Carpathian Journal of Earth and Environmental Sciences, February 2016, Vol. 11, No. 1, p. 131 - 146

EVENTS IN THE NORTHERN PALEOGENE FORELAND BASIN OF THE EASTERN CARPATHIANS (ROMANIA, BUCOVINA), AT THE YPRESIAN-LUTETIAN TRANSITION

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Abstract: Global post-Cretaceous events have triggered changes in both terrestrial and marine environments, which have left biostratigraphic, sedimentological and chemostratigraphic traces in all sedimentary basins. The present study focuses on the outcome of such events, as recorded in the sedimentary sequence of the Ypresian (Yp)-Lutetian (Lu) boundary in the northern part of the Moldavidic Basin of the Eastern Carpathians (Bucovina). With this purpose, a section from the eastern portion of the Moldavidic Paleogene foreland basin (the Tarcău Nappe), where the deposits crop out in a sedimentary continuum at the Yp/Lu boundary, was selected, and correlated with profiles exposed across an east-west direction by the Suceava River. The Yp/Lu transition was established based on biostratigraphic data (calcareous nannoplankton and agglutinated foraminifera), and the collection of samples for chemostratigraphic determinations and analyses was carried out following the succession of depositional events (one sedimentological sequence at a time). The chemostratigraphic response of the climatic evolution from the Paleocene-Eocene Thermal Maximum (PETM), followed by the evolution toward the Early Eocene Climatic Optimum (EECO), was recorded in the variation curves of $CaCO_3$, total carbon (TC), total organic carbon (TOC), total inorganic carbon (TIC), and the $^{88}Sr/^{85}Rb$ ratio.

Keywords: Ypresian/Lutetian, biostratigraphy, chemostratigraphy, petrofacies, Moldavides, paleogeography, Eastern Carpathian foreland basin, Bucovina, Romania.

1. INTRODUCTION

The changes triggered by geotectonic movements and paleoclimatic evolution are reflected, with more or less inertia, within sedimentary basins. The biostratigraphic, magnetostratigraphic, sedimentological, chemostratigraphic etc. recording of an event within sedimentary sequences is generally heterochronous. As a result, researchers practically operate with transition ranges and different time spans for different sections. In GSSP Gorrondatxe (Western Pyrenees), the Yp/Lu boundary was estimated, based on sedimentation rates, at roughly 800 thousand years (Molina et al., 2011).

The present paper deals with the study of the paleogeographic events which occurred at the Early Eocene (Yp) / Middle Eocene (Lu) transition, as recorded within the sedimentary sequences of the Outer Moldavides of the Eastern Carpathians, Bucovina (Tarcău Nappe) (Fig. 1). A correlation was sought withthe events described by Guerrera et al., (2012) across the eastern boundary of the Outer Moldavides, as well as with those recorded in the Eocene foreland basins of the Western Pyrenees (Bernaola et al., 2006; Payros et al., 2006, 2007; Larrasoaña et al., 2008; Molina et al., 2000, 2006, 2011).

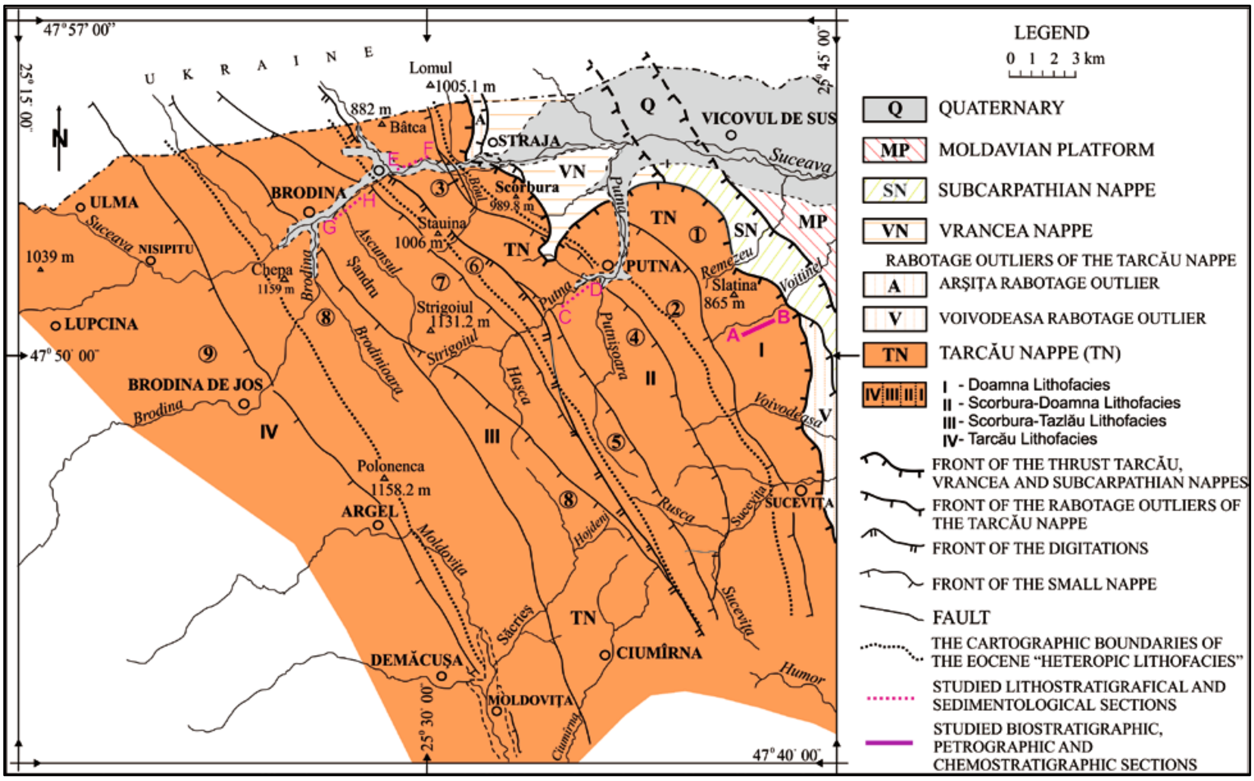

Figure 1. Simplified geological map of the Outer Moldavides from the Suceava basin (Bucovina, Eastern Carpathians). area with location of the studied logs (based on references Joja et al., 1968; Juravle et al., 2008, 2009; Micu, 1981).
The subunits of the Tarcău Nappe: ***Outer digitation***: 1 – the Dealul Rău-Cociniş Small Nappe; 2 – Lomul-Scorbura-Suceviţa; 3 – the Straja Small Nappe; 4 – Bâtca-Glodul-Bercheza Small Nappe; 5 – the Poiana Crucii Small Nappe; ***Inner digitation***: 6 – the Stauina-Sihăstria Small Nappe; 7 – the Obcina Mare-Hojdeni Small Nappe; 8 – the Solovanu-Polonenca Small Nappe; 9 – the Ulma-Demăcuşa Syncline.

