

Planktic foraminiferal biostratigraphy, paleoecology and chronostratigraphy across the Eocene/Oligocene boundary in northern Tunisia

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Abstract

The biostratigraphic analysis of the Eocene-Oligocene transition of the Menzel Bou Zelfa and Jhaff sections in northeastern Tunisia (Cap Bon peninsula) allows us to identify a continuous planktic foraminiferal biozonation. The following biozones were recognized: *Globigerinatheka semiinvoluta* Zone (E14), *Globigerinatheka index* Zone (E15), (*Hantkenina alabamensis* Zone (E16) of the upper Eocene and *Pseudohastigerina naguwichiensis* Zone (O1) of the lower Oligocene. A rapid mass extinction event in planktic foraminifera occurred at the Eocene-Oligocene transition, including the extinction of the turborotalids (*Turborotalia cerroazulensis*, *Turborotalia cocoaensis* and *Turborotalia cunialensis*) followed by a significant size reduction of the genus *Pseudohastigerina* and the extinction of the hantkeninids (*Hantkenina alabamensis*, *Hantkenina brevispina*, *Hantkenina nanggulanensis* and *Cribrorhantkenina lazzarii*), which mark the Eocene/Oligocene boundary. These species were tropical and subtropical surface and intermediate dwellers, with distinctive morphologies (carinate turborotalids and spinose hantkeninids), which were well adapted species of k-strategy. The surviving planktic foraminifera species were quite similar in morphology with globular chambers (globigerinids) and small planispiral (pseudohastigerinids), which were opportunistic species of r-strategy. The recognition of a 4 m thick interval, between the extinction of turborotalids and hantkeninids, indicates that the section is continuous and one of the most expanded throughout the Eocene-Oligocene transition. This section could serve as an auxiliary section (hypostratotype) for the complete definition of the Global Stratotype Section and Point for the Eocene/Oligocene boundary, which mark the base of the Rupelian Stage.

Keywords: Planktic foraminifera; Eocene/Oligocene; Biostratigraphy; Paleoecology; Chronostratigraphy; Tunisia

1 Introduction

The Eocene-Oligocene (E-O) transition was an epoch of great turnover, in both terrestrial and marine environments. Mammals were highly affected by an extinction event called *grande coupure* of Stehlin, which has been very well documented in Europe and Asia ([Hartenberger, 1998](#)). In America the tropical molluscs underwent a significant extinction event at the beginning of the Oi-1 glaciation in the Oligocene ([Hickman, 2003](#)). This drop in temperature was caused by the opening of the Drake Strait, thereby giving rise to the circum Antarctic current, the formation of ice caps on the poles and the development of the psychrosphere in the deep ocean ([Shackleton and Kennett, 1975](#); [Kennett and Shackleton, 1976](#); [Barker and Thomas, 2004](#); [Livermore et al., 2005](#)). Evidence and causes of the Eocene/Oligocene event, based on extinction and survival patterns of foraminifera, were reviewed by Molina (2015, see other references herein).

In order to establish the precise chronology of the turnover at the E-O transition, as the Priabonian and Rupelian stage stratotypes duration was imprecise, the International Commission on Stratigraphy organized a working group in 1980 to define the Eocene/Oligocene (E/O) boundary, which officially corresponded to the base of the Rupelian Stage. This task was undertaken by the International Geological

Correlation Programme, Project 174 led by Charles Pomerol and Isabella Premoli Silva ([Premoli Silva and Jenkins, 1993](#)). The working group searched worldwide for suitable sections, mainly in Spain and Italy. Several sections were visited, sampled and studied in the Betic Cordillera, southern Spain and the proposed candidates were the Fuente Caldera section ([Molina, 1980, 1986; Comas et al., 1985](#)), the Torre Cardela section ([Martínez-Gallego and Molina, 1975](#)) and the Molino de Cobo section ([Molina et al., 1988](#)). These three sections showed an expanded stratigraphic interval based on planktic foraminifera, between the extinction of the turborotalids and the hantkeninids, spanning about 1 m in thickness, never previously found in other sections, but also found in the Massignano section in Italy ([Molina et al., 1986, 1993; Nocchi et al., 1988; Gonzalvo and Molina, 1992](#)). In the Massignano section this critical stratigraphic interval was less expanded, but when the section was multidisciplinary studied ([Premoli Silva et al., 1988](#)), other interesting data were found. Consequently, the Global Stratotype Section and Point (GSSP) for the base of the Oligocene (Rupelian) was defined at meter 19 of the Massignano section, coinciding with the extinction of the hantkeninids ([Premoli Silva and Jenkins, 1993](#)).

