The Cretaceous/Tertiary boundary impact hypothesis and the paleontological record

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ABSTRACT

Planktonic foraminifera show 30 to 45 percent of the species disappearing during the 300,000 to 400,000 years prior to the Cretaceous/Tertiary (K/T) boundary in continental shelf (El Kef, Tunisia) and epicontinental sea (Brazos River, Texas) sections. Their disappearance appears to be linked to a sea-level regression and global cooling. At the K/T boundary a 26 percent species reduction coincides with the geochemical anomalies at El Kef; their disappearance appears to be a direct consequence of the K/T boundary event. No change is observed at Brazos River. At both El Kef and Brazos River, many species (11 and 33 percent, respectively) disappear shortly after the K/T boundary, and all but one of the Cretaceous survivors terminally decline in relative abundance beginning at the K/T boundary. This pattern of species extinctions clearly shows a significant decline in species diversity during the latest Maastrichtian, followed by a sudden decline in diversity at the K/T boundary, which drastically and permanently altered planktonic foraminiferal communities. The K/T boundary event, however, did not cause instantaneous extinctions of nearly all species, as commonly claimed. Initial recovery of the ecosystem appears to have occurred about 230,000 years after the K/T boundary event, as implied by an increase in carbonate sedimentation, carbon isotope values, and diversification of planktonic foraminifera.

Carbon and oxygen isotope records of benthic and planktonic foraminifera at Brazos River reveal remarkable new data with far-reaching implications. For instance, the $\delta^{13}C$ shift, which characterizes the K/T boundary globally, coincides with the micropaleontologically defined boundary and not with the tsunami deposit of Bourgeois and others (1988), indicating that the latter deposit is independent of the boundary event. Moreover, the $\delta^{13}C$ shift occurs gradually over thousands of years, and not instantaneously as recorded in deep-sea sections, implying a more gradual and long-term effect than commonly assumed. Furthermore, stable isotopic data unequivocally show the survivorship of many Cretaceous species well into the early Tertiary.

INTRODUCTION

The Cretaceous/Tertiary (K/T) boundary impact theory proposes a simple and effective mechanism to explain mass extinctions in Earth history and, by extension, the driving force behind rapid evolutionary changes following extinction episodes. This hypothesis is attractive because of its beauty and simplicity, but does it fit the fossil record? There is no doubt that objects from space have bombarded the Earth through time (Shoemaker, 1983; Shoemaker and others, 1988), and there is strong evidence from iridium enrichments and the presence of shocked mineral grains that an impact occurred at the K/T boundary (e.g., Al-

varez and others, 1980; Bohor and others, 1984; Bohor and Izett, 1986; Izett and Pillmore, 1985; Izett, 1987). Thus, the question is not whether impacts occur, but what effect they have on life on Earth.

What was the effect of a K/T boundary impact on the fauna and flora? The fossil record provides scant evidence in support of a catastrophic and geologically instantaneous mass extinction directly coinciding with the geochemical impact signatures. Each fossil group (dinosaurs, invertebrates, marine plankton, plants) shows a gradual decline in diversity through the late Maastrichtian and accelerated species extinctions beginning at least 300,000 to 400,000 years before the K/T boundary (Van Valen and Sloan, 1977; Keller, 1988a, 1989a; Sweet and others, this volume), which can be attributed to rapidly deteriorating climatic conditions and a sea-level regression (Peypouquet and others, 1986; Hallam, 1987; Keller, 1988b, 1989a, b; Brinkhuis and Zachariasse, 1988). Nevertheless, there is strong evidence of a major pulse of accelerated extinctions coinciding with the K/T boundary and the geochemical signatures supporting a bolide impact. Moreover, the faunal record leaves no doubt that this K/T boundary event initiated a dramatic and sustained environmental change; more stable environmental conditions resumed only several hundred thousand years later (Zachos and Arthur, 1986; Gerstel and others, 1987; Keller and Lindinger, 1989).

The nature of the K/T boundary mass extinction—the rate of species extinctions, background extinctions, and extinctions that can be directly attributed to this catastrophic event—is not well understood. The major difficulty for paleontologists is to isolate faunal changes as a result of catastrophic causes from those caused by facies changes, local endemic conditions, sea-level changes, climate fluctuations, or hiatuses. A way must be found to separate these varied effects before the effect of an extraordinary cause can be evaluated. The most serious problem has been the incomplete stratigraphic record (Officer and Drake, 1985). It is well known that more than 90 percent of all K/T boundary sections contain hiatuses, nondeposition, or extremely reduced sedimentation rates, which are commonly explained as a result of greatly reduced primary productivity presumably caused by a bolide impact (Hsü and others, 1982; Shackleton and others, 1984; Zachos and Arthur, 1986). This results in a condensed record that gives the appearance of abrupt species extinctions or population changes that may, in fact, have occurred gradually over an extended time period. Many K/T boundary sections that record instantaneous mass extinctions are, in fact, stratigraphically incomplete.

In recent years, paleontologists have begun investigating the nature of the K/T boundary mass extinction record on the centimeter-scale level in stratigraphic sequences with high sedimentation rates (Peypouquet and others, 1986; Gerstel and others, 1986, 1987; Brinkhuis and Zachariasse, 1988; Keller, 1988a, b, 1989a, b; Smit and others, 1988; D'Hondt, 1989). Increasingly, high-resolution stable isotope studies across the K/T boundary have become available (Zachos and Arthur, 1986; D'Hondt, 1989; Keller and Lindinger, 1989; Barrera and Keller,

1990; Stott and Kennett, 1988, 1990). These studies, combined with the faunal data, provide an unprecedented high-resolution stratigraphic record that reveals the complexities of this mass extinction event and permits us to isolate species extinctions and long-term faunal and environmental changes that appear to be direct consequences of a geologically instantaneous event (presumably a bolide impact) at the K/T boundary. We review and discuss this record in this chapter. First, we briefly review the paleontologic records for dinosaurs, invertebrates, plants, and nannoplankton in order to evaluate their evidence for catastrophic extinctions at the K/T boundary. In the second part we discuss and illustrate the high-resolution planktonic foraminiferal and oxygen and carbon isotope records of the two stratigraphically most complete K/T boundary sections known to date: the Tethyan continental shelf section at El Kef, Tunisia, and the epicontinental sea section at Brazos River, Texas. Based on these combined faunal and isotope records we are now able to isolate species extinctions apparently caused directly by the K/T boundary event, species extinctions apparently caused by long-term environmental consequences of this event, and species extinctions due to independent environmental changes. In addition, we are now able to answer conclusively the recent controversy regarding the placement of the K/T boundary in the Brazos River sections and the question of Cretaceous species survivorship in earliest Paleocene strata versus upward reworking of specimens from older sediments.

