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Foraminiferal turnover across the Eocene–Oligocene transition at Fuente Caldera, southern Spain: No cause–effect relationship between meteorite impacts and extinctions

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Abstract

We studied planktic and small benthic foraminifera from the Fuente Caldera section, southern Spain, across the Eocene–Oligocene transition. Benthic foraminifera indicate lower bathyal depths for the late Eocene and earliest Oligocene. Detailed high-resolution sampling and biostratigraphical data allowed us to date precisely layers with evidence for meteorite impact (Ni-rich spinel), which occur in the lower part of the planktic foraminiferal *Globigerapsis index* Biozone and in the middle part of the small benthic foraminiferal *Cibicidoides truncanus* (BB4) Biozone (middle Priabonian, late Eocene). Major turnovers of foraminifera occur at the Eocene/Oligocene boundary, only. The impact did not occur at a time of planktic or benthic foraminiferal extinction events, and the late Eocene meteorite impacts did thus not cause extinction of foraminifera. The most plausible cause of the Eocene/Oligocene boundary extinctions is the significant cooling, which generated glaciation in Antarctica and eliminated most of the warm and surface-dwelling foraminifera.

Keywords: Eocene; foraminifera; extinction; impact; Ni-spinel

1. Introduction

In the Fuente Caldera section, southern Spain, the discovery of one major and two minor Ni-rich spinel anomalies (Molina et al., 2004), which are indicative of one or possibly several meteorite impacts and thus permit research into the possibility of a cause–effect relationship between late Eocene meteorite impacts and the extinction of foraminifera. Planktic foraminifera were a key group of microfossils used to establish a cause–effect relationship between meteorite impact and extinctions at the Cretaceous/Paleogene boundary (see Smit and Hertogen, 1980; Alvarez et al., 1980; Molina et al., 1996, 1998, 2005, among others).

In contrast, cause(s) of the late Eocene extinction are not well established, although meteorite impact was suggested as its cause (e.g., Ganapathy, 1982; Alvarez et al., 1982). Several levels with impact evidence, such as microtektites and Ir anomalies, were discovered (Glass et al., 1973; Keller, 1986; Keller et al., 1987) and Hut et al. (1987) proposed a model of stepwise mass extinctions caused by comet showers. Some

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authors argued that there had been multiple impacts; using graphic correlation, Hazel (1989) concluded that there might be at least six levels in the upper Eocene. Molina et al. (1993) suggested that there were three late Eocene impact events within about 1 Ma (34.7–35.7 myr) in the middle Priabonian, and concluded that major species extinctions did not coincide with those impact events. Similarly, Coccioni et al. (2000) and Spezzaferri et al. (2002) concluded that the impact event (35.5 Ma) had no dramatic effects on planktic foraminifera in the Massignano section (Italy).

Recently, more impact evidence was discovered in upper Eocene sediments, including iridium anomalies (Montanari et al., 1993), shocked quartz (Glass and Wu, 1993; Clymer et al., 1996), and Ni-rich spinel (Pierrard et al., 1998; Molina et al., 2004). Three about coeval impact craters were found at Popigai (100 km), northern Siberia (Bottomley et al., 1993), Chesapeake Bay (90 km) and Toms Canyon (20 km) on the North American continental shelf (Koeberl et al., 1996; Poag and Pope, 1998).

In the Fuente Caldera section a major anomaly of Ni-rich spinel and two minor anomalies appeared in the upper Eocene (middle Priabonian) A preliminary paper was published (Molina et al., 2004) and a detailed paper on the chronostratigraphy and composition of Ni-rich spinel is submitted for publication by Robin and Molina. The major anomaly is indicative of a meteorite impact, and is coeval with the Massignano impact horizon of 35.5 Ma. The two minor anomalies might be the result of reworking from the major anomaly or correspond to different impacts. The third anomaly is the smallest and very probably reworked but the second anomaly might correspond to the second, small iridium anomaly at Massignano (Montanari et al., 1993). Another impact layer, or possibly two, appeared in the upper part of the *Globigerapsis index* Biozone (about 34.5 Ma) at Site 292 (Pacific Ocean) and Site 94 (Atlantic Ocean) (Molina et al., 1993).

To determine whether those extraterrestrial impacts affected the global evolution and extinction of planktic and small benthic foraminifera, we studied the Fuente Caldera section, southern Spain, and provide quantitative analyses of planktic and small benthic foraminifera, as well as biostratigraphical and palaeoenvironmental data.

2. Materials and methods

The Fuente Caldera section is located in the Gavilán Ravine, near the Fuente Caldera farmhouse, in the township of Pedro Martínez, northern Granada

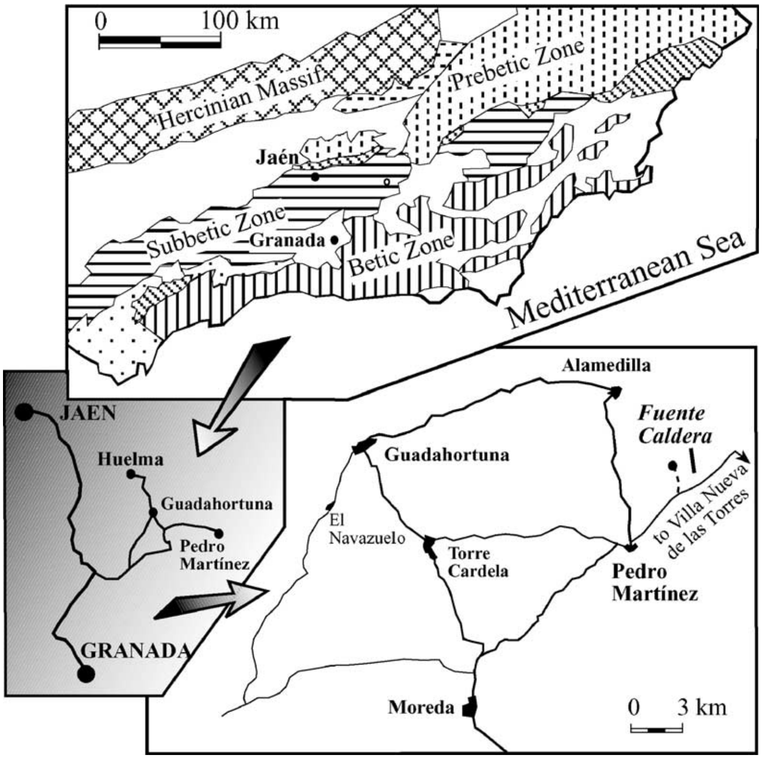


Fig. 1. Location of the Fuente Caldera section (southern Spain).