Since then the E/O boundary has been recognized worldwide and the biostratigraphy of the E-O interval has been improved. A revised geochronology and chronostratigraphy was proposed by [Berggren et al. \(1995\)](#) and a revised tropical and subtropical Paleogene planktic foraminiferal zonation was proposed by [Berggren and Pearson \(2005\)](#), Pearson et al. Eds. (2006) and [Wade et al. \(2011\)](#). The upper Paleogene deposits attracted the interest of some researchers in Tunisia, who were able to find the Eocene and lowermost Oligocene in north eastern and central Tunisia ([Ben Ismail-Lattrache, 1981, 2000; Boukhalfa et al., 2009; Amami Hamdi, 2014; Ben Ismail-Lattrache et al., 2014](#)), in Jordan ([Farouk et al., 2013, 2015](#)) and in Egypt ([Orabi et al., 2015](#)). However, they were never able to find the critical expanded interval of the E/O boundary.

The aim of this study was to search for an expanded continuous marine section crossing the E/O boundary in northern Tunisia. A composite section has been found in the Cap Bon peninsula: Menzel Bou Zelfa and Jhaff sections. The planktic foraminiferal biostratigraphy indicates that this composite section includes a very expanded critical interval between the extinction of the turborotalids and hantkeninids. Consequently, this section is suitable and could be a potential auxiliary section (hypostratotype) to complement the definition of the E/O boundary that was defined in the Massignano section, Italy.

2 Material and methods

2.1 Geological and geographical location

The Menzel Bou Zelfa section is located in the Cap Bon peninsula, north-eastern Tunisia, 36°43'30.22"N and 10°42'15.57"E. The section was sampled in the NE flank of the Jebel Abderrahman anticline that rises to 602 m in height. The stratigraphic series is essentially composed of marls, limestones and sands ranging in age from the middle Eocene to Quaternary ([Fig. 1](#)). The E/O boundary in this section was covered by vegetation and soil, preventing a detailed sampling. However, this interval appears very well exposed at the Jhaff section in the same area about 1 km southward, which is located between the coordinate points 36°42'16.44"N and 10°41'42.58"E. At this critical interval the samples, which are named J 6 to J 13, are located by correlation between samples MBZ 26 and MBZ 25.

MBZ 6	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 7	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 8	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 9	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 10	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 11	X	0	0	0	0,19	0	0	0,38	2,2	1,7	0	0	0
MBZ 12	X	0	0	0	0,2	0	0	0,4	0	3,5	0	0	0
MBZ 13	0	0	0	0	X	0	0	0,3	0	2,6	0	0	0
MBZ 14	X	0	0	0	0,3	0	0	0	5,5	7,9	0	0	0
MBZ 15	X	0	0	0	X	0	0	0,6	0	1,5	0	0	0
MBZ 16	0	0	0	0	X	0	0	7,2	2,4	1,9	0	0	0
MBZ 17	X	0	0	0	X	0	0	0	1,1	2,5	0	0	0
MBZ 18	X	0	0	0	0	0	0	1,3	0	7,4	0	0	0
MBZ 19	X	0	0	0	0	0	0	0,7	0,5	1,1	0	0	0
MBZ 21	X	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 22	0	0	0	0	0	0	0	0	0,3	0	0	0	0
MBZ 23	0.31	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 24	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 25	X	0	0	0	0	0	0	0,3	0	0	0	0	0
Jhaff 13	0	0	0	0	0,1	0	0	0,18	0,5	0	0	0	0
Jhaff 12	0.19	0	0	0	0,06	0	0	0,19	1,2	0,6	0	0	0
Jhaff 10	0	0	0	0	0	0	0	0	0,5	0	0	0	0
Jhaff 9	0	0	0	0	0	0	0	0	0,6	0	0	0	0
Jhaff 8	0	0	0,05	0	0,05	0,05	0	0,21	0,5	0	0	0	0
Jhaff 7	0	0	0,1	0	0	0,05	0	0,26	1,4	0,9	0	0	0
Jhaff 6	0	0	0	0	0,36	X	0	0	0,5	0,3	0	0	0
MBZ 26	0	0	0	0	X	0	0,27	0,27	0	2,6	0	0	0
MBZ 27	0	0	0,8	0	0	X	X	0	0	2,5	0	0	0
MBZ 28	0	0	0,3	0	X	0	0	0	0	0	0	0	0,8
MBZ 29	0	0.15	0,3	0	0	0	0	0	0	0,9	0	0	0,1
MBZ 30	0	0.32	0,32	0,3	0	0	X	2,9	4,5	5,8	1,6	1,9	1,9

