Bartonian-Priabonian larger benthic foraminiferal events in the Western Tethys

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KEYWORDS

larger benthic foraminifera
extinction
Eocene
Tethys

Abstract

The composition of Western Tethyan larger benthic foraminifera (LBF) significantly changed as a consequence of the general climate cooling trend in the late Bartonian and Priabonian. Major events are characterized by the disappearance of giant forms of both *Nummulites* and *Assilina* and also of the genus *Alveolina* and some orthophragminid lineages. Simultaneously, radiate and especially reticulate *Nummulites*, the *N. fabianii* lineage, and nummulitids with secondary chamberlets such as *Heterostegina* and *Spiroclypeus* emerged. Based both on first/last occurrence (FO/LO) data and the evolution of these forms and integrating geological information such as field observations, other LBF and planktonic data, a high-resolution stratigraphy of the Bartonian and Priabonian could be established in the frame of the Tethyan shallow benthic zonation (with SBZ zones and newly erected subzones for SBZ 18 and 19 based on the exceptionally rapid evolution of *Heterostegina*). We distinguish eight Western Tethyan LBF events in this timespan, mainly based on FO/LO data of selected lineages. These are: (1) FO of the *Operculina gomezi*-group (SBZ 16/17), (2) FO of genus *Heterostegina* (SBZ 17/18a), (3) FO of the *H. reticulata*-lineage (SBZ 18a/b), (4) LO of giant *Nummulites* (with supposed eastward migration during SBZ 18b–c), (5) FO of genus *Spiroclypeus* (SBZ 18c/19a), (6) LO of some survivor Middle Eocene orthophragminid lineages (around SBZ 19a/b), (7) FO of *Heterostegina* with granules (SBZ 19b/20) and (8) LO of the majority of survivor Eocene LBF (SBZ 20/21). The most dramatic change happened between event 4, followed by the successive expansion of reticulate *Nummulites*, and event 5. Due to its easy recognition by field methods, the Middle/Late Eocene boundary is traditionally drawn at the base of SBZ 19 (Serra-Kiel et al., 1998), corresponding to event 5 and marked also by the intraphyletic appearance of both *Nummulites fabianii* and *Heterostegina reticulata mossanensis*. This change falls, however, within P 15 (planktic foraminifera) and NP 19–20 (nannoplankton) zones, and is therefore considerably younger than the Bartonian/Priabonian boundary placed at the boundary of NP 17/18 zones by planktonic experts.

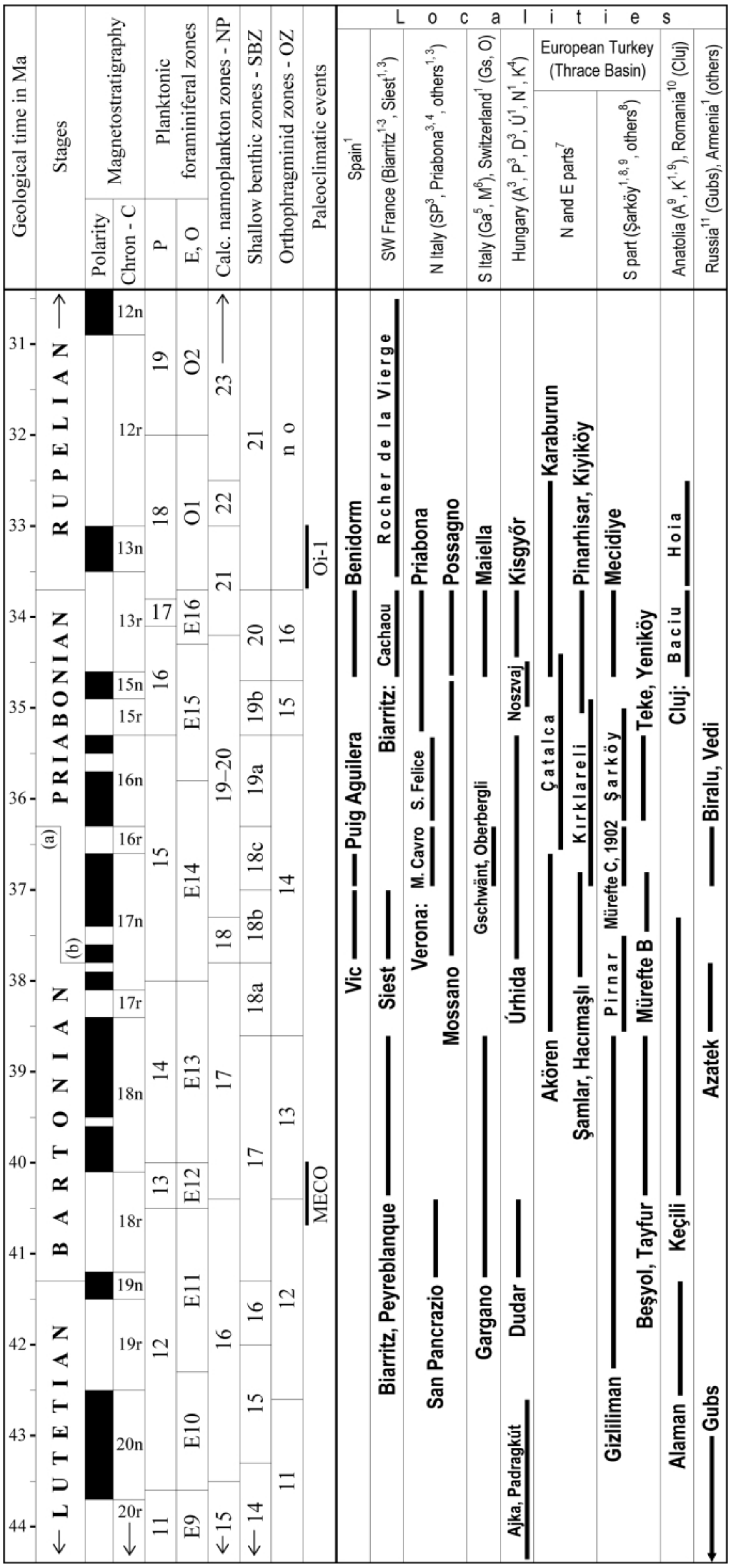
1. Introduction

The phyletic composition of Western Tethyan larger benthic foraminifera (LBF; dominated by three main groups, namely nummulitids, alveolinids and orthophragmines) remained almost unchanged during more than 15 myr, from the larger foraminiferal turnover (LFT) most probably generated by the Paleocene-Eocene Thermal Maximum (PETM) at about 55 Ma, through the Early Eocene climatic optimum (EECO) followed by a slow but gradual cooling interrupted by the Middle Eocene climatic optimum (MECO) in the Early Bartonian (Bohaty and Zachos, 2003). According to Bohaty et al. (2009) this climatic excursion was followed by a sudden return to the generally gradual cooling trend still in the Early Bartonian. This trend continued until the Eocene/Oligocene boundary, marked by a drastic decrease of the temperature caused by permanent Antarctic glaciation (the Oi-1 glaciation event, Miller et al., 1991).

Due to the gradual cooling of the Earth from the MECO, greenhouse conditions were gradually changed into an icehouse regime until the beginning of the Oligocene (Zachos et al., 1996). This is well reflected in the different composition of Western Tethyan larger benthic foraminifera (LBF) (1) in most of the Middle Eocene, characterized first of all by giant nummulitids of the genera *Nummulites* and *Assilina*, but also by alveolinids, (2) in the Late Eocene with reticulate and small radiate *Nummulites* and with nummulitids bearing secondary chamberlets, such as *Heterostegina* and *Spiroclypeus*, (3) and in the early Oligocene with a much restricted fauna containing only three small *Nummulites* and lacking orthophragmines and small *Assilina* crossing through the whole Eocene as well as *Heterostegina*, *Spiroclypeus* and most *Nummulites* lineages.

