

## BADENIAN CALCAREOUS NANNOFOSSIL FLUCTUATION IN THE EASTERN CARPATHIANS: PALAEOENVIRONMENTAL SIGNIFICANCE

Mihaela Carmen Melinte-Dobrinescu<sup>1</sup> & Marius Stoica<sup>2</sup>

**Abstract** Badenian calcareous nannofossils have been investigated from two outcrops situated at the southern end of the Eastern Carpathians. Both qualitative and quantitative nannofloral analyses have been performed. In the Slănic Formation, below the ‘Evaporitic Formation’, the calcareous nannoplankton standard zone NN5 has been recorded within the oldest part, mainly made by marlstones and claystones, interbedded with levels rich in *Globigerina* foraminiferal tests and with tuffitic layers; towards the top of this unit, above the youngest *Globigerina* marly level, where the tuffs are prevailing, the NN6 zone has been recognized. The aforementioned nannofossil zone has been also recorded above the ‘Evaporitic Formation’, in the ‘Radiolarian Shale’ Formation. Hence, the Badenian Salinity Crisis of the Eastern Carpathians is constrained by the LO (last occurrence) of *Sphenolithus heteromorphus* and the LO of *Cyclicargolithus floridanus*, being placed within the NN6 calcareous nannofossil zone. Below the Badenian Salinity Crisis, in the NN5 zone, the nannofloras are dominated by the *Sphenolithus* and *Discoaster* genera that characterised warm surface waters. The abundance of these taxa starts to gently decrease from the base of the NN6 zone, below the Badenian Salinity Crisis, but a more significant shift has been encountered above this salinity crisis, where a bloom of *Braarudosphaera bigelowii*, reaching 20 % of nannofloral assemblages, has been identified. This calcareous nannofossil event is possibly linked to the end of the Badenian Salinity Crisis in the Eastern Carpathians, involving a decrease in the salinity of water-surface together with a significant influx of fresh water into the Carpathian basin.

**Keywords:** Central Paratethys; Badenian Salinity Crisis; nannofloras; Romania.

### INTRODUCTION

The Badenian Stage of the Paratethys, defined Papp & Steininger (1978), was divided, based on palaeogeographic, palaeontological and palaeoecologic features, into three substages (Papp et al., 1978; Rögl et al., 2002 and 2008; Kováč et al., 2004): (i) the Early Badenian (Moravian), (ii) the Middle Badenian (Wielician) and (iii) the Late Badenian (Kossovian). The Badenian stage, developed between 16.3 and 12.8 Ma corresponds to the global stages latest Burdigalian - Langhian – lower part of the Serravallian (Hartzhauser & Piller, 2007; Hohenegger et al., 2014).

During the Middle Badenian Paratethyan substage (=Wielician), a significant increase in salinity, due to palaeogeographical changes (Rögl, 1998; Popov et al., 2004), is known to occur, expressed in ‘the Middle Badenian Salinity Crisis’ (Băbel, 2004; Peryt, 2006; Piller et al., 2007). The evaporitic deposition related to the above-mentioned event was described since long time from several regions of the Romanian territory (i.e., Romanian Carpathians and Transylvanian Basin); the associated nannofloral assemblages (Dumitrică et al., 1975; Măruțeanu, 1999; Măruțeanu et al., 2000; Chira et al., 2000; Chira, 2001) of this depositional interval belong to the NN6 calcareous nannoplankton zone of Martini (1971), similarly to the findings from other Central Paratethys regions (Andreyeva-Grigorovich et al., 2003; Kováč et al., 2007; Śliwiński et al., 2012). Recently, Hohenegger et al. (2014), by correlating the subdivisions of the Badenian with palaeoclimatic changes, indicate that the Early Badenian approximately corresponds to the “Middle Miocene Climate Optimum”, the Mid Badenian is characterized by the “Middle Miocene Climate Transition”, while the Late Badenian corresponds to the instauration of the “Middle Miocene

Icehouse”, linked to the reoccurrence of the Antarctic glaciation. To note that the above-mentioned authors include in the Early and Middle Badenian the Moravian substage, while in the Late Badenian extend the substages Wielician and Kossovian, a stratigraphic scheme used for correlation herein.

The main aim of this work is to present fluctuation in calcareous nannofossil diversity and abundance observed in the Badenian, below and above the Badenian Salinity Crisis of the Eastern Carpathians. Palaeoenvironmental changes mirrored by nannofloral fluctuations are also discussed herein.

