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Planktic foraminiferal and $\partial^{13}C$ isotopic changes across the Paleocene/Eocene boundary at Possagno (Italy)

Abstract The interval spanning the Paleocene–Eocene (P/E) transition in the Possagno section consists of 1 m of red marls, including a 4-cm-thick, dark-red "dissolution" clay, which represents the Paleocene/Eocene boundary event. The Possagno section is much more condensed than other Tethyan and North Atlantic sections previously studied; however, in this section the most significant biotic, isotopic and sedimentological events across the P/E boundary can be recognized. The Possagno section spans the following planktic foraminiferal subzones: upper part of *M. gracilis* Subzone, *A. berggreni* Subzone, *A. sibaiyaensis* Subzone and probably lowermost part of *P. wilcoxensis* Subzone. The quantitative analysis indicates a major increase of low-latitude acarininids, including compressed tropical acarininids just above the boundary clay. This acarininid incursion begins just below the boundary clay but reaches its maximum just above the clay. The planktic foraminiferal faunal turnover is gradual except for the acarininid incursion. The isotopic results show a negative excursion in $\partial^{13}C$ values at the small benthic foraminifera mass extinction event. The acarininid maximum diversity coincides with this isotopic excursion, and reflects an increase in surface seawater temperature. Despite being very condensed, the Possagno section allows us to further confirm that the different biotic, isotopic and sedimentological events recognized in the Spanish sections (Alamedilla, Campo, Caravaca, Zumaya) are not local in nature and allows the establishment of a detailed chronostratigraphic framework to define the P/E boundary stratotype.

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Introduction

Although the placement of the Paleocene/Eocene (P/E) boundary has not been officially defined, it has become common practice to place the P/E boundary at a negative $\delta^{13}C$ excursion coinciding with a bathyal and abyssal benthic foraminiferal mass extinction event. This remarkable short-term global shift occurred approximately 55 Ma ago and it is the most important event of the P/E transition. The P/E boundary should be placed at this event which happened close to the deposition of the base of the Ypresian stratotype (Molina 1994, 1995, 1996; Pardo et al. 1994). However, it is difficult to find a biozonal boundary in planktic foraminiferal biozonation that coincides with the P/E boundary event. By convention, many biostratigraphers used to place this boundary at the extinction of *Morozovella velascoensis* that marks the P5/P6a boundary and is assigned an estimated age of 54.7 Ma (Berggren et al. 1995). However, the last occurrence (LO) of *M. velascoensis* appears to be diachronous and this species is not present in high latitudes or in shallow sections (Canudo et al. 1995). Furthermore, this extinction datum occurs later than the major isotopic and biotic changes at approximately 55 Ma, represented by the benthic foraminiferal extinction event (BFEE) at the BB1/BB2 Biozone of Berggren and Miller (1989). Approximately 35–50% of the bathyal and abyssal benthic species became extinct at this event (Tjalsma

and Lohman 1983; Thomas 1990; Kennett and Stott 1991; Pak and Miller 1992; Kaiho 1994; Ortiz 1995).

The BFEE coincides with large negative $\delta^{18}O$ and $\delta^{13}C$ shifts, which are believed to be caused by global warming and changes in oceanic water circulation with the production of warm saline deep waters and low oxygen content (Kennet and Stott 1991). A quantitative turnover in the planktic foraminiferal assemblages has been recorded in connection with the BFEE in Spain (Molina et al. 1994, 1999; Canudo et al. 1995; Arenillas and Molina 1996), and worldwide (Kennett and Stott 1990; Lu and Keller 1993; Pardo et al. 1997, 1999), and were probably caused by a reorganization of tectonic plates associated with the increase of volcanic and hydrothermal activity, a sea-level transgression, a temporary absence of cold deep water formation in the Antarctica region and the production of warm saline deep waters in the Tethys region (Shackleton et al. 1985a; Shackleton 1986; Haq et al. 1987; Miller et al. 1987; Kennett and Stott 1990, 1991; Stott and Kennett 1990; Barrera and Huber 1991; Hovan and Rea 1992; Stott 1992; Canudo and Molina 1992; Lu and Keller 1993; Robert and Kennett 1994; Charisi and Schmitz 1994, 1995; Canudo et al. 1995; Lu et al. 1996). According to Rea et al. (1990) the BFEE was a response to low nutrient content and chemically changes in bottom waters, related to enhanced sea-floor hydrothermal activity caused by the global tectonism that resulted in a flooding of the atmosphere with CO_2. The greenhouse effect of enhanced CO_2 and CH_4 in the atmosphere (Sloan et al. 1992; Dickens et al. 1997) may have triggered the BFEE, explosion of North America land mammals, from primates to rodents, and proliferation of thermophilic species both in planktic foraminifera and terrestrial plants (Wing et al. 1991; Thomas 1990; Maas et al. 1995; Berggren et al. 1996).

The Tethyan region is one of the critical regions for investigating the potential causes and mechanisms behind the changes at the P/E transition. This region generally has played an important role in the evolution of global and climatic change (Kennet and Stott 1990, 1991). During the P/E boundary times the Tethys was a semi-restricted basin due to the displacement of the Indian plate towards north (Laughton et al. 1973), with vast areas of shallow epicontinental seas (Oberhänsli and Hsü 1986; Oberhänsli 1992). The paleogeography suggests that the Tethys region was potentially a major source of warm saline deep water (Kennett and Stott 1990, 1991), a possible driving force for the P/E deep ocean warming. The quick warm-up episode of the marine shallow-water in high latitudes and the bathyal and abyssal water in all latitudes during the P/E transition (Kennett and Sott 1990, 1991; Stott and Kennett 1990; Barrera and Huber 1991) are therefore associated with global atmospheric and oceanic circulation and chemical changes (Barron and Paterson 1991; Robert and Kennett 1994; O'Connell et al. 1996; Schmitz et al. 1996).

In this work we report on the planktic foraminiferal assemblages turnover and $\delta^{13}C$ isotopic changes across the P/E boundary in the Possagno section, which is located in a critical region of Centre-Occidental Tethys (Fig. 1). This study provides details about the faunal and isotopic changes across the P/E boundary to elucidate (based also on the comparison with other middle- and low-latitude sections) the geographic magnitude of this event and its reliability to mark in the future the P/E boundary.