FOSSIL RECORD

Dinosaurs

Extinction of dinosaurs as a result of a major asteroid impact is the popular symbol of the K/T boundary catastrophe. In fact, this is a major misconception. Vertebrate experts generally agree that there was no mass extinction of dinosaurs caused by a sudden cataclysmic event, but that the extinction appears to have occurred at different times, in different ways, and in different environments (e.g., Van Valen and Sloan, 1977; Clemens and Archibald, 1980; for a recent review see Clemens, 1986, and Sloan and others, 1986). The precise pattern and rate of extinction, however, are still controversial, primarily due to questions regarding post-depositional sorting and reworking of fossils (Russell, 1982; Smit and van der Kaars, 1984; Padian and Clemens, 1985; Fastovsky and Dott, 1986; Archibald and Bryant, 1988).

The most detailed record is known from western North America. This fossil record indicates that dinosaur diversity had already declined by about 60 percent during the 7 m.y. prior to the latest Maastrichtian sea-level regression (Van Valen and Sloan, 1977; Sloan and others, 1986). This steady reduction in diversity is believed to be linked to climatic cooling. A long-term late Maastrichtian cooling trend has been confirmed by stable isotope analysis from the Weddel Sea, Antarctica, by Stott and Kennett (1988, 1990) and Barrera and Huber (1990). Accelerated species reductions affect the remaining fauna during the last

300,000 years of the Cretaceous in Montana (Sloan and others, 1986). Species extinctions are not sudden, but continuous over this time interval. They have been linked to paleoecological changes such as continued climatic cooling, the immigration of new mammals, and consequent competition as a result of the latest Maastrichtian sea-level regression (Sloan and others, 1986; Sloan, 1988).

The precise relation of the extinction of the last dinosaurs and a postulated asteroid impact is still unresolved. This is largely because of the scarcity of fossils and the likelihood of postdepositional transport and reworking of older fossils into younger sedimentary deposits (Fastovsky and Dott, 1986). Hansen (1988, this volume) reports the last occurrence of terrestrial dinosaurs in France and Canada about 200,000 to 400,000 years and 135,000 to 157,000 years, respectively, before the K/T boundary. In Montana, four localities revealed the last dinosaur remains in sediments deposited during the first 200,000 years of the Paleocene (Sloan and others, 1986; Sloan, 1988). Given the poor fossil record, one can only say that there is no certain evidence of a sudden extinction at the K/T boundary, but the case for gradual extinction across the boundary is also weak.

Marine invertebrates

Richly fossiliferous and relatively complete records of marine invertebrates across the K/T boundary are rare. The sections most commonly cited in the literature are from localities in Denmark (Stevns Klint and Nye Kløv), Texas (Brazos River), Alabama (Braggs), and Spain (Zumaya). The marine extinction record has recently been reviewed by Hallam (1987), and Kauffman (1984) discussed the general decline in diversity of marine invertebrates through the Maastrichtian. Some Cretaceous molluscs, such as belemnites, rudists, and inoceramids, became extinct before the K/T boundary or were nearly extinct by that time (Ward and others, 1986; Ward and MacLeod, 1988; Johansen, 1987, 1990).

In the Braggs and Brazos River sections, diverse molluscan assemblages characterize the upper Maastrichtian (Jones and others, 1986; Hansen and others, 1984, 1987). Species diversity and abundance decline sharply in the lowermost part of magnetic anomaly C29R, or about 300,000 years below the K/T boundary, as illustrated by Jones and others (1986) for the Braggs, Alabama, section. In the Brazos River sections this decline begins just below the unconformity at the base of the "tsunami bed" of Bourgeois and others (1988), which these authors interpret as the boundary event. Diversity remains low across the micropaleontologically defined K/T boundary and into the early Tertiary.

Among other invertebrates, brachiopods also show a decline in diversity during the uppermost Maastrichtian (Surlyk and Johansen, 1984; Johansen, 1987, 1990). At the Nye Kløv section, diversity declines from 27 to 13 species at the K/T boundary. Six species are common in both upper Maastrichtian and Danian strata and apparently represent survivors. These species are environmentally tolerant, long-ranging generalists of simple morphology. Rapid evolution and diversification of species occurs in the Damian about 4 to 5 m above the K/T boundary in the Nye Kløv section (Surlyk and Johansen, 1984; Johansen, 1987).

Extinction patterns of marine invertebrates during the uppermost Maastrichtian and lowermost Paleocene are still not fully understood largely because of the paucity of fossiliferous and continuous sedimentary sequences. Nevertheless, the present sparse data set suggests a general decline in species diversity through the Late Cretaceous but does not permit the identification of species directly affected by the boundary event.

Plants

Fossilized leaf imprints, pollen, and spores provide a rare glimpse of terrestrial environments during the Late Cretaceous and early Tertiary. Until recently, paleobotanists generally found no evidence of a catastrophic event; rather they described a gradual decrease in diversity during the Late Cretaceous, possibly confined to the Northern Hemisphere and related to climatic cooling (Hickey, 1984; Johnson and Hickey, 1988). This view has been challenged by some investigators (Tschudy and others, 1984; Tschudy and Tschudy, 1986; Nichols and others, 1986; Nichols and Fleming, 1988) working in the western United States and southern Canada who favor a pronounced temporary disruption of plant life at the time of the proposed impact event. The evidence is an unusually high abundance of fern spores immediately above an enrichment in iridium and shocked minerals. The fern-spore spike is interpreted as recolonization of a nearly barren landscape by opportunistic plant species. Flowering plants (angiosperm) appear to have suffered major losses, with 30 percent of the species extinct (Nichols and others, 1986).

Patterns of extinction and the severity of the extinction event appear to have varied from one region to another. Lerbekmo and others (1987), Sweet (1988), and Sweet and others (this volume) studied the more northern plant communities in western Canada between paleolatitudes 60° and 75°N and found surprisingly different results. In contrast to lower latitudes, no fern-spore spike was found, and only a few species disappeared at the K/T boundary defined by an Ir enrichment. The major change was observed in the relative abundance of angiosperm pollen species beginning 26 cm below and continuing 21 cm above the K/T boundary. Sweet (1988) interprets these data to indicate that there was no single continent-wide floral response to the boundary event. He concludes that the component of change related to extraordinary causes appears less catastrophic when isolated from the effects of facies and latitudinal changes. Floral studies of North America thus indicate that the effect of a K/T boundary event was localized and most severe in the western United States, decreasing into northern latitudes; a pattern consistent with a relatively small bolide impact somewhere in North America.

Nannofossils

Nannofossil extinction patterns across the K/T boundary have been difficult to interpret largely because of their small size,

which allows them to be readily transported and redeposited. Separation of redeposited species from in situ fauna is very difficult. With these limitations, Cretaceous species, which are common in basal Tertiary strata, are usually interpreted as redeposited (Thierstein, 1982). Perch-Nielsen and others (1982), however, demonstrated that Late Cretaceous nannofossils in basal Tertiary strata have a Tertiary isotopic signal, indicating that some nannofossil species survived the boundary event.