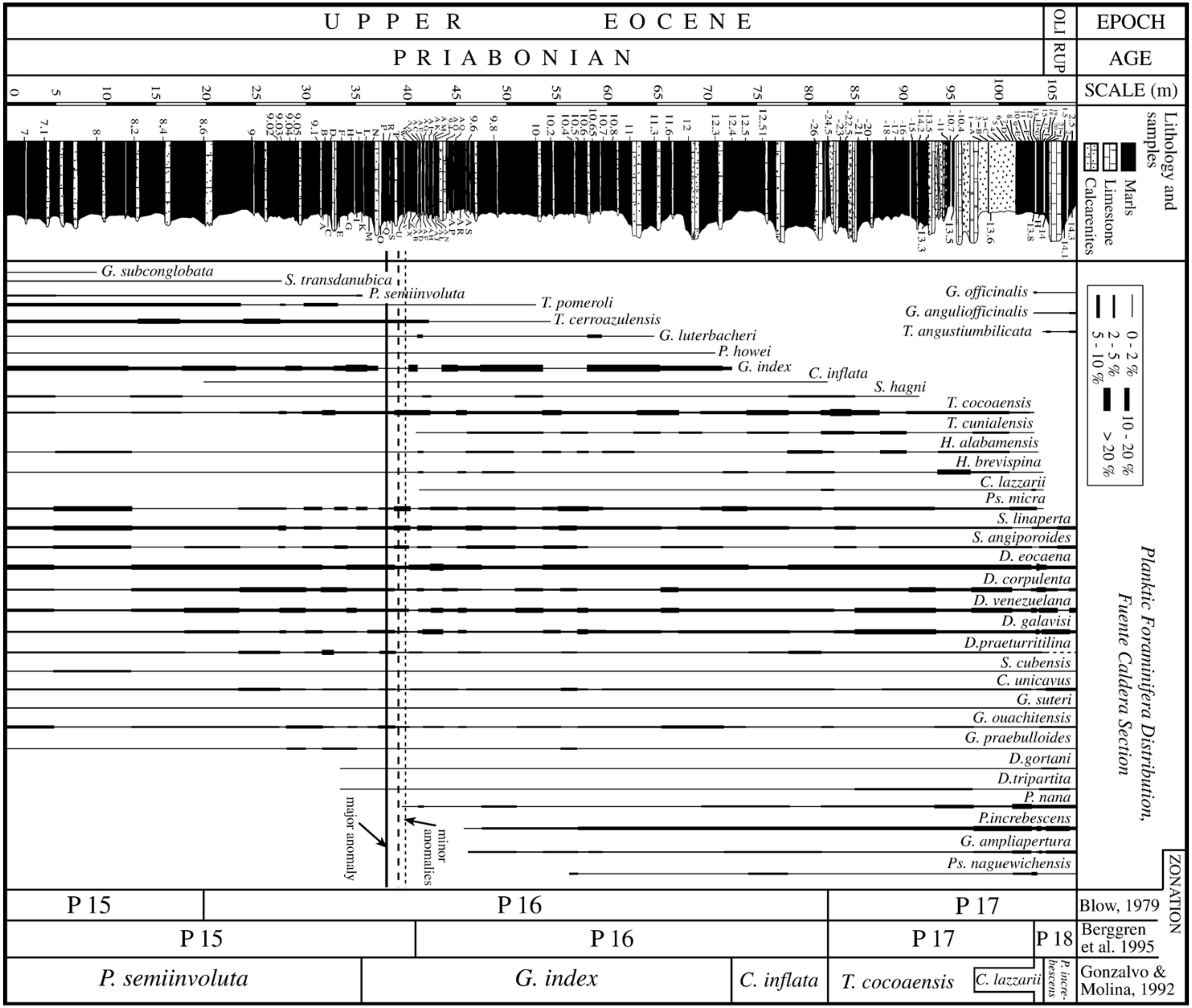


Fig. 2. Semi-quantitative distribution of planktic foraminifera in the Fuente Caldera section.

province, southern Spain (Fig. 1). The UTM coordinates of the points delimiting the section are base 30SVG836571 and top 30SVG835575. The section was proposed as a candidate for the Eocene/Oligocene (E/O) Global Stratotype Section and Point (GSSP), which was, however, defined in Massignano, Italy (Premoli Silva et al., eds., 1988). Geologically, the section is located in the external zones of the Betic Cordillera within the median Subbetic realm, which was a marine subsidence trough during the Eocene. The sequence of the Fuente Caldera section corresponds to the Cañada Formation of the Cardela Group (Comas, 1978; Comas et al., 1984–85), the formal lithostratigrafical units for Eocene–Oligocene median Subbetic sediments of the northern Granada province.

The lithology of the 109 m studied section is composed of hemipelagic marls interbedded with turbiditic sandstone layers (Fig. 2). This interval spans about 3 myr, from the late Eocene to early Oligocene, and apparently constitutes a complete, marine section. The hemipelagic marls contain abundant planktic foraminifera, calcareous nannofossils, and common small benthic foraminifera, some ostracodes, and rare fragments of echinids and molluscs. The foraminifera were sampled in the autochthonous marls and are fairly well preserved. The calcareous sandstone strata contain abundant larger foraminifera reworked from the shelf, which were not studied.

We collected 91 samples at 1-m intervals along the section, with closer spaced sampling at decimeter intervals across the E/O boundary and at continuous intervals across the boundary between the planktic foraminiferal *Porticulasphaera semiinvoluta* and *G. index* Biozones (Fig. 2). Samples were disaggregated in water with dilute H_2O_2, washed through a 63-μm sieve, and dried at 50 °C. The quantitative and taxonomic studies were based on representative splits of approximately 300 specimens of the >100 μm fraction, obtained with a modified Otto micro-splitter. The remaining residue was searched for rare species. All representative specimens were mounted on microslides for identification and permanent record at the Department of Earth Sciences, University of Zaragoza, Spain.

3. Results

3.1. Planktic foraminifera

The planktic foraminiferal biostratigraphy of the Fuente Caldera section (Plate 1) was first established by Molina (1986), who recognized Zones P15 to P20 of the Blow (1979) biozonation and established a parallel regional biozonation consisting of the *P. semiinvoluta* Biozone, *Cribrohantkenina inflata* Biozone and *Cribrohantkenina lazzarii* Biozone (late Eocene) and the *Globigerina gortanii* Biozone, *Globigerina tapuriensis* Biozone and *Globigerina sellii* Biozone (early Oligocene). Molina et al. (2004) revised and updated the biostratigraphy, of which the upper Eocene and lowermost Oligocene are shown here (Fig. 2). Biozones P15 through P18 (Berggren et al., 1995) were recognized. Those biozones correlate with the *P. semiinvoluta*, *G. index*, *C. inflata*, *T. cocoaensis*, *C. lazzarii* Biozones (late Eocene) and the *Paragloborotalia increbescens* Biozone (early Oligocene) of Gonzalvo and Molina (1992). According to that planktic biostratigraphy, the Fuente Caldera section is complete, without unconformities. The lowermost 35 m of the section belongs to the *P. semiinvoluta* Biozone, the base of which does not outcrop. We estimate that most of the zone is represented because of its thickness and the species distribution. The uppermost 4 m of the section belongs to the lower part of the *P. increbescens* Biozone. The section continues upward, but is not of interest in this paper. Those biostratigraphical data agree with data for the nearby sections of Torre Cardela (Martínez-Gallego and Molina, 1975) and Molino de Cobo (Molina et al., 1988).

Planktic foraminiferal species are grouped by their paleoenvironmental preferences (Table 1). Some species were not included because their paleoenvironmental distribution is not well known or they are not biogeographically and paleobathymetrically diagnostic. The paleoclimatical and paleoecological significance of Eocene planktic foraminifera are deduced from oxygen and carbon isotope composition of the test and from comparisons with recent taxa. Based on previous research (Boersma et al., 1987; Premoli Silva and Boersma, 1988, 1989; Keller et al., 1992; Coxal et al., 2000; Spezzaferri et al., 2002), we grouped the species by their position in the water column into surface-, intermediate-, and deep-dwelling forms. We also grouped them into four latitudinal groups: high, high–medium, medium–low, and low latitudes. The relative abundances of high and high–medium groups were added to create the cool-water species abundance curve. In the same way, the relative abundances of low and low–medium species were added to generate the warm-water species abundance curve (Fig. 3).