Location, materials, and methods

The studied section is located approximately 1.5 km west of the town of Possagno (Fig. 1), in a quarry in the Cave di Carcoselle, at North of the Marche-Umbria basin in the Southern Alps (Trevise-Veneto, North Italy), at a latitude of 45°50'2" and a longitude 11°31'1". The P/E transition occurs between the Scaglia rossa and Scaglia variegata limestone (Cita and Bolli 1966). Preliminary Paleogene biostratigraphic analyses with planktic and benthic foraminifera and calcareous nannoplankton and ostracods have been carried out by Ascoli (1969) and Proto-Decima et al. (1975). The planktic foraminifera of the Paleocene and Eocene Scaglia rossa and Scaglia variegata at Possagno were initially studied by Cita and Bolli (1966) and Luter-bacher (1975), showing its continuity and its good exposure. The Scaglia rossa and Scaglia variegata represent a pelagic sedimentary environment in which the sand-size fraction consists mostly of planktic foraminifera (Cita 1975). The P/E transition in the Possagno section consists of 1-m-thick red marls including a 4-cm-thick dark-red clay with high carbonate dissolution that represents the P/E boundary event.

We studied 16 samples for the planktic foraminiferal biostratigraphic and quantitative analyses. Samples were collected at centimeter or decimeter intervals, with closer sampling across the P/E boundary interval. Samples were disaggregated in tap water and diluted H_2O_2, then washed through a 63-μm sieve and dried at 50 °C. The quantitative planktic foraminiferal analysis was based on representative splits, using a modified Otto microspliter, of approximately 300 specimens in the size fraction larger than 106 μm (Table 1). All the representative specimens were picked, identified, and mounted on microslides for a permanent record. Finally, the remaining sample was scanned for rare species. The preservation of the planktic foraminifera is moderate to poor due to the calcareous facies of the Scaglia rossa and Scaglia variegata.

A total of 18 samples were analyzed for stable carbon isotopic composition. The isotopic analyses were performed on bulk samples. These analyses were performed with a VG Prism Series II mass spectrometer attached to an Isocarb automated carbonate preparation system. The values are expressed as per mil differences with respect to the PDB standard.

Fig. 1 Geographic and paleogeographic location of the Possagno section and other sections studied. (Modified from Denham and Scotesse 1987)
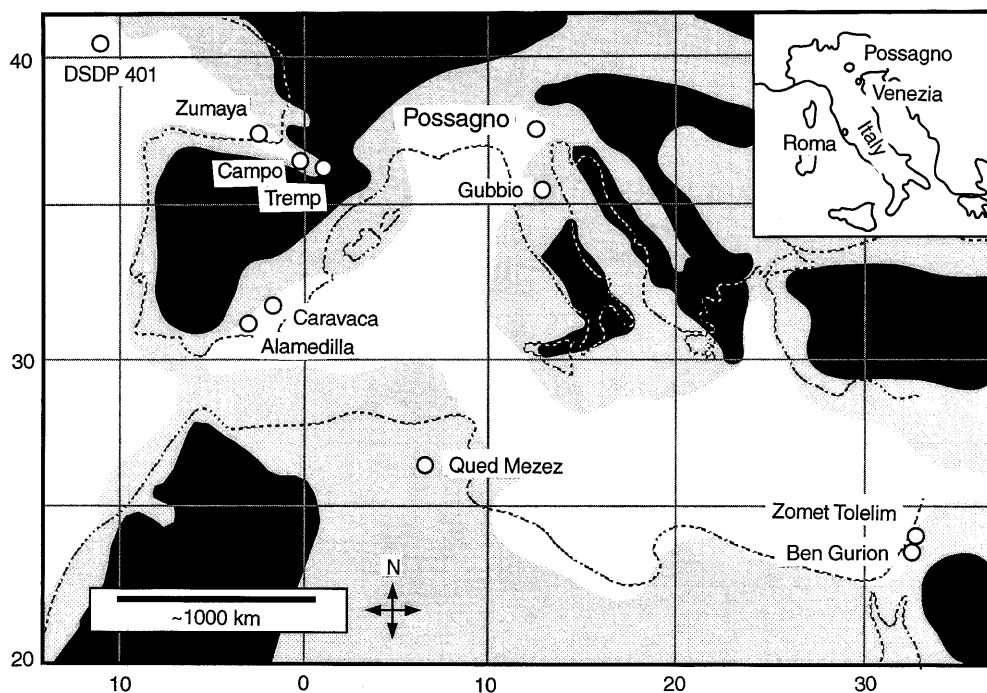
Biostratigraphy

We applied the biozonation of Molina et al. (1999), which is a more detailed modification of the Toumarkine and Luterbacher (1985) and Berggren et al. (1995) biozonations and subdivides the P/E transition in three biozones: *Luterbacheria pseudomenardii* (=P4) Biozone, *Morozovella velascoensis* (=P5) Biozone, and *Morozovella subbotinae* (=P6) Biozone. The boundaries between the *L. pseudomenardii* and *M. velascoensis* biozones, and between *M. velascoensis* and *M. subbotinae* biozones, are respectively placed at the last occurrence (LO) of *L. pseudomenardii* and at the LO of *M. velascoensis*. The Molina et al. (1999) biozonation allows us to place the event of the P/E boundary in relation to a detailed planktic foraminiferal subzonation (Fig. 2). This subzonation is based on index species used in previous biozonations (Bolli 1966; Blow 1979; Toumarkine and Luterbacher 1985; Berggren and Miller 1988; Berggren et al. 1995; Arenillas and Molina 1996; Pardo et al. 1999).

The biozonation of Arenillas and Molina (1996) was also defined in order to place the event of the P/E boundary and represented a more detailed modification of the biozonation of Toumarkine and Luterbacher (1985). This biozonation used the LO of *Igorina laevigata* to subdivide the classic *Morozovella velascoensis* Biozone of Tourmakine and Luterbacher (1985) and subdivided this biozone in two biozones: *Igorina laevigata* Biozone (=P5, lower part) and *Morozovella velascoensis* Biozone (=P5, upper part). The LO of *I. laevigata* coincides with the P/E boundary at Alamedilla, Zumaya, Caravaca and Site 401 (Canudo and Molina 1992; Canudo et al. 1995; Arenillas and

Molina 1996, 1997; Pardo et al. 1997). However, at the Possagno section it is difficult to place the P/E boundary with the LO of *I. laevigata* due to the absence of this index fossil (Fig. 3). This apparent absence could be caused by the poor preservation of the planktic foraminifera and, therefore, the *I. laevigata* Biozone cannot be used in this section. Furthermore, this species seems to have also some taxonomic problems since it has been considered a junior synonym of *Igorina albeari* (Berggren and Norris 1997). Pardo et al. (1999) also proposed a subdivision of Zone P5 of Berggren et al. (1995) based on the first occurrence (FO) of *A. sibaiyaensis* and *A. africana*. The FO of this species coincides with the P/E boundary event at Possagno (Fig. 3) and also at Kaurtakapy, Site 865, Alamedilla, and Caravaca (Arenillas and Molina 1996, 1997; Kelly et al. 1998; Pardo et al. 1999).

