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Planktic foraminiferal turnover and $\delta^{13}\text{C}$ isotopes across the Paleocene–Eocene transition at Caravaca and Zumaya, Spain

José I. Canudo ^a, Gerta Keller ^b, Eustoquio Molina ^a, Nieves Ortiz ^{a,b}

^a *Departamento de Ciencias de la Tierra (Paleontología), Universidad de Zaragoza, 50009 Zaragoza, Spain*

^b *Department of Geological and Geophysical Sciences, Princeton University, Princeton, NJ 08544, USA*

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Abstract

Biostratigraphic and faunal analysis of planktic foraminifera and benthic foraminiferal isotopes at Zumaya and Caravaca sections in Spain indicate that Zumaya has a continuous record with high sediment accumulation rates across the Paleocene–Eocene transition whereas Caravaca has a hiatus with the uppermost Zone P4, Zone P5 and the lower part of Zone P6 missing. Both sections contain nearly continuous and expanded records of the global $\delta^{13}\text{C}$ excursion at Zumaya and Caravaca respectively. The $\delta^{13}\text{C}$ excursion is associated with dark grey shale deposition in a dysaerobic benthic environment. This $\delta^{13}\text{C}$ event is associated with a major planktic foraminiferal turnover marked by the gradual extinction and evolution of 33% and 18% of the species respectively. A rapid change in the relative abundances of these taxa occurs at the $\delta^{13}\text{C}$ excursion coincident with the extinction of 50% of the small benthic foraminiferal taxa. The entire water column was affected by this faunal turnover (surface, intermediate, deep dwellers), but in contrast to benthic foraminifera there was no net loss of habitats since species extinctions of planktic foraminifera were largely replaced by originations.

1. Introduction

The Paleocene–Eocene (P–E) transition is characterized by the warmest climate with the lowest average $\delta^{13}\text{C}$ values of the Cenozoic (e.g. Shackleton et al., 1984; Shackleton, 1986; Miller et al., 1987; Corfield and Shackleton, 1988; Kennett and Stott, 1990, 1991; Stott and Kennett, 1990). During this time, deep water temperatures rose 5–10°C globally and surface temperatures rose 5°C in Antarctic waters, but remained relatively stable in low latitudes (Kennett and Stott, 1990, 1991; Barrera and Huber, 1991; Pak and Miller, 1992; Corfield and Shackleton, 1988; Corfield and Cartlidge, 1992; Stott, 1992). Near the P/E boundary Kennett and Stott (1990, 1991) documented sudden negative $\delta^{13}\text{C}$ and $\delta^{18}\text{O}$ excursions estimated to have occurred over a few thou-

sand years and lasting less than 100 k.y. This $\delta^{13}\text{C}$ excursion has now been documented worldwide in low and high latitude deep-sea sections and is found to coincide with the most severe benthic foraminiferal mass extinction during the past 90 m.y. when 35–50% of the taxa became extinct (Tjalsma and Lohmann, 1983; Thomas, 1989, 1990; Kaiho, 1991; Pak and Miller, 1992). This mass extinction and isotopic shift is generally attributed to a major change in oceanic deep circulation related to global warming, a temporary shut-off of cold Antarctic deep water and production of warm saline deep waters possibly in the Tethys region (Kennett and Stott, 1990, 1991; Pak and Miller, 1992).

Planktic foraminifera are often considered to have been relatively unaffected by this global climatic and oceanographic change. This is largely

because during the peak global warming, tropical and subtropical taxa (acarinids, morozovellids) temporarily invaded high latitudes and displaced cooler water taxa (subbotinids) (Boersma and Premoli Silva, 1989; Kennett and Stott, 1990; Canudo and Molina, 1992a; Lu and Keller, 1993). Since this faunal turnover generally resulted in the replacement of one fauna by another, there was no net loss in species diversity and conversely, no mass extinction (Lu and Keller, 1993). The effect and magnitude of regional faunal turnover, however, cannot be evaluated solely based on simple species diversity or species extinctions and originations. Quantitative data are necessary to evaluate the effect on each species population and to deter-

mine which taxa and habitats suffered the most. Such a study by Lu and Keller (1993) of the southern Indian Ocean ODP Site 738 and Pacific DSDP Site 577 revealed major faunal turnovers not only coinciding with the rapid $\delta^{13}\text{C}$ excursion, but also near the beginning and end of this global warming trend. Thus, planktic foraminifera, which are highly sensitive to oceanographic changes, yield important clues to the nature of the Paleocene–Eocene warm event.

In this study we focus on the benthic carbon isotopes and faunal turnover in planktic foraminifera across the Paleocene–Eocene transition at Zumaya in northern Spain and Caravaca in southern Spain (Fig. 1). The two sections were chosen

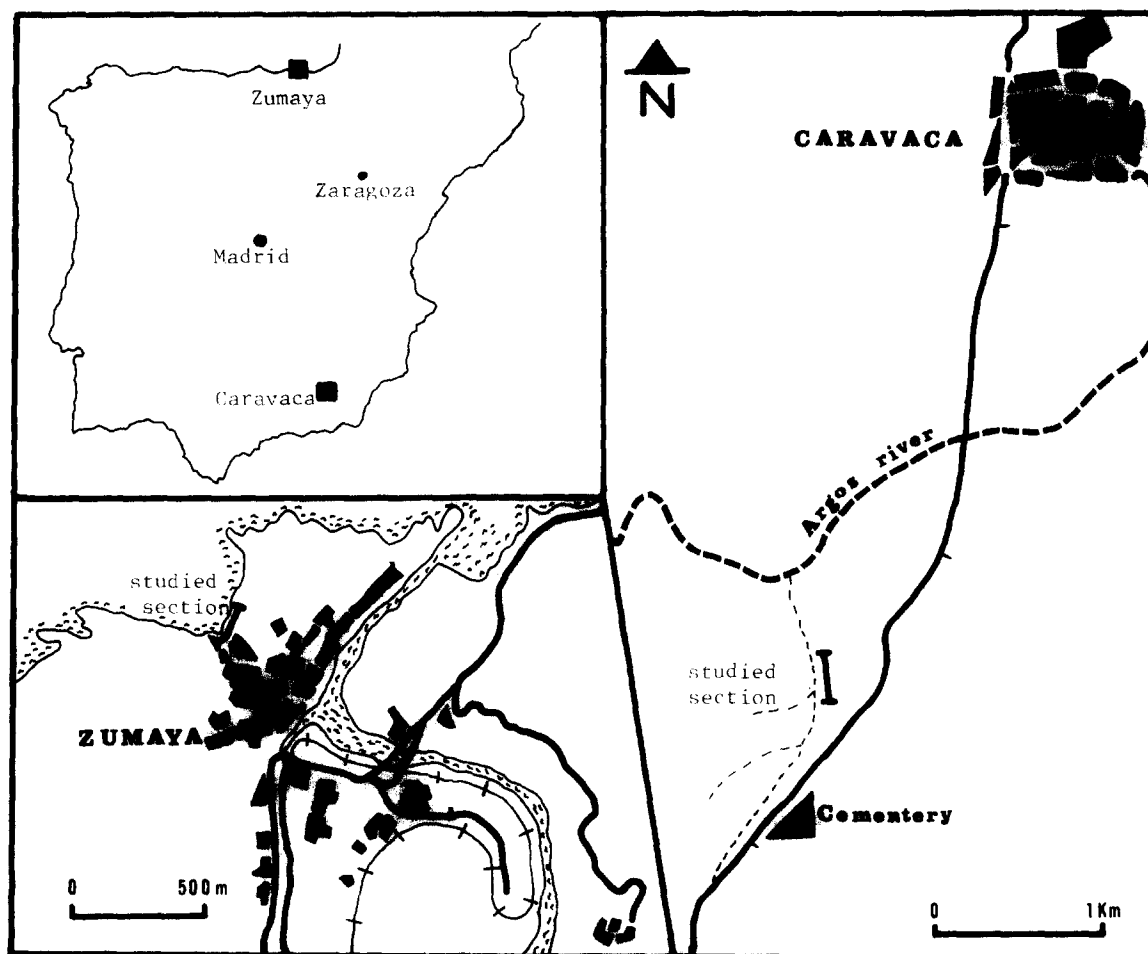


Fig. 1. Location map of the studied sections.

because of their location near the theorized source of bottom water production in the Tethys (Kennett and Stott, 1990, 1991), and because they contain a much expanded sedimentation record as compared to deep-sea sections. We document detailed high resolution quantitative planktic foraminiferal and benthic $\delta^{13}\text{C}$ records of these two sections based on sample spacing of 5–10 k.y. during the critical interval of the $\delta^{13}\text{C}$ shift. Specifically, we focus on (1) high resolution stratigraphy, (2) the benthic $\delta^{13}\text{C}$ record and (3) the planktic foraminiferal turnover.

The Paleocene and the Lower Eocene are relatively continuous and well developed at Zumaya. This section is located in San Telmo beach NW of the town of Zumaya. It is accessible by a narrow road that reaches the beach at the point where the Paleocene–Eocene transition section begins. The Paleocene and Lower Eocene foraminifers from this Pyrenean section were studied by Hillebrandt (1965) who published a significant biostratigraphic analysis but did not include details of the Paleocene/Eocene boundary. Later, Orue Etxebarria and Lamolda (1985) studied the paleogeography of the Basque–Cantabrian basin by means of planktic foraminifera from the Paleocene to Middle Eocene. Pujalte et al. (1989) analyzed the sedimentary response to changing tectonics at the beginning of the Pyrenean convergence, and recently, Canudo and Molina (1992a) studied the planktic foraminiferal faunal turnover and biostratigraphy of the Paleocene/Eocene boundary.

The Caravaca section is located 4 km south of the town of Caravaca (Murcia province) in the Barranco del Gredero near the cemetery. Structurally, the section is within the Betic Cordillera and is part of the Jorquera Formation (Veen, 1969). The biostratigraphy of the Paleocene–Eocene transition was earlier studied by Hillebrandt (1974, foraminifers) and Romein (1979, calcareous nannoplankton). Neither of these studies detected a hiatus near the Paleocene/Eocene boundary.

2. Methods

The Paleocene–Eocene (P–E) transition spanning Zones P4–P6b was collected at Caravaca

and Zumaya in closely spaced intervals of 10–20 cm across the P/E boundary (Zones P6a and P6b) and at 50 cm intervals in Zones P4–P5. A total of 59 and 48 samples were analyzed for Caravaca and Zumaya respectively. Samples for foraminiferal isotope and faunal analyses were disaggregated with water, washed through a 63 μm sieve and dried at 50°C. For quantitative planktic foraminiferal analysis 300–500 specimens were picked from the size fraction greater than 105 μm . The specimens were identified and mounted on microslides for a permanent record. Relative abundance data percentages are listed in Tables 1, 2 and 3.

