The Cretaceous–Tertiary boundary transition in the Antarctic Ocean and its global implications

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ABSTRACT

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Three Antarctic Ocean K/T boundary sequences from ODP Site 738C on the Kerguelen Plateau, ODP Site, 752B on Broken Ridge and ODP Site 690C on Maud Rise, Weddell Sea, have been analyzed for stratigraphic completeness and faunal turnover based on quantitative planktic foraminiferal studies. Results show that Site 738C, which has a laminated clay layer spanning the K/T boundary, is biostratigraphically complete with the earliest Tertiary Zones P0 and P1a present, but with short intrazonal hiatuses. Site 752B may be biostratigraphically complete and Site 690C has a hiatus at the K/T boundary with Zones P0 and P1a missing.

Latest Cretaceous to earliest Tertiary planktic foraminiferal faunas from the Antarctic Ocean are cosmopolitan and similar to coeval faunas dominating in low, middle and northern high latitudes, although a few endemic species are present. This allows application of the current low and middle latitude zonation to Antarctic K/T boundary sequences. The most abundant endemic species is *Chiloguembelina waiparaensis*, which was believed to have evolved in the early Tertiary, but which apparently evolved as early as Chron 30N at Site 738C. Since this species is only rare in sediments of Site 690C in the Weddell Sea, this suggests that a watermass oceanographic barrier may have existed between the Indian and Atlantic Antarctic Oceans.

The cosmopolitan nature of the dominant fauna began during the last 200,000 to 300,000 years of the Cretaceous and continued at least 300,000 years into the Tertiary. This indicates a long-term environmental crisis that led to gradual elimination of specialized forms and takeover by generalists tolerant of wide ranging temperature, oxygen, salinity and nutrient conditions. A few thousand years before the K/T boundary these generalists gradually declined in abundance and species became generally dwarfed due to increased environmental stress. There is no evidence of a sudden mass killing of the Cretaceous fauna associated with a bolide impact at the K/T boundary. Instead, the already declining Cretaceous taxa gradually disappear in the early Danian and the opportunistic survivor taxa (*Ch. waiparaensis* and *Guembelitria cretacea*) increase in relative abundance coincident with the evolution of the first new Tertiary species.

Introduction

The Cretaceous/Tertiary (K/T) boundary is the most intensively studied interval by the most diverse teams of investigators ranging from paleontologists to chemists and astrophysicists. Each of these teams of investigators aims at sleuthing the step by step history of one or more bolide impacts, period of global volcanism and mass extinction of Cretaceous dinosaurs, invertebrates and marine plankton.

For each team the presence of a continuous record of sedimentation is critical to reconstruct this time interval in Earth history. It is not surprising then, that of over 29 Cretaceous/Tertiary boundary sections from deep-sea and onshore marine deposits published, nearly all claim a continuous record of sedimentation across this critical boundary. If true, this would be a feat unrivaled by any other Epoch boundary characterized by environmental upheavals. Since, as a rule, major stratigraphic age

boundaries are placed at major lithologic changes and faunal discontinuities, their very nature tends to record a break in the history of sedimentation.

Contrary to the numerous claims of a continuous sedimentation record, the K/T boundary transition is no exception. High resolution centimeter-scale litho-, chemo-, chrono-, and biostratigraphic analyses and quantitative faunal studies of 15 K/T sections and integration of these data via graphic correlation has provided a composite temporal sequence of 75 latest Maastrichtian to early Paleocene (Zones P0–P1c) planktic foraminiferal and nannofossil datum events (MacLeod and Keller, 1991a,b). This composite data set allows individual K/T sequences to be related to one another within a common chronostratigraphic model. Evaluation of all 29 "complete" K/T boundary sequences reveals the presence of intrazonal hiatuses of varying duration in virtually all sections.

Only six sections were found to have a temporally complete record across the K/T boundary with sedimentation continuing for at least several tens of thousand years after deposition of the Ir layer: El Kef in Tunisia, Agost and Caravaca in Spain and 3 sections along the Brazos River in Texas (MacLeod and Keller, 1991a,b). Each of these sections was deposited in the relatively shallow water upper slope and continental shelf regions of the Tethyan Seaway and Gulf of Mexico. In contrast, all deep-sea sections examined have a hiatus that removed sediments representing between 50 and 400 kyr of the basal Tertiary. Hence, reports of instantaneous mass extinctions and abrupt geochemical anomalies in these sections are largely artifacts of a temporally incomplete record.

The 15 sections investigated by our team span from the mid-latitude South Atlantic (Site 528, 30°S, D'Hondt and Keller, 1991) to the high latitude North Atlantic (Stevns Klint and Nye Klov, 50°N; Schmitz et al., 1992; Keller et al., 1993) with most sections centered in the Tethyan Sea (Spain, Tunisia, Israel; Canudo et al., 1991; Keller, 1988; Keller et al., 1990; Keller and Benjamini, 1991), Gulf of Mexico (Brazos Texas; Keller, 1989) and tropical Pacific (Site 577; D'Hondt and Keller, 1991). Absent from this N–S transect is the high latitude southern ocean. Could it be that a continuous deep-sea record across the K/T boundary was preserved in the Antarctic Ocean? Cretaceous/Tertiary boundary sequences recently recovered from ODP Site 690C, on Maud Rise, Site 738C on Kerguelen Plateau and Site 752B on Broken Ridge seemed most promising (Fig. 1). In each section a well defined iridium anomaly is present at the K/T boundary (Michel et al., 1990; Schmitz et al., 1991; Asaro et al., 1991) and shipboard studies, based on wider sampling spacing, reported a relatively complete biostratigraphic record (Stott and Kennett, 1990a; Pospichal and Wise, 1990; Huber, 1991; Thierstein et al., 1991; Pospichal et al., 1991; Pospichal, 1991).

The search for this elusive temporally complete deep-sea marine K/T boundary record prompted this study. The most complete K/T boundary sections known to date (Brazos River, El Kef, Agost, Caravaca, Nye Klov, Mimbral) indicate a prolonged period of environmental instability beginning 200–300 kyr
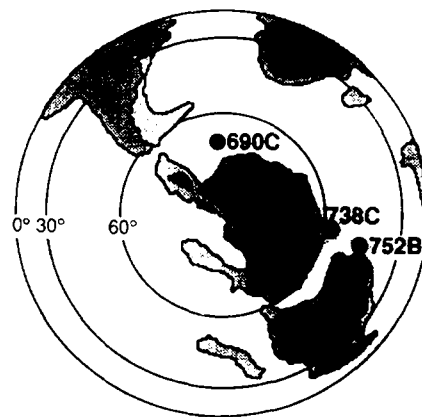

Fig. 1. Locations of ODP Sites examined plotted on a paleogeographic reconstruction of continental positions at the time of the K/T boundary (66.4 Ma).

before the K/T boundary and continuing 300–500 kyr into the early Tertiary. During the late Maastrichtian the climate cooled (Stott and Kennett, 1991b) accompanied by a sea-level drop (Schmitz et al., 1992) and many tropical foraminiferal taxa gradually disappeared (Keller and Barrera, 1991). By K/T boundary time most large, complex tropical planktic foraminifers had disappeared and a small low diversity cosmopolitan fauna dominated (Keller, 1988, 1989a,b). Many of these taxa survived well into the earliest Tertiary and gradually declined coincident with a gradual decrease in $\delta^{13}C$ values of surface waters, not a sudden shift as reported from biostratigraphically incomplete deep-sea sections (Barrera and Keller, 1990). Is this species survivorship and gradual $\delta^{13}C$ shift limited to continental shelf regions that may have acted as refugia, or is the apparently catastrophic nature of this mass extinction in the deep sea exaggerated because of the temporally incomplete deep-sea record? It was hoped that the southern high latitude sites with their reported complete records may answer these questions especially since the survivor fauna in low latitudes is a cool water cosmopolitan assemblage. Of the three sites examined, Site 752B has rare and poorly preserved foraminifera and biostratigraphic determination is not certain; Site 690C has a brief hiatus at the K/T boundary and Site 738C has two very brief hiatuses 8 cm and 14 cm above the K/T boundary. However, between the boundary clay layer and these hiatuses at Site 738C is a lithologically undisturbed laminated interval that represents the earliest Tertiary. Thus, a nearly continuous, albeit condensed boundary transition, may have been found in the Indian Antarctic Ocean.

This study reports on the bio- and chronostratigraphic records and oceanographic implications of major variations in planktic foraminiferal faunas of ODP Sites 690C, 738C and 752B. The primary goals of this investigation are: (1) the evaluation of the temporal completeness of the K/T boundary transition in the Antarctic Ocean, (2) the stratigraphic correlation of these sections to mid- and low-latitude sequences, (3) the similarities and differences between Weddell Sea and southern Indian Ocean and their oceanographic implications and (4) the global implications of a cosmopolitan fauna spanning from equator to poles during the latest Cretaceous to earliest Tertiary.

Methods

Five-cm^3 samples were collected at 20 cm and at 5 cm intervals across the K/T boundary transition at ODP Sites 752B, 738C and 690C. The laminated layer across the K/T boundary at Site 738C was sampled at 1 cm intervals (1 cm^3 samples). Samples were processed for foraminiferal analysis by standard micropaleontological techniques and quantitative faunal counts were based on washed sample splits (using a microsplitter) of 300–400 individuals in the size fraction > 63 μm except for the laminated interval where the > 38 μm size fraction was used because most species are very small (< 63 μm). The remaining sample residue was searched for rare species. All specimens were picked from each sample split and mounted on microslides for a permanent record and identified. Preservation of planktic foraminifera was generally good in Sites 738C and 690C, but poor in Site 752B. Nevertheless, 17 out of 20 samples examined between cores 10R section 4 through 12R section 1 yielded sufficiently diagnostic planktic foraminifers for biostratigraphic zonation. At Site 738C (cores 20R, 21R, and 22R) 55 samples were analyzed and at Site 690C (core 14, sections 1 to 5) a total of 53 samples were analyzed. In the laminated clay layer of Site 738C benthic foraminifera average between 350 and 600 specimens per cubic centimeter and planktic foraminifera average between 250 and 500 specimens, except for the 1 cm immediately above the K/T boundary and Ir anomaly (20R-5, 96–95 cm) where only 84 specimens

TABLE 1

Relative percent abundance of planktic foraminifera across the K/T transition at ODP site 738C

Core-section Depth in centimeters	22R-1 100–102	22R-1 74–76	22R-1 49–51	22R-1 25–27	22R-1 5–6	21R-1 60–61	21R-1 48–50	21R-1 39–41	21R-1 29–31	21R-1 20–22	21R-1 9–11
Abathomphalus intermedius						0.61	0.99	0.28	0.71	1.23	0.40
Abathomphalus mayaroensis						0.61	0.33	0.28	0.48	0.41	0.40
Globigerinelloides aspera	24.77	11.96	13.52	12.16	10.93	18.29	25.08	22.75	23.33	20.16	20.40
Globigerinelloides multispinatus	0.93		0.56	0.68			0.33	1.40		3.29	1.60
Globigerinelloides subcarinatus	19.81	12.50	9.86	8.11	6.56	25.00	19.14	8.15	7.14	11.11	5.60
Globigerinoides monmouthensis	0.31		0.56	0.68	0.55		0.66	1.69	1.43	1.23	2.40
Globotruncanella caravacaensis											
Globotruncanella citae						1.22	0.33	0.28		0.82	
Globotruncanella petaloidea		0.54	0.56	2.70	6.56	1.22	2.64	1.69	4.76	3.70	2.40
Guembelitria cretacea											0.40
Guembelitria danica											
Guembelitria trifolia											
Gublerina robusta					0.27	0.61		0.28	0.24	0.41	3.20
Hedbergella holmdelensis	2.17	3.80	4.79	4.73	3.01		0.66	1.40	1.43		
Hedbergella monmouthensis	7.12	5.43	11.27	11.71	10.11	4.27	5.61	5.06	5.24	4.53	2.00
Hedbergella sliteri	0.62						0.99	1.40			
Hedbergella sp.	1.55					1.22					
Heterohelix carinata	0.62	0.54	0.28	0.68	0.55	0.61					
Heterohelix complanata	4.33	16.30	12.11	11.04	23.77	9.76	8.58	10.39	10.24	7.82	8.40
Heterohelix dentata	0.62	2.72		0.45	1.37	0.61	1.32	0.84	0.95	1.23	3.20
Heterochelix globulosa	25.70	28.26	32.11	27.03	24.59	13.41	19.80	37.64	29.52	25.10	32.40
Heterohelix navarroensis				0.90	0.55		0.33	0.28			
Heterohelix planata	0.62	0.27	3.38	7.43	5.74	7.93		1.40	0.95		
Pseudoguembelina palpebra	0.93	1.36	1.41	1.13	0.82				1.90	0.41	
Pseudoguembelina punctulata						0.61	0.99	0.28		0.41	0.40
Pseudotextularia deformis								0.28			
Pseudotextularia elegans				0.23				0.28	0.24		
Rugoglobigerina rugosa	0.62	0.82	1.69	2.03	0.27			0.28			
Shackoina multispinatus	0.31			0.23			0.33	0.28			
Chiloguembelina crinita											
Chiloguembelina midwayensis											
Chiloguembelina morsei											
Chiloguembelina strombiformis											
Chiloguembelina waiparaensis	8.05	14.13	7.89	6.98	4.10	9.76	9.57	5.34	7.62	18.11	16.80
Woodringina claytonensis											
Woodringina hornerstownensis											
Eoglobigerina danica											
Eoglobigerina cf. *edita*											
Eoglobigerina eobulloides											
Eoglobigerina fringa											
Eoglobigerina simplicissima											
Eoglobigerina trivialis											
Globanomalina pentagona											
Globanomalina taurica											
Globoconusa conusa											
Globoconusa daubjergensis											
Globoconusa extensa											
Igorina spiralis											
Morozovella inconstans											
Murciglobigerina aquiensis											
Murciglobigerina chascanona											
Parvularugoglobigerina eugubina											
Planorotalites compressus											
Subbotina moskvini											
Subbotina pseudobulloides											
Subbotina triangularis											
Subbotina triloculinoides											
Subbotina varianta											
Zeuvigerina teuria											
Juveniles no identification	0.93	1.36		1.13	0.27						
Total number counted	323	368	355	444	366	164	303	356	420	243	250

20R-5 114–115	20R-5 100–111	20R-5 102–103	20R-5 100–101	20R-5 98–100	20R-5 97–98	20R-5 96–97	20R-5 95–96	20R-5 94–95	20R-5 93–94	20R-5 92–93
	0.31									
0.31										
19.57	12.62	13.56	10.19	6.61	6.74	8.55	1.19	2.37	3.86	9.03
3.36	0.62	0.42								
7.03	5.54	10.17	15.74	7.71	3.52	8.32	3.57	2.37	2.81	4.17
2.45	2.77	1.69	0.93		0.59	0.11				
								1.19	1.40	4.17
0.61	1.85	1.27	1.85			0.23				
		0.85		0.28	0.88	0.34	3.57	5.14	3.16	12.50
										9.03
	0.31			0.28	1.76					
0.31		0.42								
	0.31	0.85		9.64	9.97	5.13	1.19			
6.12	5.54	3.39	5.56			3.19				
	2.15									
						0.46				
4.89	7.38	10.59	7.41	5.51	2.93					
6.42	6.15	5.51	6.48			0.91			1.40	
33.33	38.77	34.75	31.48	28.10	16.42	3.99	7.14	2.37	2.81	2.08
0.61		0.42	2.78							
0.31										
2.45	1.85									
		0.42								
			0.28			4.76	0.40			
12.23	13.85	15.25	17.59	41.60	57.18	68.76	77.38	84.58	82.81	52.08
						1.19	0.79	0.70	4.17	
							0.79	1.05	2.78	
327	325	236	108	363	341	877	84	253	285	144

TABLE 1 (*continued*)