### GEOLOGICAL SETTING

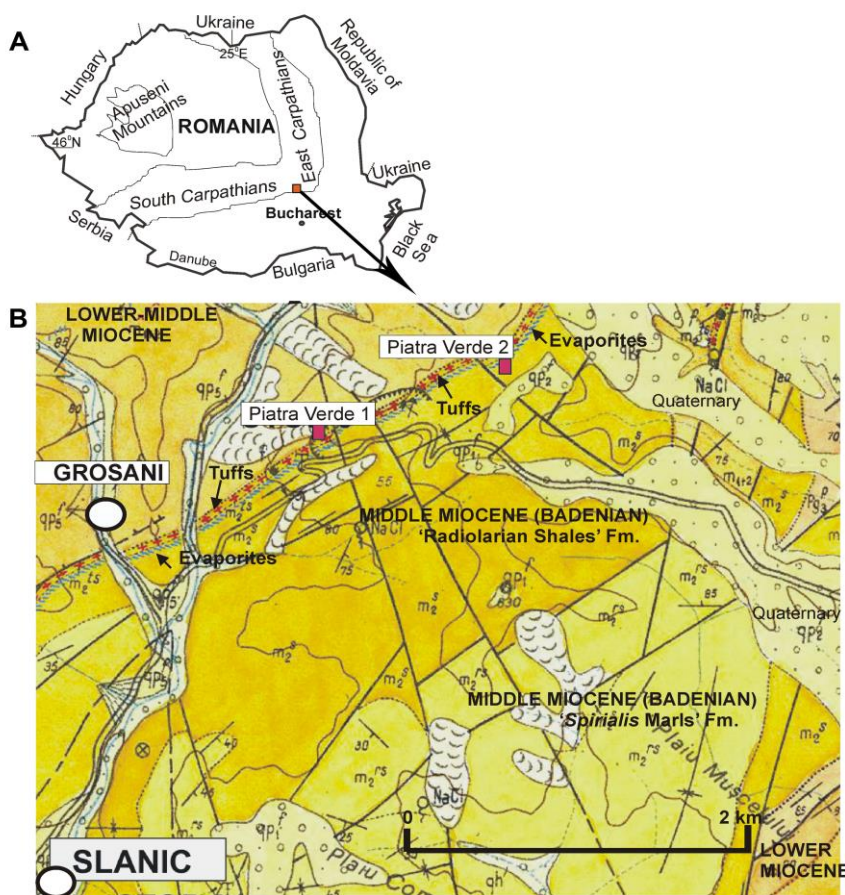
The southern end of the Eastern Carpathians display several Badenian complete sections, well dated based on their micropalaeontological content, i.e., foraminifers and calcareous nannofossils (Popescu, 1987; Măruțeanu et al., 2000; Popescu & Crihan, 2004, 2011). The investigated sections are situated towards the southern end of the Eastern Carpathians, N of the Slănic-Prahova locality (Fig. 1).

From a geological point of view, the studied area is placed towards the southern end of the Tarcău Nappe, the most areal widespread tectonic unit of the Moldavide nappes (Outer Flysch Zone of the Eastern Carpathians) – Săndulescu, 1984. Towards the southern part of the Eastern Carpathians, in the Prahova County, this nappe ends on two main anticlines, namely Homorâciu and Văleni, which are separated by two synclines, Slănic and Drajna, both filled with Miocene sediments (Fig. 1).

The post-tectonic sedimentary cover of the Tarcău Nappe are made by molasse units, such as the Doftana Formation that started to be accumulated in Early Miocene times (Ștefănescu & Măruțeanu, 1980), within

<sup>1</sup> National Institute of Marine Geology and Geo-ecology, 23-25 Dimitrie Onciul Street, RO-024053 Bucharest, Romania, melinte@geocomar.ro

<sup>2</sup> University of Bucharest, Faculty of Geology and Geophysics, Av. Nicolae Bălcescu 1, Bucharest, Romania, marius.stoica@g.unibuc.ro



**Fig. 1** Location of the studied outcrops. – **A:** Palaeogeography of the Badenian (after Rögl, 1998 and Popov et al., 2004). **B:** map of Romania showing the location of the studied area placed at the southern end of the Eastern Carpathians. **C** - Geological map of the Slănic area from Ștefănescu et al. (1978), showing the location of the studied outcrops: Piatra Verde 1 – the Slănic Formation; Piatra Verde 2 – the upper part of the ‘Evaporitic Formation’ followed by the ‘Radiolarian Shale’ Formation.

the Burdigalian and, respectively Eggenburgian (in term of the Paratethyan stages), being followed by the Slănic Formation (= the Slănic Tuff), Middle Miocene in age (Popescu, 1987; Papaianopol & Mărușeanu, 1992; Marinescu et al., 1998).

A representative succession of the Badenian deposits of the Outer Moldavides (Tarcău Nappe) is exposed in the axial part of the Slănic syncline, N of the Slănic-Prahova locality. The Slănic syncline appears as a normal fold, pitching to the NW, with asymmetric flanks: the SE one is sharply inclined, opposed to the NW one. The whole syncline is fragmented by longitudinal and transverse faults. The evaporites, which are mainly salt deposits, appear as a lens-like accumulation, with widest thickness, up to 500 m, in its central area (Popescu, 1951; Ștefănescu et al., 1978). The Badenian deposits (Figs. 2 and 3) that crop out in this structure are the following (from old to young):

(i) The Slănic Formation (= the Slănic Tuff), which is composed of interbedded volcanic tuffs, claystones and marlstones; levels very rich in foraminifera, described as the ‘*Globigerina* Marls’ occur, mainly in the lower part of the unit (Fig. 3 A); this unit was firstly assigned to the NN5 calcareous nannofossil zone, with *Sphenolithus heteromorphus* by Dumitrică et al. (1975); based on foraminiferal assemblages, the above-mentioned author identified towards the base of this unit the boundary

between the N8 and N9 zone, i.e., between *Praeorbulina* and *Orbulina suturalis*/*Globorotalia bykovae* zones, while towards the top of the Slănic Tuff, the foraminiferal zone N10 occurs, based on the occurrence of *Globorotalia peripheroacuta* and *G. ex. gr. foshi*.

(ii) The ‘Evaporitic Formation’, which is mainly made by salt breccias, gypsum as beds or lenses, salt accumulation and very thin, cm up to dm, silty clay beds (Fig. 3B); in this unit, based on calcareous nannofloras, Dumitrică et al. (1975) identified the boundary between the NN5 and NN6 zones, while from foraminiferal point of view this unit represents the upper part of the *Orbulina suturalis*/*Globorotalia bykovae* zone. The above-mentioned authors noted that the microfaunas and nannofloras are generally lacking in the Evaporitic Formation; however, the presence of the nannofossil *Discoaster brouweri* at the top of the Slănic Formation, below the Evaporitic Formation and the occurrence of *Triquetrorhabdulus rugosus* above the Evaporitic Formation, in the ‘Radiolarian Shale’ unit, argue that the NN5/NN6 boundary is situated in the Badenian evaporites of the Carpathian area;

