

The Middle/Late Eocene transition in the Eastern Carpathians (Romania) based on foraminifera and calcareous nannofossil assemblages

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Foraminiferal and calcareous nannofossil assemblages from the Eastern Carpathians (northern part of the Tarcău Nappe, Romania) were documented and correlated in order to reconstruct the palaeoenvironmental settings and provide a biostratigraphic framework of the Plopu Formation. The benthic foraminiferal assemblages are dominated by flysch-type agglutinated taxa, suggesting a bathyal palaeodepth with frequent oscillations of the carbon compensation depth. The agglutinated foraminifera morphogroup analyses suggest different levels of organic matter influx and oxygenation. Both the foraminifera and calcareous nannofossil assemblages suggest a shift between the warm Middle Eocene to the cooler Late Eocene climate. Biostratigraphic data based on calcareous nannofossils (NP15–NP19/NNTe8–NNTe12 biozones) helped to establish the age of the formation. Four assemblages of benthic agglutinated foraminifera (*Psammosiphonella cylindrica*–*Nothia excelsa*; *Paratrochamminoides* spp.–*Trochamminoides* spp.; *Karrerulina* spp.–*Reticulophragmium amplexens*; *Spiroplectammina spectabilis*) correlated with calcareous nannofossil bioevents supported the placement of the Middle to Late Eocene transition within the Plopu Formation.

Key words: microfossils, biostratigraphy, palaeoecology, turbidites, Tarcău Nappe.

INTRODUCTION

A detailed micropalaeontological study was carried out in the Eocene deep-water deposits of the northern part of the Eastern Carpathians (Plopu Formation, Tarcău Nappe) in order to provide an accurate biostratigraphic framework and palaeoenvironmental reconstructions. Although a significant amount of information on the lithostratigraphy and tectonic settings of the Tarcău Nappe in the Suceava River valley is already available (Joja, 1952, 1955; Joja et al., 1963, 1967; Joja and Manoliu, 1978; Juravle, 2007; Juravle et al., 2008; Bindiu and Filipescu, 2011; Bindiu et al., 2013), the biostratigraphical data are very scarce. This has resulted in prolonged dispute regarding the age of the Plopu Formation due to the fact that the flysch deposits are strongly affected by tectonics, and the biostratigraphical analyses were not consistent throughout all of the lithostratigraphic units.

The continuity and extensive development of the deposits from the Suceava River valley section allowed the documenting

of the biostratigraphy of the Middle to Late Eocene interval and the succession of changes in the benthic foraminifera and calcareous nannofossil assemblages as a result of environmental changes in the basin.

LOCATION AND GEOLOGICAL SETTING

The area investigated is located in the Suceava River valley, near the village of Brodina (N 47.89052°, E 25.43590°). Geologically, it belongs to the northern part of the Outer Moldavides (Săndulescu, 1984) of the Eastern Carpathian flysch, more precisely to the Eocene part of its most important unit, which is the Tarcău Nappe (Joja, 1955; Fig. 1). The geotectonic evolution of the area during the Eocene (Pandele and Stănescu, 2001; Bădescu, 2005; Juravle, 2007) accelerated the dynamics of the basin, leading to more prominent environmental changes when compared to the Paleocene. In the proximal areas related to the Carpathian source, sandy formations are present; while the distal areas are characterized by alternations of sandy and silty/muddy deposits with a calcareous character (Juravle et al., 2008). This resulted in the occurrence of three different lithofacies with different lithologies and palaeontological content (Ionesi, 1971; Gigliuto et al., 2004; Juravle et al., 2008), on going from west to east (Fig. 2): Tarcău, Tazlău, and Doamna. The Tarcău lithofacies is defined by the

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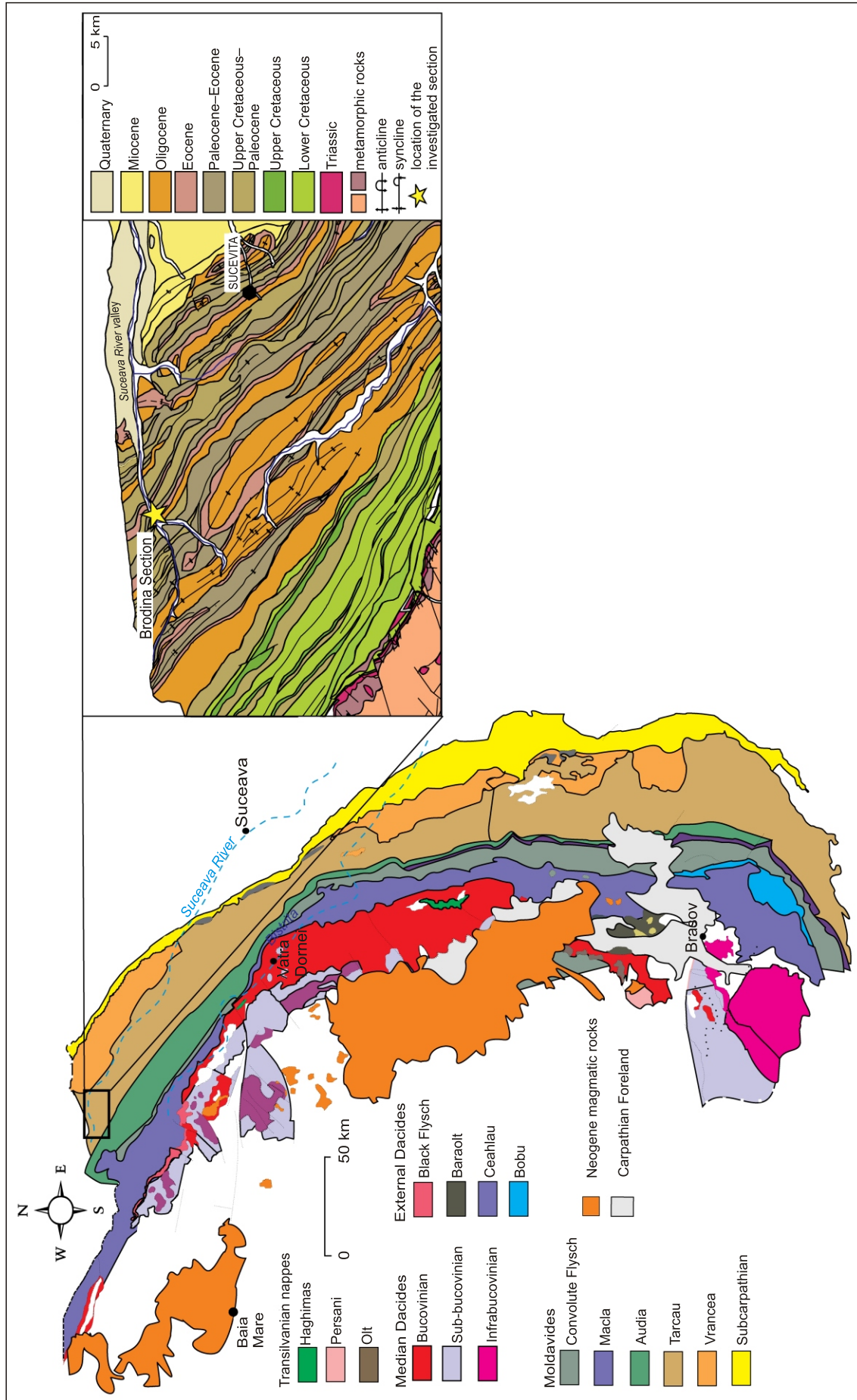


Fig. 1. Simplified geological map of the Eastern Carpathians (modified after Bădescu, 2005) and the detailed map of the area studied (modified after the Geological Map of Romania, 1:200 000, Rădăuţi sheet; Joja et al., 1968)

TARCĂU NAPPE			Age	
TARCĂU LITHOFACIES	TAZLĂU LITHOFACIES	DOAMNA LITHOFACIES		
Ardeluța Formation	Lupoia Formation	Lucăcești sandstone Formation and Globigerina Marls	Eocene	PRIABONIAN
Secu Formation	Plopu Formation	Bisericani Formation		BARTONIAN
Tarcău Formation "basal member"		Tazlău Formation	Doamna-Viteu Limestone "Asterocyclina sandstone"	LUTETIAN
	Sucevița Fm.		Sucevița Formation	YPRESIAN
	Straja Formation			PALEOCENE
Izvor Formation				
Runcu Formation				

Fig. 2. Paleogene lithostratigraphic scheme of the Tarcău Nappe (modified after Ionesi, 1971)

predominance of a sandy flysch where the percentage of sandstone present in the lithological column exceeds 80% (Mutihac and Ionesi, 1974; Grasu et al., 1988); the Doamna lithofacies is characterized by the presence of sandy-calcareous-clay flysch in the lower part (Joja, 1960), and in the upper part the Doamna limestone is present (Athanasiu et al., 1927; Mutihac and Ionesi, 1974); the Tazlău lithofacies has a mixed character of both the Tarcău and Doamna lithofacies (Ionesi, 1971; Mutihac and Ionesi, 1974). In the area studied, the Plopu Formation belongs to the Tazlău lithofacies and is represented by turbidites with a rhythmical alternation of green and grey calcareous clays with thin sandstones, and by three intervals of red clays in the lower part of the section (Ionesi, 1971; Mutihac and Ionesi, 1974; Juravle, 2007; Juravle et al., 2008).

