

EXTENDED CRETACEOUS/TERTIARY  
BOUNDARY EXTINCTIONS AND DELAYED  
POPULATION CHANGE IN PLANKTONIC  
FORAMINIFERA FROM BRAZOS RIVER,  
TEXAS

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**Abstract.** High-resolution planktonic foraminiferal analysis of three Brazos River sections indicates a nearly continuous Cretaceous/Tertiary [K/T] boundary sedimentary record second only to the world's most complete record at El Kef, Tunisia. Species extinctions occur over an extended period of time and with two major extinction episodes. The first extinction episode with 46% of the species extinct occurs at and just below [10-15 cm] a short hiatus at the base of a sandy shell hash and clay-sand unit which was interpreted by Bourgeois et al. [1988] to represent a tsunami bed generated by the K/T boundary bolide impact. The top of this tsunami bed is about 17-20 cm below the K/T boundary as defined by the first appearance of Tertiary planktonic foraminifera. The second extinction phase with 45% of the species extinct occurs 25 cm above the K/T boundary [Zone P0/P1a boundary]. Of the remaining seven surviving Cretaceous species, six gradually disappear during planktonic foraminiferal Subzones P1a and basal P1b. No species extinctions or major faunal assemblage changes are directly associated with the K/T boundary. Iridium distribution is ambiguous, with one peak in the upper part of the tsunami bed and a second peak at the micropaleontologically defined K/T boundary. Relative abundances of dominant species are stable through the Late Maastrichtian, and only minor abundance changes coincide with the first extinction episode or the K/T boundary. The first major faunal

change in the dominant species group coincides with the second extinction episode and leads to decline and eventual extinction of this group in Subzone P1a. Species disappearing at the two extinction episodes [46% and 45%] constitute only a small percentage [8% and 5%] of the individuals of the total planktonic foraminiferal population. This suggests that weakened species with low numbers of individuals and sensitive to relatively minor environmental changes were primarily affected by these extinction episodes. Magnetostratigraphy indicates that the first extinction phase began about 310,000 years before the K/T boundary, and the second extinction phase occurred 50,000 years after the K/T boundary. This stepped pattern of species extinctions suggests a progressively stressed ecosystem in continental shelf settings which may be related to an observed sea level regression and global cooling. The hypothesis of a global catastrophic mass extinction at the K/T boundary caused by a large extraterrestrial impact is not supported by the Brazos River planktonic foraminiferal data.

## INTRODUCTION

Ever since the discovery of mass extinctions across the Cretaceous/Tertiary [K/T] boundary the quest for a complete K/T boundary section elucidating the catastrophic faunal and floral changes has continued. Paleontologists generally assumed that the most complete sections would be found in deep-sea sediments. But contrary to expectations, virtually all deep-sea cores have revealed hiatuses, nondeposition, or highly condensed sedimentation across this boundary interval [Thierstein, 1982; Perch-Nielsen et al., 1982]. This has led to the

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Paper number 89PA00115.  
0883-8305/89/89PA-00115\$10.00

common belief that the K/T boundary event was catastrophic and near instantaneous particularly in planktonic foraminifera [Smit, 1982; Smit and Romein, 1985]. This belief persisted despite evidence compiled by nanofossil workers which showed that some nanofossil species survived into the early Tertiary [Perch-Nielsen, 1979a, b; Perch-Nielsen et al., 1982].

Nevertheless, the quest for the elusive K/T boundary transition assemblage continued primarily in land sections with investigators examining more and more closely spaced samples, achieving a resolution of a few thousand years. It was found that a more complete Cretaceous/Tertiary boundary record was present in sediments deposited in waters shallower than 1000-1500 m depth as, for instance, in Denmark [Perch-Nielsen, 1979b], Spain [Percival and Fischer, 1977; Smit, 1982], and the alps [Herm et al., 1981; Graup, 1989]. Eventually, it was found that the most complete sedimentary record with the best preserved carbonate record was present in relatively shallow continental shelf/platform regions such as the Negev, Israel [Magaritz et al., 1985; Keller and Benjamini, 1988]; El Kef, Tunisia [Salaj, 1973; Perch-Nielsen 1979a, b; Perch-Nielsen et al., 1982; Smit, 1982; Keller, 1988a, b]; and Brazos River, Texas [Jiang, 1980; Jiang and Gartner, 1986]. Among these shallow sediment sequences the El Kef section in Tunisia has been most thoroughly studied in terms of ostracods [Peypouquet et al, 1986], nanofossils [Perch-Nielsen, 1979a, b; Romein, 1977], foraminifera [Smit, 1982; Keller, 1988a, b, 1989; Brinkhuis and Zachariasse, 1988], iridium [Kuslys and Krahenbuhl, 1983], and stable isotopes [Keller and Lindinger, 1989].

Microfossil studies at El Kef revealed the presence of one more earliest Tertiary planktonic foraminiferal zone [P0] [Smit, 1982; Keller, 1988a] and nanofossil zone [*Biscutum romeini*] [Perch-Nielsen et al., 1982] than observed in the deep sea. Moreover, the boundary clay containing this new zone is at least 50 cm thick as compared to a thickness of a few millimeters in the deep sea. Hence, the missing transition interval has been found. Careful studies have shown significant differences in the number and rate of species extinctions across the K/T boundary. About 25 to 30% of Cretaceous planktonic foraminiferal species survived up to about 150,000 to 200,000 years into the Tertiary [Keller, 1988a]. This survivorship of Cretaceous species has not been observed in the deep sea but is similar to that observed in nanofossil assemblages [Perch-Nielsen et al., 1982]. Because the faunal succession across the K/T boundary at El Kef is so different from the deep sea, many workers have considered it an anomalous and isolated region despite its location at the margin of the Tethyan Seaway.

To test whether the El Kef section represents an

isolated region with an anomalous evolutionary development, it became necessary to search for similar shelf-platform K/T boundary sections. The K/T boundary sections exposed at several locations in east central Texas along the Brazos River in Falls County, Texas [Hansen et al., 1984, 1987] have long been known. It was assumed, however, that the boundary was missing due to a hiatus largely because of a lithological change and the absence of the Upper Maastrichtian planktonic foraminiferal marker *Abathomphalus mayaroensis* [Smith and Pessagno, 1973]. This species is also absent at El Kef [Keller, 1988a], but its absence represents shallow-water conditions, rather than a hiatus. Renewed interest in the Brazos River sections was sparked by Kocurek and Hansen [1982], Hansen et al. [1984, 1987], and Bourgeois et al. [1988], who interpret the sandstone-mudstone-siltstone complex near the K/T boundary to represent an unusually coarse grained tsunami deposit generated by a bolide impact. These studies plus recent detailed nanofossil studies by Jiang [1980], Gartner and Jiang [1985], and Jiang and Gartner [1986], which revealed that the Brazos River sections are relatively complete and comparable to the El Kef section of Tunisia, have persuaded the author to investigate the planktonic foraminiferal faunas. The samples used in this study were generously supplied by T. Hansen and E. Kauffman. Paleomagnetic analysis of samples from a cored section was done by W. Gose [unpublished data, 1987].

The main objective of this study was to determine the nature of the K/T boundary mass extinction in a relatively shallow continental platform setting similar to El Kef. Similar faunal successions in the two regions would show that the boundary transition interval is present in continental shelf/platform regions due to high sedimentation rates but is absent in the deep sea. The presence of the boundary transition interval therefore provides the missing link between the apparent abruptness of Cretaceous species extinctions and the equally sudden appearance of Tertiary species observed in deep-sea sections.

This investigation of three Brazos River area sections shows that the K/T boundary transition interval is present. Species extinctions and survivorship across the K/T boundary as well as evolutionary first appearances of Tertiary species are similar to El Kef. In contrast to El Kef where Cretaceous survivors are relatively rare in Danian deposits, surviving Cretaceous species in Brazos River sections thrived in the Early Danian apparently unaffected by the hypothesized K/T boundary event. This paper focuses on the stratigraphic completeness of the section; the nature of species extinctions before, during, and after the K/T boundary interval; and the behavior of planktonic foraminiferal populations through the Upper Maastrichtian, the K/T boundary transition, and the lower Tertiary.

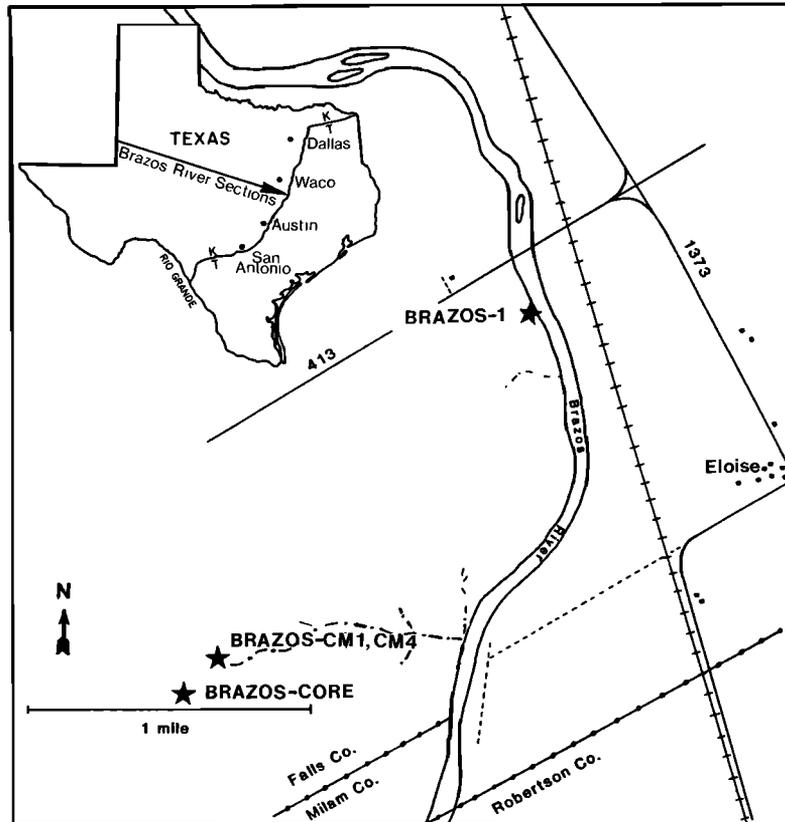


Fig. 1. Location map of measured sections across the K/T boundary on the Brazos River.

The K/T boundary impact generated tsunami deposit theory of Bourgeois et al. [1988] is evaluated in the light of these new faunal data.

#### BRAZOS RIVER SECTION

The lithology and geologic setting of the Brazos River sections have been described in detail by Hansen et al. [1984, 1987], Jiang and Gartner [1986], and Bourgeois et al. [1988], and only a short summary is given here. Three sections, two surface outcrops and one core, have been studied for planktonic foraminifera from the Brazos River locality [Figure 1]. One outcrop labeled Brazos 1 has been known in the literature as the "Brazos River Section." This section was previously studied by Smith and Pessagno [1973], who interpreted the K/T boundary as unconformable due to the absence of the Upper Maastrichtian marker species *Abathomphalus mayaroensis*. This species, however, is also absent from similarly shallow sections at Braggs, Alabama [Jones et al., 1986], and El Kef, Tunisia [Keller, 1988a] where its absence appears to be related to water depth. Based on a study of nannofossils Jiang and Gartner [1986] concluded that the Brazos 1 sequence was conformable. Their conclusion was

based on the presence of the uppermost Maastrichtian *Prediscosphaera quadripunctata* acme Zone which marks the top of *Micula murus* Zone.

A second surface outcrop section labeled Brazos CM is located in a small tributary to the Brazos River informally known as Cottonmonth Creek about 1/2 mile upstream from its intersection with the Brazos River at the locality known as Brazos 3 of Hansen et al. [1984]. The Brazos CM section was collected in two parts. Samples from CM 1 span the uppermost 2 m of the Maastrichtian. But because the basal Tertiary is not well-exposed at this locality, this part was sampled in a well exposed nearby outcrop (CM-4). In addition a 5-cm-diameter core, labeled Brazos Core, was taken with a mobile drilling rig near the Brazos CM-1 locality [Figure 1]. The 25.5 m cored section spans most of the Upper Maastrichtian and the lowermost 2 m of the Tertiary.

In all Brazos localities the uppermost Cretaceous consists of a grey calcareous claystone of the Corsicana Formation (Kemp Clay), and the overlying Paleocene Kincaid Formation consists of a grey calcareous clay. A distinct relatively coarse grained lithologic sequence of variable thickness separates the two units. At the CM-1 locality this sequence is most developed consisting of about 1 m

marked by a basal 0.3 m sandy shell-hash bed (unit B, C, and D of Hansen et al., [1987]) with an irregular scoured contact and basal rip-up clasts. This unit grades upward into a silty sandstone and sandy claystone (unit E), a calcareous siltstone (unit F), massive grey clay (unit G), clay with sandy laminations (unit H), and a homogenized silt-clay (unit I) [Hansen et al., 1987]. Various authors interpret units B to G to represent the deposit of a very large storm [Hansen et al., 1987] or a giant tsunami wave [Bourgeois et al., 1988]. These authors also observed a variable thickness of this deposit within the Brazos sections examined. In each of the sections, however, erosion at the base of this deposit and reworking of Upper Maastrichtian sediments into Paleocene sediments is possible as will be discussed later. In the following discussion the sandstone-siltstone-claystone deposit is referred to as the tsunami bed of Bourgeois et al. [1988].

Iridium Concentration

An iridium analysis for the Brazos 1 section was published by Ganapathy et al. [1981] and Asaro et al. [1982]. A double peak of iridium in excess of background levels was found. The lower Ir peak occurs within the tsunami bed of Bourgeois et al. [1988] (sample G of Brazos 1). The upper Ir peak of both Asaro et al. [1982] and Ganapathy et al. [1981] coincides with the planktonic foraminiferal and nannofossil K/T boundary [Jiang and Gartner, 1986].

Carbonate Sedimentation

The percent carbonate record for the Brazos CM and Brazos Core sections is illustrated in Figures 5, 8, and 9, and the data are given in Table 1. In both sections carbonate sedimentation is low [ $<10\%$ ] during the Upper Maastrichtian and increases in the lowermost Paleocene near the Zone P0/P1a boundary or, alternatively, clastic sedimentation decreases.

