Evidence for planktonic foraminifer reworking versus survivorship across the Cretaceous-Tertiary boundary at high latitudes

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ABSTRACT

Comparison of nannofossil and planktonic foraminifer distributions and carbon isotope analyses across the Cretaceous/Tertiary (K/T) boundary at Ocean Drilling Program (ODP) Sites 738, 690, and 750 in the Southern Ocean indicates extensive reworking of Cretaceous specimens into Tertiary sediments.

At Site 738, which yields the most complete K/T boundary sequence recovered from the deep sea, Cretaceous nannofossil and planktonic foraminifer species consistently occur throughout the Danian sequence, and several Cretaceous species have been identified in lower Eocene samples more than 100 m above the K/T boundary. In addition, the planktonic foraminifer *Globigerinelloides impensus* and inoceramid prisms have been identified in several Danian samples at Site 738, although these are known to have become extinct in the uppermost Campanian and in the mid-Maastrichtian, respectively. Strontium isotope analysis of reworked inoceramid prisms yield $^{87}Sr/^{86}Sr$ ratios expected for late Campanian biogenic calcite, whereas the $^{87}Sr/^{86}Sr$ ratios of planktonic foraminifera from near their evolutionary appearance are appropriate for their stratigraphic position.

Previous studies of K/T boundary sections from the low latitudes have determined that surface waters during the earliest Danian were more enriched in ^{12}C than in the late Maastrichtian, and the $\delta^{13}C$ vertical gradient was markedly reduced. Thus, it is possible to use the $\delta^{13}C$ values of postboundary Cretaceous species as a test of whether they lived in the Danian ocean or were reworked.

In the Southern Oceans, carbon isotope measurements of the putative K/T survivor taxon *Globigerinelloides* show no difference between Cretaceous and Tertiary values. Moreover, the $\delta^{13}C$ values of this taxon in Danian sediments are consistently higher than those of co-occurring in situ Danian species, and at Site 738 the $\delta^{13}C$ values of in situ Danian species follow a different trend than that of the *Globigerinelloides* values. This suggests that these specimens, and probably other specimens of *Globigerinelloides* in Danian sediments, were redeposited.

Taken together, these data indicate that reworking at these sites compromises arguments for enhanced postboundary survivorship of Cretaceous species in the southern high-latitude oceans.

INTRODUCTION

The pronounced turnover of planktonic foraminifera at the Cretaceous-Tertiary (K/T) boundary has been well documented for over 30 years (e.g., Olsson, 1960; Berggren, 1962; Luterbacher and Premoli Silva, 1964). These and many other studies have revealed that very large, ornate, and diverse assemblages from Maastrichtian sequences were completely replaced by minute, unornamented, low-diversity assemblages within a small stratigraphic interval. Discovery of iridium at

the K/T boundary and a proposal that the terminal Cretaceous extinctions were caused by a bolide impact (Alvarez et al., 1980) served to stimulate intensive efforts toward precisely defining the duration of this turnover. Rather than resolving this issue, however, the detailed studies that followed have led to considerable debate as to whether the planktonic foraminiferal extinctions were abrupt, occurring over the course of a few days to hundreds of years, or gradual, with extinctions spanning hundreds of thousands of years below and above the K/T boundary.

This disagreement stems from different opinions on the significance of the last species occurrences below and above the boundary. According to some workers, the gradual pattern of extinction below the K/T boundary may be an artifact of the low probability of identifying the true last occurrence of rare species, and post-K/T occurrences of Maastrichtian planktonic foraminifera may result from sediment reworking by currents or bioturbation (e.g., Smit, 1982; Smit and Romein, 1985; Huber, 1991a; Olsson and Liu, 1993; Huber et al., 1994). The number of planktonic foraminifer species thought to have survived into the Danian by proponents of an abrupt extinction scenario range from one (Smit, 1982) to three (Olsson et al., 1992; Olsson and Liu, 1993) and, most recently, four (Huber and Boersma, 1994). On the other hand, a more literal interpretation of the pattern of planktonic foraminiferal turnover has led other workers to infer that long-term endogenous factors, such as changes in sea level, temperature, and global volcanism, led to prolonged extinctions below and above the K/T boundary (e.g., Brinkhuis and Zachariasse, 1988; Keller, 1988, 1989a, 1989b, 1993; Canudo et al., 1991; MacLeod and Keller, 1994). According to authors ascribing to this view, the number of Maastrichtian species surviving into the Danian ranges from one (Brinkhuis and Zachariasse, 1988) to 21 (Keller, 1989a) or 26 (MacLeod and Keller, 1991).

Determination of whether the post-K/T occurrences of Maastrichtian species represent true survivorship or result from sediment reworking is critical to understanding what factor or factors triggered the planktonic foraminiferal turnover. This is not a simple problem, as criteria used to identify reworked microfossils are often equivocal. For example, differences in shell color and preservation may be used to distinguish reworked from *in situ* specimens, but this can only be applied to moderately to well-preserved assemblages obtained from sections where there is a significant difference between Maastrichtian and Danian lithologies. Consistency at different localities in the last occurrence ordering of Cretaceous taxa above the K/T boundary has been used as evidence of Cretaceous survivorship (Keller, 1989b), but this may be an artifact of the greater probability that the most abundant Cretaceous species will be reworked higher in a section (Liu and Olsson, 1992; Olsson and Liu, 1993). Rare species with a discontinuous stratigraphic record should not be used to characterize patterns of species turnover since their absence above their recorded last occurrence may be an artifact of sampling effects (Signor and Lipps, 1982). A change in the

relative abundance of some trans-K/T species has been used as evidence for survivorship (e.g., Smit, 1982; Keller, D'Hondt and Keller, 1991; Liu and Olsson, 1992), but such abundance changes may have been strongly influenced by differential preservation or reworking (Olsson and Liu, 1993).

A less equivocal approach for identifying survivorship and/or reworking is by comparison of the carbon isotope compositions of foraminifera and calcareous nannofossils (from fine-fraction bulk carbonate) in samples below and above the K/T boundary and with those of species that first occur within the Danian (Perch-Nielsen et al., 1982; Barrera and Keller, 1990a). This approach is based on the assumption that $\delta^{13}C$ values of near-surface water carbonates and the vertical carbon isotopic gradient (the difference between the $\delta^{13}C$ values of nannofossil carbonate or planktonic foraminifers and those of benthic foraminifers) decreased across the K/T boundary to relatively low values throughout the world's oceans during the early Danian, as a result of a decline in surface water productivity (Boersma and Shackleton, 1981; Hsü et al., 1982; Zachos and Arthur, 1986; Barrera and Keller, 1990a, 1990b, 1994; Zachos et al., 1989, 1992).

Barrera and Keller (1990a, b) used $\delta^{13}C$ analyses as a test for survivorship of the Cretaceous planktonic species *Heterohelix globulosa* and *Guembelitria cretacea* in a core from Brazos River, Texas. Their study revealed that the vertical $\delta^{13}C$ gradient dropped to negative values and the $\delta^{13}C$ composition of *H. globulosa, G. cretacea,* and the benthic *Lenticulina* sp. gradually decreased by 2.5 to 3.0‰ beginning at the K/T boundary and extending to the P1a Zone. They interpreted this as evidence that *G. cretacea* and *H. globulosa* did survive to inhabit the early Danian ocean for at least 40,000 yr. On the other hand, Zachos et al. (1992) found no difference between Maastrichtian and Danian $\delta^{13}C$ values of *H. globulosa* and *Globigerinelloides* at ODP Site 750 (southern Indian Ocean) and suggested that the Danian occurrences of those species were due to reworking. However, a significant amount of the lowermost Danian record is missing at Site 750 because of a hiatus, so comparison with the record from Brazos River may be irrelevant. Moreover, reworking is common in sediments directly above deep-sea unconformities (J. Pospichal, personal communication, 1994).

Barrera and Keller (1994) have determined that there is little change in $\delta^{13}C$ values at the K/T boundary and no significant decrease in the $\delta^{13}C$ vertical gradient in high latitudes, but there is a decrease followed by an increase in bulk carbonate, and to a lesser extent planktonic foraminiferal, $\delta^{13}C$ values beginning about 200,000 years after the K/T event. The decoupling of the low- versus high-latitude $\delta^{13}C$ records and the bulk carbonate versus planktonic foraminiferal $\delta^{13}C$ records confounds interpretation of the cause for changes in seawater $\delta^{13}C$ during the early Danian.

The purpose of this study is to compare the planktonic foraminiferal and nannofossil distributions and carbon isotope records across the K/T boundaries at ODP sites 738 and 750 in

the southern Indian Ocean and ODP Site 690 in the southern South Atlantic to evaluate the possibility of reworking of Cretaceous specimens in Tertiary sediments. This issue is important because it sheds light on whether the relatively high abundance of Cretaceous planktonic foraminifera and nannofossils in Tertiary sediments in these sections represents a low extinction rate or extended survival in high latitudes after the K/T boundary event, as some have suggested (e.g., Keller, 1993; Keller et al., 1993; MacLeod and Keller, 1994), or whether the Cretaceous specimens were simply redeposited. The Site 738 section is considered biostratigraphically complete (Thierstein et al., 1991; Pospichal and Huber, 1992), whereas a hiatus interrupts the lowermost Danian record at Site 750 (Ehrendorfer and Aubry, 1992; Pospichal and Huber, 1992) and bioturbation obscures the K/T depositional record at Site 690 (Pospichal and Wise, 1990). Planktonic and benthic foraminifera that cross the K/T boundary at all these sites are sufficiently preserved for isotopic analysis.

