THE CRETAUCEOUS/TERTIARY BOUNDARY EVENT IN THE NORTH PACIFIC: PLANKTONIC FORAMINIFERAL RESULTS FROM DEEP SEA DRILLING PROJECT SITE 577, SHATSKY RISE

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Abstract. A detailed micropaleontologic analysis of sediments from Deep-Sea Drilling Project site 577 from the Shatsky Rise, North Pacific, was undertaken to describe extinction and radiation patterns of planktonic foraminifera in a continuous carbonate sequence spanning the Cretaceous/Tertiary (K/T) boundary. A 15-m section containing the boundary was closely sampled and contained planktonic foraminiferal assemblages characteristic of the late Maastrichtian Abathomphalus mayaroensis zone through the Danian Globorotalia uncinata zone. The Cretaceous/Tertiary boundary was placed at the abrupt disappearance of almost all Maastrichtian planktonic foraminifera. Coincident with these extinctions was the presence of a large number of "microtektitelike" spherules. The most important faunal change in the late Maastrichtian was an abrupt increase in the relative abundance of the high-latitude species Hedbergella monmouthensis, together with the appearance of diminutive populations of Guembelitria cretacea and Globigerina eugubina approximately 20,000 years before the boundary. These changes are interpreted as indicating a cooling of surface water conditions. Globigerina eugubina and G. cretacea were the only planktonic foraminiferal species to survive the Cretaceous/Tertiary boundary event at this locality. The $\delta^{18}O$ and $\delta^{13}C$ values of G. eugubina from below the K/T boundary are nearly the same as those from above the boundary, but in both cases the $\delta^{18}O$ values indicate relatively cooler paleotemperatures than those from other coexisting planktonic foraminiferal species. In addition, the $\delta^{13}C$ values of G. eugubina are lighter than those of the other planktonic foraminifera. Such a relationship might suggest that G. eugubina lived in cooler, shallow intermediate water masses advected from higher latitudes during a latest Maastrichtian cooling episode. Better preservation of planktonic foraminifera, a progressive change in the $\delta^{13}C$ of benthic foraminifera, and a brief positive excursion in $\delta^{13}C$ of the carbonate fine fraction and of planktonic foraminifera within 20 to 30 cm below the K/T boundary all suggest important paleoceanographic changes that preceded the extinction event. A large population of aberrant G. eugubina and Eoglobigerina was observed in the earliest Danian. These forms are characterized by the development of secondary apertures, bullae, and abnormal final chambers. These abnormal morphotypes are considered to be ecophenotypic variants reflecting ecologic stress or instability in the earliest Cenozoic marine environment.
INTRODUCTION

The rapid faunal and floral changes that occurred near the Cretaceous/Tertiary (K/T) boundary represent the most dramatic biological turnover that can be studied in deep-sea sediments. It has been well documented that planktonic foraminifera and coccolithophorids underwent rapid and widespread extinction at the K/T boundary [Loeblich and Tappan, 1957; Bramlette, 1965; Tappan and Loeblich, 1973; Tappan, 1982], although Perch-Nielsen et al. [1982] and Smit and Romein [1985] have suggested that the mass extinctions of these two groups were not simultaneous. Toward the end of the Cretaceous, planktonic foraminiferal diversity was very high, perhaps higher than at any other time in the past [Cifelli, 1969]. Many multichambered, morphologically ornate forms as well as a diverse stock of serial forms have been described from shelf and deep marine sections of this age [Bolli, 1957; Blow, 1979]. Stable isotopic studies [Saito and Van Donk, 1974; Douglas and Savin, 1975; Boersma et al., 1979; Boersma and Shackleton, 1981] suggest that this diverse Late Cretaceous assemblage lived in a warm, stable habitat and that the different morphologic forms occupied discrete depth-stratified niches.

While the massive extinction of planktonic foraminifera that occurred at the K/T boundary was by far the most severe in the history of Globigerinacean evolution, it was by no means unique in character. The ecologic and evolutionary significance of the selective extinction and survival of certain morphologic forms has been recognized for many years [Cifelli, 1969]. Iterative evolution, the repetition of evolutionary trends, which often results in diachronous homeomorphy, is a well-documented phenomenon of planktonic foraminiferal phylogeny [Cifelli, 1969; Steinbeck and Fleisher, 1978; Caron and Homewood, 1983]. Recent theories have suggested that this repeated occurrence of certain morphotypes is attributable to successive attempts to invade deeper water habitats [Douglas and Savin, 1978; Hart, 1980]. Periods of stress are characterized by oligotaxic assemblages [Fischer and Arthur, 1977] composed of primitive, opportunistic species. The heartiest group of planktonic foraminifera are the simple globigerine morphotypes [Cifelli, 1969]. Highly ornate forms tend to be associated with tropical provinces in the modern ocean, while globigerine forms are characteristic of boreal or higher-latitude regions [Cifelli, 1969]. Thus the extinction of tropical forms and invasion of boreal forms may be associated with climatic instability or cooling. The extinctions at the end of the Cretaceous, which included all Globotruncanidae and most Heterohelicidae, illustrate the selectivity of extinction in planktonic foraminifera. Selective survivals have been reported for the boreal species Hedbergella mommouthensis [Olsson, 1964; Smit, 1982; Boersma, 1984], for Globotruncanella caravacaensis and Globigerinelloides messinae [Smit, 1982], and for Guembelitria cretacea, a simple, diminutive species [Smit, 1982].

