Geological Society of America
Special Paper 356
2002

Sequence stratigraphy and sea-level change across the Cretaceous-Tertiary boundary on the New Jersey passive margin

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ABSTRACT

In the New Jersey coastal plain the Cretaceous-Tertiary (K-T) boundary is within an unconformity-bounded Navesink depositional sequence (ca. 69.1-64.5 Ma). At the Bass River, New Jersey, borehole, a 2.2 m.y. hiatus separates the Navesink sequence from underlying Campanian sequences, and an ~1.5 m.y. hiatus separates Danian zone P1a from zone P1c and younger sequences. A 6-cm-thick spherule layer that contains shocked minerals and an iridium anomaly marks the K-T boundary at this site. Benthic foraminiferal biofacies and biostratigraphy indicate that sedimentation was continuous across the K-T boundary. During deposition of the Navesink sequence, relative sea level fell from 100–150 m above present sea level in the lower part of the sequence (transgressive systems tract) to ~50 m (highstand systems tract) at the K-T boundary.

Three significant events are inferred from the Navesink depositional record: (1) an ~5°C warming of sea-surface temperatures perhaps related to the main outpouring of the Deccan Traps in India that began ~500 k.y. and ended ~22 k.y. before the K-T boundary; (2) the K-T event caused by an asteroid impact at Chicxulub, Mexico; and (3) a tsunami event immediately following the ballistic fallout of tektites from the Chicxulub ejecta vapor cloud, possibly triggered by massive slumping on the Atlantic slope. There is no relationship between these events and sea-level change during deposition of the Navesink sequence.

INTRODUCTION

Sea-level change has played a prominent role in interpreting the cause of mass extinctions either by regression reducing marine habitat or by transgression leading to widespread anoxia (Hallam and Wignall, 1997, 1999; Hallam, 2000). According to these authors, no general pattern to extinction at the major extinction boundaries has been unequivocally shown to be related either to regression or transgression. The Cretaceous-Tertiary boundary (K-T) has the additional consideration that it is associated with the Chicxulub asteroid impact. Nevertheless, Hallam and Wignall (1997) pointed out that there was evidence for major sea-level change at the K-T boundary that needed further evaluation. A general viewpoint summarized by Hallam

Olsson, R.K., Miller, K.G., Browning, J.V., Wright, J.D., and Cramer, B.S., 2002, Sequence stratigraphy and sea-level change across the Cretaceous-Tertiary boundary on the New Jersey passive margin, *in* Koeberl, C., and MacLeod, K.G., eds., Catastrophic Events and Mass Extinctions: Impacts and Beyond: Boulder, Colorado, Geological Society of America Special Paper 356, p. 97–108.

(1990) is that the K-T boundary marks a global regression followed by a transgression. This viewpoint is based on the fact that most shallow-water stratigraphic sections have a hiatus at the K-T boundary. Studies of Alabama sections have interpreted a hiatus at the K-T boundary as being caused by an impact-generated tsunami event and not due to regression (Olsson et al., 1996; Smit et al., 1996). Another general viewpoint is that continuous sedimentation across the K-T boundary is found only in deeper water pelagic facies (see Olsson and Liu, 1993, for discussion). It is difficult to determine relative sea-level changes in deep-water paleoenvironments, because sea-level changes generally do not cause significant changes in sediment and biota, as they do in shallower water paleoenvironments.

Inferred sea-level change across the K-T boundary is based primarily on studies of shallow-water deposits, and can be controversial. For example, based on a section in the coastal plain at Braggs, Alabama, the EXXON group (Donovan et al., 1988) placed the K-T boundary in the lowermost Clayton Formation (Pine Barren Member) within sequence TA 1.1 on the EXXON coastal onlap chart (Haq et al., 1987, 1988). They placed the sequence boundary at an unconformity separating the Clayton Formation from the Prairie Bluff Chalk (upper Maastrichtian); thus, they inferred a sea-level fall that predated slightly the K-T boundary. However, Habib et al. (1992) and Olsson and Liu (1993) showed that the K-T boundary was misplaced at Braggs. At the Braggs section, Olsson et al. (1996) identified Danian zone Pα (*Parvularugoglobigerina eugubina*) in the basal beds of the Clayton Formation just above the Prairie Bluff Chalk and 0.9 m below where Donovan et al. (1988) placed the K-T boundary. According to Olsson et al. (1996), the surface separating the Maastrichtian Prairie Bluff Chalk from the Danian Clayton Formation is not a sequence boundary. Rather, this surface was eroded by a giant tsunami wave that was generated by the K-T asteroid impact at Chicxulub, Mexico. Using benthic foraminiferal biofacies, Olsson et al. estimated paleodepth as ~30 m across the K-T boundary and concluded that sea level was at a lowstand. However, due to limited exposure, the K-T boundary sections in Alabama do not show the entire stratigraphic extent of the K-T sequence and its relationship with sequences above and below, which is important to understanding sequence stratigraphy and long-term sea-level change.

The New Jersey coastal plain is regarded as a classic passive margin and has received much study since the 1970s, including extensive seismic reflection surveys, petroleum exploration wells, Deep Sea Drilling Project (DSDP) and Ocean Drilling Project (ODP) drill sites, and coastal plain drilling. The New Jersey coastal plain contains a marine record of the Cenomanian to the Miocene and is ideally situated to study sequence stratigraphy and sea-level change. The New Jersey Coastal Plain Drilling Project (ODP Legs 150X and 174AX, Miller et al., 1994, 1996, 1997, 1998, 1999b) represents the onshore component of the New Jersey Sea-Level Transect, which included the Ocean Drilling Program (ODP) shelf and slope drilling on Legs 150X (Mountain et al., 1996) and 174A (Austin et al., 1998). The objective of this drilling program was to study sea-level history and depositional sequences on a classic passive margin, where these events should be unambiguously expressed in the geologic record.

Leg 150X drilling focused on the Miocene, Oligocene, and Eocene sea-level cycles and their corresponding depositional sequences. Studies showed that depositional sequences can be recognized by their bounding unconformities, by lithologic criteria, and by benthic foraminiferal biofacies that reflect changes in relative sea level (Browning et al., 1996; Miller et al., 1998). Hiatuses separating depositional sequences range in age from 100 to 500 k.y. in the Oligocene and 100 k.y. to 1 m.y. in the Miocene, and are correlated by the New Jersey $\delta^{18}O$ isotope record to periods of glaciation (Miller et al., 1998). Hiatuses in the Eocene range from 500 k.y. to ~ 2 m.y., but correlation to glacial events is uncertain (Browning et al., 1996).

The Ancora and Bass River boreholes (Fig. 1) were drilled during Leg 174AX. They were cored continuously, penetrated the K-T boundary, and bottomed in the upper Cenomanian. Seven unconformity-bounded sequences were identified in the Cenomanian to Maastrichtian section (Miller et al., 1998). In the lowermost Cenomanian-Turonian sequence, deposited in in-

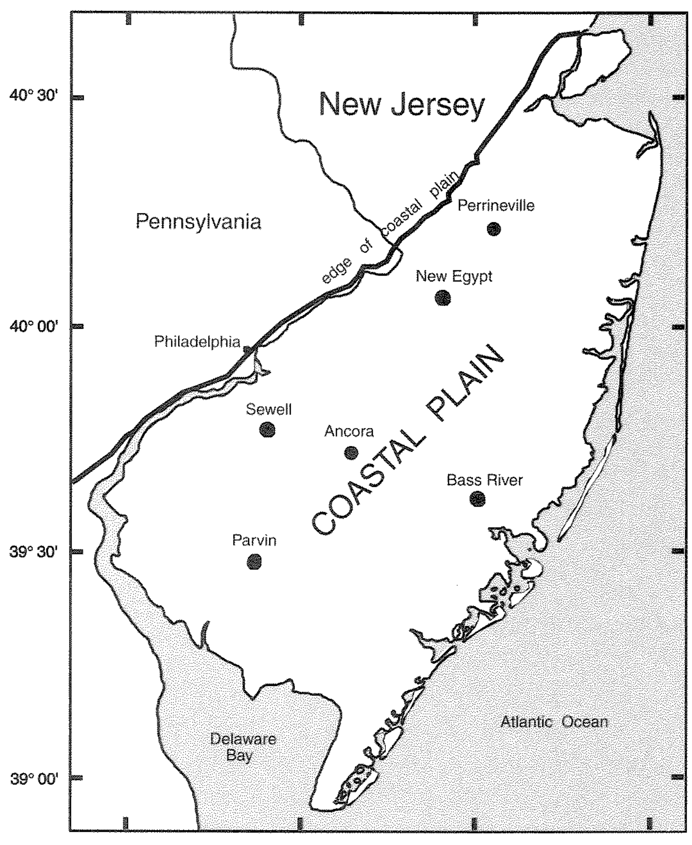

Figure 1. Location of Ancora and Bass River boreholes (Ocean Drilling Program Leg 174AX) and other Cretaceous-Tertiary boundary sections mentioned in text.