METHODS

Most Site 738 samples discussed in this paper were included in the biostratigraphic study of Huber (1991a, b), who described the foraminiferal preservation, species distributions, relative abundance, and biozonation as well as the sample preparation methods. The abundance, preservation, and size of the trans-K/T species and undoubtedly *in situ* Danian species dictated which samples were analyzed for oxygen and carbon isotopic ratios. *Globigerinelloides multispinus* (=*G. asperus* and *G. messinae* of other authors) was chosen because it is the most common, most consistently occurring, and largest trans-K/T species in the Danian sequence and because this species has been cited as a high-latitude K/T survivor species (Keller, 1993; Keller et al., 1993). Although *G. multispinus* occurs in every sample analyzed from Section 738C-20R-5 and makes up a significant proportion of the lower Danian assemblages, no samples from the laminated interval and few samples above yielded an adequate number of sufficiently preserved specimens larger than 125 µm for stable isotopic analyses. Such is also the case for the *in situ* Danian species *Eoglobigerina eobulloides*. Results of the isotopic analyses of these species are included in Table 1. Sample preparation and techniques for isotopic analysis are in Barrera and Keller (1994), who reported carbon and oxygen isotope values of other planktonic foraminifer taxa and bulk carbonate from the Site 738 samples discussed in this chapter and from additional Site 738 samples.

Because conventional marker species are often absent, the biostratigraphy of calcareous plankton from the southern high latitudes differs from low-latitude zonations. The Antarctic zonations used by Wei and Pospichal (1991) for calcareous nannoplankton and Huber (1991a) for planktonic foraminifera are shown in Figure 2 relative to zonal schemes used at lower latitudes.

HOLE 738C—KERGUELEN PLATEAU

Stratigraphy

The most complete deep-sea K/T boundary sequence in the southern high latitudes was recovered from Hole 738C on the southern Kerguelen Plateau (62°42'S, 82°47'E) at 2,253-m water depth (Fig. 1). The paleodepth of this site was estimated at less than 1,000 m during the early Paleocene (Barrera and Huber, 1991). The boundary is placed at a thin clay layer 96.2 cm from the top of Section 119-738C-20R-5 (377.16 m below seafloor or mbsf), about 2 cm above the base of a clay-rich, laminated interval that is about 15 cm thick (Fig. 2). Presence of the laminated interval eliminates bioturbation as a cause for upward reworking of Cretaceous material into Danian sediments at this site. Immediately underlying the boundary clay is a 6-cm-thick, well-indurated white chalk of latest Maastrichtian age, followed by a 14-cm-thick chert layer and about 2 m of unrecovered core (Barron, Larsen, et al., 1989). Above the laminated interval is a less indurated, dark-colored chalk of early Danian age that lightens and becomes increasingly bioturbated upward. Carbonate content of the bulk sediment changes from 97% in the Maastrichtian chalk to 69% in the boundary clay, then fluctuates between about 77 and 84% up to 43 cm in the K/T core section (Ehrmann, 1991; Thierstein et al., 1991). By Section 119-738C-20R-3, carbonate is about 93%.

Schmitz et al. (1991) recorded 18 parts per billion (ppb) iridium within the boundary clay, which is four times the values obtained from the uppermost Maastrichtian chalk and over 100 times the Danian background values. High concentrations of Ir gradually tail off to low values over a 1.1-m interval in Core 738C-20R. This profile was interpreted by Schmitz et al. (1991) as evidence for a single input of extraterrestrial Ir and subsequent reworking by oceanographic processes. Elevated Ir concentrations in the uppermost Maastrichtian chalk probably resulted from postdepositional transport by microbes or by downward absorption and diffusion processes (Schmitz et al., 1991; Thierstein et al., 1991).

The nannofossil and planktonic foraminiferal biostratigraphies of this sequence indicate that the K/T boundary interval is biostratigraphically complete (Wei and Pospichal,1991; Huber, 1991a; Pospichal and Huber, 1992; Keller, 1993). The calcareous nannofossil biostratigraphy of Wei and Pospichal (1991) was modified by Pospichal and Huber (1992) such that the top of Zone NA1 (based on the first occurrence [FO] of the Tertiary genus *Hornibrookina*) is now placed at 86 cm and the top of Zone NA2 (= top of Zone NP1) is at 16 cm in Section 738C-20R-5. The last high-latitude Mesozoic marker, *Nephrolithus frequens*, is common to abundant throughout the upper Maastrichtian section (Wei and Thierstein, 1991).

The upper Maastrichtian foraminiferal zonal marker *Abathomphalus mayaroensis* was not identified in the limestone immediately below the boundary clay in Section 119-738C-20R-5 (Fig. 2), perhaps because of the strongly indurated

TABLE 1. OXYGEN AND CARBON ISOTOPIC VALUES OBTAINED FOR THIS STUDY FROM FINE
FRACTION (<38 μm) CARBONATE AND PLANKTONIC FORAMINIFERA ACROSS THE K/T
BOUNDARY AT SITE 738*

Core interval, ODP Hole 738C	Depth (mbsf)	*Globigerinelloides multispinus*		*Eoglobigerina* spp.		Bulk Carbonate	
		$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$	$\delta^{18}O$	$\delta^{13}C$
20R-3, 139-141	374.49			-0.08	1.52		
20R-4, 17-19	374.77			0.19	1.54	-0.35	2.48
20R-4, 19-21	374.79			0.80	1.54		
20R-4, 59-61	375.19			0.21	1.54		
20R-4, 99-100	375.59			0.20	1.31		
20R-4, 108-110	375.68					0.01	1.79
20R-4, 129-130	375.89	-0.06	2.25				
20R-4, 130-131	375.90			0.18	1.54		
20R-4, 134-135	375.94			0.24	1.32		
20R-5, 4-5	376.14			-0.04	1.42	-0.07	0.55
20R-5, 8-10	376.18			0.11	1.61	-0.45	0.94
20R-5, 15-16	376.25	-0.35	2.13	-0.11	1.69		
20R-5, 16-17	376.26					-0.35	0.78
20R-5, 27-28	376.37	-0.25	2.10	-0.26	1.51	-0.27	0.86
20R-5, 33-34	376.53	-0.49	1.95	-0.21	1.62		
20R-5, 55-56	376.75	-0.42	2.04	-0.17	1.67	-0.38	1.55
20R-5, 65-66	376.85	-0.38	2.06	-0.19	1.91		
20R-5, 66-67	376.86					-0.59	1.54
21R-1, 34-36	380.25	-0.30	2.50				
22R-1, 10-12	389.76	-0.11	2.01			-0.32	2.04

*All stable isotope values are expressed relative to the PDB standard.

nature of the sediment. This species occurs consistently in samples below, from the core-catcher of Core 119-738C-20R through Core 119-738C-23R. The foraminifer Zone P0 was not recognized by Huber (1991a) since the marker species *Parvularugoglobigerina eugubina*, whose first occurrence defines the upper P0 zonal boundary, was not found in any Site 738 sample. A subsequent search for this taxon by Huber et al. (1994) using a larger number of specimens has yielded similar results. Because of the absence of this species, Huber (1991a) used the

Antarctic Paleogene zonal scheme of Stott and Kennett (1990a), with a modified definition of Zone AP1 for subdivision of the Paleogene sequence. Zone APα, defined from the FO of *Eoglobigerina fringa* to the FO of *Globoconusa daubjergensis*, extends from the K/T boundary clay to 57 cm in the K/T core section. Although the nominate species of this zone is now considered a junior synonym of *Eoglobigerina eobulloides* (Olsson et al., 1992), the latter species was also reported by Huber (1991a) immediately above the boundary clay. Zone
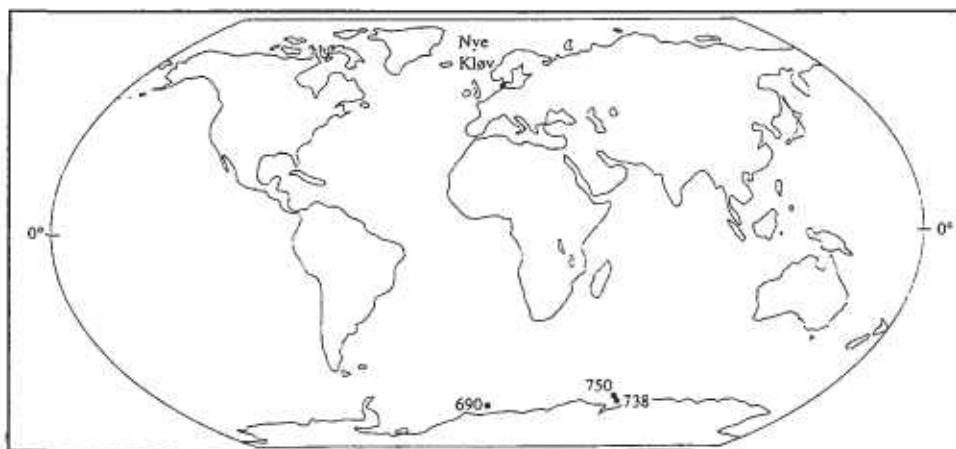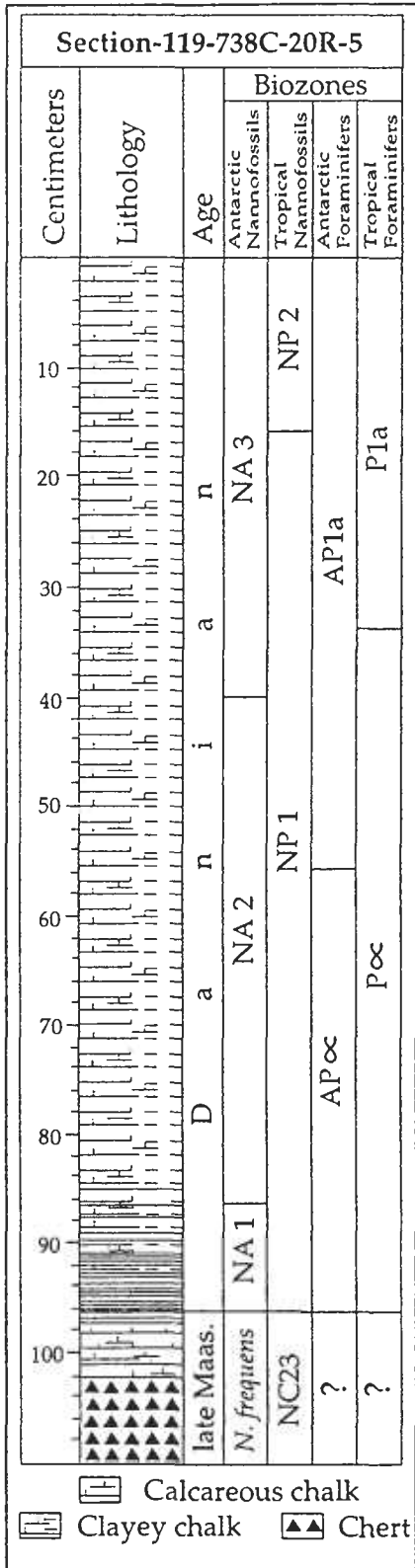