MATERIAL AND METHODS

Thirty-six samples were collected from a continuous succession of the Plopu Formation in the Suceava River valley, the Brodina section (Fig. 3), in order to investigate the foraminifera and calcareous nannofossil assemblages. The samples were split into two sub-samples; the first set of samples was used to study foraminiferal assemblages, while the second was analysed in order to capture the changes in calcareous nannofossil assemblages.

The samples for foraminifera were prepared using the standard micropalaeontological method; they were dried, weighed, and disintegrated in a solution of sodium carbonate. Then the material was washed on a 63 µm-mesh sieve (Armstrong and Brasier, 2005). Wherever possible, 300 foraminiferal tests were picked and identified under a stereomicroscope. Several specimens were examined in detail using a JSM-JEOL 5510 LV scanning electron microscope. Abundant data were processed at the species level. Specimens of tubular taxa (*Rhizammina*,

Bathysiphon, *Rhabdammina*, *Nothia*), usually recovered only as fragments, were counted just for consistency. Palaeoecological methods include the agglutinated foraminifera morphogroups (Nagy et al., 1995; Van der Akker et al., 2000; Kaminski and Gradstein, 2005; Cetean et al., 2011; Murray et al., 2011; Setoyama et al., 2011, 2013) and the diversity of foraminiferal assemblages (Hulbert, 1971). The morphogroup analysis is based on the concept of foraminifera morphology and the idea that individuals with different test shapes have different habitats and different feeding strategies, therefore the changes in the relative abundance of morphogroups in the assemblages can reflect environmental changes (Corliss, 1985; Jones and Charnock, 1985; Murray et al., 2011). The samples for calcareous nannofossils were processed using the gravity settling technique (Bown and Young, 1998). The calcareous nannofossils study was performed using a light microscope at 1000x magnification and the photographs were captured with a AxioCam ERc5s digital microscopy camera. At least 300 specimens were counted for the quantitative study. Another 1000 FOV (fields of view) were examined to identify rare taxa. The individual abundance of the taxa observed was assessed as follows: VR – very rare: 1 specimen to more than 50 FOV; R – rare: 1 specimen to 21–50 FOV; F – few: 1 specimen to 11–20 FOV; C – common: 1 specimen to 2–10 FOV; A – abundant: more than 1 specimen per FOV.

Some reworked specimens (Cretaceous) were identified in the samples studied. This is due to erosion processes during tectonic instability. The Late Eocene interval is characterized by an increasing number of specimens of reworked species.

The biozones were defined using the biozonation schemes of Martini (1971) and Varol (1998) for calcareous nannofossils, and of Bratu (1975), Geroch and Nowak (1984), Berggren et al. (1995), Kaminski (2005) and Kaminski et al. (1989) for foraminifera. The agglutinated foraminifera taxa identified are listed in Appendix 1*, while the calcareous nannofossils are

* Supplementary data associated with this article can be found, in the online version, at doi: 10.7306/gq.1237

listed in [Appendix 2](#). The distribution of foraminifera within the studied samples can be observed in the [Appendix 3](#). The method used for determination of the calcium carbonate content consisted of the following steps: the sample was treated with hydrochloric acid, the resulted volume of the carbon dioxide was measured, and the equivalent percentage of calcium carbonate content was calculated (STAS 7107/3-74, 1974).

The lithological logs were drawn using the StratDraw program (Hoelzel, 2004), while the abundance graphics were generated by the *GpalWin* application (Goeury, 1997).

RESULTS

PRESERVATION, SPECIES DIVERSITY AND ABUNDANCE

Foraminiferal assemblages are quite abundant in the section studied, while preservation of the individuals varies from moderate to good. 119 species of foraminifera ([Appendix 1](#)) were identified, the agglutinated foraminifera group being the most abundant ([Appendix 1](#)). The diversity index (Hulbert index) varies from 5 to 22.4 in the foraminiferal assemblages ([Fig. 4](#)). The most common foraminifera are *Psammosiphonella cylindrica*, *Karrerulina* spp., *Spiroplectammina spectabilis*, *Trochamminoides* spp., *Paratrochamminoides* spp., *Recurvoides* spp., *Saccammina placenta*, *Reophax* spp., and *Reticulophragmium amplexens*, which occur in different proportions ([Fig. 5](#)). The diversity of the foraminiferal assemblages correlates with the CaCO₃ content of the samples along the section studied ([Fig. 4](#)).

Fifty-six calcareous nannofossil species were identified ([Fig. 6](#)). Diversity varies between 0 and 2.6 (Shannon_H index). The preservation is moderate to poor and the assemblages are dominated by Noelaerhabdaceae, such as: *Reticulofenestra dictyoda* (12–58%), *R. bisecta* (2–9%), *R. scrippsae* (1–15%), and *Cribocentrum reticulatum* (0.3–26.3%), followed by Coccolithaceae: *Coccolithus pelagicus* (4–17%), *C. formosus* (0.3–17%), and *C. eopelagicus* (3–13%). Helicosphaeraceae and nannoliths are other important groups: Discoasteraceae, Braarudosphaeraceae, and Sphenolithaceae ([Appendix 2](#)). Some species (i.e. *Chiasmolithus* spp., *Clausicoccus fenestratus*, *Discoaster* spp., *Lanternithus minutus*, *Micrantolithus* spp., *Pontosphaera* spp., *Sphenolithus* spp., *Zigrhablithus bijugatus*) occur irregularly along the section ([Fig. 6](#)). The relative abundance of calcareous nannofossils is low in the samples with low values of CaCO₃, probably due to dissolution processes. Blaj et al. (2009) described a similar situation from the near-equatorial Pacific (Ocean Drilling Program – Site 1218), where the relative abundance of calcareous nannofossils is strongly controlled by the CaCO₃ content. The intervals with low CaCO₃ content are dominated by the dissolution-resistant species, such as *Coccolithus pelagicus* or *Cyclicargolithus floridanus*, similarly to the samples studied ([Fig. 7](#)).

BIOSTRATIGRAPHY

The calcareous nannofossil assemblages document the age of the deposits. A series of bioevents were recorded in the samples studied ([Fig. 3](#)). The most important are:

- LO (last occurrence) of *Nannotetrina alata* (in sample 5) marking the NNTe8/NNTe9 boundary;

- LO of *Chiasmolithus solitus* (in sample 10) marking the NP16/NP17 and NNTe10/NNTe11 boundaries;
- FO (first occurrence) of *Chiasmolithus oamaruensis* (in sample 14) marking the NP17/NP18 boundary;
- LO of *Chiasmolithus grandis* (in sample 17) marking the NNTe11/NNTe12 boundary and Middle to Late Eocene transition;
- FO of *Istmolithus recurvus* (in sample 25) marking the NP18/NP19 boundary.

In addition, some other bioevents have been identified along the section studied:

- FO of *Cribocentrum reticulatum* (in sample 7);
- LO of *Helicosphaera lophota* (in sample 10);
- FO of *Reticulofenestra bisecta* (in sample 10);
- FO of *Reticulofenestra lockeri* (in sample 14);
- LO of *Cruciplacolithus edwardsii* (in sample 21);
- LO of *Sphenolithus spiniger* (in sample 22).

Based on these bioevents, the section studied falls in the Middle to Late Eocene, NP15–NP19 biozone (Martini, 1971), which corresponds to NNTe8–NNTe12 zones in the biozonation scheme of Varol (1998).

The foraminiferal assemblages complete the biostratigraphical data provided by the calcareous nannofossil assemblages. The base of the section contains planktonic foraminifera, e.g., *Subbotina linaperta* (Finlay), and *Morozovelloides lehneri* (Cushman and Jarvis). The assemblage is not diverse but it is indicative of the Middle Eocene.

