

Benthic foraminifera and environmental turnover across the Cretaceous/Paleogene boundary at Blake Nose (ODP Hole 1049C, Northwestern Atlantic)

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Abstract

Sediments recovered at lower bathyal ODP Site 1049 on Blake Nose (Northwestern Atlantic) offer an opportunity to study environmental changes at the Cretaceous/Paleogene (K/P) boundary relatively close to the Chicxulub impact structure on the Yucatan peninsula, Mexico. In Hole 1049C, the boundary is located at the base of a 9-cm-thick layer with abundant spherules, considered to be impact ejecta. Uppermost Maastrichtian oozes below, and lowermost Danian pelagic oozes above the spherule-bed contain well-preserved bathyal benthic foraminifera. The spherule-bed itself, in contrast, contains a mixture of shallow (neritic) and deeper (bathyal) species, and specimens vary strongly in preservation. This assemblage was probably formed by reworking and down-slope transport triggered by the K/P impact. Across the spherule-bed (i.e., the K/P boundary) only ~7% of benthic foraminiferal species became extinct, similar to the low extinction rates of benthic foraminifera worldwide. Quantitative analysis of benthic foraminiferal assemblages and morphogroups in the >63- μ m size fraction indicates a relatively eutrophic, stable environment during the latest Maastrichtian, interrupted by a sudden decrease in the food supply to the benthos at the K/P boundary and a decrease in diversity of the faunas, followed by a stepped recovery during the earliest Danian. The recovery was probably linked to the gradual recovery of surface-dwelling primary producers.

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1. Introduction

1.1. Benthic foraminifera at the K/P boundary

During the last decades, the Cretaceous/Paleogene (K/P) boundary (commonly known as the Cretaceous/Tertiary (K/T) boundary) has been studied extensively, but there is still controversy regarding the origin of the characteristic K/P deposits and the cause(s) of

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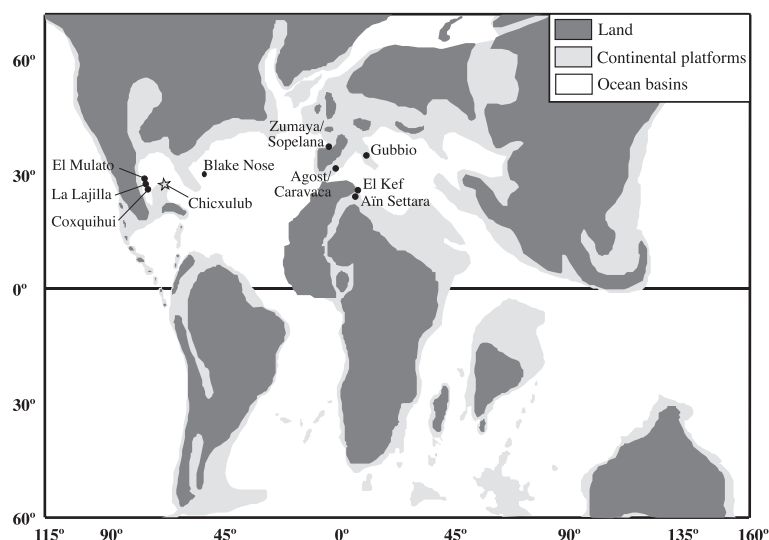


Fig. 1. Paleogeographic distribution of land masses, shallow seas and deep ocean basins at the time of the K/P boundary, showing the Chicxulub structure (Yucatan peninsula, Mexico) and some K/P boundary sections. Modified after Denham and Scotese (1987) and Alegret et al. (2003).

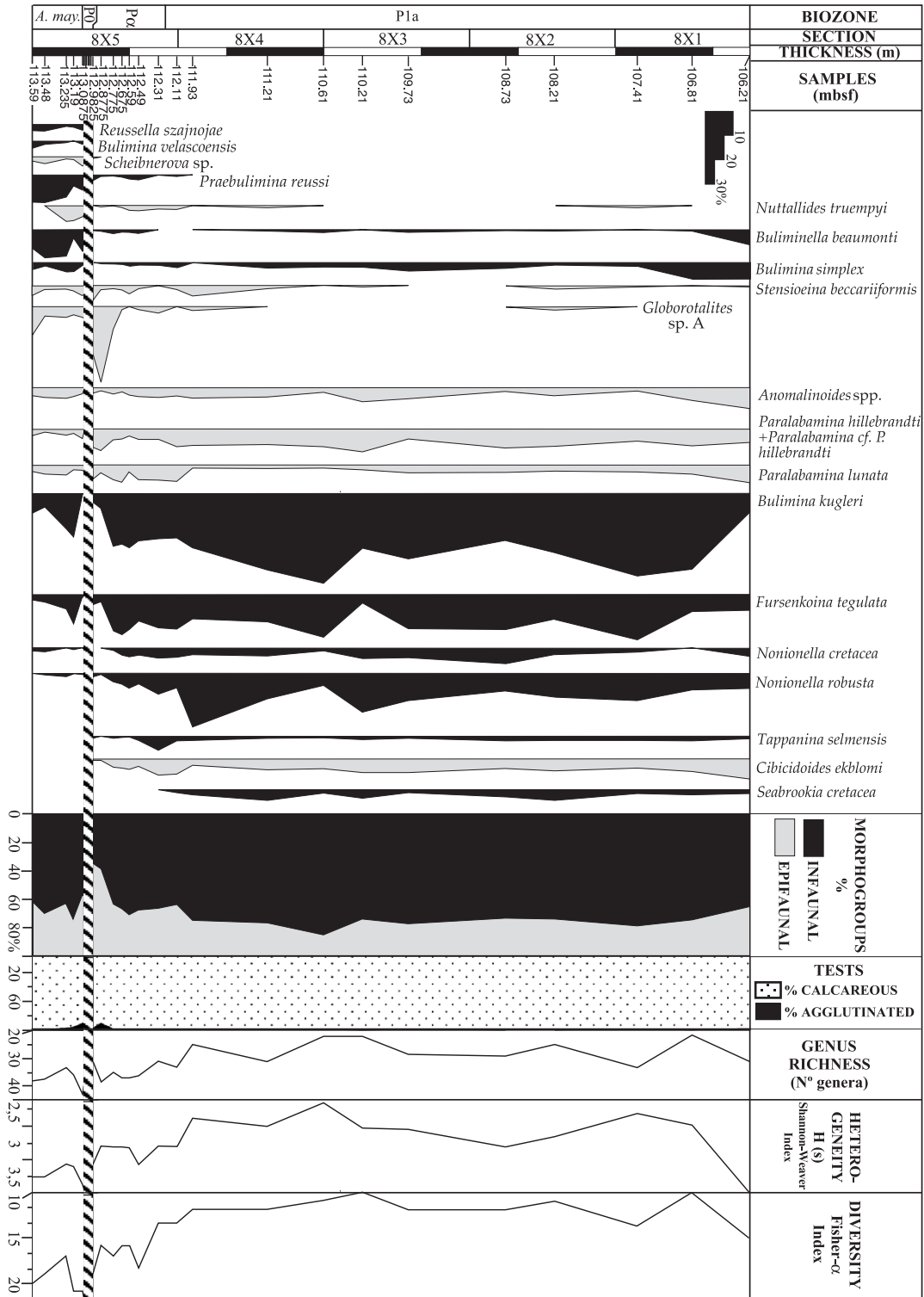
the global mass extinctions. Most researchers accept the hypothesis that the deposition of a spherule-rich clastic sediment unit at the K/P boundary in sections around the Gulf of Mexico and North Atlantic was caused by destabilization on the continental margin caused by an asteroid impact at Chicxulub, on the northern Yucatan peninsula, followed by mass wasting (e.g., Bohor, 1996; Smit et al., 1996; Bralower et al., 1998; Klaus et al., 2000; Soria et al., 2001; Alegret et al., 2002a,b; Norris and Firth, 2002). Some, however, argue that these deposits resulted from changing sea-level and regional tectonics (Keller and Stinnesbeck, 1996; Stinnesbeck et al., 1996; Keller et al., 1997). Most researchers accept that calcareous micro- and nannoplankton suffered a catastrophic, sudden mass extinction at the K/P boundary (e.g., Luterbacher and Premoli-Silva, 1964; Romein, 1977; Romein and Smit, 1981; Smit, 1990; Molina et al., 1998), although others maintain that the extinction was more gradual or stepped (e.g., Keller, 1989a,b). At many locations, specimens of

