

PALEOBIOGEOGRAPHY OF *PSEUDOTEXTULARIA ELEGANS* DURING THE LATEST MAASTRICHTIAN GLOBAL WARMING EVENT

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ABSTRACT

A latest Maastrichtian global warming event, which began approximately 450 k.y. and ended about 22 k.y. prior to the K/T boundary, is associated with the poleward migration of the warm-water planktonic foraminifer *Pseudotextularia elegans*. The warming event was apparently initiated by greenhouse warming due to the main outpouring of the Deccan Traps in India and is now well documented in the North and South Atlantic Oceans and in North America by the poleward migration of warm-water planktonic foraminifera and subtropical vegetation.

A cooling trend ca 22 kyr prior to the K/T boundary caused marine $\delta^{18}\text{O}$ values to return to climatic conditions recorded prior to the onset of warming and thus does not represent a significant change in long-term climate. Planktonic foraminifera responded by migration to the latest Maastrichtian global warming and cooling before their mass extinction at the K/T.

INTRODUCTION

Planktonic foraminiferal studies by Troelsen (1955) and Wicker (1953) first noted the possibility of a late Maastrichtian shifting of water masses in the "Cretaceous Baltic Sea". Wicker (1953) was the first to draw attention to a cooling trend, indicated by the progressive southward retreat of *Globotruncana* in the Late Cretaceous of southern Sweden, northwestern Germany, and Poland. Also, according to Wicker, warmer waters returned in the late Maastrichtian with the appearance of *Pseudotextularia elegans* (Rzehak) in northwestern Germany, Denmark, and Sweden. He believed that this species was brought into this region by a warm current from the south. Troelsen (1955) pointed to the occurrence of *Contusotruncana contusa* (Cushman) in the upper Maastrichtian Kjölby Gaard Marl of the White Chalk of Denmark and concluded that, due to its absence in the ordinary chalk facies of Denmark and Sweden, it must be a southern species brought northward by an incursion of warm water. These early studies, although generalized, established the value of planktonic foraminifera as biogeographic tracers of water masses in the Cretaceous. In this study we show the importance of *P. elegans* as a tracer of water mass movement in the North and South Atlantic during the latest Maastrichtian.

METHODS

Clean specimens of the planktonic foraminifer *Rugoglobigerina* and the benthic foraminifer *Anomalinoidea midwayensis* were picked from the $>125\ \mu\text{m}$ size fraction. Sta-

ble 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 were react-

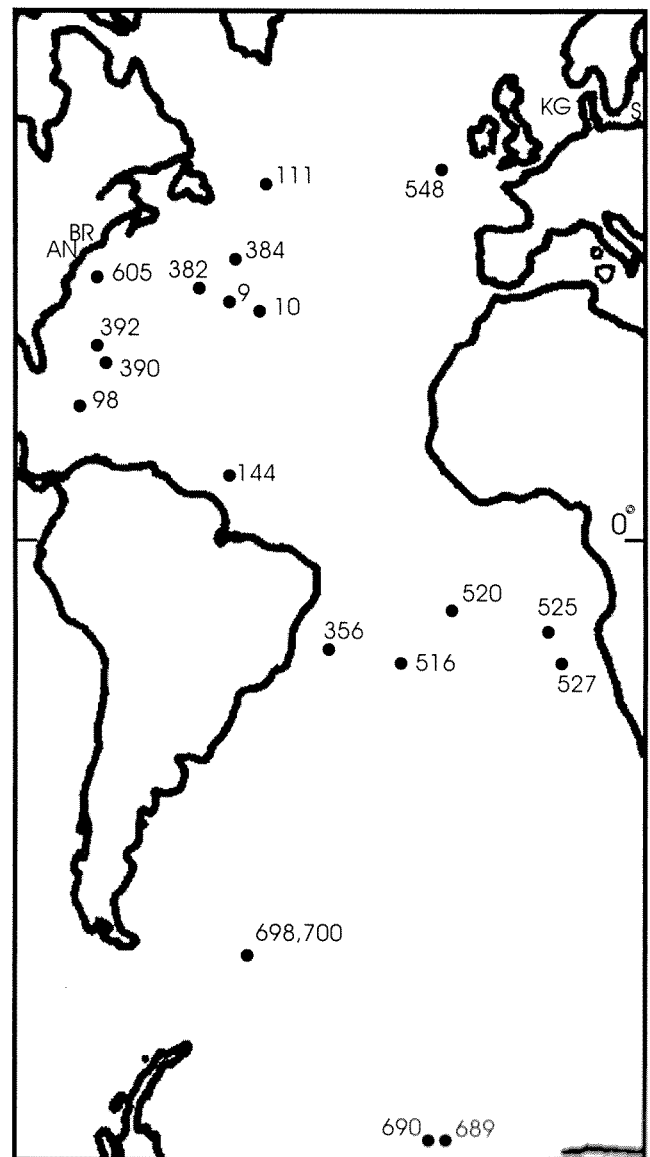


FIGURE 1. Location of the Ancora (AN), Bass River (BR) boreholes (Ocean Drilling Program Leg 174AX), outcrop sections in Denmark (KG = Kjölby Gaard Marl) and Sweden (S = Maastrichtian White Chalk), and deep sea drill sites used in this study.

