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Age, Deposition and Biotic Effects of the Cretaceous/Tertiary Boundary Event at Mimbral, NE Mexico

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The Mimbral outcrop in northeastern Mexico represents nearly continuous sedimentation across the Cretaceous/Tertiary (K/T) transition. The K/T boundary is present in a 4 cm clay layer and 3 mm red layer above the top of a channel-fill deposit. The 60 m wide and 3 m high channel-fill deposit is of latest Maastrichtian age (A. mayarensis Zone). It consists of faunally, lithologically and mineralogically distinct units that appear to represent a series of gravity flows related to the latest Maastrichtian sea-level lowstand.

The biotic effects of the K/T boundary event were not catastrophic for planktic foraminiferal faunas at Mimbral, NE Mexico. Although 2/3 of the species disappeared at or below the K/T boundary, the effect on the overall foraminiferal population was small (<17%) because only rare, already endangered taxa disappeared. These taxa were specialized tropical and subtropical forms intolerant of environmental changes. The dominant taxa (>83%) consist of cosmopolitan forms tolerant of wide ranging environmental conditions. These survived the K/T boundary event without any sudden changes in their relative abundance. Their terminal decline about 100,000 years after the K/T boundary appears to be related to competition from the evolving Tertiary fauna. The limited biotic effects observed across the K/T boundary at Mimbral are consistent with other low latitude sections, and indicate that if a bolide impact occurred in the Caribbean, the biologic consequences were not as catastrophic as generally assumed even within a radius of 2000 miles.

INTRODUCTION

Recent discoveries of unusual clastic and glass bearing deposits at the K/T boundary in Haiti (Izett et al., 1990; Sigurdsson et al., 1991; Jéhanno et al., 1992) and Mimbral

in northeastern Mexico (Smit et al., 1992), and the interpretation of a circular 180 km-in-diameter buried structure on Yucatan as the elusive K/T boundary impact crater (Hildebrand et al., 1991; Pope et al., 1991), have focused the debate over the nature and origin of the K/T boundary event on the Caribbean region. At the center of the debate is the search for the impact crater, the impact generated megawave deposits, and the effects such a catastrophe may have had on life on earth.

Investigation of numerous K/T boundary sequences worldwide has generally revealed a boundary clay, frequently with a thin oxidized red layer that contains maximum Ir values (Schmitz, 1988) and Ni-rich spinels (Jéhanno et al., 1992). But, there has been no evidence of breccia deposits that could be attributed to an impact generated tsunami or megawave. Such deposits, however, have been claimed to be present in the Caribbean (Hildebrand and Boynton, 1990; Alvarez et al., 1992), Brazos, Texas (Bourgeois et al., 1988) and Mimbral, northeastern Mexico (Smit et al., 1992). The age and nature of these "megawave" deposits, however, are in dispute (Keller, 1989; Iturralde-Vincent, 1992; Jéhanno et al., 1992; Lyons and Officer, 1992; Stinnesbeck et al., in press; Keller et al., 1993a). If an impact occurred in the Caribbean region, not only would one expect to find megawave deposits, but the biotic effects would have been more severe near the impact location and diminish with increasing distance from the source area. Quantitative investigations of planktic foraminifers globally indicate that the biotic effects were most severe in tropical and subtropical regions, diminished into middle latitudes and became negligible at high latitudes (Keller, 1993; Keller et al., 1993b). The carbon isotopic record parallels the faunal record showing a dramatic reduction in surface productivity in low to middle latitudes (Zachos et al., 1989; Keller and Lindinger, 1989), but stable or slightly increasing surface productivity in high latitudes (Barrera and Keller, in prep., Keller et al., 1993b). To date no quantitative faunal data are available from Caribbean K/T boundary sections to test this scenario. The Mimbral section located on the southwestern flank of the Sierra de

Tamaulipas in northeastern Mexico provides the first opportunity for investigation of a relatively continuous K/T boundary transition near the hypothesized impact location.

We have collected and analyzed three transects across the K/T boundary and clastic deposits at the Mimbral outcrop (Fig. 1). Our study focused on three main objectives: (1) Determine the stratigraphic completeness of the Mimbral section, (2) examine the nature and depositional environment of the clastic deposit, and (3) evaluate the biotic effects of the K/T boundary event on planktic foraminifers. The sedimentologic, mineralogic and petrologic aspects of the Mimbral clastic deposits have been discussed in Stinnesbeck et al. (1993) and are briefly summarized below.

MIMBRAL OUTCROP

The Mimbral section is located on the south bank of the Mimbral creek approximately 10 km east of the main road from Ciudad Victoria to Tampico (lat. 23°13' N, long. 98°40' W). The outcrop is 152 m long and of variable height (1 m to 36 m). Most of the outcrop (30 m) exposes the Upper Cretaceous Mendez Formation which consists of rhythmically bedded marls and limestones and occasional thin bentonite layers. A clastic deposit of variable thickness (0.2 to 3 m), apparently representing a channel-fill, extends for about 60 m along the outcrop. This deposit reaches 3 m height at 28 m along the outcrop and has three lithologically distinct units (Fig. 1). The basal unit 1 is characterized by a spherule-rich bed that contains a 20 cm thick sandy limestone with few spherules. The middle unit 2 consists of a massive laminated sandstone with mud-clasts and discrete layers of plant debris near its base. The upper unit 3 consists of alternating sand, silt and shale layers topped by a rippled sandy limestone. The top of this sandy limestone layer is marked by numerous burrows all of which are infilled with sand, rather than the overlying clay layer, indicating a period of non-deposition between the Cretaceous sandy limestone layer and the Tertiary clay sediments. Disconformities, erosion, and rip-up clasts of the Mendez Formation mark the contacts between the Mendez marls and unit 1, between units 1 and 2, and between units 2 and 3 (Fig. 1).

Outside the channel, only the topmost 25 cm of the channel-fill deposit is present (rippled sandy limestone) and the most continuous K/T transition is found at 150 m to 152 m along the outcrop (Fig. 1). At this location the K/T boundary is marked by a thin (4 cm) clay layer, containing a 3 mm thick red layer that overlies the rippled sandy limestone. The clay layer grades into 2.2 m of exposed gray shales and marls of the Lower Tertiary Velasco Formation. Thin ash (bentonite) layers are present about 30 cm below the top of the Mendez Formation and at 6–8 cm and 2.0 m above the base of the Velasco Formation (Fig. 1).

Smit et al. (1992) interpreted the Mimbral clastic deposit as an impact generated tsunami or megawave deposit based primarily on their reported occurrence of glass

spherules and abundant shocked quartz grains. A subsequent sedimentologic, mineralogic and petrologic investigation by Stinnesbeck et al. (1993), however, failed to confirm these observations. These authors concluded that the channel-fill deposit is unrelated to the K/T boundary event and represents a series of gravity flows alternating with normal sedimentation. They based their interpretation on (1) disconformities, (2) lithologically and mineralogically distinct units and subunits, (3) horizontal laminations, upward fining and ripple marks, (4) wood and leaves in discrete layers near the base of unit 2, (5) intervals of normal pelagic sedimentation, (6) bioturbation, (7) discrete layers with zeolites indicating volcanism, (8) multiple origins of spherules including volcanic, precipitational (oolites, oncolites) and organic, and (9) the presence of only very rare glass fragments, and shocked quartz grains and absence of Ni-rich spinels, and significant Ir concentration that would provide evidence for a bolide impact.

Sample Collection and Analysis

Three transects were sampled at Mimbral, one across the maximum height of the clastic deposit at 28 cm along the outcrop and two outside the channel-fill at 150 m and 152 m along the outcrop (Fig. 1). The outcrop at the 150 m mark was trenched and samples collected at 5 cm contiguous intervals for the 2.2 m exposed Tertiary Velasco Formation and 50 cm upper Cretaceous Mendez Formation. A second trench at 152 m revealed the same lithological sequence, but lacked any evidence of spherules. The outcrop at the 28 m mark was sampled at 2 cm intervals through the basal 25 cm of the Velasco Formation and at 20 cm intervals through the three units of the channel-fill. Unusual features of the clastic deposit, such as mud-clasts, trough-filling lenses and different lithologies were also sampled.