TABLE 1. Percent CaCO<sub>3</sub> Data From the Brazos Core and Brazos CM-4 Sections

Sample	Depth, m	CaCO <sub>3</sub> , %
<u>Brazos Core</u>		
1	-23.5	7.5
81	-14.0	3.9
111	-11.0	6.0
138	- 9.9	3.5
165	- 5.0	9.3
180	- 3.25	8.4
190	- 2.75	8.6
197	- 2.25	8.2
203	- 1.75	8.1
209	- 1.45	8.7

TABLE 1. (continued)

Sample	Depth, m	CaCO <sub>3</sub> , %
210	- 1.40	7.9
215	- 1.15	6.8
218	- 0.85	10.3
225	- 0.50	11.1
230	- 0.27	9.3
241	- 0.05	4.3
246	0.07	21.2
248	0.15	7.3
250	0.20	5.5
253	0.27	5.5
256	0.35	11.7
257	0.38	21.5
260	0.45	31.6
261	0.48	37.6
262	0.62	24.5
264	0.68	20.6
265	0.70	23.7
266	0.73	22.0
268	0.77	18.3
269	0.80	17.8
270	0.87	13.3
274	0.93	15.3
279	1.05	10.1
283	1.15	15.7
286	1.22	9.3
287	1.45	22.0
<u>Brazos CM-4</u>		
-3	-1.11-1.39	7.16
-2	-0.58-0.66	6.12
-1	-0.15-0.20	8.43
1	0-0.08	5.83
3	0.10-0.20	6.53
4	0.20-0.30	5.81
5	0.30-0.40	8.66
6	0.40-0.50	23.18
7	0.50-0.60	23.18
8	0.60-0.70	22.80
9	0.70-0.80	15.64
10	0.80-0.90	13.56
11	0.90-1.0	14.29
12	1.0-1.2	14.29
13	1.1-1.2	14.52
14	1.2-1.3	29.48
15	1.3-1.4	24.64
16	1.4-1.5	24.30
17	1.5-1.6	21.25
18	1.6-1.7	23.80
19	1.7-1.8	17.65

Carbonate levels peak in the lower part of Subzone P1a (25-35%) and decrease to 10-15% in the upper part of Subzone P1a and lower part of Subzone P1b. Carbonate increases again to 25-30% in the upper part of Subzone P1b.

This pattern of carbonate sedimentation is unlike the deep-sea carbonate record and may reflect sea level variations, nearshore sedimentation patterns, and terrestrial sediment input rather than primary productivity. G. Baum (written communication, 1988) interprets the uppermost Maastrichtian sediments of the Gulf Coast as representing a sea level regression followed by a transgression in the Early Danian with the surface of maximum starvation near the planktonic foraminiferal Zone P1a/P1b boundary. Our carbonate and sediment data appear to support this interpretation. Low carbonate and high terrestrial input (sands) mark the uppermost Maastrichtian, reflecting proximity to a shoreline. The maximum sea level lowstand may coincide with the unconformity at the base of the tsunami bed. Clay sedimentation and an increase in CaCO<sub>3</sub> in the Early Danian suggest a transition to a deeper shelf facies as a result of a sea level transgression. The decrease in CaCO<sub>3</sub> and short hiatus at the Zone P1a/P1b boundary associated with glauconite may represent the maximum starvation at the transgressive peak.

## METHODS

Samples were processed for foraminiferal analysis by standard micropaleontological techniques [Keller, 1986]. Quantitative analyses are based on sample counts of 300-500 individuals of the size fraction >63 $\mu$ . The remaining sample was carefully searched for rare species. The >63- $\mu$ m size fraction was chosen because of the multitude of small species which would be lost if the larger standard >150- $\mu$ m size fraction were used. For comparison, and to show the difference in the population data, both size fractions were counted for the Brazos CM section. The >150- $\mu$ m size fraction was also examined for the Lower Paleocene in all three sections. All specimens were mounted on microslides for a permanent record and identified. Tabulation of the species abundance data in percent is given in Tables 2-7. Characteristic Danian species are illustrated in Figure 2 and 3. Sedimentary carbonate analysis was done for Brazos CM4 and the Brazos Core with a coulometer at a precision of  $\pm 0.5\%$  [Table 1].

## REWORKED CRETACEOUS SPECIES AND SURVIVORSHIP

The rate and order of species extinctions across the K/T boundary is perhaps the single most important data set in deciphering the events at this boundary. This data set can provide decisive evidence in favor of several of the competing theories: extraterrestrial impact, extended volcanism, and not always unrelated climatic and facies changes associated with marine transgressions or regressions. Did species die out catastrophically (i.e., instantaneously) due to an extraterrestrial cause as is believed

by some workers? Or did they die out more gradually beginning below and ending above the K/T boundary as would support the theory of gradual environmental change? Or did they die out in distinct episodes of accelerated species extinctions representing a stepwise pattern?

Reworking of Cretaceous faunas into Lower Paleocene sediments poses a potential problem in documenting species extinctions because ranges are artificially lengthened. This problem is magnified by the assumption of a few workers who believe that only one Cretaceous planktonic foraminiferal species survived the K/T boundary mass extinction (e.g., Smit, 1982). Cretaceous species present in Lower Paleocene deposits are therefore frequently viewed as reworked. Nevertheless, studies of El Kef and Brazos River sections clearly show that about 1/3 of the Upper Cretaceous species survived [Keller, 1988a]. It is therefore necessary to recognize and differentiate between Cretaceous reworked species and Cretaceous survivors in Lower Tertiary deposits.

Occasional reworked species are a common occurrence among microfossil assemblages of any age. They can generally be recognized without difficulty by their anomalous age and isolated occurrence, discoloration and poor preservation as compared to the in situ assemblage. A more systematic approach is required to recognize the sometimes high percentage of reworked species in Lower Paleocene assemblages. Two approaches have been tried in this study.

One approach, also used in the study of the El Kef section [Keller, 1988a], recognizes species as reworked if they occur outside their normal range and are present only as isolated specimens. Usually, such specimens are poorly preserved and frequently co-occur with other isolated species outside their normal range. Such species occurrences are marked with a diamond in the range chart (Figures 5 and 8). In contrast, Late Cretaceous species which are present in successive samples and do not show differential preservation are considered as survivors.

The second, more quantitative approach is based on the relative abundance of all species present in the Lower Danian in the size fraction >63 $\mu$ . This provides a numerical estimate of abundance through time. An asymptotic decline in abundance is unlikely to represent random reworking of species. In all three Brazos River sections there is an asymptotic abundance decline in all Cretaceous species present in the Early Danian which strongly suggests that these species represent survivors rather than random reworking of Cretaceous sediments.

A systematic search of the >150- $\mu$ m size fraction in Early Danian deposits also allows a semiquantitative evaluation of the presence of reworked faunas because most Cretaceous species are larger than 150  $\mu$ m, but dwarfing of survivors is apparent after the K/T boundary. If a significant number of Cretaceous species is present in the larger









TABLE 4. Relative Percent Abundances of Planktonic Foraminifera Greater than 150µ in the Brazos CMI Section

Species	Sample																				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
<i>G. carvacaensis</i>							x					x									
<i>G. aspera</i>	9	14	16	13	3	5	5	2	2	5	6	x	8	10	5	6	2	2	3	3	
<i>G. multispina</i>	3	x	4	x	x	x	x	x	x	2	x	6	x	x	3	3	4	3	3	8	13
<i>G. volutus</i>					x										x						
<i>G. rosebudensis</i>															x						
<i>G. monmouthensis</i>	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	2	2	x	x	x	2
<i>G. sp. A</i>	+	x									x	x	x	x	2						x
<i>G. subcarinatus</i>	x	x			x					x	x	x	x	x	x	x		x			x
<i>Rugoglobig. sp A</i>	2	x	x	2		x				3	2	2	3	3	3	3	x	3	x	x	x
<i>R. hexacamerata</i>	3	2	x	x	3	x	x	x	x	2	8	2	8	4	3	3	9	3	4	3	2
<i>R. macrocephala</i>	x		2	x	x	x	x	x	x	2	2	4	2	4	2	x	3	x	x	x	x
<i>R. robusta</i>			x	x	x	2	3	x	x	x	x	x	x	x	2	x	2	x	x	x	x
<i>R. reichelti</i>						x				x											
<i>R. rugosa</i>	3	2	x	6	x	3	x	3	2	2	2	3	5	2	4	2	7	5	5	3	x
<i>R. scotti</i>	3		x	x	x	2	x	x	x	x	2	x	x	x	3	2	2	2	x	4	4
<i>G. duwi</i>	x		x							x											
<i>G. aegyptiaca</i>	x	x	x	3	x	x	2	2	x	x	x	x	x	2	x	x	2	x	x	x	2
<i>G. arca</i>	x	x	x	x	x	x	x	x	x	x	x	x	2	2	2	x	.	x	x	x	4
<i>G. conica</i>	x	x	x	x			x	x	x	x	x	x	2	2	x			x	x	x	4
<i>G. stuarti</i>	x	x								x	x	x			x			x			x
<i>G. stuartiformis</i>	x									x	x	x									x
<i>G. trinidadensis</i>	x	x	x	x	x	x	x	x	x	x	x	2	2	x	2	x	x	x	x	x	x
<i>H. americana</i>	5	x	14	16	10	9	8	13	7	7	7	5	4	8	4	4	10	7	11	10	2
<i>H. pulchra</i>						x	x					x									x
<i>H. globulosa</i>	49	52	39	39	57	34	42	53	62	42	26	43	44	47	45	53	57	43	36	48	34
<i>H. navarroensis</i>	5	4	3	x	x	3	3	2	2	4	x	2	x	x	2	x	5	x	x	2	x
<i>H. striata</i>	2	5	x	3	2	3	x	4	x	3	8	3	3	2	2	2	x	4	2	2	5
<i>P. brazoensis</i>							x														x
<i>P. excolata</i>			x	x		x	x	x	x	3	3	2	x	x	x	x	3	x	2	7	x
<i>P. costulata</i>	3	5	4	2	5	3	3	2	2	2	x	5	3	x	x	x	x	x	3	x	3
<i>P. carseyae s.s.</i>	x				x	x	x	2	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>P. carseyae s.l.</i>	7	4	6	5	4	15	12	6	4	8	11	4	7	9	4	9	12	10	12	10	13
<i>P. deformis</i>	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
<i>P. elegans</i>										x	x	2	3	x	2			x	2	x	x
<i>P. kempensis</i>			x			x				x	x	x	x	x	x	x	x	x	x	x	x
<i>P. palpebra</i>	x	x				x				x	x	x	x	x	x	x	x	x	x	x	x
<i>P. punctulata</i>										x	x	x	x	x	x	x	x	x	x	x	x
<i>G. cretacea</i>	x	x								x	x	x	x	x	x	x	2	x	x	x	x
<i>R. intermedia</i>			x							3	x	x	x								
<i>R. powelli</i>																					
<i>A. blowi</i>																					
Total number counted	350	376	384	319	307	255	223	313	353	320	316	320	342	305	327	381	256	327	400	292	344

Species	Sample																			
	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41
<i>G. caravacaensis</i>																				
<i>G. aspera</i>	x	5	x	x	6	5	x	4	8	x	(2)	6	2	(1)	(1)		3	2	9	9
<i>G. multispina</i>	10		6	10	2	4	8	5	x	x	x	10	11			5	6	2	2	2
<i>G. volutus</i>	x		x	x	x		x		x	x		4	3	(1)					x	
<i>G. rosebudensis</i>																				
<i>G. monmouthensis</i>	x	2	2	x	x	x		x	2	x		2	3				x			
<i>G. sp. A</i>		x					x									(1)				
<i>G. subcarinatus</i>	x	x	x																3	x
<i>Rugoglobig. sp A</i>	x	x	x	x	x	x	2	2	2	2	4	x	4	(2)		3	5	9	7	7
<i>R. hexacamerata</i>	3	3	3	3	2	2	3	x	x	4		x	2	(2)		5	5	3	4	4
<i>R. macrocephala</i>	x	x	x	x	3	x	x	3	x											
<i>R. robusta</i>	x	x	x	x	x	x	x	x	x	x										
<i>R. reicheli</i>				x															x	
<i>R. rugosa</i>	x	7	5	4	13	4	7	11	5	9	(14)	15	10	(7)	(3)	(1)	10	6	7	3
<i>R. scotti</i>	3	2	4	2	6	5	4	2	2	4	(2)	2	3		(1)	(1)	x		3	
<i>G. duwi</i>																				x
<i>G. aegyptiaca</i>	x	x	x	x	2	x	x	x	2	x	(2)	2	x	(1)			x	x	x	x
<i>G. arca</i>	x	x	x	x	x	x	x	x	3	x	(1)	x					x	x	x	x
<i>G. conica</i>	x	x	x	x	x		x			x										
<i>G. stuarti</i>					x	x	x													
<i>G. stuartiformis</i>																				
<i>G. trinidadensis</i>	x	x	x	x	x	x	x	2				x						x	x	2
<i>H. americana</i>	6	6	8	3	9	7	6	4	5	6		4	6	(2)		11	x	3	2	
<i>H. pulchra</i>	x									x										
<i>H. globulosa</i>	39	41	35	42	18	42	37	45	30	32	(16)	32	29	(15)	(2)	(1)	42	52	43	57
<i>H. navarroensis</i>	x	x	x	3	x	x	x	x	x	x		x	3		(1)	(1)	3	4	x	x
<i>H. striata</i>	5	4	4	4	9	4	4	x	5	5	(3)	x	4				x			
<i>P. brazoensis</i>	x	x																		
<i>P. excolata</i>	x	x	x	x	3	x	2	x	5											7
<i>P. costulata</i>	2	4	x	x	3	x	2	3	2	3			x					x		
<i>P. carseyae s.s.</i>	x		x	x	x	x	x	x												
<i>P. carseyae s.l.</i>	9	9	12	11	14	11	9	2	14	19	(9)	8	13	(6)	(1)	(2)	10	8	8	5
<i>P. deformis</i>	x	x	x	x	x	x	x	x	2	x	(2)	x	x	(1)						
<i>P. elegans</i>	x	x	x	x	x	x	x	x	x	x	(3)	x	x			x				
<i>P. kempensis</i>	x	x	x	x	x	x	x	x	x	x	(1)	x								
<i>P. palpebra</i>	x	x	x	x	x	x	x	x	x	x		x	x				x			
<i>P. punctulata</i>	x	x	x	x	x	x	x	x	4	x		2	x							x
<i>G. cretacea</i>	x	x	x	x	x	x	x	x												
<i>R. intermedia</i>																				
<i>R. powelli</i>																(1)				
<i>A. blowi</i>																				
Total number counted	391	336	337	366	232	366	310	228	152	265	56	114	172	35	8	8	138	324	232	256

X marks percent abundance of less than 2%. Values in parentheses represent number of individuals counted for samples where the total number equals less than 100 specimens.





