

Productivity across the Cretaceous/Tertiary boundary in high latitudes

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ABSTRACT

In low and middle latitudes, the Cretaceous/Tertiary boundary is marked by a sudden and pronounced decrease in $\delta^{13}\text{C}$ values of near-surface-water carbonates and a reduction in the surface-to-bottom $\delta^{13}\text{C}$ gradient. These isotopic data have been interpreted as evidence of a decline in surface-water productivity that was responsible for the extinction of many planktic foraminiferal species and other marine organisms at or near the K/T boundary. We present planktic and benthic foraminiferal isotopic data from two almost biostratigraphically complete sections at Ocean Drilling Program Site 738 in the antarctic Indian Ocean and at Nye Kløv in Denmark. These data suggest that planktic carbonate $\delta^{13}\text{C}$ values in high latitudes may not have decreased dramatically at the K/T boundary; thus, surface-water productivity may not have been reduced as much as in low and middle latitudes. Comparison of the records of Site 738 with those of ODP Sites 690 and 750 indicates a pronounced decline in $\delta^{13}\text{C}$ values of planktic and benthic foraminifera and fine-fraction/bulk carbonate $\sim 200\,000$ yr after the K/T boundary. This reflects a regional shift in the carbon isotopic composition of oceanic total dissolved carbon (TDC) and correlates with a similar change in benthic foraminiferal $\delta^{13}\text{C}$ values at mid- and low-latitude Deep Sea Drilling Project Sites 527 and 577. This oceanographic event was followed by the ecosystem's global recovery $\sim 500\,000$ yr after the K/T boundary. These data suggest that the environmental effects of the K/T boundary may have been less severe in the high-latitude oceans than in tropical and subtropical regions.

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INTRODUCTION

Recent studies of the stratigraphic completeness of K/T boundary sections show that almost all of the low- and high-latitude deep-sea sections studied to date are incomplete, with various parts of the basal Paleocene missing or very condensed sedimentation across the boundary (MacLeod and Keller, 1991; Keller, 1993; Olsson and Liu, 1993). Intervals not preserved in deep-sea material are often present in the more stratigraphically complete continental shelf sections. These more complete sections show that all Cretaceous planktic foraminiferal species did not disappear at the K/T boundary (Keller, 1988, 1989; Barrera and Keller, 1990). It is possible, therefore, that the apparent sudden mass extinctions in the deep sea may be an artifact of an incomplete sedimentary record. Thus, the recovery of a more complete sedimentary record in a deep-sea setting may elucidate the nature of widespread oceanographic changes and ecologic effects of the boundary event.

A global decline in marine surface-water productivity may have occurred at the K/T boundary. Evidence for this is a sudden decrease of $\delta^{13}\text{C}$ values of near-surface-water carbonate and a subsequent low surface-to-bottom $\delta^{13}\text{C}$ gradient, and the decrease of barium (Ba) concentrations in lowermost Tertiary sediments (Hsü and others, 1982; Shackleton and Hall, 1984; Zachos and Arthur, 1986; Zachos and others, 1989; Barrera and Keller, 1990). This decline in productivity was thought to have affected both low- and high-latitude marine environments (Hsü and others, 1982; Zachos and Arthur, 1986). This idea was supported by data from high latitudes of the southern ocean, which indicate that $\delta^{13}\text{C}$ values of Tertiary near-surface-water carbonate are lower than those of Maestrichtian sediments, and the vertical $\delta^{13}\text{C}$ gradient was reduced in the earliest Paleocene (Stott and Kennett, 1989, 1990; Zachos and others, 1992). The ob-

served K/T $\delta^{13}\text{C}$ decrease, however, appears to be much less severe in high southern latitudes than in low-latitude regions (Stott and Kennett, 1989).

The present study is an attempt to determine if the environmental response to the K/T boundary event differed between high and low latitudes. We compared the stable carbon and oxygen isotope compositions of planktic and benthic foraminifera and fine-fraction/bulk sediments across the K/T boundary in two nearly biostratigraphically and chronostratigraphically complete sections, ODP Site 738 in the antarctic Indian Ocean and Nye Kløv in Denmark (Fig. 1). This study differs from most previous K/T boundary studies in that it is based on more continuous isotopic records of specimens of single species of planktic and benthic foraminifera within a narrow size range (Tables 1 and 2), minimizing the possible effects of differences in life habitats, vital effects, and diagenetic potential on $^{13}\text{C}/^{12}\text{C}$ and $^{18}\text{O}/^{16}\text{O}$ ratios. These data help to evaluate productivity levels in the high-latitude oceans, the extent of the global environmental perturbation after the K/T boundary event, and the long-delayed global recovery of productivity in early Tertiary oceans. They indicate that the decline in surface-water productivity at the K/T boundary in the high latitudes may have been reduced relative to that in low latitudes. Correlation of the isotopic records of ODP Sites 738, 690, and 750 demonstrates a southern high-latitude lowering of $\delta^{13}\text{C}$ values of oceanic total dissolved carbon (TDC) $\sim 200\,000$ yr after the boundary.

STRATIGRAPHY AND GEOCHEMISTRY

Site 738

ODP Site 738, at the southern end of the Kerguelen Plateau at $62^{\circ}42'\text{S}$ and $82^{\circ}47'\text{E}$ in 2253 m of water, is the closest deep-sea site to Antarctica (~ 700 km), with nearly con-

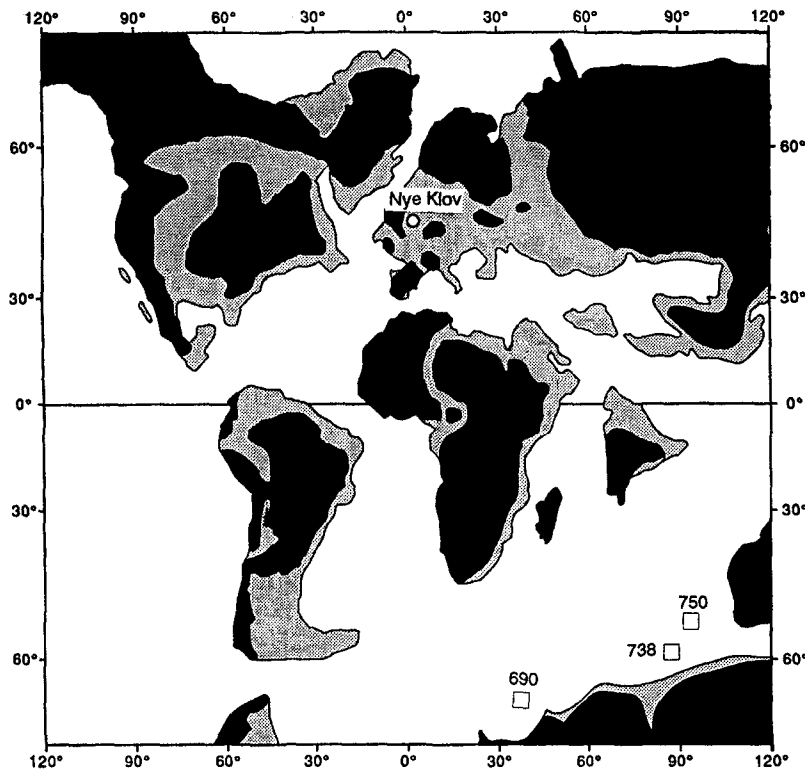


Figure 1. Geographic reconstruction at 65 Ma, according to Scotese and Denham (1988), showing the location of K/T boundary sections discussed in this study.

tinuous carbonate sedimentation across the K/T boundary (Fig. 1). A paleodepth of <1000 m is estimated for lowermost Paleocene sediments (Barrera and Huber, 1991).

The K/T boundary is contained within ~1 m of clay-rich chalk in Core 20R-5. It occurs at 96.2 cm, ~2.0 cm above the base of a laminated clay-rich interval from 82 to 98 cm, although faint irregular laminations begin at 100 cm (Fig. 2A). The boundary is characterized by a 2-mm-thick gray clay layer (at 96.2 cm) with high iridium (Ir) concentrations (Schmitz and others, 1991). The K/T boundary planktic foraminiferal and calcareous nannofossil biostratigraphies have been described by Keller (1993; see also Huber, 1991) and Pospichal and Huber (1992) and are illustrated in Figure 2B. They indicate a biostratigraphically complete K/T boundary section.

The Ir profile at Site 738 is unusual in that very high concentrations persist over at least a 1.1-m interval, including both laminated and clay-rich chalk (Schmitz and others, 1991). Ir concentrations are 1.6 to 1.7 parts per billion (ppb) in the 6 cm of chalk below the boundary and increase sharply to ~18 ppb in the boundary clay (Fig. 2A). Thereafter, they decrease in the first 10 cm, but

remain at an average of ~5.5 ppb throughout the upper part of the laminated interval, and between 1.2 and 0.1 ppb in the chalk above. This profile is independent of the clay content as shown by concentrations normalized to scandium (Sc) (Fig. 3). (Sc, like aluminum, is assumed to be contributed only by the clays). Schmitz and others (1991) interpreted this Ir pattern as a single input of extraterrestrial Ir and subsequent reworking, precipitation, and settling on the ocean floor by oceanographic processes. Uppermost Maestrichtian high Ir concentrations may result from postdepositional transport by microbes or by absorption and diffusion processes from the maxima in the boundary clay layer (see Schmitz and others, 1988; Wallace and others, 1990; Thierstein and others, 1991).

