



# Effects of the Oligocene climatic events on the foraminiferal record from Fuente Caldera section (Spain, western Tethys)

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## ABSTRACT

An expanded succession of upper Priabonian (upper Eocene) to Chattian (upper Oligocene) hemipelagic marls interbedded with turbiditic sandstone layers is present in the Spanish Fuente Caldera section (Subbetic Zone, western Tethys). We analyzed foraminifera from this section quantitatively, with emphasis on biostratigraphy and paleoecology.

Benthic foraminifera indicate an upper to possibly upper-middle bathyal depth of deposition for most of the studied section, with paleobathymetric analysis made difficult because of the common presence of shallow-water taxa, some reworked by turbidites and others epiphytic taxa, which may have been transported by turbidites or by floating plant material. We identified three major biotic and paleoenvironmental events. 1) The major planktonic foraminiferal turnover across the Eocene/Oligocene boundary, which includes several first and last occurrences as well as a decrease in the percentage of surface water-dwellers, possibly linked to global cooling. 2) A dramatic sea-level drop indicated by the presence of a 37-m-thick sequence of calcarenites (lower half of planktonic foraminiferal Zone O2, ~31.5 Ma) with abundant trace fossils and allochthonous foraminifera. This sea-level fall, which triggered erosion of material in shallow marine settings and transport by turbidity currents into the basin, apparently post-dated the major glacial expansion on the Antarctic continent (Oi1, 33.7 Ma), and predated the later major expansion (Oi2 through Oi2b, 27–30.5 Ma), thus may have been tectonically controlled. 3) A warming event starting in the Chattian (lowermost part of Zone O6, ~27.1 Ma), which could be correlated to the globally recognised Late Oligocene Warming Event, but apparently started somewhat earlier (~27.1 Ma as compared to 26.5 Ma).

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## 1. Introduction

The study of the Oligocene and Eocene epochs is of broad interest because this time corresponds to a transitional phase between the Paleogene greenhouse and Neogene icehouse climates. The Oligocene in particular is considered a period marked by large and abrupt climate changes, paleogeographic changes including the opening of the Tasmanian Gateway and Drake Passage, large fluctuations in the volume of the Antarctic Ice Sheet after its initiation in the earliest Oligocene, with related eustatic changes at orbital frequencies (e.g., Wade and Pälike, 2004; Pälike et al., 2006). The formation of cold deep water in the Southern Ocean and/or in the northern Atlantic may have started in the earliest Oligocene (Kennett, 1977; Lawler and Gahagan, 2003; Miller et al., 1991, 2005; Zachos et al., 2001), but the timing and pattern of these circulation changes is under vigorous debate (e.g., Barker and Thomas, 2004; Scher and Martin, 2004; Via and Thomas,

2006; Thomas and Via, 2007; Thomas et al., 2008). This transitional period in Earth's history was characterised by strong, short-term fluctuations between warmer and colder intervals that have been recognised and at least tentatively correlated around the world (Zachos et al., 2001). These climate fluctuations occur at orbital frequencies (Wade and Pälike, 2004; Coxall et al., 2005; Pälike et al., 2006), with some of the more extreme cold events (formerly called Oi-events) occurring at low obliquity.

Although traditionally it has been argued that glaciation in Antarctica started much earlier than in the northern hemisphere, leading to the existence of an unusual world with continental ice sheets only in the southern hemisphere (Zachos et al., 2001), there is more recent evidence that at least some level of glaciation in the Northern Hemisphere started at about the same time as in the southern hemisphere, during the middle Eocene to early Oligocene (Moran et al., 2006; Eldrett et al., 2007; Tripathi et al., 2005, 2008), or even slightly earlier (St. John, 2008).

In order to trace global paleoenvironmental evolution across the Oligocene, it is important to investigate sites and sections that are

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diverse regionally and bathymetrically. Microfossils are a useful tool for such paleoenvironmental reconstructions: benthic foraminifera are excellent indicators of ocean productivity and/or oxygenation at the sea floor (e.g., Van der Zwaan et al., 1999; Jorissen et al., 2007), whereas planktic foraminifera will provide information on biostratigraphy as well as on paleoenvironmental conditions in the water column (e.g., Kucera, 2007).

Oligocene benthic foraminifera from the Atlantic (Katz et al., 2003) and the North Sea Basin (Van Simaey, 2004; De Man and Van Simaey, 2004; Van Simaey et al., 2004, 2005) have been studied in detail. In contrast, no studies of benthic foraminifera and paleoenvironmental turnover across the Oligocene are available for the Subbetic Zone (western Tethys), an important region because of its paleogeographical location (Fig. 1) intermediate between the North Atlantic and the Italian sections where the Global Stratotype Sections and Points (GSSPs) for the base of the Oligocene and the Miocene are located. The Oligocene Stratigraphy Working Group recently proposed the Monte Cagnero section (pelagic Scaglia Cinerea Formation, Umbria–Marche region, central Italy) as a candidate for the GSSP of the Rupelian/Chattian (R/C) boundary (Coccioni et al., 2008).

An expanded Eocene (Priabonian) to Oligocene (Chattian) succession is present at Fuente Caldera (Subbetic Zone, western Tethys; Fig. 1; Molina et al., 1986). Major planktic and benthic foraminiferal turnover at the E/O boundary in this section has been documented (Molina et al., 1993, 2006), but the Oligocene part of the section has not been studied, so far. We present a quantitative analysis of benthic and planktic foraminiferal assemblages from the Oligocene part of the Fuente Caldera section (Southern Spain) in order to establish the

biostratigraphical framework of the Oligocene, infer paleoenvironmental turnover and define Oligocene climatic events.

## 2. Materials and methods

The Fuente Caldera section is located in northern Granada province, Southern Spain (Fig. 1), within the median Subbetic realm of the Betic Cordillera, in a marine subsidence trough during the Eocene. The sequence of the Fuente Caldera section corresponds to the Cañada Formation of the Cardela Group (Comas et al., 1984–85), the formal lithostratigraphical units for Eocene–Oligocene median Subbetic sediments.

