

# ***Abrupt extinction and subsequent reworking of Cretaceous planktonic foraminifera across the Cretaceous-Tertiary boundary: Evidence from the subtropical North Atlantic***

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## **ABSTRACT**

An impact ejecta bed containing shocked quartz and diagenetically altered tektite spherules coincides exactly with biostratigraphic placement of the Cretaceous-Tertiary (K-T) boundary in three drill cores recovered from Ocean Drilling Program Site 1049 (located in the subtropical North Atlantic Ocean). Both the bracketing pelagic ooze and the ejecta bed are undisturbed at Site 1049, allowing detailed examination of the expression of the boundary event in an open ocean setting. The youngest Cretaceous sediments contain a diverse assemblage of well-preserved upper Maastichtian Tethyan microfossils. The overlying ejecta bed varies laterally in thickness, has sharp lower and upper contacts, and contains features (e.g., presence of a foraminiferal grainstone layer at its base and large chalk clasts in its middle, and dominance of poorly sorted coarse grains throughout) that suggest it was deposited by one or several mass-flow events. The oldest Danian ooze contains abundant, tiny planktonic foraminifera characteristic of the early Danian P $\alpha$  Zone as well as common, large Cretaceous individuals. The lowermost Danian P0 Zone (assemblage dominated by *Guembelitria cretacea*) is apparently absent. This absence could reflect restriction of the P0 assemblage to shallower settings, slow sedimentation rates coupled with bioturbation mixing Tertiary forms into (and thus obscuring) the P0 Zone, or an interval of erosion or nondeposition. Cretaceous species decline and last occur in the first several meters of section above the ejecta bed. This pattern could be interpreted as evidence for gradual extinction above the impact bed, but thin-section observations, relative abundance counts, size-distribution analyses, and comparison with species extinctions at other K-T sections demonstrate sudden extinction, nearly all post-K-T occurrences of Cretaceous planktonic foraminiferal species being explained as the result of sediment reworking.

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## INTRODUCTION

One of the long-standing controversies in the Cretaceous-Tertiary (K-T) boundary debate is whether the terminal Cretaceous extinctions were abrupt and coincident with physical evidence for bolide impact, or gradual and linked to Earth-bound environmental changes. Although there is abundant evidence that a large bolide impact occurred at the K-T boundary (e.g., Ryder et al., 1996) and that the K-T turnover is exceptionally sharp relative to other Phanerozoic extinctions (Ryder, 1996), some workers maintain that the Chicxulub impact event was not the major cause of the end-Cretaceous extinctions (e.g., Keller, 1996; Archibald, 1996; Sarjant, 1996; Pardo et al., 1999).

Differing interpretations of the planktonic foraminiferal biostratigraphic record have been the focus of much of this controversy. Some authors argue that changes in sea level, temperature, and global volcanism led to prolonged extinctions before and after the K-T boundary (e.g., MacLeod and Keller, 1994; Keller and Stinnesbeck, 1996; Keller et al., 1998; Li and Keller, 1998; Pardo et al., 1999). Others suggest that the pattern of gradual preboundary extinction among these organisms can be explained as a combination of sampling or taxonomic artifacts and low-level, background extinctions, while the post-boundary occurrences mostly result from sediment reworking (e.g., Olsson and Liu, 1993; Huber, 1996). The reworking hypothesis is strongly supported by recognition of offsets between the strontium and carbon isotopic composition of trans-K-T boundary Cretaceous species and co-occurring in situ Danian species (Zachos et al., 1992; Huber, 1996; MacLeod and Huber, 1996; Kaiho et al., 1999; MacLeod et al., 2001).

A remarkably complete and well-preserved K-T boundary sequence was recovered in the three holes drilled at Ocean Drilling Program (ODP) Site 1049, which is located in the subtropical North Atlantic and ~1600 km from the Chicxulub impact site (Fig. 1). Between uppermost Maastrichtian and lowermost Danian nannofossil ooze in these three holes, there is a 9–17-cm-thick layer of asteroid impact ejecta that was presumably derived from the Chicxulub impact site (Norris et al., 1998, 1999; Klaus et al., 2000). The ejecta bed is capped by a 1–3-mm-thick red limonitic layer that is coincident with a zone of low iridium enrichment and is bracketed by intervals of higher Ir concentration above and below (Smit et al., 1997). The uppermost Maastrichtian sediments reveal evidence of soft-sediment deformation, perhaps resulting from seismicity caused by the Chicxulub impact (Klaus et al., 2000; Norris and Firth, this volume). The lowermost Danian sequence reveals no physical or biostratigraphic evidence of deformation or discontinuous sedimentation, yet it contains 36 species of Cretaceous planktonic foraminifera. In this study we focused on analyses of changes in planktonic foraminiferal population structure, stratigraphic distributions, and shell size/mass ratios across the boundary succession to evaluate evidence for post-K-T reworking.

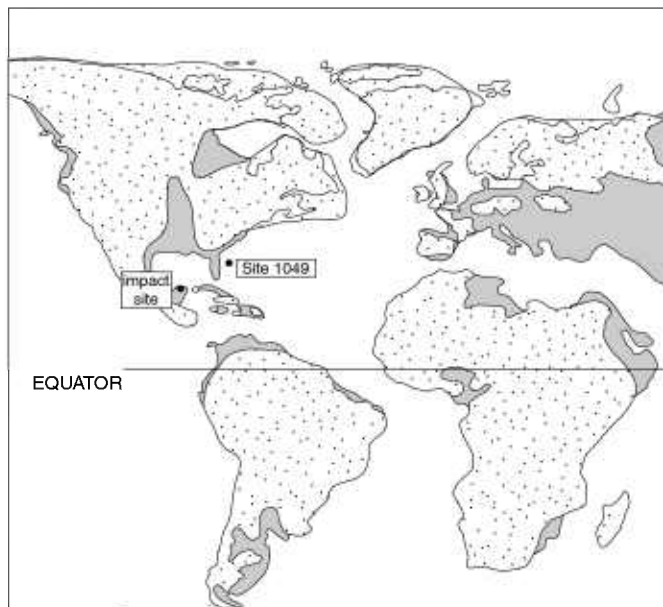


Figure 1. Paleogeography for 65 Ma showing approximate locations of Site 1049 and Chicxulub impact crater. Three holes drilled ~30 m apart at Site 1049 yielded complete Cretaceous-Tertiary sequences containing ejecta bed varying from 9 to 17 cm in thickness. Continental positions were generated using PGIS/Mac<sup>®</sup> software package and land and sea distributions are modified from Barron (1987).