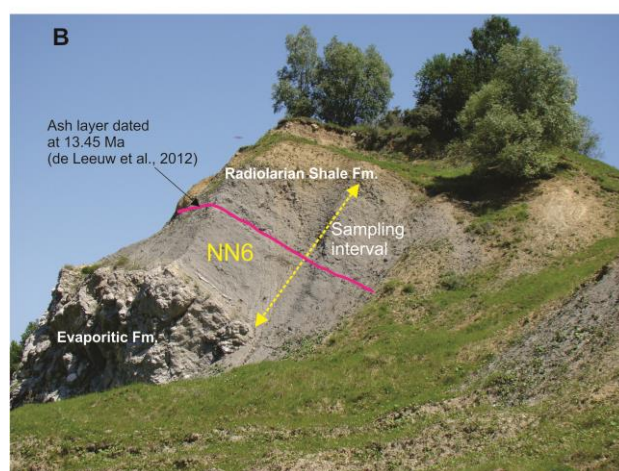
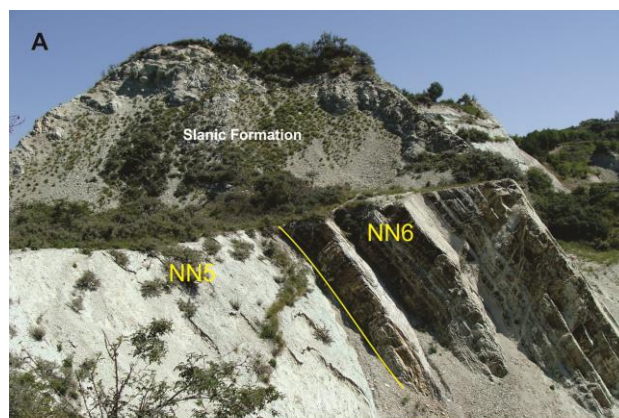
(iii) The ‘Radiolarian Shale’ Formation that is composed by argillaceous shales, rich in radiolarians, frequently containing taxa such as *Dictyocoryne*, *Rhopalodictyum*, and *Spongodiscus* (Dumitrică, 1978a), as well as sands and sandstones (Fig. 3B); this unit is, characterised,

according to Dumitrică et al. (1975), by the presence of the NN6 calcareous nannofossil zone, which has been found also in the next lithological unit, namely the ‘*Spirialis* Marl’ Formation. The above-mentioned authors indicated the occurrence of the foraminiferal taxa belonging to the *Velapertina* genus in the ‘Radiolarian Shale’ Formation and, of siliceous microfossils belonging to the *Distephanus stauracanthus* silicoflagellate zone and *Cannartus laticonus* radiolarian zone.

The ‘*Spirialis* Marl’ Formation, which developed in a predominant pelitic facies; in this unit, the pioneer investigations of Dumitrică et al. (1975) identified the same microfaunas and nannofloras as in the older ‘Radiolarian Shale’ Formation.

‘ <i>Spirialis</i> Marl’ Fm. (up to 50 m)	Upper Badenian NN6b nannofossil subzones
Radiolarian Shale’ Fm (up to 30 m)	Middle Badenian to Upper Badenian <i>pro parte</i> NN6a and NN6b nannofossil subzones
Evaporitic Fm. (up to 180 m)	Middle Badenian NN6a nannofossil subzone
Slanic Fm. (up to 70 m)	Lower Badenian to Middle Badenian <i>pro parte</i> NN5b and NN6a nannofossil subzones
Doftana Fm. (up to 900 m)	Upper Karpatian-Lower Badenian <i>pro parte</i> NN4a, NN4b and NN5a nannofossil subzones

**Fig. 2** Middle Miocene lithostratigraphy of the Tarcău Nappe post-tectonic cover in the investigated region of the southern end of the Eastern Carpathians; in brackets total stratigraphical thickness. Age of the lithostratigraphic units and nannofossil subzones after MăruŃeanu, 1999.



**Fig. 3** Photograph of the studied outcrops (Photos by Dr. Andrei Briceag); **A** The Slănic Formation in the Piatra Verde Hill (outcrop Piatra Verde 1 in Fig.1), NN5 and NN6 calcareous nannofossil zones; **B** The contact between the ‘Evaporitic Formation’ and the Radiolarian Shale Formation (outcrop Piatra Verde 1 in Fig.2), NN6 calcareous nannofossil zone; red line – the tuff level dated by de Leeuw et al. (2012); yellow line – interval sampled for nannofossil studies.

## MATERIAL AND METHODS

Several samples have been analysed for calcareous nannoplankton investigations, proceeding from below and above the ‘Evaporitic Formation’. From the outcrop of the ‘Slănic Formation’ (below the ‘Evaporitic Formation’) exposed in the Piatra Verde (‘the Green Stone’) Hill, noted as Piatra Verde 1 in Fig. 1 (latitude 45°15’20.86’’ N and longitude 25°57’28.52’’E), 29 samples, collected at a sampling interval of around 1 m, have been studied (Figs. 3 and 4). From the outcrop showing the contact between the ‘Evaporitic Formation’ and the ‘Radiolarian Shale’ Formation, noted as Piatra Verde 2 in Fig. 1 and situated at around 3 km NE from Piatra Verde 1 (latitude 45°15’31.63’’N and longitude 25°58’02.79’’E), a number of 29 samples have been collected, the sampling interval being around 50 cm (Figs. 3 and 6).

The smear-slides have been prepared directly from the untreated samples, in order to ensure the original composition. The calcareous nannofloral analyses have been performed by using a polarizing light Olympus microscope at 1600x magnification. Both qualitative and quantitative studies have been achieved. For the quantitative analysis, at least 300 calcareous nannofloral specimens have been counted in each smear slide, the investigation being completed at 250 fields of view. In the counting, several taxonomic groups have been included, as follows: *Helicosphaera* taxa, *Sphenolithus* taxa, *Discoaster* taxa, *Braarudosphaera* taxa, *Calcidiscus* taxa, *Cyclicargolithus floridanus*, *Pontosphaera* taxa and *Reticulofenestra* taxa. These taxonomic groups represent over 90 % of the total recorded specimens in both outcrops. Taxonomic identification follows Perch-Nielsen (1985) and Young (1998).