Samples are well-indurated and a strong detergent plus cooking for several hours was necessary to disaggregate the sediments. Samples were then washed through a 63 μm screen and dried in the oven. Nearly all samples contained abundant and diverse foraminiferal assemblages suitable for quantitative analysis. A random split of 300 individuals per sample in the size fraction $>63 \mu\text{m}$ was picked and identified for biostratigraphic analysis. The remaining sample was carefully searched for rare species. The data are tabulated in Table 1.

BIOSTRATIGRAPHY AND DEPOSITIONAL ENVIRONMENT

The planktic foraminiferal presence and relative abundances at Mimbral are illustrated in two outcrop transects across the channel-fill at 28 m (Fig. 2) and outside the channel at 150 m (Fig. 3) along the outcrop. These figures demonstrate the apparent disruption of normal sedimentation by sediment influx within the channel and the relatively continuous nature of normal pelagic sedimentation outside the channel.

TABLE 1a.—Relative percent abundance of planktic foraminifera in the Lower Tertiary Velasco Formation, at Arroyo El Mimbral, Mexico.

	Sample no.:	44	43	42	41	40	39	38	37	36
	Depth in cm above K/T:	0-1	1-4	4-9	9-15	15-20	20-25	25-30	30-35	35-40
<i>Globigerinelloides aspera</i>			*1	5.65	5.98	3.02	3.64	0.99	1.72	7.63
<i>Globigerinelloides multispinatus</i>										
<i>Globigerinelloides subcarinatus</i>				0.71	0.85					0.76
<i>Globigerinelloides yaucoensis</i>										
<i>Globotruncanella monmouthensis</i>				1.06	1.71	1.29	1.82			
<i>Globotruncanella caravacaensis</i>				0.71						
<i>Globotruncanella petaloidea</i>				5.65	2.56	1.72				
<i>Guembelitra cretacea</i>				10.95	13.68	3.88		1.97	2.59	3.05
<i>Guembelitra trifolia</i>				5.65	7.69				5.17	
<i>Globotruncana arca</i>				0.71		1.29				0.38
<i>Globotruncana aegyptiaca</i>						0.43				
<i>Globotruncana duwi</i>				0.35						
<i>Hedbergella holmdelensis</i>				1.41					0.86	0.76
<i>Hedbergella monmouthensis</i>				1.77	1.71	2.59	3.64	0.49	0.86	1.91
<i>Heterohelix complanata</i>		*1		3.18		0.43	1.82	0.99		2.67
<i>Heterohelix glabrans</i>				2.12			1.82			0.38
<i>Heterohelix globulosa</i>			*1	11.31	8.55	9.05	5.45	1.48		4.58
<i>Heterohelix navarroensis</i>				16.61	12.82	18.97	9.09	4.93	4.31	19.47
<i>Heterohelix planata</i>										
<i>Heterohelix pulchra</i>								0.99		
<i>Heterohelix striata</i>					0.85	1.29				
<i>Pseudoguembelina costulata</i>		*2		12.72	21.37	11.21	27.27	12.32	12.93	4.20
<i>Pseudoguembelina punctulata</i>						0.43				
<i>Pseudotextularia elegans</i>				1.06						
<i>Rugoglobigerina macrocephala</i>				0.35		1.72				
<i>Rugoglobigerina hexacamerata</i>				3.18	1.71	2.59				
<i>Rugoglobigerina rugosa</i>		*1				0.86				1.15
<i>Chiloguembelina crinita</i>										
<i>Chiloguembelina midwayensis</i>										
<i>Chiloguembelina morsei</i>										
<i>Chiloguembelina cf. waiparaensis</i>										
<i>Woodringina claytonensis</i>										
<i>Woodringina hornerstownensis</i>				1.41	2.56	3.45		3.45	5.17	4.20
<i>Eoglobigerina edita</i>				5.30	2.56	8.19		1.48	2.59	5.34
<i>Eoglobigerina fringa</i>				3.53	5.13	6.03		6.40	7.76	5.73
<i>Eoglobigerina simplicissima</i>										
<i>Eoglobigerina trivialis</i>										0.38
<i>Globanomalina pentagona</i>									1 cf	
<i>Globanomalina taurica</i>										
<i>Globanomalina tetragona</i>										
<i>Globoconusa conusa</i>				1.06				0.99	1.72	
<i>Globoconusa daubjergensis</i>					2.56	3.88	5.45	11.33	11.21	3.05
<i>Globastica</i> sp.										
<i>Parvularugoglobigerina eugubina</i>				1.06	4.27	2.16	9.09	4.93	1.72	3.44
<i>Parvularugoglobigerina longiapertura</i>				2.12	3.42	12.07	30.91	47.29	34.48	28.63
<i>Planorotalites compressus</i>									6.03	1.91
<i>Subbotina moskvini</i>										
<i>Subbotina pseudobulloides</i>										
<i>Subbotina triloculinoides</i>										
Juveniles no identification				0.35		1.29				0.38
Total number counted		4	2	283	117	232	55	203	116	262

* Asterisk indicates number of specimens.

TABLE 1a.—Continued.

	Sample no.:	35	34	33	32	30	28	26	24	22
Depth in cm above K/T:		40–45	45–50	50–55	55–60	65–70	75–80	85–90	94–100	105–110
<i>Globigerinelloides aspera</i>		2.87	1.76	1.20	0.27			0.44		0.72
<i>Globigerinelloides multispinatus</i>										
<i>Globigerinelloides rosebudensis</i>							0.80			
<i>Globigerinelloides subcarinatus</i>		0.41								
<i>Globigerinelloides yaucoensis</i>										
<i>Globotruncanella monmouthensis</i>										
<i>Globotruncanella caravacaensis</i>			0.59							
<i>Globotruncanella petaloidea</i>		1.23	2.35							
<i>Guembelitra cretacea</i>		2.46	1.76	3.01	3.01	1.74	0.80	0.44	0.46	0.72
<i>Guembelitra trifolia</i>										
<i>Globotruncana arca</i>		0.41		0.60						
<i>Globotruncana aegyptiaca</i>		0.82								
<i>Globotruncana duwi</i>										
<i>Hedbergella holmdelensis</i>		4.00		3.01	0.82					
<i>Hedbergella monmouthensis</i>			1.18	2.41						
<i>Heterohelix complanata</i>		2.87		1.20	0.82					
<i>Heterohelix glabrans</i>		0.82	1.18		0.55					
<i>Heterohelix globulosa</i>		6.56	5.29	1.20	1.64	0.87				0.36
<i>Heterohelix navarroensis</i>		13.11	20.59	5.42	3.01	4.35	2.40	3.95	2.74	1.45
<i>Heterohelix planata</i>										
<i>Heterohelix pulchra</i>										
<i>Heterohelix striata</i>								0.88	1.37	
<i>Pseudoguembelina costulata</i>		8.20	12.94	7.83	4.38	0.87	1.60	3.51	2.28	2.17
<i>Pseudoguembelina punctulata</i>					0.27					
<i>Pseudotextularia elegans</i>										
<i>Rugoglobigerina macrocephala</i>				0.60						
<i>Rugoglobigerina hexacamerata</i>										
<i>Rugoglobigerina rugosa</i>										
<i>Chiloguembelina crinita</i>								0.44	0.46	0.72
<i>Chiloguembelina midwayensis</i>			1.76	1.20	0.55			1.32	1.37	2.54
<i>Chiloguembelina morsei</i>						1.74		0.44	0.46	
<i>Chiloguembelina cf. waiparaensis</i>										
<i>Woodringina claytonensis</i>										
<i>Woodringina hornerstownensis</i>		10.25	2.94	3.61	3.84	8.70	2.40	2.63	4.57	1.45
<i>Eoglobigerina edita</i>		5.33	7.65	7.83	4.66	0.87		1.32	1.37	2.17
<i>Eoglobigerina fringa</i>		1.64	2.35	1.20	3.01	2.61	3.20	1.32	1.37	1.45
<i>Eoglobigerina simplicissima</i>			2.35	7.23	7.40		0.80	4.39	3.20	0.36
<i>Eoglobigerina trivialis</i>										
<i>Globanomalina pentagona</i>		1.64	1.18		2.47	6.09	10.40	9.21	13.24	7.25
<i>Globanomalina taurica</i>					4.38	1.74	6.40	10.09	12.33	5.07
<i>Globanomalina tetragona</i>					1 cf.	0.87	0.80			
<i>Globoconusa conusa</i>				3.01	1.64	1.74				
<i>Globoconusa daubjergensis</i>		3.69	3.53	7.83	12.33	19.13	20.80	20.61	18.26	29.71
<i>Globastica sp.</i>		3.69	5.88	8.43	5.48					
<i>Parvularugoglobigerina eugubina</i>		4.92	1.76	3.01	5.48	5.22		8.33	2.74	8.33
<i>Parvularugoglobigerina longiapertura</i>		14.75	11.18	16.27	25.21	23.48	7.20	6.58	11.42	14.13
<i>Planorotalites compressus</i>		10.25	10.59	12.05	6.85	14.78	26.40	16.67	16.44	13.04
<i>Subbotina moskvini</i>		2.46	0.59		0.55	0.87	7.20	3.95	1.37	3.62
<i>Subbotina pseudobulloides</i>			0.59	1.20	0.54	4.35	8.80	3.51	4.57	4.71
<i>Subbotina triloculinooides</i>										
Juveniles no identification				0.60						
Total number counted		244	170	166	367	115	125	228	219	276