## MATERIAL AND METHODS

The analyzed samples are from section 1049C-8X-5, between 112.10 and 113.15 m below seafloor (mbsf). The spacing of samples used in abundance and size/mass determinations is between 6 and 10 cm. Bulk samples ranging from 0.5 to 1.0 cm<sup>3</sup> were disaggregated in tap water, washed over a 38  $\mu$ m sieve, and dried in an oven at ~50°C. The size/mass ratio of Cretaceous species in Danian sediments was determined by pouring the samples through a nest of sieves ranging from 125 to 500  $\mu$ m in size and separated at 1/4 phi size intervals. All Cretaceous planktonic foraminifera were picked from each size interval and weighed on a microbalance. Because nonforaminiferal grains compose <2% of the total >125  $\mu$ m size fraction, the residue without Cretaceous specimens closely approximates the proportion of Danian planktonic foraminifera in each size fraction. This residue was also weighed to determine the total mass of foraminifera in each sample.

Numerical abundance counts were based on identification of all Cretaceous specimens picked from the >125  $\mu$ m size intervals. Relative abundance estimates of the Danian species were made from visual observation of the >38  $\mu$ m size fraction. Taxonomic concepts for Cretaceous species are the same as those used in MacLeod et al. (2000) for Deep Sea Drilling Project Site 390A, which was drilled at the same location as Site 1049. Taxonomic concepts for Danian species and Danian biozone definitions are based on those used in Olsson et al. (1999).

Three thin sections were prepared from a continuous 15.2 × 3.6 × 1.3 cm slab of sediment that was removed from the K-T interval of Hole 1049C. Thin sectioning was accomplished by building a Plexiglas epoxy case around the slab of sediment, impregnating the slab with Epo-Tech 301 epoxy in a vacuum chamber, cutting the block lengthwise, dividing one half of one length into thirds, and grinding these into thin sections to the petrographic thickness of calcite (20 µm or less). The remaining sediment block was reimpregnated and attached to a 3 mil clear polyester plastic sheet on one side and a 3-mm-thick Plexiglas sheet on the other. Some minor disturbance of the ejecta bed occurred during this procedure as a result of dehydration and development of shrinkage cracks in the slab of sediment and swelling of the porous, smectite-rich spherule layer when the epoxy was added (Fig. 2).

## GEOLOGIC SETTING

The K-T boundary was cored at three sites along a depth transect extending from 1344 to 2670 m water depth on Blake Nose during ODP Leg 171B, but only the deepest site (Site 1049) yielded an impact-derived ejecta bed. The oldest sediments on Blake Nose are Jurassic and Lower Cretaceous platform carbonates that were deposited on the rifted margin of North America (Benson et al., 1978). These shallow-water limestones are overlain by a relatively thin succession of hemipelagic and pelagic carbonates that range from late Aptian through late Eocene in age. Capping the Cretaceous-Eocene sequence is a thin layer of manganiferous nodules and sand containing Pleistocene to Holocene foraminifera (Norris et al., 1998). The shallow burial depths account for the remarkably good preservation of biogenic calcite throughout most of the Upper Cretaceous-Eocene sequence at all of the Leg 171B drill sites.

Soft-sediment deformation features such as contorted bedding, microfaults, and variably angled dips are pervasive in the upper Maastrichtian core sections. Such deformation features are absent from the overlying Danian sediments. Analysis of Maastrichtian sediment cores and seismic reflection data along the Leg 171B depth transect led Klaus et al. (2000) as well as Norris and Firth (this volume) to conclude that mass wasting occurred across Blake Nose as a result of the Chicxulub impact event. Despite this evidence for sediment deformation, the middle through upper Maastrichtian sequence at Site 1049 is biostratigraphically complete and there is no evidence for stratigraphic repetition (Norris et al., 1999; Self-Trail, 2001).

Benthic foraminifera from the Maastrichtian-Danian sequence at Site 1049 compose <2% of the total foraminiferal assemblage. Their rarity and dominance by species that are not found at upper slope or shelfal depths suggest that this site occupied middle to upper bathyal paleodepths during K-T boundary time (Norris et al., 1998).

## RESULTS

Maastrichtian sediments at Site 1049 are composed of foraminifer-nannofossil chalk and ooze and contain very little detrital material (Fig. 2A). Ooze immediately below the ejecta bed contains well-preserved planktonic foraminiferal (Fig. 3A) and calcareous nannofossil assemblages from the *Abathomphalus mayaroensis* and *Micula prinsii* zones, respectively, and have been assigned to the latest Maastrichtian portion of magnetic polarity chron 29R (Norris et al., 1998). Although Pardo et al. (1999) identified *Plummerita hantkenoides* as a planktonic foraminiferal marker species for the uppermost Maastrichtian, its absence at Site 1049 is consistent with its absence from deep-sea sediments worldwide, suggesting that this species is restricted to shallower water biofacies. Nonetheless, the presence of *Pseudoguembelina hariaensis* within 1.5 m below the ejecta bed (Table 1) confirms assignment of this interval to the uppermost Maastrichtian, because this species is restricted to the upper *A. mayaroensis* zone elsewhere (Nederbragt, 1991; Li and Keller, 1998).

### Petrology

The ejecta bed is in sharp contact with the underlying ooze. It is predominantly composed of unconsolidated, circular to ovoid spherules (Fig. 3B) that range to 3 mm in size and vary in color from dark green to pale yellow. X-ray diffraction analyses indicate that the originally glassy spherules have been diagenetically altered to smectite (Martínez-Ruiz et al., 2001). Rare spherules composed of calcite have been observed in thin section. Large Cretaceous planktonic foraminifera are concentrated in discrete layers within the basal 1 cm of the ejecta bed (Fig. 2B), and are abundant and randomly distributed through the rest of the bed. Thin-section and macroscopic observations of the core reveal that the ejecta bed contains little fine-grained matrix and, apart from the foraminiferal grainstone, is poorly sorted throughout and lacks any sedimentary structures. Chalk clasts to 1 cm in diameter, grains of euhedral dolomite that reach 0.1 mm in length, and rare grains of shocked quartz (Fig. 2D) and euhedral zeolite occur in the middle and upper portions of the ejecta bed. An echinoid spine found in the middle of the ejecta bed (Fig. 2C) is considered exotic because none were found in the pelagic carbonate below and above. The thickness of the ejecta bed is 17 cm at Hole 1049A, 13 cm at Hole 1049B, and 9 cm at Hole 1049C (see Klaus et al., 2000, for color images). At the top of the ejecta bed is a 1–3-mm-thick orange, limonitic layer that contains flat goethite concretions (Fig. 2E). Lateral variation in the thickness of the limonitic layer is consistent with evidence for upward diffusion and precipitation of trace elements in the upper part of the ejecta bed (Martínez-Ruiz et al., 2001).