typically Cretaceous species of planktic foraminifera occur somewhat above the level of the most severe extinction marked by the signature of an asteroid impact such as high iridium-levels and spherules, but there is considerable evidence that these represent reworking (e.g., Huber et al., 2002; Soria et al., 2001).

Benthic foraminifera, in contrast, do not show significant extinction above background levels at the end of the Cretaceous (Culver, 2003), but show temporary changes in community structure, which have been interpreted as resulting from the collapse of the pelagic food web and the subsequent drop in food supply to the benthos (e.g., Thomas, 1990a,b; Kuhnt and Kaminski, 1993; Alegret et al., 2001a, 2002a,b, 2003; Culver, 2003).

During Ocean Drilling Program Leg 171B, the K/P boundary interval was cored at Blake Nose, Northwestern Atlantic (Fig. 1), ~1600 km from the Chicxulub impact site (Norris et al., 1998). A complete K/P interval was recovered in three holes (1049A, 1049B

Fig. 2. Relative abundances of the most common benthic foraminiferal species in Hole 1049C, as well as relative abundances of infaunal and epifaunal morphogroups, calcareous and agglutinated taxa, genus richness, the Shannon-Weaver index of heterogeneity, and the Fisher- α index (diversity). Biostratigraphy modified after Norris et al. (1999) and Huber et al. (2002).



and 1049C) on the eastern margin of Blake Nose, at a present water depth of 2671 m. ODP Site 1049 was a re-drill of Deep Sea Drilling Project (DSDP) Site 390 (Benson et al., 1978). A paleodepth of about 2500 m during the late Maastrichtian has been assigned to this site (Frank and Arthur, 1999; D'Hondt and Arthur, 2002). This paleodepth was constructed by backtracking, which in our opinion is not valid because the site is not located on oceanic basement (Dillon and Popenoe, 1988; Norris et al., 2001b).

Maastrichtian benthic foraminifera from Site 390 were described superficially in the site chapter (Benson et al., 1978), where the paleodepth was estimated to be between 600 and 1600 m on benthic foraminiferal evidence. A few samples from Site 390 were included in the study by Widmark and Speijer (1997a,b), who argued for a paleodepth of about 1200 m, in agreement with Benson et al. (1978). Widmark and Speijer (1997b) tentatively placed Site 390 in a region of enhanced northern summer upwelling (their Fig. 2), and thus presumably enhanced seasonal productivity, but at considerably lower intensity than upwelling at the North African margin.

Various aspects of the sediment record from Blake Nose Site 1049 have been studied in detail. The geochemistry was documented by Martínez-Ruiz et al. (2001, 2002), inorganic chemistry and mineralogy by Speed and Kroon (2000) and the planktic foraminiferal turnover across the K/P boundary by Norris et al. (1998, 1999) and Huber et al. (2002). No detailed benthic foraminiferal studies have been performed after the original shipboard description (Norris et al., 1998). We present the first detailed analysis of uppermost Maastrichtian and lowermost Danian benthic foraminiferal assemblages at Blake Nose, infer the paleobathymetry of the deposits, and illustrate the environmental changes across the K/P boundary.

1.2. The K/P boundary interval at Blake Nose

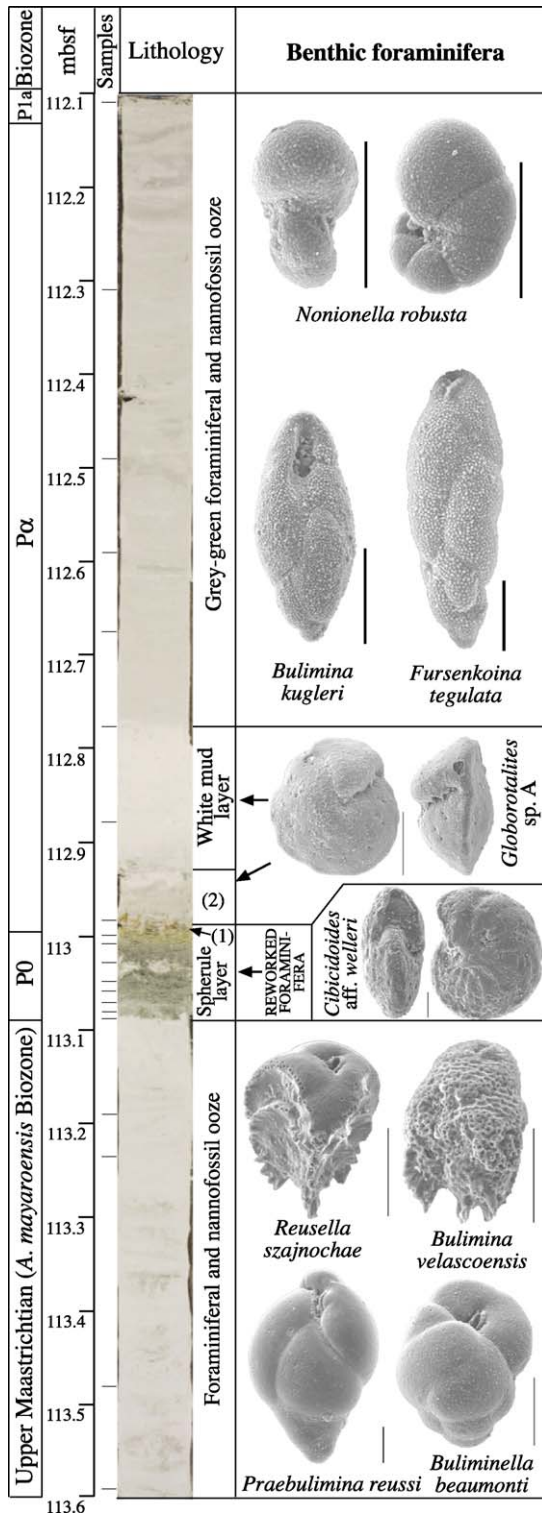
We studied upper Maastrichtian and lower Danian samples from Hole 1049C (30°08.5370'N, 76°06.7271'W), where the K/P boundary is located at the base of a spherule-bed intercalated between the uppermost Maastrichtian and the lowermost Danian pelagic foraminiferal and nannofossil oozes

(e.g., Huber et al., 2002). There is evidence for uppermost Maastrichtian soft-sediment deformation, but the series is reported to be biostratigraphically complete and without stratigraphic repetition (Norris et al., 1999; Huber et al., 2002). Deformation features in the Maastrichtian part of the section have been related to seismicity caused by the impact at the K/P boundary (Klaus et al., 2000; Norris and Firth, 2002).