The deposits that make up the Moldavides of the Eastern Carpathians are of Cretaceous-Miocene age, having accumulated in the old Eastern-Carpathian foreland basin (*sensu* Grasu et al., 1999, Miclăuş et al., 2009). The lithofacies is characterized by the development of heteropic formations, triggered by the west-east migration of the Carpathian foreland depozones. Basin architecture in the Moldavides was rendered complex by the geotectonic dynamics, at least across the eastern border of the outer flysch (the Vrancea Nappe, *sensu* Ionesi, 1968; the Marginal Folds Nappe, *sensu* Săndulescu, 1984). The Paleogene-Miocene subduction of the East-European craton under the Tisza-Dacia block, combined with the rotational movements of the latter, determined the formation of strike-slip basins, in which the deposits of the Paleogene-Miocene formations from the tectonic semi-windows of the Vrancea Nappe accumulated (Guerrera et al., 2012). The effects of the compressional tectogenetic events of the Miocene (Styrian and Moldavidian), including the formation of the Moldavidian nappes (from west to east: Teleajen, Audia, Tarcău, Vrancea and Subcarpathian), have been studied by Săndulescu (1984), Maţenco & Bertotti (2000) *etc*.

The Outer Moldavides of the northern Carpathian foreland basin crop out visibly within the basins of Suceava and Moldova, where heteropic lithofacies can be studied (*sensu* Ionesi, 1971; Gigliuto et al., 2004). Numerous papers on the Paleogene deposits of Bucovina have been published, the most relevant for the present topic being those of Chira et al., (2011a, 2011b), Joja (1954), Juravle (2007), Juravle et al., (2008, 2009). The development of heteropic facies during the Eocene, and the lithofacial variations of the Vrancea and Tarcău nappes have been studied in detail by Ionesi (1971), Juravle (2007), Juravle et al., (2008, 2009), and Miclăuş et al., (2009). The research carried out, up to the present moment, on the chemostratigraphic *traces*" left on the lithologic sequences of the Moldavidian flysch Basin is, on the other hand, insufficient.

The present study focuses, therefore, on the imprints ofevents atthe Yp/Lu transitionacross a series of sections from the Tarcău Nappe outcropping in the Suceava Basin (Figs. 1, 2). Four profiles disposed along an east-west direction, transversely in relation to the direction in which the tectonic units developed, were analyzed. They revealed in detail the lithostratigraphic variations of the Paleogene deposits, emphasizing an increase toward the west of the frequency of debris flows

(Lowe sequences) and sandy turbidity currents (Bouma sequences, Tab), compared to silty turbidity currents (Bouma turbidity sequences, Tde). As a result, toward the west, the Straja Formation acquires a strong arenitic character, the Suceviţa Formation is substituted by the Scorbura Formation, the Doamna Formation loses its individuality, finding its correspondent in the upper portion of the greso-calcareous turbidites of the Tazlău Formation, the Strujinoasa and Bisericani formations (lutitic turbidites) are substituted by the Plopu Formation, while the "*Globigerina Marls*" are substituted by the Lucăceşti quartzy sandstones (Juravle 2007, Juravle et al., 2008) (Fig. 2).

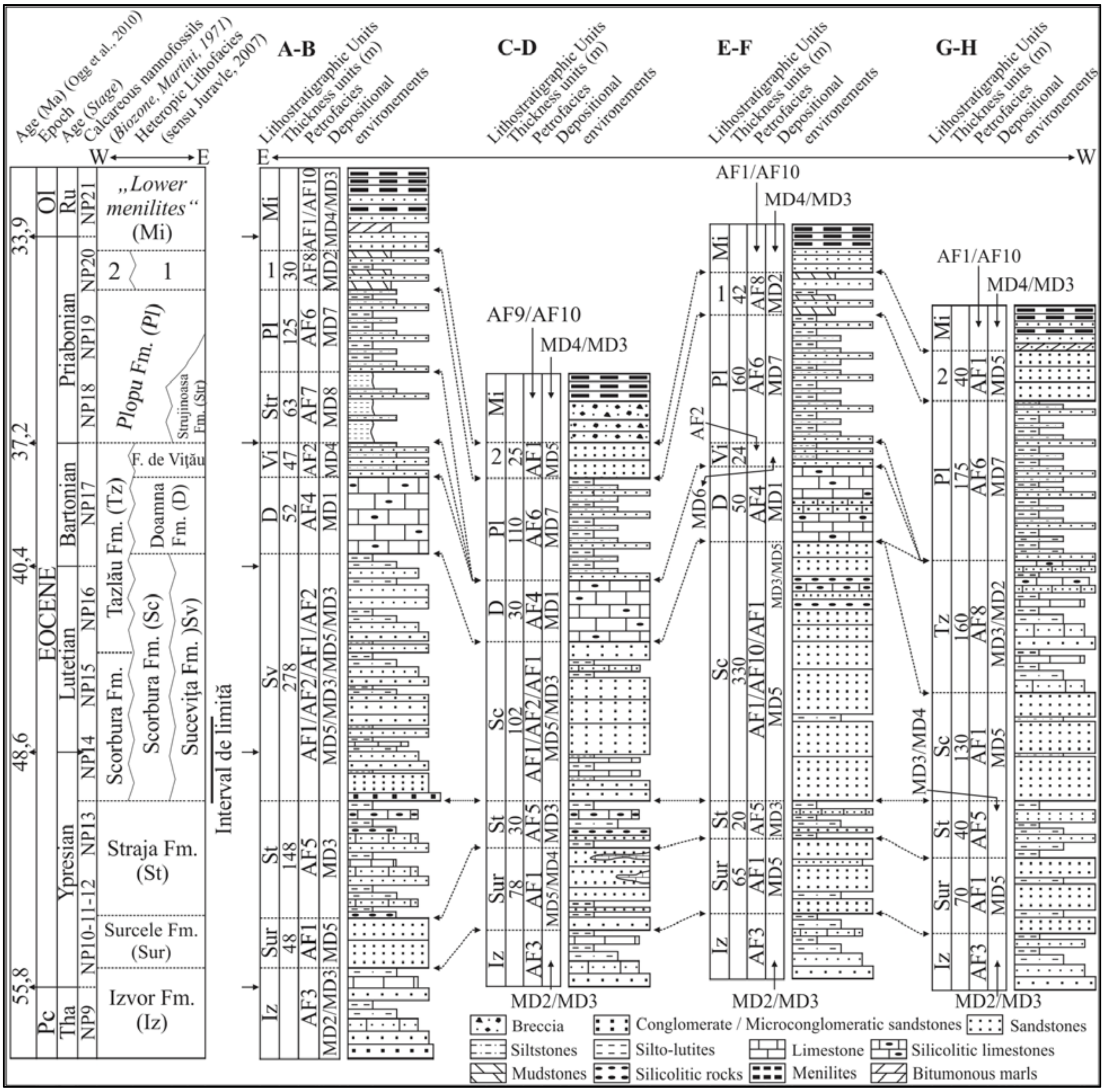

Figure 2. Lithofacial variation of the Eocene deposits from the northern portion of the Moldavidian Domain, across the Tarcău Nappe (Bucovina, Eastern Carpathians).

