bass River, New Jersey.

Sample depth (ft)	<i>Epistomina</i> spp. $\delta^{18}\text{O}$	<i>Epistomina</i> spp. $\delta^{13}\text{C}$
1807	3.00	-2.85
1807.6	3.09	-2.84
1809	2.97	-2.84
1809.6	3.05	-2.83
1815	2.74	-2.98
1839	2.74	-2.76
1843.5	1.43	-3.14
1845.5	2.46	-2.68
1849.5	3.01	-2.49
1851.5	3.00	-2.58
1853.5	3.25	-2.54
1853.5	2.68	-2.70
1855	3.12	-2.36
1855.5	2.78	-2.58
1856	3.42	-2.43
1857.5	2.10	-3.33
1859.5	2.82	-3.34
1861.5	3.72	-2.31
1863.5	3.74	-2.45
1865.5	3.24	-2.78
1867.5	3.78	-2.50
1869.6	3.76	-2.13
1870	3.79	-2.15
1871.5	4.21	-2.14
1873.4	3.77	-2.71
1875.5	3.60	-2.62
1877.5	3.61	-2.50
1879.5	3.82	-2.46
1881	3.83	-2.33
1885	3.68	-2.92
1885	3.64	-2.65
1887	3.85	-2.52
1889	3.70	-2.79
1891	4.03	-2.47
1893.7	4.27	-2.29
1897.5	3.86	-2.49
1899.5	3.91	-2.75
1905	3.28	-2.87
1907.5	4.60	-2.30
1909.5	4.69	-2.34
1911.5	4.80	-2.23
1915	5.18	-2.41
1915	5.31	-2.19
1915.5	5.09	-2.18
1917.5	5.22	-2.09
1919.5	5.29	-2.42
1921.5	5.76	-2.44
1923.5	5.77	-2.13
1925	5.37	-1.77
1925	5.39	-1.65
1927.5	5.38	-2.23
1932.8	5.57	-2.26
1936.7	5.53	-2.34
1937.5	6.02	-2.00
1939.7	5.26	-1.82
1940.6	4.95	-2.17
1943.5	4.66	-2.27
1943.9	4.58	-2.46
1945	3.42	-2.64
1945	3.77	-2.12
1947.6	3.96	-2.41
1949.5	3.54	-2.67
1955	3.75	-1.24

TABLE 1. Continued.

Sample depth (ft)	<i>Gavelinella</i> spp. $\delta^{13}\text{C}$	<i>Gavelinella</i> spp. $\delta^{18}\text{O}$
1807.6	1.77	-3.06
1809.6	1.70	-3.26
1815	1.44	-3.48
1825	1.28	-3.07
1829.1	1.59	-2.82
1843.5	1.00	-3.40
1849.5	1.19	-3.36
1851.01	1.63	-3.01
1851.5	1.26	-3.05
1853.5	1.14	-3.58
1855.5	0.84	-3.22
1856	1.30	-2.78
1857.6	1.76	-3.58
1859.5	1.78	-3.81
1861.5	1.13	-3.46
1863.5	1.09	-3.34
1865	2.06	-3.00
1867.5	2.08	-3.24
1869.6	1.92	-2.93
1870	1.28	-2.48
1871.5	1.94	-3.04
1873.4	2.19	-3.13
1875.5	1.55	-3.51
1877.5	1.47	-3.53
1879.5	1.66	-3.44
1881	1.72	-3.40
1883	2.04	-2.91
1885	2.12	-2.71
1887	1.89	-3.01
1889	2.14	-2.88
1905	1.72	-2.71
1925	2.87	-2.11
1932.8	3.69	-2.74
1936	3.14	-2.01
1936.7	1.99	-3.41
1936.7	2.30	-3.08
1937.5	4.31	-2.36
1937.5	4.10	-2.64
1940.6	1.58	-3.79
1947.6	1.23	-3.73
1955	2.02	-1.66

Cenomanian-Turonian  $\delta^{13}\text{C}$  events and sea-level change on the m.y. scale are less clear; Gale (1995, 1996) and Mitchell et al. (1996) suggested such a correlation. However, their studies of pelagic sections lacked direct evidence for sea-level change. The only detailed record of sea-level for this interval was provided in the synthesis of Haq and others (1987), but public documentation of this portion of their record has been very limited. The Bass River borehole provides an opportunity to assess directly the relationship between sea-level expressed in the sequence stratigraphic record and global  $\delta^{13}\text{C}$  variations.

Studies of shallow-marine sections collected from the New Jersey Coastal Plain have demonstrated that sequences deposited in the updip section of this passive margin can preserve detailed records for studies of eustasy. In addition, contrasting facies and other paleoenvironmental indicators including well-preserved benthic foraminifera allow for clear identification of water-depth variations within sequences. This paper presents stratigraphic, isotopic, and paleoecological results from the continuously cored Cenomanian to Turonian section from the Bass River borehole. We specif-

ically focus on comparing sea-level changes on the m.y. and k.y. scale with the  $\delta^{13}\text{C}$  record across the C/T boundary.

## METHODS

Core descriptions, core recovery, downhole gamma-ray log, and cumulative coarse fraction percentages (Fig. 1) are taken from the Bass River borehole site report (39°36' 42" N, 74°26' 12" W; Miller, Sugarman, Browning, and others, 1998). Cumulative percentages were computed from the weight percent coarse fraction, with the percentage of glauconite vs. quartz sand fraction estimated visually.

Benthic foraminifera were picked from the >63  $\mu\text{m}$  size fraction and ultrasonically cleaned in distilled water. Stable-isotope values of foraminifera were measured in the University of Maine Stable Isotope Laboratory on a VG Prism II mass spectrometer, using an IsoCarb automated carbonate prep system, and are reported relative to the VPDB standard (Table 1). Samples were reacted in 100% phosphoric acid at 90°C for ten minutes. Each run of ~30 samples was preceded and followed by at least three standards of NBS-20, with reported values of -4.14‰ and -1.06‰ for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , respectively (Coplen and others, 1983). The standard deviation (1  $\sigma$ ) of the NBS-20 standards analyzed with the samples was 0.06‰ and 0.05‰ for  $\delta^{18}\text{O}$  and  $\delta^{13}\text{C}$ , respectively.

We tentatively present  $\delta^{18}\text{O}$  records from Bass River (Table 1), acknowledging that the burial depth (nearly 600 m) and the variability in the  $\delta^{18}\text{O}$  data probably indicate some diagenetic overprinting. Such overprinting is much less of a concern for  $\delta^{13}\text{C}$  given its lower thermal coefficient and its different pore water geochemistry (e.g., Bottinga, 1968). In the case of Bass River, the excellent match of  $\delta^{13}\text{C}$  records with global records indicates minimal diagenetic affect on carbon isotopic composition.

Total carbon and carbonate carbon were measured at Penn State University using a carbon dioxide coulometer with total carbon and acidification modules. Carbonate carbon was calculated by acidifying each sample with phosphoric acid in a heated reaction vessel. Evolved  $\text{CO}_2$  was directed into the carbon dioxide coulometer cell where it was measured by coulometric titration. Total carbon was measured by combusting samples in an oxygen atmosphere at 950°C. Evolved  $\text{CO}_2$  was handled in the same manner as acid-evolved  $\text{CO}_2$ . Total organic carbon was calculated by the difference between total carbon and carbonate carbon. Sample runs were preceded by standard calibration and blank runs. Analytical runs of ten samples were bracketed by standard calibration; at least one duplicate was run during each set of ten samples. The precision of coulometric analyses at Penn State University is regularly better than 1% of the carbon present (Sageman and others, 1997).

Foraminifera were evaluated semi-quantitatively from the >63  $\mu\text{m}$  size fraction (Table 2). Benthic foraminiferal changes were used to infer paleobathymetric variations. Benthic foraminifera indicate that the entire section was deposited in shallow shelf (probably inner neritic; <30 m) environments. Relative abundance changes of *Epistomina*, *Ceratobulimina*, and *Reinholdella* provide evidence for water-depth variations; biofacies dominated by these taxa rep-

resent progressively shallower environments, respectively (Sikora and Olsson, 1991).

Nannofossil biostratigraphy was initially provided by D. Bukry (in Miller, Sugarman, Browning, and others, 1998) using the CC zonal scheme of Sissingh (1977). Additional samples near the C/T boundary were examined for nannofossils (Table 3; L. de Romero, this study) using the boundary zonation of Bralower (1988). Smear slides were prepared using standard techniques. The slides were examined with a light microscope at 1250X magnification. Pollen zones were provided by G. Brenner (in Miller, Sugarman, Browning, and others, 1998) using the zonal scheme of Christopher (1979).