Nye Kløv, Denmark

The Nye Kløv section spans the K/T boundary in ~19 m of exposed sediments, with 6 m of Maestrichtian pelagic chalk overlain by a 3 cm brownish gray marly clay that marks the boundary and contains an Ir anomaly of ~1.6 ppb (Nazarov and others, 1983). Above the K/T clay layer is 0.5 m of

grayish marly chalk followed by bryozoan limestone passing into pelagic chalks (Håkanson and Thomsen, 1979). These lithologic variations are reflected in the lower carbonate percentage of the basal 30 cm of Danian sediments (Table 2, Fig. 6). The section's foraminiferal and nannofossil stratigraphies are described by Keller and others (1993; see also Bang, 1979) and Perch-Nielsen (1979a, 1979b).

METHODS

At Site 738, 1 cm³ sediment samples were taken at 1-cm intervals from the laminated interval and in the chalk in the lower part of Core 20R-5 between 98 and 104 cm (Fig. 2A); 5 cm³ sediment samples were taken at both 20- and 5-cm intervals above and below the laminated interval. Samples from both the laminated interval and underlying chalk layer above the chert were taken (by Barrera) from the core center to avoid contamination with younger sediments squeezed down along the core liner (Thierstein and others, 1991). The Nye Kløv sequence was sampled as described in Keller and others (1993).

Approximately 0.1 mg of sediment from Site 738 was dried, ground to a fine powder (bulk carbonate), and analyzed isotopically. Fine-fraction samples consisted of carbonate particles <38 μm in size. From Site 738, oxygen and carbon isotope analyses were performed on benthic foraminifers *Gavelinella beccariiiformis*, *Alabamina creta*, and *Neoeponides lunata*, the planktic taxa *Chiloguembelina waiparaensis*, *Heterohelix globulosa*, *Globigerinelloides* spp., and Tertiary planktic foraminifers *Subbotina pseudobulboides* and *Eoglobigerina* spp. Except for smaller specimens collected from within the laminated interval, benthic and planktic taxa were in the size fraction 150–200 μm. Specimens of *C. waiparaensis* were between 106 and 150 μm. Individual specimens of these Site 738 species were broken in the laboratory, and fragments were ultrasonically agitated in distilled water and rinsed in methyl alcohol to remove adhering fine particles from test surfaces before isotopic analysis.

From Nye Kløv sediments, oxygen and carbon isotope analyses were made on the benthic taxa *Cibicidoides succedens* and *Gavelinella planata*, the planktic species *Heterohelix globulosa*, *Guembelitra danica*, *Guembelitra cretacea*, *Guembelitra trifolia*, *Globigerinelloides aspera*, *Rugoglobigerina rugosa*, *Goglobigerina danica*, *Woodringina*

PRODUCTIVITY ACROSS THE CRETACEOUS/TERTIARY BOUNDARY

TABLE 2. OXYGEN AND CARBON ISOTOPE DATA OF FORAMINIFERAL SPECIES AND FINE-FRACTION CARBONATE, AND PERCENT CARBONATE ACROSS THE K/T BOUNDARY AT NYE KLØV, DENMARK

Distance from boundary (cm)	Foram zone	Carbonate (%)	<i>Gavelinella planata</i>		Fine-fraction carbonate		<i>Heterohelix globulosa</i>		<i>Guembelitra cretacea</i>		<i>Guembelitra danica</i>		<i>Guembelitra trifolia</i>		<i>Globigerinelloides aspera</i>		<i>Hedbergella holmdelensis</i>		<i>Eoglobigerina danica</i>		<i>Woodringina homerstownensis</i>			
			$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$
120	P1a						-1.43	1.10*																
110	P1a						-1.38	1.11*																
100	P1a	96			-1.49	1.38																		
90	P1a						-1.44	1.00*																
80	P1a						-1.30	1.10*																
50	P1a	94	-1.32	1.51					-1.27	1.19*	-1.03	1.14*												
40	P1a						-1.46	1.12*			-0.95	1.23*												
30	P1a	95	-1.13	1.47	-1.02	1.69	-1.47	1.15*																
20	P1a						-1.40	1.15*	-1.46	1.26*														
15	P1a		-1.64	1.35			-1.26	1.11*	-1.61	1.19*	-1.01	1.28*	-1.93	1.21*										
9	P0						-1.36	1.14*			-0.95	1.34*												
7	P0						-0.98	1.29*																
5	P0	88	-1.32	1.49	-1.65	1.64	-1.38	1.09*																
3	P0	69			-0.61	1.71																		
1	P0	54	0.16	1.53	-1.26	1.58																		
1.5	Unzoned						-1.24	1.31*			-1.03	1.30*												
5	Unzoned						-1.51	1.65*			-0.84	1.31*												
5	Unzoned						-1.49	1.27*																
6	Unzoned						-1.53	1.44*																
8	Unzoned						-1.53	1.47*																
10	Unzoned	97			-1.25	1.69	-1.51	1.68*	-1.67	1.41*	-1.11	1.39*	-2.05	1.21*	-1.28	2.42*								
11	Unzoned						-1.39	1.34*																
15	Unzoned																							
15	Unzoned						-1.49	1.15*																
20	Unzoned						-1.40	1.32*			-1.19	1.22*												
30	Unzoned	97			-1.51	1.55	-1.45	1.46*			-1.23	1.12*												
30	Unzoned						-1.41	1.13*																
40	Unzoned						-1.48	1.35*			-1.03	1.08*												
40	Unzoned						-1.46	1.06*																
50	Unzoned	94			-1.15	1.66	-1.40	1.42*			-0.96	1.14*												
50	Unzoned						-1.41	1.08*																
75	Unzoned						-1.49	1.57*			-1.07	1.17*												

Note: Symbols represent analysis of specimens in the following size fractions: * (63–106 μm) and ^ (125–150 μm). Specimens of *Gavelinella planata* listed above and *Cibicides succedens* reported in Keller and others (1993) were between 150 and 200 μm . All other samples were smaller than 150 μm .

about half in the number of planktic specimens per area and in the preservation of foraminiferal tests from the uppermost Maestrichtian to the lowermost Danian portion of the laminated interval. These poorly preserved specimens have $\delta^{18}\text{O}$ values similar to those of better preserved specimens in uppermost Maestrichtian and Danian sediments (Figs. 4 and 5). This similarity and the presence of interspecific isotopic differences suggest that diagenesis may not have greatly altered isotopic ratios. Nevertheless, $\delta^{18}\text{O}$ values of benthic and planktic species as well as bulk sediment from Site 738 are consistently lower than those from the shallower water, more northern Site 750 (Zachos and others, 1992) and the deeper, more southern Weddell Sea Site 690 (Stott and Kennett, 1989, 1990). In contrast, coeval *G. beccariiiformis* $\delta^{13}\text{C}$ values from Site 738 are intermediate between higher ratios at Site 690 and lower ratios at Site 750, as expected according to their geographic locations, because young deep waters close to their source have higher $\delta^{13}\text{C}$ values than older waters (Kroopnick, 1974).

Our bulk and fine-fraction carbonate results are similar to those reported by Thierstein and others (1991) for the fine size fraction <38 μm , which is mostly composed of calcareous phytoplankton remains. Nanno-

fossils from low- and mid-latitude Tertiary sediments have higher $\delta^{18}\text{O}$ values and lower $\delta^{13}\text{C}$ values than the shallow-dwelling foraminifers (Margolis and others, 1975; Goodney and others, 1980; Dudley and others, 1986). This is the case for Maestrichtian sediments from Site 690 (Barrera and Huber, 1990). No comparable data are available for Site 738. Thierstein and others (1991) estimated that recrystallized micritic carbonate particles, among other particles, varied between 50% and >95% in the K/T boundary transition, with the highest percent abundance in the laminated interval between 80 and 90 cm. This means that $\delta^{18}\text{O}$ values of bulk carbonate, like those of the foraminifera in the laminated interval and above (at the base of Foraminiferal Zone P1b), may reflect extensive recrystallization processes and are consequently suspect. Thus, foraminiferal and bulk carbonate $\delta^{18}\text{O}$ data from these levels are not discussed further.

Foraminiferal specimens from Nye Kløv show diagenetic calcite encrustation and variable wall structure replacement, particularly in samples from Zone P0 and above. Because foraminiferal $\delta^{18}\text{O}$ values are likely altered to an unknown degree, only $\delta^{13}\text{C}$ results will be discussed in detail. Nevertheless, $\delta^{18}\text{O}$ data are presented to clarify the isotopic relationship between species and

their depth habitat inferred from the $\delta^{13}\text{C}$ data (Fig. 6). It is worth noting the similarity in the isotopic trends of coeval benthic *C. succedens* samples below and across the K/T boundary from Nye Kløv (this study) and the shallower water section at Stevns Klint in eastern Denmark (Schmitz and others, 1992). Nye Kløv benthic foraminiferal $\delta^{13}\text{C}$ values are similar, and $\delta^{18}\text{O}$ values are higher than at Stevns Klint. This suggests that $\delta^{13}\text{C}$ values reflect regional depositional environmental conditions. At Nye Kløv, bulk and fine-carbonate $\delta^{13}\text{C}$ values are intermediate between those of *C. succedens* and the planktic species *H. globulosa* (Mattsson, 1992; this study), indicating that foraminiferal isotopic signatures differ from those of the sediment component with the highest diagenetic potential.