We used samples from Core 1049C-8X. There are non-recovered intervals of several meters between Core 1049C-8X and the overlying and underlying cores. We limited our study to Core 1049C-8X, limiting our study to a fully recovered interval of sediment.

There is a sharp contact between the upper Maastrichtian ooze and the 'spherule-bed' at 1049C-8X-99 cm (113.09 mbsf). In Hole 1049C, this bed is a 9-cm-thick layer with green spherules (Fig. 3) that have been interpreted to be asteroid impact ejecta and consist mainly of smectite and carbonate (Norris et al., 1999; Klaus et al., 2000; Martínez-Ruiz et al., 2001, 2002). The spherule-bed contains reworked Cretaceous planktic foraminifera, shocked quartz, and clasts of dolomite, limestone and chert (Norris et al., 1998, 1999; Klaus et al., 2000). The spherule-bed is topped by a 3-mm-thick limonitic layer with goethite concretions, which is enriched in iridium (Smit et al., 1997). The limonitic layer is overlain by a 7-cm-thick layer of dark grey, burrow-mottled clays, enriched in Ir, with Cretaceous and Danian planktic foraminifera (e.g., Norris et al., 1998; Klaus et al., 2000). Above this burrow-mottled clay is a 15-cm-thick white mud layer containing Danian planktic foraminifera and calcareous nannofossils. The white layer is thicker in Hole 1049C than in Holes 1049A and 1049B, and is overlain by a grey–green ooze with abundant, well-preserved, Danian planktic foraminifera and calcareous nannofossils.

We use the biostratigraphic zonation in the works of Norris et al. (1999) and Huber et al. (2002), who identified the upper Cretaceous planktic foraminiferal *Abathomphalus mayaroensis* Biozone in the lower four studied samples (Fig. 3). They did not find specimens of *Plummerita hantkeninoides*, which marks the uppermost part of the Maastrichtian, but they identified the calcareous nannofossil *Micula prinsii* Biozone, typical for the latest Maastrichtian.



In the lower Danian, they recognized the Pα (*Parvularugoglobigerina eugubina*) and P1a Biozones (Figs. 2 and 3).

According to Norris et al. (1999), there may be an unconformity between the spherule-bed and the overlying, grey, mottled clays. In the K/P stratotype (El Kef, Tunisia), the boundary is defined at the base of a dark clay layer containing an Ir anomaly and microspherules (e.g., Cowie et al., 1989; Arenillas et al., 2002). Therefore, we consider that the K/P boundary at Blake Nose is located just below the spherule-bed (Smit et al., 1996), and we include this layer into the P0 Biozone (Fig. 3) following Arenillas et al. (2002), although Huber et al. (2002) left the spherule-bed unzoned.

We analyzed 30 samples from sections 1049C-8X-1 to 8X-5 (106.21–113.59 mbsf), comprising the upper 52 cm of the Maastrichtian and the lower 7 m of the Danian (Fig. 2). Samples are spaced at decimeter-intervals in the Maastrichtian, at centimeters in the lowermost Danian, and between 20 and 80 cm in upper section 8X-5 and sections 8X-4 to 8X-1.

2. Methods

Quantitative studies and species richness calculations were based on representative splits of approximately 300 specimens of benthic foraminifera larger than 63 µm, mounted on microslides for a permanent record and identification. Samples from the spherule layer contain rare benthic foraminifera, and less than 50 specimens were found in some of these samples (Appendix A). Benthic foraminifera are well preserved, except for those from the spherule-bed where different degrees of preservation occur. The classification at the generic level follows Loeblich and Tappan (1987); when possible, benthic foraminifera were identified at the specific level largely following

Fig. 3. Detail of Leg 1049C section 8X-5, and Scanning Electron Microscope photographs of some of the most characteristic benthic foraminiferal species in each unit. The scale bars correspond to 100 µm. (1): limonitic layer; (2): dark grey burrow-mottled clays. Biostratigraphy modified after Norris et al. (1999) and Huber et al. (2002). (For color see online version).

the taxonomy of Alegret and Thomas (2001). The Mexican faunas studied by these authors contain around 83% of the benthic foraminiferal species identified at Blake Nose. Benthic foraminiferal counts are presented in Appendix A.

The comparison of fossil and recent communities of benthic foraminifera, in addition to morphotype analysis (e.g., Corliss, 1985; Corliss and Chen, 1988; Jones and Charnock, 1985), allows us to infer probable microhabitat preferences and environmental parameters such as the nutrient supply to the sea-floor, its seasonality, and sea water oxygenation (e.g., Bernhard, 1986; Jorissen et al., 1995; Fontanier et al., 2002). One should be careful with the interpretation of these comparisons because the ecology of present foraminifera is complex and not fully understood (e.g., Murray, 2001), and we do not know to what extent the Cretaceous and early Paleogene faunas were anal-

ogous to Recent faunas (e.g., Thomas et al., 2000; Alegret and Thomas, 2001; Alegret et al., 2001a, 2003; Gooday, 2003).

We allocated all specimens to morphogroups following Corliss (1985), Jones and Charnock (1985) and Corliss and Chen (1988). In general, benthic foraminifera with plano-convex, biconvex and rounded trochospiral tests, tubular and coiled-flattened, are inferred to have an epifaunal mode of life, living at the sediment surface or in its uppermost layers, as seen in living faunas. Infaunal foraminifera, living in the deeper layers of the sediment, have cylindrical or flattened tapered, spherical, rounded planispiral, flattened ovoid, globular unilocular or elongate multi-locular tests. Caution again is necessary: for many taxa, the close relationship between test morphology and microhabitat has not been observed, but it is extrapolated from data on other taxa (e.g., Jorissen,

Table 1
Distribution of bathymetric indicator species

Depth-related species	Upper-depth limit	Common distribution
<i>Anomalinoidea acutus</i> (Plummer) ^a		Neritic-upper bathyal (5)
<i>Bolivinoidea delicatulus</i> Cushman ^a		Bathyal (1, p. 338); Most common upper-middle bathyal, less common lower bathyal (7)
<i>Bolivinoidea draco</i> (Marsson) ^a		Outer neritic and bathyal (1, p. 378); Most common upper-middle bathyal, less common lower bathyal (7)
<i>Bulimina kugleri</i> Cushman and Renz		Most common lower bathyal and abyssal depths (10)
<i>Bulimina velascoensis</i> (Cushman)		Most common lower bathyal and abyssal depths (3)
<i>Buliminella beaumonti</i> Cushman and Renz		Most common lower bathyal and abyssal depths (3)
<i>Cibicidoides hyphalus</i> (Fisher)	100 m (1c), 200–600 m (6)	Lower bathyal (1, 3); Common at middle bathyal depths (7)
<i>Gyroidinoides globosus</i> (Hagenow)	200–300 m (2)	Middle bathyal–abyssal (3); Bathyal–abyssal (1c, 2)
<i>Nuttallides truempyi</i> (Nuttall)	500–700 m (1, 2, 6)	Bathyal and abyssal (5); Middle-lower bathyal and abyssal (1, 2, 3, 4)
<i>Nuttallinella florealis</i> (White)		Bathyal and abyssal (5); Bathyal and abyssal (1c)
<i>Oridorsalis plummerae</i> (Cushman) ^a		Most common upper-middle bathyal, less common lower bathyal (7); bathyal (8)
<i>Osangularia velascoensis</i> (Cushman)		Bathyal to abyssal (5)
<i>Paralabamina hillebrandti</i> (Fisher)		Abyssal (3)
<i>Paralabamina lunata</i> (Brotzen)		Bathyal to abyssal (7)
<i>Praebulimina reussi</i> (Morrow)		Bathyal to abyssal (7); Middle bathyal (500–1500m; 8)
<i>Pyramidina rudita</i> (Cushman and Parker)		Common at middle bathyal depths (7)
<i>Spiroplectammina spectabilis</i> (Grzybowski)	500–700m (1)	Bathyal (9)
<i>Stensioeina beccariiiformis</i> (White)	500–700 m (1, 3, 5)	Bathyal–abyssal (5); Lower bathyal (3, 4); Bathyal (2) and Abyssal (2, 4); Bathyal to abyssal (7)