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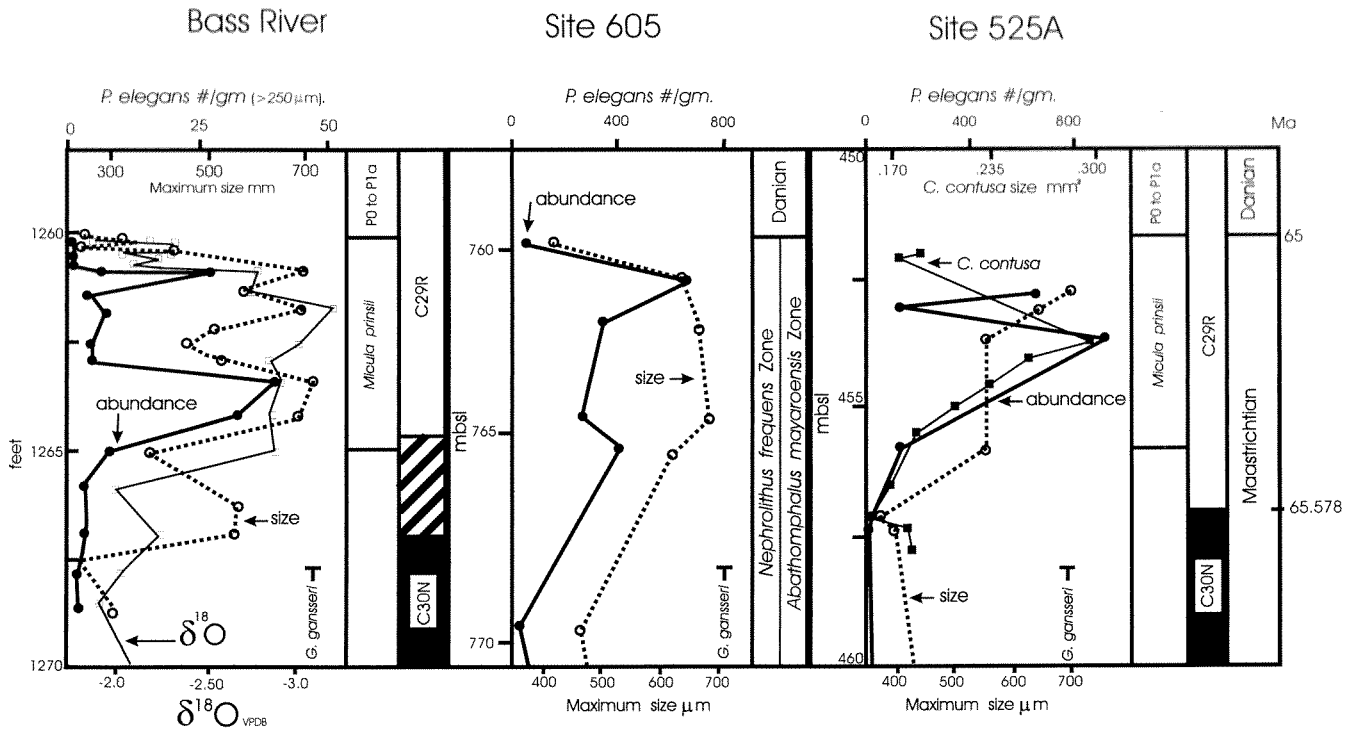


FIGURE 2. Comparison of abundance and size of *Pseudotextularia elegans* between Bass River Borehole and Deep Sea Drilling Sites 605 and 525. $\delta^{18}\text{O}$ values for the planktonic foraminifer *Rugoglobigerina* are shown for Bass River, and size of *Contusotruncana contusa* (data from Kucera and Malmgren, 1998) is shown for Hole 525A. *Abathomphalus mayaroensis* and *Nephrolithus frequens* Zones identified at Site 605 by Jansen and Kroon (1987) and Lang and Wise (1987), respectively are shown. Although Lang and Wise did not identify *Micula prinsii* at Site 606, they placed the base of the *N. frequens* Zone between 765.5 and 779.4 mbsl. This suggests that the *M. prinsii* Subzone, (= upper part of the *N. frequens* Zone) would encompass the abundance and size peaks of *P. elegans* at Site 605.

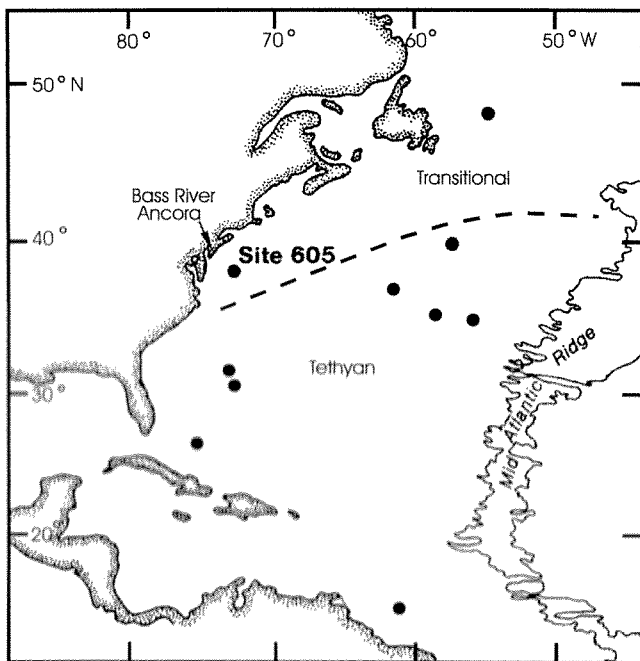


FIGURE 3. Boundary between late Maastrichtian Transitional and Tethyan water masses in the North Atlantic as interpreted by Nyong (1985) and Jansen and Kroon (1987).