Pc - Paleocen, Tha - Thanetian, Ol - Oligocen, Ru – Rupellian (*Geologic Time Scale* according to Ogg et al., 2010); **Heteropic Lithofacies** (described from East to West) (*sensu* Juravle, 2007): **A-B.** ***Section Pietroasa*** - Doamna Lithofacies, **C-D** şi **E-F.** ***Sections Putna*** and ***Caraula*** - Scorbura-Doamna Lithofacies, **G-H.** ***Section Frasin*** - Scorbura-Tazlău Lithofacies; **Lithostratigraphic Units**: Vi - Viţău Formation, Str – Strujinoasa Formation, 1 – „*Globigerina marls and Lucăceşti sandstone*" Formation, 2 - „*Lucăceşti sandstone*" Formation; **Petrofacies** (*sensu* Anastasiu et al., 2007): AF1 – sandstones petrofacies, AF2 – lutitic-sandstones petrofacies, AF3 – calcareous-sandstones petrofacies, AF4 – limestones petrofacies; AF5 – heterolitic petrofacies; AF6 – sandstones-lutit petrofacies; AF7 – claystones petrofacies; AF8 – calcareous-claystones petrofacies with sandstone intercalations, AF9 – sandstone petrofacies with heterolitic intraclastes, AF10 – silicolitic petrofacies; **Depositional environments** (*sensu* Juravle et al., 2009; Miclăuş et al., 2009; Guerrera et al., 2012): MD1 – platform/ramp carbonates, MD2 – oxic shelf, MD3 – upper continental slope, MD4 – lower continental slope, MD5 – proximal sand rich submarine fan, MD6 – proximal/mid submarin fan; MD7 – fringe fan / basinal plain, MD8 – basinal plain.

Sedimentologically speaking, the Early and Middle Eocene (Yp-Lu-Bt) are characterized by the predominance of depositional environments such as largely sandy submarine cones, with a succession of proximal-distal turbidites and, subordinately, continental slopes (the upper part) and proximal basinal plains. In the Late Eocene (Pr), deposits mostly accumulate in areas of proximal basinal plain – distal cone/oxic shelf (in agreement with Miclăuş et al., 2009). From a petrofacial point of view, the formations display the following facies / facies alternations: the Surcele Formation – AF2/AF1, the Straja Formation– AF5, the Suceviţa Formation – AF1/AF2/AF1/AF2, the Scorbura Formation – AF1/AF10/AF1, the Doamna Formation – AF4, the Strujinoasa Formation – AF7, the Plopu Formation – AF6, the Lucăceşti and "*Globigerina Marls*" Formation – AF8, the Lucăceşti Formation – AF1. (Fig. 2).

2. MATERIALS AND METHODS

Out of the 4 profiles analyzed across the east-west direction within the Suceava Basin (Tarcău Nappe), based on field mapping and research, the Pietroasa section (**A-B**, Figs. 1, 3, 5) was selected as reference point for the integrated study of the Yp/Lu boundary. The section crops out on the Pietroasa brook, a left-side tributary of the Voitinel brook, upstream the Voitinel village, Suceava County. The geographic coordinates of the confluence between the Pietroasa and Voitinel brooks are the following: x=47,84604^0 N, y=25,6966^0 E, z = 570,00 m. The Yp/Lu boundary is located upstream the confluence point, on the right bank of the Pietroasa brook (x=47,845520^0 N, y=25,69055^0 E, z = 591,00 m).

The initial boundary, selected based on stratigraphic data regarding the Yp/Lu transition in the Tarcău and Vrancea nappes provided by Ionesi (1971) and Juravle et al., (2008), was established as the base of the Suceviţa Formation, with a stratigraphic thickness of 22 m, measured from the contact point with the Straja Formation. The analysis of calcareous nannoplankton collected from this initial Yp/Lu boundary, has, however, led to a narrower range, namely the portion of the base of the Suceviţa Formation which corresponds to a stratigraphic thickness of 10-16.5 m and coincides with the first turbiditic sequence of the formation. The determination of calcareous nannoplankton and microforaminifera assemblages was carried out on samples harvested from the silto-lutitic deposits (Tde) of the first turbiditic sequence of the Suceviţa Formation (Fig. 3). This narrower range was tested both petrographically and chemically ($CaCO_3$, total carbon – TC, total inorganic carbon – TIC, total organic carbon – TOC, and a series of stable isotopes: ^{44}Ca, ^{85}Rb, ^{88}Sr, ^{238}U, ^{138}Ba, ^{27}Al, ^{23}Na, ^{24}Mg, ^{39}K).

The determination of foraminifera, 100 g from each sample, previously dried in the oven for 2 hours, at 105^{0}C, were analyzed. The separation of microfossils was carried out using the water-immersion and successive decantation method. Sample 22 was the only one to require disaggregation using liquid nitrogen prior to the use of this method. The total residue obtained following decantation was passed through 3 sieves, and the microfossils were collected from all the fractions, except the very fine one (less than 0.122 mm). The determinations were performed using a Carl Zeiss Jena SM XX binocular stereo microscope, while the photographs were taken with the help of the Vega/Tescan SEM microscope belonging to the Faculty of Biology of the "Alexandru Ioan Cuza" University of Iasi.

Smear slides of 12 samples were prepared for the **calcareous nannoplankton**. Qualitative analyses were performed. Standard light microscope techniques were used on a Zeiss Axioskop 40, at the Babes-Bolyai University in Cluj-Napoca. Zonations of calcareous nannoplankton is based on Martini (1971), Bukry (1973), Okada & Bukry (1980), and Varol (1998).

The chemical analyses were conducted according to the methodology and regulations in place, as follows:

Carbon content. The carbon concentrations were measured with a Multi N/C 2100 Analyzer, containing an HT 1500 Solid Module, from Analytik Jena AG, Germany. In order to remove the inorganic carbon, the soil samples were treated with hydrochloric acid for 16–24 h before being dried for 3 h in the oven at 105°C (Midwood & Boutton, 1998), after which the Soil Total Carbon and Soil Organic Carbon were measured.

Carbonate content. The $CaCO_3$ concentrations in the soils were determined with an Eijkelkamp Calcimeter, through the volumetric method, by measuring the CO_2 resulted from the reaction between the dried samples and 4M HCl (in agreement with BS 7755-3.10:1995).

Isotope abundances (ICP-MS)**.** The capability to determine isotope abundances is a main feature of mass spectrometry. Inductively coupled plasma mass spectrometry (ICP-MS) provides excellent sensitivity, precision and good accuracy for isotope ratio measurements with practically no restriction with respect to the ionization potential of the element investigated (Becker, 2002).