(1) Van Morkhoven et al. (1986), p. 8, Fig. 5; (1c) Van Morkhoven et al. (1986), fold out; modified after Van Morkhoven et al., 1986; (2) Speijer (1994), p. 84, Fig. 6; (3) Tjalsma and Lohmann (1983); (4) Widmark (2000), pp. 376–377; (5) Berggren and Aubert (1975); (6) R. Speijer, personal communication, 2001; (7) Widmark and Speijer, 1997a; (8) Nyong and Olsson (1984); (9) Kaiho, 1992; (10) Thomas, 2003. Paleodepth estimates following Van Morkhoven et al. (1986).

^a Species most common at the spherule-bed.

1999); this is necessarily so for extinct taxa. In addition, many foraminifera move actively, vertically through the sediment (e.g., Kaminski et al., 1988; Bormmalm et al., 1997; Gooday and Rathburn, 1999; Jorissen, 1999; Gross, 2000; Fontanier et al., 2002). In one of the few studies evaluating the linkage between test morphology and microhabitat statistically, the authors argued that such assignments for modern foraminifera may be accurate about 75% of the time (Buzas et al., 1993). We thus argue that only major changes in percentages of the morphogroups are likely to be significant (Gooday, 2003).

The genus richness (number of genera), the Fisher- α diversity index and the H(S) Shannon-Weaver information function, another index of diversity, were calculated in order to observe possible changes in diversity across the K–P interval (Murray, 1991; Hayek and Buzas, 1996). High values of H(S) indicate an even distribution of specimens over species; Murray (1991) calls H(S) the index of heterogeneity, with high heterogeneity values indicating high diversity.

We used the bathymetric subdivision in the works of Van Morkhoven et al. (1986) and Berggren and Miller (1989): neritic=0–200 m, upper bathyal=200–600 m, middle bathyal=600–1000 m, lower bathyal=1000–2000 m and abyssal >2000 m. We document our paleodepth assignments and their sources in Table 1.

3. Results

3.1. Paleobathymetry

Benthic foraminifera are commonly used as paleobathymetric indicators because their depth distribution in the oceans is controlled by a series of depth-related parameters (e.g., Nyong and Olsson, 1984; Van Morkhoven et al., 1986; Culver, 2003). The comparison between fossil and recent assemblages, the occurrence and abundance of depth-related species, and their upper-depth limits (e.g., Van Morkhoven et al., 1986; Alegret and Thomas, 2001; Alegret et al., 2001a, 2002a,b, 2003) thus allowed us to infer the paleobathymetry of the uppermost Cretaceous and lowermost Paleogene sediments at Blake Nose (Table 1).

Benthic foraminiferal assemblages at Hole 1049C contain abundant buliminids such as *Bulimina kugleri*, *Bulimina velascoensis* and *Buliminella beaumonti*, which proliferate at deep-bathyal and abyssal depths (e.g., Tjalsma and Lohmann, 1983; Thomas, 2003). Species described from the deep-bathyal Velasco Formation in Mexico (see Alegret and Thomas, 2001), such as *Cibicidoides hyphalus*, *Nuttallides truempyi*, *Nuttallinella florealis*, *Osangularia velascoensis* and *Stensioeina beccariiiformis* are present but not abundant. Other species typical for deep bathyal environments present in the samples are *Oridorsalis umbonatus* and *Praebulimina reussi* (mainly in the Cretaceous), as well as common paralabaminids (*Paralabamina hillebrandti*, *Paralabamina* cf. *P. hillebrandti* and *Paralabamina lunata*). These data apparently indicate that uppermost Maastrichtian and lower Danian sediments at Blake Nose were deposited in the upper part of a lower bathyal environment, at about 1000–1200-m depth, in good agreement with the depth assignment for Site 390 by Widmark and Speijer (1997a,b). Paleodepths, however, most probably were somewhat deeper than estimated from the benthic foraminiferal evidence, probably in the middle part of the lower bathyal zone (1500–1600 m). The depth difference between Site 1049 and Site 1052, which are both situated on a depth-transect along Blake Nose, is about 1300 m (e.g., Norris et al., 2001a), and water depths at Site 1052 were at least a few hundreds of meters in the late Maastrichtian (MacLeod and Huber, 2001). We suggest that the Blake Nose faunas lived at slightly greater depths than at other locations because of the relatively high productivity (see below), which depresses benthic faunal zones (e.g., Gooday, 2003). The faunal composition does not indicate significant changes in depth at any level in the studied section.

In contrast to faunas in the oozes, benthic foraminiferal assemblages in the spherule-bed contain members of both the shallow water Midway-type fauna (e.g., *Cibicidoides* aff. *welleri*, *Lenticulina rotulata*, *Oridorsalis plummerae*) and the deeper Velasco-type fauna (*Aragonia velascoensis*, *Clavulinoides trilatera*, *Gaudryina pyramidata*, *Gyroidinoides globosus*, *Nuttallides truempyi*, *Nuttallinella florealis*, *Osangularia velascoensis* and *Stensioeina beccariiiformis*). Many of the species in the spherule-bed (e.g., the agglutinated *Arenobulimina truncata*,

Clavulinoides amorphus, *Gaudryina laevigata* and *Spiroplectammina dentata*, and the calcareous *Bolivoides draco*, *Buliminella grata*, *Cibicidoides* aff. *welleri*, *L. rotulata*, *Nonion havanense*, *O. plummerae* and *Stensioeina excolata*) occur in that layer only, and not in the underlying Maastrichtian nor in the overlying Danian sediments. Preservation of the tests is not uniform, and some have been affected by dissolution or abrasion.

