Micropalaeontological evidence for the late Oligocene Oi-2b global glaciation event at the Zarabanda section, Spain

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ABSTRACT

We present an integrated micropalaeontological study (using smaller and larger benthic foraminifera, planktonic foraminifera and calcareous nannofossils) of the late Oligocene from the Zarabanda section (western Tethys), in order to reconstruct the palaeoenvironmental turnover and to precisely establish the chronology of the palaeoclimatic events. Planktonic foraminifera show that the Zarabanda section is apparently continuous and spans the planktonic foraminiferal zones O5 (upper part), O6 and O7, and the calcareous nannofossil zones CP19b and CN1a (lower part). The quantitative analysis of smaller benthic foraminiferal assemblages enabled us to determine a middle–lower bathyal depth of deposition for most part of the section. The smaller benthic foraminifera show a bloom of neritic species, an increase in the percentages of cool-water species, a decrease of the Planktonic/Benthic ratio, generic richness, heterogeneity and diversity all around a 10 m thick succession of calcarenites, in the lower part of the planktonic foraminifera O6 Zone and the middle part of the calcareous nannofossil CP19b Zone. These changes coincide with the major turnover in the larger benthic foraminiferal assemblages; the last occurrence of *Eulepidina dilatata* and the first occurrence of *Nephrolepidina morgani*. These variations in the smaller and larger benthic foraminiferal assemblages may be associated with the major expansion of the Antarctic Ice Sheet at approximately 26.7 Ma, which is known as the Oi-2b global glaciation event.

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1. Introduction

The Oligocene climate was variable, with several cooling events (formerly known as Oi-events; Miller et al., 1991; Miller et al., 2008; Miller et al., 2009) caused by large fluctuations in the Antarctic Ice Sheet and the formation of cold deep water in the Southern Ocean (Zachos et al., 2001; Lawyer and Gahagan, 2003). The first and largest Oxygen isotope ($\delta^{18}O$) shift of the Oligocene is the Oi-1 glaciation event at approximately 33.5–33.7 Ma (Miller et al., 1998; Zachos et al., 2001; Eldrett et al., 2009). This event marks a profound global change from Paleocene–Eocene greenhouse to Oligocene icehouse climatic conditions, with development of the Antarctic ice sheet (Zachos et al., 2001; Coxall et al., 2005). The Oi-1 was followed by a second large $\delta^{18}O$ excursion at approximately 26.7 Ma, which is the Oi-2b glaciation event (Miller et al., 1998; Wade and Pälike, 2004; Flower and Chisholm, 2006; Pekar et al., 2006), also sometimes referred to as the "Oligocene Glacial Maximum" (e.g., Van Simaeys et al., 2005). Additionally, Haq et al. (1987) recognised a sea-level fall at approximately 30 Ma which may correspond to the Oi-2 glaciation event (e.g., Pekar and Miller, 1996; Miller et al., 1998; Wade and Pälike, 2004; Pekar et al., 2006; Coccioni et al., 2008). One additional increase in $\delta^{18}O$ values is recognised in the late Oligocene, e.g., the Oi-2c glaciation event (~25.1 Ma) (e.g., Pekar et al., 2006). Proposed driving mechanisms for the global climate change include Antarctica ice build-up and large reduction in atmospheric CO_2 from the high Eocene levels to low levels in the Oligocene (Coxall et al., 2005; Pagani et al., 2005). Development of the Antarctic ice sheet and the CO_2 atmospheric concentrations exerted a profound influence in global climate. Within these scenarios, the Oi-2b glaciation and warming events during the late Oligocene become important to understand the forcing mechanisms and for accurate climate reconstructions.

Previously a warming event was thought to have occurred in the late Oligocene, which was attributed to a combination of Antarctic ice volume decrease and deep-sea warming (Zachos et al., 2001). However, this was later recognised as an artefact caused by combining records from different locations (Cramer et al., 2009). De Man and Van Simaeys (2004) argued that warming occurred in the North Sea Basin directly after the Rupelian/Chattian boundary, e.g., considerably earlier than the late Oligocene warming events seen in Southern Ocean records. The extent, timing and even the existence of a warming event in the late Oligocene are therefore not well defined at present.

Oligocene benthic foraminiferal successions from various water depths have been analysed for the Atlantic Ocean (Katz et al., 2003),

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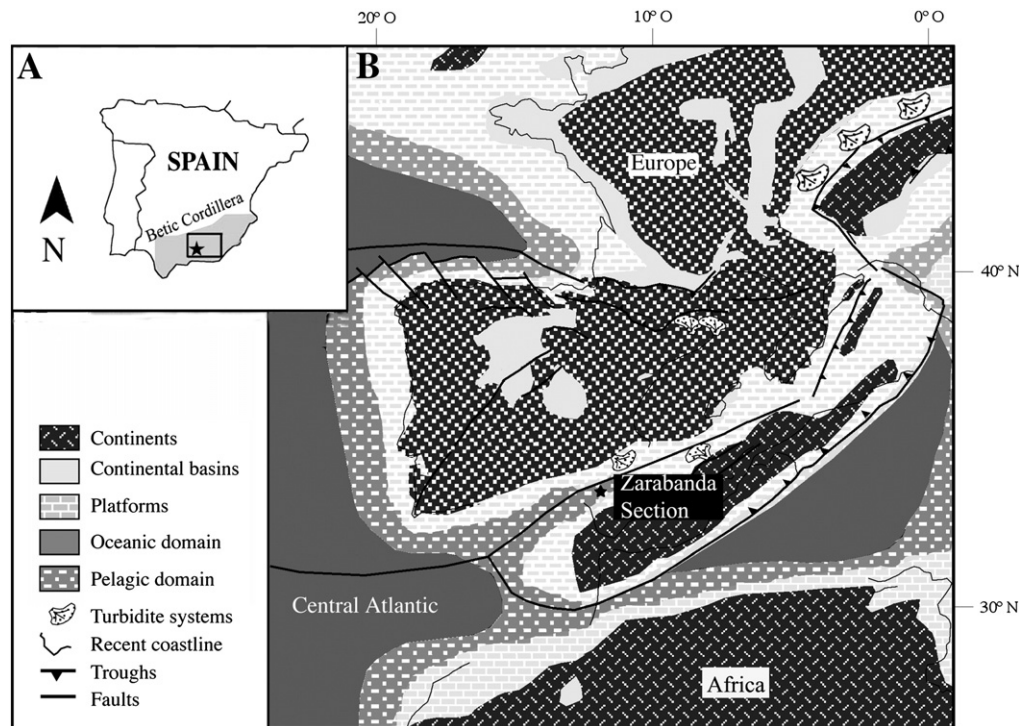E-mail address: rfenero@unizar.es (R. Fenero).

Fig. 1. A. Position of the Fuente Caldera section relative to modern geography. B. Palaeogeographic reconstruction of the European continent during the Eocene–Oligocene Transition, and location of the Zarabanda section (Betic Cordillera, southern Spain).
Modified from Andeweg (2002).

the Indian Ocean (Nomura, 1995), the eastern Equatorial Pacific Ocean (Takata and Nomura, 2005) and Weddell Sea (Thomas, 1992). Despite this, our knowledge of short-term fluctuations in the late Oligocene benthic foraminiferal assemblages remains limited, particularly within the western Tethyan region. The Zarabanda section of southern Spain therefore provides an ideal succession for studying this interval. This region is highly relevant due to its palaeogeographic location in the western Tethys, situated between the North Sea basin where there are several investigations about the late Oligocene palaeoclimatic events (e.g., Van Simaeys, 2004; Van Simaeys et al., 2004, 2005; Nielsen et al., 2007) and the Aquitanian Global Boundary Stratotype Section and Point (GSSP) at the Italian Lemme-Carrosio section (e.g., Coccioni et al., 2008). The section is extremely rich in micro-fossils and continuously spans ~1.7 Ma of the Upper Oligocene in a middle to lower bathyal setting.