The Fuente Caldera section consists of a 460-m-thick sequence of hemipelagic marls interbedded with turbiditic sandstone layers, spanning the Priabonian (upper Eocene) through Chattian (upper Oligocene). The hemipelagic marls contain abundant planktic foraminifera, calcareous nannofossils, common small benthic foraminifera, some ostracodes, and rare fragments of echinoids and molluscs. The foraminifera were sampled in the at least partially autochthonous marls and are fairly well preserved. The calcareous sandstone strata contain abundant larger foraminifera reworked from the shelf. Two olistostromes have been identified in the studied section, one 81 to 102 m above the E/O boundary, the other 197 to 205 m above the E/O boundary (Figs. 3 and 4). These olistostromes have been previously interpreted as the result of tectonic activity in the Paleogene Subbetic trough (Comas et al., 1984–85).

A 37-m-thick interval (167–132 m above the E/O boundary) is intensively burrowed, with *Skolithos*-type ichnofacies, indicative of

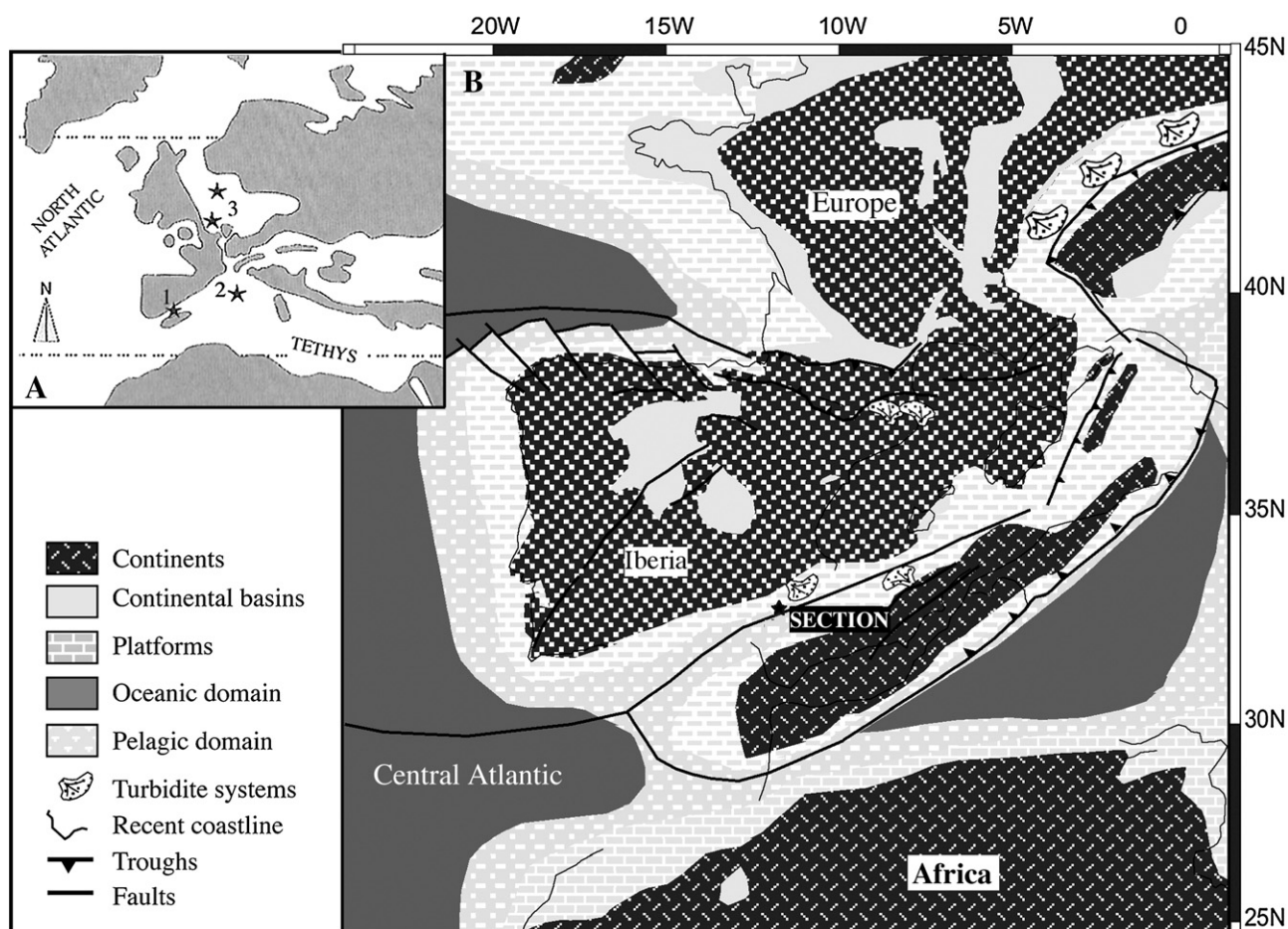


Fig. 1. A, Paleogeographic reconstruction of the European continent during (A) mid Oligocene times and (B) the Eocene/Oligocene transition. 1, Fuente Caldera section; 2, central Italian sections; 3, southern and central North Sea Basin successions. Modified from Andeweg (2002) and Van Simaey (2004).