These great differences allow easily to distinguish Middle Eocene, Upper Eocene and Lower Oligocene shallow-marine deposits from each other, since the first two of them in many cases contain diverse LBF (though of a quite different look each) in mass quantity while the latter is usually very poor or even lacks LBF. Recently, the positioning of the GSSP for the Middle/Late Eocene (=Bartonian/Priabonian) boundary is in progress (Agnini et al., 2011). The Alano di Piave section in NE Italy, the leading candidate for the GSSP, contains all the important magnetostratigraphic and planktonic (both foraminiferal and nannofossil) signals around this boundary necessary for the worldwide identification. Because of the deep-water character of the profile, however, the significant change in the LBF assemblages cannot directly be identified in this section.

In this paper we try to give a closer insight into the character of the change of LBF around the Bartonian/Priabonian boundary. Fortunately, based on new data from drill-cores in Tanzania, the drastic reduction of LBF and the extinction of the family Hantkeninidae (the worldwide signal for the Eocene/Oli-



gocene boundary) proved to be coeval (Cotton and Pearson, 2011). We argue that the Bartonian/Priabonian boundary will be placed in between the last occurrence of giant *Nummulites*, the best signal for recognizing shallow-marine Middle Eocene, and the first appearance of *N. fabianii* defined formerly as the base of the Priabonian (Hardenbol, 1968; Cita, 1969).

2. Principles

The change of LBF assemblages from the Middle to the Late Eocene includes extinctions and first appearances of various lineages. Simultaneously, some evolutionary lineages crossed the Middle/Late Eocene boundary displaying evolution in different degree. For the definition of larger foraminiferal zones of the Paleocene-Eocene shallow benthic zonation (SBZ zones of Serra-Kiel et al., 1998) both types (i.e. real – first/last occurrence – events and

Figure 1: Stratigraphic position of studied localities calibrated to the shallow benthic zones by Cahuzac and Poignat (1997) and Serra-Kiel et al. (1998) refined by Less et al. (2008) and to the orthophragminid zones by Less (1998). Their correlation to the time-scale and magnetostratigraphy by Cande and Kent (1995) is based on Less et al. (2011), with modifications. Planktonic foraminiferal zones marked by P are according to Berggren et al. (1995), while those marked by E and O according to Berggren and Pearson (2005). Calibration to the above time-scale is by Wade et al. (2011). Calcareous nannoplankton zones (NP) are based on Martini (1971), their correlation to the above time-scale is according to Berggren et al. (1995) with modifications by Agnini et al. (2011). The positioning of MECO is based on Edgar et al. (2010) while that of the Oi-1 glaciation event on Zachos et al. (1996). The Bartonian/Priabonian boundary is (a) according to the base of the SBZ 19 Zone and (b) according to the base of the NP 18 Zone. Detailed information on localities are in [1]Less et al. (2008), [2]Schaub (1981), [3]Less and Kovács (1996) and Less (1998), [4]Less and Özcan (2008), [5]Matteucci (1971), [6]Bernoulli et al. (1992), [7]Less et al. (2011), [8]Özcan et al. (2010), [9]Özcan et al. (2007), [10]Popescu (1984) and [11]Zakrevskaya et al. (2011).

phyletic changes) are used. In particular, the SBZ 18/19 (late Bartonian/early Priabonian by Serra-Kiel et al., 1998) zonal boundary is defined by the last occurrence of *Nummulites beidai*, *N. cyrenaicus*, *N. vicaryi* and *N. boulangeri* and by the first occurrence of *Nummulites fabianii*, *N. garnieri garnieri*, *N. cunialensis*, *Discocyclina pratti* minor and *Asterocyclina alticostata danubica*. All the disappearing taxa are the last representatives of their lineages but only the first of them belongs to the so-called giant *Nummulites*, the other three are rather rarely reported. Meanwhile all but the very rare *N. cunialensis* first appearing taxa belong to lineages bearing precursors in the Middle Eocene from which they only differ in their quantitative parameters, the evaluation of which (in the case of *Nummulites*) is subjective due to the typological discrimination of successive taxa within lineages. In the case of nummulitids, the character of these intraphyletic changes, whether they are gradual or of punctuated equilibrium, was not identified, either, whereas in the case of orthophragmines these changes appeared to be rather gradual (Less and Kovács, 1996).

Although the first appearance of *Nummulites fabianii* cannot be considered as a real event, in practice it is usable because reticulate *Nummulites*, to which *N. fabianii* belongs, became extremely abundant after the extinction of giant *Nummulites*, comprising the *N. perforatus-biedai*, *N. millecaput-maximus*, *N. gizehensis-lyelli* and some other lineages. Reticulate *Nummulites* occupied their former ecological niche in nummulitic banks separating the inner and outer shelf (Less et al., 2011).

Recently, Less et al. (2008) refined the above mentioned two zones based on the first appearance and also on evolutionary data of *Heterostegina* and *Spiroclypeus*, and added into the definition of the base of the SBZ 19 Zone (identified with the base of the Priabonian) the first appearance of the latter genus as well as the gradual but very rapid change of *H. reticulata reticulata* to *H. r. mossanensis*.

We think that due to their instantaneous nature the real first/last occurrence data of particular lineages should have a primary role in defining events around the Bartonian/Priabonian boundary.

In order to arrange LBF events into a time-table continuous sections would be the most preferable. However, such a Bartonian/Priabonian boundary section where the superposition of different events can well be traced is known so far only from Mossano (N Italy). Moreover, reticulate *Nummulites* are restricted to the lower, Bartonian part of this profile bearing inner shelf character, whereas they are practically missing from the upper, probably Priabonian part containing abundant *Spiroclypeus* characteristic for the outer shelf (Papazzoni, 1994).

Since LBF needed light necessary for their endosymbiontic zooxanthellae, and, therefore, lived in the photic part of the shelf, co-occurrence data with planktonic organisms are rather sporadic, as well as magnetostratigraphic data. Therefore, apart from some sporadic data, the co-occurrence data of different LBF lineages in particular localities including the quantified evolutionary degree of co-occurring lineages passing the Bartonian/Priabonian boundary had to be taken into account in constructing the time-table of LBF events.

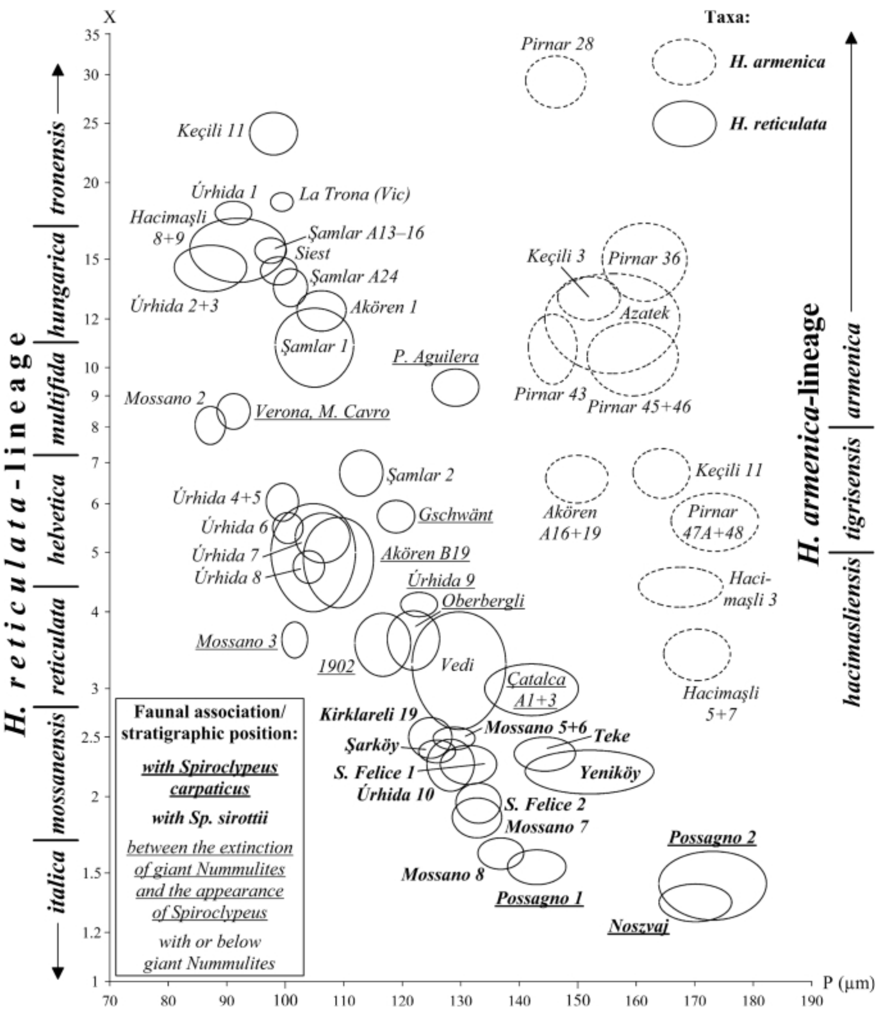


Figure 2: Distribution of heterosteginid populations of the *Heterostegina reticulata* and *H. armenica* lineages (with their subspecific subdivision based on Less et al., 2008 and extended by Less et al., 2011) from the Western Tethys (mean values at the 68% confidence level corresponding to 1 s.e.) on the P-X (proloculus diameter versus number of undivided post-embryonic chambers) bivariate plot (X is on logarithmic scale). For localities see Fig. 1.