## RESULTS

### BIOSTRATIGRAPHY AND AGE ESTIMATES

The Bass River borehole recovered approximately 200 ft (61 m) of upper Cenomanian to lower Turonian strata (nannofossil Zones CC10-CC11; pollen Zone IV). The Cenomanian/Turonian boundary recognized by nannofossils was originally placed at the Zone CC10/CC11 boundary between 1930.9 and 1937.9 ft (588.5 and 590.7 m; Bukry, in Miller, Sugarman, Browning, and others, 1998). Re-evaluation of the nannofossil data indicates that the highest occurrence (HO) of *Lithraphidites acutum* is at 1938.5 ft (590.9 m); this species is restricted to the Cenomanian (e.g., Perch-Nielson, 1985; Bralower, 1988). The lowest occurrence (LO) of *Eiffellithus eximius* at 1936.5 ft (590.2 m) is immediately below lowermost Turonian *E. eximius* Subzone of the *Parhabdolithus asper* Zone (Bralower, 1988). The major marker for the C/T boundary, *Microstaurus chiastius*, is not found at Bass River. Thus, the C/T boundary at Bass River is placed at ~1935.5 ft (590.6 m) based on the contact of nannofossil *Microstaurus chiastius* and *Eiffellithus eximius* Subzones. Ancillary taxa support the placement of the boundary at 1935.5 ft (589.9 m): 1) the HO of *Parhabdolithus asper* is 1932.5 ft (589 m); this species ranges into the earliest Turonian (Bralower, 1988); and 2) the HO of *Axopodorhabdus albianus* is at 1946.5 ft (593.3 m); this taxon disappeared immediately prior to the C/T boundary (Bralower, 1988). We conclude that the best estimate for the placement of the C/T boundary based on nannofossils is at 1935.5 ft (589.9 m).

The initial report placed the Cenomanian/Turonian (C/T) boundary at 1920 ft (585.2 m) based on the HO of the planktonic foraminifera *Rotalipora* (Olsson in Miller, Sugarman, Browning, and others, 1998), at least 15.5 ft (4.7 m) higher than the nannofossil placement. This initial report relied on the identification of a single isolated specimen of *R. brotzeni* at 1920 ft (585.2 m). Subsequent examination of samples indicates that the highest consistent occurrence of the genus *Rotalipora* is at 1945 ft (592.8 m) at Bass River (Table 2), suggesting strongly that the one specimen above this is reworked or a contaminant. Because planktonic foraminifera are generally rare due to the shallow marine environment at Bass River, the definitive zonal marker *R. cushmani* was not identified. Nevertheless, sufficient planktonic foraminifera were recovered from the section (Table 2) for us to identify Cenomanian strata at 1945 ft (592.8 m)

TABLE 2. Foraminiferal data from the upper Cenomanian/lower Turonian strata, Bass River, New Jersey. x = present; VR = very rare (1–2 specimens); R = rare (3–5 specimens); F = frequent (5–10 specimens); C = common (10–15 specimens); A = Abundant (> 15 specimens). S = single, isolated specimen.

BASS RIVER TURONIAN-CENOMANIAN SECTION																												
Planktonic foraminifera	1955	1950	1945	1936	1930	1925	1920	1915	1910	1905	1900	1898	1896	1890	1885	1880	1875	1870	1865	1861	1855.9	1853	1840	1835	1830	1825		
<i>Globigerinelloides ultramicra</i>	x	x	x																									
<i>Guembellitria cenomana</i>	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x							
<i>Hedbergella delrioensis</i>	x					x		x	x													x	x					
<i>Hedbergella planispira</i>	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
<i>Hedbergella simplex</i>	x	x	x	x			x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
<i>Helvetoglobotr. praehelvetica</i>															x													
<i>Heterohelix moremani</i>	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
<i>Heterohelix ruessi</i>						x	x	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	
<i>Praeglobotruncana delrioensis</i>	x		x		x	x																						
<i>Praeglobotruncana gibba</i>									x		x	x	x															
<i>Praeglobotruncana stephani</i>	x	x	x		x	x	x			x	x	x	x	x	x	x	x	x	x				x		x		x	
<i>Rotalipora brotzeni</i>								s																				
<i>Rotalipora greenhomensis</i>	x	x	x																									
<i>Whiteinella archeocretacea</i>	x				x		x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	
<i>Whiteinella baltica</i>	x		x				x	x	x	x	x	x	x	x	x	x	x	x	x				x	x	x	x	x	
<i>Whiteinella inornata</i>										x	x																	
<i>Whiteinella paradubia</i>	x	x	x			x	x	x	x	x	x	x	x	x	x	x	x	x	x			x	x	x		x		
Benthic foraminifera																												
<i>Ceratobulimina parva</i>																												
<i>Citharina</i>																												
<i>Dentalina</i> sp.																												
<i>Dorothyia</i> sp.																												
<i>Epistomina chapmani</i>																												
<i>Epistomina cretosa</i>																												
<i>Epistomina lenticularia</i>																												
<i>Epistomina sliteri</i> n. sp.																												
<i>Epistomina carpenteri</i>																												
<i>Epistomina stelligera</i>																												
<i>Epistomina suturalis</i>																												
Total Epistominas	x	C	C	C	VR	A	A	A	A	A	F	A	C	F	C	F	F	R	C	A	A							
<i>Fronicularia</i>																												
<i>Gavelinella cenomana</i>	x																											
<i>Gavelinella dakotensis</i>																												
<i>Gyrogonoides</i> sm.																												
<i>Haplophragmoides</i> sp.																												
<i>Lenticulina</i>	x	VR																										
<i>Nodosaria</i> sp.																												
<i>Pamula</i> sp.																												
<i>Praebulimina</i> sm.																												
<i>Reinholdella</i> sp.																												
<i>Reophax</i> sp.																												
<i>Trochammina</i> sp.																												
<i>Valvulineria</i>	x																											

and below (i.e., the presence of this genus is a positive indicator of Cenomanian strata; Caron, 1985).

The Bass River sequence also contains palynomorphs assigned to Pollen Zone IV (Christopher, 1979). The age of Zone IV generally has been interpreted as upper Cenomanian (Christopher, 1979), although it has been argued that this zone continues into the early Turonian (Doyle and Robins, 1977). Based on foraminiferal and nannofossil correlations summarized here, Pollen Zone IV is late Cenomanian to early Turonian.

Biostratigraphic control is not sufficient to constrain rigorously sedimentation rates and durations of events, although there is sufficient control on the Bass River sequence to estimate rates and durations. Using an age of 93.5 Ma for the C/T boundary and 91.8 Ma for the lower/middle Turonian boundary (Gradstein and others, 1995), the lower Turonian portion of the Bass River sequence (131.1 ft, 40 m; Fig. 1) conservatively spans at most 1.7 m. y., and was deposited at moderate to high sedimentation rates of 2.35 cm/k.y. Because the top of the sequence is truncated, the section almost certainly does not span the entire early Turonian. W. Cobban (written communication, 1998) tentatively identified the late early Turonian marker *Mammites nodosoides* at 1855 ft (565.4 m) at Bass River, suggesting that this ammonite zone is at least partly represented (Fig.

2). This zone is ~0.7 m.y. in duration (Gradstein and others, 1995). Assuming that at least 1.3 m.y. of the early Turonian is represented yields a sedimentation rate of 3.07 cm/k.y. (corresponding to 20 to 29 k.y. sampling for the 2 to 3 ft [0.6 to 0.9 m] sampling interval).

LITHO- AND SEQUENCE STRATIGRAPHY

We recognize two major unconformity-bounded sequences in the 200 ft (61.0 m) Cenomanian-Turonian section at Bass River: 1) a lower sequence (the Bass River sequence; Fig. 1) spans the C/T boundary and shallows upsection from inner neritic to prodelta environments; this sequence corresponds with the Bass River Formation of Petters (1976) who showed that this unit is Cenomanian to lower Turonian (see also Sikora and Olsson, 1991); and 2) a more terrestrial upper sequence (the Magothy sequence; Fig. 1) coarsens and shallows upsection from prodelta to delta front to fluvial environments; this sequence corresponds with the Magothy Formation and perhaps part of the Raritan Formation (Miller, Sugarman, Browning, and others, 1998). This paper concentrates on the Bass River sequence because it is fossiliferous (containing well-preserved benthic foraminifera for paleontologic, paleogeographic and isotopic analyses) and spans the Cenomanian/Turonian boundary.

TABLE 2. Continued.

BASS RIVER TURONIAN-CEN				
Planktonic foraminifera	1821	1816.3	1810	1809
<i>Globigerinelloides ultramicra</i>				
<i>Guembellina cenomana</i>				
<i>Hedbergella delrioensis</i>				
<i>Hedbergella planispira</i>		x		
<i>Hedbergella simplex</i>				
<i>Helvetoglobtr. praehelvetica</i>				
<i>Heterohelix moremani</i>		x		
<i>Heterohelix ruessi</i>		x		
<i>Praeglobotruncana delrioensis</i>				
<i>Praeglobotruncana gibba</i>				
<i>Praeglobotruncana stephani</i>				
<i>Rotalipora brotzeni</i>				
<i>Rotalipora greenhornensis</i>				
<i>Whiteinella archeocretacea</i>				
<i>Whiteinella ballica</i>		x		
<i>Whiteinella inornata</i>				
<i>Whiteinella paradubia</i>				
Benthic foraminifera				
<i>Ceratobulimina parva</i>				
<i>Citharina</i>				
<i>Dentalina</i> sp.			VR	
<i>Dorothia</i> sp.				
<i>Epistomina chapmani</i>				
<i>Epistomina cretosa</i>				
<i>Epistomina lenticularia</i>				
<i>Epistomina sliteri</i> n. sp.				
<i>Epistomina carpenteri</i>				
<i>Epistomina stelligera</i>				
<i>Epistomina suturalis</i>				
Total Epistominas			R	VR
<i>Fronculularia</i>			VR	
<i>Gavelinella cenomana</i>				
<i>Gavelinella dakotensis</i>			R	VR
<i>Gyrodinoides</i> sm.				
<i>Haplophragmoides</i> sp.			VR	
<i>Lenticulina</i>				
<i>Nodosaria</i> sp.				
<i>Pamula</i> sp.				
<i>Praebulimina</i> sm.				
<i>Reinholdella</i> sp.	C	C		
<i>Reophax</i> sp.				
<i>Trochammina</i> sp.				
<i>Valvulineria</i>			VR	

In the Bass River borehole, the Bass River sequence is at least 150 ft (45.7 m) thick (1956.5–1806.4 ft; 596.3–550.6 m; Fig. 1), and consists predominantly of a very dark gray laminated, fossiliferous silty clay at the base (to 1914 ft; 583.4 m), grading upward into fossiliferous sandy silt to clay (to 1859 ft; 566.6 m), and upward into fine sandy fossiliferous micaceous silts and clays. The unconformity at the base of the Bass River sequence is below the total depth (TD) of 1956.5 ft (596.3 m); an increase in glauconite near the base of the borehole is typical of the lower portion of sequences in New Jersey (Sugarman and others, 1995). This indicates that the lower part of the sequence was penetrated (Fig. 1). The Bass River sequence generally reflects a shallowing upward trend within the inner neritic environment (Miller, Sugarman, Browning, and others, 1998).