High latitude species are generally more frequent than low latitude species, except in the *C. inflata*

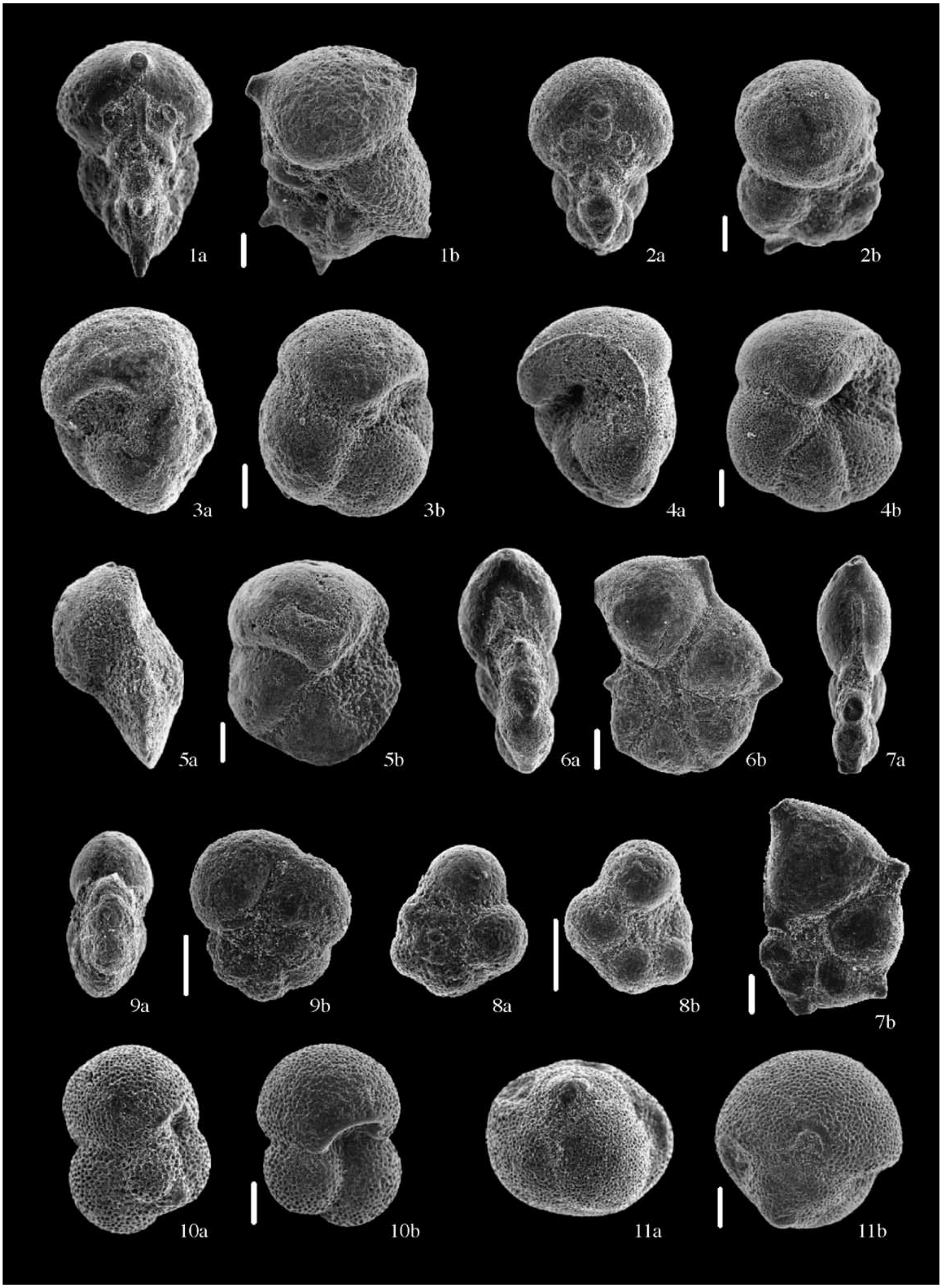


Plate 1. Planktic foraminifera. 1a–b. *Cribrohantkenina lazzarii*, sample Fcal-03-(-26); 2a–b. *Cribrohantkenina inflata*, sample Fcal-03-(-24); 3a–b. *Turborotalia pomeroli*, sample Fcal-9,1; 4a–b. *Turborotalia cerroazulensis*, sample Fcal-9,1; 5a–b. *Turborotalia cocoaensis*, sample Fcal-12,5; 6a–b. *Hantkenina brevispina*, sample Fcal-03-(-26); 7a–b. *Hantkenina alabamensis*, sample Fcal-7; 8a–b. *Tenuitellinata angustiumbilicata*, sample Fcal-03-2,5; 9 a–b. *Pseudohastigerina micra*, sample Fcal-13,8; 10a–b. *Globigerapsis index*, sample Fcal-10,8; 11a–b. *Porticulasphaera semiinvoluta*, sample Fcal-7. All scale bars: 100 μm.

Table 1
Planktic foraminiferal groups of species by depth and latitude in the Fuente Caldera section

Surface-dwelling	Intermediate-dwelling	Deep-dwelling
Porticulasphaera semiinvoluta	*Subbotina transdanubica*	*Globigerapsis subconglobata*
Globigerina ampliapertura	*Paragloborotalia nana*	*Globigerapsis luterbacheri*
Globigerapsis index	*Pseudohastigerina micra*	*Dentoglobigerina venezuelana*
Pseudohastigerina naguewichensis	*Subbotina linaperta*	*Dentoglobigerina tripartita*
Cribrohantkenina inflata	*Subbotina angiporoides*	*Catapsydrax unicavus*
Turborotalia cocoaensis	*Dentoglobigerina eocaena*	*Globorotaloides suteri*
Turborotalia cunialensis	*Dentoglobigerina corpulenta*	
Hantkenina alabamensis	*Dentoglobigerina galavisi*	
Hantkenina brevispina	*Globigerina praebulloides*	
Cribrohantkenina lazzarii		
Streptochilus cubensis		
Globigerina ouachitensis		
Globigerina officinalis		

High latitude	High–medium latitude
Paragloborotalia nana	*Pseudohastigerina micra*
Pseudohastigerina naguewichensis	*Subbotina linaperta*
Subbotina angiporoides	*Dentoglobigerina gortanii*
Dentoglobigerina eocaena	
Dentoglobigerina corpulenta	
Streptochilus cubensis	
Catapsydrax unicavus	
Globorotaloides suteri	
Globigerina ouachitensis	
Globigerina praebulloides	
Globigerina officinalis	

Low–medium latitude	Low latitude
Globigerina ampliapertura	*Porticulasphaera semiinvoluta*
Turborotalia cerroazulensis	*Turborotalia pomeroli*
Globigerapsis index	*Cribrohantkenina inflata*
Turborotalia cocoaensis	*Turborotalia cunialensis*
Tenuitellinata angustiumbilicata	*Hantkenina alabamensis*
	Hantkenina brevispina
	Cribrohantkenina lazzarii
	Dentoglobigerina galavisi
	Dentoglobigerina tripartita

Biozone and most of the *Turborotalia cocoaensis* Biozone, where percentages are below 50%. The percentage of high latitude species increased toward the early Oligocene, with the icehouse climate generally thought to have initiated at the early Oligocene oxygen isotope Oi-1 event (see Zachos et al., 2001, among others). Although high-latitude species dominate the assemblages, the more typical high latitude index (tenuitellids) are very rare across the upper Eocene, and *Tenuitellinata angustiumbilicata* appears only in the lowermost Oligocene.