Figure 1. Location of land-based and deep-sea K/T boundary sites discussed in this study.

AP1a comprises the interval from the FO of *G. daubjergensis* to the FO of *Praemurica inconstans*, extending from 376.76 to 372.88 mbsf (Huber, 1991b).

Trans-K/T species occurrences

Relative abundance counts of nannofossils below and above the Site 738 K/T boundary (Wei and Pospichal, 1991) reveal that Cretaceous species decrease from 100% of the total assemblage at the top of the Maastrichtian chalk to less than 5% within 2 m above the boundary (Fig. 3). Wei and Pospichal (1991) recognized a significant reworking component among the Danian nannofossil assemblages they identified; 12 species were considered by these authors as reworked, and some of these were found at sporadic intervals throughout the Danian sequence up to the middle of Zone NA-6. Four species were identified as K/T survivors. These occur sporadically in the lower Danian sequence in common to rare abundance. Incoming Tertiary species gradually increase in abundance and diversity upward from 8 cm above the boundary. After noting a strong correlation between the decreasing abundance of Cretaceous nannofossils and the iridium profile above the K/T at Site 738, Pospichal (1996) suggested that most of the trans-K/T nannofossils were probably redeposited by bottom currents.

Fourteen species of Cretaceous planktonic foraminifera have been identified in sediments above the K/T boundary at Site 738 (Fig. 4). *Globigerinelloides multispinus, G. subcarinatus, Heterohelix planata, H. globulosa*, and *Archaeoglobigerina australis* are the most common and consistently occurring of the trans-K/T species, and three of these species—*G. multispinus, G. subcarinatus*, and *H. planata*—occur in samples as high as lower Eocene foraminiferal Zone AP6a. Such anomalously high stratigraphic occurrences of Cretaceous taxa and similar abundances of Cretaceous species above and below the K/T boundary strongly indicate postboundary reworking.

Evidence for reworking of the coarser sediment fraction at Site 738 is also derived from the occurrence in Tertiary sediments of species whose extinction level is below the K/T boundary as well as by comparison of the strontium isotope ratios of suspected reworked specimens with *in situ* specimens. A single specimen of *Globigerinelloides impensus*, which has a well-documented last occurrence datum that correlates with upper polarity Subchron C33N and is used to identify the Campanian/Maastrichtian boundary in the southern high latitudes (Huber, 1992), was identified in one sample from Zone AP1a in Section 119-738C-20R-5 (Huber, 1991a). *Inoceramus* prisms were also identified in Danian sediments, well above their

Figure 2. Lithology and biostratigraphy of Section 20R-5 at ODP Site 738. The Antarctic nannofossil zonal scheme of Wei and Pospichal (1991) is shown correlated with the tropical nannofossil zonation of Martini (1971). The Antarctic Paleogene planktonic foraminifer zonal scheme of Huber (1991a), modified from Stott and Kennett (1990a), is shown relative to the tropical planktonic foraminifer scheme of Berggren and Miller (1988).
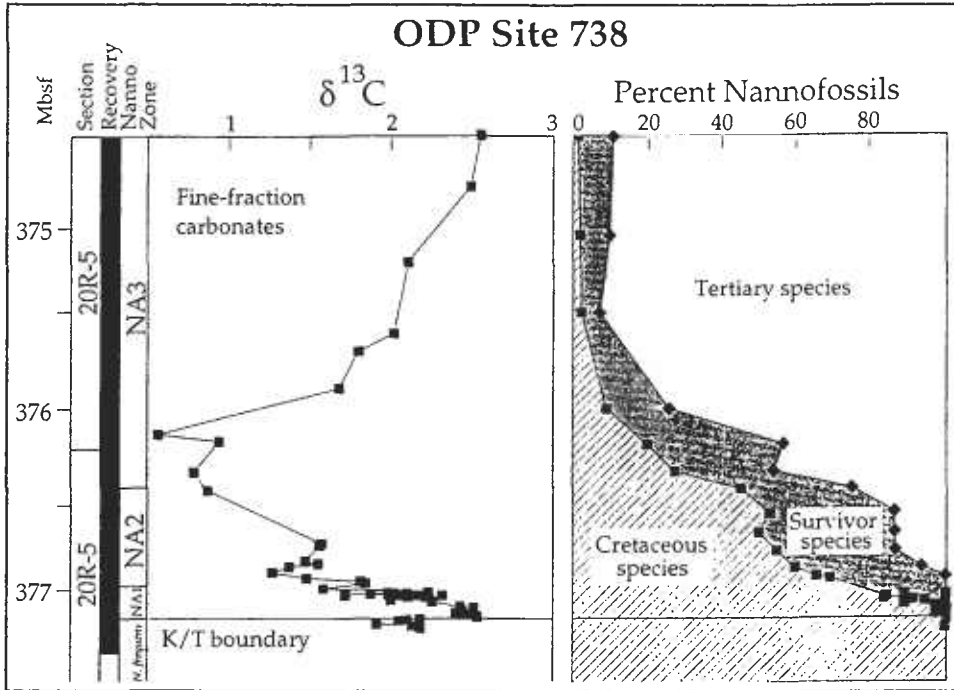
Figure 3. Carbon isotopic composition of fine-fraction carbonate and relative abundance of Creta-
ceous, survivor, and Tertiary nannofossils in sections 4 and 5 of Core 119-738C-20R. Nannofossil
zonation and abundance data from Wei and Pospichal (1991), Pospichal and Huber (1992), and
Pospichal (1996). Modified after Barrera and Keller (1994). Solid black represents interval recov-
ered. All carbon isotope values are expressed relative to the PDB (Peedee belemnite) standard. Mbsf
= meters below sea floor.

extinction level, which occurred during the mid-Maastrichtian,
near the base of the *Abathomphalus mayaroensis* Zone (Mac-
Leod, 1994; MacLeod et al., this volume). MacLeod and Huber
(1996) have documented that prisms isolated from upper Maas-
trichtian and Danian intervals of Site 738 yield strontium iso-
topic ratios expected for late Campanian fossils, whereas
samples of co-occurring planktonic foraminifera near their evo-
lutionary first appearance yield strontium isotopic ratios appro-
priate for their stratigraphic position. Occurrence of *G. impensus*
in Danian sediments at Site 738 and the strontium isotope data
provide strong evidence of an upper Campanian source bed for
the reworked microfossils. Occurrence of *A. mayaroensis* and *G.
subcarinatus* in Danian cores indicates that upper Maastrichtian
units also served as a source for the reworked sediments.

Among the trans-K/T planktonic foraminifera, three species,
including *Guembelitria cretacea*, *Hedbergella monmouthensis*,
and *Zeauvigerina waiparaensis*, have been well documented as
survivors of the terminal Cretaceous extinction event (Liu and
Olsson, 1992; Keller, 1993; Huber and Boersma, 1994). The spo-
radic distribution within the Danian of *G. cretacea* and *H. mon-
mouthensis* precludes assumptions as to whether or not their
occurrences at Site 738 represent survivorship or reworking. But
Z. waiparaensis is one of the most abundant and consistently
occurring planktonic species in the lower Danian at Site 738

(Huber, 1991a, b; Keller, 1993; Huber and Boersma, 1994), and
its distribution within the Danian sediments therefore is not con-
sidered an artifact of reworking.

The information presented above clearly indicates that there
is a significant reworked component among the Danian micro-
fossil assemblages at Site 738. However, it is still possible that
some of the trans-K/T species considered as reworked also
include *in situ* survivors within the lower Danian. Further insight
to the survivorship versus reworking question can be gained by
isolating specimens of the most common "reworked" species
and obtaining measurements of their carbon isotopic ratios.