Core-section Depth in centimeters	20R-5 91–92	20R-5 90–91	20R-5 89–90	20R-5 88–89	20R-5 87–88	20R-5 86–87	20R-5 85–86	20R-5 84–85	20R-5 83–84	20R-5 82–83	20R-5 81–82
Abathomphalus intermedius											
Abathomphalus mayaroensis											
Globigerinelloides aspera	3.10	6.79	1.84	2.24	6.15	2.56	9.22	8.49	7.88	4.42	2.20
Globigerinelloides multispinatus											
Globigerinelloides subcarinatus	4.07	3.21	2.76	2.56	2.77	2.27	3.28	0.74	4.89	3.54	2.27
Globigerinoides monmouthensis							0.20				
Globotruncanella caravacaensis	0.58	1.89	0.92	0.32	0.31	0.85	0.61			3.10	
Globotruncanella citae											
Globotruncanella petaloidea		0.75	0.23		1.85		2.05	0.37		0.44	1.52
Guembelitria cretacea	15.50	7.92	19.54	10.22	1.85	5.68	0.20	1.48	0.82	0.44	
Guembelitria danica	2.52	2.26	0.69								
Guembelitria trifolia		0.75	6.90	4.47					0.27		
Gublerina robusta			0.23				0.20				
Hedbergella holmdelensis	0.58				4.92	0.28	1.84	2.58	3.53	0.44	8.30
Hedbergella monmouthensis				0.32						1.33	
Hedbergella sliteri											
Hedbergella sp.											
Heterohelix carinata											
Heterohelix complanata		0.19	0.46					0.37			
Heterohelix dentata		0.57									
Heterochelix globulosa	2.13	4.91	2.99	2.24	2.15	0.85	1.84	1.11	1.36	1.77	1.89
Heterohelix navarroensis											
Heterohelix planata											
Pseudoguembelina palpebra											
Pseudoguembelina punctulata											
Pseudotextularia deformis											
Pseudotextularia elegans											
Rugoglobigerina rugosa							0.20			0.44	
Shackoina multispinatus											
Chiloguembelina crinita	1.16	0.75	0.46	2.24	0.31	5.68		1.11	0.82		
Chiloguembelina midwayensis											
Chiloguembelina morsei											
Chiloguembelina strombiformis											
Chiloguembelina waiparaensis	68.60	66.42	60.00	72.20	55.69	63.64	68.65	61.62	62.50	77.43	59.47
Woodringina claytonensis											
Woodringina hornerstownensis					2.15	0.57	4.10	3.32	2.17	2.65	3.79
Eoglobigerina danica											
Eoglobigerina cf. *edita*		0.38									
Eoglobigerina eobulloides											
Eoglobigerina fringa	0.97	1.89	0.92	0.32	6.77	5.40	2.46	5.54	3.53		
Eoglobigerina simplicissima			0.23	0.64	5.23	0.57		0.74			
Eoglobigerina trivialis											0.38
Globanomalina pentagona					1.85			1.48			
Globanomalina taurica											
Globoconusa conusa	0.78	1.32	1.84	2.24		1.70	0.20	0.74	0.27		
Globoconusa daubjergensis		0.92	1.70	1.43	4.80			1.52			
Globoconusa extensa											
Igorina spiralis											
Morozovella inconstans											
Murciglobigerina aquiensis											
Murciglobigerina chascanona											
Parvularugoglobigerina eugubina		1.23	5.68	0.82	2.58	4.62	0.44	0.38			
Planorotalites compressus		1.85	1.42	2.25	1.85	2.72	0.44	0.38			
Subbotina moskvini		0.92	0.28	0.41	0.74	0.54	1.33	5.68			
Subbotina pseudobulloides		2.46	0.85		0.37	2.45	1.77	6.44			
Subbotina triangularis						0.82		1.14			
Subbotina triloculinoides		0.62				0.82		2.65			
Subbotina varianta											
Zeuvigerina teuria											
Juveniles no identification											
Total number counted	516	530	435	313	325	352	488	271	368	226	264

20R-5 80-81	20R-5 79-80	20R-5 74-75	20R-5 39-40	20R-5 4-5	20R-4 134-135	20R-4 99-100	20R-4 59-61	20R-4 19-21	20R-3 139-141	20R-3 99-101
4.88	1.89	1.85	16.28	6.86	8.24	5.13	5.60	1.02	0.85	2.53
	3.30	0.62	4.65	1.63	1.96	2.33	1.60	0.26		0.28
			1.00			0.23	0.27	0.26		
			0.66			1.86				
	0.24		1.99							
	2.59				0.39			0.26	0.56	
			0.33							
				0.33	0.39					
				0.65						
			1.00	3.92		0.23				
				0.98						
	1.65		2.33	2.29	1.18	0.70		0.51	0.56	
	2.59	3.70	7.64	0.33	0.78	2.33	1.07	0.26		0.56
			0.33			1.63	0.53			
					0.39					
	0.24		0.33		0.39	0.23			0.28	
						0.70			0.28	
								0.26		1.40
						0.23		0.77		
48.78	24.76	64.20	42.52	57.19	46.27	51.52	50.13	61.13	41.41	3.09
					0.39	1.40	2.67	0.26	0.28	0.28
				0.33			0.53	0.26	1.69	1.97
4.88					2.35					
			1.99	3.59						
					9.80	9.09	8.27	0.26	1.97	
	0.24	0.62	0.66	2.29	0.78		1.07	0.51		0.84
					0.39		3.20		1.69	0.84
	2.36	0.62			2.75	2.56	8.27	1.28	1.13	1.12
			0.33	0.33						
	5.19	4.94	1.00	0.65		0.23	0.53	0.77	0.28	7.58
								0.77		0.84
								0.77	7.61	12.36
								0.51	2.54	4.21
										1.69
4.88	5.90	6.79	4.98	5.23	1.57	7.93	7.20	6.14	3.66	16.29
14.63	5.19	0.62	0.33	2.94		0.47				
12.20	16.27	16.05	9.63	9.80	18.43	10.49	4.53	13.04	6.20	3.93
9.76	14.62		0.66		3.53		1.07	2.81	9.86	17.42
	11.08									
						0.70	2.67	7.42	18.59	21.63
	1.42		1	0.65			0.80	0.51	0.56	1.12
441	424	162	301	306	255	429	375	391	355	356

TABLE 1 (*continued*)

Core-section Depth in centimeters	20R-3 64–66	20R-3 39–41	20R-3 9–11	20R-2 129–131	20R-2 89–91	20R-2 49–51	20R-2 9–11	20R-1 119–121	20R-1 84–86	20R-1 49–51	20R-1 19–21
Abathomphalus intermedius											
Abathomphalus mayaroensis											
Globigerinelloides aspera	1.48	1.66	2.39	3.49	3.63	1.37	1.80	.350	5.00		2.22
Globigerinelloides multispinatus											
Globigerinelloides subcarinatus	0.89	0.55	1.37		0.30		0.26				
Globigerinoides monmouthensis				0.58			0.26				
Globotruncanella caravacaensis		0.28		0.58	0.30			0.70			
Globotruncanella citae											
Globotruncanella petaloidea											
Guembelitria cretacea	0.30										
Guembelitria danica											
Guembelitria trifolia							0.26				
Gublerina robusta											
Hedbergella holmdelensis											
Hedbergella monmouthensis											
Hedbergella sliteri											
Hedbergella sp.											
Heterohelix carinata											
Heterohelix complanata											
Heterohelix dentata											
Heterochelix globulosa	1.19		0.68	1.16	0.60	1.03	1.80		0.88	5	1.62
Heterohelix navarroensis											
Heterohelix planata											
Pseudoguembelina palpebra											
Pseudoguembelina punctulata											
Pseudotextularia deformis											
Pseudotextularia elegans											
Rugoglobigerina rugosa											
Shackoina multispinatus											
Chiloguembelina crinita	0.30						0.26				
Chiloguembelina midwayensis	2.67	1.93	1.37	1.45		1.37		1.05	1.76		
Chiloguembelina morsei	0.59	0.55	0.68			0.34	1.55				
Chiloguembelina strombiformis			1.71	4.07	5.74	15.75	4.64	3.85	3.82		7.22
Chiloguembelina waiparaensis	6.53	5.25	2.73	2.91	4.53	1.03	0.26	1.75	9.12	5	52.22
Woodringina claytonensis	1.19	0.28	0.34	0.29			1.03				
Woodringina hornerstownensis	0.59			2.03	1.51	1.03	0.26	1.40			
Eoglobigerina danica											
Eoglobigerina cf. *edita*											
Eoglobigerina eobulloides											
Eoglobigerina fringa											
Eoglobigerina simplicissima					0.30	1.03					
Eoglobigerina trivialis		1.93	1.37	0.58				0.70			
Globanomalina pentagona	5.34	4.42	12.29	12.21	15.11	14.04	9.79	4.90	7.94	1	9.44
Globanomalina taurica	13.35	12.71	15.02	10.76	19.34	7.88	13.66	10.49	16.47	1	2.78
Globoconusa conusa											
Globoconusa daubjergensis	13.06	20.17	21.16	19.77	13.29	19.18	18.04	9.79	6.47		0.56
Globoconusa extensa	2.67	1.66	1.71	2.33	3.02	0.68	3.09	1.05	1.19		
Igorina spiralis	7.72	9.67	3.07	2.03	2.72	1.03	2.06	5.59	2.94		1.11
Morozovella inconstans	0.89	0.28	1.71	3.49	4.53	9.59	3.35	4.55	3.24		
Murciglobigerina aquiensis	1.19	2.21	2.05	1.74	0.91	0.68	0.52	1.75	0.29		3.33
Murciglobigerina chascanona	0.59	1.38									
Parvularugoglobigerina eugubina											
Planorotalites compressus	13.06	15.47	12.63	16.28	11.78	17.12	11.60	12.59	15.59	1	12.22
Subbotina moskvini											
Subbotina pseudobulloides	10.09	7.73	4.78	9.88	11.18	4.79	24.23	34.27	25.29		7.22
Subbotina triangularis	8.90	2.49	4.44	0.58							
Subbotina triloculinoides	0.89	0.55	1.71	1.45	0.60	1.37	0.77	1.40			
Subbotina varianta	6.53	6.63	5.80	1.74			0.26	0.70			
Zeuvigerina teuria	0.89	0.55	1.71	1.45							
Juveniles no identification		2.21	1.02	0.58	0.60	0.68	0.26			1	
Total number counted	337	362	293	344	331	292	388	286	340	14	180

were recovered (Table 1). This 1 cm interval contains the lowest percent CaCO₃, 69% as compared to an average of 75% to 80% in the rest of the laminated layer (Thierstein et al., 1991). Tabulation of species abundance data in percent is given in Tables 1 and 2, and characteristic species are illustrated in Plates I–V.

Cretaceous reworking

Cretaceous species including *Globigerinelloides aspera, G. subcarinatus, Hedbergella holmdelensis, H. monmouthensis, Chiloguembelina waiparaensis* and *Heterohelix globulosa* are present in most samples examined above the K/T boundary. In many samples, the very large size and different preservation make it obvious that some of these specimens are reworked. It is likely, however, that most specimens of these Cretaceous taxa are from in-situ survivors as has been observed in other sections (Keller, 1988, 1989a; Barrera and Keller, 1990; Canudo et al., 1991; Keller et al., 1993). Because stable isotope values across the Cretaceous–Tertiary transition show no ¹³C shift in Site 738C (Barrera and Keller, in prep.), stable isotope measurements cannot be used to identify survivor taxa as has been done in low latitude sediments (Barrera and Keller, 1990). For a detailed study of the biogeographic distribution of Cretaceous survivor taxa in earliest Tertiary sediments, the reader is referred to MacLeod and Keller (in press) and MacLeod (in press).

Planktic foraminiferal zonation

During the past ten years, early Tertiary (Danian) planktic foraminiferal zonations of Bolli (1966), Blow (1979), Berggren (1977) and Berggren and Miller (1988) have changed completely thanks to intensive high resolution centimeter-scale studies of K/T boundary sections worldwide. The initial revision was made by Smit (1982) and modified by Smit and Romein (1985). This zonal scheme was fur-

ther refined by Keller (1988, 1989a,b), Canudo et al. (1991) and Keller and Benjamini (1991) based on high resolution quantitative faunal studies from both deep-sea and continental shelf sections and their zonation is applied in this study. This zonation currently provides a higher stratigraphic resolution than any of the other microfossil zonal schemes. Figure 2 illustrates this zonation and the most relevant datum levels along with the correlation to the zonal scheme of Berggren and Miller (1988), the Antarctic zonation recently developed by Stott and Kennett (1990a) based on Site 690C, and the nannofossil zonation of Pospichal and Wise (1990).

The planktic foraminiferal assemblages present in the Weddell Sea Site 690C and Kerguelen Plateau Site 738C are most similar to those observed on Walvis Ridge Site 528 in the South Atlantic (D'Hondt and Keller, 1991) and at Stevns Klint and Nye Klov in Denmark (Schmitz et al., 1992; Keller et al., 1993), but they also share most of the same taxa with Tethyan faunas. A similar observation was made by Pospichal and Wise (1990) for nannoplankton assemblages. The biostratigraphy and chronostratigraphy of Antarctic assemblages can therefore be easily evaluated based on the current low to middle latitude Danian zonal scheme. This zonal scheme is illustrated in Fig. 2 along with a sequence of major planktic foraminiferal datum events based on a composite data set of 15 K/T sections. A brief definition of Danian zones is given below.

Zone P0: Guembelitria cretacea *Zone*

Partial range of the nominate taxon. The base of this zone, which marks the K/T boundary is defined by the first occurrences of Tertiary species including *Eoglobigerina fringa, E. simplicissima, E. eobulloides, E. edita, Globastica conusa* and *Woodringina hornerstownensis.* The top of Zone P0 is defined by the first appearance of *Parvularugoglobigerina eugubina* and/or *P. longiapertura* (Canudo et al., 1991).
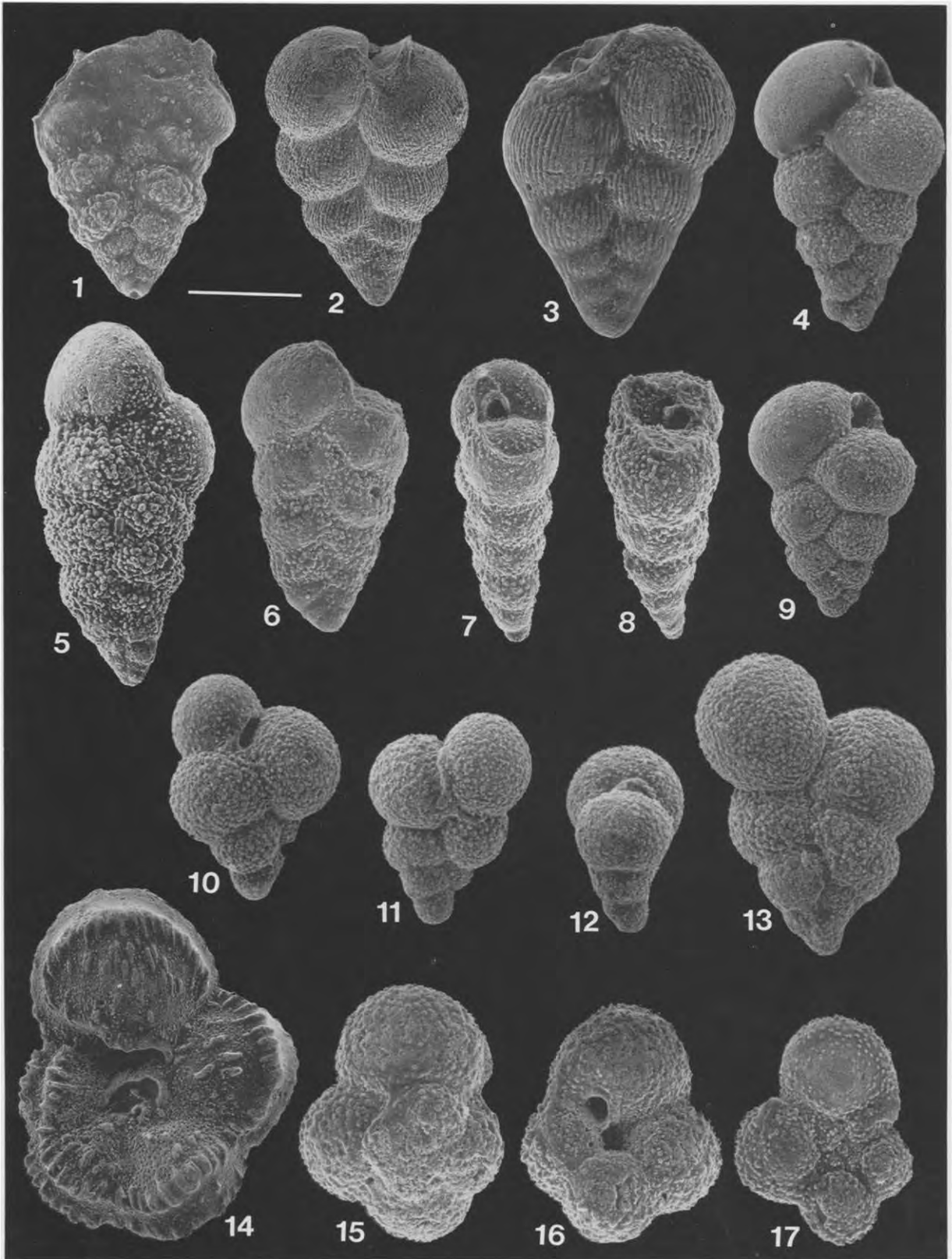
In deep-sea sections the last appearance of *Abathomphalus mayaroensis* is reported just below the first appearance of Tertiary species. This is not the case, however, in shallow continental shelf sections or in the Antarctic Ocean Site 738C where *A. mayaroensis* disappears well below the K/T boundary. *A. mayaroensis* is therefore not a reliable index taxon for identifying the K/T boundary (see also Huber, 1991). The K/T boundary is generally marked by a prominent lithological change from carbonate-rich marls to clay sedimentation and anomalously high values of iridium. Zone PO generally spans the K/T boundary clay layer and represents about 40–50 kyr (Berggren et al., 1985; Herbert and D'Hondt, 1990; MacLeod and Keller, 1991b). In the most continuous sedimentary records the K/T boundary corresponds to just above the middle of Chron 29R, whereas in sections with condensed sedimentation or hiatuses the K/T boundary often corresponds to near the Chron 29R/29N boundary (MacLeod and Keller, 1991b).

Zone P1a: Parvularugoglobigerina eugubina *Zone*

Interval from the first occurrence of *P. eugubina* and/or *P. longiapertura* to the last appearances of these taxa. The top of this zone appears to correspond to the basal part of magnetochron C29N. Zone P1a spans a minimum of 180 kyr (Berggren et al., 1985; Herbert and D'Hondt, 1990) to a maximum of 240 kyr (MacLeod and Keller, 1991b). Zone P1a is

characterized by the first major post-K/T boundary evolutionary diversification resulting in the first appearances of *Globoconusa daubjergensis, Planorotalites planocompressus, P. compressus, Globonomalina pentagona, G. taurica, Eoglobigerina trivialis, Subbotina pseudobulloides, S. triloculinoides, S. moskvini* and *Chiloguembelina midwayensis* (Plates I, II and V). Zone P1a can be subdivided into two parts P1a(1) and P1a(2) based on the first appearance of *Subbotina pseudobulloides* as proposed here:

Subzone P1a(1)

Interval from the first appearance of *P. eugubina* and/or *P. longiapertura* to the first appearance of *S. pseudobulloides* (Plates II and V).