The percentages of surface-, intermediate-, and deep-dwelling species are quite stable across the upper Eocene, but surface dwellers decreased in relative abundance at the E/O boundary. At this level, intermediate-dwellers increased in abundance, as did the deep dwellers in the lower Oligocene. That pattern is similar to observations at the Torre Cardela and Massignano sections (Gonzalvo and Molina, 1992; Molina et al., 1993). The species that became extinct are subtropical surface dwellers (*T. cocoaensis*, *Turborotalia cunialensis*, *Hantkenina alabamensis*, *Hantkenina brevispina* and *C. lazzarii*).

In the Fuente Caldera section, the planktic foraminiferal stratigraphical distribution shows a background evolution and extinction pattern across the *P. semiinvoluta* through the *T. cocoaensis* Biozones and at the *C. lazzarii* Biozone, a major extinction event has been

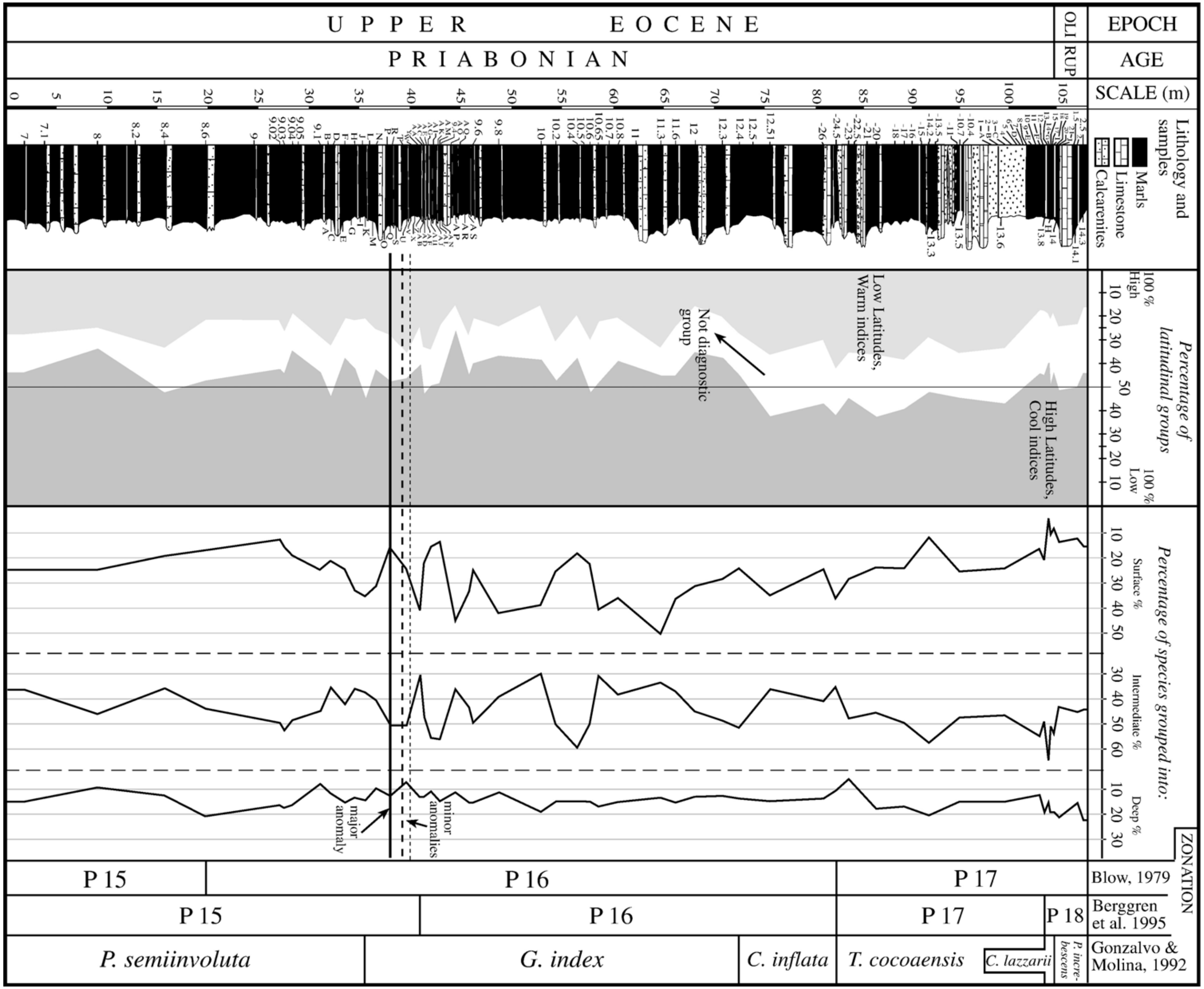


Fig. 3. Percentage curves of planktic foraminifera latitudinal groups and percentage curves of surface-, intermediate- and deep-dwelling species in the Fuente Caldera section.

recognized. This event is one of the major extinction events in the history of planktic foraminifera, comprising the disappearance of three genera (*Turborotalia*, *Hantkenina*, and *Cribrohantkenina*) and the great affection of one genus (*Pseudohastigerina*). The very small *Pseudohastigerina naguewichiensis* survived, but *Pseudohastigerina micra* larger than 150 μm became extinct. The extinction event was gradual, rather than simultaneous, and species disappeared in the following order: *T. cocoaensis*, *T. cunialensis*, *H. alabamensis*, *H. brevispina*, *C. lazzarii*, and *P. micra* (larger than 150 μm) (Fig. 2).

3.2. Benthic foraminifera

After a preliminary study of the benthic foraminifera (Molina et al., 2004), all samples were examined and those that were better preserved and biostratigraphically important were selected. This more detailed study allowed us to define the stratigraphic ranges of some of the benthic foraminiferal species identified by Molina et al. (2004). Benthic foraminifera were identified to the generic level following Loeblich and Tappan (1987) and, whenever possible, to the specific level following Cenozoic taxonomic studies (e.g., Tjalsma and Lohmann, 1983; Van Morkhoven et al., 1986; Bolli et al., 1994; Holbourn et al., in press).

The benthic foraminiferal assemblages are dominated by calcareous taxa (up to ~97% in sample Fcal 9,1-50-75C), and infaunal taxa, with relative abundances of ~51–80% in samples Fcal-17 and Fcal 9,12-260-300 K, respectively (Fig. 4). The most common calcareous species are *Bolivinoides crenulata*, *Bolivinoides floridana*, *Asterigerina* sp. A, *Cibicidoides mundulus–praemundulus* group, *Oridorsalis umbonatus*, *Globocassidulina subglobosa*, and *Angulogerina muralis*. The dominant calcareous species groups include bolivinids (*Bolivina* spp., *Bolivinoides* spp., and *Brizalina* spp.), *Cibicidoides* spp., *Asterigerina* spp., unilocular species, *Gyroidinoides* spp., and *Oridorsalis* spp. Less common calcareous groups include *Stilostomella* spp., *Bulimina* spp., *Osangularia* spp., *Anomalinoides* spp., *Pleurostomella* spp., *Uvigerina* spp, *Lenticulina* spp., and *Pullenia* spp. (listed in order of decreasing abundance) (Fig. 5). The agglutinated foraminiferal assemblages are dominated by rounded spiral taxa (e.g., *Recurvoides* spp.), uniserial taxa (e.g., *Rhabdammina cylindrica*), *Vulvulina* spp., and *Karreriella* spp (Plate 2). Some agglutinated species, such as *Reticulophragmium amplectens* and *Pseudoclavulina* sp. B show slight peaks in their relative abundance close to the E/O boundary (Fig. 4).