Carbon isotope results

Carbon isotopic data for Site 738 are presented in Table 1
and Figure 5 for bulk carbonate, the Danian planktonic foramini-
fers *Eoglobigerina* spp. and *Parasubbotina pseudobulloides*, and
the putative survivor planktonic foraminifer *Globigerinelloides
multispinus*. Most of the bulk carbonate and all of the *Gaveli-
nella beccariiformis* and *P. pseudobulloides* data presented in
Figure 5 were reported previously by Barrera and Keller (1994).
Too few specimens of trans-K/T and *in situ* Danian foraminifera
occur below 376.85 mbsf for stable isotopic analysis.

One of the most significant features of the curves illustrated
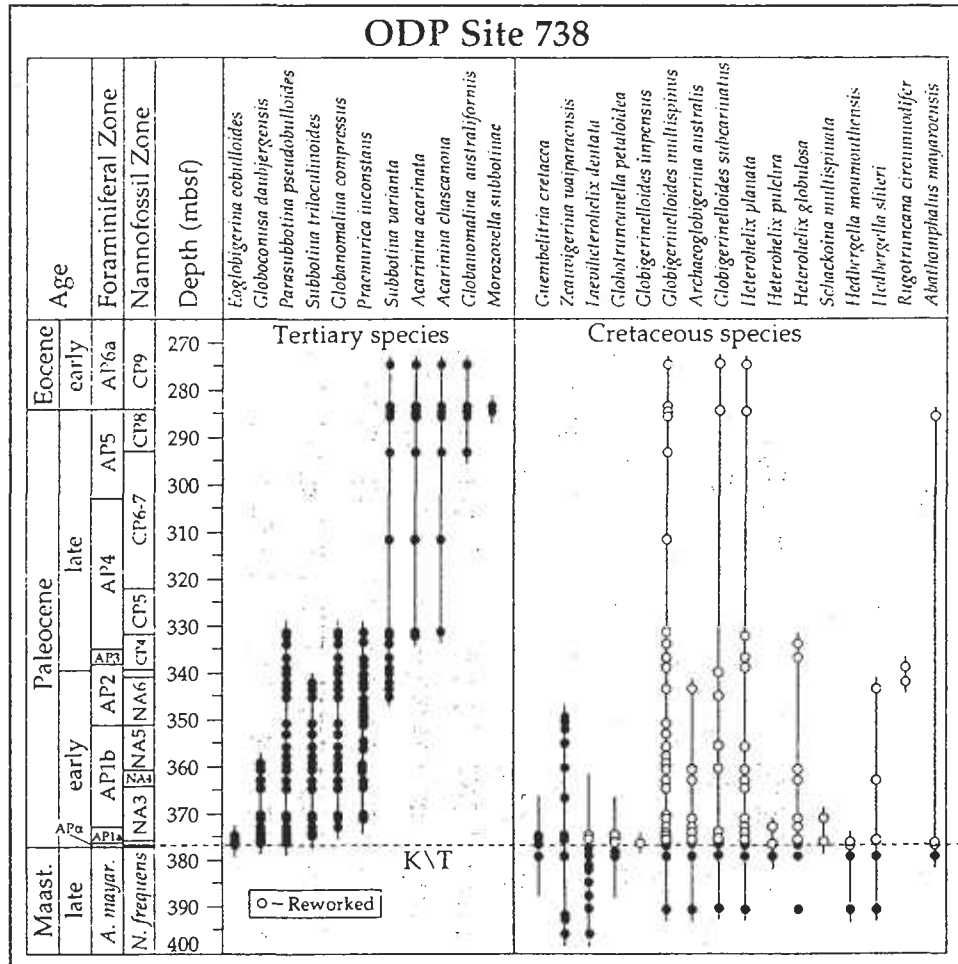in Figure 5 is that the fine-fraction bulk carbonate and *in situ*

Figure 4. Distribution of Cretaceous and selected Tertiary planktonic foraminifera in Maastrichtian through lower Eocene sediments at Site 738. Planktonic foraminifer biozonation based on Huber (1991a, b) and nannofossil biozonations based on Wei and Pospichal (1991) and Wei and Thierstein (1991).

Danian foraminifer curves are decoupled. The bulk carbonate curve shows a 0.4‰ positive shift across the boundary, with values of 2.41 and 2.52‰ up to 90 cm in Section 119-738C-20R-5. This is followed by a decrease, increase, then marked decrease to a minimum of 0.55‰ at 376.94 mbsf within lower Zone NA3. The bulk carbonate δ^{13}C values then return to about 2.0‰ by 375.84 mbsf. *Eoglobigerina* spp. shows a less dramatic change in δ^{13}C values within this stratigraphic interval, with a decrease from 1.69‰ at 376.25 mbsf to between 1.32‰ and 1.54‰ from 375.91 mbsf to 375.59 mbsf. Where they overlap, the δ^{13}C values of *Eoglobigerina* spp. and *P. pseudobulloides* are within 0.2‰ of each other and are ~1.0‰ more negative than bulk carbonate δ^{13}C by the middle of Zone NA3. A more detailed discussion of the Site 738 isotopic records and their correlation to those of Sites 690 and 750 is in Barrera and Keller (1994).

Comparison of the percentage of Cretaceous nannofossils and the bulk carbonate δ^{13}C curve at Site 738 (Fig. 3) reveals

parallel trends up to the bottom of Section 119-738C-20R-4, where Cretaceous nannofossils make up less than 5% of the total assemblage. This correspondence may suggest that the Danian bulk carbonate curve is largely controlled by changes in the taxonomic composition of nannofossil species (Thierstein et al., 1991; Barrera and Keller, 1994). Hence bulk carbonate δ^{13}C may not be a useful proxy for estimation of changes in surface water paleoproductivity without a better understanding of nannofossil vital effects.

The δ^{13}C analyses of *Globigerinelloides multispinus* reveals no significant change in δ^{13}C composition across the K/T boundary. Moreover, this species maintains a δ^{13}C composition between 1.95 and 2.25‰, while the *in situ* Danian species *Eoglobigerina* spp. became more negative in δ^{13}C, decreasing from 1.91‰ at 376.85 mbsf to a minimum of 1.31‰ at 375.89 mbsf. These results suggest that *G. multispinus* was not a survivor species but was likely redeposited from Cretaceous sediments elsewhere on the southern Kerguelen Plateau.
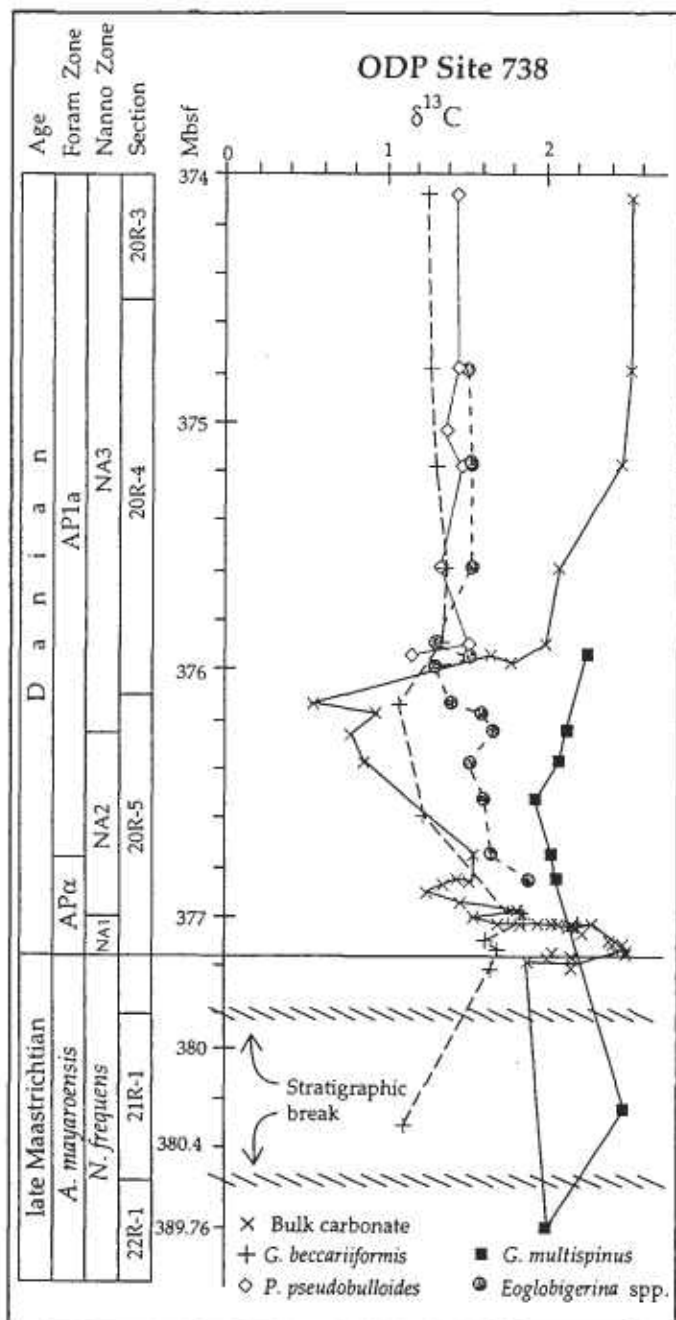
Figure 5. Carbon isotope data from fine-fraction carbonate, the benthic *Gavelinella beccariiformis*, the trans-K/T species *Globigerinelloides multispinus*, and the *in situ* Danian species *Parasubbotina pseudobulloides* and *Eoglobigerina* spp. from cores 119-738C-20R through -22R. Data from this study and Barrera and Keller (1994). All carbon isotope values are expressed relative to the PDB standard.

