

# Paleoenvironmental and ecological changes during the Eocene-Oligocene transition based on foraminifera from the Cap Bon Peninsula in North East Tunisia

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## ABSTRACT

Biostratigraphic analysis of the Eocene-Oligocene transition (E-O) at the Menzel Bou Zelfa and Jhaff composite section in the Cap Bon Peninsula (North East Tunisia) allowed us to recognize a continuous planktic foraminiferal biozonation: E14 *Globigerinatheka semiinvoluta* Zone, E15 *Globigerinatheka index* Zone, E16 *Hantkenina alabamensis* Zone and O1 *Pseudohastigerina naguiewichiensis* Zone. A quantitative study of benthic and planktic foraminifera assemblages was carried out and the richness and diversity of foraminifera allowed us to reconstruct the paleoenvironmental evolution from marine to terrestrial environments. From the Eocene E14 Zone, the foraminiferal association characterizes a relatively warm climate with considerable oxygen content and a dominance of keeled and spinose planktic foraminifera, which became extinct at the E/O boundary, possibly due to cooling of the planktic environment. Nevertheless, the small benthic foraminifera do not show an extinction event at the Eocene/Oligocene (E/O) boundary, indicating that the benthic environment was not significantly affected. In the basal Oligocene O1 Zone, the benthic environment changes to a shallower setting due to cooling of the climate. These changes generated a remarkable dominance of globular forms in the planktic environment. Small benthic foraminifera apparently have a gradual extinction event, or more likely a gradual pattern of local disappearances, that could have been caused by the Oi1 glaciation.

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## 1. Introduction

The E-O transition, around 34 Ma, was a pivotal time in Earth's evolution as the climate shifted from Early Cenozoic greenhouse to glacial conditions with significant permanent ice sheets on Antarctica (Shackleton and Kennett, 1976; Zachos et al., 1996; Wade et al., 2012; Ortiz and Kaminski, 2012). This was associated with a cooling of the regions of low, medium and high latitudes (Coxall and Pearson, 2007; Lear et al., 2008).

As the world shifted from warm Eocene climate to colder Oligocene climate, there were major changes in ecology, productivity, chemistry and also probably within the vertical structure of the water column. This major change under the climatic conditions

is reflected by similar progressive changes in the oxygen and carbon isotopes of the benthic foraminifera from deep waters (Coxall et al., 2005; Coxall and Wilson, 2011) as well as in the lithology of the pelagic sediments (Pälike et al., 2012), reflecting the cooling of the oceans and the development of large ice sheets in Antarctica (Shackleton and Kennett, 1976; Zachos et al., 1996; DeConto and Pollard, 2003; Coxall et al., 2005; Lear et al., 2008). These climate changes were associated with a reduction of atmospheric carbon dioxide (Pearson et al., 2009; Pagani et al., 2011), the extinction of many species of phytoplankton and zooplankton (Funakawa et al., 2006; Pearson et al., 2008) a deepening of the calcite compensation depth (CCD), a fall in sea level increased ocean alkalinity (Coxall et al., 2005), and the tectonic changes that have opened Oceanic gateways of flows around the Antarctic (Exon et al., 2004; Stickley et al., 2004; Barker et al., 2007).

Planktic foraminifera suffered extinction across the E/O boundary (Martínez-Gallego and Molina, 1975; Molina, 1980, 1986;

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Molina et al., 1986, 1988; 1993, 2006; Nocchi et al., 1988; Gonzalvo and Molina, 1992; Farouk et al., 2013, 2015; Pearson and Wade, 2015; Karoui-Yaakoub et al., 2017). Planktic foraminifera suffered a rapid but gradual extinction event, which is characterized by the extinction of the hantkeninids and turborotalids (*Hantkenina primitiva*, *Hantkenina compressa*, *Hantkenina alabamensis*, *Hantkenina nanggulanensis*, *Cribohantkenina lazzarii*, *Turborotalia coccaensis* and *Turborotalia cunialensis*). Furthermore, the larger *Pseudohastigerina micra* s. str. also seems to have gone extinct. These species gradually became extinct in about 0.04 Myr and account for 31% of the planktic assemblages (Molina, 2015). The E/O boundary was defined at the Massignano section, coinciding with the extinction of the hantkeninids (Premoli Silva and Jenkins, 1993).

Larger foraminifera living in shallow platforms had a turnover (Orabi et al., 2015), but did not suffer extinction coinciding with the E/O boundary (Molina et al., 2016), although the magnitude of this turnover is not yet well known. Small benthic foraminifera, living in bathyal and abyssal environments, are not so well studied as planktic and their pattern of extinction at the E/O boundary is not yet known in detail. Deep-sea benthic foraminifera underwent a mass but gradual extinction from the late Eocene-early Oligocene, with modern type assemblages becoming established (Kaminski et al., 1989; Thomas, 1992; Thomas and Gooday, 1996; Kaminski and Gradstein, 2005; Thomas and Via, 2007).

The aim of this work is to study the paleoenvironmental changes across the E/O boundary in North East Tunisia, based on the quantitative analyses of small benthic and planktic foraminiferal assemblages at the Menzel bou Zelfa and Jhaff composite section. The richness of planktic foraminiferal species reflects the climatic stability of the water, and therefore, varies depending on ocean circulation being greatest where redistribution of hot water masses is promoted (Wade and Pearson, 2008). This causes a variety of ecological habitats where the various species of life grow and proliferate. The planktic foraminiferal extinction event is known to coincide with the E/O boundary, but little is known about what happened at the sea bottom. Our study therefore, focuses on small benthic foraminifera in order to investigate the nature and timing of the benthic foraminiferal turnover and to ascertain whether the benthic extinctions coincided with the E/O boundary and the beginning of the O11 glaciation.

## 2. Geological and geographical setting

The 54 m thick Menzel Bou Zelfa (MBZ) section is located in the north-eastern of Tunisia in the Cap Bon peninsula. Section sampling was carried out on the NE flank of the anticline Jebel Abderrahmane. The stratigraphic series is essentially composed of marls, limestones and sands ranging in age from the middle Eocene to Quaternary (Fig. 1). However, in some places the E/O boundary interval was covered with Quaternary deposits, for which reason it was decided to merge two separate sections into a single composite one. It was necessary to carry out detailed sampling across the E/O boundary, which is why a better exposed section in the same area about 1 km to the south was chosen, located between the coordinate points 36° 42'16.44"N and 10°41'42.5800E. This interval of the composed section is named Jhaff (J6–J13). This detailed interval was located between MBZ 26 and MBZ 25 (Fig. 2).

This section is composed of light grey marls occasionally interbedded with centimetric argillaceous reddish limestone beds, rich in iron oxide and is called Unit 1. From sample Jhaff 11 it comprises a sandy limestone bed rich in iron oxide and is called Unit 2. This sample marks a transition to a new facies characterized by grey sandy marls. This facies is overlaid by dark grey marls intersected at the top by a centimetric bed of indurated marl with ferruginous concretions. The units 1 and 2 are marine and belong to the Tellien

Domain. The top of the section is formed by light grey marl, sometimes intercalated with yellowish to brownish rust, overlaid with a sandstone bed with yellow limestone cement known as Unit 3. This upper unit is terrestrial and belongs to the Numidian Flysch (Boukhalfa et al., 2009).

## 3. Materials and methods

In the field it was possible to select a complete section, which was accessible and presented the best outcrop. An initial scatter sampling was performed during the first visit to identify the location of the boundaries, followed by a second more detailed sampling to further characterize them.

The marly samples were washed in the laboratory. Each sample was soaked in tap water for few days, adding diluted H<sub>2</sub>O<sub>2</sub> for some very compacted samples. These samples were then washed through a column of three interlocking sieves, with meshes 250 µm, 150 µm and 63 µm. The washed residue was collected in Petri dishes and dried in a stove at a temperature of 50 °C.

The residues were sorted and observed under a binocular microscope in order to identify the foraminifera. The quantitative and taxonomic studies were based on representative splits of >300 specimens of the 63 and 150-µm fraction combined, obtained with an Otto microsplitter and the rest of the sample was scanned to look for rare species. Relative abundance of common taxa was calculated, together with faunal indices commonly used in ecology and paleoenvironmental reconstruction. The most representative taxa were photographed using the Scanning Electron Microscope at the ETAP (Tunisian National Oil Company).

The biostratigraphy of this section was previously studied and published by the present authors (Karoui-Yaakoub et al., 2017) with planktic foraminifera biozonation based on Pearson et al. (2006). The last occurrence (LO) of the index taxon *Globigerinatheka semiinvoluta* was used to recognize E14, the LO of *Globigerinatheka index* to mark E15, the LO of *Hantkenina alabamensis* to locate the E16/O1 boundary, and the LO of *Pseudohastigerina naguwichiensis* to mark the first biozone of the Rupelian (Fig. 2).