3. Material

In the last years we investigated the full spectrum of LBF in quite a great number of localities from the Western Tethys including some sections whose stratigraphic position based on oriented sections of isolated specimens is summarized in Figure 1 (see caption for particular works where information on these localities including the detailed faunal list can be found). The composition of LBF in this territory proved to be rather uniform, therefore the shallow benthic zonation by Serra-Kiel et al. (1998) and Cahuzac and Poignant (1997) can be successfully applied. This is even true for the Peritethyan area represented by the Gubs section in this work, in which the fauna is much less diverse since giant *Nummulites* with granules (the *N. perforatus-biedai*, *N. brongniarti-puschi* and *N. lorioli-ptukhiani*-groups) and alveolinids are missing (Zakrevskaya et al., 2011), and the whole Bartonian-Priabonian is lacking LBF because of the isolation of the territory. In the rest of the discussed area the presence of *Heterostegina armenica* in Turkey and Armenia is the most important biogeographic difference.

Figured specimens prefixed by E. are stored in the Eocene collection of the Geological Institute of Hungary (Budapest), while those marked by O/ in the Özcan collection of Department of Geology, İstanbul Technical University.

4. Larger foraminiferal lineages crossing the Bartonian-Priabonian boundary

Based on our studies, LBF lineages crossing the Middle/Late Eocene boundary have to be evaluated in different weight in the chronological arrangement of Bartonian-Priabonian LBF events. As shown in Less et al. (2008, 2011) and in Figure 2, after its first appearance the quite widespread *Heterostegina reticulata* lineage displays a very rapid and reliable evolution confirmed by both superpositional (detailed in Less et al., 2008, 2011 and Özcan et al., 2010) and co-occurrence data with other LBF, in particular with giant *Nummulites* and *Spiroclypeus*. Therefore, this lineage can be used as a very good proxy for ranking LBF events.

Our (still unpublished) data on reticulate *Nummulites* (the *N. fabianii* lineage) suggest (Fig. 3) that the evolution of this lineage is much slower than that of the *Heterostegina reticulata* lineage. Moreover, in one part of the Şamlar section in NE Turkey (Less et al., 2011) successive populations (Şamlar A13–16 to Şamlar 18+22) display a reverse development (such phenomena are also described in Drooger, 1993). Nevertheless, the evolution of reticulate *Nummulites* is quantified by Özcan et al. (2009, 2010) as shown in Figure 3. Moreover, and despite the evolutionary reversal mentioned above, all populations co-occurring with *Spiroclypeus* and *Heterostegina reticulata* with X_{mean} less than 2.7 (i.e. with *H. r. mossanensis* and *H. r. italica*) have a mean inner cross diameter of the proloculus (P_{mean}) exceeding 200 μm. And vice versa, populations of reticulate *Nummulites* co-occurring with giant *Nummulites*

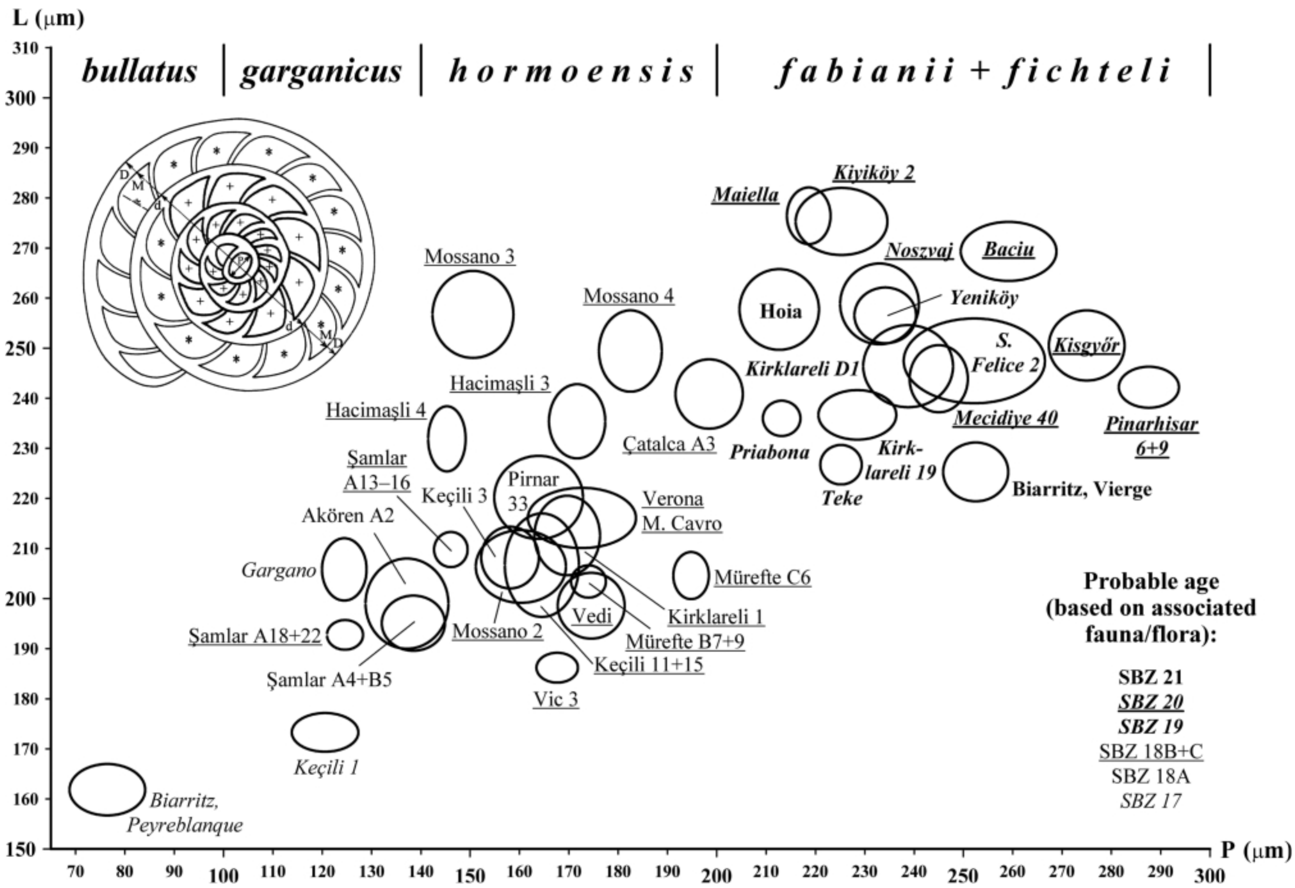


Figure 3: Distribution of populations of the *Nummulites fabianii* lineage (with their proposed specific subdivision by Özcan et al., 2010) from the Western Tethys (mean values at the 68% confidence level corresponding to 1 s.e.) on the P-L (inner cross diameter of the proloculus versus average length of chambers in the third whorl) bivariate plot. L is calculated by the formula L=d×π/N, where d is the outer diameter of the first two whorls and N is the number of chambers in the third whorl marked by asterisks in the schematic drawing (where N=13.6). For localities see Fig. 1.

and/or with *H. reticulata* with X_{mean} more than 2.7 (and also lacking *Spiroclypeus*) display P_{mean} less than 200 µm. This latter value separates *N. hormoensis* (SBZ 18 Zone) from *N. fabianii* (SBZ 19–20 Zone). This is in accordance to Papazzoni (1998) who discriminated these two taxa (see also Online Appendix) at 220 µm of the mean outer length diameter of the proloculus. It is worth also mentioning that somewhat less inflated forms (present in our samples from Maiella and Kisgyőr) can be found in the upper part of the Priabonian. As Herb and Hekel (1975) and Trevisani and Papazzoni (1996) demonstrated, they are alternating with *N. fabianii* of normal thickness and can be considered as an ecophenotypical variation having accommodated to deeper water conditions. Therefore, and because of similar internal morphology (Fig. 3) and the subjectivity of the recognition we do not separate these forms called *N. retiatus* from *N. fabianii*. Thus, reticulate *Nummulites* can also be useful in constructing the time-table of LBF events but with some caution.