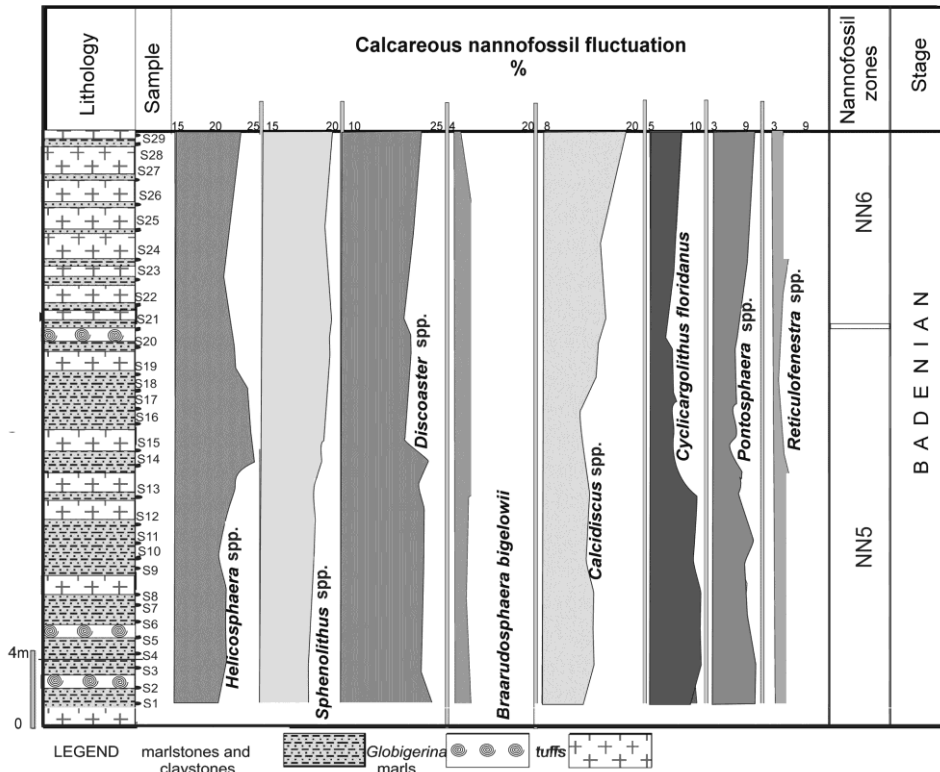
**RESULTS**

In the Piatra Verde Hill (outcrop Piatra Verde 1 in Fig. 1), the Slănic Formation (= the Slănic Tuff) is exposed in a quarry along the route, yielding about 80 m stratigraphical thickness. The unit consists of compact, hard tuffs developed in 0.5 up to 2.0 m thick beds. Its colour is mainly green, but also white and bluish, often showing brown alterations. The tuff layers are stratified, being interbedded with marlstones and claystones, features indicating that the volcanic material has been resedimented. Levels that are rich in tests of the foraminiferal *Globigerina* taxa occur within this formation, mainly in its oldest part. Due to intense diagenetic processes, mirrored also in the high zeolite content, the ash layers of the Slănic Formation could not

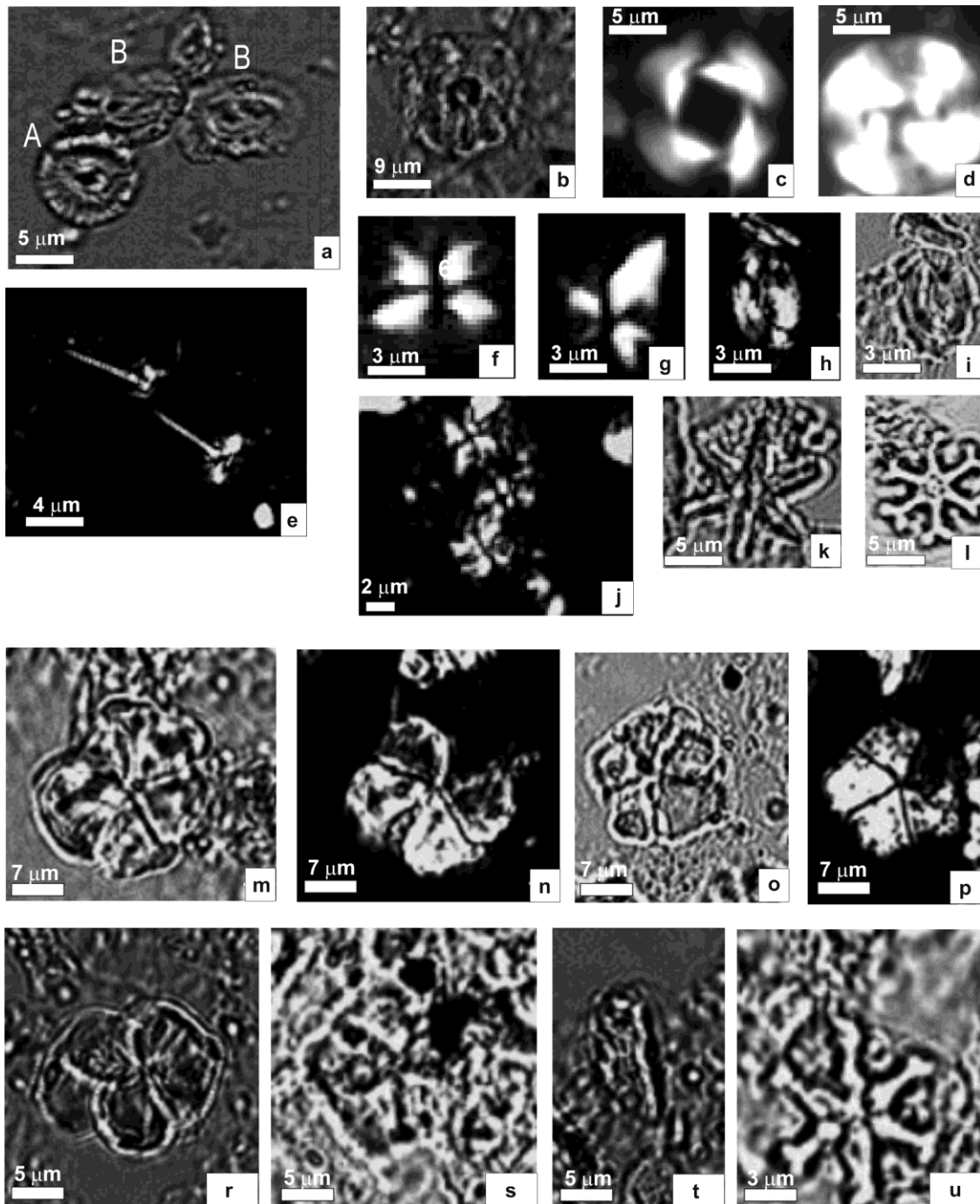
be absolutely dated, so far.