The most detailed quantitative nannofossil record across the K/T boundary has been published by Jiang and Gartner (1986) from Brazos River, Texas. These authors grouped nannofossil species into vanishing, persistent, incoming, and redeposited older species. The group of "redeposited" species (17 percent) is considered reworked because of their preservational state and because they are not known to range into the Tertiary in reference sections (Jiang and Gartner, 1986). The "vanishing" species (57 percent) are typical of Upper Cretaceous strata. Four to five species dominate this group into the earliest Tertiary where the relative abundance of these species drops to a few percentage points 1 m above the K/T boundary similar to the pattern observed in planktonic foraminifera. Jiang and Gartner (1986) interpret this pattern as redeposition of Cretaceous sediment after a catastrophic extinction event. The group of "persistent" species is dominated by the disaster forms *Braarudosphaera* and *Thoracosphaera,* which increase in abundance above the K/T boundary. These species are considered survivors. "Incoming" species (13 percent) evolve gradually above the K/T boundary after the terminal decline in abundance of the "vanishing" species. Contrary to common belief, a similar pattern of Cretaceous survivors dominated by disaster forms and their gradual disappearance above the K/T boundary is also observed among planktonic foraminifera as discussed below.

PLANKTONIC FORAMINIFERA— MASS MORTALITY?

The mass extinction of nearly all planktonic foraminiferal species is frequently cited as the major paleontological evidence in support of the impact hypothesis. In fact, Jan Smit, the leading proponent of this theory among planktonic foraminiferal experts, claims that "the mass extinction event at the K/T boundary exterminated all but one species" (Smit, 1982, p. 329). Moreover, this "clear mass-mortality" is proposed as the primary evidence supporting interruption of photosynthesis due to an impact-generated dust cloud blocking out sunlight (Smit and Romein, 1985). In view of the far-reaching implications for the impact theory, close scrutiny of the planktonic foraminiferal response to the K/T boundary event is warranted.

Until nearly a decade ago it was believed that the most complete K/T boundary record was present in deep-sea sediments. There the sedimentary record is marked by an abrupt change from a carbonate ooze rich with a diverse Cretaceous fauna to a thin, dark, carbonate-poor clay layer usually devoid of foraminifera. The first Paleocene species to appear is *Globigerina*

eugubina (Berggren, 1972). Several workers soon discovered that more expanded K/T boundary sequences could be found in relatively shallow onshore marine sequences such as Caravaca, Spain, and El Kef, Tunisia (Salaj, 1973; Smit, 1977, 1982; Perch-Nielsen, 1979; Perch-Nielsen and others, 1982). These workers discovered an additional nannofossil zone (*Biscutum romeinii*) and planktonic foraminiferal zone (P0, *Guembelitria cretacea,* Smit, 1977, 1982) between the Cretaceous and the first appearance of the Paleocene species *Globigerina eugubina.* This new Zone P0 is apparently absent in the deep-sea (Smit and Romain, 1985). In shallow marine sections, Zone P0 is of variable thickness, ranging from about 12 cm at Caravaca and 50 cm at El Kef to 100 cm in some Brazos River sections (Smit, 1982; Keller, 1988a, 1989a, b). The succeeding Zone P1a (*Globigerina eugubina*) is 2.5 m thick in the El Kef section. In contrast, in the deep-sea Zone P0 is absent, and Zone P1a is rarely present and then only a few centimeters thick. It is therefore apparent that virtually all deep-sea sections are marked by a hiatus, nondeposition, carbonate dissolution, or severely reduced sedimentation; hence, the mass extinction event appears more abrupt than it actually occurred.

What does the extinction record look like in the stratigraphically most complete sections known to date such as El Kef, Tunisia, and Brazos River, Texas? Do all species terminate suddenly at the K/T boundary, or is there a gradual disappearance of species during the latest Cretaceous? What type of species become extinct and what type survives? Is there a difference in the severity of extinctions among cosmopolitan versus tropical-subtropical species? Are species represented by many individuals equally affected as species with few individuals? What type of species survives and for how long? What is the rate of evolution of the new Tertiary fauna? How long after the K/T boundary event are stable conditions reestablished? Answers to these questions can provide crucial constraints on the impact theory, the size and effect of the postulated bolide impact, and the darkness scenario. Indeed, many of these questions can now be answered based on high-resolution quantitative planktonic foraminiferal and stable isotope studies of El Kef (Keller, 1988a, 1989b; Brinkhuis and Zachariasse, 1988; Keller and Lindinger, 1989) and Brazos River, Texas (Keller, 1989a, b; Barrera and Keller, 1990) as discussed below.

Extended extinction pattern

Planktonic foraminiferal species at El Kef and Brazos River show an extended K/T boundary extinction pattern beginning below and ending well above the boundary. Figures 1 and 2 illustrate the pattern and type of species becoming extinct at El Kef. About 13 species (29 percent) disappear between 25 cm and 7 cm below the K/T boundary. Twelve species (26 percent) disappear at the K/T boundary coincident with an iridium enrichment (Kuslys and Krähenbuhl, 1983), a drop in carbonate, a negative shift in ^{13}C values of fine-fraction sediment, and an increase in total organic carbon (TOC) (Fig. 2; Keller and Lin-
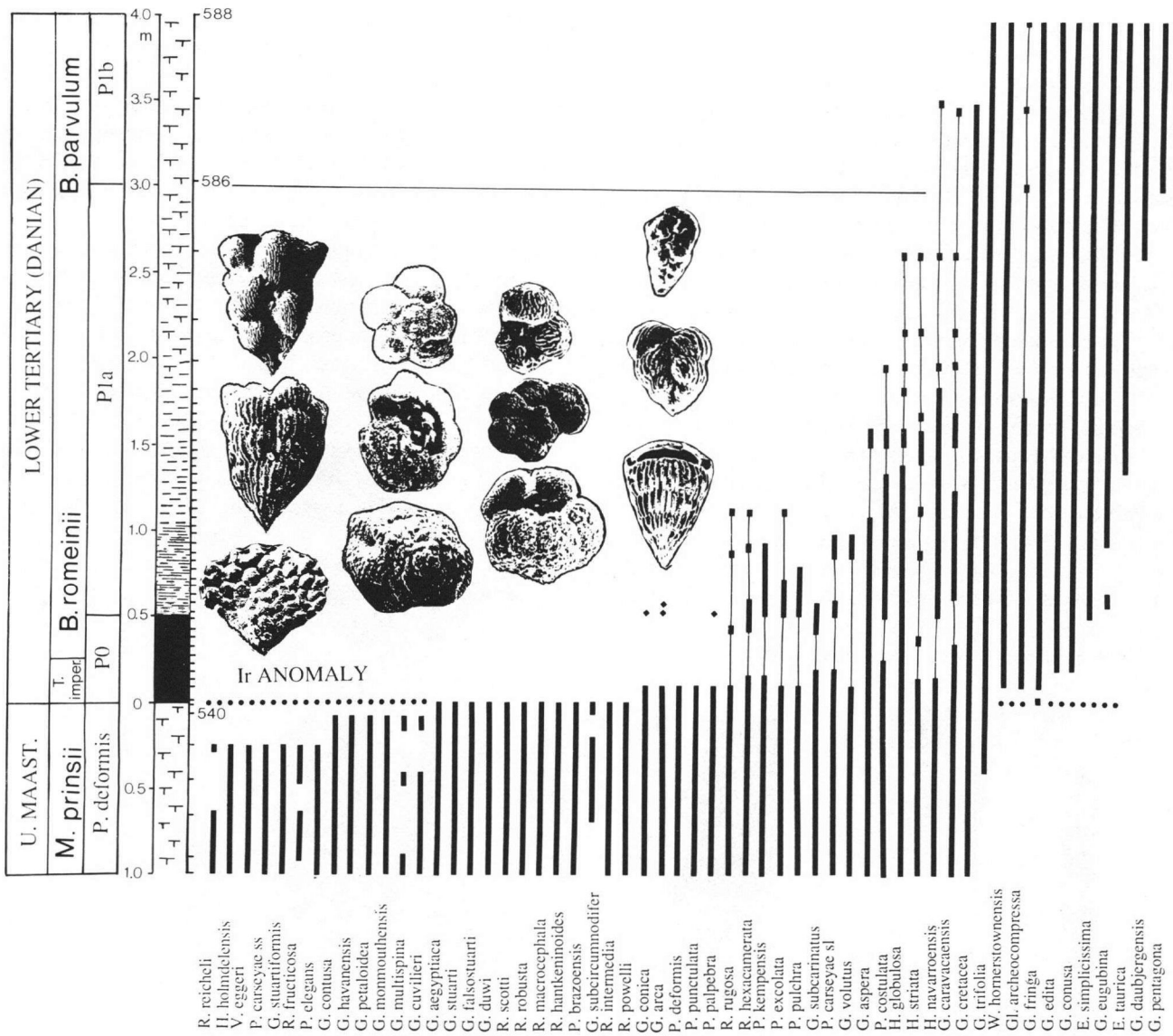
Figure 1. Planktonic foraminiferal species extinctions across the K/T boundary at El Kef, Tunisia. Note the extended species extinction pattern and survivorship of Cretaceous species. Selectivity in extinctions pattern is indicated by early disappearance of large complex tropical forms and later disappearance of smaller, less complex forms. Data from Keller (1988a).