The biozonation of the Molina et al. (1999) is more detailed than Arenillas and Molina (1996) and Pardo et al. (1999). This biozonation uses the first occurrence (FO) of the *Morozovella gracilis, Acarinina berggreni, Acarinina sibaiyaensis,* and *Pseudohastigerina wilcoxensis* to subdivide the *Morozovella velascoensis* Biozone of Tourmakine and Luterbacher (1985), named P5 by Berggren et al. (1995), into five subzones: *Morozovella aequa* Subzone, *M. gracilis* Subzone, *A. berggreni* Subzone, *A. sibaiyaensis* Subzone, and *P. wilcoxensis* Subzone. This subdivision is useful in order to have a most detailed biostratigraphic scale for correlation between different sections and basins. We have applied the biozonation of Molina et al. (1999) in Figs. 3 and 4.

At the Possagno section we provisionally placed the P/E boundary at the base of the dissolution interval,

Table 1 Relative percent abundances of planktic foraminifera greater than 106 μm and $\delta^{13}C$ isotopic results at the Possagno section

Species	Samples >106 μm															
	−40	−30	−20	−10	−5	0+4	5	10	15	20	25	30	35	45	55	65
Subbotina triangularis	1.8	0.6	4.2	2.7	2.6		1.3	2.3	1.0	1.0	4.3	4.9	1.7	4.0	0.5	3.3
S. cocaenica	18.2	25.6	12.6	26.3	7.4		6.0	5.6	3.3	5.1	34.0	31.4	30.6	51.5	51.0	47.7
S. velascoensis	1.8	3.3	4.3	1.4	0.7		0.9			0.3		1.0		0.5		
S. hornibrooki	1.5	0.6	4.6	0.7	0.3			0.3		0.6	0.7	0.6	1.7	1.0	2.0	1.9
S. finlayi	10.8	14.3	7.9	6.3	4.8		0.9	1.6	1.0	3.9	5.0	2.3	8.8	7.6	17.2	10.2
S. incisa		0.6			1.4	0.7			1.0	1.0		0.6		0.5	0.5	0.3
S. pseudoeocaena									0.3	×	×	0.6	2.3	1.0		0.3
Subbotina	34.4	44.7	33.6	38.8	16.5		9.1	9.8	3.3	11.2	44.0	41.4	45.1	66.1	71.2	63.7
Acarinina pseudotopilensis	0.3	×	0.7	1.0	3.7		16.3	22.5	27.9	16.8	7.6	7.2	3.5	0.5	0.5	2.3
A. acarinata	×		×		×		×	×		1.0	×			0.5	1.0	1.0
A. primitiva	1.8	1.3	1.8	2.4	3.3		1.9	3.3	×	1.6	1.0	1.6	2.3			3.3
A. wilcoxensis		0.6	0.7	1.4	2.6		8.9	11.6	7.9	6.1	5.4	8.7	8.2	0.5		0.6
A. apanthesma	×	×			0.3		2.2	2.3	3.6	2.5	0.3	0.6	0.6			0.6
A. strabocella	×		×		1.4		2.5	3.3	8.6	8.4	6.6	1.3	1.2	0.5	0.5	
A. triplex	2.4	1.6	2.8	2.8	8.8		4.1	4.6	2.6	1.9	4.3	1.3	2.3	3.0	1.5	4.0
A. subspaerica	×	0.3														
A. berggreni					0.9		6.0	4.3	0.6	1.3	×	0.3	0.6		0.5	1.0
A. sibaiyaensis							6.0	2.0	4.0	2.6	0.3	0.6				
A. africana							0.6	0.6								
A. quetra							3.5	1.3	1.7	1.9	0.7	1.6	2.9			×
Acarinina	4.5	3.8	6.0	7.6	19.0		48.2	65.8	56.2	43.1	26.2	23.2	21.6	5.0	4.0	12.8
Muricoglobigerina aquiensis	1.5	2.0	2.8	2.4	4.4		0.6	1.3	1.3	×	×	2.6	1.7	2.5	3.5	5.9
Mg. chascanona	×	×	×		×		0.3		×			1.0				×
Mg. soldadoensis	6.2	0.6	2.5	1.4	4.0		4.8	6.3	5.3	8.4	6.5	7.2	11.7	10.6	2.5	3.3
Mg. esnehensis		0.3	0.3	0.3			0.9	1.6	1.3	0.7	2.3					
Mg. senni	×	0.3	0.6	×				×				×		2.0	4.5	2.6
Muricoglobigerina	7.7	3.2	6.5	4.1	8.4		7.2	9.2	9.9	8.7	7.5	13.1	13.0	15.1	10.5	11.8
Morozovella angulata	0.6															
M. crosswicksensis	6.5	3.3	2.9	2.1	1.1		0.3	1.0	1.0	0.3	×	×				0.3
M. occlusa	2.7	3.6	3.9	5.3	2.9		0.3	1.6	0.3		×	0.3		0.5	1.5	×
M. acutispira	×		0.3													
M. velascoensis	16.4	13.6	14.0	13.3	9.6		8.3	5.3	7.3	6.1	2.1	0.9	1.1	1.5	1.0	1.3
M.acuta	1.8	2.6	2.1	2.8	1.4		2.9	3.3	6.3	2.6	2.9	0.3				0.6
M. parva	0.6	×			1.1		1.3	2.0		1.3	1.4	0.3	0.6		0.5	
M. tholiformis	6.1	2.9	6.4	4.8	5.8		6.1	4.5	1.9	4.8	1.3	3.9	4.8	2.0	2.5	1.3
M. acqua	1.5	2.6	1.4	0.7	5.5		1.6	1.3	×	0.3	2.1	1.3	4.1	0.5		1.3
M. lacerti	×	0.3	×	1.7	2.5		0.3	0.6	0.6	1.9	×	1.9	0.6	1.0	0.5	0.3
M. subbotinae	8.6	12.6	13.6	11.9	17.7		6.7	3.3	1.3	4.5	3.6	8.5	4.7	4.0	3.0	3.0
M. marginodentata	3.7	2.6	1.8	3.5	4.0		0.9			×	0.7	0.3	0.6	2.0	2.5	0.6
M. edgari	1.8	×	0.3	×	×		0.3	0.3		0.3	×		0.6	0.5		×
M. gracilis	0.3	2.6	1.8	1.4	3.5		4.4	3.6	3.6	13.9	6.5	4.6	1.7	0.5	1.5	0.3
M. lensiformis													0.6	1.5	1.0	1.6
Morozovella	50.6	47.0	51.7	48.5	53.8		33.4	26.8	27.2	36.3	20.6	22.4	19.2	14.0	14.0	12.2
Pesudohastigerina wilcoxensis														?		?
Chiloguembelina midwayensis			0.3							×						×
Ch. subcylindrica	×											×				
Ch. crinita		×	0.3							×		×				
Ch. trinitatensis													×			×
Ch. wilcoxensis	×	×	×													
Ch. cirumlabiata	0.3															
Zeauvigerina aegyptica												×				×
Chiloguembelina + zeauvigerina	0.3		0.6													
Total	323	300	278	285	271		313	302	301	309	276	306	170	199	198	302