HOLE 750A—KERGUELEN PLATEAU

Stratigraphy

A discontinuous K/T boundary section was recovered from Hole 750A, which is located at 57°35.5′S and 81°14.4′E on the Kerguelen Plateau (southern Indian Ocean) in 2,031-m water

depth. Quilty (1992b) assigned a middle- to upper-bathyal paleodepth to this site for the Maastrichtian, based on the taxonomic composition of the benthic foraminiferal assemblages. The K/T boundary is placed at 91.5 cm in Section 120-738C-15R-3 (349.50 mbsf), where there is a fractured and discontinuous contact between a semilithified, white, nannofossil chalk of late Maastrichtian age and a more lithified dark grayish-green marl of early Danian age (Schlich, Wise et al., 1989). The sharpness of the K/T contact and breaks in the cored sediment indicate that the discontinuous recovery of the boundary interval was at least partly due to drilling disturbance. Unlike those in Site 738, the lowermost Danian sediments are not laminated. Whole-rock carbonate measurements are near 95% in the Maastrichtian chalk, then decrease to 83% just above the boundary level, and rebound to 95% by about 70 cm above the boundary (Zachos et al., 1992). The increasing carbonate content within the lower Danian sediments is reflected by a gradual lightening of the sediment color.

The biostratigraphy of the K/T sequence from Hole 750A was originally reported by Ehrendorfer and Aubry (1992) for calcareous nannofossils and by Quilty (1992a) and Berggren (1992) for planktonic foraminifera. Further discussion of the Site 750 biostratigraphy was presented in Pospichal and Huber (1992). All of these authors reported the presence of uppermost Maastrichtian biozones (*Nephrolithus frequens* Zone for nannofossils and *Abathomphalus mayaroensis* Zone, *Pseudotextularia elegans* Subzone for planktonic foraminifera), suggesting that the upper Maastrichtian is biostratigraphically complete. Absence of calcareous nannoplankton zones NA1 and lowermost NA2 indicates that the lowermost Danian is incomplete (Pospichal and Huber, 1992). Poor preservation and lack of diagnostic species has precluded recognition of planktonic foraminiferal zonal subdivisions of the lowermost Danian based on definitions of the tropical P-zones (Berggren, 1992).

Trans-K/T species occurrences

Relative abundance counts of calcareous nannoplankton across the K/T boundary at Site 750 (Fig. 6) reveal that the Cretaceous assemblages were gradually replaced by Danian assemblages within 3.58 m above the K/T contact (Ehrendorfer and Aubry, 1992). A total of 22 Cretaceous nannofossil species found in Danian sediments at Site 750 were considered by Ehrendorfer and Aubry (1992) to have been reworked. These become increasingly rare and sporadic in occurrence upward, then disappear by 3.42 m above the boundary. These authors identified eight additional taxa that cross the K/T boundary as persistent species (similar to survivor species). The first incoming species of *Hornibrookina* appears immediately above the boundary. This is followed by the gradual appearance and increasing dominance of other incoming taxa.

The distribution of planktonic foraminifera in the upper Maastrichtian–lower Danian sequence from Hole 750A is illustrated in Figure 7, which is modified from Zachos et al. (1992.
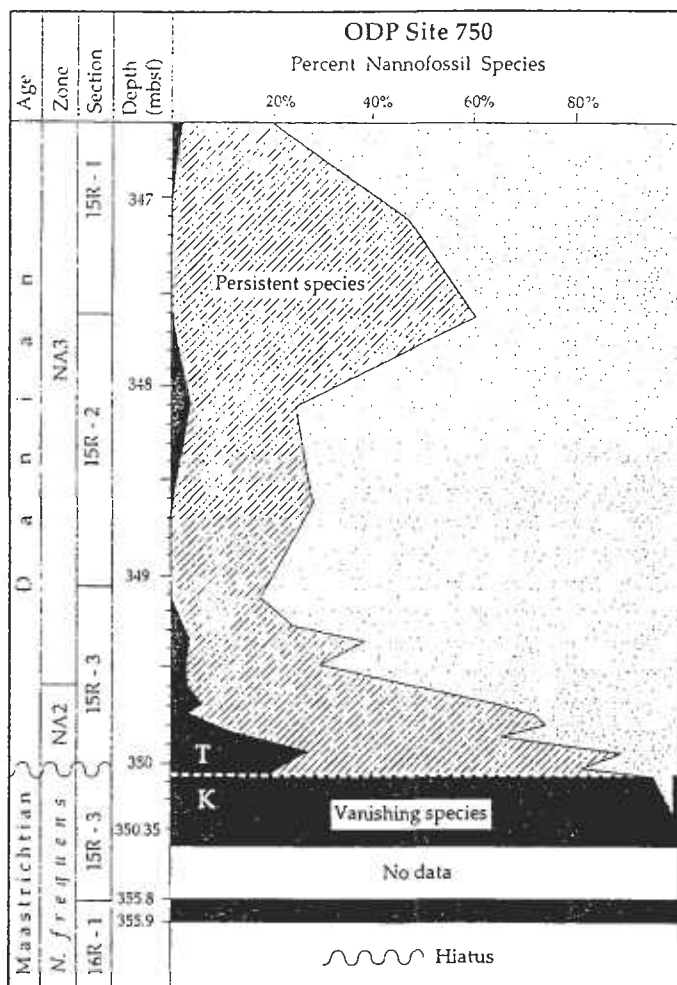
Figure 6. Relative abundance of nannofossils (excluding *Thoracosphaera* spp. and *Prinsius* sp.) from upper Maastrichtian through lower Danian sediments at Site 750 based on the quantitative data presented in Ehrendorfer and Aubry (1992, Table 8) relative to the Antarctic nannofossil zonation defined by Wei and Pospichal (1991). "Vanishing" species include all taxa that became extinct at or below the K/T boundary, "persistent" species include all taxa that lived in the Cretaceous and Tertiary ocean, and "incoming" species include all taxa that first appeared in the Danian.

Fig. 6). Three species (*Rugoglobigerina macrocephala, R. pustulata,* and *R. rugosa*) were identified in only the lowermost Danian sample, two species (*Heterohelix* sp. 1 and *Heterohelix* sp. 2) consistently occur up to the top of Zone NA2, and two species (*Globigerinelloides multispinus* and *G. subcarinatus*) have consistent occurrences into Zone NA3, 30 cm above the K/T boundary. Within the samples that were studied, these species were represented by one to several specimens.

No species with an extinction below the K/T boundary was found in the Danian sediments at Site 750, and no discernable color differences were reported for the trans-K/T species. Hence, it is not clear based on the microfossil distributions whether the post-K/T occurrences of Cretaceous species resulted from reworking or survivorship.

Carbon isotope results

A carbon isotopic record across the K/T boundary at Site 750 was obtained by Zachos et al. (1992) for bulk carbonate, the trans-K/T species *H. globulosa* and *Globigerinelloides* spp., the Danian species *Eoglobigerina eobulloides,* and the benthic species *Nuttalides truempyi.* All of the specimens analyzed by Zachos et al. (1992) were selected from the >150-µm fraction. These data are replotted in Figure 8.

Although the Paleocene sedimentary record below upper Zone NA2 is missing at Site 750, comparison of the Site 750 and Site 738 $\delta^{13}C$ plots (Figs. 5, 8) reveals a similar interval of overlap in upper Zone NA2 between the bulk carbonate and benthic foraminifer curves. This interval is followed at both sites by a positive shift in bulk carbonate values of more than 1‰ in lower Zone NA3, then relatively little change in values through middle Zone NA3. It is not clear at Site 750 whether or not the bulk carbonate record is decoupled from the Danian planktonic foraminifer $\delta^{13}C$ record, as there are too few measurements of *E. eobulloides* for comparison of long-term trends.

The trans-K/T planktonic foraminifera show little difference between their Cretaceous and Tertiary carbon isotopic compositions. As at Site 738, the mean $\delta^{13}C$ values of these taxa are significantly heavier than the bulk carbonate and Danian planktonic foraminifer values. On this basis, Zachos et al. (1992) concluded that the trans-K/T species recovered from Danian sediments were reworked.

HOLE 690C—MAUD RISE

Stratigraphy

A biostratigraphically complete, but heavily bioturbated, K/T boundary was recovered in Hole 690C, located on Maud Rise (65°9'S, 1°12'E) in the Weddell Sea sector of Antarctica at 2,925-m water depth. Thomas (1990) assigned a lower bathyal water depth to this site for K/T boundary time based on the composition of benthic foraminiferal assemblages. The boundary occurs within Section 113-690C-15X-4 and is marked by a distinct change in color from a white nannofossil ooze that contains isolated blebs of Danian marl to a pale brown marl containing isolated blebs of Maastrichtian chalk (Barker, Kennett et al., 1988). Whole-rock measurements yield percent carbonate values of 80 to 90% within the white chalk and about 44 to 60% within the pale brown marl (Stott and Kennett, 1990b).