dinger, 1989). Five species (11 percent) disappear 15 cm above the boundary. Of the remaining Cretaceous species, eight (17 percent) are sporadically present through the black clay and disappear near the P0/P1a Zone boundary. The remaining eight (17 percent) Cretaceous species are considered K/T boundary survivors; six of these die out gradually during Subzones P1a and basal P1b (Keller, 1988a, 1989b). This extended pattern of species extinctions implies changing environmental conditions beginning during the latest Maastrichtian, which caused the disappearance of about 13 species (29 percent) prior to the K/T boundary. The bolide impact implied by the geochemical anomalies appears to have caused the immediate extinction of at least 12 species (26 percent), the subsequent extinction of 5 species (11 percent), and

presumably led to the terminal decline in abundance leading to eventual extinction of the remaining Cretaceous survivors (8 species, 17 percent; Fig. 2).

Smit and others (1988) challenged this extinction pattern, claiming that each species dies out exactly at the K/T boundary; however, to date no data has been presented or published to substantiate this claim. It is possible that some of the species listed here as disappearing below the boundary may not be extinct, but rather have become so rare that they are not present in a sample of many thousand specimens examined. This would also imply that environmental conditions became intolerant for certain species before the K/T boundary event. Smit's (1982) argument that all Cretaceous species except *Guembelitria cretacea* became ex-

tinct at the boundary at El Kef, Tunisia, and redeposition accounts for the presence of all other Cretaceous species above the boundary, is untenable. Many earlier studies, including Smit's (1977), reported small Cretaceous species in Tertiary strata as likely survivors (e.g., Maurasse and others, 1979; Maurasse, 1986, 1988; Strong and others, 1987; Brinkhuis and Zachariasse, 1988; Keller, 1988a, 1989a, b). To consider these Cretaceous species as redeposited would necessitate systematic and constant reworking of a select part of the Cretaceous faunal assemblage in regions as far apart as the Mediterranean and Gulf of Mexico. Moreover, these "reworked" Cretaceous species are dwarfed and have a Tertiary isotopic signal, as discussed below (see also Barrera and Keller, 1990), providing the strongest argument for Cretaceous species survivorship to date.

Another strong argument for extended extinctions is the observation of this pattern in multiple stratigraphic sequences as observed in three Brazos River sections (Keller, 1989a). It is most remarkable that in these sections no species extinctions are directly associated with the K/T boundary based on the first appearance of Tertiary species as illustrated in Figure 3. (There is some controversy between Bourgeois and others [1988] and mi-

cropaleontologists Jiang and Gartner [1986] and Keller [1989a] regarding placement of the K/T boundary at Brazos River as discussed in a later section.) Instead, two extinction episodes are apparent, one at 25 to 30 cm below the K/T boundary, at or just below the base of the "tsunami bed" of Bourgeois and others (1988), and the second about 25 cm above the K/T boundary at the P0/P1a Zone boundary. Nearly half (46 percent) of the species disappear during the first extinction phase and about 33 percent (11 species) disappear during the second extinction phase. The remaining seven species (21 percent) survive longer. Based on the paleomagnetic time scale, datum events (Berggren and others, 1985), and rates of sediment accumulation, the pre–K/T boundary extinction phase began about 310,000 before the boundary, and the post–K/T extinction phase occurred about 50,000 years after the boundary (Keller, 1989a, b).

