REVUE DE MICROPALÉONTOLOGIE
Vol. 39, n° 3, septembre 1996, pp. 225-243

THE CRETACEOUS/TERTIARY BOUNDARY MASS EXTINCTION IN PLANKTIC FORAMINIFERA AT AGOST, SPAIN

L'EXTINCTION EN MASSE DES FORAMINIFÈRES PLANCTONIQUES À LA LIMITE CRÉTACÉ/TERTIAIRE À AGOST, ESPAGNE

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ABSTRACT. – The planktic foraminiferal mass extinction across the Cretaceous/Tertiary boundary at Agost (Spain) occurred over an extended period, with 7 species disappearing in the late Maastrichtian, 47 species extinct at the K/T boundary and 16 ranging into the earliest Danian. The species that became extinct at the K/T boundary are large, complex tropical and subtropical forms dwelling in deep and intermediate water depths, which constitute only about 20 % of the individuals in the population larger than 63 microns. Nevertheless, their disappearance constitutes the major and sudden extinction event in the history of planktic foraminifera. However, the small cosmopolitan surface dwellers with simple morphologies appear to survive and the last of them gradually disappear in the lower part of the *P. pseudobulloides* Biozone. This planktic foraminiferal extinction model can be interpreted as a catastrophic mass extinction that centred at the K/T boundary, and was superimposed on a gradual mass extinction which began in the late Maastrichtian and continued into the early Danian. The catastrophic pattern of extinction at the K/T boundary is very compatible with the effect of a large meteorite impact, whereas the gradual and extended pattern of extinction across the Maastrichtian-Danian transition is compatible with temperature and sea level changes that may be related to massive volcanism.

RÉSUMÉ. – L'extinction en masse des foraminifères planctoniques à travers la limite Crétacé/Tertiaire à Agost (Espagne) s'est produite au cours d'une certaine période ; 7 espèces disparaissant au Maastrichtien supérieur, 47 à la limite K/T et 16 au Danien inférieur. Les espèces ayant disparu à la limite K/T sont grandes et complexes, des formes vivant en milieux océaniques profonds tropicaux et subtropicaux, qui ne constituent qu'environ 20 % des individus de la population de taille supérieure à 63 microns. Cependant, leur disparition représente l'évènement d'extinction le plus important et soudain de l'histoire des foraminifères planctoniques. Toutefois, les petites formes cosmopolites ayant une morphologie simple et vivant dans les eaux superficielles semblent avoir survécu et la plupart ont disparu progressivement dans la partie inférieure de la Biozone à *P. pseudobulloides*. Ce modèle d'extinction des foraminifères planctoniques peut être considéré comme une extinction en masse catastrophique concentrée à la limite K/T et superposée à une extinction en masse graduelle qui avait commencé au Maastrichtien supérieur et continua jusqu'au Danien inférieur. Le modèle d'extinction catastrophique à la limite K/T est bien compatible avec les effets de l'impact d'un grand météorite, tandis que le patron d'extinction graduelle au cours de la transition Maastrichtien-Danien l'est avec les changements de température et du niveau de la mer qui pourraient être en rapport avec un volcanisme massif.

Key-words : Cretaceous – Tertiary – Extinction – Biostratigraphy – Foraminifera – Betics – Spain.

Mots-clés : Crétacé – Tertiaire – Extinction – Biostratigraphie – Foraminifères – Bétiques – Espagne.

INTRODUCTION

The Cretaceous/Tertiary boundary (K/T) mass extinction model in planktic foraminifera and its interpretation has been a very controversial topic. The origin of this controversy can be found in the data that Smit presented at the Snowbird I Conference in 1980, showing that all but one Cretaceous species suddenly became extinct at the K/T boundary, which he interpreted as the result of a large meteorite impact (Smit and Hertogen, 1980 ; Smit, 1982). These data were not questioned until Keller (1988) provided evidence that species extinctions extended across the K/T boundary with about 1/3 of the species surviving well into the Tertiary (Keller, 1988, 1989a, b).

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The oldest detailed studies were published by Luterbacher and Premoli Silva (1964), who established the *Globigerina eugubina* Biozone at the K/T boundary in Italy. The assemblage of this biozone was later recorded from the South Atlantic, Northwest Pacific, Gulf of Mexico and Caribbean deep-sea cores, which led Premoli Silva (1977) to conclude that the *G. eugubina* Biozone fauna is cosmopolitan, and represents the earliest Tertiary assemblage from which all Paleogene genera could be derived either directly or by inference. Subsequently, high resolution sampling of the K/T boundary at Caravaca (Spain) by Smit (1977, 1979) let to the discovery of a still earlier Tertiary planktic foraminiferal association below the *G. eugubina* Biozone. By this time Alvarez *et al.* (1979, 1980) proposed the now popular hypothesis that an extraterrestrial bolide caused the Cretaceous-Tertiary mass extinction. This has led to a tremendous interest in the K/T mass extinction across disciplines ranging from paleontology to chemistry and astrophysics. Many authors have since tried to elucidate the model of extinction and their causes but few have studied continuous sections or at the necessary high sample resolution. Consequently, as a result of large sample spacing or hiatuses, mainly based on the Italian sections, it was assumed that Cretaceous planktic foraminifera suffered near total extinction precisely at the K/T boundary.

During the late 1980's, however, some workers studied more complete sections and sampled the critical intervals at the centimetre scale. As a result, they discovered a more gradual mass extinction pattern in planktic foraminifera (Keller, 1988, 1989a, b, 1993; Canudo *et al.*, 1991). Nevertheless, studying the same sections Smit (1990) has maintained his interpretation of a catastrophic pattern with all but one Cretaceous species (*Guembelitria cretacea*) extinct precisely at the K/T boundary. To resolve this catastrophic versus gradual mass extinction controversy, a group of scientists re-sampled the El Kef section in Tunisia and samples were distributed for a "blind sample test". For this blind test six unlabeled samples were studied by four investigators, the result was exhibited at the Snowbird III Conference and both authors claimed that the data support their interpretations (Smit, 1994; Keller *et al.*, 1995).

In order to elucidate this controversy we have studied the best section in Spain, located at Agost, which is very expanded and continuous, and well exposed across the K/T boundary. The planktic foraminifera are quite well preserved, the assemblages are rich and diverse, and there is almost no evidence of reworking. Thus, this excellent K/T boundary section provides a good opportunity to test the extinction model of Cretaceous species and the evolution of Tertiary species.

MATERIALS AND METHODS

The town of Agost is located in the Betic Cordillera of southeaster Spain and the section is placed about 1 km Northeast of the town (see detailed map *in* Canudo *et al.*, 1991). The K/T boundary transition was sampled in a roadcut near the 13 km marker post and the Maastrichtian sequence closer to the town in a small gully opposite to the cemetery. Maastrichtian sediments consist of intercalated grey marls and marly limestone beds. The K/T boundary is marked by a sharp contact between Maastrichtian grey marls and a thin 10 cm black clay layer with a basal 2 mm thin rust-red layer. This red layer contains the Ir anomaly and other impact evidence such as the Ni-rich spinels. The Tertiary sediments consist of marls and marly limestones that are of gray colour in the basal Paleocene and red at the top of the section.

All the samples were taken in a well exposed outcrop, but the outcrop was trenched across the K/T boundary to remove surface contamination and obtain fresh unweathered bedrock. Samples were collected at cm-intervals across the critical K/T boundary interval and at m-intervals below and above the boundary. A total of 68 samples were analyzed for this study. Samples were disaggregated in tap water and diluted H_2O_2, then washed through a 63 micron sieve and dried at 50°C. Preservation of planktic foraminifera is good although original calcite shells are recrystalized.

The quantitative planktic foraminiferal analysis was based on representative splits (using a modified Otto microspliter) of 300 or more specimens in the size fraction larger than 63 microns. All the representative specimens were picked, identified and mounted on microslides for a permanent record. The remaining sample was scanned for rare species. Faunal counts for the picked fraction are listed in Tables 1, 2 and 3. Index species are shown in Plate 1.

TABL. 1. – Relative abundance of K/T boundary planktic foraminifera at Agost.
Abondance relative des Foraminifères planctoniques à la limite K/T à Agost.

