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#### Notes

# Extended period of extinctions across the Cretaceous/Tertiary boundary in planktonic foraminifera of continental-shelf sections: Implications for impact and volcanism theories

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## ABSTRACT

The extinction of planktonic foraminiferal species across the Cretaceous/Tertiary (K/T) boundary has been examined in continental-shelf sections at El Kef, Tunisia, and Brazos River, Texas. These sections are considered to contain the most complete boundary transition record known to date. In both sections, an extended period of species extinctions spans from about 300,000 yr below to about 200,000–300,000 yr above the K/T boundary. Distinct episodes of accelerated extinctions occur below the boundary and about 50,000 yr above the boundary. At El Kef, only 26% of the species extinctions appear directly associated with the K/T boundary and iridium anomaly. At Brazos River, no species extinctions or measurable faunal changes appear directly associated with the K/T boundary and iridium anomaly. Species extinctions selectively affect large, ornate, tropical to subtropical species first and small, primitive, nonornate, subtropical to temperate species last. This pattern of species extinction is likely caused by increased ecological stresses as a result of a late Maastrichtian sea-level regression and global cooling. The extended period of species extinctions and absence of extinctions at the K/T boundary at Brazos River is not entirely compatible with either impact or volcanism theories. Perhaps, multiple unrelated causes should be considered, including a sea-level regression, global cooling, a K/T boundary impact of limited extent, and extensive volcanism.

## INTRODUCTION

The impact hypothesis of Alvarez and others (1980) proposes that at the time of the Cretaceous/Tertiary (K/T) boundary, a large meteorite collided with the Earth, throwing up a massive dust cloud that blocked out sunlight for several weeks or months. This led to the cessation of photosynthesis and the catastrophic destruction of life throughout the food chain. With the discovery of anomalously high iridium concentrations in the K/T boundary clay world-wide associated with shocked quartz minerals, primarily in land-based sections in the Western Interior (Bohor and others, 1984, 1985; Izett and Pillmore, 1985; Bohor and Izett, 1986), the impact hypothesis has gained wide acceptance especially among physicists, geophysicists, and astrophysicists.

A growing and vocal opposition, however, has pointed out alternative hypotheses, such as mantle degassing (McLean, 1985) or a period of volcanism (McLean, 1982; Carter and others, 1986; Officer and others,

1987) that similarly could account for these K/T boundary phenomena. These authors have suggested that a period of intense volcanism marked the K/T boundary transition. The volatile volcanic emissions would lead to intense acid rain and a reduction in the alkalinity of the surface oceans, global cooling, and ozone-layer depletion with consequent ultraviolet radiation (Officer and others, 1987). The major support for this theory comes from the massive Deccan Plateau basalts of India, which were deposited during the K/T transition.

It is important to note that alternative theories do not deny the possibility of a bolide impact; they question, however, whether the observed geochemical anomalies, shocked quartz, and particularly the mass extinction are best explained by such a catastrophic event.

Paleontologists have perhaps been most skeptical of the impact theory as the most likely scenario for the K/T boundary extinctions. Most fossil groups cannot support a scenario of catastrophic extinctions. Rather, a pattern of gradual extinctions emerges, suggesting a long-term changing environment beginning well below the K/T boundary and independent of the boundary event. For instance, although a large peak in abundance of fern spores is found at the K/T boundary in the Western Interior of North America, many species survived unscathed and few became extinct (Tschudy and Tschudy, 1986; Nichols and others, 1986). Moreover, floral studies of sections in Canada north of 65°–70° paleolatitude reveal no unusual abundance of fern spores at the K/T boundary that is marked by an iridium anomaly, but floral diversity declines beginning about 300,000–400,000 yr below the boundary (Sweet, 1988). Macrofossil experts appear divided on the question of catastrophic extinctions. For instance, Birkelund (1979) and Surlyk and Johansen (1984) have described a catastrophic pattern from Danish sections, whereas Ward and others (1986) and Jones and others (1987) have described a pattern of sharply declining diversity beginning several hundred thousand years below the K/T boundary in Spain and Alabama. The differences may be due to an incomplete sedimentary record in the Danish sections. Vertebrate paleontologists have long maintained that major dinosaur extinctions occurred well below the K/T boundary and are more likely to be related to climatic changes and habitat competition than to an extraterrestrial bolide impact (Van Valen and Sloan, 1977; Clemens, 1986; Padian and Clemens, 1985; Sloan and others, 1986; Brouwers and others, 1987). Microfossil specialists find that the nannoflora shows no major species extinctions at the K/T boundary, and most Cretaceous species are found well into the Tertiary.

Some workers interpret this record as a mass extinction at the K/T boundary with massive reworking of Cretaceous sediment into the early Paleocene (Thierstein, 1982; Jiang and Gartner, 1986), whereas others believe that many Cretaceous species survived well into the early Paleocene (Perch-Nielsen and others, 1982).

The strongest support for a catastrophic mass extinction in the marine realm has come from planktonic foraminifera (Smit, 1982; Smit and Romein, 1985), and it is these observations and interpretations that are addressed in this paper. Many earlier reports on the K/T boundary mass extinction are largely based on deep-sea sections that are now known to have hiatuses and/or highly condensed K/T boundary records (Perch-Nielsen and others, 1982). In contrast, relatively shallow marine sections such as El Kef, Tunisia, and Brazos River, Texas (Fig. 1), have higher sedimentation rates and therefore more complete K/T boundary records as evident in both nannofossil and planktonic foraminiferal stratigraphies (Perch-Nielsen and others, 1982; Smit, 1982; Jiang and Gartner, 1986; Keller, 1988a, 1989). This is evident in the presence of one additional planktonic foraminiferal zone (P0), which has not been found in any deep-sea sections, and in an extended sediment record of 2.5 m at El Kef for the succeeding *Globigerina eugubina* Zone (P1a), which in the deep sea is in most cases represented by a few centimeters only. High-resolution studies of El Kef and Brazos River sections provide new evidence that seriously questions interpretation of a catastrophic mass extinction at the K/T boundary in planktonic foraminifera.

The purpose of this report is to correlate and compare the species extinction patterns and relative species abundances of the Brazos River and El Kef sections in order to determine the rate and nature of species extinctions and to evaluate whether these extinction patterns are consistent with a global catastrophic effect such as a bolide impact or whether they are more compatible with the effects of local and/or global long-term environmental changes. The El Kef and Brazos River sections were chosen for this analysis because they contain the most complete K/T boundary record known to date (Perch-Nielsen and others, 1982; Smit, 1982; Jiang and Gartner, 1986) and their high resolution planktonic foraminiferal stratigraphies have been recently published (Keller, 1988a, 1989). Moreover, these sections show astonishing differences in species extinction patterns as well as in the relative abundance of dominant species that have not been addressed previously.

The results of this study show an extended period of extinctions beginning below and ending above the K/T boundary. The actual number of species extinctions associated with the boundary event at El Kef is two-thirds smaller than that reported from the deep sea, and no species extinctions occur at the K/T boundary at Brazos River. The K/T boundary impact and volcanism theories are re-examined in the light of these findings.

## MATERIALS AND METHODS

Samples were processed for foraminiferal analysis by standard micropaleontological techniques (Keller, 1986). Quantitative planktonic foraminiferal analyses were based on sample counts of 300–500 individuals of the size fraction  $>63 \mu\text{m}$ . The remaining sample was carefully scanned for rare species. The small size fraction was chosen because it best represents planktonic foraminiferal populations during the late Maastrichtian and early Paleocene (Keller, 1988a). All specimens were identified and mounted on microslides as a permanent record. Species abundance data are published in Keller (1988a, 1989).