TABLE 1a.—Continued.

Sample no.:	20	18	16	14	12	10	8	6	1
Depth in cm above K/T:	115–120	125–130	135–140	145–150	155–160	165–170	175–180	185–190	210–215
<i>Globigerinelloides aspera</i>	0.98	0.71	0.44	1.08	2.00	0.81	0.45		
<i>Globigerinelloides multispinatus</i>								0.44	
<i>Globigerinelloides rosebundensis</i>									
<i>Globigerinelloides subcarinatus</i>	0.33		0.22	0.72		0.27			
<i>Globigerinelloides yaucoensis</i>									
<i>Globotruncanella monmouthensis</i>									
<i>Globotruncanella caravacaensis</i>									
<i>Globotruncanella petaloidea</i>									
<i>Guembelitra cretacea</i>	1.30	0.24	1.33	.072	2.33	0.81	0.23		0.67
<i>Guembelitra trifolia</i>									
<i>Globotruncana arca</i>									
<i>Globotruncana aegyptiaca</i>									
<i>Globotruncana duwi</i>									
<i>Hedbergella holmdelensis</i>									
<i>Hedbergella monmouthensis</i>									
<i>Heterohelix complanata</i>								0.22	
<i>Heterohelix glabrans</i>	0.65			0.36		0.27	0.23		
<i>Heterohelix globulosa</i>				1.08		1.08	0.68	1.11	
<i>Heterohelix navarroensis</i>	1.63	0.94	0.88	1.79	0.67	0.27	1.13	0.44	1.34
<i>Heterohelix planata</i>									
<i>Heterohelix pulchra</i>									
<i>Heterohelix striata</i>	0.65				0.33				
<i>Pseudoguembelina costulata</i>	1.63	2.59	0.22	1.43	1.00	3.51	0.90	1.77	0.67
<i>Pseudoguembelina punctulata</i>									
<i>Pseudotextularia elegans</i>									
<i>Rugoglobigerina macrocephala</i>									
<i>Rugoglobigerina hexacamerata</i>									
<i>Rugoglobigerina rugosa</i>									
<i>Chiloguembelina crinita</i>							1.13	1.55	
<i>Chiloguembelina midwayensis</i>	3.91	0.71	2.43	6.45	5.33	1.89	2.48	1.11	3.68
<i>Chiloguembelina morsei</i>	1.30			0.72		1.62	1.35	2.21	
<i>Chiloguembelina cf. waiparaensis</i>		1.65	3.10	2.15	2.00	0.81		0.88	2.01
<i>Woodringina claytonensis</i>						0.54			
<i>Woodringina hornerstownensis</i>	3.26	4.24	5.31	7.53	4.33	5.95	3.61	3.76	11.04
<i>Eoglobigerina edita</i>	2.28	1.65	0.66	1.79	1.00		0.23		2.68
<i>Eoglobigerina fringa</i>	0.65	0.94	0.66	1.43	0.67				
<i>Eoglobigerina simplicissima</i>	2.28	2.59	2.21	5.73	1.33	1.62	1.35		1.67
<i>Eoglobigerina trivialis</i>			0.66		1.00	2.70	0.68	1.55	0.67
<i>Globanomalina pentagona</i>	8.47	7.76	7.96	6.45	13.33	22.43	22.57	31.64	12.71
<i>Globanomalina taurica</i>	4.89	5.88	6.86	10.04	15.67	5.41	7.45	7.74	14.38
<i>Globanomalina tetragona</i>	0.98	0.94	1.55	1.08		1.08	0.68	1.99	
<i>Globoconusa conusa</i>				0.36					
<i>Globoconusa daubjergensis</i>	17.92	25.88	25.44	20.79	24.00	31.08	32.73	21.68	30.10
<i>Globastica</i> sp.									
<i>Parvularugoglobigerina eugubina</i>	8.47	8.71	2.88	10.39	1.67				
<i>Parvularugoglobigerina longiapertura</i>	14.01	5.41	4.20	3.58					
<i>Planorotalites compressus</i>	14.33	16.00	11.95	12.54	14.67	5.95	9.48	11.73	8.36
<i>Subbotina moskvini</i>	5.54	5.41	8.63	0.72	3.33	2.43	3.61	3.76	
<i>Subbotina pseudobulloides</i>	4.56	7.76	12.17	1.08	3.67	7.57	6.55	4.65	9.36
<i>Subbotina triloculinoides</i>			0.22		1.67	1.08	1.13	0.22	0.67
Juveniles no identification						0.81			
Total number counted	307	425	452	279	300	370	443	452	299

TABLE 1b.—Relative percent abundance of planktonic foraminifera in the Upper Cretaceous Mendez Formation at Arroyo El Mimbral, Mexico.

	Sample no.:	47	48	49	50	51	52	53	54	55	57
Depth in cm below K/T:	2-4	4-5	5-7	7-11	11-16	16-17	20-25	25-30	30-35	40-45	
<i>Abathomphalus intermedius</i>							0.45	0.31	0.35	0.28	0.33
<i>Abathomphalus mayaroensis</i>								0.31			0.33
<i>Globigerinelloides aspera</i>		*2	*1				6.82			4.24	6.84
<i>Globigerinelloides rosebudensis</i>											0.33
<i>Globigerinelloides subcarinatus</i>				*1			1.82	3.42	3.53	1.98	2.28
<i>Globigerinelloides volutus</i>		*1	*1	*1			0.91	0.93			
<i>Globigerinelloides yaucoensis</i>							0.45	0.93	1.41	1.69	1.95
<i>Globotruncanella monmouthensis</i>							3.18	2.17	1.41	3.39	3.26
<i>Globotruncanella petaloidea</i>		*1	*1				2.73	0.93	1.41	1.69	2.93
<i>Globotruncanella citae</i>											
<i>Guembelitra cretacea</i>							0.45				
<i>Hedbergella holmdelensis</i>							1.82	3.73	2.47	3.67	2.93
<i>Hedbergella monmouthensis</i>		*2					0.91	3.11	4.59	3.95	1.63
<i>Globotruncana aegyptiaca</i>				*1			0.45	0.93	0.35	0.56	0.33
<i>Globotruncana arca</i>				*1			0.91	0.31	1.06	0.56	1.30
<i>Globotruncana duwi</i>							0.45	0.31	0.35	0.28	0.33
<i>Globotruncana ventricosa</i>								0.31		0.28	0.33
<i>Globotruncanita conica</i>								0.31			
<i>Globotruncanita stuarti</i>								0.31			0.33
<i>Globotruncanita stuartiformis</i>	*1						0.45	0.31	0.71	0.56	0.33
<i>Rosita contusa</i>							0.45				
<i>Heterohelix complanta</i>		*2					6.82	3.42	3.89	4.24	4.56
<i>Heterohelix glabrans</i>		*1					5.00	2.48	1.06	1.98	0.65
<i>Heterohelix globulosa</i>				*2		*1	12.27	13.35	9.54	9.32	10.42
<i>Heterohelix navarroensis</i>		*2	*1				10.45	21.12	19.43	18.36	15.64
<i>Heterohelix planata</i>											
<i>Heterohelix pulchra</i>								1.24		1.13	
<i>Heterohelix striata</i>							0.45	1.24	1.06	1.41	0.98
<i>Plummerita hantkeninoides</i>				*1						1.13	1.30
<i>Pseudoguembelina palpebra</i>							3.64	1.24	1.06	1.13	3.58
<i>Pseudoguembelina costulata</i>	*1	*1	*2	*1			25.00	26.09	32.51	28.81	31.60
<i>Pseudoguembelina kempensis</i>		*1					1.82		0.71		
<i>Pseudoguembelina punctulata</i>							0.45	0.31	0.35	0.28	0.33
<i>Pseudotextularia deformis</i>								0.31	0.35	0.28	0.33
<i>Pseudotextularia elegans</i>							0.45	0.31	0.71	0.56	0.33
<i>Planoglobulina brazoensis</i>							0.45	0.31			
<i>Planoglobulina carseyae</i>								0.31			
<i>Racemiguembelina fructicosa</i>								0.31	0.35	0.28	
<i>Rugoglobigerina hexacamerata</i>							5.00		3.18	3.39	1.63
<i>Rugoglobigerina macrocephala</i>							3.18	0.93	0.35		
<i>Rugoglobigerina pennyi</i>							0.45	0.31	0.71	0.28	0.33
<i>Rugoglobigerina rugosa</i>		*2	*1		*1		2.27	1.55	1.77	1.41	0.98
<i>Rugoglobigerina scotti</i>			*1					0.31	0.35	0.85	1.63
<i>Shackoina multispinatus</i>								0.31			
Juveniles no identification				*2						1.98	
Total number counted	2	15	14	2	2	220	322	283	283	354	307