TABLE 5. (Continued)

Species	Sample																																								
	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41																					
<i>P. tempensis</i>	x	x	x	x	x	x				x		3				x	x	x	x																						
<i>P. palpebra</i>	x	x	x	x		x			x		x		x						x																						
<i>P. punctulata</i>	x		x	x	x	x	x		x	x	x	x	x																												
<i>Pseudotextularia deformis</i>	x	x	x	x	x	x	x		x	x	x	x	x	x																											
<i>P. elegans</i>	x		x	x	x	x	x		x	x	x	x	x																												
<i>Racemiguembelina powelli</i>																																									
<i>Guembelina cretacea</i>	25	38	28	38	35	45	36	28	27	28	24	10	12	10	17	20	20	19	23	21																					
<i>G. danica</i>		x						x												x																					
<i>G. trifolia</i>																																									
Juveniles no-identification	2	x	2	x	3	x	x	x	x	x	x	x	x	x	x	5	3	4	4	4																					
Total number counted	319	298	343	303	286	281	301	308	197	197	90	110	273	297	318	196	276	307	287	269																					

X marks percent abundance of less than 2%.

Cretaceous species into the Early Paleocene using criteria discussed in the previous section. Because of the potential for reworked as well as surviving Cretaceous species the K/T boundary is best identified by the first appearance of Paleocene species. This event occurs in the sample that spans the interval between 10 and 20 cm above the tsunami deposit, (units B-C plus overlying clay and siltstone units D-G, Figure 4) and coincides with the uppermost Ir anomaly [Ganapathy et al., 1981; Asaro et al., 1982]. The first Paleocene species to appear are *Globorotalia archeocompressa* and *Woodringina hornerstownensis*; these species mark the base of the first Paleocene Zone P0 [Keller, 1988a]. The next species evolving are *Globoconusa conusa* (20-30 cm above base) and *Globigerina fringa* (30-40 cm above base) which are also characteristic of Lower Danian deposits (Figures 3 and 4). Shortly thereafter a five-chambered *G. eugubina*-like form with rounded periphery appears. The first characteristic *Globigerina eugubina* appears later in the sample 125-135 cm above the tsunami bed and marks the boundary between P0 and P1a (Figure 6). Also evolving in Zone P0 are *Globigerina edita*, *Eoglobigerina eobulloides*, and *Globastica* sp., a precursor of *G. daubjergensis*. This evolutionary sequence is virtually identical to that observed at El Kef.

**Brazos CM Section**

The Brazos CM section spans 2 m of Upper Maastrichtian sand and calcareous mudstone (CM-1 Corsicana Formation) and 1.8 m of Lower Paleocene silty clays (CM4 Kincaid Formation). Although the two parts of this section are offset by a few meters, they can be connected by marker beds. Therefore, the entire K/T sequence was sampled continuously. The Lower Paleocene consists of a relatively uniform grey clay with clasts at 60 cm. A small unconformity is present at 1 m above the K/T boundary marked by sand and glauconite and overlain by a silty clay (Figure 5). A total of 63 samples were analyzed, and the relative percent abundance of species is tabulated in Tables 2 to 5.

The uppermost 2 m of the Cretaceous contains a relatively uniform Maastrichtian assemblage notable by its dominance of small biserial and triserial species and near absence of the characteristic large species such as *Globotruncana* and *Racemiguembelina* [Table 6]. The Upper Maastrichtian zonal marker *Abathomphalus mayaroensis* is absent as noted earlier by Smith and Pessagno [1973] and also observed at El Kef, Tunisia [Salaj, 1973; Keller, 1988a]. The absence of *A. mayaroensis* and other characteristic Upper Maastrichtian species may be due to the relatively shallow water conditions (100-150 m depth). Based on the El Kef fauna, the new *Pseudotextularia*

deformis Zone was proposed to mark Late Maastrichtian sediments lacking A. mavaroensis; P. deformis ranges to the top of the Maastrichtian.

Species ranges are illustrated in Figure 5. Species considered to be reworked from Cretaceous deposits are marked with a diamond. Unfortunately, it is not possible to provide a definitive species extinction list prior to the K/T boundary at the CM1 outcrop because a barren 50-cm-thick sandstone, sedimentary conglomerate, and siltstone interval (tsunami bed of Bourgeois et al., 1988) marks the top of the section. A sample spanning the uppermost 20 cm of this unit was analyzed at the nearby CM-4 outcrop (Tables 2, and 3), and the species present there are marked in the range chart (Figure 5). From the present data it appears that the following species disappear between 50 cm and 120 cm below the K/T boundary as defined by the first appearance of Tertiary planktonic foraminiferal species: Globotruncana conica, G. stuartiformis, Racemiguembelina powelli, Planoglobulina brazoensis, P. carseyae s.s., and Globotruncanella petaloidea. These species also disappear prior to the K/T boundary in the cored section.

Similar to the Brazos 1 outcrop, reworking of Cretaceous fauna into Lower Paleocene sediments is common in the lower 60 cm of the Paleocene and a significant number of Cretaceous species is present in the size fraction >150  $\mu$  (Figures 5 and 6). As discussed earlier, the presence of foraminiferal specimens in the larger than 150- $\mu$ m size fraction in Lower Danian sediments (Zones P0-P1a) is indicative of Cretaceous reworking because Danian species as well as Cretaceous survivor species are generally smaller than 150  $\mu$ . In addition, Cretaceous survivor species are dwarfed in the Early Tertiary (Figure 2). For this reason biostratigraphic interpretations should be based on the smaller size fraction.

The first Paleocene species appear in the basal sample (0-10 cm) of the CM-4 outcrop and include Globigerina fringa, G. edita, W. hornerstownensis, Globastica sp., and a five-chambered G. eugubina-like form. Globoconusa conusa and the first characteristic G. eugubina forms first appear 30-40 cm above the basal Paleocene and mark the Zone P0/P1a boundary (Figures 2, 3, and 7). The sequence of species appearances plus the short, 30- to 40-cm-thick Zone P0 as compared with 115-125 cm at Brazos 1 suggests that the lower part of Zone P0 may be missing.

Zone P1a is relatively short (60 cm) and characterized by the evolution of Globoconusa daubjergensis and Eoglobigerina simplicissima. An abrupt faunal change coincides with the lithologic change and unconformity at 1 m above the K/T boundary and is characterized by the appearance of G. (E.) triloculinoidea, Globigerina taurica, and G.

moskvini and followed by G. subquadratus, G. pentagona, and G. pseudobulloidea (Figures 5 and 6). These species are characteristic of Zone P1b [Keller, 1988a]. The faunal and lithological change is accompanied by abundant glauconite and quartz grains and represents a short hiatus. Based on paleomagnetic stratigraphy, planktonic foraminiferal datum events and extrapolation from average sediment accumulation rates this hiatus is estimated to span about 80,000 years as discussed below. Comparison of the Brazos CM4 section Zone P1a fauna with that at El Kef indicates that only the lower part of this zone is present [Keller, 1988a] in agreement with the estimate of hiatus duration. Above this hiatus, the lower part of Zone P1b appears to be present as indicated by faunal diversity and species abundance.

#### Brazos Core Section

The Brazos Core was drilled near the Brazos CM locality. The core spans 23.5 m of Maastrichtian strata and 2 m of Lower Paleocene. This is the most important Brazos River section because it was continuously cored and has good paleomagnetic control. Therefore the entire core was studied in detail, and 131 samples were analyzed. The first 2 m above and below the K/T boundary was examined at 2.5- to 5-cm intervals wherever possible (64 samples). The Maastrichtian between 2 m and 23.5 m was examined at 20-cm intervals (67 samples). Tables 7a, and 7b tabulate the relative percent abundance of species.

#### Lower Paleocene

Species ranges across the K/T boundary are illustrated in Figure 8. Unlike the Brazos 1 and Brazos CM sections, Cretaceous species reworked into basal Paleocene sediments are rare in the core. However, the same number and type of Cretaceous species survive. Stratigraphically and faunally, the Brazos Core is very similar to the Brazos CM section.

The first Paleocene species (G. fringa, W. hornerstownensis, and Globastica sp.) are found 25-30 cm (samples 253-256, Table 7b) above what appears to be the top of the tsunami deposit. The first G. eugubina along with G. conusa appears at 47.5 cm (sample 261, Table 7b). Thus the basal Paleocene Zone P0 is very short (22 cm), similar to the Brazos CM section, suggesting that the basal part of zone P0 may also be missing in the cored section. The first G. taurica and G. pentagona appear at 80 cm above the K/T boundary (sample 279, Table 7b) and mark the Zone P1a/P1b boundary. Faunal diversity and species abundances suggest that much of Zone P1a is missing, similar to the Brazos CM section.

TABLE 6. Relative Percent Abundances of Planktonic

Species	Sample												
	A	B	C	D	E	F	G	H	I	1	2	3	4
<i>Globigerinelloides aspera</i>	3	C			5		x	8	3	15	4	x	3
<i>G. multispina</i>	x	C			x	F							
<i>G. volutus</i>	x	F			x							x	x
<i>Globotruncanella subcarinatus</i>				(1)	x			x	x			x	
<i>G. caravacaensis</i>	x			(2)	x		2	4	x	3	2	x	x
<i>Globigerina monmouthensis</i>	x	C			x		2	x					
<i>G. fringa</i>												x	
<i>G. edita</i>													
<i>G. eugubina</i>													
<i>G. cf eugubina</i>													x
<i>Eoglobigerina sp.</i>													
<i>Globorotalia archeocompressa</i>													x
<i>Globoconusa conusa</i>												2	x
<i>Globastica daubjergensis</i>													
<i>Guembelitria cretacea</i>	20	C		(4)	15	F	20	17	15	10	15	18	23
<i>G. danica</i>	x												
<i>G. trifolia</i>	x				x		x	x	x	5	4	2	4
<i>G. midwayensis</i>													
<i>Woodringina hornerstownensis</i>											x	x	x
<i>Rugoglobigerina hexacamerata</i>	x	F											
<i>R. macrocephala</i>					x			x					
<i>R. rugosa</i>	2	C			x		x	x	x	x	x	x	
<i>R. scotti</i>		C											
<i>Archeoglobigerina blowi</i>	x							x			x		
<i>Heierohelix americana</i>	x	F			x		x				5	17	11
<i>H. globulosa</i>	53	A		(12)	52	F	49	46	56	53	50	45	47
<i>H. navarroensis</i>	9	F			14		11	7	15	6	5	3	3
<i>H. striata</i>	x	F					3	2	2	7	x		
<i>H. pulchra</i>								x					
<i>Planoglobulina brazoensis</i>		F											
<i>P. carseyae s.l.</i>	2	C			x		4	2	x		3	4	2
<i>Pseudoguembelina costulata</i>	x				3	F		3	2		2	x	x
<i>P. excolata</i>									x		x		
<i>P. kempensis</i>	x				x		x				x	x	
<i>Pseudotextularia deformis</i>	x	F											
<i>P. elegans</i>	x	F											
<i>Globotruncana arca</i>		F			x								
<i>G. aegyptiaca</i>		C											x
<i>G. conica</i>		F											
<i>G. stuarti</i>		F											
Juveniles no identification	x		(1)	x	x		x	x	x	x	x		x
Total number counted	415	-	0	19	463	-	268	260	273	85	389	428	453

X represents percent abundance of less than 2%. Sample depths are as follows: A through I, tsunami bed; A, Cretaceous clay; B, clay clasts; C, shell hash; D, rippled sandstone; E, sandy clay; F, limestone; G, clay with burrows; H, sandy clay; I, clay; 1, 0-10 cm; 2, 10-20 cm; 3, 20-30 cm; 4, 30-40 cm; 5, 40-50 cm; 6, 50-60 cm; 7, 60-70 cm; 8, 70-80 cm; 9, 80-90 cm; 10, 85-95 cm; 11, 90-100 cm; 12, 95-105 cm; 13, 100-110 cm; 14, 105-115cm; 15, 110-120 cm; 16, 115-125 cm; 17, 125-135 cm; 18, 135-145 cm; 19, 145-155 cm; 20, 155-165 cm; 21, 165-175 cm; 22, 175-185 cm. Values in parentheses represent number of individuals counted for samples where the total number equals less than 100 specimens. F=few, C=common, A=abundant.