ner shelf paleodepths, five parasequences were identified on the basis of well-preserved benthic foraminifera and lithologic criteria (Sugarman et al., 1999). In summary, the New Jersey Coastal Plain Drilling Project demonstrated that coastal plain sequences preserve detailed records for studies of eustasy and that contrasting facies and other environmental indicators, including well-preserved benthic foraminifera, allow for clear identification of water-depth variations within sequences. New Jersey coastal plain drilling also recovered spectacular records of deposition at the K-T boundary.

In the downdip Bass River borehole (Fig. 2), a 6-cm-thick spherule layer separates lowermost Danian deposits (zone P0) from uppermost Maastrichtian deposits (*Micula prinsii* zone) (Olsson et al., 1997). Reworked spherules occur above the K-T boundary at the updip Ancora borehole, but no distinct spherule layer is present. Nevertheless, an interval of clay clasts that has been interpreted as tsunami derived occurs immediately above the spherule layer at Bass River and at the K-T boundary at Ancora (Olsson et al., 2000). The Ancora section is considered biostratigraphically complete. Thus, the New Jersey coastal plain appears ideal for assessing sea-level change across the K-T boundary. Here we report on the depositional sequences in the Maastrichtian and the Danian to obtain a longer term view of sea-level change during ~10 m.y. prior to and following the K-T event.

METHODS

Weighed samples for foraminiferal analysis were washed on a 63 µm sieve, dried, and separated into three size fractions for counting (63 µm, 125 µm, 250 µm). Foraminifera were well preserved and their chambers generally free of sediment, which in most cases allowed concentration of foraminifera by flotation procedures. Samples were split with a microsplitter to a man-

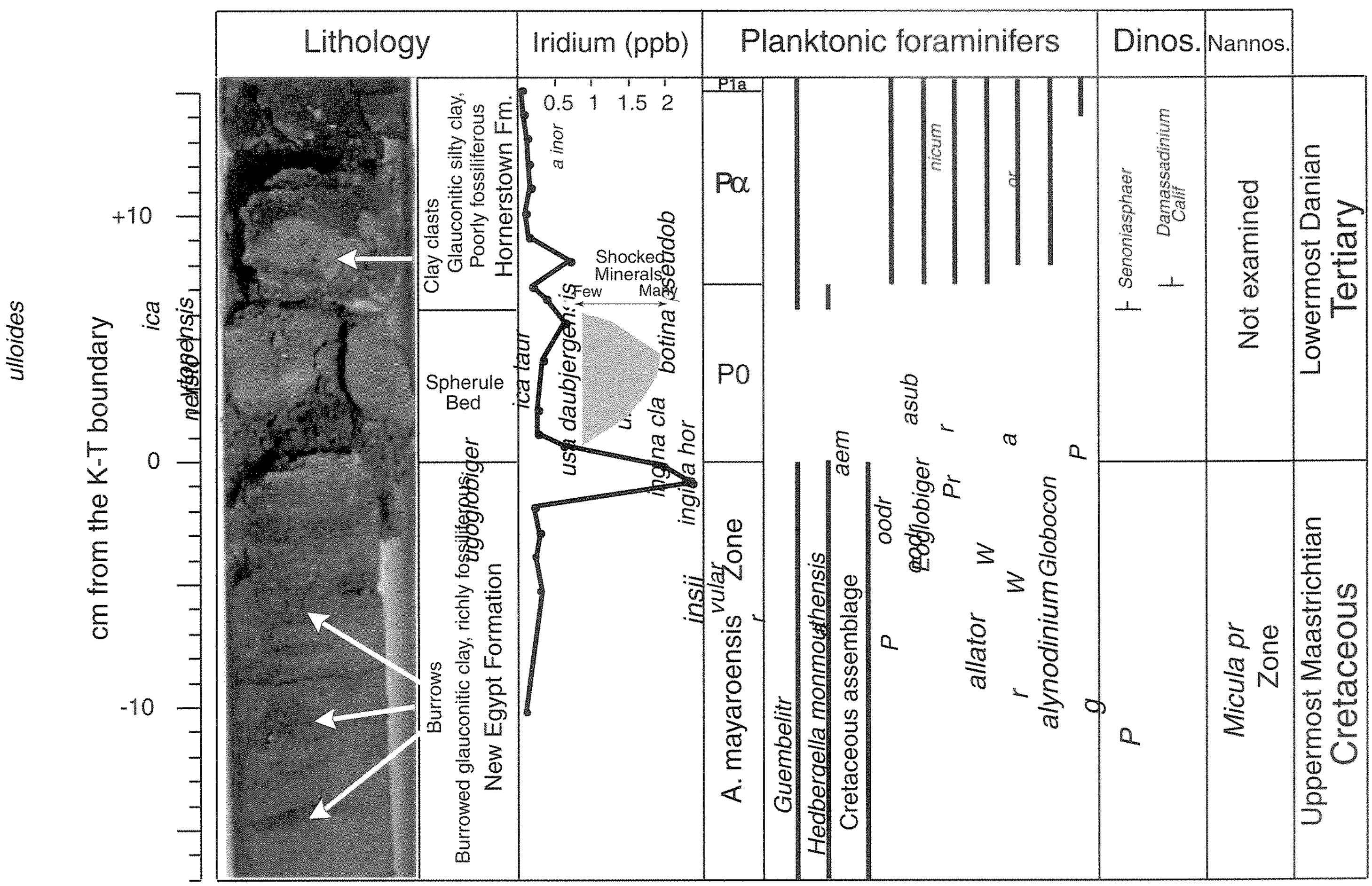

Figure 2. Cretaceous-Tertiary (K-T) boundary section with 6-cm-thick spherule layer was recovered in November 1996 in Bass River borehole (New Jersey Coastal Plain Drilling Project, Ocean Drilling Program ODP Leg 174AX). Shocked minerals (identified by Izett, 1997, personal commun.) and elevated iridium values (measurements by Asaro, 1998, personal commun.) are associated with spherule layer. Spherule bed is overlain by 10 cm zone that includes clay clasts that are surrounded by Danian sediments. Clay clasts are interpreted as being emplaced by tsunami activity associated with boundary event. Planktonic foraminifera, dinoflagellates, and calcareous nannofossils provide biostratigraphic resolution in K-T boundary section (Olsson et al., 1997). Fm.—Formation.

ageable size and at least 300 specimens were counted in each size fraction. The total number of species was summed for each size fraction and then totaled for each sample; in most instances more than 1000 specimens were counted. Benthic foraminiferal abundance data were analyzed to help estimate paleowater depth. The great number of the species *Buliminella carseyae* skewed the results, so their abundance data were eliminated from the data matrix. The dataset was normalized to percentages and Q-mode factor analysis was used to compare variations among the samples. Three factors, explaining 80.0% of the faunal variation, were extracted using a Varimax Factor rotation using Systat 5.2.1 on a Macintosh microcomputer. These factors were interpreted as biofacies.

The paleoslope model for Campanian and Maastrichtian benthic foraminifera of the New Jersey coastal plain (Olsson and Nyong, 1984) was used for estimating paleodepth for the foraminiferal biofacies.