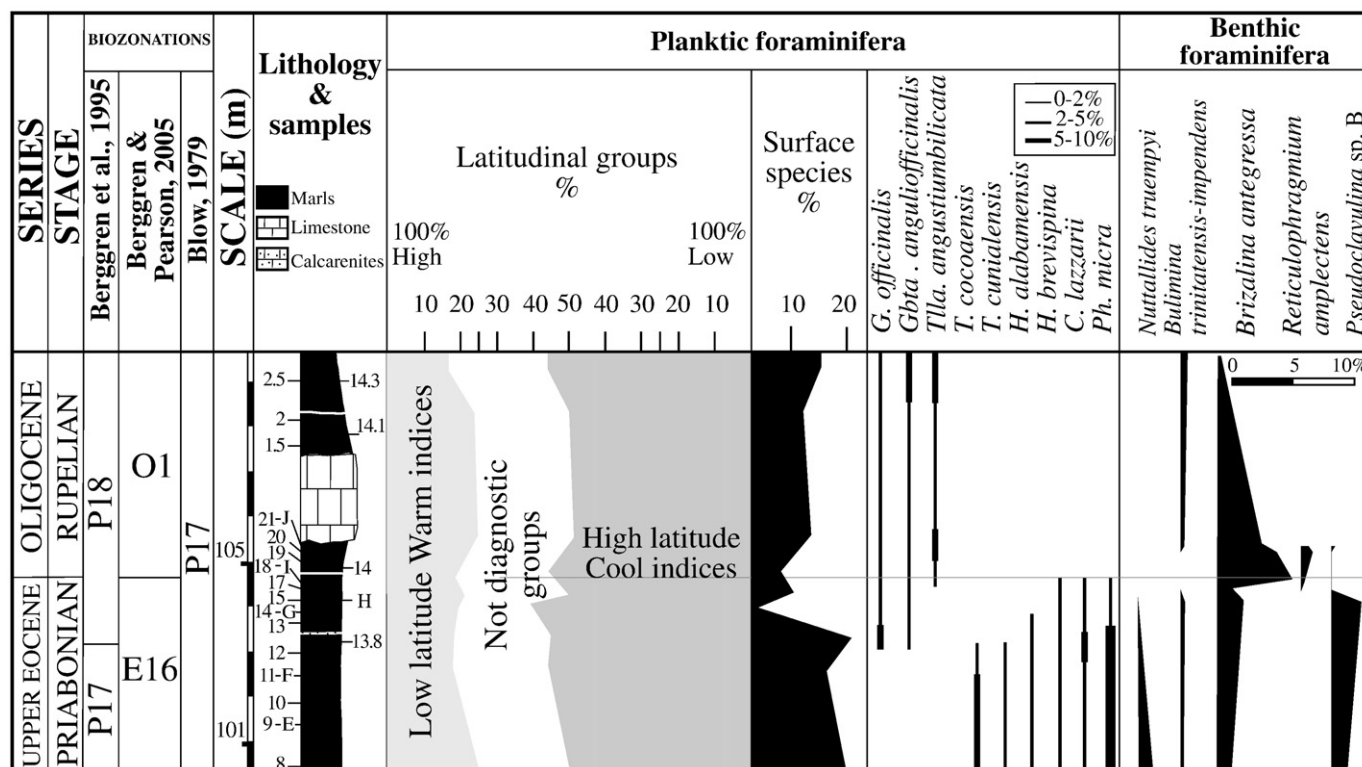


Fig. 2. Planktic and benthic foraminiferal turnover across the Eocene/Oligocene boundary at Fuente Caldera. Modified from Molina et al. (2006). G. = *Globigerina*; Gbta. = *Globoturborotalia*; Tlla. = *Tenuitellina*; T. = *Turborotalia*; H. = *Hantkenina*; C. = *Cribrohantkenina*; Ph. = *Pseudohastigerina*.

high sedimentation rates. Similar trace fossils have been attributed to thalassinidean crustacea in Oligocene and Miocene gravity-flow deposits from California (Föllmi and Grimm, 1990). In agreement with these authors, we suggest that this sediment interval was strongly burrowed by “doomed pioneers”, which are able to survive turbulent transport. We speculate that these organisms were transported from shallow areas to deeper parts of the basin during a succession of turbidite events, each one creating ephemeral ecological conditions that allowed recolonization of the seafloor by crustacean doomed pioneers.

The foraminiferal turnover from the Priabonian through the E/O boundary was documented by Molina et al. (2006). Apart from a short note on the biostratigraphy of the whole section (Comas et al., 1984–85), no studies on Oligocene foraminifera have been carried out. The Oligocene is very well represented at Fuente Caldera, corresponding to a 330-m-thick interval. We quantitatively analyzed the planktic and small benthic foraminifera in 98 samples from the uppermost Eocene and Oligocene sediments (Figs. 2 and 3). Samples were disaggregated in water with dilute  $H_2O_2$ , washed through a 63  $\mu m$  sieve, and dried at 50 °C. The quantitative and taxonomic studies are based on representative splits of approximately 300 specimens of benthic foraminifera and 300 of planktic foraminifera of the >100  $\mu m$  fraction, obtained with a modified Otto micro-splitter. The remaining residue was searched for rare species.

The planktic/benthic (P/B) ratio was calculated in all samples. For the benthic foraminiferal assemblages, we calculated the percentage of calcareous and agglutinated foraminifera, as well as the Fisher- $\alpha$  and the H(S) Shannon–Weaver indices as proxies for diversity and heterogeneity of the assemblages. Morphotypic analysis was performed following Corliss (1985), Jones and Charnock (1985) and

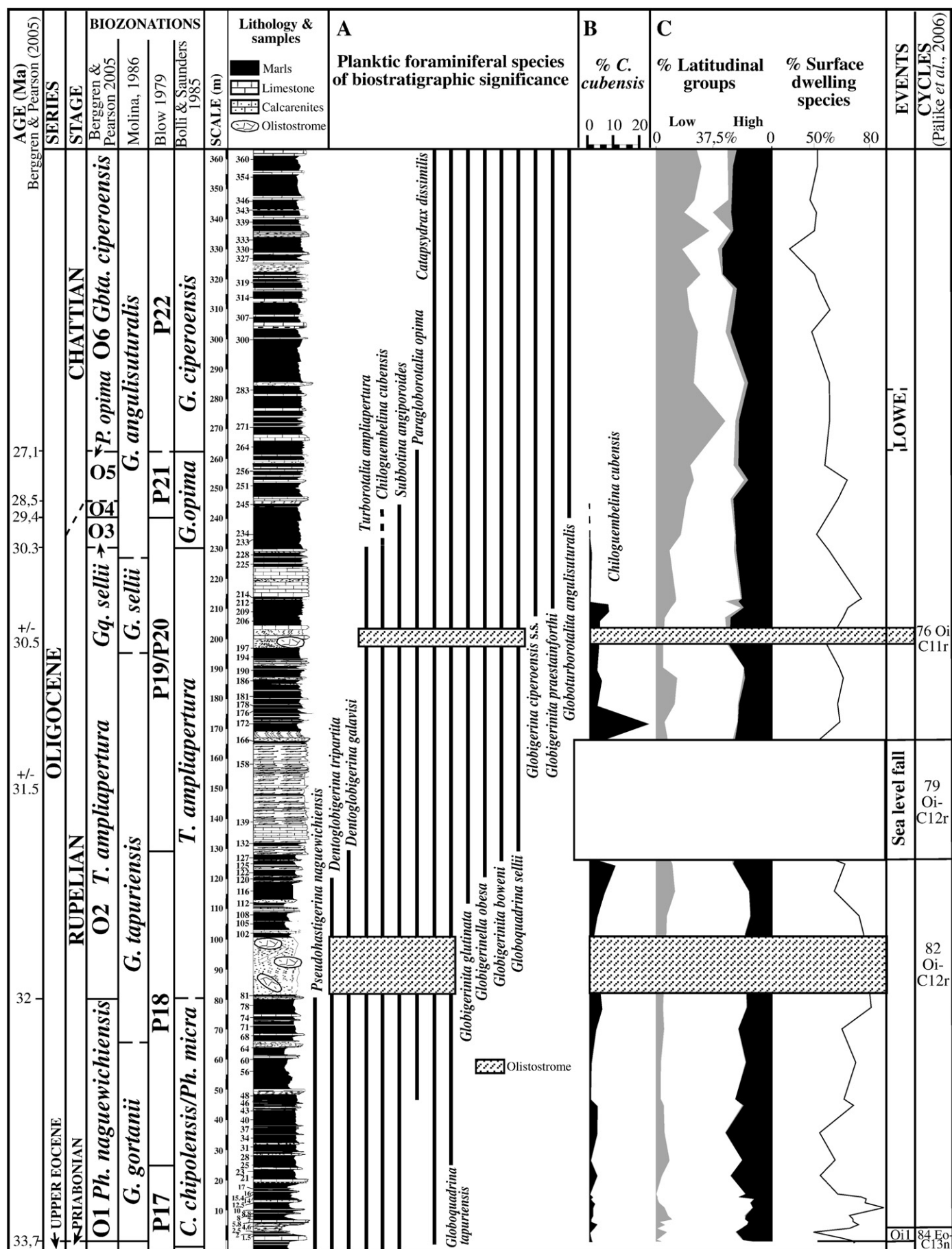
Corliss and Chen (1988). In order to obtain information on local environments, and given the abundance of reworked benthic foraminifera (neritic taxa as well as neritic epiphyte species) in the studied section, these transported taxa were subtracted from the benthic foraminiferal counts (Table 3, Supplementary material) to calculate the percentage of infaunal and epifaunal morphogroups and the diversity indices. Similarly, the relative abundance of *in situ* species was calculated after subtracting that of the reworked neritic and epiphytic foraminifera.