Although several orthophragminid lineages, each with quantified evolution (see Zakrevskaya et al., 2011), cross the Bartonian/Priabonian boundary, all of them represent practically the same evolutionary level in SBZ 18, with less advanced *Heterostegina*, giant *Nummulites* and *N. hormoensis* but lacking *Spiroclypeus*, and in SBZ 19a, with more advanced *Heterostegina*, *Spiroclypeus* and *N. fabianii* but lacking giant *Nummulites*. All these orthophragminid populations belong to OZ 14 of Less (1998) spanning from the late Bartonian to the earliest Priabonian. Therefore, orthophragmines are only used to detect the SBZ 17/18 (=OZ 13/14) and SBZ 19a/b (=OZ 14/15) boundaries.

Finally, several nummulitid lineages such as *Nummulites incrassatus*, *N. chavannesi*, *N. garnieri*, *Assilina schwageri-alpina*, *Operculina gomezi* also cross the Bartonian/Priabonian boundary. However, their evolution is in most cases not yet recorded in detail, or in the case of the *Assilina schwageri-alpina* lineage not yet quantified. In this latter case P_{mean} (see above) separating the two nominate species of the lineage, and presumably also the populations of SBZ 18 and 19 zones, is assumed to be around 120–140 µm (Papazzoni, 1998; Less et al., 2011). Thus, the lineages mentioned above are not used in our reconstruction presented below.

5. Chronostratigraphy of Bartonian-Priabonian larger foraminiferal events

Based on different data discussed above we distinguish at least eight events in the change of the composition of Western Tethyan LBF. We do not mention the first appearance of reticulate Nummulites whose most primitive representatives are already known from around the Lutetian of North Africa (Schaub, 1981). All listed events shown in Figure 4 happened in chronological order (maybe except the first of them) between the Middle Eocene Climatic Optimum (MECO) in the early Bartonian and the Oi-1 glaciation event at the Eocene/Oligocene boundary. In discussing these events we focus on the major changes in the composition of LBF whereas less important ones can be seen on Figure 4.

5.1 The first occurrence (FO) of the *Operculina gomezi*-group

Representatives of this group include the successive *O. bericensis*, *O. roselli* (Fig. 5a) and *O. gomezi*, although with no clear features to distinguish them. These are the first newcomers, which joined to the numerous long-living lineages predominating the composition of Western Tethyan LBF in the Ypresian and Lutetian. This event is recorded in the Gizliliman A section in W Turkey (Özcan et al., 2010). As discussed in detail in Özcan et al. (2007), the *O. gomezi* group is missing from Ajka (OZ 11), Alaman (OZ 12), from the upper part of the Gubs section (Zakrevskaya et al., 2011, OZ 9–11) and the lower part of the Gizliliman A section (OZ 11–12) assigned to the Lutetian. However, it is a standard element in all samples assigned to the earliest Bartonian (Fig. 1) including Dudar, San Pancrazio and the upper part of the Gizliliman A section with a rich fauna of orthophragmines of OZ 12 and partly OZ 13. Although most of these LBF datums are not precisely defined in time because of incomplete data of co-occurring planktics and magnetostratigraphy, we infer that this LBF event is at least the closest one to the still undefined Lutetian/Bartonian boundary (corresponding to the SBZ 16/17 boundary but crossing OZ 12) since the Dudar locality belongs to the upper(most) part of the NP 16 nannofossil Zone (Less and Kovács, 1996). This latter data allows the correlation of the FO of the *O. gomezi* group with the MECO.

5.2 The FO of the genus *Heterostegina*

The FO of the genus *Heterostegina* as represented by *H. armenica* (Fig. 5b), accompanied with that of *Chapmanina* (Fig. 5c) and *Silvestriella* (Fig. 5h), is recorded in the Keçili (Özcan et al., 2007) and Pirnar (Özcan et al., 2010) sections. These forms are missing from the lower part of these sections and also from Gizliliman, Beşyol and Tayfur (Özcan et al., 2010) as well as from Biarritz, Peyreblanque (Schaub, 1981; Less, 1998) which are assigned to SBZ 17 and to OZ 13. They occur in all samples assigned to the late Bartonian, corresponding to SBZ 18 and OZ 14 (Fig. 1). This event roughly corresponds to the last occurrence (LO) of some lineages of giant nummulitids, such as *Nummulites laevigatus-brongniarti*, *N. puschi*, *N. lorioli-ptukhiani* (Fig. 5e; see also Online Appendix) and *Assilina exponens*. Concerning orthophragminid lineages, *Orbitoclypeus douvillei* (Fig. 5j) can roughly be traced until this event while the quite rare *Discocyclina pulcra* (Fig. 5d) probably disappeared somewhat earlier. Radiate *Nummulites* like *N. chavannesi* (Fig. 5i) and *N. incrassatus* (Fig. 5g) are recorded from this level and are widespread in the upper Bartonian and Priabonian (Less et al., 2011). This event also corresponds to the intraphyletic FO of *N. hormoensis* (Fig. 5f – see also Online Appendix) in the lineage of reticulate *Nummulites* although the precursor *N. garganicus* can re-appear (see Chapter 4). Since the LO data of giant nummulitids listed above correspond to the SBZ 17/18 boundary (=OZ 13/14, early/late Bartonian), we conclude that this event is very close to it.

5.3 The FO of the *Heterostegina reticulata*-lineage

The FO of the *Heterostegina reticulata*-lineage is recorded above and partly together with *H. armenica* from the Keçili, Pirnar (see above) and Hacımaşlı (Less et al., 2011) sections. This event defines the boundary of SBZ 18a/b subzones (Less et al., 2008). Starting from this event *H. reticulata* (Fig. 6a) can be found in almost all samples assigned to SBZ 18b–c subzones and to SBZ 19 (Fig. 1) but *H. armenica*, restricted to the Eastern Mediterranean, disappears already in the very early part of SBZ 18b subzone. The FO of *Pellatispira* (Fig. 6b) is also very close to this event since it co-occurs with advanced *H. armenica* in sample Keçili 15 (Özcan et al., 2007). This genus (usually ranked into the Priabonian) can also be found in Puig Aguilera (Romero et al., 1999) and Mürefte C (Özcan et al., 2010) assigned by these authors to the late(st) Bartonian (SBZ 18c). Some radiate *Nummulites* such as *N. pulchellus* (Fig. 6d), *N. stellatus* (Fig. 6e) and *N. cunialensis* (Fig. 6c) are recorded approximately from this level (Less et al., 2011), and the disappearance of the genus *Alveolina* s.s. also seems to be very close to it (Serra-Kiel et al., 1998). No intraphyletic changes can be observed in the evolution of orthophragminid lineages and also in that of the reticulate *Nummulites* although *N. garganicus* can still be observed in the lower part of SBZ 18b where generally *N. hormoensis* (see Online Appendix) predominates.