#### CARBON ISOTOPES AND ORGANIC CARBON

Initial studies of the Bass River borehole (Miller, Sugarman, Browning, and others, 1998) showed that the section contained enough well-preserved carbonate for carbon isotopic studies spanning the Cenomanian/Turonian boundary. Miller, Sugarman, Browning, and others (1998) provided coarsely spaced (~10 ft, 3 m)  $\delta^{13}\text{C}$  analyses of this section, showing that the global  $\delta^{13}\text{C}$  pattern of increasing values near the C/T boundary was well represented in this section.

We increased sampling resolution to 2–3 ft (0.6–0.9 m) for the benthic foraminifera *Gavelinella* and *Epistomina* (Table 1, Fig. 1).

*Epistomina*  $\delta^{13}\text{C}$  variations are similar to those observed in *Gavelinella*, although values are offset. The latter taxon is generally rare to absent in parts of the Bass River sequence and the *Epistomina* isotopic record is much more detailed. *Epistomina* is an aragonitic taxon that yields  $\delta^{13}\text{C}$  values that are significantly (~2‰) enriched relative to *Gavelinella*. This is similar to the modern *Hoeglundina* (another aragonitic taxon of the Family Ceratobuliminidae) that yields  $\delta^{13}\text{C}$  values that are significantly (~1.3‰) enriched relative to *Cibicidoides* (Shackleton and others, 1984). *Gavelinella*, like *Cibicidoides*, is generally the preferred benthic foraminiferal taxon for stable isotopic studies (Shackleton and others, 1984), although our studies show that *Epistomina* faithfully tracks *Gavelinella* carbon isotopic values (Fig. 1). Therefore, we rely on the more closely-sampled *Epistomina*  $\delta^{13}\text{C}$  record for most of the detailed interpretations and correlations presented below.

Carbon isotopic records of both *Gavelinella* and *Epistomina* show a large (>2‰) increase below the C/T boundary, with maximum values of 6‰ in *Epistomina* and 4.3‰ in *Gavelinella* attained just below the nannofossil-recognized C/T boundary. Generally high  $\delta^{13}\text{C}$  values (>4.5‰ in *Epistomina*) persist above the increase (1907.5–1938 ft; 581.4–590.7 m) in association with high values in sedimentary organic carbon (i.e., values greater than the mean of 0.87‰; Table 4). The Bass River sequence is similar to coeval sections throughout the world that record peak organic carbon with peak  $\delta^{13}\text{C}$  values (e.g., the Bonarelli bed of Italy; Scholle and Arthur, 1980; Jenkyns and others, 1994).

There is a sharp lower Turonian decrease in  $\delta^{13}\text{C}$  values in the Bass River sequence (1905.0–1907.5 ft; 580.8–581.6 m) that is immediately below a decrease in organic carbon values (Fig. 1). Carbon isotopic values continue to decrease from ~1890–1840 ft (576.1–560.8 m). Organic carbon values are low in the lower part of this section (i.e., less than the mean; Fig. 1), but increase to the highest values noted in the section at ~1838 ft (560.2 m). This second interval of high organic carbon occurs in the shallowest paleodepths of the Bass River sequence, and is associated with low  $\delta^{13}\text{C}$  values at Bass River (Fig. 1) and globally (Jenkyns and others, 1994); thus, although this interval may reflect a local productivity event evinced by high sedimentary organic carbon, it does not appear to reflect a global carbon burial event.

Our current sampling interval does not allow detailed evaluation of 10 k.y.-scale events, although there are hints of very rapid changes. The *Gavelinella*  $\delta^{13}\text{C}$  record shows a large increase just below the C/T boundary, followed by a sharp decrease (1936.7 ft; 590.3 m), and then another increase (1936 ft; 590.1 m). If real, this sharp decrease represents extremely large, rapid fluctuations in the carbon system. Using sedimentation rate estimates of 2.35 or 3.07 cm/k.y. (see above), the sharp change in *Gavelinella* represents 5–6 k.y. or less (i.e., it occurs between two closely spaced [0.7 ft, 0.2 m] samples). However, this transient decrease is not recorded in the *Epistomina*  $\delta^{13}\text{C}$  record (Fig. 1), although resolution of this record is lower in the section of



TABLE 3. Continued.

Podorhabdids	<i>A. albianus</i>	<i>A. decorus</i>	<i>Octopodorhabdus</i> sp.	Pre-discosphaerids	<i>P. columnata</i>	<i>P. cretacea</i>	<i>P. spinosa</i>	Stephanolithids	<i>C. achylosum</i>	<i>C. exiguum</i>	<i>C. kennedyi</i>	<i>C. signuum</i>	<i>Rotelapillus</i> sp.	<i>Stoverius</i> sp.	Zygodiscids	<i>C. litterarius</i>	<i>Chiastozygus</i> sp.	<i>P. achylosaurion</i>	<i>R. angustus</i>	<i>R. asper</i>	<i>R. splendens</i>	<i>Rhagodiscus</i> sp.	<i>R. anthrophorus</i>	<i>T. stradhneri</i>	<i>T. glabalis</i>	<i>T. orionatus</i>	<i>V. octoradiata</i>	<i>V. stradhneri</i>	<i>Z. embergii</i>	<i>Z. bicrescenticus</i>	<i>Z. diplogrammus</i>	<i>A. elegans</i>	<i>Z. spiralis</i>	
					X	X			R	X		X	R	R				R	X		VR	VR		VR	VR	R	R	X				X		
						X	X		X	R						X		X	?	X	R			R	X	R					R	X	VR	
					VR	X			VR			X		R				X		VR						X				X	X	R		
						X	R		VR	R			R					R	R		R		VR		R	R		R	VR	X	X	VR		
	VR				X	X			X	X	C	R	R			X		X	VR	X	VR		R	VR	X	X	X	R	VR	X	X	VR		
	R	R			X	X	R		X	X	X	VR	R			VR	R	X	VR	X		VR		X	X	X	X	VR	X	X	X	X		
	R				X	X	X		C	X		C	R	R			X	X	X	R	X	R		R	X	X	R	R		X	X	X		
					X				X		VR	R						X	X	R						X		X			X	X		
					X	X	X		X		X					R	X		X							X		X			X	X	X	
	R				X	X			X		X					R	X		X	?	X			X		X	R	X	VR	X	X	X		
	R				X	X	X					X				X										X				X	X	X		
	R				X	X						X							X	R	X					R	X	R		R		X		
	R	VR			VR	X	X		X	R		R				VR	R	R	X	R	R		VR		X	R	X	VR		R	X	X		
	R	VR			R	X	X		R			R	R					R	VR	X			VR	VR	X		X			R	X	R		

differences ( $\ll 1$  m.y. assuming sedimentation rates at Bass River outlined above) to minor diachrony and fossil inter-calibration problems.

The thickness of the interval of high  $\delta^{13}C$  and high total organic carbon values associated with the C/T boundary suggests the carbon burial event lasted several hundred k.y. The broad  $\delta^{13}C$  maxima at Bass River (1905–1945 ft; 580.6–592.8 m) has a maximum duration of ~500 k.y. based on our conservative estimate of sedimentation rates (2.35 cm/k.y) to a minimum duration of ~400 k.y. based on the higher sedimentation rate estimate of 3.076 cm/k.y.

PALEOECOLOGY OF *EPISTOMINA*

Species of the benthic foraminifer *Epistomina* are biostratigraphically useful in Jurassic/Cretaceous stratigraphic sections principally in Europe and in eastern Canada (Williamson and Stam, 1988). Jurassic and Cretaceous *Epistomina* spp. lived primarily in shallow (inner neritic) environments where biostratigraphically useful species of planktonic foraminifera are rare to absent. Epistominids diversified first in the Jurassic and again in the Early Cretaceous (Williamson and Stam, 1988). Speciation of epistominids involved mostly ornamented morphotypes (forms with raised sutures and reticulations or pitting) that became extinct during times of "crisis"; smooth-walled morphotypes generally survived these turnovers. Following each radiation, ornamented morphotypes were largely eliminated in the late Ju-

assic and again in the late Albian turnover. New Jersey Cenomanian and Turonian sections provide one of the few records of ornamented epistominids of this age (Sikora and Olsson, 1991).