Isotopic analyses were conducted on the benthic foraminifera *Cibicidoides* and *Nuttallides truempyi* at Zumaya and *N. truempyi* at Caravaca, except for the $\delta^{13}\text{C}$ shift interval where *N. truempyi* is absent and *Lenticulina* was analyzed. Specimens were picked from the 180–250 μm size fraction and ultrasonically cleaned. Isotopic measurements were conducted with a Finnigan MAT 251 linked to a Kiel carbonate extraction system at the stable isotope laboratory of the University of Michigan, Ann Arbor. Analytical error was measured at 0.05‰ for $\delta^{13}\text{C}$. The data are reported in values referenced to PDB and are listed in Tables 4 and 5. No species correction factors were applied to the data because species offset studies are still in flux. For instance, Shackleton et al. (1984) reported that there is no species offset in $\delta^{13}\text{C}$ in paired analysis of *N. truempyi* and *Cibicidoides*, whereas Katz and Miller (1991) and Pak and Miller (1992) found that *N. truempyi* is consistently lower than *Cibicidoides* by 0.23‰ in $\delta^{13}\text{C}$, although further analyses are necessary to confirm this values.

Foraminiferal tests in both Zumaya and Caravaca sections show recrystallization of test calcite. Such dissolution and reprecipitation of large foraminiferal calcite, however, often does not significantly influence the magnitude of the $\delta^{13}\text{C}$ shift in deep sea sequences (Keigwin and Corliss, 1986). In subaerally exposed sequences, however, the effects of diagenesis on carbon isotopes can vary depending on the history of diagenetic fluids. However, while the absolute values may shift, the relative trend in carbon isotopes may not change appreciably. Therefore, the carbon isotope record,

Table 2

Relative abundance of Paleocene planktic foraminifera at Caravaca section.

Species	Samples																
	2.1	2.4	2.8	3	3.1	3.5	3.9	4	4.1	4.5	4.8	5	5.5	6	7	8	9
<i>Morozovella acuta</i>	2	2	5	2	1	1	2	3	1	3	3	1	X	1	8	2	5
<i>M. angulata</i>	5	5	7	6	4	2	3	4	6	6	4	4	X	3	4	5	6
<i>M. aequa</i>	3	5	2	1	1	1	2	2	2	2	1	2	1	2	2	6	6
<i>M. conicotruncana</i>	1	1	1	X	1	X	1	X	1	X	1	X	1	X	X	X	X
<i>M. crosswickensis</i>	7	9	4	4	1	1	5	8	3	2	4	1	1	5	1	5	4
<i>M. edgari</i>	5	5	3	5	2	5	3	3	3	X	X	3	1	3	4	6	10
<i>M. lacerti</i>	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>M. nicoli</i>					X	X	X	X	X	X	X	X	X	X	X	X	X
<i>M. oclusa</i>	X	1	X	X	X	X	2	X	X	1	X	1	X	4	3	3	3
<i>M. kolchidica</i>	X	1	1	X	X	1	8	X	2	X	1	X	X	X	3	6	1
<i>M. simulatilis</i>	X	2	1	2	1	2	5	X	5	5	4	X	1	2	10	5	1
<i>M. velascoensis</i>	3	6	3	5	4	4	2	2	7	7	7	6	6	6	18	15	8
<i>Igorina albei</i>	6	2	2	3	6	21	3	2	6	5	4	5	22	4	1	X	X
<i>I. laevigata</i>	6	1	9	1	14	1	5	10	3	7	11	1	X	2	1	X	X
<i>I. pusilla</i>	5	20	7	11	17	23	20	3	9	7	8	19	5	14	8	1	1
<i>I. cayensis</i>	3	3	3	4	7	8	5	9	2	2	4	7	10	6	4	7	1
<i>Acarinina acarinata</i>	3	7	5	5	7	9	5	8	5	5	4	8	10	2	2	5	6
<i>A. pseudotopilensis</i>	X	3	1	X	2	X	4	1	X	X	1	1	2	1	X	X	X
<i>A. strabocella</i>																	
<i>A. subsphaerica</i>	3	X	2	1	1	4	2	4	3	2	3	2	4	3	5	3	X
<i>A. triplex</i>		1	X	X	X	X	X	X	X	1	X	X	X	X	3	4	3
<i>A. wilcoxensis</i>																	
<i>Muricoglobigerina aquiensis</i>	1	X	1	3	2	4	1	3	2	3	3	7	5	2	X	X	X
<i>M. chascanona</i>	X	X	3	1	1	2	X	1	1	1	1	3	X	X	X	X	X
<i>M. mckanaii</i>	6	6	11	6	8	8	1	1	10	7	4	3	4	3	6	X	X
<i>M. soldadoensis</i>											X	5	9	2	12	5	4
<i>Globorotaloides pseudoimmitata</i>	2	1	X	X	X	X	2	2	1	1	1	2	1	4	X	1	3
<i>Eoglobigerina trivialis</i>	9	1	1														
<i>Subbotina</i> sp.				3	1	1	1	2	2	3	2	2	X	X	X	X	X
<i>S. finlayi</i>								X	X	5	X	X	X	X	1	X	X
<i>S. hornibrooki</i>															1	X	4
<i>S. eocaenica</i>																	
<i>S. triangularis</i>	6	3	6	11	9	2	5	5	6	X	8	5	3	5	6	14	8
<i>S. velascoensis</i>	4	9	10	8	3	5	7	3	9	11	12	5	5	5	14	1	13
<i>Planorotalites ehrenbergi</i>	5	X	X	1	X	X	X	1									
<i>P. elongata</i>																	
<i>P. haunsbergensis</i>	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
<i>P. pseudomenardii</i>	10	2	6	11	4	1	X	12	9	11	6	3	1	7	2	1	X
<i>P. troelseni</i>	2	1	3	4	X	X	X	X	2	1	2	X	X	3	2	X	X
<i>G. ovalis</i>	X	X	X	1	1	X	1	1	X	X	X	X	X	1	X	X	X
<i>Zeauvigerina teuria</i>	X	X	1	1	X	X	X	1	X	X	X	X	X	1	1	X	X
<i>Chiloguembelina crinita</i>	2	1	1	X	X	X	3	1	1	X	X	1	X	1	X	1	X
<i>C. subtriangularis</i>																	
TOTAL NUMBER COUNTED	320	346	351	425	351	328	347	356	318	400	363	345	334	321	298	350	333

and particularly the $\delta^{13}\text{C}$ shift near the P–E boundary, remains a useful tool for stratigraphic correlation. In contrast, the primary oxygen isotope signal is overprinted by diagenesis and can not be used for correlation purposes or for inferring paleotemperatures. (Plates I, II, III).

3. Lithology and depositional environment

The lower part of the Paleocene–Eocene (P–E) transition at Zumaya consists of 20 m of homoge-

nous grey marls intercalated with calcarenite layers (Zones P4–P6a); the upper part consists of 20 m of grey marls alternating with grey limestone beds (upper Zone P6a–P6b) (see Fig. 3). A 20 cm thick dark brown shale layer marks the benthic foraminiferal mass extinction and $\delta^{13}\text{C}$ shift and is succeeded by a 4 m interval of red clay. At Caravaca the lower part of the section consists of 25 m of homogenous marls with grey limestone layers (Zone P4) (see Fig. 5). Above this interval 15 m of grey marls contain two intervals of dark grey laminated shale (upper Zone P6a). The lower

Table 3
Relative abundance of Eocene planktic foraminifera at Caravaca section.

Species	18.9	19	19.1	19.5	20	20.5	20.9	21	21.7	21.8	21.9	22	22.9	23	24	25	26	27	28	29	30	31	32	33	34	36	37	38	40
<i>Morozovella acuta</i>	X	4	7	3	2	1	4	P	P			P	P			6	10	29		11	13	4	7	9	1	X	8	2	
<i>M. aequa</i>	5	3	1	2	1	5	2	P	P							3	4	X		1	9	X	3	6	9	4	1	2	2
<i>M. crosswickensis</i>	4	6	9	12	12	14	8	P								10	X	9		4	23	26	10	5	19	13	8	19	10
<i>M. edgari</i>	8	13	11	14	24	20	6	P				P				4	1	3		6	10	2	2	12	12	15	11	13	X
<i>M. gracilis</i>																X	X	X		X	X	X	X	X	X	X	X	X	X
<i>M. laerti</i>	X	X	X	X	X	X	X													X	X	X	13	11	X	5	11	15	16
<i>M. lensiformis</i>																													
<i>M. marginodentata</i>																													
<i>M. nicoli</i>	X	X	1	X	X	X	X									3	X	X											
<i>M. occlusa</i>	X	X	X	X	X	1	X																						
<i>M. simulatilis</i>	4	6	10	2	4											7	1	2		2	9	4	6	4	12	14	6	22	
<i>M. subbotinae</i>	5	1	6	7	5	5	8	P				P				7	23	4		6	4								
<i>M. velascoensis</i>	8	5	7	11	4	9	12	P																					
<i>Igorina albeai</i>	1	2	X	X	1	X	2																						
<i>I. laevigata</i>	4	1	1	1	3	1																							
<i>I. caylensis</i>	X	3	1	1	1	X	1									1													
<i>Acarinina acarinata</i>	16	22	10	4	7	7	5	P																					
<i>A. aff. pentacamerala</i>																4	18	11											
<i>A. pseudotopilensis</i>	X	X														21													
<i>A. strabocella</i>	X	X	6	X	2	1	1									1	12	11											
<i>A. triplex</i>	X	1	3	1	1	1	2	P								X	X	1											
<i>A. wilcoxensis</i>	8	4	3	5	1	4	4	P				P				4	X	5											
<i>Muricoglobigerina aquensis</i>	X	1	1	3	1	1	2																						
<i>M. angulosa</i>																													
<i>M. chascanona</i>	X	X	X	1			X																						
<i>M. cf. eschensis</i>	3	1	2	2	1	1	3	P								X	X	X											
<i>M. soldadoensis</i>																4	X	2											
<i>Globorotaloides pseudomitata</i>	2	2	1	1	4	2	1									4													
<i>Subbotina sp.</i>	5	2	X	2	1	X	1									X	1	X											
<i>S. finlayi</i>	X	X	X	X	X	X	X									X	X	X											
<i>S. homibrooki</i>	X	1	X	X	X	X	1									2	4	4											
<i>S. eocaenica</i>	8	2	X	X	2	3	5	P				P				8	8	1											
<i>S. triangularis</i>	10	10	13	13	14	17	23	P				P				17	X	6											
<i>S. velascoensis</i>	X	X	X	X	1	1																							
<i>Planorbulites elongata</i>	X	X	X	2	3	X	X									X	X	X											
<i>P. capdevilensis</i>	X	1	X	1	1	X	X									X	X	X											
<i>P. troelseni</i>	X	X	X	X	X											5	X	11											
<i>Globorotalina ovalis</i>	X	X	X	X	X	1	X	P																					
<i>Pseudohastigerina wilcoxensis</i>																X	X	X											
<i>Chilomenella crinita</i>	X	2	4	6	3	X	X									X	X	X											
<i>C. subtriangularis</i>	X	X	X	X	X	X	X									X	X	X											
<i>C. wilcoxensis</i>	X	X	X	X	X	X	X									X	X	X											
TOTAL NUMBER COUNTED	305	392	358	345	346	329	281	43				48		54		328	251	312		382	278	363	363	434	348	326	296	329	399