In order to determine the mobile forms of the elements, the samples were digested with HNO_3 in a closed PTFE vessels microwave system (CEM MARS 6). 200-300 mg of sample were weighed, 10 ml of concentrated HNO_3 (65% Aldrich) were added, and the samples were left for 15 minutes at room temperature for pre-digestion. The vessels were then sealed and introduced into the microwave oven; the temperature was set at 200^0C, with a ramping time of 10 minutes and a holding time of 10 minutes. When the digestion was complete, the resulting solution was diluted to a fixed volume of 50 ml. After digestion, an ICP-MS 7700x (Agilent, Japan) was used to determine As, Ba, Co, Cu, Cr, Mn, Ni,Sr, Rb, Pb, and Zn. The operating conditions were the following: a radiofrequency power of 1550 W, a carrier gas flow-rate of 1.01 $L \cdot min^{-1}$, a plasma gas flow-rate of 15 $L \cdot min^{-1}$, an auxiliary gas flow-rate of 0.70 $L \cdot min^{-1}$; an integration time of 0.3 s, with three repetitions. Internal standard (Rh) was added to compensate for acid effects and instrument drift. The measurements were performed using the^{75}As, ^{138}Ba, ^{111}Cd, ^{59}Co, ^{52}Cr· ^{63}Cu, ^{55}Mn, ^{60}Ni, ^{85}Rb, ^{88}Sr, ^{208}Pb, and ^{66}Zn isotopes, the recommended mass for the Octopole Reaction System. The data was reported as the mean±standard deviation of triplicate measurements.

3. RESULTS OBTAINED FOR THE Yp/Lu BOUNDARY

3.1. Sedimentological data

The Ypresian-Lutetian deposits compose the Straja Formation, developed in a heterolytic facies and the Suceviţa Formation (sensu Joja, 1954), developed in a sandstone/sandstone-lutitefacies. The biostratigraphic data available (the calcareous nannoflora and foraminiferal assemblages) have allowed the delineation of the Yp/Lu boundary in the lower portion of the Suceviţa Formation and the western heteropic formations, in the first 20 m from the base of the formation (the NP14 biozone; Martini, 1971) (Juravle et al., 2008) (Fig. 2).

The Suceviţa Formation accumulated in a context of turbiditic currents, interrupted by 4 debritic events. In the Pietroasa section, the formation begins with debris flows (sandstone facies), with a thickness of 9 m, overlain by Bouma turbiditic sequences (sandstone-lutite facies), 6.5 m thick, followed by debris flows (sandstone facies), 5 m in thickness. Based on the biostratigraphic analyses carried out on the sedimentary column at the base of the Suceviţa Formation, the Yp/Lu boundary was located within the turbiditic rhythm (Fig. 3).

The sedimentary assemblage of the boundary is composed of 23 Bouma turbiditic rhythms, with Tabcd Quaternary sequences (SB1-2, SB14), binary sequences of the Tcd (SB3-5), Tbc (SB11), Tad (SB7-8, SB16, SB20, SB22-23) and Tbd (Sb17-19, SB21) types, and ternary sequences of the Tbcd (SB6) and Tabd (SB15) types. The SB9-10 rhythm is of the Tbce or Tcde types (limestones in the upper part), while the SB13 rhythm is of the Tde type (siltstones with parallel lamination, limestones and clays). The sequences are positive (FUS), displaying as ThU series in the lower and middle portions of the boundary, and TkU series in the upper portion (Fig. 3).

The sandstone and siltstone facies are dominated by quartzolithic clastofacies and subordinated feldspato-lithic clastofacies, while the lutitic facies are clayey (clays) and, subordinately, clayey-calcareous (marls/calcareous clays). The calcareous facies was identified in the middle portion of the range (SB9-13).

3.2. Biostratigraphic data

Calcareous nannoplankton. From the Pietroasa section, 12 samples from the silto-lutitic sequences (Tde) of the first turbiditic event of the Suceviţa Formation were analyzed. The degree of preservation of the calcareous nannoplankton in the section is highly variable.

The calcareous nannoplankton content differs in every analysed sample. The abundance is very high in the lower part of the section, were discoasters dominate: *Discoaster lodoensis*, *D.* cf. *sublodoensis*, *D. septemradiatus*, a.o. (sample 15). In the middle part of the interval, the first occurrence of *Nannotetrina fulgens* (NP15a-NP15b; sample 20) was remarked. On top (sample 29), a high content of discoasters (*D. distinctus*, NP15; *D. barbadiensis*), *Nannotetrina fulgens*, a.o. is present. From the base of the turbiditic succession, across a thickness of 1.5 m, the nannoplankton becomes progressively abundant (samples 13-15), being extremely abundant in sample 15, where discoasterids are dominant: *Discoaster lodoensis*, *D. septemradiatus*, a.o. There are also present: *Sphenolithus spiniger*, *Toweius gammation*, *Chiasmolithus expansus*, *C. grandis*, *Nannotetrina* cf. *Cristata* (FO at the base of CP12b, after Okada & Bukry, 1980; NP14-16, after Martini, 1971), mentioned also by Larrasoaña et al., (2008). Rare reworked species from the Cretaceous are remarked. Some whole coccospheres and calcispheres are also present. The following interval, with a thickness of 0.75 m (samples 16-18), is very poor in nannofossils, small-sized *Reticulofenestra* and ascidian spicules being, however, identifiable. Throughout the following 0.30 m (sample 20), the amount of nannoplankton increases. The presence of discoasters, *Chiasmolithus* and *Nannotetrina fulgens* indicate the biozones: CP13a of Okada & Bukry (1980); NP15a-NP15b of Martini (1971). In the following interval, 1.5 m thick, the quantity of nannofossils varies to a great degree. Sample 24 revealed frequent taxa of calcareous nannoplankton. They are frequent discoasters with broken rays, and reworked species from the Cretaceous. The last interval, 2.20 m in thickness, is the richest in nannoplankton, containing *Discoaster lodoensis*, *D. distinctus* (NP15, Martini, 1971), *D. barbadiensis*, *Coccolithus crassus*, *Neococcolithus dubius* (NP12-NP18, Martini, 1971), *Sphenolithus* cf. *editus*, *Nannotetrina fulgens* and reworked species from the Cretaceous. Certain species, such as *D. lodoensis* (regarded as a marker for the Ypresian in the Agost, Fortuna and Gorrondatxe sections; Molina et al., 2000, 2006 and 2011), which were found together with species representative for the Lutetian (*D. distinctus*, NP15; *N. fulgens*, NP15a-NP15b), are most likely reworked from the lower sequences (Plates 1, 2).