ed in 100% phosphoric at 90°C. Oxygen isotopic values in Table 1 are reported relative to V-PDB by normalizing the NBS-19 or NBS-20 standards to the values reported in Coplen et al. (1983). The standard deviation (1 σ) of the standard (a minimum of 6 standards were measured with each run of 30 samples) is 0.06‰ for $\delta^{18}\text{O}$.

Pseudotextularia elegans is actually a minor component of late Maastrichtian warm Transitional and Tethyan planktonic foraminiferal assemblages but, nevertheless, it is a very important climatic indicator. Adult tests of *Pseudotextularia elegans* tests that are typical of warm Transitional and Tethyan waters are larger than +250 μm in maximum width and length so that a +250 μm size sieve (60 mesh) was used to separate each sample for ease of determining the abundance of this species. The total number of tests for each sample was counted in this size fraction. The smaller size fraction in each sample was also examined to determine if there was any significance number of small adult or neanic stage *P. elegans* in this fraction that might skew the results. The occurrence of identifiable *P. elegans* in the smaller size fraction was insignificant and in many cases the species was absent from this fraction. The total number of tests of *P. elegans* in samples varied between 0 and 450, with the greatest number recorded in the $\delta^{18}\text{O}$ defined warm interval. At DSDP Sites 525A and 605 the total abundance of this species is expressed as the number of tests per gram of sample. Due to terrigenous sediment dilution in the middle shelf setting of the Bass River Borehole the total number of tests of *P. elegans* is expressed as the number of tests