Clean specimens of the planktonic foraminifer *Rugoglobigerina* sp. and the benthic foraminifer *Anomalinoides midwayensis* were picked from the >125 μm size fraction. Stable isotope values of foraminifera were measured in stable isotope laboratories at the University of Maine and Rutgers University. The analyses from the University of Maine laboratory were made on a VG Prism II mass spectrometer using an IsoCarb automated carbonate preparation system. At Rutgers University, the measurements were made on a Micromass Optima mass spectrometer using a Multiprep automated carbonate preparation system. Samples of specimens were reacted in 100% phosphoric acid at 90°C. Oxygen and carbon isotopic values in Tables 1 and 2 are reported relative to Vienna Peedee belemnite by normalizing the NBS-19 or NBS-20 standards to the values reported in Coplen et al. (1983). The standard deviations (1σ) of the standards (minimum of 6 standards measured with each run of 30 samples) are 0.06‰ and 0.05‰ for $\delta^{18}O$ and $\delta^{13}C$, respectively.

We obtained 23 Sr isotopic measurements from foraminifer tests (~4–6 mg) at the Bass River borehole. Sediments adhering to the tests were removed by ultrasonically cleaning for 1–2 s. Samples were dissolved in 1.5 N HCL, centrifuged, and introduced into ion-exchange columns. Standard ion exchange techniques were used to separate the strontium (Hart and Brooks, 1974) and samples were analyzed on a VG Sector mass spectrometer at Rutgers University. Internal precision on the sector for the data set (Table 3) averaged 0.000011, and the external precision is ~0.000020–0.000030 (Oslick et al., 1994). NBS 987 is measured for these analysis at 0.710255 (2σ standard deviation 0.000008, n = 22) normalized to $^{87}Sr/^{86}Sr$ of 0.71194.

TABLE 1. BASS RIVER

Sample depth ft (m)	*Anomalinoides midwayensis* $\delta^{13}C$	*Anomalinoides midwayensis* $\delta^{18}O$
1260.28 (384.13)	0.79	−1.518
1260.35 (384.15)	0.95	−1.52
1260.41 (384.17)	1.067	−1.174
1260.41 (384.17)	0.917	−1.42
1260.51 (384.20)	0.894	−1.075
1260.57 (384.22)	1.13	−1.22
1260.64 (384.24)	1.25	−1.16
1260.71 (384.26)	1.35	−1.18
1260.77 (384.28)	1.229	−1.181
1261.07 (384.37)	1.16	−1.26
1261.50 (384.50)	1.224	−1.22
1262.00 (384.65)	1.133	−1.212
1263.00 (384.96)	1.083	−1.347
1263.50 (385.11)	0.922	−1.322
1264.00 (385.26)	1.056	−1.416
1265.10 (385.60)	0.592	−1.388
1266.00 (385.87)	0.554	−1.212
1267.00 (386.18)	0.428	−1.19
1268.00 (386.48)	0.512	−1.309
1269.00 (386.79)	0.175	−1.075
1271.00 (387.40)	0.45	−1.08
Sample depth ft (m)	***Rugoglobigerina* $\delta^{13}C$**	***Rugoglobigerina* $\delta^{18}O$**
1260.55 (384.31)	1.88	−1.83
1260.62 (384.33)	2.09	−2.11
1260.68 (384.35)	2.2	−2.3
1260.78 (384.38)	2.19	−2.23
1260.85 (384.40)	2.09	−1.99
1260.90 (384.42)	2.24	−2.16
1260.91 (384.42)	2.22	−2.06
1261.00 (384.45)	2.25	−2.16
1261.50 (384.50)	2.34	−2.76
1261.82 (384.70)	2.37	−2.65
1262.00 (384.65)	2.28	−3.22
1262.50 (384.90)	2.37	−3.02
1263.00 (384.96)	2.27	−2.88
1263.50 (385.11)	2.34	−2.9
1264.00 (385.26)	2.21	−2.87
1265.10 (385.60)	1.84	−2.89
1266.00 (385.87)	1.43	−1.98
1267.00 (386.18)	1.61	−2.22
1268.00 (386.48)	1.31	−1.99
1269.00 (386.79)	1.49	−1.79
1271.00 (387.40)	1.75	−2.18

UNCONFORMITIES IN THE MAASTRICHTIAN AND DANIAN SECTIONS

Sugarman et al. (1995) established that the only sequence represented in the Maastrichtian of the New Jersey coastal plain was the Navesink sequence. The Navesink sequence is characterized by shallowing-upward lithofacies, from a basal clastic sequence-bounding unconformity, to transgressive clayey, glauconite-rich deposits (the Navesink Formation), to silt-rich, glauconitic highstand deposits (the Red Bank—New Egypt Formation). Above the K-T boundary the highstand deposits (Hornerstown Formation) are more glauconite rich, but are silty without significant clay content. A prominent basal unconformity separates the Navesink sequence from an upper Campanian sequence (the Marshalltown sequence). Using strontium isotope dating on outcrops, Sugarman et al. (1995) estimated that the duration of the hiatus separating the two sequences was ~3 m.y. Miller et al. (1999a), using additional strontium isotope data from the Bass River borehole, estimated the duration of

TABLE 2. ANCORA

Sample depth ft (m)	*Anomalinoides midwayensis* $\delta^{13}C$	*Anomalinoides midwayensis* $\delta^{18}O$
618.40 (188.53)	0.68	−1.28
618.50 (188.56)	0.94	−1.21
619.00 (188.71)	0.83	−1.48
619.50 (188.87)	0.89	−1.45
620.00 (189.02)	0.94	−1.47
621.00 (189.32)	0.82	−1.38
622.00 (189.63)	0.67	−1.32
623.00 (189.93)	0.18	−1.15
624.00 (190.24)	0.06	−1.05
625.00 (190.54)	0.19	−1.12
626.00 (190.85)	0.26	−0.91
627.00 (191.15)	0.27	−0.94
628.00 (191.46)	0.34	−0.89
630.50 (192.22)	0.27	−0.97
631.00 (192.37)	0.36	−0.80
636.00 (193.90)	0.49	−0.93
641.00 (195.42)	0.781	−1.051
646.00 (196.95)	0.539	−1.146
651.00 (198.47)	0.596	−0.925
Sample depth ft (m)	***Rugoglobigerina*** $\delta^{13}C$	***Rugoglobigerina*** $\delta^{18}O$
618.40 (188.53)	2.40	−2.92
618.50 (188.56)	2.15	−2.82
619.00 (188.71)	1.763	−3.109
619.50 (188.87)	1.58	−2.67
620.00 (189.02)	1.72	−3.46
621.00 (189.32)	1.91	−3.37
622.00 (189.63)	2.02	−2.80
623.00 (189.93)	1.341	−2.519
624.00 (190.24)	1.33	−2.10
625.00 (190.54)	1.38	−2.48
626.00 (190.85)	1.56	−2.14
627.00 (191.15)	1.81	−2.54
628.00 (191.46)	1.93	−2.42
630.50 (192.22)	1.61	−2.33
631.00 (192.37)	1.77	−2.25
636.00 (193.90)	2.15	−2.23
641.00 (195.42)	1.86	−2.11
646.00 (196.95)	1.26	−2.47
651.00 (198.47)	1.61	−1.84

TABLE 3. BASS RIVER STRONTIUM

Sample depth ft (m)	$^{87}Sr/^{86}Sr$	Error
1260.60 (384.32)	0.707915	13
1260.73 (384.36)	0.707893	20
1260.90 (384.42)	0.707889	18
1261.40 (384.57)	0.707876	13
1261.75 (384.67)	0.707885	4
1262.25 (384.83)	0.707878	10
1262.50 (384.90)	0.707896	7
1263.00 (385.06)	0.707900	6
1263.25 (385.13)	0.707894	20
1263.50 (385.21)	0.707895	5
1263.75 (385.28)	0.707884	6
1264.00 (385.36)	0.707908	5
1264.50 (385.51)	0.707900	4
1265.00 (385.67)	0.707874	16
1266.00 (385.97)	0.707893	4
1266.50 (386.12)	0.707884	10
1267.00 (386.28)	0.707872	10
1267.50 (386.43)	0.707872	13
1269.00 (417.37)	0.707897	6
1269.50 (387.04)	0.707875	5
1270.00 (387.19)	0.707892	7
1274.50 (388.56)	0.707909	6
1280.00 (390.24)	0.707882	32

the hiatus as 2.2 m.y. (71.3-69.1 Ma) (Fig. 3). They correlated the sequence boundary with synchronous $\delta^{18}O$ increases in deep-water benthic and low-latitude surface-dwelling planktonic foraminifera, and speculated that changes in paleobathymetry of 30–40 m based on benthic foraminifera across the Navesink-Marshalltown sequence boundary were caused by development of a small to moderate-sized Antarctic ice sheet during the early Maastrichtian (Miller et al., 1999a).