SPECIES	SAMPLES > 63 μ											
	-220-225	-180-185	-140-145	-100-105	-60-65	-30-35	-15-20	-5-10	0-2	+1+2	+2+3	+3+4
Guembelitria cretacea	0.63	0.93	0.90	0.93	1.83	1.23	0.63	0.32	0.31	1.55	2.31	4.23
G. trifolia	x	0.31	x	0.62	0.91	0.31	x		x	0.62	0.66	1.95
H. planata	3.49	3.70	2.99	5.86	3.35	2.77	3.77	2.24	4.70	5.57	3.96	4.56
H. globulosa	38.09	37.03	41.50	36.42	38.10	42.46	39.31	30.99	42.64	34.06	39.60	43.00
H. pulchra	2.22	2.78	3.28	2.78	4.57	2.78	3.14	2.88	2.51	0.93	1.32	1.63
H. punctulata	3.17	0.62	0.90	2.16	0.91	0.92	2.20	x	0.94			
H. glabrans	0.63	0.62	0.90	0.63	0.30	1.54	1.89	0.96	1.25	x	0.33	
H. labellosa	1.27	0.31	0.90	0.31	2.74	0.62	2.20	2.24	1.25	3.41	2.97	2.28
H. navarroensis	13.65	14.20	14.03	11.42	15.24	9.54	14.78	23.64	14.73	5.57	6.93	4.23
H. carinata	1.90	0.93	1.49	1.54	1.52	0.31	0.94	0.32	0.63			
H. semicostata	x	x	x	x	x	x		x	x			
Pseudotextularia nuttalli	1.90	1.23	1.79	2.47	0.61	1.23	1.26	0.96	2.19			
P. elegans	0.32	1.23	1.19	0.93	0.91	0.31	0.31	0.32	0.94			
P. intermedia	x	0.31	0.30	x	0.30	x	0.31	x	x			
Gublerina acuta	x	0.31	0.30	x		x	x	x				
G. cuvillieri	x	x	x	0.31	x	x	x	x	x			
Pseudoguembelina kempensis	2.22	1.23	0.90	4.01	1.52	2.77	1.89	1.92	2.82	3.41	7.26	6.19
P. palpebra	0.63	1.23	0.60	1.23	0.61	0.62	x	0.64	0.31			
P. costulata	2.86	2.47	3.28	2.47	2.74	3.69	3.14	8.31	5.33	4.64	4.95	1.63
P. costellifera	x		0.30	x			0.31	x	x			
P. excolata	x	0.62	x	x	x	x	x	x	x			
P. hariaensis	x	0.31	x	0.62	x	x	x	0.32	x			
Planoglobulina acervulinoides	x	x	x	x	x	x	x	x	x			
P. carseyae	x	0.62	0.30	0.31	x	x	0.31	x	x			
P. multicamerata	x	0.31	0.30	x	x	x	x	x	x			
P. manuelensis	x		x			x		x	x			
Racemiguembelina fructicosa	x	0.31	0.30	x	x	0.31	x	x	x			
R. powelli	x	x	0.60	0.31	x	x	x	0.32	0.31			
Globigerinelloides yaucoensis	0.95	3.40	1.79	0.93	1.52	2.15	1.57	4.47	2.82	3.72	3.30	2.61
G. rosebudensis	0.32	0.62	0.30	0.31	x	x	x	x	0.31			
G. prairiehillensis	3.49	3.09	2.39	5.56	3.05	3.69	3.77	3.51	3.13	7.12	6.93	4.89
G. volutus	0.63	0.93	0.30	0.62	x	0.61	0.63	1.28	1.89	3.10	2.31	3.26
G. subcarinatus	0.95	0.93	0.30	0.31	x	x	x	0.64	x	0.62	0.33	x
Hedbergella monmouthensis	3.81	7.72	5.67	3.40	7.32	9.23	8.81	5.75	2.51	6.50	3.63	7.82
H. holmdelensis	1.59	2.78	2.39	1.85	6.40	4.31	2.20	2.24	2.19	10.53	9.24	9.77
Globotruncanella caravacaensis	0.32		x	0.93	0.30	0.31	0.63	0.32	0.31	4.02	2.31	1.30
G. havanensis	x		x	x	x	x	x	x	x			
G. petaloidea	0.65	x	0.30	x	x	0.62	x	x	x			
G. pschadae	0.32	0.31	x	x	x	x	x	x	x			
G. minuta	2.22	0.31	1.49	2.16	0.61	1.23	0.94	1.92	0.94	1.55	1.65	0.65
Archaeoglobigerina cretacea	0.32	x	x		0.30	0.31						
A. blowi	0.32	0.31		0.62	x	0.31	x	0.32	0.31			
Schackoina multispinata	0.32	0.62	1.19	x	0.61	0.31	0.31	1.28	0.31			
Plummerita hantkeninoides	0.32	0.31	x	x	0.30	0.31	0.31		x			
Rugoglobigerina reicheli	0.65	0.93	0.30	1.23	0.61	0.31	0.63		0.31			
R. rugosa	1.27	0.93	0.90	2.47	0.61	0.31	0.94	0.64	0.94			
R. hexacamerata	0.32	0.62	1.49	0.31	x	x	0.63	x	0.31			
R. rotundata	x	x	x	x	x	x	x	x	x			
R. milamensis	x	x	x	x								
R. pennyi	x	x	x	0.31	x		x	x				
R. macrocephala	x	x	x	0.31	x	x	0.31	x	x			
R. scotti	1.27	0.31	0.60	1.23	0.30	0.92	0.31	x	0.63			
Globotruncana arca	1.59	0.62	0.90	0.31	0.30	x	x	0.32	0.63			
G. aegyptiaca	0.95	1.23	0.30	0.31	0.30	0.92	0.31	x	0.63			
G. rosetta	0.32	x	x	0.31	x	0.31		x	0.31			
G. mariei	1.59	0.62	0.90	0.31	0.30	0.31	0.63	0.64	x			
Globotruncanita stuarti	0.32	x	0.30	0.31	0.30	x	x	x	x			
Gita. stuartiformis	0.32	0.31	0.60	x	x	0.62	x	0.32	x			
Gita. insignis	x		x	x	x	x	x	x	x			
Gita. fareedi	1.27	0.62	0.60	0.31	0.30	1.23	0.31	x	0.31			
Gita. conica	x	x	x	0.31	x	x	x	x	x			
Gita. elevata	x		x	x	x	x	x	x	x			
Gita. falsocalcarata	x	0.31	x		x	0.31	x		0.31			
Gita. dupeublei	x	x	x	x	x	x	x	x	x			
Contusotruncana contusa	x	x	x	x	0.30	x	x	x	x			
C. patelliformis	x	x	0.30		x	x	x	x	x			
C. walfischensis	x	x		x	x	x	x		x			
Abhatomphalus mayaroensis	x	x	x	x	x	x	x	x	x			
A. intermedius	x		x	x	x		x		x			
TOTAL NUMBER COUNTED	315	324	335	324	328	325	318	313	319	323	303	307

TABL. 2. – Relative abundance of lowermost Danian planktic forminifera at Agost.
Abondance relative des Foraminifères planctoniques au Danien inférieur à Agost

SPECIES	SAMPLES > 63 μ															
	+4+6	+6+8	+8+10	+10+12	+12+14	+14+16	+16+18	+18+20	+20+22	+22+24	+24+26	+26+28	+28+30	+35+40	+45+47	+65+70
Parvularugoglob. longiapertura	7.97	36.55	59.85	73.69	68.26	63.60	49.50	41.97	22.25	12.65	13.79	10.93	10.30	6.38		
P. sabina		0.84	1.46	1.53	3.69	8.25	15.19	18.48	10.06	6.02	7.93	8.98	9.54	5.10		
P. umbrica		4.62	9.85	4.89	5.90	2.14	1.58	0.36	0.61							
P. eugubina						3.97	6.33	10.95	17.07	10.54	10.69	10.15	9.92	16.59	20.68	10.71
P. theodosica					0.73	0.91	4.74	4.37	4.26	5.12	5.51	14.06	7.63	12.34	12.41	2.67
P. hemisphaerica						0.91	0.63	0.36	1.22	0.90	1.03	0.39	0.76	1.27	3.44	0.89
Globoconusa fodina	3.32	2.10	2.55	2.14	5.16	3.66	6.33	5.84	5.18	7.22	7.24	8.20	7.24	4.25		
G. extensa		3.78	1.32	1.53	1.47	2.75	7.59	1.46	0.91	1.20	0.69	0.78	4.58	0.42	2.06	1.73
G. conusa	10.63	4.62	8.39	7.34	1.84	2.44	2.84	x	2.13	2.71	1.72	1.56	6.48	3.83	1.38	
G. minutula		1.26	x	x	2.95	1.22	0.95	0.36	0.30	0.90	0.34	x	1.14	0.85	1.38	
Eoglobigerina simplicissima													x	0.42	0.69	0.89
E. eobulloides												0.39	0.76	1.70	1.38	1.78
E. pentagona																
E. fringa																3.57
E. trivialis																1.78
E. praedita														2.97	7.58	0.89
E. edita																
Subbotina triloculinoides															0.69?	2.67
Globanomalina danica										3.01	1.72	1.95	2.67	1.27	x	0.89
G. archeocompresa																
G. planocompresa																
Parasubbotina moskvini															2.06	0.89
P. varianta																
P. pseudobulloides																
P. inconstans																
Praemurica taurica															12.41	6.25
P. pseudoinconstans															1.38	1.78
Chiloguembelina morsei						0.60	x	5.11	18.29	28.61	31.72	26.17	19.84	17.87	18.62	38.39
Ch. midwayensis									2.13	3.01	2.06	2.73	0.76	0.85		2.67
Ch. taurica							x	3.28	7.92	9.94	13.44	8.20	10.30	15.74	4.13	8.03
Woodringina claytonensis		0.42	1.46	x	x	0.30	x	0.36	0.91	2.10	1.72	1.56	3.05	0.85	0.62	3.57
W. hornerstownensis			1.46	x	0.36	x	x	1.09	0.91	2.41	x	1.56	1.91	0.42	2.06	1.78
Guembelitria danica	2.33	5.46	1.82	x	0.73	0.61	0.63	0.36	x	x	x	0.78	x	x		
G. irregularis	0.66	4.80	x	0.91	0.73	0.61	x		x			x	0.76	x		
G. alabamensis	0.66	x	x		x		x		0.91		x		0.38	x		
G. cretacea	16.28	6.30	3.28	3.97	2.95	3.67	1.58	1.46	1.82	0.90	0.69	0.39	0.38	0.85	0.69	0.89
G. trifolia	4.65	0.84	2.19	0.31	0.36	0.30	x	1.09	x	0.30	0.34	0.39	1.52	x		
Heterohelix planata	1.99	0.42	0.37	x	x	x	0.95		x		x	x	x	0.43		0.89
H. globulosa	11.96	4.62	1.46	0.92	0.37	x	0.95	x	x	0.60	x	0.39	x	x		1.78
H. pulchra	1.66	1.26	x	0.31			0.32			0.30	x					
H. navarroensis	2.99	2.10	0.73	0.31	x	0.61	0.32	x		0.90	x	0.39		0.43		
Pseudoguembelina kempensis	1.99															
P. costulata	1.00	x	x	0.31	x	x	0.32		x							
Globigerinelloides yaucoensis	4.32	2.94	0.73	0.31	1.11	x	x	x		0.60		x		x		
G. prairiehillensis	3.99	3.78	0.37	0.31	0.37	x	x	x		x	x	x				
G. volutus	2.33	2.10	0.37	x	0.37	0.61	x	x								
G. subcarinatus	0.66	x														
Hedbergella monmouthensis	5.98	5.04	1.10	0.31	1.11	0.31	x	0.37	x		x	x	x	x	0.69	0.89
H. holmdelensis	11.63	3.36	0.37	x	0.74	x	0.95		x	x	x	x				
Globotruncanella caravacaensis	1.66	0.42	x		0.37	x										
G. minuta	1.66	0.42	0.37	0.31	0.37	x	0.32									
TOTAL NUMBER COUNTED	301	238	274	327	271	327	315	274	328	332	290	256	262	235	144	112

TABL. 3. – Relative abundance of lower Danian planktic foraminifera at Agost.
Abondance relative des Foraminifères planctoniques au Danien inférieur à Agost.