Many scenarios as to the nature of the event which may have ended the Mesozoic era have been proposed, including (1) global cooling [Hay, 1960; Saito and Van Donk, 1974], (2) rapid temperature increase [Emiliani et al., 1981; Romein and Smit, 1981], (3) injection of fresh water into the world ocean [Gartner and Berger, 1977], (4) rise of the carbonate compensation depth (CCD) into the photic zone [Worsley, 1974], (5) intense volcanic activity [Vogt, 1972; McLean, 1982; Officer and Drake, 1985], and (6) the impact of a large extraterrestrial body such as an asteroid with the earth [Alvarez et al., 1980].

Alvarez et al. [1980] proposed their asteroid impact theory after the discovery of anomalously high concentrations of iridium and other platinum group elements in the K/T boundary section at Gubbio, Italy. Since these elements are depleted in the earth's crust and mantle in relation to their concentrations in average solar material, the high concentrations at the boundary can be attributed to an extraterrestrial source. Excursions in iridium concentrations have since been found in at least 48 boundary sections [Alvarez et al., 1984], but the source of the high iridium concentrations has been questioned [Officer and Drake, 1985].

PLANKTONIC FORAMINIFERAL BIOSTRATIGRAPHY OF THE LATE MAASTRICHTIAN AND DANIAN

Many workers have contributed to the development of globally correlative planktonic foraminiferal biostratigraphic zonations for the time period surrounding the Cretaceous/Tertiary boundary (Figure 1). Many of these zones were originally de-
Fig. 1. Comparison of various planktonic foraminiferal biostratigraphic zones for the late Maastrichtian and Danian.

scribed and defined by Bolli [1957, 1966] from various sections in Trinidad. Subsequent workers have documented differences in late Maastrichtian planktonic foraminiferal faunas from boreal and temperate regions [Blow, 1979; Malmgren, 1982]. The latest Maastrichtian is generally recognized by the Abathomphalus mayaroensis range zone [Bolli, 1966], but correlations between high- and low-latitude sections are often difficult because of the frequent absence of both the nominate taxa and Globotruncana spp. in high latitudes [Berggren, 1962; Olsson, 1964; Malmgren, 1982].

The zonation of the earliest Danian has been subject to many emendations and modifications due to refinements in chron stratigraphic correlations and detailed biostratigraphic studies of more complete geographically widespread boundary sections (Figure 1). Luterbacher and Premoli Silva [1964] first described the Globigerina eugubina zone from the Central Apennines of Italy and interpreted this interval as representative of the basal Tertiary. Since that time, Herm et al. [1981] have identified an "earlier" Tertiary zone, the Globigerina fringa zone, which occurs just below the G. eugubina zone. In contrast, Smit [1977, 1982] concluded from studies of the El Kef section in Tunisia and the Gredero section in southeast Spain that the basal Tertiary consists of a zone containing G. cretacea and perhaps G. messiniae and H. monmouthensis. This G. cretacea zone of Smit [1982] occurs below the G. fringa zone of Herm et al. [1981].

There has been a great deal of speculation as to which Late Cretaceous planktonic foraminifera survived the boundary event and gave rise to the various Cenozoic lineages. Olsson [1964] concluded that H. monmouthensis, a boreal form, may have
survived the boundary crisis and given rise to the Cenozoic species. Smit [1982] contends that the cosmopolitan species *G. cretacea*, a small, hispid, high-spired form, may have been the sole Maastrichtian species from which all Cenozoic planktonic foraminifera evolved.

In the present study the large-scale extinction and subsequent radiation of planktonic foraminifera during the late Maastrichtian to Danian are described on the basis of a detailed analysis of sediments from Deep-Sea Drilling Project (DSDP) site 577, located on the Shatsky Rise in the North Pacific.

SITE DESCRIPTION

The Shatsky Rise is a large aseismic plateau located in the northwest Pacific (Figure 2). While most areas of the Pacific basin generally lack a thick sequence of carbonate sediments, the Shatsky Rise is capped by 1000 m of Late Jurassic to Recent calcareous sediments [Matter et al., 1975].

DSDP site 577 (32°26.1′N, 157°43.40′E) was hydraulically piston cored three times during leg 86 with the objective of obtaining an undisturbed sequence from across the Cretaceous/Tertiary boundary. Hole 577 was cored in a water depth of 2675 m and a total of 111 m of calcareous nannofossil ooze was recovered. The core penetrated to 118.8-m subbottom depth, and an undisturbed record of the Late Cretaceous–early Tertiary is contained in the bottom 20 m of this sequence.

The Danian sequence at hole 577 is interrupted by an 80-cm section of displaced upper Maastrichtian sediments, extending from 105.0-m to 105.8-m subbottom depth. Danian sediments are found above this interval, with no discernible temporal interruption in sediment accumulation. The Cretaceous sediments probably represent a slump deposit originating from a topographically higher area on the Shatsky Rise.