Subzone P1a(2)

Interval from the first appearance of *S. pseudobulloides* to the last appearance of *P. eugubina* and/or *P. longiapertura*.

Most workers lump *P. longiapertura* (Blow) with *P. eugubina*, although future phylogenetic studies may eventually show that these are two distinct species (see Canudo et al., 1991). *P. longiapertura* is easily identified by the elongate slit-like aperture, compressed test and smooth surface. In contrast, P. eugubina has a low-arched aperture, non-compressed test, rounded chambers and lacks a smooth surface texture. Since both species have similar age ranges, either can be used to characterize Zone P1a. At Sites 738C and 752B relatively few *P.*

PLATE I

eugubina and *P. longiapertura* are present and they are cited as *P. eugubina* in Tables 1 and 2 and two specimens are illustrated in Plate V.

Zone P1b

Interval from the last occurrence of *P. eugubina* and/or *P. longiapertura* to the first occurrence of *Subbotina varianta* (Plate IV; Keller and Benjamini, 1991). Zone P1b corresponds to the lower part of magnetochron C29N.

Zone P1c: Subbotina pseudobulloides Zone

Partial range of nominate taxon from the first occurrence of *Subbotina varianta* to the first occurrence of *Morozovella trinidadensis*. The last appearance of *G. conusa* and first appearance of *M. inconstans* occur in the lower part of Zone P1c. The first appearance of *M. inconstans* seems to be globally isochronous (MacLeod and Keller, 1991a,b) even in the Antarctic Ocean (this study) and therefore is an excellent datum event to subdivide Zone P1c into two parts P1c(1) and P1c(2). This modification is proposed here.

Subzone P1c(1)

Interval from the first appearance of *Subbotina varianta* to the first appearance of *Morozovella inconstans* (Plate III and IV).

Subzone P1c(2)

Interval from the first appearance of *Morozovella inconstans* to the first appearance of *M. trinidadensis*.

Site 738C, Kerguelen Plateau, Indian Ocean

ODP Site 738C was drilled in 2252 m water depth on the southern Kerguelen Plateau (62.7°S, 82.8°E) in the Indian Antarctic Ocean. At the time of the Cretaceous–Tertiary transition the paleodepth of the Kerguelen Plateau was about 1000 m as estimated from normal subsidence rates for oceanic crust (Detrick et al., 1977). Thus, the high latitude location and relatively shallow paleodepth of Site 738C provides an ideal monitor for oceanographic changes in surface to intermediate water depths in the Indian Antarctic Ocean.

Sediment recovery was poor in uppermost Maastrichtian sediments which consist of indurated white chalks interlayered with cherts. These strata are overlain by softer Paleocene chalks and carbonate oozes. The K/T boundary was recovered within a 15 cm thick laminated clay-rich interval. An Ir anomaly marks the K/T boundary in a 2 mm thick grey clay layer (20R-5, 96.2 cm) 2 cm above the base of the laminated layer (Schmitz et al., 1991). Huber (1991) and Thierstein et al. (1991) reported the first appearances of Tertiary planktic foraminifera and calcareous nannoplankton immediately above the Ir anomaly as also

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PLATE II

Characteristic Danian fauna from the Antarctic Ocean Site 690C, Weddell Sea and Site 738C, Kerguelen Plateau except for figs. 1–3. All figures at 400× magnification (scale bar = 75 μm) except for figs. 5–7 which are at 200× magnification (scale bar = 75 μm).

1. *Globigerinelloides multispinatus* (Lalicker), Site 738C, 21R-1 (20–22 cm), *A. mayaroensis* Zone. *G. multispinatus* differs from *G. aspera* in having two apertures instead of one.
2, 3. *Globigerinelloides aspera* Bolli, Site 738C, 21-R-1 (20–22 cm), *A. mayaroensis* Zone.
4, 8, 9. *Planorotalites compressus* (Plummer), Site 690C, 15-2 (138–140 cm), Subzone P1c(1).
10. *Eoglobigerina eobulloides* (Morozova), Site 690C, 15-2 (101–103 cm), Subzone P1c(1).
11. *Eoglobigerina trivialis* (Subbotina), Site 690C, 15-2 (28–30 cm), Subzone P1c(1).
12, 13. *Subbotina pseudobulloides* (Plummer), Site 690C, 15-4 (9–11 cm), P1b Zone.
14–16. *Globonomalina taurica* (Morozova), Site 690C, 15-4 (9–11 cm), P1b Zone.
17–18. *Morozovella inconstans* (Subbotina), Site 690C, 15-1 (39–41 cm), P1c(2) Subzone.
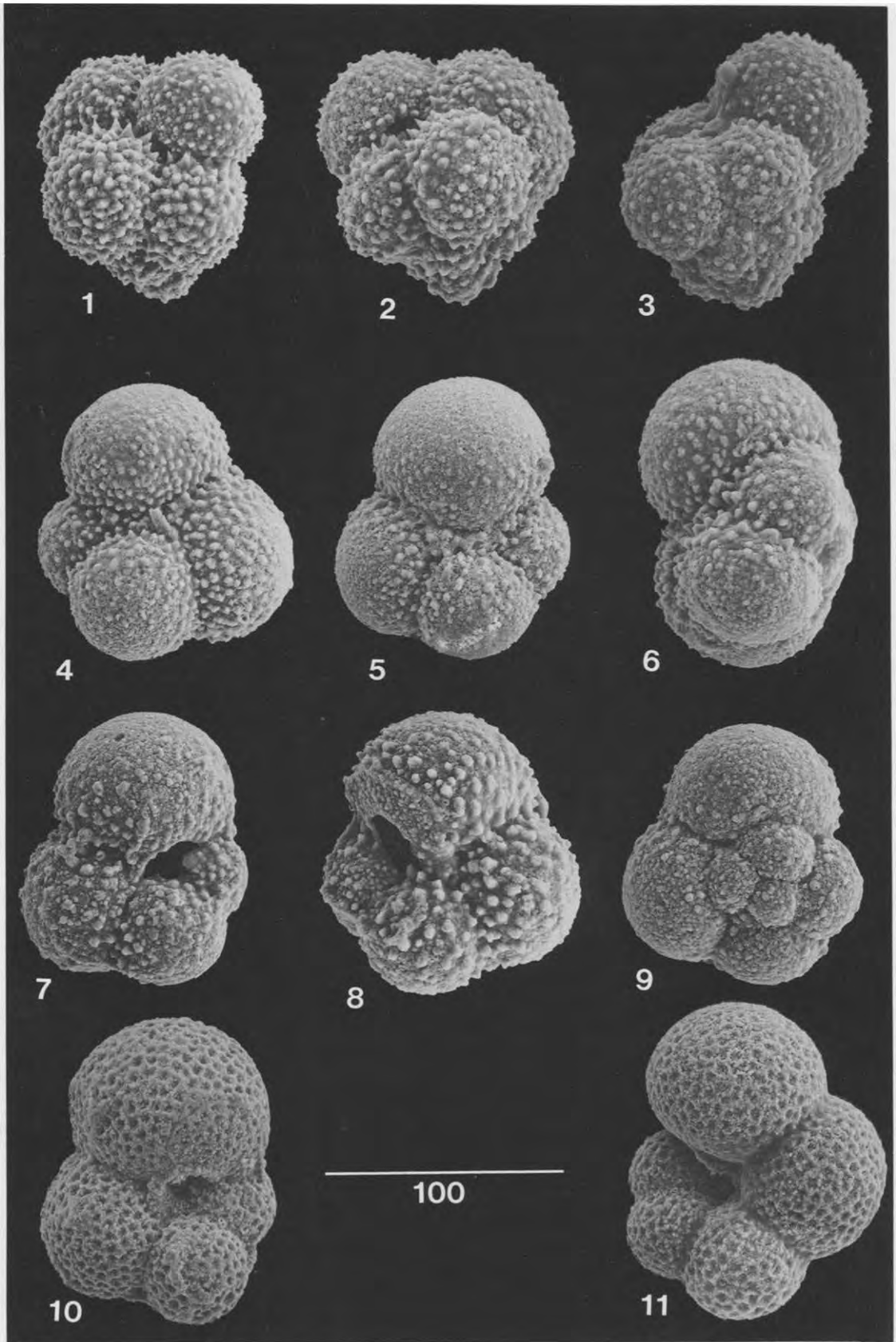
observed in this study. Magnetostratigraphy places the K/T boundary in Subchron 29R, but poor paleomagnetic data prevents closer determination of sediments above this interval (Thierstein et al., 1991).

Figure 3 illustrates the planktic foraminiferal biostratigraphy of Site 738C based on the zonation of Keller (1988, 1989a) and Keller and Benjamini (1991) and modified in this report as discussed earlier. The Antarctic planktic foraminiferal zonation of Stott and Kennett (1990a) based on this study and calcareous nannofossil zonations of Wei and Thierstein (1991) and Wei and Pospichal (1991) is provided for comparison. Huber's (1991) first and last appearances of datum events and his interpretation of Stott and Kennett's Antarctic zonation could not be confirmed in this study, nor could his taxonomic list or relative species abundances be confirmed. This is probably largely because Huber examined the >63 μm fraction, whereas most specimens of early Danian planktic foraminifera are in the smaller (38–63 μm) size fraction. Moreover, he based quantitative estimates of faunal abundances on 100 specimens, when 300 to 400 specimens are considered a minimum for a representative faunal count and statistical reproducibility (Buzas, 1990). For these reasons, no comparison can be made between this and Huber's (1991) study. The

Antarctic zonation of Stott and Kennett (1990a) shown in Fig. 3 was applied to the data set from this study.

Maastrichtian: A. mayaroensis *Zone*

Figure 4 shows the relative abundances of planktic foraminifers from the late Maastrichtian *A. mayaroensis* Zone through the early Tertiary Zone P1c. A close-up of the 1 cm scale analysis across the K/T transition spanning Zones P0 through P1a is illustrated in Fig. 5. A solid line marks the K/T boundary as defined by the first appearance of Tertiary planktic foraminifera (20R-5, 96–97 cm) which coincide with the Ir anomaly (20R-5, 96.2 cm).

From the K/T boundary downwards, the Maastrichtian is represented by 2 cm of laminated sediments, 5–6 cm of semi-soft chalk, a 14 cm thick chert layer and a few centimeters of chalk all present in the lower part of core 20R-5 (Fig. 3). Section 6 of core 20R is presumed missing, but section 1 of core 21R is present and consists of the same soft chalks as at the base of core 20R. Thus, a nearly continuous sedimentation record is present immediately below the K/T boundary. Chronologically, the age of this interval cannot be determined precisely because of poor core recovery below this interval. The sediments present, however, are reported to be C29R age
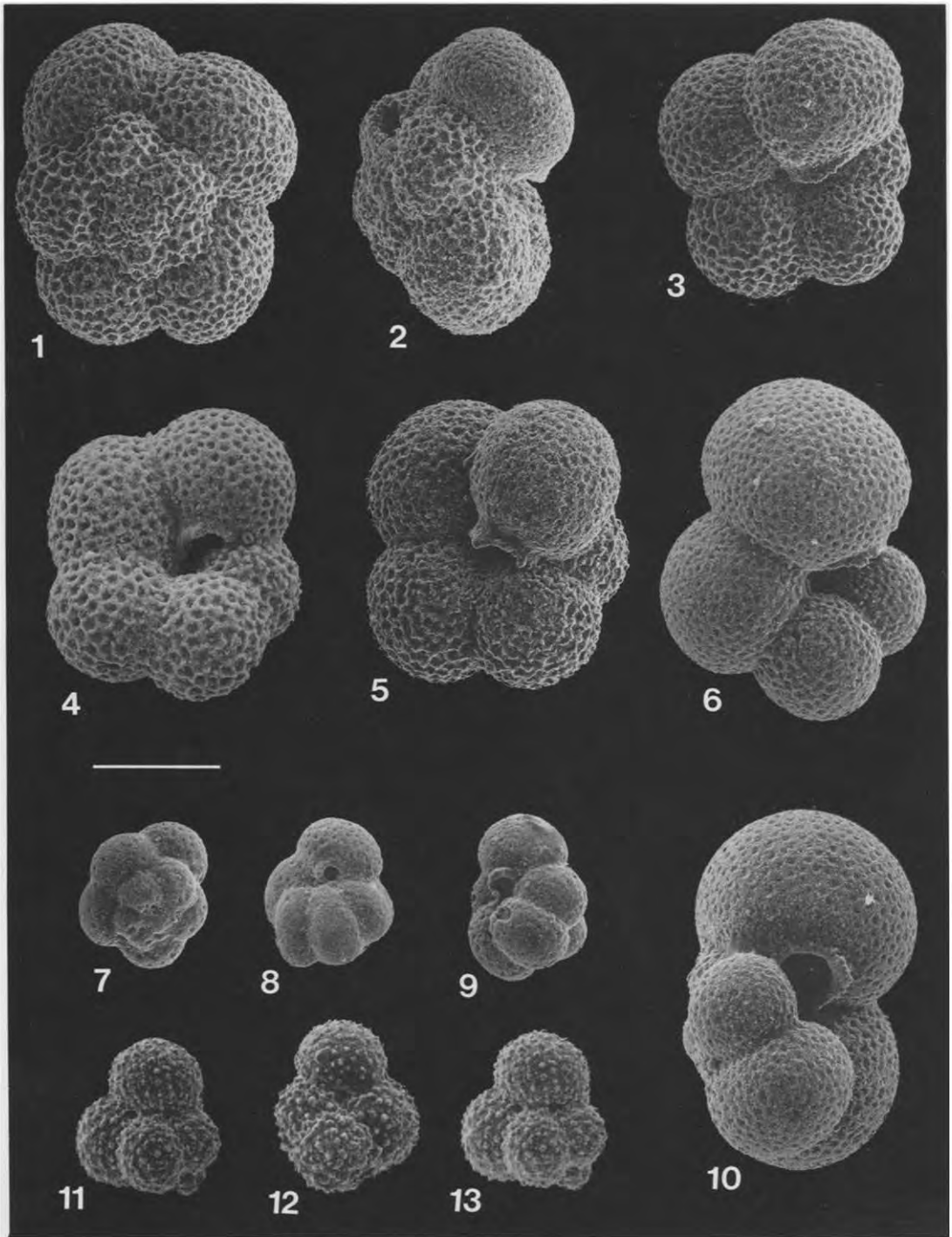

PLATE III

Characteristic Danian fauna from the Antarctic Ocean Site 690C, Weddell Sea. All figures at 650× magnification (scale bar = 100 μm).

1–3. *Globoconusa daubjergensis* (Brönnimann), Site 690C, 15-1 (19–21 cm), P1c(2) Subzone. Note the high spire of these specimens.

4–6. *Globoconusa* cf. *extensa* (Blow), this morphotype lacks the characteristic wide aperture and appears to be intermediate between *G. daubjergensis* and *G. extensa*. Site 690C, 15-1 (19–21 cm), P1c(2) Subzone.

7–9. *Globoconusa extensa* (Blow), Site 690C, 15-1 (19–21 cm), P1c(2) Subzone. Blow (1979) provisionally placed this species in the genus *Eoglobigerina* due to its wide aperture, but recognized that its finely perforate wall structure would place it in the genus *Globastica* (now *Globoconusa*). In this study *extensa* is placed in the genus *Globoconusa* due to its similar wall structure to *G. daubjergensis* and the presence of specimens without open apertures (*G.* cf. *extensa*) which indicates that apertural size is not a sufficient characteristic for placement in a different genus. Common *Globoconusa extensa* have only been observed in the Antarctic Ocean.

10. *Subbotina triloculinoides* (Plummer), Site 690C, 15-1 (19–21 cm), P1c(2) Subzone.

11. *Morozovella inconstans* (Subbotina), Site 690C, 15-1 (19–21 cm), P1c(2) Subzone.

	PLANKTIC FORAMINIFERAL ZONATION				Calc. Nanno.
Datum events		this study	Stott & Kennett 1990a	Berggren & Miller, 1988	Pospichal 1990
⊥ M. trinidadensis	P1d		AP1b	P1c	
⊥ M. inconstans	P1c	P1c(2)	AP1b		CP1b
T G. conusa / ⊥ S. varianta		P1c(1)		P1a & P1b	
T P. eugubina / T P. longiapertura	P1b		AP1a		
⊥ P. compressus / ⊥ E. trivialis / ⊥ G. pentagona / ⊥ S. pseudobulloides / ⊥ S. triloculinoides / ⊥ G. daubjergensis / ⊥ S. moskvini / ⊥ P. planocompressus / ⊥ G. taurica / ⊥ C. midwayensis	P1a	P1a(2)			
⊥ P. longiapertura / ⊥ P. eugubina		P1a(1)	unzoned	Pα	CP1a
⊥ E. eobulloides / ⊥ E. edita, W. hornerst. / ⊥ G. conusa / ⊥ E. fringa, E. simplic. / T P. deformis	P0			unzoned	
T A. mayaroensis	unzoned		A. mayaro-ensis	A. mayaro-ensis	N. frequens
	A. mayaro-ensis				

Fig. 2. Low to middle latitude planktic foraminiferal biozonation and datum level sequence based on a composite data set of 15 of the most complete K/T boundary sequences (MacLeod and Keller, 1991b) compared with biozonations of Stott and Kennett (1990a), Berggren and Miller (1988) and the nannofossil zonation of Pospichal (1990). Dashed line marks uncertain location of AP1a zonal boundary. Zonal index species are shown in bold type.

which spans the last 350,000 years of the Cretaceous and first 230,000 to 280,000 years of the Tertiary (Berggren et al., 1985; Herbert and D'Hondt, 1990; MacLeod and Keller, 1991b). Core 22R, section 1 is reported to be in C30N (Sakai and Keating, 1991).