Isotopic samples	−40	−30	−20	−10	−6	−2	0	0+1.5	1.5+3	4	6	8	15	20	30	40	50	65
$\partial^{13}C$(‰PDB)	1.499	1.454	1.575	1.382	1.336	1.222	1.094	0.750	1.281	0.188	0.006	0.062	0.043	0.294	0.347	0.863	1.068	1.239

because this horizon seems to coincide with the BFEE. On the other side, the boundaries between the *L. pseudomenardii* and *M. velascoensis* biozones, *M. aequa* and *M. gracilis* subzones, and *M. velascoensis* and *M. subbotinae* biozones have not been identified in the stratigraphic interval studied in Possagno. The FO of *P. wilcoxensis* have been provisionally placed in sample 45 because the *P. wilcoxensis* specimens found are doubtful (Fig. 3; Table 1). Consequently, in the Possagno section the upper part of *M. gracilis* Subzone, the *A. berggreni* Subzone, the *A. sibaiyaensis* Subzone, and probably the lowermost part of *P. wilcoxensis* Biozone have been recognized and studied.

Planktic foraminiferal turnover

The BFEE and $\partial^{13}C$ excursion have been well documented worldwide, including the Atlantic Ocean (Tjalsma and Lohmann 1983; Pak and Miller 1992; Pardo et al. 1997), Pacific Ocean (Douglass and Woodruff 1981; Miller et al. 1987; Kaiho 1994; Pak and Miller 1992), Indian Ocean (Hovan and Rea 1992), Antarctica (Thomas 1990; Katz and Miller 1991; Lu and Keller 1993), and Tethys (Braga et al. 1975; Molina et al. 1994; Lu et al. 1996; Schmitz et al. 1996; Speijer et al. 1996a, 1996b). On the contrary, the planktic foraminiferal turnover has received less attention and it was

AGE	DATUMS EVENTS	BIOZONATIONS							
		Molina et al. (1999) This work		Arenillas y Molina (1996)	Berggren et al. (1995)	Canudo & Molina (1992)	Toumarkine & Luterbacher (1985)	Blow (1979)	Bolli (1966) Stainforth et al. (1975)
		Zones	Subzones						
YPRESIAN	M. velascoensis ▼	Morozovella subbotinae	Morozovella edgari	Morozovella subbotinae	M. velascoensis-M. formosa P6a	Pseudohastigerina wilcoxensis	Morozovella edgari	Globorotalia (A.) wilcoxensis berggreni P7	Globorotalia subbotinae
	Ps. wilcoxensis ▲	Morozovella velascoensis	Pseudo-hastigerina wilcoxensis	Morzovella velascoensis	Morozovella velascoensis P5		Morozovella velascoensis		Globorotalia velascoensis
	A. sibaiyaensis ▲		Acarinina sibaiyaensis						
	I. laevigata		Acar. berggreni						
	A. berggreni		Morozovella gracilis	Igorina laevigata		Morozovella aequa		Globorot. (M.) subbotinae subbotinae - Globorot. (M.) velascoensis acuta P6	
THANETIAN	M. gracilis ▲		Morozovella aequa						
	L. pseudomenardii ▼	Luterbach. psedome-nardii	Muricoglobig. soldadoensis	Muricoglobig. soldadoensis	A.soldadoensis G.pseudomena. P4c	Planorotalites pseudomen.	Planorotalites pseudomen.		Globorotalia pseudomen.

Fig. 2 Comparison of uppermost Paleocene and lowermost Eocene planktic foraminiferal biozonations with the biozonations used in this paper

generally believed that this group was not affected by this global oceanographic change. However, a gradual planktic foraminiferal turnover during the P/E transition has been reported for the North Atlantic, Tethys, Pacific, Indian, and Antarctic oceans (Stott and Kennett 1990; Molina et al. 1992; Canudo and Molina 1992; Lu and Keller 1993, 1996; Pardo et al. 1994, 1997, 1999; Canudo et al. 1995; Arenillas and Molina 1996, 1997; Molina et al. 1999). The planktic foraminiferal quantitative analysis, represented by the relative abundance of the different identified species across the P/E boundary at the Possagno section, shows a continuous record except at the dissolution interval (Fig. 3).

The paleoceanographic studies and quantitative analysis allowed to group the planktic foraminiferal species according to their latitudinal trend (Fig. 4) in lower-latitude warm-water dwellers (*Morozovella, angulata* and compressed *Acarinina* and *Igorina*) and higher-latitude cool-water dwellers (*Subbotina*, rounded *Acarinina, Muricoglobigerina, Chiloguembelina*, and *Luterbacheria*,). Moreover, carbon and oxygen stable isotope measurements of individual planktic foraminiferal species provide an indication as to where in the water column they lived. The taxa with a more positive δ^{13}C and a more negative δ^{18}O, such as *Morozovella, Acarinina, Muricoglobigerina,* and *Igorina*, indicate surface dwellers, and the taxa with a

more negative δ^{13}C and a more positive δ^{18}O, such as *Subbotina, Chiloguembelina,* and *Luterbacheria*, indicate deep dwellers. Paleoecological inferences are based on criteria established in previous studies by Premoli Silva and Boersma (1988), Boersma and Premoli Silva (1988, 1989), Shackleton et al. (1985b), Corfield and Cartlidge (1992), Eijden (1995), Arenillas (1996), Pardo et al. (1997), and Berggren and Norris (1997). These inferences allowed us to use a warm/cold (W/C) species ratio by means of planktic foraminifera population (W = % low-latitude warm-water dweller species and C = % high-latitude cool-water dweller species; Fig. 4).