Stott and Kennett (1990a) placed the K/T boundary within a 10-cm interval between 35 and 45 cm in Section 113-690C-15X-4, where Tertiary planktonic foraminifera make up more than 50% of the assemblage. Foraminiferal assemblages from the white nannofossil ooze below were assigned to the *Abathomphalus mayaroensis* Zone, and assemblages from above were assigned to Zone APα, which Stott and Kennett (1990a) defined as the partial range of *Eoglobigerina fringa* from the last occurrence (LO) of *A. mayaroensis* to the initial "common"
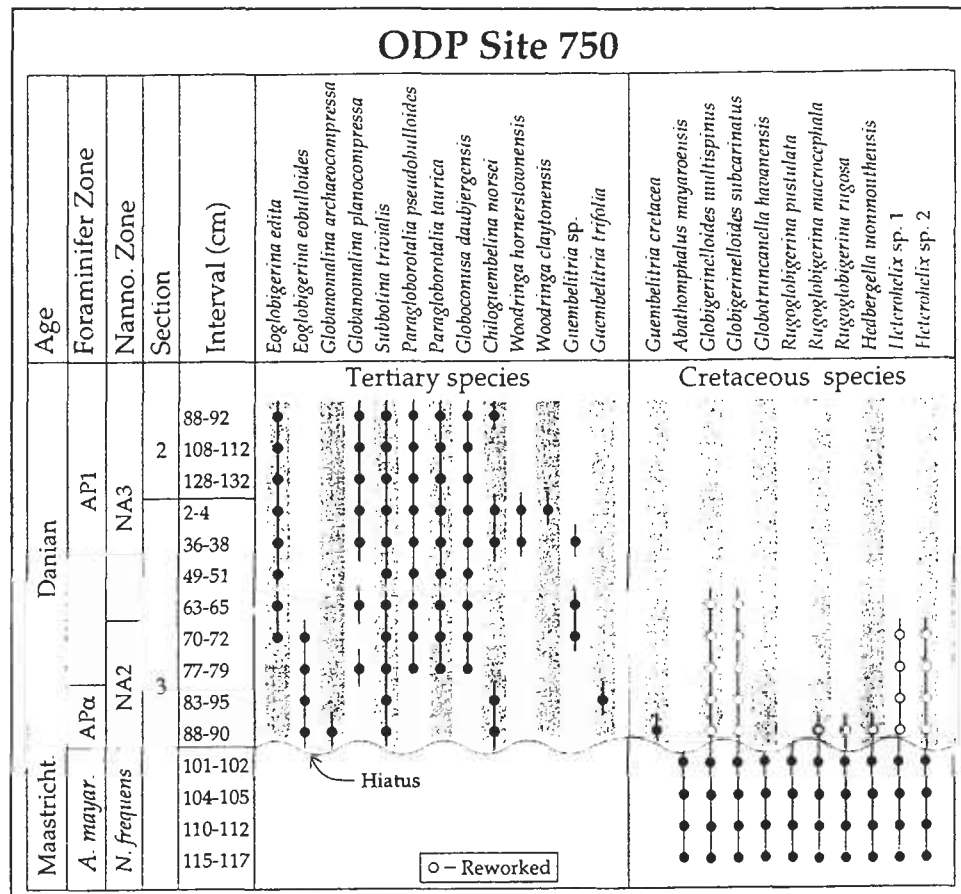
Figure 7. Distribution of Cretaceous and selected Tertiary planktonic foraminifera in Maastrichtian through lower Danian samples from Core 120-750A-15R. modified from Zachos et al. (1992) to include the Antarctic Paleogene biozonation of Huber (1991a) for planktonic foraminifera and Wei and Pospichal (1991) for nannofossils.

occurrence of *P. pseudobulloides*. These authors attributed the absence of *P. eugubina* from the lower Danian at Site 690 to the high-latitude location outside of its biogeographic range.

Pospichal and Wise (1990) more precisely constrained the boundary at 41.5 cm within Section 113-690C-15X-4 (247.815 mbsf), based on the first occurrence of the Tertiary nannofossil *Biantholithus sparsus* in sediments considered as in situ. This level is near the top of a magnetically reversed interval assigned to polarity Subchron C29R (Hamilton, 1990), and it corresponds with an iridium anomaly measuring 1,566 ± 222 parts per trillion (Michel et al.. 1990). Nannofossils from the white ooze levels below the K/T boundary were assigned to the *Nephrolithus frequens* Zone, and those from the brown marl above were assigned to Zone CP1a by Pospichal and Wise (1990). These authors did not recognize a hiatus immediately above the boundary, but they did suggest that a hiatus may separate zones CP1a and CP1b between 247.39 and 247.23 mbsf, based on distinct changes in the nannofossil assemblages and a corresponding abrupt shift in the δ13C values reported by Stott and Kennett (1990b).

More recently. Wei and Pospichal (1991) identified their

basal Danian Zone NA1 immediately above the boundary level and recognized the NA1/NA2 zonal boundary about 15 cm above the iridium enrichment layer. Lower occurrences of *Hornibrookina*, the zonal marker for the NA1/NA2 boundary, are considered the result of burrowing (Wei and Pospichal, 1991). The most recent interpretation of the nannofossil biostratigraphy suggests that the lower Danian at Site 690 is more condensed than at Site 738 and may contain hiatuses within and between Zones NA1 and NA2 (Pospichal. personal communication. 1994).

Trans-K/T species occurrences

The pattern of species turnover at the K/T boundary in Hole 690C is obscured by the intense bioturbation that has occurred from about 130 cm below to 39 cm above the boundary (Pospichal and Wise. 1990). Relative abundance counts of nannofossils reported in Pospichal and Wise (1990) reveal high proportions of Tertiary and survivor species from dark blebs well within the upper Maastrichtian *N. frequens* Zone and at
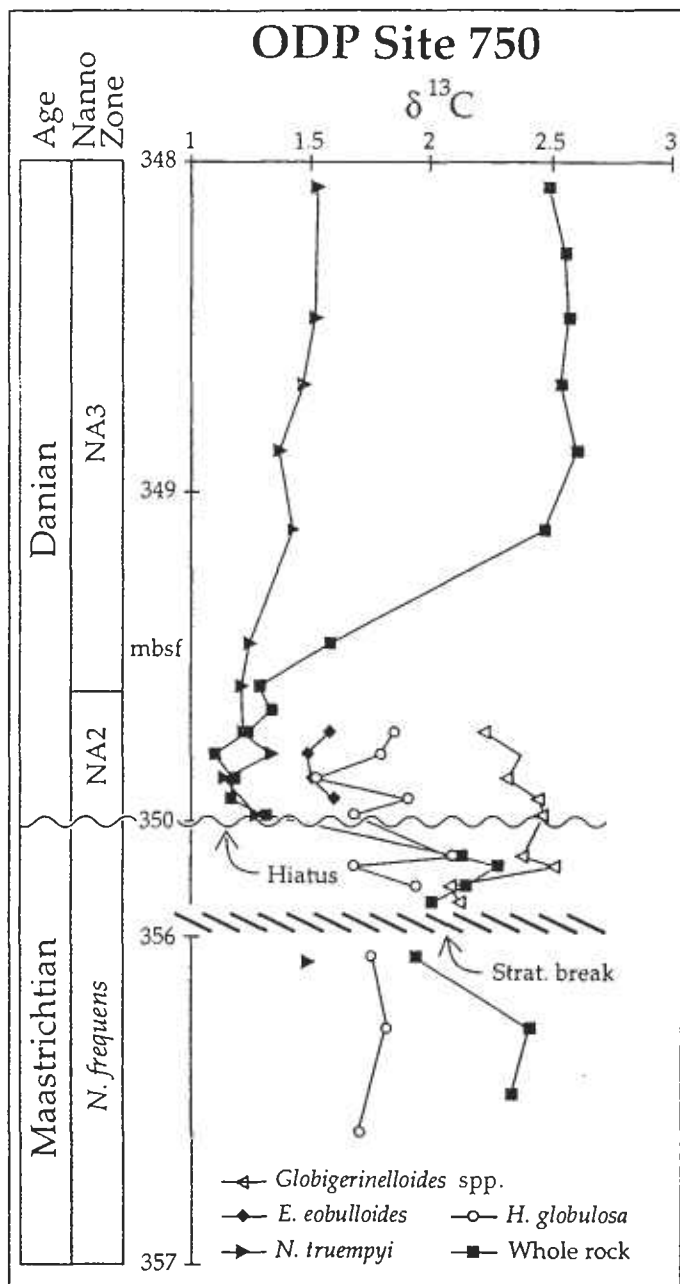
Figure 8. Carbon isotope data for ODP Hole 750A from bulk carbon-ate, the benthic foraminifer *Nuttalides truempyi*, the trans-K/T taxon *Globigerinelloides* spp.. and the Danian species *Eoglobigerina eobul-loides*. Modified from Zachos et al. (1992) to include the Antarctic nannofossil biostratigraphy of Wei and Pospichal (1991). All carbon isotope values are expressed relative to the PDB standard.

Figure 9. Relative abundance of nannofossils from upper Maastricht-ian through lower Danian sediments from ODP Hole 690C modified after Pospichal and Wise (1990). Burrowed intervals were identified by Pospichal and Wise (1990) based on sediment color differences and abrupt incursions of Tertiary and survivor species.

least one sharp increase in Cretaceous species within Zone NA2 (Fig. 9). These authors reported the presence of Creta-ceous species as high as 5 m above the boundary level.