This enables a detailed integrated micropalaeontological study (smaller and larger benthic foraminifera, planktonic foraminifera and calcareous nannofossils) from the Oligocene and across the Oi-2b global cooling event to be carried out. Marine organisms, such as foraminifera, are often sensitive to such climatic events and often show changes in abundance and/or distribution (e.g., Takata and Nomura, 2005). They are therefore exceptionally useful tools in studying the cooling events of the Oligocene. The combination of micro-fossils allows for a detailed calibration of benthic foraminiferal assemblage changes to both planktonic foraminiferal and nannofossil biostratigraphy. Additionally, the presence of larger benthic foraminifera allows the response of the carbonate platform to be studied. This research reconstructs the palaeoenvironmental changes across an interval which is crucial in

the understanding of the evolution of Earth's climate from an important, previously unstudied, region within the western Tethys.

2. Materials and methods

The Zarabanda section is located in the northern of Granada province, southern Spain. The section lies in the Subbetic realm of the external zones of the Betic Cordillera (Fig. 1). The coordinates of the points delimiting the section are: 37°31′23.96″N–3°22′29.06 W (base) and 37°31′20.70″N–3°22′26.04 W (top). During the late Oligocene the site had a palaeolatitude of approximately 30°N and in a temperate region (Andeweg, 2002). The Zarabanda section was studied by Molina (1979) who sampled on both sides of the old road, identifying the upper Oligocene (*Globigerina angulisuturalis* Zone), and the lower Miocene (*Globigerinoides primordius* Zone) on the southeast and northeast flanks of the road, respectively. More recently a parallel road was built eastward of the old one, exposing a better outcrop on the northeast flank and allowing for further investigation.

The Zarabanda section consists of an 82 m thick sequence of hemipelagic marls with interbedded limestone and turbiditic sandstone layers, which appear to continuously span ~1.7 Ma within the late Oligocene. The hemipelagic marls contain abundant planktonic foraminifera and calcareous nannofossils, common small benthic foraminifera and rare ostracods. The smaller foraminifera and calcareous nannofossils studied herein are from the autochthonous marls. The calcareous sandstone strata contain abundant larger foraminifera and small benthic foraminifera resedimented from the shelf, which appear to have been

Plate 1. Most significant late Oligocene small benthic foraminiferal species from the Zarabanda section. Scale-bars represent 100 μm. 1a–b. *Angulogerina angulosa* (Williamson, 1858), sample Zr-116-77; 2a–b. *Bolivina plicatella* Cushman, 1930, sample Zr-116-41; 3a–b. *Bolivina plicatella* Cushman, 1930, sample Zr-116-42; 4a–b. *Bolivinoides crenulata* (Cushman, 1936), sample Zr-116-14; 5. *Bulimina alazanensis* Cushman, 1927, sample Zr-116-36; 6a–b. *Cassidulina havanensis* Cushman and Bermúdez, 1936, sample Zr-116-8; 7a–b–c. *Cibicides lobatulus* (Walker and Jacob, 1798), sample Zr-116-14; 8a–b–c. *Cibicidoides mundulus* (Brady, Parker and Jones, 1888), sample Zr-116-63; 9a–b–c. *Cibicidoides eocaenus* (Gümbel, 1868), sample Zr-116-26; 10. *Globocassidulina subglobosa* (Brady, 1881), sample Zr-116-57; 11. *Globocassidulina subglobosa* (Brady, 1881), sample Zr-116-61; 12a–b–c. *Neoconorbina terquemi* (Rzehak, 1888), sample Zr-116-11; 13a–b. *Rosalina globularis* D'Orbigny, 1826, sample Zr-116-16; 14a–b. *Trifarina bradyi* Cushman, 1923, sample Zr-116-14.