Table 4

Stable isotope analysis of benthic Foraminifera across the Paleocene–Eocene transition at Zumaya, Spain

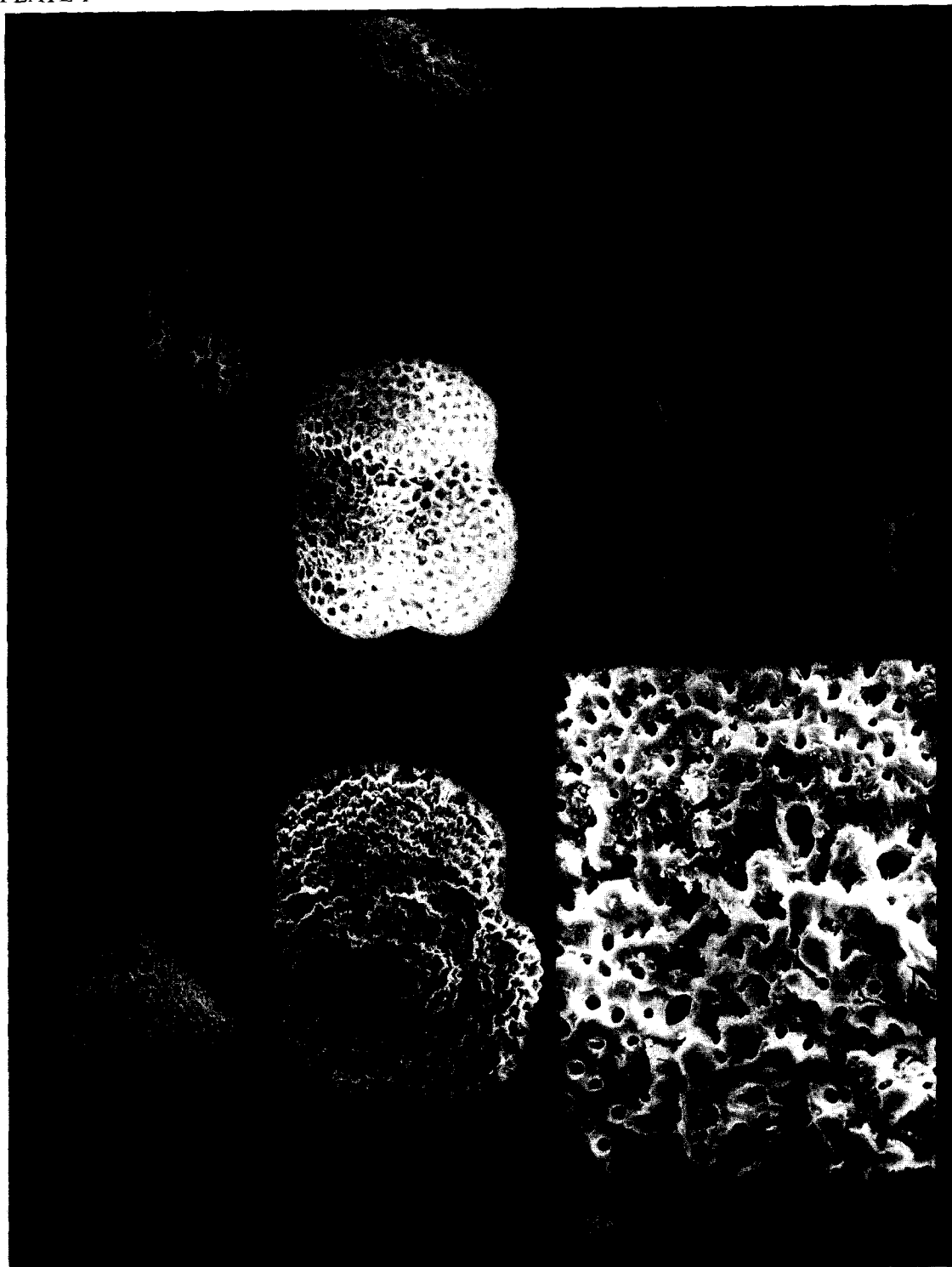
Sample no.	<i>Nuttallides truempyi</i>		<i>Cibicidoides</i> spp.	
	$\delta^{13}\text{C}$ (PDB)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$ (PDB)	$\delta^{18}\text{O}$
–1	1.27	–2.57		
0			1.32	–1.36
1			0.91	–1.32
3	0.63	–2.79		
4	1.03	–2.40		
5.5			1.43	–1.57
7			1.28	–1.66
8			1.23	–1.72
8.5			0.02	–2.11
10			–0.05	–1.94
11.4			0.75	–0.92
13	–0.24	–1.74		
14			0.55	–1.49
15			0.84	–1.28
16			0.74	–1.55
17			0.89	–1.65
18	–1.10	–1.85		
18.2	–1.37	–2.37		
20	–1.74	–2.57	–0.35	–2.11
23.5			–0.30	–1.87
23.7	0.31	–2.92		
24	0.51	–3.68		
25.5	–0.12	–2.73		
26a	–1.43	–2.68		
26b	–0.89	–2.49		
26.2	–0.28	–3.30		
26.5	–0.64	–2.50		
27.9	–0.16	–3.40		
28	–2.15	–2.65		
28.4	–2.28	–2.86		
29	–0.22	–3.07		
29.7	0.39	–3.09		
30 a	–0.73	–2.20		
30b	–1.32	–2.75		
30.4	–0.26	–3.05		
31	–0.21	–2.90		
31.4	–0.72	–2.60		
32	–1.53	–2.48		
33	–0.37	–2.60		
34	–0.64	–2.99		
35	–0.42	–2.76		
36a	–1.83	–1.89		
36b	–1.19	–2.76		
37	–0.46	–3.48	–0.56	–1.26
39	0.06	–3.28		
40	0.72	–3.28		
43			–0.09	–2.10
44	0.07	–3.61		
48	–0.38	–3.42		
52	–0.36	–3.40		

Table 5

Stable isotope analysis of benthic foraminifera across the Paleocene–Eocene transition at Caravaca, Spain

Sample no.	<i>Nuttallides truempyi</i>		<i>Lenticulina</i> spp.	
	$\delta^{13}\text{C}$ (PDB)	$\delta^{18}\text{O}$	$\delta^{13}\text{C}$ (PDB)	$\delta^{18}\text{O}$
0	1.34	–1.14		
0.5	lost			
0.9	0.93	–1.53		
2.1	lost			
2.4	1.67	–1.51		
2.8	lost			
3.1	1.54	–0.98		
3.5	lost			
3.9	lost			
4.1	–0.06	4.10		
4.5	1.65	–1.02		
4.8	1.66	–0.81		
5	1.80	–0.95		
5	1.76	–0.77		
5.5	1.80	–1.23		
6	1.47	–1.08		
7	1.62	–1.20		
8	1.62	–1.13		
9	1.56	–1.58		
11	1.51	–2.01		
12	0.62	–2.39		
13	1.64	–1.15		
14	1.53	–1.21		
15	1.54	–1.25		
16	1.33	–1.22		
17	1.48	–1.07	0.55	–0.85
18	1.15	–1.35	0.32	–1.75
19.5	0.93	–2.70		
20	0.43	–1.07	–1.02	–1.00
20.5	0.24	–1.35		
24			–4.14	–2.78
25			–3.92	–2.29
26			–4.17	–2.69
27			–4.48	–2.50
29			–4.26	–2.32
30	–2.63	–1.80		
31	–2.60	–2.27		
32	–2.60	–2.57	–3.53	–2.35
33	–2.63	–2.49		
34	–2.28	–2.17	–3.46	–2.36
36	–1.85	–1.79		
37	–0.65	–1.55		
38	–0.66	–1.40		
40	–0.30	–0.98		

PLATE 1



laminated shale interval spans nearly 2.5 m and coincides with the benthic foraminiferal mass extinction and the $\delta^{13}\text{C}$ shift. The upper shale layer is about 50 cm thick and precedes the $\delta^{13}\text{C}$ recovery near the top of Zone P6a.

Benthic foraminiferal data from Zumaya indicate that deposition across the P–E transition occurred probably in a middle or lower bathyal environment (Ortiz, 1993). This is indicated by the presence of many species which have upper depth limits between 600 m and 1500 m (e.g. *Spiroplectammina spectabilis*, *Cibicidoides hyphalus*, *Cibicidoides pseudoperlucidus*, *Stensioina beccariiformis*, *Bulimina velascoensis*, *B. trinitatis*, *B. tuxpamensis*, *Nuttallides truempyi*, Morkoven et al., 1986). At Caravaca the depositional depth appears to have been shallower and possibly of upper bathyal to outer neritic depths (200–600 m). This is suggested by a buliminid dominated fauna (e.g., *Bulimina thanetana*, *B. macillenta*, *B. callahani*, *B. alazaensis*, *B. bradbury*) and upper bathyal to outer neritic taxa such as *Thappanina selmensis*, *Angulogavelinella avnimelechi* and *Cibicidoides dayi* (Morkoven et al., 1986). Planktic foraminifera represent more than 85% of the foraminiferal fauna. The presence of common *Cibicidoides pseudoperlucidus* and *Stensioina beccariiformis* in Zones P4–P6a prior to the $\delta^{13}\text{C}$ shift indicates well oxygenated waters (Kaiho, 1991) and the common occurrence of *Cibicidoides* spp. suggests a high influx of terrestrial organic carbon (Boersma, 1985; Ortiz, 1993). The extinction of over 50% of the benthic taxa coincides with the $\delta^{13}\text{C}$ excursion and deposition of dark grey to brown shale layers with low carbonate content and strong foraminiferal dissolution at both Zumaya and Caravaca. At Caravaca nearly all foraminifera are dissolved in this interval. At Zumaya, a low diversity agglutinated assemblage and high abundance of *Bulimina tuxpamensis* suggest low oxygen conditions and waters undersaturated in calcium carbonate during

the $\delta^{13}\text{C}$ excursion. During the following interval, high abundance of *N. truempyi* (47%) suggests a return to more oxygenated waters (Ortiz, 1993). At Caravaca, the low oxygen undersaturated waters seem to prevail throughout the interval of low $\delta^{13}\text{C}$ values (~ 8 m) as indicated by the high abundance of *Bulimina bradburyi* (50%) (Ortiz, 1993).