The top of the Navesink sequence is identified by a prominent unconformity within the lower Danian (Fig. 3). In the Ancora and Bass River boreholes the sequence boundary is between planktonic foraminiferal zones P1a and P1c; zone P1b is absent at Bass River and is represented by only a thin interval at Ancora (hiatus ca. 64.5–63 Ma at Bass River and ca. 64–63 Ma at Ancora based on the time scale of Berggren et al., 1995). The sediments deposited in zone P1c are clearly transgressive, because they contain middle to outer shelf benthic foraminifera and abundant planktonic foraminifera and overlie a zone P1a inner to middle shelf benthic assemblage containing rarer planktonic foraminifera. The duration of the hiatus separating the two sequences is estimated as ~1.5 m.y. at Bass River and 1.0 m.y. at Ancora using the time scale of Berggren et al. (1995).

BENTHIC FORAMINIFERAL BIOFACIES AND PALEODEPTH ACROSS THE K-T BOUNDARY

Factor analysis of the pooled dataset identifies three benthic biofacies in the Ancora and Bass River boreholes (Figs. 4–7). Biofacies 1, which occurs in the lower part of the sections analyzed in both boreholes, is characterized by relatively high abundances of the species *Gyroidinoides imitata, Anomalinoides midwayensis, Quadrimorphina allomorphinoides*, and *Pseudouvigerina seligi*. Biofacies 1 is replaced upsection in both boreholes by biofacies 3 and is characterized by the species *Anomalinoides* cf. *welleri, Corphyostoma plaitum, Pseudouvigerina seligi*, and *Pulsiphonina prima*. Biofacies 2 is found in a thin interval spanning the K-T boundary in both boreholes. The species *Alabamina midwayensis, Anomalinoides acuta, P. prima*, and *Tappanina selmensis* characterize this biofacies. It is notable that taxa such as *A. midwayensis, A. acuta*, and *Anomalinoides welleri* that characterize Danian Midway benthic assemblages (Berggren and Aubert, 1975) in the Gulf and Atlantic coastal plains first appear in biofacies 2 in the uppermost Maastrichtian (Figs. 4 and 6). Thus, they appear to have evolved in inner shelf environments in the latest Maastrichtian.

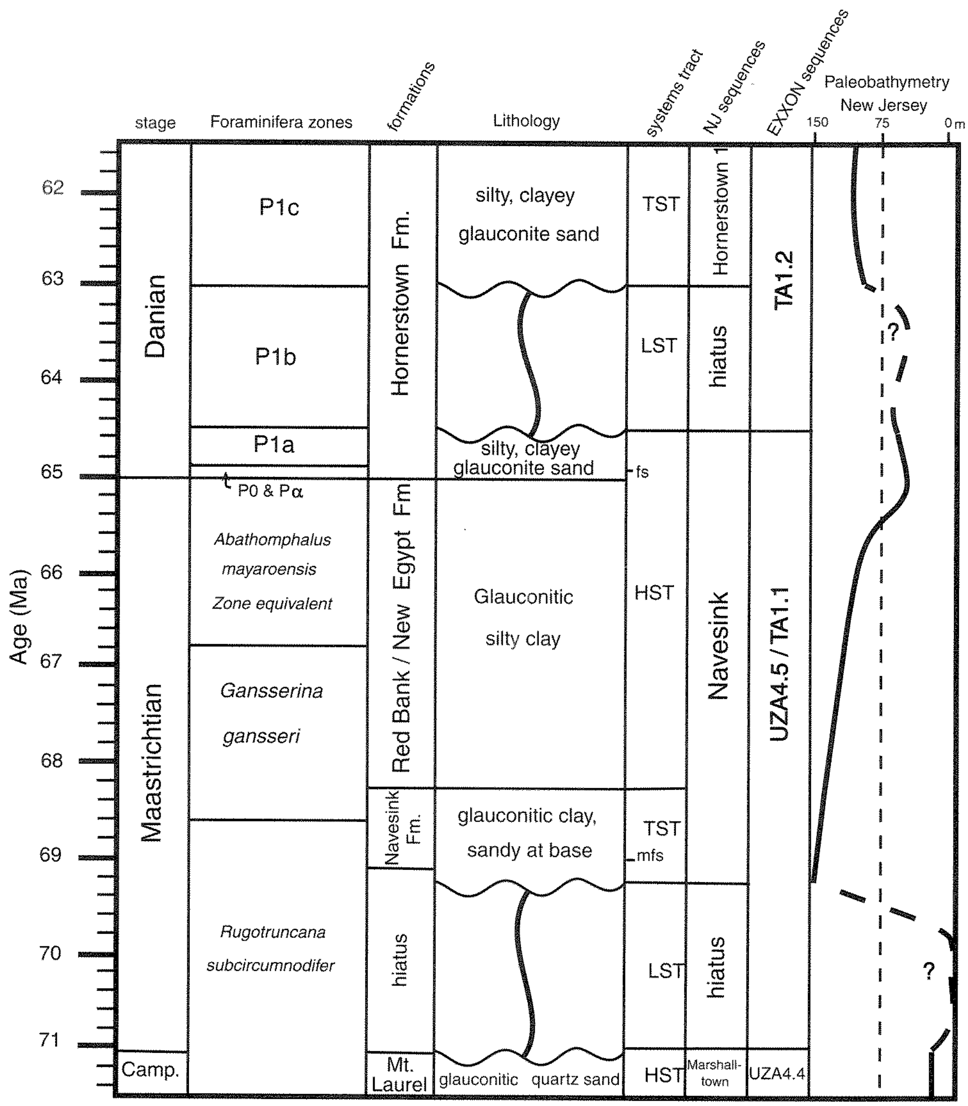

Figure 3. Navesink depositional sequence at Bass River borehole showing paleobathymetry based on benthic foraminifera. Note that the Navesink sequence spans the Cretaceous-Tertiary (K-T) boundary and is clearly separated from sequences above and below by prominent unconformities and their respective hiatuses. Navesink sequence contains Cretaceous Navesink and New Egypt Formations and lower portion of Hornerstown Formation. Portion of Hornerstown Formation (glauconite-rich unit) above Navesink sequence can be further separated into three sequences based on biostratigraphy and benthic foraminiferal biofacies. LST is lowstand, TST is transgressive, HST is highstand, msf is maximum flooding surface, fs is flooding surface.

Bass River borehole

In the downdip Bass River borehole, biofacies 1 (386.28–388.10 m) planktonic foraminifera compose as much as 85% of the assemblage, averaging 78% (Fig. 5). Paleodepth is estimated as middle to outer neritic, using the paleoslope model of Olsson and Nyong (1984). Planktonic foraminifera average ~73% of the assemblage within biofacies 3 (386.03–384.35 m). Paleodepth is estimated as middle neritic using the paleoslope model of Olsson and Nyong (1984). Water depth gradually shoaled during deposition of biofacies 3. Biofacies 3 correlates with a significant warming trend in sea-surface temperatures, as indicated by decreased $\delta^{18}O$ values of the shallow-dwelling planktonic foraminifer *Rugoglobigerina* (Fig. 5).

A sharp decrease in the planktonic foraminiferal component to ~40% of the assemblage occurs in the Maastrichtian part of biofacies 2 (384.32–384.0 m). This decrease in percent planktonics and the transition from biofacies 3 to 2 occurs immediately below the K-T boundary (384.22 m); little change is associated with the boundary. Due to the planktonic foraminiferal extinctions at the K-T boundary, the diversity and percentage of planktonic foraminifera is very low in the lowermost Danian, but it gradually increases to ~30% of the assemblage at the top of the sequence. Paleodepth is estimated to have lowered to inner shelf depths below the K-T boundary and continued at these depths above the K-T boundary to the sequence boundary.