The nannofloral assemblages observed in the lower part of the Slănic Formation have been assigned to the NN5 calcareous nannoplankton zone of Martini (1971), based on the co-occurrence of *Sphenolithus heteromorphus*, *Helicosphaera walbersdorfensis*, *H. waltrans* and *H. wallichii*. The biozone NN5 has been divided, in the Romanian Carpathian areas (Mărunțeanu, 1992 and 1999; Mărunțeanu et al., 2000) into two subzones: NN5a, the *Umbilicosphaera rotula* (= *Calcidiscus annula*) subzone and NN5b, the *Helicosphaera wallichii* subzone. Similar assemblages of NN5 have been described from other Central Paratethys areas, such Austria, Croatia, Czech Republic, Slovenia and the Romanian Intra-Carpathian, i.e., the Transylvanian Basin (Ćorić et al., 2004; Ćorić et al. 2007; Švábenická, 2002; Galović & Young, 2012; Bartol, 2009; Chira, 2001; Chira & Bălc, 2002), starting from the upper part of the Early Badenian up to the lower part of the Middle Badenian (Hohenegger et al., 2014; Bartol et al., 2014). Towards the middle part of the Slănic Formation, *Helicosphaera walbersdorfensis* shows a common occurrence; hence, this event could be used in recognizing the boundary between the MNN5a and MNN5b Mediterranean calcareous nannofossil subzones of Fornaciari et al. (1996).

In the samples belonging to NN5, frequently *Sphenolithus* taxa, i.e., mainly *S. moriformis* and *S. heteromorphus* and few specimens assigned to *S. grandis* and *S. compactus*, as well as *Discoaster* species, including common *D. challengerii*, *D. brouweri*, *D. exilis* and *D. variabilis*, together with rare *D. moorei*, *D. micros* and *D. braarudii*, have been encountered (Fig. 5). The *Sphenolithus* and *Discoaster* genera represent together almost 50 % of total nannofloras (Fig. 4).



**Fig. 4** Nannofloral fluctuation of the main groups recorded in the outcrop Piatra Verde 1, in the Slănic Formation, below the ‘Evaporitic Formation’.



**Fig. 5 a-l:** Microphotographs of calcareous nannofossils identified in the lower part of the Slănic Formation in the Piatra Verde Hill (outcrop Piatra Verde 1 in Fig. 1), belonging to **NN5** calcareous nannofossil zone. Light microscope: **a, b, i, k** and **l** in transmitted lights; **c-h** and **j** in crossed nicols. Scale bar in microns. **a:** *A-Calcidiscus leptoporus* (Murray & Blackman, 1898) Loeblich & Tappan, 1978; **B:** *Helicosphaera carteri* (Wallich, 1877) Kamptner, 1954, Sample S11; **b:** *Calcidiscus macintyreii* (Bukry & Bramlette, 1969) Loeblich & Tappan, 1978, Sample S17; **c:** *Reticulofenestra pseudoumblica* (Gartner, 1967) Gartner, 1969, Sample S3; **d:** *Cyclicargolithus floridanus* (Hay et al., 1967) Bukry, 1971, Sample S3; **e:** *Rhabdosphaera procera* (Martini, 1969) Jafar, 1975, Sample S18. **f-g:** *Sphenolithus heteromorphus* Deflandre, 1953, 6 – at 0°, 7 – at 45°. Sample S17; **h-i:** *Helicosphaera cf. walbersdorfensis* Müller, 1974, Sample S3; **j:** *Sphenolithus moriformis* (several specimens) (Brönnimann & Stradner, 1960) Bramlette & Wilcoxon, 1967, Sample S6; **k:** *Discoaster brouweri* (Tan, 1927) Bramlette & Riedel, 1954, Sample S6; **l:** *Discoaster challengeri* Bramlette & Riedel, 1954, Sample S20. **m-u:** Microphotographs of calcareous nannofossils identified in the ‘Radiolarian Shale’ Formation (outcrop Piatra Verde 2), belonging to **NN6** calcareous nannofossil zone. Scale bar in microns; light microscope: **m, o** and **r-u** in transmitted light; **n** and **p** in crossed nicols; **m-n:** *Braarudosphaera rosa* Levin & Joerger, 1967 (round shape), Sample Pv1; **o-p:** *Braarudosphaera bigelowii* Deflandre, 1947 (angular shape), Sample Pv1; **r:** *Braarudosphaera rosa* Levin & Joerger, 1967 (round shape), Sample Pv17; **s:** *Braarudosphaera bigelowii* Deflandre, 1947 (angular shape), Sample Pv17; **t:** *Triquetrorhabdulus rugosus* Bramlette & Wilcoxon, 1967, Sample Pv13; **u:** *Discoaster variabilis* Martini & Bramlette, 1963, Sample Pv5.