Samples from the El Kef section were examined at 20-cm intervals for the uppermost Maastrichtian, at 5-cm intervals for the first 1.9 m of the Tertiary, and at 20- to 50-cm intervals upsection. Preservation is good,

although Tertiary planktonic foraminiferal shells are recrystallized. The ranges of species for El Kef were discussed earlier in Keller (1988a) and are illustrated in Figure 2. Examination of an additional two samples at the K/T boundary and re-examination of earlier samples have resulted in modification of some species ranges in the present study. Samples from the Brazos River core were examined at 2.5- to 5-cm intervals for the uppermost Maastrichtian through lowermost Tertiary Subzone P1a and thereafter at 10- to 20-cm intervals upsection. The ranges of species and their relative abundances are duplicated in two nearby outcrop sections (Keller, 1989). Preservation of foraminifera is excellent, with no recrystallization of test calcite apparent.

## LITHOLOGY

At El Kef, the K/T boundary is in the El Haria Formation. The upper Maastrichtian sedimentary rocks consist of a white-gray clayey marl with about 40%  $\text{CaCO}_3$ . Overlying this unit is a 50-cm-thick black boundary clay with an average of 5%  $\text{CaCO}_3$ . The K/T boundary is at the base of the black clay, which is marked by a 1- to 3-mm-thick rust-colored ferruginous layer. This layer contains less than 1%  $\text{CaCO}_3$ , a maximum in TOC of 4.8% (Keller and Lindinger, 1989), and anomalously high Ir and Os values (Kuslys and Krahenbuhl, 1983).

Nearly 50 cm of dark gray clays with slightly higher  $\text{CaCO}_3$  (~4–7%) overlie the black clay layer. The dark gray clays grade upward into a gray clay-rich shale. The first significant post-K/T boundary increase in  $\text{CaCO}_3$  (from 6% to 16%) occurs in this shale at 1.6 m above the boundary. The clay-rich shales grade into white-gray clayey marl accompanied by a rapid increase in  $\text{CaCO}_3$  from 20% to 40% between 2.5 and 3 m above the K/T boundary.

The Brazos River core was taken using a mobile drilling rig in a small tributary of the Brazos River informally known as "Cottonmouth Creek" about a half mile upstream from its intersection with the Brazos River, at a locality known as "Brazos-3" of Hansen and others (1984). The upper Maastrichtian Corsicana Formation consists of a gray marl with about 8%–10%  $\text{CaCO}_3$ . The Paleocene Kincaid Formation consists of calcareous clay with variable carbonate content. A distinct lithologic break occurs about 90 cm above the K/T boundary. This interval is marked by abund-

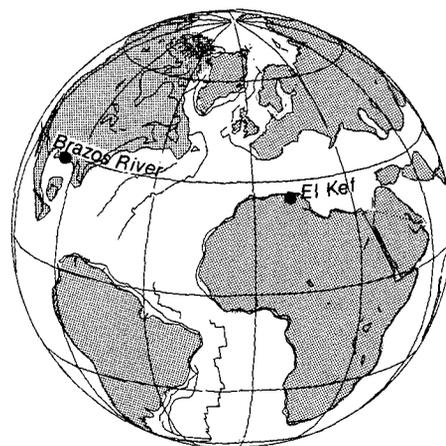
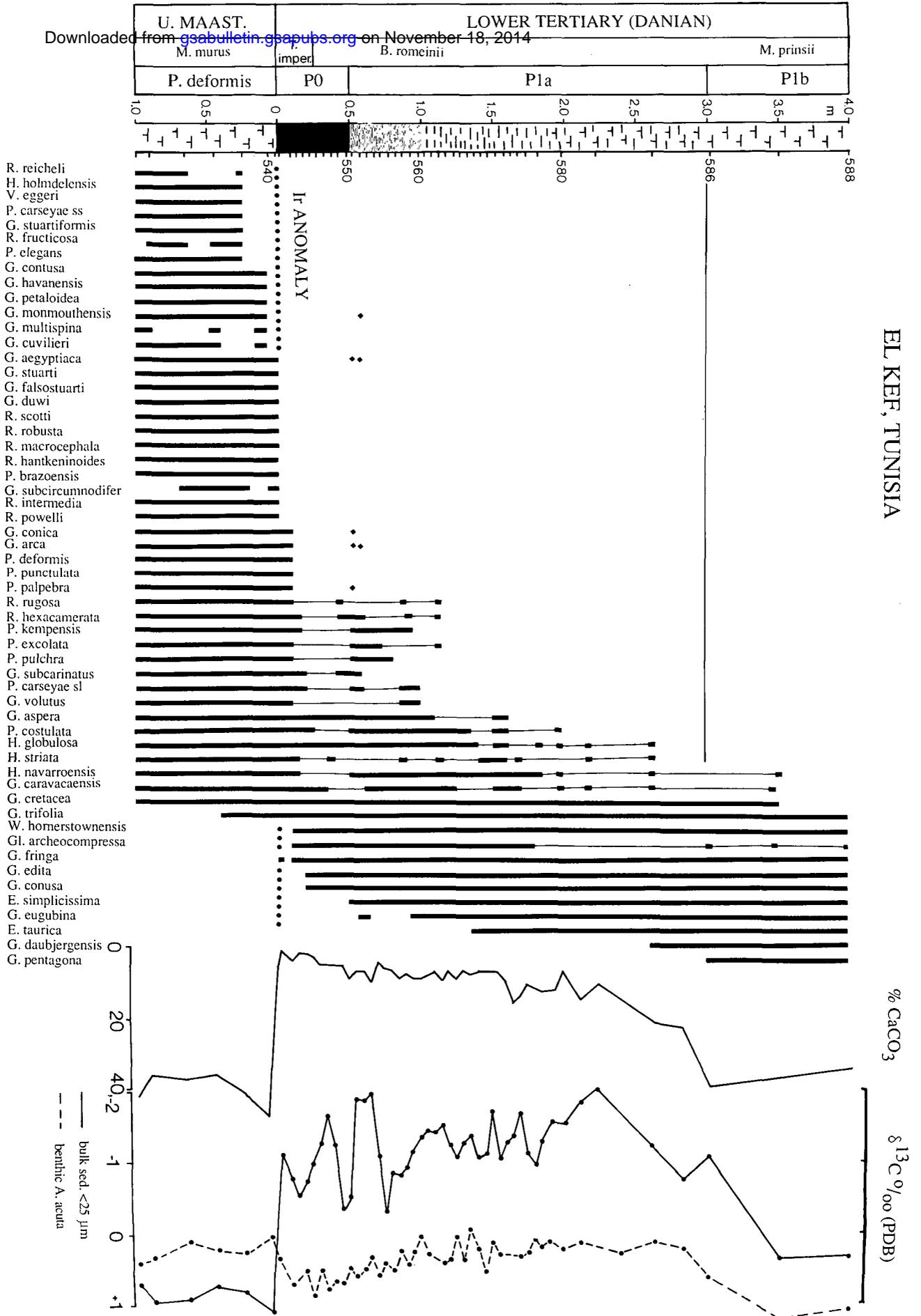


Figure 1. Locations of El Kef, Tunisia, and Brazos River, Texas, at K/T boundary time. Paleodepositions of continents based on the computer program Terra Mobilis by Scotese.



**Figure 2. Species ranges of planktonic foraminifera, percent CaCO<sub>3</sub> and δ<sup>13</sup>C isotopic data of bulk sediment (<25 μm) and benthic foraminifer *Anomalinoidea acuta* (from Keller and Lindinger, 1989) across the K/T boundary at El Kef, Tunisia. Thick lines mark actual occurrence of species; thin connecting lines indicate proposed range in the lower Tertiary. Diamonds indicate reworked specimens. Dotted line marks position of K/T boundary and Ir anomaly.**



ant sand grains and glauconite and marks a distinct faunal break indicating a short hiatus.

In all Brazos River sections, a distinct lithologic layer of variable thickness consisting of rippled sandstone, siltstone, and gray clay is sandwiched between the Corsicana Formation and the overlying Kincaid Formation. A scoured surface marks the base of this layer and indicates downward erosion. In the Brazos core, this layer is only 12 cm thick. Bourgeois and others (1988) interpreted this lithologic unit as deposited by a tsunami wave generated by a K/T boundary bolide impact. This interpretation is not supported by planktonic foraminiferal and nannofossil biostratigraphies, which place the K/T boundary 17–20 cm above the top of the tsunami bed coincident with the upper iridium peak of Asaro and others (1982) (Jiang and Gartner, 1986; Keller, 1989). Placement of the K/T boundary as defined by the first appearance of Tertiary microfossils is supported by recent stable isotope analysis, which shows the characteristic K/T boundary negative δ<sup>13</sup>C excursion beginning at this interval (Barrera and Keller, 1989). The tsunami bed of Bourgeois and others (1988) therefore does not represent the K/T boundary impact event. The variable thickness of this bed suggests a localized event perhaps related to the late Maastrichtian sea-level regression.