Benthic fauna occupies numerous and diverse ecological niches. Indeed, it yields a considerable amount of information about the conditions of the bottom of the ocean and has played an important role over the years in interpreting these conditions. Furthermore, determining the micro-habitat of benthic foraminifera is fundamental as it allows us to specify the ecological requirements of each species. This work has used quantitative analysis based primarily on the nature of foraminifera tests, whether calcitic, agglutinated or porcelaneous (Fontanier, 2003).

## 4. Results

In this work the association of planktic foraminifera in the middle and upper Eocene sediments reflects a considerable number of individuals (about 500 individuals), belonging to around 25 species. This number of planktic foraminifera is relatively small compared to the number of species of benthic foraminifera (see below). Major turnovers of planktic foraminifera occur across the E/O boundary; the quantitative analysis revealed that planktic foraminifera are very numerous but not very diversified (about 7 species). Furthermore, it showed low diversity of benthic foraminifera (about 15 species) and represented by a relatively small number of individuals (Fig. 2).

The planktic foraminifera are present in all samples of the middle Eocene to the lower Oligocene succession interval and show a variation of the assemblage composition and relative abundance. A faunal turnover occurred during the E/O transition interval and includes major extinctions of some species such as the extinction of

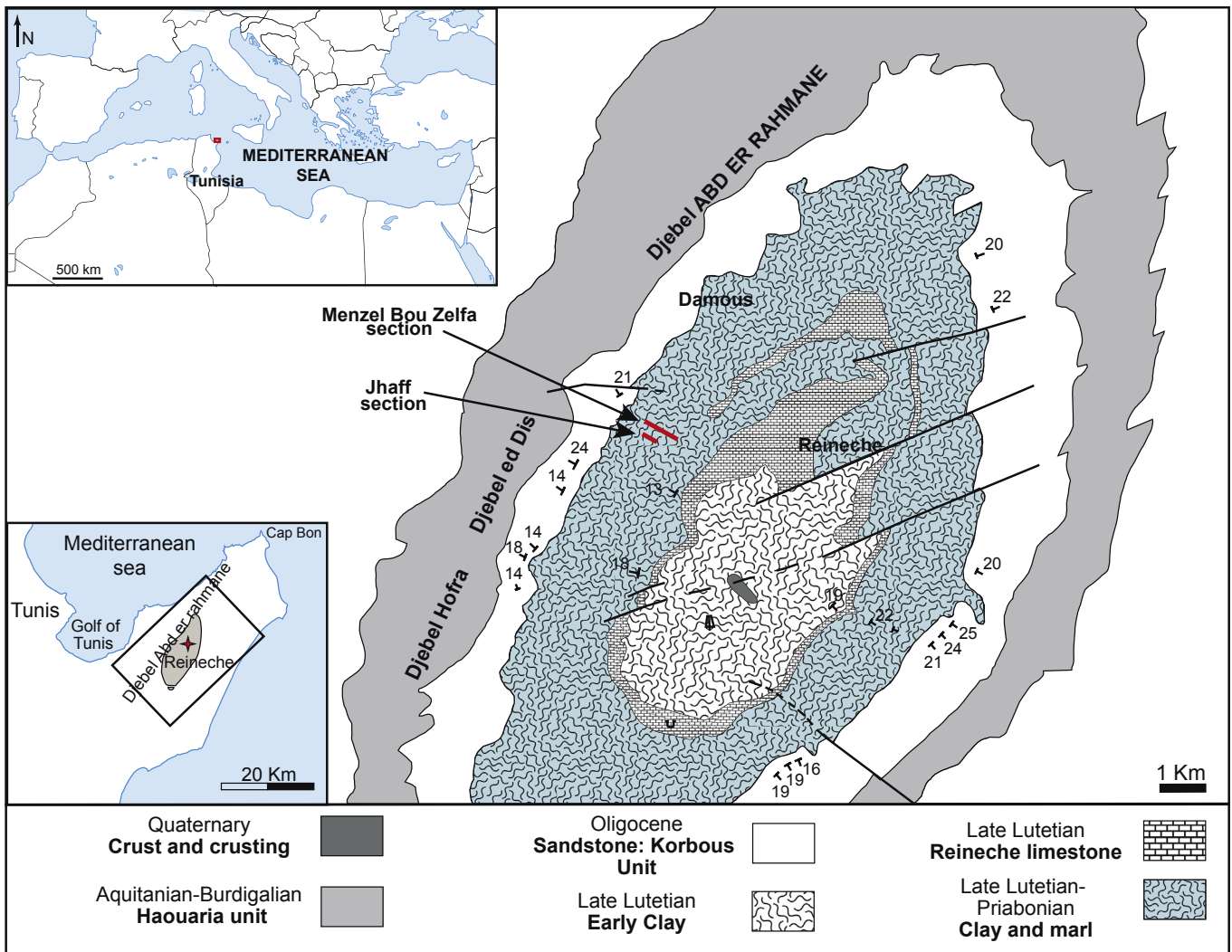


Fig. 1. Geographical and geological location of the Menzel Bou Zelfa and Jhaff sections.

all species of the genus *Hantkenina* and three species of *Turborotalia* (*T. cerroazulensis* Cole, *T. cocoaensis* Cushman, *T. cunialensis* Toumarkine and Bolli). At the same time, species such as *Pseudohastigerina micra* Cole, *P. naguwichiensis* Myatliuk, *Chilguembelina ototara* Finlay, *Streptochilus martini* Pijpers, and *Tenuitella praegemma* Li dominate the assemblages.

Above the E/O boundary, there is a gradual decrease in the influence of pelagic realm signaled by a decreased number of planktic foraminifera and a micro-faunistic undiversified association announced by a low value of species richness, 10 to 15 species per sample. According to Wade and Pearson (2008), a minor change in temperature can have an important effect on planktic foraminifera as their niches are closely grouped together and depend on the stratification of the water column.

Benthic foraminiferal species richness varies from 30 to 50 species per sample, represented mainly by calcitic test species such as *Bolivinoidea floridana* Cushman, *Brizalina antegressa* Subbotina, *Globocassidulina subglobosa* Brady, *Cibicidoides mundulus* Brady, Parker and Jones, *C. praemundulus* Berggren and Miller, *Oridorsalis umbonatus* Reuss and *Cyroidina girardana* Reuss. Indeed, the extinction of only two species (*Nuttallides truempyi* Nuttall and *Angulogerina muralis* Terquem) was observed across the E/O transition interval.

The dominance of the benthic foraminifera especially with the calcitic test, is recorded throughout the section (Fig. 3), such as *B. floridana*, *Br. antegressa* Subbotina, *Gl. Subglobosa* Brady, *C. mundulus* Brady, *C. praemundulus* Berggren and Miller, *O. umbonatus* Reuss, *G. girardana* Reuss, *C. eoacenus* Gümbel, *C. mexicanus* Nuttall, and representative species of tri-serial tests groups such as *Bulimina jarvisi* Cushman and Parker, *Bu. macilenta* Cushman and Parker, *Bu. jacksonensis* Cushman, *Bu. thanetensis* Cushman and Parker and *Bu. secaensis* Cushman and Stainforth.

On the other hand, the agglutinated test forms are less abundant (around 10%) and are represented by the species *Reticulophragmium amplexens* Gzybowski, *Valvulina peruviana* Cushman and Stainforth, *Rhodbamina samunica* Berry, *Ammodiscus* sp., *Karrierella* sp. The Miliolidae with porcelaneous tests are represented mainly by Spiroloculinidae and are very rare throughout the section.

## 5. Discussion

As foraminifera constitute the major protists in many marine ecosystems (Murray, 1991), we will discuss their role in the reconstruction of the paleoenvironment. Their potential for fossilization makes them good indicators of the physicochemical