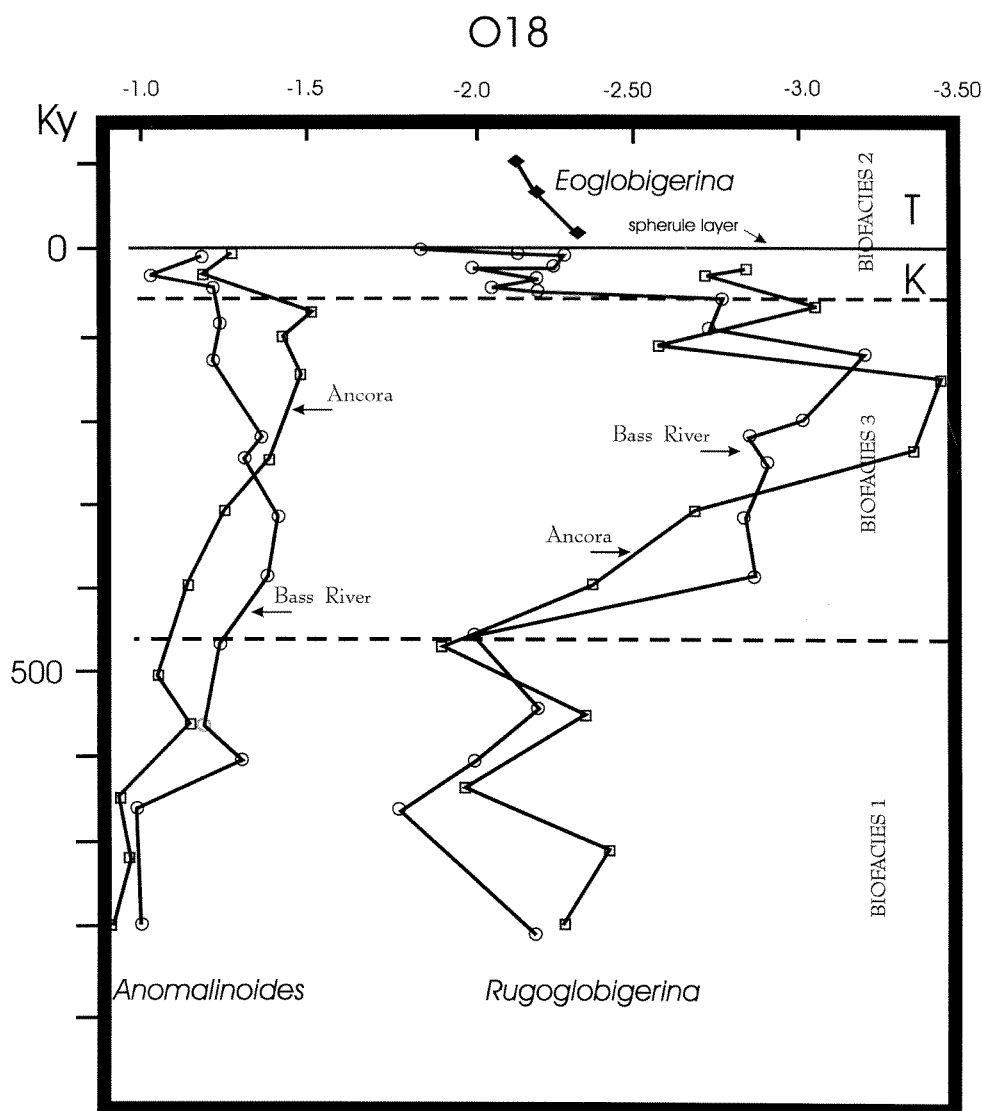


FIGURE 4. Oxygen isotope values for *Anomalinoidea* and *Rugoglobigerina* in the uppermost Maastrichtian in the Ancora and Bass River Boreholes. Note sharp negative shift of 1–1.5‰ in $\delta^{18}\text{O}$ values of *Rugoglobigerina*, indicating a significant warming of sea surface temperatures in the latest Maastrichtian. Biofacies 1, 2, 3 are benthic foraminifera biofacies identified in the Bass River Borehole (Olsson et al., 2001). Note that biofacies 3 correlates with the warming trend, suggesting that bottom waters were affected by the warming trend. See text for discussion of difference in $\delta^{18}\text{O}$ values of *Anomalinoidea* and *Rugoglobigerina*.

per gram of the 250 μm size fraction in order to show more clearly trends in the abundance of tests. The total number of tests counted among samples at Bass River varied between 1 and 123.

The maximum size of *P. elegans* was determined by measuring the length of the test, which is quickly and easily done by using an ocular micrometer during the counting procedure.

PALEOBIOGEOGRAPHY OF *PSEUDOTEXTULARIA ELEGANS*

Stratigraphic studies on the Maastrichtian white chalk of Sweden show that the first occurrence (FO) of *Pseudotextularia elegans* (low-mid latitude range: lower to upper Maastrichtian) is in the uppermost part of the chalk (Malmgren, 1982), suggesting a latest Maastrichtian poleward mi-

gration of this species. A similar latest Maastrichtian poleward migration in the Austral Realm of *Pseudotextularia elegans* about 500 k.yr. before the K/T extinction event was documented by Huber (1990, 1992) and Huber and Watkins (1992). They linked the poleward migration of *P. elegans* in both hemispheres to a brief period (estimated at 200 to 300 kyr) of surface water warming that was detected by Stott and Kennett (1990) in the $\delta^{18}\text{O}$ record at ODP Sites 689 and 690 on Maud Rise, Southern Ocean (Fig. 1). A paleobiogeographic study of the distribution of planktonic foraminifera within the calcareous nannofossil *Micula prinsii* Zone (uppermost Maastrichtian) at North and South Atlantic deep sea drill sites (Sites 356, 384, 516, 525, 527, 546) by Malmgren (1991) concluded that *P. elegans* characterized warm transitional waters (Fig. 1). A later study (Kucera and Malmgren, 1998) of the same South Atlantic

TABLE 1. Olsson, Wright, Miller

Bass River			Ancora			Sample depth (ft)	<i>Eoglobigerina</i> $\delta^{18}\text{O}$
Sample depth (ft)	<i>Anomalinoidea</i> $\delta^{18}\text{O}$	<i>Rugoglobigerina</i> $\delta^{18}\text{O}$	Sample depth (ft)	<i>Anomalinoidea</i> $\delta^{18}\text{O}$	<i>Rugoglobigerina</i> $\delta^{18}\text{O}$		
1260.41	-1.174		618.40	-1.28	-2.92	1259.58	-2.10
1260.51	-1.075		618.50	-1.21	-2.82	1259.65	-2.17
1260.55	-1.22	-1.83	619.00	-1.48	-3.11	1259.68	-2.29
1260.62	-1.16	-2.11	619.50	-1.45	-2.67		
1260.68	-1.18	-2.3	620.00	-1.47	-3.46		
1260.77	-1.181	-2.23	621.00	-1.38	-3.37		
1260.85		-1.99	622.00	-1.32	-2.80		
1260.90		-2.16	623.00	-1.15	-2.52		
1260.91		-2.06	624.00	-1.05	-2.10		
1261.00	-1.26	-2.16	625.00	-1.12	-2.48		
1261.50	-1.22	-2.76	626.00	-0.91	-2.14		
1261.82		-2.65	627.00	-0.94	-2.54		
1262.00	-1.212	-3.22	628.00	-0.89	-2.42		
1262.50		-3.02					
1263.00	-1.347	-2.88					
1263.50	-1.322	-2.9					
1264.00	-1.416	-2.87					
1265.10	-1.388	-2.89					
1266.00	-1.212	-1.98					
1267.00	-1.19	-2.22					
1268.00	-1.309	-1.99					
1269.00	-1.075	-1.79					
1271.00	-1.08	-2.18					

sites (DSDP Sites 356, 516, 525, 527) demonstrated a latest Maastrichtian (upper part of the *Micula prinsii* Zone) poleward migration in the mid-latitude South Atlantic of *Conusotruncana contusa* low-latitude morphotypes. This migration event was correlated with a terminal Maastrichtian warming event between 65.3 and 65.2 Ma, based on a linear interpolation within paleomagnetic Subchron C29R. The poleward migration of *C. contusa* low-latitude morphotypes ended with their rapid withdrawal from the mid-latitude South Atlantic Ocean before the Cretaceous-Tertiary boundary. At Hole 525A, a rapid increase in the abundance and maximum size of *P. elegans* coincides with the appearance of *C. contusa* low-latitude morphotypes (Fig. 2), suggesting that these *P. elegans* morphotypes also migrated from a low-latitude region.