	Chilguembelina ototara	Pseudohastigerina micra	Ps. nague-wichiensis	Subbotina eoacaena	Subbotina corpulenta	Subbotina jacksonensis	Subbotina angiporoides	Subbotina linaperta	Subbotina gortanii	Streptochilus martini	Tenuitella insolita	Tenuitella praegemma	Turborotalia increbescens	Turborotalia ampliapertura	Turborotalia cocoaensis
MBZ 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MBZ 11	2,4	9,5	2,4	4,94	6,65	X	0,76	0	0	4,94	0	0,57	0,95	X	0
MBZ 12	6,9	14,6	8,003	4,60	3,47	X	1,77	0	0	8,4	0	5,09	0,24	0,4	0
MBZ 13	14,5	10,7	2,6	5,37	3,22	X	0	0	X	11,11	0	0,89	0,17	0,71	0
MBZ 14	3,9	0,7	1,5	3,9	5,53	X	0,39	0	0	2,76	0	0	0	1,58	0
MBZ 15	10,8	10,4	12,6	5,68	3,18	X	4,2	0	0	9,32	0	0,79	0,45	X	0
MBZ 16	2,4	6,3	7,7	5,82	15,53	X	X	0	X	1,94	0	1,94	4,36	4,36	0
MBZ 17	3,3	5,3	8,3	8,65	7,26	X	X	X	0	2,51	0	3,91	1,95	1,11	0
MBZ 18	10,2	6,4	7,8	1,36	3,4	X	0	X	X	3,74	0	1,02	2,38	1,7	0
MBZ 19	11,9	9,04	7,5	2,95	8,11	X	X	0	0	9,04	0	0	1,6	3,5	0

MBZ 21	18,4	9,7	7,1	5,88	5,62	0	0	X	X	8,95	0	0	1,27	X	0
MBZ 22	5,1	10,2	10,6	3,85	5,78	0	0	0	0	9,64	0	0	1,92	0	0
MBZ 23	10,1	10,1	12,6	1,89	2,84	X	X	0	0	6,01	0	1,58	0,94	0,63	0
MBZ 24	21,7	8,1	15,9	1,55	1,94	X	X	X	X	12,06	0	0	0	X	0
MBZ 25	26,4	4	12	1,84	4,3	X	X	0	0,61	15,08	0	0	1,23	X	0
Jhaff 13	5,4	12,1	12,1	2	2,5	0	11,29	0	0,25	4,13	0	0	0,12	0,5	0
Jhaff 12	5,3	9,08	9,6	4,54	4,28	0	7,39	0	0,38	4,41	0	0	0	1,94	0
Jhaff 10	1,5	10,3	9,8	1,55	2,78	0	5,79	0	0,33	1,33	0	0	0,1	0,5	0
Jhaff 9	5,1	9,6	12,5	3,59	4,35	0	5,38	0	0,26	2,55	0	0	0,2	0,53	0
Jhaff 8	7,4	15,1	10,9	4,11	4,16	0	0,16	0	0,1	1,44	0	2,51	0,1	0,32	0
Jhaff 7	4,4	7,07	7,02	4,2	6,92	0,62	0,57	0,2	0,15	1,35	0	0,52	0,5	0,57	0
Jhaff 6	9,6	20,3	13,89	3,52	2,43	0,57	0	0,15	0,05	5,02	0	0	0,05	0	0,15
MBZ 26	7,8	15,2	12,47	9,86	11,51	X	0	0,13	X	3,97	0	0	0	X	2,6
MBZ 27	8,5	12,1	21,49	7,44	7,021	0	0	0	X	6,38	0	0	0,63	0	1,9
MBZ 28	6,9	14,8	15,25	2,48	5,67	X	X	0	0,35	17,38	1,41	0	0,17	0,17	0,35
MBZ 29	7,8	13,8	13,66	5,31	5,46	X	X	0	0,45	22,76	1,6	0	0,3	0,6	1,51
MBZ 30	0	0,6	0	14,84	13,55	X	2,58	6,45	0,96	0	0	0	1,9	0	3,2

3 Results

3.1 Lithostratigraphy

We subdivided the MBZ section into three lithostratigraphic units based on the facies lithological variations (Fig. 2). Unit U1 (MBZ 30-Jhaff 10) extends over 26 m and comprised friable marls, light grey in colour, occasionally interspersed with centimetric argillaceous reddish limestone beds and oxides rich in iron. The micropaleontological analysis delivered a well-developed foraminiferal association, diversified and well preserved. Planktic foraminifera in

this unit are represented by species belonging to the genera *Subbotina*, *Globigerinatheka*, *Globigerina*, *Turborotalia*, *Dentoglobigerina*, *Hantkenina*, *Cribrohantkenina*, *Catapsydrax*, *Pseudohastigerina*, *Tenuitella*, *Chiloguembelina*, *Streptochilus*, and *Globorotaloides*. In this unit, the Priabonian, which is largely developed in the Souar Formation was identified. Ben Ismail-Latrache (2000) recognized the *Globigerinatheka semiinvoluta* and the *Turborotalia cerroazulensis* Biozones and considered them as belonging to the Priabonian stage (see Fig. 3).