SPECIES	SAMPLES > 63 μ																			
	+82 +86	+98 +102	+114 +118	+130 +134	+146 +148	+160 +164	+176 +180	+192 +196	+208 +212	+224 +226	+244 +248	+260 +264	+284 +289	+309 +314	+334 +339	+364 +369	+404 +409	+434 +439	+464 +469	+489 +494
Globastica daubjergensis									x	0.33	0.72	x	x	0.61	2.86	x	0.70	x	0.72	4.71
Eoglobigerina simplicissima	0.99	x	x	0.82	0.93	0.30	x	0.29	2.16	0.33	0.36	x	x	x	1.29	1.09				
E. eobulloides	0.66	0.35	x	0.27	0.62	0.92	x	0.29	1.23	x	1.08	0.91	2.84	1.53	0.64	0.36	0.35	0.33	0.36	0.31
E. pentagona							0.74	x	0.30	0.33	x	x	x	0.61	0.32	0.36	x	0.33	0.36	x
E. fringa	x	x	0.62	0.27	1.55	1.23	2.60	1.48	2.77	0.33	0.36	1.94	1.26	2.44	0.97	0.36	0.35	0.98	1.81	3.46
E. trivialis	x	x		x	x		1.11	x	0.30	1.69	0.36	0.97	0.63	2.14	1.94	1.45	1.40	1.64	3.98	2.51
E. praedita	0.66	035	0.31	1.37	x	0.61	1.85	0.89	0.92	2.02	0.36	1.94	1.86	4.58	3.88	1.81	2.80	3.29	3.62	1.25
E. edita		x	x	x	1.55	1.23	1.85	1.18	3.08	1.01	1.08	2.92	4.10	3.36	4.53	3.63	4.91	2.30	4.71	1.57
E. polycamera											0.36	0.65	0.94	x	0.64	x	0.70	0.98	x	0.62
E. tetragona										x	x	x	x	0.30	0.64	x	x	0.33	0.72	0.31
Subbotina triloculinoides	0.66?	0.70?	0.31?	1.10?	1.55?	1.23	1.11	x	1.85	0.67	0.36	x	0.94	0.30	0.32	x	x	x	0.36	5.03
Globanomalina danica	x	1.40	0.31	1.10	4.34	2.15	6.65	x	1.23	1.35	1.80	2.27	2.84	1.53	0.64	0.36	2.45	x	0.36	x
G. archeocompresa	x	x	x	x	0.31	0.30	0.74	0.59	0.61	0.33	2.88	15.90	12.61	7.34	9.71	4.36	17.54	5.92	8.69	9.12
G. planocompresa					x	x	2.23	0.29	0.61	1.35	3.24	7.79	4.10	4.88	5.17	0.36	3.15	1.97	2.17	3.14
G. compressa															2.91?	0.72?	3.15?	2.63	1.81	3.77
G. caucasica							1.11	0.29	5.24	2.02	0.36	0.97	1.57	x	x	x	x	0.33	x	2.51
Parasubbotina moskvini	0.99	0.70	x	0.27	1.55	0.30	1.11	1.18	0.61	2.70	x	x	0.31	1.22	0.37	0.72	1.05	2.30	3.26	3.77
P. varianta	x	0.35	x	0.27	x	x	0.37	x	x	1.01	x	x	x	0.61	0.32	x	0.70	0.33	x	2.83
P. pseudobulloides	x	x	0.31	0.55	0.62	0.61	0.74	1.18	0.30	0.33	1.08	1.94	0.94	0.91	1.62	1.09	0.70	2.30	3.62	2.83
P. inconstans					x		x		x	0.67	0.36	0.32	x	2.14	0.64	3.27	2.45	7.23	10.14	3.77
Praemurica taurica	x	x	0.31	0.55	0.62	1.85	0.38	x	x	1.01	1.80	3.89	2.20	5.19	5.82	6.91	5.61	5.92	3.26	8.80
P. pseudoinconstans	x	x		x	x		x		x	0.33	x	0.65	x	x	1.29	1.09	1.75	0.33	1.08	2.51
Chiloguembelina morsei	45.21	55.48	56.25	45.05	45.34	48.30	39.03	52.82	38.58	31.03	38.62	34.41	33.12	40.06	33.98	54.90	26.66	48.68	38.04	23.58
Ch. midwayensis	2.31	4.57	2.81	3.29	5.90	9.53	7.80	3.26	1.54	0.67	7.22	4.22	5.04	6.72	3.56	5.81	4.91	2.63	2.89	3.46
Ch. taurica	5.94	4.28	7.81	12.36	9.93	9.14	9.66	16.61	9.87	12.50	13.71	10.38	16.72	12.53	13.26	8.36	15.08	8.22	5.43	8.17
Woodringina claytonensis	10.23	2.46	4.06	4.67	2.48	1.84	1.48	1.48	1.85	1.01	2.16	1.94	3.78	0.91	0.64	x	0.70	0.65	1.08	x
W. hornerstownensis	4.29	3.52	6.87	4.94	5.28	2.46	1.48	1.78	0.92	3.04	3.97	1.94	0.63	0.91	1.94	0.72	0.70	x	1.08	1.25
Guembelitria danica	2.64	2.81	4.37	5.49	2.17	4.30	3.34	2.96	1.23	5.40	2.16									
G. irregularis	5.61	4.57	0.31	5.22	3.41	1.84	x	1.18	2.47	5.74	2.16									
G. alabamensis	3.25								0.30					0.61						
G. cretacea	10.36	10.91	10.62	7-69	6.83	6.77	10.03	6.52	17.59	11.82	9.38	2.98	3.78	x	x	1.45	0.35	0.33		
G. trifolia	3.30	1.76	2.18	0.82	x	2.46	0.74	3.85	3.39	8.10	2.52	0.97	x	0.91	x	0.36				
Heterohelix planata	x	x	x	0.28	0.31	x		x												
H. globulosa	2.97	1.06	1.25	2.21	1.55	0.62	0.38	x	x	0.34										
H. navarroensis	2.31	2.11	0.94	0.83	0.93	0.31	0.38													
Globigerinelloides yaucoensis	x	0.35																		
H. holmdelensis	x																			
TOTAL NUMBER COUNTED	303	284	320	362	322	325	266	337	324	296	276	308	317	327	309	275	285	304	276	318

BIOSTRATIGRAPHY

None of the biozonations defined for the K/T transition is completely applicable for this section. The classical biozonation of Bolli (1966) did not have sufficient resolution since the K/T boundary remained unzoned at that time. Berggren (1969, 1971) and Blow (1979) generalised the use of a biostratigraphical system of numerical nomenclature for the biozones, which has been modified by different authors and the result is quite confusing. The Agost section is very similar to the Spanish section at Caravaca and quite similar to the very well known El Kef section in Tunisia. Our zonation is similar to that of Pardo *et al.* (1996) for the uppermost Maastrichtian and lowermost Danian, although we prefer to use the classical system of nomenclature, and our biozonation differs as discussed below. Figure 1 shows the datum events at the Agost section along with our biozonation and the comparison with other related biozonations.

Abathomphalus mayaroensis Biozone

This biozone was originally defined by the total range of *A. mayaroensis*, but in this study following the zonation proposed by Pardo *et al.* (1966) is restricted to the first appearance datum (FAD) of *Plummerita hantkeninoides*. The *A. mayaroensis* Biozone characterise the late Maastrichtian in low latitude and high latitude deep sea sequences such as the Tethyan palaeogeographic realm (Robaszynski

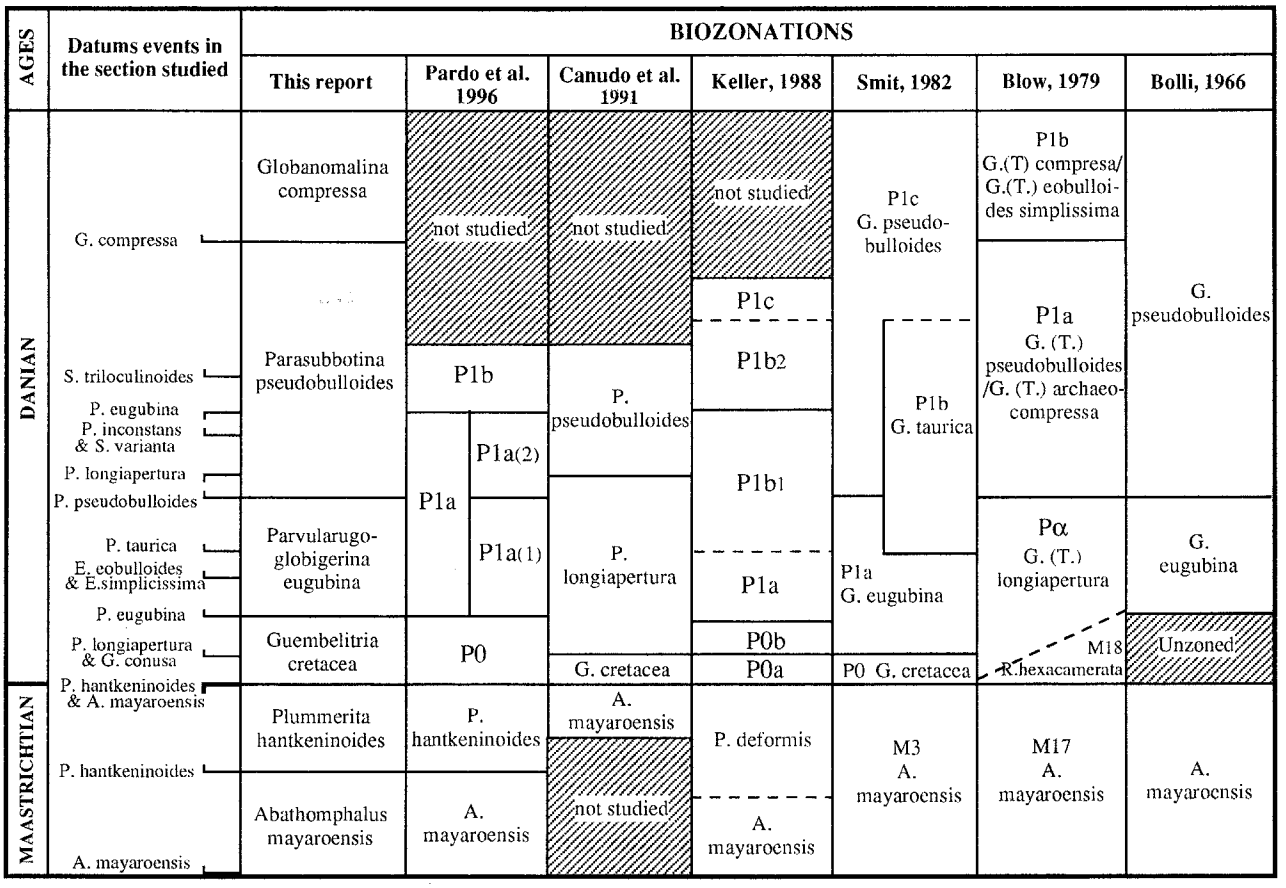


FIG. 1. – Comparison of the most relevant planktic foraminiferal biozonations across the K/T boundary.
Comparaison des biozonations de Foraminifères planctoniques les plus significatives à travers la limite K/T.