During the late Maastrichtian (Fig. 3), the New Jersey margin was situated near the boundary between North Atlantic Transitional and Tethyan faunal provinces (Nyong, 1985; Olsson and Wise, 1987). Jansen and Kroon (1987) also noted that warm-water and cold-water taxa were present in the Maastrichtian (*Abathomphalus mayaroensis* Zone) at DSDP Site 605 (paleodepth 2500 m) on the New Jersey continental slope. They concluded that a clockwise circulation, similar to the modern North Atlantic pattern, brought warm-water taxa northward from the Tethyan bioprovince. This warming observed at the slope site is well expressed in two coastal plain boreholes.

In the Ancora and Bass River Boreholes in the coastal plain, the latest Maastrichtian warming trend is clearly defined in the $\delta^{18}\text{O}$ record by a sharp decrease of 1–1.5‰ in shells of *Rugoglobigerina* near the base of Subchron C29R (Figs. 2, 4). If this signal is attributed solely to temperature change, then surface waters warmed by 4 to 7°C. Other studies have estimated a 3–4°C global warming at this time (Barrerra and Savin, 1999). Regional precipitation may have

been altered during the latest Cretaceous warming and part of the $\delta^{18}\text{O}$ signal at Ancora and Bass River may reflect increased fresh-water influence (with low $\delta^{18}\text{O}_{\text{water}}$ values). Nonetheless, it is clear that substantial surface-water warming occurred on the New Jersey shelf after 65.5 Ma, prior to the K/T boundary.

Coeval benthic foraminiferal $\delta^{18}\text{O}$ values at both Ancora and Bass River (Fig. 4) decreased by only ~0.2–0.5‰, indicating only a 1–2°C warming of bottom waters in middle-outer shelf environments. These shelf bottom waters can be used to approximate the upper thermocline water, indicating less of a warming in the upper thermocline. Before the warm excursion, the planktonic-benthic $\delta^{18}\text{O}$ difference ($\Delta\delta^{18}\text{O}$) was on the order of 1‰. During peak warmth, $\Delta\delta^{18}\text{O}$ values reached a maximum of 2‰. These data show a more pronounced warming in surface waters relative to the upper thermocline, a larger surface to bottom temperature difference, and an increase in the strength of the thermocline. Thus, it is clear not only that the waters on the NJ shelf became warmer, they also became more stratified during the latest Cretaceous.

Low $\delta^{18}\text{O}$ values continued to near the top of the *M. prinsii* Subzone. We estimate that the warming lasted ~428 k.y. and ended ~22 k.y. prior to the K/T boundary. Interpolation between two broadly spaced datum levels (C29R/C30N and base of *M. prinsii*) does not provide age resolution better than ± 0.1 m.y. or so. Thus, the age estimates provided here are tentative. Nevertheless, the constraints placed by magnetostratigraphy and biostratigraphy are firm: the warming event began after 65.5 Ma and ended immediately before (~22 k.y.) the K/T boundary. Coinciding with this warming period is an increase in the abundance and maximum size of *P. elegans* in the coastal plain sites (Fig. 5). Due to the shallow paleodepth of these locations at this time (<100 m) planktonic taxa are not as abundant as they are at the open