4. Biostratigraphy

Biostratigraphic interpretation of Zumaya and Caravaca in this report is based on planktic foraminifera following the low latitude zonation of Berggren and Miller (1988). Zone P4 is recognized by the total range of *Planorotalites pseudomenardii*, Zone P5 ranges from the last occurrence (LO) of *P. pseudomenardii* to the first occurrence (FO) of *Morozovella subbotinae*. Zone P6a ranges upward from this interval to the LO of *Morozovella velascoensis* and Zone P6b ranges upward to the FO of *M. formosa formosa* (Fig. 2). This zonation is not ideal for the P–E transition and may need modification in the future. One such modification was recently suggested for the Zumaya section by Canudo and Molina (1992a) and a new biozonation for the Pyrenean basin was proposed (Canudo and Molina, 1992b). They proposed that Zone P5 be eliminated because the defining datum events, *P. pseudomenardii* LO and *M. subbotinae* FO, may even overlap due to diachroneity (Blow, 1979; Canudo and Molina, 1992a). This may give the erroneous impression of a hiatus with Zone P5 missing. They also proposed that *M. velascoensis* LO which defines the top of Zone P6a be replaced by *P. wilcoxensis* FO because *M. velascoensis* is absent in shallow sections like Campo and Tresp (Molina et al., 1992). Because the application of these modifications has not yet been tested (*P. wilcoxensis* FO appears to be diachronous) and

PLATE I

- 1–4. *Subbotina velascoensis* (Cushman) sensu Bolli, from sample CAV- 19. 4. Detail from the umbilical part showing the reticulated wall and the good preservation.
- 4–8. *Morozovella subbotinae* (Morozova), from sample CAV-19. 8. Detail showing the presence of openings in the dorsal sutures.

PLATE II



because the Spanish sections must be correlated to coeval sections worldwide where the P-zonation of Berggren and Miller (1988) has been used, our biostratigraphic interpretation here also follows this zonation.

5. Zumaya

The Zumaya section contains the most expanded and biostratigraphically complete Paleocene–Eocene transition known to date with over 40 m representing Zones P5–P6b (lowermost part). Ranges of selected species which either originate or terminate within this interval are illustrated in Fig. 3 along with the benthic $\delta^{13}\text{C}$ curve. The ranges and relative abundances of all species are illustrated in Fig. 4. Biozonation is based on the defining taxa of Berggren and Miller (1988) as discussed above. Note that Zone P5 is very short (~ 3 m) representing less than 90 k.y. (based on sediment accumulation rate of 3.4 cm/1000 yr as discussed below). A very short Zone P5 was also identified in deep-sea Sites 401 and 577 which led Miller et al. (1987) and Pak and Miller (1992) to combine Zones P5 and P6a. In deep-sea sections with low sediment accumulation, such a short zone is easily missed by standard core sampling which is usually at 100–150 cm intervals (see Miller et al., 1987). Future modification of this zone may be appropriate.

According to Blow (1979), *M. subbotinae* overlaps with *P. pseudomenardii* and consequently Zone P5 (*sensu* Berggren and Miller, 1988) does not exist. Our data yields no clarification here because at Zumaya *M. cf. subbotinae* first appears immediately above the LO of *P. pseudomenardii* and at Caravaca this interval is missing because of a hiatus.

Zone P6a at Zumaya is represented by 33 m of marls, calcarenite and limestone layers. This represents the most expanded interval for this zone

known to date. By comparison, Zone P6a is represented only by 1.2 m in the Pacific Ocean deep-sea Site 577 (Miller et al., 1987) and by 6.4 m in the Bay of Biscay Site 401 (Pardo, unpublished data, 1993) (6.5 m for Zones P5 and P6a combined, Pak and Miller, 1992).

Zone P6a is characterized by a high planktic foraminiferal turnover with over 40% (13 species) of the taxa terminating and over 30% (9 species) originating primarily in this zone (Figs. 3 and 4). The lower 7 m of this zone is marked by the disappearance of *Muriglobigerina mckannai*, *Planorotalites haunsbergensis*, *Igorina pusilla* and the first appearances of *Morozovella subbotinae*, *Igorina caylensis* and *Morozovella gracilis*. The upper 20 m of Zone P6a are marked by a rapid, but gradual, faunal turnover characterized by the disappearance of 9 species or 30% (*Acarinina pseudotopilensis*, *Acarinina intermedia*, *Planorotalites troelseni*, *Igorina laevigata*, *Igorina albeiri*, *Subbotina velascoensis*, *Globorotalites pseudoimitata*, *Morozovella nicoli*, *Morozovella acuta*, *Morozovella velascoensis*, *Chiloguembelina wilcoxensis*) and the first appearance of 7 species or 18% (*Igorina caylensis*, *Planorotalites capdevilensis*, *Acarinina wilcoxensis*, *Morozovella marginodentata*, *Acarinina strabocella*, *Muricoglobigerina cf. esnehensis*, *Muricoglobigerina angulosa*, *Morozovella lensiformis*, Fig. 3). This upper zone P6a gradual faunal turnover begins prior to the onset of the negative benthic $\delta^{13}\text{C}$ excursion and continues thereafter. The $\delta^{13}\text{C}$ excursion coincides with a 20 cm thick dark grey shale layer, increased carbonate dissolution and the sudden extinction of over 50% of the benthic foraminifera (Ortiz, 1993). No significant species turnover is apparent in the lower part of Zone P6b (Figs. 3 and 4).

6. Caravaca

The Paleocene–Eocene transition at Caravaca is less complete than at Zumaya. This is illustrated

PLATE II

- 1–3. *Morozovella velascoensis* (Cushman) from sample CAV-26.
- 4–6. *Planorotalites troelseni* (Loeblich and Tappan) from sample CAV-20,5.
- 7–9. *Morozovella occlusa* (Loeblich and Tappan) from sample CAV-20.

PLATE III



CHRONOST. UNIT	Age in million of years Berggren & Miller, 1988	CARAVACA BIOHORIZONTS	STANDARD BIOZONATIONS			ZUMAYA BIOHORIZONTS	PYRENEAN BIOZONATIONS	
			Berggren & Miller, 1988	Blow, 1979	Bolli, 1957. 66, Toumarkine & Luterbacher, 1985		Canudo & Molina, 1992b	Hillebrandt, 1965
EOCENE	56		P6b	P6b	<i>Morozovella edgari</i>	<i>P. wilcoxensis</i> ▲	<i>Pseudohastigerina wilcoxensis</i>	<i>Globorotalia subbotinae</i>
	57	<i>M. velascoensis</i> <i>P. wilcoxensis</i> ▲				<i>M. velascoensis</i> ▼	<i>Morozovella aequa</i>	<i>Globorotalia marginodentata</i>
	58		P6a	P6a	<i>Morozovella velascoensis</i>			
PALEOCENE		<i>M. subbotinae</i> ▲	P5?			<i>P. pseudomenardii</i> ▼		<i>Globorotalia velascoensis</i>
	59	<i>P. pseudomenardii</i> ▼		P5				
	60	<i>M. soldadoensis</i> ▲	P4		<i>Planorotalites pseudomenardii</i>	<i>M. soldadoensis</i> ▲	<i>Planorotalites pseudomenardii</i>	<i>Globorotalia pseudomenardii</i>
	61	<i>P. pseudomenardii</i> ▲		P4				
	62		P3b	P3	<i>Planorotalites pusilla pusilla</i>	<i>P. pseudomenardii</i> ▲	<i>Planorotalites pusilla</i>	<i>Globorotalia pusilla</i>

Fig. 2. Biozonation used in this study and its comparison with other zonal schemes.

in Fig. 5 with the ranges of selected species which either originate or terminate during this interval along with the benthic $\delta^{13}\text{C}$ curve. The ranges and relative abundances of all species are illustrated in Fig. 6. A hiatus is present at the Zone P4/P6a interval and condensed sedimentation occurred throughout the interval of low $\delta^{13}\text{C}$ values. The lowermost 27 m of this section (Figs. 5 and 6) is

characterized by a Zone P4 fauna which suddenly terminates at a grey limestone layer. The simultaneous disappearance of 7 species at this interval (*Zeauvigerina teuria*, *Morozovella conicotruncata*, *Morozovella angulata*, *Igorina pusilla*, *Muriglobigerina mckannai*, *Acarinina subsphaerica*, *Planorotalites pseudomenardii*) and the simultaneous appearance of four species (*C. wilcoxensis*,

PLATE III

- 1–3. *Acarinina pseudotopilensis* (Subbotina) from sample CAV-19.
- 4–6. *Planorotalites pseudomenardii* (Bolli) from sample CAV-10.
7. *Muricoglobigerina soldadoensis*. (Brönniman) from sample CAV-34.
8. *Morozovella edgari* (Premoli Silva) from sample CAV-11.

In figs. 1–6 the scale is 100 μ . In figs. 7 and 8 the scale is 50 μ .