Ancora borehole

In the updip Ancora borehole (Fig. 1), planktonic foraminifera, particularly adult specimens, are not as plentiful (averaging 63%) due to the shallower environment of deposition. Due to the shallower paleodepth, benthic foraminiferal abundances differ somewhat from abundances at Bass River. Nevertheless, factor analysis identifies the same succession of biofacies that is identified at Bass River (Fig. 7). The paleodepth of biofacies 1 (192.37–189.93 m) is estimated as middle neritic using the paleoslope model of Olsson and Nyong (1984). The paleodepth of biofacies 3 (189.63–188.87 m) is estimated as inner to middle neritic. As at Bass River, biofacies 3 correlates with a significant warming trend in sea-surface temperatures indicated by decreased $\delta^{18}O$ values of the shallow-dwelling planktonic foraminifer *Rugoglobigerina* (Fig. 7). The percentage of planktonic foraminifera in biofacies 2 decreases across the K-T boundary, from 55% in the Maastrichtian to 1.7% in the lowermost Danian, increasing to 6% at the top of the analyzed section (Fig. 7). The paleodepth of biofacies 2 (188.71–188.18 m) is estimated as inner neritic using the paleoslope model of Olsson and Nyong (1984).

DISCUSSION

Biostratigraphic and paleomagnetic data show that a stratigraphically complete K-T section is present in the New Jersey coastal plain (Fig. 2). Sequence stratigraphy indicates that the K-T event occurred within a highstand systems tract of the Navesink sequence. The Navesink sequence is equivalent to sequence cycles UZA 4.5 and TA1.1 (the base of TA1.1, as defined, is not a sequence boundary) on the EXXON coastal onlap chart (Haq et al., 1988). On the basis of our data relative sea level is estimated to have fallen from ~100–150 m above present at the beginning of the Navesink sequence to <50 m prior to the K-T boundary and remained low during final deposition of the sequence in the Danian. The paleodepth across the K-T boundary in New Jersey is similar to the paleodepth estimated at Millers Ferry, Alabama (Olsson et al., 1996), which was also situated in a shallow shelf setting at K-T boundary time. As in New Jersey, relatively little change occurred in the composition of benthic foraminiferal assemblages across the K-T boundary.

Three significant events occurred during deposition of the Navesink sequence in New Jersey. The earliest event occurred ~500 k.y. before the K-T boundary and involved a significant warming of sea-surface temperatures. The $\delta^{18}O$ record of the shallow-dwelling planktonic foraminifer *Rugoglobigerina* shows a sharp negative shift in oxygen isotope values of nearly 1%, indicating a warming of surface waters by ~4 °C; peak warming during the trend was ~5 °C (Figs. 5 and 7). On the basis of estimated sedimentation rates at Bass River, this interval of warming ended ~22 k.y. before the K-T boundary. The warming trend is also evident in the benthic foraminiferal $\delta^{18}O$ record and correlates with biofacies 3 (Figs. 5 and 7). We suggest that benthic foraminiferal changes from biofacies 3 to biofacies 1 at Ancora and Bass River are in part due to warming of bottom waters. At Bass River the warming trend started near the base of C29R (Fig. 5). We support the hypothesis (Barrera and Savin, 1999) that the warming trend was due to an increase in greenhouse gases related to the main outpouring of the Deccan Traps in India, which started near the base of subchron C29R (Courtillot et al., 1986; Hansen, et al., 1996).

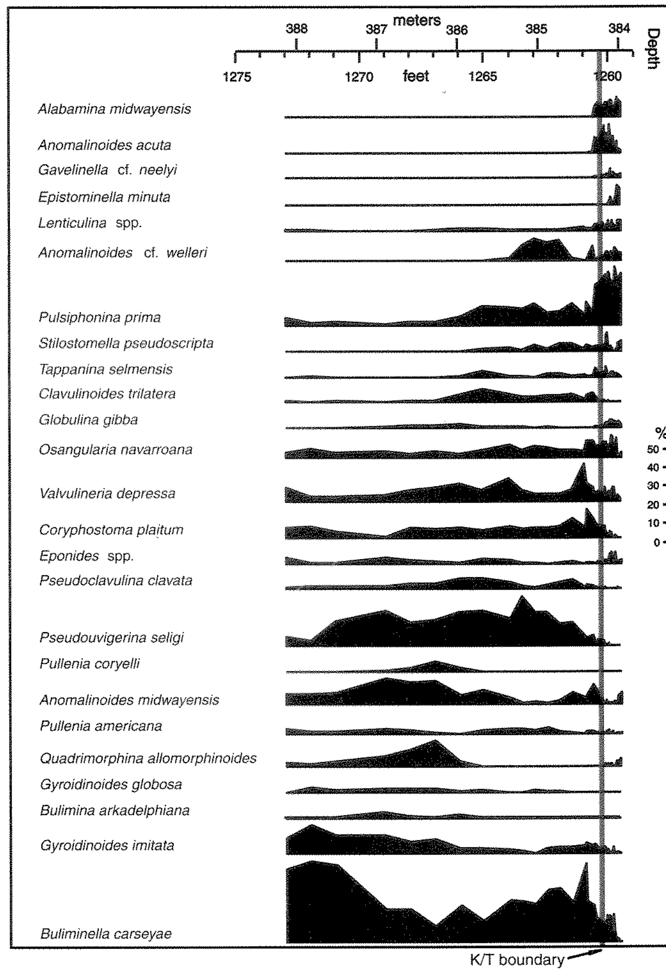

Figure 4. Relative abundances of benthic foraminifera in Maastrichtian and lower Danian Navesink sequence, Bass River borehole. These results are data used in factor analysis shown in Figure 5. K-T, Cretaceous-Tertiary.

A positive shift in $^{87}Sr/^{86}Sr$ ratios occurs at Bass River near the base of Subchron C29R and correlates with the latest Maastrichtian warming trend (Fig. 5). High-resolution (50 k.y. scale) Maastrichtian variations in $^{87}Sr/^{86}Sr$ observed at Bass River show a remarkably similar pattern to coeval sections at Bidart, France, and El Kef, Tunisia (Vonhof and Smit, 1997). However, $^{87}Sr/^{86}Sr$ values measured at Bass River (~0.707 890) are offset from the values of Vonhof and Smit (1997) (0.707 830) by ~0.000 040 ppm. Similar Sr isotopic offsets (few tens of ppm) have been noted in high-resolution Sr isotopic studies of Pliocene-Pleistocene sediments and ascribed to adhering of clay minerals to the carbonates; we speculate that a similar effect influenced the Bass River Maastrichtian section. The difference between our values and those of Vonhof and Smit cannot be ascribed to an interlaboratory calibration problem because we