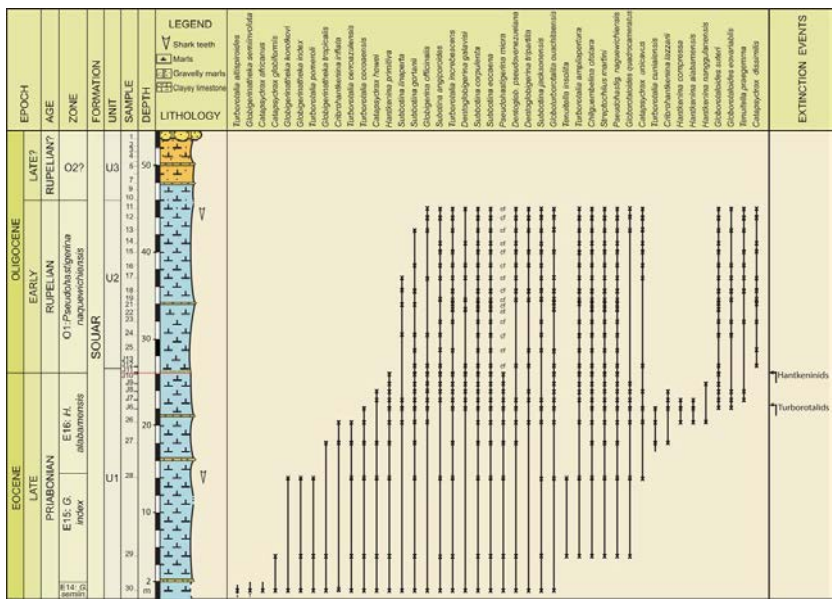


Fig. 2 Composite stratigraphical distribution of planktic foraminiferal species.

alt-text: Fig. 2

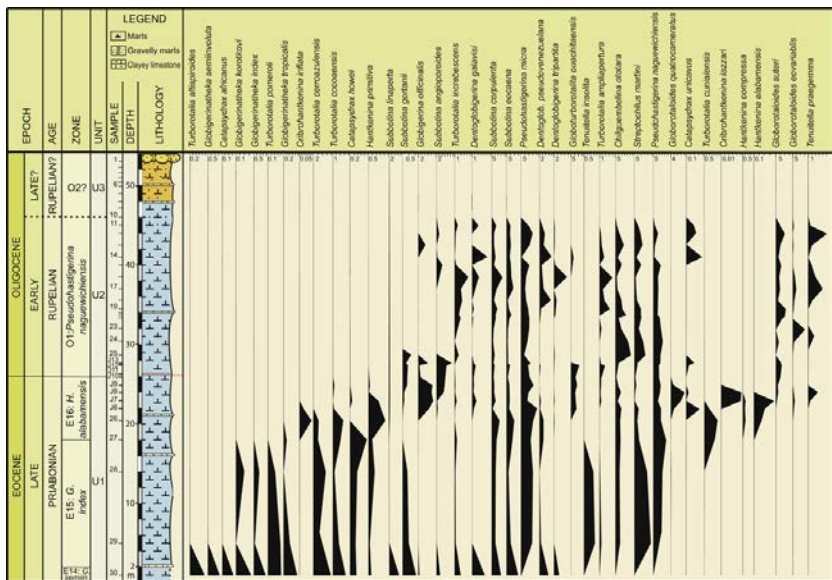


Fig. 3 Composite quantitative distribution of planktic foraminiferal species.

Unit U2 (MBZ 25–Jhaff 11) is 20 m thick and consists of marls dark grey in colour with a greenish shade, interspersed at the top by a centimetric level of indurated marl with ferruginous concretions. Sample J 11 is composed of a sandy limestone bed rich in iron oxides. This sample marks a transition to grey sandy marls. The Korbous unit, which refers to the Oligocene, overlies the late Priabonian clays. This was also reported by [Ben Ismail-Lattrache \(2000\)](#), who recognized the *Cassigerinella chipolensis*-*Pseudohastigerina micra*, “*Globigerina*” *ampliapertura*, “*Globorotalia*” *opima* and *Globigerina ciproensis* biozones. This unit is poor in planktic foraminifera and shows a remarkable reduction in the size of the taxa belonging to the *Pseudohastigerina* genus. The species found belong to the genera *Chiloguembelina*, *Pseudohastigerina*, *Streptochilus*, *Subbotina Turborotalia*, *Dentoglobigerina*, *Globorotaloides*, *Tenuitella*, *Globoturborotalita*, *Catapsydrax*, and *Globigerina*. Furthermore, it is characterized by the presence of shark's teeth. [Farouk et al. \(2015\)](#) recorded shark's teeth and phosphate particles in Jordan suggesting some reworking.