## BIOSTRATIGRAPHY

The planktonic foraminiferal biostratigraphy of the El Kef and Brazos River sections has been discussed previously by Salaj (1973), Smit (1982), Brinkhuis and Zachariasse (1988), and Keller (1988a, 1989), and the nannofossil biostratigraphy has been discussed by Perch-Nielsen (1979), Perch-Nielsen and others (1982), and Jiang and Gartner (1986). Therefore, only a brief discussion is given herein.

Benthic foraminifera and ostracods indicate that at K/T boundary time, El Kef was located in upper-slope to outer-shelf depth (250–350 m) on the North African margin of the Tethyan Seaway (Peypouquet and others, 1986; Keller, 1988b). The Brazos River section was deposited in the marginal Gulf of Mexico at middle- to outer-shelf depths (100–150 m) (Fig. 1). The Late Cretaceous index fossil *Abathomphalus mayaroensis* is not present in these relatively shallow marine sections. Therefore, the *Pseudotextalaria deformis* Zone has been named to mark the Upper Cretaceous (Keller, 1988a). The K/T boundary in deep-sea sections is generally defined by the simultaneous last appearance of nearly all Cretaceous species. In the two continental-shelf sections discussed herein, species extinctions are not simultaneous. Therefore, the K/T boundary has been placed at the first appearance of Tertiary species. The nannofossil K/T boundary coincides with the foraminiferal boundary. In both El Kef and Brazos River sections, the microfossil K/T boundary is closely associated with an iridium anomaly (Kuslys and Krahenbuhl, 1983; Ganapathy and others, 1981; Asaro and others, 1982).

The lower Danian at El Kef and Brazos River has greater and more continuous sedimentation than in any other known K/T boundary sec-

tions. In both sections, the earliest Tertiary planktonic foraminiferal Zone P0 is present and represented by 50 cm at El Kef and 25 cm in the Brazos River cored section. Jiang and Gartner (1986) defined a new earliest Tertiary nannofossil Subzone *Thorasphaera imperforata* corresponding to the lower two-thirds of Zone P0. The succeeding planktonic foraminiferal Subzone P1a (*Globigerina eugubina*) is represented by 2.5 m of sediment at El Kef and 65 cm in the Brazos core, where this subzone is truncated by a short hiatus. Subzone P1a ranges from the first appearance (FA) of *Globigerina eugubina* to the FA of *Globigerina taurica*, which is usually associated with the FA of *G. pentagona* and *G. hemisphaerica* (Keller, 1988a). The nannofossil Subzone *Biscutum romeinii* corresponds to this interval (Perch-Nielsen, 1979; Perch-Nielsen and others, 1982; Jiang and Gartner, 1986).

In deep-sea sections, Zone P0 has never been observed, and Subzone P1a is rarely present and then only as a few centimeters of sediment. The absence or near absence of sedimentation in the deep sea is caused by a sharp drop in surface paleoproductivity beginning at K/T boundary time as indicated by the δ<sup>13</sup>C record (Arthur and others, 1987; Keller and Lindinger, 1989). Carbonate dissolution at depth further reduced sedimentation. In shallow continental-shelf sections, carbonate dissolution is negligible, resulting in preservation of the K/T boundary record.

## MAGNETOSTRATIGRAPHY

Magnetostratigraphy obtained for the Brazos core (W. Gose, 1987, written commun.) indicates the presence of a continuous sedimentation record from the late Maastrichtian Chron C30R to the early Paleocene Chron C28R. Estimates for rates of species extinctions and sediment accumulation have been calculated based on bio- and magnetostratigraphic data. Ages for polarity zones are based on Berggren and others (1985).

In the Brazos core, the top of Chron C29R corresponds to the Subzone (SZ) P1a/P1b boundary in agreement with Berggren and others (1985); however, owing to a short hiatus at this interval, the top of Chron C29R may fall within the lower part of Subzone P1b. Berggren and others (1985) estimated the K/T boundary at 66.4 Ma and date the top of Chron C29R at 66.17 Ma, or 230,000 yr after the K/T boundary. The duration of Zone P0 is 50,000 yr, based on the first-appearance datum of *G. eugubina* at 66.35 Ma (Berggren and others, 1985), and Subzone P1a spans 180,000 yr. Faunal correlations of El Kef with the Brazos core indicate that about 80,000 yr is missing from the top of Subzone P1a in the latter section.

Sediment accumulation rates at El Kef are estimated at 1 cm/1,000 yr during Zone P0 and 1.4 cm/1,000 yr during Subzone P1a. These sedimentation rates are significantly higher than at Brazos River, where sedimentation averages 0.4 cm/1,000 yr for the same interval. The higher sedimentation rates at El Kef suggest proximity to shore and greater input of terrigenous material than at Brazos River.

In the uppermost Maastrichtian, the tsunami bed of Bourgeois and others (1988) rests on a scoured surface 20 cm below the K/T boundary. This indicates a hiatus or disconformity. Magnetostratigraphy permits an estimate of this hiatus. The sediment accumulation rate for Chron C30N is 0.4 cm/1,000 yr. If it is assumed that the sedimentation rate remained constant to the K/T boundary, an assumption justified by the relatively constant carbonate sedimentation, then approximately 295,000 yr is missing at the base of the tsunami bed.

## K/T BOUNDARY EXTINCTION PATTERN

### El Kef, Tunisia

Planktonic foraminiferal species at El Kef show a K/T boundary extinction pattern beginning 25 cm below and ending well above the