Biostratigraphically the Maastrichtian sediments below core 20R-5, 110 cm are in the *Abathamphalus mayaroensis* Zone as indicated by the persistent presence of this index species, but above this interval *A. mayaroensis* is absent (see also Huber, 1991). The interval

PLATE IV

Characteristic Danian fauna from the Antarctic Ocean Site 690C, Weddell Sea. All figures at 400× magnification (scale bar = 75 μm).

1-5. *Globanomalina pentagona* (Morozova), Site 690C, 15-1 (19-21 cm), P1c(2) Subzone.
6, 10. *Subbotina varianta* (Subbotina), Site 690C, 15-2 (50-52 cm), P1c(1) Subzone.
7-9. *Igorina spiralis* (Bolli), Site 690C, 15-1 (119-121 cm), P1c(2) Subzone. This species has also been observed in Danian sediments of northern high latitudes (Nye Klov, Denmark).
11-13. *Globoconusa daubjergensis* (Brönnimann), Site 690C, 15-1 (121-123 cm), P1c(2) Subzone.
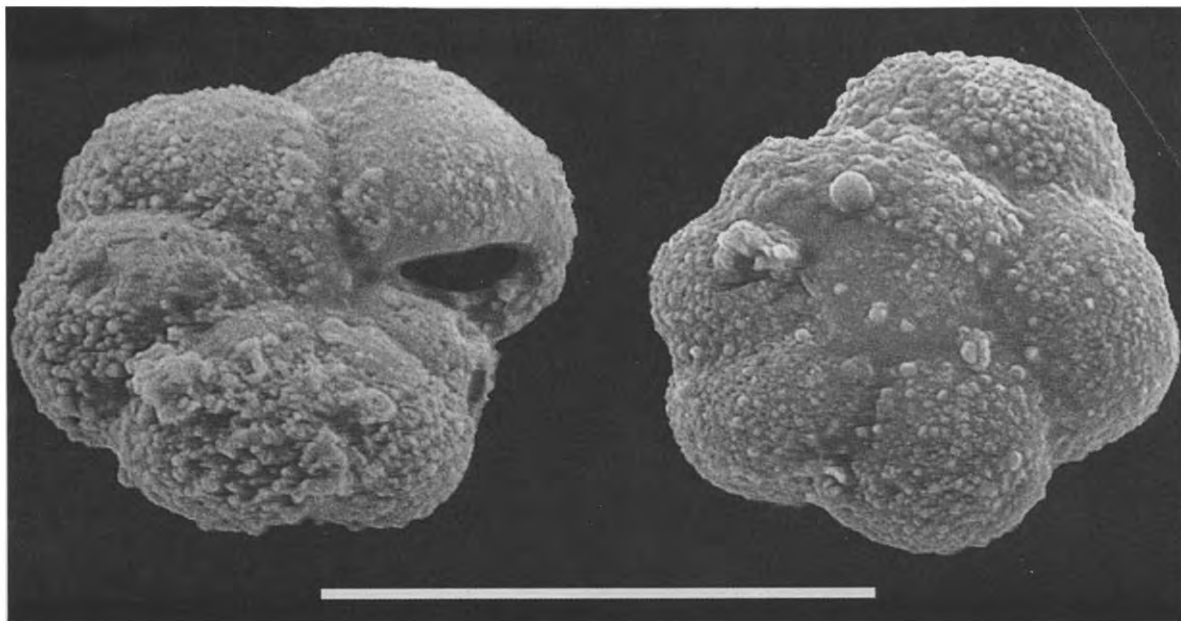
PLATE V

Parvularugoglobigerina eugubina (P. longiapertura) from ODP Site 738C, 20R-5, 86–87 cm, P1a(2) Subzone. Scale bar = 100 µm.

immediately below the K/T boundary is therefore unzoned (Figs. 4 and 5). *Abathomphalus mayaroensis* is frequently absent in uppermost Maastrichtian sediments either due to ecological exclusion, diachronous last appearance or extinction below the K/T boundary. In the latter case a hiatus could explain why in some sections this index species is found to range up to the K/T boundary (MacLeod and Keller, 1991b). Further studies are necessary to determine the extinction datum of *A. mayaroensis*.

Figures 4 and 5 illustrate that the dominant species in the uppermost Maastrichtian of Site 738C are *Heterohelix globulosa, H. complanata, Globigerinelloides aspera, G. subcarinatus, Hedbergella holmdelensis, H. monmouthensis* and *Chiloguembelina waiparaensis* (Plate I). All of these species are small, unornamented biserial, planispiral and trochospiral. Moreover, all except *Ch. waiparaensis* are cosmopolitan and common in middle and low latitudes at this time (Keller, 1988, 1989a; Canudo et al., 1991; D'Hondt and Keller, 1991;

Keller et al., in press). This indicates global dominance of a generalist fauna able to tolerate a wide range of conditions during at least the last 200,000 to 300,000 years of the Cretaceous.

Chiloguembelina waiparaensis Jenkins was originally described from the Tertiary Waipara Formation of New Zealand and until now has not been observed in Cretaceous sediments (Jenkins, 1971). Specimens from both Cretaceous and Tertiary sediments of Site 738C were examined by Jenkins who confirmed their identification as *Ch. waiparaensis* (D.G. Jenkins, pers. commun., 1991). This species apparently evolved during the late Maastrichtian in the Antarctic Ocean.

There are two major changes in the relative abundances of these generalist taxa in the Maastrichtian interval studied. The first faunal change occurs in core 21R-1 between 30 to 50 cm (Fig. 4) and results in a strong decrease in hedbergellids (*H. holmdelensis, H. monmouthensis*), some globigerinellids (*G. sub-*

Antarctic Ocean ODP Site 738C Foram. Zonations & Nanno. Zonations

EPOCH	POLAR	CORE	DATUM EVENTS	This Study	Stott & Kennett 1990a	Wei & Thierstein,1991	Wei & Pospichal, 1991
Tertiary	Polarity uncertain	20-1		P1c(2)	AP1b	CP1b	NP2
		20-2					
		20-3	⊥ M. inconstans Z. teuria ⊥ M. chascanona				
		20-4	⊥ I. spiralis, M. aquiensis G. extensa ⊥ S. varianta ⊥ W.claytonensis	P1c(1)			
				P1b	AP1a		NP1
			⊥ E. trivialis ⊤ P. eugubina			CP1a	
	C29R	20-5	G.pentagona, S. moskvini, S. triloculinoides, E. danica S. pseudobulloides, P. compressus, G. daubjergensis, ⊥ ◆P. eugubina	P1a(2)			
			⊥ E. simplicissima,E. eobull. ⊥ G. conusa, G. caravacaensis ⊥ E. fringa ⊥ C. crinita	P0	APα		
Cretaceous				unzoned	unzoned	N. frequens	NC23
		21-1	⊤ A. mayaroensis	A. maya-roensis	A.maya-roensis		

Fig. 3. Planktic foraminiferal zonation and datum level sequence of Site 738C based on this study and compared with the Antarctic zonation developed by Stott and Kennett (1990a) and nannofossil zonations of Wei and Thierstein (1991) and Wei and Pospichal (1991). Wiggly lines mark hiatuses. Zonal index species are shown in bold type.

carinatus) as well as some heterohelicids (H. complanata), whereas H. globulosa, G. aspera and G. multispina increase in relative abundance. Since the remainder of this core is missing, it is not possible to investigate this faunal change further in Site 738C. The second faunal change begins 4 cm below the K/T boundary and is marked by the terminal decline of all common Cretaceous taxa except Chiloguembelina waiparaensis which dramatically increases in relative abundance at this time as will be discussed below.

It is also instructive to examine the non-dominant taxa which vary from being consistently present, to rare or absent, in the interval below the K/T boundary. These taxa include all large specialized morphotypes including globotruncanids (A. mayaroensis, A. intermedius) and larger globular and multichambered forms (P. elegans, P. deformis, G. robusta). Taxa that are present show a gradual disappearance below the K/T boundary with larger forms generally disappearing earlier than smaller morphotypes (except for Shackoina
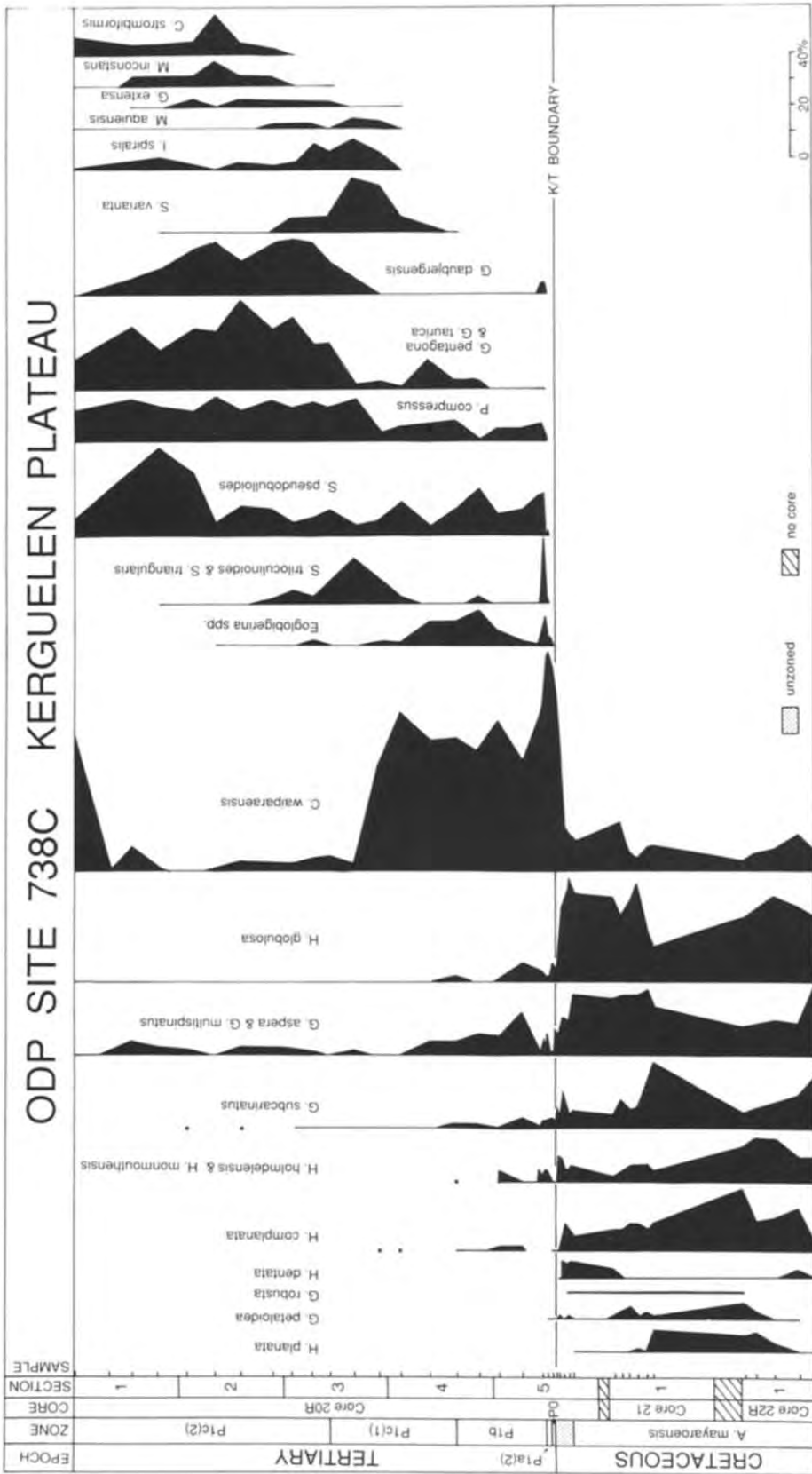
Fig. 4. Planktic foraminiferal turnover across the Cretaceous–Tertiary transition at Site 738C based on relative abundances of species. Solid line marks K/T boundary based on the first occurrence of Tertiary planktic foraminifera which coincide with the Ir anomaly. Note scale change in the Maastrichtian (diagonal lines mark missing core).
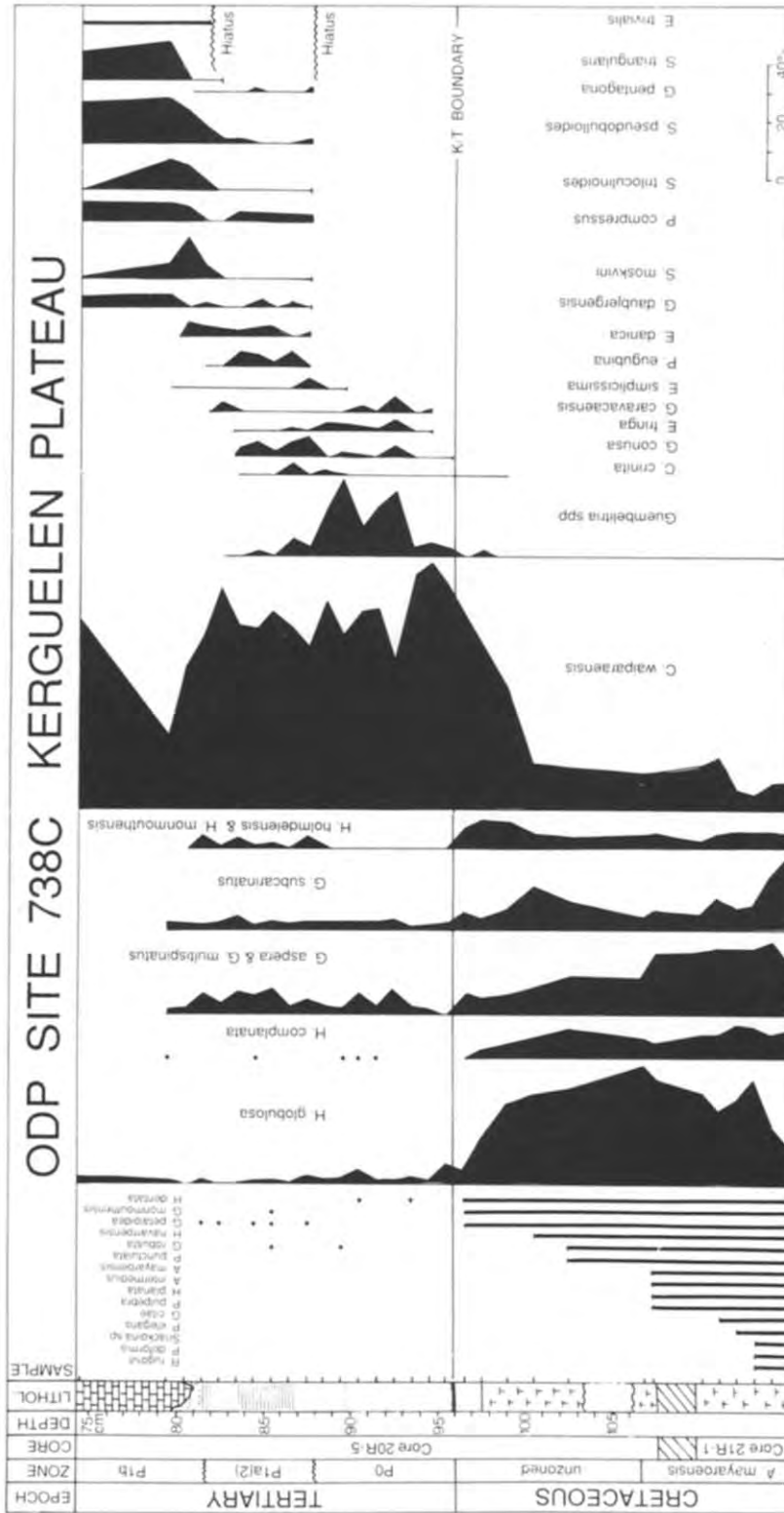
Fig. 5. Planktic foraminiferal turnover at the centimeter-scale in the laminated interval that spans the K/T boundary at Site 738C. Solid line marks the K/T boundary based on the first occurrence of Tertiary planktic foraminifera which coincide with the Ir anomaly. Two hiatuses are present at the P0/P1a and P1a/P1b boundaries. Note the sequential extinctions of relatively rare taxa in the latest Maastrichtian, the decline in the relative abundance of common taxa beginning 4 cm below the K/T boundary, and the increase in the opportunistic species *C. waipa-raensis*, all of which precede the K/T boundary impact implied by the Ir anomaly.

sp.; Fig. 5). Only small species range up to the K/T boundary (*Globotruncanella petaloidea, Globigerinoides monmouthensis,* and *Heterohelix dentata*) and some small species may have survived into the earliest Tertiary (*H. globulosa, Globigerinelloides aspera, G. subcarinatus*). This pattern of successive species disappearances, along with changes in the relative abundances of dominant species is indicative of long-term environmental changes which apparently preceded the K/T boundary. Such patterns cannot be attributed to the Signor–Lipps effect (Signor and Lipps, 1982) and dismissed with the argument that if you look hard enough you will find a specimen of each rare species right up to the K/T boundary where they "got wiped out" by the bolide impact (Ward, 1991). Implicit in this argument is the incorrect conclusion that the Signor–Lipps effect disproves gradual extinctions and proves that major extinctions are catastrophic. In fact, the Signor–Lipps theory simply cautions that because rare species may not be present in every sample, the last observed appearance may not be its absolute extinction. What is forgotten in this argument is that the behavior of stratigraphically rare taxa does not "make or break" the extinction hypothesis. Such rare and endangered species may have become extinct with or without a major environmental change.