Benthic foraminifera. One observation which must be made from the very beginning is the fact that, across the profile under analysis, only agglutinated foraminifera assemblages have been identified, calcareous plankton either lacking or being extremely rare. The assemblages in question are of the "*flysch type*", specific to the turbiditic systems of deep marine environments (Gradstein & Berggren, 1981; Kaminski & Gradstein, 2005). The biostratigraphic information they provide can be correlated with that derived from the calcareous nannoplankton, as well as with paleoenvironmental data.

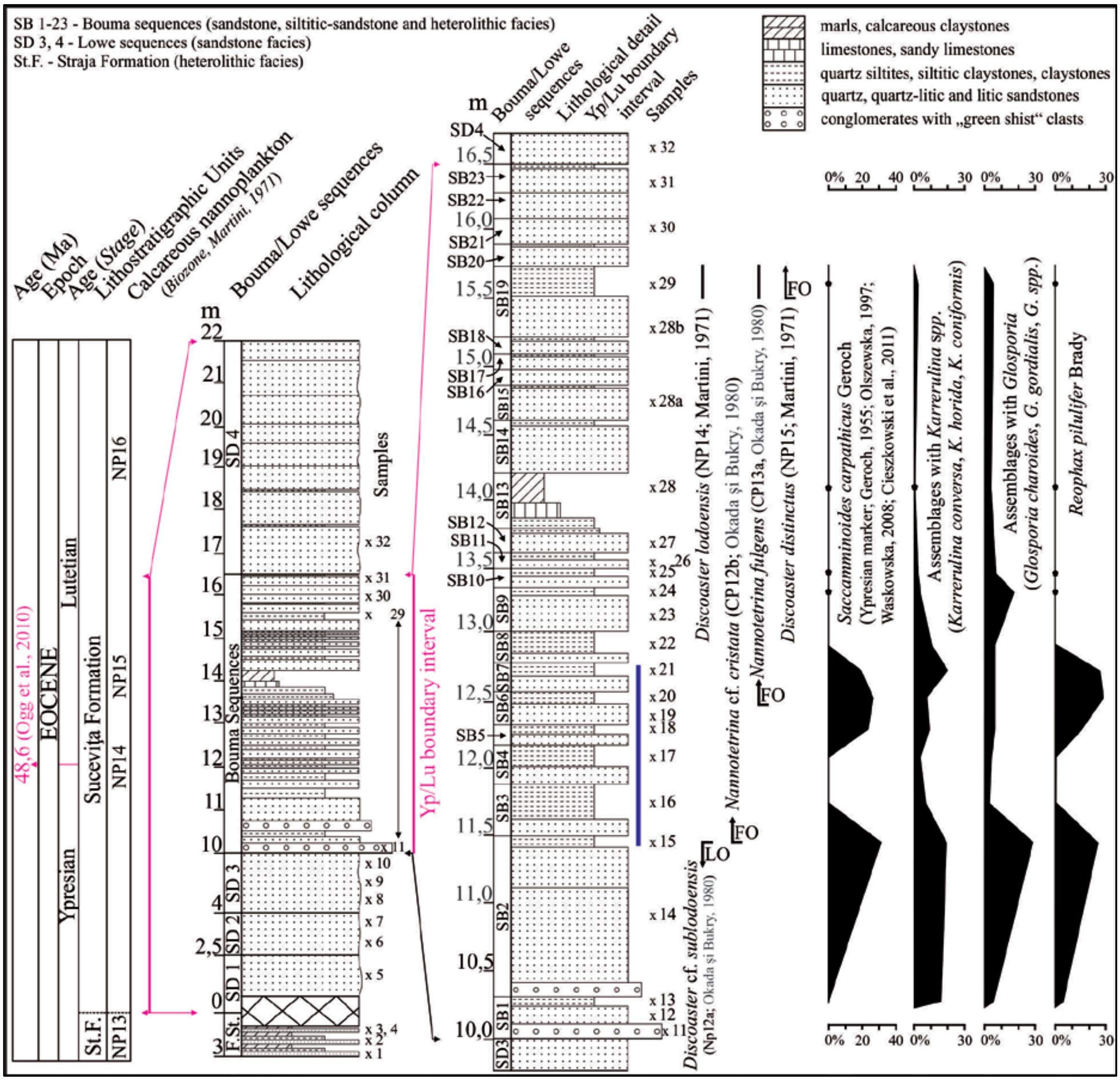

Figure 3. Biostratigraphic significance of the calcareous nannoplankton and agglutinated foraminifera assemblages identified across the Pietroasa profile. The blue vertical line represents theYp/Lu boundary, as established based on the resolution allowed by biostratigraphic data.

Of particular biostratigraphic significance are ***Saccamminoides carpathicus*** Geroch,***Reophax pilulifer*** Brady, and the assemblages with *Karrerulina spp*. and *Glomospira spp*.The ***Saccamminoides*** taxon is regarded as a marker for the Ypresian. It was first recorded in the Early Eocene, and its last recording was in assemblages with rare specimens of *Reticulophragmium amplectens* (Grzybowski), which precede the Middle Eocene (Geroch, 1955; Olszewska, 1997, Waskowska, 2008; Cieszkowski et al., 2011). The first occurrence of the species within the profile analyzed in the present study was at 11.50 m from the base of the Suceviţa Formation (sample 15), while its last was at 12.75 m from this base, being correlated with the first occurrence of the nannofossil *Nannotetrina fulgens*, specific to the NP15a-NP15b biozones. The assemblage with ***Karrerulina*** *spp*. (*Karrerulina conversa, Karrerulina horida* and *Karrerulina coniformis*), along with the abundance of *Glomospira* species, points to the Ypresian, as in the Polish Carpathians (Bindiu & Filipescu, 2011). Across the studied profile, *Karrerulina*t axa are present in its lower and middle portions. Within the Assemblage with ***Glomospira*** *spp*., the ***Glomospira charoides*** taxon (Jones & Parker) is most abundant in the lower portion of the profile (sample 15), while the greatest abundance of the ***Glomospira*** *spp*. taxon was recorded within sample 24. Bindiu & Filipescu (2011), in agreement with the literature, regard the assemblage as characteristic for the Yp/Lu boundary. The *Reophax pilulifer* species displays its highest abundance in the middle portion of the profile, between samples 18-21. The area with *Reophax pilulifer* is regarded as specific to the Middle Eocene of the Polish Carpathians (Morgiel & Olszewska, 1981) (Plates 3, 4).

From a biostratigraphic point of view, the calcareous nannoplankton identified, along with the assemblages of agglutinated foraminifera, suggest that the Yp/Lu boundary is located within the first turbiditic succession of he Suceviţa Formation, more precisely 11.40-12.75 m from the base (between samples 15 and 21) (Fig. 3).