Unit U3 (MBZ 10-MBZ 1) is 10 m thick and begins with a sandstone bed of about 2 m thick, ochre in patina and yellow-to-beige in breakage and rich in bioturbation traces. Above this unit, light grey marl predominates, sometimes intercalated with small yellowish-to-brownish rust small levels rich in iron oxides. Planktic and benthic foraminifera are very rare, poorly preserved and it was extremely difficult to identify the species, having probably been reworked. [Boukhalfa et al. \(2009\)](#) found a similar unit on several sections in Northern Tunisia, composed of clayey sandstone, very rich in *Pecten arcuatus*, fossil plants, indicating a very shallow shelf environment with terrestrial influence. Consequently, its age is very uncertain and is likely to be upper Rupelian or Chattian.

3.2 Biostratigraphy

Due to their marine environment and their abundance or frequency in planktic foraminifera, the studied material has allowed us to recognize three biozones characterizing the upper Eocene and the lowermost zone of the lower Oligocene ([Fig. 2](#)).

The *Globigerinatheka semiinvoluta* Biozone, E14 (Highest occurrence zone) corresponds to the interval between the last occurrence of *Morozovelloides crassatus* and the last occurrence of the index taxon *Globigerinatheka semiinvoluta*. It corresponds to the top of the *Porticulusphaera semiinvoluta* Biozone, P 15 of [Berggren et al. \(1995\)](#). It is equivalent to the *Globigerinatheka semiinvoluta* Biozone of [Berggren and Pearson \(2005\)](#) and [Wade et al. \(2011\)](#).

The *Globigerinatheka index* Biozone, E15 (Highest occurrence zone) is the interval between the last occurrence of *Gl. semiinvoluta* and the last occurrence of *Globigerinatheka index*, according to [Berggren and Pearson \(2005\)](#) and [Wade et al. \(2011\)](#), although there is no interval corresponding to Zone P17. It is also equivalent to the upper part of the *Gl. semiinvoluta* Biozone and to the lower part of *Turborotalia cunialensis* and *Cribrohantkenina inflata* Biozone, P16 of [Berggren et al. \(1995\)](#).

The *Hantkenina alabamensis* Biozone, E16 (Highest occurrence zone) corresponds to the interval range between the last occurrence of *Gl. index* and the last occurrence of *H. alabamensis*, according to [Berggren and Pearson \(2005\)](#) and [Wade et al. \(2011\)](#). According to [Berggren et al. \(1995\)](#) it coincides with the upper part of *Turborotalia cunialensis* and *Cribrohantkenina inflata* Biozone, P16 and to the *T. cerroazulensis* Biozone, P17.

The *Pseudohastigerina nagewichiensis* Biozone, O1 (Highest occurrence zone) corresponds to the interval range zone between the last occurrence of *H. alabamensis* and the last occurrence of *Ps. nagewichiensis*, according to [Berggren and Pearson \(2005\)](#) and [Wade et al. \(2011\)](#). It correlates to the *Turborotalia cerroazulensis*/*Pseudohastigerina* spp. Biozone, P18, according to [Berggren et al. \(1995\)](#).

4 Discussion

4.1 Biostratigraphy

The biostratigraphical analyses were carried out in order to better know a relevant planktic foraminiferal time interval across the Eocene/Oligocene boundary. The stratigraphic distributions of the most significant species shown in [Fig. 2](#) lead to the recognition of four biozones and their correlation to similar zones previously established by other authors.

In the studied section we did not find the relevant extinction event of the large muricate planktic foraminifera, such as *Acarinina* and *Morozovelloides* ([Wade, 2004](#)), which is well represented in the Torre Cardela section, Spain ([Gonzalvo and Molina, 1996](#)), the Alano section, Italy ([Agnini et al., 2011](#)) and characterizes the Bartonian-Priabonian transition ([Wade et al., 2012a](#)). The lowermost part of the Menzel Bou Zelfa section corresponds to the uppermost part of the E14 biozone (middle Priabonian).

The basal part of the section, up to 18 m, can be assigned to the upper part of the biozone E14 defined by the last occurrence of *M. crassatus* at the base and the last appearance of *G. semiinvoluta* at the top ([Berggren and Pearson \(2005\)](#); [Pearson et al., 2006](#)). This biozone is overlain by the biozone E15, the top of which is marked by the extinction of *G. index* [Berggren and Pearson \(2005\)](#); [Molina et al., 2006](#); [Wade and Pearson, 2008](#); [Wade et al., 2011](#)). These two biozones were also found in several sections in Spain ([Martínez-Gallego and Molina, 1975](#); [Molina, 1986](#); [Molina et al., 1986, 1988, 1993, 2006](#)), in Italy ([Nocchi et al., 1988](#); [Premoli Silva et al., 1988](#); [Gonzalvo and Molina, 1992](#)) and in Tanzania ([Wade and Pearson, 2008](#); [Pearson et al., 2008](#)).