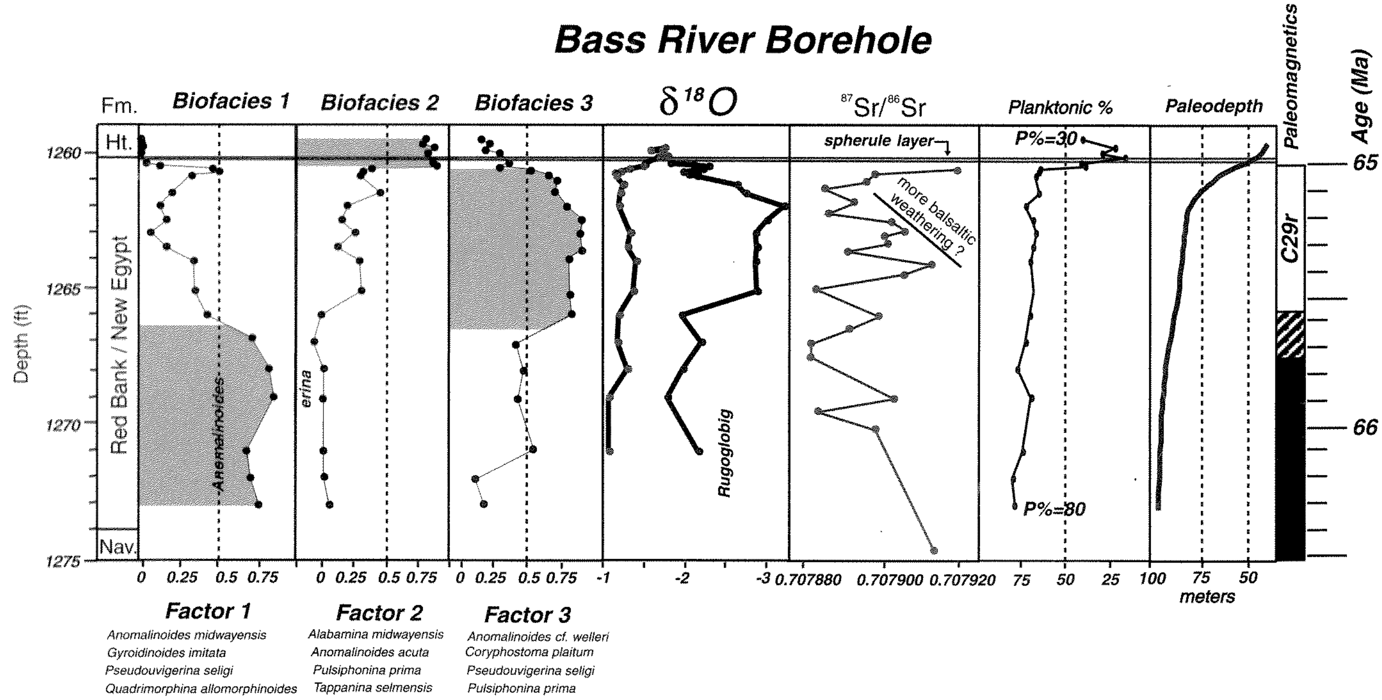

Figure 5. Three principal factors are separated by factor analysis, identifying three benthic biofacies in Bass River borehole (see text for explanation). Note that biofacies 3 is associated with negative shift in $\delta^{18}O$ isotope values indicating warming trend. Decrease of as much as 1% in ^{18}O values on shells of Cretaceous planktonic foraminifer *Rugoglobigerina* indicates significant warming trend of as much as 5°C in near sea-surface temperatures that began ~500 k.y. and ended ~22 k.y. before K-T boundary. Warming trend that starts near lower boundary of chron C29R is believed related to main outpouring of Deccan Traps in India. Benthic biofacies and planktonic foraminiferal percentages indicate that sea level fell from highstand of ~150 m in Maastrichtian to ~50 m prior to Cretaceous-Tertiary (K-T) boundary event. Sea level remained low across K-T boundary. Fm.—Formation, Ht.—AQP, Nav.–AQP.

note a similar offset between Maastrichtian $^{87}Sr/^{86}Sr$ values at Bass River versus coeval New Jersey coastal plain sections (Sugarman et al., 1995). The variations noted by Vonhof and Smit (1997) include a sharp decrease in chron C29r that they ascribe to increased weathering of basaltic rocks associated with the Deccan Traps. This strontium isotope change also correlates with this global warming trend. We conclude that Maastrichtian Sr isotopic values at Bass River must be affected by minor diagenesis, although the general global pattern of Sr isotopic variations is preserved. Diagenesis is minor because the stable isotopic values from the Maastrichtian at Bass River (Fig. 5) are similar in amplitude and pattern to coeval global values, the specimens are generally well preserved, and the Sr isotopic offset is relatively small.

Li and Keller (1998a, 1998b) identified a latest Maastrichtian (chron C29R) warming trend in $\delta^{18}O$ values of benthic foraminifera at ODP Site 525, but due to the lack of a clear warming trend in $\delta^{18}O$ values of planktonic foraminifera in this interval, they ruled out a link to the Deccan Traps volcanism. However, the study by Kucera and Malmgren (1998) of Site 525 and other South Atlantic sites showed that this warming trend affected surface waters, based on the poleward migration of the low-latitude planktonic foraminifer *Contusotruncana contusa*. Barrera and Savin (1999) concluded in their study of $\delta^{18}O$ records that intermediate and deep waters in the South and North Atlantic, Indian, and Pacific Oceans warmed globally by 3–4 °C between 65.5 and 65.3 Ma and then cooled slightly ca. 65.2 Ma. They suggested that this increase in marine temperatures correlated with the main episode of eruptions of the Deccan Traps that may have led to greenhouse global warming. Olsson et al. (2000, 2001) correlated a poleward migration in the North and South Atlantic Oceans of the subtropical planktonic foraminifera *Pseudotextularia elegans* with this warming trend. We conclude that a late Maastrichtian global warming event occurred in earliest subchron C29R (ca. 65.5 Ma).

The second event, the most significant, is the K-T event, which very briefly masked deposition of the Navesink sequence by condensation and fallout of tektites from the ejecta vapor cloud generated by the impact of the K-T asteroid at Chicxulub, Yucatan, Mexico (Hildebrand et al., 1991; Alvarez, 1996; Olsson et al., 1997). The 6-cm-thick layer of tektites that settled on the New Jersey seafloor left impressions in the soft mud that are interpreted as original, but possibly enhanced by post-depositional compaction. These impressions are preserved in the Bass River K-T boundary core (Fig. 8). The 6-cm-thick K-T boundary spherule layer that occurs as a thin layer in an otherwise continuous section at Bass River is testimony to this instantaneous event. Shocked minerals and the K-T iridium

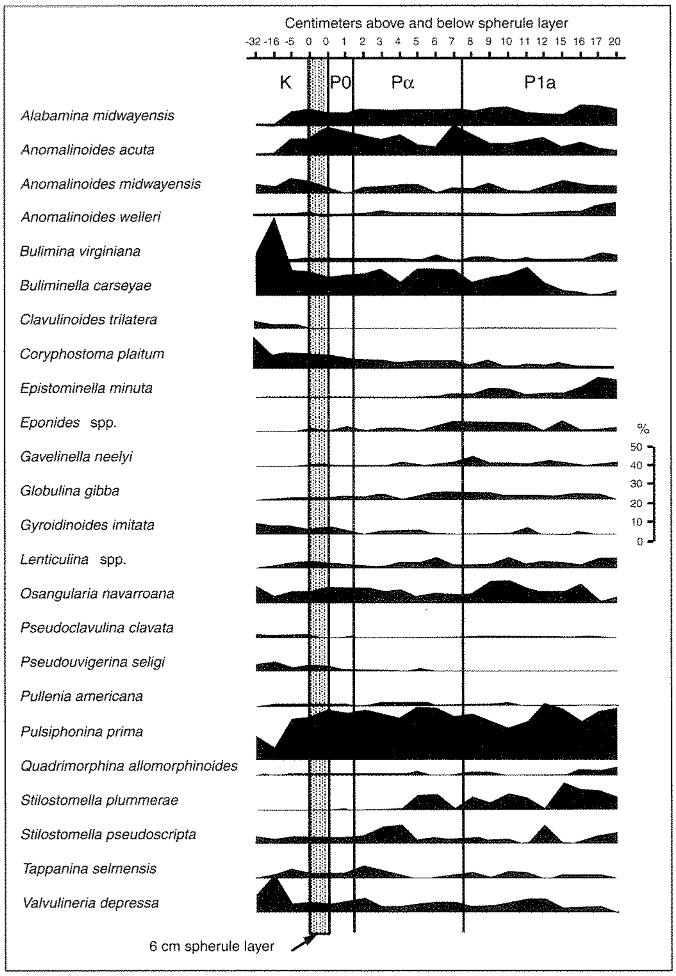

Figure 6. Relative abundance of benthic foraminiferal species in biofacies 2 across Cretaceous-Tertiary (K-T) boundary in Bass River borehole. Typical Danian species such as *Alabamina midwayensis, Anomalinoides acuta*, and *Anomalinoides welleri* first appear in uppermost Maastrichtian with lowering of sea level, suggesting that they migrated from inner shelf environments. Note that benthic foraminifera were not affected by K-T impact event.

anomaly are associated with the spherule layer that appears to be an in situ deposit at Bass River (Fig. 2). The higher concentration of iridium at the base of the spherule layer is believed to be due to the postdepositional downward diffusion of iridium through pore water in the highly permeable and porous spherule layer; the underlying Maastrichtian clayey silts act as an aquitard. Benthic foraminifera apparently were little affected by this event because biofacies 2 continues immediately above the spherule layer (Fig. 5). Planktonic foraminifera underwent a mass extinction; the only survivors appear to be the well-known taxa *Guembelitria cretacea, Hedbergella monmouthensis*, and *Hedbergella holmdelensis*. The Bass River record unequivocally links the extinctions of marine plankton to the impact (Olsson et al., 1997; Norris et al., 1999).