Immediately above the ejecta bed is a 3–7-cm-thick dark, burrow-mottled, clay-rich ooze that contains well-preserved,



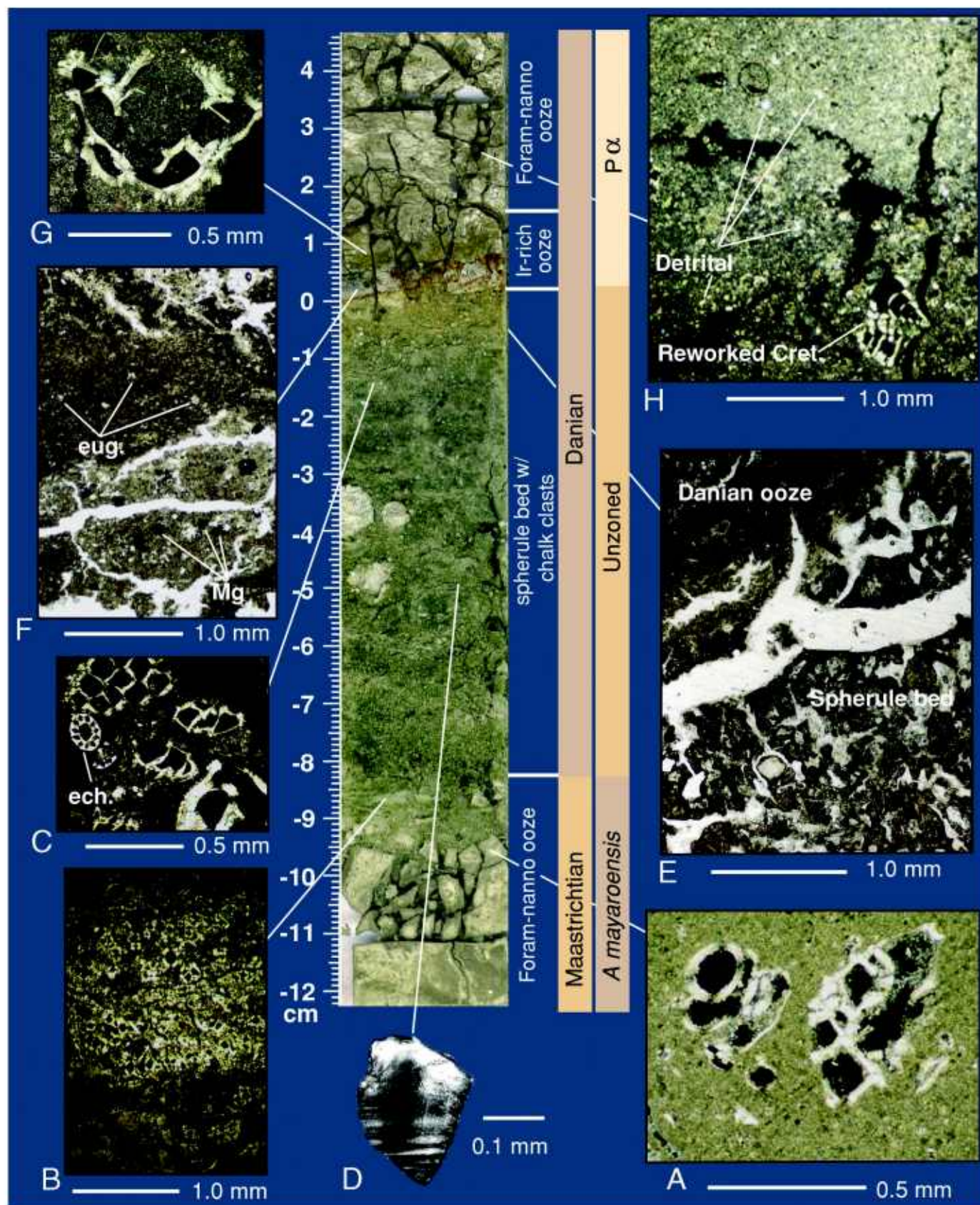


Figure 2. Epoxy block and thin sections across Cretaceous-Tertiary boundary in Hole 1049C revealing changes in lithology, sediment fabric, and species distributions. A: Uppermost Maastrichtian chalk shows large Cretaceous planktonic foraminifera floating in a matrix of nanofossil ooze. B: Basal ejecta bed shows size sorting of Cretaceous planktonic foraminifera into grainstone, suggesting winnowing and lateral transport. C: Presence of occasional echinoid spines may indicate derivation of some sediment from shallower depth. D: Shocked quartz occurs within middle and upper levels of ejecta bed. E: Contact between top of spherule bed and basal Danian ooze shows no evidence of sediment winnowing or presence of hardground, which might be expected if this contact were disconformable. F: Presence of tiny specimens of *Parvularugoglobigerina eugubina* (eug.) in basal Danian sediments indicates absence of lowermost Danian zone P0. Opaque grains within 2 mm above top of ejecta bed are Mg spinels (J. Smit, 2000, personal commun.). G: Different colored matrix within shell of *Contusotruncana contusa* compared to surrounding matrix reveals that this specimen has been reworked. H: Larger size and greater abundance of detrital clastic sediment in lower Danian vs. Cretaceous chalk indicates increased downslope sediment transport.

although strongly recrystallized, minute planktonic foraminifer species characteristic of the lower Danian P $\alpha$  Zone (Fig. 3C). The contact between this layer and the underlying ejecta bed is sharp (Fig. 2E). Smit et al. (1997) reported Ir concentrations of 1.3 ppb within the burrow-mottled ooze, in contrast to values of <0.06 ppb at the base of the ejecta bed and 3 cm above its

top. Detrital grains including quartz, pyroxene, and mica are more abundant and larger in the mottled interval than in the ooze below the ejecta bed (Fig. 2, F and H). Opaque minerals identified as Mg-rich spinels are concentrated in the lower part of this bed (Fig. 2F) and are randomly dispersed in the sediment matrix for several millimeters above the contact. A specimen of the Maastrichtian species *Contusotruncana contusa* that contains an infilling matrix of a different color than the surrounding matrix was observed in thin section within 1 cm above the limonitic layer (Fig. 2G). Scanning electron microscope (SEM) observation of the internal matrix of another trans-K-T species found in Danian sediments, *Heterohelix globulosa*, reveals an assemblage of Cretaceous calcareous nanofossil species not considered to be survivors of the K-T extinction event (Fig. 4). No Danian calcareous nanofossil species occur within the shell of this specimen, despite their abundant presence in the surrounding Danian sediments.

The sample from within 0.5 cm above the ejecta bed is dominated by *Guembelitra cretacea*, but it also contains rare *Parvularugoglobigerina extensa* and *Parvularugoglobigerina eugubina*. The presence of the latter species and absence of *Chiloguembelina morsei* or *Chiloguembelina midwayensis* indicate that this sample correlates with the lowermost P $\alpha$  Zone.