The benthic foraminiferal faunas show a similar high diversity in all samples, as expected in deep-sea faunas (e.g., Douglass and Woodruff, 1981), with 44 to 61 genera and 73 to 105 species recognized in a sample of about 300 specimens, and highly dominated by bolivinids. The high diversity, however, is probably influenced by the presence of taxa derived from shallower water because of the effect of turbidites.

The paleodepth of the benthic foraminiferal assemblages is inferred from the bathymetric distribution of the individual species or genera reported for the Paleogene (e.g., Tjalsma and Lohmann, 1983; Miller, 1983; Wood et al., 1985; Van Morkhoven et al., 1986; Müller-Merz and Oberhänsli, 1991; Katz et al., 2003; Holbourn et al., in press). Bathyal and upper abyssal groups are abundant in the Fuente Caldera section. The bathyal groups include bolivinids, buliminids, lenticulinids, osangularids, and uvigerinids (e.g., Tjalsma and Lohmann, 1983; Wood et al., 1985; Nocchi et al., 1988), and the abyssal groups include gyroidinoids and vulvulinids (Nocchi et al., 1988). *G. subglobosa*, which is very rare to common in Fuente Caldera section, is considered a lower bathyal–upper abyssal species (Holbourn et al., in press). Species known to be abundant at bathyal water depths include *Hanzawaia ammophila*, *Osangularia mexicana*, *Cibicidoides eocaenus*, *Cibicidoides barnetti*, *Bolivinoides byramensis*, *Buliminella grata*, *Bulimina alazanensis*, *Pleurostomella brevis*, *Brizalina antegressa*, *Bulimina tuxpamensis*, and the *Bulimina trinitatensis–impendens* group. Typical lower abyssal (i.e., greater than 3000 m) Eocene forms, such as *Alabamina dissonata*, *Abyssamina* spp., and *Clinapertina* spp., were absent, except for very few *Alabamina* spp. *Cibicidoides havanensis* and *C. grimsdalei*, typical of abyssal depths, are not abundant.

Atlantic Ocean deep-sea Eocene sections are characterized by *C. praemundulus*, *G. subglobosa*, *Gyroidinoides* spp., and *Oridorsalis* spp. at bathyal to abyssal depths (e.g., Tjalsma and Lohmann, 1983; Miller, 1983; Wood et al., 1985; Miller and Katz, 1987b) *C. praemundulus* is more common at bathyal depths (200–2000 m) (Müller-Merz and Oberhänsli, 1991; Katz et al., 2003), and this is the most common *Cibicidoides* species in the Fuente Caldera section, included in the *C. mundulus–praemundulus* group. *Asterigerina* spp. and other taxa more common at sublitoral to upper bathyal depths, such as *Pararotalia audouini*, *Cibicidina walli*, *Angulogerina angu-*

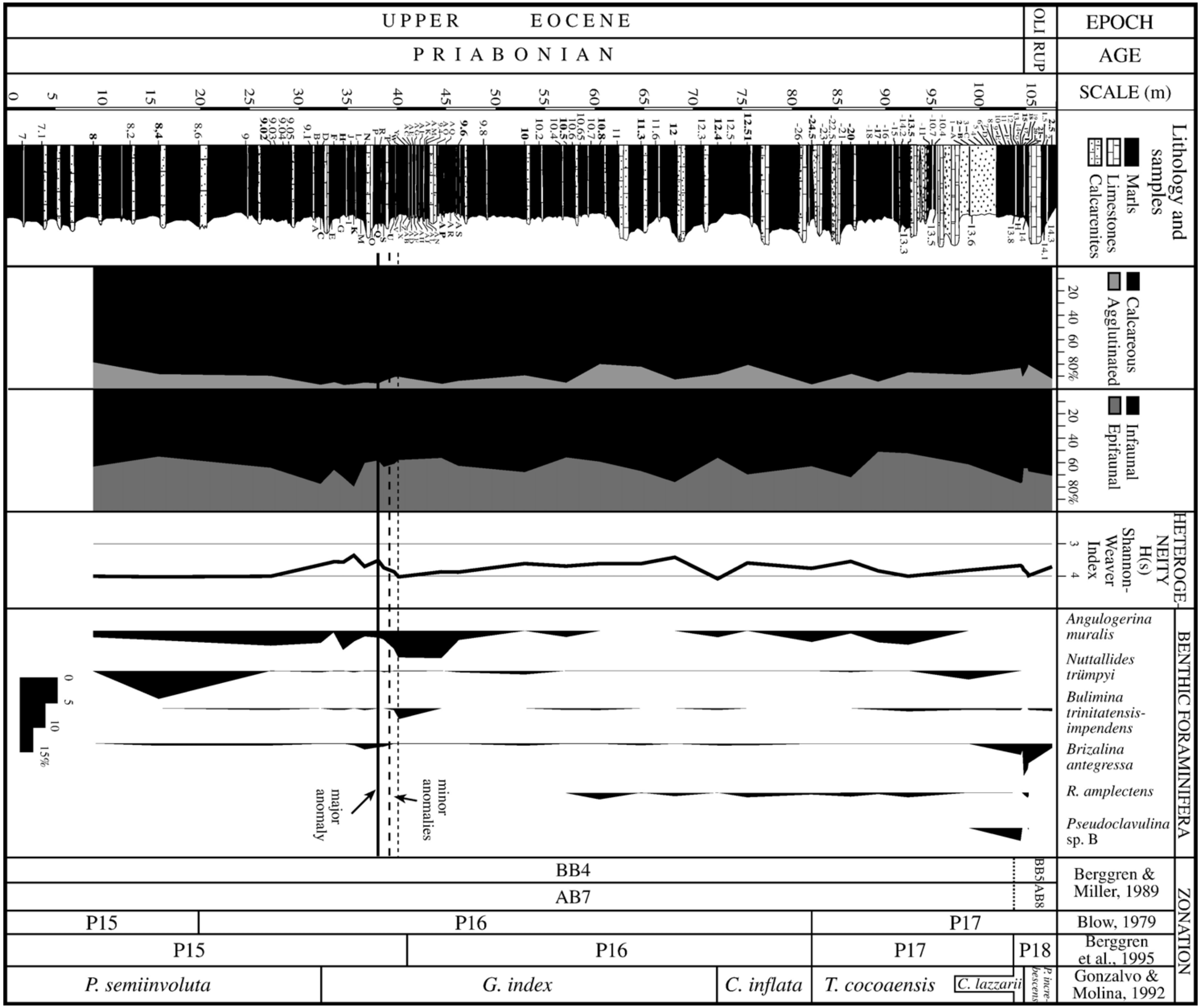


Fig. 4. Percentages of benthic foraminifera, relative abundance of infaunal and epifaunal morphogroups, and $H(s)$ heterogeneity index of benthic foraminiferal species in the Fuente Caldera section.