Based on the paleoclimatical and paleoecological significance of planktic foraminifera (see Molina et al., 2006, and references therein), all taxa were grouped into surface-, intermediate-, and deep-dwelling forms (corresponding to mixed layer, thermocline and sub-thermocline forms, respectively; e.g., Boersma et al., 1987; Premoli Silva and Boersma, 1988, 1989; Keller et al., 1992; Coxall et al., 2000; Spezzaferri et al., 2002) according to their position in the water column (Fig. 3; Table 1), and into high, high-medium, medium-low and low latitudes (e.g., Pearson et al., 2006; Sexton et al., 2006; Wade et al., 2007) according to their latitudinal distribution (Fig. 3; Table 2).

We followed the biozonal definitions according to Berggren et al. (1995), updated by Berggren and Pearson (2005): we used the last occurrence (LO) of *Pseudohastigerina naguewichensis* to recognise the O1/O2 zonal boundary, the LO of *Turborotalia ampliapertura* for the O2/O3 zonal boundary, the first occurrence (FO) of *Globigerina angulituralis* for the O3/O4 zonal boundary, and the LO of *Paragloboborotalia opima* for the O5/O6 zonal boundary (Fig. 3). We used the bathymetric division as designed in Van Morkhoven et al. (1986): neritic (0–200 m depth), upper bathyal (200–600 m), middle bathyal (600–1000 m), lower bathyal (1000–2000 m; abyssal >2000 m).

Fig. 3. A, Distribution of planktic foraminiferal species with biostratigraphical significance across the Oligocene section of Fuente Caldera; B, Relative abundance of *Chiloguembelina cubensis*; C, Distribution and relative abundance of planktic foraminiferal latitudinal groups and of surface-dwelling species. LOWE = Lower Oligocene Warming Event. Ph. = *Pseudohastigerina*; T. = *Turborotalia*; Gq. = *Globoquadrina*; P. = *Paragloboborotalia*; Gbta. = *Globoturborotalia*; G. = *Globigerina*; C. = *Cassigerinella*.





### 3. Paleobathymetry

Oligocene benthic foraminiferal assemblages are dominated by calcareous taxa (95–99%) in all samples, indicating deposition well above the calcite compensation depth. We identified common bathyal taxa (e.g., *Brizalina antegressa*, *Bulimina alazanensis*, *Bulimina impendens*, *Cibicidoides barnetti*, *C. mundulus*, *Gyroidinoides* spp., *Hanzawaia ammophila*, *Osangularia* spp., abundant bolivinids) and very few abyssal taxa such as *Cibicidoides grimsdalei* and *Vulvulina spinosa* (Tjalsma and Lohmann, 1983; Wood et al., 1985; Nocchi et al., 1988;

Katz et al., 2003). However, neritic taxa including *Pararotalia audouini*, *Quinqueloculina* spp., *Reusella* spp., *Elphidium* spp. and such warm water taxa as *Nodobolivinella jhingrani*, *Rectobolovina costifera* and *Tubulogerina vicksburgensis* are common to abundant in many samples through the section. These are probably reworked taxa (e.g., Murray, 1991, 2006) and transported downslope by turbidity currents. In addition, taxa considered to live epiphytically (e.g., *Cibicides lobatulus*, *Planorbulina mediterraneensis*, asterigerinids, and *Rosalina globularis*) are common to abundant in many samples. These specimens could have been transported by turbidity currents as well, but might also have been brought in floating on plant material, and being deposited when this floating algal matter decayed.

The data indicate an upper- to upper-middle bathyal depth of deposition for most of the studied section, with a strong influence of turbidity currents. This paleodepth is supported by the high diversity and heterogeneity of the benthic assemblages (Fig. 4), and the high P/B ratio (>90%) in all samples.