The patterns of species disappearances at El Kef and Brazos River are not precisely the same and suggest regional paleoecological differences. For instance, 11 out of 17 species disappearing at the pre–K/T boundary extinction phase at Brazos River range to the boundary at El Kef (Keller, 1989b) and hence appear to be regional disappearances in the Gulf of Mexico. The species af-
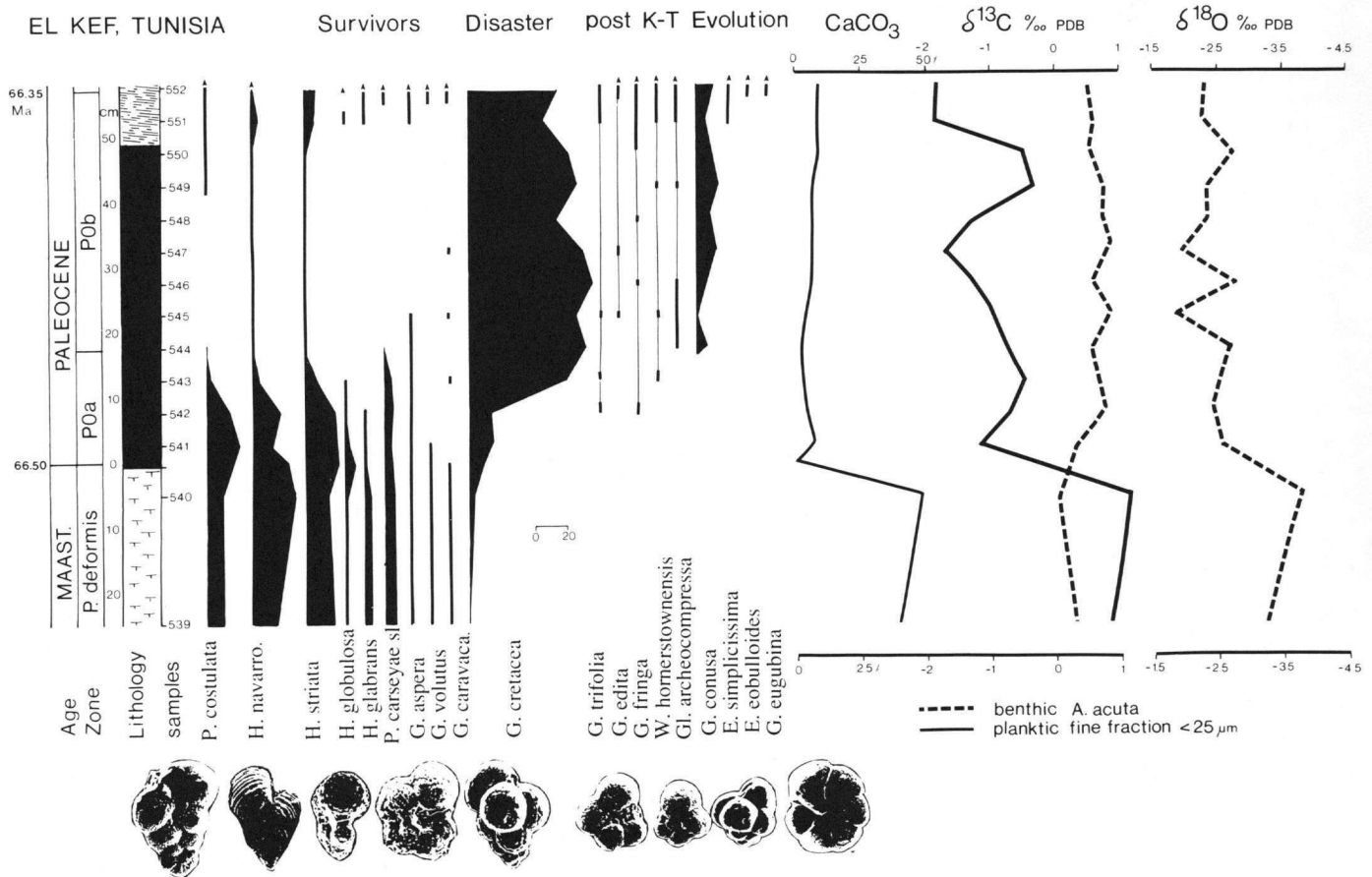