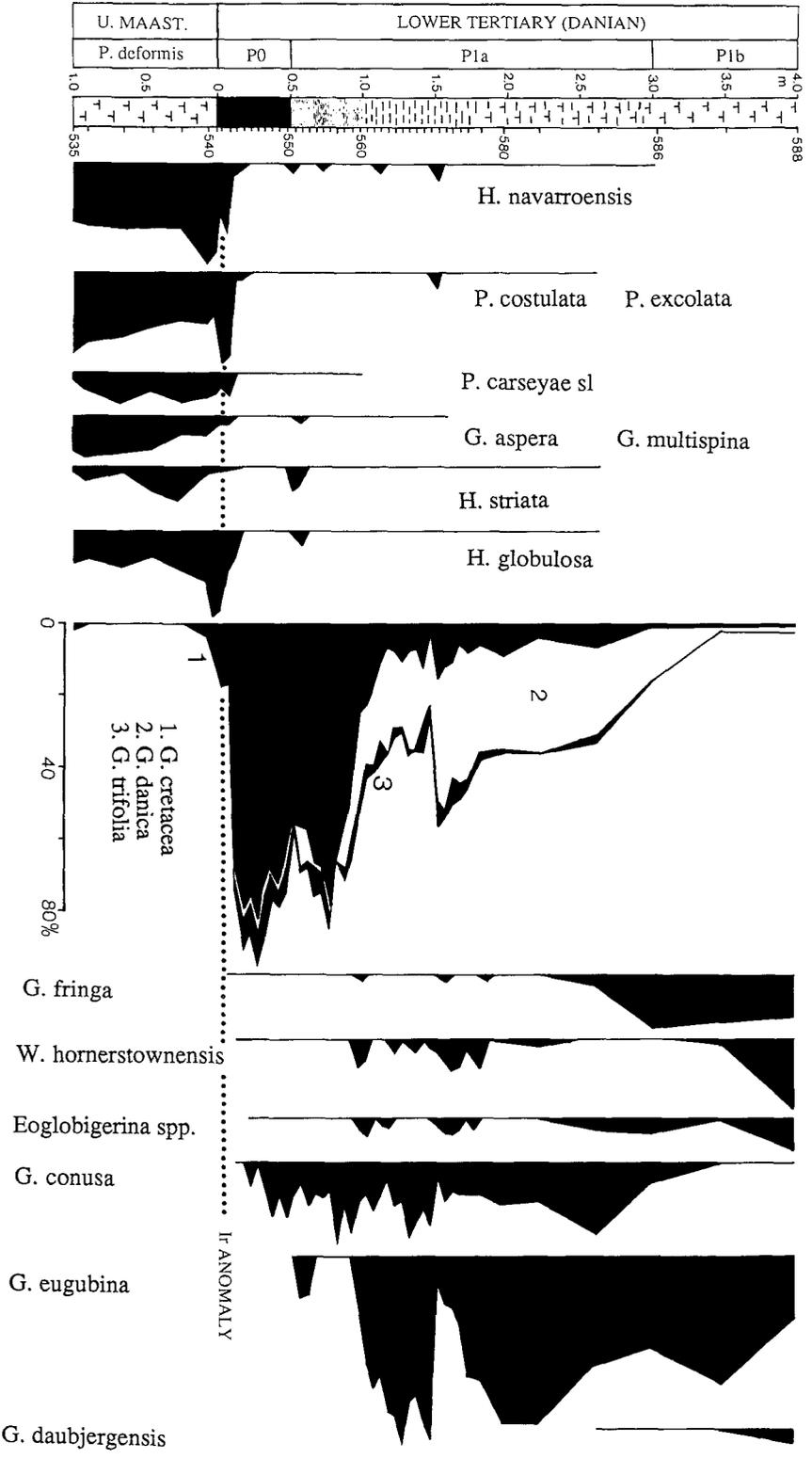


Figure 3. Relative percent abundance of dominant planktonic foraminifera across the K/T boundary at El Kef, Tunisia. Dotted line marks position of K/T boundary and Ir anomaly.

# BRAZOS - CORE, TEXAS

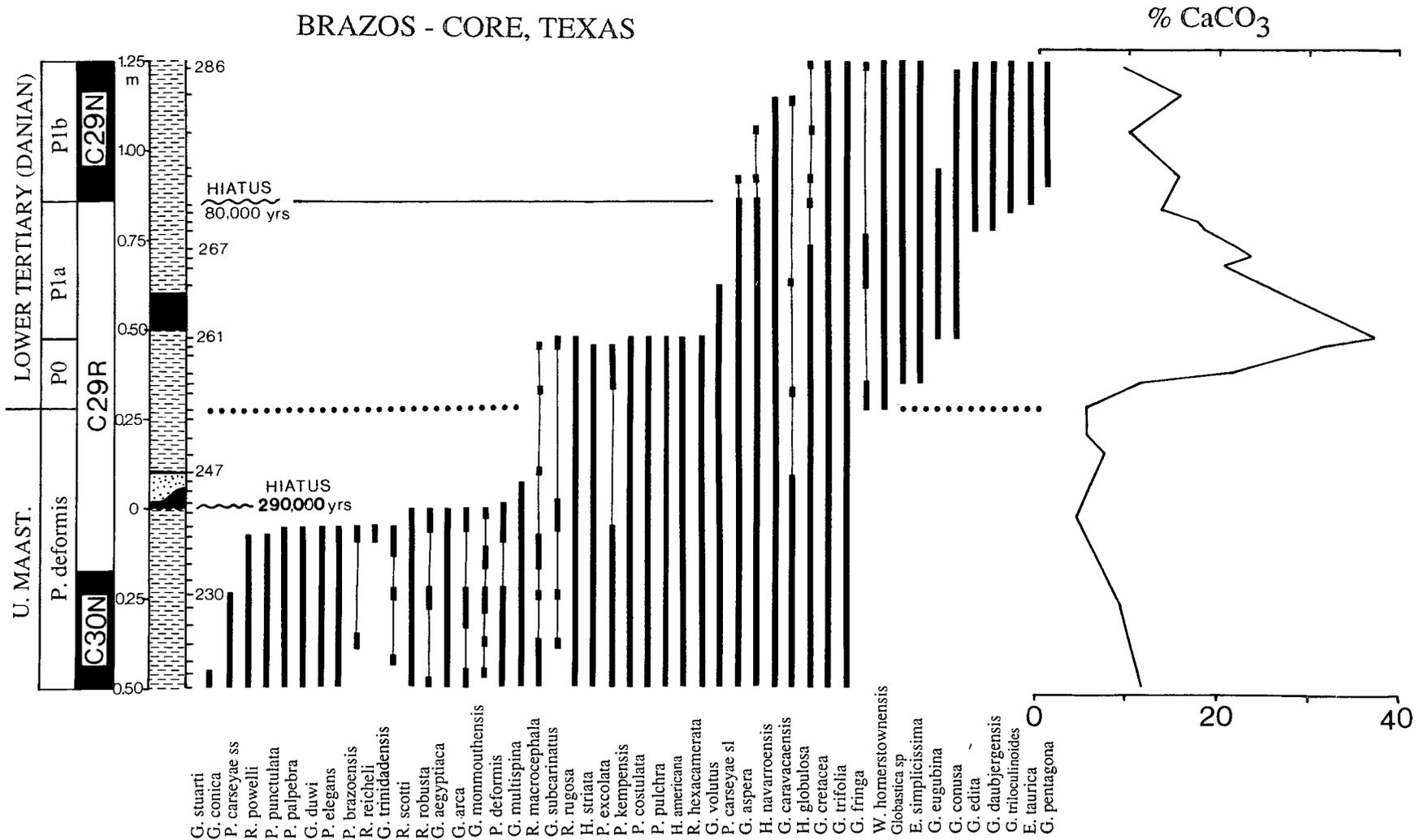


Figure 4. Species ranges of planktonic foraminifera and percent  $\text{CaCO}_3$  across the K/T boundary in a cored section at Brazos River, Texas. Thick lines mark actual occurrence of species; thin connecting lines indicate proposed range in the lower Tertiary. Dotted line marks position of K/T boundary. Wavy lines mark short hiatuses at the P1a/P1b Subzone boundary (~80,000 yr) and at the base of the tsunami bed (295,000 yr) of Bourgeois and others (1988). Paleomagnetic data from W. Gose (1987, written commun.).

boundary (Fig. 2). Thirteen species or 29% disappear at 25 cm (7 species) and 7 cm (6 species) below the K/T boundary. Twelve species extinctions or 26% coincide with the K/T boundary, and 5 species (11%) disappear 15 cm above the boundary. Of the remaining Cretaceous species, eight are sporadically present through the black boundary clay and disappear in the basal part of Subzone P1a. The remaining eight Cretaceous species are considered K/T boundary survivors; six of these die out gradually during Subzones P1a and basal P1b. Two species, *Guembelitra cretacea* and *G. trifolia*, survive longer and give rise to many new Tertiary species (for example, *Globoconusa conusa*, *G. daubjergensis*, *Woodringina hornertownensis*) (D'Hondt and Keller, 1987).

This extended pattern of species extinctions implies prolonged adverse environmental conditions beginning in the late Maastrichtian and continuing into the early Paleocene. Such an extinction pattern is not compatible with the hypothesized catastrophic effects of a single large K/T boundary bolide impact.

Foraminiferal workers generally have considered the presence of Cretaceous species, except for *Guembelitra cretacea*, in lower Tertiary deposits as a result of reworking from older sediments. The continued presence of many Cretaceous species in lower Paleocene sedimentary rocks of both El Kef and Brazos River sections strongly suggests, however, that many species survived the boundary event. Occasional reworked species are a common occurrence among microfossils of any age. They can generally be recognized by their anomalous age, isolated occurrence, discoloration, and poor preservation as compared to the *in situ* fauna. In the El Kef section, reworked specimens were found particularly in samples 551, 552, 571, and 572. Species considered to be Cretaceous survivors (*Heterohelix globulosa*, *H. striata*, *H. navarroensis*, *Globigerinelloides aspera*, *Pseudo-*

*guembelina costulata*, *Globotruncanella caravacaensis*, *Guembelitra cretacea*, *G. trifolia*) are as persistently present and as well preserved as the *in situ* Tertiary fauna. Moreover, there is a distinct dwarfing among these species above the K/T boundary, suggesting a stressed environment as also observed by Brinkhuis and Zachariasse (1988). Reworked Cretaceous specimens of *Heterohelix* in samples 571 and 572 are larger by a magnitude of two to three. Stressed conditions in the early Tertiary marine environment are also indicated by the generally low but fluctuating  $\delta^{13}\text{C}$  values, which indicate low marine productivity at this time (Fig. 2).