### 4. Paleoenvironmental reconstruction based on foraminifera

The percentage of reworked and epiphytic benthic foraminifera is very high throughout the studied section, consistent with the paleogeographical location of Fuente Caldera along a very steep continental slope, with deep-water settings very close to the coastal photic zones (Fig. 1). This scenario would account for the transport of abundant epiphyte species into deep-water settings, as well as for the common occurrence of shallow-water, warm species such as *N. jhingrani*, *R. costifera* and *T. vicksburgensis*. *In situ* benthic foraminiferal assemblages (obtained subtracting all reworked neritic and epiphyte/neritic species from the benthic foraminiferal counts in Table 3; Fig. 4) are diverse and dominated by infaunal morphogroups (e.g., *Tortoliplectella rhomboidalis*, *Sigmavirgulina tortuosa*, *Bolivina crenulata*, *Globocassidulina subglobosa*, *Oridorsalis umbonatus*) throughout the section, suggesting relatively eutrophic conditions at the seafloor (e.g., Jorissen et al., 1995, 2007).

The beginning of the Oligocene is marked by a faunal turnover at the E/O boundary, including the first and last occurrence of several benthic (LO *Nuttallides truempyi*) and planktic (LO *Turborotalia cocoaensis*, LO *T. cunialensis*, LO *Hantkenina alabamensis*, LO *H. brevispira*, LO *Cribro-hantkenina lazzarii*, LO *Pseudohastigerina micra*) foraminiferal species at or a few tens of cm below the boundary (Fig. 2). The planktic foraminiferal turnover has been related to the significant cooling starting in the latest Eocene (e.g., Wade and Pearson, 2008), which triggered glaciation in Antarctica and eliminated most of the warm and surface-dwelling foraminifera (Molina et al., 2006). This cooling period may correspond to the Oi1 glaciation, which in the astronomical naming scheme based on the 450-ky cycle of Earth's eccentricity corresponds to cycle 84<sub>Eo-C13n</sub> (Pälike et al., 2006). Higher in the section (upper half of Zone O1, lower Rupelian, 56 to 64 m above the E/O boundary), benthic foraminiferal assemblages are dominated by infaunal morphogroups (81–93% of the assemblages), especially by bolivinids such as *Bolivina crenulata* (60% of the assemblages), *B. antiqua*, *B. mississippiensis*, *Tortoliplectella rhomboidalis*, and others. Abundant bolivinids indicate high organic carbon flux rates to the seafloor in the Recent oceans, and dominance may indicate low-oxygen conditions (e.g., Thomas et al., 2000). Abundant bolivinids, however have also been reported from environments with well-oxygenated bottom waters (e.g., Fontanier et al., 2005; Jorissen et al., 2007). Since we found no independent evidence (e.g., laminated sediment, high organic carbon levels) for low-oxygen conditions, we suggest that the dramatic increase in the percentage of bolivinids was the response of the benthic communities to a local increase in the flux of organic matter to the seafloor. The high percentage of surface-dwelling planktic foraminifera in this interval suggests increased surface temperatures, as supported by the decreased percentages of high latitude planktic foraminiferal groups (Fig. 3). Possibly, relative high sea levels during this warm interval led to flooding

**Table 1**  
Planktic foraminiferal species grouped according to their position in the water column

<b>Surface-dwelling</b>		
<i>Acarinina? medizai</i> (4)	<i>Cassigerinella</i> (8)	<i>Globigerina officinalis</i> (3), (5)
Small acarininids (3)	<i>Cassigerinella chipolensis</i> (5)	<i>Globigerina praebulloides</i> (2), (3)
<i>Catapsydrax martini</i> (4)	<i>Chiloguembelina cubensis</i> (5)	<i>Globoturborotalita ouachitaensis</i> (4)
<i>Dentoglobigerina globularis</i> (6)	<i>Guembelitra</i> (= <i>Jenkinsina</i> ) (8)	<i>Globoturborotalita fariasi</i> (5)
<i>Globoquadrina venezuelana</i> (6)	<i>Globigerinita glutinata</i> (8), (9)	<i>Globoturborotalita anguliofficialis</i> (2)
<i>Subbotina gortanii</i> , lower Oligocene (3)	<i>Globigerinita incrusta</i>	<i>Globigerina ciperoensis</i> (8)
<i>Turborotalia ampliapertura</i> (3), (5)	<i>Pseudohastigerina barbadoensis</i> (5)	<i>Globoturborotalita angulisuturalis</i> (7)
<i>Turborotalia increbescens</i> (5)	<i>Pseudohastigerina nagewichensis</i> (5)	<i>Globoturborotalita woodi</i> (1), (2)
<i>Turborotalia euapertura</i> (6)	<i>Pseudohastigerina micra</i> (5)	<i>Turborotalita carcoselleensis</i> (11)
<i>Turborotalia cerroazulensis</i> (4)	<i>Tenuitella</i> (1), (3)	<i>Turborotalita quinqueloba</i> (9)
<i>Turborotalia cocoaensis</i> (4)	<i>Tenuitellinata</i> (1)	
<i>Hantkenina alabamensis</i> (4)	<i>Tenuitellinata angustiumbilicata</i> (2)	
	<i>Tenuitellinata juvenilis</i> (10)	
<b>Intermediate-dwelling</b>		
<i>Dentoglobigerina galavisi</i> (3), (4)	<i>Catapsydrax unicavus</i> (4)	<i>Globigerinella obesa</i> (9)
<i>Dentoglobigerina globularis</i> (3)	<i>Globorotaloides quadrocameratus</i> (4)	<i>Globigerinella praesiphonifera</i> (11)
<i>Dentoglobigerina pseudovenezuelana</i> (4)	<i>Subbotina linaperta</i> (4)	<i>Chiloguembelina cubensis</i> (6)
<i>Dentoglobigerina tripartita</i> (3), (4)	<i>Subbotina angiporoides</i> (4)	<i>Streptochilus martini</i> (4)
<i>Dentoglobigerina yeguaensis</i> (4)	<i>Subbotina utilisindex</i> (4)	<i>Chiloguembelina</i> (3)
<i>Globoturborotalita woodi</i> (9)	<i>Subbotina eocaena</i> (6)	<i>Pseudohastigerina</i> (3)
<i>Paragloborotalia opima</i> (6)		
<i>Paragloborotalia pseudocontinua</i> (6)		
<b>Deep-dwelling</b>		
<i>Catapsydrax</i> (1), (3)	<i>Dentoglobigerina tripartita</i> (5), (4)	<i>Chiloguembelina ototara</i> (4)
<i>Catapsydrax dissimilis</i> (2)	<i>Dentoglobigerina pseudovenezuelana</i> (5)	<i>Dipsidripella danvillensis</i> (5)
<i>Catapsydrax unicavus</i> (2), (4)	<i>Globoquadrina</i> (1)	<i>Globorotalia</i> (1)
<i>Globorotaloides</i> (3)	<i>Globoquadrina venezuelana</i> (3)	<i>Paragloborotalia</i> (1)
<i>Globorotaloides</i> sp. (1)	<i>Subbotina angiporoides</i> (4)	<i>Paragloborotalia nana</i> (4), (5)
<i>Globorotaloides</i> sp2. (4)	<i>Subbotina corpulenta</i> (5)	<i>Paragloborotalia grifinoides</i> (5)
<i>Globorotaloides quadrocameratus</i> (4)	<i>Subbotina eocaena</i> (3), (5)	<i>Streptochilus</i> (8)
<i>Globoturborotalita gnaucki</i> (1)	<i>Subbotina gortanii</i> , upper Eocene (5)	<i>Streptochilus martini</i> (4)
	<i>Subbotina linaperta</i> (3)	<i>Turborotalita? laccadivensis</i> (1)
	<i>Subbotina utilisindex</i> (3)	<i>Tenuitella</i> (9)
		<i>Tenuitella gemma</i> (5)