5.4 The extinction of giant *Nummulites*

The extinction of giant *Nummulites* of the *N. perforatus-biedai* (Fig. 7a), *N. millecaput-maximus* (Fig. 7d) and *N. gizehensis-lyelli* (Fig. 7c) groups together with the successive expansion of reticulate *Nummulites* is probably the most dramatic change around the Bartonian/Priabonian boundary. It is recorded directly in the Mossano section (Papazzoni and Sirotti, 1995; Bassi et al., 2000; Less et al., 2008) and can also be followed in the scattered outcrops of Úrhida (Less et al., 2008). The co-occurrence of giant *Nummulites* with forms

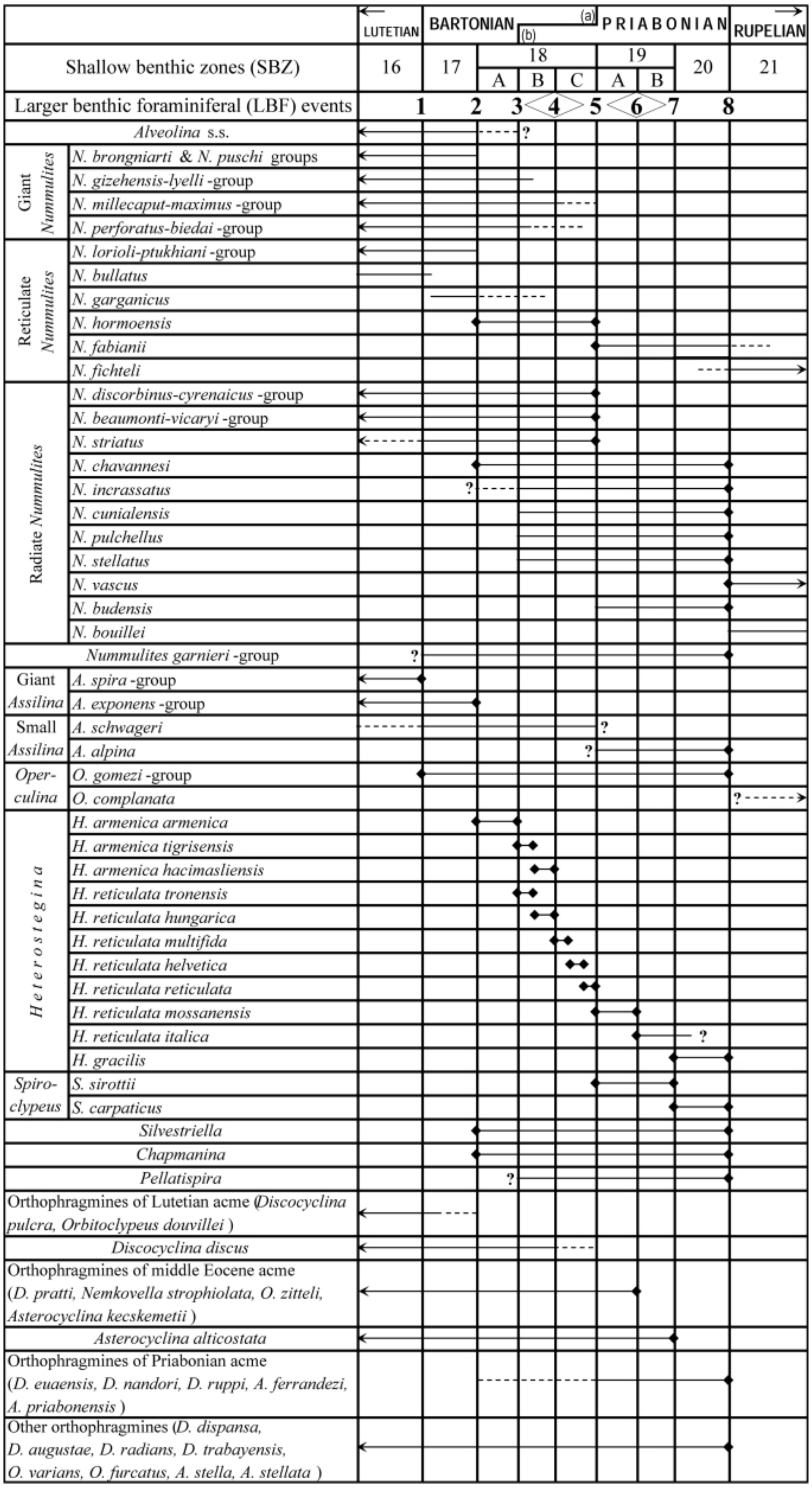


Figure 4: Range-chart for some late Lutetian to early Rupelian larger benthic foraminiferal taxa of the Western Tethys based on Less et al. (2008) with modifications. The subdivision of the stratigraphic scale is not time-proportional; the Bartonian/Priabonian boundary is shown in two versions explained in the caption to Fig. 1.

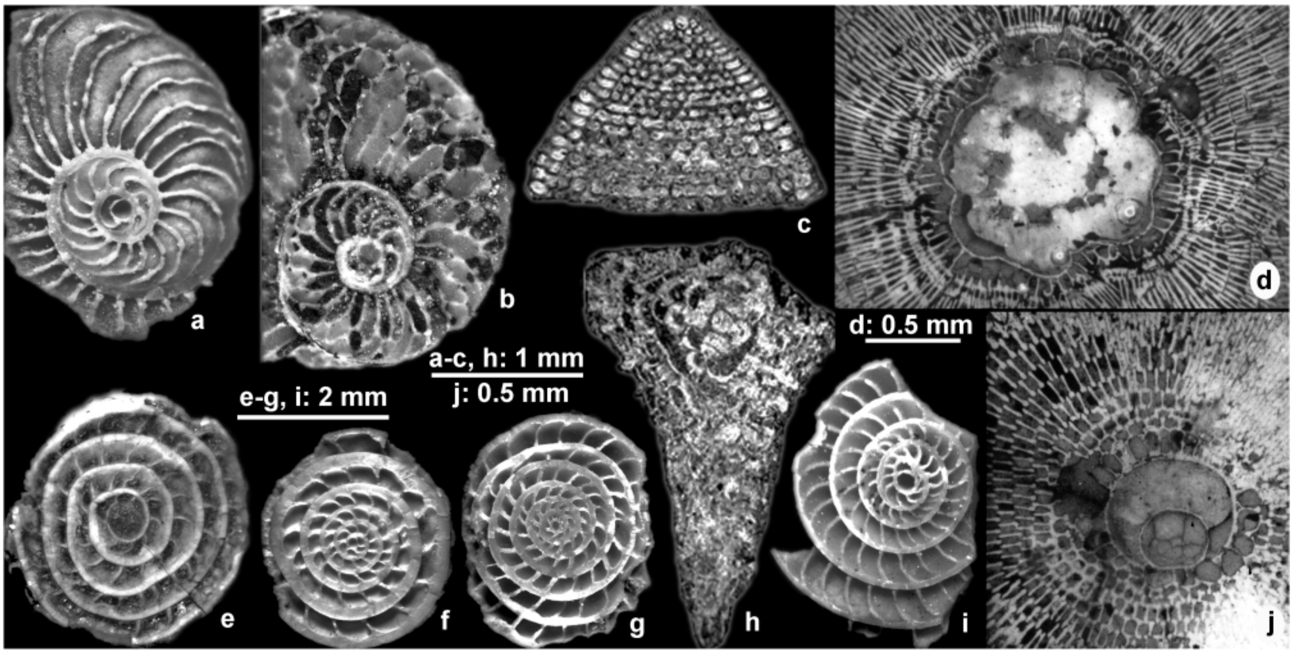


Figure 5: First and last occurring taxa of events 1 and 2. (a) *Operculina* ex. gr. *gomezi* Colom & Bauzá, Şamlar 1, SBZ 18b, E.09.184; (b) *Heterostegina armenica armenica* Grigoryan, Azatek, SBZ 18a, E.9505; (c) *Chapmanina gassinensis* (Silvestri), Mürefte B, SBZ 18b–c, O/MÜF.B.2; (d) *Discocyclina pulcra baconica* Less, Padragkút, SBZ 15, E.11.1; (e) *Nummulites ptukhiani* Z. Kacharava, Keçili 1, SBZ 17, E.06.9; (f) *Nummulites hormoensis* Nuttal & Brighton, Şamlar A4, SBZ 18a–b, E.11.2; (g) *Nummulites incrassatus* de la Harpe, Şamlar A22, SBZ 18b, E.09.139; (h) *Silvestriella tetraedra* (Gümbel), Mürefte C, SBZ 18b–c, O/MÜF.C.2; (i) *Nummulites chavannesi* de la Harpe, Akören A2, SBZ 18a. E.09.149; (j) *Orbitoclypeus douvillei pannonicus* Less, Padragkút, SBZ 15, E.11.3. All A-forms. c, h: vertical sections, all the others are equatorial sections. a-c, h: 20×, d: 25×, e-g, i: 10×, j: 40×.