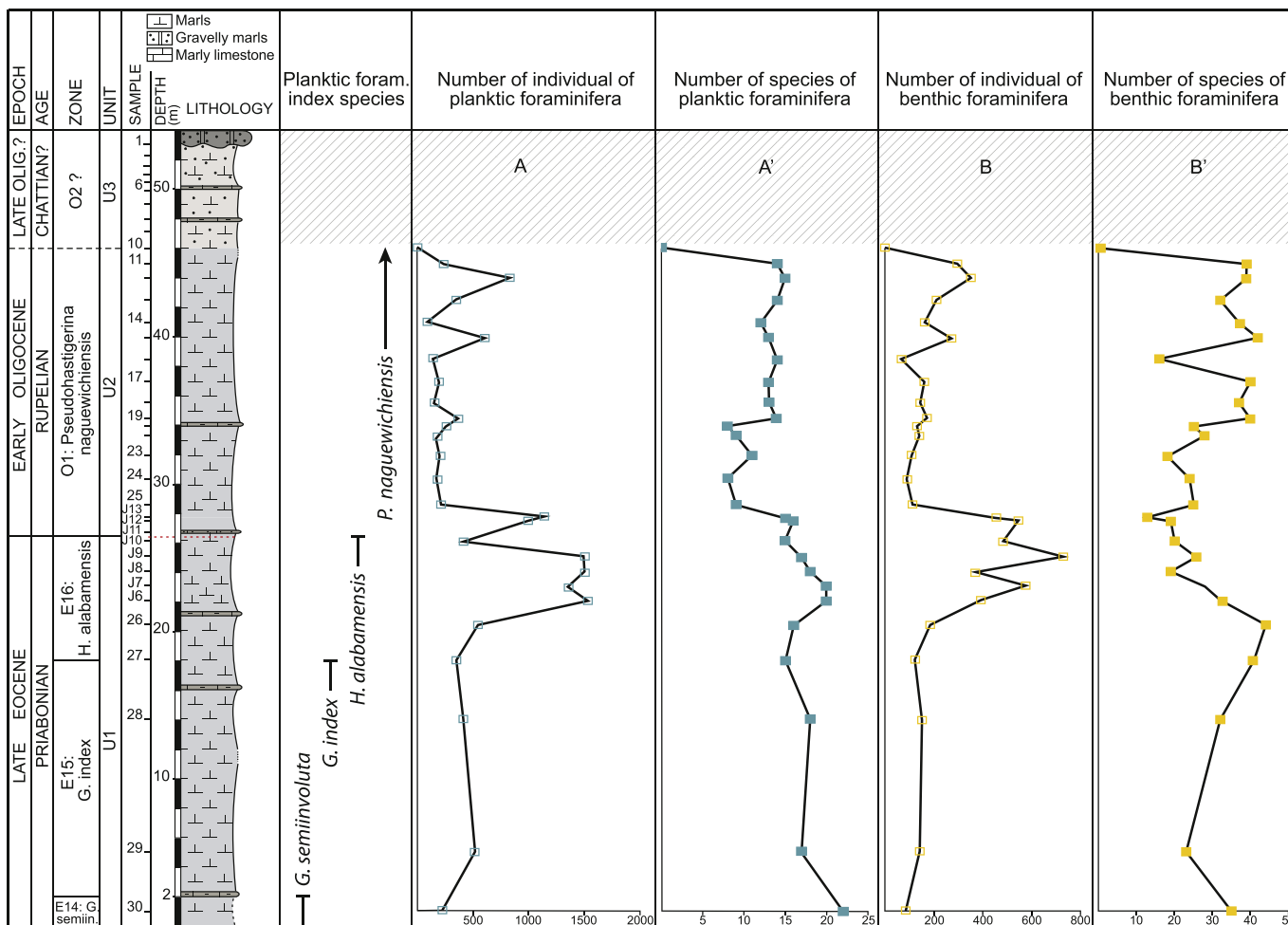


Fig. 2. Planktic foraminiferal biostratigraphy and specific richness of foraminifera.

conditions of deposition environment where they were buried. Changes in relative abundances and diversity have been used to infer changes in carbonate saturation state, oxygenation and food supply (Gooday, 2003).

The calcitic test assemblages found are typical of bathyal and abyssal environments; generally, the Bolivinidae, Buliminidae, Uvigerinidae and Cibicidoidae genera require bathyal environments (Holbourn et al., 2013). On the contrary, Gyroidinoidinae indicates an abyssal domain. We also noticed the coexistence of several species such as *C. mexicanus* Nuttall, *Bu. Jarvisi* Cushman and Parker, *C. grimsdalei* Nuttall, indicators of a low to median bathyal environment (Holbourn et al., 2013) (Fig. 3).

Furthermore, we identified cosmopolitan species which thrive in deep sea basins such as *Nuttallides umboniferus* rarely found on the Oligocene sediment, *Epistominella exigua* which was also rarely found on the Eocene and Oligocene sediment, and *Cibicidoides wuellerstorfi* which are distributed all along the section (Jorissen et al., 2007). However, below the E/O boundary we recorded the LO of the species *Nuttallides truempyi* which is proposed to reflect fluctuations in organic matter flux to the seafloor (meso-to eutrophic) under oxygenated bottom-water conditions. Indeed, it is one of the dominant lower bathyal-abyssal taxa with an age range of Late Cretaceous (Maastrichtian) to latest Eocene, which was reported in Molina et al. (2006), Berggren and Miller (1989) and Holbourn et al. (2013). *Angulogerina muralis*, which refer to the Eocene (Ortiz and Thomas, 2006; Molina et al., 2006) was also

found in this section and we marked the LO close to the E/O which was also reported in the Fuente Caldera section in Spain (Molina et al., 2006) (Fig. 3a).

The assemblages of small benthic foraminifera in Menzel Bou Zelfa and Jhaff sections are very diverse. Species with calcitic test are significantly the most dominant and have a very high frequency ranging from 85.63 to 100%. This percentage reflects sedimentation above the CCD. The quantitative study of benthic foraminifera species immediately below the E/O boundary (Fig. 4) shows the abundance of bathyal forms, the most important among them being *Br. antegressa* (around 8%) and *B. floridana* (around 6%). Moreover, we cannot exclude the presence of some foraminifera with calcitic test but typical of neritic environment such as Lagenidae and Lenticulininae (around 0.1–0.7%). Their presence is interpreted as the result of erosion of the shallow levels and thus transport from the platform to the bathyal environment. On the other hand, we noticed the presence of some agglutinated forms mostly represented by clavulinids, *Ammodiscus*, *Karrierella*, vulvulinids, and *Plectina* such as *Cyclamina cancellata*, *Ammodiscus incertus* and *Reticulophragmium amplexens*, which coincide with Alano section NE Italy (Agnini et al., 2011). These forms show relatively small percentages (about 0.05%).

Approaching the E/O boundary, the abundance of these agglutinated forms shows a slight increase, particularly of the species *Cyclamina cancellata*, which shows a maximum value 0.68% (Table 1). This increase is negligible compared to percentages of

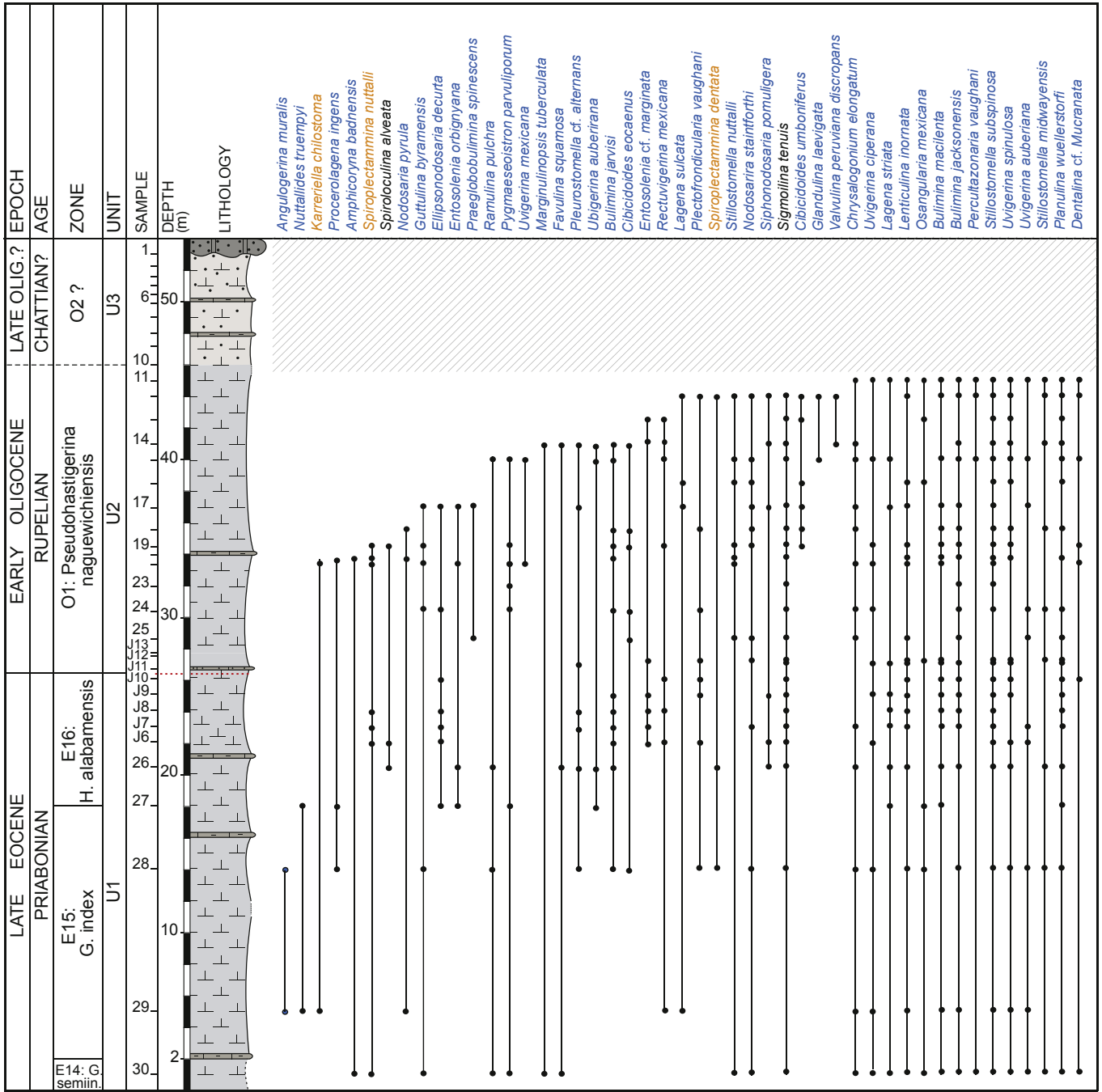


Fig. 3a. Stratigraphic distribution of benthic foraminifera species.

forms of hyaline tests that showed considerable ability to survive and thrive during the limit. While the frequency of species with hyaline tests increased steadily up to the upper part of the O1 Zone reaching a high frequency of around 98.3%.