Similarly. the planktonic foraminiferal turnover is spread across several tens of centimeters as the result of bioturbation. There is no way to determine, based on distributional analysis, whether some of the trans-K/T species from within the biotur-
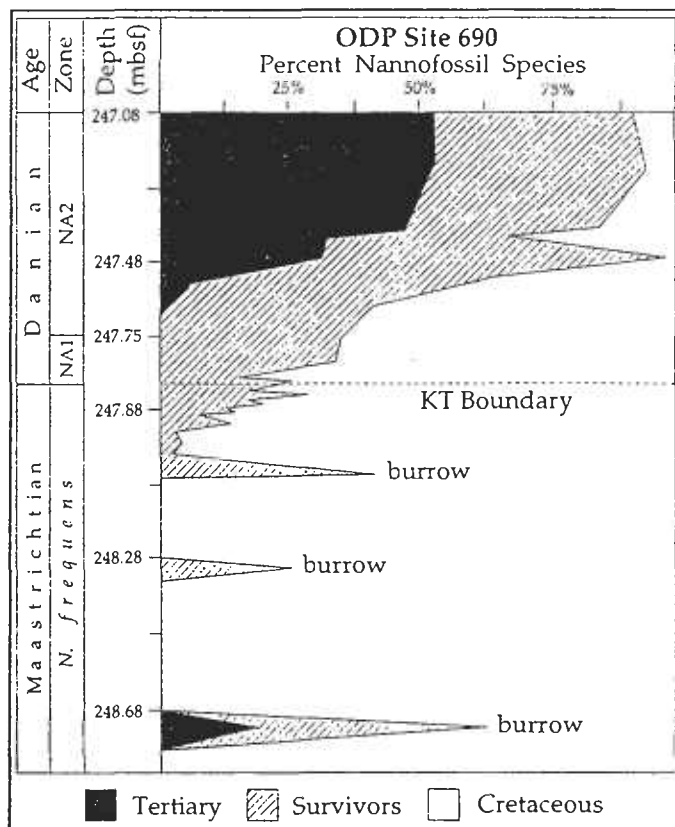
bated interval were survivors of the terminal Cretaceous extinction event. But occurrences of *G. subcarinatus* and *G. multispinus* at sample levels that are 10 m and as high as 32 m above the K/T (Fig. 10) are clearly the result of sediment rede-position.

Carbon isotope results

The stable isotopic stratigraphy of the K/T transition at Site 690 was reported by Stott and Kennett (1990b). Material analyzed includes fine-fraction carbonate. the benthic species *Gavelinella beccariiformis*, the Danian species *Eoglobigerina fringa* and *P. pseudobulloides*, and the trans-K/T species *H. globulosa* and *Globigerinelloides multispinus*. Results of those analyses are plotted in Figure 11.

The $\delta^{13}C$ values of fine-fraction carbonate are similar to the co-occurring *Globigerinelloides multispinus* values and are consistently heavier than the *H. globulosa* and benthic foraminifer values throughout the upper Maastrichtian sec-tion. As occurs at sites 738 and 750. the fine-fraction carbon-ate then becomes very negative in the lower Danian. with the
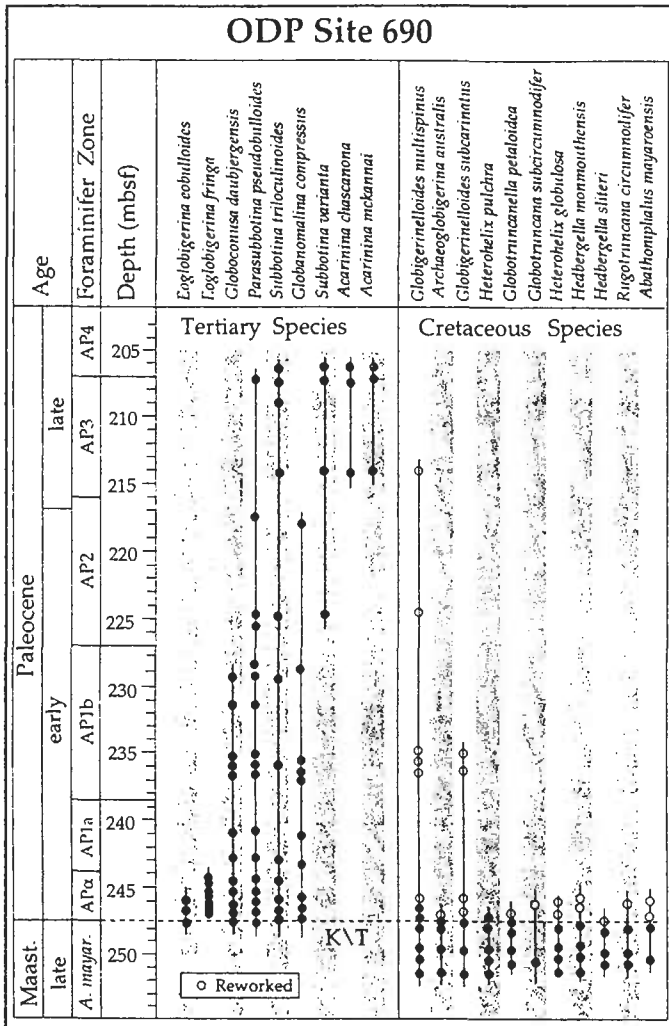
Figure 10. Cretaceous and selected Tertiary planktonic foraminifer distributions at ODP Site 690, based on the biostratigraphy of Stott and Kennett (1990a).
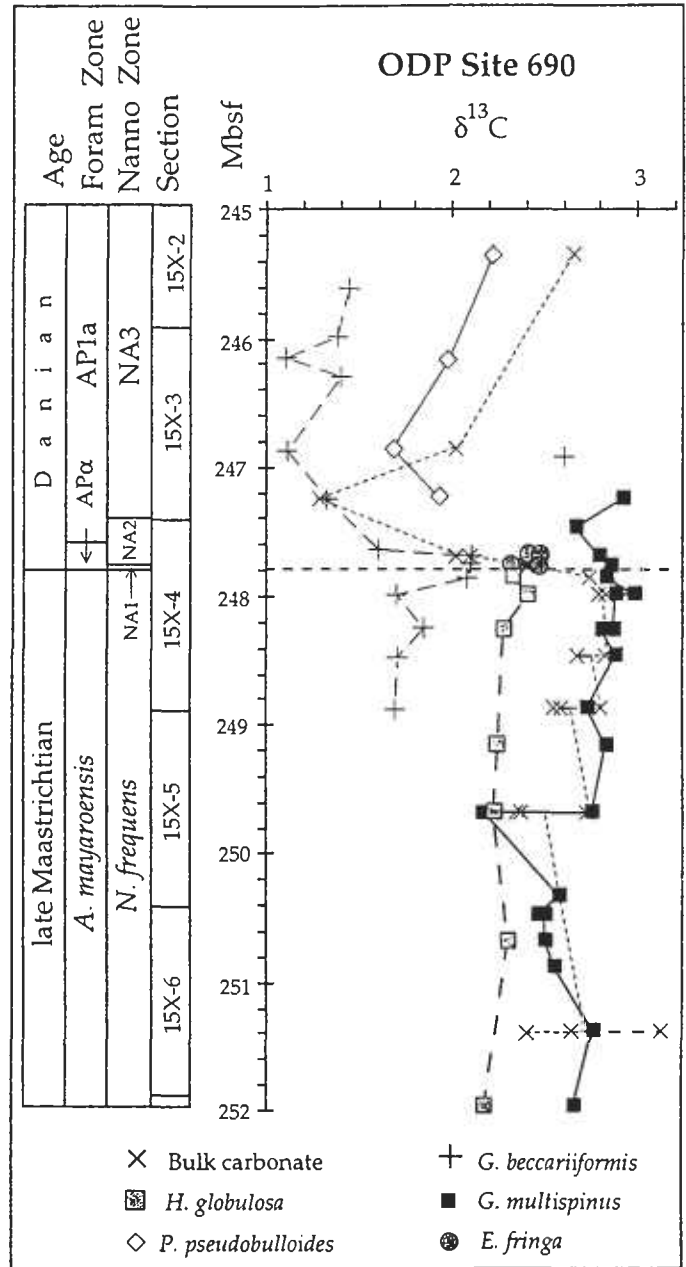

Figure 11. Carbon isotope data for ODP Hole 690C from bulk carbonate, the benthic foraminifer *Gavelinella beccariiformis*, the trans-K/T species *Heterohelix (H.) globulosa* and *Globigerinelloides (G.) multispinus*, and the Danian species *Eoglobigerina (E.) fringa* and *Parasubbotina (P.) pseudobulloides*. Modified from Stott and Kennett (1990b) to include the Antarctic Paleogene foraminifer biozonation of Huber (1991a) and the Antarctic nannofossil biostratigraphy of Wei and Pospichal (1991). All carbon isotope values are relative to the PDB standard.

lowest value at 247.24 mbsf in lowermost Zone NA3, where the benthic foraminfer and fine-fraction carbonate values overlap. The fine-fraction $\delta^{13}C$ then returns to more positive values in lower to middle Zone NA3.

Lowermost Danian values of *E. fringa* are similar to the upper Maastrichtian $^{13}C/^{12}C$ ratios of *H. globulosa* but are heavier by about 0.5‰ than the lowermost value of *P. pseudobulloides* from 0.45 m higher in the core. Since the isotopic records of the latter two species do not overlap, the significance of this offset is uncertain. But the 0.64‰ difference between the $\delta^{13}C$ composition of *P. pseudobulloides* and the fine-fraction carbonate and their contrasting isotopic trends in lowermost Zone NA3 suggest that, like Site 738, the Danian planktonic $\delta^{13}C$ record is decoupled from the fine-fraction carbonate record.