Based on the total ranges and relative abundances of agglutinated foraminifera, four assemblages were separated on the interval studied ([Fig. 5](#)):

- *Psammosiphonella cylindrica*–*Nothia excelsa* (Middle Eocene, corresponding to the NP15–NP16 biozones);
- *Paratrochamminoides* spp.–*Trochamminoides* spp. (Middle Eocene, corresponding to the NP17 Biozone);
- *Karrerulina* spp.–*Reticulophragmium amplexens* (Upper Eocene, corresponding to the NP18 Biozone);
- *Spiroplectammina spectabilis* (Upper Eocene, corresponding to the NP 19 Biozone).

The agglutinated foraminifera biozonation used follows the Eocene to Oligocene scheme of Kaminski (2005) and Kaminski et al. (1989) for the North Atlantic and Western Tethys, and the Maastrichtian to early Oligocene scheme of Bratu (1975) for the Eastern Carpathians. The foraminiferal biozones were established by acmes or local stratigraphic ranges ([Fig. 3](#)).

The absence of index planktonic foraminifera prevented the application of the standard biozonation schemes (Berggren et al., 1995) and consequently the correlation between calcareous nannofossils and foraminifera.

The Middle Eocene *Psammosiphonella cylindrica*–*Nothia excelsa* and *Paratrochamminoides* spp.–*Trochamminoides* spp. ([Figs. 8 and 9](#)) assemblages are characterized by high abundances of the nominal species.

Two stratigraphically important species, *Reticulophragmium amplexens* and *Spiroplectammina spectabilis* ([Fig. 10](#)), are present in the section studied. *R. amplexens* is one of the markers of the Eocene, ranging in the Carpathians from the Early to Late Eocene (Morgiel and Olszewska, 1981). A peak in *Karrerulina* spp. can be observed just above the Middle–Late Eocene transition ([Fig. 5](#)). A peak in the relative abundance of *Spiroplectammina spectabilis* occurs in sample 25 (at the base of the NP 19 Zone; [Fig. 5](#)), reaching 52% of the assemblage.

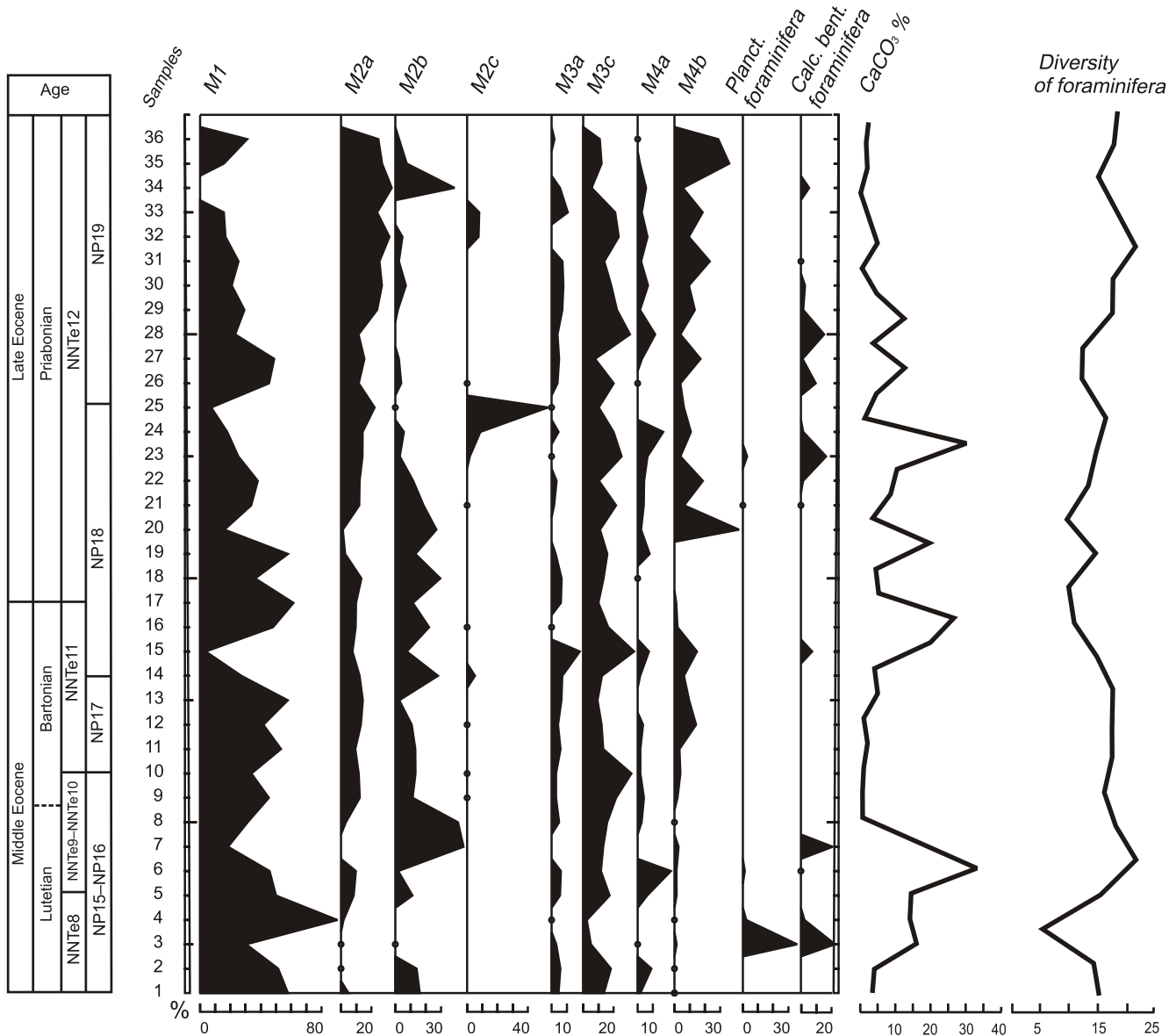


Fig. 4. Distribution (in percentages) of the agglutinated foraminifera morphogroups (M1 – tubular; M2a – globular; M2b – rounded trochospiral and streptospiral/planconvex trochospiral; M2c – elongate keeled; M3a – flattened trochospiral/ flattened planispiral and streptospiral; M3c – flattened streptospiral; M4a – rounded planispiral; M4b – elongate subcylindrical/elongate tapered), planktonic foraminifera (in percentages), calcareous benthic foraminifera (in percentages), CaCO₃ content and diversity (Hurlbert index)

PALAEOECOLOGY

Except for the flattened irregular *Ammolagena* specimens (M3b), all the morphogroups of agglutinated foraminifera described by Nagy et al. (1995), Van der Akker et al. (2000), Kaminski and Gradstein (2005), Cetean et al. (2011), Murray et al. (2011), and Setoyama et al. (2011, 2013) are present in the section investigated. The graphic distribution of the morphogroups (Fig. 4) reveals several events along the section:

- a dominance of tubular foraminifera (M1) in sample 4;
- a negative correlation between the trocho-, streptospiral (M2b), and elongated (M4b) versus tubular forms (M1) in samples 7, 8, 20, and 34;
- peaks of elongated forms (M4b) in sample 20, and of elongated keeled forms (M2c) in sample 25.

Except for the intervals containing samples 19 and 27, an increase of infaunal M2a and M4b morphotypes and the peak of epifaunal M2c morphotype characterize the Late Eocene.

High abundances of *Karrerulina* spp. and *Recurvoides* spp. (M2b and M4b morphogroups) can be observed just above the transition between the Middle and Late Eocene strata (Fig. 4), followed by a peak of *Spiroplectammina spectabilis* (M2c – shallow taxa).

A cooling episode is highlighted by a decrease in the relative abundance of *Reticulofenestra scrippsae*, *Coccolithus formosus*, and the nannoliths group, together with an increase in the relative abundance of *Reticulofenestra bisecta* and *Criboecentrum reticulatum* (Fig. 7) from the lower to the upper part of the section.