1.0 mm

1.0 mm
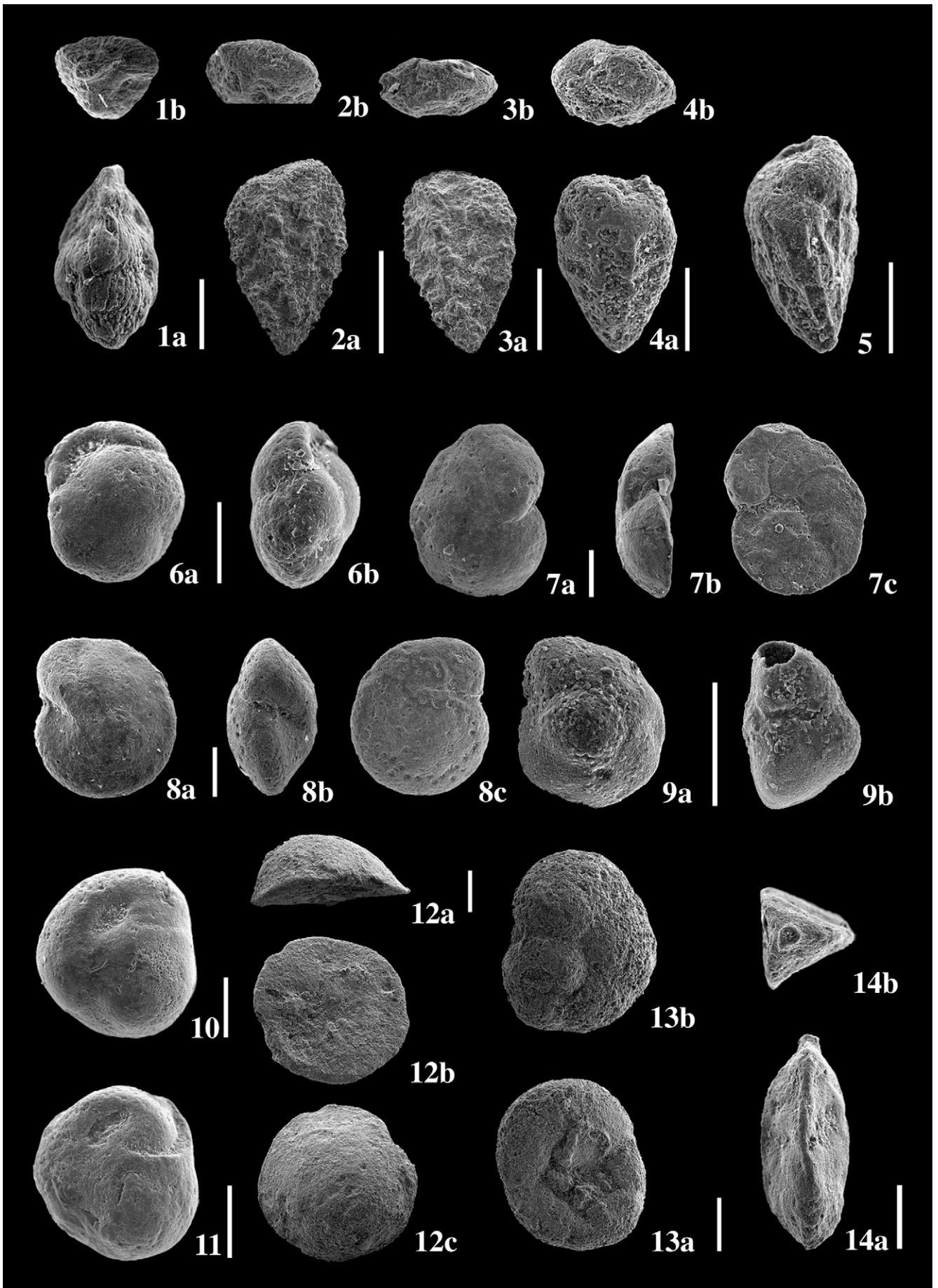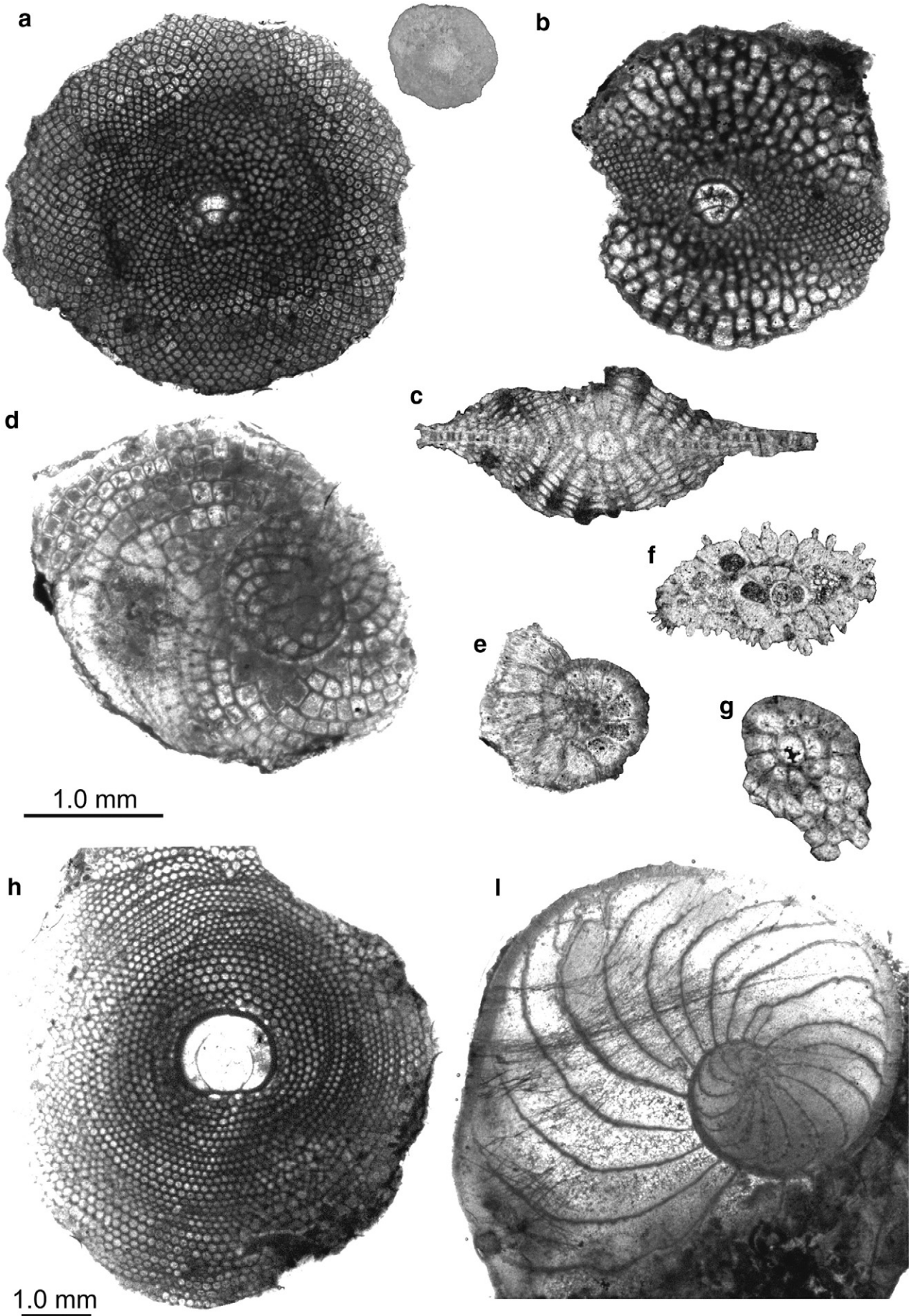
deposited penecontemporaneously with the marls and are therefore also included in this work. The preservation of calcareous nannofossils, planktonic and benthic foraminifera and larger benthic foraminifera ranges from moderate to poor.

A total of 42 samples were collected at the Zarabanda section for an integrated study of foraminifera and calcareous nannofossils.

Calcareous nannofossils were studied on 29 of the collected samples for biostratigraphical purposes. Calcareous nannofossils were analysed qualitatively using smear slides and standard light microscope techniques. The nannofossil assemblages are abundant but poorly preserved due to re-crystallization and dissolution problems and showed low diversity. Reworking of calcareous nannofossils is present throughout the section and consists mainly of Cretaceous and Eocene specimens.

For larger benthic foraminifera, 8 samples from the calcareous sandstone and limestone beds were collected. Samples were generally collected towards the base of beds, where foraminifera had been naturally weathered out and were clearly visible. Samples were then studied using petrographic thin sections, and oriented thin sections of individual foraminifera, with the exception of sample Zb A, which was studied using oriented individual sections only. In total 15 petrographic thin sections and 60 oriented individual thin sections were used in this study (Plate 2).

A total of 34 samples were collected preferentially from the marl beds for studying planktonic and benthic foraminifera. After a preliminary study of the planktonic and benthic foraminifera (Molina, 1979; Cruz, 2008; Fenero, 2010), all samples were examined and those that were better preserved and more biostratigraphically relevant were selected. Each sample was cleaned using an ultrasonic bath washing repeatedly until a clean foraminiferal residue was recovered. The final residue was dried in an oven at a temperature below 50 °C. For the quantitative studies, a representative split of about 300 planktonic and benthic foraminiferal specimens from the 100 μm size fraction was picked from each sample (Plate 1).

3. Biostratigraphy

3.1. Calcareous nannofossils

The Oligocene–Miocene transition is characterized, in nannofossil biostratigraphy, by a succession of lowest and highest occurrences of species belonging to the genus *Sphenolithus*: the Highest Occurrence (HO) of *Sphenolithus ciperoensis*, short ranges of *Sphenolithus delphix* and *Sphenolithus capricornutus* and the Lowest Occurrence (LO) of *Sphenolithus disbelemnos* (Fig. 2; Aubry and Villa, 1996; Fornaciari and Rio, 1996; Steininger et al. 1997a, b; Shackleton et al., 2000). Accurate and precise biostratigraphic analyses performed by Raffi (1999) on the Aquitanian GSSP Lemme-Carrosio section and several ODP sites showed the distribution, reliability and the magnetostratigraphic correlation of these events. The analyses revealed that the HO of *S. ciperoensis* occurs in the late Oligocene and correlates with the top of C7n.2n; the short range of *S. delphix* is correlated with the lower part of C6Cn and it is the most relevant marker for the recognition of the Oligocene/Miocene boundary (Shackleton et al., 2000). *Sphenolithus capricornutus* is often associated with *S. delphix* although it is rare and therefore not highly reliable for biostratigraphic correlation. The LO of *S. disbelemnos* is a useful bioevent, occurring slightly above the Oligocene/Miocene boundary. The HO of *S. ciperoensis* is the primary definition criterion for the CP19b/CN1a zonal boundary of Okada and Bukry (1980). The LO of *Helicosphaera recta* defined the NP25/NN1 boundary of Martini
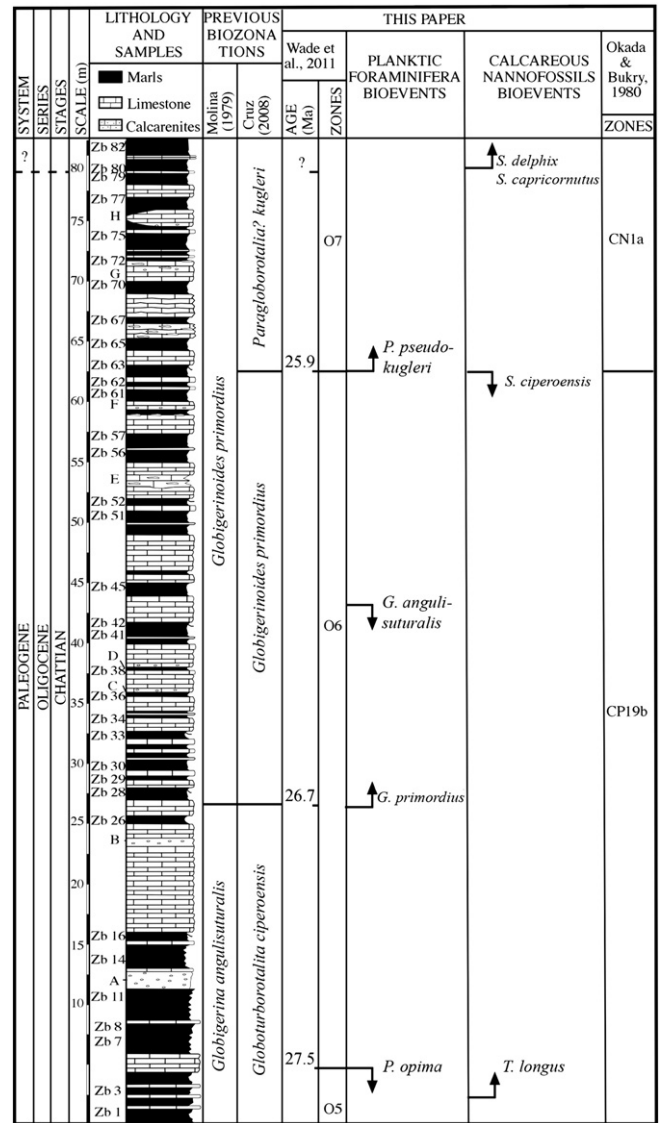