A major extinction event of planktic foraminifera occurred across the E/O boundary. Indeed, just below the boundary, in the upper part of the Biozone E16 (sample J 6) there is a sudden extinction of three species belonging to the *Turborotalia* genus: *T. cerroazulensis*, *T. cocoaensis* and *T. cunialensis*. They disappear 4 m below the Eocene/Oligocene boundary, which is marked by the extinction of hantkeninids, the event used to officially define this boundary by Premoli Silva and Jenkins (1993). The interval between the extinction of the turborotalids and hantkeninids was also recorded in the boundary stratotype section in Massignano, Italy (Nocchi et al., 1988; Premoli Silva et al., 1988; Gonzalvo and Molina, 1992) spanning only 0.4 m. The extinction pattern across the E/O boundary can be considered a rapid mass extinction event (Molina, 2015).

At the top of the E16 zone, we found the extinction of the last species belonging to the Family Hantkeninidae: *Hantkenina primitiva* and *H. alabamensis* (very rare in the uppermost part); the other species: *Hantkenina compressa*, *Hantkenina nangulanensis* and *Cribohantkenina lazzarii* became extinct just below. However, the highest occurrence of *Cribohantkenina inflata*, characterized by very inflated globular chambers, is questionable, in our section it became extinct just above the extinction of *Globigerinatheka index*, in the lower part of the zone E16 and did not reach the E/O boundary. On the other hand, Wade and Pearson (2008) and Berggren and Pearson (2005), did not recognize *C. lazzarii*, with the rugose square chambers; they considered it a junior synonym of *C. inflata* and indicated a simultaneous extinction of *Hantkenina* and *Cribohantkenina inflata*.

Furthermore, we note that other species belonging to the *Pseudohastigerina* genus underwent a major turnover, the larger ones becoming extinct at the E/O boundary and the smaller ones surviving into the Oligocene. It is remarkable that the genus *Pseudohastigerina* apparently shows dwarfing synchronous with the *Hantkeninidae* extinction (Miller et al., 2008; Wade and Pearson, 2008). *P. naguwichiensis* survived through the boundary and rare specimens of *P. micra* are present in the Oligocene, but they are smaller than 150 µm and are considered *Pseudohastigerina* cf. *micra*. Those biostratigraphic data are consistent with the Fuente Caldera section in southern Spain (Molina et al., 2006), the Tanzania section (Wade and Pearson, 2008; Pearson and Wade, 2015) and the Noroña section in Cuba (Molina et al., 2016).

On the other hand, we noticed that some species are found to survive above the E/O boundary, such as *Subbotina gortanii*, *Subbotina angiporoides*, *Subbotina eocaena*, *Subbotina corpulenta*, *Catapsydrax unicavus*, *Globoturborotalita ouachitaensis*. At the base of the Oligocene, five other species recorded a relative abundance in number of individuals. These species are *Dentoglobigerina tripartita*, *Dentoglobigerina galavisi*, *Dentoglobigerina pseudovenezuelana*, *Turborotalia ampliapertura* and *Turborotalia increbescens* (Table 1).

Subbotina jacksonensis and *Catapsydrax howei* are identified consistently during the middle to late Eocene. They disappear at the E/O boundary, unlike to some other Globigerinidae. According to Berggren and Pearson (2005), *Catapsydrax howei* and *Subbotina jacksonensis* became extinct at the same time, in the top of the E16 biozone. However, in our study we noticed that *Catapsydrax howei* disappears just before *Subbotina jacksonensis*, which continue to the uppermost Eocene and became extinct at the same time as the *Hantkeninidae*.

Furthermore, Molina (1980, 1986, 2015) noted that in the Betic Cordillera the species *Catapsydrax dissimilis* was never found in the upper Eocene and appears in the base of the Rupelian stage. However, this species was found by Berggren and Pearson (2005) from the late Eocene, continued in the Oligocene, and was considered a survivor species. In MBZ and Jhaff sections, we identified the lowest occurrence of this species in the first biozone of the Oligocene, similar to what happened in the Betic Cordillera, Spain.