et al., 1983-1984), including the Alamedilla (Linares, 1977) and Caravaca sections (Canudo *et al.*, 1991) and the southern Indian Ocean Sites 690 and 738 (Huber, 1991 ; Keller, 1993). However, *A. mayaroensis* is very rare or absent in shallow sections such as El Kef (Keller, 1988), Brazos River (Keller, 1989a, b) and Stevns Klint and Nye Klov in Denmark (Schmitz *et al.*, 1992 ; Keller *et al.*, 1993). This biozone is thus restricted mainly because *A. mayaroensis* is a deep water dweller. Therefore, alternative biozones have been proposed to characterise the terminal Maastrichtian. The *Globutruncana falsocalcarata* Biozone was originally proposed by Kassab (1976) based on sections in northern Iraq and applied by Solakius *et al.* (1984) in the Ain Mdeker section in Tunisia. However, few workers have observed the first appearance of the index species prior to the FAD of *A. mayaroensis*. The *Pseudotextularia deformis* Biozone was proposed by Keller (1988) but this index species has taxonomical problems.

Plummerita hantkeninoides Biozone

This biozone is defined by the total range of *Plummerita hantkeninoides* and has been recognised by Pardo *et al.* (1996) at the Agost section. Nevertheless, Masters (1993) had previously suggested that *P. hantkeninoides* is a junior synonym of *Rugoglobigerina reicheli*, but we think that both morphotypes belong to different species. It is used in this paper due to the scarcity of *A. mayaroensis* in the terminal Maastrichtian mainly in shallow sections as indicated above. Nevertheless, in the two uppermost Cretaceous samples *A. mayaroensis* is more frequent that *P. hantkeninoides*. The abundance of *A. mayaroensis* just below the layer with the iridium anomaly has also been observed in some

continuous sections in the Basque Country in Northern Spain (Orúe-Etxebarría *et al.*, 1991; Orúe-Etxebarría, com. pers.). The presence of *A. mayaroensis* just below the K/T boundary in these sections could be associated with a sea-level rise during the last 50kyr of the Maastrichtian (Li and Keller, in press). All large tropical Cretaceous taxa suddenly disappear at the top of this biozone. At the Agost section, the total range of *P. hantkeninoides* spans the top 3.45 m of the Maastrichtian, whereas at the El Kef stratotype it corresponds to the top 6 m. This suggest that the El Kef section has a higher rate of sedimentation than the Agost section.

Guembelitria cretacea Biozone

This biozone spans the interval between the last appearance datum (LAD) of *Plummerita hantkeninoides* precisely at the K/T boundary and the first appearance datum of *G. eugubina*. The *G. cretacea* Biozone is the equivalent to Zone P0 of Smit (1982), Keller (1988) and Pardo *et al.* (1996). The K/T boundary was recently defined at the base of a clay layer at the El Kef boundary stratotype section, where the K/T boundary is recognised by a thin red oxidized layer, an Ir anomaly, an increase in Ni-rich spinels, an increase in total organic carbon (TOC), a decrease in $\partial^{13}C$, and the first appearance of the Tertiary planktic foraminifera. This boundary clay and its basal red layer is easily correlated with the basal yellow-red layer of Jarosite and FeO, which is just below an interval of 10 centimetres thick dark clay at the Agost section. This yellow-red layer contains geochemical evidence that is related to the effect of a large meteorite impact (Smit and ten Kate; 1982, Smit, 1990). Most of the *G. cretacea* Biozone is characterised by black clay which contains a well preserved autochthonous fauna and the Tertiary planktic foraminifera first appeared in the lower part of this biozone.

Parvularugoglobigerina eugubina Biozone

This biozone defines the interval between the *P. eugubina* FAD and the *P. pseudobulloides* LAD. Keller (1993) defines the *P. eugubina* Biozone as the total range of this species and uses the *P. pseudobulloides* FAD to subdivide this biozone into P1a(1) and P1a(2). Canudo *et al.*(1991) follow Blow (1979) and used *P. longiapertura* to characterise this biozone because this species has a very distinct and stable morphology with its compressed test and high slit-like aperture and thus may be a more suitable index taxon. Nevertheless, to date this alternative biozone has been less accepted and most workers have included *P. longiapertura* within the *P. eugubina* group. For this reason we decided to continue the use of the classical *P. eugubina* Biozone.

Parasubbotina pseudobulloides Biozone

This biozone defines the interval between the *P. pseudobulloides* FAD and *Globanomalina compressa* FAD. *Parasubbotina pseudobulloides* is an index taxon that has been used in most of the classical biozonations. Nevertheless, the FAD of *S. pseudobulloides* appears to be very diachronous (MacLeod and Keller, 1991ab) and Canudo *et al.* (1991) suggested the *P. longiapertura* LAD as alternate datum event. However, this proposal also has taxonomic and biostratigraphic problems and we decided to follow the standard biozonation of Bolli (1966). In the lower part of this zone, planktic foraminifera reach normal size and can be found in the fraction larger than 150 microns, as also observed by Keller (1988) for the El Kef section.

Globanomalina compressa Biozone

This biozone defines the interval between the *G. compressa* FAD and the top of the section studied. This event was used by Blow (1979) to define the base of the *G.(T.) compressa/G(T.) eobulloides simplicissima* (P1b) Biozone. This interval is well above the K/T boundary and not relevant for the K/T boundary event, since all but one Cretaceous taxa (*G. cretacea)* became extinct earlier, and the adaptive radiation of early Tertiary taxa is well established.

FAUNAL TURNOVER

Late Maastrichtian assemblages from the Agost section are largely dominated by biserial species (heterohelicids). Planispiral (globigerinelloids) and trochospiral (hedbergellids, rugoglobigerinids and globotruncanids) species are frequent, triserial species (guembelitriids) are common and tubulospinose (schackoinids) species are rare. The stratigraphic ranges of these taxa during the late Maastrichtian indicate various changes in the faunal assemblages but most of species are present in the *A. mayaroensis* and *P. hantkeninoides* Biozones. Environ-

mental changes are indicated by a sequence of species extinctions that begin at the base of the upper Maastrichtian (base of *A. mayaroensis* Biozone) and continue up to the K/T boundary. The first species to disappear are *Gansserina wiedenmayeri*, *Gansserina gansseri* and *Contusotruncana plicata* in the *A. mayaronensis* Biozone. The rest of the species (*Racemiguembelina milamensis*, *Archaeoglobigerina cretacea*, *Gublerina acuta* and *Rugoglobigerina pennyi*) disappear in the upper part of the *P. hantkeninoides* Biozone. Only one species has its first appearance in this interval : *P. hantkeninoides*. Therefore, more species disappear than appear in the late Maastrichtian and this tendency is more evident in the uppermost metre where 4 species went extinct and no species originated (Fig. 2). This suggests adverse environmental conditions during the latest Maastrichtian.

A total of 47 species disappear in coincidence with the yellow-red layer that marks the K/T boundary. We double checked this coincidence by scanning the residue of the uppermost Cretaceous samples. This methodology is necessary in order to avoid the Signor-Lipps (1982) effect, because certain rare species could appear to become extinct before their real moment of extinction. The large, complex, tropical and deep dwelling forms are less frequent in the terminal Cretaceous, indicating that these latitudinal restricted species were declining (Fig. 3).

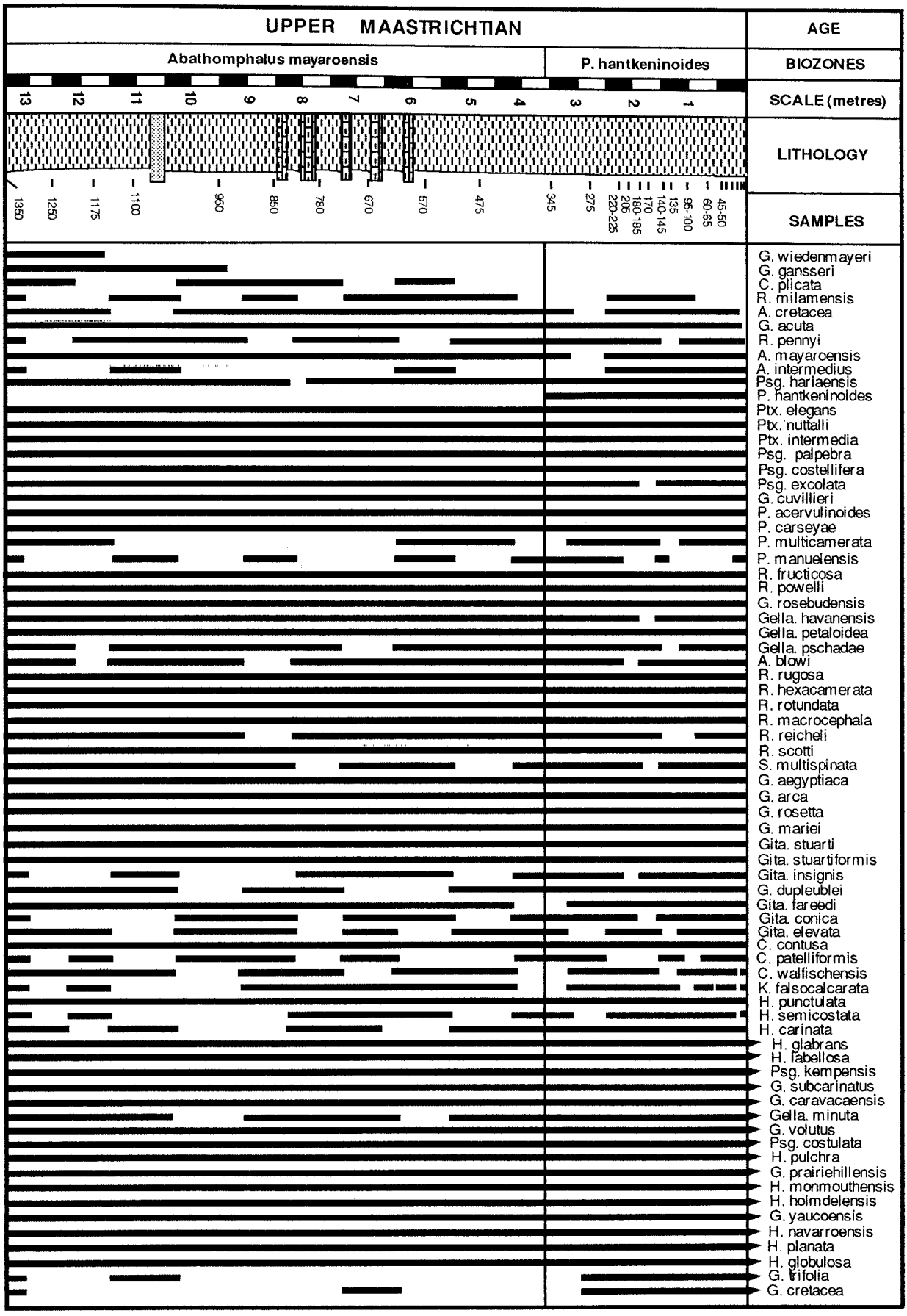
In the Agost section there is almost no evidence of reworking, the sedimentology shows no evidence of currents or other indications of bioturbation. To eliminate the potential problem of reworking, that could interfere in high resolution sampling, we ignored the presence of isolated specimens in a sample, assuming them to be reworked and hence did not list them in our data tables or figures. In the lowermost Tertiary (*G. cretacea*, *P. eugubina*, *P. pseudobulloides* and the lower part of *G. compressa* Biozones) a total of 16 Cretaceous species are present that can be considered Cretaceous survivors. The 16 Cretaceous survivors are cosmopolitan small, simple surface dwellers that disappeared gradually during the early Danian (Fig.4). Survivorship of cosmopolitan Cretaceous species was first noted by Keller (1988, 1989a,b) and later documented in numerous sections worldwide (Canudo *et al.*, 1991 ; Keller *et al.*, 1993 ; MacLeod and Keller, 1994).