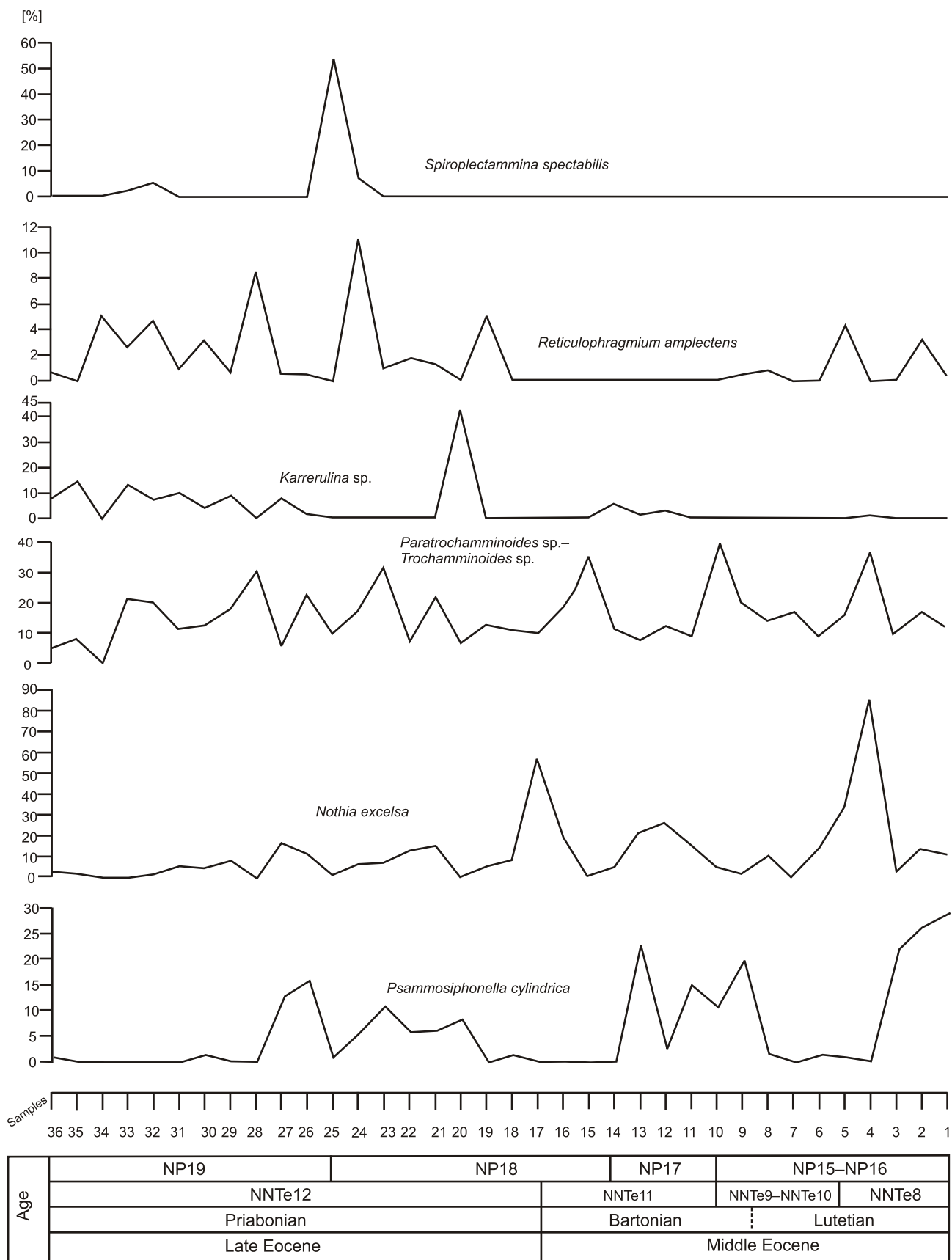


Fig. 5. Relative abundances of characteristic foraminiferal taxa in the Middle to Late Eocene strata of the Plopu Formation from the Suceava River valley