Planktic foraminifera populations indicate significant environmental changes across the P/E boundary. The BFEE at the P/E boundary coincides with a planktic foraminiferal turnover marked by a major increase in the W/C planktic foraminifera ratio that suggests a surface water warming. The Possagno section shows an increase of tropical–subtropical species near to 80%. The change of the W/C ratio at the P/E boundary is related mainly to a short-term incursion of acarininids (Fig. 4). The quantitative analysis indicates a major increase of low-latitude acarininids (*A. apanthesma, A. berggreni, A. quetra, A. stra-*

Fig. 3 Species ranges and relative abundance of planktic foraminifera species across the P/E boundary at the Possagno section in the size fraction bigger than 106 μm
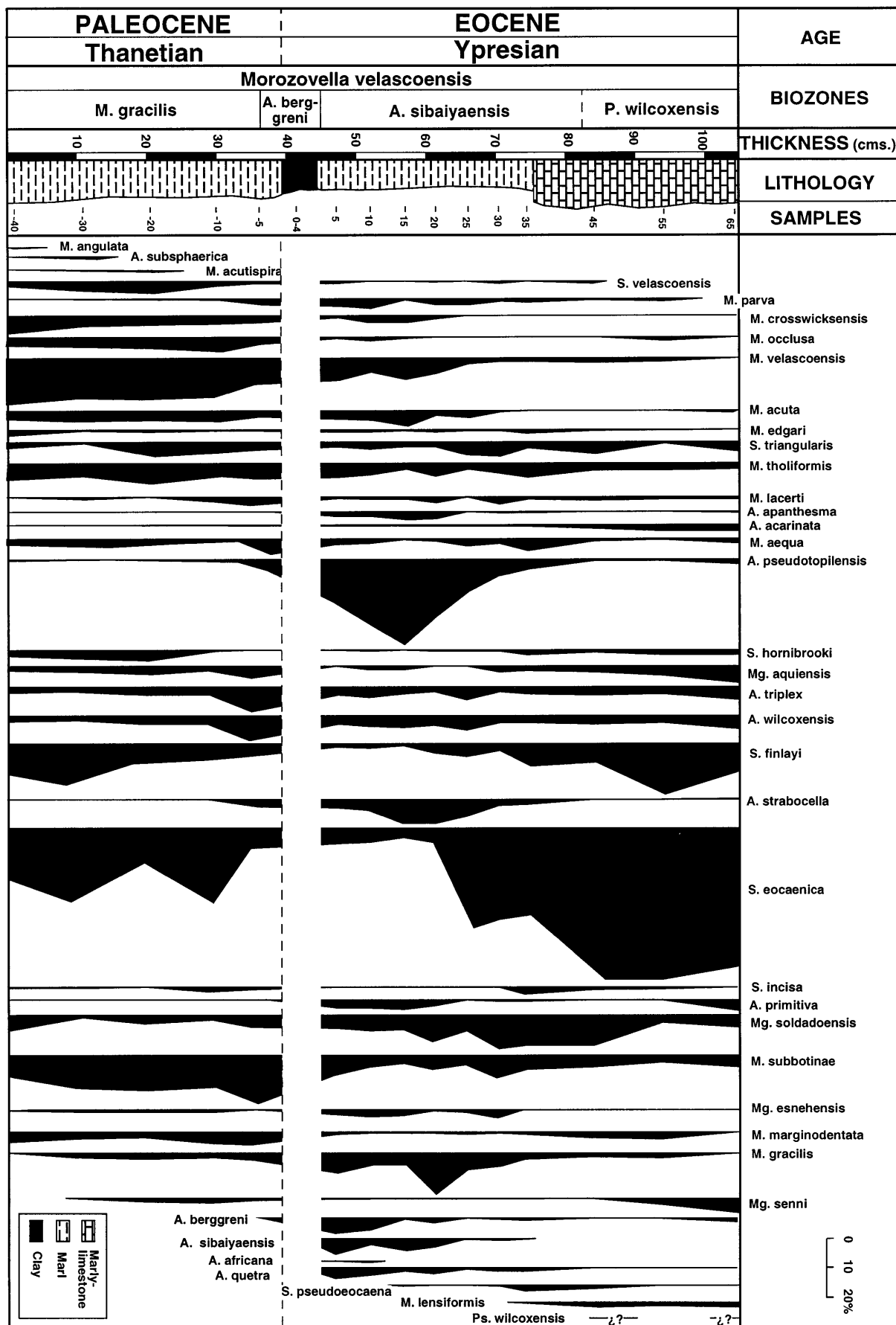
bocella, and *A. wilcoxensis*) just above the boundary clay, including compressed tropical acarininids (*A. africana* and *A. sibaiyaensis*). The maximum diversity of acarininids coincides with the $\partial^{13}C$ isotopic excursion and corresponds to an increase of temperature of sea waters across the dissolution interval. The acarininid incursion begins just below the boundary clay layer and shows maximum peak above it. Acarininid abundance is approximately 5–10% in the Upper Paleocene at Possagno, but their abundance increases approximately 20% just below the P/E boundary and 40–55% just above.

The sudden increase in *Acarinina* coincides with the FO of new evolving acarininids, such as *A. berggreni, A. sibaiyaensis, A. africana,* and *A. quetra* (Fig. 3). The first three species were first recognized and described by El Naggar (1966) at the Esna-Idfu region of Egypt near the P/E transition. Up to date, *A. sibaiyaensis* and *A. africana* have been observed mainly in the Tethys region, but also in the tropical Pacific (ODP Site 865) by Kelly et al. (1995, 1998). At Possagno their ranges are confined within the post-P/E acarininids increase, where they reached a maximum combined relative of 4–6%. This spatial and temporal distribution of the compressed acarininids suggest a warm environment in the Tethys region during the P/E transition. The Tethyan restrictive environmental conditions during the P/E transitional global warming can be the cause of the evolution of this new acarininids species (Arenillas and Molina 1996; Arenillas 1996).

On the other side, the FO of *A. berggreni* occurred just at the beginning of the increase in acarininids below the P/E boundary clay. It is possible that a release of warm-water masses began just before the BFEE and the deposition of the clay dissolution interval. Therefore, whereas benthic foraminiferal extinctions and originations associated with the P/E maximum warming have been well documented and can be defined as a typical mass extinction event, the planktic extinctions and originations occurred gradually. The planktic faunal composition across the P/E boundary is characterized by a relatively gradual change between disappearing typical Paleocene taxa and appearing typical Eocene taxa. In Possagno the LO of *M. angulata, A. subsphaerica,* and *M. acutispira* have been identified in the *M. gracilis* Subzone near the P/E boundary, LO the *S. velascoensis,* and *M. parva* in the *P. wilcoxensis* Subzone boundary. Furthermore, the FO the *S. pseudoeocaena* have been identified above the P/E boundary in the acarininid peak interval and *M. lensiformis* just above the acarininids peak interval in the *A. sibaiyaensis* Biozone.