* Asterisk indicates number of specimens.

STRATIGRAPHIC SECTIONS AT MIMBRAL

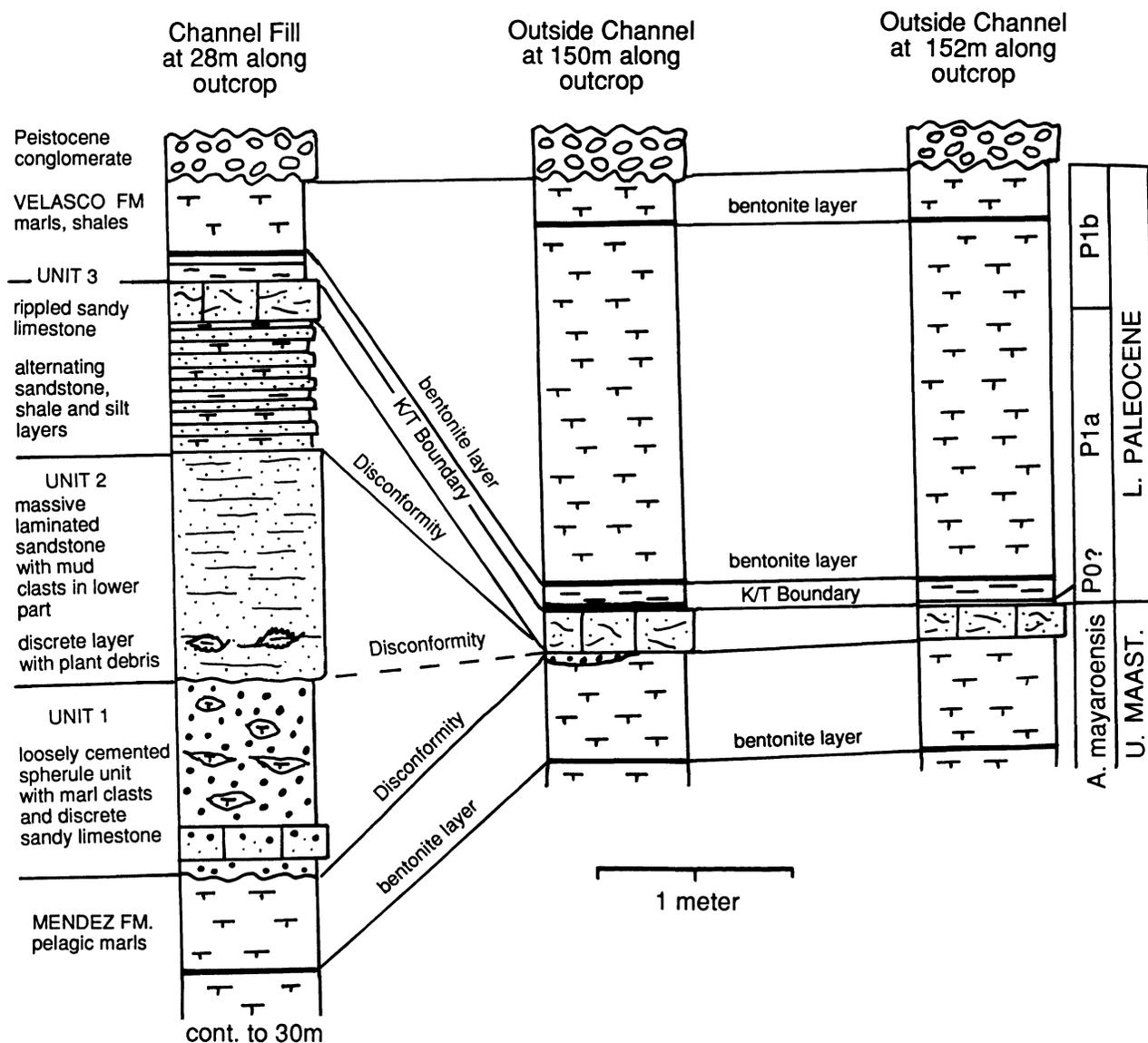


FIGURE 1—Stratigraphic sections collected at Mimbral (NE Mexico) at 28 m, 150 m and 152 m along the outcrop. Note that the channel-fill deposit is 3 m high at 28 m, but nearly absent outside the channel (at 150 m) except for the topmost 20 cm thick rippled sandy limestone layer.

Channel-Fill Transect at 28 m

The 3 m thick channel-fill deposit is sandwiched between normal pelagic sedimentation of the Mendez and Velasco Formations. However, the presence of upper Cretaceous planktic foraminifers, including the index taxon *Abathomphalus mayaroensis* throughout the channel-fill deposit, indicates that deposition occurred during the uppermost Maastrichtian *A. mayaroensis* Zone. Within the spherule-rich unit 1, both mud-clasts and matrix contain diverse *A. mayaroensis* Zone planktic foraminifers similar to the underlying Mendez Formation. In contrast, benthic

foraminiferal assemblages are different. Whereas in the Mendez Formation benthic foraminifers are small, rare and indicative of upper slope (~400–500 m) depth (gyroidinids, eponidids, gavelinellids), in the overlying unit 1 they are common, large and indicative of shallower outer neritic to upper slope depths (*Bolivina incrassata gigantea*, *Praebulimina reussi*, *Anomalinoides acuta*, *A. praecuta*, *Cibicidoides succedens*, *Globorotalites michelinus*). This may indicate a sea-level lowstand and/or downslope transport from shallower neritic environments. Transport from shallower areas is indicated by the presence of microspherules which enclose lithic clasts and glau-