In the same Danian levels in which the surviving Cretaceous species are disappearing, new Tertiary species are evolving. These new species are also opportunistic cosmopolitan taxa which can be divided into two main assemblages. The first assemblage to appear consists of the small cosmopolitan surface dwellers which originate in the *G. cretacea* Biozone and become extinct in the lower part of the *P. pseudobulloides* Biozone. The second assemblage originates in the *P. eugubina* Biozone and diversifies during the lower part of the P. *pseudobulloides* Biozone where these taxa reach normal size. This assemblage colonises the intermediate and deeper water environments in the upper part of this biozone and they continue to be abundant at least to the top of the interval studied (Fig. 5).

Quantitative planktic foraminiferal analysis of the uppermost 2.25 m of the Cretaceous shows little variation among the relative abundances of the different species (Fig. 3). The total percentage of the species that became extinct at or below the K/T boundary is about 20 % in the size fraction larger than 63 microns. All of these taxa are large, complex forms adapted to deep environments. In contrast, the small, cosmopolitan forms which were largely surface dwellers were most abundant (e.g., *Heterohelix globulosa* and *Heterohelix navarroensis*). The guembelitriids (*Guembelitria trifolia* and *G. cretacea*) are rare in the upper Cretaceous, but these opportunistic species are very abundant in the lowermost Tertiary, just after the main planktic foraminiferal extinction event. The rest of the Cretaceous surface dwellers are less abundant in the Danian than in the Maastrichtian (Fig. 3).

The relative abundance of species that evolved in the lower Danian are dominant during the early Danian and most of them became extinct near the base of the *P. pseudobulloides* Biozone (e.g., *Parvularugoglobigerina longiapertura*, *P. eugubina*, *P. sabina*, *Globoconusa fodina* and *Globoconusa conusa*). After the disappearance of these species, the dominant species are *Woodringina hornerstownensis*, *Woodringina claytonensis*, *Chiloguembelina morsei*, *Chiloguembelina taurica* and *Chiloguembelina midwayensis* (Fig. 5).

FIG. 2. – Species ranges of upper Maastrichtian planktic foraminifera at Agost.
Distribution stratigraphique des Foraminifères planctoniques au Maastrichtien supérieur à Agost.


UPPER MAASTRICHTIAN
AGE
Abathomphalus mayaroensis
P. hantkeninoides
BIOZONES
13 12 11 10 9 8 7 6 5 4 3 2 1
SCALE (metres)
LITHOLOGY
1350 1250 1175 1100 960 850 780 670 570 475 345 275 220-225 205 180-185 170 140-145 135 95-100 60-65 45-50
SAMPLES
G. wiedenmayeri
G. gansseri
C. plicata
R. milamensis
A. cretacea
G. acuta
R. pennyi
A. mayaroensis
A. intermedius
Psg. hariaensis
P. hantkeninoides
Ptx. elegans
Ptx. nuttalli
Ptx. intermedia
Psg. palpebra
Psg. costellifera
Psg. excolata
G. cuvillieri
P. acervulinoides
P. carseyae
P. multicamerata
P. manuelensis
R. fructicosa
R. powelli
G. rosebudensis
Gella. havanensis
Gella. petaloidea
Gella. pschadae
A. blowi
R. rugosa
R. hexacamerata
R. rotundata
R. macrocephala
R. reicheli
R. scotti
S. multispinata
G. aegyptiaca
G. arca
G. rosetta
G. mariei
Gita. stuarti
Gita. stuartiformis
Gita. insignis
G. dupleublei
Gita. fareedi
Gita. conica
Gita. elevata
C. contusa
C. patelliformis
C. walfischensis
K. falsocalcarata
H. punctulata
H. semicostata
H. carinata
H. glabrans
H. fabellosa
Psg. kempensis
G. subcarinatus
G. caravacaensis
Gella. minuta
G. volutus
Psg. costulata
H. pulchra
G. prairiehillensis
H. monmouthensis
H. holmdelensis
G. yaucoensis
H. navarroensis
H. planata
H. globulosa
G. trifolia
G. cretacea

MODELS AND CAUSES OF EXTINCTION

The planktic foraminiferal extinction model for the K/T boundary is a controversial topic because it depends on different interpretations of the data and on the methodology used to obtain these data (Molina, 1994). The continuity of the Agost section, the abundance of planktic foraminifera, the high resolution sampling and the quantitative study provide an excellent opportunity to evaluate the K/T boundary mass extinction and elucidate the real nature of this controversy.

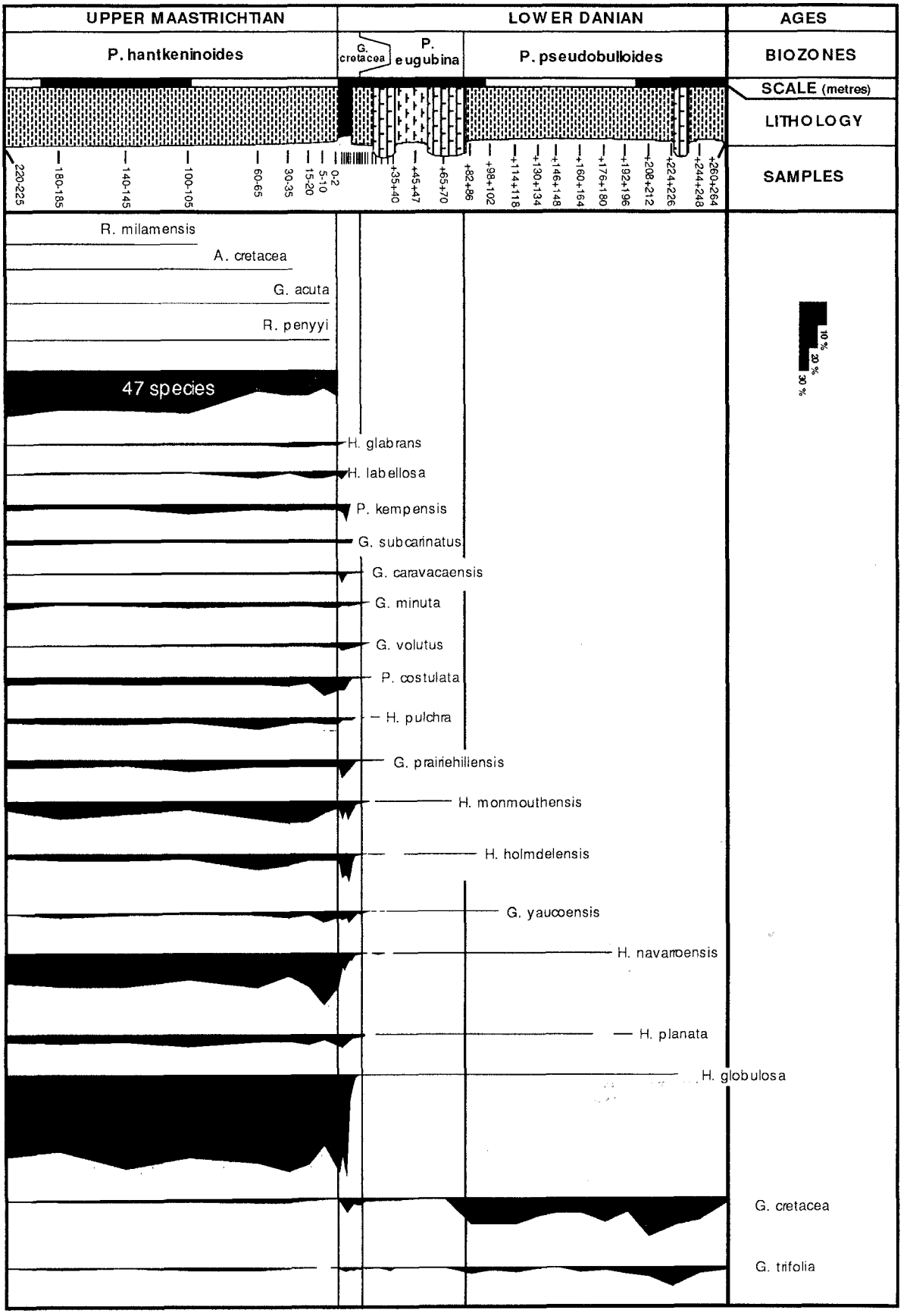
The oldest and least detailed studies of the K/T transition were performed on widely spaced samples (Bolli, 1966) or on sections which contained hiatuses (Linares and Martínez-Gallego, 1971). At present it is quite obvious that such methodology, or discontinuous sections are unsuitable to establish the pattern of extinction in planktic foraminifera, and that by default such studies will show a catastrophic extinction pattern. An additional constraint in evaluating this mass extinction is the thickness of the K/T transition, or the rate of sediment deposition. Luterbacher and Premoli-Silva (1964) sampled and studied Gubbio section in great detail. They defined several new species and named a new biozone (*G. eugubina* Biozone). However, this Italian section is very condensed and contains a hiatus (MacLeod and Keller, 1991a,b) and thus can not be used as the real model of extinction. Alvarez *et al.* (1980) proposed the bolide impact hypothesis for the Cretaceous-Tertiary mass extinction based on these Italian sections, and hence assumed the nearly total extinction of the planktic foraminifera. This concept of near total extinction was the prevailing view among micropaleontologists at that time.