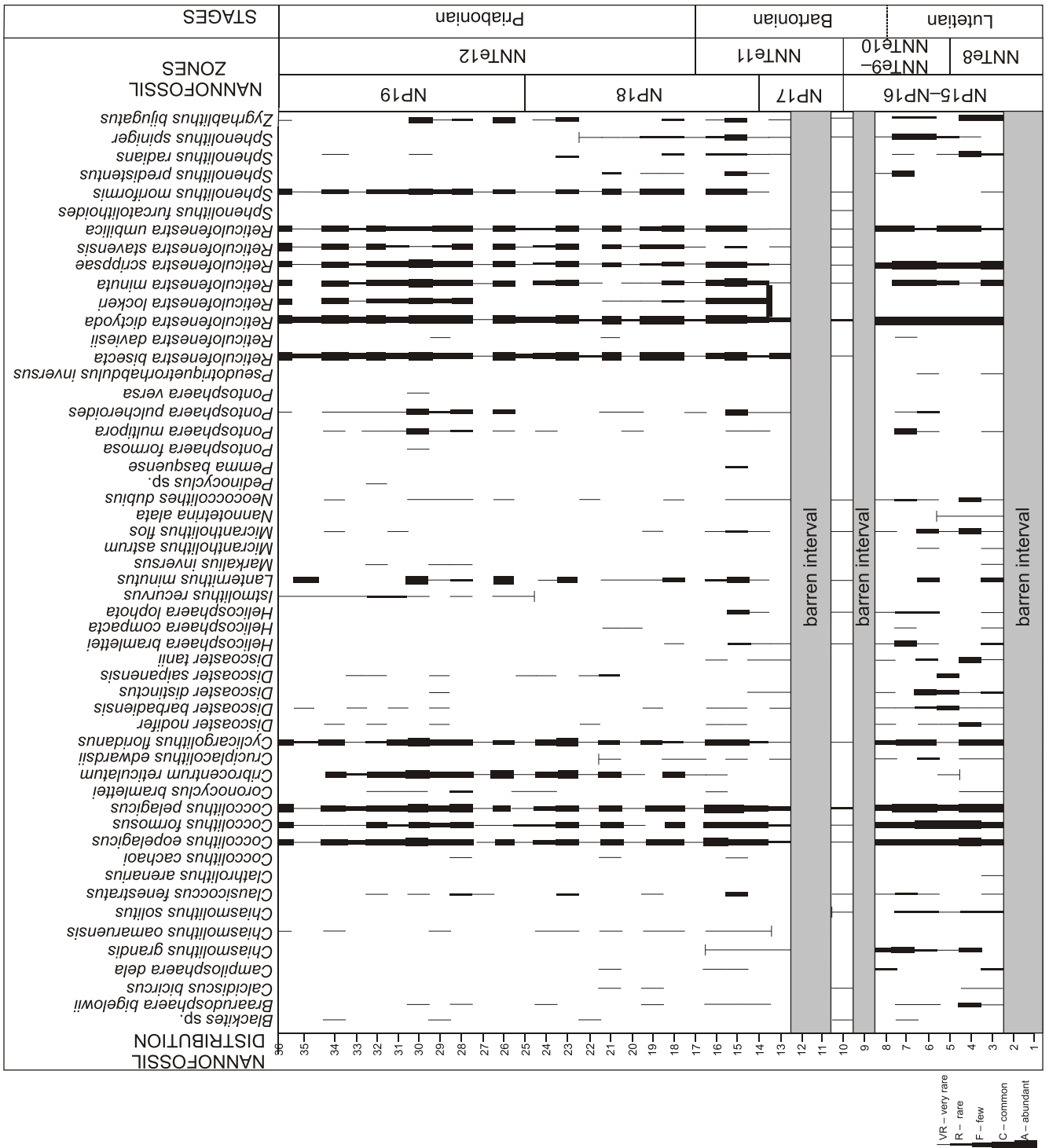


Fig. 6. Individual abundances of the calcareous nannofossil taxa identified

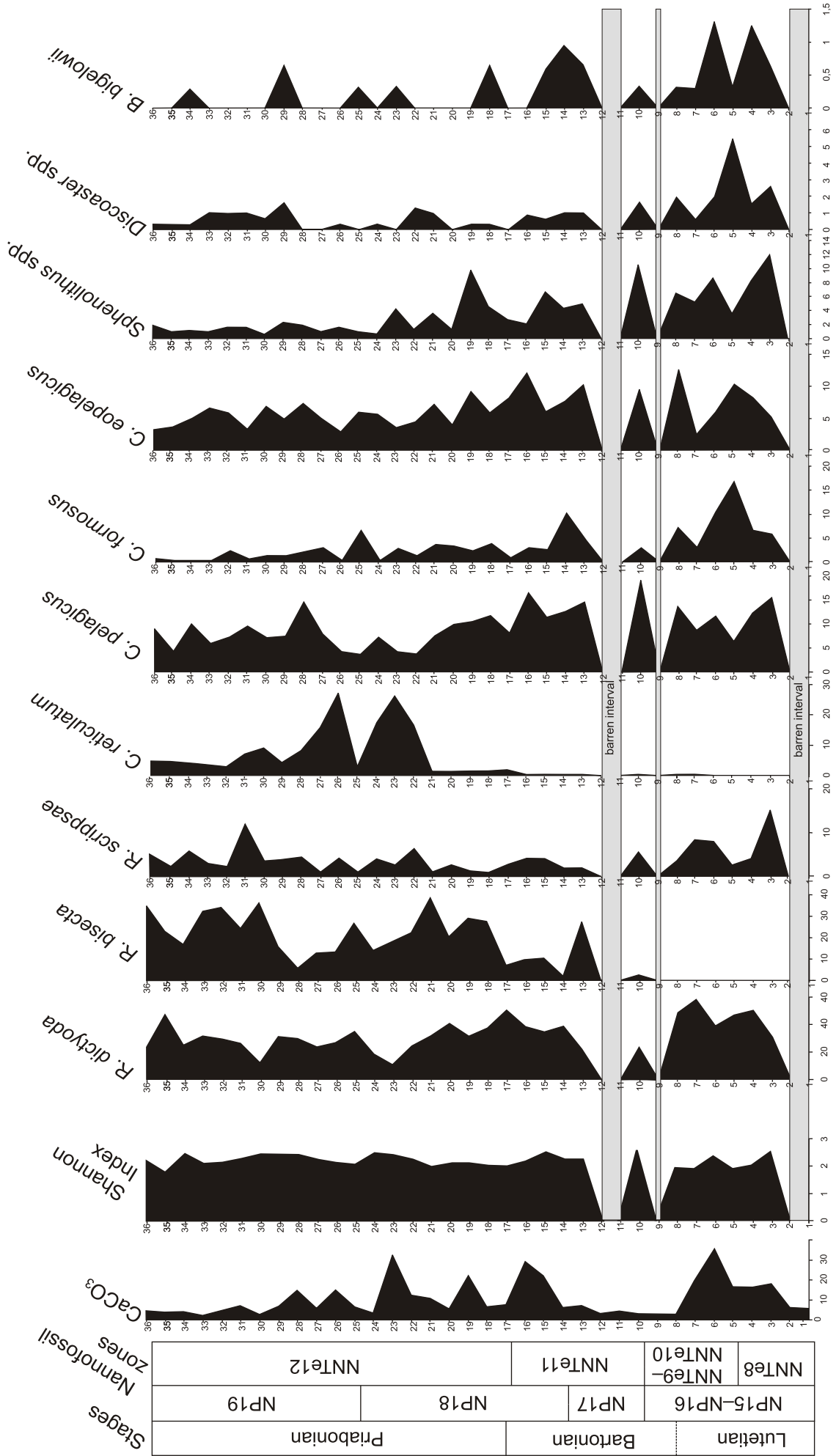


Fig. 7. Relative abundance fluctuations of some calcareous nanofossil species

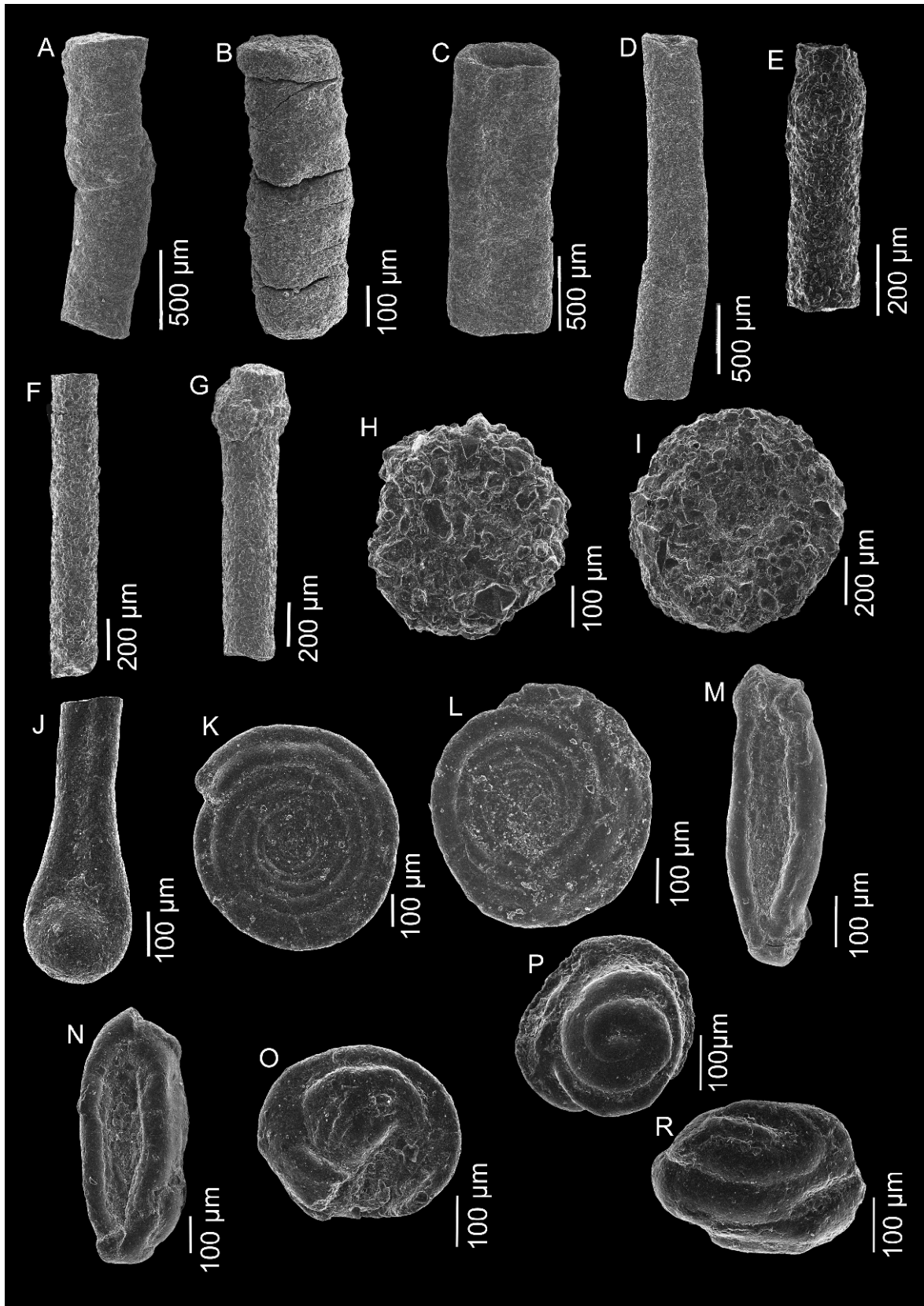


Fig. 8A – *Bathysiphon* sp. 1 (sample 1); B – *Bathysiphon* sp. 2 (sample 11); C – *Bathysiphon* sp. 3 (sample 16); D – *Nothia excelsa* (Grzybowski) (sample 17); E – *Psammosiphonella discreta* (Brady) (sample 27); F – *Psammosiphonella cylindrica* (Glaessner) (sample 27); G – *Rhabdammina linearis* Brady (sample 19); H – *Psammosphaera irregularis* (Grzybowski) (sample 19); I – *Psammosphaera irregularis* (Grzybowski) (sample 20); J – *Hyperammina elongata* Brady (sample 6); K – *Ammodiscus cretaceus* (Reuss) (sample 9); L – *Ammodiscus* sp. (sample 18); M, N – *Ammodiscus peruvianus* Berry (M – sample 13, N – sample 22); O – *Glomospira* sp. (sample 30); P, R – *Glomospira charoides* (Jones & Parker) (P – sample 22, R – sample 31)