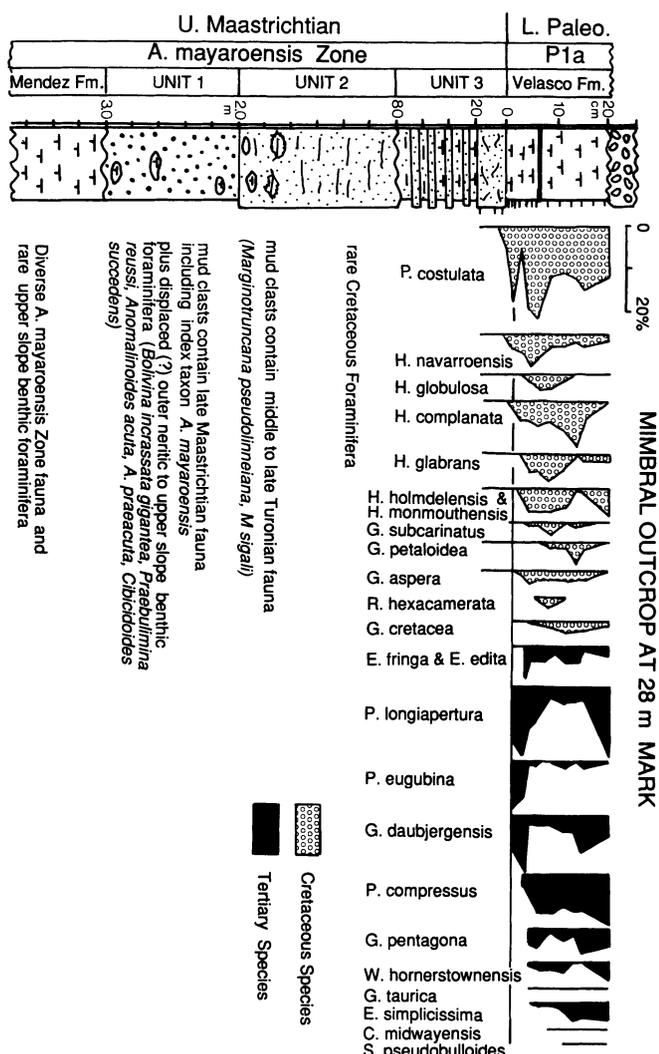


FIGURE 2—Biostratigraphic information of the channel deposit and overlying Velasco Formation (at 28 m along the outcrop) at Mimbral, NE Mexico. Common benthic foraminifera of the Velasco Formation: *Anomalinoidea acuta*, *Globulina subsphaerica*, *Anomalinoidea praeacuta*, *Lagena* sp., *Angulogerina cuneata*, *Lenticulina* sp., *Bolivinoidea incrassata*, *Dentalina gracilis*, *Coryphostoma plaitum*, *Osangularia cordieriana*, *Cibicoides succedens*, *Pyramidina rudita*, *Cibicoides beadnelli*, *Tappanina selmensis*, *Eouvigerina aculeata*, *Gyroidina depressa*, *Eouvigerina hispida*, *Gavelinella beccariformis*, *Eponides plummerae*, *Dorothia oxygona*.

conite-infilled foraminifers (oolites, oncolites). Such spherules, including glauconite, currently form in the Caribbean in shallow water environments. Periodic transport from shallow near-shore regions is also indicated by the presence of abundant wood and leaves in discrete layers near the base of unit 2 (Fig. 2).

Unit 2 consists of a massive laminated sandstone which contains only rare upper Maastrichtian foraminifers and the same outer neritic benthic foraminifers as unit 1. Mudclasts near the base of unit 2 contain lower to middle Turonian age foraminifers (*Marginotruncana sigali*, *M.*

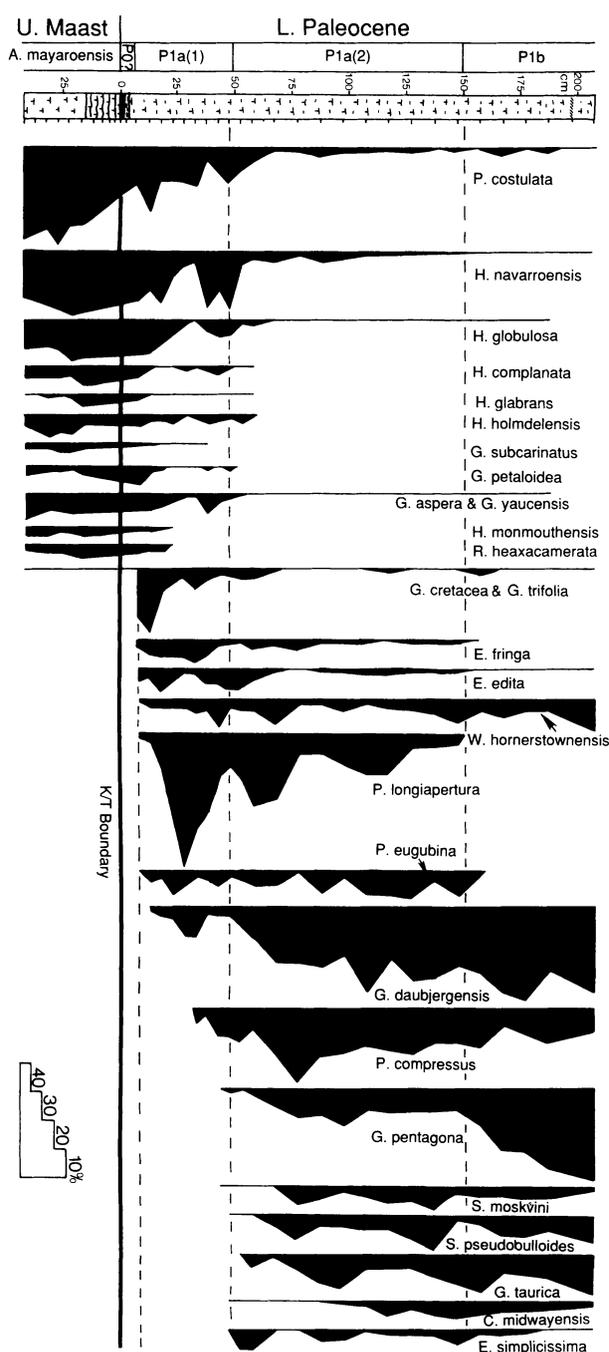


FIGURE 3—Biostratigraphic and faunal abundance data of planktic foraminifers across the K/T boundary in a nearly continuous sedimentary sequence (at 150 m along the outcrop) outside the channel deposit at Mimbral, NE Mexico. Note that cosmopolitan Cretaceous taxa survive the K/T boundary event without major changes in their relative abundances.

pseudolinneiana, Sliter, pers. comm. 1992) which appear to have been eroded from the Cretaceous Agua Nueva Formation. This indicates sediment transport from an additional source area at this time.

Unit 3 consists of alternating laminated sandstone, shale and silt layers topped by a 25 cm thick sandy rippled limestone. Bioturbation by chondrites is apparent at the top of unit 3 and indicates a normal depositional environment rather than a storm deposit. Foraminifers are few, except in a shale layer below the rippled limestone which contains abundant *A. mayaroensis* Zone planktic foraminifers (including *Rosita contusa*, *Racemiguembelina fructicosa* and *A. mayaroensis*) and only rare benthic foraminifera similar to the Mendez Formation. This assemblage, like the bioturbated interval, suggests that intervals of normal pelagic sedimentation occurred during deposition of unit 3.

Above the channel-fill deposit, thin layers of shale, sand and bentonite mark the first 8 cm of the Tertiary Velasco Formation (Fig. 2). No bioturbation is apparent. The first Tertiary planktic foraminifers are present in the basal shale layer along with many Cretaceous taxa. The abundant presence of *Parvularugoglobigerina eugubina*, *P. longiapertura* and *Globoconusa daubjergensis* (Fig. 2) in this basal shale layer indicates that the earliest Tertiary Zone P0 and part of the succeeding Zone P1a is missing in this channel transect. This is also apparent in the absence of the K/T boundary clay and red layer that is present outside the channel.

Foraminiferal data thus suggest that the channel-fill deposits represent a series of sediment transports from shallower areas. These transports, however, alternated with normal pelagic sedimentation including intervals of bioturbation as well as erosion and non-deposition, and hence must have continued over tens of thousands of years. This interpretation is contrary to Smit et al. (1992) who viewed the clastic deposit as having accumulated over a period of hours to days as a result of a giant impact generated megawave.

Similar clastic deposits have now been found in 10 sections spread over an area of 200–300 km in northeastern Mexico (Alvarez et al., 1992; Stinnesbeck et al., 1993), but they are absent to the north and south of Mexico. If an impact generated megawave (hypothesized Chicxulub impact) was responsible for the Mimbral and other northeastern Mexico channel-fill deposits, one would expect to find similar deposits in other regions of Mexico bordering the Gulf of Mexico. This is apparently not the case. Our field investigations of several sections in Chiapas uncovered no evidence of impact-generated breccia deposits near the K/T boundary. The Mimbral channel-fill deposits are thus restricted to northeastern Mexico where erosion and gravity flows may have been associated with the Laramide orogeny in the Sierra Madre Oriental (Stinnesbeck et al., 1993).