STABLE ISOTOPE RESULTS

Site 738: Oxygen Isotopic Records

The most striking $\delta^{18}\text{O}$ results in foraminiferal Zones P1b and P1c are the inversion and relative stability of benthic and planktic foraminiferal values. Beginning in Zone P1b and continuing in P1c, $\delta^{18}\text{O}$ values of planktic *C. waiparaensis* and *Eoglobigerina* spp. become higher than those of the benthic foraminifer *G. beccariiiformis*. Isotopic compo-

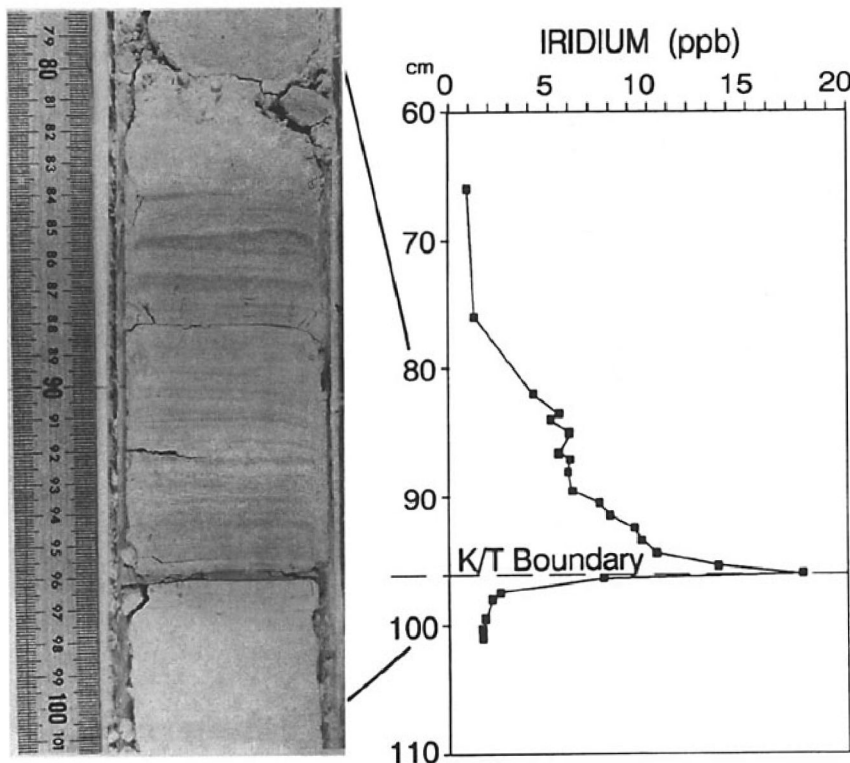
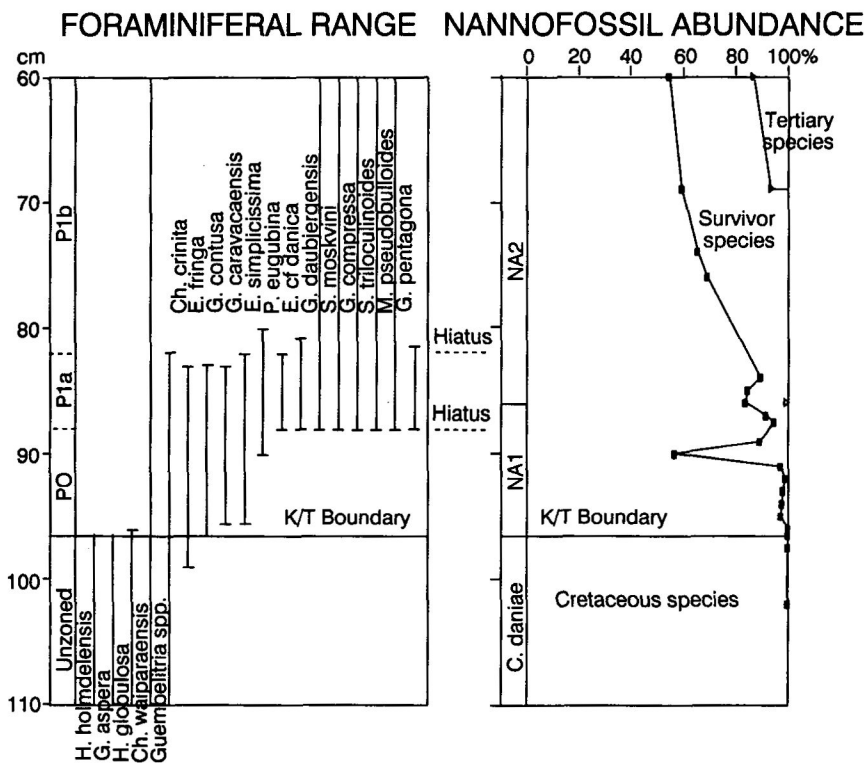


Figure 2. (A). Photographs of sediments in Site 738 Core 20R-5, 79–101 cm, containing the K/T boundary. Figures show iridium concentrations from Core 20R-5, 60–110 cm (Schmitz and others, 1991). Note that the K/T boundary clay layer is within a laminated interval extending from 82.5 to 98 cm. Iridium concentrations are high below the boundary, reach a maxima in the clay layer at the K/T boundary clay layer, and decrease gradually above in the laminated interval. (B). Planktic foraminiferal zonation and species ranges (Keller, 1993), and calcareous nannofossil zonation and relative abundance of Cretaceous, survivor, and Tertiary nannofossils (Pospichal and Huber, 1992; J. Pospichal, 1993, unpub. data) in sediments from Core 20R-5, 60–110 cm, across the K/T boundary at Site 738. The location of the hiatus separating foraminiferal Zone P0 and P1a is at 88 cm. The next hiatus, between Zones P1a and P1b, is at the top of the laminated interval at ~82 cm.

A



B

sitions of these species range between -0.2‰ and 0.3‰ in this interval (Fig. 4). The lower $\delta^{18}\text{O}$ values of the benthic taxon relative to those of the planktic species may be explained by one or more of the following factors: (1) disequilibrium biogenic calcite precipitation, (2) deep water habitat of the planktic species, and/or (3) warming and cooling of deep and surface waters, respectively. The $\delta^{13}\text{C}$ values of *C. waiparaensis*, unlike those of *Eoglobigerina* spp. and *S. pseudobulloides*, are lower than benthic foraminifer values. This and the similarity in $\delta^{18}\text{O}$ values of planktic *C. waiparaensis* and benthic *G. beccariiformis* may therefore be due to the former species' deeper water habitat at or below thermocline depth in the water column. In addition, Shackleton and others (1984) suggested that benthic *Gavelinella* (cf. *G. beccariiformis*) precipitates calcite depleted in ^{18}O by 0.3‰ from estimated equilibrium values, which would result in values similar to the deeper surface dwelling *C. waiparaensis* in Zone P1c. In the upper part of Zone P1b and in Zone P1c, *S. pseudobulloides* exhibits a distinctive trend of decreasing $\delta^{18}\text{O}$ values, whereas bulk carbonate values become much higher than those of *G. beccariiformis* and *C. waiparaensis*. The $\delta^{18}\text{O}$ data of *C. waiparaensis*, *Eoglobigerina* spp., and *G. beccariiformis* suggest that near-surface waters may have cooled slightly, while deep waters warmed during the time of Zone P1b and remained stable in P1c (Fig. 4). In agreement with this

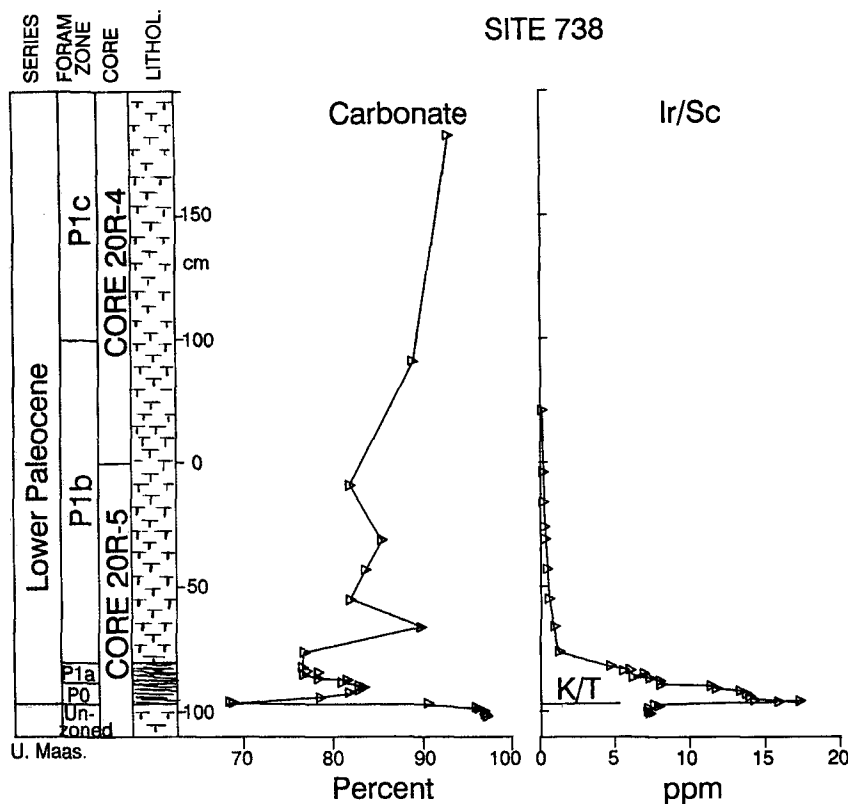


Figure 3. Carbonate content (in percent), and Ir/Sc ratios across the K/T boundary transition in Cores 20R-5 and 20R-4 of Site 738. Carbonate content data from Thierstein and others (1991), Ehrmann (1991), and this study. Elemental data are normalized as reported in Schmitz and others (1991).

interpretation, the positive $\delta^{18}\text{O}$ trend in bulk carbonate samples may reflect cooling of near-surface water and/or an isotopic fractionation or habitat effect associated with changes in the species composition of the nannofossil assemblage (Pospichal and Huber, 1992; J. Pospichal, personal commun., 1992). A similar trend is apparent in the fine-fraction carbonate $\delta^{18}\text{O}$ record of the nearby Site 750 during this time (Zachos and others, 1992). The trend in *S. pseudobulloides* $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ values may have been caused by the migration of this species into shallower depths or warmer waters and/or by a change in the growth season from the upper part of Zone P1b into P1c.