Nevertheless, more expanded sections were studied by Smit (1977, 1979) at that time who established the new *G. cretacea* Biozone based on the Caravaca section (Spain). But he also assumed the total extinction of all the planktic foraminifera, except *G. cretacea* and probably *H. monmouthensis* and *G. messinae*. Although Smit studied closely spaced samples across the K/T boundary, he concluded that the extinction of planktic foraminifera was abrupt and without any previous warning in the sedimentary record (Smit and Hertogen, 1980). Smit also studied the Spanish section at Agost (Groot *et al.*, 1989) and the Tunisian section at El Kef, and maintained and even further developed the idea that the impact event at the K/T boundary suddenly exterminated all but one species (Smit, 1982, 1990). In order to maintain this interpretation, he considered all Cretaceous specimens present above the K/T boundary as reworked. These data were not questioned until Keller (1988) also studied the El Kef section and provided evidence that species extinction extended across the K/T boundary with 10 of the species surviving well into the Tertiary. She also found 14 species disappearing below the boundary and concluded that these extinctions appear unrelated to an impact event. These ideas were also documented studying other sections distributed all over the world (Keller, 1989a,b, 1990, 1994). Nevertheless, some authors critically commented those ideas (Huber *et al.*, 1994), which were well defended and largely replied (Keller and MacLeod, 1994).

One of the most controversial aspect in the K/T extinction pattern is the decline of the fauna prior to the K/T boundary. Our data from Agost indicate that 7 species disappeared but just one evolved during the late Maastrichtian. This decline is most apparent in the terminal Maastrichtian (uppermost meter) where 4 species disappeared, but no species appeared (Fig. 2). The quantitative data show that other large species decreased in abundance and are rare in the terminal Cretaceous (Table 1, Fig. 2 and 3). Changes prior to the K/T boundary were also noted in the Spanish sections of Zumaya (Herm, 1965 ; Lamolda, 1983 ; 1990), Sopelana (Lamolda *et al.*, 1983 ; Orúe-Etxebarría *et al.*, 1984), Caravaca (Canudo *et al.*, 1991 ; Canudo 1994 ; Pardo *et al.*, 1996) and in the Tunisian section of El Kef (Brinkhuis and Zachariasse, 1988). However, the magnitude of the decline shown by the former authors is less notable than the one found at El Kef (Keller, 1988, Li and Keller, in press), at Brazos River (Keller, 1989a,b) and in the Antarctic Ocean (Keller, 1993).

The differences among the patterns of extinction found in all of these sections are primarily due to latitudinal effects, with large specialized forms disappearing first from high latitudes. This indicates that the decline prior to the K/T boundary is mainly due to a gradual decrease in temperature (Schmitz *et al.*, 1992 ; Keller *et al.*, 1993 ; Barrera, 1994 ;

FIG. 3. – Relative abundances of typical Maastrichtian species at Agost.
Abondance relative des espèces typiques du Maastrichtien à Agost.


UPPER MAASTRICHTIAN
LOWER DANIAN
AGES
P. hantkeninoides
G. cretacea
P. eugubina
P. pseudobulloides
BIOZONES
SCALE (metres)
LITHOLOGY
SAMPLES
220-225
180-185
140-145
100-105
60-65
30-35
15-20
5-10
0-2
+35+40
+45+47
+65+70
+82+86
+98+102
+114+118
+130+134
+146+148
+160+164
+176+180
+192+196
+208+212
+224+226
+244+248
+260+264
R. milamensis
A. cretacea
G. acuta
R. penyyi
47 species
10 %
20 %
30 %
H. glabrans
H. labellosa
P. kempensis
G. subcarinatus
G. caravacaensis
G. minuta
G. volutus
P. costulata
H. pulchra
G. prairiehillensis
H. monmouthensis
H. holmdelensis
G. yaucoensis
H. navarroensis
H. planata
H. globulosa
G. cretacea
G. trifolia

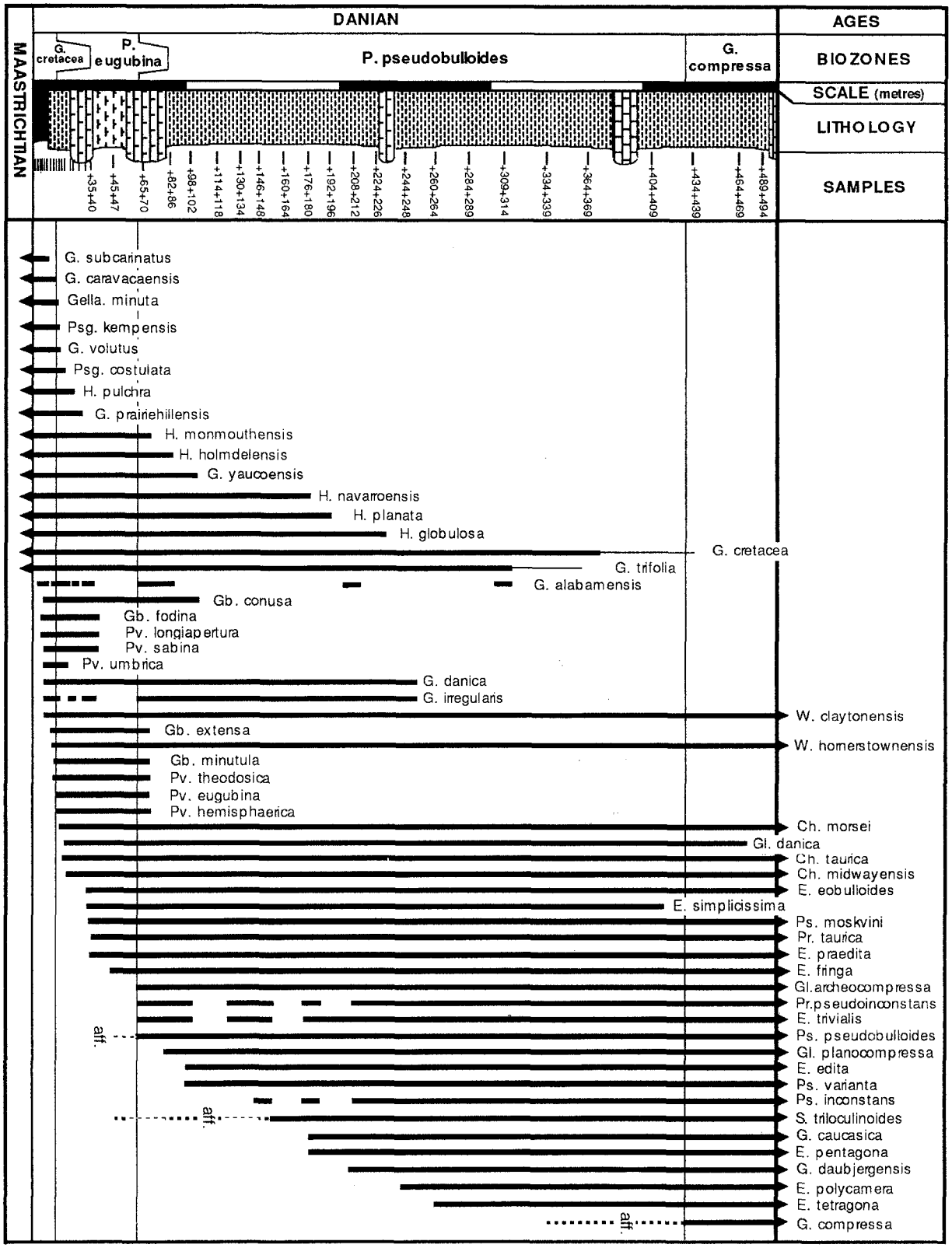


FIG. 4. – Species ranges of Danian planktic foraminifera at Agost.
Distribution stratigraphique des Foraminifères planctoniques au Danien à Agost.

D'Hondt and Lindinger, 1994), which produced the retreat to low latitudes of certain species. However, the discrepancies in interpretations in low latitudes and even in the same sections, are due to different taxonomic interpretations and the Signor-Lipps effect. Nevertheless, the Signor-Lipps effect does not explain the absence of extinctions prior the K/T boundary (Smit, 1982, 1990) and can not be invoked to conclude that there were no significant plankton extinctions before the K/T boundary (Smit, 1994). According to our data from Agost the extinctions prior to the K/T boundary are significant, although they seem not to be very important in magnitude because species affected were already rare and retreating from high latitudes to refuge in low latitudes. The extinction of *G. wiedenmayeri*, *G. gansseri* and *C. plicata* in the *A. mayaroensis* Biozone could be considered as the result of background extinction, but the extinction of *R. milamensis*, *A. cretacea*, *G. acuta* and *R. pennyi* in the *P. hantkeninoides* Biozone are very probably part of a gradual mass extinction that ended in the *P. pseudobulloides* Biozone.

In order to establish the magnitude of the extinction, which precisely coincides with the layer that characterises the K/T boundary, suitable sections and the right methodology are necessary. The sections have to be continuous, well expanded, not very shallow and located in low latitudes where the most diversified faunas lived. These qualifications apply to the Agost section which is very continuous since all the planktic biozones have been found. This section is similar to El Kef and Caravaca which are the most complete sections known world wide (MacLeod and Keller, 1991a, b). The paleoenvironment at Agost was a subtropical upper slope, based on small benthic foraminifera (Pardo *et al.*, 1996), with a very diversified planktic foraminifera fauna. The high resolution methodology and the intensive search in every terminal Cretaceous sample (to avoid the Signor-Lipps effect) indicate that 47 species suddenly disappeared at the K/T boundary at Agost section (Fig. 2, 3 and 6). Although this extinction event represents only about 20 % of the individuals in the population in the fraction larger than 63 microns, it is the major extinction event in the history of planktic foraminifera, and it exactly coincides with the layer containing the impact evidence. Regarding the causes of this major extinction, now it is generally accepted that a meteorite impacted at the K/T boundary (D'Hontd, 1994; Schmitz, 1994). The species that suddenly became extinct were the deep dwellers and the majority of the intermediate dwellers, whereas the cosmopolitan surface dwellers suffered less, the very probable reason being that they were protected in high latitudes, recolonizing the low latitudes after the impact event.