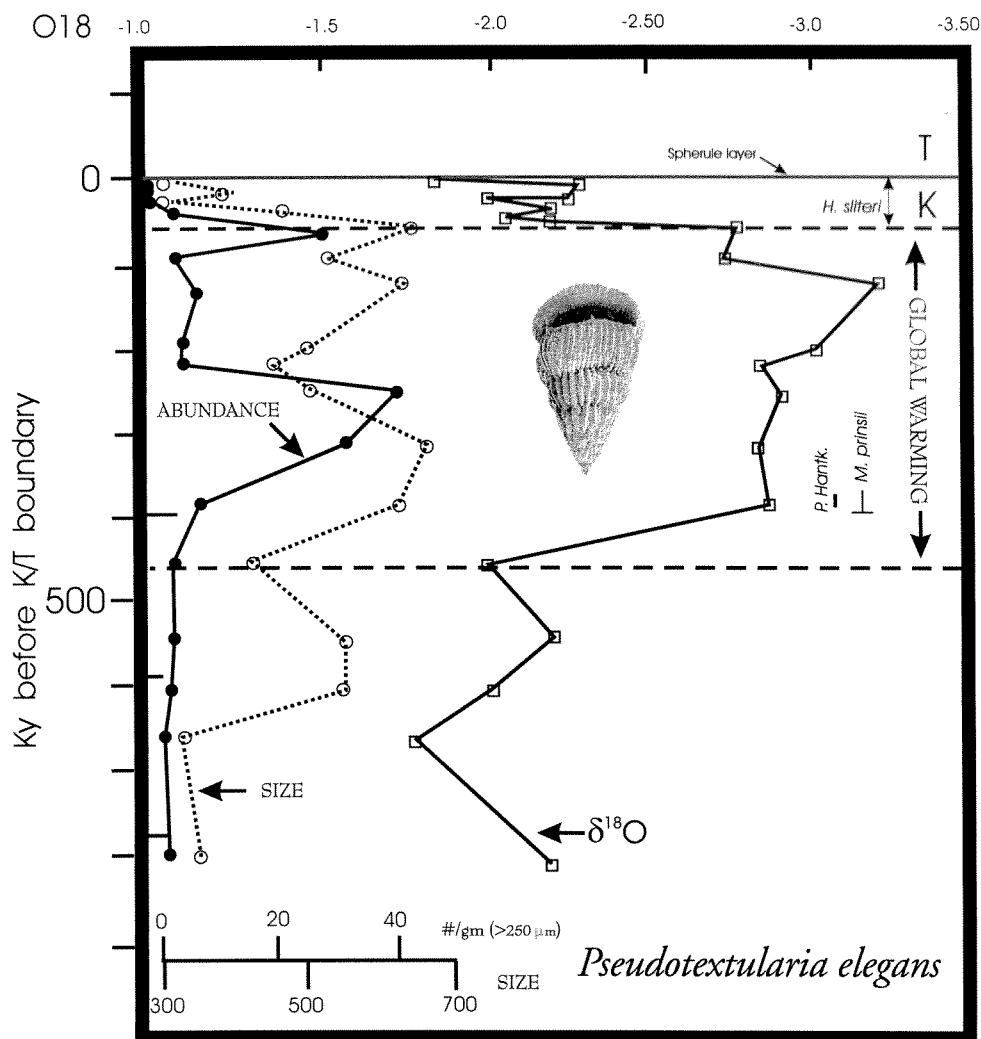


FIGURE 5. Comparison of the abundance and size of *Pseudotextularia elegans* with the $\delta^{18}\text{O}$ values measured on *Rugoglobigerina* in the Bass River Borehole. A $\sim 5^\circ\text{C}$ warming of sea surface temperatures is associated with an increase in abundance and size of *Pseudotextularia elegans* indicating that this species was adapted to the warm tethyan waters that had shifted into the New Jersey area. The occurrences of the planktonic foraminifers *Hedbergella sliteri* and *Plummerita hantkeninoides* are shown in the figure.

ocean deep sea drill sites. Nevertheless, the consistent occurrence of *P. elegans* with species such as *Globotruncana aegyptiaca* Nakkady and *Pseudoguembelina costulata* (Cushman) indicates the influence of warm Tethyan waters (Malmgren, 1991). In addition, *Planoglobulina acervulinoides* (Egger) and *Racemiguembelina fruticosa* (Egger), warm transitional species according to Malmgren (1991), first occur rarely in this interval. Very rare occurrences of *Plummerita hantkeninoides* Brönnimann, an uppermost Maastrichtian tropical Tethyan species, are observed at the beginning of the warming trend in the Bass River Borehole (Fig. 5). Thus, the $\delta^{18}\text{O}$, abundance, and size data all indicate a latest Maastrichtian warming in the North Atlantic.

At Site 605 (paleodepth 2500 m) on the New Jersey slope, a marked increase in abundance and size of *P. elegans* begins just above the highest occurrence (HO) of *Gansserina gansseri* (Bolli) (Fig. 2). At Bass River, the HO of *G. gansseri* occurs just below the warming trend. Site 605 is unsuitable for $\delta^{18}\text{O}$ analysis due to diagenesis. Although dissolution has affected some parts of the uppermost

Maastrichtian section at Site 605 (Nederbragt, 1989), the marked increase in abundance and size of *P. elegans* occurs in an interval relatively unaffected by dissolution, indicating that the increase is not due to selective destruction of dissolution-prone species. In addition, *Contusotruncana contusa* has abundance and maximum size peaks parallel to those of *P. elegans*, indicating a poleward shifting of warm transitional and/or Tethyan waters in the North Atlantic.

DISCUSSION

Barrera and Savin (1999) concluded in their study of $\delta^{18}\text{O}$ records that intermediate and deep waters in the South and North Atlantic, Indian, and Pacific Oceans warmed globally by $3\text{--}4^\circ\text{C}$ between 65.5 and 65.3 Ma and then cooled slightly about 65.2 Ma. They suggested that this increase in marine temperatures correlated with the main episode of Decan Trap eruptions which may have led to greenhouse global warming. Li and Keller (1998) identified a latest Maastrichtian (Chron C29R) warming trend in $\delta^{18}\text{O}$ values of benthic