This mixture of foraminifera, comprising 3 types of test, could be indicative of a decrease in sea level and an increase in erosion that caused the transport of certain non-native species from the platform to the bathyal domain. This decrease could be linked to the cooling and global glaciation characterizing the E-O transition (Molina et al., 2006). Approaches based on micro-organisms for the estimation of paleo-depth have been developed by determining the index of oceanicity which normally increases with depth (Bellier et al., 2010). The density of planktic foraminifera is therefore

maximal in open marine environments. Moreover, we have also used some species of benthic foraminifera considered to be indicator species for paleobathymetry (Nyong and Olsson, 1984; Van Morkhoven et al., 1986; Culver, 2003; Alegret and Thomas, 2004).

The index of oceanicity shows values close to 80% (Fig. 5) at the base of the series, decreasing to 40% at sample Jhaff 10. Indeed, the index marks some fluctuations in the last 30 m (from sample MBZ 26). The percentages of around 80% recorded at the base of the series indicate sedimentation in nearby bathymetries 200 m and more precisely the upper bathyal domain. This is confirmed by the presence of an association of planktic foraminifera typical of the surface dwellings and intermediate environments (Molina et al., 2006) such as *T. cunialensis*, *T. cocoaensis*, *Cr. inflata*, *H.*

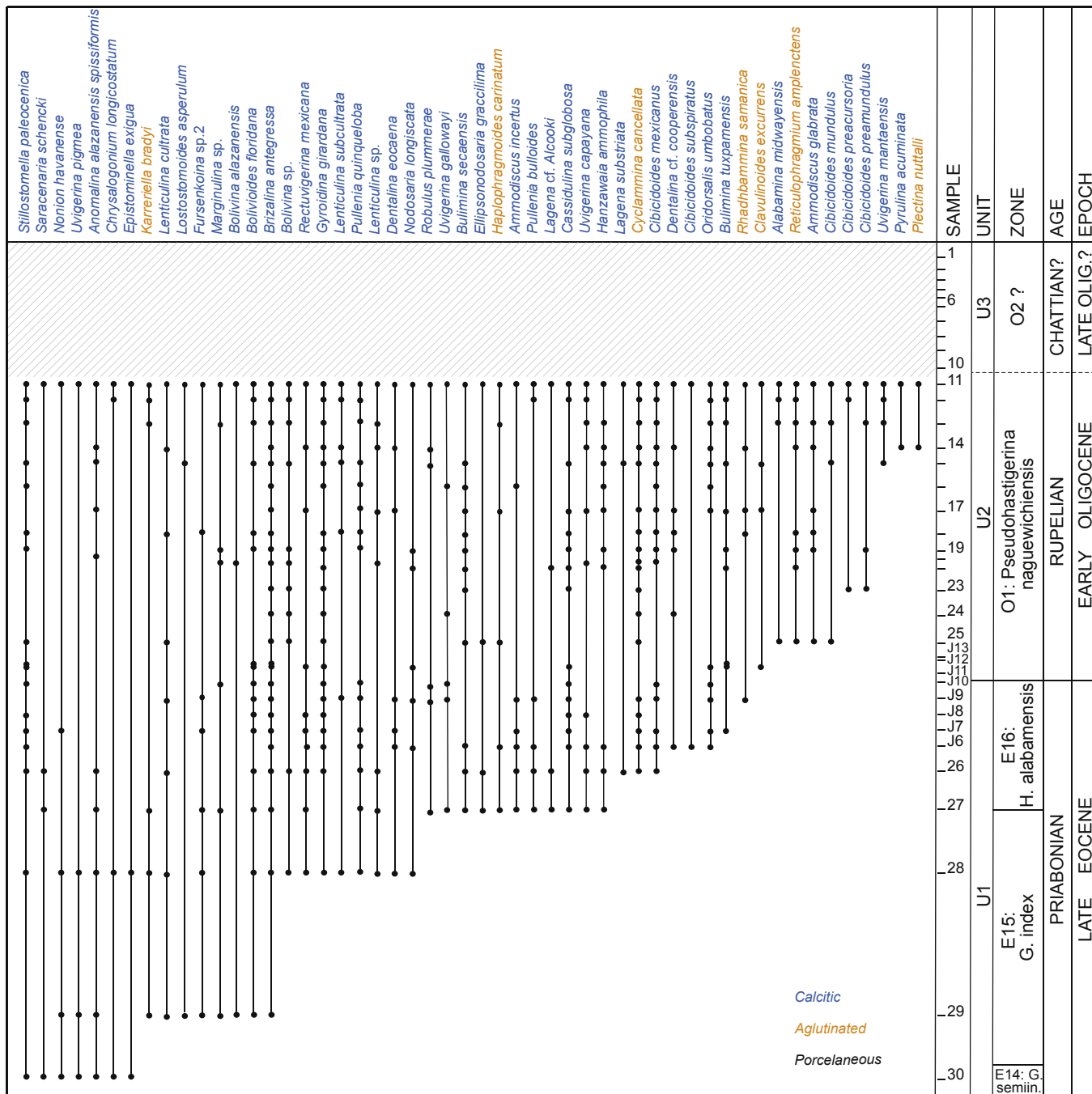


Fig. 3b. Stratigraphic distribution of benthic foraminifera species.

alabamensis, S. linaperta, S. corpulenta, S. eoacena that showed a relative abundance at the base of this series (Fig. 5). However, it should be noted that values below 80% indicating low bathymetries are probably related to a fall in the number of planktic foraminifera and therefore the state of preservation of these microorganisms. This reflects a disturbance of stratification of the water column caused by the decline in sea level. Moreover, the upheaval in the behavior of foraminifera is essentially due to the disappearance of the latest keeled forms and therefore a fall in the index of oceanicity at the E/O boundary. However, this change is followed by the development of typical forms of deep dwellings such as

D. pseudovenezuelana, D. tripartita, C. unicavus, Gl. suteri. At the same time, we note that the assemblages of benthic foraminifera are dominated by the calcitic test forms of the upper bathyal domain such as B. floridana, Br. antegressa, Gl. subglobosa, C. mundulus, O. umbonatus.

The abundance of benthic forms is continuous throughout the series, causing the decrease of the index of oceanicity, showing the eustatic variation during the late Eocene and the base of Oligocene. The relative fall of this index at the E/O boundary could indicate a decrease in sea level, from the decline of the sea spawned during global cooling.