METHODS

Hole 577 was sampled at intervals ranging from 10 cm to 2 cm, providing us with a sample spacing of 10,000 years or less. In preparation for micropaleontologic analysis, samples were dried, weighed, disaggregated with a hot calgon solution, and wet sieved through a 63-μm screen. The >63-μm portion of the sample was reweighed and dry sieved on a 150-μm screen.
Relative abundances of planktonic foraminiferal species were calculated from random splits of 300 or more specimens obtained from the >150-μm size fraction. Specimens of individual planktonic foraminiferal species were identified and counted from each of a total of 99 samples. We realize that counting the 150-μm fraction results in biasing toward the larger species, but this is the standard size fraction used in most quantitative micropaleontological studies. The 63-μm to 150-μm fraction of each sample was scanned to check for the presence of diminutive species which did not occur in the larger size fraction. Relative abundances of the different planktonic foraminifera in this smaller size fraction were not calculated. In addition, the number of "microtetikite-like" spherules [Smit and Romein, 1985] and the presence of "micarb" particles were determined for each sample. Smit and Romein [1985] have shown that the microtetikite-like spherules found at site 577 are composed primarily of glauconite and magnetite. The micarb particles consist of aggregates of subhedral to euhedral micritic particles and are produced through dissolution and reprecipitation of carbonate [van der Lingen and Packham, 1975].

Carbonate accumulation rates were calculated using the gamma ray attenuation porosity evaluator (GRAPE) wet bulk density and porosity data provided by DSDP for the core, and percent carbonate data. Absolute ages were assigned to stratigraphic levels from hole 577 using the available palaeomagnetic stratigraphy [Bleil, 1985] and the polarity time scale of Berggren et al. [1985]. Sedimentation rates were assumed to be constant between palaeomagnetic datums.

Using this time framework the Danian planktonic foraminiferal data were used to calculate the rate of faunal turnover (Rt) as defined by Sepkoski [1978]. The rate of faunal turnover is a function of speciation and extinction and can be used as a measure of relative stability in faunal assemblages.

This rate is calculated as

\[ Rt = \frac{1}{D} \times \frac{S}{\Delta t} + \frac{1}{D} \times \frac{E}{\Delta t} \]

where D is the number of taxa, S is the number of speciations that occurred during a time interval \(\Delta t\), and E is the number of extinctions during that time interval. A duration of 100,000 years was selected for \(\Delta t\).

Stable isotopic analyses were carried out using the techniques described by Zachos et al. [1985]. All isotopic results are reported as per mil deviations from Pee Dee Belemnite (PDB) standard. Precision of isotopic analyses is better than ±0.11 per mil for oxygen and ±0.08 per mil for carbon.

RESULTS

Faunal Results

Fifty-two species of planktonic foraminifera were identified from 15.2 m of late Maastrichtian and Danian sediments from site 577. Twenty-nine of these species are typical of the upper Maastrichtian A. mayaroensis zone, with the other 23 species being characteristic of the Danian G. eugubina through Globorotalia uncinata zones [e.g. Luterbacher and Premoli Silva, 1964; Bolli, 1966; Stainforth et al., 1975]. The biostratigraphic ranges of these taxa are shown in Figure 3. Except for those of G. cretacea and G. eugubina, these ranges are based on the presence or absence of a species in the >150-μm fraction. The ranges for G. cretacea and G. eugubina are based on their occurrence in the >63-μm fraction. The Cretaceous/Tertiary boundary was placed at 109.09 m on the basis of a complete species turnover in the >150-μm portion of the samples. Specifically, all species from the genera Globotruncana, Heterohelix, Pseudotextularia, Pseudoguembelina, and Praeglobotruncana, which flourished in the late Maastrichtian, as well as the genera Hedbergella, Abathomphalus, Trinitella, Racemiguembelina, and Rugoglobigerina, which occurred in lesser abundances, last appeared at this particular level (Figures 3 and 4). The Cretaceous/Tertiary boundary was placed at 109.09 m on the basis of a complete species turnover in the >150-μm portion of the samples. Specifically, all species from the genera Globotruncana, Heterohelix, Pseudotextularia, Pseudoguembelina, and Praeglobotruncana, which flourished in the late Maastrichtian, as well as the genera Hedbergella, Abathomphalus, Trinitella, Racemiguembelina, and Rugoglobigerina, which occurred in lesser abundances, last appeared at this particular level (Figures 3 and 4). The K/T boundary was placed at the same level by Monechi [1985] on the basis of an abrupt increase in the frequency of Thoracosphaera and the first occurrence of small Biscutum romeinii, a nanofossil described from the lowermost Palaeocene of the El Kef section [Perch-Nielsen, 1981]. However, as was demonstrated by Perch-Nielsen et al. [1982], many Cretaceous coccoliths survived the K/T boundary event and persisted into the early Danian.

The most significant changes in the Maastrichtian assemblage prior to the boundary extinctions are a sudden increase in the abundance of H. mommouthensis about 16 cm below the boundary (Figure 4), and the simultaneous introduction of diminutive...
Fig. 3. Late Maastrichtian-Danian planktonic foraminiferal range chart for site 577. The ranges for all species except G. eugubina and G. cretacea are based on occurrence in the greater than 150-μm size fraction. The ranges for these two particular species are based on their occurrence in the greater than 63-μm size fraction. Subbottom depth, sample position, and foraminiferal preservation are indicated on the left.

populations (<150-μm) of G. eugubina and G. cretacea (Figure 3). No other "Danian" foraminifera were observed below the boundary. Globigerina eugubina and G. cretacea were the only planktonic foraminifera to survive the boundary extinction event at this North Pacific locality.