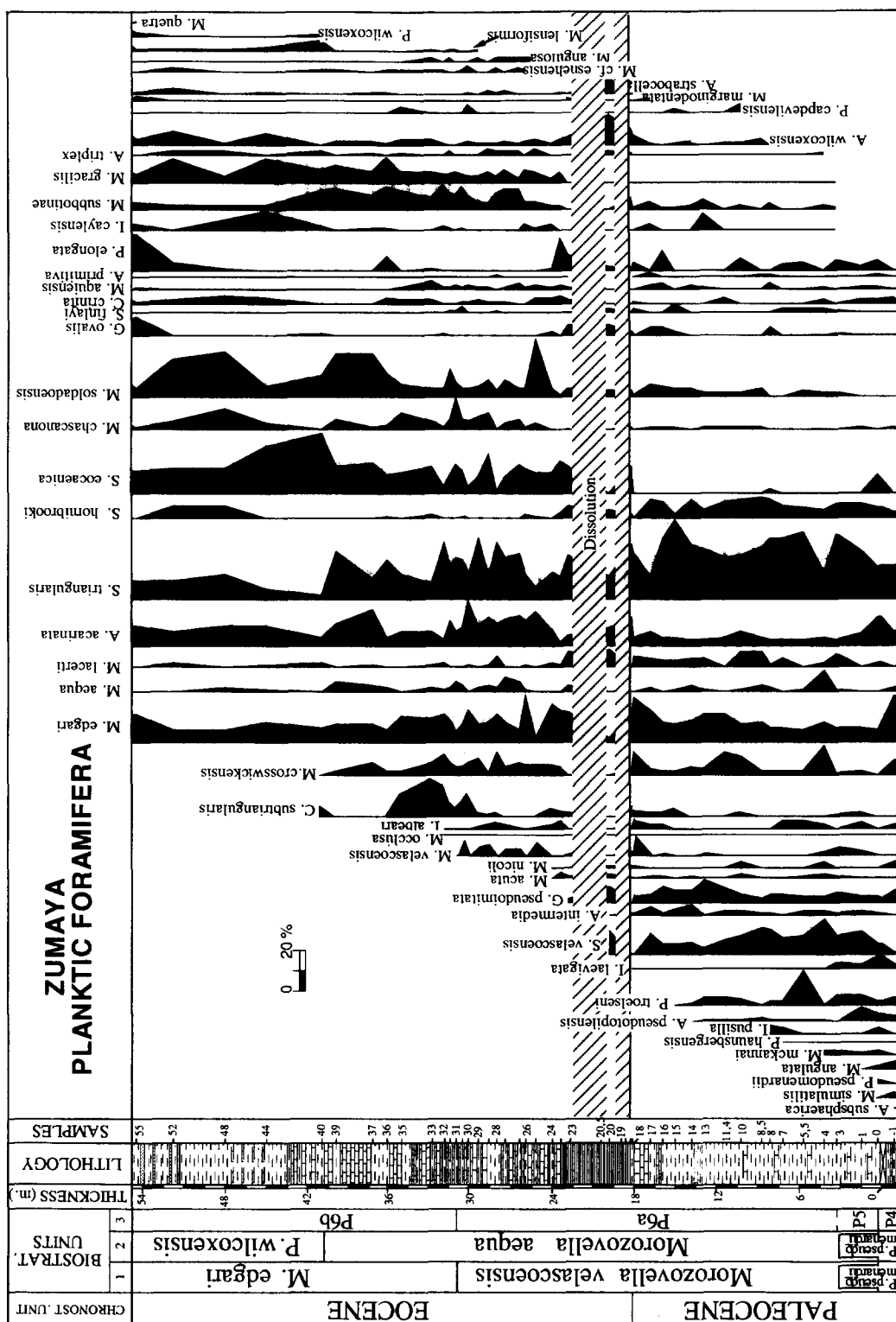


Fig. 4. Stratigraphic ranges and relative percent abundances of all taxa across the Paleocene-Eocene transition at Zumaya.

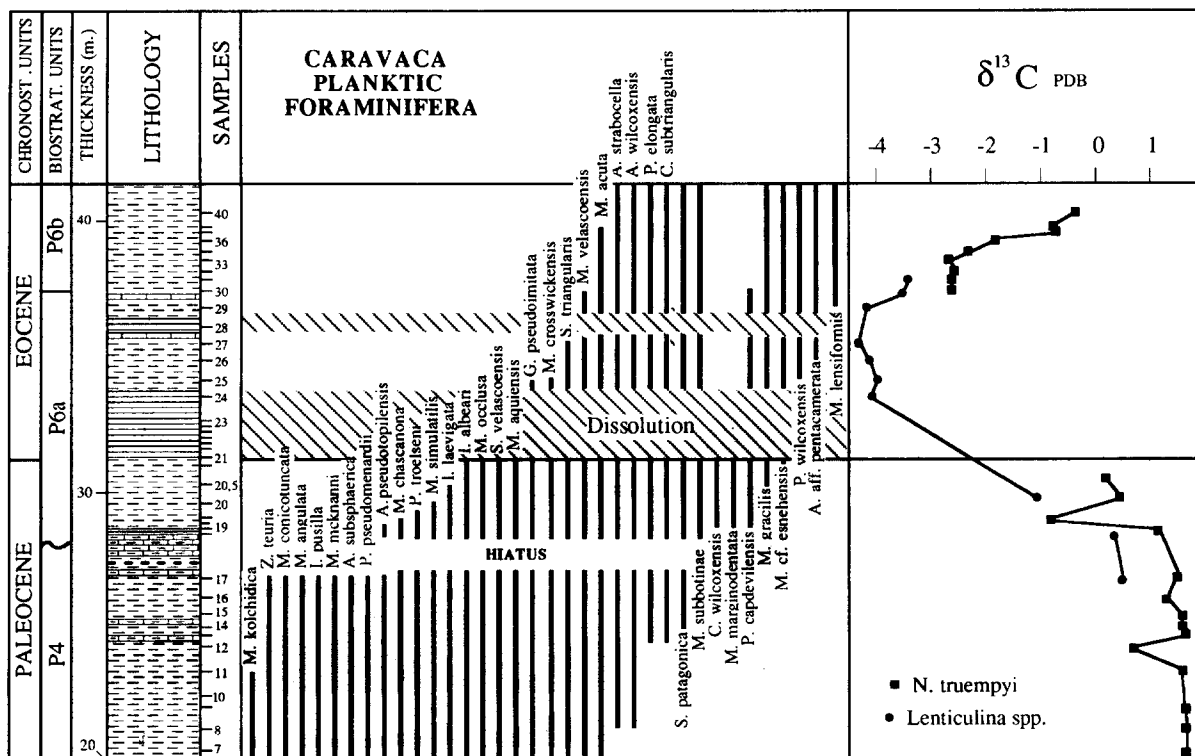


Fig. 5. Stratigraphic ranges of taxa originating and terminating across the Paleocene–Eocene transition at Caravaca along with the benthic carbon isotope curve. Note that Zone P5 and the lower part of Zone P6a are missing due to a hiatus, and planktic foraminifera are dissolved in the two dark shale layers that characterize the interval of low $\delta^{13}\text{C}$ values.

M. marginodentata, *P. capdevilensis*, *M. subbotinae*, Figs. 5 and 6) mark the presence of this hiatus. By comparison and correlation with the Zumaya section, this hiatus spans the uppermost part of Zone P4, Zone P5 and the lower middle part of Zone P6a of the Berggren and Miller (1988) biozonation. The 9 species that terminate in the 3 m above this hiatus include many of the same taxa that gradually disappear below and across the $\delta^{13}\text{C}$ shift at Zumaya including *P. troelseni*, *M. nicoli*, *I. laevigata*, and *S. velascoensis* (Figs. 3 and 5). Above this interval, foraminifera are dissolved in a 2.5 m laminated dark grey shale layer. The apparent sudden termination of four species at the base of this layer is due to dissolution. There is no lithologic or faunal evidence of a hiatus at this interval, although faunal comparisons with Zumaya suggest a more condensed interval at Caravaca. Continuous sedimentation

above the P4/P6a hiatus is also suggested by the first appearance of several taxa at similar stratigraphic positions as at Zumaya (e.g. *M. gracilis*, *M. cf. esnehensis*, *P. wilcoxensis*, *M. lensiformis*, Figs. 3 and 5).

The biostratigraphic correlation of the two sections is supported by the global $\delta^{13}\text{C}$ excursion which provides an excellent marker horizon. At both Zumaya and Caravaca the $\delta^{13}\text{C}$ excursion coincides with a dark grey shale layer and carbonate dissolution and coincides with similar faunal turnovers in planktic as well as benthic foraminifera. The duration of low $\delta^{13}\text{C}$ values and subsequent recovery also appears to be similar in the two sections and marks a second marker horizon. At Caravaca the $\delta^{13}\text{C}$ recovery occurs just above the LO of *M. velascoensis*, the index taxon for the P6a/P6b boundary, whereas at Zumaya this recovery occurs 6 m below this datum event. The

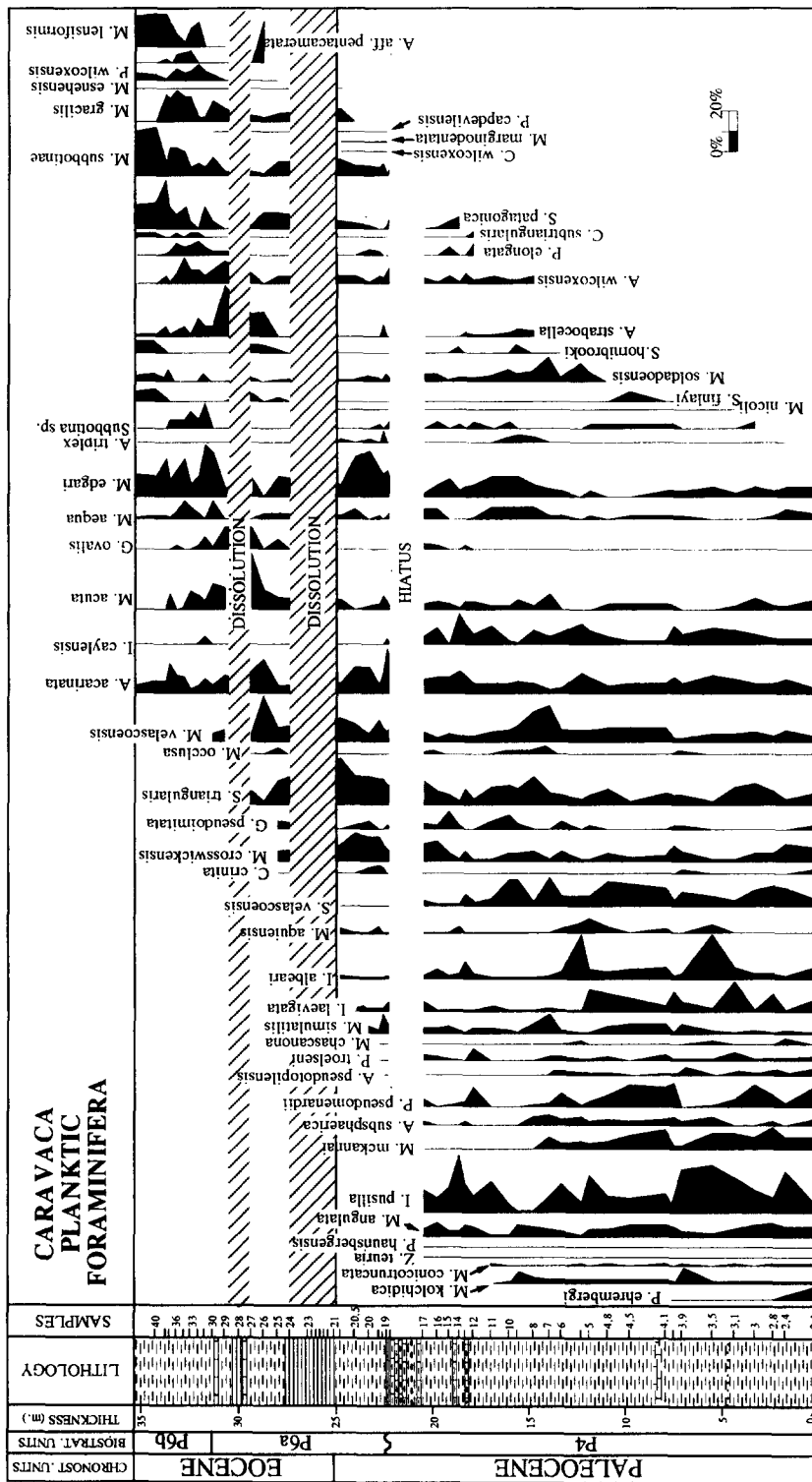


Fig. 6. Stratigraphic ranges and relative percent abundances of all taxa across the Paleocene-Eocene transition at Caravaca.

discrepancy between the $\delta^{13}\text{C}$ horizon with the *M. velascoensis* LO datum is either due to the diachronous disappearance of this taxon or to the more condensed sedimentation above the dissolution interval at Caravaca.