Outside-Channel Transect at 150 m

An estimate of the biostratigraphy, age and normal depositional environment of the Mimbral region can be obtained from a transect outside the channel at 150 m along the outcrop. At this location, the channel deposit is represented only by the topmost 20 cm of sandy rippled lime-

stone of unit 3 and a thin discontinuous lens (1 cm) of the spherule layer of unit 1 (the latter is absent at 152 m). Figure 3 illustrates the relative abundance of common planktic foraminifers and the ranges of all taxa are shown in Figure 4. These figures show that a nearly continuous K/T boundary transition is present at Mimbral, similar to the biostratigraphic records of Agost and Caravaca in Spain (Canudo et al., 1991).

A diverse upper Maastrichtian assemblage of the *A. mayaroensis* Zone, including the index taxon *A. mayaroensis*, is present to just below the sandy rippled limestone (Fig. 4). The dominance of small cosmopolitan taxa and relative rarity of large complex, tropical and subtropical taxa in the uppermost Mendez marls is representative of the last 0.5 m.y. of the Maastrichtian in other low latitude sections, including Spain and Tunisia (Keller, 1988; Canudo et al., 1991). Without analysis of additional sections in Mexico that lack the gravity flow deposits of Mimbral, however, it is not possible to determine how much, if any, of the latest Maastrichtian is missing.

The K/T boundary is marked by a 4 cm thick clay layer containing a 3 mm thick red layer 1 cm above the sandy rippled limestone bed. As noted earlier, the top of the rippled sandy limestone layer has many burrows made by sediment feeding organisms. All feeding burrows are infilled with the same sand as the underlying sediment and there is no evidence of mixing with, or burrowing into, the overlying clay. This suggests a period of non-deposition between the Cretaceous and Tertiary sediments; it does not support deposition by an impact-generated tsunami wave (rippled sandy limestone) followed by air-fallout settling of the boundary clay as suggested by Smit et al. (1992). Rather, it suggests a hiatus or non-deposition surface with part of the boundary clay missing. No planktic foraminifera are present in the clay layer due to carbonate dissolution. Stratigraphically, this clay layer (including the red layer) is equivalent to Zone P0 in similar K/T boundary lithologies in Spain, Tunisia and Denmark which also contain maximum Ir abundances (Schmitz, 1988; Graup and Spettel, 1989; Rocchia et al., 1984). It is therefore possible that the Mimbral clay layer also represents Zone P0. This interpretation is supported by the disappearance of all large subtropical and tropical taxa at the top or below the sandy rippled limestone, and the first appearance of *Parvularugoglobigerina eugubina* and *P. longiapertura*, the index taxa for Zone P1a, above the clay layer (Fig. 4). We therefore place the K/T boundary at Mimbral at the red layer and base of clay layer immediately above the sandy rippled limestone. As noted above, however, the K/T boundary interval is very condensed (4 cm as compared to 50 cm at El Kef, Tunisia) and maybe missing in part as indicated by the bioturbated top of the sandy limestone layer. This is also suggested by the presence of a very small iridium anomaly (<1 ppb) in this interval, as compared to other K/T sections (e.g., Haiti where Ir anomaly is 28 ppb, Jéhanno et al., 1992). No elevated levels of Ir are present in the gravity flow deposits (Smit et al., 1992; Stinnesbeck et al., 1993).

The first Tertiary planktic foraminifers appear in a sam-

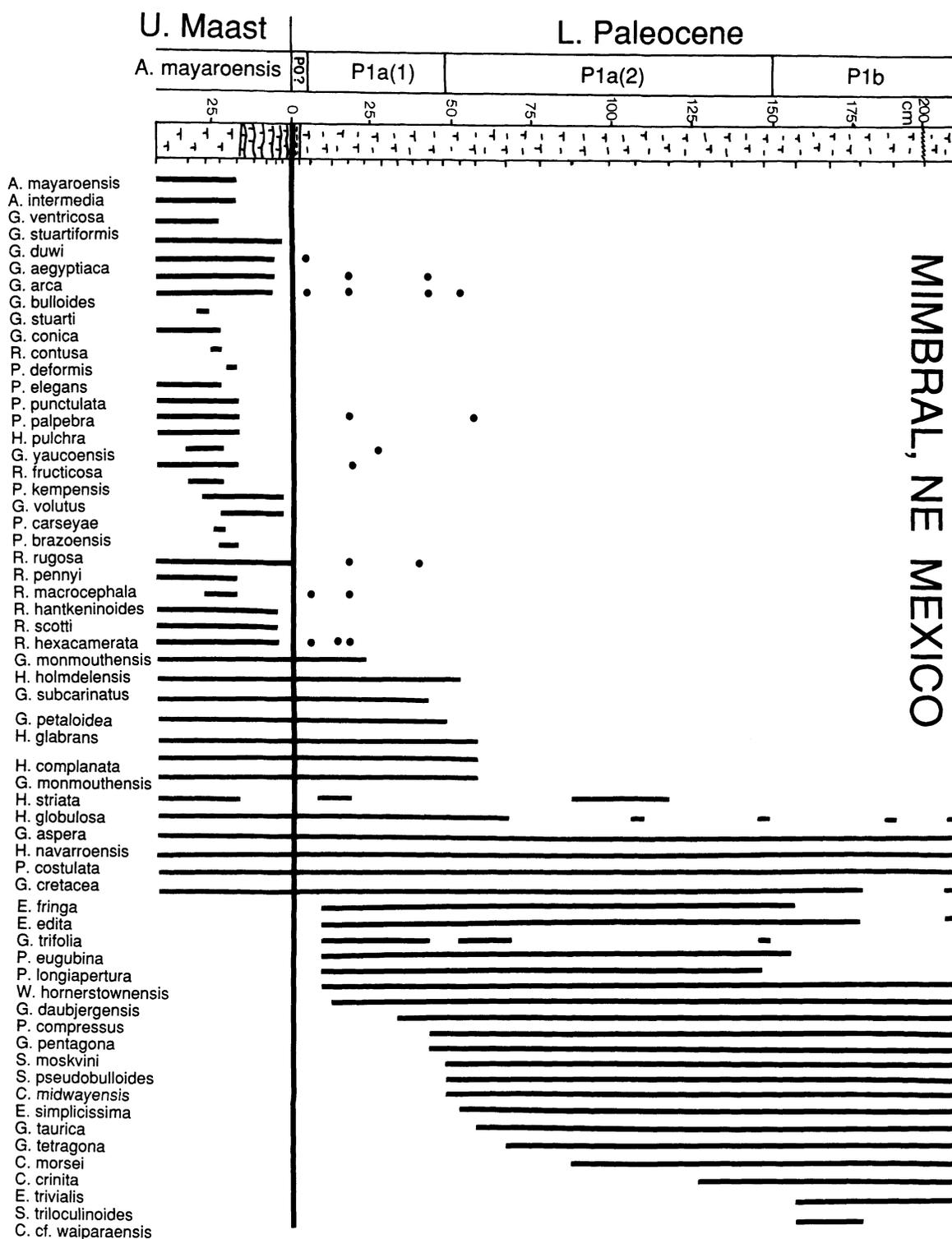


FIGURE 4—Biostratigraphy and ranges of all planktic foraminifera across the K/T boundary in a nearly continuous sedimentary sequence (at 150 m along the outcrop) outside the clastic channel deposit at Mimbral, NE Mexico. Note that all large, complex, tropical and subtropical Cretaceous taxa disappear at or below the K/T boundary. (Isolated dots above the K/T boundary indicate the presence of reworked specimens.) Cosmopolitan Cretaceous taxa survive well into the Tertiary.

ple between 4–9 cm above the rippled sandy limestone. This sample contains a well developed early Zone P1a fauna with *P. eugubina*, *P. longiapertura*, *W. hornerstownensis*, *G. fringa*, *G. edita*, *Guembelitra cretacea* and *G. trifolia* (Figs. 3, 4). Zone P1a spans 1.5 m upsection, as indicated by the range of the index taxa *P. eugubina* and *P. longiapertura*, and has a comparable sedimentation rate to Agost and Caravaca in southern Spain (Canudo et al., 1991). The uppermost 70 cm of the Velasco shales and marls exposed at Mimbral is of Zone P1b age. Sedimentation appears to have been nearly continuous throughout the Zones P1a and P1b intervals.