How many species survived the K/T boundary event ? This question constitutes one of the most controversial aspects of this topic. According to Smit (1982, 1990) only *Guembelitria cretacea* survived. In contrast, Keller (1988, 1989a, b, 1993, 1994), Keller *et al.* (1993) and MacLeod and Keller (1994) reported that about 1/3 of the species survived. Historically it was assumed by most of the micropaleontologists that almost all planktic foraminifera became extinct at the K/T boundary; consequently, all Cretaceous specimens found in the basal Danian were considered as reworked. However, isotopic analyses of some Cretaceous species present in earliest Tertiary sediments allowed Barrera and Keller, (1990) and Keller *et al.* (1993) to conclude that most of the abundant Cretaceous species present in Tertiary sediments have Tertiary signals and are therefore Cretaceous survivors. Most of the 16 species found in the basal Tertiary of the Agost section can be considered survivors on the base of their constant presence in several samples and their geographic distribution in other sections (Keller, 1988, 1989a,b, 1993; Canudo *et al.*, 1991; Keller *et al.*, 1993; MacLeod and Keller, 1994). Nevertheless, not all Cretaceous specimens present in earliest Tertiary samples are survivors; for instance, in samples from the basal 3 cm of the *G. cretacea* Biozone we found some globotruncanids, and in samples up section, we found isolated specimens with different preservation, which we considered reworked. Most of the Cretaceous species frequent and present in several Tertiary samples are considered as autochthonous. However, *Heterohelix glabrans* and *Heterolelix labellosa* that are frequent only in the basal samples of the Tertiary may be reworked and need further confirmation in other sections. Lately, certain foraminiferal specialists that have criticised the Cretaceous species survivorship data, are now accepting that some species, such as *Hedbergella holmdelensis* and *Hedbergella monmouthensis*, survived apart from *G. cretacea* (Liu and Olsson, 1994). Even Smit (1995) now admits some, "unimportant", Cretaceous species survivors above the K/T boundary and that "the final extinctions may have lingered on for a while". At the same time that the Cretaceous survivors are gradually disappearing in the basal Danian, other small species are gradually originating. The absence of certain primitive species in the lower part of *G. cretacea* Biozone could be due to carbonate dissolution in this deep sea section or to the delay in the recolonization of this latitude (Fig. 6).

The Tertiary species ecologically replaced the Cretaceous species that could not successfully adapt to new environmental conditions (MacLeod, 1993). By the *P. pseudobulloides* Biozone, this adaptive radiation began to colonise the vacant deep environments and species morphology reached again normal size for planktic foraminifera. This gradual pattern of extinction and origination along the K/T transition is difficult to explain by the impact theory. The gradual pattern of extinction seems to be mainly controlled by geological causes (volcanism, temperature changes, ocean circulation changes, sea level changes) and although biological causes (competition, endemism) could be subordinated, they would play an important role (Molina, 1995). The gradual pattern is plausibly explained by a decrease in temperature that began in the uppermost Cretaceous (Schmitz *et al.*, 1992 ; Barrera, 1994 ; D'Hondt and Lindinger, 1994). The decrease in temperature could probably be associated with a sea level change (Ginsburg, 1964, 1984, Brinkhuis and Zachariasse, 1988 ; Keller, 1988). This gradual pattern is also consistent with the effect of massive volcanism (Officer y Drake, 1985 ; Courtillot *et al.*, 1986) that lasted at least 3 million years beginning about 2 million years before the K/T boundary (Venkatesan *et al.*, 1993). Consequently, the probable cause that produced the gradual mass extinction of 23 species during the upper Maastrichtian and lower Danian, is not as simple as an extraterrestrial impact that produced the catastrophic mass extinction of the 47 species at the K/T boundary.

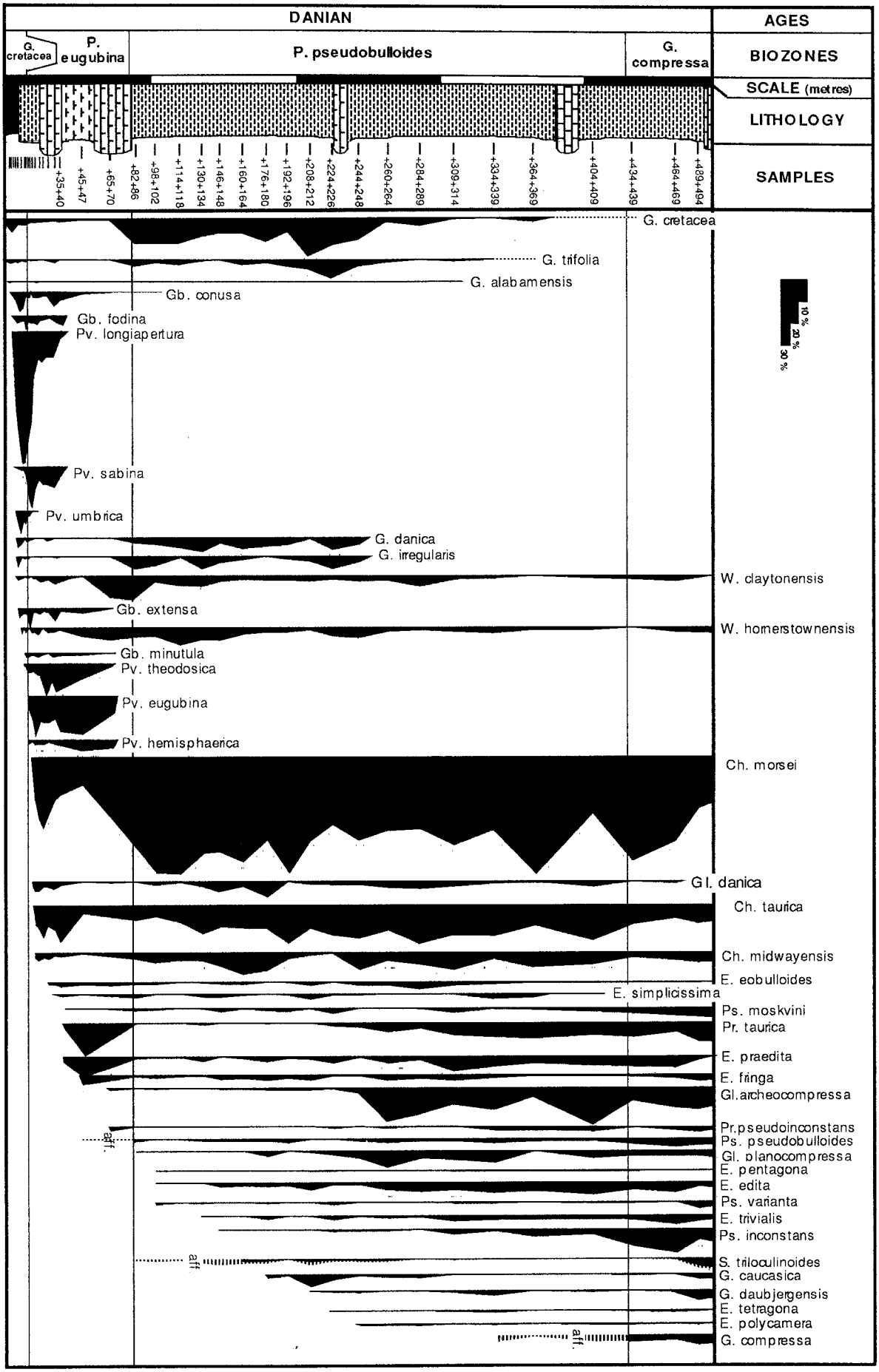
CONCLUSIONS

The section of Agost in Spain is one of the most continuous and expanded marine record of the K/T transition known so far. The planktic foraminiferal assemblages are very rich, diversified and well preserved. Six biozones have been recognised across the K/T boundary : *Abathomphalus mayaroensis* Biozone and *Plummerita hantkeninoides* Biozone (late Maastrichtian), *Guembelitria cretacea* Biozone, *Parvularugoglobigerina eugubina* Biozone, *Parasubbotina pseudobulloides* Biozone and *Globanomalina compressa* Biozone (early Danian). These biozones have been correlated with other biozonations established in different geographical regions.

The quantitative study and the high resolution sampling allow us to test the model of extinction in planktic foraminifera across the K/T boundary. The mass extinction occurred over an extended time period similar to the Tunisian stratotype section of El Kef and the Spanish section of Caravaca. At Agost, 7 species disappeared in the late Maastrichtian, 47 became extinct precisely at the K/T boundary and 16 disappeared in the earliest Tertiary. The species that became extinct at the K/T boundary constitute only about 20 % of the individuals in the population larger than 63 microns. The 47 species that suddenly became extinct are large, complex tropical-subtropical forms that lived in deeper to intermediate waters. Their extinction at the K/T boundary constitutes the major and catastrophic mass extinction in the history of planktic foraminifera. This pattern of extinction is superimposed onto a gradual pattern of extinctions of 23 species that began in the *A. mayaroensis* Biozone (late Maastrichtian) and ended in the lower part of the *P. pseudobulloides* Biozone (early Danian). Cretaceous species which disappeared gradually are all simple, small forms, of cosmopolitan distribution that lived in surface waters. This group constitutes about 80 % of the individuals in the populations and their disappearance over the latest Maastrichtian to early Danian can be considered a gradual mass extinction.

Our data provide an excellent opportunity to elucidate the ongoing controversy between Smit and Keller, as to whether the K/T mass extinction was catastrophic or gradual. Our mass extinction model in planktic foraminifera is consistent with both patterns, since our data show that a major catastrophic mass extinction that centred at the K/T boundary was superimposed on a gradual mass extinction which began in the late Maastrichtian and continued into the early Danian. Our interpretations regarding the causes of the mass extinction in planktic foraminifera are mainly based on the two superimposed patterns we observed and we acknowledge the need for further multidisciplinary studies. The catastrophic mass extinction of 47

FIG. 5. – Relative abundances of Danian species at Agost.
Abondance relative des espèces du Danien à Agost.