Changes in the relative abundances of the dominant genera within the Cretaceous interval of the core are shown in Figure 4. The most abundant members of the Maastrichtian assemblage were the genera Globotruncana, Praeglobotruncana, and Pseudoguembelina. Praeglobotruncana is a large, helical, and solution-resistant species. It is the most abundant foraminiferal species in the lower portion of the core.

Globotruncana, members of the family Globotruncanae, tended to decrease in abundance relative to Heterohelicidae (including Pseudotextulariidae, Heterohelix, and Pseudoguembelidae) as the boundary was approached. Many samples from below the boundary show signs of severe dissolution, and as a result, some of the Maastrichtian faunal fluctuations may be attributed to preferential preservation of certain taxa, as suggested by Smit and Romein [1985]. For example, Praeglobotruncana, Pseudoguembelina, Globotruncana stuarti and Globotruncana stuartiformis are solution-resistant species that survived the boundary extinction event.
forms and occur more commonly in the poorly preserved samples. Samples which displayed severe dissolution were not included.

The sequential changes in the abundance of the most common Danian species are illustrated in Figure 5. *Globigerina eugubina* and *Eoglobigerina eobulloides* (normal and aberrant morphotypes) were found together with the last Cretaceous fauna at 109.09-m subbottom depth. These forms are characteristic of the first 30 cm of Danian sediments, at which point they rapidly decrease in abundance and *Chiloguembelina taurica* becomes the dominant species. This form is subsequently replaced by *Globigerina pseudobulloides* and the other nominate taxa of the biostratigraphic zones of Bolli [1966]. Most of the important early
Fig. 5. Downcore changes in the relative abundances of the most common Danian planktonic foraminiferal species in the greater than 150-μm size fraction.
Tertiary zonal indicator species occur in low abundances when they initially appear and then gradually increase in abundance until they become the dominant species of the assemblage.

The sequential evolution and extinction of planktonic foraminifera during the Danian (Figure 5) resulted in a high rate of faunal turnover (Rt) (Figure 6). As is expected, there is nearly a complete turnover associated with the K/T boundary event. This is followed by an interval approximately 1.3 m.y. in duration that is marked by rapid large-scale changes in the makeup of the total assemblage. Between approximately 64 and 65 Ma (within the G. uncinata zone) the fauna remained relatively stable; there were few speciations and extinctions. The rate of turnover is plotted next to the δC-13 records for the benthic foraminifera Aragonia and fine-fraction carbonate from Zachos et al. [1985].

A relatively abundant and diverse assemblage of morphologically complex aberrant forms of G. eugubina and Eoglobigerina was found in association with normal morphotypes in the early Danian (Figures 7 and 8). The aberrant forms exhibit such features as secondary apertures, bullae, and distorted final chambers. These changes in test form are considerably different from those associated with evolutionary change, such as those described by Cifelli [1969] and Hart [1980]. Instead, intra-specific variation of this nature has been attributed to ecological or environmental factors [Steineck and Fleisher, 1978]. These forms of G. eugubina and Eoglobigerina are considered to be ecophenotypic variants and are not assigned to a new genus or species. Samples from the G. eugubina zone of DSDP site 524 in the Cape basin of the South Atlantic were also examined and found to contain similar aberrant forms.

Microtektitelike Spherules

An abundance of reddish spheroids were found at the K/T boundary (Figure 9d). These spheroids are composed of glauconite and magnetite [Smit and Romein, 1985] and are similar in texture to the spherules described by Smit and Kyte [1984] in the boundary sections in Umbria, Italy. Smit and Romein [1985] have recently proposed that these spherules, which are commonly...
Fig. 7. Aberrant morphotypes of G. eugubina and Eoglobigerina. Panel 1 shows the spiral side of G. eugubina showing a secondary aperture, 12-5-108, 160X. Panel 2 shows the umbilical side of the G. eugubina specimen shown in figure 1, 12-5-108, 160X. Panels 3-6 show aberrant Eoglobigerina. Panel 3 is a side view, 12-5-129, 173X; Panel 4 shows the spiral, 12-5-129, 173X; Panel 5 shows the spiral side of the form shown in Panels 3 and 6, 12-5-108, 200X; and Panel 5 shows the umbilical side of E. eobulloidés with a secondary aperture, 12-5-108, 200X. Panels 7 and 8 show an aberrant transitional form with a bulla, 12-5-98, 173X. Panel 9 shows aberrant G. eugubina with an areal aperture, 12-5-98, 200X.

found at the K/T boundary, be referred to as "microtektitite-like" spherules. At site 577 the spherules occur over an interval of less than 25 cm, with a dramatic peak of over 800 spherules per cubic centimeter of sediment in the boundary sample (Figure 9d). If these spherules were deposited instantaneously, as has been suggested by several authors [Montanari et al., 1983; Smit and Kyte, 1984], their distribution over the boundary interval should reflect the extent of bioturbation and mixing within the core. The spherules are mixed to a subbottom depth of 109.15-m, or 6 cm below the boundary, and extend 15 cm above the boundary.