K/T transition

The faunal transition across the K/T boundary in Site 738C begins 2 cm below the base of the laminated layer and 4 cm below the K/T boundary. Changes are dramatic in the fauna, in size variation of species, and in geochemical indicators (Figs. 5 and 6). All species are dwarfed in this interval (as well as through Zone P0) and in most cases reach maturity in less than half their usual size. Moreover, there is a sharp decline in abundances of *H. globulosa* from 40% to 4% by K/T boundary time, a decline and disappearance of *H. complanata,*

and gradual declines in *G. aspera* and *G. subcarinatus* (Fig. 5). Hedbergellids show a small relative abundance increase from 5 to 10% between 2 and 4 cm below the K/T boundary and decline and disappear near the boundary. The most dramatic change is seen, however, in *Chiloguembelina waiparaensis* which increases from 15% to 90% in the 4 cm immediately below the K/T boundary and presumably invaded niches vacated by other species. *Chiloguembelina waiparaensis* remains dominant throughout the laminated layer but decreases 2 cm above the K/T boundary from an average of 90% to 70% as triserial taxa (guembelitrids) increase and new Tertiary species evolve (Fig. 5).

Figure 6 illustrates the Ir concentrations with respect to the relative abundance, size variation and stable isotope values of *Chiloguembelina waiparaensis,* and geochemical ratios of Ba/Sc and Fe/Sc (Schmitz et al., 1991). Faunal abundance changes (Fig. 5) and dwarfing of *Ch. waiparaensis* clearly precede the Ir anomaly and the marked increases in Ba/Sc. and Fe/Sc ratios at the K/T boundary. The Ir anomaly is very large (17.76 ppb) with a sharp increase at the K/T boundary compared to other K/T boundary sections and it is unusual in that it tails off gradually while remaining high (> 4 ppb) throughout the laminated layers of Zones P0 and P1a. Above the laminated interval Ir concentrations are below 1 ppb (Schmitz et al., 1991).

The sharp increase in Ir concentration from 2.5 to 17.7 ppb occurs in the 1.8 cm laminated interval below the K/T boundary. A similarly sharp increase occurs in the Fe/Sc and Ba/Sc ratios, although the latter values temporarily drop in the 2 mm thin clay layer that contains the maximum Ir concentration (Fig. 6). These sharp geochemical anomalies clearly argue against sediment mixing or bioturbation as cause for the strong pre-K/T boundary species abundance and size variation changes (Figs. 5 and 6). If the pre-K/T boundary faunal changes were due to sediment mixing (no bio-
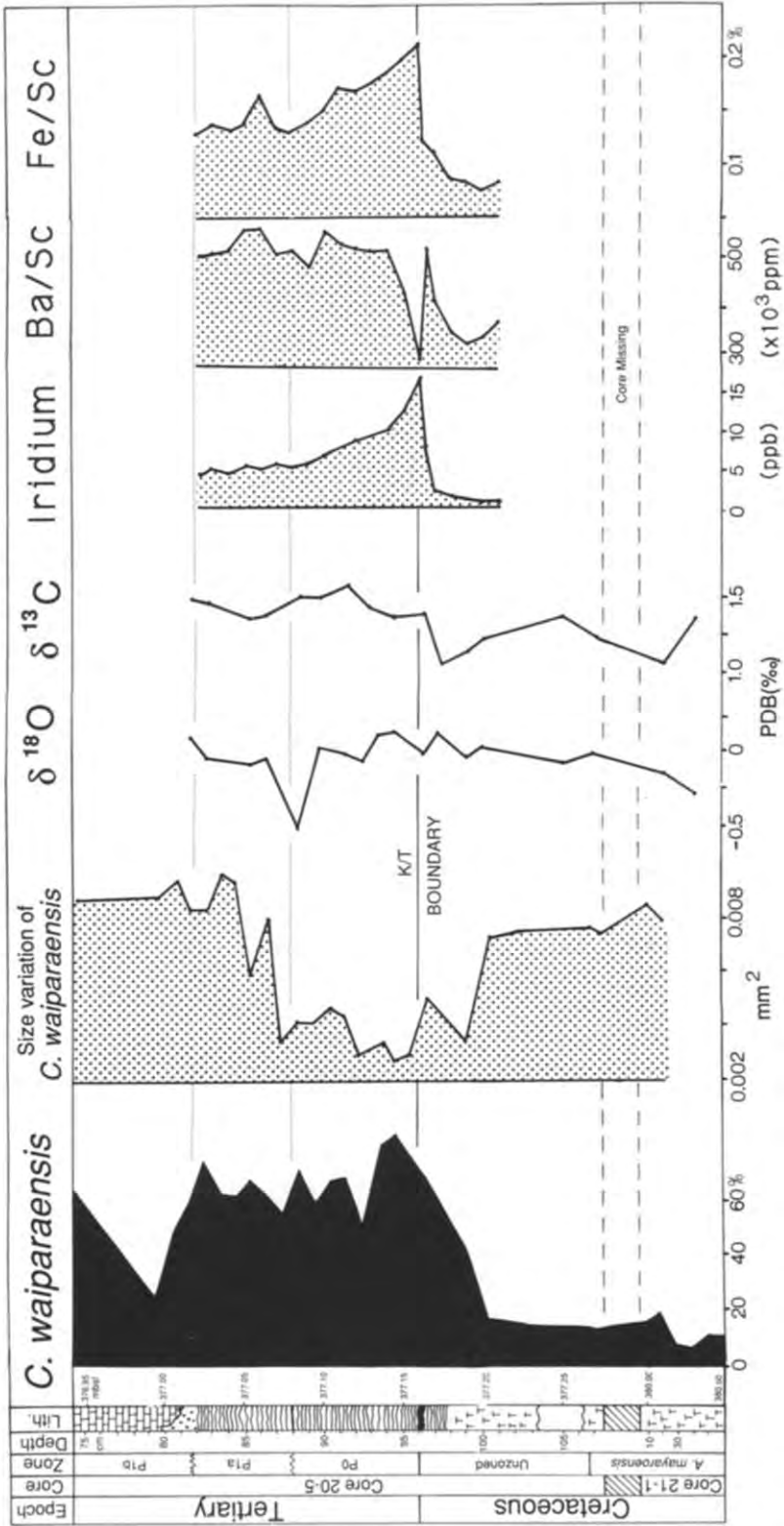
Fig. 6. Changing geochemical and faunal parameters across the K/T boundary at ODP Site 738C. Note the dramatic faunal change in relative abundance and size variation in *C. waiparaensis* beginning below the K/T boundary and the abrupt change in iridium concentrations, Ba/Sc and Fe/Se ratios at the boundary. Ir and geochemical data from Schmitz et al. (1991); stable isotope data based on *C. waiparaensis* from Barrera and Keller (in prep.).

turbation is evident in the laminated layer), one would expect the geochemical records to be equally mixed, which they are not. The faunal and geochemical data thus strongly support environmental changes immediately preceding the K/T boundary event.

Stable isotope data of *Ch. waiparaensis* show no major variations in either $\delta^{18}O$ or $\delta^{13}C$ values across the K/T boundary (Fig. 6). Surface temperatures remained stable whereas $\delta^{13}C$ values suggest a slight increase in surface productivity (Barrera and Keller, in prep.) in contrast to the productivity drop of 3 permil generally recorded in low latitudes (Zachos and Arthur, 1986; Zachos et al., 1989; Keller and Lindinger, 1989). Thus, unlike in the low latitudes, the environmental changes across the K/T transition in the Antarctic Indian Ocean were not related to climate and productivity changes, and they precede the Ir anomaly which is thought to be indicative of a bolide impact.

What then is the effect of the bolide impact on the planktic foraminiferal faunas? This is very difficult to determine in Site 738C as well as all other K/T sections with the most continuous sedimentation records. Clearly there was no sudden and catastrophic mass extinction at Site 738C, nor in other lower latitude regions (Keller, 1988, 1989a,b; Canudo et al., 1991; Keller et al., in press), as commonly claimed by impact proponents. In fact, at Site 738C it seems impossible to separate the effects of the proposed impact from the continued environmental changes in progress. It is likely, however, that a bolide impact hastened the demise of an already declining latest Cretaceous cosmopolitan fauna.

A clue to the nature of the K/T boundary environmental change in the Indian Antarctic Ocean can be gained from the geochemistry and the morphology of Cretaceous survivor taxa. For instance, as *C. waiparaensis* began to dominate the polar Indian Ocean, its test size (measured as total area of test) decreased by over 50% and continued through Zone P0 (Fig. 6). Similar dwarfing of test size beginning 4–5 cm below the K/T boundary is also observed in all other Cretaceous planktic and benthic foraminiferal species of Site 738C and thus implies changing oceanographic parameters in the surface to deep ocean. Similar species dwarfing across the K/T boundary has also been observed at El Kef, Brazos River and Nye Klov (Keller, 1988, 1989; MacLeod and Keller, 1990; Keller et al., 1993). Foraminiferal test size can be affected by changes in fertility and environmental stress (Berger, 1969; McNamarra, 1990; MacLeod and Keller, 1990). In fertile areas, planktic foraminifers exhibit rapid growth and reach early sexual maturation at relatively small test sizes.

Increased surface productivity may have been responsible for the species dwarfing at Site 738C. This is suggested by the increased Barium (Ba) concentrations, a proxy for productivity, beginning at the base of the clay-rich laminated interval (Schmitz et al., 1991). Figure 6 shows a significant increase in Barium normalized to Scadium (Ba/Sc) (Sc is an element contributed only by clay minerals) which most likely reflects enhanced surface water productivity. There is also a strong indication of higher surface productivity in the carbon isotopic composition of bulk sediments (Barrera and Keller, in prep.). $\delta^{13}C$ values of *C. waiparaensis*, however, do not indicate significantly higher productivity (Fig. 6). This is probably because *C. waiparaensis* lived at depth within the oxygen minimum zone and its isotopic composition may be affected by the oxidation of organic matter in the water column as also observed at Nye Klov by Keller et al. (1993).

The enhanced productivity suggested by the increased Barium concentrations may be related to the Fe enrichment (Fe normalized to Sc) which began at the base of the clay-rich laminated interval (Fig. 6). Martin (1990) proposed that in an iron deficient ocean phytoplankton are unable to utilize excess surface nitrate/phosphate, whereas Fe enrichment would greatly enhance phytoplankton growth.

It is possible that the Fe enrichment at Site 738 is due to Fe-rich atmospheric dust derived from terrestrial arid regions. There is some stable isotopic evidence for high latitude climate warming at this time in Denmark (Schmitz et al., 1992; Keller et al., 1993) as well as the Atlantic Antarctic Ocean Site 690 (Stott and Kennett, 1990b).

Thus, increased abundance and dwarfing of *C. waiparaensis* and increased Ba and Fe concentrations strongly indicate enhanced surface water productivity beginning at the base of the clay-rich laminated interval several thousand years prior to the K/T boundary. This increased surface productivity in polar regions is in marked contrast to the decreased surface productivity generally observed in low latitude regions. It is still unclear, however, what triggered these pre-K/T boundary changes in sedimentation, faunal turnover and surface productivity although available data point towards a climatic warming associated with a sea level rise which continued across the K/T boundary and Zone PO (MacLeod and Keller, 1991a,b; Schmitz et al., 1992; Keller et al., 1993).

Zone PO

In the most continuous K/T boundary sequences known to date, Zone PO is present at the base of the Tertiary. This zone spans from the first appearance of Tertiary planktic foraminifers (*E. fringa, E. simplicissima, G. conusa, W. hornerstownensis*) to the first appearance of *Parvularugoglobigerina eugubina* (or *P. longiapertura*). To date only seven K/T boundary sequences are known with such a continuous sedimentation record (El Kef, Tunisia (Smit, 1982; Keller, 1988), Agost and Caravaca, Spain, (Canudo et al., 1991), 3 sections at Brazos River, Texas (Keller, 1989a,b), and Nye Klov, Denmark (Keller et al., 1993). In all of these sections, except for the shallow water Brazos River sections, Zone PO is represented by a dark grey to black clay layer (see also Smit and Romein, 1985). Moreover, sed-

iment deposition occurred in less than 500 m depth in all of these sections. In contrast, all deep-sea sections that were deposited at depths greater than 1000 m appear to have a hiatus or condensed interval with Zone PO and frequently Zone P1a missing (MacLeod and Keller, 1991a,b).

Site 738C, which was deposited at about 1000 m depth, is the first deep-sea section recovered with Zone PO present. Figure 5 shows this zone with maximum abundances in triserial guembelitrid species and the first Tertiary taxa *Globoconusa conusa, Eoglobigerina fringa, E. simplicissima* and *Globotruncanella caravacaensis* all of which are characteristic of this zone at all latitudes. What is different and endemic to the Indian Antarctic Ocean is the dominance of biserial *Chiloguembelina waiparaensis* and the presence of rare *C. crinita*. Zone PO is represented by only 8 cm of laminated sediments. This is comparable to Zones PO in the Agost and Caravaca sections (Canudo et al., 1991) where a hiatus is present at the PO/P1a Zone boundary as also observed at Site 738C.

Zone P1a

Zone P1a spans the interval from the first to the last appearance of *Parvularugoglobigerina eugubina* or *P. longiapertura*. In Site 738C this zone is very short and represented by only 6 cm of laminated sediments (Fig. 5). At the base of this zone, (sample 20R-5, 88–87 cm) eight new Tertiary species appear (*P. eugubina, Eoglobigerina danica, Globoconusa daubjergensis, Subbotina moskvini, S. triloculinoides, Planorotalites compressus, S. pseudubulloides, Globonomalina pentagona*). Since these eight species evolve sequentially in the lower part of Zone P1a (Keller, 1988, 1989; MacLeod and Keller, 1991b), their sudden appearance in the same 1 cm interval marks a short hiatus or interval of nondeposition at the PO/P1a zone boundary, similar to the hiatus observed in the Agost and Caravaca sections

(Canudo et al., 1991; MacLeod and Keller, 1991b). The lower part of Zone P1a [Subzone P1a(1)] appears to be missing at this hiatus as well as part of Zone P0 (Figs. 3 and 5). Most species present are characteristic of Zone P1a at all latitudes. Endemic high latitude species present are *C. waiparaensis* and *C. crinita* as well as *Eoglobigerina danica*, a species known from K/T boundary sections in Denmark.

The top of Zone P1a coincides with the top of the laminated clay layer (20R-5, 82 cm). Above this layer is a 1.5 cm thick disturbed interval (probably due to coring) followed by a well indurated chalk layer. Foraminifera are recrystallized in this chalk layer and most earliest Tertiary taxa have disappeared, including *P. eugubina, G. conusa, E. fringa* and *E. danica* (Fig. 5). This interval is thus characteristic of Zone P1b. A hiatus is present at the P1a/P1b Zone boundary that has removed part of the upper part of Subzone P1a(2). This is indicated by the lithologic break that juxtaposes the laminated clay layer and the overlying indurated chalk, the sudden disappearance of Danian species and the sudden rise to dominance of Tertiary nannofossils at this interval (Thierstein et al., 1991). In addition, Zone P1a is very short (6cm) at Site 738C as compared to Brazos River (50 cm), Agost and Caravaca (70 cm) and El Kef (300 cm). In all of these sections, except El Kef, a hiatus can be recognized at the P1a/P1b boundary (Keller, 1988, 1989; Canudo et al., 1991; MacLeod and Keller, 1991b).

Zone P1b

Relative species abundances in the early Tertiary Zones P1b and P1c are illustrated in Fig. 4. Zone P1b is present in the interval between the top of the laminated layer in Core 20R-5, 81 cm and Core 20R-4, 100 cm which is characterized by continued abundance of *C. waiparaensis*, common *Eoglobigerina* sp., *S. pseudobulloides, G. pentagona*, and few *G. daubjergensis* (Fig. 4; Plate III). The absence

of *P. eugubina* in this interval and first appearance of *Subbotina varianta* at the top of this interval characterizes Zone P1b (Fig. 3). As discussed earlier a hiatus appears to be present between Zones P1a and P1b.

Zone P1c

The interval from the first appearance of *Subbotina varianta* which marks the Zone P1b/P1c boundary in core 20R-4, 100 cm to the top of the section examined (top of core 20) is characteristic of Zone P1c (Fig. 4). Datum events of Zone P1c which appear to be endemic to the Antarctic Ocean Sites 738C and 690C, as well as northern high latitudes (Nye Klov, Denmark), include *Igorina spiralis, Murciglobigerina aquiensis* and *Globoconusa extensa* near the base of Zone P1c followed by *M. chascanona* and *Zeuvigerina teuria* (Plates III and IV; Huber reported a single occurrence of *Z. teuria* in Core 21R-cc). These taxa have not been observed in lower latitudes during the Danian. *Morozovella inconstans* first appears (together with *Z. teuria*) in core 20R-3, 65 cm and seems to have a globally synchronous first appearance (MacLeod and Keller, 1991b) that makes it an excellent index species for subdividing Zone P1c into two parts P1c(1) and P1c(2) (Fig. 3). *Morozovella inconstans* also marks the AP1a/AP1b zonal boundary of Stott and Kennett (1990a).