Benthic foraminifers of the Early Tertiary (Zones P1a and P1b) Velasco Formation indicate a significantly shallower depositional environment than in the upper Maastrichtian Mendez Formation. In contrast to the rare deeper water (~400–500 m) benthic assemblage of the Mendez Formation, benthic foraminifera of the Velasco Formation are common, diverse and indicative of deposition in an outer neritic environment at about 200–350 m depth. The assemblages present (taxa listed in caption of Fig. 2) are similar in composition, although not in relative species abundances, to coeval benthic assemblages at Agost, Caravaca and the Negev (Keller, 1992). In all of these sections, late Maastrichtian deposition occurred in an upper bathyal environment at about 400–500 m depth, but shallowed in the latest Maastrichtian to outer neritic depth due to a sea-level lowstand. There is strong evidence that a global sea-level lowstand occurred near the end of the Cretaceous (Haq et al., 1987; Donovan et al., 1988; Schmitz et al., 1992; Keller et al., 1993). At Mimbral, this sea-level lowstand apparently coincided with deposition of the channel-fill deposit and may have intensified the erosion and gravity flows associated with the Laramide orogeny in the Sierra Madre Oriental.

BIOTIC EFFECTS OF K/T BOUNDARY EVENT

Although the evidence for a large K/T boundary bolide impact near Chicxulub on the Yucatan peninsula (Hildebrand et al., 1991; Pope et al., 1991; Swisher et al., 1992; Sharpton et al., 1992) is still in dispute (Officer et al., 1992; Lyons and Officer, 1992; Jéhanno et al., 1992), such a catastrophe would have exacerbated the biotic effects in nearby areas. Here we examine the biotic effects of the K/T boundary event at Mimbral based on species diversity, extinctions and relative abundance of dominant planktic foraminiferal populations, and evaluate the evidence for increased biotic effects in Mexico.

Figure 4 shows the ranges of all species observed at Mimbral. About $\frac{2}{3}$ of the Cretaceous species (28 taxa) disappeared at the base or top of the rippled sandy limestone. Isolated specimens of some of these taxa are also found in the Lower Tertiary and are assumed to be reworked (black dots). Because foraminifers are rare in the rippled sandy limestone, the exact level of species extinctions cannot be determined. In the absence of further information, we assume that all 28 taxa (68%) may have

disappeared at the K/T boundary (Fig. 5). All but 3 of these taxa are relatively large complex tropical and subtropical forms (e.g., globotruncanids, racemiguembelinids, pseudotextularids, rugoglobigerinids) with low environmental tolerances. They are generally rare in the latest Maastrichtian and the relative abundance of all 28 taxa is consistently less than 17% of the total foraminiferal populations (Fig. 5). Thus, although $\frac{2}{3}$ of the species population disappeared at the K/T boundary, the effect on the total foraminiferal population was relatively small (<17%), because only rare and endangered species disappeared. Similar high rates of tropical and subtropical species extinctions, but low relative abundance in the foraminiferal population were earlier observed at El Kef, Tunisia (Keller, 1988), and Agost and Caravaca in southern Spain (Canudo et al., 1991).

About $\frac{1}{3}$ of the Cretaceous species (13 taxa) are consistently present well into Zone P1a and 5 species continue into Zone P1b. These taxa are generally small cosmopolitan forms (pseudotextularids, heterohelicids, hedbergellids, globigerinellids, guembelitrids) tolerant of environmental changes. They have been observed to range into the Tertiary in numerous sections spanning low to high latitudes and are considered Cretaceous survivors (Keller, 1988, 1989, 1993; MacLeod and Keller, in press). Figure 3 illustrates the dominance of these taxa in the latest Maastrichtian and their gradual decline in the lower part of Zone P1a (Subzone P1a (1)). Their combined relative abundance across the K/T boundary transition is illustrated in Figure 5. Cretaceous survivor taxa dominate latest Maastrichtian planktic foraminiferal populations by more than 80% and gradually decline in Zone P1a. Their relative abundance decline appears to be related to the evolution and rise to dominance of Tertiary species (Fig. 3), rather than the effects of the K/T event as discussed below. Similar survivorship patterns have been observed in many K/T boundary sections including El Kef, Brazos, Agost, Caravaca, Nye Klov and Indian Antarctic Ocean Site 738 (Keller, 1988, 1989, 1993; Canudo et al., 1991; Keller et al., 1993b; MacLeod and Keller, in press). The Mimbral section thus indicates that if a bolide impact occurred in the Caribbean, the biotic effects on surface plankton were no more severe than in other low latitude sections (Tethys Ocean). Moreover, the biotic effects were not catastrophic and apparently limited to taxa with low environmental tolerances even within a radius of 2000 miles.

Post-K/T Environment

The post-K/T boundary environment in northeastern Mexico was not much different from the Tethys (Keller, 1988, 1989; Keller and Benjamini, 1991; Canudo et al., 1991), the boreal seas of Denmark (Keller et al., 1993b), or the Antarctic Ocean (Keller, 1993). The world oceans were populated by an impoverished planktic foraminiferal fauna consisting of Cretaceous survivors tolerant of wide ranging temperature, oxygen, salinity and nutrient conditions. The first new Tertiary species evolved in an environment that resulted in deposition of a dark gray to

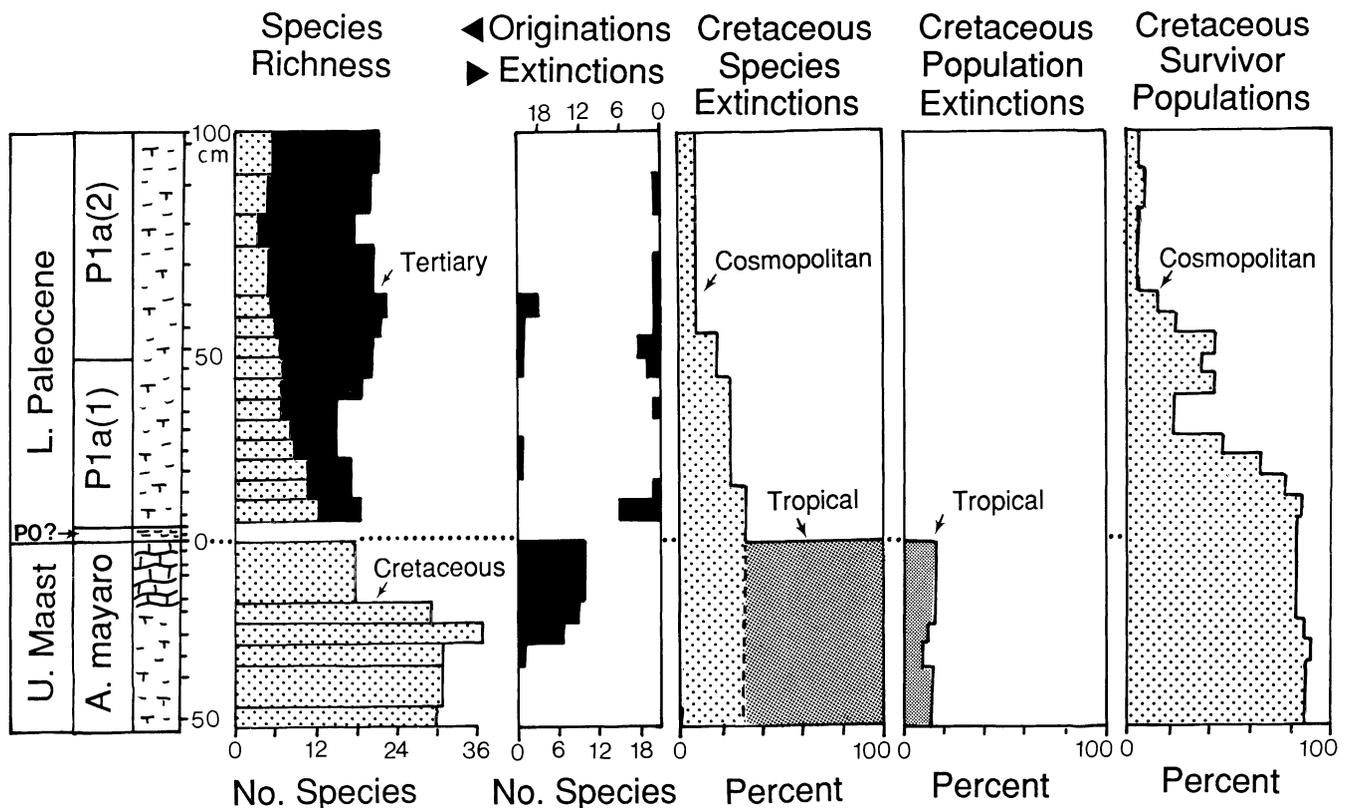


FIGURE 5—Species richness, species extinctions and relative abundances of Cretaceous populations extinct and Cretaceous populations surviving across the K/T boundary. Note that although $\frac{2}{3}$ of the tropical species disappear at the K/T boundary they comprise only 17% of the population (individuals), indicating that only rare and endangered species became extinct.