The co-occurrence of shallow- and deep-water species, the presence of species different from those of the under and overlying sediments, together with the different preservation states of foraminifera, indicates that the foraminiferal assemblages in the spherule-bed were reworked and transported from shallow areas to deeper environments, where they were deposited together with the autochthonous fauna, in agreement with Norris et al. (1999), who identified

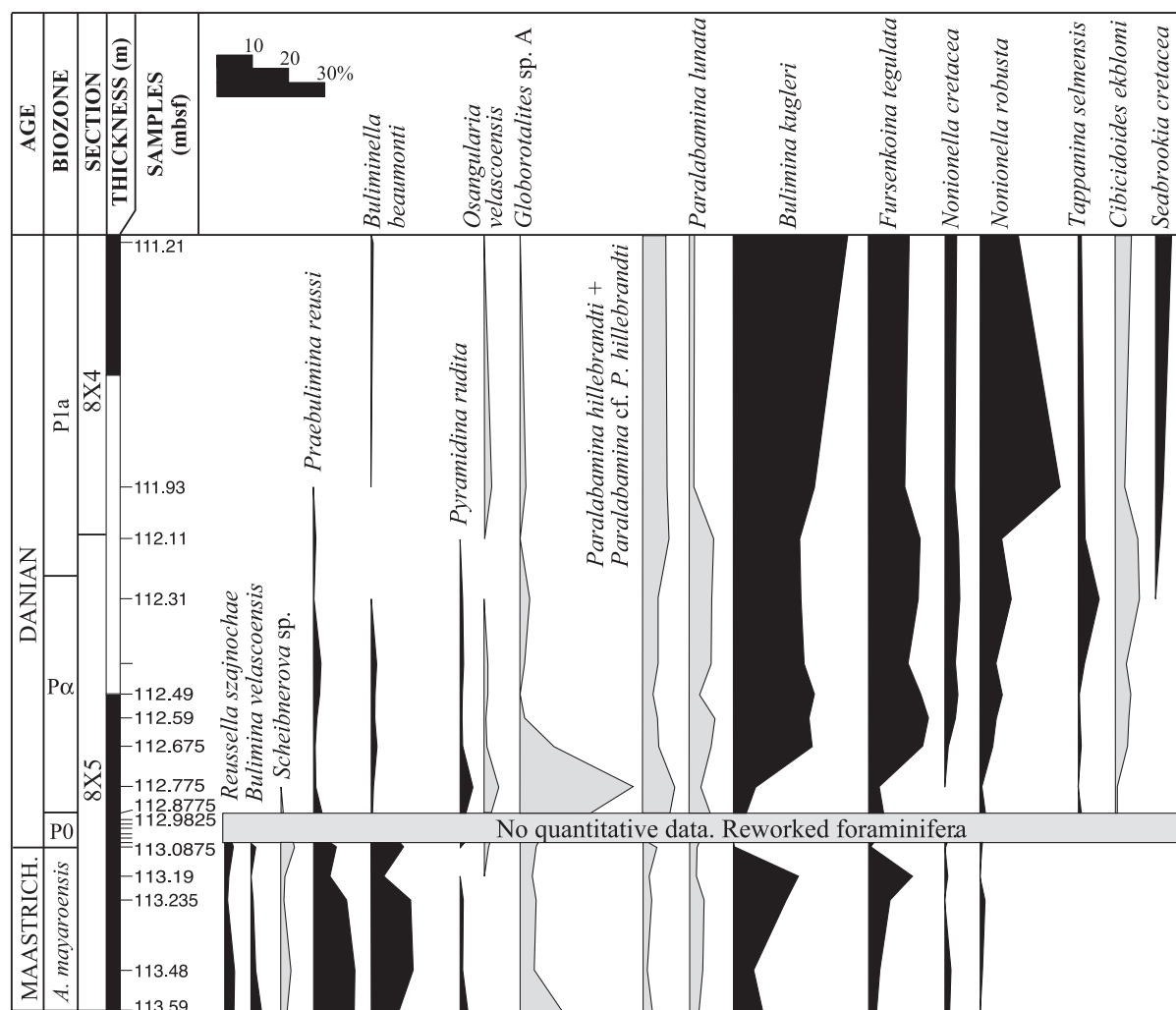


Fig. 4. Detail of relative abundances of selected benthic foraminiferal species in samples close to the K/P boundary. Species whose abundance is presented in black are thought to be infaunal, whereas those in grey belong to epifaunal morphogroups. Biostratigraphy modified after Norris et al. (1999) and Huber et al. (2002).

reworked Maastrichtian planktic foraminifera in the spherule-bed.

3.2. Benthic foraminiferal assemblages and paleo-environmental turnover

The benthic foraminiferal assemblages in Hole 1049C are dominated by calcareous forms (~94% of the assemblages; Fig. 2) throughout the studied interval. Uppermost Maastrichtian (*Abathomphalus mayaroensis* Biozone) assemblages are highly diverse, and contain both infaunal (e.g., *Bulimina kugleri*, *Buliminella beaumonti*, *Praebulimina reussi*) and epifaunal morphogroups (e.g., *Globorotalites* sp. A, *Nuttallides truempyi*, *Gyroidinoides depressus*, *Anomalinoides* spp.). Infaunal morphotypes make up 58–74% of the assemblages (Fig. 2).

Only two species of benthic foraminifera (*Reussella szajnochae* and *Bulimina velascoensis*, Figs. 2 and 3) last appeared at the K/P boundary at Blake Nose. Few specimens of *Scheibnerova* sp. occur a few centimeters above the spherule-bed (Fig. 4), and we consider these to be reworked. This species thus probably also had its uppermost occurrence (at least locally) at the K/P boundary.

The green spherule-bed contains rare benthic foraminifera, and no significant quantitative data were obtained for this layer. The first appearances of *Tappanina selmensis* and *Cibicidoides ekbloimi* occurred just above the top of the spherule-bed (Fig. 4). Genus richness, and the Fisher- α and Shannon-Weaver indices of diversity of the assemblages as well as the percentage of the infaunal morphotypes decreased just above the K/P boundary (Fig. 2). Benthic foraminiferal assemblages from the grey, mottled clays directly above the spherule-bed are dominated by epifaunal morphogroups, especially by paralamminids and *Globorotalites* sp. A (Figs. 2, 3 and 4). The latter species is still more abundant in the overlying white mud layer, where it reaches up to 31% of the assemblages.

Benthic foraminiferal assemblages from the higher parts of section 8X-5 (P α Biozone) are again dominated by infaunal species, in this case *Bulimina kugleri* and *Fursenkoina tegulata*. *Nonionella robusta* is abundant in sections 8X-4, 8X-3 and 8X-2 (P1a Biozone). Other common species are *Anomalinoides* spp., *Bulimina simplex*, *Cibicidoides ekbloimi*, *Nonionella cre-*

tacea, *Paralabamina hillebrandti*, *Paralabamina* cf. *P. hillebrandti* and *Paralabamina lunata* (Fig. 2). The dominance of infaunal morphogroups (up to 84%) and the high percentage of buliminids indicate a high food supply to the sea-bottom floor during this interval. In these sections (8X-4, 8X-3 and 8X-2) genus diversity and the values of the Fisher- α and heterogeneity indices are the lowest of the studied interval. Diversity and heterogeneity increased in section 8X-1, where the relative abundance of the formerly dominant species (*B. kugleri*, *F. tegulata* and *N. robusta*) decreases (Fig. 2). This, however, is the top of the studied interval and the trend is thus not well defined.

4. Discussion

Benthic foraminiferal assemblages in the Maastrichtian and most of the Danian are dominated by infaunal species (Fig. 2), especially buliminid taxa. In the Cretaceous, these taxa include *Bulimina simplex*, *Bulimina velascoensis* and *Buliminella beaumonti*. In the Danian, the most common buliminid taxa are *Bulimina kugleri* and *Fursenkoina tegulata*. In addition, *Nonionella robusta* is common in the lower part of Biozone P1a. This genus in the modern oceans is abundant in low oxygen, high productivity settings (e.g., Gooday and Rathburn, 1999). A high relative abundance of buliminid taxa indicates a high productivity and a year-round or seasonally fluctuating high delivery of food to the sea floor, such as is commonly occurring along continental margins where upwelling takes place (e.g., Lutze and Coulbourn, 1984; Jorissen et al., 1995; Gooday and Rathburn, 1999; Loubere and Fariduddin, 1999; Morigi et al., 2001). Most of these taxa tolerate reduced oxygen concentrations (e.g., Bernhard and Reimers, 1991; Sen Gupta and Machain-Castillo, 1993; Bernhard et al., 1997; Gooday, 2003), but their high relative abundance is thought to be mainly caused by an abundant food supply, not by low oxygenation (e.g., Fontanier et al., 2002; Gooday, 2003).