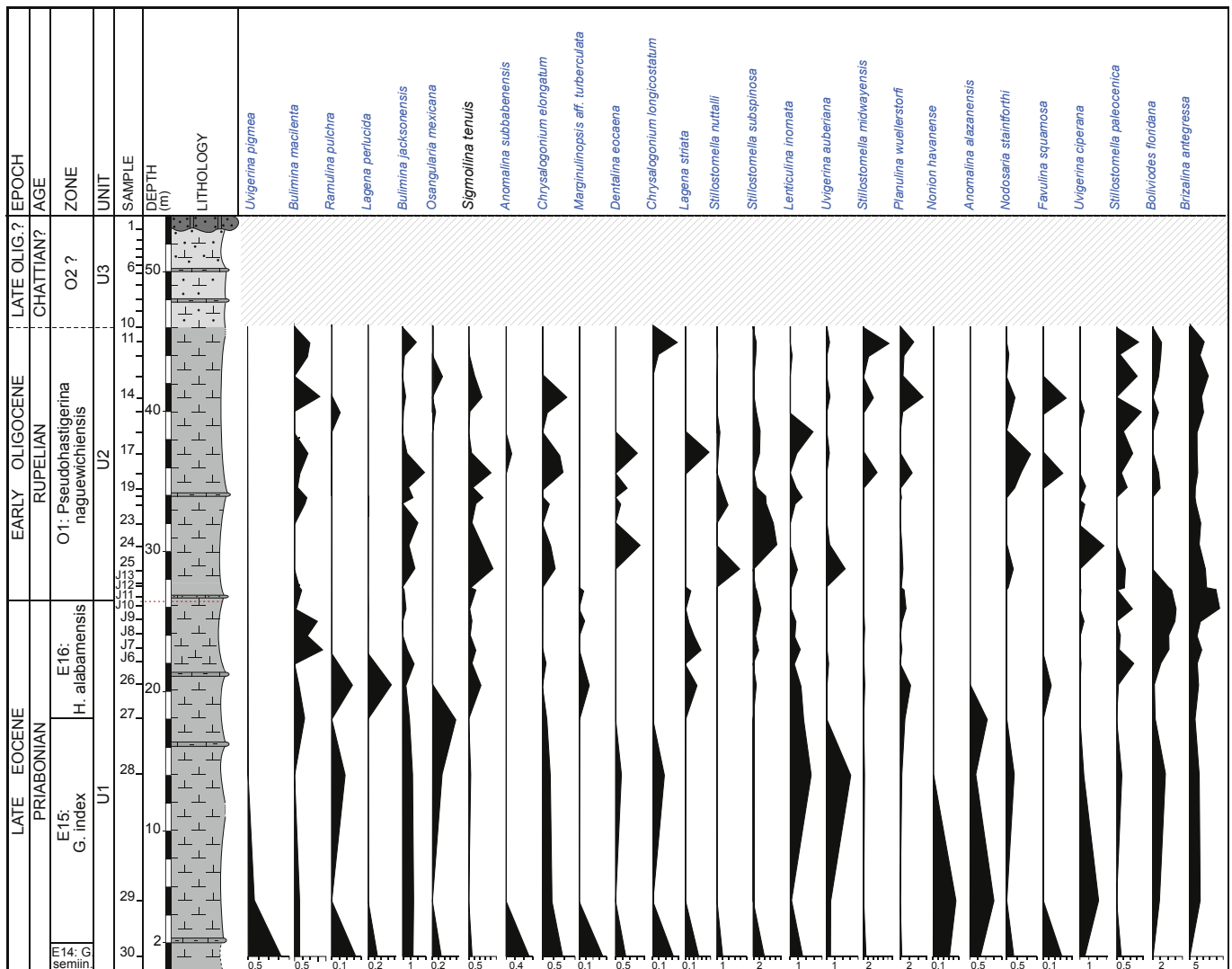


Fig. 4a. Relative abundances of the most common benthic foraminifera species.

Foraminifera have a rapid adaptation to environmental changes, a potential for fossilization and a strong correlation with the latitudinal distributions of surface temperatures, and the use of approaches based on the morphology of their test could provide an estimation of the paleotemperature and paleobathymetry (Murray, 1991). The change in the water column structure is mainly due to the variation of the thermocline, which is defined as the depth where we find the highest temperature transition. Even in the general case, the warm surface waters or deep thermocline favors the establishment of shallow dwellings with warm waters. However, the reduction in depth of the thermocline favors deep niches and forms that thrive in cold waters (Wade and Pearson, 2008).

In the section of Menzel Bou Zelfa and Jhaff, planktic foraminifera present a well-preserved test in all samples. At the base of the section, precisely in the E14, E15 biozones of *Gl. semiinvoluta* and *Gl. index*, we notice a major faunal change in the history of the evolution of planktic foraminifera, which involves paleoenvironmental implications in determining the Bartonian/Priabonian boundary (Fig. 5). These changes are manifested by the absence of keeled forms such as *Morozovelloides* and *Acarinina* that are abundant in low and middle latitudes (Agnini et al., 2011). In fact, these forms normally record the low values of  $\delta^{18}\text{O}$  and the greatest

values of  $\delta^{13}\text{C}$  and are typical of warm waters (Pearson et al., 1993, 2001; Norris, 1996). The absence of these typical forms of surface water, with no disruption of those living in deeper waters, generally reflects a drop in temperature or more precisely the cooling of surface waters.

According to Wade (2004), the extinction of these keeled forms may result from the destruction of their dwellings, due initially to sudden cooling of the thermocline. In addition, the drop in temperature is accompanied mainly by a decrease in the depth of the thermocline. These forms are therefore disturbed by the installation of a low temperature zone, meaning an inability to adapt to these conditions caused their major extinction. This structural change in the water column may also have impacts on the reproductive side of foraminifera, leading to a gradually decreasing frequency. This change was followed by the invasion of the mixed level by the genera *Hantkenina*, *Turborotalia* and *Subbotina* at the reduced level of the thermocline, and thus the change in the depth of their niches (Wade, 2004).

This extinction can be associated with several factors including the main cause, which is the inability of *acarininids* to overcome this temperature decrease. A small increase in the number of keeled forms on the upper Eocene at samples (J6, J7, J8, J9, MBZ 26, MBZ27,

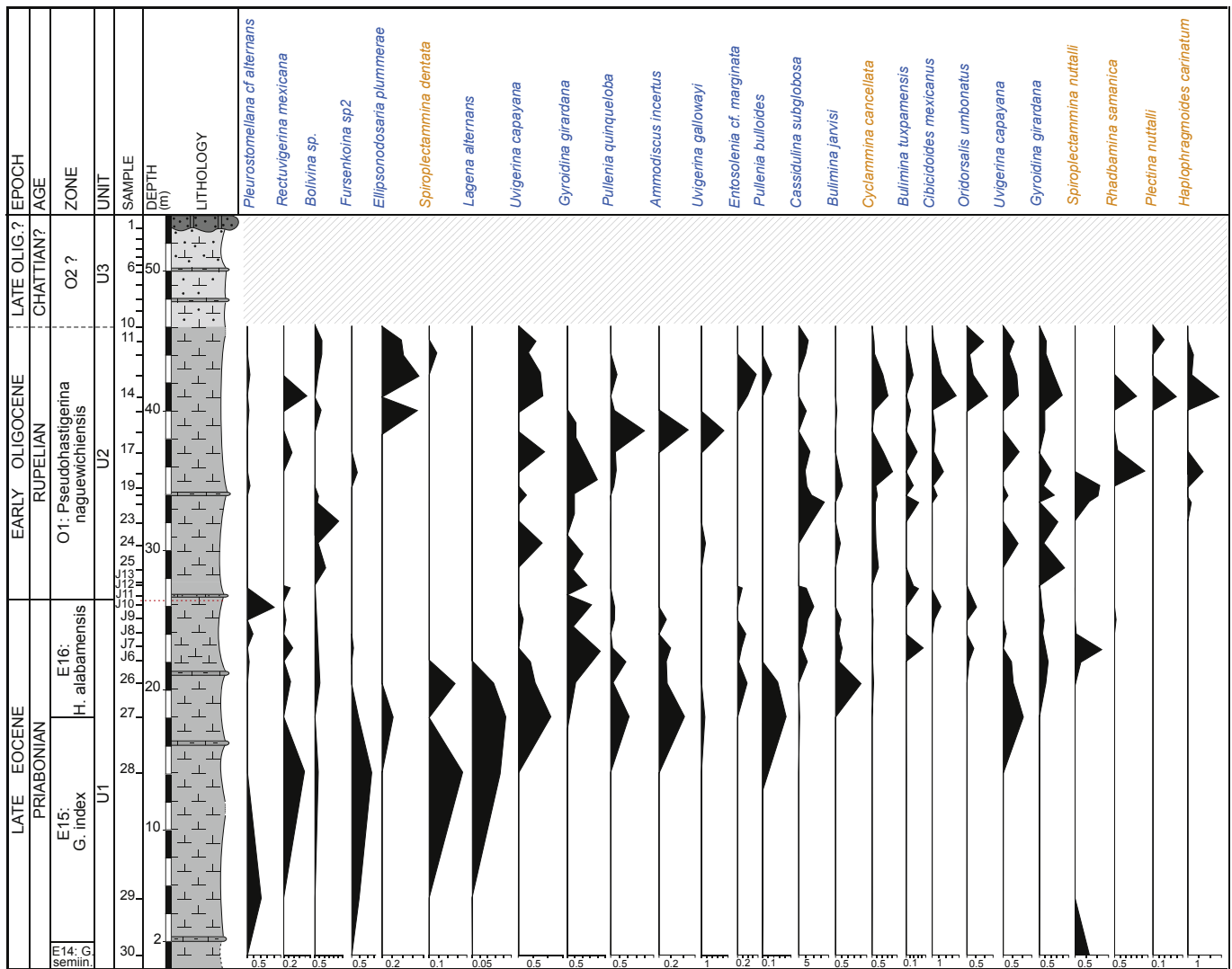


Fig. 4b. Relative abundances of the most common benthic foraminifera species.

MBZ28, MBZ 29) could be explained by a particular abundance of the species: *T. cunialensis*, *T. cocoaensis*, *T. cerroazulensis*, *H. primitiva*, *H. compressa*.

The top of the Eocene, precisely the top of the E16 zone, is characterized by the last appearance of five species of the genus *Hantkenina*, typical of surface dwellings; *H. compressa*, *H. primitiva*, *H. nanggulanensis*, *H. alabamensis* and *Cribohantkenina lazzarii*, is associated with the extinction of *T. cerroazulensis*, *T. cunialensis* and *T. cocoaensis*. According to Coxall and Pearson (2007), these species require the establishment of a warm climate with considerable oxygen levels, which explains their development during the Middle to Upper Eocene. In addition, Molina et al. (2006) pointed out that these species would be linked to a lower rate of  $\delta^{18}\text{O}$  and a high rate of  $\delta^{13}\text{C}$ , belonging to the group of low and middle latitudes reflecting a mixed level of warm water. Thus, the species which survived the beginning of the cooling would subsequently be affected by this event.