3.3. Chemostratigraphic data

In order to assess the manner in which the events are recorded chemostratigraphically at the Yp/Lu boundary, the following were analyzed: $CaCO_3$ content, total organic carbon (TOC), total inorganic carbon (TIC), total carbon (TC), as well as a series of stable isotopes (^{44}Ca, ^{85}Rb, ^{88}Sr, ^{238}U, ^{138}Ba, ^{27}Al, ^{23}Na, ^{24}Mg, ^{39}K). Significant variations were noticed in the case of $CaCO_3$, TOC, TIC, TC and the ^{88}Sr/^{85}Rb ratio. (Table 1).

Table 1. The $CaCO_3$, total carbon (TC), total inorganic carbon (TIC) and total organic carbon (TOC) and the amount of stable isotopes ^{88}Sr and ^{85}Rb present in the silto-lutitic sequences at the Yp/Lu boundary.

Elem./ Sam.	$CaCO_3$ ‰	^{88}Sr (ppm)	^{85}Rb (ppm)	^{88}Sr/ ^{85}Rb (%)	TC ‰	TIC ‰	TOC ‰
13	13,65	76,10	549,40	13,85	10,90	2,00	8,86
15	11,83	75,50	552,40	13,67	12,44	1,90	10,54
16	31,86	71,60	535,90	13,36	22,66	9,80	12,84
17	13,05	62,60	578,40	10,82	17,97	9,90	8,07
18	5,16	82,80	578,50	14,31	8,67	1,20	7,47
20	8,80	79,10	211,90	37,33	10,92	1,70	9,19
21	1,52	63,20	545,80	11,58	12,27	2,70	9,62
22	1,82	93,20	667,60	13,96	12,81	0,70	12,07
24	30,04	101,20	580,60	17,43	13,48	0,90	12,58
25	0,30	59,70	596,00	10,02	11,86	0,50	11,39
28	37,92	78,10	470,40	16,60	21,61	6,20	15,41
29	29,43	116,40	187,10	62,21	22,71	4,60	18,12

4. DISCUSSION

Bioevents. The relative abundance of the agglutinated foraminifera, the development of the calcareous nannoflora and the geochemical parameters of the depositional environment at the Yp/Lu boundary reveal a logical correlation. Thus, the maximum abundance of the agglutinated foraminifera is recorded within sample 21, which lacks calcareous nannoplankton and displays mimimum $CaCO_3$ and^{88}Sr/^{85}Rb values. The range corresponding to samples 21-22 coincides with the greatest decrease in the number of lower bathyal – abyssal agglutinated forms, and a maximum development of those specific to the inner shelf – upper bathyal (Figs. 4, 5).

Agglutinated foraminifera. Across the studied profile, 48 exclusively agglutinated foraminifera have been identified, numbering a total of 2079 individuals. The following 15 species display relative abundances exceeding 1%: *Bathysiphon* sp. (4.95%), *Nothia excelsa* (Grzybowski) (8.99%), *Psammosiphonella cylindrica* (Glaessner) (31.07%), *Hyperammina rugosa* (Vardenius & van Hinte) (1.68%), *Psammosphaera irregularis* (Grzybowski) (12.45%), *Saccamminoides carpathicus* (Geroch) (1.25%), *Ammodiscus tenuissimus* (Grzybowski) (2.21%), *Glomospira charoides* (Jones & Parker) (3.03%), *Glomospira sp.* (2.02%), *Reophax pilulifer* (Brady) (4.57%), *Recurvoides sp.* (3.51%), *Karrerulina coniformis* (Grzybowski) (2.36%), *Karrerulina conversa* (Grzybowski) (2.93%), *Karrerulina horrida* (Mjatliuk) (1.78%), *Karrerulina sp.* (10.75%).