Sediment Preservation and Accumulation

Carbonate dissolution was far more severe in the Cretaceous sediments than in the Paleocene sediments. Many authors have
used the ratios of planktonic to benthic foraminifera as an index of preservation in calcareous sediments [Matter et al., 1975; Thunell, 1976]. This is based on the fact that planktonic foraminifera are less solution-resistant than benthic foraminifera, since the planktonics generally have thinner, more porous test walls. This approach could not be used in this case because in many Maastrichtian samples the benthic foraminifera are also broken and dissolved. Instead, variations in planktonic foraminiferal number (number of planktonic foraminifera per cubic centimeter of sediment) were used to monitor changes in preservation (Figure 9a). This index clearly illustrates the overall better preservation of the Danian assem-
Fig. 9. Downcore changes in (a) foraminiferal number, (b) carbonate accumulation rate, (c) abundance of microtektite-like spherules, and (d) the carbon isotopic composition of fine fraction carbonate. The isotopic data are from Zachos et al. [1985].
blages compared with those of the Maastrichtian. The most severe dissolution occurs between 110.0- and 114.5-m sub-bottom depth (Figure 9a). Approximately 50 cm below the K/T boundary, foraminiferal preservation begins to improve and is very good throughout the Danian (except for within the Cretaceous slump deposit).

Samples containing only a few poorly preserved planktonic foraminifera are primarily composed of unusual agglomerations of micritic crystals or "micarb" particles. These sand-sized particles comprise a large proportion of the >63-μm fraction of many of the Cretaceous samples and are interpreted as having recrystallized from calcium carbonate dissolved in situ. Similar carbonate aggregations were described from the Cretaceous/Tertiary boundary section of DSDP site 465 on the Hess Rise [Vallier et al., 1981]. Since foraminiferal calcite is more susceptible to dissolution than nannofossil calcite [Schlanger and Douglas, 1974], most of the recrystallized calcite is probably derived from the solution of foraminifera and consists of overgrowths on calcareous nannofossils. Sediment accumulation rates also change significantly at the K/T boundary (Figure 9b). The average sedimentation rate calculated for the late Maastrichtian is approximately 1.0 cm/kyr, while in the Danian, sedimentation rates range from 0.1 to 0.3 cm/kyr. Likewise, carbonate accumulation rates below the boundary are greater than 1.1 g/cm2/kyr and are only 0.1 to 0.3 g/cm2/kyr in the Danian (Figure 9b).

DISCUSSION

Cretaceous/Tertiary Boundary Event at Site 577

At site 577 in the North Pacific a number of distinct faunal, sedimentological, and geochemical events occur in close proximity to the K/T boundary (109.09-m depth). These events include (1) an improvement in carbonate preservation at approximately 109.6 m, (2) the first appearances of G. eugubina and G. cretacea at 109.25 m, and at 109.09-m, respectively, (3) the last occurrence of nearly all Cretaceous planktonic foraminifera, (4) the first occurrence of Paleocene nannofossils [Monechi, 1985], (5) the abundant occurrence of microtektitlike spherules, (6) a decrease in carbonate accumulation, and (7) a depletion in the carbon isotopic composition of fine-fraction carbonate [Zachos et al., 1985]. The first two changes occur below the boundary in the latest Maastrichtian, whereas the last five occur simultaneously and mark the K/T boundary.

The presence of G. cretacea in the latest Maastrichtian and its persistence into the early Danian has previously been reported for the Gredero section in Spain and the El Kef section in Tunisia [Smit, 1977, and 1982]. However, the cooccurrence of G. cretacea and G. eugubina below the K/T boundary at site 577 has not been observed at other localities. Globigerina eugubina is considered by most workers to have evolved at the base of the Danian [Luterbacher and Premoli Silva, 1964; Smit, 1982]. The question then arises as to whether the occurrence of these two species, and in particular that of G. eugubina below the boundary at site 577 is real or an artifact of either mixing or burrowing.

Ruddiman et al. [1980] have demonstrated that mixing due to bioturbation is neither size-dependent nor shape-dependent. The deposition of the microtektitlike spherules found at site 577 should represent an "instantaneous" geologic event, and therefore the distribution of these spherules should be an accurate measure of how much sediment mixing has occurred. Officer and Drake [1985] have estimated that if the rate of bioturbation at the K/T boundary was similar to that of today, mixing would occur through depth intervals of approximately 5 to 6 cm. Figure 9d shows that the spherules are in fact mixed only to a depth of 6 cm below the K/T boundary, suggesting that the presence of G. eugubina 16 cm below the boundary is not due to normal mixing. A number of other lines of evidence also support this conclusion. Globigerina eugubina is the only "Paleocene" species found below the boundary, and if mixing had occurred to this level (16 cm below the boundary), we would expect other early Danian species to be present. Similarly, Monechi [1985] reported that no Paleocene nannofossils were mixed below the K/T boundary. These findings seem to suggest that G. eugubina evolved in the latest Cretaceous and together with G. cretacea survived the K/T boundary event at this locality.

The presence of G. eugubina below the boundary could also be explained by a different scenario. J. Smit (personal communication, 1985) has suggested that the G. eugubina specimens found below the K/T boundary may be displaced within a discrete burrow. While this remains a possibility,
it is difficult to explain why no other "Danian" species or microtektite-like spherules are similarly displaced.