Site 738: Carbon Isotopic Records

Compared with most published K/T boundary $\delta^{13}\text{C}$ records, the most significant features of Site 738 are the following (Figs. 4 and 5): (1) the absence of a negative $\delta^{13}\text{C}$ shift in planktic carbonate at the K/T boundary and (2) the presence of the first negative planktic and benthic foraminiferal

$\delta^{13}\text{C}$ shift in foraminiferal Zone P1b well after the K/T boundary event.

The $\delta^{13}\text{C}$ values of *G. beccariiiformis* increase in uppermost Maestrichtian and Zone P1a sediments (Fig. 5). *C. waiparaensis* $\delta^{13}\text{C}$ followed a somewhat similar trend, except that there is a negative shift of $\sim 0.2\text{‰}$ just below the K/T boundary where no *G. beccariiiformis* values are available. The benthic taxon *N. lunata*, however, also mirrors this change. *C. waiparaensis* $\delta^{13}\text{C}$ values average $1.21 \pm 0.1\text{‰}$ in the upper Maestrichtian and $1.43 \pm 0.07\text{‰}$ in Zones P0 and P1a. The lower $\delta^{13}\text{C}$ values of this species relative to *G. beccariiiformis*, instead of higher values as would be expected for a near-surface water habitat, may be due to a vital effect or habitat within the oxygen minimum zone as described by Boersma and Premoli-Silva (1988, 1989) for biserial heterohelicids from stable isotope evidence. The bulk carbonate $\delta^{13}\text{C}$ trend is somewhat similar to that of foraminifera across the K/T boundary and in Zone P0, although changes are amplified (Figs. 4 and 5). There is a 0.4‰ increase across the K/T boundary

with relatively stable high values in Zone P0, and decreasing gradually in Zones P1a and into P1b. These data show that the seemingly ubiquitous $\delta^{13}\text{C}$ shift to lower values of near-surface-water carbonates and the reduction in the surface-to-bottom $\delta^{13}\text{C}$ gradient at the K/T boundary reported from low- and mid-latitude sections is absent in the planktic carbonate record of southern high-latitude Site 738.

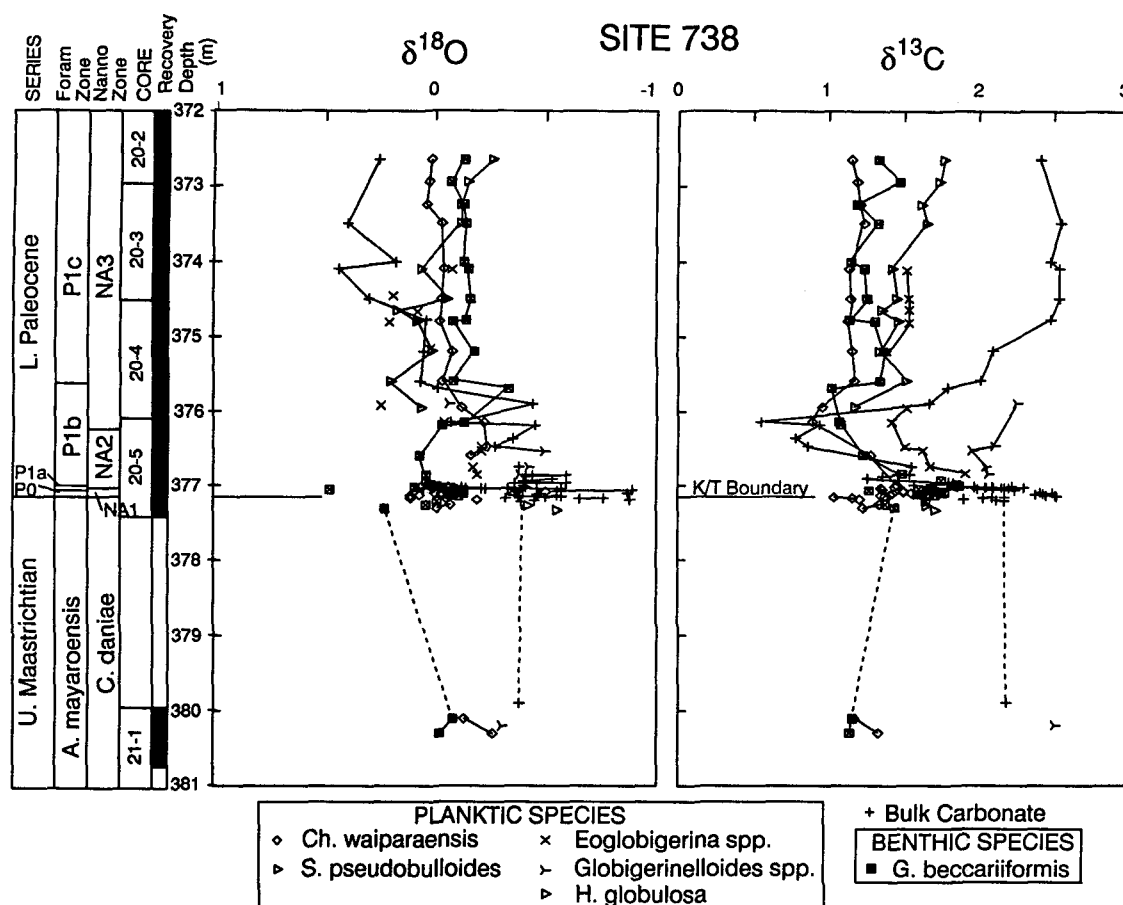
The first negative $\delta^{13}\text{C}$ shift in foraminifera and bulk carbonate occurs in Zone P1b (top of antarctic nannofossil Zone NA2 to base of NA3) at Site 738. At this time, *Eoglobigerina* spp., *C. waiparaensis*, *G. beccariiiformis*, and fine-fraction carbonate show a ^{13}C depletion of $\sim 0.5\text{‰}$ – 1‰ . This decline in surface and sea-floor $\delta^{13}\text{C}$ values occurred possibly $>200\,000$ yr after the K/T boundary. This time estimate is based on the correlation of the top of antarctic nannofossil Zone NA2 to that of the low-latitude Zone NP1 of Martini (1971) (Wei and Pospichal, 1991), which is usually found within Submagnetochron 29N (Berggren and others, 1985) as identified at Site 690 (Pospichal and Wise, 1990). The base of 29N is estimated at 230 000 yr above the K/T boundary, which is placed at 66.4 Ma (Berggren and others, 1985; Herbert and D'Hondt, 1990). However, at Site 738, the top of NP1 appears to occur within Subchron 29R (see Fig. 7) (Sakai and Keating, 1991; Wei and Pospichal, 1991) as in the Contessa section in Italy, where it has been dated at ca. 66.2 Ma (Monechi and Thierstein, 1985).

Toward the top of Zone P1b, $\delta^{13}\text{C}$ values of *C. waiparaensis* and *G. beccariiiformis* increase slightly and then remain stable through Zone P1c. In contrast, $^{13}\text{C}/^{12}\text{C}$ ratios of bulk carbonate and the Tertiary planktic foraminifers *S. pseudobulloides* and *Eoglobigerina* spp., which are consistently higher than those of *C. waiparaensis* and *G. beccariiiformis*, begin a well-defined trend of increasing values throughout Zone P1c. This Zone P1c (antarctic nannofossil Zone NA3; low-latitude nannofossil Zone NP2) increase in the surface-to-seafloor $\delta^{13}\text{C}$ gradient correlates to the global post-K/T boundary recovery of the ecosystem (Zachos and others, 1989, 1992).