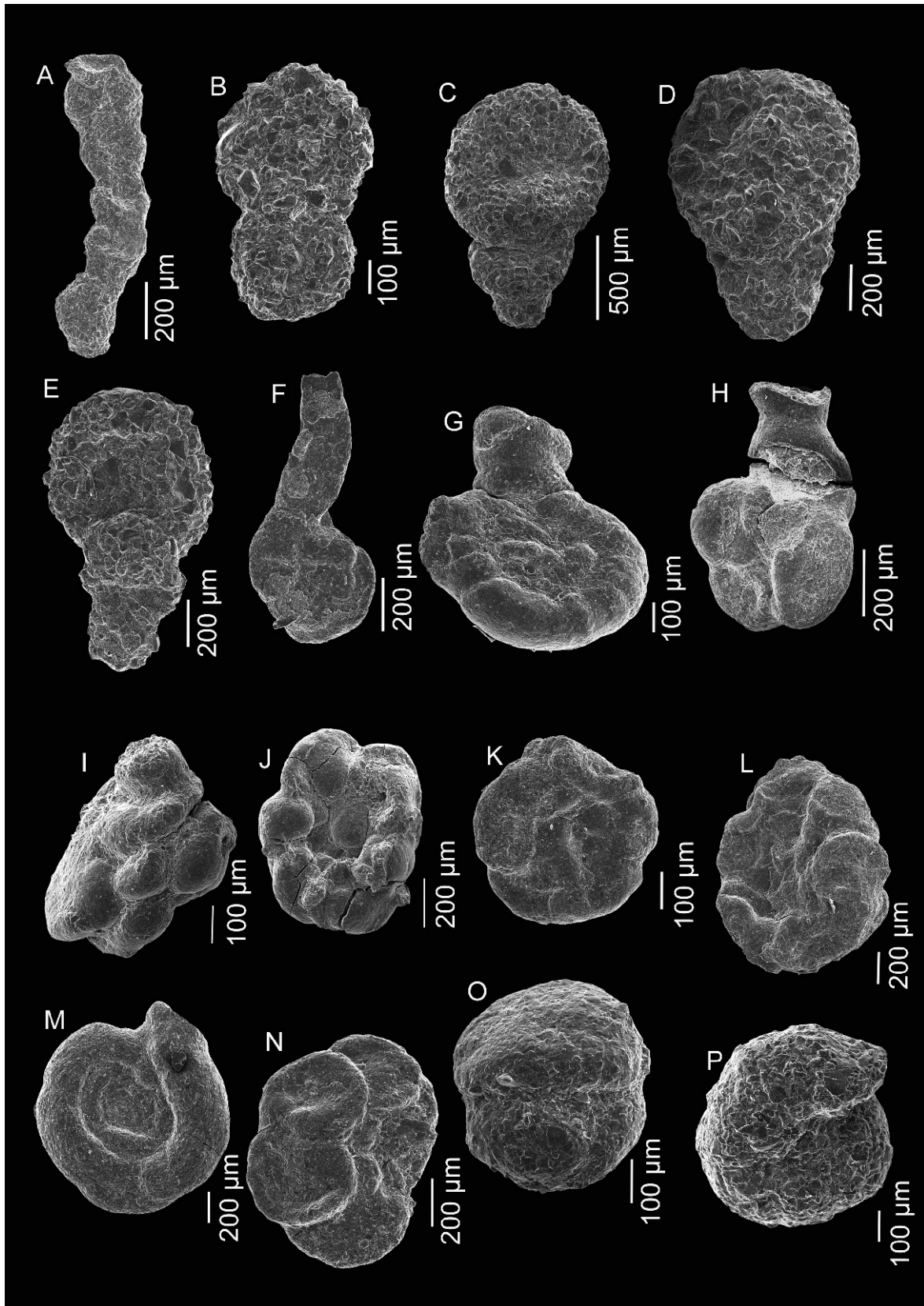


Fig. 9A – *Subreophax scalaris* (Grzybowski) (sample 31); B – *Reophax duplex* Grzybowski – (sample 22); C–E – *Hormosina trinitatensis* Cushman & Renz (C – sample 25, D – sample 27, E – sample 29); F – *Lituotuba lituiformis* (Brady) (sample 31); G, H – *Paratrochamminoides heteromorphus* (Grzybowski) (G – sample 10, H – sample 13); I, J – *Paratrochamminoides acervulatus* (Grzybowski) (I – sample 10, J – sample 11); K – *Paratrochamminoides* sp. 1 (sample 2); L – *Paratrochamminoides* sp. 2 (sample 10); M – *Trochamminoides dubius* (sample 9); N – *Trochamminoides subcoronatus* (Grzybowski) (sample 10); O – *Praesphaerammina subgaleata* (Vašíček) (sample 6); P – *Recurvoides* sp. (sample 5)

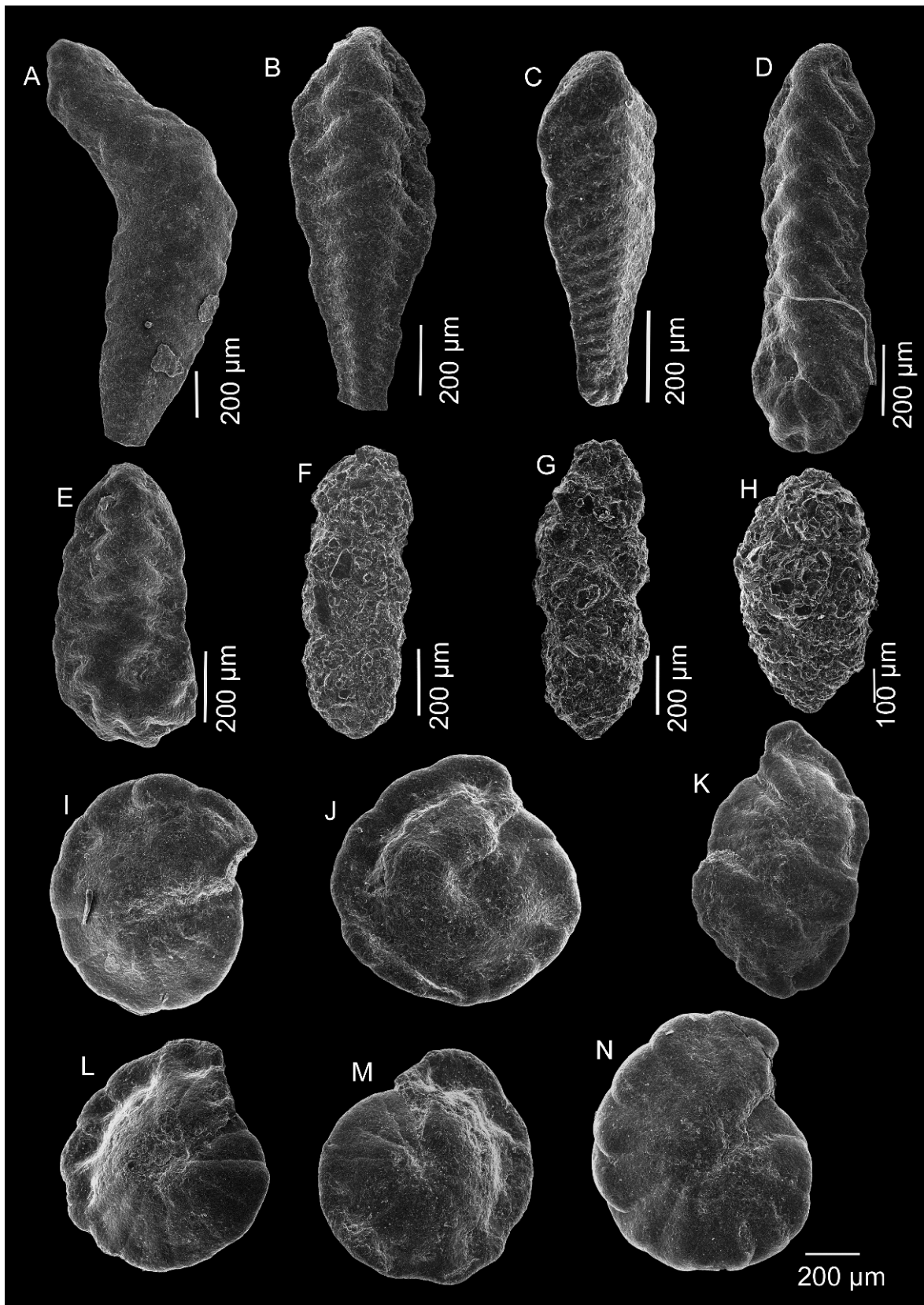


Fig. 10A–E – *Spiroplectammina spectabilis* (Grzybowski) (sample 25); F, G – *Karrerulina horrida* (Mjatliuk) (F – sample 20, G – sample 29); H – *Karrerulina coniformis* (Grzybowski) (sample 35); I–N – *Reticulophragmium amplectens* (Grzybowski) (sample 24)