The P1c(1) to P1c(2) zonal subdivision is characterized by a dramatic drop in abundance of *C. waiparaensis* from 70% to 5%, high abundance in *I. spiralis* and *S. varianta* and increasing abundances in *G. daubjergensis, P. compressus* and the *G. pentagona–G. taurica* group. The upper part of Zone P1c [P1c(2)] is marked by common *C. strombiformis*, high abundance in *S. pseudobulloides, G. pentagona–G. taurica* group, *P. compressus, G. daubjergensis*, and increasing abundance in *M. inconstans* (Fig. 4). Moreover, the last sample examined in Site 738C shows an increase in the abundance of *C. waiparaensis*. The sudden

drop in *C. waiparaensis* and their continued low abundance through most of Subzone P1c(2) seems to imply a change in oceanographic conditions in the Indian Antarctic Ocean. Little is known regarding environmental preferences of chiloguembelinids. Boersma and Premoli Silva (1987) proposed that they may have thrived in low oxygen environments. If this is the case, then dominance of *C. waiparaensis* in Zones P0 to P1c(1) would indicate an expanded O_2 minimum zone in the southern Kerguelen Plateau which was deposited at about 1000 m depth. Stable isotope data of *C. waiparaensis* at Site 738C as well as from Nye Klov suggest that this is the case (see Keller et al., 1993). It seems, however, that these conditions would have been localized (isolated basin?) since chiloguembelinids are nearly absent in the Weddell Sea Site 690C which was deposited at 2000 m depth (Zones P1b-P1c).

Site 752B Broken Ridge, Indian Ocean

Site 752B was drilled in 1086 m water depth on Broken Ridge in the Southern Indian Ocean (30°53'S, 93°34'E). At the time of the Cretaceous-Tertiary transition, Broken Ridge was located between paleolatitudes 50° to 55°S near the northern part of the Kerguelen Plateau at a paleodepth of 1000 m (Pospichal et al., 1991). The K/T boundary transition was recovered in an expanded sequence of indurated Maastrichtian chalks overlain by a sequence of uppermost Maastrichtian to Tertiary ash (6.5 m thick), chert and chalk layers. Sediment recovery consists of numerous drilling biscuits as a result of the chert and indurated chalk layers. An iridium anomaly was found at the K/T boundary (11R-3, 94 cm) and high Ir values, possibly due to reworking, are also present 80 cm above the K/T boundary (Asaro et al., 1991). The last Cretaceous planktic foraminifera are reported to occur at the first Ir anomaly (Van Eijden and Smit, 1991). The first Tertiary nannofossil *Bianthol-*

ithus sparsus appears in 11R-3, 72 cm, 22 cm above the Ir anomaly (Pospichal, 1991). No planktic foraminifers were identified immediately above the K/T boundary. Magnetostratigraphy places the K/T boundary near the middle of C29R (Gee et al., 1991).

For this study 20 samples were examined across the K/T transition. Foraminiferal preservation is generally good in uppermost Cretaceous sediments, but very poor in the basal Tertiary interval and no quantitative study was possible. The biostratigraphy of Site 752B based on this study is illustrated in Fig. 7 along with the magnetostratigraphy and calcareous nannofossil zonations.

Maastrichtian: A. mayaroensis Zone

The uppermost Maastrichtian sediments examined (12R-1, 150 cm to 11R-3, 88–89 cm) contain a typical latest Cretaceous fauna similar to Site 738C including the nominate taxa *A. mayaroensis* and common *Chiloguembelina waiparaensis*. In the well-indurated chalks immediately below the K/T boundary (11R-3, 119–120 cm) no planktic foraminifers could be separated although the sediments contain abundant clasts. Van Eijden and Smit (1991), however, report Cretaceous planktic foraminifers including *A. mayaroensis* in core IIR-3, 96–77 cm just 1 cm below the Ir anomaly. Sample spacing in their study, however, is 1 sample per core, or about 9 m; the continuity of *A. mayaroensis* in the uppermost Maastrichtian at site 752 is therefore still uncertain. No planktic foraminifera were recovered from sediments immediately above the K/T boundary (11R-3, 89 cm) and no samples were available for the K/T boundary interval.

K/T transition

The biostratigraphic completeness of Site 752B cannot be determined precisely based on planktic foraminifers because of dissolution and poor preservation. The first Tertiary

Fig. 7. Planktic foraminiferal zonation and datum level sequence of Site 752B based on this study and compared with Van Eijden and Smit (1991) and nannofossil zonations of Resiwati (1991) and Pospichal (1991). Zonal index species are shown in bold type.

planktic foraminifers were found in a glauconite-rich sample about 55 cm above the K/T boundary (11R-3, 30-40 cm). A diverse although poorly preserved assemblage is present in this sample containing *Subbotina pseudobulloides, Globoconusa daubjergensis, Planorotalites compressus, Eoglobigerina eobulloides, E. fringa, Guembelitria cretacea, Chiloguembelina waiparaensis, C. midwayensis, Parvularugoglobigerina eugubina* and *P. longiapertura*. This species assemblage is characteristic of Zone P1a because of the presence of the in-

dex taxa *P. eugubina* and *P. longiapertura* (Fig. 6). In this study no data was available for the 55 cm interval between the Ir anomaly and the Zone P1a assemblage and it cannot be ruled out that Zone P0 and hence a biostratigraphically complete sequence may be present. Van Eijden and Smit (1991) did not find any planktic foraminifers between the K/T boundary and core 10R-6, including the interval reported here. This may be due to the rarity of samples containing foraminifers (many samples are barren), the fewer samples they ex-

amined, and their examination of only the larger (>63 μm) size fraction.

No *Parvularugoglobigerina eugubina* or *P. longiapertura* were found in samples 11-2, 135 cm and 11R-2, 115 cm, however, *Globanomalina taurica, G. pentagona* and *Subbotina triloculinoides* are present. In the absence of Zone P1a index taxa and *S. varianta*, this interval is probably part of Zone P1b. *Subbotina varianta* which marks the P1b/P1c boundary first appears in 10R-6, 110 cm along with *E. trivalis*. The first appearance of *Morozovella inconstans*, the marker species for the P1c(1)/ P1c(2) boundary was observed in 10R-4, 49 cm. Resiwati (1991) reported the CP1a/CP1b nannofossil boundary in 11R-2, 135 cm and Pospichal (1991) reported the NP1/NP2 nannofossil boundary in 10R-6. The relative positions of these calcareous nannofossil zonal boundaries with respect to the planktic foraminiferal zonal boundaries of this study are approximately the same in Sites 738C and 752B. This indicates that these two sections are biostratigraphically comparable at this interval (Figs. 3 and 7).

Site 690C Maud Rise, Weddell Sea

Site 690C was drilled in 2914 m water depth on the southwestern flank of Maud Rise in the Weddell Sea (65°10'S, 1°12'E). Depth of deposition at K/T boundary time is estimated at about 2000 m (Stott and Kennett, 1990a). Sediment recovery across the Cretaceous–Tertiary transition is excellent. The K/T boundary interval, however, is intensely bioturbated as observed by the mixing of Maastrichtian light colored chalks with brown clay-rich Tertiary chalks, as well as by the mixing of Cretaceous and Tertiary microfossils. A prominent iridium anomaly is present (Michel et al., 1990) coincident with the first occurrence of Tertiary nannofossils (Pospichal and Wise, 1990) and planktic foraminifera (Stott and Kennett, 1990a) and thus marks the K/T boundary. Magnetostratigraphy places the K/

T boundary near the top, as compared to the upper one third, of C29R which is usually the case in pelagic sections (Channell and Dobson, 1989). Despite this anomaly most shipboard studies found the K/T transition to be essentially continuous, albeit condensed because of the presence of an Ir anomaly. Pospichal and Wise (1990), however, argued for the presence of a hiatus near the K/T boundary (CP1a/CP1b boundary). Our study supports their observation.

Figure 8 illustrates the planktic foraminiferal biostratigraphy of Site 690C based on this study and its correlation to the magnetostratigraphy (Hamilton, 1990), the nannofossil zonation of Pospichal and Wise (1990) and the Antarctic planktic foraminiferal zonation by Stott and Kennett (1990a). Strong bioturbation across the K/T boundary has resulted in the common presence of Tertiary taxa in Cretaceous sediments as shown in Fig. 9 and Table 2. Since this anomalous Cretaceous occurrence of Tertiary taxa is obviously an artifact of bioturbation, their first appearances are listed at the base of Tertiary sediments in Fig. 8.

Maastrichtian: A. mayaroensis Zone

The uppermost Maastrichtian at Site 690C correlates to the top of *A. mayaroensis* Zone with the nominate taxon consistently present. The topmost sediments of the Maastrichtian, however, may not be present. This is suggested by the early Danian hiatus at the K/T boundary that is apparent in planktic foraminifera as discussed below. The similarities in relative abundance variations between Sites 690C and 738C in the uppermost Maastrichtian suggest, however, that only the top few tens of centimeters may be missing (Figs. 4 and 9).

As at Site 690C, planktic foraminiferal assemblages are dominated by small cosmopolitan heterohelicid, globigerinellid, globotruncanellids and hedbergellid taxa including

Antarctic Ocean ODP Site 690C Foram. & Nanno. Zonations						
EPOCH	POLAR	CORE	DATUM EVENTS	This Study	Stott &Kennett 1990a	Pospichal & Wise, 1990
Tertiary	NO DATA	14		P1c(2)	AP1b	
		15-1				
		15-2	⊥ M. Inconstans			CP1b
		15-3	⊥ I. spiralis, M. aquiensis M. chascanona	P1c(1)	AP1a	
			⊥ S. varianta			
			⊥ W. claytonensis C. midwayensis, W. hornerst. ⊥ S. triloculinoides, S. pseudobulloides, P. compressus, G. extensa, G. daubjergensis, E. eobulli, G. trivialis, S. moskvini, G. pentagona, G. taurica	P1b		CP1a
Cretaceous	C29R	15-4	⊥ A. mayaroensis			
		15-5		A. maya- roensis	A.maya- roensis	N. frequens
		15-6				
		18				

Fig. 8. Planktic foraminiferal zonation and datum level sequence of Site 690C based on this study and compared with Stott and Kennett (1990a) and Pospichal and Wise (1990). Wiggly line marks hiatus at K/T boundary. Zonal index species are shown in bold type.

Heterohelix globulosa, H. complanata, H. dentata, Hedbergella monmouthensis, Globigerinelloides aspera, G. multispinatus and G. subcarinatus (Fig. 9; Plates I and II). Guembelitria cretacea, a nearshore taxon, is conspicuously rare or absent. High abundance of Gublerina robusta in Site 690C (Plate I) and its near absence in Site 738C suggests that this species is endemic to the Atlantic Antarctic Ocean. In contrast, the rare occurrence of Chiloguembelina waiparaensis in Site 690C and its high abundance in Site 738C suggests that this species is endemic to the Indian Antarctic Ocean. These faunal differences may indicate the existence of a geographic watermass barrier between the Atlantic and Indian Antarctic Oceans at this time. Despite these differences the relative abundances of the dominant taxa in Chron 29R of Sites 690C and 738C are similar although the faunal change observed in Site 738C cannot be identified in Site 690C. This is probably due to the major abundance fluctuations induced by carbonate dissolution and the resultant peak abundances in dissolution
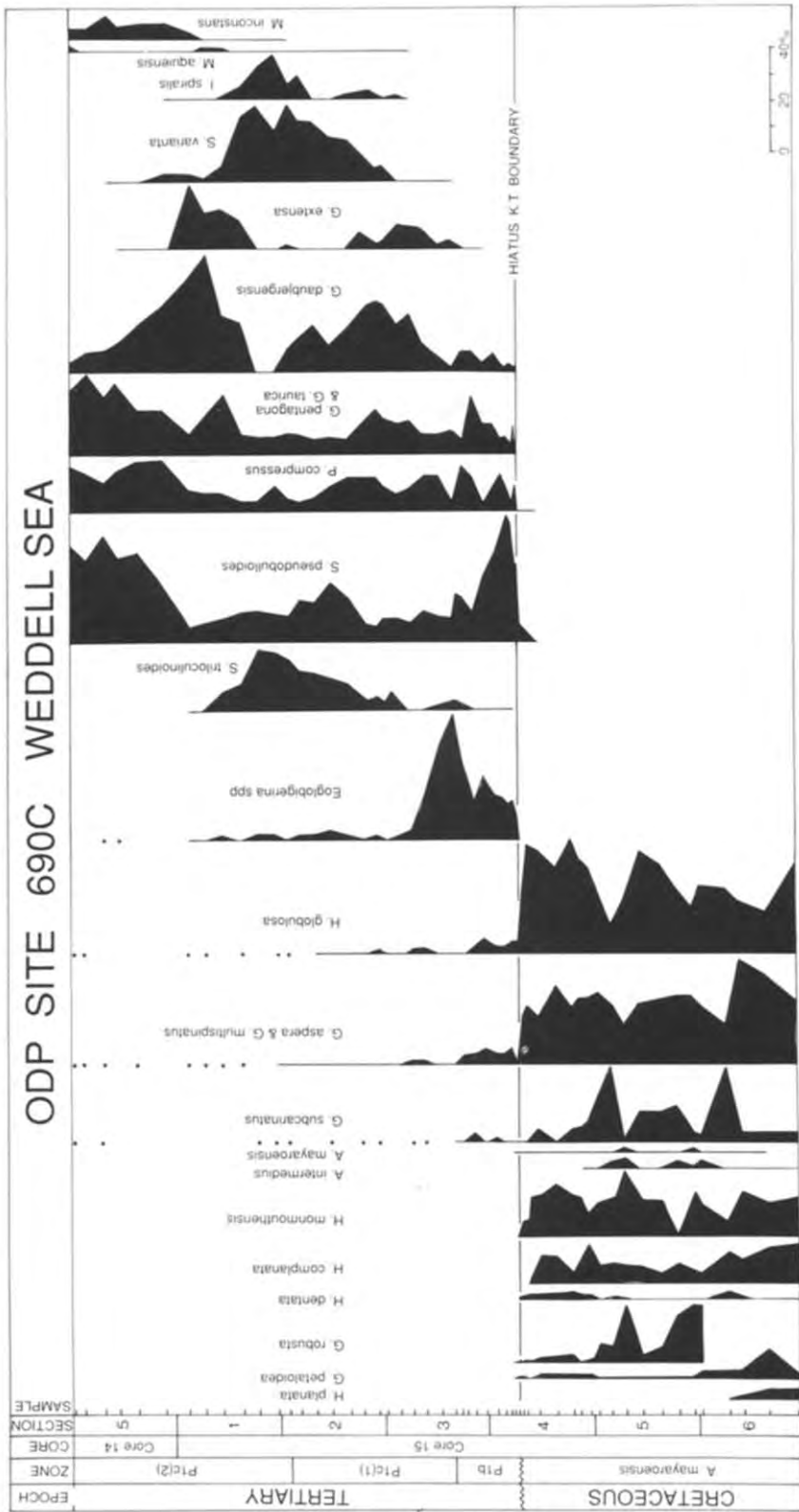
Fig. 9. Planktic foraminiferal turnover across the Cretaceous–Tertiary transition at Site 690C based on relative abundances of species. Solid line marks K/T boundary and Ir anomaly. Note a hiatus in the earliest Tertiary has removed Zones P0 and P1a.