Foraminifera Greater than 63μ in the Brazos 1 Section

Sample																	
5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
4	4	3	5	3	5	6	5	4		x	2	2	x	x	x	x	x
x	x	x	x	x		x	x	x			x						
2	2	x	x	x	x	4	x	x		x	x	x	x	x			
x				x	x					x	x	x	2	x	x		x
					x		x						2	2	2	2	x
					x						x	x		3	x	3	4
x	x						2				x	4	9	10	9	4	10
20	22	24	28	31	32	19	35	32		35	47	49	36	34	32	21	10
			x			x							x				
3	2	2	2	2	2	2	x	2		3	4	5	15	14	20	35	47
3	3	3	3	7	4	3	8	2		3	11	4	23	14	12	19	7
	x	x	x		x	x				x	x						
		x			x	x	x	x			x						
			x		x	x	x	x			x						
					x												
7	11	5	4	x	x	x	x	x		3	x						
49	44	47	44	42	40	53	31	47		40	18	24	12	6	8	10	10
4	5	3	3	5	7	7	7	6		7	5	5	3	10	5	3	x
x		x	x		x		2			x	5		2			x	x
							x			x							
2	3	2	x	x	2	x	2	x		x	x			x	x		
x		x	x		x	x	x	x				x	x				x
x		x		x	x						x	x					
		x	x		x	x											
x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x
325	367	333	375	379	252	350	330	412	0	331	295	293	346	320	283	337	297

















TABLE 7b. (Continued)

Species	Sample																			
	230	232	236	238	240	241	242	244	245	246	247	248	250	252	253	255	256	257	259	
<i>Globigerina monmouthensis</i>	x	x	x	x			2													
<i>Globotruncanella petaloidea</i>																				
<i>G. subcarinatus</i>	x					x	x													
<i>G. caravacaensis</i>	x				x			x	x	3						x				
<i>H. holmdelensis</i>																				
<i>Rugoglobigerina</i> sp. A																				
<i>R. hanikeninoides</i>	x	x	x		x	x	x	x	x	x	x	x	x	x	3					
<i>R. hexacamerata</i>																				
<i>R. macrocephala</i>																				
<i>R. reicheli</i>																				
<i>R. robusta</i>	x	x					x													
<i>R. rugosa</i>	x	x	x		x	x	4	x	x	2			x			x	x	x	x	
<i>R. scotti</i>	x	x	x		x	x	x													
<i>Archeoglobigerina blowi</i>																				
<i>Globotruncana aegyptiaca</i>	x	x	x		x		x													
<i>Gi. ara</i>	x	x				x							x							
<i>Gi. comica</i>																				
<i>Gi. duwi</i>	x																			
<i>Gi. cf. gansseri</i>																				
<i>Gi. paleiformis</i>																				
<i>Gi. stuarti</i>																				
<i>Gi. stuartiformis</i>																				
<i>Gi. trinidadensis</i>																				
<i>Gi. subspinosa</i>																				
<i>Heterohelix americana</i>																				
<i>H. globulosa</i>	51	52	46	47	37	49	42	51	7	4	5	3	4	2	2	3	x	5	2	2
<i>H. navarroensis</i>	6	15	15	13	13	11	8	13	7	52	52	54	64	48	47	59	48	47	37	37
<i>H. striata</i>		2	2	x		x	x		8	11	9	15	5	8	11	6	7	5	8	8
<i>H. pulchra</i>									x	x	x	x	x					x	x	x
<i>Planoglobulina brazaensis</i>																				
<i>P. carseyae</i> s.l.	2	3	3	6	3	x	4	2	3	x	2	x	2	4	5	x	5	2	x	x
<i>P. carseyae</i> s.s.			x	x	x															
<i>Pseudoguembelina costulata</i>	x	x	x	x	2	x	x	x	2		x	5	2	3	3	2		2		x
<i>P. excolata</i>	2	x	x		x	x	x	x	x	x	2	4	x	3	x	x	x	x		
<i>P. kempensis</i>			x				x					x				x	x	x		
<i>P. palpebra</i>																				
<i>P. punctulata</i>	x	x	x				x													
<i>Pseudotextularia deiformis</i>	x	x					x	x												
<i>P. elegans</i>							x													
<i>Racemi guembelina powelli</i>																				
<i>Guembelina cretacea</i>	29	15	16	18	28	33	26	16	18	15	11	6	14	24	15	22	23	22	22	40





The early Tertiary zonation outlined here on the basis of first appearances of evolving Tertiary species is consistent in all three Brazos sections and comparable to the El Kef section. The isochronous nature of the first appearances of these species is supported by major changes in the relative abundance of dominant species as will be discussed below. The absence of common *G. eugubina*, characteristic of Zone P1a at El Kef but rare at the Brazos sections, appears related to a short hiatus which includes the upper part of Zone P1a. On the basis of paleomagnetic control and sediment accumulation rates, approximately 80,000 years, or 32 cm, is missing from the top of Subzone P1a.

### Maastrichtian

The Maastrichtian species ranges of the Brazos Core are illustrated in Figure 9 (Table 7a) and details of the Uppermost Maastrichtian are shown in Figure 8. The Maastrichtian foraminiferal fauna at Brazos are surprisingly uniform and unchanging through time except for the last 310,000 years before the K/T boundary beginning about 15-25 cm below the tsunami bed deposit. As a result biozonation is very difficult. In addition, the sporadic occurrence or general absence of open ocean or deeper-dwelling species in the shallow marginal seas of the Gulf of Mexico makes it difficult to apply the standard biozonation of Bolli [1966]. In recognition of these difficulties Smith and Pessagno [1973] subdivided the *Globotruncana gansseri* Zone into a lower *G. aegyptiaca* Zone and upper *Racemiguembelina fructicosa* Subzone. This subdivision, however, could not be followed due to the absence of *R. fructicosa*. The uppermost Maastrichtian *Abathomphalus mayaroensis* remained unzoned by these authors due to the absence of this index species.

In this study the ranges of species in the Brazos Core were compared with those of Smith and Pessagno [1973] from north central Texas localities and with those of Caron [1985] based largely on low-latitude deep-sea cores. Based on these comparisons the lower half of the Brazos Core is determined to be part of the *G. gansseri* Zone because of the presence of *Globotruncana conica*, *G. gansseri*, and *Rugoglobigerina reicheli*, which are absent below this zone and the extinction of *G. subspinosa* in the lower part of the section (Figure 9). The top of the *G. gansseri* Zone is defined by the first occurrence of *A. mayaroensis* which is not present in Texas. In the absence of this index species the extinction of *Globigerinelloides rosebudensis* is used to mark this boundary. Smith and Pessagno [1973] earlier observed the extinction of this species to coincide with the *G. gansseri/A. mayaroensis* Zone boundary. The uppermost Maastrichtian is named the *Pseudotextularia deformis*

Zone [Keller, 1988a]. Characteristic species disappearing in the lower part of the *P. deformis* Zone are *Globotruncana gansseri* and *G. stuartiformis*. The uppermost part of the *P. deformis* Zone is defined by the extinction of *P. deformis*, *P. elegans*, most rugoglobigerinids, pseudotextularids, and globotruncanids.

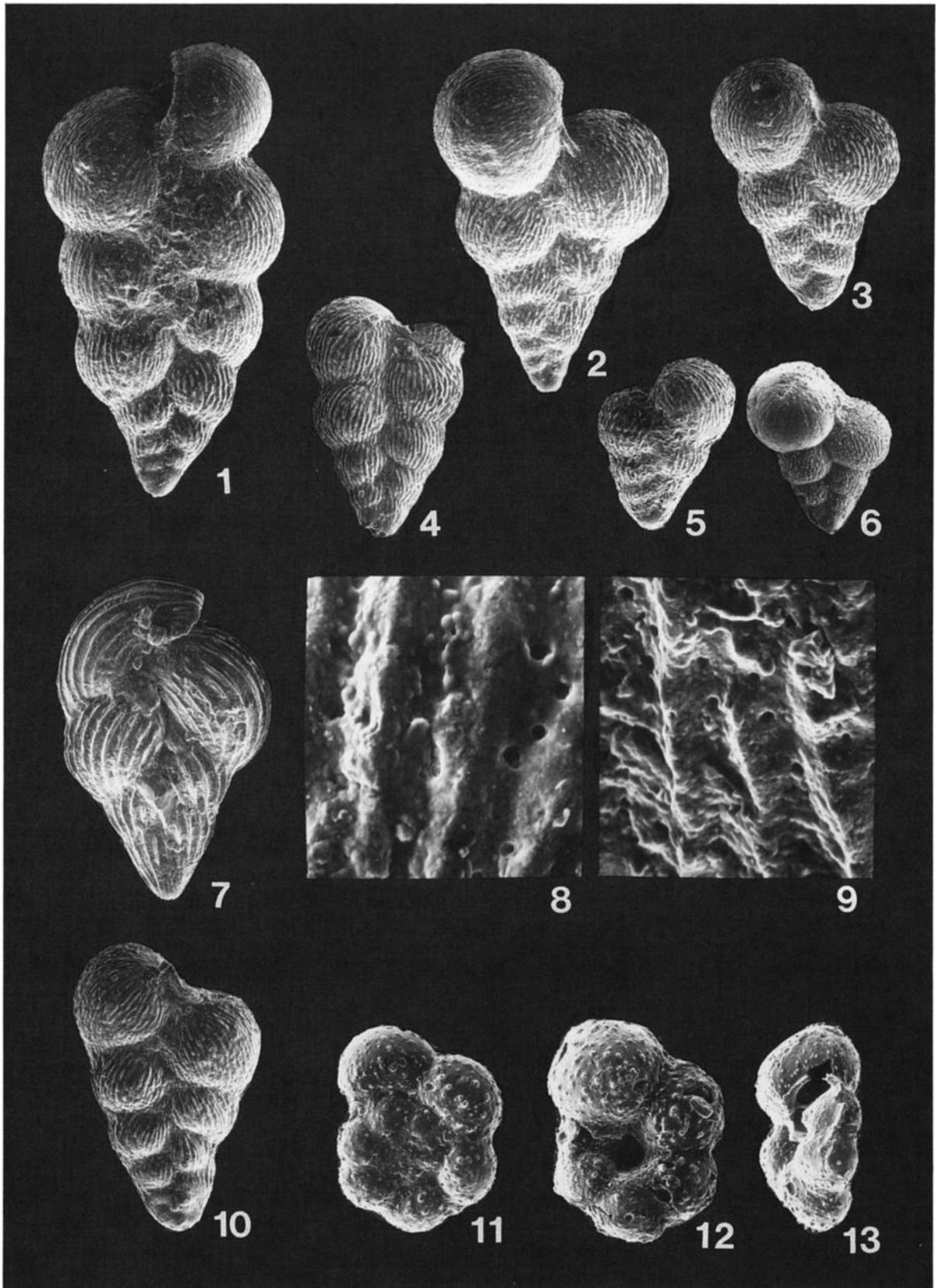
### MAGNETOSTRATIGRAPHY

Magnetostratigraphy obtained for the Brazos Core (W. A. Gose, written communication, 1987) indicates the presence of a continuous sedimentation record from the Late Maastrichtian Chron C32.1N to the reversed polarity interval of Chron C28R. In this study ages for polarity intervals are based on the time scale of Berggren et al. [1985]. Based on these data estimates for ages and rates of species extinctions have been calculated using sediment accumulation rates [Table 8].

Berggren et al. [1985] estimated an age of 66.4 Ma for the K/T boundary. In the Brazos Core the top of Chron C29R (age 66.17 Ma) coincides with the top of planktonic foraminiferal Subzone P1a as also observed by Berggren et al. [1985]. Planktonic foraminiferal Zones P0 through P1a therefore span 230,000 years. Zone P0 spans about 50,000 years based on the first appearance datum of *Globigerina eugubina* at 66.35 Ma [Berggren et al., 1985]. Biostratigraphic analysis of the Brazos Core as well as the Brazos CM section indicates a short hiatus at the Subzone P1a/P1b boundary. This interval is lithologically marked by a glauconite and quartz-rich layer in the Brazos CM section. Based on faunal comparisons with El Kef, it is estimated that about half of Subzone P1a and possibly the lowermost part of P1b is missing. The sedimentation rate for Zone P0 is 0.4 cm/1000 years. If we assume the same average sedimentation rates to continue through Subzone P1a, a reasonable assumption based on the average sedimentary carbonate content (Figure 8, Table 1), then about 32 cm representing 80,000 years is missing at this hiatus [Table 8].

The sandstone-siltstone complex, or tsunami bed, below the K/T boundary rests on a scoured surface. An estimate of the amount of sediment eroded can be obtained if we assume that the sediment accumulation rate above and below the tsunami bed remained constant through Chrons C30N and C29R. This assumption seems justified by the similar average sedimentation rates for Zone P0 (0.4 cm/1000 years) and Chron C30N (0.4 cm/1000 years, Figure 10, Table 8). Thus, assuming a constant sedimentation rate of 0.4 cm/1000 years the portion of Chron C29R from the top of the tsunami bed to the K/T boundary [17 cm] represents about 45,000 years. This implies that about 295,000 years representing about 118 cm is missing at this unconformity.

Age estimates for the two major extinction



episodes below and above the K/T boundary were also calculated on the basis of sedimentation rates. Extinction phase I below the tsunami bed begins at about 66.71 Ma, or 310,000 years before the K/T boundary. The duration of this extinction phase is 20,000 years with the upper part most likely eroded at the base of the tsunami deposit. Extinction phase II occurs at 66.35 Ma, or 50,000 years after the K/T boundary. This event may span the missing 10 cm of the Brazos Core above the extinction level, or a maximum of 25,000 years [Table 8].

#### K/T BOUNDARY EXTINCTIONS

Planktonic foraminiferal extinctions across the K/T boundary at Brazos River show no evidence of a single catastrophic ecologic event. Rather, they indicate two phases of a rapidly deteriorating environment with the first phase beginning about 310,000 years before the K/T boundary with its upper limit terminated at the scoured surface at the base of the tsunami bed. The second extinction phase occurs about 50,000 years above the K/T boundary and appears to have spanned about 25,000 years. The two major Ir spikes which have been detected near the top of the tsunami bed, and which coincide with the micropaleontologically defined K/T boundary [Asaro et al., 1982; Ganapathy, et al., 1981] are not directly associated with the onset of either of the two extinction phases.

The record of species extinctions in the Brazos River sections is illustrated in Figures 4, 5, 8, and 9.