The upper Cenomanian-lower Turonian section in the Bass River borehole contains abundant, diverse, and well-preserved epistominids. Six of the seven recognized species in this section have their origins in the Early Cretaceous (Albian or older) and one species, *Epistomina sliteri* n. sp., had its origin in the early Turonian (Fig. 3). Of the ornamented species, two (*E. suturalis*, *E. cretosa*) disappeared in the Cenomanian and one (*E. carpenteri*) disappeared in the Turonian at Bass River (Fig. 3). Three smooth-walled species (*E. chapmani*, *E. lenticularia*, *E. stelligera*) had their HO's in the Turonian at Bass River. *Epistomina sliteri* n. sp., an ornamented species, evolved from the smooth-walled species *E. lenticularia* in the early Turonian.

Recurrent, upsection changes occur in upper Cenomanian to lower Turonian benthic foraminifera at Bass River, with *Epistomina* at the base, *Ceratobulimina* in the middle and *Reinholdella* at the top of four repeating successions (Table 2). We interpret these successions as shallowing upward parasequences bounded by flooding surfaces (FS). At least 4 FS's are recognized in the Bass River section (Fig. 3). Epistominids are most abundant, often dominating the benthic assemblage, in the basal transgressive parts of parasequences and become rarer or even absent in the upper parts

TABLE 4. Total organic carbon from the upper Cenomanian/lower Turonian strata, Bass River, New Jersey.

Depth (ft)	%TOC	Depth (ft)	%TOC	Depth (ft)	%TOC
1954	0.34	1909	0.69	1865	0.38
1953	0.5	1908	0.89	1864	0.36
1952	0.72	1907	0.95	1863	0.48
1951	0.57	1906.5	1.22	1862	0.39
1950	0.78	1906	1.16	1859	1.36
1949	1.01	1905	1.03	1856	0.83
1948	0.35	1904	0.78	1855	0.61
1947	0.69	1903	1.01	1854	1.59
1946	0.98	1902	0.86	1852	1.32
1945	0.94	1901	0.58	1849	1.15
1944	1.09	1900	0.7	1847	0.9
1943	0.82	1898	0.6	1844	1.21
1942	0.83	1897	0.75	1841	1.99
1941	1.16	1896	0.52	1838	1.1
1940	0.74	1894	0.46	1835	1.11
1938	1.3	1893.5	0.15	1832.8	0.83
1937	0.88	1893	0.63	1830	1.33
1936	0.72	1892	0.78	1827	1.21
1935	1.55	1891	0.98	1824	0.28
1934	1.32	1890	0.87	1822	0.99
1933	0.95	1889	1	1819	0.45
1932	0.89	1888	0.82	1817	1.49
1931	1.14	1887	0.71	1814	0.33
1930	1.03	1886	0.73	1811	0.35
1929	1.18	1885	0.8	1808	0.35
1928	0.89	1884	1	1805	1.48
1927	0.66	1883	1.29	1803A	1.4
1926	0.88	1882	0.5	1800	1.8
1925	0.89	1881	0.71	1795	2.61
1924	1.31	1880	0.6	1792	1.35
1923	1.09	1879	0.58	1789	0.86
1922	1.39	1878	0.91	1787	1.06
1921	1.11	1877	0.85	1784	1.45
1920	1.06	1876	0.81	1776	0.13
1919	1.29	1875	0.78	1773	0.72
1918	1.06	1874	0.64	1770	0.07
1917	0.97	1873	0.53	1763	0
1916	0.86	1872	0.64	1760	0.02
1915	1.27	1871	0.24	1751	0.03
1914	0.8	1870	1.25	1744	1.3
1913	0.92	1869	0.29		
1912	0.97	1868	1.15		
1911	0.44	1867	0.97		
1910	0.59	1866	0.87		

of the parasequences (Table 2). The significance of these parasequences is discussed below.

The Bass River borehole provides insights into epistominid evolution and paleoecology. Epistominid assemblages are often dominated by one or two species and other species are rare or even absent. This pattern suggests that *Epistomina* species may have been narrowly adapted to certain microenvironments or ecological relationships, which may help explain their variable stratigraphic ranges noted elsewhere in the record (Williamson and Stam, 1988). Epistominid species generally have their HO's within the lower parts of parasequences at Bass River except for *E. suturalis*, which had its HO at the base of a parasequence (Fig. 3). Because the epistominids were shallow, inner-shelf dwellers, the stress of sea level and temperature fluctuations may explain their disappearance in the late Cenomanian and early Turonian. There is no clear correlation of epistominid disappearances with the Bonarelli/OAE2  $\delta^{13}\text{C}$  excursion;

therefore, variations in carbon cycling appear to be unrelated to epistominid evolution.

We speculate that disappearances of epistominid species may be associated with periods of cooler temperatures because the HO's of six species is in the lower parts of parasequences associated with higher  $\delta^{18}\text{O}$  values (Fig. 3). As noted above, the  $\delta^{18}\text{O}$  records from Bass River probably reflect some diagenetic overprinting by isotopically depleted pore water. Nevertheless, the  $\delta^{18}\text{O}$  data (Fig. 3) do show a relatively coherent pattern with maximum values attained near the bases of parasequences and the highest occurrences of epistominid species.

#### COMPARISON OF $\delta^{13}\text{C}$ WITH SEA LEVEL CHANGES

Million year-scale (i.e., the 2nd- and 3rd-order events of Haq and others, 1987) sea-level falls did not cause the initiation or the termination of the organic carbon burial event. The Bass River borehole contains a continuous C/T boundary section and a global record of the C/T  $\delta^{13}\text{C}$  excursion (Fig. 2). The entire carbon burial event is contained within the Bass River sequence. In general, sequence-bounding unconformities represent lowerings of regional baselevel (Mitchum and others, 1977), usually associated with global sea-level lowerings or tectonic events (Christie-Blick, 1991). Sequence boundaries noted throughout the New Jersey Coastal Plain are interpreted as reflecting lowering of sea level (i.e., Olsson, 1991; Miller and others, 1998). It is clear from the results at the Bass River borehole that there is no sequence boundary or major lowering of baselevel associated with the C/T organic carbon burial event, either its initiation or termination. This argues against any correlation between eustatic lowering on the m.y. scale and carbon burial.

Although the OAE2 carbon burial event is independent of sea-level lowering, global carbon extraction appears to be associated with a long-term tectono-eustatic sea-level rise and the highest sea level of the past 100 m.y. (Haq and others, 1987; Sahagian and Jones, 1993). It is possible that such a relationship occurs on a m.y.-scale (e.g., Mitchell and others, 1996): the initiation of the carbon extraction event at Bass River could be associated with a Maximum Flooding Surface (MSF). Such MFSs are inferred to represent the maximum rates of sea-level rise (e.g., Posamentier and others, 1988). We test the possible relationship between MFS (= inferred sea-level rises) and the carbon extraction event below.

The placement of the MFS in the Bass River sequence is not clear. We initially placed the MFS at ~1950 ft (594.4 m) at the top of a glauconitic layer (Fig. 1; Miller, Sugarman, Browning, and others, 1998) similar to other MFSs in the Upper Cretaceous of New Jersey (Sugarman and others, 1995). While we still favor this placement, we note that the MSF could be placed at two other levels: 1) it is possible to place the MFS at 1925 ft at a lithologic change from clays below to silty clays above; this minor coarsening is also associated with the base of a FS identified using benthic foraminifera (see below); 2) a MFS could be inferred at 1935–1940 ft (589.8–591.3 m) based on a sharp increase in *Gavelinella*  $\delta^{18}\text{O}$  values (Fig. 3; Table 1). However, this increase is not noted in *Epistomina*  $\delta^{18}\text{O}$  values and, as not-