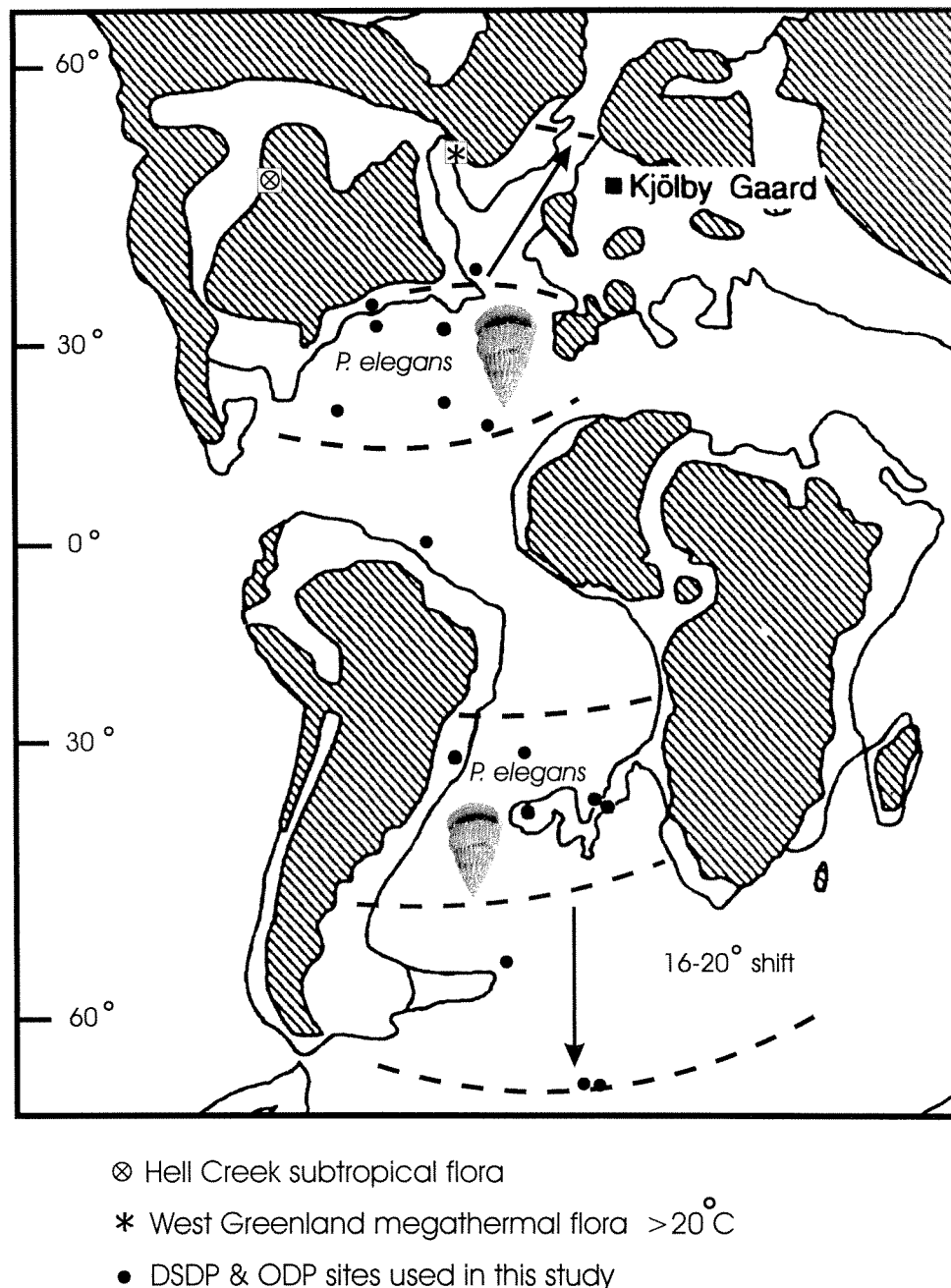


FIGURE 6. Paleogeographic map of the Maastrichtian North and South Atlantic showing the habitat of *Pseudotextularia elegans*. A 16–20° latitudinal poleward shift of this species is interpreted to have occurred during the latest Maastrichtian global warming trend. Dots are locations of deep sea drill sites used in this reconstruction. Also shown are the locations of the Hell Creek subtropical flora and the West Greenland megathermal flora.

foraminifera at ODP Site 525, but due to lack of a clear warming trend in $\delta^{18}\text{O}$ values of planktonic foraminifera in this interval, they ruled out a link to the Deccan Traps volcanism. Our analysis of North and South Atlantic deep sea drilling sites indicates that a poleward shift of populations of *Pseudotextularia elegans* of 16–20 degrees latitude occurred during this latest Maastrichtian warming trend (Fig. 6). Olsson et al. (2001) suggested that the warming trend observed at Bass River was due to an increase in greenhouse gases initiated by the main outpouring of the Deccan Traps in India, which started near the base of Subchron C29R

(Courtilot et al., 1986; Hansen, et al., 1996). At Bass River, Olsson et al. (2001) recorded a positive shift in $^{87}\text{Sr}/^{86}\text{Sr}$ ratios near the base of Subchron C29R that clearly correlates with the latest Maastrichtian warming trend. High-resolution (50 k.y.-scale) Maastrichtian variations in $^{87}\text{Sr}/^{86}\text{Sr}$ observed at Bass River showed a remarkably similar pattern to coeval sections at Bidart, France and El Kef, Tunisia (Vanhof and Smit, 1997). The variations include a sharp decrease in Chron C29r that can be ascribed to increased weathering of basaltic rocks associated with the Deccan Traps (Vanhof and Smit, 1997).