Nye Kløv: Carbon Isotopic Records

The most conspicuous features of the northern boreal Nye Kløv records are the absence of a decline in planktic carbonate $\delta^{13}\text{C}$ at the K/T boundary and a decrease in

Figure 4. Oxygen and carbon isotope compositions of foraminiferal species, and fine-fraction and bulk carbonate in uppermost Maestrichtian and Danian sediments at Site 738. Isotopic data of *Eoglobigerina* spp. and fine-fraction carbonate samples not in Table 1 are from Barrera (unpub. data). Foraminiferal zonation is from Keller (1993). The antarctic nannofossil zonation is from Wei and Pospichal (1991) and Pospichal and Huber (1992).



benthic foraminiferal $\delta^{13}\text{C}$ from Zone P0 into P1a (Fig. 6). At Nye Kløv, there is little change in $\delta^{13}\text{C}$ values of planktic foraminiferal species *G. danica*, *R. rugosa*, and *H. globulosa*, or of fine-fraction carbonate across the K/T boundary. *G. danica* $^{13}\text{C}/^{12}\text{C}$ ratios show a slight increase in the latest Maestrichtian, no change across the K/T boundary, and a very small, gradual decline in Zone P1a. *R. rugosa* $\delta^{13}\text{C}$ values exhibit no significant change across the boundary and are then followed by a one data point 0.3‰ decline in Zone P0. The $\delta^{13}\text{C}$ values of *H. globulosa* in the size fraction between 63 and 106 μm are similar in Maestrichtian and Danian sediments, with a small decrease across the boundary of $\sim 0.2\%$. Larger specimens (125–150 μm) of *H. globulosa* that are abundant in Maestrichtian sediments and the smaller specimens from Danian sediments were used by Keller and others (1993) and MacLeod (1993). Those in the smaller size fraction produce different isotopic values, indicating the presence of a size-related isotopic effect (Oppo and Fairbanks, 1989; D'Hondt and Zachos, 1993).

In contrast to the relative stability of planktic $\delta^{13}\text{C}$ values, those of the benthic

species *C. succeedens* are high and variable in the uppermost Maestrichtian and decline by $\sim 0.6\%$ from Zone P0 into P1a. Schmitz and others (1992) described a similar trend and shift of about the same magnitude in *C. succeedens* at nearby Stevns Klint. They interpreted the data as reflecting the negative carbon isotope anomaly measured in planktic carbonate at other K/T boundary sections and suggested that it likewise indicated decreased biological productivity in the euphotic zone. Similar results were obtained from benthic foraminifera $\delta^{13}\text{C}$ at Brazos River, Texas (Barrera and Keller, 1990). Taken together, these observations suggest that a similar situation existed at Nye Kløv.

The higher $\delta^{13}\text{C}$ values of the benthic foraminifera *C. succeedens* and *G. planata* (Table 2) at Nye Kløv and Stevns Klint (Schmitz and others, 1992), relative to those of the planktic taxa *G. danica*, *G. cretacea*, and *H. globulosa*, are opposite to the pattern expected in a normally stratified marine environment where surface waters are more ^{13}C enriched than deeper waters. The normal $\delta^{13}\text{C}$ relation existed between Cretaceous surface-dwelling taxa *R. rugosa* and *G. aspera* (see also Barrera and Huber, 1990;

Boersma and Shackleton, 1981), and *C. succeedens*. Modern representatives of this benthic taxon precipitate calcite with $\delta^{13}\text{C}$ values similar to ambient dissolved HCO_3^- but depleted in ^{18}O by $\sim 0.7\%$ relative to equilibrium values (Belanger and others, 1981). At Stevns Klint, $\delta^{13}\text{C}$ of Maestrichtian *H. globulosa* is only slightly lower, whereas at Brazos River, Texas, it is slightly more positive than that of benthic foraminifera (Schmitz and others, 1992; Barrera and Keller, 1990). At Nye Kløv, the significantly more negative $\delta^{13}\text{C}$ of these planktic taxa relative to the benthic species is probably due to a deeper subsurface water habitat within the thermocline layer or the oxygen minimum zone, similar to the previously discussed relation between *G. beccariiformis* and *C. waiparaensis* at Site 738. Another possibility, though one that we consider less likely, is that negative planktic-to-benthic $\delta^{13}\text{C}$ gradient is the result of preferential incorporation of metabolic carbon due to the small size of the planktic specimens that were analyzed (D'Hondt and Zachos, 1993). The $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ data also indicate that at Nye Kløv, guembelitrid species, in particular the dominant taxon *G.*

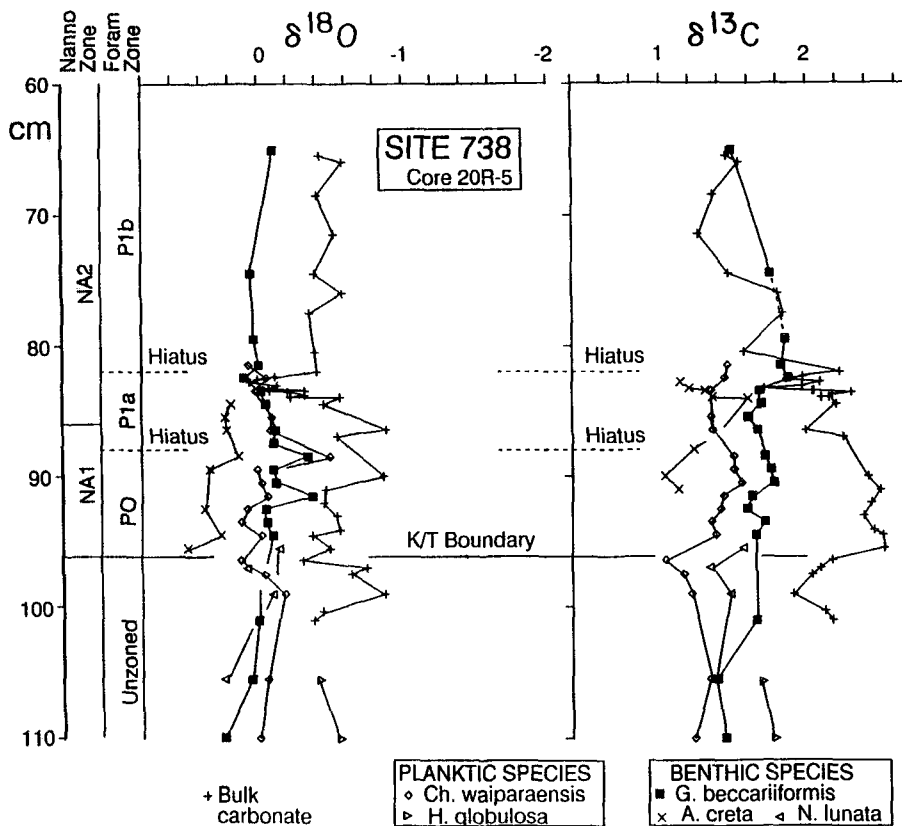


Figure 5. Oxygen and carbon isotope compositions of foraminiferal species and bulk carbonate samples across the K/T boundary transition in Site 738 Core 20R-5. Foraminiferal zonation from Keller (1993) and nannofossil zonation from Wei and Pospichal (1991) and Pospichal and Huber (1992).

danica, lived consistently deeper in the water column than *H. globulosa*, contrary to interpretations on sea-level variations based on changes in the relative abundance of these taxa (Keller and others, 1993).

COMPARISON OF SOUTHERN HIGH-LATITUDE ISOTOPIC RECORDS

Are the foraminiferal and bulk carbonate $\delta^{13}\text{C}$ trends of Site 738 apparent in other southern high-latitude sections? Isotopic records have been published for two other deep-sea K/T boundary sections from the southern polar oceans: Site 750 (Zachos and others, 1992) in the southeastern part of the Kerguelen Plateau in the Indian Ocean, and Site 690 (Stott and Kennett, 1989, 1990). The K/T boundary sedimentary record in both of these sections is less complete than at Site 738. Sediments representing slightly less than $\sim 300,000$ yr are missing at the base of the Paleocene at Site 750, where no Ir anomaly was found (Ehrendorfer and

Aubry, 1992; Pospichal and Huber, 1992; Zachos and others, 1992). This hiatus, then, spans Zones P0, P1a, and probably part of P1b (antarctic nannofossil Zones NA1 and most of NA2; Pospichal and Huber, 1992) corresponding to the interval of high bulk carbonate, benthic and planktic foraminifera $\delta^{13}\text{C}$ values in P0, P1a, and the base of P1b at Site 738 (Fig. 7). The $\delta^{13}\text{C}$ values of planktic foraminifera and fine-fraction carbonate of the basal Paleocene interval present at Site 750 are lower than those in the upper Maestrichtian and are followed by higher fine fraction carbonate values in antarctic nannofossil Zone NA3 $\sim 500,000$ yr after the K/T boundary (Zachos and others, 1992). This pattern is also observed at Site 738.