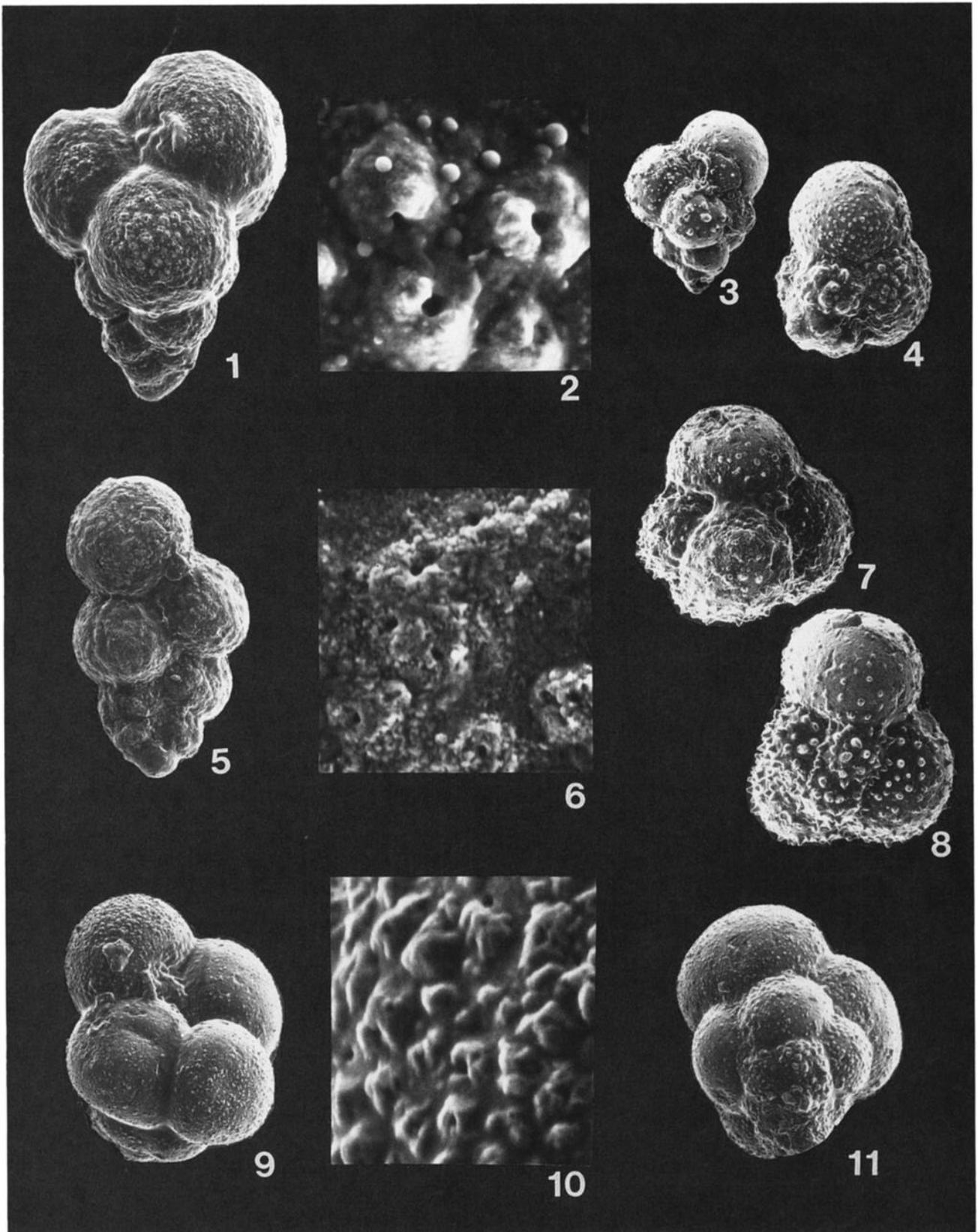
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Fig. 2. (Opposite) (1)-(3) *Heterohelix globulosa* (Ehrenberg), Brazos Core sample 232, magnification X270, Late Maastrichtian illustrating size variation within population. (4)-(6) *Heterohelix globulosa* (Ehrenberg), Brazos Core sample 255 (Figures 7 and 8) and sample 264 (Figure 9), magnification X270, Early Danian Zone P0 and P1a, illustrating size variation within population; note smaller average size of Danian species. (7) *Pseudoguembelina costulata* (Cushman), Brazos Core sample 253, magnification X270, Cretaceous/Tertiary boundary. (8) *Heterohelix globulosa* surface structure, Brazos Core sample 264, magnification X4500, Early Danian Zone P1a. (9) *Heterohelix globulosa* surface structure, Brazos Core sample 232, magnification X4500, Late Maastrichtian. Note the similarity in surface structure between Danian and Maastrichtian morphotypes indicating they are the same species. (10) *Heterohelix navarroensis* Loeblich, Brazos Core sample 232, magnification X270, Late Maastrichtian. (11)-(13) *Globotruncanella caravacaensis* Smit, Brazos Core sample 269, magnification X500, Early Danian Subzone P1a.

The most detailed data are from the cored section (Figures 8 and 9) which shows little evidence of Cretaceous reworking in the basal Paleocene. The Brazos CM section does not have a good faunal record for the lower part of the tsunami bed, and the Brazos 1 section was studied from the tsunami bed upward. Both the CM and Brazos 1 sections contain significant numbers of Cretaceous reworked species in the basal Paleocene (see diamonds in Figures 4 and 5). Nevertheless, the species extinction record is very similar in all three sections.

Species extinctions begin well below (~310,000 years) the K/T boundary and continue for 200,000-300,000 years (1.25 m) thereafter. Species extinctions below the K/T boundary appear to begin about 15 cm below and end at the unconformity at the base of the tsunami bed. The planktonic foraminiferal K/T boundary (based on the first appearance of Tertiary species) is about 7 cm and 16 cm above the top of the tsunami bed in the Brazos 1 and Brazos-Core sections respectively. Therefore, stratigraphically the tsunami bed is not coeval with the K/T boundary as defined by the first appearance of Paleocene planktonic foraminiferal species or nannofossils, but precedes the boundary. As noted earlier, the tsunami bed rests on a scoured surface which suggests that some downward erosion occurred. Based on magnetostratigraphy and sedimentation rates the missing interval is estimated to represent at least 295,000 years. The species extinctions recorded at this erosion level may therefore have occurred during the eroded interval or at the time of the tsunami deposit. In the Brazos Core, six species disappear at the base of the tsunami bed, seven species disappear 5 cm below, and two species disappear 7.5 cm below the base of this complex (Figure 8). Because most of these species occur only sporadically during the uppermost Maastrichtian, their disappearances below the tsunami bed do not necessarily represent extinctions. Nevertheless, nine of these species also disappear at or just below the tsunami bed in the CM section, which suggests at least regional extinctions at this time (*Globotruncana arca*, *G. aegyptiaca*, *G. duwi*, *G. trinidadensis*, *Pseudotextularia deformis*, *P. elegans*, *Pseudoguembelina palpebra*, *P. punctulata*, and *Rugoglobigerina rotundata*). Two species, *R. scotti* and *R. macrocephala*, occur only in isolated samples above this extinction interval in both the Core and CM sections. These occurrences may represent reworked specimens. Few species disappear below this extinction phase in the Maastrichtian. Based on the magnetostratigraphy and the paleomagnetic time scale of Berggren et al. [1985] this extinction episode began about 310,000 years before the K/T boundary [Table 8].

The second phase of species extinctions occurs near the P0/P1a zonal boundary, or about 50,000



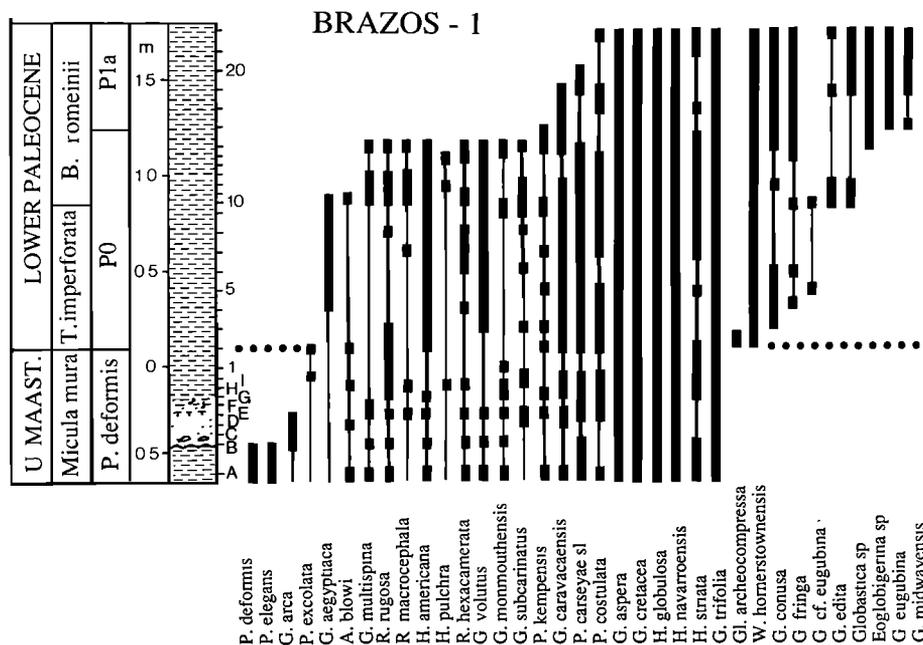


Fig. 4. Species ranges of planktonic foraminifera at the Brazos 1 section. Thick lines mark the actual occurrence of species in the section. The dotted line marks the K/T boundary and Ir anomaly. Nannofossil stratigraphy is from Jiang and Gartner, [1986].

Fig. 3. (Opposite) (1) *Guembelitra cretacea* (Cushman), Brazos Core sample 264, magnification X500, Early Danian Subzone P1a. (2) *Guembelitra cretacea* surface structure illustrating characteristic pore volcanoes, Brazos Core sample 264, magnification X800, Early Danian Subzone P1a. (3)-(4) *Guembelitra trifolia*, Brazos Core sample 288, magnification X500, Early Danian Subzone P1b, showing the Figure 7 view of initial short spire and surface pore-volcanoes. (5) *Woodringina hornerstownensis* Olsson, Brazos Core sample 262, magnification X450, Early Danian Subzone P1a. (6) *Woodringina hornerstownensis* surface structure showing pore volcanoes, Brazos Core sample 262, magnification X6500, Early Danian Subzone P1a. (7)-(8) *Globastica daubjergensis* (Bronnimann), Brazos Core sample 288, magnification X500, Early Danian Subzone P1b. (9) *Globoconusa conusa* Chalilov, Brazos Core sample 264, magnification X700, Early Danian Subzone P1a. (10) *Globoconusa conusa* surface structure showing pore volcanoes, Brazos Core sample 264, magnification X8000, Early Danian Subzone P1a. (11) *Globoconusa conusa* Chalilov, Brazos Core sample 264, magnification X700, Early Danian Subzone P1a.

years after the K/T boundary. In the cored section about 10 cm is missing at this interval, and the species extinctions may be more spread out as suggested by the CM section (Figure 5). Nine species disappear at this level in both the Core and CM sections and seven of these species also disappear at this level in Brazos 1 (*Globigerinelloides multispina*, *Rugoglobigerina rugosa*, *R. hexacamerata*, *Heterohelix striata*, *H. pulchra*, *H. americana*, *Pseudoguembelina excolata*, *P. costulata*, and *P. kempensis*). Because many of these species have similar last occurrences in all three Brazos sections examined as well as in the El Kef section, they are considered to be in situ and not reworked [Keller, 1989].

After this extinction episode the remaining seven Cretaceous survivors die out gradually through Zone P1a and into the lower part of Zone P1b, or between about 100,000 and 250,000 years after the K/T boundary (Figures 5 and 8). The species extinct during this interval are *Globigerinelloides volutus*, *G. aspera*, *G. caravacaensis*, *G. subcarinatus*, *Planoglobulina carseyae* s.l., *Heterohelix globulosa*, and *H. navarroensis* (Figure 2).

The most important and surprising information from this data set is (1) the accelerated species