The eight species that disappear at the top of Zone P0 or the base of Subzone P1a were earlier considered as possibly reworked (Keller, 1988a). The same species group, however, is also present through Zone P0 in the Brazos core. This suggests that these species also survived the K/T boundary event.

A clue to ancient environments can be obtained from the relative abundance of dominant species. Figure 3 illustrates the dominant species at El Kef. It is interesting that all the species that were dominant during the Late Cretaceous survived well into the early Tertiary (~230,000 yr). Their abundance, however, is drastically reduced immediately after the K/T boundary event. In contrast, the Cretaceous species *Guembelitra cretacea* dominates the assemblage after the K/T boundary. Evolution of early Tertiary species is rapid, and their rise to dominance coincides with the decline of *G. cretacea*.

The Cretaceous survivors are generally small, of primitive morphology, and with little surface ornamentation (heterohelicids, pseudoguembelinids, guembelinids, globigerinellids). In these aspects, they are similar to the evolving Tertiary fauna. Oxygen isotopic ranking of species indicates that the Cretaceous survivors are largely surface-water dwellers. In contrast, the larger, more complex species that became extinct at or below the K/T boundary (globotruncanids, racemiguembelinids, planoglobulinids) are largely deeper-water dwellers (Boersma and Shackleton, 1981; G.

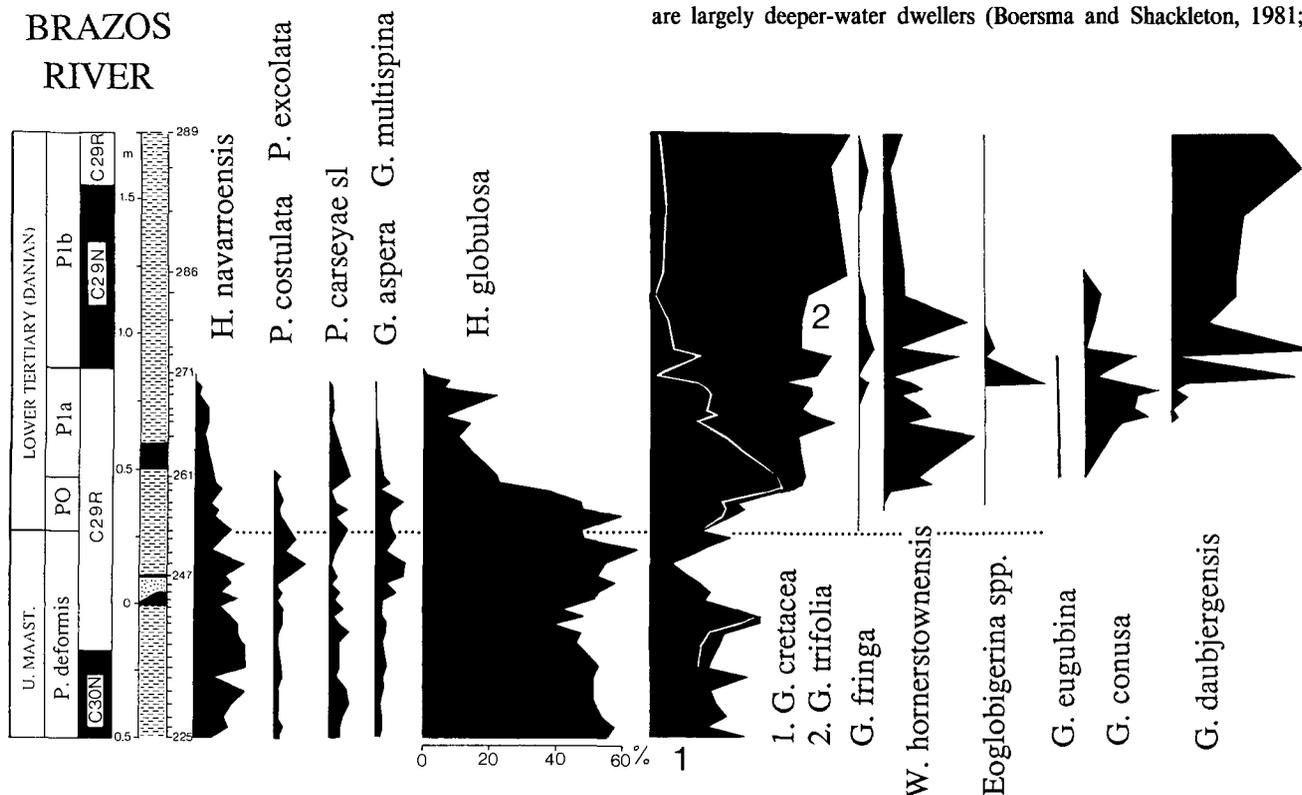


Figure 5. Relative percent abundance of dominant planktonic foraminifera across the K/T boundary in a Brazos River, Texas, cored section. Dotted line marks position of K/T boundary. Paleomagnetic data from W. Gose (1987, written commun.).

Keller and H. R. Thierstein, unpub. data). This suggests a progressive systematic disruption of habitats with pre-K/T boundary extinctions unrelated to a boundary event.

Geochemical data from El Kef indicate a sudden change at the K/T boundary, expressed by an iridium anomaly (Kuslys and Krahenbuhl, 1983) and a sudden drop in percent  $\text{CaCO}_3$  and  $\delta^{13}\text{C}$  values (Fig. 2), the latter implying a drastic reduction in surface-water productivity. Pre-K/T-boundary extinctions, however, imply changing adverse environmental conditions already, preceding the boundary event. What environmental conditions could have caused these pre-boundary conditions? At this time, there is no evidence for multiple impacts or prolonged volcanic activity at El Kef, although neither can be ruled out as a possible ultimate cause. There is evidence, however, for a sea-level regression (Peypouquet and others, 1986; Keller, 1988b; Brinkhuis and Zachariasse, 1988) and a change in the structure of the water column as indicated by stable-isotope data (Keller and Lindinger, 1989).

Stable-isotope data from El Kef show a change in  $\delta^{18}\text{O}$  beginning about 60–80 cm below the K/T boundary. Below this interval, there is an average difference of 1.8‰ between benthic and planktonic  $\delta^{18}\text{O}$  signals; this difference decreases to an average 0.6‰ in the uppermost Maastrichtian. The decrease is primarily due to more negative benthic  $\delta^{18}\text{O}$  values. A similar upper Maastrichtian converging trend associated with cooler temperatures was observed at Deep Sea Drilling Project Sites 689, 690, and Seymour Island in the high-latitude South Pacific (Stott and Kennett, 1988; Barrera and Huber, 1989). These data suggest a global climatic

change. At El Kef, the bottom-water warming may have been caused by the sea-level drop coupled with production of warm saline bottom water (Brass and others, 1982) at low latitudes. These conditions may have caused the species extinctions prior to the K/T boundary event that is indicated by both geochemical anomalies and faunal changes. Environmental conditions in the Brazos River region, however, appear to have been significantly different.