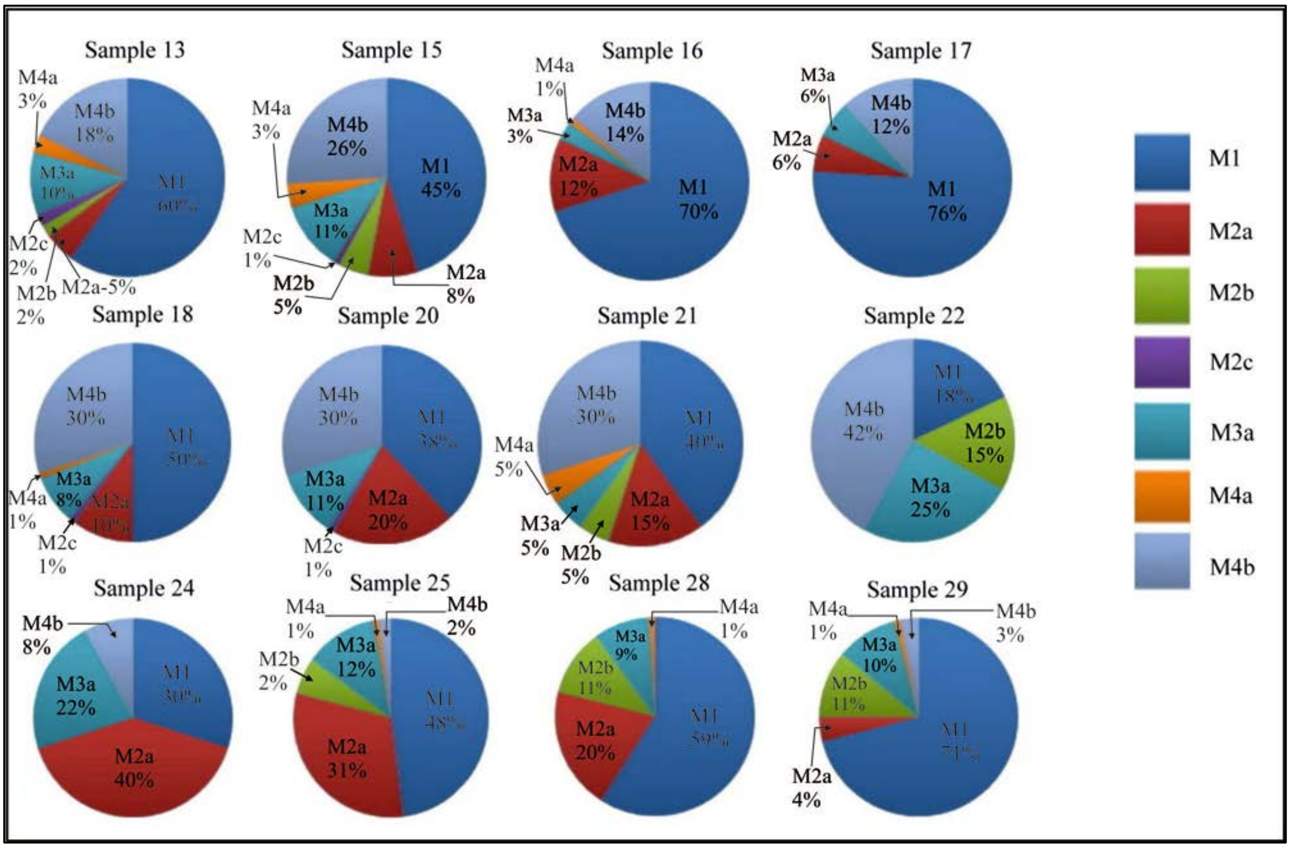

Figure 4. The abundance of agglutinated foraminifera morphogroups identified at theYp/Lu boundary. Morphogroups: M1- tubular, represented by forms as *Bathysiphon* sp., *Nothia* spp., *Psammosiphonella* spp., bathyal and abyssal; M2a – globular, represented by forms as *Psammosphaera* spp., *Saccammina grzybowskii,* bathyal and abyssal; M2b – rounded, trochospiral and streptospiral, represented by forms as *Recurvoides anormis* Mjatliuk and *Saccamminoides carpathicus,* shelf to deep marine; M2c - elongate keeled, represented by *Spiroplectammina spectabilis* (Grzybowski), shelf to deep marine; M3a - flattened planispiral and streptospiral represented by forms as *Ammodiscus* spp., *Glomospira* spp., *Paratrochamminoides* spp., *Trochamminoides* spp., high energy lagoon and estuary; M4a - rounded planispiral, represented by *Haplophragmoides* spp., inner shelf and upper bathyal; M4b - elongate subcylindrical, represented by forms as *Karrerulina* spp., *Reophax* spp., *Subreophax* spp., inner shelf and upper bathyal.

Noteworthy biostratigraphic events are the last occurrence of the *Saccamminoides carpathicus* Geroch taxon, and the correlated development of the assemblages with Karrerulina and Glomospira, a marker for the Ypresian (Figs. 3, 5).

Calcareous nannoplankton. The analyzed section has revealed the presence of a series of taxa which mark the base of certain biozones and, therefore, play a major role in the biostratigraphic determination of the Yp/Lu boundary. Thus, the lower occurence (LO) of the species *Discoaster* cf. *sublodoensis* and first occurrence (FO) of the species ***Nannotetrina cristata*** (marker for the base of the CP12b biozone), *Nannotetrina fulgens* (marker for the base of the CP13a biozone) (according to the biozonation by Okada & Bukry, 1980) and *Discoaster distinctus* (marker for the base of the NP15 biozone, according to the biozonation by Martini, 1971) was recorded (Fig. 3).

Depositional and paleoenvironmental conditions. Agglutinated foraminifera assemblages display great paleoenvironmental signficance, as they provide data on paleobathymetry, available nutrients and degree of oxygenation of water bodies, carbonate compensation depth and marine dynamics (currents).

The assemblages identified during the present study are of the "*flysch*" type, specific for the siliciclastic deposits of the Carpathian foreland (*sensu* Kaminski & Gradstein, 2005). Such assemblages develop on continental and basinal slopes, with a strong sediment flow and a moderate nutrient flow. They are located close to the carbonate compensation limit, therefore they can be associated, to a small degree, with calcareous forms. In order to acquire paleoenvironmental information, the following morphogroups were separated based on the model of Van Den Akker et al., (2000), Nagy et al., (2004) and Kaminski & Gradstein (2005): M1, M2a, M2b, M2c, M3a, M4a and M4b. The distribution of these morphogroups at the boundary analyzed indicates the predominance of tubular forms belonging to M1 (*Bathysiphon*, *Nothia*, *Rhabdammina*, *Rhizammina*, *Hyperammina*, *Psammosiphonella*). This morphogroup points to a marine depositional environment located at the base of the slope – basinal plain (lower bathyal – abyssal), in agreement with the sedimentological succession of the profile. Across the profile, the M1 morphogroup represents between 18% (sample 22) and 76% (sample 17). The highest percentange is recorded within the 11.50-12.50 m range, while the lowest is recorded within the 12.75-13.25 m range. This variation in basin depth is confirmed by the maximum development of the M4b morphogroup (*Reophax*, *Karrerulina*) within the 12.75-13.75 m range (inner shelf – upper bathyal) (Figs. 4, 5).

As far as the abundance of species is concerned, very high values are recorded at the base of the profile (samples 13 (52.08%) and 15 (47.92%)) and in its middle portion (samples 18 (37.50%), 20 (33.33%) and 21 (39.58%). Minimum values range between 18.75-22.92%. Species abundance is an indicator of the variation of favourable/adverse paleoenvironmental conditions, a high number of species pointing to a favourable paleoecological context.

Climatic events. The studies carried out on the paleoclimatic trend of the Eocene suggest that the climatic optimum of the Middle Ypresian was followed by a period of cooling which lasted throughout the entire Eocene (Gradstein & Berggren, 1981; Zachos et al., 2001; Pekar et al., 2005; Payros et al., 2006). Payros et al., (2006), who analyzed the paleoenvironmental significance of Eocene planktonic foraminifera from the foreland basins of the Pyrenees (Basque and Pamplona, roughly 37^0 lat. N), distinguished between 3 warm climatic cycles and 3 cold ones, which they correlated with the Ei4-Ei9 climatic events of Eocene sub-Antarctic areas (δ^{18}O event Ei4-Ei9, Pekar et al., 2005).