of the *Heterostegina reticulata* lineage is reported from many localities by Less et al. (2008), Özcan et al. (2010) and Less et al. (2011). However, no localities are known where they are associated with *Spiroclypeus* whose FO defines the subsequent event. The exceptionally rapid evolution of co-occurring *H. reticulata* allows to constrain this extinction event more precisely. The LO of giant *Nummulites* in different regions can be fixed in different developmental degrees of *H. reticulata* (Fig. 8). Moreover, the extinction has a certain eastward younging trend, which is in contrast to the FO of *Spiroclypeus* recognizable at the same developmental degree of *H. reticulata* (Less and Özcan, 2008). Thus, the LO of giant *Nummulites* cannot be considered as a simultaneous event but can be constrained to an interval during SBZ 18b–c. Reticulate *Nummulites*, represented by *N. hormoensis* (see Online Appendix) and almost all orthophragmines belonging to OZ 14 do not display any significant evolution during this time-span. The only exception is *Discocyclina discus* (Fig. 7e) having disappeared in the SBZ 18c, since it does not co-occur with forms having appeared at the next event. The same is true for some radiate *Nummulites* such as *N. striatus* (Fig. 7b) and the *N. discorbinus-cyrenaicus* and *N. beaumonti-vicaryi* groups.

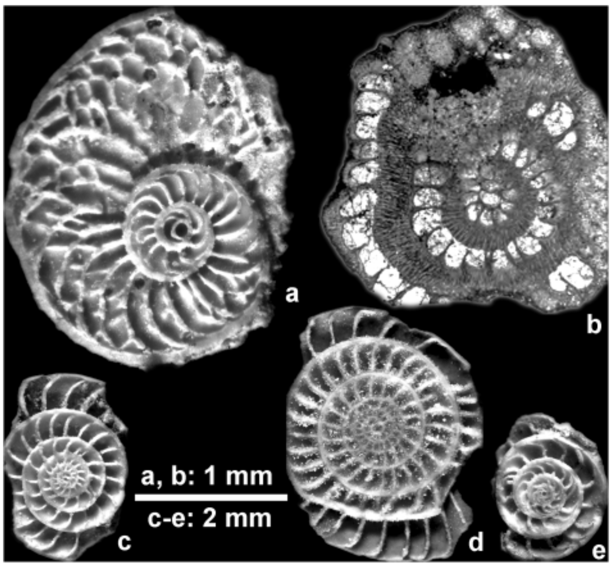


Figure 6: First and last occurring taxa of event 3. (a) *Heterostegina reticulata hungarica* Less et al., Şamlar A14, SBZ 18b, E.09.197; (b) *Pellatispira madaraszi* Hantken, Mürefte C, SBZ 18b–c, O/MÜF.C.6–8; (c) *Nummulites cunialensis* Herb & Hekel, Şamlar A16, SBZ 18b, E.09.159; (d) *Nummulites pulchellus* Hantken in de la Harpe, Şamlar A13, SBZ 18b, E.09.161; (e) *Nummulites stellatus* Roveda, Şamlar A16, SBZ 18b, e.09.171. All A-form, equatorial sections. a, b: 20×, c-e: 10×.

Unlike the previous two events, the LO of giant *Nummulites* can be somehow tied to magneto- and planktic stratigraphies. According to Cascella and Dinarès-Turell (2009) this event falls into NP 18 or into the lowest part of NP 19/20 corresponding to Chron C16n.2n in the Vic Basin (NE Spain). From the neighboring Igualada Basin Costa et al. (in press) report calcareous nannoplankton of the NP 19/20 Zone from the middle part of the Igualada Marls, whereas according to Ferrer (1971) giant *Nummulites* (*N. biedai*) still occur in the upper part of this unit, which he assigns already to P15. Based on data by Krashenninikov et al. (1985) the highest, non-redeposited occurrences of giant *Nummulites* in some Armenian localities

(Vedi, Biralu, Shagap) are already in NP 18 and P 15 zones. This means that giant *Nummulites* became extinct considerably later than the Bartonian/Priabonian boundary proposed by Agnini et al. (2011) as GSSP in the Alano di Piave section at about the base of both NP 18 and chron C17n.2n and below the base of P 15.

5.5 The FO of genus *Spiroclypeus*

The FO of genus Spiroclypeus is recorded (Less et al., 2008) in the Mossano section above a lithological change from shallow-water limestone to deeper water marls and in Úrhida with no such change. Based on Less and Özcan (2008), Özcan et al. (2010) and Less et al. (2011) in both localities, as well as in other sites (Verona, Şarköy, Teke Hill, Yeniköy 2, Kirklareli 19) less advanced *Spiroclypeus* (*S. sirottii*, Fig. 9a) occurs together with *Heterostegina reticulata* of the same evolutionary level (*H. r. mossanensis*, Fig. 9b) and in some of them (Verona, Şarköy, Teke Hill, Yeniköy 2, Kirklareli 19 but not in the Priabona marls of the Mossano section) with more advanced reticulate *Nummulites* belonging to *N. fabianii* (Fig. 9c) in the sense of both Papazzoni (1998) and Özcan et al. (2009, 2010). Moreover, we could not find *N. fabianii* with *Heterostegina reticulata* less advanced than *H. r. mossanensis*. This means that the FO of *Spiroclypeus* can be considered as co-eval with the