7. The Paleocene/Eocene boundary

Placement of the Paleocene/Eocene (P/E) boundary has not been officially defined. By convention, many biostratigraphers place this boundary at the extinction of *Morozovella velascoensis* that marks the P6a/P6b boundary and is assigned an age estimate of 57.8 Ma (Berggren et al., 1985; Berggren and Miller, 1988, 1989). Since the last occurrence of *M. velascoensis* appears diachronous and this species is not present in high latitudes or in shallow sections, this datum is a very poor marker for a major series boundary.

The *Pseudoshastigerina* “datum” has also been used by some authors to define the Paleocene/Eocene boundary, but the *Pseudoshastigerina* first appearance is not isochronous (Molina et al., 1992; Canudo and Molina, 1992a,b; Pardo et al., 1994), as is evident when Zumaya and Caravaca species ranges are compared. The *Pseudoshastigerina wilcoxensis* first appearance is not a reliable datum, since it appears later in high latitudes and because of the difficulty in discriminating it from *Globanomalina ovalis*. The $\delta^{13}\text{C}$ excursion, which has been determined to be globally synchronous and coincides with a major mass extinction in benthic foraminifera (Thomas, 1989, 1990; Kaiho, 1991; Kennett and Stott, 1990, 1991; Pak and Miller, 1992), appears to be the best and most reliable marker horizon for the Paleocene/Eocene boundary. In this study, we have placed the P/E boundary at this $\delta^{13}\text{C}$ excursion and the extinction in benthic foraminifera.

Based on paleomagnetic and biostratigraphic data from Site 577, Pak and Miller (1992) estimated that the $\delta^{13}\text{C}$ excursion occurred at 58.0 Ma, about 200 ky prior to the disappearance of *M. velascoensis*. Kennett and Stott (1991) estimated a younger age of 57.3 Ma for this $\delta^{13}\text{C}$ excursion based on paleomagnetic data at Site 690 in the Antarctic Ocean. Pak and Miller (1992)

argue, however, that the Site 690 age is less reliable because it is based on polarity data with significant scatter. In this paper, we tentatively use Pak and Miller's (1992) 58.0 Ma age for the $\delta^{13}\text{C}$ excursion and the P/E boundary.

8. Chronostratigraphy and rates of sediment accumulation

Magnetostratigraphy is not available for the P–E transition at Zumaya or Caravaca. At Zumaya the magnetostratigraphy of the Early Paleocene was reported by Roggenthen (1976) and the P–E transition is currently being analysed. In the absence of paleomagnetic data at Zumaya chronostratigraphic estimates can be obtained based on biostratigraphic correlation with deep-sea Site 577 where magnetostratigraphy is available. For instance, at Site 577 the base of Zone P5 is correlated to the top of Chron 25N at 58.64 Ma, the onset of the $\delta^{13}\text{C}$ shift at 58.0 Ma and the top of Zone P6a (LO *M. velascoensis*) at 57.8 Ma (Berggren et al., 1985; Pak and Miller, 1992). Based on these age estimates, the 19 m of sediment that represent Zones P5 and P6a up to the $\delta^{13}\text{C}$ shift at Zumaya were deposited at an average rate of 3 cm per 1000 years and after the onset of the $\delta^{13}\text{C}$ shift at an average rate of 6 cm per 1000 years (13 m of sediments). A different post- $\delta^{13}\text{C}$ shift rate of sediment deposition is indicated for Caravaca for the interval of low $\delta^{13}\text{C}$ values (8 m and 6 m for Caravaca and Zumaya, respectively). The lower sediment accumulation rate after the onset of the $\delta^{13}\text{C}$ shift appears to be largely a function of increased carbonate dissolution which is particularly evident in the deposition of the shale layers at Caravaca. These average sediment accumulation rates are high when compared with deep-sea sections (e.g. 0.4 cm/10³ yr at Site 577, Pak and Miller, 1992; 1.23 cm/10³ yr at Site 690, Kennett and Stott, 1990, 1991). The high rate of sediment accumulation in the Spanish sections may be due to proximity to shore and high terrestrial influx.

9. Paleocene–Eocene $\delta^{13}\text{C}$ excursion

The P–E $\delta^{13}\text{C}$ excursion has been documented from the Pacific, Atlantic and Antarctic Oceans where it appears to be a globally synchronous event (Shackleton, 1986; Miller et al., 1987; Kennett and Stott, 1990, 1991; Corfield and Shackleton, 1988; Corfield and Cartlidge, 1992; Pak and Miller, 1992; Lu and Keller, 1993). Kennett and Stott (1990, 1991) suggested that this event marks a major short-term change in the oceanic thermal structure and circulation that may be related to the temporary elimination of an Antarctic source of bottom water and its replacement by a low latitude source of warm saline deep waters during the time of maximum warming. We present here the first $\delta^{13}\text{C}$ records from the western Tethys Seaway which represents a potential low latitude source of saline warm bottom water (Tables 4 and 5).

As discussed earlier, the $\delta^{13}\text{C}$ values of both the Caravaca and Zumaya sections are affected by subaerial diagenetic alterations. Therefore, absolute values may shift, although the relative trend in carbon isotopes may not change appreciably. For this reason, the discussion of the carbon isotope data is limited to evaluating overall trends. During the late Paleocene (Zones P4 to lower P6a) $\delta^{13}\text{C}$ values are relatively high and constant in both the Zumaya and Caravaca sections. In the upper part of Zone P6a there is a major negative shift in benthic foraminifers *Cibicidoides* and *Nuttallides truempyi* at Zumaya and in *Lenticulina* values at Caravaca. This $\delta^{13}\text{C}$ excursion coincides with the sudden extinction of 50% of benthic foraminifera (Ortiz, 1993).

At Caravaca, the $\delta^{13}\text{C}$ shift occurred during deposition of a 2.5 m thick dark grey shale layer where most foraminifera are dissolved. In the succeeding marls and second shale layer *Lenticulina* values remain low and then gradually increase returning to the $\delta^{13}\text{C}$ values that precede the $\delta^{13}\text{C}$ shift (Fig. 5). At Zumaya, the $\delta^{13}\text{C}$ shift also coincides with deposition of a dark grey to brown shale layer (~20 cm) with strong carbonate dissolution. Benthic foraminifera are present in this interval and indicate that the negative $\delta^{13}\text{C}$ excursion to the initial increase spans over 1 m or

50 k.y. (Fig. 3). In the 9 m of sediment above this clay layer, $\delta^{13}\text{C}$ values fluctuate rapidly between -1.5 and 2.2‰ (Fig. 3). Since no other $\delta^{13}\text{C}$ logs are known with similar high amplitude fluctuations, a partly diagenetic effect cannot be ruled out. Above this interval, $\delta^{13}\text{C}$ values gradually increase similar to Caravaca, and reach near pre-shift values.

By all current interpretations the initial negative $\delta^{13}\text{C}$ excursion occurred over a very short time. Estimates range from 35 k.y. at Sites 577 and 401 (Pak and Miller, 1992) to 63 k.y. at Site 738 (Lu and Keller, 1993, and unpubl. data) and a few thousand years at Site 690 (Kennett and Stott, 1991). Our estimate of 12 k.y. at Zumaya (sediment accumulation rate $3\text{ cm}/10^3\text{ yr}$ as discussed above) is well within the observed range. Between the initial $\delta^{13}\text{C}$ excursion and the recovery of $\delta^{13}\text{C}$ values there seems to be a range of patterns. In southern Spain, $\delta^{13}\text{C}$ values remain low for about 400 k.y. (~8 m at $2\text{ cm}/10^3\text{ yr}$) and deposition continues in a dysaerobic environment dominated by low oxygen tolerant infaunal buliminid species (Ortiz, 1993). In northern Spain, $\delta^{13}\text{C}$ values are very unstable with deposition alternating between marl and limestone layers. This interval of unstable but low $\delta^{13}\text{C}$ values lasted about 300 k.y. similar to Caravaca. But unlike at Caravaca, deposition occurred in a more oxygenated environment dominated by epifaunal taxa (*N. truempyi*, *Oridorsalis umbonatus*, Ortiz, 1993) after the initial $\delta^{13}\text{C}$ excursion. It is unclear at this time whether these differences in $\delta^{13}\text{C}$ profiles and depositional environments between the northern and southern Spanish sections reflect local conditions or are related to paleobathymetry and to the broader oceanographic changes in the Tethyan Seaway and North Atlantic. Additional studies of the eastern Tethys will be necessary to determine the latter.

The $\delta^{13}\text{C}$ profiles from deep-sea sections are difficult to compare with the Spanish sections because sediment accumulation rates are several times lower. For instance, at Pacific Ocean Site 577 and Bay of Biscay Site 401, the $\delta^{13}\text{C}$ recovery follows immediately after the $\delta^{13}\text{C}$ shift which is represented by a single data point in each site (Pak and Miller, 1992). Since the entire $\delta^{13}\text{C}$ shift and recovery spans only 14–20 cm at these sites, as

compared to 8 m and 6 m at Caravaca and Zumaya respectively, a hiatus or very condensed interval must be present. In the Indian Antarctic Ocean Site 738, the initial $\delta^{13}\text{C}$ excursion is followed by a second decrease in $\delta^{13}\text{C}$ values followed by a gradual increase (Lu and Keller, 1992). Based on Site 738 sediment accumulation rates, this broad interval of decreased $\delta^{13}\text{C}$ values spans about 600 ky, as compared with 300 ky for the Spanish sections.

10. Faunal turnover

The sudden species extinctions and relative abundance changes in small benthic foraminifera associated with the P–E maximum warming and $\delta^{13}\text{C}$ excursion have been well documented (Tjalsma and Lohmann, 1983; Miller et al., 1987; Boltovskoy and Boltovskoy, 1988, 1989; Thomas, 1989, 1990; Kaiho, 1991; Nomura, 1991; Pak and Miller, 1992; Katz and Miller, 1991; Ortiz, 1993). In contrast, the planktic foraminiferal turnover has received little attention. Nevertheless, it is generally believed that this group was little affected by this major global oceanographic change. In the first detailed quantitative study of planktic foraminifera across this critical interval, Lu and Keller (1993) demonstrated that in the Antarctic Ocean Site 738 and Pacific Ocean Site 577 major faunal turnovers characterized not only the onset of maximum warming and negative $\delta^{13}\text{C}$ excursion, but also the subsequent cooling episode. In an earlier assessment of planktic foraminiferal changes across the P–E transition at Zumaya, Canudo and Molina (1992a) grouped taxa based on wall structure (i.e. muricate, reticulate and smooth-walled tests) following Premoli-Silva and Boersma (1988) and found a significant abundance increase in the warm water taxa *Morozovella* and *Acarinina* near the Paleocene–Eocene boundary which they correlated to the global maximum warming.