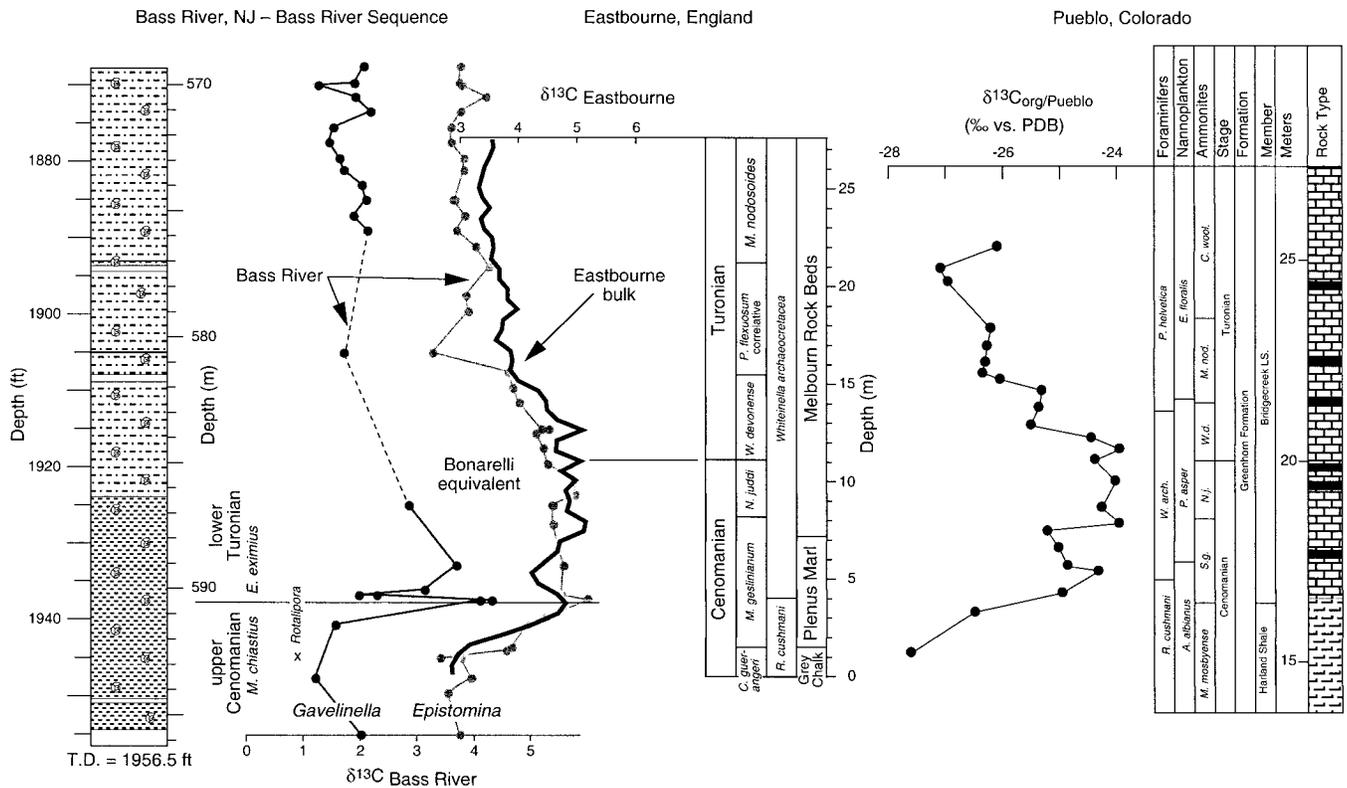


FIGURE 2. Comparison of upper Cenomanian  $\delta^{13}\text{C}$  records from Bass River, New Jersey and Eastbourne, England. The Eastbourne section is from Jenkyns and others (1994). Note that the depth scales vary, with the Bass River 78% of Eastbourne. The carbon isotopic scale at Eastbourne is offset from Bass River by + 0.75‰. On right is the  $\delta^{13}\text{C}$  of organic carbon and stratigraphy from a section near Pueblo, Colorado (Pratt and Threlkeld, 1984). x = highest occurrence of the genus *Rotalipora* at Bass River.

ed above, there is probably some diagenetic overprinting of  $\delta^{18}\text{O}$  values. We conclude that the most likely placements of the MSF (either 1950 or 1925 ft) both preclude a close association of sea-level rise and the initiation or termination of the organic carbon burial event.

We further examine the relationship of sea-level and the major C/T carbon burial event by evaluating minor changes in water depth on the 100 k.y. scale associated within the Bass River sequence. The identification of the flooding surfaces within this sequence allows recognition of parasequences (packages bounded by flooding surfaces; Van Wagoner and others, 1988).

We tentatively identify 4–5 parasequences in the Bass River sequence based predominantly on paleoenvironmental interpretations using benthic foraminifera (especially the relative abundances of *Epistomina*, *Ceratobulimina* and *Reinholdella*), changes in the  $\delta^{18}\text{O}$  record (Fig. 3), and variations in sedimentary facies and grain size (there are increases in foraminifera comprising coarse-fraction carbonate associated with 3 out of 4 FS's; Fig. 1). These parasequences represent small variations in water depth that may or may not reflect eustatic changes. Benthic foraminifera indicate deposition in the inner neritic zone throughout (<30 m), although deposition probably was somewhat deeper at the base of parasequences. Nevertheless, the water-depth variations delineated here are <30 m; if ascribed entirely to eustasy and correcting for water loading, they would correspond to eustatic variations of <20 m (Watts and Steckler, 1979).

The parasequence boundaries and attendant water-depth changes tentatively identified (Fig. 3) are not associated with the carbon burial event at Bass River. The base of the lowermost parasequence in the Bass River borehole is uncertain. Of the 4–5 FSs identified in the Bass River section, none are associated with the initiation of the C/T carbon burial event. One FS (1900 ft; 579.1 m) just overlies the termination of the C/T carbon burial event at 1907.5 ft (581.4 m). While it is possible that other variations in water depth occurred in this section, they would be low amplitude (<<30 m water depth and <<20 m of eustasy; Fig. 3). Thus, we conclude that there appears to be no relationship between the carbon burial event and flooding surfaces on the 100 k.y. scale.

The high  $\delta^{18}\text{O}$  values associated with the base of parasequences may be due to cooler temperatures associated with greater paleodepths. Although some may argue that high  $\delta^{18}\text{O}$  values represent ice volume increases in this purportedly ice-free world (Stoll and Schrag, 1996), our data clearly contradict this on the 100 k.y. scale because the  $\delta^{18}\text{O}$  maxima are associated with maximum water depths (flooding surfaces), not eustatic lowerings. Note also that the  $\delta^{18}\text{O}$  values show little or no correspondence with the  $\delta^{13}\text{C}$  data, again indicating little or no association between water-depth variations and the carbon burial event.

The parasequences at Bass River represent minor changes in water depth (<30 m) that occurred on the 300–600 k.y. scale. With bounding surfaces at 1924.5, 1900, 1856, and 1818 ft (586.6, 579.1, 565.7, and 554.1 m) the parasequenc-

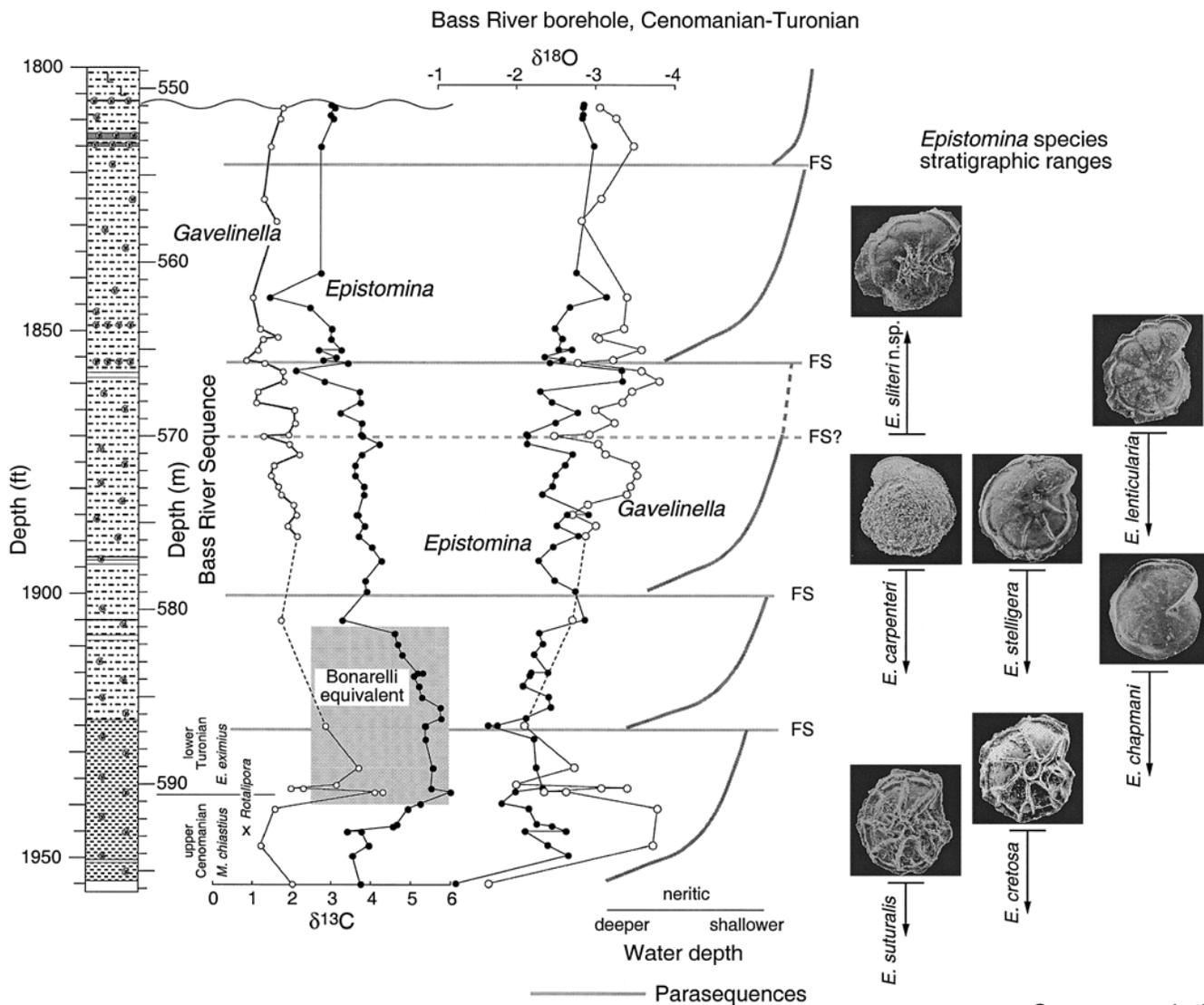


FIGURE 3. Comparison of  $\delta^{13}\text{C}$  and  $\delta^{18}\text{O}$  data with parasequences from upper Cenomanian/lower Turonian Sequence 1 from the Bass River borehole. Also shown are the range terminations of the epistominids in the borehole. FS = flooding surfaces defining the bases of parasequences. x = highest occurrence of the genus *Rotalipora* at Bass River.

es have thicknesses of >35, 24.5, 44, and 38 ft (10.7, 7.5, 13.4, and 11.6 m). These correspond to durations of >455, 318, 571, and 493 k.y. assuming a constant sedimentation rate of 2.35 cm/k.y., and 348, 243, 436, and 377 k.y. assuming a sedimentation rate of 3.07 cm/k.y. Although not definitive, the cyclicity observed is close to the ca. 400 k.y. eccentricity cycle.