The third event, which immediately followed the deposition of tektites, was a tsunami. The tsunami generated in the Gulf of Mexico by the impact at Chicxulub probably would have been blocked by the shallow Florida platform and prevented from crossing into the North Atlantic. However, a tsunami may have been triggered by slope failure on the New Jersey margin due to earthquakes generated by the Chicxulub impact (Klaus et al., 2000; Norris et al., 2000; Olsson et al., 2000). Small clay clasts, ranging from a few centimeters to millimeters in size and containing Cretaceous foraminifera and calcite-replaced tektites (possibly original calcite tektites), occur directly above the spherule layer at Bass River and form a marker for the K-T boundary throughout the New Jersey coastal plain where the spherule bed is absent (Fig. 9). We have noted this clast layer at Ancora, Bass River, and a well at Parvin, and outcrops at New Egypt, Perrineville, and Sewell (Fig. 1). Cretaceous planktonic foraminifera that are found in the Danian occur within clay clasts and are confined to a 10-cm-thick zone above the spherule layer. The clay clasts are surrounded by Danian sediment containing typical Danian planktonic foraminiferal species and dinoflagellates (Olsson et al., 1997) that indicate that the clasts are confined to zone P0 to the lowermost part of zone P1a (Fig. 10).

At Bass River a concentrated layer of echinoid fecal pellets (Fig. 11) that is interpreted as a condensed interval occurs in zone P1a. This interval probably represents a flooding surface and may be a parasequence boundary in the upper part of the Navesink sequence. This condensed interval may correspond to a flooding surface that Donovan et al. (1988) associated with the K-T boundary at Braggs, Alabama, and to a flooding surface identified by Olsson et al. (1996) at Millers Ferry, Alabama.

CONCLUSIONS

The K-T boundary occurs in a highstand systems tract within an unconformity-bounded depositional sequence, the Navesink sequence in New Jersey. Sea level fell to ~50 m prior to the K-T boundary and remained low for the remainder of the sequence. Three significant events occurred during deposition of the Navesink sequence. (1) A global warming event possibly brought on by the main outpouring of the Deccan Traps in India began ~500 k.y. and ended ~22 k.y. prior to the K-T boundary. (2) The K-T boundary event at Chicxulub, Mexico led to fallout of tektites on the New Jersey margin (the spherule layer at Bass River) and the mass extinction of marine calcareous plankton. (3) A possible tsunami event, triggered by mass slumping of the New Jersey outer continental margin or elsewhere, may have immediately followed the K-T boundary event.

Sea-level changes do not appear to be a significant cause or influence on any of these three events.

ACKNOWLEDGMENTS

Drilling of the Bass River and Ancora boreholes (Ocean Drilling Program Leg 174AX) was supported by National Science

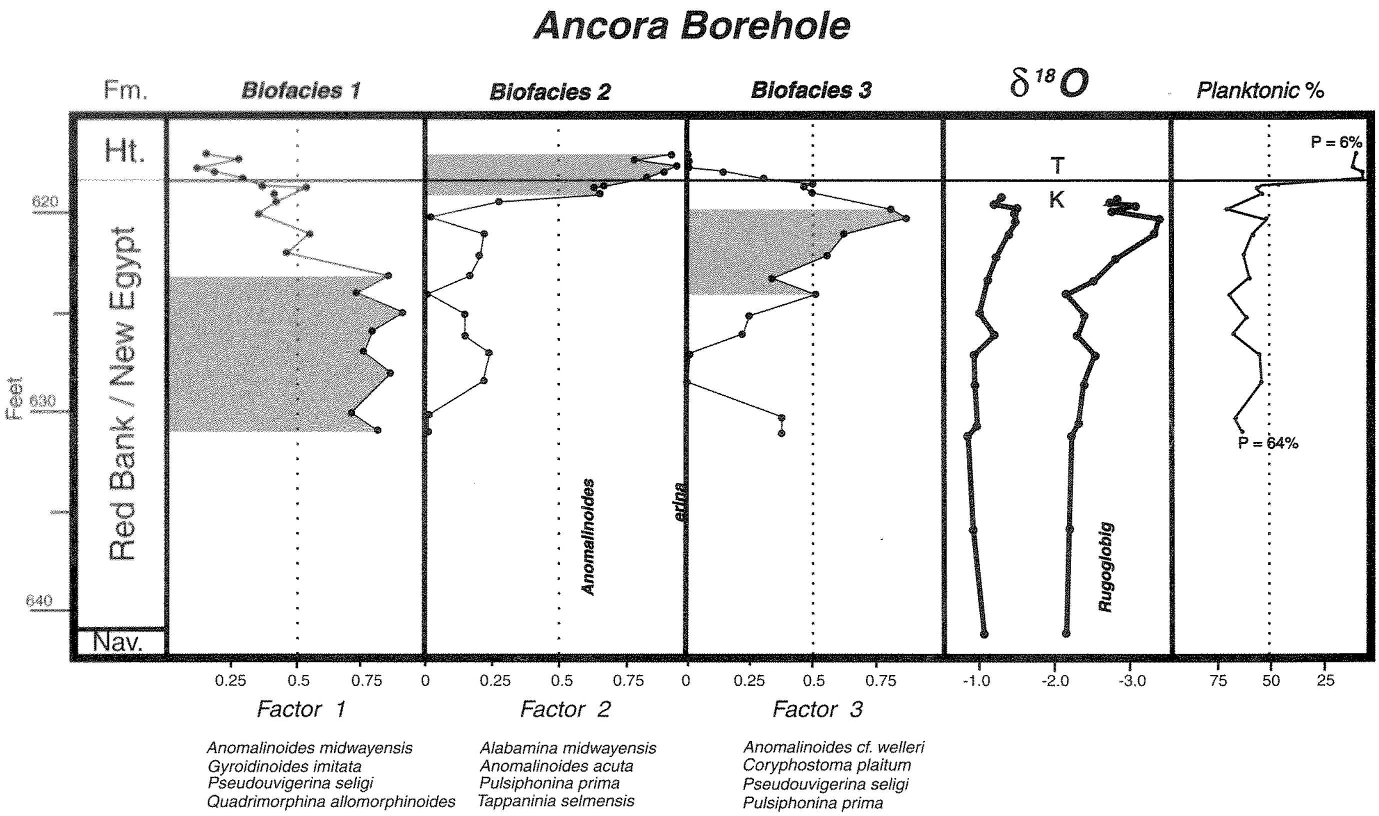

Figure 7. Factor analysis identifies same succession of three biofacies that are identified at Bass River (see Fig. 5 and text for explanation). Note that factor 3, as at Bass River, is associated with negative shift in $\delta^{18}O$ isotope values of Cretaceous planktonic foraminifer *Rugoglobigerina*, indicating warming trend. Decrease of as much as 1% in ^{18}O values on shells of Cretaceous planktonic foraminifer *Rugoglobigerina* indicates significant warming trend of as much as 5°C in near sea-surface temperatures that began ~500 k.y. and ended ~22 k.y. before Cretaceous-Tertiary boundary.

Foundation grants (EAR-94-17108 and EAR-97-08664 to Miller), by the New Jersey Geological Survey, and by the U.S. Geological Survey. We thank the science staff and many who assisted during drilling and recovery of cores at Bass River and Ancora. B. Huber, M. Leckie, and K. MacLeod provided helpful reviews.