### Brazos River, Texas

The Brazos River cored section is most remarkable in that no species extinctions are directly associated with the K/T boundary event (Fig. 4). Instead, two phases of accelerated species extinctions are apparent, the first about 30 cm below the K/T boundary and just below the tsunami bed of Bourgeois and others (1988) and the second 25 cm above the boundary. Many of these species disappear earlier in the Brazos River region than at El Kef and are therefore considered local disappearances. Nevertheless, the two phases of accelerated species extinctions are present in both regions and are therefore considered to represent global events as discussed below. In the first extinction phase, nearly half (46%) of the species disappear; 9 species disappear at 5 and 10 cm below the base of the tsunami bed, and 7 species disappear at the scoured base. This extinction phase correlates to near the base of paleomagnetic anomaly C29R (Fig. 4), which is 340,000 yr below the K/T boundary (Berggren and others, 1985). As noted earlier, a hiatus (~295,000 yr) is present at the base of the tsunami bed. This

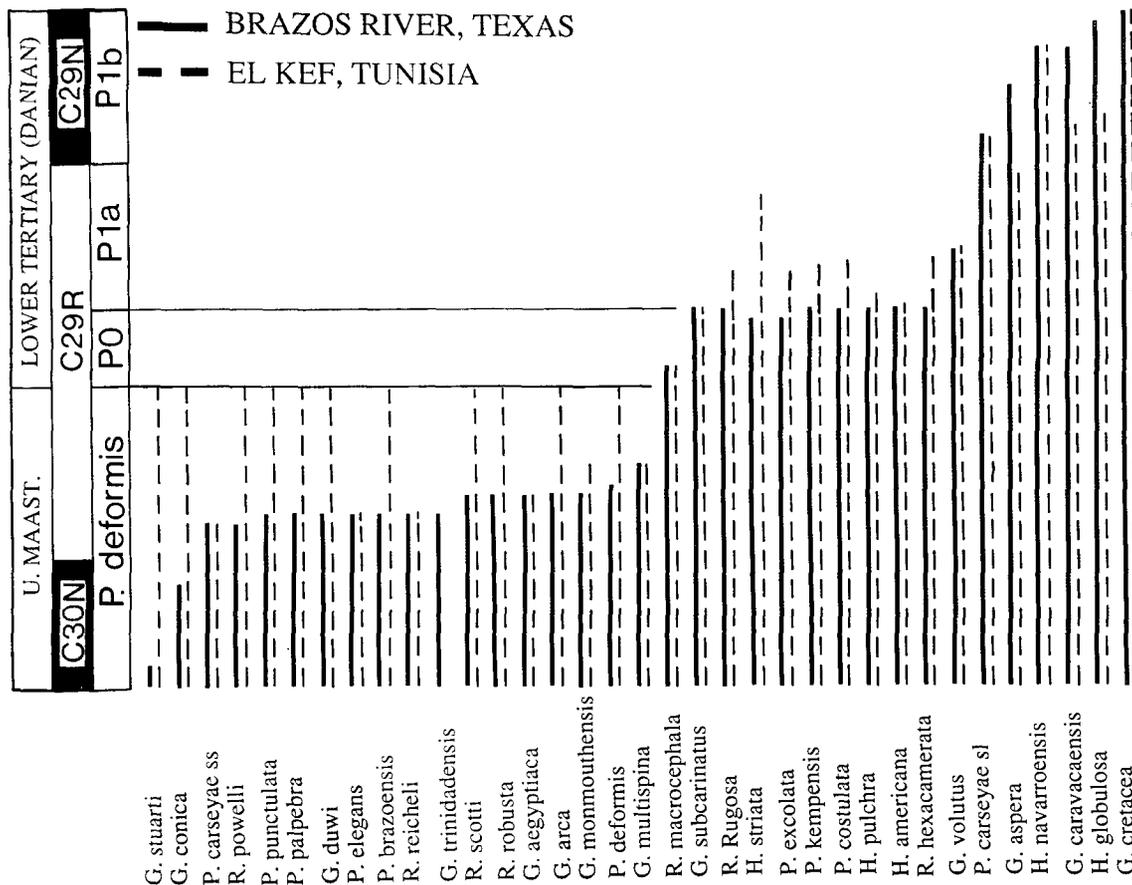


Figure 6. Comparison of planktonic foraminiferal species ranges across the K/T boundary at El Kef (dashed lines) and Brazos River (solid lines).

suggests that the first extinction phase may have occurred much more gradually than implied by Figure 4. The second extinction phase occurs near the P0/P1a Zone boundary about 25 cm, or 50,000 yr, above the K/T boundary (Fig. 4). Eleven Cretaceous species disappear at this level. Seven Cretaceous species survive longer; five of these gradually become extinct during Subzones P1a or base P1b, whereas *Guembelitra cretacea* and *G. trifolia* range higher upsection, similar to El Kef (Fig. 4).

It has been suggested that the K/T boundary based on the first appearance of Tertiary species is misplaced in the Brazos River section and that its position should be at the first extinction phase and at the tsunami bed of Bourgeois and others (1988). By this interpretation, the 17–20 cm of sediment between the top of the tsunami bed and the first appearance of Tertiary species is the result of settling from the water column after the

tsunami event, and the dwarfed Cretaceous survivors are a result of size sorting of redeposited sediment. This scenario appears unlikely for the following reasons. (1) There is no grain size sorting apparent in the sediment above the tsunami bed. (2) The sharp iridium anomaly that coincides with the K/T boundary as defined by microfossils cannot be explained by settling from the water column. (3) A major negative excursion of nearly 3‰ in  $\delta^{13}\text{C}$  begins at the K/T boundary as defined by the first appearance of Tertiary planktonic foraminifera. This  $\delta^{13}\text{C}$  excursion defines the K/T boundary in virtually all sections world-wide (Zachos and Arthur, 1986). (4) The Cretaceous survivors above the K/T boundary have a Tertiary isotopic signal and can therefore not be of Cretaceous origin (Barrera and Keller, 1989). (5) The standard sequence of evolutionary first appearances of early Tertiary planktonic foraminiferal species is present. (6) Analysis of three Brazos River sections shows virtually identical faunal records (Keller, 1989). Such similarities are unlikely to be caused by random reworking of older sediments. Thus, faunal and stable-isotopic data conclusively show that the K/T boundary in the Brazos River sections coincides with the first appearance of Tertiary species as also observed at El Kef, Tunisia. The absence of species extinctions at the K/T boundary in the Brazos River region must therefore be considered as due to real, if isolated, conditions.

Major differences in the environmental conditions between El Kef, Tunisia, and Brazos River, Texas, can be observed in the relative abundances of dominant species as illustrated in Figure 5. Although the same group of species dominates the late Maastrichtian and the same evolutionary sequence of Tertiary species is present in both regions, individual species abundances vary (Figs. 3 and 5). For instance, *Heterohelix globulosa* is the single most abundant species averaging 60%, and *Guembelitra cretacea* averages 20% at Brazos River. In contrast, no single species dominates at El Kef, and *G. cretacea* is only a minor component in upper Maastrichtian sedimentary deposits. *Guembelitra trifolia* is most abundant in the early Tertiary, whereas at El Kef a related species (*G. danica*) is abundant.

The most dramatic differences in the faunal assemblage are seen at the K/T boundary. In contrast to the sudden change in the relative abundance of species at El Kef, there is no significant change in the relative abundance of species across the K/T boundary or the tsunami bed at Brazos River. Dominant species appear to continue into the earliest Tertiary virtually unaffected. Individual species abundances begin to decline gradually during the upper part of Zone P0, about 30,000–40,000 yr after the K/T boundary, and disappear at the top of Subzone P1a. The decline of the Cretaceous survivor species coincides with the second species extinction phase near the top of Zone P0.

#### K/T BOUNDARY EVENT: TETHYAN SEAWAY VERSUS MARGINAL GULF OF MEXICO

How similar or dissimilar are the species extinction patterns of the Tethyan Seaway (El Kef) and the marginal Gulf of Mexico (Brazos River)? A comparison of species ranges of the two sections can provide a clue as to which last appearances of species are due to adverse regional paleoecological conditions. This may also show whether the pre- and post-K/T boundary extinction phases are regional or global events.