CONCLUSIONS

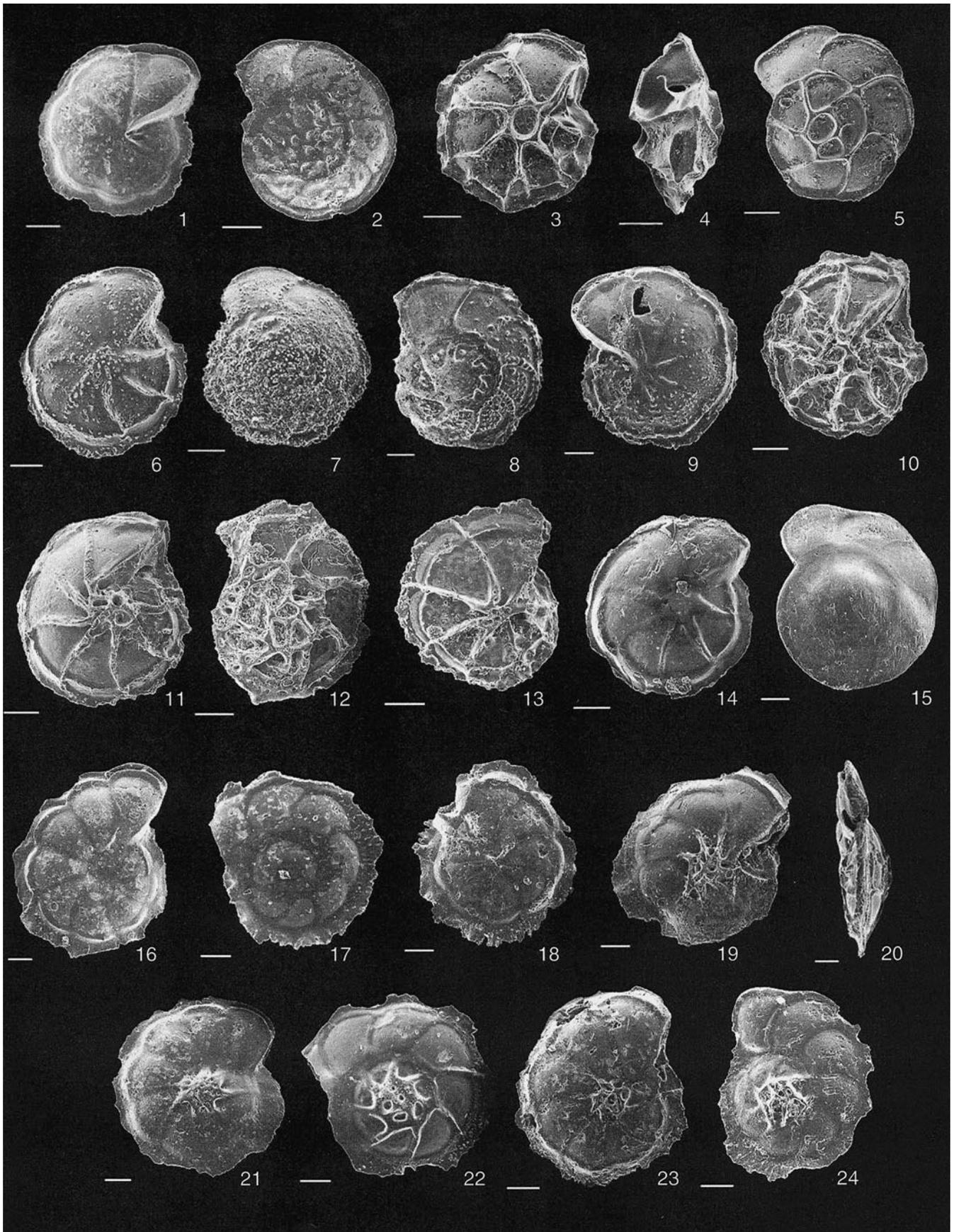
The Bass River 174AX borehole recovered a complete C/T boundary section. The section is predominantly lower Tu-

ronian (>35m), with at least 6 m of upper Cenomanian strata. Using an age of 93.5 Ma for the C/T boundary and 91.8 Ma for the lower/middle Turonian boundary (Gradstein and others, 1995), the lower Turonian section conservatively spans 1.7 m.y., and was deposited at sedimentation rates of >2 cm/k.y.

The Cenomanian/Turonian isotopic section was compiled from samples taken every 2-3 ft (0.6-0.9 m) for a 20 to 29 k.y. sampling interval. The more detailed *Epistomina*  $\delta^{13}\text{C}$  record was positively offset by 2‰ versus the *Gavelinella* profile. Our peak  $\delta^{13}\text{C}$  values of 6‰ for *Epistomina* and

PLATE 1

All specimens from Bass River Borehole, bar = 100µm. 1-2 *Epistomina chapmani* Ten Dam. Sample 1950.0-.1 ft (594.5 m). 3-5 *Epistomina cretosa* Ten Dam. Sample 1945.0-.1 ft (593.0 m). 6-9 *Epistomina carpenteri* (Reuss). Sample 1910.0-.1 ft (582.3 m). 10-13 *Epistomina suturalis* Ten Dam. Sample 1955.0-.1 ft (596.0 m). 14, 15 *Epistomina stelligera* (Reuss). Sample 1910.0-.1 ft (582.3 m). 16-18 *Epistomina lenticularia* Tappan. Sample 1936.0-.1 ft (590.2m). 19-24 *Epistomina sliteri* n. sp. Sample 1853.0-.1 ft (564.9 m). 19 holotype (USNM #499265), 20-24 paratypes (USNM #499266-499270).



4.3‰ for *Gavelinella* at 1937 ft (41.8 m) near the C/T boundary. The global C/T carbon burial (Bonarelli/OAE2) event is correlated with a broad  $\delta^{13}\text{C}$  maxima from 1945–1905 ft (592.8–580.6 m) at Bass River. This interval also has corresponding high total organic carbon values. The broad  $\delta^{13}\text{C}$  maxima has a duration of 400–500 k.y. based on sedimentation rate estimates and shows excellent correlation with other global records.

The broad latest Cenomanian  $\delta^{13}\text{C}$  increase, latest Cenomanian-early Turonian  $\delta^{13}\text{C}$  maxima, and early Turonian  $\delta^{13}\text{C}$  decrease are all contained within one m.y.-scale sequence at Bass River, arguing against any correlation between eustatic lowering and carbon burial on the m.y. scale. We find no definitive evidence for the association of  $\delta^{13}\text{C}$  and flooding surfaces (including MFSs). Within the Bass River sequence, there are at least 4–5 parasequences (units bounded by flooding surfaces) identified on minor lithologic variations, benthic foraminiferal variations, and  $\delta^{18}\text{O}$  maxima. Comparison of parasequence boundaries and the  $\delta^{13}\text{C}$  record also shows a lack of correlation between water depth and  $\delta^{13}\text{C}$  variations on the 100 k.y. scale. There is a general correlation of the HO's of six species and the origin of one species of *Epistomina* with periods of cooler temperatures indicated by higher  $\delta^{18}\text{O}$  values. We conclude that, while epistominid extinction and evolution probably was related to sea-level change, the initiation and termination of the Bonarelli/OAE2 carbon burial event was unrelated to sea-level change on the m.y. or k.y. scale.

#### SYSTEMATIC DESCRIPTIONS

Family CERATOBULIMINIDAE Cushman, 1927

Subfamily EPISTOMINIDAE Wedekind, 1937

*Epistomina* Terquem, 1883

*Epistomina carpenteri* (Reuss) 1862

Plate 1, figs. 6–9

*Rotalia carpenteri*, p. 94, pl. 13, fig. 6a–c.

**Remarks.** This species is identified by its convex test and thin slightly raised sutures on the ventral side. The raised dorsal sutures are usually discontinuous and sometimes absent between the last-formed chambers. Small reticulations or pits are sometimes present in the umbilicus and on the dorsal sutures. The surface of the test wall is lightly to heavily covered, more so on the dorsal side, with small pustules. The species was described from the Albian of north Germany and subsequently has been recorded from the Albian of England (Hart and others, 1981), the Netherlands (Ten Dam, 1948) and eastern Canada (Scotian shelf, Ascoli, 1976). In the Bass River borehole *Epistomina carpenteri* is present in the upper Cenomanian and disappears in the lower Turonian.

*Epistomina chapmani* Ten Dam 1948

Plate 1, figs. 1, 2

*Epistomina chapmani*, p. 166, pl. 1, fig. 5.

**Remarks.** This smooth-walled, biconvex species was described from the Albian of the Netherlands. Hart and others (1981) record an Aptian to lower Cenomanian range in Europe and Ascoli (1976) records an Aptian to Albian range in eastern Canada (Scotian shelf). Sikora and Olsson (1991) reported an upper Albian to upper Cenomanian range in the New Jersey coastal plain. In the Bass River borehole the species disappears in the lowermost Turonian.

*Epistomina cretosa* Ten Dam 1947

Plate 1, figs. 3–5

*Epistomina cretosa*, p. 29, fig. 6.