DISCUSSION

PALAEOECOLOGY

BIOSTRATIGRAPHY

Based on the foraminifera and calcareous nannofossil assemblages, some authors (Ionesi, 1967; Dicea, 1974; Dicea and Dicea, 1976, 1980; Juravle, 2007; Juravle et al., 2008) considered the Plopu Formation as Late Eocene (Priabonian), while others (Joja et al., 1963; Agheorghiresei et al., 1967; Săndulescu et al., 1987; Bădescu, 2005) claimed that the Middle/Late Eocene (Bartonian/Priabonian) boundary is observed in this unit. The section studied is representative for this long-time age discussion; the results obtained supporting the second theory based on micropalaeontological assemblages. Thus, a revision of the lithostratigraphical units from the northern part of the Tarcău Nappe is necessary. Based on larger benthic foraminifera, the Bartonian/Priabonian boundary was traced at the first occurrence of *Nummulites fabianii*, *Assilina alpina*, *Discocyclusina pratti minor*, and *Asterocyclina alticostata danubica* (Papazzoni and Sirotti, 1995; Serra-Kiel et al., 1998; Ionesi, 1999; Bassi et al., 2000). From the calcareous nannofossils point of view, the boundary between the Bartonian and Priabonian is placed within the basal part of the NP18 zone, based on the LO of *Chiasmolithus grandis* (Varol, 1998) and/or at the lowest occurrence of *Chiasmolithus oamaruensis* (Berggren et al., 1985, 1995). These events were used to approximate the Bartonian/Priabonian boundary, being consistent with the results obtained in the Priabonian stratotype and parastratotype at Bressana (Verhallen and Romein, 1983).

The *Paratrochamminoides* spp.–*Trochamminoides* spp. (Fig. 9) assemblages have been noticed in the Middle Eocene deposits of the Outer Carpathians in Poland (Kender et al., 2005). These assemblages are known to make acmes at different times: Morgiel and Szymakowska (1978) placed the event in the earliest Eocene, Morgiel and Olszewska (1981) in the Paleocene of the Polish Carpathians, while Kaminski et al. (1996) reported such an event from the Late Cretaceous of the Numidian Rif. The *Reticulophragmium amplexens* abundance defines the Middle Eocene *R. amplexens* Zone mentioned by Joja et al. (1963), Agheorghiresei et al. (1967), Bratu (1975), and Săndulescu et al. (1987) in the Romanian Carpathians, and by Geroch and Nowak (1984) in the Polish Carpathians. Gradstein et al. (1994) extended the range of the *R. amplexens* Zone into the late Eocene for the North Sea and Labrador Shelf. This species was observed in all samples studied, with the highest proportion in sample 24 (11%). The *Karrerullina* spp. acmes were mentioned at different stratigraphic intervals: Gradstein et al. (1994) and Kaminski et al. (1996) reported it from the upper part of the Lower Eocene; Băk (2004) and Bindiu and Filipescu (2011) from the Lower Eocene, just above the *Glomospira* acme; while Kaminski (2005) from the lower part of the Middle Eocene. In the Romanian Eastern Carpathians, Bratu (1975) mentioned a peak of *Spiroplectammina spectabilis* in the Bisericani Formation, which is an equivalent of the Plopu Formation. This taxon was mentioned to form acmes just above the Cretaceous/Paleogene boundary in Gubbio, southern Spain, and in the equatorial Atlantic (Kuhnt and Kaminski, 1996; Kuhnt et al., 1998) in the Paleocene deposits from the Central North Sea basin and Labrador Shelf (Gradstein et al., 1994). This almost monospecific assemblage has been reported from Late Eocene deposits from Atlantic and western Tethyan regions (Kaminski et al., 1989; Kaminski, 2005).

The distribution of morphogroups shows a low organic matter flux and moderate oxygenation during the Middle Eocene (dominance of the morphotype M1), and alternating eutrophic (low oxygenation) – oligotrophic (relatively well-oxygenated) intervals around the Middle/Late Eocene transition (reflected by a negative correlation of M2b + M4b with M1). The increased bottom current activity and bottom water oxygenation are defined by intervals with epifaunal and infaunal opportunists, according to Kaminski and Schroder (1987) and Kaiho (1994).

The four assemblages of foraminifera offer the following palaeoecological information: the *Psammosiphonella cylindrica*–*Nothia excelsa* (Fig. 9) assemblage suggests relatively low organic matter flux and moderately oxygenated bottom waters (Table 1), while the *Paratrochamminoides* spp.–*Trochamminoides* spp. assemblage points to a lower-energy deep-water environment with low sedimentation rates. The *Psammosiphonella cylindrica*–*Nothia excelsa* (Fig. 8) and *Paratrochamminoides* spp.–*Trochamminoides* spp. (Fig. 9) assemblages are common in bathyal deposits (Schroder, 1986; Nagy et al., 1995).

The abundance of the *Karrerullina* spp. in sample 20 suggests an increase in the organic matter flux (Kaminski, 2005). The *Spiroplectammina spectabilis* taxa is known to be an opportunistic “disaster species” related to the trophic continuum (Kaminski and Gradstein, 2005); in the Atlantic and western Tethyan regions (Kaminski et al., 1989; Kaminski, 2005) and an acme of *Spiroplectammina spectabilis* was related to eutrophic conditions (Kaminski and Gradstein, 2005).

Tubular forms (such as *Psammosiphonella cylindrica*, *Nothia* spp., *Bathysiphon* sp.), as well as globular (*Saccamina* spp., *Psammosphaera* spp.), rounded (*Recurvoides* spp., *Reticulophragmium* spp.) or flattened streptospiral ones (*Paratrochamminoides* spp., *Trochamminoides* spp.), together with coarsely agglutinated taxa are typical of the “flysch-type” agglutinated foraminiferal biofacies (Gradstein and Berggren, 1981; Kaminski and Gradstein, 2005). The composition of the microfossil assemblages, associated with variable CaCO₃ content in all of the samples, indicates an upper bathyal depositional environment with frequent oscillations of the CCD. This is consistent with the hypothesis of Miller et al. (1982) that the flysch-type agglutinated assemblages are not restricted only to environments placed below the CCD.

The different values of the foraminiferal diversity index suggest changes in the palaeoenvironmental conditions.

Based on the distribution of the agglutinated foraminiferal morphogroups and assemblages, a sea level drop and a cooling interval are suggested. This is consistent with the already known change between the warm Middle Eocene to the cool Late Eocene (Keller et al., 1987; Gedl and Garecka, 2008).

The calcareous nannofossil assemblages (Fig. 11) also suggest a cooling trend along the section (Table 1). Even if the cold-water taxa (*chiasmoliths*, *Istmolithus recurvus*, *Reticulofenestra daviesii*) are not present in high numbers, a cooling episode can be inferred due to a drop in the abundance of warm-water taxa. The Middle Eocene oligotrophic conditions and warm waters are indicated by the following taxa: *Discoaster* spp., *Sphenolithus* spp. (*S. moriformis* being an exception), and *Helicosphaera compacta* (Bralower, 2002; Agnini et al., 2006; Bown and Pearson, 2009). This cooling trend was revealed by several other authors (e.g., Edwards and Perch-Nielsen, 1975; Beckmann et al., 1981; Wei and Wise, 1990; Oszczypko-Clowes, 2001; Bralower, 2002; Melinte, 2005; Agnini et al., 2006, 2007; Bown and Pearson, 2009; Cascella and Dinares-Turell, 2009).

Table 1

Palaeoecological affinities of the main species identified

Species\General Group	Palaeobathymetry, palaeoecology, temperature	References
Foraminifera		
<i>Psammosiphonella cylindrica</i>	Bathyal to abyssal, low organic matter flux	Kaminski and Gradstein (2005)
<i>Nothia excelsa</i>	Bathyal to abyssal, low organic matter flux	
<i>Trochamminoides</i> spp. <i>Paratrochamminoides</i> spp.	Upper bathyal to abyssal, lower energy deep-water environment, low sedimentary rates	Kender et al. (2005), Setoyama et al. (2013)
<i>Karrerulina</i> spp.	Upper bathyal to abyssal, high organic matter flux	Kaminski and Gradstein (2005), Bindu et al. (2013)
<i>Reticulophragmium amplexens</i>	Bathyal to abyssal, relatively stable environmental conditions	Kaminski and Gradstein (2005), Kender et al. (2008)
<i>Spiroplectammina spectabilis</i>	Bathyal to abyssal, high organic matter flux, eutrophic conditions, cool water	Kaminski (1984, 2005), Kaminski et al. (1989), Kaminski and Gradstein (2005)
Calcareous Nannofossils		
<i>Chiasmolithus</i> sp. <i>Istmolithus recurvus</i> <i>Reticulofenestra daviesii</i>	Cool- or cold-water taxa	Bukry (1973), Wei and Wise (1990), Firth and Wise (1992), Bralower (2002), Persico and Villa (2004), Tremolada and Bralower (2004), Villa and Persico (2006), Villa et al. (2008), Oszczypko-Clowes and Zydek (2012)
<i>Coccolithus formosus</i> <i>Discoaster</i> sp. <i>Helicosphaera</i> sp. <i>Sphenolithus</i> sp.	Warm-water taxa	Wei and Wise (1990), Aubry (1992a,b), Wei et al. (1992), Kelly et al. (1996), Bralower (2002), Kahn and Aubry (2004), Tremolada and Bralower (2004), Gibbs et al. (2006), Villa et al. (2008), Oszczypko-Clowes and Zydek (2012)

CONCLUSIONS

Foraminifera and calcareous nannofossil assemblages revealed new biostratigraphical and palaeoenvironmental data for the Popu Formation in the northern part of the Tarcău Nappe, Eastern Carpathians.