(1) Spezzaferri (1995); (2) Pearson et al. (1997); (3) Spezzaferri et al. (2002); (4) Sexton et al. (2006); (5) Pearson et al. (2006); (6) Wade et al. (2007); (7) Spezzaferri (1994); (8) Chaisson and Leckie (1993); (9) Chaisson and Ravelo (1997); (10) Pearson et al. (2001); (11) Molina et al. (2006).

**Table 2**  
Planktic foraminiferal species grouped according to their latitudinal distribution

High latitude		High–medium latitude
<i>Catapsydrax dissimilis</i> (4)	<i>Globigerinita boweni</i>	<i>Dipsidripella danvillensis</i> (3)
<i>Subbotina angiporoides</i> (3)	<i>Globigerinita glutinata</i> (4)	<i>Globoturborotalita woodi</i> (1)
<i>Subbotina linaperta</i> (3)	<i>Globigerinita incrusta</i> (4)	<i>Paragloborotalia pseudocontinua</i> (1)
<i>Subbotina utilisindex</i> (3)	<i>Globigerinita glutinata</i> (4)	<i>Paragloborotalia incognita</i> (4)
<i>Globigerina praebuloides</i> (1)	<i>Tenuitella clemenciae</i> (1)	<i>Paragloborotalia acrostoma</i> (2)
<i>Globorotaloides eovariabilis</i> (3)	<i>Tenuitella neoclemenciae</i> (1)	
<i>Globorotaloides permicrus</i> (4)	<i>Tenuitella munda</i> (1)	
<i>Globorotaloides testarugosa</i> (1)	<i>Tenuitella gemma</i> (4)	
<i>Globorotaloides</i> sp. (4)	<i>Tenuitellina juvenilis</i> (5)	
Small acarininids (1)	<i>Turborotalita? laccadivensis</i> (1)	
	<i>Turborotalita? primitiva</i>	
Cosmopolitan, no diagnostic		Medium latitude, no diagnostic
<i>Acarinina? echinata</i> (3)	<i>Chiloguembelina cubensis</i> (3)	<i>Globigerinella obesa</i> (1)
<i>Acarinina? medizai</i> (3)	<i>Chiloguembelina ototora</i> (3)	<i>Globigerinella praesiphonifera</i> (1)
<i>Dentoglobigerina yeguaensis</i> (4)	<i>Globoquadrina venezuelana</i> (1)	<i>Globigerinita glutinata</i> (1)
<i>Globorotaloides quadrocameratus</i> (3)	<i>Globoquadrina tapuriensis</i> (1)	<i>Globigerinita incrusta</i> (1)
<i>Hantkenina primitiva</i> (3)	<i>Streptochilus martini</i> (3)	<i>Globigerinita praestainforthi</i> (1)
<i>Paragloborotalia continua</i> (4)	<i>Tenuitella evoluta</i>	<i>Globoturborotalita ottangiensis</i> (1)
<i>Turborotalia ampliapertura</i> (3)	<i>Tenuitella gemma</i> (3)	<i>Paragloborotalia semivera</i> (1)
<i>Turborotalia increbescens</i> (3)	<i>Tenuitella insolita</i> (3)	<i>Paragloborotalia siakensis</i> (1)
<i>Turborotalia euapertura</i> (1)	<i>Tenuitella liverovskae</i> (2)	<i>Tenuitellina juvenilis</i> (1)
<i>Turborotalia cerroazulensis</i> (3)	<i>Turborotalita carcoselleensis</i> (3)	<i>Tenuitellina</i> sp. (1)
Low–medium latitude		Low latitude
<i>Globigerina officinalis</i> (3)	<i>Cassigerinella chipolensis</i> (3)	<i>Acarinina? cijellii</i> (1)
<i>Globoturborotalita anguliofficialis</i> (3)	<i>Cribrorhantkenina inflata</i> (3)	<i>Cassigerinella chipolensis</i> (1)
<i>Globoturborotalita gnaucki</i> (3)	<i>Catapsydrax martini</i> (3)	<i>Dentoglobigerina globosa</i> (1)
<i>Globoturborotalita ouachitaensis</i> (3)	<i>Catapsydrax unicavus</i> (3)	<i>Dentoglobigerina globularis</i> (1)
<i>Globoturborotalita</i> sp. (1)	<i>Dentoglobigerina galavisi</i> (3)	<i>Dentoglobigerina pseudovenezuelana</i> (3)
<i>Paragloborotalia acrostoma</i> (1)	<i>Dentoglobigerina tripartita</i> (3)	<i>Globoquadrina selli</i> (1)
<i>Paragloborotalia nana</i> (3)	<i>Dentoglobigerina yeguaensis</i> (3)	<i>Globorotalia? denseconnexa</i> (1)
<i>Paragloborotalia opima</i> (1)	<i>Globorotaloides variabilis</i> (2)	<i>Globoturborotalita angulituralis</i> (1)
<i>Paragloborotalia griffinoides</i> (3)	<i>Hantkenina alabamensis</i> (3)	<i>Globigerina cipoensis</i> (1)
<i>Subbotina corpulenta</i> (3)	<i>Hantkenina nanggulanensis</i> (3)	<i>Globoturborotalita fariasi</i> (4)
<i>Subbotina eocaena</i> (3)	<i>Pseudohastigerina barbadoensis</i> (3)	<i>Jenkinsina samwelli</i> (1)
<i>Subbotina gortanii</i> (3)	<i>Pseudohastigerina micra</i> (3)	<i>Sphaeroidinellopsis</i> sp. (4)
<i>Subbotina jacksonensis</i> (3)	<i>Pseudohastigerina naguewichensis</i> (3)	<i>Turborotalita praequinquelo</i> (3)
<i>Turborotalia cunialensis</i> (3)	<i>Tenuitella pseudoedita</i> (1)	<i>Tenuitellina angustiumbilita</i> (5)
<i>Turborotalia cocoaensis</i> (3)	<i>Tenuitellina angustiumbilita</i> (1)	