The Danian $\delta^{13}C$ record of *G. multispinus* does not overlap sufficiently with co-occurring *in situ* planktonic species for

longer-term comparison of their isotopic trends. Nonetheless, the carbon isotopic composition of *G. multispinus* from above and below the K/T boundary is nearly identical, and lowermost Danian values are about 0.4‰ heavier than *E. fringa* from the same stratigraphic interval. It is therefore possible that the lower

Danian occurrences of *G. multispinus* are due to reworking. As no samples of *H. globulosa* were measured from above the K/T boundary level at Site 690. the cause for post-K/T occurrences of this species remains an open question at this site.

NYE KLØV, DENMARK

The K/T boundary exposed at Nye Kløv. Denmark (~58°N). occurs in a thin clay-rich marl that separates a 6-m section of light-colored Maastrichtian chalk from a 6.5-m section of dark gray. clay-rich marl of Danian age that contains several layers of flint nodules (Keller et al.. 1993). An iridium anomaly of 1.6 ppb has been identified within the boundary clay (Nazarov et al., 1983: Hansen et al.. 1986). Keller et al. (1993) reported that with the exception of a short hiatus at the base of Zone P0, the K/T transition is biostratigraphically continuous. Although biomarkers for the uppermost Maastrichtian are absent from the section. these authors assumed that the Cretaceous record is complete. based on comparison with the stratigraphic record at Stevns Klint, Denmark.

No detailed calcareous nannofossil distributions have been reported for this sequence.

Trans-K/T species occurrences

Several Cretaceous planktonic foraminifer species. including *Guembelitria cretacea. Heterohelix* spp., *Globigerinella* sp., *Hedbergella* sp.. and *Rugoglobigerina* sp., were reported by Bang (1979) as reworked within the Danian section at Nye Kløv. However, no criteria for identifying these specimens as reworked were specified. Trans-K/T species identified within the same section by Keller et al. (1993) include *Guembelitria* spp., *Heterohelix complanata, Globigerinelloides aspera*, *H. globulosa*., and *Hedbergella* spp. *Guembelitria* spp. and *H. globulosa* were characterized by these authors as common to abundant within 1 m above the boundary, with last occurrences at about 5.2 and 3.9 m above the K/T respectively. Similarity in the extinction patterns at Nye Kløv and Brazos River. Texas, and a difference in $\delta^{13}C$ values of *H. globulosa* above and below the K/T boundary were cited by Keller et al. (1993) as evidence that the trans-K/T species identified at Nye Kløv were survivors.

Carbon isotope results

Results of $\delta^{13}C$ measurements of small (63 to 110 μm) *H. globulosa* from below the K/T at Nye Klov (Fig. 12) and comparison with the isotopic values of small specimens from above the boundary reveal that there is no significant change in $\delta^{13}C$ values (Barrera and Keller. 1994). Measurement of the larger (125 to 150 μm) *H. globulosa* specimens from Cretaceous sediments revealed ^{13}C values that are consistently more positive by about 0.3‰. A number of authors have demonstrated that size-related disequilibrium fractionation of ^{13}C can be signifi-
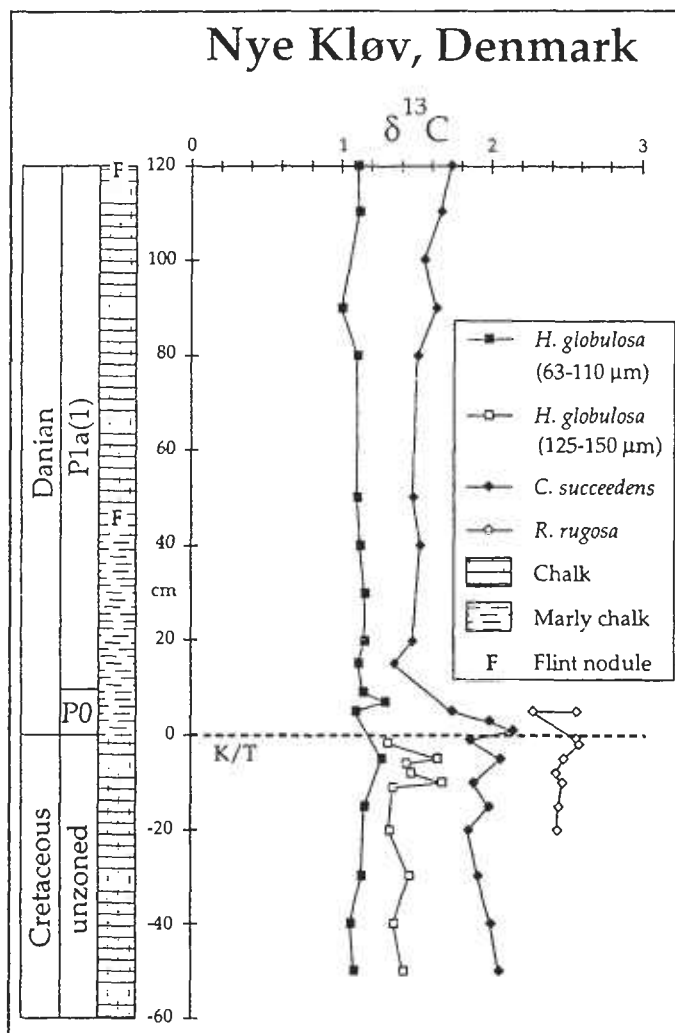

Figure 12. Carbon isotopic values across the K/T boundary at Nye Kløv, Denmark, of the benthic foraminifer *Cibicides (C.) succeedens* and the planktonic foraminifera *Heterohelix (H.) globulosa* and *Rugoglobigerina (R.) rugosa*. Data published in Keller et al. (1993) and Barrera and Keller (1994). Note that there is no significant change in the $\delta^{13}C$ values of *H. globulosa* from the small-size fraction (63 to 110 μm) across the K/T boundary. There is an apparent shift in values when comparing larger-sized Maastrichtian specimens of this species with small-sized specimens from Danian sediments, an approach used by Keller et al. (1993). All carbon isotope values are expressed relative to the PDB standard.

cant within planktonic foraminifer species. with an increase of as much as 2.0‰ over a 500-μm range in test diameter in modern species (Berger et al.. 1978) and an increase of as much as 1.1‰ over a 130-μm range in lower Danian species (D'Hondt and Zachos. 1993). These results demonstrate that the same size fraction must be used when comparing the $\delta^{13}C$ values of a species from below and above the K/T boundary.

The absence of a $\delta^{13}C$ shift across the K/T boundary at Nye Kløv for *H. globulosa* cannot be used as unequivocal evidence for survivorship or reworking. The extinction pattern in that section may be further elucidated by analyzing the $\delta^{13}C$

composition of other trans-K/T species from below and above the boundary together with at least one co-occurring Danian species.

CONCLUSIONS

Distributional analyses of planktonic foraminifera and nannofossil faunas and determination of the carbon isotope composition of trans-K/T boundary species at ODP sites 738, 750, and 690 in the region of the Southern Oceans suggest that the high occurrences of Cretaceous species in lower Paleocene sediments is likely the result of extensive reworking in these sections.

Evidence for reworking in Hole 738C, which has yielded the most complete K/T boundary sequence drilled in the deep sea, includes (1) Cretaceous nannofossils and foraminifer species occur consistently throughout the Danian section, with some species occurrences documented in lower Eocene sediments, more than 100 m above the K/T boundary (Wei and Pospichal, 1991; Huber, 1991b); (2) *Inoceramus* prisms and the planktonic foraminifer *Globigerinelloides impensus*, which are known to have become extinct in the mid Maastrichtian and uppermost Campanian, respectively, occur in Danian sediments; (3) reworked *Inoceramus* prisms within upper Maastrichtian and lower Danian sediments have strontium isotope ratios expected for late Campanian biogenic calcite, whereas samples of co-occurring planktonic foraminifera near their evolutionary first appearance have strontium isotope ratios appropriate for their stratigraphic position; and (4) carbon isotope ratios of the putative survivor *Globigerinelloides multispinus* show very little difference above and below the boundary, although values of co-occurring Danian planktonic species are consistently lighter and have a different trend. .

At Site 690, specimens of Cretaceous taxa are found as high as 10 to 32 m above the boundary in upper Paleocene sediments. Moreover, carbon isotope analyses of *Globigerinelloides* from Sites 690 and 750 (Stott and Kennett, 1990; Zachos et al., 1992) also show no change across the K/T boundary and yield consistently higher values than co-occurring in situ Danian species. More conclusive evidence bearing on survivorship vs. reworking at these sites will require additional carbon isotope analyses of trans-K/T and in situ Danian species to determine whether or not their δ^{13}C stratigraphy plots independently.

The only trans-K/T species considered ancestral to Cenozoic planktonic foraminifer lineages are *Guembelitria cretacea*, *Zeauvigerina waiparaensis*, *Hedbergella holmdelensis*, and *H. monmouthensis* (Olsson et al., 1992; Liu and Olsson, 1992, 1994; Huber and Boersma, 1994). The possibility remains that some additional Cretaceous species did survive the terminal Cretaceous extinction and grew in the earliest Danian ocean (e.g., *H. globulosa* at Brazos River, Texas; Barrera and Keller, 1990a, b). However, those species are considered inconsequential to the evolutionary radiation that followed the mass extinction at the K/T boundary. We conclude that the magnitude of

survivorship after the K/T boundary event was probably minimal and that the K/T boundary event was the cause of the termination of most Cretaceous planktonic foraminifer lineages at this time.

ACKNOWLEDGMENTS

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