Smit and Romein [1985] have recently suggested that "planktonic foraminifera and nannoplankton apparently show a different extinction-recovery pattern at the K/T boundary" and specifically that the final extinction of all Cretaceous nannoplankton occurred up to 10,000 years after the massive extinction of the Cretaceous planktonic foraminifera. Such a scenario implies a differential response of these two groups of plankton to the change in the marine environment that accompanied the K/T boundary event. The "asteroid impact theory" of Alvarez et al. [1980] hypothesizes that dust thrown up into the atmosphere would have blocked out sunlight and suppressed photosynthesis, the net result being a progressive breakdown of the food chain. The fine-fraction δC-13 and carbonate accumulation records for site 577 clearly show that there was a major decrease in plankton productivity at the K/T boundary (Figure 9). If such a decrease in productivity did occur, it seems unlikely that the higher trophic level zooplankton (foraminifera) would have been affected before the photosynthetic nannoplankton which they are dependent upon. According to the model of Milne and McKay [1982], the hypothesized global atmospheric darkening at the end of the Cretaceous would have stopped phytoplankton production within a matter of weeks and shortly thereafter resulted in starvation of zooplankton. Within the resolution of the geologic record, the impact of this event on both groups of plankton should appear coincident. Our planktonic foraminiferal results and the nannoplankton results of Monechi [1985] indicate that the major faunal and floral changes do occur simultaneously at site 577, in association with the peak in microtektite-like spherules.

Late Cretaceous-Early Tertiary Paleoenvironments

The faunal, sedimentological, and geochemical records for site 577 indicate that in addition to the "catastrophic" event at the K/T boundary, there were other significant changes in the marine environment during the late Maastrichtian and Danian.

Numerous workers [Monechi, 1977; Hofker, 1978; Thierstein, 1982; Hsu et al., 1982; Smit and Romein, 1985] have made the general observation that the preservation of calcareous plankton was substantially poorer during the late Maastrichtian than during the Danian. This same observation had previously led Worsley [1976] to hypothesize that the CDP rose into the photic zone at the end of the Cretaceous. The results of our work at site 577 may indicate that the change from poor preservation to good preservation did not occur instantaneously at the K/T boundary but began at least 50,000 years earlier (Figure 9a). Such a change in preservation indicates that a change in the physical-chemical properties of deep waters must have occurred at this time, making these waters less corrosive. This change in preservation was not induced by whatever phenomenon occurred at the boundary.

Likewise, we find evidence at site 577 for a change in surface water conditions prior to the boundary event. The Globotruncanidae and Heterohelicidae are the dominant groups of planktonic foraminifera found at site 577 during the late Maastrichtian (Figure 4), with their abundances varying inversely through time. In general, the tropical Globotruncanidae are dominant throughout the Maastrichtian at site 577 until approximately 30,000 years prior to the K/T boundary. At this point there is an increase in abundance of the more temperate Heterohelicidae, followed by the introduction of the boreal genus Hedbergella approximately 15,000 years before the boundary. This sequence of faunal events at site 577 is indicative of a cooling of surface waters in this region of the North Pacific in the latest Maastrichtian.

As with the change in carbonate preservation, these faunal changes occur prior to, and therefore cannot be attributed to, the K/T boundary event.

The stable isotopic composition of G. eugubina was determined for three samples from below and two samples from above the K/T boundary (Table 1 and Figure 10). The δ0-18 and δC-13 values of all samples are not significantly different, although the δ0-18 values of the G. eugubina just below the boundary are slightly heavier and the δC-13 values are slightly lighter than those of G. eugubina at or above the boundary. The δ0-18 and δC-13 values of G. eugubina below the K/T boundary are also significantly heavier and lighter, respectively, than those of coexisting late Maastrichtian planktonic foraminifera. Such a relationship could be used to argue that the G. eugubina that occur in samples below the boundary were burrowed down from above
TABLE 1. Stable Isotopic Compositions of Selected Planktonic Foraminifera Species Across the K/T Boundary at Site 577

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<tr>
<th>Core/Section Interval</th>
<th>Species</th>
<th>(\delta^{18}O) o/oo, (PDB)</th>
<th>(\delta^{13}C) o/oo, (PDB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/4/19-21</td>
<td>G. ganserri</td>
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</tr>
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<td>G. eugubina</td>
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</tbody>
</table>

and therefore have earliest Tertiary isotopic signals. However, because of the relatively slow sedimentation rates and the thin G. eugubina zone above the boundary, we would expect to also see downward mixing of the spherules that mark the boundary, as was previously discussed. In addition, there are none of the aberrant forms of G. eugubina below the boundary that are relatively abundant at and above it. Therefore we still conclude that the first occurrence of G. eugubina below the K/T boundary, as supported by several other criteria, is real and not due strictly to bionturbational mixing. Such an interpretation suggests that marked paleoceanographic changes occurred prior to what has been termed the "K/T boundary event".

The combination of better preservation of latest Maastrichtian planktonic foraminifera, the progressive positive \(\delta^{13}C\) trend in benthic foraminifera, and the brief positive excursion in the \(\delta^{13}C\) of the carbonate fine fraction and planktonic foraminifera below the K/T boundary support the inference of paleoceanographic changes as discussed above. One possible interpretation of the data is that cooling began at high latitudes during the latest Maastrichtian and progressively affected lower-latitude regions, thereby explaining the floods of heterohelicids and hedbergellids just below the boundary. Cooling at high latitudes could have produced surface waters that were more dense than warmer subtropical waters. The high-latitude surface waters could therefore have served as a source for shallow intermediate water masses that were advected into subtropical regions. Planktonic foraminifera such as
G. eugubina and other heterohelicids and Hedbergella could have lived in the shallow intermediate water masses in the subtropics for a period prior to the K/T boundary while a more normal late Maastrichtian subtropical planktonic fauna persisted in a warmer water mass above. Such a model would explain the cooler isotopic paleotemperature and lighter carbon isotopic composition of G. eugubina below the boundary.