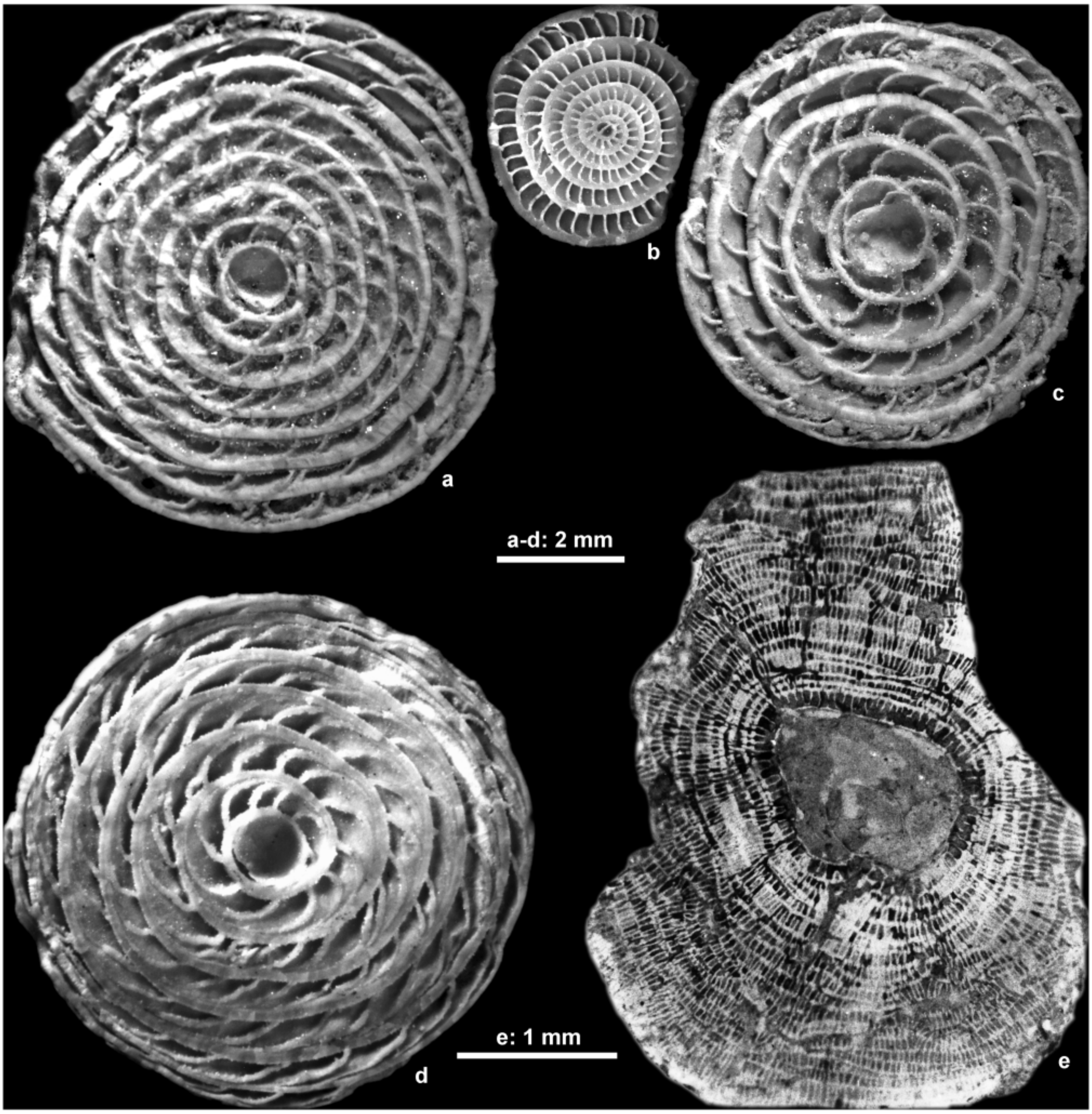


Figure 7: Last occurring taxa of event 4. (a) *Nummulites biedai* Schaub, Akören A16, SBZ 18b, E.10.4; (b) *Nummulites striatus* Brugière, Şamlar A22, SBZ 18b, E.09.111; (c) *Nummulites lyelli* d'Archiac & Haime, Akören A16, SBZ 18b, E.10.3; (d) *Nummulites maximus* d'Archiac, Şamlar 1, SBZ 18b, E.09.121; (e) *Discocyclina discus* discus (Rütimeyer), Padragkút, SBZ 15, E.11.4. All A-form, equatorial sections. a-d: 10×, e: 25×.

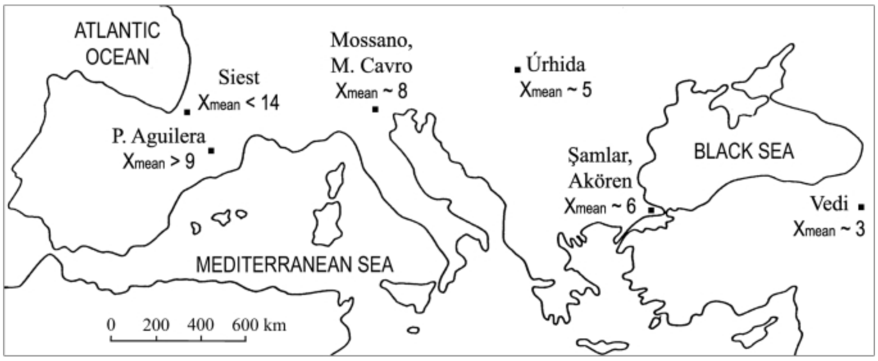


Figure 8: Distribution of developmental levels of the *Heterostegina reticulata* lineage (marked by the mean of X, the number of unsubdivided post-embryonic chambers), in which the last occurrence of giant *Nummulites* is recorded in different regions.

intraphyletic FO of both *N. fabianii* and *H. r. mossanensis*, and, therefore defines the boundary of SBZ 18/19 zones. Small-sized, radiate *Nummulites budensis* (Fig. 9d) is recorded around this level (Less et al., 2011). Among lineages crossing this event an intraphyletic change is recorded between *Assilina schwageri* and *A. alpina* (Fig. 9e), whereas almost all orthophragminid lineages except of *Discocyclina discus* survived this event with no apparent evolution. Their assemblages co-occur with forms characteristic for the lower part of SBZ 19.

In order to correlate this event, data on planktics are only available from the Mossano section (Luciani et al., 2002). According to them, the base of this section belongs to the upper part of P 15 and E 14 zones and to NP 18. This latter data are, however, re-interpreted by Agnini et al. (2011) suggesting already NP 19/20 zones, and, consequently an age, much younger than the level in the Alano di Piave section proposed by them as GSSP for the Bartonian/Priabonian boundary.

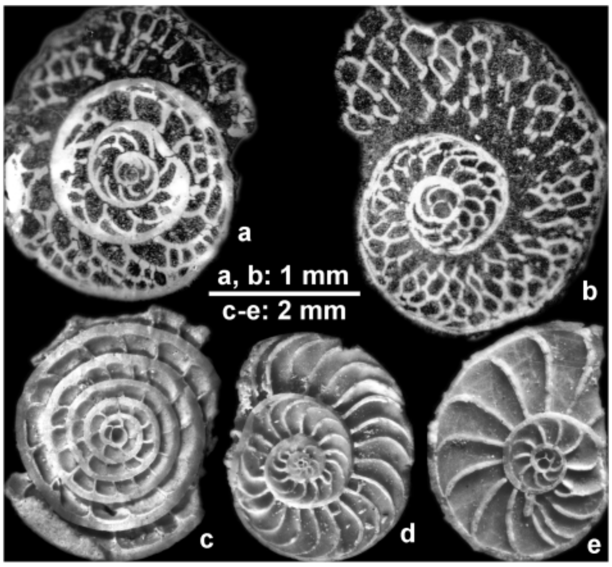


Figure 9: First occurring taxa of event 5. (a) *Spiroclypeus sirottii* Less & Özcan, Mossano 6, SBZ 19a, E.9591; (b) *Heterostegina reticulata mossanensis* Less et al., Mossano 6, SBZ 19a, E.9555; (c) *Nummulites fabianii* (Prever in Fabiani), Kiyiköy 2, SBZ 19b–20, E.09.101; (d) *Nummulites budensis* Hantken, Pinarhisar A1, SBZ 20, E.09.165; (e) *Asssilina alpina* (Douvillé), Kisgyőr, Remete-kút 2, SBZ 20, E.9501. All A-form, equatorial sections. a, b: 20×, c-e: 10×.

5.6 The LO of some survivor Middle Eocene orthophragminid lineages

Some orthophragminid lineages such as *Discocyclina pratti* (Fig. 10a), *Nemkovella strophiolata* (Fig. 10b), *N. daguini* (Fig. 10c), *Orbitoclypeus zitteli* (Fig. 10d), *Asterocyclina alticostata* (Fig. 10e) and *A. kecskemetii* (Fig. 10f) disappeared after having crossed the SBZ 18/19 boundary. These forms co-occur in several localities (Mossano, Verona, Úrhida, Şarköy, Teke Hill, Yeniköy, Kırklareli) with *Spiroclypeus sirottii* whose FO defines event 5, and *Heterostegina reticulata mossanensis* but can never be found together with *H. gracilis*, whose FO defines event 7, and/or *S. carpaticus* characteristic for SBZ 20. The synchroneity of these events is not proven, the LO of *A. alticostata* seems to be slightly younger. These orthophragminid events define roughly the boundary of the OZ 14/15 zones. They are approximately co-eval with the intraphyletic substitution of *H. r. mossanensis* by *H. r. italica* defining the boundary of SBZ 19a/b subzones as recorded in the Mossano section (Less et al., 2008). According to Luciani et al. (2002) the base of P 16 is very close to the boundaries mentioned above.