The absence of the basal Danian *Guembelitra cretacea* Zone (P0 Zone) at all deep-sea sites, including Site 1049, has previously been attributed to the temporary absence or rare

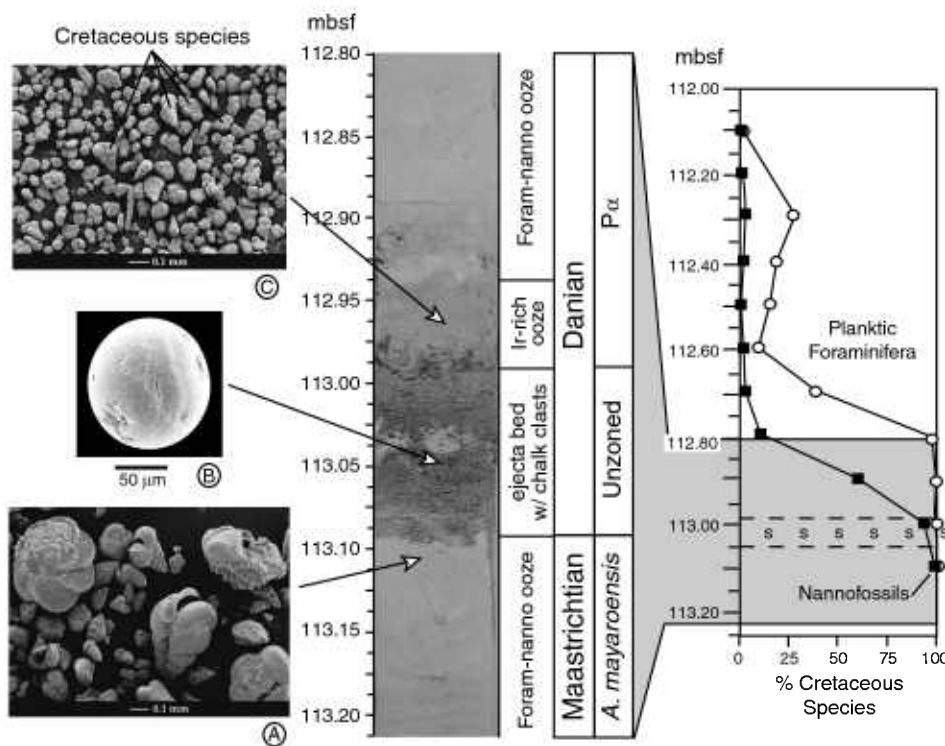


Figure 3. Comparison of pre-Cretaceous-Tertiary (K-T) (A) and post-K-T (C) planktonic foraminiferal assemblages and example of spherule (B) from K-T boundary interval of Ocean Drilling Program Hole 1049C. Relative abundances of planktonic foraminifera (wt% Cretaceous species in >125  $\mu$ m fraction) and calcareous nanofossils (counts of 450 specimens/sample at 1600 $\times$  along random smear slide traverse) are from Norris et al. (1999). Abrupt and dramatic turnover in planktonic foraminifera coincident with K-T impact event is evident from comparison of Cretaceous assemblage from 1 cm below top of Maastrichtian chalk (A) with basal Danian assemblage from 2 cm above ejecta bed (C). Scanning electron microscope images shown were prepared using randomly poured >38  $\mu$ m sieved residues from two sample levels. Note that Danian assemblage is strikingly smaller in size and lower in species diversity than Cretaceous assemblage, and that shells of Danian species are much simpler in morphology. Also note that Cretaceous species that occur in Danian (denoted by K) are relatively rare (mbsf is meters below sea floor).



HOLE  
1049C[illegible]

2 = present in <125  $\mu\text{m}$  fraction.

A burrowed contact marks the base of an overlying 5–15-cm-thick, white foraminiferal-nannofossil ooze that also contains a P $\alpha$  Zone foraminiferal assemblage and fossils typical of calcareous nannofossil biozone NP1 (Norris et al., 1999; Self-Trail, 2001). In sharp contact with the top of the white interval is greenish-gray nannofossil foraminiferal ooze, which is the final bed of the studied sequence. The base of the P1a Zone, identified at the level of the extinction of *P. eugubina*, is placed within this greenish-gray interval, 88.5 cm above the top of the ejecta bed (Table 1).

### Relative abundance changes

Of the 37 species identified in the uppermost Maastrichtian sample studied, 33 species (89%) occur in the overlying P $\alpha$  Zone sediments and 19 species (51%) range into Zone P1a (Table 2). The lowermost 20 cm of the P $\alpha$  Zone is dominated by Cretaceous taxa, but by the top of this zone, the Cretaceous component represents <1% of the total assemblage (Fig. 3). A similar, but more rapid, pattern of gradual replacement of Cretaceous by Danian taxa at this site has been observed for calcareous nannofossils (Norris et al., 1999; Self-Trail, 2001).

The most abundant and consistently occurring Cretaceous species in the Danian sediments, such as *Heterohelix globulosa*, tend to be the most abundant species below the K-T ejecta bed. Similarly, the rare species with sporadic distributions in Maastrichtian sediments, such as *Globotruncana aegyptiaca* (see also MacLeod et al., 2000, Table 8.4), also tend to be rare in Danian sediments. Some Cretaceous species, such as *Racemiguembelina fructicosa*, have erratic changes in abundance in the Danian sediments. Although this species usually composes <5% of upper Maastrichtian planktonic foraminiferal assemblages and is consistently present in all samples throughout its upper Maastrichtian range (e.g., MacLeod et al., 2000), its abundance is >12% in one Danian sample but it is absent from others.

### Mass/size ratios

Comparison between the masses of Cretaceous planktonic foraminiferal shells per size fraction from below versus above

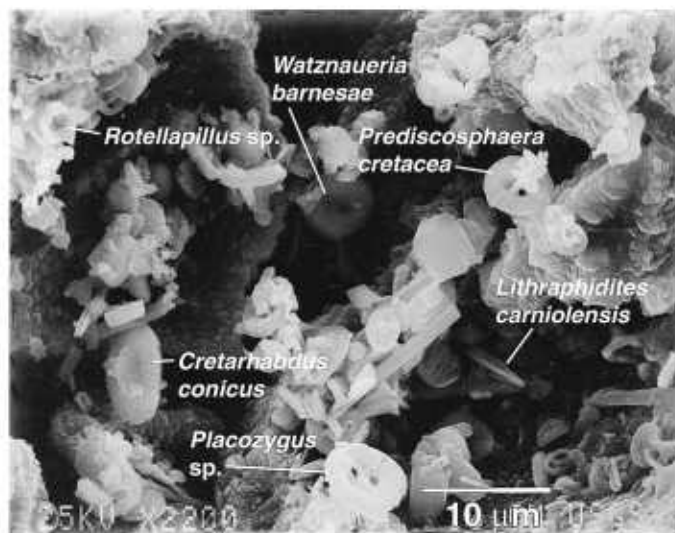


Figure 4. Scanning electron micrograph of calcareous nannofossils from within shell of *Heterohelix globulosa*, trans-Cretaceous-Tertiary (K-T) planktonic foraminifer found in sample 1049C-8X-5, 75.0–75.5 cm, 13.5 cm above top of spherule bed. Only Cretaceous nannofossil species that lived during Maastrichtian occur in matrix, despite abundant presence of Danian species in surrounding sediments, and none are considered as K-T survivor species in the sense of Pospichal (1996). Calcareous nannofossil species identifications were done by J. Self-Trail (2001, personal commun.).

the K-T ejecta bed reveals a significant change in size distributions. The largest percentage of specimens in the upper Maastrichtian sample from 113.16 mbsf occurs in the smallest size fractions (Fig. 5). This is similar to the size distribution of living populations, which tend to be dominated by small individuals (Berger, 1971). However, the Danian samples analyzed yield a size distribution with the greatest percentage of specimens in the  $>212\ \mu\text{m}$  size fractions. The most extreme departure from the expected size distribution occurs in the sample from 112.70 mbsf,  $\sim 28$  cm above the top of the ejecta bed, with nearly 60% of the assemblage comprising the  $>500\ \mu\text{m}$  size fraction.