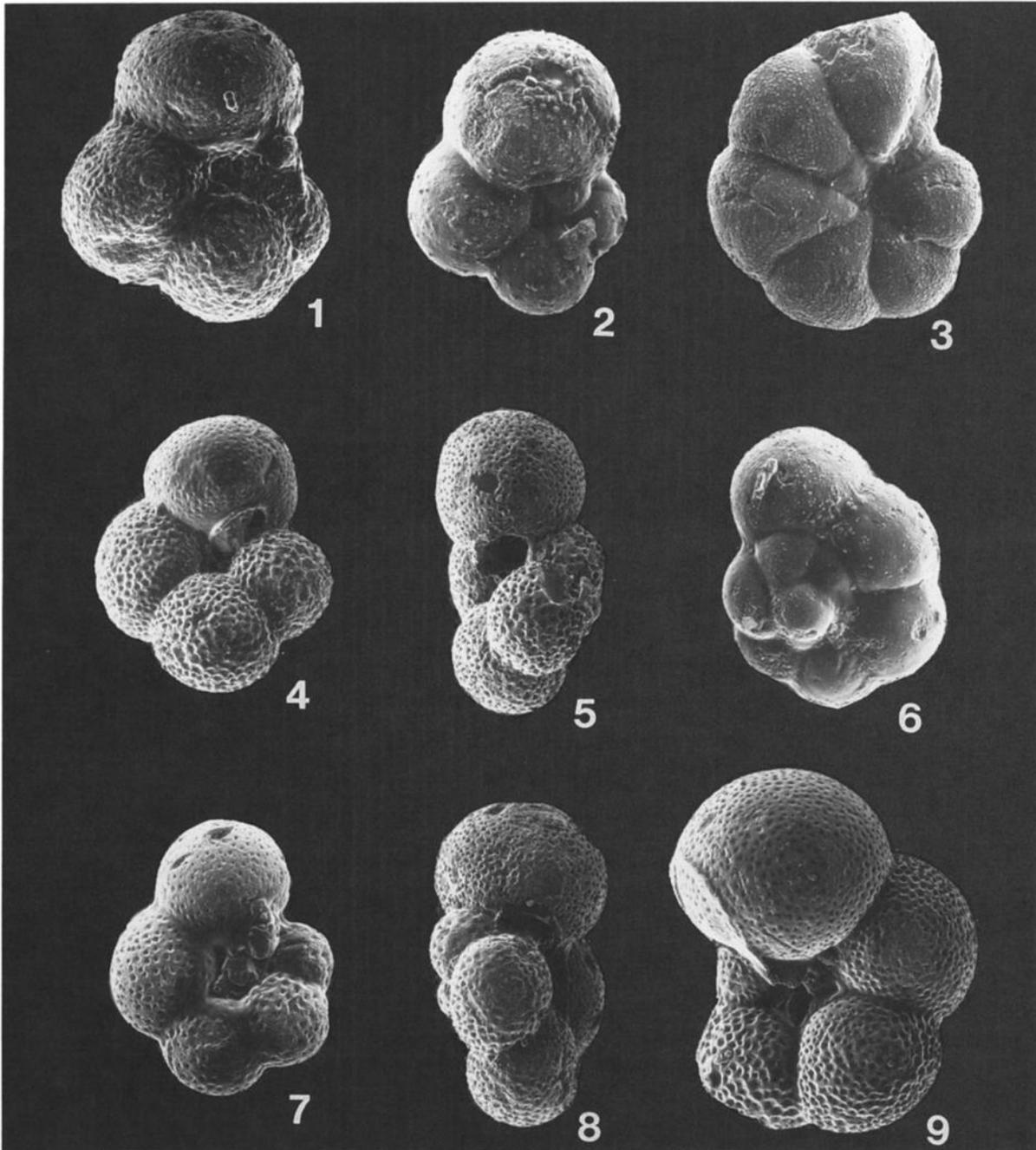


Fig. 6. (1) *Globigerina (Eoglobigerina) fringa* Subbotina, Brazos Core sample 287, magnification X500, Early Danian Subzone P1b. (2) *Eoglobigerina eobulloides* Blow, Brazos CM sample 18, magnification X500, Early Danian Subzone P1b. (3) *Globigerina eugubina* Luterbacher and Premoli Silva (the same as *Globorotalia longiapertura* Blow), Brazos CM sample 13, magnification X550, Early Danian Subzone P1b. (4)-(5) *Globigerina moskvini* Shutskaya, Brazos CM sample 18, magnification X270, Early Danian Subzone P1b. (6) *Globigerina eugubina* Luterbacher and Premoli Silva (the same as *Globorotalia longiapertura* Blow), Brazos CM sample 13, magnification X550, Early Danian Subzone P1b. (7) *Globigerina (Eoglobigerina) pentagona* Morozova, Brazos CM sample 18, magnification X350, Early Danian Subzone P1b. (8)-(9) *Globorotalia pseudobulloides* (Plummer), Brazos CM sample 18, magnification X270, Early Danian Subzone P1b.

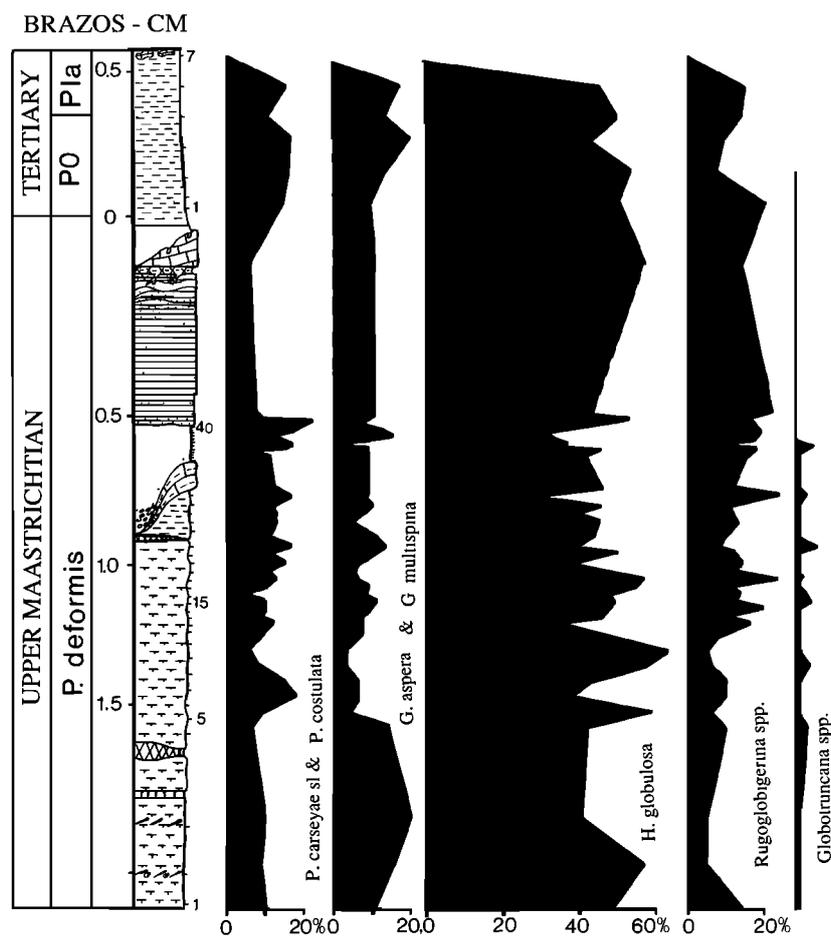


Fig. 7. Dominant planktonic foraminiferal species during the uppermost Maastrichtian and lowermost Paleocene of the Brazos CM section (size fraction >150  $\mu\text{m}$ ).

extinction phase beginning in the Late Maastrichtian about 310,000 years before the K/T boundary and ending sometime within the eroded interval and/or the tsunami bed deposit, (2) the near absence of species extinctions coinciding with the microfossil-defined K/T boundary and upper Ir peak, (3) the accelerated post-K/T species extinction phase at the Zone P0/P1a boundary about 50,000 years above the K/T boundary, and [4] the gradual extinction of the surviving Cretaceous species in the Early Danian. We shall now examine the magnitude of these events on the basis of abundance changes of dominant species relative to the total planktonic foraminiferal population.

#### DOMINANT SPECIES POPULATIONS

Relative abundance changes of dominant species in response to environmental changes yield clues to

paleoecological stresses associated before, during, and after the K/T boundary event. In Figures 10–13 relative population abundances of dominant species are illustrated for each of the three Brazos River sections, and data are given in Tables 2–7. Significantly, each section shows nearly identical planktonic foraminiferal populations in the size fraction >63  $\mu$  which indicates a uniform regional paleoecological environment. Moreover, the same group of species is dominant in the El Kef section of Tunisia, although individual species abundances vary [Keller, 1988a]. This strongly argues against accidental reworking in the Brazos River sections. Nevertheless, the unique absence of a faunal turnover across the K/T boundary in the Brazos sections is assumed to represent ecological conditions prevalent in the marginal Gulf of Mexico and appears not to be representative of shallow continental shelf regions elsewhere.

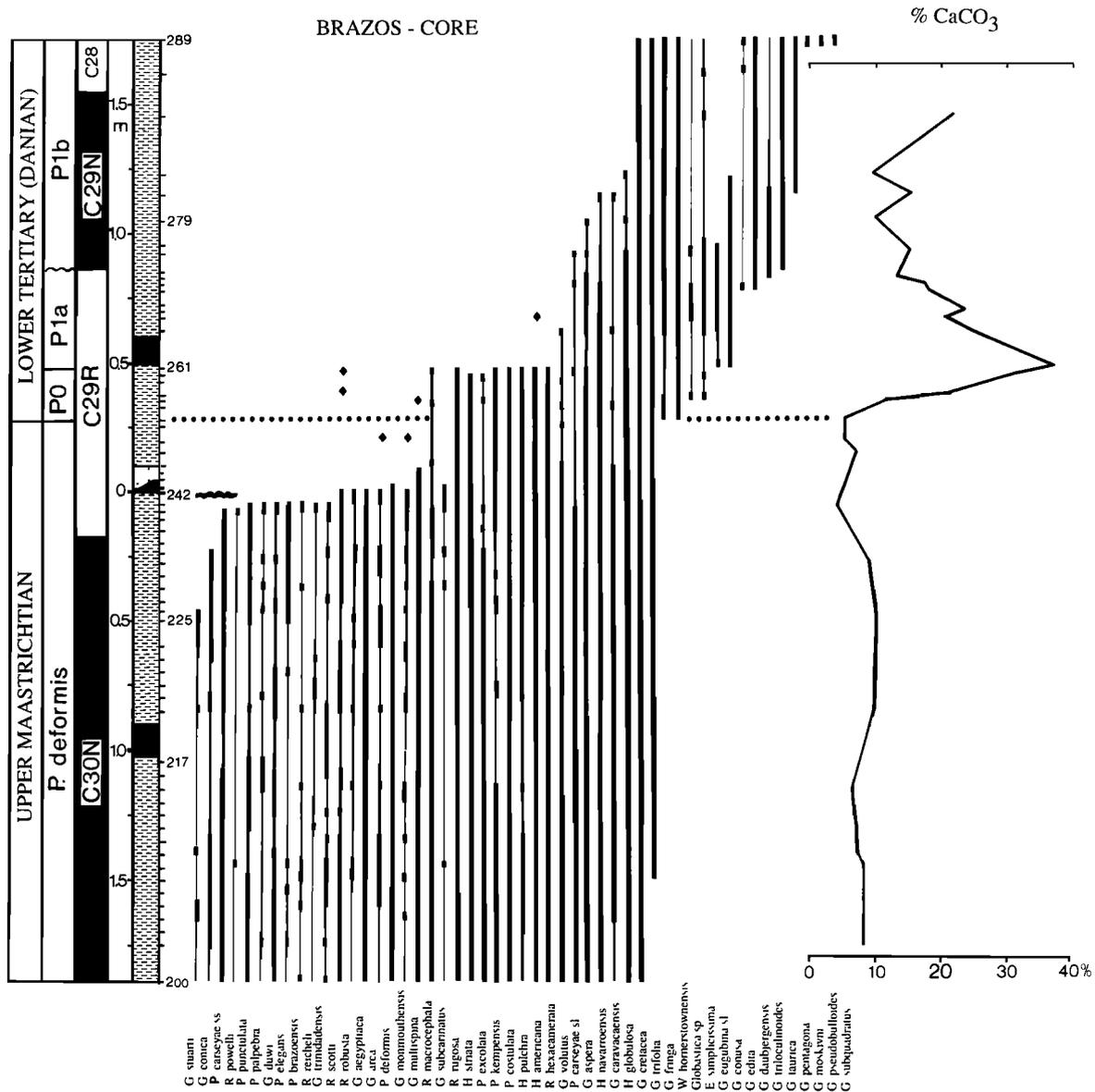


Fig. 8. Species ranges of planktonic foraminifera and percent CaCO<sub>3</sub> analysis of the uppermost Maastrichtian and lowermost Paleocene of the Brazos Core. Paleomagnetic data are from W. Gose (written communication, 1987). Percent CaCO<sub>3</sub> data are in Table 1. The sandstone-siltstone complex at 0 m is marked by a short hiatus. Black intervals in the core indicate missing section. Thick lines mark the actual occurrence of species in the section. The dotted line marks the K/T boundary.

**Maastrichtian**

Dominant species populations during the Late Maastrichtian are illustrated in Figure 10. Two observations are immediately obvious, namely the

relative stability of the dominant fauna, suggesting a highly stable Late Maastrichtian environment, and the fact that only relatively primitive small species thrive. The more characteristic large Late Cretaceous species such as globotruncanids, globotruncanellids,

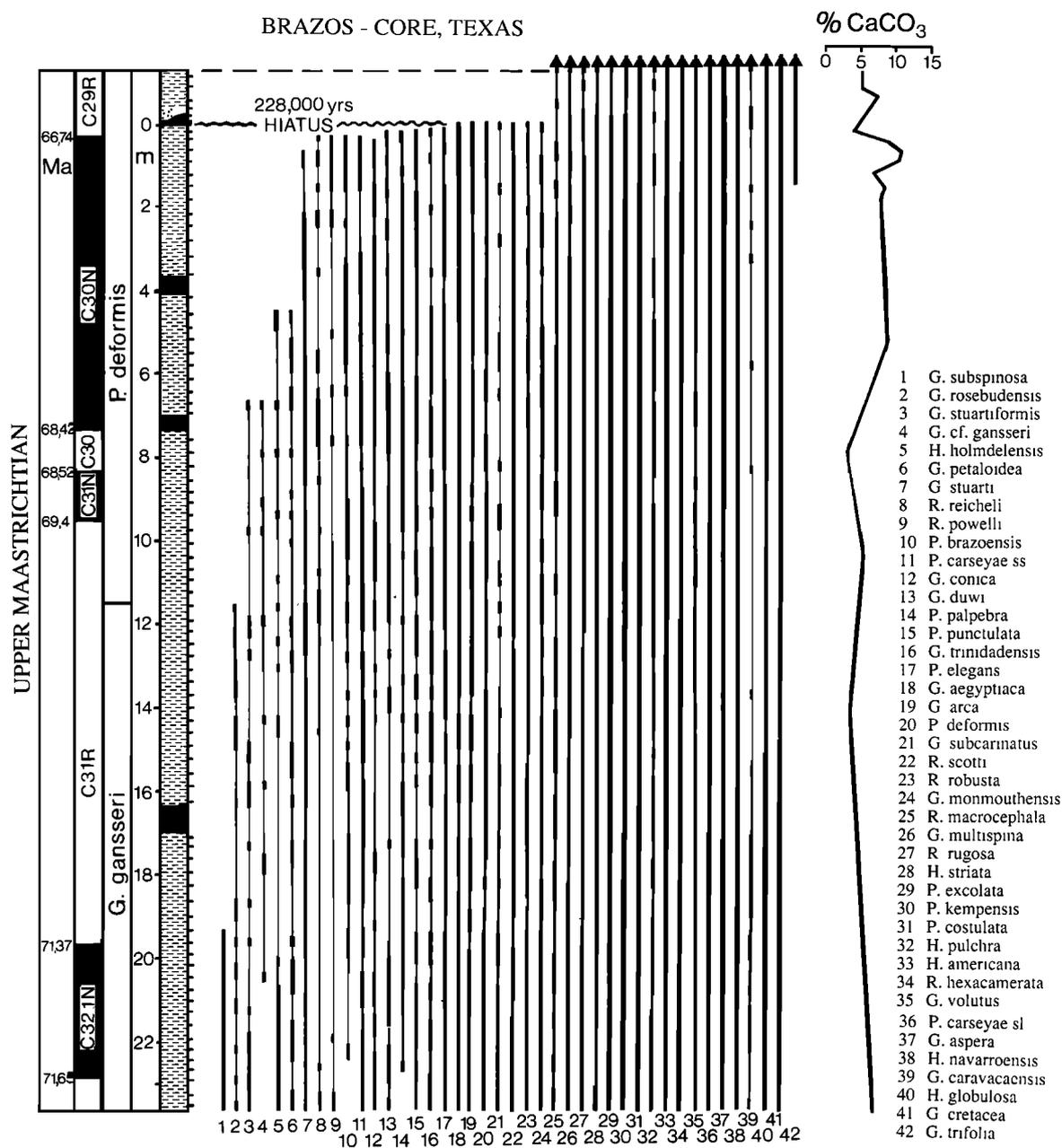


Fig. 9. Species ranges of planktonic foraminifera and percent CaCO<sub>3</sub> analysis of the Upper Maastrichtian of the Brazos Core. For a complete caption see Figure 8.