From the boundary, this extinction of tropical and subtropical forms is followed by an increase in the number of species belonging to the families Globigerinidae, Globoquadrinidae and the species *T. ampliapertura*. However, at the base of the Oligocene the species *S. corpulenta* and *S. eocaena* and the Globoquadrinidae

*Dentoglobigerina galavisi*, *Dentoglobigerina pseudovenezuelana* constantly increase in number. According to Wade and Pearson (2008), these species show high values of  $\delta^{18}\text{O}$  which reflect dwellings belonging to a deep cold thermocline. It should be noted that *Catapsydrax unicavus* which appears on the lower Eocene is one of the species that has shown a considerable abundance after the E/O boundary and is considered a good indicator of deep, cold environments (sub thermocline) (Pearson et al., 2001). Based on these data, some species are indicators of cold deep water. These species have survived despite the crisis by adapting to the new way of life; the others were not able to survive and underwent a major extinction.

However, we noticed the existence of a third group of foraminifera that was affected by this crisis but was able to adapt to these conditions, these are the *Pseudohastigerina* group. According to Wade and Pearson (2008), the species *Ps. naguewichiensis* is associated with values depleted in  $\delta^{18}\text{O}$ , indicating that it has been calcified in the mixed levels. Indeed we notice the existence of this species in the samples above the E/O boundary, but in the fractions less than 150  $\mu\text{m}$ , meaning it suffered an actual reduction in size. Furthermore, the species *Ps. micra* has been able also adapt to these conditions using a different strategy. Indeed, they are smaller than







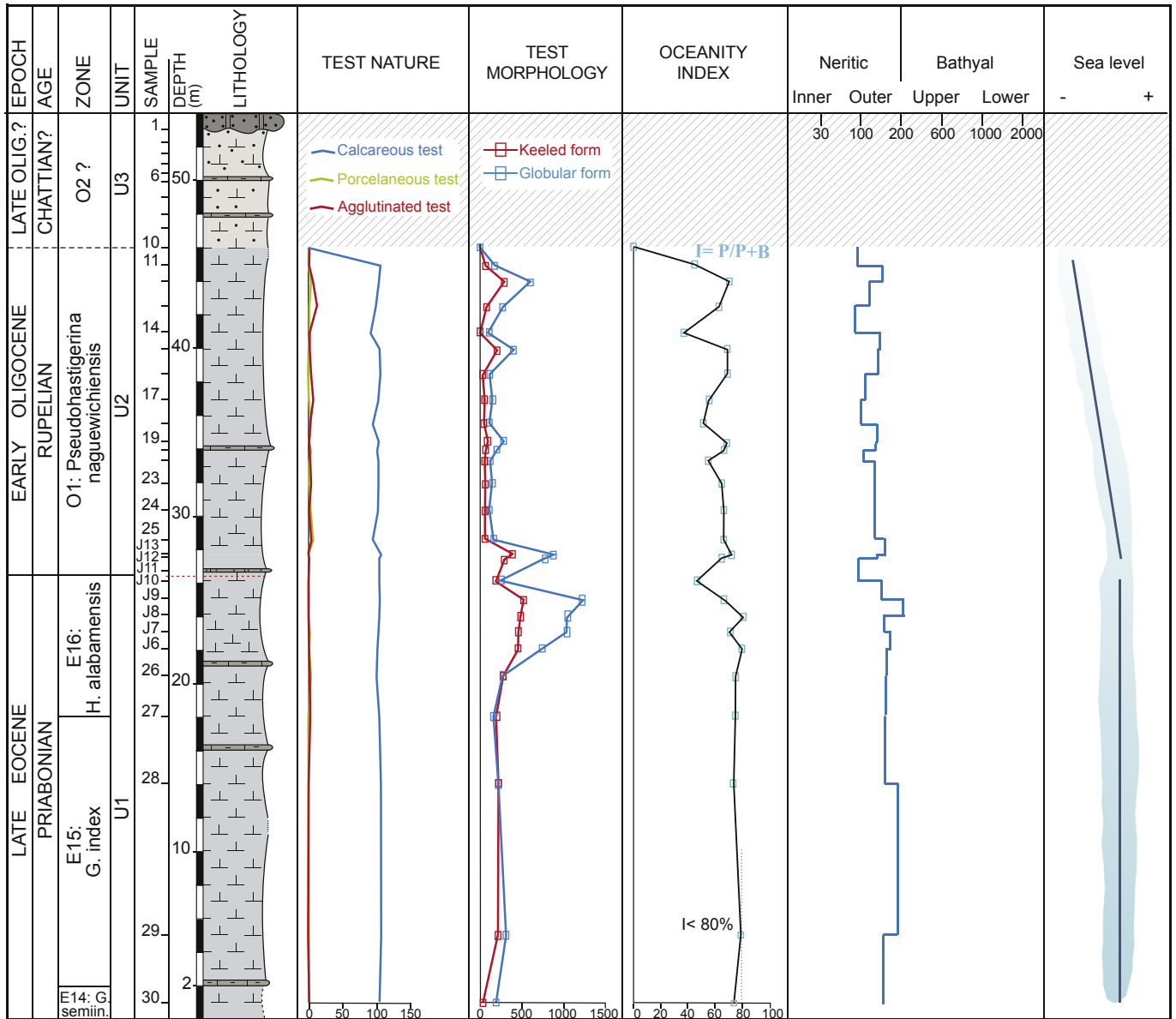


Fig. 5. Relative abundance of muricate and globular taxa, calcareous, agglutinated and porcelaneous taxa and the oceanity index.

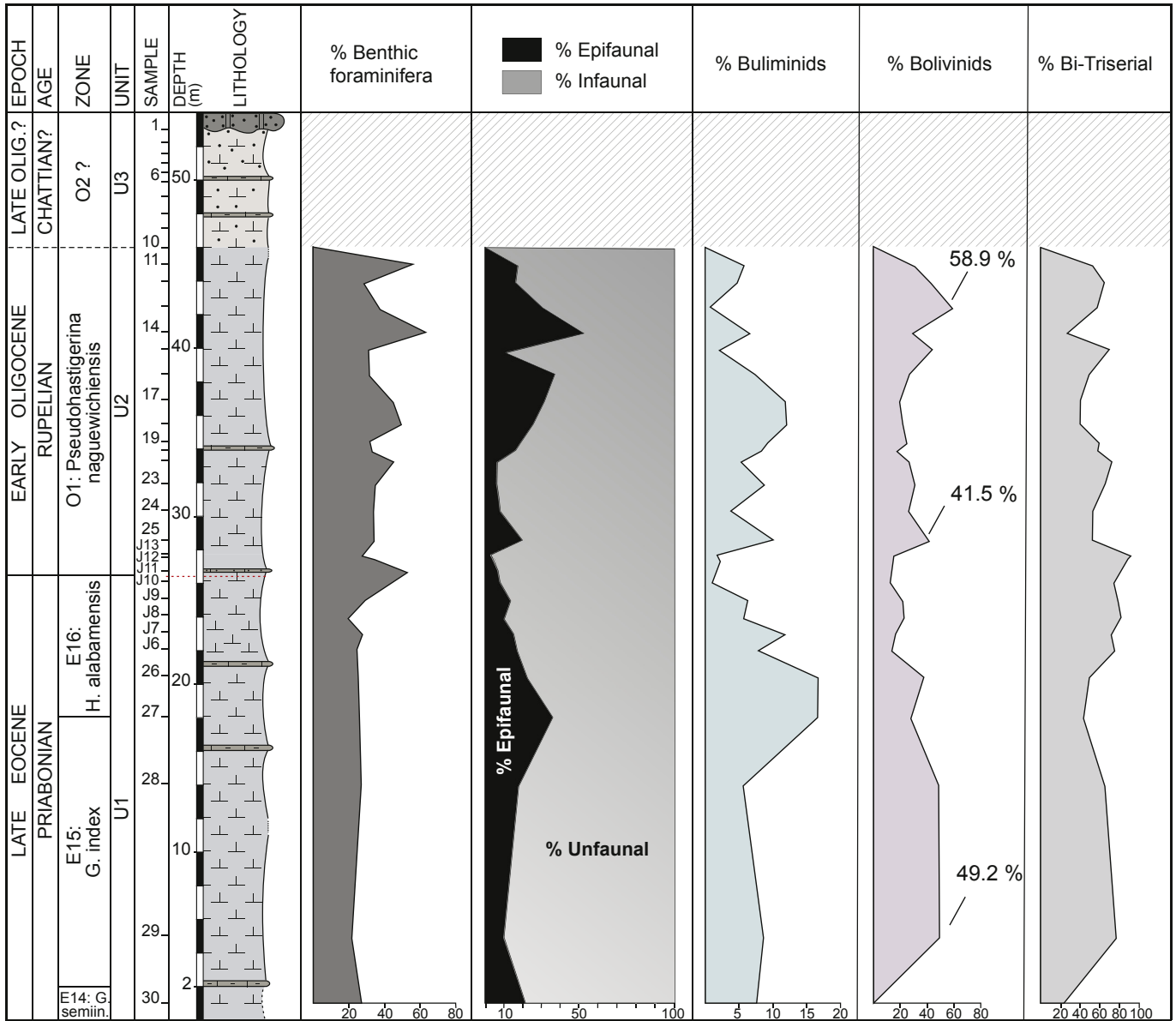


Fig. 6. Relative abundance of infaunal and epifaunal morphogroups.