**Remarks.** This distinctive species is recognized by its sharply raised

sutures and umbilical collar on the ventral side. The dorsal keel is strongly developed and the ventral keel less so. The species is described from the Albian of the Netherlands. The species occurs widely in the Albian of Europe (Hart, 1983; Williamson and Stam, 1988). A Hauterivian to Albian range is recorded by Ascoli (1976) in eastern Canada (Scotian shelf). It has previously been reported from the upper Albian and upper Cenomanian of New Jersey (Sikora and Olsson, 1991). In the Bass River borehole the species disappears in the uppermost Cenomanian just below the Bonarelli/OAE2  $\delta^{13}\text{C}$  excursion.

*Epistomina lenticularia* Tappan 1943

Plate 1, figs. 16–18

*Epistomina lenticularia*, p. 512, pl. 82, fig. 12a–c.

**Remarks.** This distinctive species is easily recognized by its compressed, flattened test and wide dorsal keel. The dorsal side is planar or slightly concave, suggesting that this species in life was attached to marine grasses. The species was described from the Albian of the Gulf Coastal Plain (Tappan, 1943). Ten Dam (1948) reported it in the Albian of the Netherlands. The only other record of this species is from the upper Albian and upper Cenomanian of the New Jersey coastal plain (Sikora and Olsson, 1991). Sikora and Olsson reported sporadic occurrences of this species in the upper Cenomanian. In the Bass River borehole the species is common to abundant in the Cenomanian and Turonian. The species gave rise to *Epistomina sliteri* n. sp. in the Turonian.

*Epistomina stelligera* (Reuss) 1854

Plate 1, figs. 14, 15

*Rotalina stelligera*, p. 69, figs. 15a–c.

**Remarks.** This species is recognized by its smooth wall and slightly elevated sutures which merge into a raised massive umbilicus. Ohm (1967) gives a Turonian to Coniacian range in Europe for this species and Ascoli (1976) records a similar range in eastern Canada (Scotian shelf). Sikora and Olsson (1991) reported an upper Cenomanian to lower Turonian distribution in the New Jersey coastal plain. In the Bass River borehole it ranges into the middle part of the Turonian section. *Epistomina stelligera* appears closely related to *Epistomina chapmani*. Intermediate morphotypes between the two species were noted in the New Jersey upper Albian and upper Cenomanian by Sikora and Olsson (1991) and are also noted in this study.

*Epistomina suturalis* Ten Dam 1947

Plate 1, figs. 10–13

*Epistomina reticulata* (Reuss) 1862 var. *suturalis*, p. 169, pl. 2, fig. 5.

**Remarks.** Its biconvex test, sharply raised sutures and small umbilical reticulations or pits on the ventral side, and raised sutures and larger reticulations on the dorsal side characterize this species. A sharp, narrow dorsal keel is present. The species was described from the Albian of the Netherlands. The morphologically similar *Epistomina reticulata* (Reuss) has a Barremian to Albian range. It differs from *E. suturalis* in having less distinctly raised ventral sutures and larger umbilical reticulations. In the Bass River borehole *E. suturalis* occurs in the basal part of the upper Cenomanian section where it has a short range before disappearing prior to the Bonarelli/OAE2  $\delta^{13}\text{C}$  excursion.

*Epistomina sliteri* Olsson n. sp.

Plate 1, figs. 19–24

**Diagnosis.** Test with 8–9 chambers in the final whorl, compressed, flattened, with a planodorsal side and slightly inflated ventral side. Test periphery sharply acute with a broad thin keel, and a subdued secondary keel which is slightly stepped back on the ventral side. Dorsal chambers reniform in shape and overlap equally on preceding chambers and whorls, describing a flattened V-shaped inner margin. Dorsal sutures thickened and may be slightly raised, especially on the inner spiral where pitting or reticulate ornamentation may occur. Ventral sutures slightly depressed between the later formed chambers in the final whorl but sometimes raised as thin ridges within slight depressions on the earlier formed chambers. Sutures are pitted and reticulate in the umbilical area. Primary aperture is a thin slit on the face of the ultimate chamber, secondary lateral apertures are closed on all chambers except the final one.

Maximum diameter: 571–780  $\mu\text{m}$

*Deposition of types.* Holotype from sample 1853.0–1 ft (564.9 m) and paratypes from sample 1853.0–1 ft, Bass River borehole were deposited in the U.S. National Museum of Natural History (holotype, USNM #499265; paratypes, USNM #499266–499270).

*Remarks.* This distinctive species is named in recognition of the contributions to Cretaceous geology made by the late William (Bill) Sliter. The species is characterized by a broad, thin, fringing keel and by the presence of pitting and reticulations in the umbilical area and sometimes on the spiral area of the dorsal side. It differs from *Epistomina lenticularia*, which is regarded as the ancestral species, by the presence of the pitting and reticulations. Both *E. lenticularia* and *E. sliteri* n. sp. have flattened, sometimes slightly concave dorsal sides which suggests that they were probably attached to flat surfaces such as marine grasses.

#### ACKNOWLEDGMENTS

We thank T. Bralower, B. Huber, and M. Leckie for inviting us to participate in the Sliter memorial symposium at the 1998 GSA annual meeting. Supported by National Science Foundation grant NSF EAR97-08664 and the N. J. Geological Survey. Cores were obtained by the N. J. Coastal Plain Drilling Project supported by the Continental Dynamics and Ocean Drilling Programs. We thank K. MacLeod and S. Hesselbo for reviews, and B. Huber and T. Bralower for comments. SEM's were taken at the Institute and Museum for Geology and Paleontology at the University of Tübingen, Germany through the courtesy of C. Hemleben.

#### REFERENCES

- ARTHUR, M. A., DEAN, W. E., and SCHLANGER, S. O., 1985, Variation in the global carbon cycle during the Cretaceous related to climate, volcanism and changes in atmospheric  $\text{CO}_2$ , in Sundquist, E. T., and Broecker, W. S. (eds.), *The Carbon Cycle and Atmospheric  $\text{CO}_2$ : Natural Variations Archean to Present*. AGU Geophysical Monograph 32, Washington, D.C., p. 504–529.
- ARTHUR, M. A., SCHLANGER, S. O., and JENKYN, H. C., 1987, The Cenomanian-Turonian Oceanic Anoxic Event, II. Palaeoceanographic controls on organic-matter production and preservation, in Brooks, J., and Fleet, A. J. (eds.), *Marine Petroleum Source Rocks*. Geological Society Special Publication No. 26, p. 401–420.
- ASCOLI, P., 1976, Foraminiferal and ostracod biostratigraphy of the Mesozoic-Cenozoic, Scotian Shelf, Atlantic Canada, in Schaefer, C. T., and Pelletier, B. R. (eds.), *1st International Symposium on benthonic foraminifera of continental margins*. Maritime Sediments, Special Publication 1, p. 653–771.
- BOTTINGA, Y., 1968, Calculation of fractionation factors for carbon and oxygen exchange in the system calcite-carbon dioxide-water: *Journal of Physical Chemistry*, v. 72, p. 800–808.
- BRALOWER, T. J., 1988, Calcareous nannofossil biostratigraphy and assemblages of the Cenomanian-Turonian boundary interval: Implications for the origin and timing of ocean anoxia: *Paleoceanography*, v. 3, p. 275–316.
- BROECKER, W. S., and PENG, T., 1982, *Tracers in the Sea*. Lamont-Doherty Geological Observatory, Columbia University, Palisades, NY, 690p.
- CARON, 1985, Cretaceous planktonic foraminifera, in Bolli, J. B., Saunders, J. B., and Perch-Nielsen, K. (eds.), *Planktonic Stratigraphy*. Cambridge University Press, New York, p. 17–86.
- CHRISTIE-BLICK, N., 1991, Onlap, offlap, and the origin of unconformity-bounded depositional sequences: *Marine Geology*, v. 97, p. 35–56.
- CHRISTOPHER, R. A., 1979, Normapolles and Triporate pollen assemblages of the Raritan and Magothy Formations (Upper Cretaceous) of New Jersey: *Palynology*, v. 3, p. 73–121.
- COPLEN, T. B., KENDALL, C., and HOPPLE, J., 1983, Comparison of stable isotope reference sections: *Nature*, v. 302, p. 236–238.
- 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.
- GALE, A. S., 1995, Cyclostratigraphy and correlation of the Cenomanian Stage in Western Europe, in House, M. R., and Gale, A. S. (eds.), *Orbital Forcing Timescales and Cyclostratigraphy*. Geological Society Special Publication No. 85, London, p. 177–197.
- , 1996, Turonian correlation and sequence stratigraphy of the Chalk in southern England, in Hesselbo, S. P., and Parkinson, D. N. (eds.), *Sequence Stratigraphy in British Geology*. Geological Society Special Publication No. 103, London, p. 177–195.
- GALE, A. S., JENKYN, H. C., KENNEDY, W. J., and CORFIELD, M., 1993, Chemostratigraphy versus biostratigraphy: data from around the Cenomanian-Turonian boundary: *Journal of the Geological Society*, London, v. 150, p. 29–32.
- GRADSTEIN, F. M., AGTERBERG, F. P., OGG, J. G., HARDENBOL, J., VAN VEEN, P., THIERRY, J., and HUANG, Z., 1995, A Triassic, Jurassic and Cretaceous Time Scale, in Berggren, W. A., Kent, D. V., Aubry, M. P., and Hardenbol, J. (eds.), *Geochronology, Time Scales and Global Stratigraphic Correlation*. SEPM Special Publication No. 54, Tulsa, Oklahoma, p. 95–126.
- HART, M., BAILEY, H. W., FLETCHER, B. N., PRICE, R. J., and SWIECICKI, A., 1981, Cretaceous, in Jenkins, G. J., and Murray, J. W. (eds.), *Stratigraphical Atlas of fossil foraminifera*, Chichester, p. 148–227.
- , 1984, The superfamily Robertinacea in the lower Cretaceous of the UK and adjacent areas of NW Europe, in Oertli, H. J. (ed.), *Benthos '83; 2<sup>nd</sup> International Symposium on benthic foraminifera* (Pau, April 1983). Elf aquitaine, Esso REP and Total CFP, Pau and Bordeaux 1984, p. 289–298.
- 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.
- JENKYN, H. C., GALE, A. S., and CORFIELD, R. M., 1994, Carbon and Oxygen-isotope stratigraphy of the English Chalk and Italian Scaglia and its paleoclimatic significance: *Geological Magazine*, v. 131, p. 1–34.
- KOUTSOUKOS, E. A. M., and HART, M. B., 1990, Cretaceous foraminiferal morphogroup distribution patterns, palaeocommunities and trophic structures: a case study from the Sergipe Basin, Brazil. *Transactions Royal Society of Edinburgh: Earth Sciences*, v. 81, p. 221–246.
- MILLER, K. G., MOUNTAIN, G. S., BROWNING, J. V., KOMINZ, M., SUGARMAN, P. J., CHRISTIE-BLICK, N., KATZ, M. E., and WRIGHT, J. D., 1998, Cenozoic global sea level, sequences, and the New Jersey Transect: Results from Coastal Plain and Continental Slope drilling: *Review of Geophysics*, v. 36, p. 569–601.
- , SUGARMAN, P. J., BROWNING, J. V., OLSSON, R. K., PEKAR, S. F., REILLY, T. R., CRAMER, B. S., AUBRY, M.-P., LAWRENCE, R. P., CURRAN, J., STEWART, M., METZGER, J. M., URTEGROVE, J., BUKRY, D., BURCKLE, L. H., WRIGHT, J. D., FEIGENSON, M. D., BRENNER, G. J., and DALTON, R. F., 1998, Bass River Site Report, Proc. ODP, Initial Reports, 174AX: College Station, TX (Ocean Drilling Program), p. 5–43.
- MITCHELL, S. F., PAUL, C. R., and GALE, A. S., 1996, Carbon isotopes and sequence stratigraphy, in Howell, J. A., and Aitken, J. F. (eds.), *High Resolution Sequence Stratigraphy: Innovations and Applications*. Geological Society Special Publication No. 104, London, p. 11–24.
- MITCHUM, R. M., VAIL, P. R., and THOMPSON, S., 1977, The depositional sequence as a basic unit for stratigraphic analysis, in *Seismic Stratigraphy—Applications to Hydrocarbon Exploration* (Payton, C. E., ed.), American Association of Petroleum Geologists, Memoir 26, p. 53–62.
- OHM, U., 1967, Zur Kenntnis der Gattungen *Reinholdella*, *Garantella*, und *Epistomina* (Foramin.): *Paleontographica*, v. 127, p. 103–188.
- OLSSON, R. K., 1991, Cretaceous to Eocene sea-level fluctuations on the New Jersey margin. *Sedimentary Geology*, v. 70, p. 195–208.
- , and USMANI, P., 1992, Upper Cretaceous foraminifera in Santonian to Maestrichtian depositional sequences in the New Jersey coastal plain, in Ishizaki, K. and Saito, I. (eds.), *Centenary of Japanese Micropaleontology*, Terra Scientific Publishing Company, p. 301–315.
- , MILLER, K. G., BROWNING, J. V., HABIB, D., and SUGARMAN, P. J., 1997, Ejecta layer at the Cretaceous-Tertiary boundary, Bass