Faunal turnovers can be measured by (1) species richness (i.e. number of species present), (2) the number of extinctions and originations of species, (3) the relative abundance change in each species population, (4) the relative abundance of all species terminating as compared with that of

all species evolving and (5) the depth habitats of species (i.e. surface, intermediate or deep water dwellers based on isotopic ranking). Variable 3 is illustrated in Figs. 4 and 6 and variables 1, 2, 4 and 5 are illustrated for Zumaya in Fig. 7. Species richness, the most frequently quoted index of faunal turnovers, decreases by 10% from an average of 33 species to an average of 30 species across the P/E boundary and $\delta^{13}\text{C}$ shift. This is a relatively insignificant change when compared to the 50% decline in benthic species richness at this site (Ortiz, 1993). The reason for this relatively stable species richness pattern is evident in variable 2, where the number of species extinctions at any particular time nearly equals the number of originations with fourteen species extinct and 11 species originating in Zone P6a (Figs. 3 and 4). Thus, although a major faunal turnover occurs, it is not always detected in the species richness pattern.

The pattern of species extinctions and originations in Fig. 7 illustrates this faunal turnover. Accelerated species extinctions begin about 3 m below the P/E boundary and $\delta^{13}\text{C}$ shift and continue about 4 m above it. About 30%, or 8 species, terminate and 18% (6 species) originate in this interval. What distinguishes the benthic and planktic faunal turnovers primarily is the rate of change. While benthic foraminiferal extinctions and originations largely coincide with the $\delta^{13}\text{C}$ excursion at Zumaya and elsewhere (Thomas, 1989, 1990; Kaiho, 1991; Miller et al., 1987; Pak and Miller, 1992), the planktic extinctions and originations occurred gradually (see also Fig. 4). Does this mean that changes in the upper water column occurred more gradually than in the ocean bottom? Not necessarily so. It could imply that species extinctions and originations are not very sensitive indicators of environmental change. To test this hypothesis we need to examine variable 3, the relative abundance changes in the population of each species.

In Figs. 8 and 9 we illustrate this faunal turnover in terms of species extinctions, originations and those which undergo major changes in relative abundances across the P/E boundary and $\delta^{13}\text{C}$ shift. At Caravaca, the hiatus 3 m below the P/E boundary and dissolution of foraminifera in the two dark shale layers result in abrupt terminations

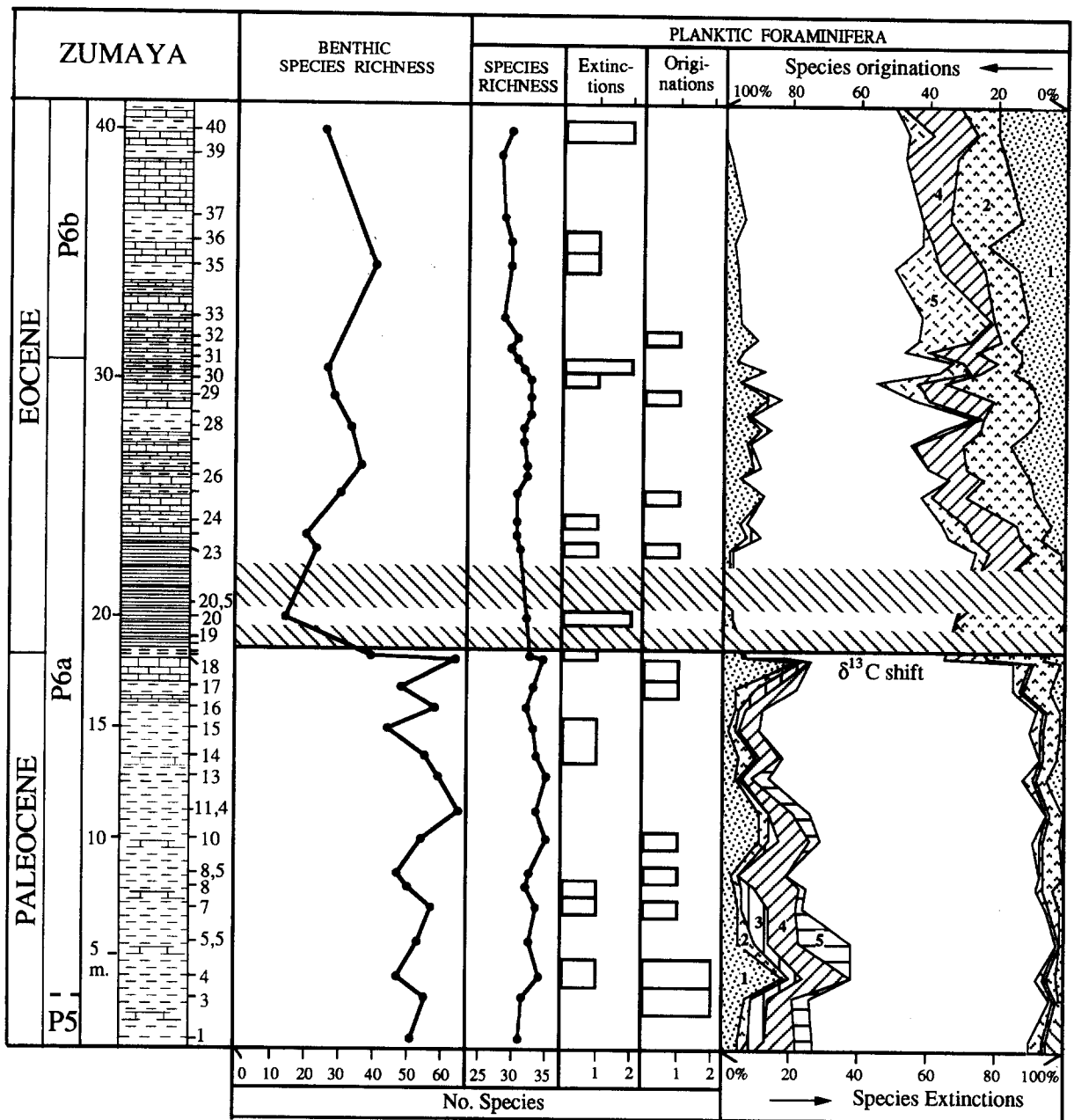


Fig. 7. Species richness, the number of species extinctions and originations, the relative percent abundances of all species becoming extinct and those originating across the P–E transition. Note the rapid abundance change of the latter group coincides with the $\delta^{13}\text{C}$ shift. Key to taxa and depth habitats: 1 = *Morozovella* (surface), 2 = *Acarinina* (surface), 3 = *Igorina* (surface), 4 = *Subbotina* (intermediate), 5 = *Chiloguembelina* (intermediate, oxygen minimum zone), 6 = *Planorotalites* (deep).

of species and abundance peaks of dissolution resistant taxa (Fig. 9). In the Zumaya section where deposition appears to have been continuous,

relative abundance changes of species indicate a significantly more rapid rate of turnover than is implied by the gradual pattern of species extinc-

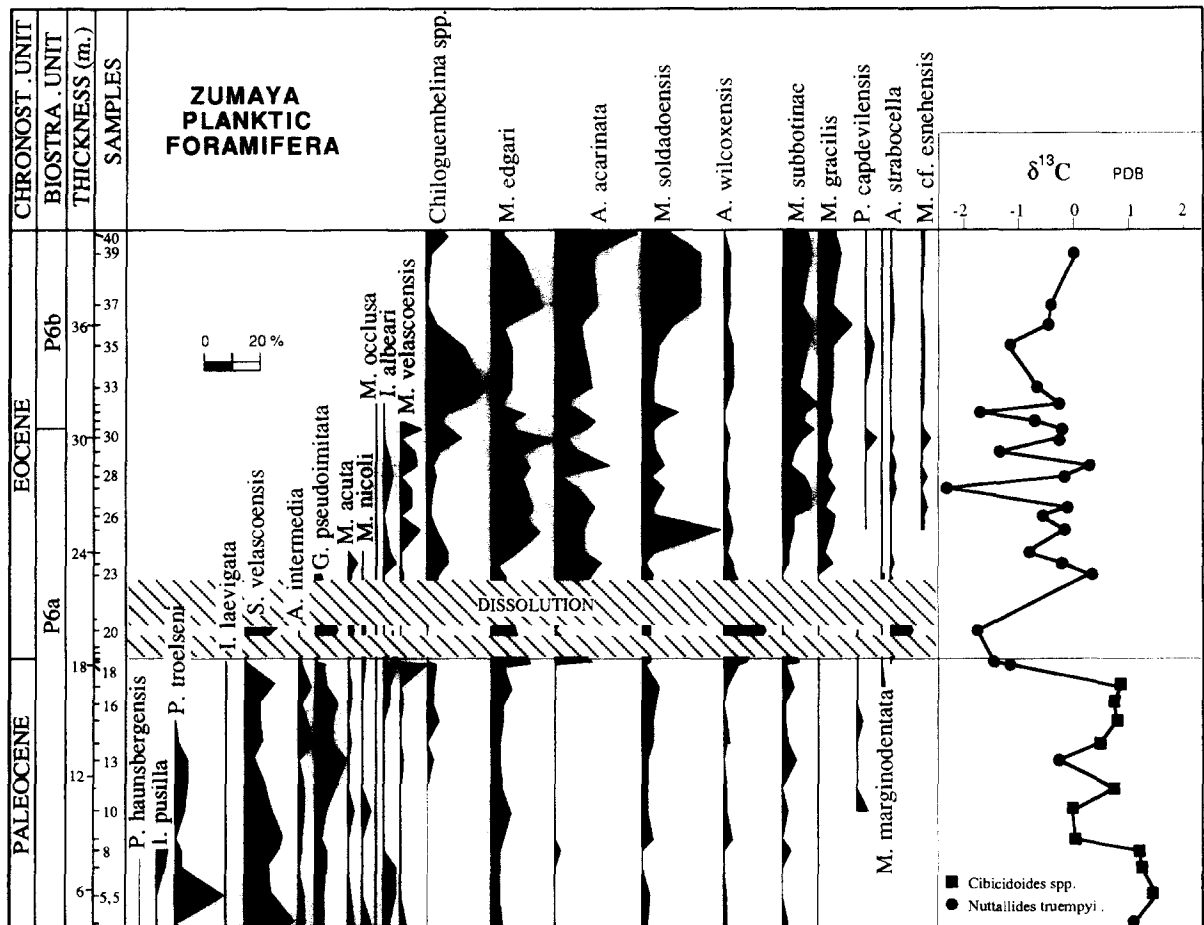


Fig. 8. $\delta^{13}\text{C}$ data and relative abundances of species affected by the Paleocene/Eocene oceanographic event at Zumaya. Note that the faunal turnover is more rapid when measured in relative species abundance changes as compared with species extinctions and originations (see Fig. 3).

tions and originations (compare Figs. 3 and 8). In fact, Fig. 8 suggests that the $\delta^{13}\text{C}$ shift coincides with a faunal turnover in planktic foraminifera that is similar to the sudden benthic foraminiferal turnover at Zumaya.