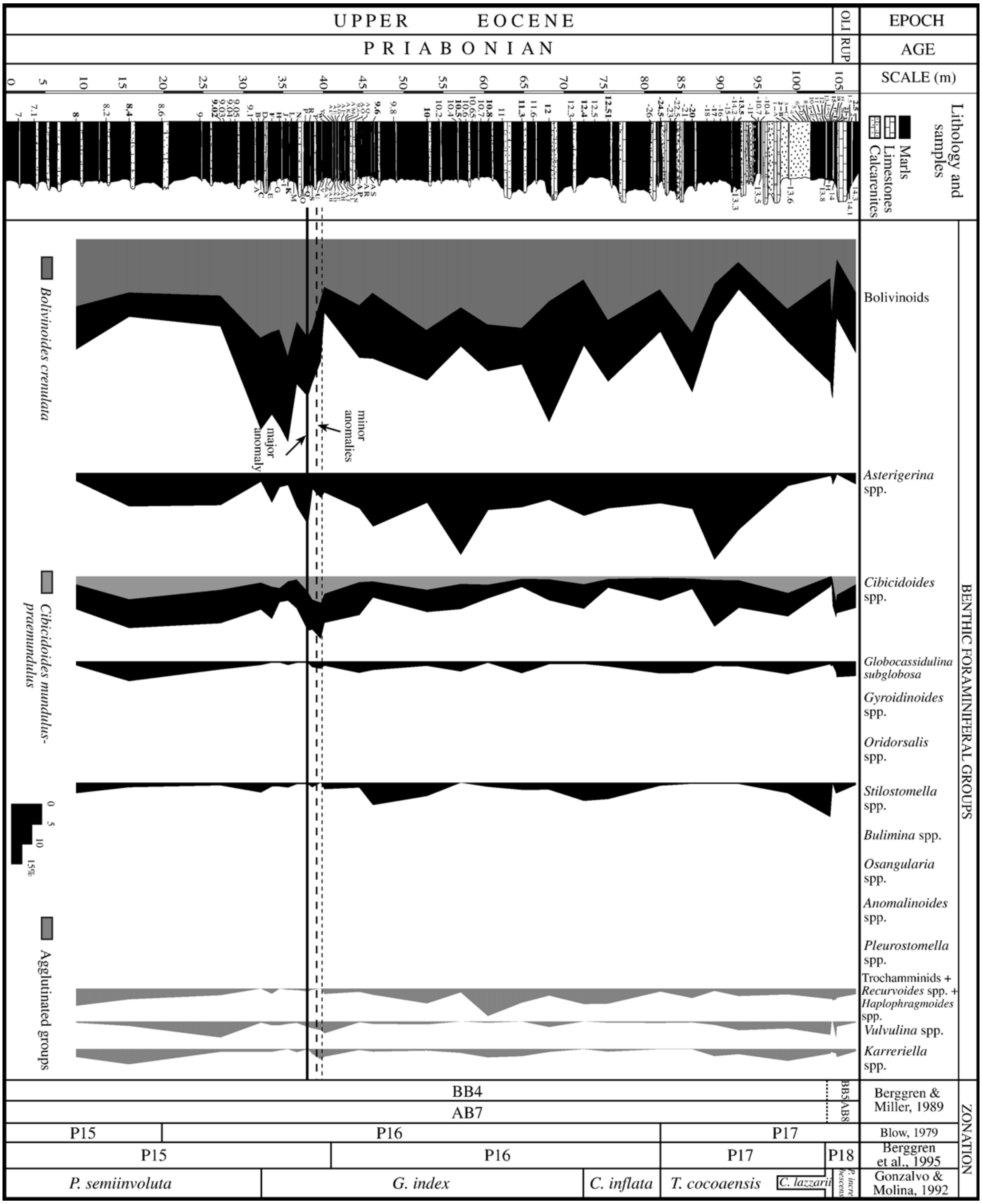


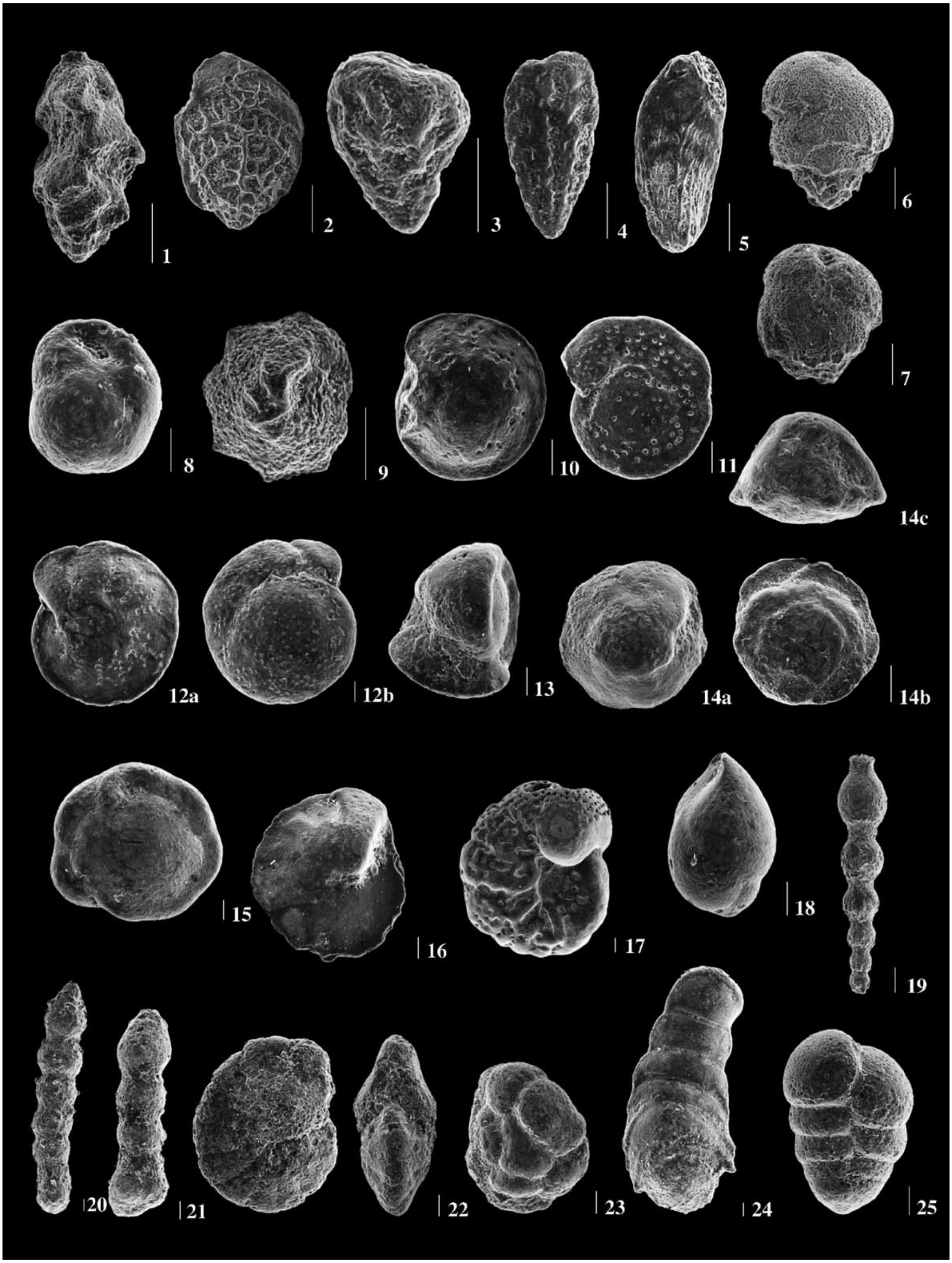
Fig. 5. Occurrence and relative abundance of the most characteristic benthic foraminiferal groups in the Fuente Caldera section.

losa, and *A. muralis* are abundant. Those shallow water species probably represent allochthonous material derived from the self by turbidity currents (Molina et al., 1986).