5.7 The FO of *Heterostegina* with granules

The FO of *Heterostegina* with granules (*H. gracilis*, Fig. 11a) defines the base of SBZ 20 (Serra-Kiel et al., 1998) but it is not yet recorded from continuous sections (Fig. 1). Approximately co-eval intraphyletic changes are recognized in the genus *Spiroclypeus*, i.e. *S. sirottii* is substituted by *S. carpaticus* (Fig. 11b) and in a few orthophragminid lineages such as *Discocyclina trabayensis* and *Asterocyclina stellata* defining the base of OZ 16. No significant quantitative change in the internal morphology of the *Nummulites fabianii* lineage can be observed (Fig. 3; for comments on *N. "retiatus"* see Chapter 4). Based on the correlation of event 6 with the base of P 16 and on data from Possagno (Toumarkine and Bolli, 1975) and Biarritz, Cachaou (Mathelin and Sztrákos, 1993), event 7 falls within P 16.

5.8 The LO of the majority of Eocene LBF

This event is characterized by the LO of the majority of Eocene LBF including all orthophragmines, most nummulitids and some other genera such as *Pellatispira*, *Chapmanina*, and *Silvestriella*. Nummulitids include the LO of radiate *Nummulites* except of the *N. incrassatus-vascus* lineage, the *Assilina schwageri-alpina* lineage and all Eocene forms with secondary chamberlets, i.e. genus *Heterostegina* and *Spiroclypeus*. This event corresponding to the boundary of SBZ 20/21 zones seems to be instantaneous as recorded in both the Mossano and Priabona sections. As mentioned above, this drastic reduction is proven to be co-eval with the extinction of the genus *Hantkenina* (Cotton and Pearson, 2011), and thus it falls at the boundary of the E16 and O1 zones defining the Eocene/Oligocene (=Priabonian/Rupelian) boundary. Reticulate *Nummulites* survived this dramatic cooling event, reflected in the decrease of the proloculus size (Fig. 3) and recorded in the Transylvanian Basin near Cluj (compare samples Baciu and Hoia). The change in the surface ornamentation from *N. fabianii* with heavy reticulation to *N. fichteli* displaying weak reticulation to irregular mesh cannot definitely be tied to this event.

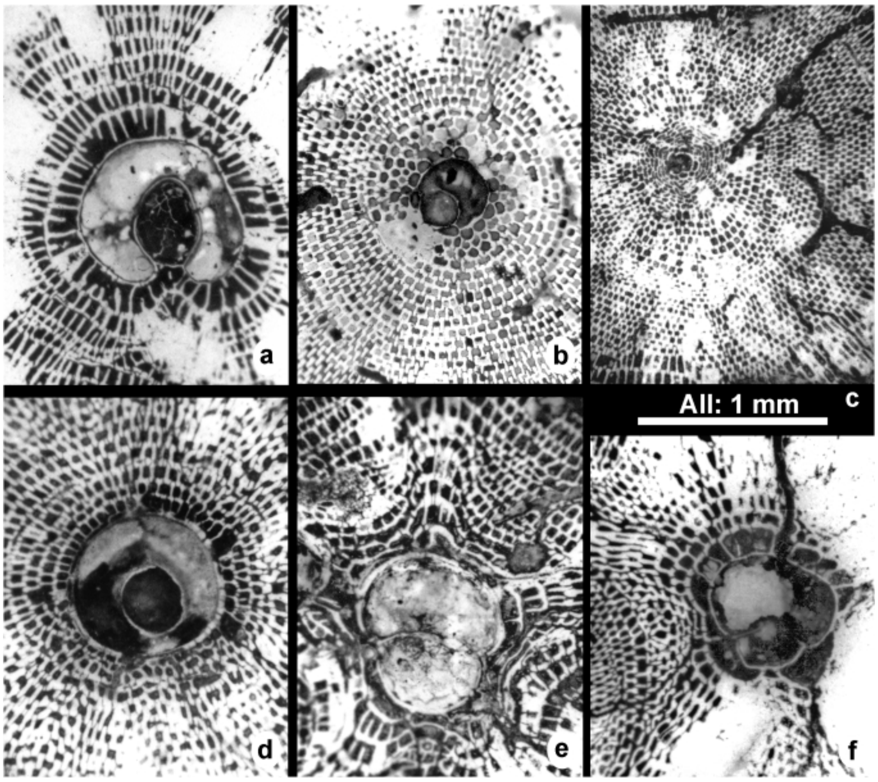


Figure 10: Last occurring taxa of event 6. (a) *Discocyclina pratti pratti* (Michelin), Úrhida 10, SBZ19a, E.11.5; (b) *Nemkovella strophiolata* ex. interc *tenella* (Gümbel) et *strophiolata* (Gümbel), Úrhida 10, SBZ19a, E.11.6; (c) *Nemkovella daguini* (Neumann), Úrhida 3, SBZ 18b, E.11.7; (d) *Orbitoclypeus zitteli* (Checcia-Rispoli), Biarritz, rocher de Peyreblanque, SBZ 17, E.11.8; (e) *Asterocyclina alticostata* ex. interc *alticostata* (Nuttall) et *danubica* Less, Úrhida 10, SBZ19a, E.11.9; (f) *Asterocyclina kecskemetii* Less, Úrhida 10, SBZ19a, E.11.10. All A-form, equatorial sections, 40×.

6. Conclusions

1) The gradual cooling of the Earth after the MECO in the early Bartonian until the drastic temperature decrease at the Eocene/Oligocene boundary caused the gradual disappearance of the extremely rich larger foraminiferal fauna of the Early-Middle Eocene in the Western Tethys. Except of the instantaneous character of the extinction exactly at the Eocene/Oligocene boundary (event 8 of this paper) caused by a very drastic temperature decrease, in the other three waves of disappearances (events 2, 4 and 6) the synchronism of the extinctions of different lineages cannot be proven. Moreover, in the case of the second wave of the disappearance of giant *Nummulites* (event 4) an eastward migration in time of the event can reasonably be supposed. This is in accord with the gradual character of the cooling itself. Ecological niches having become free due to extinctions were occupied either by previously subordinate forms like reticulate *Nummulites* in the interval between events 4 and 5, or by newcomers (events 1 to 3, 5 and 7).
2) The most dramatic change in the composition of Western Tethyan LBF is the extinction of giant nummulitids followed by the successive expansion of reticulate *Nummulites*, which happened between events 4 and 5. This change can easily be recognized already in the field. Therefore, the boundary between Middle and Late Eocene is traditionally drawn here, at the base of the SBZ 19 (Serra-Kiel et al., 1998) corresponding to event 5. As it is discussed for events 4 and 5, the Middle/Late Eocene boundary is inferred to be placed by planktic groups at a considerably older level (Agnini et al., 2011), most likely at around the base of SBZ 18b when giant *Nummulites* still can be found. We would rather suggest to place the GSSP for the base of the Priabonian at a worldwide recognizable magnetic reversal, which is higher than the late C17n.2n Chron at which Agnini et al. (2011) proposed to place the GSSP in the Alano di Piave section.

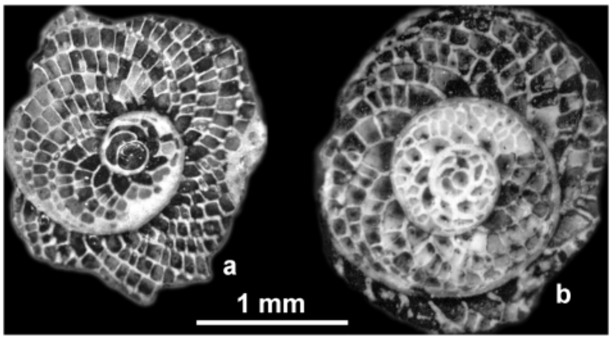


Figure 11: First occurring taxa of event 7. (a) *Heterostegina gracilis* Herb, Biarritz, Cachaou, SBZ 20, E.9581; (b) *Spiroclypeus carpaticus* (Uhlig), Kisgyőr, Remete-kút 3, SBZ 20, E.9195. Both A-form, equatorial sections, 20×.

Acknowledgements

This study was supported by the National Scientific Fund of Hungary (OTKA grant K 100538 to Gy. Less), by the project TÁMOP-4.2.1.B-10/2/KONV-2010-0001 (to Gy. Less) and by TÜBİTAK (Turkey) 106Y202 (to E. Özcan). We thank K. Drobne (Ljubljana) and A. Briguglio (Vienna) for their helpful comments.

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Received: 17 October 2011
Accepted: 19 March 2012

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