150  $\mu\text{m}$  and are considered *Pseudohastigerina cf. micra* (see Plate 1).

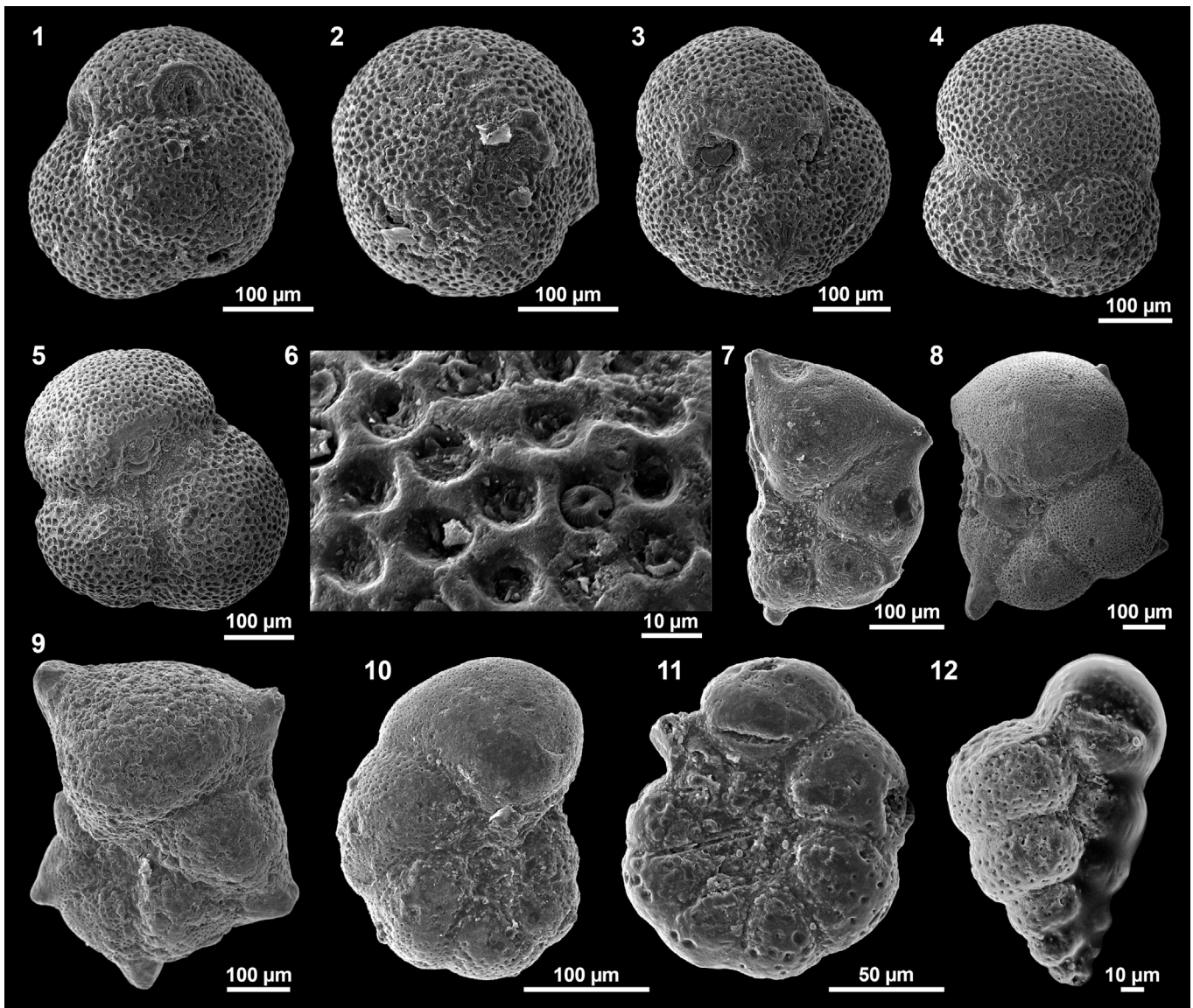
In conclusion, we can note a remarkable dominance of globular forms during the late Eocene to the Oligocene, adapting to the cold climate (Fig. 6). This can be explained by the instability of the environment in the tropical zones caused mainly by the decrease in temperature and thus the paleoecological changes of the foraminiferal habitat. These changes would likely be in conjunction with the predominance of glaciation in the high latitudes and a change in the circulation of deep waters (Wade and Pearson, 2008).

Due to their lifestyle, their ubiquity and richness in marine environments as well as their potential fossilization, benthic foraminifera are good markers of paleo-depth due to their ability to rapidly respond to environmental parameters. Based on the results obtained, it is noted that the benthic foraminifera assemblages reflect the variations in their relative abundances along the section, reacting to the cooling which starts at the upper Eocene. Below the boundary, there is a dominance of infaunal species characterized by

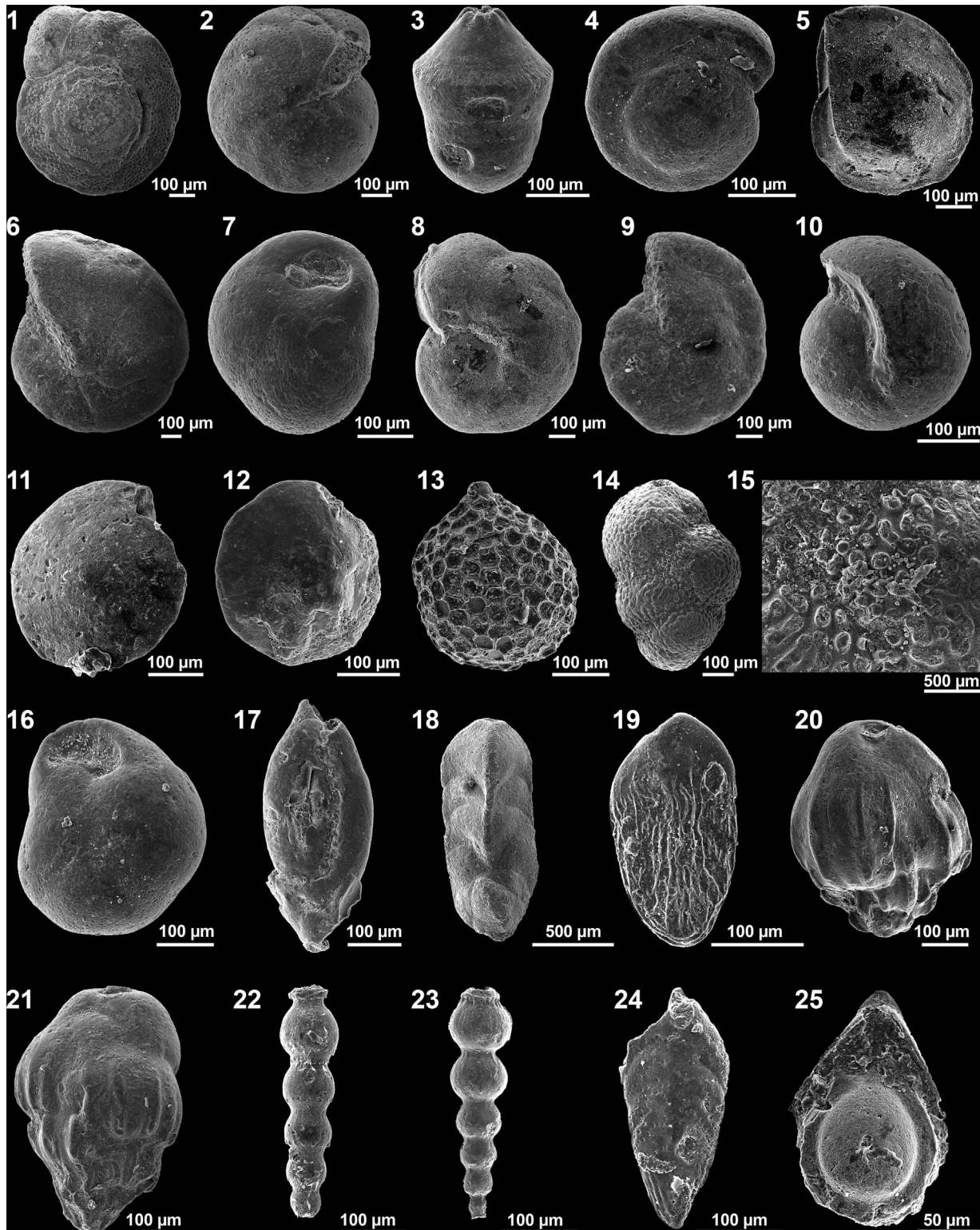
percentage around 80%, due particularly to the high frequency of Buliminids and Bolivinids. Their high abundance could be related to a significant transfer of the organic matter to the bottom of the sea as they proliferate in these environments (Molina et al., 2006; Alegret et al., 2008; Fenero et al., 2012) (see Plate 2).