Fig. 2. Planktonic foraminifera and calcareous nannofossil biostratigraphy across the late Oligocene in the Zarabanda section.

(1971), although the event is considered to be unreliable within the Mediterranean region (Fornaciari and Rio, 1996).

Most of the studied samples from the Zarabanda section show typical late Oligocene assemblages. These are characterized by the presence of *Sphenolithus ciperoensis, Dictyococcites bisectus, Cyclicargolithus floridanus, Cyclicargolithus abisectus, Clausicoccus fenestratus, Coccolithus pelagicus, Zygrablithus bijugatus* and rare discoasters. The genus *Helicosphaera* continuously occurs throughout the section, but it is rare and primarily consists of the species *Helicosphaera euphratis. Sphenolithus distentus* was not recorded in any sample. The Highest Common Occurrence (HCO) of *S. distentus* has been used to define the base of Zone NP25 and Subzone CP19b (Maiorano and Monechi, 2006). Accordingly the lower part of the section belongs to the aforementioned zones. In agreement with the results of Maiorano and Monechi 2006 the HCO of *S. distentus* was observed well below

Plate 2. Larger benthic foraminifera from the Zarabanda section: a) *Nephrolepidina morgani*, equatorial section and external view. b) *Nephrolepidina morgani*, equatorial section. c) *Nephrolepidina morgani*, axial section. d) *Heterostegina* sp., equatorial section. e) *Neorolatia* sp., (sub) equatorial section. f) *Neorolatia* sp., axial slightly, oblique section. g) Miogypsinid, equatorial or near equatorial section. h) *Eulepidina dilatata*, equatorial section. i) *Operculina? complanata*, equatorial section. a–g, Shown at same scale with scale bar below d; h and i, shown at half this scale with scale bar below h.

the HO of *Paragloborotalia opima* at around 27.7 Myr. The LO of *Triquetrorhabdulus longus*, a new species described by Blaj and Young (2010) and identified at ODP Site 1218 (palaeo-equatorial Pacific Ocean) and ODP Site 242 (Indian Ocean) has been observed slightly below the HO of *P. opima* in sample Zb 3. The presence of this nannofossil taxon in the Zarabanda section could support the potential biostratigraphical usefulness of *T. longus*.

Sphenolithus ciperoensis, which is the marker of the base of NP24 and CP19 Zones, is present continuously from the bottom of the sequence up to sample Zb 62. It is then absent for the successive few samples and very rare in the upper part of the section. Thus, the HCO of *S. ciperoensis* occurs between sample Zb 62 and Zb 65 (Fig. 2) and therefore, the CP19b/CN1a boundary was placed within this interval. In this same interval a strong reduction in the abundance of *Cyclicargolithus abisectus* was observed, which is in agreement with De Kaenel and Villa (1996) and Fornaciari and Rio (1996). *Dictyococcites bisectus* is present, though not necessarily abundant, throughout the studied stratigraphic succession. The HO of *D. bisectus* has been suggested as a secondary criterion for the recognition of the CP19b/CN1a zonal boundary and to approximate the NP25/NN1 zonal boundary of Martini (1971). Fornaciari and Rio (1996) used the common presence and the HCO of *D. bisectus* to define the interval between the HO of *S. ciperoensis* and LO of *S. delphix* (MNP25b/MNN1a boundary). However, in the Zarabanda section *D. bisectus* does not show important changes in abundance and, so, cannot be used as a supplementary event. Very few specimens of *Sphenolithus delphix* were recognised and all occur between samples Zb 77 and Zb 80 (Fig. 2). *Sphenolithus capricornutus* has only been found in sample Zb 77 (Fig. 2). In the uppermost samples of the section a diverse assemblage of *Sphenolithus* was observed with the occurrence, amongst other spheroliths, of few specimens of *Sphenolithus conicus*, *Sphenolithus* cf. *dissimilis* and *Sphenolithus* spp. According to the distribution of *S. delphix* the uppermost part of the section is interpreted to be close to the Oligocene/Miocene boundary.

On the basis of the calcareous nannofossil analyses, the studied section belongs to CP19b–CN1 Zones of Okada and Bukry (1980) and to MNP25 Zones and lower part of MNN1 of Fornaciari and Rio (1996).

3.2. Planktonic foraminifera

Oligocene to earliest Miocene planktonic foraminifera from the central sector of the Betic Cordillera were first studied by González Donoso and Molina (1977–1978) and Molina (1979). The Zarabanda section was one of several sections proposed as the potential stratotype for the Oligocene/Miocene boundary, which were analysed by a multidisciplinary working group (Baldi-Beke et al., 1983) and was considered one of/amongst the most relevant.

Planktonic foraminifera are very abundant in the hemipelagic intervals, though preservation is moderate to poor. The most frequently occurring species along the section are: *Dentoglobigerina tripartita*, *Globoquadrina venezuelana*, *Globoquadrina sellii*, *Globoquadrina globularis*, *Subbotina eocaena*, *Subbotina corpulenta*, *Globigerina officinalis*, *Globigerina praebulloides*, *Globoturborotalita ouachitaensis*, *Globigerinella obesa*, *Catapsydrax dissimilis*, *Catapsydrax ciperoensis*, *Catapsydarx unicavus*, *Turborotalia euapertura*, *Paragloborotalia siakensis*, *Paragloborotalia nana* and *Casigerinella chipolensis*. The two basal samples contain few specimens of *Paragloborotalia opima* (Fig. 2), allowing recognition of the O5 Zone of Wade et al. (2011). These samples also contain *Globoturborotalita angulisuturalis*, which has a HO in sample Zb 42, overlapping with *Globigerinoides primordius* that appears in sample Zb 28 (Fig. 2). This is the clearest bioevent in the section, as *G. primordius* occurs frequently and is easily recognisable. It was used by planktonic foraminifera specialists to mark the Oligocene/Miocene boundary until the Aquitanian GSSP was defined by Steininger et al. (1997a,b) in a younger level. Since then,