Biostratigraphic data assigned the section studied to the following biozones:

- NP15–NP16 zones (corresponding with *Psammosiphonella cylindrica*–*Nothia excelsa* foraminiferal assemblage – Middle Eocene);
- NP17 Zone (corresponding with *Paratrochamminoides* spp.–*Trochamminoides* spp. assemblage – Middle Eocene);
- NP18 Zone (corresponding with *Karrerulina* spp.–*Reticulophragmium amplexens* assemblage – Late Eocene);
- NP 19 Zone (*Spiroplectammina spectabilis* assemblage – Late Eocene). These correspond with the NNTe8–NNTe12 biozones.

Thus, it was demonstrated that the Middle–Late Eocene transition is located within the Popu Formation.

The foraminiferal assemblages are dominated by agglutinated taxa; planktonic and calcareous benthic forms occur sporadically and suggest environments placed above the CCD. The foraminiferal assemblages suggest an upper bathyal setting with hemipelagic deposition, palaeoenvironmental instabil-

ity, oscillations of the CCD, and normal salinity, as part of a “fleysch-type” biofacies.

The calcareous nannofossil together with the foraminiferal assemblages indicate a warm period with low organic matter flux and moderate oxygenation during the Middle Eocene, followed by a cooling episode with increasing organic matter and siliciclastic flux during the Late Eocene.

Palaeoenvironmental instability is suggested by the distribution of the agglutinated morphogroups, the foraminifera diversity, the calcareous nannofossil assemblages, and the CaCO₃ content which correlate along the section studied.

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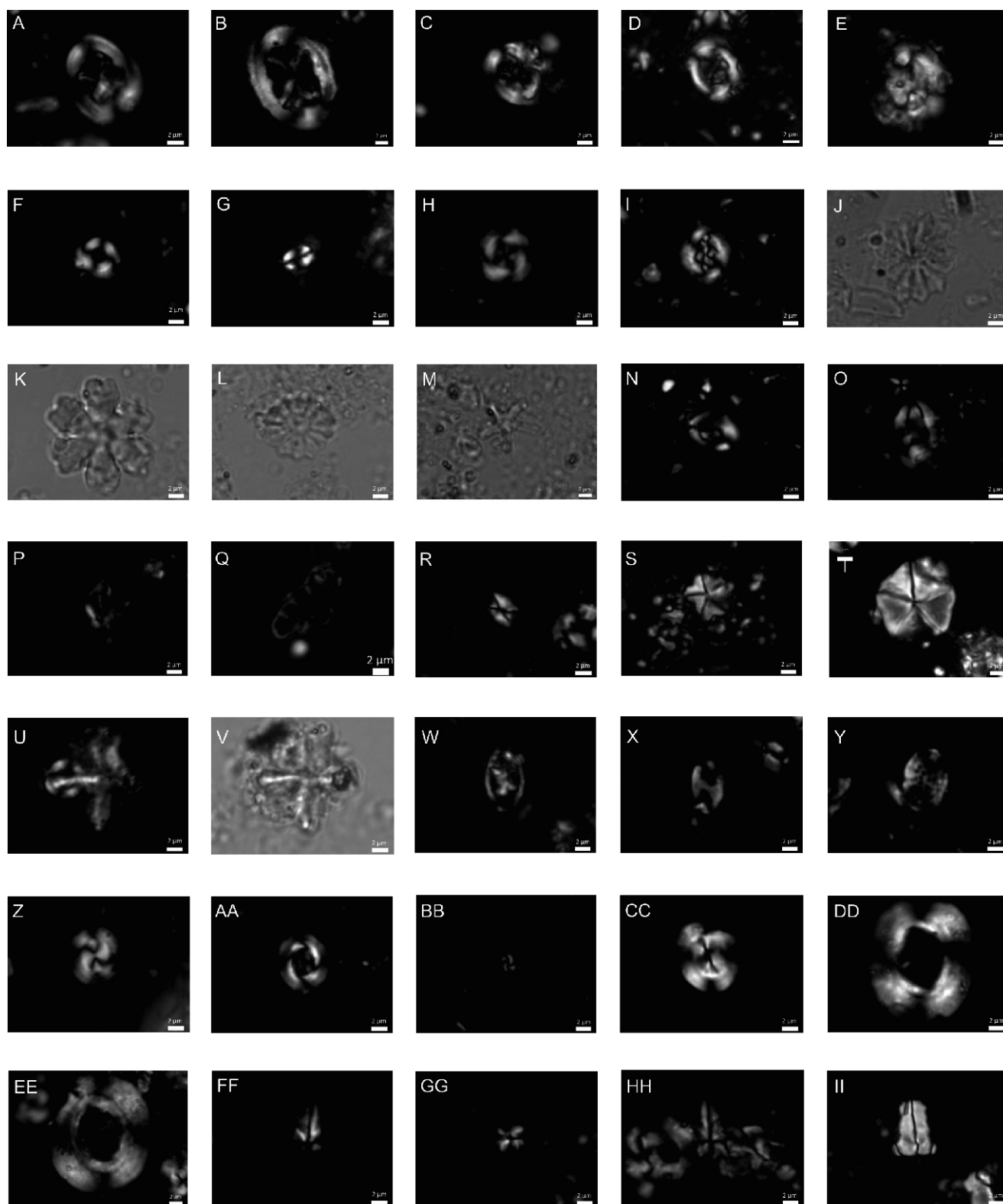


Fig. 11. Calcareous nannofossils from Brodina Valley section

A – *Chiasmolithus eoaltus* – sample 7; **B** – *Chiasmolithus grandis* – sample 14; **C** – *Chiasmolithus oamaruensis* – sample 14; **D** – *Chiasmolithus solitus* – sample 5; **E** – *Coccolithus eopelagicus* – sample 21; **F** – *Coccolithus formosus* – sample 10; **G** – *Coccolithus pelagicus* – sample 32; **H** – *Cribocentrum reticulatum* – sample 22; **I** – *Cruciplacolithus edwardsii* – sample 17; **J** – *Discoaster barbadiensis* – sample 5; **K** – *Discoaster deflandrei* – sample 10; **L** – *Discoaster saipanensis* – sample 7; **M** – *Discoaster tani* – sample 7; **N** – *Helicosphaera bramlettei* – sample 8; **O** – *Helicosphaera compacta* – sample 4; **P** – *Helicosphaera lophota* – sample 4; **Q** – *Isthmolithus recurvus* – sample 27; **R** – *Lanternithus minutus* – sample 34; **S** – *Micrantholithus breviradiatus* – sample 7; **T** – *Micrantholithus flos* – sample 30; **U, V** – *Nannotetrina alata* – sample 4; **W** – *Neococcolithes dubius* – sample 22; **X** – *Pontosphaera exilis* – sample 3; **Y** – *Pontosphaera multipora* – sample 30; **Z** – *Reticulofenestra bisecta* – sample 20; **AA** – *Reticulofenestra dictyoda* – sample 16; **BB** – *Reticulofenestra minuta* – sample 18; **CC** – *Reticulofenestra stavensis* – sample 16; **DD, EE** – *Reticulofenestra umbilica* – sample 7 and 27; **FF** – *Sphenolithus furcatolithoides* – sample 7; **GG** – *Sphenolithus moriformis* – sample 31; **HH** – *Sphenolithus radians* – sample 6; **II** – *Zygrabliithus bijugatus* – sample 5; the photographs taken under cross-polarized light; scale bar – 2 μm

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