We estimate a constant depositional environment corresponding to the lower bathyal zone, at a water depth of more than 1000 m, and not outer sublitoral to upper bathyal as estimated preliminarily by Molina et al.

(2004). The latter estimate was made because of the high relative abundance of *Asterigerina* species, which we now regard as allochthonous.

One of the most important changes in assemblage composition of the Tertiary occurred across the middle/late Eocene boundary throughout the deep sea. During



the middle/late Eocene, a *Nuttallides trümpyi* abyssal assemblage was replaced by a *G. subglobosa–Gyroidinoides* spp.–*C. praemundulus–O. umbonatus* assemblage (Tjalsma and Lohmann, 1983; Miller, 1983; Wood et al., 1985). That assemblage continued to dominate in the Oligocene. At middle–lower bathyal depths, a *N. trümpyi–Lenticulina* spp. assemblage was replaced by a *Gyroidinoides–B. alazanensis–G. subglobosa* assemblage (Tjalsma, 1983; Miller et al., 1985; Miller and Katz, 1987a). That transition was not found in the Fuente Caldera section because no middle Eocene sediments were studied; however, those post–middle Eocene benthic foraminiferal assemblages occur at the upper Eocene from the Fuente Caldera section (Fig. 5).

Sediments from the Umbrian "Scaglia" (Italy; including the Massignano section) are lithologically and sedimentologically similar to these of to the Fuente Caldera section (Molina et al., 1986), and have benthic assemblages similar to those found at middle Eocene–Oligocene drill sites in the Atlantic and Pacific Oceans (Molina et al., 1986; Parisi and Coccioni, 1988; Nocchi et al., 1988; Coccioni and Galeotti, 2003). The middle Eocene to early Oligocene Umbrian faunas have been inferred to have been deposited at lower bathyal depths.

The Massignano section contains paleobathymetric indicators such as *Anomalinoides capitatus*, *Bulimina jarvisi*, *C. eocaenus*, *C. grimsdalei*, *H. ammophila*, *N. trümpyi* and *Planulina costata*, which all occur in the Fuente Caldera section, and indicate a lower–middle bathyal depth (Parisi and Coccioni, 1988; Coccioni and Galeotti, 2003). However, *Cibicidoides praemundulus*, which is the most abundant *Cibicidoides* species in the Fuente Caldera section, is absent in the Massignano section.

Coccioni and Galeotti (2003) established several discrete calibrated bio-events in the Massignano section: the general increase in abundance of *Oridorsalis* spp., *Gyroidinoides* spp., and *G. subglobosa* close to the last occurrence (LO) of *N. trümpyi*; the decrease in abundance of buliminids, also reported by Miller et al. (1985) and Thomas (1992); and a remarkable bloom of bolivinids just below the E/O boundary. We have not observed the buliminid crisis in the Fuente Caldera section. In the Umbrian sections, two acmes of bolivinids (mainly *B. antegressa* group) occur at the middle/upper Eocene and E/O boundaries. We observed a small acme (up to 6.5%) of *B. antegressa* at the E/O boundary, but total bolivinids do not reach percentages that are higher than background. *B. antegressa* is considered by Tjalsma (1983) and Wood et al. (1985) as appearing at the E/O boundary, but we have recorded it before the E/O, in agreement with Miller and Katz (1987a) and Holbourn et al. (in press). The extinction of *N. trümpyi* marks the E/O boundary in the abyssal zone AB7 (Berggren and Miller, 1989), although its last appearance locally may occur below the E/O boundary, and its relative abundance commonly starts to decrease in the middle Eocene (e.g., Tjalsma and Lohmann, 1983; Tjalsma, 1983; Miller et al., 1985, 1992; Thomas, 1998), as also occur in Fuente Caldera where it shows its LO at sample Fcal 2B (Fig. 4). Berggren and Miller (1989) recorded *N. trümpyi* as intermittently ranging through bathyal zone BB3. These authors defined the bathyal zone boundary BB4/BB5 by the LO of *Cibicidoides truncanus*. Coccioni and Galeotti (2003) recorded the LO of *C. truncanus* in the upper part of Zone P15 (Berggren et al., 1995) so, they established its LO in the western Tethys much earlier than in other sites. Our data support it since we have not found *C. truncanus* in the Fuente Caldera section.

We thus argue, in agreement with earlier workers (e.g., Miller and Katz, 1987a; Berggren and Miller, 1989; Thomas, 1990) that discrete first (FOs) and last occurrences (LOs) of smaller benthic foraminifera are not coeval over long distances, although the benthic faunal record from the Fuente Caldera section is correlated with other geographic regions. Furthermore, many deep-sea species are rare and thus have discontinuous occurrences (Thomas, 1985; Kawagata et al., 2005).

We recorded *B. trinitatensis* above the E/O boundary (Fig. 4), although this species is reported to have gone extinct at this boundary (e.g., Holbourn et al., in press). We do not extend the range of this species into the Oligocene, because we consider it to be in one group

Plate 2. Benthic foraminifera. 1, *Angulogerina muralis*, sample Fcal-9,19-1560-160AP; 2, *Bolivina byramensis*, sample Fcal-9,6; 3, *Bolivinoides crenulata*, sample Fcal-9,12-260-300K; 4, *Bolivinoides floridana*, sample Fcal-9,11-100-135F; 5, *Brizalina antegressa*, sample Fcal-17; 6, *Bulimina trinitatensis*, sample Fcal-03-(-13,5); 7, *Bulimina trinitatensis*, sample Fcal-9,15-810-840W; 8, *Globocassidulina subglobosa*, sample Fcal-8,4; 9, *Asterigerina brencei*, sample Fcal-9,6; 10, *Cibicidoides mundulus*, sample Fcal-9,11-100-135F; 11, *Cibicidoides mundulus*, sample Fcal-9,02; 12a–b, *Cibicidoides praemundulus*, sample Fcal-9,02; 13, *Gyroidinoides girardanus*, sample Fcal-8,4; 14a–c, *Nuttallides trümpyi*, sample Fcal-8,4; 15, *Oridorsalis umbonatus*, sample Fcal-9,11-100-135F; 16, *Osangularia mexicana*, sample Fcal-8,4; 17, *Anomalinoides semicribratus*, sample Fcal-8,4; 18, *Pleurostomella brevis*, sample Fcal-9,19-1560-160AP; 19, *Stilostomella subspinosa*, sample Fcal-9,6; 20, *Pseudocalvulina* sp. B, sample Fcal-15; 21, *Pseudoclavulina trinitatensis*, sample Fcal-8; 22, *Reticulophragmium amplectens*, sample Fcal-20; 23, *Paratrochamminoides* sp., sample Fcal-18-I; 24, *Vulvulina spinosa*, sample Fcal-15; 25, *Karreriella bradyi*, sample Fcal-03-(-17). All scale bars: 100 μm.

with *B. impendens* (middle Eocene through early Miocene; Van Morkhoven et al., 1986; Holbourn et al., in press), and the species appear to intergrade (Clark and Wright, 1984).

A. muralis, which is documented from the Eocene (e.g., Ortiz and Thomas, in press), is a common and distinctive species in the Fuente Caldera section, with a LO close to the E/O boundary (sample Fcal-13,5).