A high productivity at Site 1049C, as inferred by the oceanic circulation leading to upwelling in that region (Widmark and Speijer, 1997b), may explain why species typical for bathyal environments in more open ocean settings with a lower food supply, such as *Stensioeina beccariiformis*, *Cibicidoides*

hyphalus, *Nuttallides truempyi* and *Gyroidinoides globosus* (Widmark and Malmgren, 1992a,b; Speijer and Van der Zwaan, 1996), are not common at Blake Nose. A much smaller supply of terrigenous sediment at Blake Nose as compared to the coeval Mexican sections (Alegret et al., 2001a,b, 2002a,b) may explain why agglutinated taxa such as *Clavulinoides* spp., which are abundant in the Mexican K/P sections, are rare to absent at Blake Nose, with the exception of the reworked specimens in the spherule-bed. The interval with abundant *Globorotalites* sp. A. at Blake Nose might be the equivalent of the section with common *Cibicidoides pseudoacutus* in the Tunisian sections (Speijer and Van der Zwaan, 1996; Alegret et al., 1999; Peryt et al., 2002). This is speculative, precise correlation is not possible.

The increase in relative abundance of epifaunal taxa (especially *Globorotalites* sp. A) in the sediment just above the spherule-bed (Figs. 2 and 4) most probably reflects a decrease in the nutrient supply to the sea floor, but the drop was not as drastic as in the Mexican K/P sections (Alegret et al., 2001a, 2002a,b) or in the Tunisian section Aïn Settara (Alegret et al., 1999; Peryt et al., 2002) (Fig. 5). The interval of decreased organic flux (i.e., high relative abundance of *Globorotalites* sp. A) was considerably shorter than the duration of Biozone P α (Fig. 4).

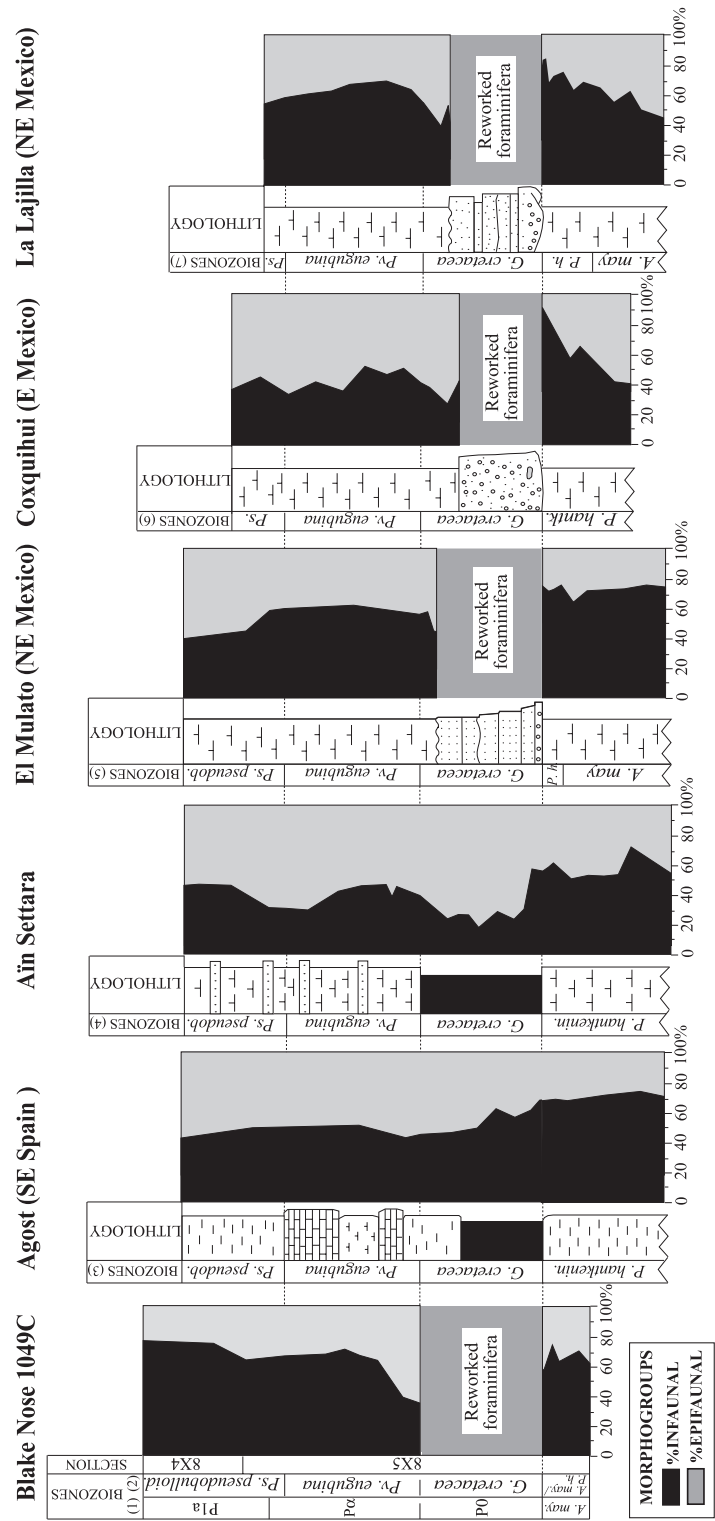
At Blake Nose, the faunas do not reflect severely oligotrophic conditions, but a moderate decrease in food delivery to the sea floor. In our opinion, a decrease in organic flux from the surface waters as the result of the mass extinction of primary producers (e.g., D'Hondt et al., 1998) was the main parameter that determined the benthic foraminiferal turnover directly after the K/P boundary. The relative abundance of infaunal taxa returned to Cretaceous values early in Biozone P α , in contrast to a slower return in the Spanish, Tunisian and Mexican sections (Fig. 5). Possibly, the early return to high productivity by

primary producers at Blake Nose was the result of the presence of upwelling, thus an abundant nutrient supply to primary producers.

The environment at Blake Nose, however, did not return to Cretaceous conditions with the return of a high food supply, because faunas in the higher parts of section 8X-5 (P α Biozone), and in sections 8X-4, 8X-3 and 8X-2 reached the lowest values of genus richness and of both Fisher- α and heterogeneity indices of the studied interval (Fig. 2). The assemblages are dominated by relatively few species, suggesting environmental stress (e.g., Kouwenhoven et al., 1997; Gooday, 2003). Possibly, such stress came from a high food supply by primary producers which could not easily be used by the benthos, such as various bloom species of dinoflagellates, as also was argued for the Agost section (Alegret et al., 2003). It is presently argued that transport of phytal material to the sea floor does not depend dominantly on fecal pellets, as argued by D'Hondt et al. (1998). Dominant transport is now thought to occur by the rapid deposition of aggregates (De la Rocha, 2004). If this is correct, there is no reason to suppose that delivery of food from the photic zone to the sea floor was interrupted after the K/P boundary for hundred of thousands of years: as soon as phytoplankton biomass became available (even biomass consisting of a low-diversity, opportunistic flora) aggregates such as these formed by sticky cyanobacteria and diatoms could re-form.