A restudy of Site 690, which contains a highly bioturbated K/T boundary interval with an Ir anomaly, reveals that, like Site 750, the lowermost Paleocene sediments spanning foraminiferal Zones P0, P1a, and the lower portion of P1b are missing (Keller, 1993). Slightly different stratigraphic results

have been reported based on calcareous nannofossils, indicating the presence of the basal Danian nannofossil Zone NA1 and a hiatus in NA2 (Pospichal and Wise, 1990). Regardless of which biostratigraphic interpretation is used, the isotopic data from Sites 738 and 690 are very similar (Fig. 7). At Site 690, $\delta^{13}\text{C}$ values of the fine-fraction carbonate and *G. beccariiiformis* increased in the uppermost Maestrichtian, as previously noted by Stott and Kennett (1989, 1990) and also observed at low-latitude deep-sea sites (Shackleton and Hall, 1984; Zachos and Arthur, 1986; Zachos and others, 1989). In the lowermost Paleocene at Site 690, the planktic species *Eoglobigerina fringa* had similar $^{13}\text{C}/^{12}\text{C}$ ratios to upper Maestrichtian *H. globulosa*. Likewise, *G. beccariiiformis* had comparable $\delta^{13}\text{C}$ values in this interval to the youngest sample in the uppermost Maestrichtian. Within Zone P1b near the base of Chron 29N (Hamilton, 1990), fine-fraction $\delta^{13}\text{C}$ values decline, followed by those of benthic and Tertiary planktic foraminifers. The $\delta^{13}\text{C}$ decline of $\sim 0.5\text{‰}$ – 1.0‰ is of similar magnitude as at Site 738, and at both sites bulk and fine-fraction carbonate values became nearly as low or lower than those of benthic foraminifera. In contrast, the planktic data of the Tertiary species *S. pseudobulloides* from Site 690 and *Eoglobigerina* spp. from Site 738 suggest that a well-developed vertical $\delta^{13}\text{C}$ gradient existed at this time. Within Zone P1c at Site 690 (Chron 29N, Hamilton, 1990), planktic foraminifers and *G. beccariiiformis* $\delta^{13}\text{C}$ values increased gradually, and bulk/fine-fraction carbonate became sharply enriched in ^{13}C , as also observed at Site 738. At both sites, a well-developed water-column stratification was established in Zone P1c (nannofossil Zone NA3).

The increase in the fine-fraction carbonate $\delta^{13}\text{C}$ across the K/T boundary at Site 738 is unusual. Thierstein and others (1991) suggested a possible polytaxic or diagenetic cause for this shift. The fine fraction in the Danian laminated interval could be reasonably expected to have a Maestrichtian isotopic signature. This is because it is composed of etched and overgrown Cretaceous nannofossils with a small number of specimens of survivor taxa (Figs. 2B and 8) (J. Pospichal, unpub. data, 1993) and micritic particles whose carbonate is probably derived from these fossils. (Survivors are Cretaceous taxa whose abundance was low in the uppermost Maestrichtian and increased in the lowermost Danian.) Yet, its carbon isotope composition is higher than

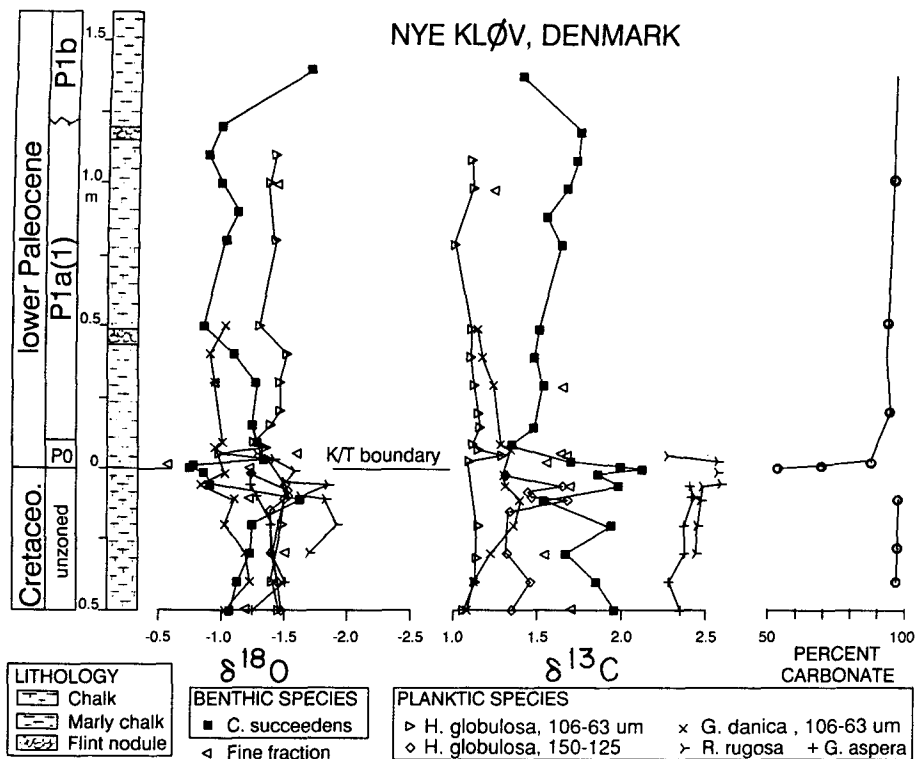


Figure 6. Oxygen and carbon isotope ratios of foraminiferal species and fine-fraction carbonate, and sediment carbonate percentage across the K/T boundary in the section at Nye Kløv, Denmark. The entire K/T boundary section of pelagic carbonates contains scattered flint layers (Hakanson and Thomsen, 1979). Isotopic ratios are listed in Table 2 and Keller and others (1993). The $\delta^{13}\text{C}$ values of *G. danica* and *H. globulosa* in the size fraction from 63 to 106 μm show no significant change across the K/T boundary.

that in the uppermost Maestrichtian. Although ^{13}C enrichment of reprecipitated carbonate can occur during methanogenesis (Claypool and Kaplan, 1974), there is no evidence for this process occurring in these sediments (Schmitz and others, 1991; Thierstein and others, 1991). Thus, Site 738 fine-fraction/bulk carbonate $^{18}\text{O}/^{16}\text{O}$ ratios across the boundary may reflect in part ambient conditions, because they are consistent with foraminiferal $\delta^{13}\text{C}$ values.

Fine-carbonate $\delta^{13}\text{C}$ and nanofossil abundance patterns of Sites 738 and 690 appear to be similar (Fig. 7). At Site 690, the lowermost Danian fine-fraction carbonate with high $\delta^{13}\text{C}$ values is composed of Cretaceous nanofossils with ~30% abundance of survivor species (Pospichal and Wise, 1990). At both sites, the numbers of survivor and Tertiary nanofossil specimens increase gradually in sediments in Zones P1a and P1b (antarctic nanofossil Zones NA1 and NA2). Tertiary forms dominate the assemblage in both the intervals of low $\delta^{13}\text{C}$ in Zone P1b and increasing values in P1c (ant-

arctic nanofossil Zones NA2 and NA3) (Fig. 8) (Pospichal and Wise, 1990; Pospichal and Huber, 1992; J. Pospichal, unpub. data, 1993). It is likely that the fine-fraction $\delta^{13}\text{C}$ pattern, corresponding to the gradual decrease in Zone P1a and the sharp drop in values in Zone P1b (not reproduced by the foraminiferal data), is controlled to some extent by polytaxic effects. Although there is no apparent variation in the relative abundance of any one taxon associated with $\delta^{13}\text{C}$ changes at Site 738 (J. Pospichal, unpub. data, 1993), further isotopic work on individual nanofossil components may clarify these relations.

DISCUSSION

These data suggest that planktic carbonate $\delta^{13}\text{C}$ values in high latitudes may not have dramatically decreased at the K/T boundary; thus, near-surface water productivity may not have been reduced as much in low and middle latitudes. Secondly, the data suggest that the first decline in planktic and

benthic foraminifera and fine-fraction carbonate $\delta^{13}\text{C}$ values in the southern high-latitude oceans occurred in Zone P1b, >200 000 yr after the K/T boundary. Finally, the data suggest that this event was followed by a global increase in the vertical $\delta^{13}\text{C}$ gradient, reflecting the recovery of surface-water productivity in Zone P1c, ~500 000 yr after the K/T boundary. Possible implications of the data are discussed below.

K/T Boundary Event

We have presented isotopic evidence that suggests that the K/T boundary event may not have affected the marine ecosystem uniformly in that its effect may have been less severe in the high latitudes than in low and middle latitudes. At Site 738, the K/T boundary event occurred during an environmental change that is recorded with the onset of clay-rich laminated sedimentation in the latest Maestrichtian, continuing into the early Paleocene. As a result of this, carbonate percent abundance decreased gradually from 95% to 90% in the uppermost Maestrichtian to 80% in sediments deposited in Zones P0 and P1a, and then it increased gradually in Zones P1b and P1c (Fig. 3). Hiatuses in the lower Danian do not permit sediment accumulation rate estimates (Fig. 2B) (Keller, 1993). The decrease in carbonate abundance and number of foraminiferal tests across the boundary may reflect either lower surface-water productivity, as observed in other K/T boundary sections, or dilution by noncarbonate components.