4.2 Paleocology

In addition to their utility in biostratigraphy, the sequence of assemblages of the planktic foraminifera provides paleoecological data about the water column structure (Coxall and Pearson, 2007; Pearson et al., 2008; Alegret et al., 2008). The quantitative analysis of the planktic foraminifera in the Menzel Bou Zelfa and Jhaff sections (Table 1) shows that these pelagic forms are present and constantly abundant throughout the section except in a few turbiditic levels (Fig. 4)(Fig. 3). Indeed, just below the Eocene/Oligocene boundary, the planktic foraminifera are represented mainly by typical species of the intermediate surface dwelling, such as *Turborotalia pomeroli*, *T. cocoaensis*, *T. cunialensis*, *T. cerroazulensis*, *T. ampliapertura*, *Globigerinatheka tropicalis*, *H. compressa*, *H. primitiva*, *H. alabamensis*, *Cr. inflata*, *Cr. lazzarii*, *Ps. naguwichiensis*, *Ps. micra*, *D. galavisi*, *S. eocaena*, *S. corpulenta*, *S. linaperta*, *S. jacksonensis*. This assemblage of tropical species (such as *T. cocoaensis* and *T. cunialensis*) and subtropical species (*Ps. naguwichiensis*) in fact reflects a favorable environment for the development of these species, among which the most abundant are *S. corpulenta*, *S. eocaena*, *Ps. micra* (about 10-15%), which require intermediate dwelling (see Plate 1).

EPOCH	AGE	This study		Berggren et al.(1995)	Berggren & Pearson (2005)	Wade et al. (2011)	
		BIOZONES	Planktic foraminifera				
Oligocene	Rupelian	O1		P18	<i>T. ampliapertura</i> IZ	O1	<i>P.naguewichiensis</i> HOZ
	Eocene	E16		P17	<i>T.corroazulensis</i> IZ	E16	<i>H.alabamensis</i> HOZ
		E15		P16	<i>T.cunialensis</i> / <i>Cr.inflata</i> CRZ	E15	<i>G.index</i> HOZ
		E14		P15	<i>Po.semiinvoluta</i> IZ	E14	<i>G.semiinvoluta</i> HOZ

Fig. 4 Biostratigraphic correlation across the Eocene/Oligocene boundary.

alt-text: Fig. 4



Plate 1 Photographs A-C: *Globigerinatheka semiinvoluta* KEIJZER. Sample MBZ30. Zone E14. Scale bar = 100 µm. D-F: *Globigerinatheka index* FINLAY. Sample MBZ 29. Zone E15. Scale bar = 100 µm. G-I: *Turborotalia cocoaensis* (CUSHMAN). Sample MBZ 27. Zone E16. Scale bar = 50 µm. J-L: *Turborotalia cunialensis* (TOUMARKINE ET BOLLI). Sample MBZ 26. Zone E16. Scale bar = 100 µm. M, N: *Cribohantkenina inflata* (HOWE). Sample MBZ 27. Zone E16. Scale bar = 100 µm. O-Q: *Cribohantkenina lazzarii* (PERICOLI). Sample Jhaff 8. Zone E16. Scale bar = 100 µm. R-T: *Hantkenina alabamensis* CUSHMAN. Sample MBZ 27. Zone E16. Scale bar = 100 µm. U: *Streptochilus martini* PIJPERS. Sample MBZ 27. Zone E16. Scale bar = 50 µm. V: *Pseudohastigerina micra* (COLE). Sample MBZ 12. Zone O1. Scale bar = 50 µm. W: *Pseudohastigerina naguewichiensis* MYATLIUK. Sample MBZ 12. Zone O1. Scale bar = 50 µm.

Approaching the boundary E/O, the percentages of typical surface dwellers decline and this change was characterized by the extinction of a major number of foraminifera species which characterizes the tropical climate, such as the species of the genus *Turborotalia* (*T. cerroazulensis*, *T. cocoaensis*) and the *Hantkeninidae* family and the species *S. linaperta*. These changes were also accompanied by a relative decrease in the number of *Ps. nagewichiensis* of size greater than 150 µm, reflecting a significant change in the ecology of the environment in accordance with the cooling of the sea surface (Wade et al., 2012b). Furthermore, at the Eocene/Oligocene boundary, the curves of frequency show a slight decrease in the frequency of most forms except some species such as *Ch. ototara* and *St. martini*, which are considered indicators of stress (Gebhardt et al., 2013).

Other species were found consistently through the section and survived despite these climate changes, such as *T. ampliapertura*, *D. pseudovenezuelana*, *D. galavisi*, *D. tripartita*, *T. increbescens*, *C. unicavus*, *Ps. micra*, *Ps. nagewichiensis*, *S. eocaena*, *S. corpulenta*, with increasing abundance in all Oligocene samples and are considered opportunistic species. On the other hand, the base of the Oligocene is a suitable environment for these opportunistic species that showed a slight decrease in percentage just below the E/O boundary. The considerable increase in their frequency reflects a drop in the temperature of the surface water and therefore an expansion of the global volume of ice culminating in the Oi-1 glaciation. The global climate decrease in temperature during the upper Eocene was triggered by the opening of the Drake Strait, the isolation of Antarctica, the albedo effect, the formation of the circum Antarctic current and the psychrosphere (Shackleton and Kennett, 1975; Kennett and Shackleton, 1976; Kennett, 1977; Barker and Thomas, 2004; Livermore et al., 2005).