Figure 2. Percent CaCO₃, δ¹⁸O, and δ¹³C stable isotopic data and relative abundance of Cretaceous species surviving into the early Tertiary at El Kef and evolution of Tertiary species. Note the terminal abundance decline of species shortly after the K/T boundary. Faunal data from Keller (1988a), geochemical data from Keller and Lindinger (1989).
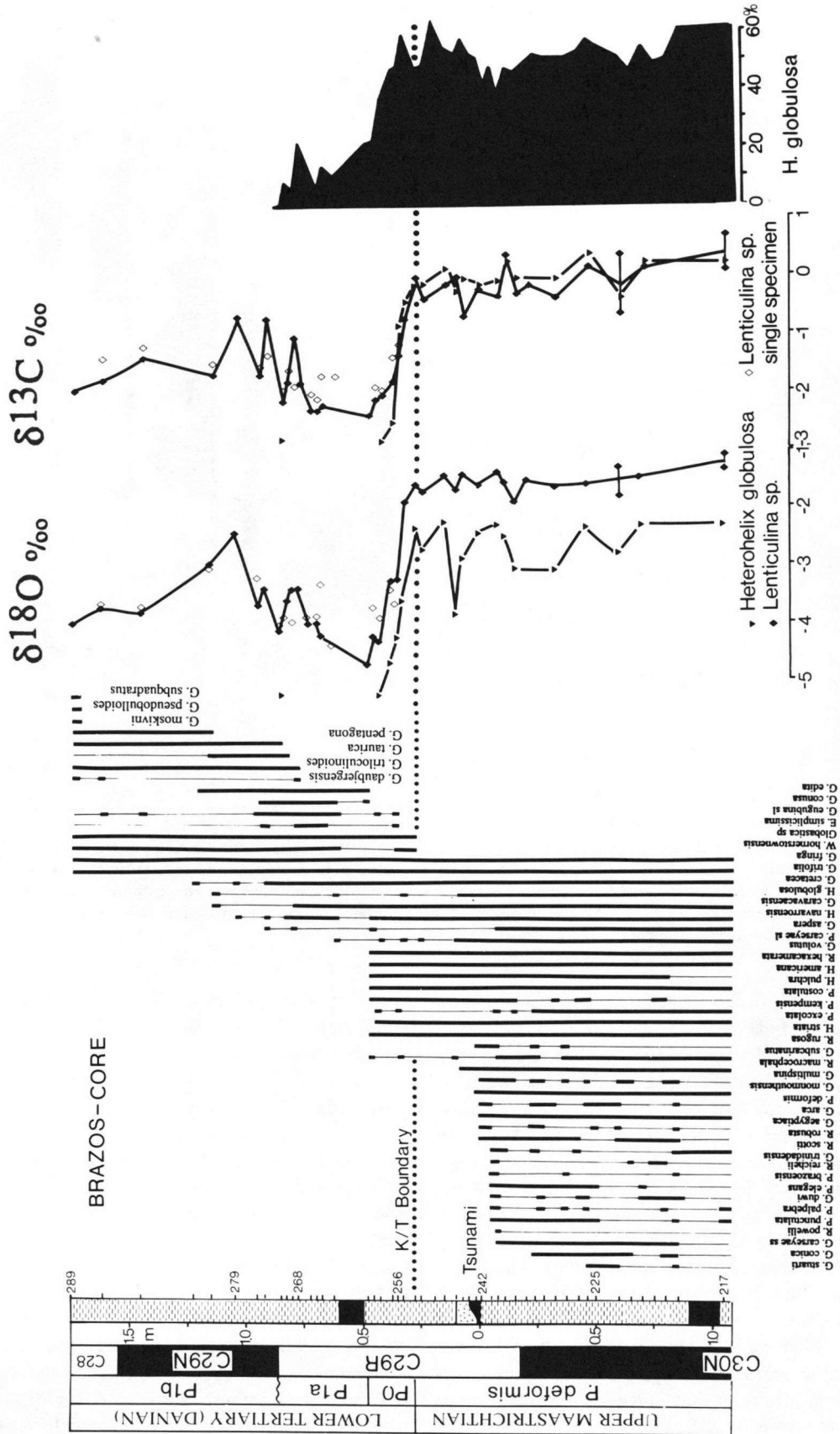
Figure 3. Planktonic foraminiferal species ranges, stable isotopes, and relative abundance of *Heterohelix globulosa* across the K/T boundary interval in a cored section from Brazos River, Texas. Note the two phases of species extinctions below and above the K/T boundary, but absence of extinctions at the boundary, the gradual shift in both carbon and oxygen isotope ratios, and the parallel decline in relative abundance of *H. globulosa*. Faunal data from Keller (1989a), stable isotope data from Barrera and Keller (1990).
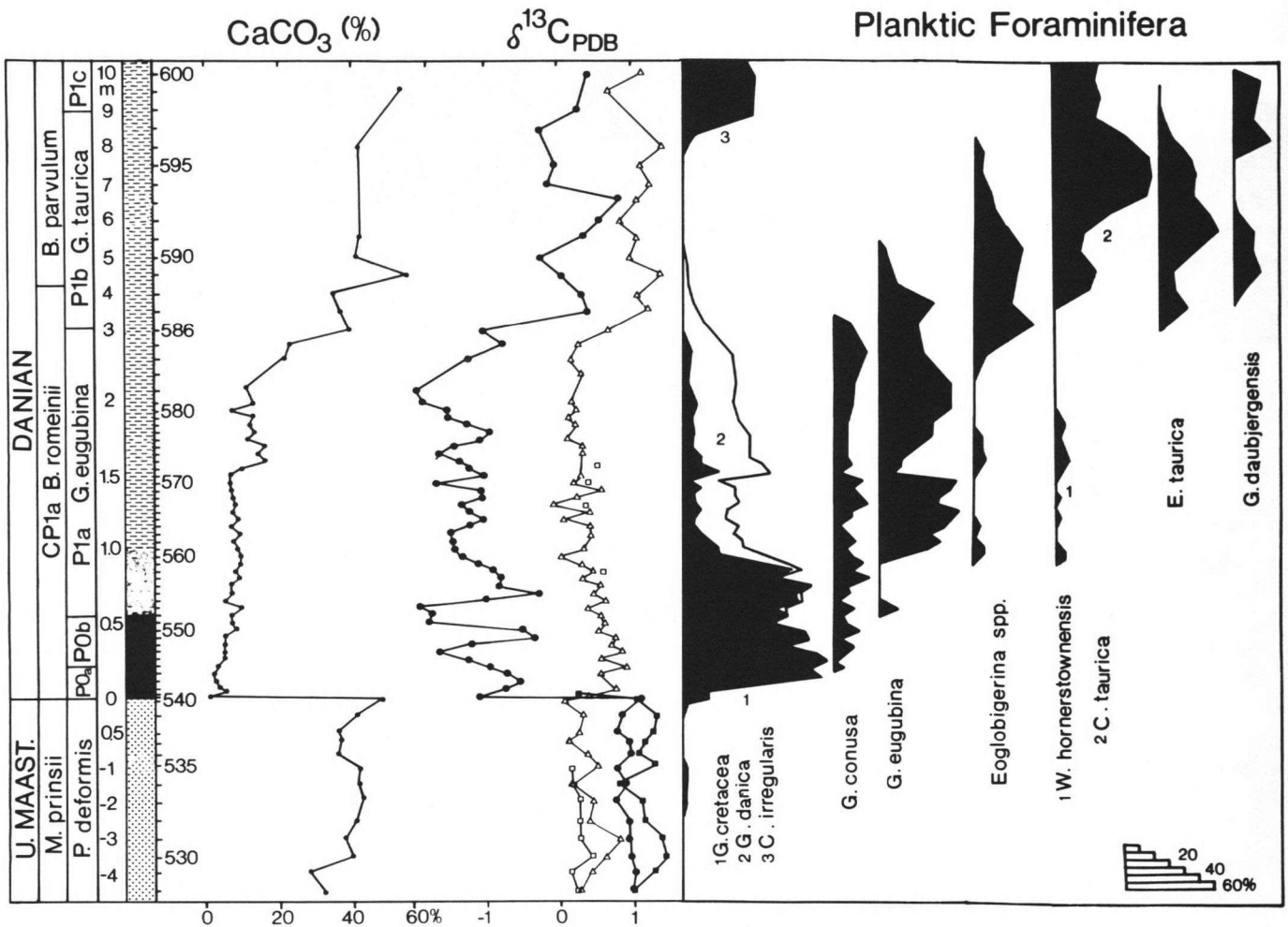
Figure 4. Carbonate and stable isotope records compared with relative abundance pattern of early Tertiary species at El Kef, Tunisia. Note, the initial increases in carbonate and carbon isotope ratios occur near the extinction of *Globigerina eugubina* (Pla; near the top of paleomagnetic anomaly C29R) coincident with faunal diversification in planktonic foraminifera. Geochemical data from Keller and Lindinger (1989), faunal data from Keller (1988a).

fected are largely tropical to subtropical open ocean forms; their disappearance may be linked to the Late Cretaceous sea-level regression (Peypouquet and others, 1986; Brinkhuis and Zachariasse, 1988; Keller 1988a, b, 1989a) and cooling (Stott and Kennett, 1988, 1990; Keller and Lindinger, 1989; Barrera and Huber, 1990). The absence of species extinctions at the K/T boundary suggests either that there was no major environmental change associated with this event in the Gulf of Mexico, or that the remaining Cretaceous species were generalists able to survive the environmental perturbations. The latter interpretation seems more likely because the same group of species survived also at El Kef. Both El Kef and Brazos River sections indicate a post–K/T boundary extinction phase at or near the P0/P1a Zone boundary about 50,000 years after the K/T boundary. Nine species disappear at this interval in Brazos River sections; seven of these species also disappear at this interval at El Kef, whereas two range higher up-section (*Heterohelix striata, Pseudoguembelina costu-*

lata). This post–K/T extinction phase appears to represent a real event, rather than upward reworking of Cretaceous species as discussed below.

Post-extinction recovery

The recovery of the marine plankton ecosystem after the K/T boundary event took unusually long; current estimates range from less than 500,000 years to about 2 m.y. (Zachos and Arthur, 1986; Gerstel and others, 1987; Keller, 1988a; Keller and Lindinger, 1989; D'Hondt, 1989). The unusually detailed carbonate, carbon isotope, and planktonic foraminiferal records of El Kef for the early Paleocene provide a clue to the initial permanent recovery. Figure 4 illustrates that after negative $\delta^{13}C$ excursion at the K/T boundary, both percent carbonate and $\delta^{13}C$ values remain low through the earliest Paleocene Zones P0 and P1a. During the lower part of this interval (Zone P0 and lower part of Zone P1a)

the Cretaceous survivor *Guembelitria cretacea* dominates. Low-diversity assemblages continue through Zone P1a, with *Guembelitria danica, Globoconusa conusa,* and *Globigerina eugubina* dominating. At the top of Zone P1a, percent carbonate and $\delta^{13}C$ values rapidly increase coincident with the decline and eventual extinction of the dominant earliest Tertiary species. Carbonate and $\delta^{13}C$ values reach the first stable plateau during Subzone P1b coincident with the establishment of a new, more diverse faunal assemblage (Fig. 4). This initial recovery can be dated to have occurred near the top of Chron 29R as also observed at Brazos River (Fig. 3), or about 230,000 years after the K/T boundary (Berggren and others, 1985). Full recovery to pre–K/T boundary conditions, however, did not occur until later.