TABLE 2

Relative percent abundance of planktic foraminifera across the Cretaceous–Tertiary transition at ODP site 690C

| Core-section | 15-6 | 15-6 | 15-6 | 15-6 | 15-6 | 15-5 | 15-5 | 15-5 | 15-5 | 15-5 | 15-5 |
Depth in centimeters	139–140	99–100	75–76	50–51	4–6	143–145	121–123	95–96	67–69	44–46	23–25
Abathomphalus intermedius	0.26		0.90	0.68	3.83	1.28	3.61	0.60	0.44	4.72	2.69
Abathomphalus mayaroensis		0.69	0.90	0.68	1.05	2.30	1.08	0.89	0.44	2.52	0.90
Globigerinelloides aspera	13.72	19.72	22.99	11.49	17.77	22.51	25.99	23.21	20.04	11.32	20.96
Globigerinelloides multispinatus	10.82	14.22	17.31	4.05	4.88	3.32	0.36	2.08	2.64	3.77	2.10
Globigerinelloides subcarinatus	4.49	4.82	4.18	29.05	3.14	4.09	14.08	12.80	11.67	1.26	29.94
Globotruncanella caravacaensis											
Globotruncanella petaloidea	2.11	11.01	3.28	3.38	2.79	1.02	1.44	0.89	0.88	0.94	0.90
Guembelitria cretacea											
Guembelitria danica											
Guembelitria trifolia											
Gublerina robusta					22.65	22.51	18.05	6.25	3.30	22.01	6.59
Hedbergella holmdelensis						0.51					
Hedbergella monmouthensis	15.04	13.30	16.72	6.08	12.20	17.39	0.36	14.29	13.88	24.84	15.27
Hedbergella planispira											
Hedbergella sp.											
Heterohelix complanata	15.04	13.76	8.96	12.16	4.18	5.37	8.30	3.87	6.83	1.23	8.08
Heterohelix dentata	0.26	0.46	1.49	3.38		0.77	0.72	0.89	0.44	0.63	1.20
Heterohelix globulosa	32.72	16.06	19.70	25.00	26.48	17.90	24.91	33.93	38.77	20.75	11.38
Heterohelix planata	4.22	4.36	2.39	0.68							
Pseudoguembelina punctulata					0.70	0.26	0.36				
Rugoglobigerina rugosa	0.53	0.23	0.30								
Chiloguembelina crinita											
Chiloguembelina midwayensis											
Chiloguembelina morsei											
Chiloguembelina strombiformis											
Chiloguembelina waiparaensis	0.53	0.92	0.60	1.35					0.66		
Woodringina claytonensis											
Woodringina hornerstownensis											
Eoglobigerina cf. edita											
Eoglobigerina eobulloides											
Eoglobigerina simplicissima											
Eoglobigerina trivialis											
Globanomalina pentagona											
Globanomalina taurica											
Globoconusa conusa											
Globoconusa daubjergensis											
Globoconusa extensa											
Globoconusa cf. extensa											
Igorina spiralis											
Morozovella inconstans											
Murciglobigerina aquiensis											
Murciglobigerina chascanona											
Planorotalites compressus											
Subbotina moskvini											
Subbotina pseudobulloides											
Subbotina triloculinoides											
Subbotina varianta											
Juveniles no identification	0.26	0.46	0.30	2.03	0.35	0.77	0.72	0.30			
Total number counted	379	436	335	148	287	391	277	336	454	318	334

15-5 3-5	15-4 144-145	15-4 124-126	15-4 119-121	15-4 95-96	15-4 69-71	15-4 49-51	15-4 44-46	15-4 39-41	15-4 34-36	15-4 29-31
0.54	0.83									
1.63	1.10	1.42	0.80		0.79	1.13	0.52	0.84	0.29	
23.91	23.14	24.08	17.43	29.52	16.84	20.00	19.06		5.85	3.13
3.80	1.65	1.42	4.83	0.95	1.05	2.82		0.42	0.29	
16.30	7.99	6.23	5.09	0.32	4.74	1.41	1.31		0.29	0.35
	0.55									
0.82	1.93	0.57	2.68	1.90	2.37	0.56	1.04	0.84		0.35
6.79	2.48	3.40	2.68	0.95	0.79	1.69	0.78			
					1.05					
12.77	8.82	14.73	16.35	20.63	16.05	15.49	6.53	5.88	0.29	
7.61	15.98	9.63	4.02	10.48	11.32	2.54				
0.54	1.93	1.98	3.22	2.22	2.63	1.97	1.04			
25.27	33.61	36.54	42.90	33.02	40.26	42.25	25.54	5.88	4.97	4.51
								0.42		
										1.04
						1.13	0.52	0.42		
									1.46	1.74
									2.63	3.13
							1.83	9.24	12.57	10.42
								0.42	1.17	0.35
							0.78	0.84	0.29	5.21
							1.31	10.92	3.22	1.74
									0.29	0.35
							1.57	2.52	0.58	2.78
								10.08	3.22	10.07
								20.17	16.37	6.94
					1.32	1.69	5.22	30.67	45.32	47.92
					0.53	1.13	5.22			
					0.26	6.20	28.72			
									0.29	
								0.42	0.58	
368	363	353	373	315	380	355	383	238	342	288

TABLE 2 (*continued*)

Core-section Depth in centimeters	15-4 19-21	15-4 9-11	15-3 149-150	15-3 139-141	15-3 129-131	15-3 109-111	15-3 99-101	15-3 79-81	15-3 59-61	15-3 40-41	15-3 19-21
Abathomphalus intermedius											
Abathomphalus mayaroensis											
Globigerinelloides aspera	5.41	4.08	6.23	4.26	2.69	0.33			0.76	2.37	64	1.00
Globigerinelloides multispinatus											
Globigerinelloides subcarinatus	1.69	2.17	0.73	3.99	0.90	0.33				1.02	·10	
Globotruncanella caravacaensis											
Globotruncanella petaloidea											
Guembelitria cretacea											
Guembelitria danica											
Guembelitria trifolia											
Gublerina robusta											
Hedbergella holmdelensis											
Hedbergella monmouthensis											
Hedbergella planispira											
Hedbergella sp.											
Heterohelix complanata											
Heterohelix dentata											
Heterohelix globulosa	3.38	3.26	6.23	3.45	1.20	1.30			0.76	3.05	2.19	0.33
Heterohelix planata											
Pseudoguembelina punctulata											
Rugoglobigerina rugosa											
Chiloguembelina crinita											
Chiloguembelina midwayensis		0.27	0.37	0.53	0.60		0.40			1.69	4.38	2.33
Chiloguembelina morsei	0.34		1.10	0.27	0.30					1.36	·10	0.33
Chiloguembelina strombiformis											
Chiloguembelina waiparaensis	0.34			0.80								
Woodringina claytonensis		0.27			2.10	3.26	3.95	6.31	11.19	1·53	15.28
Woodringina hornerstownensis		0.54			0.30						
Eoglobigerina cf. edita					0.60	0.65		0.76			0.66
Eoglobigerina eobulloides	12.84	8.42	11.72	6.38	14.97	22.80	35.57	24.75	13.56	3.56	
Eoglobigerina simplicissima		2.17			7.49	4.23					
Eoglobigerina trivialis	3.38	6.25	12.82	7.98	3.59	7.82	13.44	12.12	3.39	0.82	1.99
Globanomalina pentagona	3.04	5.43	6.59	18.09	2.99	6.19	7.11	5.30	5.76	5.75	5.32
Globanomalina taurica	3.38	6.25	5.13	5.32	3.89	1.95	2.37	3.28	2.71	·40	6.98
Globoconusa conusa					0.30		0.40				
Globoconusa daubjergensis	2.70	7.07	3.30	7.98	8.08	4.89	1.58	6.06	11.19	22.47	17.94
Globoconusa extensa			0.73	0.80	0.30	0.98	3.16	2.02	4.75	7.67	9.30
Globoconusa cf. extensa				0.27	0.30		0.79		3.05	1.37	0.33
Igorina spiralis										0.82	2.33
Morozovella inconstans											
Murciglobigerina aquiensis										0.27	0.33
Murciglobigerina chascanona										0.27	0.33
Planorotalites compressus	14.86	10.33	2.93	14.36	18.26	10.75	3.95	13.89	13.56	9.86	6.98
Subbotina moskvini	5.74	9.24	15.75	13.30	12.28	11.73	14.62	12.12	8.14	3.56	9.97
Subbotina pseudobulloides	42.91	33.15	24.91	11.44	16.77	18.24	9.09	10.10	12.20	6.85	9.30
Subbotina triloculinoides		0.37			2.10	4.56	2.77	0.25	0.68		7.97
Subbotina varianta							0.79	1.26	0.34	0.55	0.66
Juveniles no identification		1.09	1.10	0.80				0.25		0.82	0.33
Total number counted	296	368	273	376	334	307	253	396	295	365	301

15-3 1-2	15-2 138-140	15-2 121-123	15-2 99-100	15-2 73-75	15-2 50-52	15-2 25-30	15-2 9-11	15-1 144-145	15-1 119-120	15-1 89-91
0.87	0.94	0.51	1.08	0.58	0.88	0.56	1.13	0.96		0.25
	0.94	0.25		0.58			0.28	0.32	0.32	
0.29										
	2.20	0.51	0.54	0.87	0.29		0.28	0.64		0.25
0.29									0.32	
2.92	1.57	2.03	2.15	2.89	2.34	1.69	0.56	0.64	3.48	1.53
2.04		1.02	0.81	0.29	0.29	0.85	0.28	1.27	0.63	0.51
									0.63	
0.87				0.58	0.88	0.85	0.28	0.64		
16.62	11.64	6.35	9.68	5.49	7.60	5.07	2.26	1.91	0.63	
0.58	0.63	0.25				0.29		0.64	0.63	
0.29	1.89	1.52	2.15	3.76	2.34	1.97	1.13	2.55	2.85	1.53
7.00	6.29	3.81	2.96	4.91	3.80	6.20	5.08	2.87	3.48	5.09
7.00	10.38	10.66	2.69	2.31	2.63	1.97	3.67	4.14	3.48	2.80
26.24	27.67	26.14	17.47	9.83	18.71	12.39	9.04			18.07
2.92	1.89	6.09	0.27	1.45	1.17	0.28	2.26			11.20
		1.27	0.27							0.51
0.58	2.20	3.81	1.88	0.58	1.46	9.30	5.65	17.83	12.03	4.58
							0.28	0.96	0.32	1.02
	0.31	1.02	0.81	1.16	0.58	0.28	1.69	1.91	1.27	1.02
	0.31	0.25	0.27	0.58	0.29	0.28	0.85	0.32	0.63	0.76
10.20	12.58	12.69	13.17	9.83	5.26	4.23	5.08	9.55	4.43	3.82
2.62	1.89	1.52	0.27	1.73						
9.33	6.29	7.61	17.74	23.12	14.62	15.77	9.60	10.83	12.03	11.20
2.92	5.03	4.31	9.68	12.72	13.74	15.21	19.77	21.66	22.78	10.43
6.12	4.72	8.38	16.13	16.76	22.81	23.10	30.51	20.38	30.06	25.45
0.29	0.63						0.28			
343	318	394	372	346	342	355	354	314	316	393

TABLE 2 (*continued*)

Core-section Depth in centimeters	15-1 64–66	15-1 39–441	15-1 19–21	14-5 134–136	14-5 104–106	14-5 69–71	14-5 49–51	14-5 24–26	14-5 4–6
Abathomphalus intermedius									
Abathomphalus mayaroensis									
Globigerinelloides aspera	0.27	0.96	0.24		0.34		0.35	0.31	0.33
Globigerinelloides multispinatus									
Globigerinelloides subcarinatus							0.35		0.33
Globotruncanella caravacaensis									
Globotruncanella petaloidea									
Guembelitria cretacea									
Guembelitria danica									
Guembelitria trifolia									
Gublerina robusta									
Hedbergella holmdelensis									
Hedbergella monmouthensis									
Hedbergella planispira									
Hedbergella sp.									
Heterohelix complanata									
Heterohelix dentata									
Heterohelix globulosa		0.24	0.24					0.31	0.33
Heterohelix planata									
Pseudoguembelina punctulata									
Rugoglobigerina rugosa									
Chiloguembelina crinita			0.24					0.31	
Chiloguembelina midwayensis	1.61	5.26	3.86	0.49	0.68	1.88	1.06	4.60	3.97
Chiloguembelina morsei	1.07	0.72	0.97			1.25	1.77		1.32
Chiloguembelina strombiformis									
Chiloguembelina waiparaensis				0.49	0.68	0.31		0.31	0.66
Woodringina claytonensis	0.27	1.20		0.74	0.34	2.19	1.77	1.53	
Woodringina hornerstownensis									
Eoglobigerina cf. *edita*									
Eoglobigerina eobulloides									
Eoglobigerina simplicissima									
Eoglobigerina trivialis	1.61	0.24	0.97			0.31	0.35		
Globanomalina pentagona	18.77	7.89	6.52	13.83	13.36	22.26	18.79	27.91	23.18
Globanomalina taurica	5.90	4.78	0.72	3.46	3.77	5.64	3.19	3.07	3.64
Globoconusa conusa									
Globoconusa daubjergensis	21.45	45.93	36.23	25.19	17.81	10.03	8.16	7.36	3.97
Globoconusa extensa	13.94	13.64	25.36	0.99	0.34	0.31			
Globoconusa cf. *extensa*	1.34								
Igorina spiralis	1.88		1.69	0.99			0.35		
Morozovella inconstans	1.07	0.96	3.38	6.42	6.16	5.33	9.93	4.29	3.97
Murciglobigerina aquiensis	2.68	1.91	0.24	1.48	1.37	1.88	1.06	0.92	2.98
Murciglobigerina chascanona	0.27	0.72	2.17	1.48	1.71	0.63	0.71	0.61	0.66
Planorotalites compressus	6.97	6.94	7.73	20.00	18.84	14.73	10.64	15.34	17.22
Subbotina moskvini								1.84	0.99
Subbotina pseudobulloides	8.04	7.18	5.56	20.99	34.25	32.29	41.13	31.29	36.42
Subbotina triloculinoides	6.70		0.24						
Subbotina varianta	6.17	1.44	3.62	3.21	0.34	0.94	0.35		
Juveniles no identification				0.25					
Total number counted	373	418	414	405	292	319	282	326	302

resistant species (e.g. *G. subcarinatus* in 15-6, 50 cm, 15-5, 35 cm; Fig. 9).

The age of magnetochron C29R from the K/T boundary to the top of C30N is well constrained with the K/T boundary calibrated at 66.4 Ma (Berggren et al., 1985) and the C29R/C30N boundary 350 kyr earlier based on analysis of orbitally driven bedding cycles at Site 528 (Herbert and D'Hondt, 1990). By this age estimate and assuming near continuous sedimentation, depositional rates for this interval averaged 1.28 cm/10^3 years which compares favorably with average sedimentation rates of 1.71 cm/10^3 years for the same interval at Site 528. It must be cautioned, however, that these rates may be too low for Site 690C since a hiatus is present at or near the base of C29R that has removed most of C30N.

K/T transition

A bioturbated interval, mixing brown clay-rich Tertiary and light colored Maastrichtian chalks, marks the K/T boundary in Site 690C. This suggests that a major change occurred in biogenic and pelagic sedimentation at the K/T boundary (Ir anomaly) as earlier suggested by Stott and Kennett (1990a,b). Because of this bioturbated interval, first and last appearances of taxa are suspect. Nevertheless, the boundary conditions can be evaluated from quantitative planktic foraminiferal analysis which show a sudden shift from a Cretaceous to a well developed and diverse Danian fauna in core 15-4, 44–46 cm coincident with the major increase in iridium (Michel et al., 1990; Fig. 9). Pospichal and Wise (1990) observed a similar shift in calcareous nannofossil assemblages at this interval.

The most common species observed within the first 40 cm of the Tertiary is *Subbotina pseudobulloides* (Plate II, 13, 14) ranging between 25% and 47% in relative abundance of the total assemblage (Fig. 9). In contrast, Stott

and Kennett (1990a) recorded the first common (12%) *S. pseudobulloides* higher upsection in core 15-3, 132–136 cm. This difference is likely due to the higher resolution sample spacing in this study (53 samples as opposed to 15 analyzed by Stott and Kennett for the same interval). Stott and Kennett (1990a) defined their new Antarctic Zone APa/AP1a boundary by the first common occurrence of *S. pseudobulloides* which in this study would coincide with the K/T boundary (Fig. 9). This illustrates that the first common occurrence of a species may not be a good zonal marker. Recognizing this problem, Huber (1991) proposed to use the first appearance of *Globoconusa daubjergensis* instead of the first common *S. pseudobulloides*. Since *G. daubjergensis* already evolved in Zone P1a and is also present at the K/T boundary in Site 690C, this will not provide a better biostratigraphic marker for the APa/AP1a boundary.

Zone P1b (Hiatus P0–P1a)

At Site 690C eight Tertiary species first appear simultaneously at the K/T boundary (*Eoglobigerina eobulloides, E. trivialis, Glabanomalina pentagona, G. taurica (= G. polycamera* of Stott and Kennett, 1990a), *Planorotalites compressus, Globoconusa daubjergensis, G. conusa, Subbotina pseudobulloides*). Another 6 species first appear within the first 30 cm above the K/T boundary (*S. triloculinoides, E. edita, Woodringina hornerstownensis, W. claytonensis, Chiloguembelina midwayensis, C. morsei* (Table 2; Fig. 9). Although bioturbation may have obscured the sequence of evolutionary first occurrences, this high species diversity (14 taxa) is unknown for the basal Tertiary (Smit, 1982; Keller, 1988, 1989a; Canudo et al., 1991), but is characteristic of Zones P1a to P1c (Keller et al., 1990; Keller and Benjamini, 1991; Keller et al., in press). Moreover, in K/T sections with relatively continuous sedimentation these 14 spe-

cies evolve sequentially in Zones P0 and P1a (see Fig. 2) an interval spanning the first 240 to 280 kyr of the Tertiary. At Site 690C the high species diversity and abundance of Tertiary species at the K/T boundary, and the absence of *P. eugubina* and *Subbotina varianta* which mark Zones P1a and P1c, places this interval in Zone P1b. This study shows that a hiatus spanning at least Zones P0 and P1a (240–280 kyr) and probably part of Zone P1b is present at or near the K/T boundary although bioturbation rules out precise placement.

There is also independent evidence for a hiatus from calcareous nannofossils, and magnetostratigraphy. In nannofossil assemblages, Pospichal and Wise (1990) noted an abrupt abundance change in *Cruciplacolithus* and *Hornibrookina* along with the co-occurrence of *Cruciplacolithus primus* and *C. tenuis* where the former should precede *C. tenuis*. They concluded that a hiatus at the CP1a/CP1b boundary (45 cm above the K/T boundary) is a "distinct possibility". Planktic foraminifera show major abundance changes at this interval in Zone P1b along with the first occurrences of *C. claytonensis* and *G. extensa* (Fig. 9; Plates I and III). It is therefore possible that a second short hiatus is present within Zone P1b.