Plots of the percentage mass of Cretaceous specimens relative to the combined mass of Cretaceous and Danian specimens document the prolonged presence of Cretaceous specimens in the larger size fractions and gradual increase in Danian species beginning in the smallest size fractions (Fig. 6). In the sample from within 1 cm above the ejecta bed (112.98 mbsf), Danian species are only present in the  $<125\ \mu\text{m}$  size fraction. Danian species are included in 4% of the 125–150  $\mu\text{m}$  size interval 8 cm above this sample (112.90 mbsf), but 100% of the  $>150\ \mu\text{m}$  size fraction is composed of Cretaceous specimens only. Within 28 cm above the ejecta bed (112.70 mbsf) Danian species dominate the  $<212\ \mu\text{m}$  size fraction sample, but Cretaceous specimens compose 100% of the  $>300\ \mu\text{m}$  fraction. Cretaceous specimens continue to represent 100% of the  $>300\ \mu\text{m}$  fraction to 78 cm above the ejecta bed (112.20 mbsf) and dom-

inate that fraction throughout the P $\alpha$  Zone and into the lower P1a Zone.

## DISCUSSION

### Redeposition of the ejecta bed

The composition of the spherule bed at Site 1049 suggests an impact origin for most of the nonbiogenic grains (Norris et al., 1998, 1999; Martinez-Ruiz et al., 2001), but the bed does not seem to solely represent material deposited directly after settling through the water column. The sedimentary features of the spherule bed are more consistent with deposition from one or several mass-flow events. Evidence for this interpretation includes the presence of: (1) a scoured basal contact with the underlying Maastrichtian chalk; (2) a size-sorted foraminiferal grainstone in the lowermost 1 cm, immediately above a layer of spherules; (3) large foraminifera scattered throughout the bed; (4) an exotic echinoid spine and large chalk clasts in the middle and upper portion of the bed; and (5) a slight decrease in grain size in the uppermost portion of the bed (Fig. 2).

Because it occurs precisely at the K-T boundary, it is tempting to interpret the mass flow(s) as being related to impact seismicity (e.g., Klaus et al., 2000). However, the sedimentology of the K-T succession at Site 1049 suggests a more complex history. Immediately after the impact, but before there was time for the ejecta to settle to the seafloor, impact seismicity probably caused slumping of the Maastrichtian ooze (Klaus et al., 2000). The redeposited chalk and ooze probably predated gravity settling of the tektites through  $\sim 2$  km of water by a several hours or less. The source for the planktonic foraminifera in the ejecta bed seems to have been upslope equivalents of the underlying upper Maastrichtian ooze, because all species identified (including those in the chalk clasts) occur in underlying upper Maastrichtian samples. There is no evidence at Site 1049 for reworking of older Cretaceous material into the boundary bed as seen in the Caribbean area (cf. Bralower et al., 1998), which likely reflects details of the local geology and the location of Site 1049 on the protected side of the Florida carbonate platform. Absence from the ejecta bed of shelf-dwelling benthic foraminifera suggests that the source of reworked specimens was from below the shelf-slope break.

The tektites could have been remobilized following their rapid accumulation on already disturbed sediments, or they could have originated by gravity flows from the continental shelf and slope following impact-generated aftershocks or tsunamis generated by mass gravity flows elsewhere on the continental slope following margin collapse (e.g., Olsson et al., this volume). The different grain sizes in various parts of the ejecta bed could reflect deposition of ejecta by multiple plumes of sediment coming off Blake Plateau, some of which would have flowed directly down Blake Nose (delivering relatively coarse sediments) and others bypassing Blake Nose but delivering finer grained ejecta in laterally spreading plumes (Norris and

TABLE 2. VISUAL RELATIVE ABUNDANCE ESTIMATES FOR DANIAN PLANKTONIC FORAMINIFERA IN HOLE 1049C (>38  $\mu$ m FRACTION)

HOLE 1049C	Top Depth (mbsf)	Zone	<i>Guenbelitina cretacea</i>	<i>Woodringina? sp.</i>	<i>Globanomalina archeocompressa</i>	<i>Parasubbotina aff. pseudobulboides</i>	<i>Parvarugoglobigerina eugubina</i>	<i>Parvarugoglobigerina alabamensis</i>	<i>Woodringina homerstownensis</i>	<i>Chiloguembelina midwayensis</i>	<i>Parvarugoglobigerina extensa</i>	<i>Woodringina claytonensis</i>	<i>Eoglobigerina eobulboides</i>	<i>Parasubbotina pseudobulboides</i>	<i>Globocanusa daubjergensis</i>	<i>Chiloguembelina morsei</i>	<i>Eoglobigerina edita</i>	<i>Globanomalina planocompressa</i>	<i>Praenurica taurica</i>	<i>Subbotina trivialis</i>
8X-5, 0–2	112.10	P1a							R			R	C	C	P	P	F	F		R
8X-5, 10–12	112.20	P $\alpha$					P		C	C		C	F	A	F	R	C	C	F	
8X-5, 20–22	112.30	P $\alpha$	R				R		C	C		C	F	F	R	R	F	F	R	
8X-5, 30–32	112.40	P $\alpha$	C				C		A	C	R	C	F	C	R	R	C	F	R	
8X-5, 40–42	112.50	P $\alpha$	C				C		A	C		C	F	C	R	R	R	R	P	
8X-5, 50–52	112.60	P $\alpha$	C				F		C	C	R	C	F	F	R	R	R	R	P	
8X-5, 60–61	112.70	P $\alpha$	C		?		C		A	A	F	F	C	F	F	F	R	R	F	
8X-5, 70–71	112.80	P $\alpha$	C		R	R	C	R	R	C	F	F	F	F	?					
8X-5, 80–80.5	112.90	P $\alpha$	C		R	R	C	P	R	P	F									
8X-5, 88–88.5	112.96	P $\alpha$	C	P	R	P	P	P												
8X-5, 105–106	113.16	A. may.	P																	

A = abundant (>15%); C = common (5%–15%); F = few (1%–5%); R = rare (< 1%); P = present; ? = uncertain; mbsf = meters below sea floor.

Firth, this volume). The foraminiferal grainstone at the base of the ejecta bed may reflect either sorting produced by the initial slump of the upper Maastrichtian section or a different plume of ejecta and carbonate sediment than the coarser grained middle and upper parts of the ejecta bed. Lateral variation in thickness of the ejecta bed could be explained by mass-flow accumulation on the irregular, slumped surface of Maastrichtian ooze or lateral variation in mass-flow sediment volume.