The significant increase in the W/C ratio is attributed to the P/E boundary global maximum warming (Canudo and Molina 1992; Canudo et al. 1995; Arenillas and Molina 1996; Pardo et al. 1997). Nevertheless, the low-latitude species show a different behavior at this boundary event. For instance, the morozovellids, considered as low-latitude and surface dwellers, show a decrease in relative abundance just above the boundary clay (Fig. 4). The *Morozovella* abundance in the upper Paleocene is 40–50%, whereas in the lower Eocene it is only 10–20%. Their abundance seems to decrease progressively across the *A. sibaiyaensis* and *P. wilcoxensis* subzones in the Possagno section. This decrease is related mainly to the decline of "large" morozovellids, which include *M. velascoensis, M. acuta, M. parva, M. occlussa,* and *M. crosswicksensis.*

The $\partial^{13}C$ shift and the BFEE mark the beginning of the progressive displacement of morozovellids population by incoming acarininids in surface water. The extinction of the large Paleocene morozovellids, which occurred across the boundary between the *M. velascoensis* Biozone and *M. subbotinae* Biozone (Arenillas and Molina 1996; Molina et al. 1999), can be the end of this paleoecological and evolutive event. In fact, when the acarininids decrease in the upper part of the *A. sibaiyaensis* Subzone, the W/C ratio (20–30%) is less prominent than the upper Paleocene W/C ratio (50–60%) and much less than the W/C ratio (80%) of the post-P/E stage (Fig. 4). This W/C shift could be caused by a cooling trend in the earliest Eocene, but the environmental changes during the P/E transition were complex and all of them can have affected the turnover of the planktic foraminifera assemblage. In contrast, other morozovellids do not show significant changes in abundance during the P/E boundary event at Possagno, except only for the slight decrease in *M. subbotinae* abundance and slight increase in *M. gracilis* abundance. The "small" morozovellids (*M. subbotinae, M. aequa, M. tholiformis, M. gracilis, M. marginodentata, M. dolabrata, M. edgari*) seem to replace in abundance to the large morozovellids in the upper part of the *M. velascoensis* Subzone. In fact, the only morozovellid species that appears in this interval is *M. lensiformis,* which belongs to the small morozovellids group.

$\partial^{13}C$ isotopic changes

In the Possagno section, in the 40-cm-thick interval below the dark-red "dissolution" clay, the bulk-rock $\partial^{13}C$ values are relatively stable, close to 1.5. The lower 3 cm of the "dissolution" clay contains prominent veins of diagenetic calcite. In this interval the relatively positive $\partial^{13}C$ values, in the range 0.75–1.3‰, most likely partly reflects the diagenetic calcite. This calcite may have precipitated from pore solutions with carbonate deriving from the underlying marls. In the interval from +4 to +15 cm $\partial^{13}C$ values are 1.5‰ more negative than below the base of the red clay. Over the interval from +20 to +40 cm $\partial^{13}C$ values gradually recover from 0.29 to 0.86‰. The two uppermost samples at +50 and +65 cm show values of 1.1–1.2‰, which is slightly lower than in the interval below the base of the dark-red clay.

Fig. 4 Relative abundance of planktic foraminifera genera and warm/cold ratio in the size fraction bigger than 106 μm and whole-rock carbon isotopic curve across the P/E boundary at the Possagno section
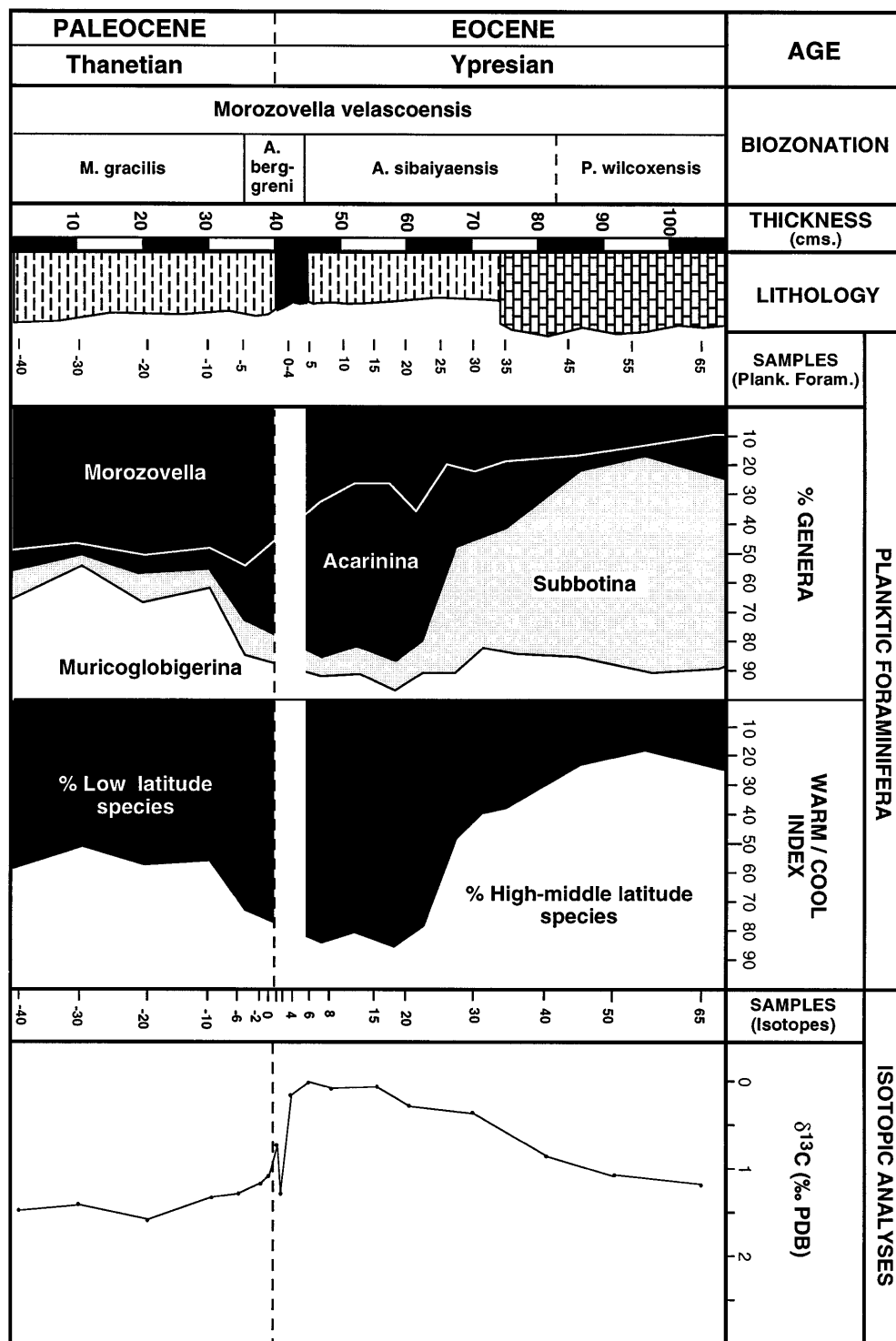
The general carbon isotopic trend and lithological succession at Possagno is very similar to that across the P/E transition at Zumaya in northern Spain (Schmitz et al. 1997); however, the Possagno record is condensed by an order of magnitude compared with Zumaya. At Zumaya a detailed whole-rock isotopic record has been measured and similarly to Possagno very low $\partial^{13}C$ values coincide with high acarininid abundances. These low $\partial^{13}C$ values reflect the global $\partial^{13}C$ excursion in connection with the BFEE (Schmitz et al. 1997). At Zumaya high acarininid abundances and low $\partial^{13}C$ values extend over approximately 4 m; however, at Possagno the same features are registered over 30–40 cm. The absolute $\partial^{13}C$ values in the intervals above and below the interval rich in acarininids are almost identical at the two sites (see Schmitz et al.