R. amplectens is most abundant in the middle Eocene (Kaminski and Gradstein, 2005), and defines several zones (e.g., Geroch and Nowak, 1984; Kaminski et al., 1989). In the Fuente Caldera section, we recorded the species in the latest Eocene samples (Fig. 4). Parisi and Coccioni (1988) recorded an increase in the abundance of agglutinated foraminifera and, in particular, large *Cyclammina* just below the E/O boundary. *Cyclammina* and *Reticulophragmium* can be confused, but the specimens presented by Parisi and Coccioni (1988) are not considered *R. amplectens*.

Pseudoclavulina trinitatensis is a distinct agglutinated foraminifer, with a LO at the E/O boundary in Trinidad (Bolli et al., 1994). In the Fuente Caldera section, it may also have a LO at the E/O boundary, but we found one broken specimen higher. *Pseudoclavulina* sp. B is a coarsely agglutinated species, which peaks in its relative abundance close to the E/O boundary.

Agglutinated foraminifera have low relative abundances, which fluctuate little through the section. The agglutinated benthic assemblages show a mixture of organically cemented taxa, such as *Rhabadammina* spp., *Rhizammina* spp., *Recurvoides* spp., and *Paratrochamminoides* spp., and calcareous-cemented species, such as *Karreriella* spp.

4. Discussion

If a meteorite impact caused foraminiferal extinctions, the levels of impact and extinction must coincide. To establish a cause–effect relationship that coincidence is necessary. The planktic foraminiferal biostratigraphy indicates that the Ni-rich spinel anomalies are in the lower part of the *G. index* Biozone, following the biozonation of Gonzalvo and Molina (1992), which corresponds to the lower part of Biozone P16 (sensu Blow, 1979) and to the upper part of the Biozone P15 (sensu Berggren et al., 1995). This level corresponds to the middle Priabonian, correlates with the Massignano major anomaly and suggest an age of 35.5 Ma (Montanari et al., 1993; Pierrard et al., 1998).

The planktic foraminifera extinction event at the *C. lazzarii* Biozone peaks at the E/O boundary (33.9 Ma), and thus does not coincide with the impact layers in the lower part of the *G. index* Biozone (35.5 Ma). Impact layers found in other sections (Site 94 and Site 292) in the upper part of the *G. index* Biozone (Molina et al., 1993; Montanari et al., 1993; Poag et al., 2003) have not been found in the Fuente Caldera section, possibly because the sampling is not detailed enough, but these events also predate the planktic extinction.

The series of Ni-rich spinel horizons recorded at Fuente Caldera likely results from the erosion, local transport and redeposition by turbiditic currents of a unique and single impact event, mainly because the chemical composition of the Ni-rich spinel in the three layers is very similar (Robin and Molina, submitted for publication).

In the Fuente Caldera section, benthic foraminiferal species turnover and changes in faunal abundance were associated with the E/O boundary, and we found no changes at the level of impact evidence. The benthic foraminiferal assemblages show a slight rise in the heterogeneity (as reflected by the $H(s)$ index, Fig. 4), but the rise is not significant.

Infaunal species dominate epifaunal species, primarily because of the high abundance of bolivinids, which indicate a high input of organic matter to the sea floor, possibly associated with somewhat reduced bottom-water oxygenation (e.g., Murray, 1991; Gooday, 1994; Bernhard and Sen Gupta, 1999; Thomas et al., 2000). We suggest that the high diversity values and high relative abundances of bolivinids are products of the turbidites, which may have transferred organic matter laterally (Fontanier et al., 2005). High relative abundances of *O. umbonatus* and *Cibicidoides* spp. suggest that conditions overall were rather oligotrophic, with well-oxygenated bottom waters (Huang et al., 2002).

During the middle Eocene–Oligocene, high-latitude surface waters and global deep-waters cooled (e.g., Zachos et al., 1993). Global changes in benthic foraminiferal faunas occurred gradually over the late Eocene–early Oligocene (Thomas et al., 2000). In southern high latitudes, productivity may have increased (e.g., Thomas, 1989; Hallock et al., 1991; Prothero and Berggren, 1992 eds.; Diester-Haass, 1995; Hartl et al., 1995), whereas in equatorial oceans, productivity did not change or decreased (Schumacher and Lazarus, 2004). At the Fuente Caldera section, situated at a low latitude (close to 30°N), we did not observe a significant change in the productivity across the E/O boundary.

At the Fuente Caldera section, the turnovers did not coincide with the extraterrestrial impact levels, but with the climatic cooling at the E/O boundary. No single species extinction or first appearance coincides with the impact layers (Figs. 2 and 4), and no indices show a significant anomaly (Figs. 3 and 5).

What was the cause of the foraminiferal turnovers in the late Eocene? The transition from the global warmth of the early Eocene "greenhouse" climate to the glaciated state of the Oligocene is one of the most significant changes in the Cenozoic evolution of Earth's climate (e.g., Zachos et al., 2001; Tripati et al., 2005). The cooling might have been triggered by the opening of the Drake Passage and the establishment of the circumantarctic current (Livermore et al., 2005), although others suggest that the opening of Southern Ocean gateways alone could not have caused major changes in meridional heat transport and show that abrupt cooling could have resulted from a steady decline in atmospheric CO_2 (DeConto and Pollard, 2003; Huber et al., 2004; Tripati et al., 2005) and that the timing of opening of Drake Passage is not well constrained (Barker and Thomas, 2004). The cause of cooling remains controversial, and some (Vonhof et al., 2000) suggest that the cooling might have been accelerated by the meteorite impacts at 35.5 Ma, more than a million years earlier. However, foraminiferal isotope data (Tripati et al., 2005) indicate that the cooling started to accelerate before this event, at the middle–late Eocene transition (41.5 Ma) and after the event, at the E/O boundary (33.9 Ma).

Our data on planktic and small-benthic foraminifera at the Fuente Caldera section show that layers containing evidence for an impact do not coincide with evidence for faunal turnover or climatic cooling; thus, a cause–effect relationship cannot be established. The main planktic and benthic foraminiferal turnovers occur at the E/O boundary and are most likely the result of the cooling that peaks in the early Oligocene.

5. Conclusions

Layers containing meteorite impact evidence (Ni-rich spinel) have been found at Fuente Caldera section, Spain. According to planktic foraminiferal biostratigraphy, the spinel anomalies are in the lower part of the *G. index* Biozone of the Gonzalvo and Molina (1992) biozonation, which correspond to the lower part of the P16 Biozone (sensu Blow, 1979) and to the upper part of the P15 Biozone, sensu Berggren et al. (1995), corresponding to the late Eocene, middle Priabonian (35.5 Ma). Data on small benthic foraminifera indicate deposition in the lower bathyal zone, and the spinel anomalies are in the middle part of the BB4 benthic foraminiferal zonation (= AB7) of Berggren and Miller (1989). Turnovers of planktic and benthic foraminifera occur at the E/O boundary and not at the impact layer, which occurred more than one million year earlier. Consequently, in this case a cause–effect relationship between impacts and extinctions cannot be established for the late Eocene events, and the stepwise mass extinction pattern which had been suggested to have been caused by comet showers (Hut et al., 1987), was an artifact of poor correlations. In contrast to the catastrophic mass extinction event at the Cretaceous/Tertiary boundary, meteorite impact in the late Eocene did not cause the extinction of foraminifera, probably because the impacts were relatively smaller, as suggested by the size of the coeval craters. The most plausible cause of extinctions at the E/O boundary is the significant cooling, which eliminated most of the warm- and surface-dwelling foraminifera.

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