The uppermost 1–3 mm of the spherule bed may have been deposited by direct settling of impact dust several weeks to many months after the impact event. This possibility is suggested by the fine-grained nature of this interval and concentration of iron oxide and iridium, which probably originated from vaporization of the K-T asteroid, although diagenetic mobilization of some elements has modified original depositional patterns (Martinez-Ruiz et al., 2001).

### Evidence for Danian reworking

The thin section and SEM observations show that some Cretaceous taxa in the Danian are reworked (e.g., exotic internal matrix; Figs. 2G and 4), and reworking of Cretaceous deposits during the early Danian would explain peculiarities in the stratigraphic and size distribution of Cretaceous assemblages present above the K-T boundary (Norris et al., 1999; Norris and Firth, this volume). Unlike living and in situ fossil foraminiferal assemblages, which have progressively greater abundance in smaller size fractions (Berger, 1971), the distribution of Cretaceous taxa in the Danian shows (1) a peak abundance above the smallest size fraction, with some samples exhibiting extreme departures from the expected pattern (e.g., 112.98, 112.70, 112.10 mbsf in Fig. 5); (2) the modes of the size-

distribution plots vary from sample to sample in the Danian interval; and (3) bimodal size distributions in some samples, suggesting that the foraminiferal shells were derived from multiple source beds. In addition, some species that are consistently present in low abundance in Maastrichtian samples have sporadic and highly variable abundance in the Danian samples, and several species that have been accepted as likely victims of the K-T event (e.g., *Globotruncanites stuartiformis*, *Globotruncana arca*, *Globotruncana insignis*, *Racemiguembelina fructifera*, *Pseudotextularia elegans*) by those espousing gradual post-K-T foraminiferal extinctions (e.g., Keller, 1996; MacLeod and Keller, 1994; Pardo et al., 1999) are abundant above the Site 1049 ejecta bed. Complementary studies of the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of Cretaceous and Tertiary foraminifera tests from Hole 1049C showed that Cretaceous foraminifera occurring above the boundary have the isotopic signature of the upper Maastrichtian and did not live with the co-occurring Tertiary forms; i.e., they are reworked (MacLeod et al., 2001). The greater abundance and larger size of detrital grains in the ooze above the ejecta bed compared to below (Fig. 2) suggest that winnowing and downslope transport was more active during the earliest Danian than in the latest Maastrichtian.

Norris and Firth (this volume) showed that turbidites of K-T boundary age occur in the Bermuda Rise, where they consist largely of calcareous nannofossils and extremely small (<63  $\mu$ m) planktonic foraminifera. Apparently slumping of the continental margin suspended large quantities of upper Maastrichtian sediments, some of which was transported off the margin into the deep sea. Size sorting within these resuspended sediments separated the fine fraction, dominated by calcareous nannofossils and small foraminifera, from the coarse fraction, dominated by large foraminifera and rock debris. The coarse



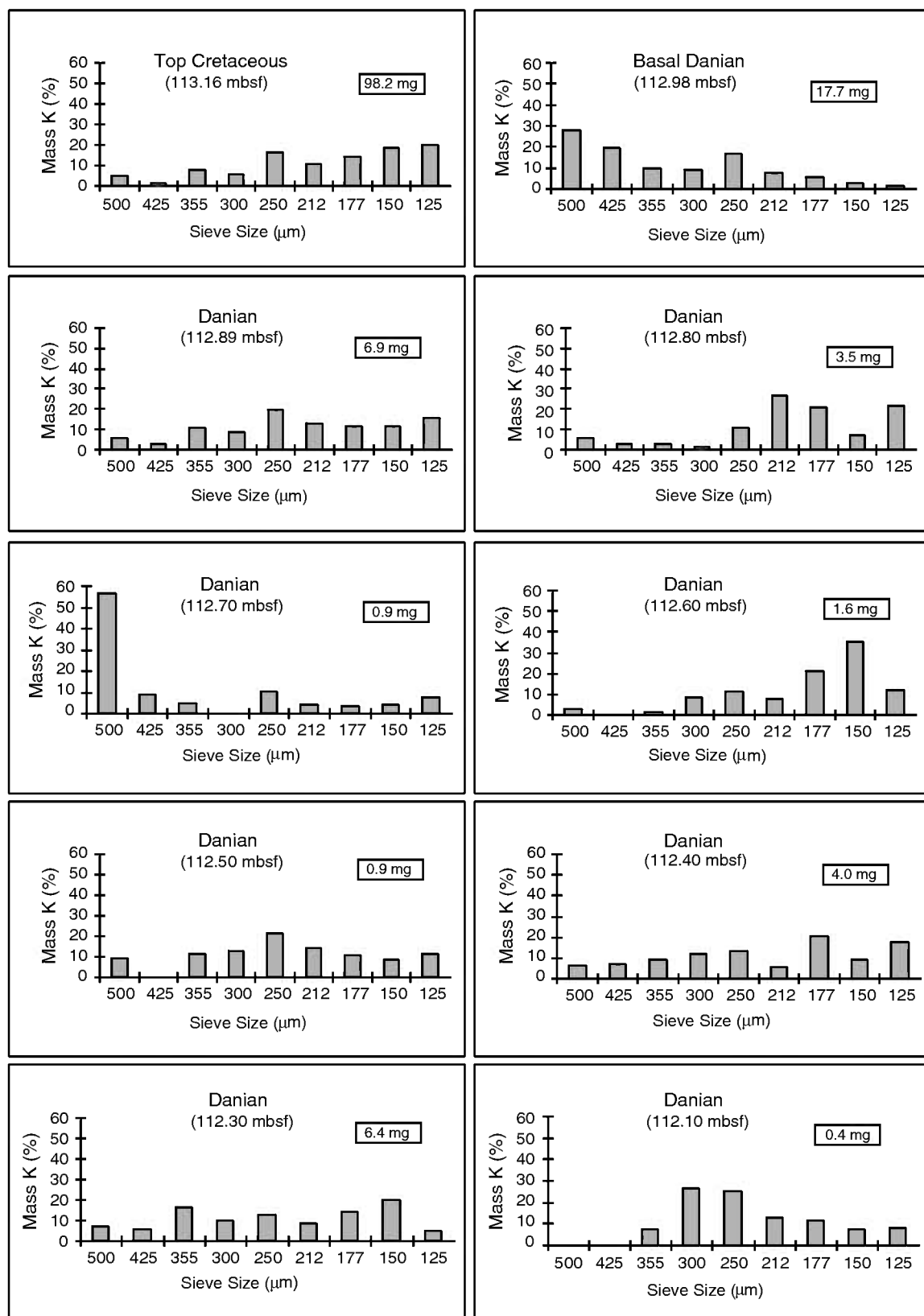


Figure 5. Weight percentage of Cretaceous (K) specimens from 1/4 phi sieve size intervals relative to total >125 μm fraction mass of Cretaceous specimens (shown in boxes) for uppermost Cretaceous and Danian samples. Note that bulk of mass of foraminifera occurs in <300 μm size fraction in Cretaceous sample (113.16 m below seafloor, mbsf), which is typical for Cenozoic and modern assemblages. Samples from above Cretaceous-Tertiary boundary have greatest mass of Cretaceous specimens concentrated in largest and intermediate size fractions.