the appearance of *G. primordius* is an upper Oligocene bioevent. Another Oligocene bioevent is the appearance of *Paragloborotalia pseudokugleri* at sample Zb 63 that allows recognition of the O7 Zone of Wade et al. (2011) and consequently the interval in between corresponds to Zone O6 (Fig. 2). Initially, *Paragloborotalia? kugleri* was thought to appear in sample Zb 63 indicating the Miocene, but a more detailed taxonomic study allows us to conclude that these specimens belong to *P. pseudokugleri* and therefore, they also belong to the late Oligocene. The section studied by Cruz (2008) is less expanded than the section studied by Molina (1979) which is shown to clearly extend to the lower Miocene by the presence of true *P. kugleri* in the upper part, an interval which was not sampled for the present research. Correlating planktonic foraminifera with the Neogene GSSP section at Lemme-Carrosio, Italy (Iaccarino et al. 1996) shows no evidence that the Zarabanda section presented herein extends into the Miocene. According to the Wade et al. (2011) revision of Cenozoic planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale, the extinction of *P. opima* has an estimated age of 27.5 Ma, the appearance of *G. primordius* has an estimated age of 26.7 Ma, the appearance of *P. pseudokugleri* has an estimated age of 25.9 Ma, and the Oligocene/Miocene boundary has an estimated age of 23.80 Ma.

3.3. Larger benthic foraminifera

Within the marl sequence at the Zarabanda section there are secondary beds composed of carbonate platform debris, primarily larger benthic foraminifera (LBF). These secondary beds, though redeposited, are believed to have been deposited as uncemented grains penecontemporaneous with the deposition of the surrounding clays. The limestones therefore, can be used to examine the shallow water LBF assemblages and biostratigraphic age across the section and to compare them with the planktonic and smaller benthic foraminiferal ages determined from the clay layers.

The larger benthic foraminiferal assemblage present in the limestone samples is fairly consistent through the log (Fig. 6), and is common for the upper Oligocene of the Tethyan region. The key foraminifera present for determining the biostratigraphical age of the samples are the lepidocyclinids, *Eulepidina dilatata* and *Nephrolepidina morgani*, and the presence of the miogypsinids (Cahuzac and Poignant, 1997). *Operculina? complanata*, *Heterostegina* and *Neorotalia* have long ranges, though within the Oligocene–Miocene (Cahuzac and Poignant, 1997).

In the lowermost bed, of the diagnostic species mentioned, only *Eulepidina dilatata* is present. This indicates that the lowermost bed has a maximum middle to lower Oligocene age, e.g., within the SB 22A following the Shallow Benthic Zonation of Cahuzac and Poignant, 1997, and can be no younger than the latest Oligocene—just below the Oligocene/Miocene boundary (top of the SB 23 zone). In sample Zb B no *E. dilatata* was found, although *Nephrolepidina morgani* is present which has a range from the lower part of the upper Oligocene to ~mid lower Miocene (SB 22B zone to within SB 25 zone). Sample Zb C contains an indeterminate miogypsinid fragment. Miogypsinids have a first occurrence in the upper Oligocene (base of SB 23) and continue to the top of the Lower Miocene (top of SB 25). Samples Zb D, Zb E and Zb G all contain *N. morgani* and are, therefore, upper Oligocene to lower Miocene (SB 22B zone to within SB 25 zone) in age. Sample Zb F contains lepidocyclinid fragments. It is likely that these also belong to *N. morgani*, however, there were no clear equatorial sections of A forms for this sample for species level identification. Finally sample Zb H contains *N. morgani* and a miogypsinid specimen. Therefore, the maximum age of Zb H is late Oligocene—base of SB 23, and the minimum age ~middle to early Miocene (mid SB25).

The age, as indicated by the larger benthic foraminifera from the stratigraphic succession is therefore late Oligocene to early Miocene, though it is possible that bed A is slightly older—within the upper part of the lower Oligocene. When compared with the planktonic and smaller benthic foraminiferal dates it seems most likely that the

larger benthic foraminiferal limestones are late Oligocene in age, e.g., belonging to the SB 23 Zone.

4. Palaeoenvironmental inferences

4.1. Small benthic foraminifera

Benthic foraminifera have been used extensively to reconstruct past variability in deep-water properties in different ocean basins (e.g., Miller and Lohmann, 1982; Schmiedl and Mackensen, 1997). Benthic foraminiferal morphotype analysis along with changes in the abundance of selected taxa and in generic richness allowed us to infer probable microhabitat preferences and environmental parameters (e.g., Bernhard, 1986; Jorissen et al., 1995). The Fisher-α diversity index and the H (S) Shannon–Weaver information function were calculated in order to document changes in diversity (Murray, 1991).

Benthic foraminifera are widely used for palaeobathymetric estimates (e.g., Tjalsma and Lohmann, 1983; Van Morkhoven et al., 1986). Benthic foraminiferal assemblages from the Zarabanda section are characterized by taxa typical of deep-bathyal environments, including *Cibicidoides eocaenus*, *Cibicidoides mundulus*, *Bulimina alazanensis*, *Globocassidulina subglobosa*, *Epistominella exigua*, *Turrilina alsatica*, *Hanzawaia ammophila*, *Bulimina trinitatensis*, and the bolivinids group (e.g., Van Morkhoven et al., 1986). Many of these bathyal species show a decrease in relative abundance across samples Zb 16 to Zb 26 and an increase in the upper part of the Zarabanda section.

Also present are *Cibicides lobatulus*, *Ciblicides refulgens*, *Ciblicides westi*, *Ciblicides laurisae*, *Asterigerina campanella*, *Asterigerinoides subacutus*, *Neoconorbina terquemi*, *Rosalina globularis*, *Amphistegina radiata*, *Pararotalia audouini* and the genus *Elphidium* which have an upper water depth limit of 50–200 m, at middle sublittoral depths (Wright, 1978; Van Morkhoven et al., 1986; Browning et al., 1997; Hayward, 2004). These species occur in high percentages throughout the section, but become more abundant and widespread during the Zb 16 to Zb 26 interval in a 10 m thick succession of calcarenites, at approximately 26.7 Ma. This increase in the percentage of shallow-water taxa may have been triggered by the erosion of a shallow platform with sediment transported by turbidity currents into the middle–lower bathyal zone, possibly linked to a major sea-level fall. Additionally, these shallow-water taxa are better preserved within the calcarenite sequence.

This data suggests that upper Oligocene interval from the Zarabanda section was deposited in a middle–lower bathyal depth for most of the studied section (~1000 m depth). This palaeodepth is supported by the high diversity and heterogeneity of the benthic assemblages, the high P/B ratio (>90%) in almost samples, and the abundance of bathyal taxa. However, we interpret a relative sea-level fall for the lower part of the studied section (Zb 16–Zb 26 interval).

We used morphotype analysis of benthic foraminifera (e.g., Corliss, 1985; Jones and Charnock, 1985) to infer probable microhabitat preferences and environmental parameters such as the nutrient supply to the seafloor and seawater oxygenation (e.g., Jorissen et al., 1995). However, these data must be interpreted with caution since microhabitat assignments on the basis of morphology only have a 75% accuracy (Buzas et al., 1993).

The benthic foraminiferal assemblages from the Zarabanda section are generally heterogeneous and highly diverse (Fisher-α index between 16 and 27; Fig. 3). Assemblages consist of a mixture of infaunal and epifaunal morphogroups. Infaunal species usually dominate over epifaunal species (Fig. 3). These assemblages are dominated by calcareous taxa (up to ~88% for most of the studied section), and contain a few dominant species together with many rare ones. Agglutinated foraminifera assemblages have a low diversity and are dominated by cylindrical, tapered genera such as *Vulvulina*, *Batysiphon*, *Rhabdammina* and *Rhizammina*. Amongst calcareous taxa, *Bolivinoides crenulata*, *Globocassidulina*

subglobosa, *Oridorsalis umbonatus*, *Cibicides lobatulus*, *Cibicides refulgens*, *Cibicidoides mundulus* and *Angulogerina angulosa* are the most abundant species (Figs. 4, 5). Benthic foraminifera in the samples were highly dominated by groups such as bolivinids, asterigerinids, angulogerinids, and *Cibicides* spp. Other common groups and genera included buliminids, *Anomalinoides* spp., *Cibicidoides* spp. and *Elphidium* spp. (Figs. 4, 5), which are present throughout this section.