4.3 Chronostratigraphy

The E/O boundary was formally defined by the Rupelian GSSP at meter 19 of the Massignano section in Italy, coinciding precisely with the hantkeninids extinction (Premoli Silva and Jenkins, 1993). The E/O boundary was dated as 33.9 Ma (Vandenberghé et al., 2012). The sediments of the Massignano section are pelagic marine with no evidence of any hiatus, but the uppermost Eocene is characterized by a 0.4 m thick condensed interval between the extinction of the turborotalids and the hantkeninids. Another section in Italy, the Monte Cagnero section, was proposed as a potential parastratotype for the Massignano global stratotype section and point (GSSP) due to its good integrated stratigraphic and astrochronological calibration of the Eocene-Oligocene transition (Hyland et al., 2009), although the interval is similarly condensed.

The recognition of this interval in the Tunisian section is a very relevant finding because it is 4 m thick and is one of the most expanded known to date (Fig. 4). Only in Tanzania is this interval more expanded, since it is 5.2 m thick and its duration was estimated at 65 ky (Pearson et al., 2008). In the Fuente Caldera, Torre Cardela and Molino de Cobo sections in the Betic Cordillera, southern Spain, this interval is 1.2 m thick and its duration has been estimated at 40 ky (Molina, 2015). Nevertheless, in Jordan Farouk et al. (2013, 2015) found a hiatus missing this interval.

Auxiliary sections should be proposed in order to improve the definition of the E/O boundary. These auxiliary sections, also known as hypostratotypes, must be placed in different regions to better correlate the E/O boundary worldwide. The most expanded and continuous sections known so far are located in Tanzania (drilling site 12), Spain (Fuente Caldera section) and Tunisia (Jhaff section), which are very suitable and should be proposed as auxiliary hypostratotypes.

5 Conclusions

The planktic foraminifera detailed study of the MBZ and Jhaff composite section allowed us to establish a detailed biozonation. In this Tunisian section we were able to recognize the following biozones: the upper part of the *Globigerinatheka semiinvoluta* Zone (E14), the *Globigerinatheka index* Zone (E15), the *Hantkenina alabamensis* Zone (E16) of the upper Eocene and the *Pseudohastigerina nagewichiensis* Zone (O1) of the lower Oligocene.

We noticed a major turnover event across the Eocene/Oligocene boundary, that was marked by an interval between the extinction of turborotalids and hantkeninids. The extinction pattern can be considered a rapid mass extinction event since it lasted about 40–65 ky. The recognition of this interval indicates that the section is very continuous and expanded. At the top of this interval there is dwarfing of the *Pseudohastigerina* genus, with only the specimens no larger than 150 µm surviving into the Oligocene.

The species that became extinct across the E/O boundary were tropical and subtropical surface and intermediate dwellers, with distinctive morphologies (carinate turborotalids and spinose hantkeninids), which were well adapted species of k-strategy. This extinction event was triggered by the cooling that culminated in the Oi-1 glaciation in the lowermost Oligocene. The surviving planktic foraminifera Oligocene species were quite similar in morphology with globular chambers (globigerinids) and small planispiral pseudohastigerinids, which were mainly opportunistic species of r-strategy.

The Tunisian section allows us to recognize a 4 m thick interval between extinction of the turborotalids and hantkeninids, which is one of the most expanded known to date. Only in Tanzania is this interval more expanded, since it is 5.2 m. In Spain this interval is 1.2 m. In the E/O boundary stratotype defined in Italy it is 0.4 m thick. As a result, the Tunisian section could be a very suitable auxiliary hypostratotype to correlate the E/O boundary worldwide.

Acknowledgements

We would like to thank the research unit team “Pétrologie sédimentaire et cristalline” of the Faculty of Sciences of Tunis. This study received financial support and assistance through Project [CGL2014-58794P](#) from the [Spanish Ministry of Science and Technology](#) (FEDER funds) and the Consolidated Group E05 from the [Government of Aragón](#).

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Highlights

- Planktic foraminifera E14, E15, E16, O1 Zones are identified across the E/O boundary.
- The section is correlated with others in Tanzania, Spain and the E/O GSSP in Italy.
- Turborotalids and hantkeninids underwent a rapid mass extinction across the E/O.
- The extinction event at the E-O transition is recorded in a very expanded interval.
- The Tunisian section is a very suitable auxiliary section for the E/O boundary.

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