Magnetostratigraphy also supports the presence of a greatly reduced C29R interval above the K/T boundary. As noted earlier, the K/T boundary generally correlates to the upper one third of magnetochron C29R (Channell and Dobson, 1989), whereas at Site 690C this boundary correlates to near the top of C29R, or (about 35 cm above the K/T boundary Hamilton, 1990). The age for C29R from the K/T boundary to the C29R/C29N boundary is calibrated at 240 to 280 Ka by Herbert and D'Hondt (1990), Berggren et al. (1985) and MacLeod and Keller (1991b). If sedimentation was continuous, this would indicate a very low average sedimentation rate of $0.15 \text{ cm}/10^3$ yr for this interval which is highly unlikely given the high calcareous content of these sediments.

Zone P1c

The first occurrence of *Subbotina varianta* which marks the P1b/P1c boundary was observed in core 15-3, 99–101 cm correlative with the lower part of C29N (Fig. 8). Similar to Site 738C, the high latitude endemic species *Igorina spiralis, Murcigobigerina aquiensis* and *M. chascanona* first appear in the lower part of Subzone P1c(1) (Figs. 8 and 9; Plate IV). *Morozovella inconstans*, the marker species for the P1c(1)/P1c(2) and AP1a/AP1b boundaries first appears in core 15-2, 10 cm. Similar to the Kerguelen Plateau Site 738C Subzone P1c(1) is characterized by peak abundances in *I. spiralis* and *S. varianta* (Figs. 4 an 9). But in contrast to Site 738C *Chiloguembelina waiparaensis* is very rare in Site 690C whereas *Woodringina claytonensis* is common. This pronounced difference in biserial taxa between the Indian and Atlantic Antarctic Oceans suggests an ecologic barrier (oxygen minima?) existed at this time. This faunal difference seems to decrease in P1c(2) when few biserial taxa are present and the faunal assemblages are dominated by *S. pseudobulloides, G. pentagona–G. taurica, G. daubjergensis* and *P. compressus* at both sites (Figs. 4 and 9).

Discussion

Ir anomalies and hiatuses

It is commonly assumed that the presence of an iridium anomaly a priori proves the continuous nature of sedimentation across the K/T boundary. However, this is not the case since an iridium anomaly can still be present when a hiatus is present. This is because when a hiatus is formed iridium and other rare earth metals may concentrate as a result of associated dissolution or non-deposition (Keller et al., 1987; Donovan et al., 1988; Schmitz, 1988). At the K/T boundary these rare earth metals tend to concentrate in a few millimeters thin red or rust-brown clay layer that is devoid of carbon-

ate (Schmitz, 1988). In a survey of 29 K/T boundary sections, an Ir anomaly is present in only 4 biostratigraphically continuous sections (El Kef, Agost, Caravaca, Sopelana) and each contains a well defined clay layer above the thin Ir-rich red layer. In each section, this clay layer contains a characteristic basal Tertiary Zone P0 fauna (Smit and Romein, 1985; Keller, 1988; Canudo et al., 1991). In seven of the 29 K/T boundary sections however, an iridium anomaly is present even though the earliest Danian Zones P0 and part of P1a are absent (Stevns Klint, Gubbio, DSDP Sites 465, 524, 525, 527, 516; MacLeod and Keller, 1991a,b). The maximum duration of these hiatuses, while still preserving an iridium anomaly, is about 200,000 years (upper part of C29R). With the exception of Stevns Klint, all of these sections were deposited in a bathyal environment with dissolution and non-deposition (and hence concentration of clay minerals and rare earth metals) rather than physical erosion, the primary cause of the hiatus formation. The increased dissolution and consequently non-deposition during the early Danian is related to the dramatically decreased surface productivity in low latitudes (Zachos and Arthur, 1986; Zachos et al., 1989; Keller and Lindinger, 1989).

The Antarctic K/T boundary sections seem to conform to this pattern also. Even though all three sections examined (Sites 738C, 752B and 690C) have Ir anomalies at the K/T boundary, they are not equally complete chronostratigraphically. Site 738C, which has a laminated clay layer spanning the K/T boundary, is biostratigraphically the most complete Antarctic Ocean K/T boundary sequence recovered to date. Site 752B which has a thin clay layer, but poor microfossil preservation, may also be biostratigraphically complete, whereas Site 690 which lacks a clay layer, has a hiatus at or just above the K/T boundary.

The fact that all biostratigraphic zones are recognizably present in a section (e.g., the section is biostratigraphically complete) does not imply that a complete and continuous sedimentation record is present. It only means that at least some part of each biozone is represented. Short intrazonal hiatuses are common, although more difficult to demonstrate than hiatuses that result in removal of one or more biozones. At Site 738C, the most complete Antarctic section, short intrazonal hiatuses appear to be present at the P0/P1a and P1a/P1b boundaries, whereas at Site 690C the first two Tertiary Zones (P0-P1a) are missing. Intrazonal hiatuses have been documented globally at these times and seem to represent global oceanographic events related to decreased surface productivity in low latitudes and sea level fluctuations (Keller and Benjamini, 1991; Canudo et al., 1991; MacLeod and Keller, 1991a,b; Schmitz et al., 1992).

Cretaceous-Tertiary cosmopolitan fauna

It is generally assumed that southern high latitude faunas (Austral Province of Sliter, 1977; Krasheninkov and Basov, 1983, 1986; Huber, 1991) are uniquely different, characterized by their low species diversity and dominance of small biserial (heterohelicid), trochospiral (hedbergellid) and planispiral (globigerinellid) morphotypes. One of the more surprising results of this study, however, is the great similarity of latest Maastrichtian to earliest Tertiary Antarctic planktic foraminiferal assemblages with northern high latitude (Denmark) and low latitude assemblages (Spain, Tunisia, Israel, Texas, Mexico). This similarity is present both in the morphotypes of species present and in the species which are dominant across latitudes. For instance, the latest Maastrichtian (C29R) assemblages of Antarctic Sites 738C and 690C are of a cosmopolitan nature dominated by small biserial, trochospiral and planispiral taxa such as *Heterohelix globulosa, H. complanata, H. dentata, Hedbergella monmouthensis, H. holmdelensis, Globigerinelloides aspera, G. multispinatus* and *G. subcarinatus*. These taxa, however, also

dominate in middle latitudes (Site 528; D'Hondt and Keller, 1991), low latitudes (Mexico, Texas, Tunisia, Spain; Keller 1988, 1989a,b; Canudo et al., 1991; Keller et al., in press) and northern high latitudes (Denmark; Schmitz et al., 1992; Keller et al., 1993), spanning open ocean to shallow continental shelves. Each region, however, also has a few endemic species.

Examination of the relative species abundance distributions (> 63 μm size fraction) in these sections indicates that dominance of small biserial, trochospiral and planispiral morphotypes is not unique to the Austral Province, but instead is a global phenomena during at least the last 300,000 years of the Cretaceous. For instance, in the southern high latitudes: Sites 738C, 690C and Walvis Ridge Site 528, *Heterohelix globulosa, H. complanata, Globigerinelloides aspera, G. multispina, G. subcarinatus* and *Hedbergella monmouthensis* dominate. In the northern high latitudes, the same group of species dominates in addition to common triserial taxa (*Guembelitria danica, G. cretacea*) due to shallow water and proximity to shore of the Danish sections. In the Tethyan Province (Spain, Tunisia, Negev, Mexico) a more diverse assemblage of small biserial taxa dominates (*H. globulosa, H. navarroensis, H. glabrans, P. costulata, H. complanata*) along with reduced abundances of *Hedbergella monmouthensis* and *Globigerinelloides aspera*. In the very shallow and nearshore Brazos River sections the faunal assemblage is dominated by *H. globulosa* and *G. cretacea* with reduced abundances of *G. aspera, H. complanata* and *H. navarroensis*. Thus, the dominant faunal constituents are essentially the same across latitudes with differences restricted to shallow nearshore regions and higher diversity of small dominant biserial taxa in low latitudes. The major difference, however, is in the higher diversity of subsidiary taxa in middle to low latitudes. For instance, at El Kef, Agost, Caravaca and Mimbral taxic diversity is twice that of Sites 738C

and 690C. Taxic diversity is also reduced in shallow water regions such as Brazos River (30% reduction compared to El Kef) and Stevns Klint (60% reduction compared to Sites 738C and 690C). The increase in taxic diversity in low latitudes is largely due to the presence (although rare) of large, complex, ornate taxa which gradually disappeared during the end Cretaceous (Keller, 1988). The global similarity in planktic foraminiferal faunas during the last 300,000 years of the Cretaceous accompanied by the elimination of large tropical taxa during this time, is indicative of increasing environmental stress, and in particular, of global climatic cooling for which there is evidence from stable isotopes and plants in the Antarctic Ocean and Seymour Island (Stott and Kennett, 1990b; Askin, 1988, 1992).

Near the Cretaceous/Tertiary boundary continued or increasing environmental stress led to the decline and eventual extinction of even the small cosmopolitan heterohelicid, hedbergellid, globigerinellid and globotruncanellid taxa. But similar to the outgoing latest Maastrichtian fauna, the evolving and dominating Tertiary fauna is also cosmopolitan consisting of small biserial (chiloguembelinids and woodringinids), triserial (guembelitrids), and trochospiral (globigerinids) forms. In the earliest Tertiary Zone P0 (~40,000 years) only surviving Cretaceous biserial and triserial taxa dominate. In the succeeding Zone P1a (180–240 kyr) globigerinid and trochospiral taxa increase and eventually dominate in Zones P1b and P1c. With few exceptions the faunal assemblages present in the earliest Tertiary Zones P0 to P1c of Sites 738C and 690C (Figs. 4 and 8) are characteristic of this time interval worldwide (Keller, 1988, 1989a,b; Canudo et al., 1990; Keller and Benjamini, 1991; Keller et al., 1993; in press). The few species endemic to southern high latitudes include the biserial taxa *Eoglobigerina danica, C. waiparaensis, C. crinita* and *W. claytonensis* and the trochospiral taxa *Igorina spiralis, Murciglobigerina aquiensis* and *M. chascanona*. Preliminary

study of northern high latitude sections suggests that most or all of these species are endemic to northern and southern high latitudes where they appear to have evolved and at a later time migrated to lower latitudes (Keller et al., 1993). This suggests that high latitude regions, particularly of the Southern Hemisphere, acted as a center of origin and dispersal for planktic foraminifera as earlier observed for invertebrates by Zinsmeister and Feldmann (1984).

The remarkable lack of species extinctions in the Antarctic Ocean and survivorship of generalist taxa is also not unique to planktic foraminifera. For instance in a study of invertebrates across the K/T boundary transition of Seymour Island, Antarctica, Zinsmeister et al. (1989) observed no major extinction horizon but a gradual faunal turnover spanning 30 m. A study of dinocyst assemblages of this section by Askin (1992) placed this boundary in the lower part of the 30 m interval near an iridium enrichment. However, also in this group no major ecologic trauma was observed. Dominant components of the palynomorph assemblages continued unchanged across the K/T boundary while only a few rare pollen species disappeared at or near the K/T boundary (Askin, 1988, 1992). Similar survival phenomena were reported for nonmarine vertebrates of North America by Archibald and Bryant (1990). These investigators recorded that as much as 48% of nonmarine invertebrates (amphibians, reptiles and mammals) survived the K/T boundary, a level of extinction that is comparable to the Campanian/Maastrichtian (55%) and Puercan/Torrejonian (early/middle Paleocene, 58%) survival rates. Since amphibians and reptiles were less specialized than the dinosaurs, and mammals were primitive at this time, one might argue that survival in the terrestrial realm also favored nonspecialized generalists capable of adapting to changing environmental conditions.

The generalist and cosmopolitan nature of the latest Maastrichtian planktic foraminiferal fauna dominated by small, simple biserial, trochospiral and planispiral forms and the similarly generalist cosmopolitan earliest Tertiary fauna dominated by the same general morphotypes, points towards a long-term global environmental crisis. Although we do not yet fully understand the cause or nature of this environmental change, it is clear that it began well before the K/T boundary and continued long thereafter. It fostered an environment that excluded specialized forms in the Cretaceous and led to dominance of generalists that could tolerate a wide range of conditions. Moreover, it lead to the evolution of similarly small simple morphotypes in the Tertiary that gradually replaced the Cretaceous survivors. It is possible that an extraterrestrial bolide impact at K/T boundary time hastened the demise of the already declining cosmopolitan fauna, but the decline of the end Maastrichtian fauna was caused by an earlier environmental change that may be related to major global volcanism accompanied by a greenhouse effect and rapid global warming. Evidence of high latitude warming beginning 5000 to 10,000 years before the K/T boundary is present in northern high latitude sections (Denmark; Schmitz et al., 1992; Keller et al., 1993).

A clue to this environmental change is now also emerging from high latitude stable isotope analyses of individual planktic and benthic foraminiferal species at Nye Klov, Denmark and ODP Site 738C (Keller et al., 1993; Barrera and Keller, in prep.). These data indicate that the 3 permil negative $\delta^{13}C$ shift and elimination of the surface-to-deep $\delta^{13}C$ gradient that characterizes low latitudes (e.g., Zachos et al., 1989; Zachos and Arthur, 1986; Keller and Lindinger, 1989), is diminished or absent in high latitudes. For instance, at Nye Klov the $\delta^{13}C$ shift is only 0.6‰ (Keller et al., 1993) and in ODP Site 738C there is no evidence of decreased $\delta^{13}C$ values near the K/T boundary, but rather slightly increased surface values (Barrera and Keller, in prep.). In neither of these two sections is there a change in the sur-

face-to-deep $\delta^{13}C$ gradient. Since the $\delta^{13}C$ shift and elimination of the surface-to-deep gradient in low latitudes is generally interpreted as the near shut-off of surface water productivity in the marine realm (Zachos and Arthur, 1986; Zachos et al., 1989), this effect was either minimal or absent in high latitudes. This could account for the near absence of species extinctions and the only minor faunal changes associated with the K/T boundary event in high latitudes. The cause for this high–low latitude stable/isotopic difference is still unclear.

Conclusions

Contrary to current assumptions, latest Maastrichtian to earliest Tertiary planktic foraminiferal assemblages from the Indian and Atlantic Antarctic Oceans (Sites 738C, 752B and 690C) are not restricted to a southern high latitude province, but are cosmopolitan dominating high to low latitudes. Only very few species are endemic to different latitudinal provinces and all low latitude datum levels are present. As a result of this cosmopolitan fauna, the high resolution low latitude zonation of Smit (1982), Smit and Romein (1985) and modified by Keller (1988, 1989a) and Canudo et al. (1991) can be directly applied to Antarctic faunas.

Kerguelen Plateau Site 738C is the biostratigraphically most complete deep-sea K/T boundary sequence recovered to date. This site contains a biostratigraphically complete (e.g., all biozones present, P0–P1a) K/T boundary transition in a 15 cm thick laminated clay layer. Two intrazonal hiatuses are present at the P0/P1a and P1a/P1b boundaries. Site 752B may also be biostratigraphically complete, but poor microfossil preservation prevents high resolution studies. Weddell Sea Site 690C has a hiatus at the K/T boundary that removed at least Zones P0 and P1a, or about 230,000 to 280,000 years.

Planktic foraminiferal assemblages from the Indian Antarctic (Site 738C) and Atlantic Antarctic Oceans (Site 690C) are very similar during the latest Maastrichtian and early Tertiary with few significant exceptions. During the latest Maastrichtian the biserial species *Chiloguembelina waiparaensis* is a dominant element in Site 738C, but extremely rare in Site 690C, whereas *Gublerina robusta* is a dominant form in Site 690C, but nearly absent in Site 738C. The genus *Chiloguembelina* was believed to have evolved during the early Tertiary, but it is already present in the late Maastrichtian C30N and seems to have evolved in the southern Indian Ocean. During the early Tertiary (P0–P1c) *C. waiparaensis* dominates (> 60%) the faunal assemblage in Site 738C, but biserials are nearly absent in Site 690C. This faunal difference suggests that a oceanic water mass barrier existed between the southern Atlantic and southern Indian Ocean that prevented early migration of the evolving chiloguembelinids.

The cosmopolitan nature of the dominant latest Maastrichtian fauna began at least 200,000 to 300,000 years before the end of the Cretaceous and continued at least for 300,000 years into the Tertiary. An environmental crisis, of yet unknown origin but accompanied by climatic cooling followed by warming resulted in the gradual elimination of specialized taxa permitting expansion of generalists able to tolerate a wide range of conditions. The terminal decline of this Cretaceous cosmopolitan fauna in the Antarctic Ocean began at least several thousand years before the K/T boundary and Ir anomaly at Site 738C as estimated from deposition of 5 cm of calcareous ooze and laminated clay-rich sediments. Highly stressed environmental conditions are indicated beginning at this time by the terminal abundance decline of common and cosmopolitan species, the concurrent increase in the opportunistic *Chiloguembelina waiparaensis*, the onset of laminated clay-rich sediments and the onset of dwarfing of all taxa in both planktic and benthic foraminiferal assemblages. Dwarfing of foraminifera continues through

deposition of Zone P0 of the clay-rich laminated layer. The terminal decline of this cosmopolitan fauna may be due to increased stress and the attainment of threshold conditions for their existence. Whether volcanism played a major role is unknown, but there is evidence of major volcanic activity on Broken Ridge Site 752 where 6.5 m of volcanic sediments were deposited across the K/T boundary. There is no evidence of a sudden mass killing of the entire Cretaceous fauna as a result of a bolide impact at the K/T boundary and there is no evidence of earlier extraterrestrial bolide impacts that could explain the onset of the terminal decline of the Cretaceous planktic foraminiferal faunas.

Acknowledgments

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