It could be argued that the slight increase in *C. waiparaensis* $\delta^{13}\text{C}$ values across the boundary and the absence of a decrease in the vertical *C. waiparaensis*-*G. beccariiformis* $\delta^{13}\text{C}$ gradient at Site 738 is not indicative of the lack of a significant drop in surface water productivity. As previously discussed, the similarity in the trends and absolute oxygen and carbon isotope values of *C. waiparaensis* and *G. beccariiformis* suggest a deep water habitat below the thermocline and/or in the oxygen minimum zone for the planktic taxon. The $\delta^{13}\text{C}$ values of this species may be more representative of deep water conditions and, hence, may not have recorded a decrease in surface-water primary production. Nevertheless, the high $\delta^{13}\text{C}$ values of the near-surface dwelling *Eoglobigerina* spp. near the base of Zone P1b at Site 738 and *E. fringa* in the lowermost Danian samples at Site 690, relative to Maestrichtian values of the deep near-surface *H. globulosa*, support the above interpretation

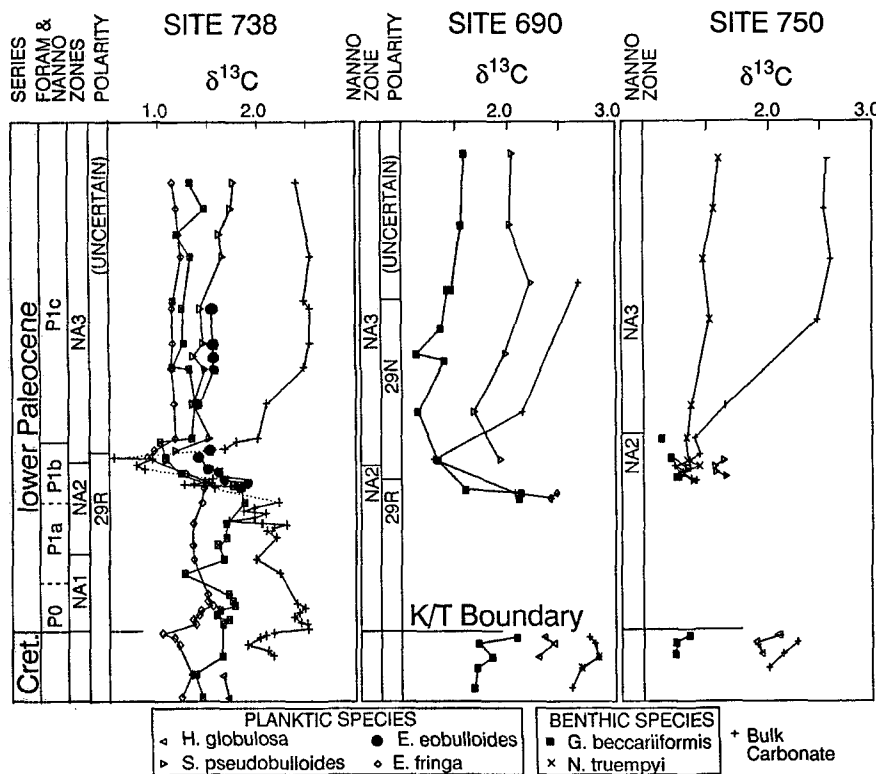


Figure 7. Comparison of carbon isotopic ratios of foraminiferal species and carbonate samples of Sites 738, 690, and 750. For Site 738, isotopic data are from this study, foraminiferal zonation from Keller (1993), nannofossil zonation from Wei and Pospichal (1991) and Pospichal and Huber (1992), and magnetostratigraphy from Sakai and Keating (1991). For Site 690, isotopic data and magnetostratigraphy are from Stott and Kennett (1990) and Hamilton (1990), respectively; nannofossil zonation is from Pospichal and Wise (1990). Sediment ages used to correlate isotopic records of Sites 738 and 690 are based on datums in Table 3 and planktic foraminiferal zonations in Keller (1993). Site 750 nannofossil zonation is from Ehrendorfer and Aubry (1992) and Pospichal and Huber (1992), and isotopic data and sediment age estimates are from Zachos and others (1992). The position of the NA2/NA3 boundary at Site 750 is drawn based on data from Ehrendorfer and Aubry (1992). Pospichal and Huber (1992) placed this boundary lower, just above the level of the first Danian isotopic data point.

of the *C. waiparaensis*–*G. beccariiformis* data. They also suggest either a small or no productivity decline at this later time.

The apparent absence of a dramatic change in surface water productivity in the southern high-latitude oceans contrasts with the productivity change observed in low-latitude regions at the K/T boundary. At lower latitudes, the K/T boundary event is characterized by a pronounced decline in near-surface water carbonate $\delta^{13}C$ values of up to several per mille with a virtual elimination of the surface-to-bottom $\delta^{13}C$ gradient (Zachos and Arthur, 1986; Barrera and Keller, 1990). At Brazos River, Texas, planktic and benthic foraminiferal carbonate $\delta^{13}C$ dropped by ~2.5‰ at the boundary (Barrera and Keller, 1990). In low and middle

latitudes, surface productivity is inferred to have remained low through the earliest Tertiary Zones P0 to P1b. At or below the K/T boundary, most tropical and subtropical planktic foraminiferal species became extinct, whereas some of the smaller cosmopolitan taxa appear to have survived into the Tertiary (Keller, 1988, 1989; Barrera and Keller, 1990; D'Hondt and Keller, 1991). Surviving species seem to have lived deep in the water column. No isotopic record of a surviving surface-dwelling taxa is yet available to document Danian surface-water conditions. For example, the distinctive higher $\delta^{13}C$ values of Cretaceous near-surface to deep-dwelling *H. globulosa* and *G. cretacea* within a narrow size fraction from Cretaceous sediments compared to values

TABLE 3. AGES OF DATUMS USED TO CORRELATE ISOTOPE RECORDS

Datum	Site 738		Site 690	Source
	Age (m.y.)	Depth (m)	Depth (m)	
FO <i>Chiasmolitus danicus</i>	64.8	366.35		5
FO <i>Subbotina varianta</i>	66.08	375.59	246.90	3
Chron 29N (base)	66.17		247.55	4
P1a (top)	66.16	377.01		3
P0 (top)	66.32	377.08		3
K/T boundary	66.39	377.15	247.82	1, 2

Note: FO = first appearance. P0 and P1a foraminiferal zones are from (3). Source of information: 1 = Thierstein and others, (1991); 2 = Stott and Kennett, (1990); 3 = Keller, (1993); 4 = Hamilton, (1990); 5 = Wei and Pospichal, (1991). Sediment ages above the FO *S. varianta* are from (2).

from Tertiary sediments at Brazos River, Texas, demonstrates that these species survived into Danian Zones P0 and P1a (Barrera and Keller, 1990; Barrera, unpub. data, 1993).

What, then, was the effect of the K/T boundary event in the high latitudes? In high-latitude regions (southern ocean and Denmark), latest Cretaceous planktic foraminiferal faunas were mostly composed of small, cosmopolitan, biserial, triserial, and planispiral taxa, most of which disappeared gradually in sediments deposited after the K/T boundary (Keller, 1993; Keller and others, 1993) (Fig. 9). At Site 738, a major change in the faunal composition occurred with the onset of clay-rich laminated sedimentation before the K/T boundary and into the early Tertiary Zone P1c. The biserial *C. waiparaensis* became the dominant species of the planktic foraminiferal assemblage. Other Cretaceous biserial and planispiral taxa suffered a pronounced decrease in their relative abundance (Keller, 1993). The Cretaceous survivor *C. waiparaensis* was a deep-water dweller as previously discussed.

It is not possible to demonstrate that all of these Cretaceous planktic species in Tertiary sediments were survivors. In fact, the similarity between $\delta^{13}C$ values of *G. multi-spina*, *G. aspera*, and *H. globulosa* in Cretaceous and lower Tertiary sediments at Sites 738 (this study; Fig. 4), 750 (Zachos and others, 1992), and 690 (Stott and Kennett, 1990) suggests reworking of older (either Cretaceous or earliest Danian) specimens into Zones P1b and P1c sediments. Reworking of older specimens at Site 738 may be severe in some intervals, as specimens of *Globigerinelloides* have been documented in upper Paleocene sediments (Huber, 1991) and fragments of Cretaceous bivalve inoceramids are in lower Paleocene sediments (K. MacLeod, 1993, personal commun.).

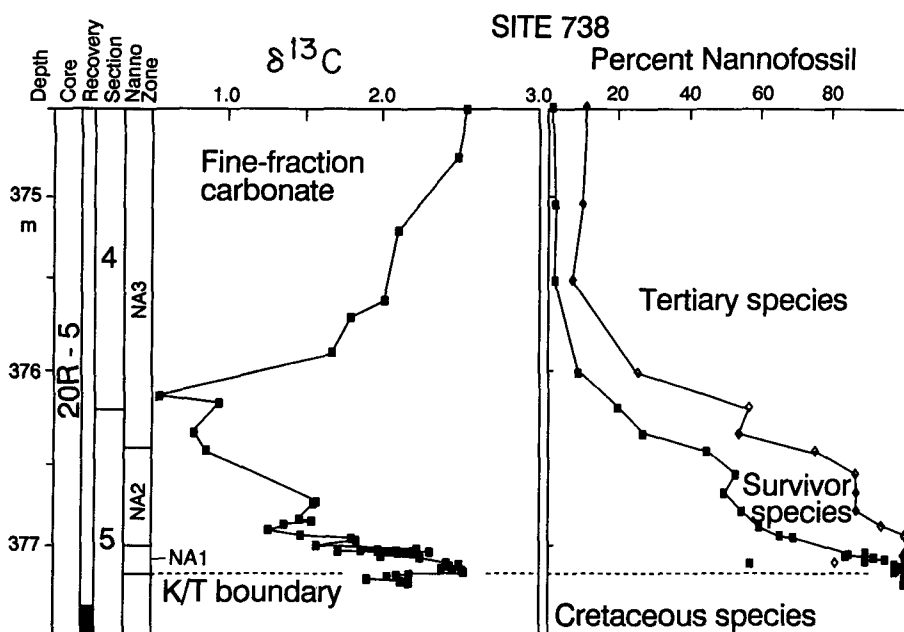


Figure 8. Carbon isotopic composition of fine-fraction carbonate, and percent abundance of Cretaceous, survivor, and Tertiary nannofossil specimens in Site 738 Core 20, sections 4 and 5. Nannofossil zonation and abundance data from Wei and Pospichal (1991) and Pospichal and Huber (1992) and Pospichal (1993, unpub. data).