(1) Spezzaferri (1995); (2) Kennett and Srinivasan (1983); (3) Pearson et al. (2006); (4) Spezzaferri (1994); (5) Li et al. (1992).

of the shelves and downslope transport of refractory organic matter, triggering increase in abundance of bolivinids.

As described above, a 37-m-thick sequence of strongly burrowed (*Skolithos*) calcarenites occurs ~130 to 167 m above the E/O boundary

(lower half of Zone O2; Fig. 3). This interval contains abundant benthic foraminifera typical for sublittoral to upper bathyal depths, such as *Pararotalia audouini*, *Quinqueloculina*, *Reusella spinulosa*, *Elphidium incertum*, *Protoelphidium sublaeve* (Murray, 1991, 2006), and epiphytes such as asterigerinids, *Neoconorbina terquemi*, *Cibicides refulgens*, *C. carinatus*, *C. lobatulus*, *Rosalina globularis* (Table 3). Discocyclinids (larger benthic foraminifera) occur below and within this interval, and the first occurrence of lepidocyclinids (also larger benthic foraminifera) occurs just above it. These specimens are transported from shallow settings (typically occurring within the photic zone), but show a similar biostratigraphic distribution to that reported from other Oligocene sections in the Subbetic Zone (Molina et al., 1988). Among planktic foraminiferal species, several first and last occurrences occur towards the base of this interval (Fig. 3). Molina et al. (1986) related these first and last occurrences to a sea-level fall that triggered erosion in shallow marine settings and transport of allochthonous elements, re-deposited in deeper (upper–middle bathyal) parts of the basin together with the autochthonous fauna.

This interval has an estimate age of ~31.5 Ma (Fig. 3), an approximate age because sedimentation rates cannot be linearly extrapolated because of the presence of turbidites and olistostromes. A ~31.5 Ma age may correspond to cycle 79<sub>O1–C12r</sub> of Pälike et al. (2006), a low intensity cooling that cannot be correlated to major, global events. Therefore, we suggest that this severe relative sea-level fall in the lower half of Zone O2 at Fuente Caldera (~130 to 167 m above the E/O boundary; Fig. 3) may have been tectonically controlled.

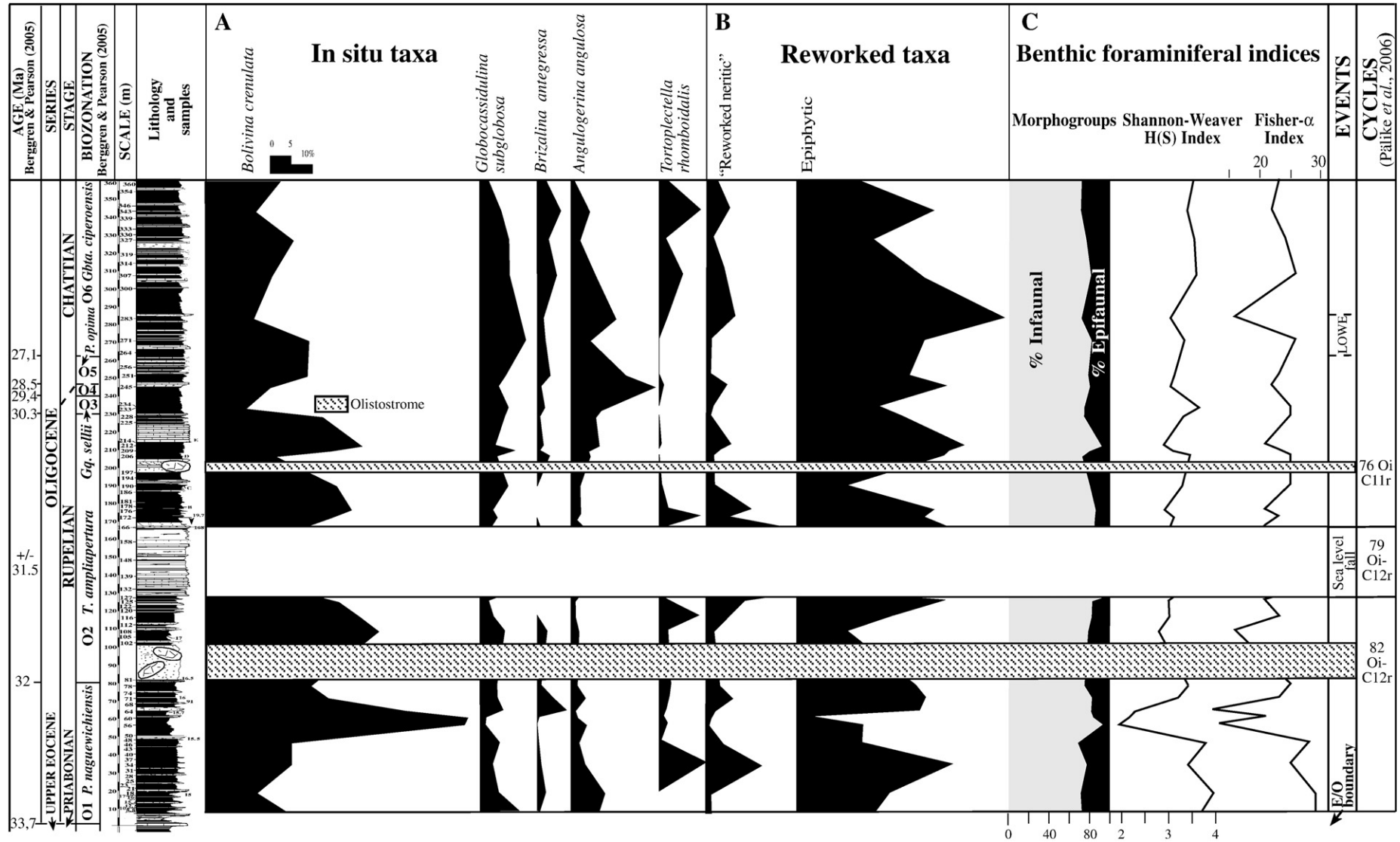
The upper half of Zone O2 is characterised by a maximum in the percentage of the biserial planktic form *Chiloguembelina cubensis* (Fig. 3), while bolivinids make up 50% of the benthic assemblages, suggesting high productivity in surface waters and eutrophic conditions at the seafloor. The percentage of epiphytic taxa strongly fluctuates through Zone O2 (Fig. 4).