Figure 6 compares species ranges of both sections for species present in the Brazos core. El Kef has a greater species diversity owing to the presence of more tropical species (Fig. 2). It is apparent that the magnitude of the pre-K/T boundary extinction phase is exaggerated in the Brazos core. Eleven of 17 species disappearing at this extinction phase at Brazos River range to the K/T boundary at El Kef and are therefore regional disappearances in the marginal Gulf of Mexico. The species affected are

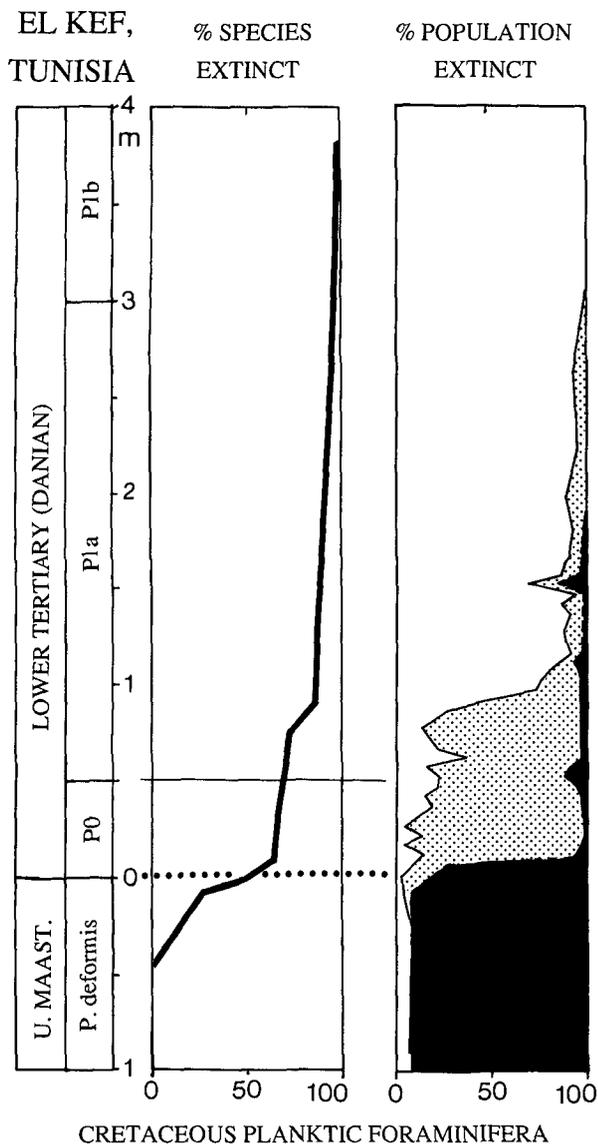
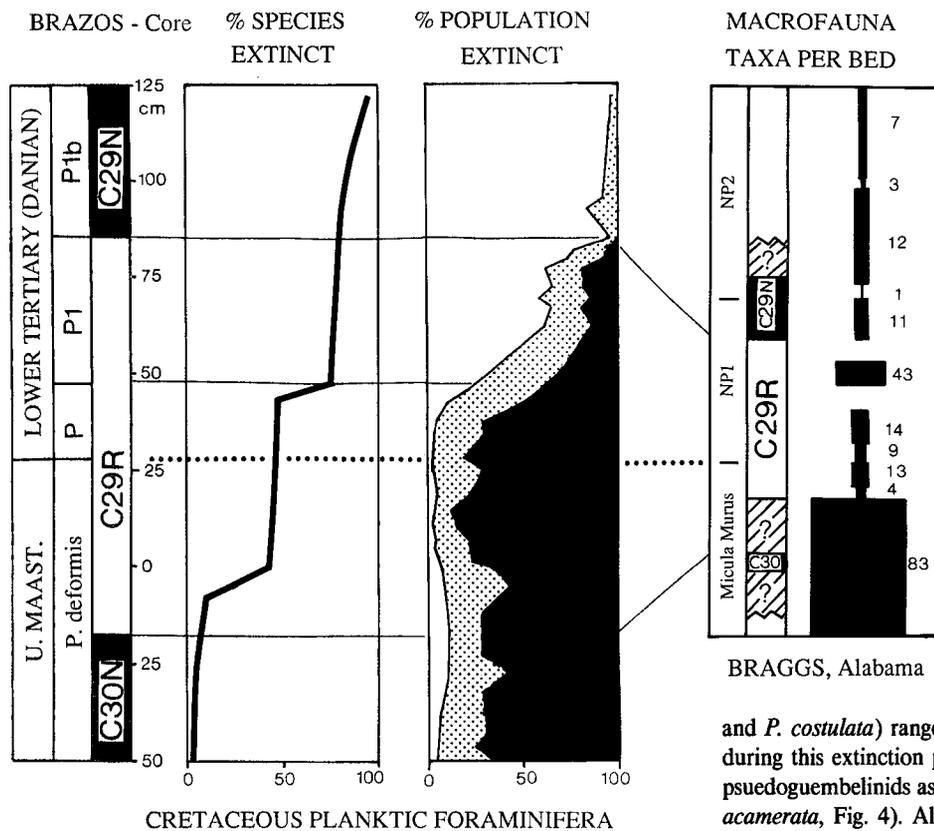


Figure 7. Percent species extinct and relative percent Cretaceous population (individuals) extinct across the K/T boundary at El Kef, Tunisia. Black pattern marks percent abundance of Cretaceous species excluding *Guembelitra cretacea*, which is marked by dotted pattern. Dotted line marks K/T boundary and Ir anomaly.



**Figure 8.** Percent species extinct and relative percent Cretaceous population (individuals) extinct across the K/T boundary at Brazos River, Texas. Black pattern marks percent abundance of Cretaceous species excluding *Guembeltria cretacea*, which is marked by dotted pattern. Dotted line marks K/T boundary. Macrofossil extinction data at Braggs, Alabama, is from Jones and others (1987).

largely tropical to subtropical open-ocean forms: *Globotruncana arca*, *G. conica*, *G. duwi*, *G. stuarti*, *Racemiguembelina powelli*, *Pseudotextularia deformis*, *Pseudoguembelina punctulata*, *P. palpebra*, *Planoglobulina brazoensis*, *Rugoglobigerina scotti*, *R. robusta*. The six species extinct below the boundary in both regions are *Planoglobulina carseyae* ss, *Pseudotextularia elegans*, *Rugoglobigerina reicheli*, *Globotruncana aegyptiaca*, *Globigerina monmouthensis*, and *Globigerinelloides multispina*.

These data imply that a significant pre-K/T boundary extinction phase occurred in both regions, with 13 species extinct at El Kef (Fig. 2), 6 species extinct at Brazos River, and an additional 11 species disappearing early in the latter section owing to regional adverse conditions. The cause for this extinction phase appears to be gradual environmental changes, including a shallowing sea level (Keller, 1988b; Peypouquet and others, 1986; Jones and others, 1987; Brinkhuis and Zachariasse, 1988) and a cooling of surface-water temperatures (Jones and others, 1987; Stott and Kennett, 1988; Keller and Lindinger, 1989). The shallower depth (100–150 m) at Brazos River as compared to El Kef (250–350 m) may be responsible for the early disappearance of 11 species in the Brazos River region.

The absence of K/T boundary species extinctions at Brazos River suggests either that there was no major environmental change associated with this event in the marginal Gulf of Mexico or that the remaining Cretaceous species were generalists able to survive the environmental perturbations. The latter interpretation is more likely because the same species group also survived at El Kef.

Both El Kef and Brazos River sections indicate a post-K/T boundary extinction episode at or near the Zone P0/P1a boundary. This extinction episode appears slightly later at El Kef. A diachronous first appearance of *Globigerina eugubina* may account for this discrepancy. Nine species disappear at this extinction phase at Brazos River, but two of these (*H. striata*

and *P. costulata*) range higher upsection at El Kef. The species affected during this extinction phase are largely small biserial heterohelicids and pseudoguembelinids as well as two rugoglobigerinids (*R. rugosa*, *R. hexacamerata*, Fig. 4). All of these species are isotopically light or surface dwellers (Boersma and Shackleton, 1981).