1997). At both Possagno and Zumaya the lower part of the acarininid-rich interval has very low concentrations of original calcite. Calcite concentrations increase in the upper part of the interval. The recovery of $\partial^{13}C$ values to near pre-excursion values coincides at both sites with a transition from marls to limestones.

The general similarity of the Possagno and Zumaya $\partial^{13}C$ records across the P/E transition speaks in favor of that the main features of the two records reflect original sea-water $\partial^{13}C$ trends. Another fact in favor of this view is the similarity of the bulk-rock $\partial^{13}C$ record established for the entire Paleocene part of the Zumaya section with coeval $\partial^{13}C$ records measured on well-preserved foraminifera from deep-sea sediments (Schmitz et al. 1997). Limestones and marls that have become indurated or compacted during early diagenesis may represent closed systems with respect to carbon isotopes, and therefore have a great potential for retaining original $\partial^{13}C$ signals (Marshall 1992; Charisi and Schmitz 1995, 1998). The preservation of original $\partial^{13}C$ signals is particularly likely in sediments with high calcite/organic matter ratios as at Possagno and Zumaya.

Discussion

The BFEE and isotopic shifts are a consequence of unusual and complex global changes across the P/E boundary. This change affected not only the small benthic foraminifera and isotopic signals, but the planktic foraminiferal faunal assemblages too. The low-latitude acarininid peak seems to be a global feature since it has been reported in different sections worldwide, such as at Alamedilla, Caravaca and Zumaya in Spain (Molina et al. 1994; Canudo et al. 1995; Arenillas and Molina 1996; Arenillas 1996; Lu et al. 1996), Kaurtakapy in Kazakstan (Pardo et al. 1999), Site 401 in the North Atlantic (Pardo et al. 1997), Site 738 in the Antarctic (Lu and Keller 1993), and Site 865 and Site 577 in the Pacific (Lu and Keller 1993; Kelly et al. 1995, 1998). The P/E transition faunal turnover suggests that the paleoclimatic and paleoceanographic event affected the entire water column, since all the bathymetric habitats were affected. This event may have triggered a migration of tropical–subtropical planktic foraminiferal assemblages toward the high-latitude regions that caused the sudden increase of the acarininids in different P/E sections (Arenillas and Molina 1996; Arenillas et al. 1996; Pardo et al. 1997, 1999; Lu et al. 1996; Molina et al. 1999). The migration of the planktic fauna towards higher latitudes has also been recorded in the paleoceanographic studies based on nannoplankton (Haq 1973; Pospichal and Wise 1990) and dinoflagellates (Bujak and Williams 1979).

At Possagno the BFEE coincides with the deposition of a dark-red clay layer with low carbonate content and strong foraminiferal dissolution. This dissolution interval has also been recognized in the Alamedilla, Caravaca, Ermua, Trabakua, and Zumaya sections in Spain (Canudo and Molina 1992; Molina et al. 1994; Canudo et al. 1995; Arenillas and Molina 1996; Orue-Etxebarría et al. 1996; Schmitz et al. 1997) and other marine records (Thomas and Shackleton 1996; Schmitz et al. 1996; Thomas 1996). The dissolution clay layer may have been caused by the rise of the calcite compensation depth (CCD) and lysocline (Molina et al. 1994; Canudo et al. 1995), which occurred during a eustatic sea-level rise between the uppermost Paleocene and lowest Eocene (Haq et al. 1987). Dissolution of $CaCO_3$ during the isotope excursion appears to be most pronounced in bathyal and abyssal sequences (Thomas 1996; Dickens et al. 1997). The depth of the lysocline and CCD could rise to 400 m, being most pronounced in the oceanic regions (Dickens et al. 1997). It is possible that the cause of the BFEE in bathyal and abyssal environments is related to volcanism. Release of volcanic CO_2 and CH_4 from oceanic hydrates could have induced the rise of the CCD and lysocline and leading to the extinction of the small benthic foraminifera in bathyal and abyssal environments at a worldwide scale.

The sedimentological sequence across the P/E boundary event consists, in general, of a detrital unit, a marl, and a clay unit and a marly limestone unit, just like at Possagno, Zumaya, Caravaca, and Alamedilla (Molina et al. 1994; Canudo et al. 1995; Pujalte et al. 1996; Arenillas and Molina 1996). The detrital unit can be attributed to a lowstand systems tract (LST). This basal detrital unit is not present at the Possagno section due probably to its distal basin facies. However, the dissolution clay is present in this section like in all the other continuous bathyal and abyssal sections, and may be a suitable level to define the P/E boundary. The marl and clay unit seem to correspond to a transgressive systems tract (TST) and the simultaneous rise of the CCD and lysocline, which produced strong foraminiferal dissolution. The dark-red clay is 4 cm thick at Possagno compared with 3.5 m thick clay at Zumaya, 2 m at Caravaca, and 40 cm at Alamedilla (Canudo and Molina 1992; Molina 1994; Molina et al. 1994; Canudo et al. 1995; Arenillas and Molina 1996, 1997). Finally, the pelagic marly limestone unit placed above corresponds to a highstand systems tract (HST).

The main cause of all these short-term changes in P/E transition may be related to the reorganization of tectonic plates that produced an increase of volcanic activity and a rise of sea level. Various important paleogeographic events occurred during the late Paleocene and early Eocene, like the separation of Greenland and Scandinavia, with the formation of embryonic Greenland and Norwegian Seas, and/or the displacement of Indian plate that may have arrived at a subduction zone in the Tethys Sea in the early Eocene and thereafter severely restricted the Tethys current (Haq 1981; Haq et al. 1987). An increase in the submarine hydrothermal and volcanic activity on the sea floor (Knox and Morton 1988; Owen and Rea 1992; Sloan et al. 1992;

Eldhom and Thomas 1993) and a rise in the sea level were related to this tectonic readjustment (Haq et al. 1987; Pujalte et al. 1995; Arenillas and Molina 1996).