The Danian faunal record is characterized by a very distinctive pattern in which new species evolve, become dominant and then give way to other newly evolving forms (Figure 5). This pattern, which has been previously observed [Smit, 1982; Smit and Romein, 1985], results in a high rate of turnover (Rt) in the assemblage, particularly during the early Danian (Figure 6). The high turnover rates reflect high rates of speciation and extinction and are not significantly affected by diversity, which is relatively constant (8-11 species) at this site throughout this time interval.

These rapid faunal changes may reflect repeated attempts to colonize an unstable or stressful marine environment.

The benthic foraminiferal and fine-fraction carbon isotope records for this site [Zachos et al., 1985] indicate that the surface water to deepwater carbon isotope gradient was virtually nonexistent for the first 300,000 years of the Danian and then was gradually reestablished throughout the remainder of the Danian (Figure 6). A similar observation was made at DSDP sites 465 in the North Pacific [Boersma and Shackleton, 1981] and 524 in the South Atlantic [Hsu et al., 1982]. Surface water to deepwater carbon isotope gradients in the modern ocean are controlled by primary productivity in surface waters and carbon oxidation in deep waters [Broecker, 1974; Kroopnick, 1974, 1980]. The low surface water and high bottom water δC-13 values observed in the early Danian at site 577 suggest that photosynthesis was greatly reduced and that there was little oxidation of organic matter in bottom waters [Zachos
and Arthur, 1985]. *Globigerina eugubina*, *E. eobulloides*, and *C. taurica* became dominant and then declined during this interval of very low surface productivity (Figure 5), resulting in the high turnover rates (Figure 6).

The surface to bottom carbon isotope gradient began to be reestablished approximately 300,000 years after the K/T boundary, indicating an increase in surface productivity (Figure 6). At this time, *G. pseudobulloides* and *G. trinidadensis* become the dominant components of the assemblage. By approximately 65 Ma a surface to bottom carbon isotope gradient (1.5 ‰) was reestablished at site 577 that is comparable in magnitude to the present-day gradient in the North Pacific [Boersma and Shackleton, 1981]. This may signify the point at which a more normal, stable marine environment developed following the K/T boundary event. *Globorotalia uncinata* becomes the dominant member of the planktonic foraminiferal fauna at this time and remains so throughout the rest of the Danian (Figure 5). This faunal stability is reflected by the low rates of faunal turnover above 65 Ma.

**Early Danian Planktonic Foraminiferal Morphologic Variability**

Morphologically complex, aberrant forms of *G. eugubina* and *G. uncinata* occur in high abundances in the basal Danian section of site 577. The morphologic variation exhibited by these forms includes the development of secondary apertures and areal bullae as well as distorted final chambers (Figures 7 and 8). In the past, this type of morphologic variability has been used to distinguish globigerinids at the generic level [Bolli et al., 1957]. However, an understanding of the phylogenetic relationships between foraminiferal groups has improved, it has become apparent that the iterative development of certain biocharacters is controlled not by common ancestry but by functional adaptations which are often convergent [Steineck and Fleisher, 1978]. The misinterpretation of ecophenotypic variants as phyletically significant species has led to overcomplication of planktonic foraminiferal taxonomy, while the ecologic significance of these traits has usually been overlooked [Be, 1965; Berger, 1969; Kennett, 1976]. For example, the Neogene genus *Globigerinoides* is distinguishe from *Globigerina* by the presence of secondary apertures. However, the independent evolution of supplementary apertures in unrelated lineages has occurred at least four times during the Neogene [Steineck and Fleisher, 1978] and twice each in the Paleogene and the Cretaceous [Frerichs, 1971]. Morphologic characters which do not reflect evolutionary descent cannot be used in a phylogenetically significant scheme of taxonomic classification.

Secondary apertures are present on the spiral side of both normal and inflated forms of *G. eugubina*, as well as on forms of *Eoglobigerina* (Figure 7, panels 1-8). Most of these secondary apertures occur on the basal sutures of chambers in the last whorl, although some tests exhibit areal apertures on the final chamber as well (Figure 7, panel 9). Aberrant final chambers and sutural bullae appear only on inflated forms, most of which more closely resemble *E. edita* and *E. eobulloides* than *G. eugubina* (Figure 7, panel 7; Figure 8, panels 1-4). In some cases the final chamber embraces a large portion of the test, resulting in some tests having no discernible primary or secondary apertures. In such extreme cases it becomes very difficult to identify the normal species affinities of the specimen (Figure 8, panel 6).

Where bullae occur, they usually cover or partially cover secondary apertures, which may be visible through an infralaminar aperture (Figure 7, panel 7; Figure 8, panels 1-4). In addition, some specimens have infralaminar apertures parallel to the primary umbilical aperture, resulting in a symmetric or almost planispiral appearance and producing a form which could easily be mistaken for the Cretaceous species *G. messinae* (Figure 8, panel 8). In some extremely distorted forms, chamber addition becomes so irregular that it is difficult to identify the dorsal and ventral sides of the test (Figure 8, panel 9).