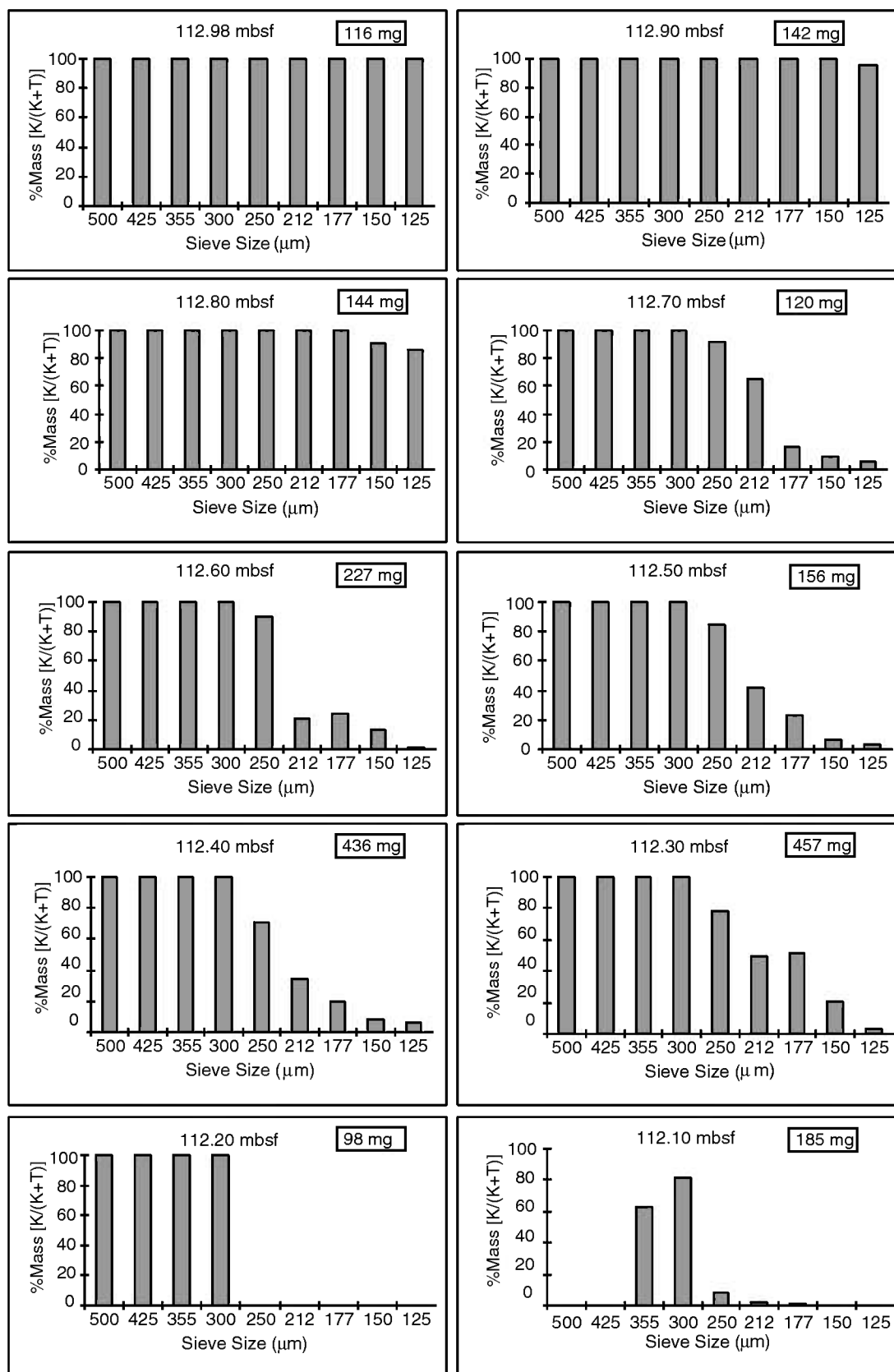


Figure 6. Percentage of Cretaceous planktonic foraminifera relative to total Cretaceous (K) and Tertiary (T) species in each of 1/4 phi size fractions above 125  $\mu\text{m}$ . Note that Danian planktonic foraminifera are initially absent from all  $>125 \mu\text{m}$  size intervals then gradually increase in abundance beginning in smallest size fractions (mbsf is meters below sea floor).

fraction was mostly redeposited on or adjacent to the continental margin, and the fine fraction was carried offshore, which contributed to the near absence of small Cretaceous foraminifera in lowermost Paleocene sediments at ODP Site 1049.

#### *Trans-K-T survivors*

Only three Cretaceous species are considered to be definite survivors of the impact event, because their shell morphology

has been linked to earliest Danian descendent species (Olsson et al., 1999). Two of these three species, *Guembelitra cretacea* and *Hedbergella monmouthensis*, were identified at Site 1049 (Fig. 7). If, on the basis of evidence presented here, all other Cretaceous species found in Danian sediments are considered reworked from underlying upper Maastrichtian sediments, then 35 of 37 species present (95%) in the topmost Maastrichtian sample studied at Site 1049 became extinct at the K-T boundary.