4.2. Larger benthic foraminifera

As the deposition of the larger benthic foraminifera is believed to be penecontemporaneous with the oceanic Zarabanda succession, they can be used to give an insight into the palaeoenvironmental changes occurring on the shallow water platform during this interval.

Beds are coarse bioclastic packstones, with the majority showing strong pressure solution structures. Larger benthic foraminifera are highly abraded with significant test damage, and are comparable with category 3 in the scale of transportation damage as described by Beavington-Penney (2004). This category indicates extensive transport by wave action or within turbidity currents (Beavington-Penney, 2004). There is very little matrix in the limestone samples, with only occasional clasts of micritic material, which frequently contain planktonic foraminifera and further suggests that the limestones were deposited as turbidites.

The limestones are primarily composed of larger benthic foraminifera (LBF). Rhodophyte fragments are also common throughout and in addition peyssonnelid algae that are seen in sample Zb C. Coral, echinoid, bryozoan, bivalve and worm tube (possibly of the genus ?*Ditrupa*) fragments also frequently occur in the samples, all of which are commonly found in platform sediments (Flügel, 2004).

Lepidocyclinids are the most commonly occurring LBF, tending to dominate the assemblages. *Operculina* and *Heterostegina* occur frequently along with *Neorotalia* and *Amphistegina*. *Nummulites* are uncommon, though several species are present and miogypsinids are very rare. It is generally accepted that assemblages of LBF were strongly zoned across shallow carbonate platforms due to many factors, including light levels and energy (e.g., Beavington-Penney and Racey, 2004; Renema, 2005, 2006). The above indicated assemblage of LBF is typical of an Oligocene–Miocene outer or mid to outer ramp carbonate setting (e.g., Beavington-Penney and Racey, 2004), thus suggesting this is the source of the carbonate sediment. Turbidites therefore may have occurred due to destabilisation of the outer ramp sediment. The lack of miogypsinids in the limestone beds may, therefore, be due to them living outside of the source area of the turbidites e.g., in shallower waters.

The major change in the assemblage is the disappearance of *Eulepidina dilatata* and the appearance of *Nephrolepidina morgani* (Fig. 6). The last occurrence of *E. dilatata* is in sample Zb A, before the 10 m thick calcarenite succession, whereas the first occurrence of *N. morgani* occurs in sample Zb B which is taken in the upper part of this calcarenite sequence. This is the same interval in which we see an increase in the shallow water, and a decrease in the deep water smaller benthic foraminifera taxa. *Eulepidina* is thought to have inhabited slightly deeper waters than *Nephrolepidina* (e.g., Schiavinotto and Verrubbi, 1994). A sea-level fall would cause an overall shallowing of the platform and therefore *Eulepidina* may not have been able to survive in the new shallower platform conditions and was replaced by *Nephrolepidina*. This change seen in the larger benthic foraminifera further supports that a sea-level fall occurred within the interval at around 26.7 Ma.

5. Discussion

The most important relative microfaunal abundance throughout the Zarabanda section is that of the bolivinids group, which indicates high organic carbon flux rates to the seafloor in the recent oceans (e.g., Thomas et al., 2000) and environments with low oxygen conditions (e.g., Murray, 1991; Bernhard and Sen Gupta, 1999; Murray, 2006).
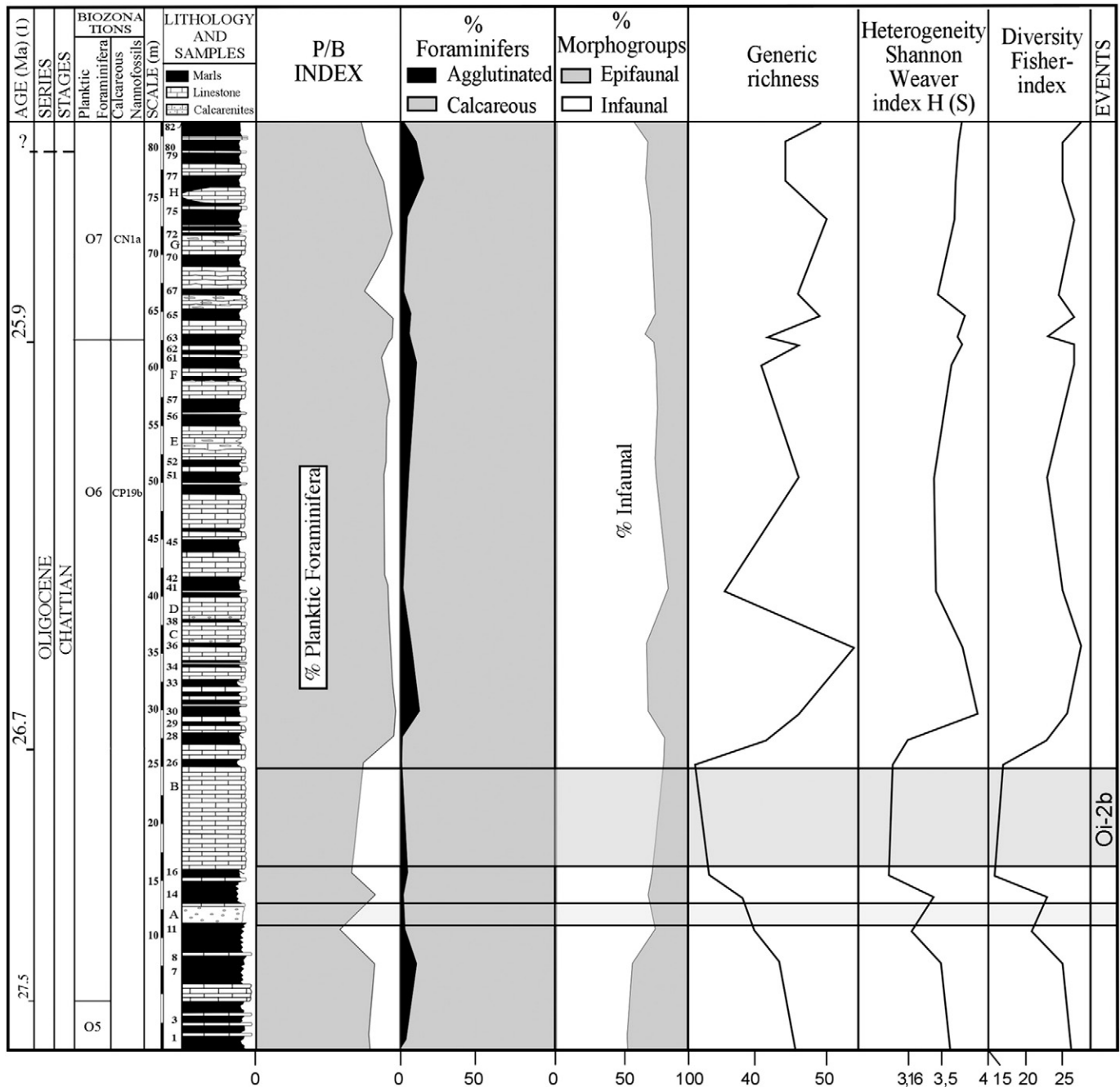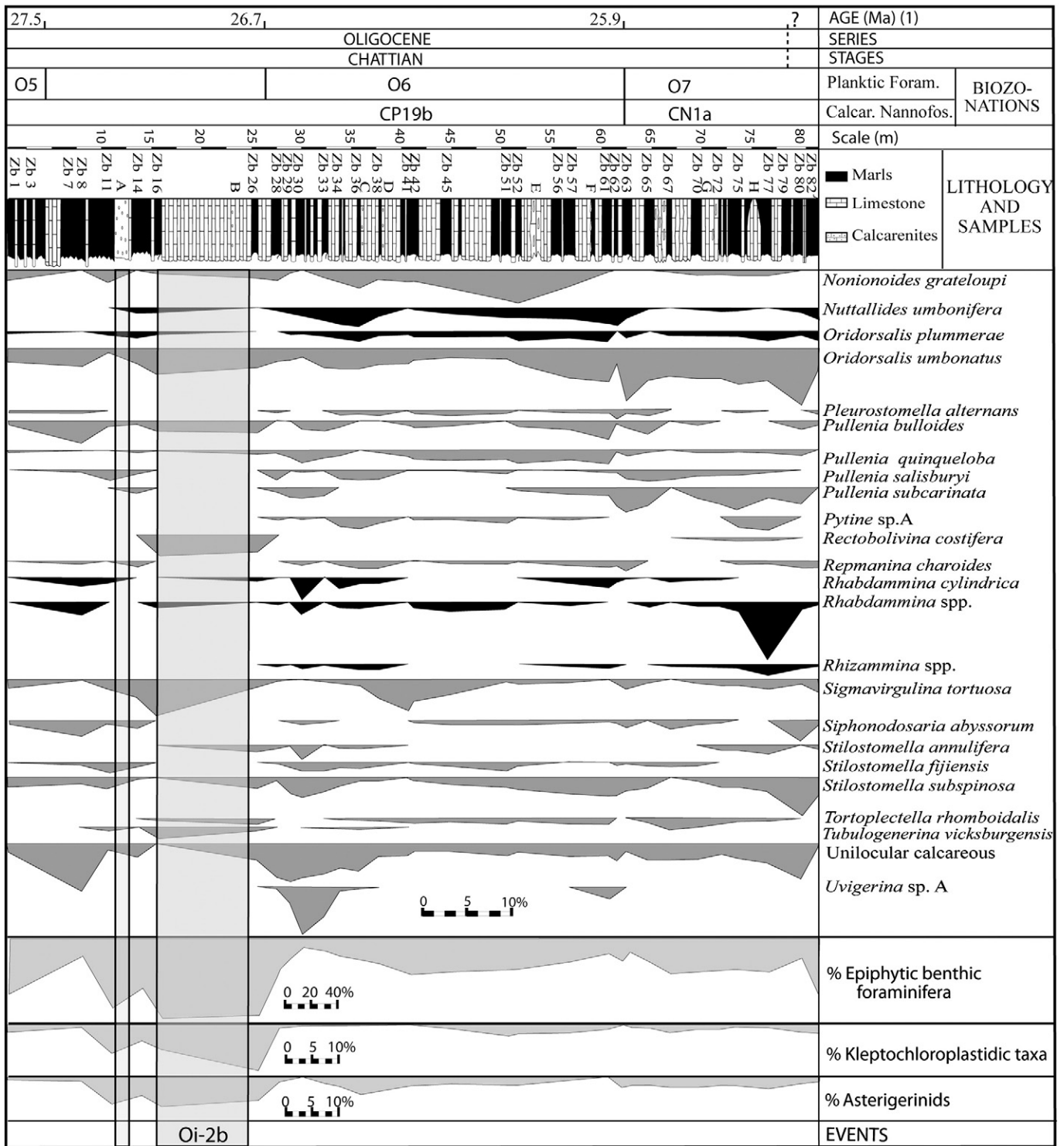
Fig. 3. Smaller benthic foraminiferal data at the Zarabanda section: Planktonic/Benthic (P/B) index, % abundance of agglutinated/calcareous foraminifers, % abundance of infaunal/epifaunal morphogroups, generic richness, Shannon–Weaver heterogeneity index and Fisher-α diversity index. (1) Age of biozone boundaries, after Berggren and Pearson (2005).