We do not believe that the environmental stress in this interval in Biozone P1a was caused by low oxygen conditions. In the Spanish sections such as Agost (Alegret et al., 2003) and Caravaca (Keller, 1992; Coccioni et al., 1993; Coccioni and Galeotti, 1994, 1998), the benthic faunas as well as geochemical indicators strongly suggest that there was a short interval of hypoxia–anoxia. It has likewise been suggested that hypoxia occurred just after the K/P

Fig. 5. Comparison of relative abundance of epifaunal and infaunal taxa at Blake Nose, Agost (Spain; Alegret et al., 2003), Aïn Settara (Tunisia; Alegret et al., 1999; Peryt et al., 2002) and El Mulato, La Lajilla and Coxquihui (Mexico; Alegret et al., 2002a,b) sections; see Fig. 1 for location of sections. Biostratigraphy modified after (1) Norris et al. (1999) and Huber et al. (2002); (2) comparison to the biozonation proposed by Molina et al. (1996a). Biostratigraphy modified after (3) Molina et al. (1996b); (4) Arenillas et al. (2000); (5) Alegret et al. (2002a); (6) Arz et al. (2001); (7) Alegret et al. (2001b). The vertical scale has been adjusted so that the thickness of the planktonic foraminiferal zones is the same in all sections.



boundary in the Tunisian section of El Kef (Keller, 1992; Speijer and Van der Zwaan, 1996), but the evidence in this section and the close-by section Aïn Settara is equivocal (Peryt et al., 2002). At Blake Nose, the faunas do not indicate that there were low-oxygen conditions in the bottom waters directly after the K/P boundary, because the lowermost, autochthonous samples have low relative abundances of infaunal taxa. Neither geochemical nor mineralogical data indicate low oxygen conditions in bottom waters, only mildly low oxygen in pore waters (Speed and Kroon, 2000; Martínez-Ruiz et al., 2001, 2002). It is possible, however, that a short episode of hypoxia or anoxia is not represented in the sediment as the result of the mass wasting at Blake Nose (Klaus et al., 2000; Norris et al., 2001b; Norris and Firth, 2002), similar to the situation in the Mexican sections (Alegret et al., 2001a, 2002a,b; see also Fig. 5). One could interpret the relatively high abundance of buliminids higher in the section as resulting from somewhat lowered oxygen concentrations (e.g., Kaiho, 1999), but most researchers interpret such abundances as related to a high food supply rather than slightly lowered oxygen concentrations (e.g., Morigi et al., 2001; Gooday, 2003).

Diversity and heterogeneity increased in section 8X-1, and the relative abundance of the formerly dominant species (*Bulimina kugleri*, *Fursenkoina tegulata* and *Nonionella robusta*) decreased, indicating the recovery of the assemblages, and the return to environmental conditions similar to those in the Maastrichtian (Sen Gupta and Machain-Castillo, 1993; Kouwenhoven et al., 1997). However, we did not study enough samples to establish that this is a true, continuing trend.

5. Conclusions

Benthic foraminiferal evidence apparently indicates upper lower bathyal depths (~1200 m) during the latest Maastrichtian and earliest Danian at Blake Nose Site 1049, and there is no evidence for significant sea-level fluctuations. The position of Site 1049 relative to that of the 1300 m shallower Site 1052, however, suggests that this depth estimate is too low by about 300–400 m, and that the paleodepth at Site 1049 must have been at least about

1500–1600 m. We suggest that benthic biozones were somewhat depressed as a result of local high productivity.

Benthic foraminifera did not suffer a mass extinction at the K/P boundary, with only about 7% of species having an uppermost occurrence at the K/P boundary, as has been seen at many other locations (Culver, 2003). In the latest Maastrichtian, Site 1049 probably was located in a stable environment characterized by an abundant organic flux to the sea-bottom floor. Possibly, high organic productivity resulted from upwelling in the region of Blake Nose (Widmark and Speijer, 1997b).

A spherule-bed deposited just after the K/P boundary contains a mixture of allochthonous, neritic benthic foraminifera mixed with autochthonous, deep-water species, together with reworked planktic foraminifera. The spherule-bed at Blake Nose thus is similar to the clastic unit in Mexican K/P sections. The deposition of this clastic unit with spherules as well as that of an overlying sandstone unit may have been triggered by the bolide impact on the Yucatan peninsula (Chicxulub) that caused continental margin destabilization (Bohor, 1996; Smit et al., 1996; Soria et al., 2001; Alegret et al., 2001a, 2002a,b).

After the deposition of the spherule-bed due to mass wasting processes, the nutrient supply to the sea-bottom floor at Blake Nose decreased during the earliest Danian, as indicated by a decrease in the relative abundance of infaunal taxa in lowermost Biozone P α . In our opinion, a decrease in primary productivity as the result of mass extinction of primary producers in the surface waters most probably triggered these significant changes in benthic foraminiferal assemblages. This period of reduced organic flux to the sea floor had a duration shorter than that of Biozone P α . Increased relative abundances of infaunal taxa indicate a recovery of the food flux, but diversity and heterogeneity of the assemblages, thus normal marine conditions, did not return until the upper part of section 8X-1, about 400 kyr after the K/P boundary. We suggest that primary productivity during the period of low diversity could have been dominated by blooms of non-calcareous primary producers, which created a stressful environment for the benthos. Primary productivity appeared to have returned to high levels early at Blake Nose, possibly as the result

of the site location in an area of upwelling and abundant nutrient supply to the planktic primary producers.

6. Taxonomic note

Cibicidoides welleri is similar to *Anomalinoides acutus* in its trochospiral, biconvex, compressed test, ventral side involute and dorsal side evolute, and numerous chambers (10–12) in the last whorl; the peripheral margin is subacute. It differs from that species in its depressed sutures, and the typical boss on the dorsal side is lacking in *C. welleri*. In contrast to *C. welleri*, *Anomalinoides affinis* is plano-convex, biumbonate, it has a smoother wall, periphery rounded to broadly rounded, and there are less differences in the degree of evoluteness between the evolute and the involute side. *C. welleri* is much more laterally

compressed than *A. affinis*, which has fewer chambers (about eight) visible in the last whorl (Alegret and Thomas, 2001).