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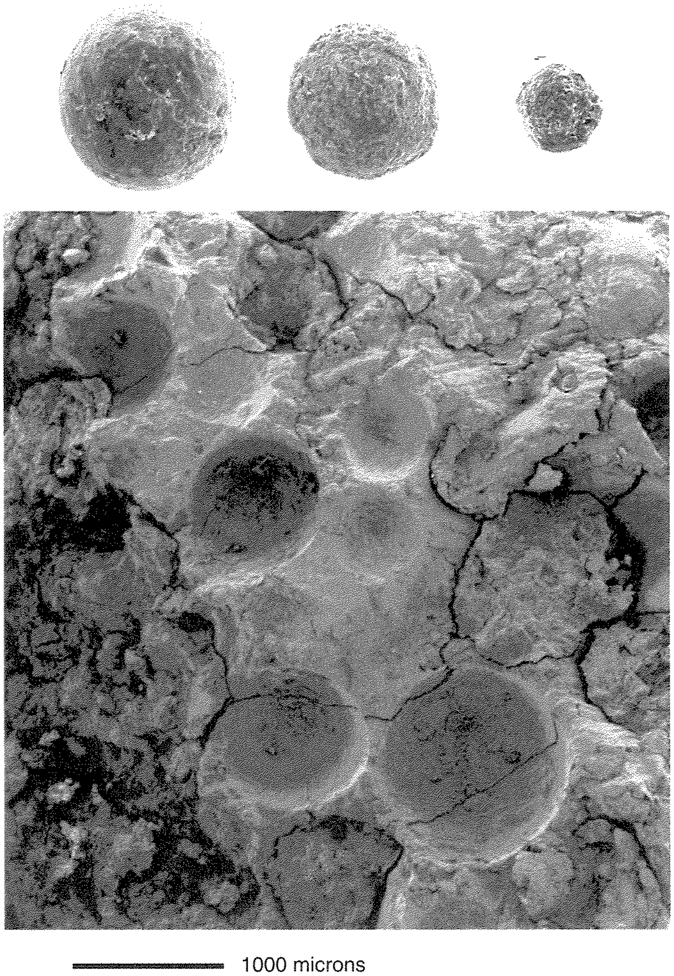

Figure 8. Impressions made by tektites when they settled on surface of Maastrichtian glauconitic clays at Cretaceous-Tertiary boundary time, Bass River borehole. Altered tektites (spherules) are shown at top.

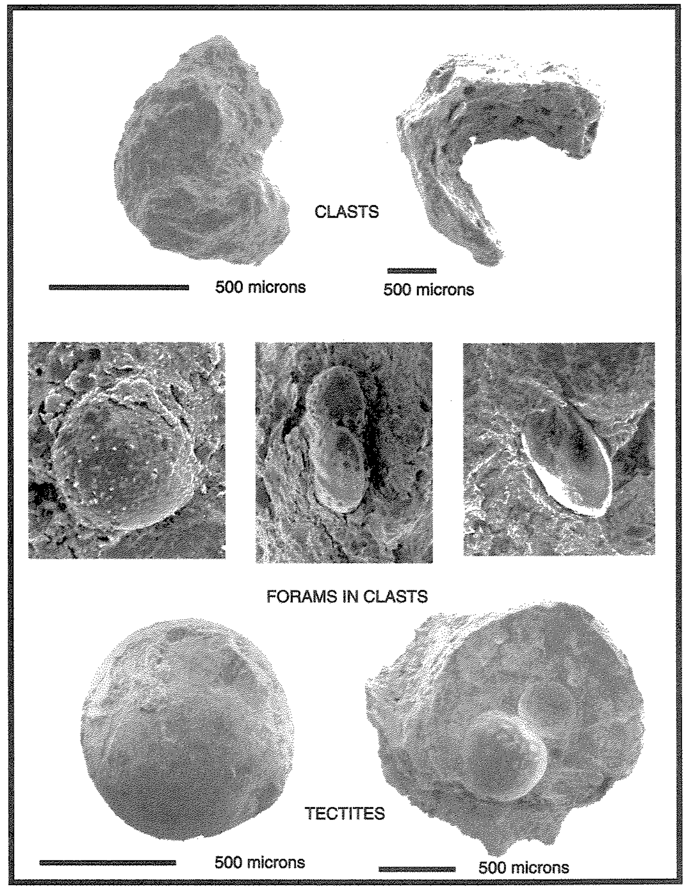

Figure 9. Above spherule layer, small clay clasts, containing calcite-replaced tektites and Cretaceous foraminifera and dinoflagellates, occur in lower 10 cm of Danian. Clasts are interpreted as ripups that were transported by tsunami activity shoreward from deeper part of Maastrichtian seafloor. Note internal globules, typical of Cretaceous-Tertiary boundary tektites, in tectite on right. From left to right ultimate chamber of *Heterohelix globulosa*, gavelinid, and *Alabamina midwayensis* are identified in clay clasts.

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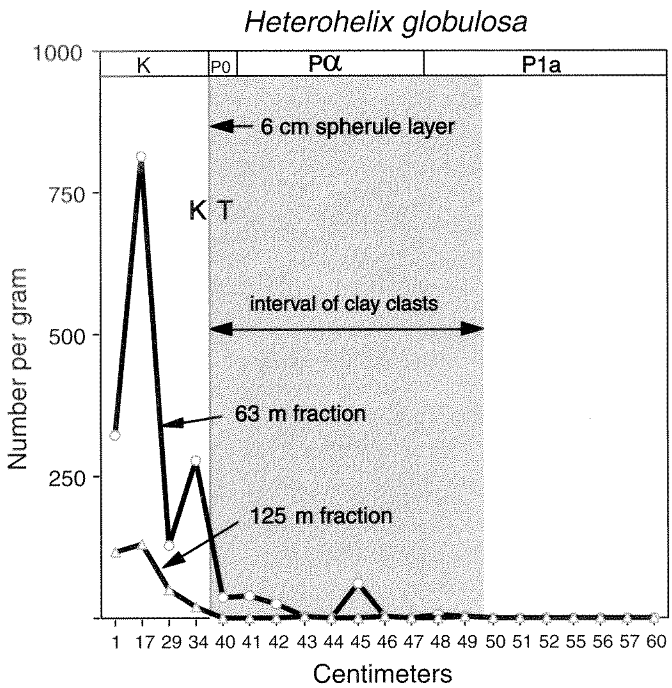

Figure 10. Cretaceous planktonic foraminifer, *Heterohelix globulosa*, is most abundant foraminifer in clay clasts. This species is absent above zone of clay clasts, indicating that its presence in Danian comes from clay clasts.

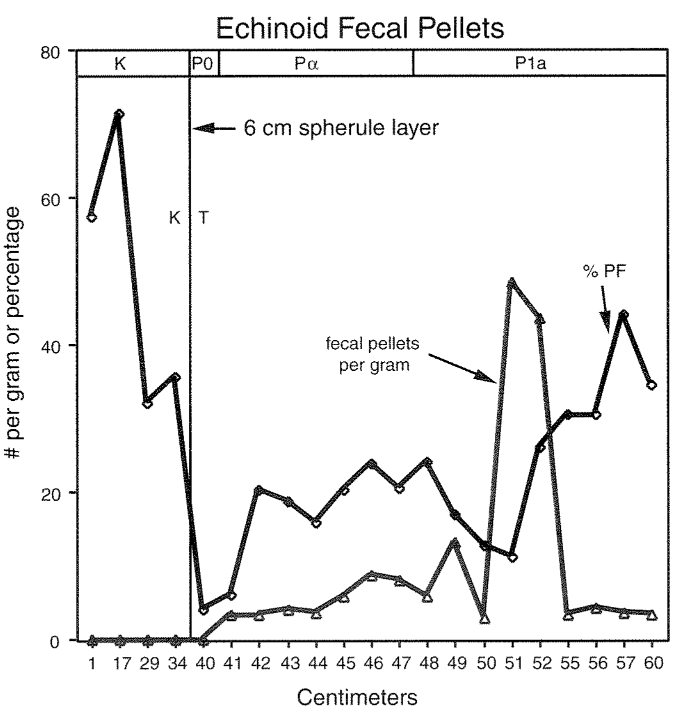

Figure 11. Concentration of echinoid fecal pellets in upper part (Danian) of Navesink sequence in Bass River borehole. Peak concentration of fecal pellets is interpreted as condensed interval, suggesting flooding surface of parasequence. See text for explanation.

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Manuscript Submitted October 5, 2000; Accepted by the Society March 22, 2001