As we approach to the E/O boundary, we notice that the diversity of the assemblages decline, reaching the lowest values. This decrease is partly due to a decline in relative abundance of rectilinear species with complex apertures (Pleurostomella, Buliminidae, etc.) (Thomas and Via, 2007; Bordiga et al., 2015). We noticed also a temporary decrease in abundance of buliminids reaching 1.03%, also reported by Miller et al. (1985), Thomas (1992), and Coccioni and Galeotti (2003) in the Massignano section.

The presence of infauna increases after the boundary, reaching a maximum value of about 89%. This abundance of infauna is due to the proliferation of the Bi and Tri-serial forms (Fig. 6). Therefore, we interpret a high relative abundance of the infaunal, triserial



**Plate 1.** 1–3: *Globigerinatheka semiinvoluta* KEIJZER. Zone E14. Sample MBZ30. 4–5: *Globigerinatheka index* FINLAY. Sample MBZ29. Zone E15. 6: *Globigerinatheka index* FINLAY. Sample MBZ29. Zone E15. 7: *Hantkenina alabamensis* CUSHMAN. Sample MBZ 27. Zone E16. 8: *Cribrohantkenina inflata* HOWE. Sample MBZ 27. Zone E16. 9: *Cribrohantkenina lazzarii*. Sample Jhaff 8. Zone E16. 10: *Pseudohastigerina micra* COLE. Sample MBZ 12. Zone O1. 11: *Pseudohastigerina nagewichiensis* MYATLIUK. Sample MBZ 12. Zone O1. 12: *Streptochilus martini* PIJPER. Sample MBZ 27. Zone E16.



**Plate 2.** 1–2: *Cibicoides mexicanus* NUTTALL. Sample MBZ15. Zone O1. 3: *Pseudoglandulina manifesta* REUSS. Sample MBZ29. Zone E15. 4: *Gyroidina girardana* REUSS. Sample MBZ29. Zone E15. 5: *Lenticulina inornata* D'ORBIGNY. Sample J12. Zone O1. 6: *Cyclammina cancellata* BRADY. Sample MBZ14. Zone O1. 7: *Globocassidulina subglobosa* BRADY. Sample MBZ16. Zone O1. 8: *Planulina wuellerstorfi* SCHWAGER. Sample J12. Zone O1. 9: *Reticulophragmium amplectens* GRZYBOWSKI. Sample MBZ12. Zone O1. 10: *Pullenia quinqueloba* REUSS. Sample MBZ28. Zone E15. 11–12: *Oridorsalis umbonatus* REUSS Cole. Sample J12. Zone O1. 13: *Favulina squamosa* MONTAGU. Sample MBZ30. Zone E14. 14: *Plectina nuttalli* CUSHMAN & STAINFORTH. Sample MBZ11. Zone O1. 15: *Plectina nuttalli* CUSHMAN & STAINFORTH. Sample MBZ11. Zone O1. 16: *Cassidulina caudriae* CUSHMAN & STAINFORTH. Sample MBZ13. Zone O1. 17: *Sigmoilina tenuis* CZJZEK. Sample J7. Zone E16. 18: *Clavulinoides eucarinatus* CUSHMAN & BERMUDEZ. Sample MBZ17. Zone O1. 19: *Coryphostoma midwayensis* CUSHMAN. Sample MBZ22. Zone O1. 20: *Bulimina macilenta* CUSHMAN & PARKER. Sample J12. Zone O1. 21: *Bulimina secaensis* CUSHMAN & STAINFORTH. Sample MBZ27. Zone E15. 22: *Stilostomella subspinosa* CUSHMAN. Sample MBZ22. Zone O1. 23: *Stilostomella paleocenica* CUSHMAN & TODD. Sample MBZ19. Zone O1. 24: *Brizalina antegressa* SUBBOTINA. Sample MBZ24. Zone O1. 25: *Entosolenia flintiana* CUSHMAN. Sample J8. Zone E16.

buliminids as indicative of a high food supply (Gooday, 2003; Bordiga et al., 2015). They are represented mainly by small size forms and smooth test or lightly ornamented by longitudinal costae, which generally explains a significant transfer of the potent supply to the bottom of the sea. Indeed, two peaks (around 50%) of Boliviniidae are recorded during the upper Eocene and at the E/O boundary. These peaks in fact correspond to an increase in the percentage of the species *Br. antegressa* and *B. floridana*, which are representative of bathyal domain. We suggest that this remarkable increase in the percentage of bolivinids is the response of benthic foraminifera to a local increase in the flux of organic matter to the sea floor. In parallel with the dominance of the infaunal group recorded throughout the section, we notice the presence of some epifaunal species also characteristic of bathyal domain such as *C. eocaenus*, *C. mexicanus*, *Planulina wuellerstorfi* and *Alabamina dissonata*.

This high influence of infaunal species typical of bathyal domains, markers of the environments with minimum oxygen and an important flow of organic matter (Gooday, 2003) such as *Bu. macilenta*, *Bu. jacksonensis*, *Bu. jarvisi*, *Br. antegressa*, *B. floridana*, *U. spinulosa* and *Glo. subglobosa* associated with a small percentage of epifaunal foraminifera (about 20%), undoubtedly indicates a bathyal environment with eutrophic conditions.

The assemblages of the benthic foraminifera found are the result of an accumulation of autochthonous and allochthonous forms, the latter being typical of neritic domains towards the deeper levels such *L. inornata*, *La. sulcata*, *Si. tenuis*, as well as the distribution of the organic substances in the bathyal zone. This mixture of forms could be related to the decrease in sea level at the beginning of the Oi1 glaciation, facilitating the transport of this shallow species towards deeper environments. The retreat of the sea is also accompanied by an increase in detrital elements observed from the sample MBZ 12.

Small benthic foraminifera do not show an extinction event at the E/O boundary, indicating that the benthic environment was not significantly affected. The extinction of *N. truempyi* is similarly not recorded up to the boundary, although it was considered a marker for the E/O boundary (Molina et al., 2006), possibly because the environment was not yet enough deep for this species to live in the section studied.

In the basal Oligocene O1 Zone, the small benthic foraminifera shows an apparently gradual pattern of extinction, which more likely could be a pattern of local disappearances caused by the decrease in temperature and depth. This pattern was not previously reported (Bolli et al., 1994; among others), although Hayward et al. (2010) suggested that it could be a benthic faunal turnover after the rapid E-O cooling event. The maximum glacial conditions occurred about 200 k.y. after the E/O boundary (Pearson et al., 2008). Consequently, this pattern of extinctions or disappearances could be caused by the Oi1 glaciation.

## 6. Conclusions

The detailed micropaleontological study of the samples of the Menzel Bou Zelfa and Jhaff section allowed us to establish different characteristics of the planktic and benthic associations of foraminifera, which meant we could reconstruct the paleoenvironment and highlight the global and regional eustatic changes.

The exploitation of all the micropaleontological data for planktic foraminifera led us to establish a regional scale of biozonation which we used to highlight the biological events recorded in the deposits of the E-O transition in accordance with the differential behavior of planktic and benthic foraminifera. In the biostratigraphic paper, we were able to recognize in the of Menzel Bou Zelfa and Jhaff section the following zones: E14. *Globigerinatheka*

*seminvoluta*, E15. *Globigerinatheka index*, E16. *Hantkenina alabamensis* for the late Eocene and zone O1. *Pseudohastigerina naguiewichiensis* for the lower Oligocene.

Based on a quantitative analysis and paleoecological preferences for planktic and benthic foraminifera, we have established a general paleoenvironment reconstruction during the Eocene. From the base to the top of the Menzel Bou Zelfa and Jhaff section, these analyses revealed that the associations of foraminifera are characteristic of a relatively warm climate with considerable oxygen content during the middle to late Eocene, whereas at base of Oligocene the data indicates a cooling of the climate.

The diversity of foraminifera reveals that the top of the Eocene is marked by a massive extinction event of a distinctive group of planktic foraminifera, probably caused by the decrease in temperature, bathymetry and reduction in depth of the thermocline. Nevertheless, the small benthic foraminifera do not show an extinction event at the E/O boundary, indicating that the benthic environment was not significantly affected. Similarly, the extinction of *N. truempyi*, which is considered a marker for the E/O boundary, is recorded at the boundary due to bathymetry.

In the basal Oligocene a clear dominance of infaunal morphotypes with calcitic test, especially the bolivinids, indicates bathyal domains with cold-water, eutrophic seas and oxygen minimum. In the basal Oligocene O1 Zone, the benthic environment is apparently affected by a gradual extinction event that could be caused by the Oi1 glaciation. The small benthic foraminifera show a gradual pattern of extinction, which more likely could be local disappearances caused by the decrease in temperature and depth. Consequently, further studies are necessary to confirm whether this pattern is a global extinction event or just a local pattern of disappearances.

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