DANIAN
AGES
G. cretacea
P. eugubina
P. pseudobulloides
G. compressa
BIOZONES
SCALE (metres)
LITHOLOGY
SAMPLES
+35+40
+45+47
+65+70
+82+86
+98+102
+114+118
+130+134
+146+148
+160+164
+176+180
+192+196
+208+212
+224+226
+244+248
+260+264
+284+289
+309+314
+334+339
+364+369
+404+409
+434+439
+464+469
+489+494
G. cretacea
G. trifolia
G. alabamensis
Gb. conusa
Gb. fodina
Pv. longiapertura
10 %
20 %
30 %
Pv. sabina
Pv. umbrica
G. danica
G. irregularis
W. claytonensis
Gb. extensa
W. homerstownensis
Gb. minutula
Pv. theodosica
Pv. eugubina
Pv. hemisphaerica
Ch. morsei
Gl. danica
Ch. taurica
Ch. midwayensis
E. eobulloides
E. simplicissima
Ps. moskvini
Pr. taurica
E. praedita
E. fringa
Gl.archeocompressa
Pr.pseudoinconstans
Ps. pseudobulloides
Gl. planocompressa
E. pentagona
E. edita
Ps. varianta
E. trivialis
Ps. inconstans
S. triloculinoides
G. caucasica
G. daubjergensis
E. tetragona
E. polycamera
G. compressa
aff.
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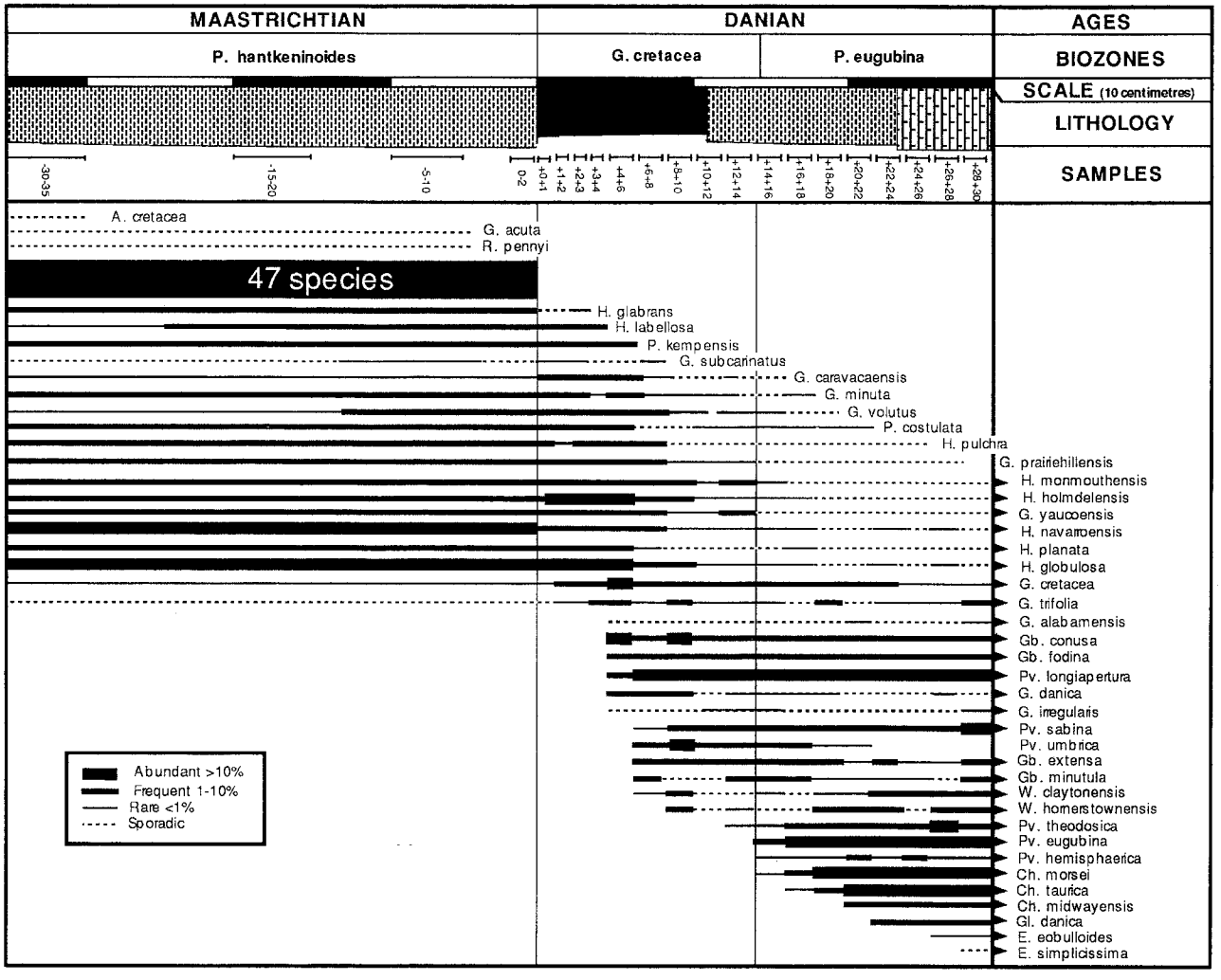
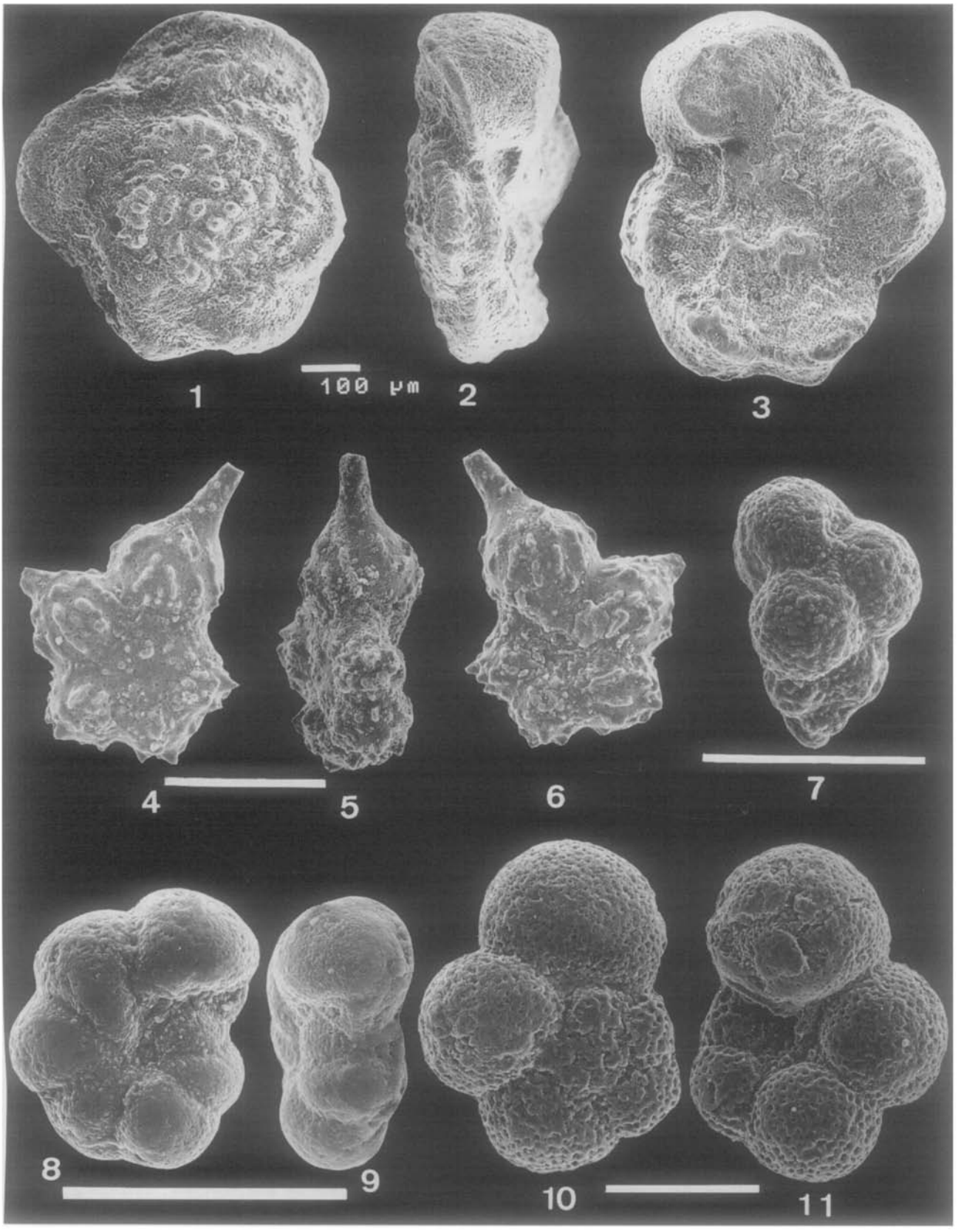


FIG. 6. – Semiquantitative species reanges across the K/T boundary at Agost.
Distribution stratigraphique semi-quantitative des espèces à la limite K/T à Agost.

species at the K/T boundary is very compatible with the sudden effects of a large meteorite impact, whereas the gradual mass extinction of 23 species during the Maastrichtian-Danian transition is compatible with temperature and sea level changes that may be related to massive volcanism. Thus, the K/T boundary mass extinction in planktic foraminifera is a more complex phenomenon than that of either a bolide impact or environmental changes alone.

PLATE 1

1-3. *Abathomphalus mayaroensis* (BOLLI), sample Agost, 0-2 cm.
4-6. *Plummerita hantkeninoides* (BRÖNNIMANN), sample Agost, 15-20 cm.
7. *Guembelitria cretacea* (CUSHMAN), sample Agost, 82+86 cm.
8-9. *Parvularugoglobigerina eugubina* (LUTERBACHER and PREMOLI SILVA), sample Agost, 28+26 cm.
10-11. *Parasubbotina pseudobulloides* (PLUMMER), sample Agost, 260+264 cm.


100 µm
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ACKNOWLEDGEMENTS

This research was funded by DGICYT project PB94-0566, by Diputación General de Aragón grant BCB3692 and by Gobierno de Navarra grant OF/478/92.

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