racemiguembelinids, and planoglobulinids are rare (Tables 2, and 7; Figures 7 and 10). The same observations have been made for El Kef faunas [Keller, 1988a]. Two species dominate: *Heterohelix globulosa* and *Guembelitra cretacea* (Figure 3). *Heterohelix* averages about 35% during the *G. gansseri* Zone and about 50% during the *P. deformis*

Zone (Figure 9). *Guembelitra cretacea* is more variable averaging 10% in the lower parts of both *G. gansseri* and *P. deformis* Zones but averaging 20% during the remainder of these zones. The environmental implications of these fluctuations are not yet clear and await results of stable isotope analysis. Six other species range in abundance

TABLE 8. Sediment Accumulation Rates and Ages of Extinction Episodes Across the K/T Boundary Based on the Paleomagnetic Time Scale of Berggren et al [1985]

	Age, Ma	Duration, years	Sedimentary Rates, cm/10 <sup>3</sup> years
Anomaly C29N	65.50-66.17	670,000	0.09
Anomaly C29R	66.17-66.74	570,000	see below
Anomaly C30N	66.74-68.42	1,680,000	0.41
K/T boundary	66.40		
K/T to base C29R	66.40-66.74	340,000	0.41
Zone P0	66.40-66.35	50,000	0.40
Subzone P1a	66.17-66.35	180,000	0.40
Hiatus P1a		80,000	32 cm missing
Hiatus tsunami bed		295,000	118 cm missing
Extinction phase I	66.71	20,000+	
Extinction phase II	66.35	25,000	

between 5 and 20%, four are small biserial species [*Pseudoguembelina costulata*, *P. excolata*, *Heterohelix navarroensis*, and *Planoglobulina carseyae* s.l., a small possibly juvenile form without supplemental apertures] and two are Globigerinelloides [*Globigerinelloides aspera* and *G. multispina*]. None of these species show significant abundance fluctuations (Figure 10). These species abundance data together with the data on species ranges (Figure 9) indicate a stable Late Maastrichtian with only minor environmental fluctuations until the Latest Maastrichtian, when a period of rapid species extinctions begins.

#### K/T Boundary Transition

Figures 11 and 12 illustrate relative abundances of dominant species (size fraction >63  $\mu\text{m}$ ) from 2 m below the K/T boundary to 1.8 m above the boundary in the Brazos Core and Brazos CM sections. In addition, species abundances are shown for Brazos 1 across the tsunami bed and through the lower 1.8 m of the Tertiary (Figure 13). All three sections show nearly identical faunal changes and therefore strongly indicate an in situ fauna.

The most significant and surprising result of this data set is the total absence of a catastrophic effect on the dominant planktonic foraminiferal population either at the time of deposition of the tsunami bed or at the K/T boundary. The dominant species of the Late Maastrichtian continue essentially undisturbed through most of the earliest Tertiary Zone P0, or for about 30,000-40,000 years after the K/T boundary. Thereafter, the dominant species decline sharply, and all but one become extinct in Zone P1a, or about 100,000-230,000 years after the K/T boundary. The one surviving species, *Guembelitra cretacea*, is being replaced by its short spired morphotype *G. trifolia* and gives rise to several new Tertiary species (e.g., *Woodringina hornerstownensis*, *Globoconusa*

*conusa*, and *Globastica* sp.). The niches vacated by the disappearing Cretaceous survivors are rapidly filled by new evolving species, especially *W. hornerstownensis*, *G. conusa*, and *G. daubiensis*.

The population changes illustrated by these Brazos River sections show a noncatastrophic replacement of the surviving and dominant Cretaceous fauna between about 50,000 and 230,000 years after the K/T boundary. The high-resolution record of the Brazos Core also shows some low-amplitude abundance fluctuations at the K/T boundary and just below the tsunami bed (Figure 11). These may be related to temperature, salinity and productivity fluctuations.

The major faunal change at the P0/P1a boundary may be related to the global drop in marine productivity beginning at the K/T boundary as noted in many marine sequences [Zachos and Arthur, 1986; Keller and Lindinger, 1989]. Detailed stable isotope analysis of *Heterohelix globulosa* and *Lenticulina* sp. from the Brazos Core shows a gradual ‰ change in carbon-13 beginning at the K/T boundary [sample 253] and culminating at the P0/P1a boundary (sample 261) (E. Barrera and G. Keller, unpublished manuscript, 1989). A carbon-13 shift in the earliest Paleocene was also observed in bulk sediments of the Bragg section of Alabama [Jones et al., 1986] where it was interpreted as a diagenetic signal. Our monospecific foraminiferal samples from the Brazos Core, however, do not show significant recrystallization which suggests that this signal is not due to diagenesis and represents a change in environmental conditions.

Relative abundance changes of dominant species thus indicate only one major faunal change beginning well after the K/T boundary and declining gradually into the Early Tertiary. This gradual population change is associated with a major but also gradual change in carbon-13 isotopic ratios (E. Barrera and G. Keller, unpublished manuscript, 1989). This

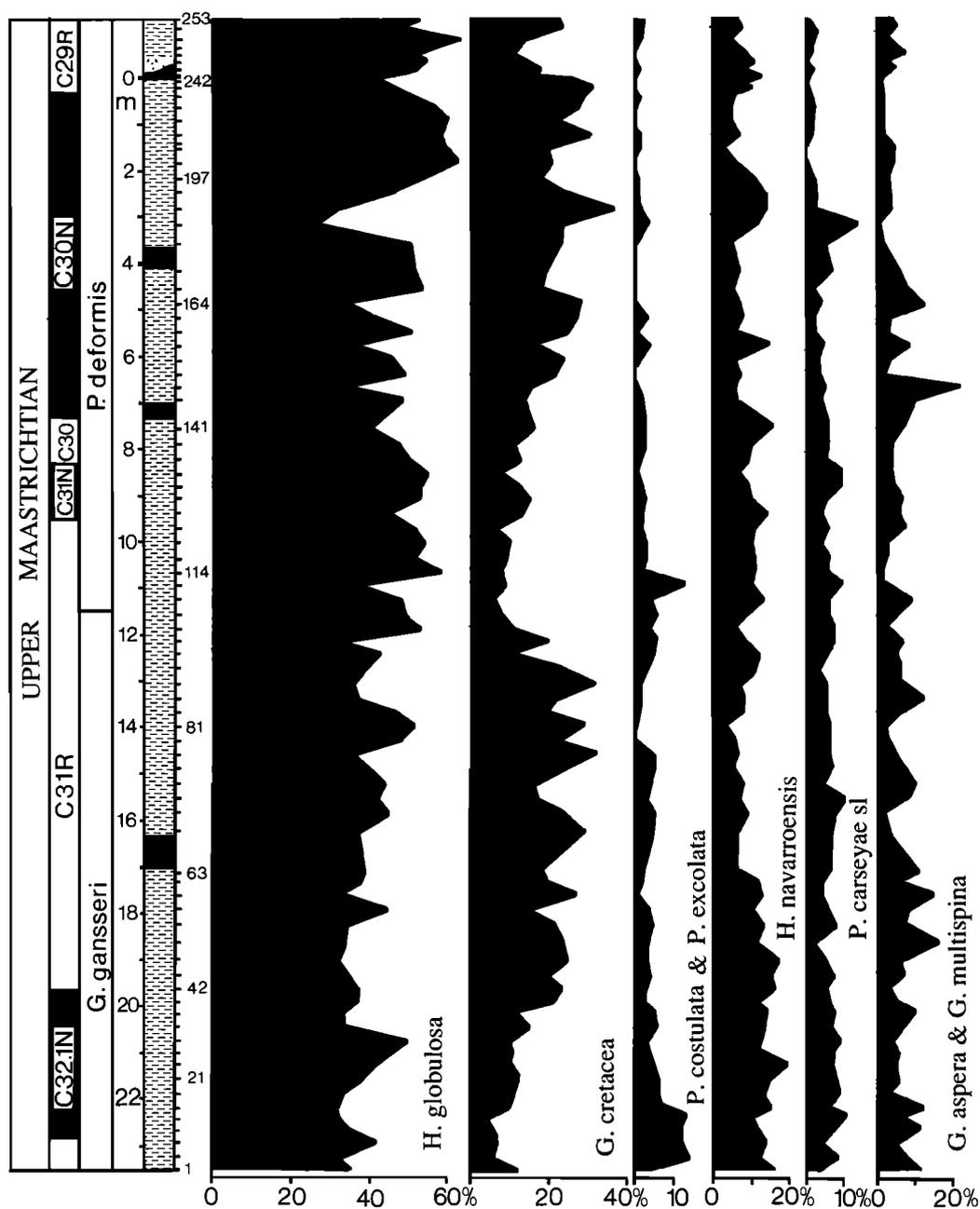


Fig. 10. Dominant planktonic foraminiferal species during the Upper Maastrichtian in the Brazos Core (size fraction >63  $\mu$ m). For a complete caption see Figure 5.

implies that the pre-K/T boundary extinction phase affected largely less dominant species which may have been intolerant of relatively minor environmental fluctuations, whereas the major post-K/T boundary faunal change appears to be related to a major environmental perturbation resulting in a global decrease in marine productivity.

#### DISCUSSION AND CONCLUSIONS

What caused the observed differences between species extinction phases and population changes of dominant species? Brazos River data indicate that species going extinct are generally represented by few individuals and constitute only a small

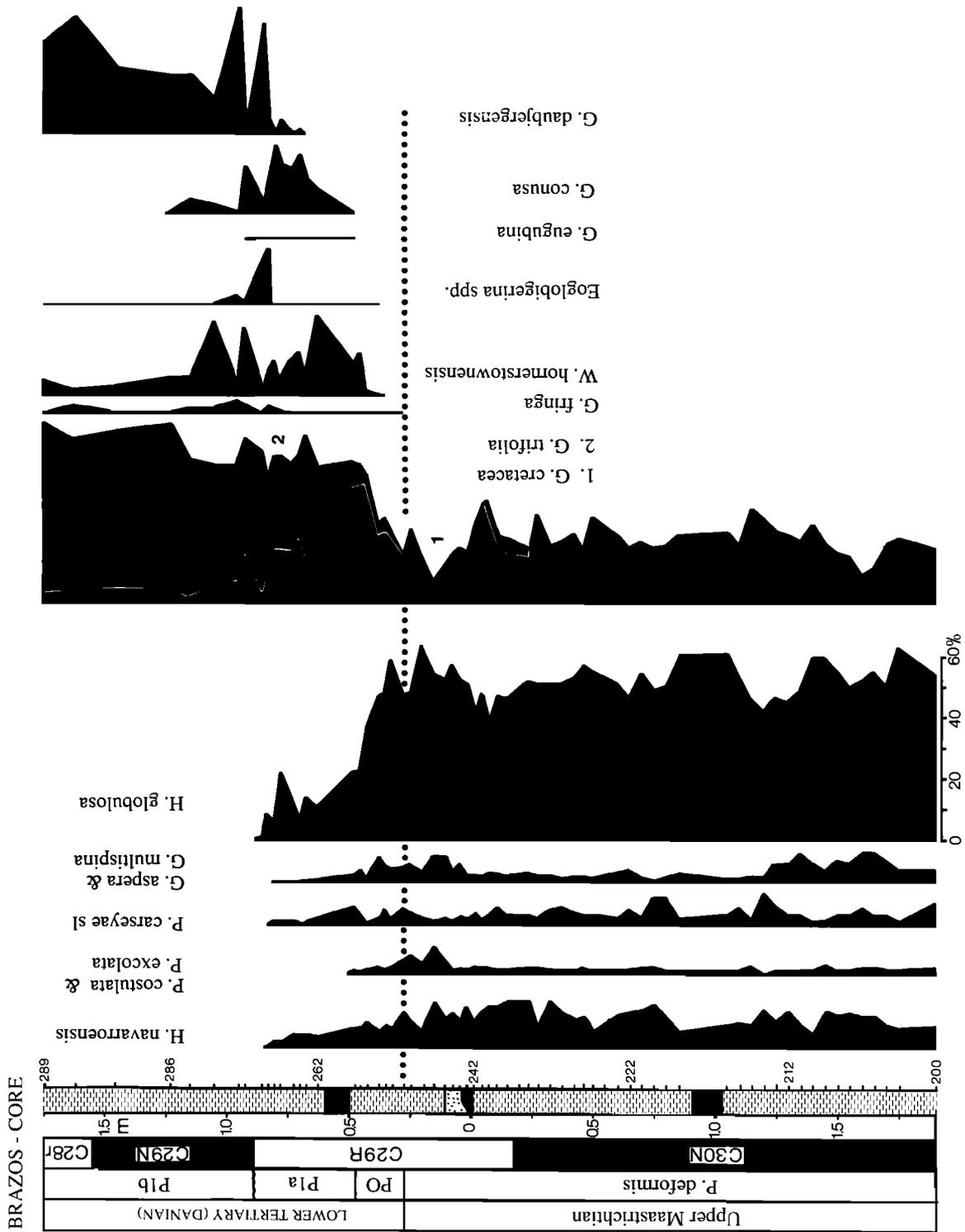


Fig. 11. Dominant planktonic foraminiferal species during the uppermost Maastrichtian and lowermost Paleocene in the Brazos Core (size fraction >63 µm). See Figure 8 for a complete caption.