The degree to which this planktic faunal turnover affected species populations can be estimated by plotting the relative percent abundances of all species originating and those becoming extinct in Zone P6 (Fig. 7). This plot indicates a gradual decline in the relative abundance of terminating taxa through Zone P6a from a high of 45% to a low of 18% 1 m below the $\delta^{13}\text{C}$ shift. Just below the $\delta^{13}\text{C}$ shift a rapid increase to 26% occurs

followed by a sudden drop to 6% at the $\delta^{13}\text{C}$ shift. This group disappears in the succeeding interval of low $\delta^{13}\text{C}$ values. The relative abundances of species originating below the $\delta^{13}\text{C}$ shift generally account for less than 10% of the population. At the $\delta^{13}\text{C}$ shift, these taxa increase in relative abundance to 34% of the population and continue to rise to 50% in the following interval of low $\delta^{13}\text{C}$ values (Fig. 7). Thus, the faunal turnover in planktic foraminifera is sudden when viewed in terms of numerical species abundance changes and is related to the oceanographic event that caused the negative $\delta^{13}\text{C}$ excursion.

What parts of the water column were affected

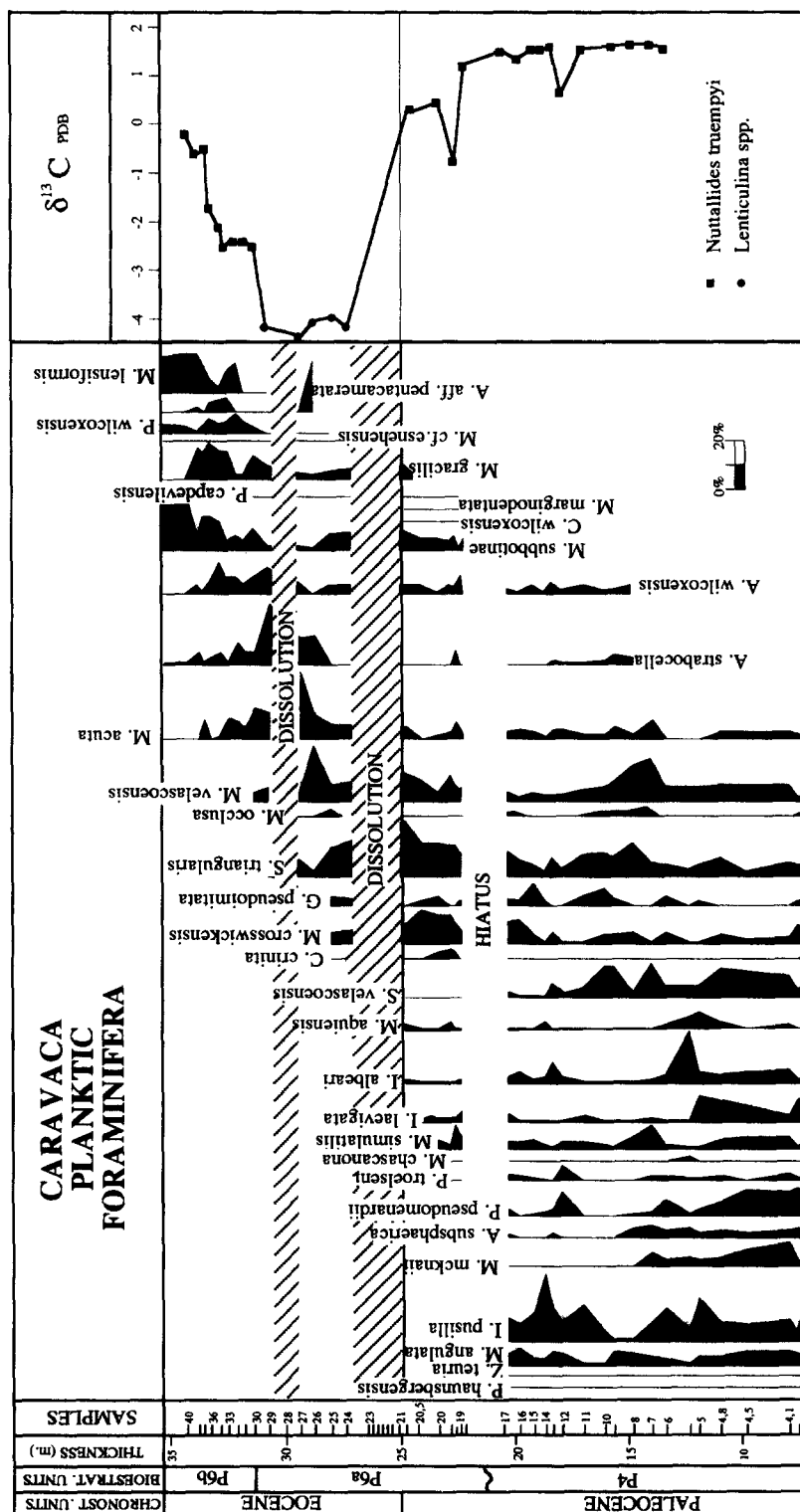


Fig. 9. Relative abundances of species affected by the Paleocene/Eocene oceanographic event at Caravaca. Note that Zone P5 and the lower part of Zone P6a is missing due to a hiatus and planktic foraminifera are dissolved in the two dark shale layers that characterize the interval of low $\delta^{13}\text{C}$ values.

by this oceanographic event? It is well known that planktic foraminifera are depth stratified in the water column with some species living in the surface or mixed layer and others living at thermocline depth or deeper. Carbon and oxygen isotope measurements of individual species provide a record as to where in the water column they lived. For instance, taxa with more positive $\delta^{13}\text{C}$ and more negative $\delta^{18}\text{O}$ values indicate surface dwellers (*Morozovella*, *Acarinina*, *Igorina*) whereas more negative $\delta^{13}\text{C}$ and more positive $\delta^{18}\text{O}$ values indicate deeper habitats (*Subbotina*, *Chiloguembelina*, *Planorotalites*, Shackleton et al., 1985; Corfield and Cartlidge, 1992). Isotopic depth ranking studies at Site 577 indicate that *Subbotina* and *Chiloguembelina* taxa lived at or near the thermocline, whereas *Planorotalites* taxa lived at greater depth (Corfield, in press; Lu et al., unpublished data, 1992). Moreover, *Chiloguembelinids* appear to thrive in the oxygen minimum zone (Boersma and Premoli-Silva, 1989; Keller, 1993; Keller et al., 1993). All of these habitats were affected by the P–E faunal turnover at Zumaya as shown in Fig. 7. The Paleocene–Eocene climatic and oceanographic event thus affected the entire water column. Moreover, the maximum warming and low $\delta^{13}\text{C}$ values after the $\delta^{13}\text{C}$ shift also resulted in the development of a strong oxygen minimum zone as indicated by the high abundance of *Chiloguembelina* at Zumaya (Fig. 7).

11. Summary and conclusions

The planktic foraminiferal biostratigraphy, faunal turnover and benthic carbon isotopes were analyzed across the P–E transition at Caravaca in southern Spain and Zumaya in northern Spain. These two sections contain the most expanded sediment record across the Paleocene–Eocene (P–E) transition known to date with 28 m of marls and limestone layers representing Zone P6a. The upper part of this zone contains the $\delta^{13}\text{C}$ excursion that characterizes the P–E transition. Based on biostratigraphic correlations with DSDP Site 577, sediment accumulation rates at Zumaya average 3 cm/10³ yr prior to the $\delta^{13}\text{C}$ shift and 6 cm/10³ during the succeeding 8–16 m interval of low $\delta^{13}\text{C}$

values at both Caravaca and Zumaya. The Zumaya section appears to have continuous sedimentation across the P–E transition spanning Zones P5, P6a and P6b. At Caravaca, a hiatus 3 m below the $\delta^{13}\text{C}$ shift indicates that the uppermost part of Zone P4, Zone P5 and the lower part of Zone P6a is missing.

Benthic carbon isotope measurement of *Cibicidoides*, *Nuttallides truempyi* and *Lenticulina* reveal that the $\delta^{13}\text{C}$ excursion occurred in the upper part of Zone P6a prior to the *Morozovella velascoensis* extinction. Similar to deep-sea records, this negative excursion was rapid and occurred over 12 k.y. as estimated from sediment accumulation rates at Zumaya. After this initial excursion, $\delta^{13}\text{C}$ values fluctuate rapidly at Zumaya, but remain stable and low at Caravaca. After this time, $\delta^{13}\text{C}$ values increased gradually to near pre- $\delta^{13}\text{C}$ shift values in both sections.

Planktic foraminifera indicate that a major faunal turnover occurred across the $\delta^{13}\text{C}$ shift with the gradual extinction of 30% of the species. But, because of high species originations, the average species richness decreased by only 10%. In contrast, benthic species extinctions exceeded 50% and because of low species originations, the average species richness decreased by 50%. Moreover, benthic extinctions occurred suddenly at the $\delta^{13}\text{C}$ excursion whereas planktic extinctions began prior to and continued after the $\delta^{13}\text{C}$ excursion. Although this suggests a more gradual change in the upper water column than on the seafloor, this difference diminishes when relative abundance changes in species populations (instead of extinctions) are examined. By this more sensitive environmental indicator, the major faunal turnover in the upper water mass also coincides with the $\delta^{13}\text{C}$ excursion.

By examining the depth stratification of planktic foraminifera in the water column, it is possible to infer the structure of the upper water column and to determine which part was affected by the P–E maximum warming and $\delta^{13}\text{C}$ event. Our analysis of Caravaca and Zumaya indicate that the entire water column was affected by this environmental change as evidenced by species extinctions and originations in surface, intermediate and deeper waters. Since there was little net loss in species

richness, this environmental change does not appear to have significantly changed the overall water mass structure. At Zumaya, however, a low oxygen minimum zone developed after the $\delta^{13}\text{C}$ excursion and prevailed throughout the interval of low $\delta^{13}\text{C}$ values as indicated by the increased abundance of low oxygen tolerant *Chiloguembelina* spp. No similar increase in *Chiloguembelina* spp. occurred at Caravaca.

Our study thus indicates that in the western Tethys the maximum warming and $\delta^{13}\text{C}$ excursion across the P–E transition resulted in a major faunal turnover in planktic foraminifera that affected the entire water column. There are significant differences in both benthic and planktic foraminiferal turnovers and $\delta^{13}\text{C}$ curves between Caravaca and Zumaya that suggest that these two regions were influenced by different water masses. Caravaca in southern Spain may have been more strongly influenced by the Tethyan Seaway whereas Zumaya in northern Spain may reflect the influence of North Atlantic waters. Further faunal and isotopic studies of the Tethyan Seaway are needed to evaluate the role of this region in the Paleocene–Eocene warming.

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