The cause for this delayed recovery of the ecosystem is still speculative. A change in atmospheric CO_2 levels is generally favored for the $\delta^{13}C$ shift at the K/T boundary (Zachos and Arthur, 1986; Baur, 1988). Baur (1988) suggests that such a change could easily be brought about by an oceanic impact resulting in a major turnover of water masses, which would bring to the surface deep ocean water undersaturated with respect to CO_2. This would result in a drawdown of atmospheric CO_2 into the oceanic reservoir and reduce photosynthetic activity to levels too low to sustain existing biota. However, it is expected that rapid oxidative recycling of the biomass would soon restore the atmospheric CO_2 inventory. Thus, this scenario must still explain the delayed recovery of the ecosystem for several hundred thousand years.

BRAZOS RIVER: CONTROVERSY AND THE ISOTOPE RECORD

The placement of the K/T boundary in Brazos River sections has been controversial. Keller (1989a) placed this boundary at the first appearance of Tertiary planktonic foraminifera, in agreement with placement of the K/T boundary by nannofossil experts (Jiang and Gartner, 1986). Hansen and others (1987) and Bourgeois and others (1988), however, favor placing this boundary at the top of a sandstone-siltstone complex, which they interpret to have been deposited by a giant tsunami wave generated by an extraterrestrial impact. The sediment strata (17 cm to 20 cm) between the top of the tsunami deposit and the micropaleontologically defined K/T boundary they interpret as settling from the water column after the giant tsunami wave. While this interpretation would allow placement of the K/T boundary closer to the first major phase of species extinctions, faunal and isotopic data and some sedimentary features are in apparent conflict. For instance, the sediment strata in question is devoid of grain-size grading that would be expected from settling through the water column, and a thin brown layer of finely laminated sediments is present at the micropaleontologically defined boundary. Neither of these sedimentary features would be expected as a result of sediment settling after a giant tsunami wave. Also difficult to explain by this hypothesis is the absence within the settling strata of Maastrichtian species that are present at the erosion surface at the base of the tsunami bed, and the continued presence of abundant small Cretaceous species up to at least 1 m above the disputed interval (Keller, 1989a; Fig. 3). The presence of three iridium spikes (Ganapathy and others, 1981; Asaro and others, 1982) within and near the top of the tsunami bed and at the micropaleontologically defined boundary further complicates this problem. Recent stable carbon and oxygen isotope data, however, provide more definitive answers.

To determine the location of the K/T boundary and the pattern of foraminiferal extinction associated with it at Brazos River, oxygen and carbon isotope analyses were performed on closely spaced samples over a 2.5-m interval (Barrera and Keller, 1990). The results, illustrated in Figure 3, are surprising. $\delta^{18}O$ and $\delta^{13}C$ values of the biserial planktonic foraminifera *Heterohelix globulosa* and the benthic foraminifera *Lenticulina* sp. exhibit similar trends: a gradual decrease of about 2 to 3 permil, relative to values of stratigraphically lower samples, beginning about 3 cm above the first appearance of Tertiary foraminiferal taxa and reaching minimum values about 20 cm above. Isotopic values remain low and are more variable in the remaining upper part of the section. Excellent preservation of foraminifera and organic matter–poor sediments at Brazos River ($\leqslant 1$ weight percent organic matter) indicate that the carbon isotope ratios are not significantly altered by diagenesis and hence appear to reflect largely global oceanographic conditions (Barrera and Keller, 1990).

Stable isotopic measurements at Brazos River thus provide important data that help clarify the ongoing controversies regarding placement of the K/T boundary and species survivorship. For instance, there is no significant change in isotopic ratios at the tsunami bed horizon, although there is a one-point excursion in the planktonic foraminifer *H. heterohelix* (Fig. 3). The major isotopic shift begins immediately above the first appearance of Tertiary planktonic foraminifera as also observed at El Kef, Tunisia (Fig. 2; Keller and Lindinger, 1989), and numerous deep-sea sections (Hsü and others, 1982; Shackleton and others, 1984; Zachos and Arthur, 1986; D'Hondt, 1989). The Cretaceous/Tertiary boundary at Brazos River is therefore accurately placed at the first appearance of Tertiary species (Keller, 1989a) and not at the tsunami bed horizon (Hansen and others, 1987; Bourgeois and others, 1988).

Most surprising in our data set is the gradual 2 to 3 permil depletion of isotopic ratios of both benthic and planktonic foraminifera over about 20 cm of earliest Paleocene (Zone P0) sediment spanning about 30,000 to 40,000 years (based on extrapolation from the paleomagnetic record, the K/T boundary at 66.4 Ma, and the first appearance of *Globigerina eugubina* at 66.35 Ma; Berggren and others, 1985). In contrast, in the deep sea and El Kef (Fig. 2) a sudden depletion in planktonic foraminiferal and/or bulk $\delta^{13}C$ values ranging from 1 to 2.5 permil is characteristic of K/T boundary transitions (Zachos and Arthur, 1986; Keller and Lindinger, 1989; D'Hondt, 1989). The sudden $\delta^{13}C$ depletion in deep-sea sections may be explained by the relatively condensed sediment record. At El Kef, sediment ac-

cumulation rates during Zone P0 are about half of those at Brazos River. This may explain why the $\delta^{13}C$ depletion at El Kef appears relatively sudden (over a 7-cm interval) in contrast to the more expanded (20-cm interval) at Brazos River. The decline in $\delta^{13}C$ of total dissolved carbon in surface water has generally been interpreted to reflect a drop in primary oceanic productivity (Hsü and others, 1982; Shackleton and others, 1984; Zachos and Arthur, 1986). Our $\delta^{13}C$ data from Brazos River indicate that this drop in productivity was not instantaneous in epicontinental seas, but occurred gradually over a few tens of thousands of years. In addition, both surface and bottom shelf waters at Brazos River were affected by the global productivity crisis, probably as a consequence of the shallow water depth ($\leqslant 150$ cm; Keller, 1989a). The decrease in $\delta^{13}C$ values of the planktonic foraminifer *H. globulosa* below values of the benthic *Lenticulina* species just above the K/T boundary is similar to the pattern observed in deep-sea sections (Zachos and Arthur, 1986) and reflects greater $\delta^{13}C$ depletion in surface waters.