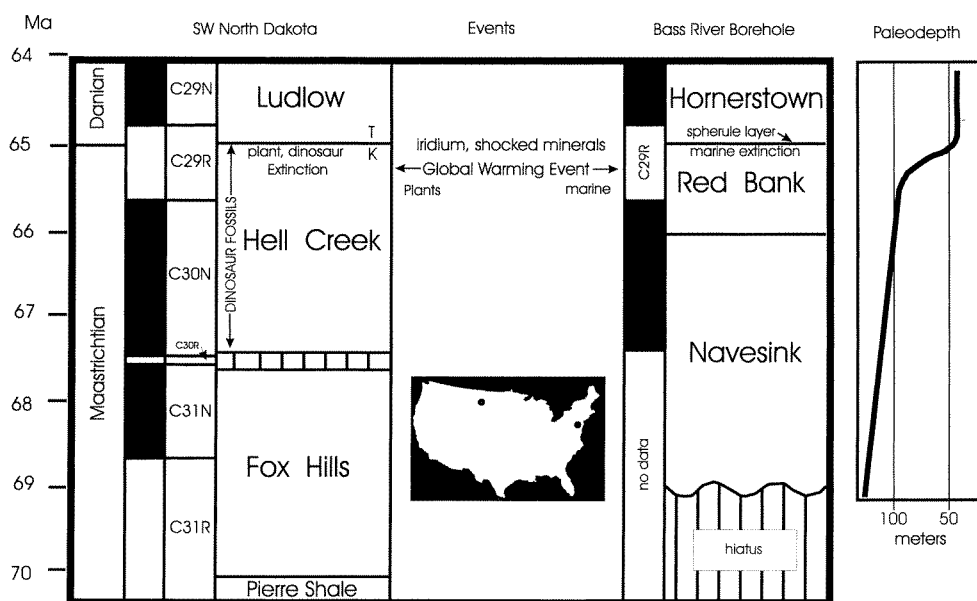


FIGURE 7. Correlation of marine and nonmarine K/T boundary sections at Bass River and southwest North Dakota.

Significant climate warming during the latest Maastrichtian is indicated by the megafloora in the upper part of the Hell Creek Formation, South Dakota (Johnson, 1999) (Fig. 6). A diverse, subtropical flora as characterized by leaf physiognomy appears near the beginning of Subchron C29R. Latest Maastrichtian warm climate may also be reflected in the flora of the Lower Atanekerdluk of West Greenland (Fig. 6). Although the Lower Atanekerdluk is not precisely dated, other than being older than late Danian, Wolfe and Upchurch (1987) suggest that the flora could represent a late Maastrichtian warm interval. They further suggest that the strong floristic similarity of the Lower Atanekerdluk with Late Cretaceous floras of southeastern North America indicates that its flora represents a megathermal climate. A significant warming of North Atlantic waters around Greenland, as is indicated by the late Maastrichtian shift in populations of *P. elegans* and the $\delta^{18}\text{O}$ record, is consistent with their contention.

Oxygen isotope values at Bass River returned to values recorded prior to the onset of warming at about 65.02 Ma (Figs. 4, 5). Barrera and Savin (1999) also noted a slight cooling in their latest Maastrichtian $\delta^{18}\text{O}$ records. Kucera and Malmgren (1998) recorded a rapid withdrawal of low-latitude *C. contusa* morphotypes from the mid-latitude South Atlantic Ocean following the end of the warming trend. This cooling following the Maastrichtian warm event thus appears to be global in extent.

The latest Maastrichtian warming trend appears not to have greatly affected planktonic foraminiferal assemblages, which simply migrated with the shifting of water masses. However, the first occurrence (FO) of *Plummerita hantkeninoides* appears to be associated with the onset of warming as does the FO of the calcareous nannofossil *Micula prinsii* (Fig. 5). Towards the end of the warming event at Bass River *Hedbergella sliteri* Huber, a high-latitude middle to upper Maastrichtian Austral species (Huber, 1992, 1994), appears and ranges to the top of the Maastrichtian (Fig. 5). This first known northern hemisphere presence of *H. sliteri*

shows that *H. sliteri* achieved a bipolar distribution in the latest Maastrichtian, which is important to understanding late Maastrichtian ocean climate and the dispersal of planktonic foraminifera.

CONCLUSIONS

The latest Maastrichtian global warming event began approximately 450 k.y. and ended about 22 k.y. prior to the K/T boundary. It apparently was initiated by greenhouse warming due to the main outpouring of the Deccan Traps in India. The warming event is now well documented in the North and South Atlantic Oceans and in North America by the poleward migration of warm-water planktonic foraminifera and subtropical vegetation. Correlation of this event within Subchron C29R in marine and nonmarine stratigraphic sections (Fig. 7) provides a framework for assessing the end Cretaceous extinctions of marine and nonmarine biota. Plant, dinosaur, and marine extinctions coincide with the K/T boundary ca 22 kyr after the climate shifted to cooler conditions. Cooling is associated with a longer term lowering of sea level prior to K/T boundary time (Fig. 7). However, the cooling trend caused marine $\delta^{18}\text{O}$ values to return to climatic conditions recorded prior to the onset of warming (Barrera and Savin, 1999; this paper), and thus does not represent a significant change in long-term climate. Planktonic foraminifera responded by migration to the latest Maastrichtian global warming and cooling before their mass extinction at the K/T.

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