However, this group has also been reported from well-oxygenated conditions (e.g., Fontanier et al., 2005; Jorissen et al., 2007). *Cibicides pseudoungerianus*, a species closely resembling *Cibicides ungerianus*, is common in the Zarabada section and is known to be intolerant to low-oxygen conditions (Barmawidjaja et al., 1992; Den Dulk et al., 2000). These assemblages suggest intermediate trophic environment with a local high flux of organic matter to the sea floor and well-oxygenated conditions during the late Oligocene at the Zarabanda section. This high flux of organic matter might be related to the influence of turbidity currents, which is consistent with the palaeogeography of the Zarabanda section, in a steep continental slope very near to the coastal photic zone. *Bolivinoides crenulata* shows a peak in abundance at 28–29 m (at the base of the *Globigerinoides primordius* Zone), which may be related

with an increase in the organic carbon flux rates to the seafloor due to strong turbidity currents.

Intensified bottom-water currents (e.g., slope currents) have been shown to influence the microhabitat and composition of the benthic foraminiferal fauna (e.g., Schönfeld, 1997, 2002a, b). Benthic foraminifera show a conspicuous assemblage change at the Zb 16–Zb 26 interval, in a 10-m-thick sequence of calcarenites at approximately 26.7 Ma. The assemblages in this interval are dominated by inner neritic taxa such as *Cibicides lobatulus*, *Cibicides refulgens*, *Cibicides westi*, *Cibicides laurisae*, *Neoconorbina terquemi*, *Rosalina globularis*, *Amphistegina radiata*, *Asterigerina campanella*, *Asterigerinoides subacutus*, *Pararotalia audouini*, *Tubulogerina vicksburgensis* and *Elphidium* (Murray, 1991), which we consider
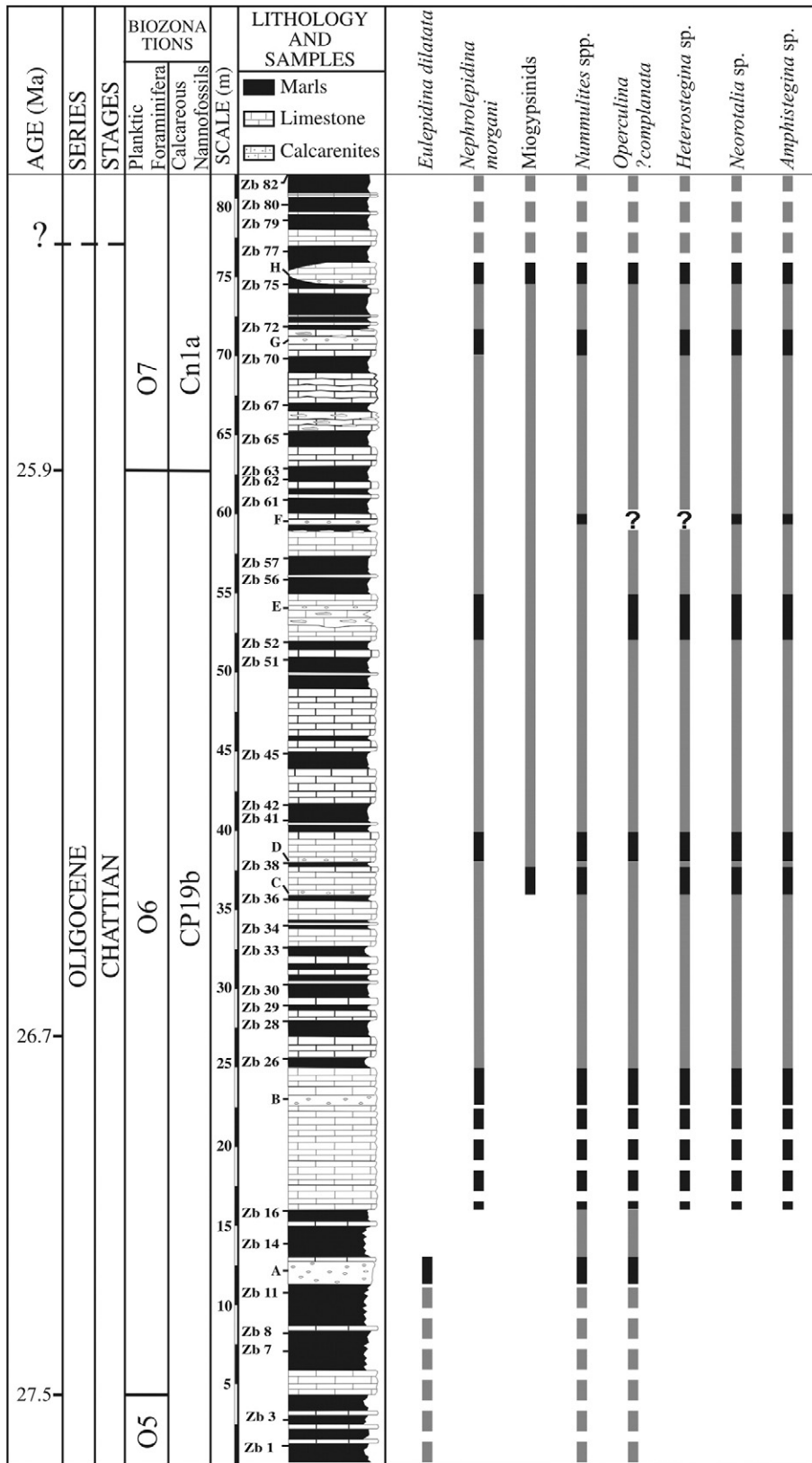
Fig. 4. Distribution and percentage of small benthic foraminiferal species across the late Oligocene of the Zarabanda section. (1) Age of biozone boundaries, after Berggren and Pearson (2005).