- River, New Jersey (Ocean Drilling Program Leg 174AX): *Geology*, v. 25, p. 759–762.
- PERCH-NIELSON, K., 1985, Mesozoic calcareous nannofossils, *in* Bolli, H. M., Saunders, J. B., and Perch-Nielsen (eds.), *Planktonic stratigraphy*. Cambridge, United Kingdom, Cambridge University Press, p. 329–426.
- PETTERS, S. W., 1976, Upper Cretaceous subsurface stratigraphy of Atlantic coastal plain of New Jersey. American Association of Petroleum Geologists, *Bulletin*, v. 60, p. 87–107.
- PRATT, L. M., and THRELKELD, C. N., 1984, Stratigraphic significance of  $^{13}\text{C}/^{12}\text{C}$  ratios in mid-Cretaceous rocks of the Western Interior, U.S.A., *in* Stott, D. F., and Glass, D. J. (eds.), *The Mesozoic of Middle North America, A selection of Papers from the Symposium on the Mesozoic of Middle North America*, Calgary, Alberta, Canada, May 1983. Canadian Society of Petroleum Geologists Memoir, 9. Calgary, Alberta, Canada, 1984, p. 305–312.
- REUSS, A.E., 1854, Beiträge zur Charakteristik der Kreideschichten in den Ostalpen, besonders im Gosauthale und am Wolfgangsee: *Denkschriften der Kaiserlichen Akademie der Wissenschaften, Mathematisch-Naturwissenschaftliche Klasse* v. 7, p. 1–156.
- , 1862, Die Foraminiferen des norddeutschen Hils und Gault: *Kaiserlichen Akademie der Wissenschaften zu Wien, Mathematische-Naturwissenschaftliche Classe, Sitzungsberichte*, v. 46, p. 5–100.
- REVELLE, R. R., BARNETT, T. P., and others, 1990, Overview and Recommendations, *in* Revelle, R. R., Barnett, T. P., and others (eds.), *Sea-Level Change/Geophysical Study Committee, Commission on Physical Sciences and Resources, National Resource Council, National Academy Press, Washington, D.C.*, p. 3–34.
- SAGEMAN, B. B., RICH, J., ARTHUR, M. A., BIRCHFIELD, G. E., and DEAN, W. E., 1997, Evidence for Milankovitch periodocities in Cenomanian-Turonian lithologic and geochemical cycles, Western Interior U.S.A: *Journal of Sedimentary research*, v. 67, p. 286–302.
- SAHAGIAN, D. L., and JONES, M., 1993, Quantified Middle Jurassic to Paleocene eustatic variations based on Russian Platform stratigraphy: Stage level resolution: *Geological Society of America Bulletin*, v. 105, p. 1109–1118.
- SCHOLLE, P. A., and ARTHUR, M. A., 1980, Carbon isotope fluctuations in Cretaceous pelagic limestones: potential stratigraphic and petroleum exploration tools: *Bulletin of the American Association of Petroleum Geologists*, v. 64, p. 67–87.
- SHACKLETON, N.J., 1987, The carbon isotopic record of the Cenozoic: history of organic carbon burial and of oxygen in the ocean and atmosphere, *in* Brooks, J., and Fleet, A. J., (eds.), *Marine Petroleum Source Rocks*, Geological Society Special Publication No. 26, London, p. 423–434.
- SHACKLETON, N. J., HALL, M. A., and BOERSMA, A., 1984, Oxygen and carbon isotope data from Leg 74 foraminifers: Initial Reports of the Deep Sea Drilling Project, 74, p. 599–612.
- SIKORA, P. J., and OLSSON, R. K., 1991, A paleoslope model of late Albian to early Turonian foraminifera of the western Atlantic Margin and North Atlantic basin.: *Marine Micropaleontology*, v. 18, p. 25–72.
- SISSINGH, W., 1977, Biostratigraphy of Cretaceous calcareous nannoplankton: *Mijnbouw*, v. 56, p. 37–65.
- STOLL, H. M., and SCHRAG, D. P., 1996, Evidence for glacial control of rapid sea level changes in the early Cretaceous: *Science* 272, p. 1771–1774.
- SUGARMAN, P. J., MILLER, K. G., BUKRY, D., and FEIGENSON, M. D., 1995, Uppermost Campanian-Maestrichtian strontium isotopic, biostratigraphic, and sequence stratigraphic framework of the New Jersey Coastal Plain: *Geological Society of America Bulletin*, v. 107, p. 19–37.
- TAPPAN, H., 1943, Foraminifera from the Duck Creek Formation of Oklahoma and Texas: *Journal of Paleontology*, v. 17, p. 476–517.
- TEN DAM, A., 1947, On foraminifera of the Netherlands; No. 9-Sur quelques espèces nouvelles ou peu connues dans le Crétacé inférieur (Albian) des Pays-Bas: *Géologie en Mijnbouw*, v. 9(2), p. 25–29.
- , 1948, Les espèces du genre *Epistomina* Terquem 1883: *Revue del l'Institut Français du Pétrole et Annuaire des Combustibles liquides*, v. 3, p. 161–170.
- 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 seismic stratigraphy, *in* Wilgus, C. K., Posamentier, H., Ross, C. A., and Kendall, C. G. (eds.), *Sea-level changes: An integrated approach: Society of Economic Paleontologists and Mineralogists Special Publication no. 42*, p. 39–45.
- WATTS, A. B., and M. S. STECKLER, 1979, Subsidence and eustasy at the continental margin of eastern North America. *AGU Maurice Ewing series* 3, p. 218–234.
- WILLIAMSON, M. A., and STAM, B., 1988, Jurassic/Cretaceous Epistominidae from Canada and Europe: *Micropaleontology*, v. 34, p. 136–158.

Received 11 February 1999

Accepted 20 June 1999