This tectonic and eustatic event may have been responsible for the shift in the locus of ongoing deep-water formation from cold and nutrient-depleted deep waters produced in the polar (Artic and Antarctic) region to warm, saline, and oxygen-deficient deep waters formed in Tethyan evaporative basins (Miller et al. 1987; Kennett and Stott 1990, 1991; Thomas 1990; Katz and Miller 1991; Pak and Miller 1992; Charisi and Schmitz 1994, 1995, 1998; Lu et al. 1996). Therefore, the P/E boundary event is usually explained by quick incursions of warm, saline, and nutrient-depleted water masses towards the poles that triggered the high-latitude warming (Rea et al. 1990). The decrease in latitudinal temperature gradient (Barron 1987; Covey and Barron 1988) caused a decrease of the surface wind intensity (Janecek and Rea 1983; Rea et al. 1985, 1990; Covey and Barron 1988; Hovan and Rea 1992). Finally, the decrease of the atmospheric circulation intensity produced a consequent decrease in surface-water marine circulation and a decline in biological productivity (Rea et al. 1985, 1990).

The thermal and geochemical changes across the P/E transition are unprecedented in the geological record and comparable to present anthropogenic action (Lu et al. 1996; Dickens et al. 1997). The large negative $\delta^{13}C$ shift, measured in benthic, planktic foraminiferal shells and whole-rock samples of sea-floor sediments have been related to amplified oxygen minimum zone, emanating from enhanced biological productivity and with elevated organic-carbon accumulation rates (Shackleton 1987; Hovan and Rea 1992; Charisi and Schmitz 1995). This isotopic shift suggests that the CO_2 was transported from the sediments into combined ocean-atmosphere reservoirs, due to addition of volcanogenic CO_2 and transfer of terrestrial biomass (Kennett and Stott 1991; Stott 1992; Pak and Miller 1992; Zachos et al. 1993; Lu et al. 1996; Thomas and Shackleton 1996).

However, the mantle CO_2 and terrestrial biomass is not sufficiently large to explain the P/E event. It has been hypothesized that the $\delta^{13}C$ shift signifies a transfer of CH_4 from oceanic hydrates to the ocean-atmosphere inorganic carbon reservoir (Dickens et al. 1997). This flux could be of similar magnitude to present-day anthropogenic CH_4 sources and could create the carbon isotopic shift as well as the sudden increase of greenhouse warming. The oceanic methane hydrates constitute an immense inorganic carbon reservoir, enriched in $\partial^{12}C$. The stability of these methane hydrates depends on temperature and, therefore, it is possible that the abrupt deep-sea warming induced a shift in sediment geotherms and the release of CH_4 from oceanic hydrates (Dickens et al. 1997). Furthermore, because CH_4 and its oxidation product CO_2 are greenhouse gases, they could have been the cause of the warming P/E pulse.

Since this event is global and produced isochronic effects that can be recognized worldwide, this event can be used to define the P/E boundary. These P/E events have been recognized in other studied sections of the Tethys and North Atlantic, such as Alamedilla, Caravaca, Ben Gurion, Kaurtakapy, Site 401, Zumaya, and Campo sections, all of them are much more expanded than the Possagno section (Canudo et al. 1989, 1995; Canudo and Molina 1992; Molina et al. 1994; Arenillas and Molina 1996; Arenillas 1996; Pardo and Arenillas 1996; Pardo et al. 1997; Molina et al. 1999; Pardo et al. 1999) and some of them have been proposed as candidates for the P/E Boundary stratotype. The Tethyan sections (Alamedilla, Kaurtakapy, Possagno) show a dramatic increase in acarininids as it would be expected in subtropical sections belonging to the critical Tethyan region. However, this acarininid peak has not been recorded to a great extent in other Tethyan sections such as Caravaca where the dissolution interval is more expanded in time, and Ben Gurion due to a hiatus just at the P/E boundary (Molina et al. 1999). The acarininid peak at Pyrenean (Zumaya and Campo) and Atlantic (Site 401) sections is clearly present but is less severe than at the Tethyan sections and the compressed acarininids are less abundant.

Alamedilla and Zumaya sections are the best exposed and most continuous studied P/E sections known thus far. These sections show the same planktic foraminiferal turnover, isotopic changes, and sedimentological turnover as Possagno, including the acarininids peak and dissolved boundary clay layer. Whereas the upper part of the *M. velascoensis* Biozone (from the P/E boundary to the LO of *M. velascoensis*) is 13 and 7 m thick at Zumaya and Alamedilla, respectively, this interval is only 57 cm thick at Possagno. Furthermore, this interval is 7 and 6 m thick at Caravaca and Ben Gurion sections, respectively, but these sections are not well exposed and have hiatus at or near the P/E boundary. Although the sedimentological condensation at Possagno is higher than at the Spanish and Israelii sections, the Possagno section allows confirmation that the different biotic, isotopic, and sedimentological events recognized in the Spanish sections are not local.

Conclusion

The interval spanning the P/E transition in the Possagno section consists of 1 m of red marls including a 4-cm-thick dark-red, "dissolution" clay which constitutes the P/E boundary event. The Possagno section is much more condensed than other Tethyan and North Atlantic sections; however, the most important biotic, isotopic, and sedimentological events across the P/E boundary can be recognized in this section.

The following subzones have been recognized: upper part of *M. gracilis* Subzone, *A. berggreni* Subzone, *A. sibaiyaensis* Subzone, and probably lower-

most part of *P. wilcoxensis* Subzone. The quantitative analysis indicates a major increase in low-latitude acarininids (*A. apanthesma, A. berggreni, A. quetra, A. strabocella, and A. wilcoxensis*) just above the boundary clay, including compressed tropical acarininids (*A. africana* and *A. sibaiyaensis*). The acarininids incursion begins just below the boundary clay, from the base of the *A. berggreni* Subzone, but reaches its maximum just above the clay. The planktic foraminiferal faunal turnover is gradual with the exception of the warm-water acarininid incursion. The isotopic results show a negative excursion in $\partial^{13}C$ values at the small benthic foraminifera mass extinction event. The maximum diversity of acarininids coincides with this isotopic excursion and suggests an increase in sea-surface temperatures. The bathyal and abyssal BFEE, the acarininid incursion, the dissolution clay, and the $\partial^{13}C$ negative excursion constitute an apparently isochronous event which would be very suitable for the definition of the P/E boundary stratotype.

These biotic and isotopic events have been recognized in other sections of the Tethys (Alamedilla, Caravaca, and Ben Gurion) and the North Atlantic (Zumaya and Campo) which are much more expanded that the Possagno section. In general, the sedimentological sequence across the P/E consists of a detrital unit (LST) a marl and a clay unit (TST), and a marly limestone unit (HST). The basal detrital unit is not present in this section due to its distal basin facies, but the dissolution clay is present like in all other continuous bathyal and abyssal sections. The Alamedilla and Zumaya sections are the best exposed and most continuously studied sections. The Ben Gurion and Caravaca sections have a hiatus at or near the P/E boundary. Despite being very condensed, the Possagno section allows confirmation that the different biotic, isotopic, and sedimentological events recognized in the Spanish sections are not local and allow establishment of a detailed chronostratigraphic framework to define the P/E boundary stratotype.

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