black boundary clay worldwide. Stable isotope data and benthic and planktic foraminiferal studies indicate that the black clay layer was deposited at a time of low surface productivity in low and middle latitudes (Zachos and Arthur, 1986; Zachos et al., 1989; Keller and Lindinger, 1989; Barrera and Keller, 1990) and during a global sea-level high-stand (Donovan et al., 1988; Schmitz et al., 1992; Keller et al., 1993b).

Surface productivity did not fully recover for at least 300,000 years (upper Zone P1b to lower P1c) in low and middle latitudes (Zachos and Arthur, 1986; Zachos et al., 1989; Keller and Lindinger, 1989; Keller and Benjamini, 1991). In contrast, in boreal seas and high latitude regions, surface productivity remained nearly stable across the K/T boundary and may have increased slightly, indicating that major effects of the K/T boundary event may have been restricted to the lower latitudes (Keller, 1993; Barrera and Keller, in press). Nevertheless, the dramatic difference in surface productivity between low and high latitudes seems to have had little effect on the cosmopolitan Cretaceous survivor fauna, or the evolving Tertiary fauna, attesting to their adaptive abilities. In contrast, the more specialized tropical and subtropical taxa disappeared.

In the Mimbral section the K/T boundary clay layer is

very condensed (4 cm) probably due to dissolution and non-deposition. The new Tertiary fauna (5 species, Figs. 3, 4) appears immediately above the clay layer and thrives along with Cretaceous survivors for about 50,000 years, or 50 cm above the K/T boundary. (Age estimate is based on sedimentation rates of $0.83 \text{ cm}/10^3 \text{ yrs.}$ for Zone P1a which spans 180,000 years to the top of Chron 29 R (Herbert and D'Hondt, 1990).) Around that time 8 new species appear (Figs. 3, 4) and the Tertiary foraminiferal population begins to dominate (Fig. 3), whereas 6 Cretaceous survivors disappear with the remaining survivor taxa rare. These data indicate that the terminal abundance decline of the Cretaceous survivor taxa seems to be related not to major changes in the environment, but to the successful competition for the same ecologic niches by the evolving Tertiary fauna.

Thus, the Cretaceous cosmopolitan taxa, unchallenged during the latest Maastrichtian and surviving the K/T boundary event nearly intact, seem to have succumbed to competition by the new Tertiary cosmopolitan fauna. This new early Tertiary fauna dominated the oceans from equator to poles for about 300,000 years, until the recovery of the ecosystem brought competition from evolving new species.

DISCUSSION AND CONCLUSIONS

We set out to examine whether the Mimbral K/T boundary channel-fill sediments represent a single-event deposit caused by a K/T boundary bolide impact generated megawave (Smit et al., 1992), whether the section is biostratigraphically complete, and to evaluate the biotic effects of the K/T boundary event on planktic foraminiferal populations.

Our investigation indicates that the 3 m thick channel-fill deposit at Mimbral does not represent a single-event deposit, but rather a series of gravity flows, and appears to be unrelated to the K/T boundary event which is marked by a 4 cm clay layer and 3 mm red layer above the channel-fill. Stratigraphic evidence in support of this interpretation include discrete intervals with bioturbation, foraminiferal assemblages that indicate periods of normal pelagic sedimentation, and at least three lithologically distinct units separated by disconformities and rip-up clasts. Most debris flows originated in shallower neritic environments as indicated by the presence of oolites, oncolites, glauconite, meritic benthic foraminifers and plant debris. Transported material of each unit is lithologically and mineralogically different. The basal unit 1 is rich in spherules and mud-clasts of the underlying Mendez Formation. The middle unit 2 is distinct in mud-clasts with Turonian age foraminifers of the Agua Nueva Formation and discrete layers of plant debris. The upper unit 3 is lithologically and mineralogically variable with chlorite and zeolite (probably heulandite-clinoptilolite group, Stinnesbeck et al., 1993) reflecting a new detrital and volcanic influx.

These data do not support the Smit et al. (1992) interpretation of the three lithological units as (1) "the arrival of proximal impact ejecta" (p. 102) and megawave depositing the spherules (which they consider tektites) in the basal unit, (2) "A megawave backwash from the coast" (p. 103) depositing the laminated sands and discrete layers of plant debris of unit 2, (3) reflected back and forth waves depositing the alternating sand, silt and shale layers and topmost sandy rippled limestone of unit 3, and (4) airborne impact fallout depositing the boundary clay.

Smit et al.'s (1992) interpretation is based primarily on their reported presence of glass spherules (in unit 1) assumed to be of impact origin, abundant shocked quartz grains and a very small Ir anomaly (<1 ppb). Stinnesbeck et al. (1993), however, found only very rare glass fragments (3 fragments per pound of sediment), only very rare shocked quartz grains (3 grains) and a small Ir anomaly (<0.9 ppb) in the boundary clay and at 7.5 cm above the top of the channel-fill. No glass spherules have been found in any of the other nine K/T sections in NE Mexico which contain similar channel-fill deposits (Alvarez et al., 1992; Stinnesbeck et al., 1993). Thus, there appears to be no evidence to relate the channel deposits to the K/T boundary event. A depositional scenario of the channel-fill units that is more consistent with the sedimentologic, mineralogic and faunal data is a series of gravity flows related to the Laramide orogeny of the Sierra Madre Oriental and the latest Maastrichtian sea-level lowstand.

How complete is the Mimbral K/T transition? Our study suggests that this section represents relatively continuous deposition comparable to the K/T boundary sections at Agost and Caravaca and hence must be ranked among the seven best K/T sections (El Kef, Agost, Caravaca, Brazos, Nye Klov, Site 738). At Mimbral and the Spanish sections, however, the K/T boundary clay is very thin (4–6 cm as compared to 50 cm at El Kef) due to carbonate dissolution, and probably non-deposition. The absence of a significant Ir anomaly in the boundary clay at Mimbral, and absence of Ni-rich spinels further suggests that the boundary is incomplete.

Are the biotic effects more severe at Mimbral (proximity to proposed impact on Yucatan) than in other low latitude sections? This study indicates that the biotic effects of the K/T boundary event on planktic foraminifers in the Mimbral section are similar to those observed in other low latitude Tethyan sections including El Kef in Tunisia, Agost and Caravaca in Spain and the Negev of Israel (Keller, 1988; Canudo et al., 1991; Keller and Benjamini, 1991). About 2/3 of the taxa disappeared at or near the K/T boundary. They are the highly specialized large, complex tropical and subtropical forms that are already rare in the latest Maastrichtian and their combined relative abundance at Mimbral is only 17% of the total foraminiferal population. The disappearance of these already endangered species did not constitute a catastrophe for the marine plankton. The pre-K/T planktic foraminiferal fauna was already dominated by small cosmopolitan taxa able to tolerate wide ranging conditions in temperature, oxygen, salinity and nutrients. The relative abundance of this cosmopolitan fauna exceeded 80% of the total population at Mimbral and no sudden change is observed at the K/T boundary. Instead, their relative abundance declined gradually during the first 100,000 years of the Tertiary coincident with the rise to dominance of the newly evolved Tertiary fauna. Mimbral thus provides no support for a major sudden environmental catastrophe associated with the hypothesized bolide impact on nearby Yucatan.

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