Other taxa, identified as abundant in the NN5 nannofossil zone, are *Calcidiscus leptoporus* and *C. macintyreii* that jointly amounted to 10 up to 15 %. A significant abundance is shown also by *Helicosphaera* (mainly represented by *H. carteri* and rarely by *H. walbersdorfensis*, *H. waltrans* and *H. wallichii*), and *Reticulofenestra* that is mainly composed of *R. pseudumbilica* (5-7 µm) and small-sized species, i.e., *R. haqii*, *R. gelida*, *R. minuta* and *R. minutula*. In all the studied samples, a continuous occurrence of *Braarudosphaera bigelowii* has been observed, but with low percentages, up to 5-6 %. *Cyclicargolithus floridanus* is common throughout all the section, more frequent towards the lower part (up to 10 %), while *Pontosphaera* spp. (*P. multipora* and *P. japonica*) represent 7-9 % of nannofloras.

The samples collected from the upper part of the Slănic Formation, where the dominant lithology is the green tuff, were assigned to the NN6 calcareous nannoplankton zone of Martini (1971), based on the LO (last occurrence) of *Sphenolithus heteromorphus* that marks the boundary between the NN5 and NN6 nannofloral zones, and, respectively the boundary between the subzones MNN5b and MNN6a of Fornaciari et al. (1996). The assemblages are still dominated by the genera *Sphenolithus* and *Discoaster*, but the latter one shows a slight decrease as comparing with its abundance in the older NN5 zone. Concomitantly, *Calcidiscus* spp. (*C. leptoporus* and *C.*

*macintyreii*) increased up to 20 % of total nannofloras. *Cyclicargolithus floridanus* shows a slight and continuous decline in abundance (Fig. 4).

The other outcrop investigated (Piatra Verde 2 in Fig. 1) displays the contact between the Evaporitic Formation and the Radiolarian Shale Formation. The Evaporitic Formation is mainly composed, in this outcrop, by gypsum and very thin silty clay beds yielding a few molluscs belonging to the *Pycnodonta*, *Ostrea*, *Glycimeris*, *Chlamys*, *Diloma*, *Callistoma* and *Vermetus* genera (Popescu, 1951). The gypsum is divided into two piles of sulphatic lithons, separated from breccia, each lithons having obvious reworking features. The low sulphatic pile shows features of gravity flow stages with few breaks of algal/clastic rhythmic accumulation. The upper sulphatic pile contains clastic rhythmites, followed by 20 meters of clastic debris (Frunzescu, 1998; 2012).

In the studied outcrop, the boundary between the 'Evaporitic Formation' and the 'Radiolarian Shale' Formation occurs. The later unit is mainly made of argillaceous shales, with rarely interbedded thin cm sands and sandstones. To note that the radiolarians could be found mainly towards the top of this formation, while its lowest part is usually barren of these microfossils or it contains very few (Dumitrică, 1978a).

In the section studied (Piatra Verde 2 outcrop in Fig. 1), the presence of thin, up to 5-7 cm thick, ash layers is to be noted (Fig. 6).

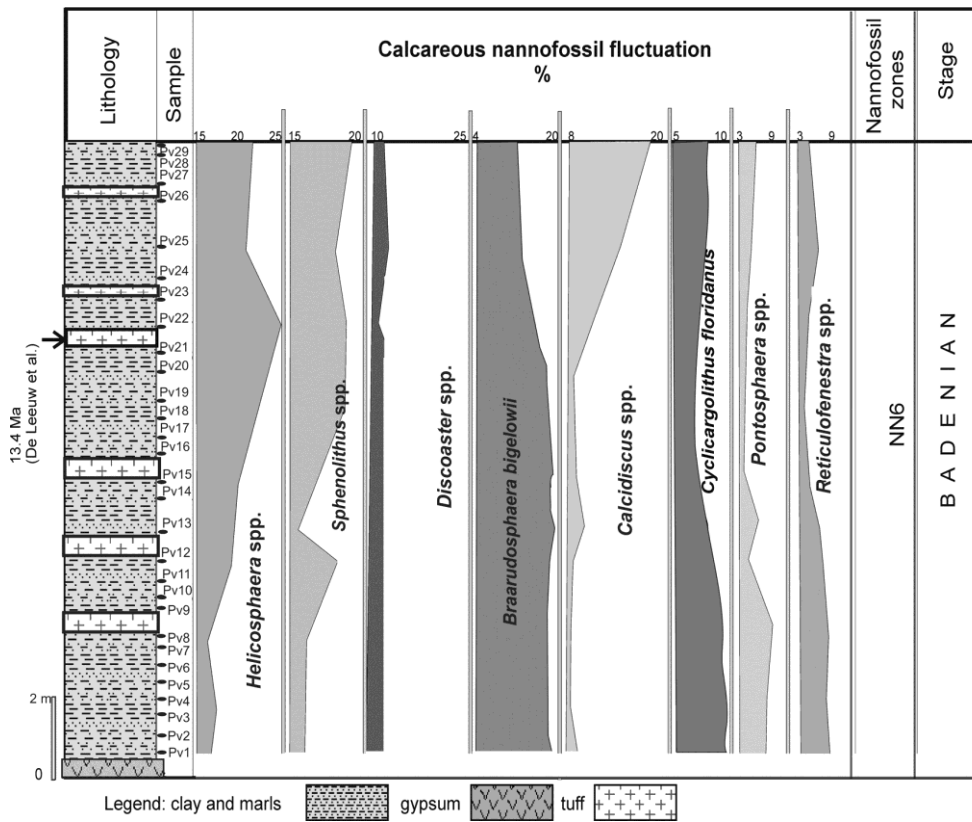


Fig. 6 Nannofloral fluctuation of the main groups recorded in the outcrop Piatra Verde 2, in the 'Radiolarian Shale' Formation, above the 'Evaporitic Formation'.