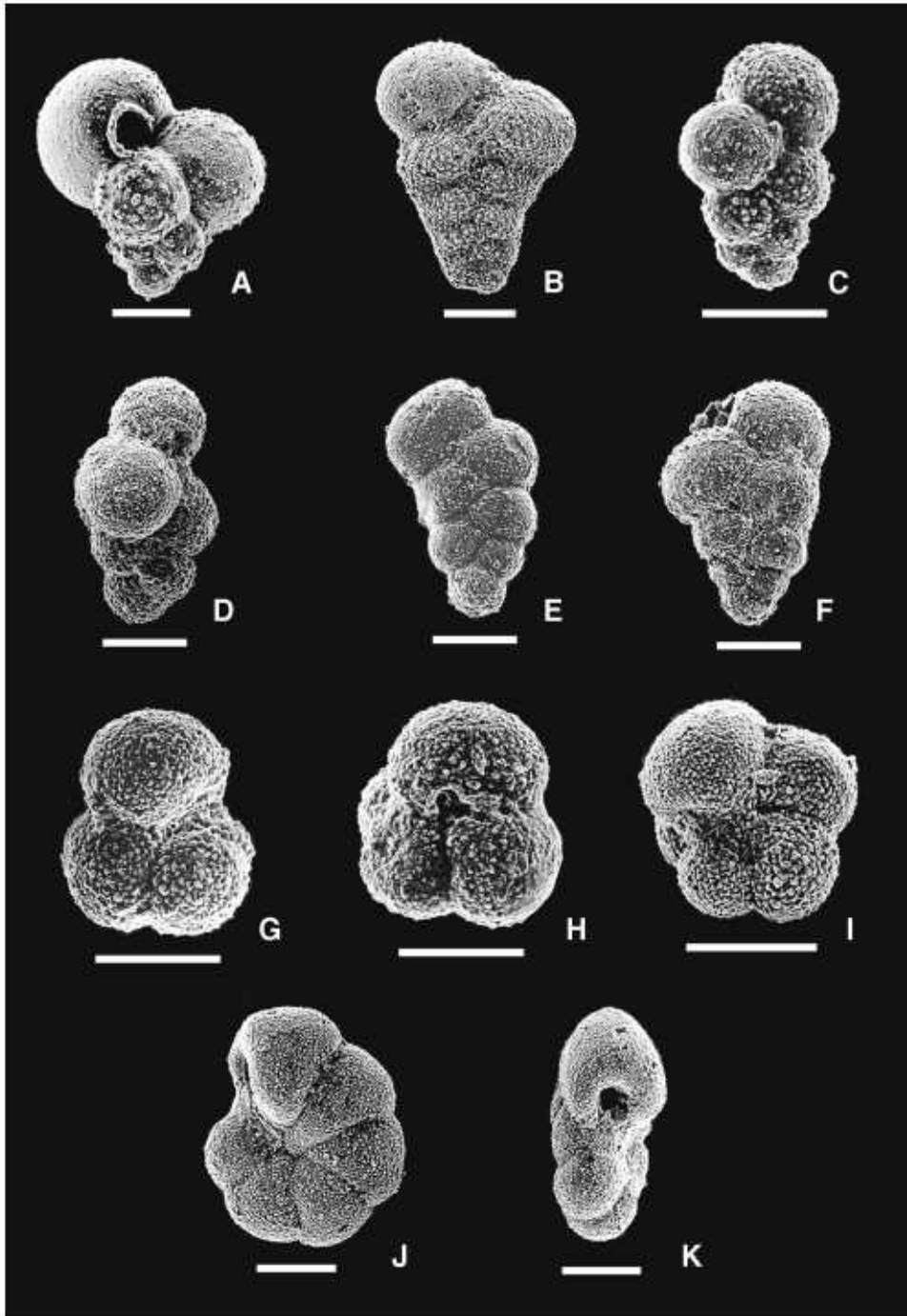


Figure 7. Planktonic foraminifera from lower Danian of Site 1049. Scale bars represent 30  $\mu\text{m}$ . A: *Guembelitra cretacea* (1049C-8X-5, 87–89 cm). B: Side view of *Heterohelix navarroensis* (1049C-8X-5, 87–89 cm). C: Side view of *Woodringina claytonensis* (1049C-8X-5, 78–80 cm). D: Edge view of *Woodringina claytonensis* (1049C-8X-5, 78–80 cm). E: Side view of *Chiloguembelina* sp. (1049A-17X-2, 64–66 cm). F: Side view of *Chiloguembelina midwayensis* (1049C-8X-5, 78–80 cm). G: Umbilical view of *Parvularugoglobigerina alabamensis* (1049C-8X-5, 78–80 cm). H: Umbilical view of *Parvularugoglobigerina extensa* (1049C-8X-5, 78–80 cm). I: Umbilical view of *Eoglobigerina eobulloides* (1049C-8X-5, 87–89 cm). J: Umbilical and (K) edge view of *Parvularugoglobigerina eugubina* (1049C-8X-5, 87–89 cm).

Although not considered as ancestral to any Danian planktonic foraminiferal lineages, the Cretaceous species *Heterohelix globulosa* is consistently more abundant than any other trans-K-T species (Table 1) and is also abundant in the smallest (>38  $\mu\text{m}$ ) size fractions relative to co-occurring Danian species, suggesting that it also may have survived the bolide impact event. However, SEM analysis of calcareous nannofossils from within the shell of a *H. globulosa* found in Danian sediments reveals the presence of Cretaceous species and the absence of Danian species (Fig. 4), which indicates that the observed specimen was reworked. Carbon isotope ratios of Danian specimens of *H. globulosa* should be compared with co-occurring Danian species to resolve this uncertainty. This approach has been effectively used to identify trans-K-T reworking at several deep-sea sites (e.g., Zachos et al., 1992; Huber, 1996) and it was used to suggest that *H. globulosa* was a K-T survivor in the Brazos River, Texas, K-T sequence (Barrera and Keller, 1990).

## CONCLUSIONS

A single 9–17-cm-thick meteorite impact ejecta bed containing shocked quartz and diagenetically altered tektite spherules marks the K-T boundary at three holes drilled at ODP Site 1049. Several features of the ejecta bed, including (1) irregularity of its basal contact with the underlying chalk, (2) presence of a foraminiferal grainstone in the lowermost 1 cm, (3) occurrence of clasts of chalk to 1 cm in diameter, (4) poor size sorting of the impact debris, and (5) variable thickness, suggest that the ejecta bed was probably emplaced during a slump or turbidity flow triggered by sediment overloading during the rapid accumulation of ejecta higher up on the continental slope.

Thin-section study reveals a sharp contact between the top of the ejecta bed and the overlying calcareous ooze containing abundant, tiny planktonic foraminifera characteristic of the early Danian P $\alpha$  Zone. It is not clear why the lowermost Danian P0 Zone is absent at Site 1049. A hiatus is one possibility, but there is no physical evidence for an unconformity at this contact (e.g., scour or hardground surface). It is also possible that the P0 Zone is facies controlled (Norris et al., 1999). The absence of this zone might have indirectly resulted from the extremely slow sedimentation rates that would have been characteristic of deep-sea pelagic carbonate environments immediately after the mass extinction of a large proportion of the calcareous plankton biomass. Slow accumulation rates in combination with bioturbation could have resulted in mixing thorough enough to obliterate the distinction between the P0 and P $\alpha$  zones.

Foraminifer distribution analysis and thin-section study indicate that the post-K-T occurrences of nearly all Cretaceous planktonic foraminiferal species are the result of reworking and that the extinction rate of foraminifera at the boundary was very high (95%) and abrupt. The rarity of small specimens of most Cretaceous species found in Danian sediments and the presence of trans-K-T specimens in Danian sediments that contain an exotic or unequivocally Cretaceous internal matrix provide the

strongest evidence that they were redeposited. The bias toward intermediate and larger sizes among these trans-K-T species is unlikely to be an artifact of in situ winnowing of an assemblage once dominated by smaller specimens, because small Danian taxa constitute nearly the entire <125  $\mu\text{m}$  fraction of the total assemblage. Instead, the widespread blanket of Cretaceous sediment underlying the Danian pelagic ooze would have been easily eroded and resuspended by lateral and downslope current activity. Such reworking of older sediments is commonly found in continental slope settings today.

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