At Nye Kløv, the significant difference between $\delta^{13}C$ values of *C. succeedens* in uppermost Cretaceous and lower Tertiary sediments suggests that these specimens are not reworked. On the other hand, if benthic fo-

raminifera recorded the lower $\delta^{13}C$ values of Danian surface waters due to decreased primary productivity, there is no obvious explanation why this was not similarly recorded by planktic species living higher up

in the water column. If this interpretation of the benthic foraminifera carbon isotope data is correct, it is possible that the constancy of the planktic foraminiferal $\delta^{13}C$ data across the boundary could result from reworking of Cretaceous specimens into lower Danian sediments. Nevertheless, $^{13}C/^{12}C$ ratios of evolving Tertiary planktic species are similar to those of co-occurring Cretaceous planktic taxa (see Table 2). Moreover, the increase in the percent abundance of *Guembelitra* species in the basal Paleocene Zones P0 and P1a before its disappearance in P1c suggests this taxon's survivorship (Keller and others, 1993; Olson and Liu, 1993). Other Cretaceous planispiral and biserial species, such as the dominant taxon *H. globulosa*, which did not change in relative abundance at the K/T boundary, decreased near the top of Zone P1a and disappeared within P1b sediments (Keller and others, 1993).

Thus, in the northern high latitudes at Nye Kløv, there is no evidence of a sudden mass extinction of the planktic foraminiferal fauna at the K/T boundary. Cretaceous species disappeared in Zones P1a and P1b sediments. The $\delta^{13}C$ values of the dominant taxa *H. globulosa* and *G. danica*, which appear to have had a deep-water habitat below the thermocline, do not change across the boundary. This may reflect either reworking

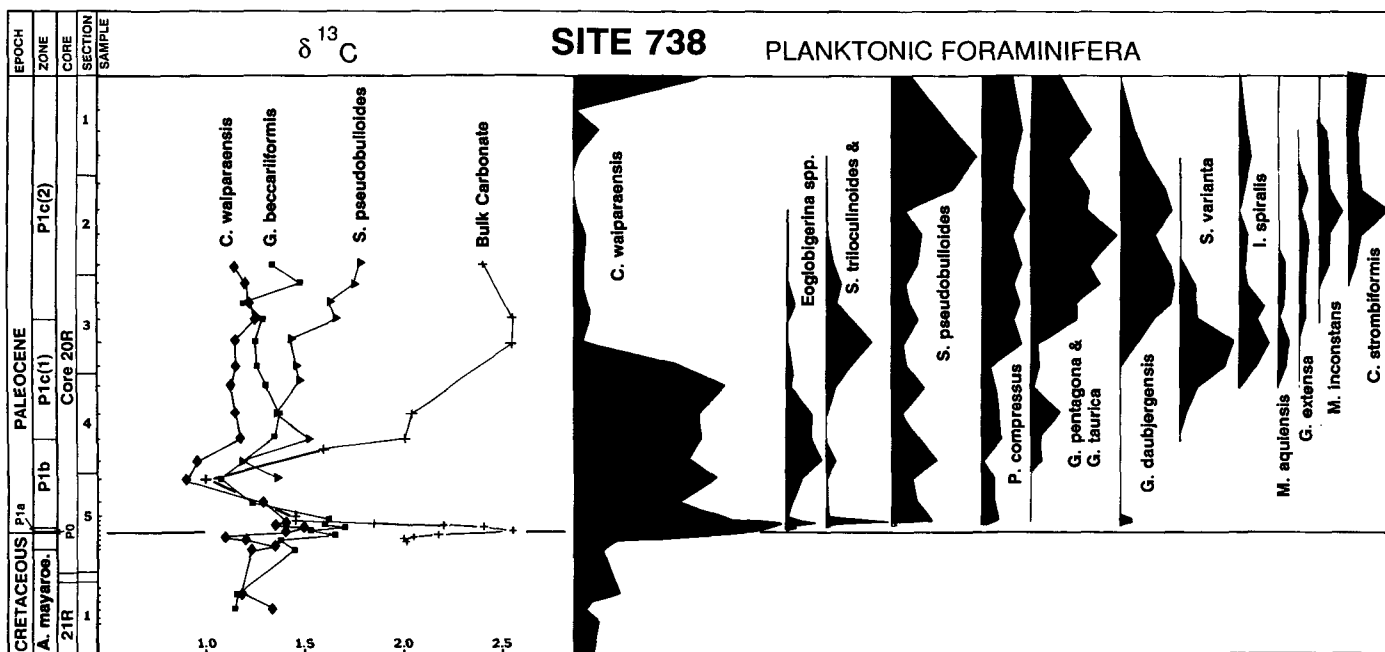


Figure 9. Carbon isotopic composition of bulk carbonate and foraminifers and relative abundances of selected planktic species from uppermost Maestrichtian to lower Danian, Zone P1c, sediments of Site 738. Note that the ecosystem recovery in Zone P1c is evidenced by the major increase in the surface-to-deep $\delta^{13}C$ gradient, indicating increased water-mass stratification and the evolution of the first diverse longer ranging and relatively stable planktic foraminiferal assemblages.

of older specimens in Danian sediments or, less likely, no change in the carbon isotopic composition of surface water. In the southern high latitudes at Site 738, the K/T boundary event appears to have been incidental to environmental processes and changes already in progress. It is possible that the effects of the K/T boundary event involved changes in environmental factors such as light, temperature, and salinity. Because high-latitude plankton was composed of environmentally tolerant cosmopolitan species adapted to large seasonal fluctuations, the ecological effect may have been less severe than in the low latitudes.

Decline in Oceanic $\delta^{13}\text{C}$ Values in Zone P1b

In the high southern latitude oceans, the first post-K/T boundary decline in planktic and sea-floor carbonate $\delta^{13}\text{C}$ values of $\sim 0.5\text{‰}$ – 1‰ occurred at Sites 738 and 690 in Zone P1b (base of antarctic nannofossil Zone NA3 and low-latitude Zone NP2), $>200\,000$ yr after the K/T boundary (Fig. 7). Because this is represented by a change of about the same magnitude in $\delta^{13}\text{C}$ values of both planktic and benthic foraminifera of the polar Indian Ocean and the Weddell Sea, it must reflect a regional shift in the carbon isotopic composition of oceanic total dissolved carbon (TDC). A similar $\delta^{13}\text{C}$ decrease from high values in the earliest Paleocene was recorded by benthic foraminifera from mid-latitude South Atlantic DSDP Site 527 (Shackleton and Hall, 1984) and northwest Pacific DSDP Site 577 (Zachos and others, 1989, 1992).

Stott and Kennett (1989) suggested that, during the Paleocene, deep waters in the world ocean may not have formed in the antarctic as they do today. They argued, from the plankton carbonate isotope data and their interpretation of the biostratigraphy of Site 690, that reduced surface-water productivity at the K/T boundary in the antarctic should have been reflected in lower $\delta^{13}\text{C}$ values of deep waters that formed at the surface. Yet, the plankton carbonate data from Site 738 suggest that surface-water productivity in the antarctic may not have been reduced at the boundary. Moreover, the $\delta^{13}\text{C}$ decrease of oceanic TDC in the southern high latitudes $\sim 200\,000$ yr after the K/T boundary is also recorded by deep-sea benthic foraminifera in the Atlantic and Pacific Oceans. This suggests that the antarctic was the most significant source of

deep water to the oceans in the early Paleocene.

Productivity Recovery in Zone P1c

Increased surface-water productivity in Zone P1c marks the first global post-K/T boundary recovery of the ecosystem, $\sim 500\,000$ yr after the boundary. This recovery is characterized by several factors: (1) $\delta^{13}\text{C}$ of bulk and fine-fraction carbonate that nearly reach pre-K/T boundary levels; (2) the first major increase in the surface-to-deep $\delta^{13}\text{C}$ gradient recorded by the increased difference between benthic foraminifera, planktic foraminifera, and fine/bulk carbonate compositions, indicating increased watermass stratification; (3) the evolution of the first diverse, longer ranging, and relatively stable planktic foraminiferal assemblages; and (4) the first major pulse of evolutionary activity in nannofossils. Evidence for these factors is unequivocal in the high southern latitude oceans as shown in Figure 9.

Equally strong evidence exists from lower latitudes. For instance, in Tunisia, a major evolutionary diversification occurs in planktic foraminifera and nannofossils in Zone P1c (Keller, 1988; Lindinger, 1988). In the deep sea, this recovery is observed also in the first establishment of a "normal" surface-to-deep $\delta^{13}\text{C}$ gradient (Shackleton and Hall, 1984; Zachos and others, 1989, 1992) as well as the first evolutionary activity in nannofossils (Pospichal and Wise, 1990; Ehrendorfer and Aubry, 1992). In the shallow-water Nye Kløv section, increased foraminiferal diversity in Zone P1c coincides with the first post-K/T boundary reappearance of brachiopod faunas (Surlyk and Johansen, 1984; Surlyk, 1990; Keller and others, 1993). Thus, there is ample evidence that the ecosystem returned to "normal" conditions during the time when Zone P1c sediments were deposited, $\sim 500\,000$ yr after the K/T boundary.

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