Given the presence of common turbidites at Fuente Caldera, the thin section of sediment deposited during Zones O3 to O5 (Fig. 3) may be due to the presence of some unconformities. The lower part of Zone O6 is characterised by maximum percentages of epiphytic taxa, whereas the relative abundance of bolivinids decreases among the *in situ* assemblages (Fig. 4). Among planktic foraminifera, the high abundance of low latitude taxa (40% of the assemblages; Fig. 3) indicates increased sea surface temperatures, especially towards the base of Zone O6. This warming event starting in the Chattian, in the lowermost part of Zone O6 (~27.1 Ma) and to some extent extending through the remainder of the Oligocene, might represent the globally recognised Late Oligocene Warming Event (LOWE; Pekar et al., 2006; Villa and Persico, 2006), but apparently started somewhat earlier (~27.1 Ma as compared to 26.5 Ma) at Fuente Caldera. The LOWE induced a major sea-level rise (e.g., Van Simaey et al., 2004), possibly resulting in flooding of the shelves with transport of epiphytes to deeper parts of the basin.

## 5. The Rupelian/Chattian (R/C) boundary: biostratigraphic discussion

The last occurrence (LO) of *Chiloguembelina cubensis* has been traditionally used as the criterion for the recognition of the R/C boundary worldwide (e.g., Luterbacher et al., 2004), although sporadic occurrences of *C. cubensis* have been reported through the upper Oligocene (Leckie et al., 1993). Some authors (Stott and Kennet, 1990; Berggren, 1992) thus suggested that the chiloguembelinid extinction was time transgressive, from the early Oligocene at high latitudes to the middle and late Oligocene at low latitudes (Van Simaey et al., 2005). The species *C. cubensis* is very small, however, so that its LO may easily be affected by reworking, as argued by Poore et al. (1982) and Poore (1984). In view of these problems with the LO of *C. cubensis*, Berggren et al. (1995) used the last common occurrence (LCO) of *C. cubensis* rather than its LO to mark the R/C boundary, placed between planktic foraminiferal Zones O4 and O5 of Berggren and Pearson (2005), with a numerical age of 28.426 Ma





**Fig. 4.** Distribution and relative abundance of significant *in situ* (A) and reworked (B) benthic foraminiferal species across the Oligocene section of Fuente Caldera; C, Benthic foraminiferal indices (calculated in the *in situ* assemblages): infaunal and epifaunal morphogroups, Shannon–Weaver heterogeneity index, and Fisher- $\alpha$  diversity index. LOWE = Lower Oligocene Warming Event. Ph. = *Pseudohastigerina*; T. = *Turborotalia*; Gq. = *Globoquadrina*; P. = *Paragloborotalia*; Gbta. = *Globoturborotalia*.

according to Wade et al. (2007),  $28.3 \pm 0.2$  Ma according to Coccioni et al. (2008). Wade et al. (2007) document that the LCO of *C. cubensis* is synchronous at a number of ODP sites, and may be correlated directly or indirectly with Chron 10n.

The Oligocene Stratigraphy Working Group proposed the Monte Cagnero section (pelagic Scaglia Cinerea Formation, Umbria–Marche region, central Italy) as a candidate for the GSSP of the R/C boundary (Coccioni et al., 2008), and agree that the LCO of *C. cubensis* is a robust bioevent that can be used to recognise the O4/O5 (P21a/P21b) zonal boundary. Since the R/C boundary has not yet been formally defined, we tentatively placed the R/C boundary between the LO of *C. cubensis* (at 245 m above the E/O boundary) and its LCO at 234 m above the E/O boundary (Figs. 3 and 4).

## 6. Conclusions

The quantitative analysis of benthic and planktic foraminiferal assemblages from the upper to upper-middle bathyal Oligocene section of Fuente Caldera (Southern Spain) allowed us to define the biostratigraphy and describe changes in paleoenvironment during the Oligocene. Shallow-water taxa were common at Fuente Caldera, some reworked by turbidites, others epiphytic taxa which may have been transported by turbidites or floating plant material. We identified the following major biotic, paleoenvironmental and paleoclimatic events.

- The major foraminiferal turnover across the Eocene/Oligocene boundary includes several first and last occurrences of benthic and planktic foraminifera as well as a decrease in the percentage of surface-dwelling planktic foraminifera, pointing to decreased temperatures that may be linked to the Oi1 glaciation.
- The dominance of bolivinids in the upper half of Zone O1 (lower Rupelian) suggests a sudden increase in the nutrient flux to the seafloor. The high percentage of surface-dwelling planktic foraminifera indicates increased surface temperatures during this interval, possibly leading to a relative sea-level rise, flooding of the shelf, and downslope transport of refractory organic matter triggering the high abundance of bolivinids.
- Deposition of a 37-m-thick sequence of intensively burrowed (*Skolithos*) calcarenites in the lower half of Zone O2 represents a sea-level drop that triggered erosion at shallow marine settings and transport of allochthonous elements towards deeper (upper-middle bathyal) parts of the basin. The deposition of this sequence during several turbidite events was probably tectonically controlled.
- A warming event recognised in the lowermost part of Zone O6 (~27.1 Ma, Chattian), may reflect the globally recognised Late Oligocene Warming Event, but apparently started somewhat early at Fuente Caldera (~27.1 Ma as compared to 26.5 Ma at other locations). This interval was marked by an increase in the percentage of low latitude taxa and common transport of allochthonous, epiphytic benthic foraminifera. High relative sea level during this warm episode may have caused flooding of the shelves and transport of submerged aquatic vegetation and its epiphytes.

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## Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.palaeo.2008.08.006.

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