Fig. 5. Distribution and relative abundance of small benthic foraminiferal species across the late Oligocene of Zarabanda section. Distribution and relative abundance of epiphytic benthic species (asteriginids, *Cibicides lobatulus*, *Ciblicides refulgens*, *Rosalina globularis*, *Neoconorbina terquemi*), kleptocholoroplastidic taxa (*Elphidium*, and possibly *Pararotalia audouini* and *Proelphidium laeve*), asteriginids (*Asterigerina campanella*, *Asterigerinoides subacutus*). (1) Age of biozone boundaries, after Berggren and Pearson (2005).

allochthonous, due to down-slope transport by turbidity currents. *Cibicides* spp. is usually found, at in modern environments, to attach itself to hard substrates in high-energy settings (e.g., Murray, 1991, 2006). These neritic taxa are abundant, probably as a result of the erosion of shallow sediments and transport from the shelf towards the base of the slope, due to a decrease in sea level. This interval is characterized by the high percentage of shallow-water benthic foraminifera, and the decrease in the P/B ratio, genus richness, diversity and heterogeneity

of the assemblages. Coeval changes include an increase in the relative abundance of the percentages of cool-water benthic species (e.g., *Angulogerina angulosa*, *Astrononion novozealandicum*, *Globocassidulina subglobosa*, *Oridorsalis umbonatus*, *Hyalinea* sp. A). Small benthic foraminifera changes coincide with the major change in the larger benthic foraminiferal assemblages; the last occurrence of *Eulepidina dilatata* and the first occurrence of *Nephrolepidina morgani* species, which may indicate shallowing of the platform. This event also coincides with the first

Fig. 6. Stratigraphic column of the Zarabanda section showing limestone samples (A–H) and ranges of larger benthic foraminifera (LBF). Due to the discrete nature of the limestone beds, LBF occurrences in the limestones are shown in black, whereas ranges between occurrences are shown in grey. Dashed lines show the presumed continuation of biostratigraphic ranges.

occurrence of *Globigerinoides primordius* at the top of this interval, in the planktonic foraminiferal zone O6. The data both in the small and larger foraminifera may therefore be associated with the major expansion of

the Antarctic ice sheet and the glacio-eustatic sea level drop which occurred at approximately 26.7 Ma, indicating the globally recognised Oi-2b glaciation event. All these appreciably short-term

fluctuations of the small and larger benthic foraminifera, planktic foraminifera and calcareous nannofossils of the western Tethys are likely related to Oi2b glaciation event.

The late Oligocene warming event is not clear in the Zarabanda section. Although we observe warmer species such as *Pararotalia audouini*, *Tubulogerina vicksburgensis* and *Elphidium genera* (Gibson, 1989; Murray, 1991) within the 10-m-thick sequence of calcarenites at approximately 26.7 Ma, the percentage abundance of these species is low (1–8%). Therefore they may be present in this interval due to transport within turbidity currents, as seen in the other neritic species (e.g., *Cibicides lobatulus*, *Cibicides refulgens*, *Cibicides westi*, *Cibicides laurisae*, *Neoconorbina terquemi*, *Rosalina globularis*, *Amphistegina radiata*, *Asterigerina campanella*, *Asterigerinoides subacutus*). Thus, benthic foraminifera from the Zarabanda section appear to indicate a temperate climate covering the western Tethys area of southern Spain during the late Oligocene with a conspicuous cooling event (Oi-2b glaciation event) in the lower part of the section. We cannot determinate the warming event during the late Oligocene in the western Tethys; we have not found evidence of change in the analysed microorganism groups (distribution, extinction or a high abundance in the warmer species) in any studied intervals.

6. Conclusions

This integrated data allow us to define for the first time one of the most relevant late Oligocene climatic events at intermediate latitudes. The analysis of this integrated study shows clearly a micropalaeontological turnover in all studied groups, and palaeoenvironmental and palaeobathymetry changes. Thus, we suggest that the Oi-2b global cooling event might be responsible for such relatively short-term fluctuations in these four micropalaeontological groups.

Palaeodepth reconstruction, based on benthic foraminifera, suggests that water depth at the site was 1000 m deep in the late Oligocene throughout most of the section. Benthic foraminifera suggest intermediate trophic levels with a local high flux of organic matter to the sea floor and well-oxygenated conditions during the late Oligocene at the Zarabanda section. The high percentage of the bolivinids group indicates a high flux of organic matter that may correspond to the influence of turbidity currents, consistent with the palaeogeographical setting of the Zarabanda section, in a steep continental slope setting very near to the coastal photic zone.

The calcarenite interval in the lower part of the section (*Globigerina angulisuturalis* Biozone) shows abundant trace fossils, larger benthic foraminifera, a bloom of neritic small benthic foraminifera and an increase in the percentage of cool-water benthic species. Moreover, the Planktonic/Benthic ratio, generic richness, heterogeneity and diversity of the assemblages decrease in this interval. Significant cooling at the palaeolatitude of the Zarabanda section during the Oligocene would not be expected, however our data show a relevant change in the small benthic foraminifera which coincides with the major change in the larger benthic foraminiferal assemblages; the last occurrence of *Eulepidina dilatata* and the first occurrence of *Nephrolepidina morgani* species. This event also coincides with the first occurrence of *G. primordius* species at the top of this interval, in the planktonic foraminiferal O6 Zone.

The data from micropalaeontological study (foraminifera and calcareous nannofossils) are helpful for the further development of the sequence stratigraphic analysis and for the understanding of the causes of an interpreted relative sea-level change of the global climatic event (Oi-2b) in the western Tethys for the first time. Thus, the exhaustive analysis of Zarabanda section suggests that this event indicates a sea level fall, which can be correlated to the major expansion of the Antarctic Ice Sheet that occurred at approximately 26.7 Ma, e.g. the Oi-2b global glaciation event.

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