The unusual survivorship pattern of Cretaceous species in Paleocene sediments at Brazos River (Keller, 1989a) has been questioned as possibly resulting from upward reworking of Cretaceous sediments. There is now conclusive evidence from stable isotope analysis of the most abundant of these "survivor" species, *Heterohelix globulosa,* that this species lived well into the Tertiary. Figure 3 illustrates that the $\delta^{18}C$ and $\delta^{13}C$ isotopic ratios of *H. globulosa* in the early Tertiary are 2.5 to 3.0 permil lighter relative to Cretaceous values; this excludes the possibility that these specimens represent reworked Cretaceous forms (Barrera and Keller, 1990). Interestingly, the terminal decline in the relative abundance of this species parallels the gradual decline in isotopic ratios. Moreover, the post–K/T boundary extinction phase coincides with the maximum negative excursion in both $\delta^{18}O$ and $\delta^{13}C$ values, suggesting that severely stressed environmental conditions led to the demise of the Cretaceous survivors.

DISCUSSION AND CONCLUSIONS

The paleontologic records based on vertebrates, invertebrates, plants, and nannofossils generally indicate major faunal and floral changes during the latest Cretaceous and earliest Tertiary; however, with the exception of plants, these records are inconclusive with respect to catastrophic extinctions directly associated with the K/T boundary. Many fossil records, however, show decreasing species diversity through the Late Cretaceous apparently related to climate and sea-level changes (Hallam, 1987; Stott and Kennett, 1988, 1990; Barrera and Huber, 1990). The best-documented fossil record across the K/T boundary is currently available from planktonic foraminifera. This record permits a breakdown of this mass extinction into species extinctions caused by the K/T boundary event and species extinctions or disappearances unrelated to this event. For instance, a pre–K/T boundary species extinction phase results in a 30 to 45 percent reduction in species diversity at both El Kef and Brazos River, but the effect on the number of individuals in the forami-

niferal population is minimal, with a reduction of only 5 to 10 percent (Keller, 1989b). This strongly implies preboundary extinctions due to noncatastrophic environmental changes such as climate and sea-level fluctuations, as also suggested by other fossil records. The K/T boundary event at El Kef coincides with a 26 percent species reduction, but generally only the rare species are affected, representing about 5 to 10 percent of the individuals in the foraminiferal population. However, an additional 11 percent disappear shortly after the boundary event, and all but one (*Guembelitria cretacea*) surviving Cretaceous species terminally decline in abundance beginning immediately after the K/T boundary (Fig. 2).

At Brazos River no change is observed in species diversity at the K/T boundary. However, as at El Kef, many species (33 percent) disappear shortly above the K/T boundary (P0/P1a), and all but one (*G. cretacea*) of the Cretaceous survivors immediately and terminally begin to decline in relative species abundance at the K/T boundary. This pattern of species extinctions clearly implies that the K/T boundary event drastically and permanently altered planktonic foraminiferal communities, but it did not cause instantaneous extinctions of nearly all species as commonly claimed (Smit and Romein, 1985). The extinction record discussed here, however, is specific to the Tethyan shelf (El Kef) and the epicontinental sea (Brazos River) and has not been observed in the deep sea where current records indicate a near-instantaneous extinction of most planktonic foraminiferal species and survivorship of only a few species (Smit and Romein, 1985; D'Hondt, 1989). It is conceivable that these differences are caused by a condensed sedimentation record in the deep sea. Alternatively, the impact event may have affected open-ocean faunas differently (i.e., more severely) than continental shelf or epicontinental sea regions, although we are unable to explain how such differential faunal effects could have been caused.

The nature of species extinctions across the K/T boundary in Tethyan shelf and epicontinental seas appears systematic rather than random, and linked to environmental conditions (Keller, 1989b). Large, complex, ornate species of tropical to subtropical environments seem to disappear earlier than the more cosmopolitan but less ornate smaller forms. For instance, the early disappearance of large biserial to multiserial forms is followed by globotruncanid species and subsequently by the smaller robust rugoglobigerinids and finally by the simpler biserial pseudotextularids (Figs. 1, 3). Small, simple, unornamented forms such as heterohelicids, globigerinellids, hedbergellids, and guembelitrids survived longest and appear to have been best adapted for survival (Fig. 2). This pattern of extinctions implies a progressive, systematic disruption of habitats affecting specialized species from tropical to subtropical regions most severely and favoring survival of cosmopolitan generalists. This selectivity in species extinctions also implies that the hypothesized impact did not result in instantaneous random extinctions, but caused relatively rapid environmental changes resulting in survival of species best adapted to prevailing conditions.

Available data from continental shelf and epicontinental

seas indicate that pre–K/T boundary species extinctions may be related primarily to the latest Cretaceous sea-level regression (Keller, 1989a, b), which could explain their continued presence in the deep sea. Faunal data combined with stable isotope data indicate that the rate of species extinctions accelerated, although selectivity of extinctions prevailed, beginning at the K/T boundary coincident with increasingly stressful environmental conditions possibly as a result of an extraterrestrial bolide impact. Brazos River stable-isotope data demonstrate that the effect of the K/T boundary impact on the environment was probably not instantaneous as generally assumed. Rather, continued environmental deterioration over thousands of years culminated with a post–K/T boundary extinction phase. At El Kef the major negative $\delta^{13}C$ excursion appears geologically nearly instantaneous at the K/T boundary, followed by fluctuating, but generally more negative values, culminating at the post–K/T boundary extinction phase (Fig. 4). The sudden $\delta^{13}C$ excursion may be partly due to a more condensed sedimentary record in the basal Tertiary than at Brazos River. However, it cannot be ruled out that some regions may have been differentially affected by the K/T boundary event. Nevertheless, the sudden $\delta^{13}C$ shift observed in deep-sea sections appears most likely due to a condensed sediment record. Adverse environmental conditions initiated by the K/T boundary event prevailed to the top of Chron 29R (top of Zone P1a) or for about 230,000 years. Initial stabilization of the ecosystem is evident in increased stable-carbonate sedimentation and $\delta^{13}C$ values coincident with the decline and disappearance of the dominant earliest Tertiary fauna and establishment of a more diverse faunal assemblage.

A major outstanding paleontological problem in planktonic foraminifera is the apparent discrepancy between species extinctions in the deep sea and shallow epicontinental sea and continental shelf sections. Are these differences due to a condensed deep-sea record, or are they specific to certain environments such as open ocean versus near-shore habitats? The gradual stable-isotope change observed from Brazos River, in contrast to the sudden shift observed from the deep sea (assuming this record is not due to condensed sedimentation), suggests the possibility that the effect of a bolide impact in near-shore environments was either less strong or manifested itself more gradually. A more gradual environmental effect in epicontinental seas could allow these regions to become refugia for species as appears to have happened at El Kef, Tunisia, and Brazos River, Texas. Alternatively, it cannot be ruled out that deep-sea sections are stratigraphically incomplete due to decreased sedimentation as a result of reduced primary marine surface productivity.

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