The forms described above are considered morphologic variants of the primitive early Danian species from which they are derived. The occurrence of these aberrant forms immediately above the Cretaceous/Tertiary boundary is a good example of the high degree of genetic plasticity that exists in the morphologic development of planktonic foraminifera [Kennett, 1976]. According to Be [1965] the formation of aberrant terminal structures may be related to environmental or reproductive factors. The question of greatest significance to paleocean-
ographers regarding the development of these aberrant test forms is, what is the adaptational significance of such morphologic structures? Unfortunately, little is known about the evolutionary biology and functional morphology of planktonic foraminifera [Lipps, 1981]. Be [1965] suggested that the formation of abnormal terminal structures in several modern-day species could be related to the occupation of relatively deeper depth habitats than their "normal" counterparts. Likewise, Berger [197t] found abundant kummerforms associated with a tongue of advected intermediate water in an oceanic front off Baja California. He attributed this abnormal growth of final chambers to the submergence by burrowing organisms, other available evidence supports a primary first occurrence of G. eugubina below the boundary. The occurrence of G. eugubina below the boundary requires explanation. The oxygen and carbon isotopic composition of G. eugubina from above and below the K/T boundary are not significantly different. Although this could be interpreted as indicating reworking of specimens with early Tertiary isotopic signals into uppermost Maastrichtian strata by burrowing organisms, other available evidence supports a primary first occurrence of G. eugubina below the boundary. The occurrence of G. eugubina below the K/T boundary requires explanation. The δ18O and δ13C values of this species are heavier and lighter, respectively, than those of the other Cretaceous planktonic species from the same intervals. One possibility is that cooling began at higher latitudes several tens of thousands of years prior to the K/T boundary and that cool, high-latitude surface waters sank to become shallow intermediate water masses that were then advected into subtropical regions. The overlying subtropical surface waters would have been warmer and characterized by a normal late Maastrichtian planktonic foraminiferal and nannofossil assemblage. These shallow intermediate water masses carried with them a high-latitude planktonic foraminiferal fauna that included G. eugubina. Globoigerina eugubina therefore would record cooler oxygen isotopic paleotemperatures and lighter carbon isotope values than the near-surface Maastrichtian forms. The disappearance of the latest Cretaceous forms was accompanied by further cooling of surface waters and less thermal and carbon isotopic differentiation above the thermocline.

CONCLUSIONS

1. Globigerina eugubina first appears approximately 20,000 years below the K/T boundary at site 577. The distribution pattern of microtektite-like spherules and the lack of reworked Danian nannofossils below the boundary indicate that this appearance is not the result of core disturbance or bioturbation. Globigerina eugubina and G. cretacea were the only planktonic foraminifers to survive the K/T boundary event at this locality.

2. There is a gradual improvement in foraminiferal preservation beginning approximately 50,000 years (50 cm) before the K/T boundary. This change in preservation is interpreted as reflecting a change in the physicochemical properties of deep waters during the latest Maastrichtian.

3. An increase in the abundance of the temperate Heterohelicidae approximately 30,000 years (30 cm) before the K/T boundary, followed by the introduction of the boreal genus Hedbergella approximately 15,000 years later (15 cm below the K/T boundary), is indicative of a cooling of surface waters in this region during the latest Maastrichtian.

4. The oxygen and carbon isotopic composition of G. eugubina from above and below the K/T boundary are not significantly different. Although this could be interpreted as indicating reworking of specimens with early Tertiary isotopic signals into uppermost Maastrichtian strata by burrowing organisms, other available evidence supports a primary first occurrence of G. eugubina below the boundary. The occurrence of G. eugubina below the boundary requires explanation. The δ18O and δ13C values of this species are heavier and lighter, respectively, than those of the other Cretaceous planktonic species from the same intervals. One possibility is that cooling began at higher latitudes several tens of thousands of years prior to the K/T boundary and that cool, high-latitude surface waters sank to become shallow intermediate water masses that were then advected into subtropical regions. The overlying subtropical surface waters would have been warmer and characterized by a normal late Maastrichtian planktonic foraminiferal and nannofossil assemblage. These shallow intermediate water masses carried with them a high-latitude planktonic foraminiferal fauna that included G. eugubina. Globoigerina eugubina therefore would record cooler oxygen isotopic paleotemperatures and lighter carbon isotope values than the near-surface Maastrichtian forms. The disappearance of the latest Cretaceous forms was accompanied by further cooling of surface waters and less thermal and carbon isotopic differentiation above the thermocline.

5. Carbonate accumulation rates and the fine-fraction carbonate δ13C record indicate a major decrease in surface water productivity at the K/T boundary. Within the resolution of the record, calcareous nannoplankton and planktonic foraminifera were influenced simultaneously by this decrease in productivity.

6. The rapid speciation and high turnover rate of planktonic foraminifera in the early Danian may be related to a highly unstable marine environment. In particular, the surface to bottom δ13C gradient indi-
icates that surface productivity was greatly diminished at the K/T boundary and was only gradually reestablished during the early Danian.

7. Aberrant forms of G. eugubina and Eoglobigerina are abundant in the earliest Danian. These forms exhibit a high degree of morphologic variability including such structures as secondary apertures, bullae, and distorted final chambers. Variations of this nature can be attributed to ecologic or environmental stress and have no phyletic significance.

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