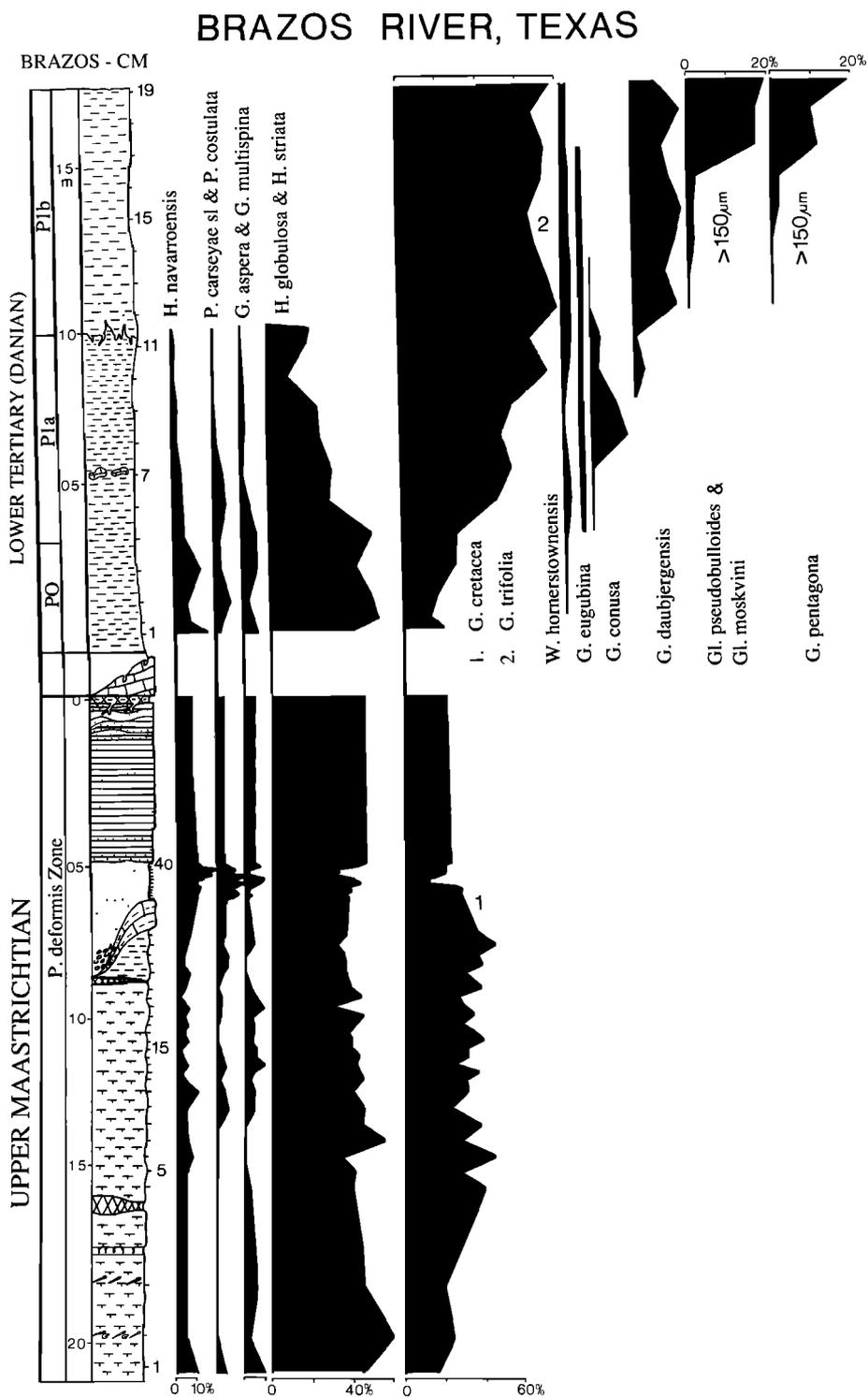


Fig. 12. Dominant planktonic foraminiferal species during the uppermost Maastrichtian and Lowermost Paleocene of the Brazos CM section (size fraction >63 μm). The offset at the K/T boundary illustrates the fact that the section was collected in two nearby sequences.

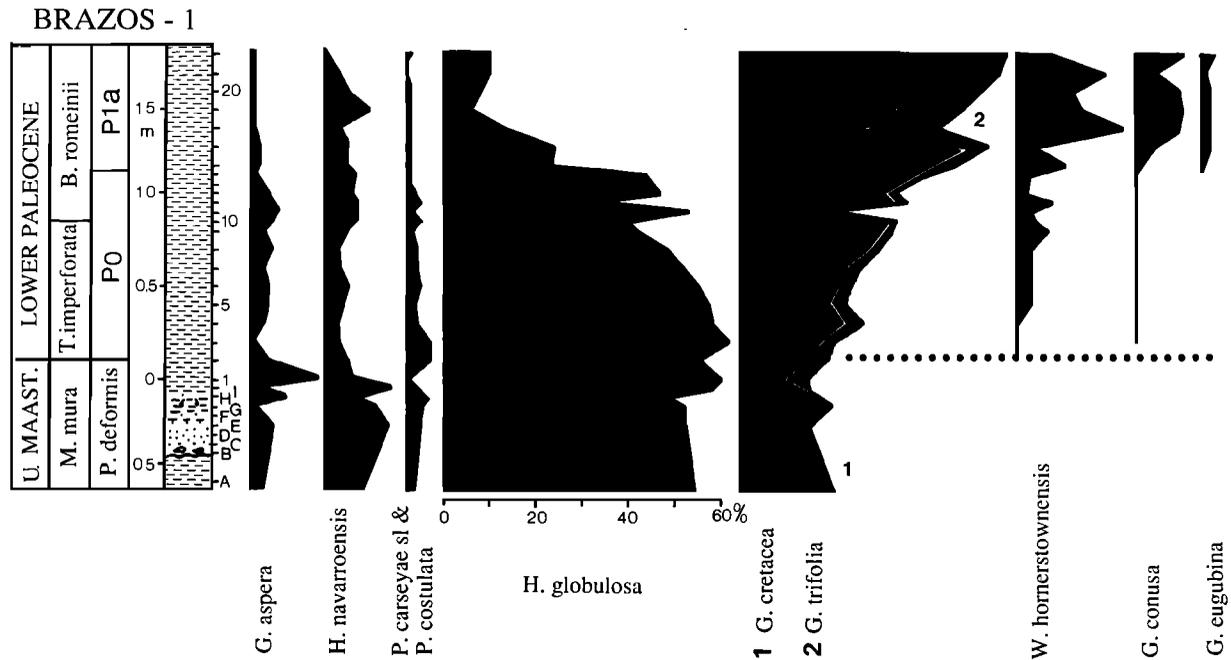


Fig. 13. Dominant planktonic foraminiferal species during the uppermost Maastrichtian and lowermost Paleocene of the Brazos 1 section. The dotted line marks the K/T boundary and Ir anomaly.

percentage of the total population (see globotruncanids in Figure 7). Such numerically weakened species are more sensitive to small environmental changes in temperature, salinity, thermal stratification, and surface productivity. In the Brazos Core section the relative abundance of each of the outgoing species (15 species, Figure 8) at the extinction episode below the K/T boundary is less than 1% (Table 7), or a total of less than 8% of the individuals of the total population extinct. Yet 47% (15 species) of the species disappear, resulting in a highly reduced species diversity. Similarly, at El Kef 30% [13 species] of the species disappear below the K/T boundary with individuals constituting less than 6% of the total population [Keller, 1988a, 1989]. The species disappearing are primarily tropical to subtropical, complex, large, and highly ornamented [e.g., *Racemiguembelina*, *Planoglobulina*, and *Globotruncana*]. Oxygen isotopic ranking indicates that these species lived in deeper waters [Boersma and Shackleton, 1981; G. Keller and H.R. Thierstein, unpublished data, 1987]. Their disappearance in shallow-water sections may largely be due to migration seaward during a sea level regression.

Extinctions above the K/T boundary affect 45% of the species, but less than 5% of the individuals in the population disappear. The species affected are primarily surface water dwellers (*Rugoglobigerina*, *Pseudoguembelina*, and *Heterohelix*), indicating that changes in the surface water environment are largely

responsible for this extinction phase. Each extinction episode therefore affects only a relatively small percentage of the individuals in the total population, although species diversity is significantly reduced.

Of the remaining seven Cretaceous survivors, six die out gradually and one species gives rise to several new Tertiary species. Importantly, there is a gradual decline in the relative abundance of the dominant Cretaceous survivors beginning well after the K/T boundary. A similar decline in carbon-13 stable isotopic ratios suggests a major change in marine productivity at this time. All seven Cretaceous survivors are largely temperate to subtropical surface water dwellers [Boersma and Shackleton, 1981; G. Keller and H.R. Thierstein, unpublished data, 1987] which dominated throughout the Late Maastrichtian. Without exception they are small robust species with simple morphologies, little or no surface ornamentation and capable of surviving a wide range of environmental changes. Their ultimate demise appears largely due to a major change in marine productivity and to niche competition of newly evolving Tertiary species of similar primitive morphology.

Dominant nannofossil species across the K/T boundary show an abundance distribution similar to planktonic foraminifera with a gradual decline in the Early Danian in both Brazos River and El Kef sections [Perch-Nielsen, 1979a, b; Perch-Nielsen et al., 1982; Jiang and Gartner, 1986]. This pattern is interpreted by Perch-Nielsen et al., [1982] as

evidence of noncatastrophic extinctions and by Jiang and Gartner [1986] as catastrophic extinctions with massive reworking of Cretaceous sediment into Lower Paleocene deposits. Macrofossil species begin to disappear well below the K/T boundary. Jones et al. [1986] report 42% of the molluscan species extinct within the uppermost 1 m of the Cretaceous, or about 300,000 years below the K/T boundary at a facies change at Braggs, Alabama. The same pattern was observed in the Brazos River sections by Hansen et al. [1984, 1987], who suggested that the absence of catastrophic macrofossil extinctions associated with the K/T boundary was due in part to local environmental stresses and reworking. Thus, neither macrofossils, nannofossils nor planktonic foraminiferal groups show evidence of a catastrophic and instantaneous destruction as hypothesized as a result of a large extraterrestrial impact [Alvarez et al., 1980].

The observed patterns of species extinctions in the Brazos River sections are complex and cannot be explained by a single large K/T boundary impact. Similarly complex and difficult to explain are the multiple Ir spikes observed in the Brazos River sections by Ganapathy et al. [1981] and Asaro et al. [1982]. Because the postdepositional behavior of Ir is not well understood, we cannot assume that the present stratigraphic horizons containing the Ir anomalies necessarily represent the original time of deposition. With these uncertainties several alternative interpretations are possible based on either the faunal, sedimentary, or geochemical records.

A recent hypothesis favored by Bourgeois et al. [1988] places the K/T boundary at the top of the sandstone-siltstone complex which they regard to have been deposited by a giant tsunami wave generated by an extraterrestrial impact. The sediment strata between the top of the tsunami deposit and the micropaleontologically defined K/T boundary are interpreted as settling from the water column after a giant tsunami wave. The Ir spike at the top of the tsunami bed appears to support the tsunami wave hypothesis. What is difficult to explain by this hypothesis, however, is the absence of grain size grading in the strata above the tsunami deposit, the absence within these strata of Maastrichtian species which are present at the erosion surface at the base of the tsunami bed, and the continuation of abundant small Cretaceous species 1 m to 1.5 m above this interval. The impact-generated tsunami hypothesis does not attempt to explain the post-K/T extinction phase.

Another alternative scenario invokes a series of closely spaced impacts to explain the observed faunal, geochemical, and lithological changes. There are insufficient data at present to support this scenario.

A scenario of successive environmental changes is supported by the planktonic foraminiferal data of this report. Species extinction data suggest that

environmental changes prior to the tsunami bed event may have caused the disappearance of 27%, or nine species, from the Brazos River area. An additional 18%, or six species, disappear at the hiatus at the base of the tsunami bed. Their disappearance may be directly related to the tsunami event, or they may have gradually disappeared during the 295,000-year interval that was subsequently eroded at this hiatus. The interpretation favored by the author is environmental changes resulting in ecologic exclusion of less tolerant species and survival of the more tolerant cosmopolitan species by K/T boundary time. This would imply that more stressful conditions prevailed in the latest Maastrichtian in the Gulf coastal plane shelf seas than in the marginal Tethys shelf where 1/3 of the less tolerant species survived up to K/T boundary time [Keller, 1988a, 1989]. A possible explanation for this difference is seaward migration of species during a Late Maastrichtian sea level regression as discussed earlier. The second extinction phase [46% of species] about 50,000 years after the K/T boundary and the subsequent gradual extinction of the remaining Cretaceous survivors are interpreted primarily as a result of global marine productivity changes as indicated by stable isotope data from the Brazos Core (E. Barrera and G. Keller, unpublished manuscript, 1989) and deep-sea sections [Zachos and Arthur, 1986; Keller and Lindinger, 1989]. This interpretation does not exclude the possibility of one or more extraterrestrial impacts, but it suggests that they not necessarily triggered but perhaps merely accelerated some of the environmental changes leading to the demise of the Cretaceous fauna.

Acknowledgments. I would like to thank E. Kauffman, T. Hansen, S. Gartner, J. Zachos, G. Baum, and K. Perch-Nielsen for their comments and many helpful discussions. Special thanks are due to E. Kauffman and T. Hansen, who generously provided the samples for this study, and to T. Hansen who also provided laboratory assistance through NSF grant 84112020. I also thank W. Gose for permission to use unpublished paleomagnetic data from the Brazos Core. Carbonate analysis was done by C. Perry and M. Carpenter as part of their junior thesis work at Princeton University. This study was supported in part by National Geographic grant 3667-87 and NSF grant OCE-8811732.

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(Received September 27, 1988;  
revised January 16, 1989;  
accepted January 18, 1989.)