#### SPECIES EXTINCTIONS VERSUS ABUNDANCE CHANGE

The two parameters of faunal change, species extinctions and abundance fluctuations in the dominant species groups, record different sensitivities to environmental change. Extinction generally occurs when a species is weakened and represented by relatively few individuals (<2%) in the foraminiferal population as seen at El Kef and Brazos River (Keller, 1988a, 1989). If no preservational bias is assumed, minor environmental oscillations in temperature, salinity, nutrient level, or niche competition may lead to the extinction of such species. With few exceptions, the extended K/T boundary extinctions affected such weakened species. Their demise greatly reduced species diversity. Nonetheless, because of their low combined relative abundance, their decline had little effect on the over-all foraminiferal population. In contrast, changes in the abundance of dominant species generally reflect major environmental perturbations, which do not necessarily coincide with species extinction episodes.

Figures 7 and 8 illustrate the timing and rate of Cretaceous species extinctions across the K/T boundary and the percent individuals in the total foraminiferal population lost owing to their demise. The two curves are significantly different, reflecting immediate environmental effects (species extinctions) and major environmental perturbations. Both El Kef and Brazos River sections show a major pre-K/T boundary reduction in species diversity. Although 30%–40% of the species become extinct, the effect on the over-all number of individuals in the foraminiferal population is minimal, with a reduction of only 5%–10% (Figs. 7 and 8). The pre-K/T boundary extinction phase also appears to have been the major extinction event among macrofossils. Hansen and others (1984) reported a major decline in the macrofauna of Brazos River beginning with a molluscan extinction 50 cm below the K/T boundary and continuing through the early Paleocene. Jones and others (1987) reported a species reduction

from 83 to 4 species in the lowermost part of Chron C29R in the Braggs, Alabama, section, which correlates to the same chron interval and foraminiferal extinction phase at Brazos River (Fig. 8).

At the K/T boundary at El Kef, a further species reduction of 26% is accompanied by a dramatic reduction in the number of individuals of Cretaceous foraminifers to less than 5%, except for *G. cretacea* (Fig. 7). This opportunistic species is relatively unsuccessful during the late Maastrichtian, but its population blooms during the earliest Tertiary. With its expansion, the Cretaceous population dominated by one species survives up to the post-K/T boundary extinction phase. At this time, *G. cretacea* abundance declines rapidly and Tertiary species ascend to dominance. A small increase in the Cretaceous population at 1.5 m (sample 572) appears to be due to reworking.

At Brazos River, the patterns are different largely because there are no K/T boundary species extinctions, and Cretaceous survivors continue their dominance through much of Zone P0 (Fig. 8). The post-K/T extinction phase and species abundance decline appear coeval at Brazos River and El Kef. The discrepancy in zonation may be due to a diachronous first appearance of *G. eugubina*.

## DISCUSSION

The data presented herein show a major global pre-K/T boundary species extinction phase beginning about 310,000 yr before the K/T boundary and affecting planktonic foraminifera and macrofossils. The dominant species group (heterohelicids, pseudoguembelinids, guembelinids) is not significantly affected. The extinct and disappearing species are primarily large, complex, ornate, tropical to subtropical deeper-water dwellers. In contrast, the dominant species are largely small, primitive, subtropical to temperate surface-water dwellers with little shell ornamentation. This selective elimination of tropical deep-water dwellers is likely to have been caused by a sea-level drop accompanied by cooler temperatures. There is strong evidence for a late Maastrichtian sea-level lowering at El Kef (Peypouquet and others, 1986; Keller, 1988b; Brinkhuis and Zachariasse, 1988), Brazos River, and Braggs, Alabama (Jones and others, 1987). Stable-isotope data indicate a cooling trend at El Kef (Keller and Lindinger, 1989), at Braggs (Jones and others, 1987), and in high-latitude deep-sea sections, (Stott and Kennett, 1988; Barrera and Huber, 1989).

The post-K/T boundary extinction phase also appears to be of global extent. Species extinctions occur among the less robust subtropical to temperate species. The primitive, smaller, temperate Cretaceous species survive longer. Their populations, however, decline rapidly during this extinction phase. The cause for the post-K/T boundary extinction phase is most likely the long-term accumulated effect of environmental changes including continued sea-level lowering, global cooling, and the long-term effects of a possible K/T boundary bolide impact. The disappearance of the last Cretaceous survivors in Subzones P1a and P1b about 200,000 to 300,000 yr after the K/T boundary appears largely due to niche competition in a rapidly diversifying Tertiary population.

The absence of a significant K/T boundary imprint on planktonic foraminiferal faunas at Brazos River remains a puzzle. It suggests that if there was a bolide impact, the effect was more severe in open-ocean environments than in shallow continental-shelf regions; only 26% of the species disappear at the boundary and iridium anomaly at El Kef. It also implies that the effect of a bolide impact was not of global extent. Moreover, if K/T boundary extinctions were caused by a global decrease in solar radiation due to impact-generated dust in the atmosphere then, why were faunas in the marginal Gulf of Mexico not affected?

The continental-shelf faunal data prompt a re-evaluation of the current impact and volcanism theories. How well does each theory explain the

observed faunal record? Clearly, the extended period of species extinctions across the K/T boundary cannot be explained by a bolide impact. Nevertheless, the K/T boundary extinctions at El Kef and the associated geochemical changes imply a catastrophic and geologically instantaneous event that may be best explained by a bolide impact. This implies, however, that the effect of the impact was of more limited scope than generally assumed and that the size of the bolide may have been overestimated. There is growing evidence that suggests that the Manson crater of Iowa may represent the K/T boundary impact structure (Izett, 1987; Hartung and others, 1988).

The volcanism theory is less specific in its timing and effect on flora and fauna than the impact theory and is therefore more difficult to test. Nevertheless, it appears to fare better in explaining the extended period of extinctions. For a general discussion and overview of this topic, the reader is referred to Officer and others (1987). The volcanism scenario proposes a period of intense volcanic activity associated with volatile emissions leading to acid rain and global cooling. The acid rain causes a reduction in the alkalinity and pH of surface oceans that could explain the observed decrease in surface-water productivity and carbonate dissolution at depth. These combined effects coupled with a sea-level regression could explain the selective nature of species extinctions; however, the volcanism theory is not specific as to why a drop in surface productivity should occur exactly at the K/T boundary. One would expect an extended period of volcanism coupled with acid rain to show a more gradual effect. One would also expect more intense volcanism to be associated with each extinction phase.

Neither the impact nor the volcanism scenario is entirely satisfactory to explain the observed K/T boundary phenomena in continental-shelf sections. It is unlikely, however, that a single catastrophe was the sole cause for the extended period of extinctions. Perhaps multiple unrelated causes should be considered, including a sea-level regression, global cooling, a K/T boundary impact of limited effect, and extensive volcanism. There is evidence for each of the above; however, their interrelationship is unclear.

## CONCLUSIONS

1. An extended period of species extinctions spans the K/T boundary from about 300,000 yr below to 200,000–300,000 yr above the boundary in the shallow continental-shelf sections of El Kef, Tunisia, and Brazos River, Texas.

2. Apart from the K/T boundary, there are two distinct extinction episodes beginning about 300,000 yr below the boundary and at about 50,000 yr above the boundary.

3. Cretaceous/Tertiary boundary extinctions at El Kef affect only 26% of the planktic foraminiferal species; 29% disappear earlier 11% disappear 15 cm above the K/T boundary, 18% disappear at the extinction phase near the Zone P0/P1a boundary, and the remaining Cretaceous survivors disappear gradually between 150,000 and 300,000 yr after the K/T boundary.

4. There are no species extinctions or measurable faunal changes associated with the K/T boundary in the Brazos River sections.

5. Species extinctions are selective, affecting large, ornate, tropical to subtropical deeper-water dwellers first and small, primitive, nonornate, subtropical to temperate surface-water dwellers last. This selectivity in extinctions is likely caused by a late Maastrichtian sea-level regression and global cooling.

6. The pattern of selective extinctions over an extended time period and absence of extinctions at the K/T boundary in the marginal Gulf of Mexico is not entirely compatible with either impact or volcanism theories.

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