All the samples proceeding from the ‘Radiolarian Shale’ Formation belong to the NN6 calcareous nannoplankton zone of Martini (1971), interval placed between the LO (last occurrence) of the nannofossil *Sphenolithus heteromorphus* and the FO (first occurrence) of the nannofossil *Discoaster kugleri*. In the intra- and extra-Romanian Carpathian areas, the biozone NN6 has been divided (Mărunțeanu, 1992, 1999; Mărunțeanu et al., 2000) into several subzones: NN6a, between the LO of *Sphenolithus heteromorphus* and the FO of *Syracolithus dalmaticus*; NN6b, between the FO of *Syracolithus dalmaticus* and the FO of *Calcidiscus pataecus*, and NN6c, between the FO of *Calcidiscus pataecus* and the LO of *Cyclicargolithus floridanus*, and/or the FO of *Discoaster kugleri*. *Syracolithus dalmaticus* and *Calcidiscus pataecus* have been not observed in the studied samples; therefore, we assume that the whole investigated succession situated above the ‘Evaporitic Formation’ belongs to the NN6a subzone. The nannofloral quantitative analysis of the ‘Radiolarian Shale’ Formation pointed out that, just above the top of the ‘Evaporitic Formation’, the most abundant nannofossils are *Helicosphaera* and *Sphenolithus* taxa that mainly included *S. moriformis*, as well as *Braarudosphaera bigelowii* (Fig. 6); the three taxonomic groups are making together over 50 % of nannofloras. *Braarudosphaera bigelowii* records its maximum, almost 20 %, within the oldest 8 m of the ‘Radiolarian’Shale’ Formation; afterwards it decreases in abundance, representing around 10 % at the top of the section. *Cyclicargolithus floridanus* consistently occurs above the top of the gypsum and represents almost 10 % of the total nannofloras, showing a continuous decrease top section. The abundance of the discoasterids is around one half, up to 10 %, as comparing with older intervals of below the ‘Evaporitic Formation’. *Calcidiscus* spp. (*C. leptoporus* and *C. macintyreii*) are minor components of nannofloras in the lower part of the section, they do not exceed 8-9 %, but the abundance significantly increases top section, reaching up to 20 %. Both *Pontosphaera* and *Reticulofenestra* species show a similar abundance within the lower part of the ‘Radiolarian’Shale’ Formation as recorded in the Slănic unit, but towards the top section both genera have a tendency of decreasing in abundance (Fig. 6).

## DISCUSSION

Below the ‘Evaporitic Formation’, towards the top of the Slănic Formation, the boundary between the NN5 and NN6 calcareous nannofossil zones has been identified, based on the LO (last occurrence) of *Sphenolithus heteromorphus*, bioevent that took place at 13.6 Ma (Raffi et al., 2006). Above the ‘Evaporitic Formation’, significant biostratigraphical nannofossils have been encountered, i.e., *Cyclicargolithus floridanus* (with the LCO, last common occurrence at 13.29 Ma), *Calcidiscus premacintyreii* (LCO at 12.45 Ma) and *Coronocyclus nitescens* (LO at 12.25) - all the absolute ages are given in Raffi et al. (2006). To note that both *Cyclicargolithus floridanus* and *Coronocyclus nitescens* occur commonly above the ‘Evaporitic Formation’. Therefore, the age of

the Badenian Salinity Crisis of the Eastern Carpathians, expressed in the studied section by the deposition of the ‘Evaporitic Formation’, is constrained, based on the nannofossils events, between 13.6 Ma and 13.29 Ma, being placed within the NN6 calcareous nannofossil zone.

As it was mentioned before, above the ‘Evaporitic Formation’, in the outcrop Piatra Verde 2, several cm ash layers have been identified (Fig. 6). One of these levels has been dated by de Leeuw et al. (2012), who identified an age of 13.4 Ma. Hence, we may assume that the termination of the Middle Badenian Salinity Crisis is, in the Eastern Carpathians, older than 13.4 Ma. To note that in other Carpathian regions, i.e. southern Poland, radioisotopic ages performed by de Leeuw et al. (2010) for volcanic tuff layers situated below the evaporites show that the evaporite deposition started shortly after 13.8 Ma. In the same region, Śliwiński et al. (2012) obtained an age of 13.6 Ma for a tuff found in the Badenian salt and 13.06 Ma for a volcanic tuff identified in the ‘*Pecten* Beds’ Formation overlying the Badenian evaporates. Recently, de Leeuw et al. (2013), by studying the Middle Miocene of the intra-Carpathian area, i.e. the Transylvanian Basin, identified in basal levels of the Dej Tuff, lithological unit that is probably synchronous with the Slănic Tuff of the Eastern Carpathians, an age of  $14.38 \pm 0.06$  Ma. In the Transylvanian area, the tuff accumulation ends before the onset of the Badenian Salinity Crisis, which is placed at 13.82 Ma (de Leeuw et al., 2010).

Interestingly, below the tuff level of the studied section dated as 13.4 Ma (de Leeuw et al., 2012), a remarkable increase in pentoliths such as *Braarudosphaera bigelowii*, which reaches almost 20 % of nannofloral assemblages, was observed. This bio-event started just above the boundary between the ‘Evaporitic Formation’ and the ‘Radiolarian Shale’ Formation.

Previously studies of other Central Paratethyan areas (i.e., Slovenia) reported a significant frequency of pentoliths such as *Braarudosphaera bigelowii* and *Micrantholithus vesper* in Early Miocene deposits (Bartol et al., 2008). This nannofloral event, coincident with a decrease in isotope  $\delta^{13}\text{C}$  values, is linked by the above-mentioned authors to short-lived episode of hyposaline conditions. Additionally, in the Lower Miocene deposits of Slovenia, *Braarudosphaera bigelowii* yielded two distinct morphotypes, rounded and angular, as described by Bartol et al. (2008). Recently, Bartol et al. (2014) found enrichment in *B. bigelowii* pentoliths in the Badenian deposits of NE Slovenia, in the NN5 nannofossil zone, and interpreted this event to be linked also to salinity fluctuations. The specimens found by them belong to a single morphotype, the ‘classical’ one, with sharp corners and trapezoidal segments.