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B8*05 67–68	B8*05 57–58	B8*05 48–50	B8*05 38–40	B8*05 20–22	B8*05 0–2	B8*04 132–134	B8*04 60–62	B8*04 0–2	B8*03 110–112	B8*03 62–64	B8*02 112–114	B8*02 60–62	B8*01 130–132	B8*01 70–72	B8*01 10–12
112.775	112.675	112.59	112.49	112.31	112.11	111.93	111.21	110.61	110.21	109.73	108.73	108.21	107.41	106.81	106.21
6	8	1	1	1	1		1			1	2		1		1
					1		1			1					
5	4		5 1	6	5	2	3 7	1 1	5	4			1	6	11
5	4	9	5	5	7	5	3	2	8	6	6	6	2	7	13
5	2	2	3	1									2		
	1					2				1	2		1		
2	1	1	5		3	1							2	1	1
3	4	5	3	3	8		7	5	5	7	9	2	6	18	21
90	93	79	74	66	78	46	111	97	59	58	77	54	129	80	22
1			1												
3			6		11	2	8	10	20	1	17		3	6	6
1		5	1					10	6		4	1		6	10
3	2	2	8				3		1	2			2		3
7	5	4	7				1	3		4	1	1		1	17
1	8		1	13	5	3			2		10	2	3	8	
14	17	14	11	24	28	5	15	9	13	11	14	11	14	13	23
3	3	4	9	3	3	1		2			7	3	1	2	6
6	12	5	4	5	2	2		3	4	1	3	1	3	3	
1															

B8*05 67–68	B8*05 57–58	B8*05 48–50	B8*05 38–40	B8*05 20–22	B8*05 0–2	B8*04 132–134	B8*04 60–62	B8*04 0–2	B8*03 110–112	B8*03 62–64	B8*02 112–114	B8*02 60–62	B8*01 130–132	B8*01 70–72	B8*01 10–12
112.775	112.675	112.59	112.49	112.31	112.11	111.93	111.21	110.61	110.21	109.73	108.73	108.21	107.41	106.81	106.21
	1						1						2		
6	6	1 5	6	7	7	1	5	2	3	5	15		8	3	6
1	1	1					1								
1	1			1									1	1	
1			4	1	5		2		2		2			1	5
		1	2	1						1	4	2			1
60	68	50	42	49	60	19	39	45	10	31	58	22	67	18	17
			1 2												
36	8		6	9	2	3					1				1
		3										3			
1		3	2	1			1	1	1			1	1		
1		2	1		1						1				
	1	3	2	4	2			1			2	4		4	5
6	11	6	9	7	8	1	5	1	3	2	2	1	4	5	4
1	1	1	1		2	2	1				1				
	2			1							1				1
1		1	1		1	2		1				1			1

B8*05 67–68	B8*05 57–58	B8*05 48–50	B8*05 38–40	B8*05 20–22	B8*05 0–2	B8*04 132–134	B8*04 60–62	B8*04 0–2	B8*03 110–112	B8*03 62–64	B8*02 112–114	B8*02 60–62	B8*01 130–132	B8*01 70–72	B8*01 10–12
112.775	112.675	112.59	112.49	112.31	112.11	111.93	111.21	110.61	110.21	109.73	108.73	108.21	107.41	106.81	106.21
2		1								1			2		2
4	4	2	2	4	3		1	3	1	1	1	1	1	2	3
2	1	3	1		1	1		1					2		
1															
									3		1				
3	9	13	9	12	11	3	8	1	9	3	14	5	2		1
15	21	19	18	28	23	44	36	13	40	24	30	22	38	18	19
				2	5	1	1	1	2	5	7		4		10
	3	6	7	4	5		2						2		
8	1	11	6		1		1						2		3
	2		3	12	30	2	6		1	3	7	5	10	2	4
2	5	2	3	3	4		4	1	5	2	14	9	5	9	10
3	1	2	3			3							1		
1					1						1	2	2		2
			1							1			1		
17	18	9	17	15	27	12	21	18	22	8	30	16		16	15
21	30	9	21	19	24	2	5	3	5	7	11	5	9	8	19
1	1														
4	4	3	1	4	3	1	1	2	3					2	2

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(continued on next page)

Appendix A (continued)

Sample	B8*05 148– 150	B8*05 137– 139	B8*05 113– 114	B8*05 108– 110	B8*05 98.5– 99	B8*05 97.5– 98.5	B8*05 96.5– 97.5	B8*05 95.5– 96	B8*05 94.5– 95	B8*05 92.5– 93	B8*05 90.5– 91	B8*05 89– 89.5	B8*05 88– 88.5	B8*05 77.5– 78
mbsf	113.59	113.48	113.235	113.19	113.0875	113.08	113.07	113.0575	113.0475	113.0275	113.0075	112.9925	112.9825	112.8775
Species														
<i>Polymorphinella</i> sp.		1				1								
<i>Praebulimina reussi</i>	31	33	24	8	18	11	3		1				4	3
<i>Praebulimina</i> sp.	3	3	4		1	3	1					2	1	6
<i>Pseudouvigerina plummerae</i>	3	1	1	1										
<i>Pullenia cretacea</i>		1												
<i>Pullenia jarvisi</i>		3			6	5		1		1				
<i>Pyramidina rudita</i>	4	1	1			2						2	2	16
<i>Pyramidina</i> sp.														
<i>Pyrulina</i> spp.	1	4												4
<i>Pyrulinoidea</i> sp.	2			1										1
<i>Quadriformina</i> <i>allomorphinoides</i>				1	1									
<i>Quadriformina</i> spp.	6	18	2											1
<i>Quinqueloculina</i> sp.		1			2									
<i>Ramulina</i> spp.														
<i>Reophax</i> spp.														2
<i>Reussella szajnochae</i>	5	7	1	1	7	5	2	1	2					
<i>Rhizammina</i> spp.														
<i>Scheibnerova</i> sp.	3	8	1	1	11	8		1		1		1	1	
<i>Seabrookia cretacea</i>														
<i>Siphogerenoides</i> sp.		1												
<i>Sitella</i> sp.														
<i>Sliteria varsoviensis</i>			1		2		1	1						
<i>Spiroplectammina dentata</i>						1			1					
<i>Spiroplectammina</i> <i>spectabilis</i>	1	2	2		7	10	3			1	2	2		
<i>Spiroplectammina</i> spp.				2	1									6
<i>Stensioeina beccariiiformis</i>	11	5	3	3	12	7	3	1	2	2		9	11	8
<i>Stensioeina excolata</i>											1			
<i>Stillostomella</i> spp.	8			3		3	3					1	1	5
<i>Stillostomella subspinosa</i>	3	13	6	4	1									
<i>Tappanina selmensis</i>													1	
<i>Tappanina</i> spp.														
<i>Uvigerina</i> spp.														
<i>Vaginulina trilobata</i>	1									1		1		
<i>Valvalabamina lenticula</i>	7	4	3	1	2		2						2	3

B8*05 67–68	B8*05 57–58	B8*05 48–50	B8*05 38–40	B8*05 20–22	B8*05 0–2	B8*04 132–134	B8*04 60–62	B8*04 0–2	B8*03 110–112	B8*03 62–64	B8*02 112–114	B8*02 60–62	B8*01 130–132	B8*01 70–72	B8*01 10–12
112.775	112.675	112.59	112.49	112.31	112.11	111.93	111.21	110.61	110.21	109.73	108.73	108.21	107.41	106.81	106.21
2 8	3 11	4 5	7 6	3	1 11	3	4	4			4	9	2	6	2
	1 1 1	2 1 1			1		1			1			1 1 1		
3	1		3	2				2		2 1 7 4	1 2 2 7	1 1	2	1	3
	2 9	2 11	1 17	1 6	1 5	4	2 9	4							8
							2	6	1			6		6	
	1														
		1													
					4	4	15	4	10	3	11	10	5	5	3
		1													
6	2			1				1							
	1 6		2 4	2		1 7									5
4		10			3		3		1			2	2		1
9	13	5	6	2	4	1	13	4	2		7	7	2 1	1	1
2 1 1	2 1	1	7	18 1	8	3	2	1	3	1	6	3	5	4	2
										3					
2	8		5	4	3	1	3	1		1		1	1		1 3

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