In the studied sections of the Eastern Carpathians, the *Braarudosphaera bigelowii* bloom was observed in the NN6 nannofossil zone, above the Badenian Salinity Crisis. Both morphotypes (Fig. 5), the trapezoidal one, i.e., *Braarudosphaera bigelowii* and the round-shaped one, i.e., *Braarudosphaera rosa*, have been observed, as reported by Bartol et al. (2008) in the Early Miocene sediments of Slovenia, but not in the Badenian ones,

where only the trapezoidal specimens are present (Bartol et al., 2014).

Blooms of *Braarudosphaera bigelowii* are known to occur in several Mesozoic-Cenozoic intervals. In the Romanian Carpathians and Transylvanian Basin, such event was observed in Early Oligocene and seems to be synchronous with the isolation of the Paratethys from the Tethys Realm (Melinte, 2005; Melinte-Dobinescu & Brustur, 2008), being linked to a shift of the salinity in the whole Paratethyan area. Probably, in the Badenian sediments of the southern part of the Eastern Carpathians, the enrichment in *Braarudosphaera bigelowii* is linked to the end of the Badenian Salinity Crisis, and mirrors a salinity decrease of surface-water related to a significant influx of fresh water into the Eastern Carpathian basin.

**CONCLUSIONS**

The investigations based on nannofloral assemblages revealed that the boundary between the NN5 and NN6 calcareous nannofloral zones, and, respectively between the MNN5b and MNN6a Mediterranean subzones, could be traced towards the upper part of the Slănic Formation (=Slănic Tuff), above the youngest level containing enrichment in planktonic foraminiferal *Globigerina*, below the 'Evaporitic Formation'. Above this unit, in the 'Radiolarian Shale Formation', the nannofossil assemblages are characteristic for the NN6 zone as well (Fig. 7).

These findings are in agreement with former works (MăruŃeanu, 1999; MăruŃeanu et al., 2000), which identified in the deposits of the Slănic Formation, the NN5b and NN6a nannofloral subzones zones, and in the 'Radiolarian Shale' Formation the NN6a subzone. In the Transylvanian Basin, the boundary between the NN5 and NN6 zones was found in the upper part of the Dej Tuff, below the evaporitic deposition, while above this event the NN6 zone is still present (Chira et al., 2000; Chira, 2001). Hence, based on nannofloras biostratigraphy, the Slănic Tuff of the Eastern Carpathians correlated with the Dej Tuff of the Transylvanian Basin, both being placed within the upper part of NN5 and lower part of NN6 calcareous nannofossil zones.

If we take into account the character of the nannofossil assemblages of NN5 zone, characterized by the dominance of warm taxa *Discoaster* and *Sphenolithus*, as well as by a significant diversity and high abundance of the nannofloras, we may assume that the depositional interval of the Slănic Formation (up to the above the youngest levels of *Globigerina* enrichment) corresponds to the "Middle Miocene Climate Transition", described by Hohenegger et al. (2014). The change in nannofloral composition, expressed in the decline of discoasterid diversity and abundance, as well as in a gentle decline of *Sphenolithus* taxa from the base of the NN6 zone, below and above the Evaporitic Formation, could be linked to the starting of to the instauration of the "Middle Miocene

Epoch	Global Stage	Paratethys		Formation	Calcareous nannofossil		Events	
		Stage	Substage		Zones NN	MNN		
MIOCENE MIDDLE	SERAVALLIAN	SARMATIAN	EARLY	Volhynian	NOT STUDIED			
			12.829 Ma			MNN6b		<i>Reticulofenestra pseudumbilicus</i> FCO
	LANGHIAN	BADENIAN	LATE	Kosovian	'RADIOLARIAN SHALE' FM.	NN6	MNN6a	
			13.82 Ma	Wielician	'EVAPORITIC' FM.			
EARLY	BURDIGALIAN	KARPATIAN	MIDDLE		SLANIC FM.	NN5	MNN5b MNN5a	<i>Helicosphaera walbersdorfensis</i> FCO
			15.032 Ma	Moravian				MNN4b
			EARLY		NOT STUDIED	NN4	MNN4a	<i>Helicosphaera ampliaperta</i> LCO
			16.303 Ma					

**Fig. 7** Age of the analyzed lithostratigraphic units from the Eastern Carpathians and correlation with Middle Miocene stages and substages; correlation scheme between global and Paratethys stages and substages after Hohenegger et al. (2014); NN – Neogene calcareous nannofossil zones after Martini (1971); MNN – Mediterranean calcareous nannofossil zones after Fornaciari et al. (1996); LO – last occurrence; LCO – last common occurrence; FCO – first common occurrence; PE- paracme end.

Icehouse”, linked to the reoccurrence of the Antarctic glaciation (Hohenegger et al., 2014). This palaeoenvironmental setting was earlier assumed by Dumitrică (1978b) based on the silicoflagellate assemblages identified in Vienna Basin and Romania. Hence, the above-mentioned author observed that the silicoflagellates are indicative for a warm climate during the Early Badenian in the Central Paratethys, while for the Late Badenian a cooling is hypothesized for this region. This palaeoenvironmental shift is shown not only by the fluctuation in the silicoflagellate assemblages, but also by the palynofloras (Dumitrică, 1978b).

As concerning the palaeoenvironmental setting, an open marine one, with a normal salinity is to be assumed for the depositional interval of NN5 and basal NN6 zones, while starting from the lower part of the NN6 zone, a decrease in the salinity and a restricted circulation, based on bloom of *Braarudosphaera bigelowii*, could be supposed. We may hypothesize that the aforementioned blooms are related also to a high nutrient input in the Eastern Carpathian basin, brought by significant influx of fresh waters.

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