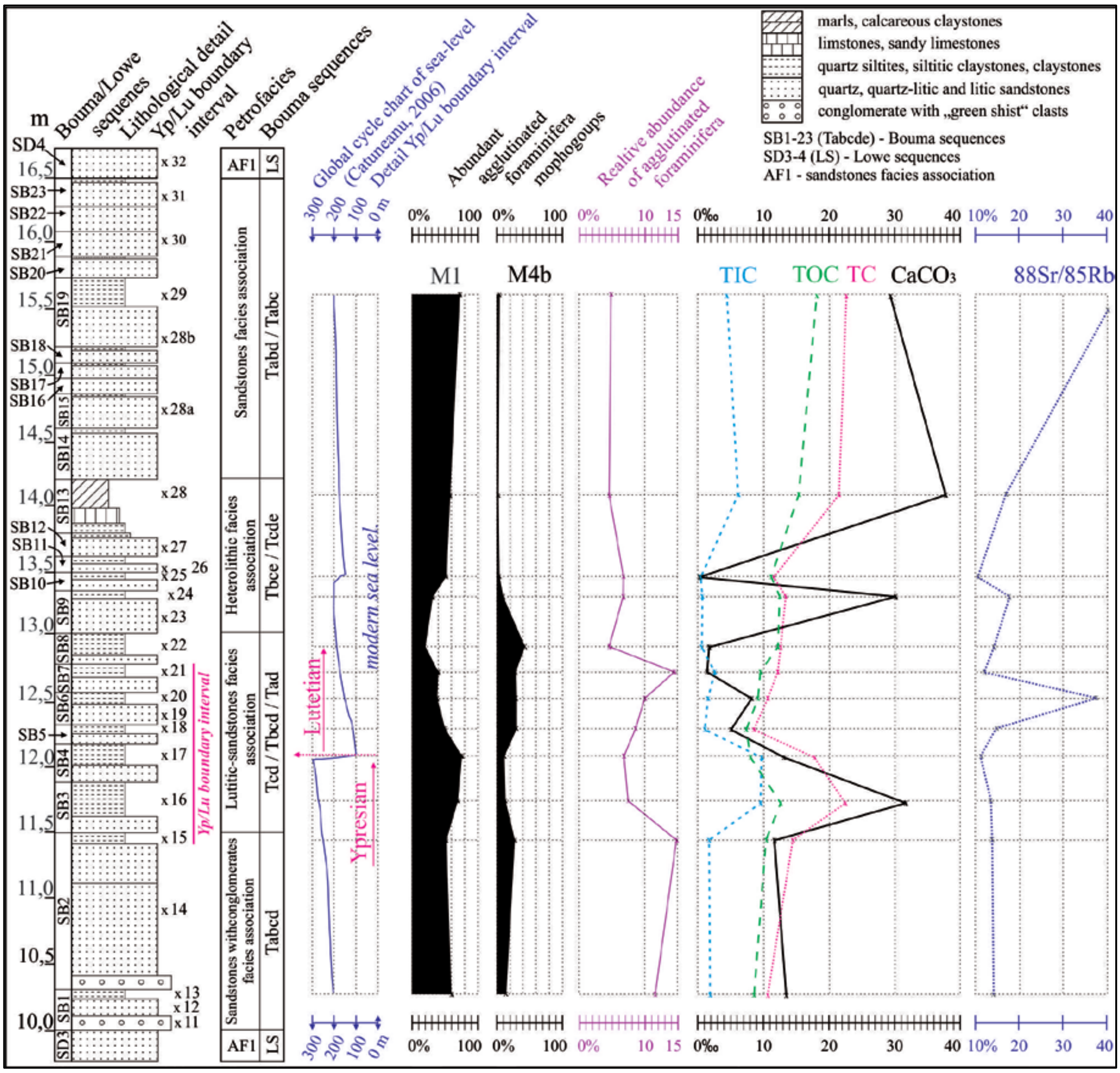

Figure 5. The imprints left by biostratigraphic, sedimentological and chemostratigraphic events on the silto-lutitic deposits of the Pietroasa section, at the Yp/Lu boundary.

The Yp/Lu transition is placed within the second cold interval, which spans between Ei5-Ei6. Moreover, the eustatic curves at the Yp/Lu boundary (*sensu* Vail et al., 1977; Cătuneanu; 2006; Haq et al., 1987) indicate a negative eustatic variation, with amplitude of roughly 200-150 m. This suggests a forced regression, which can partially be attributed to the cold interval.

The abundance of agglutinated foraminifera across the profile analyzed is highly variable within the 11.25-13.50 m range (between samples 15 and 25). The explanation lies in the bathymetric oscillations of the depositional environment, which are linked to eustatic variation.

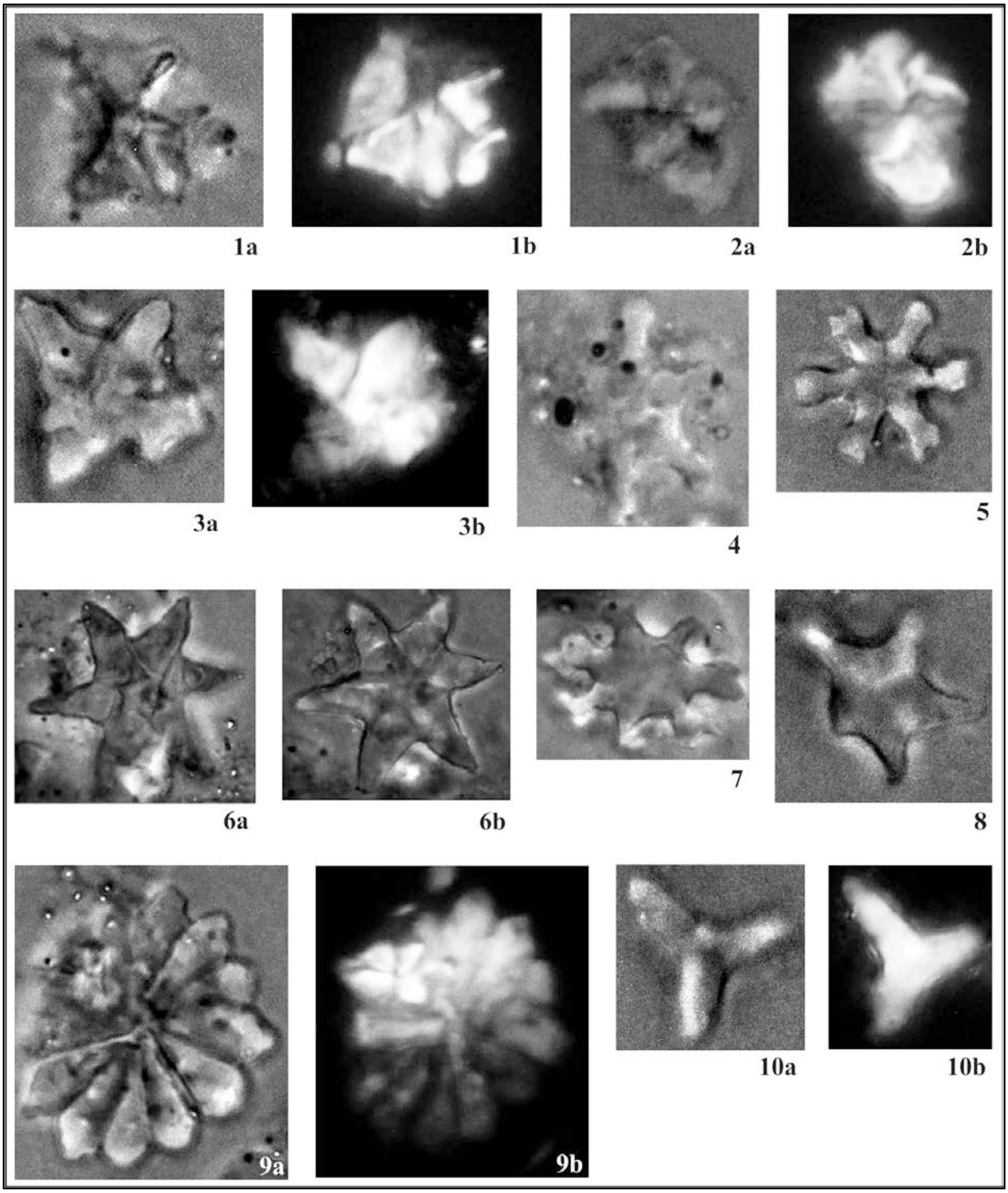

Plate 1. 1a, 1b, 2a, 2b. *Nannotetrina fulgens* (Stradner, 1960) Achuthan and Stradner, 1969. Sample 20; **3a, 3b**. *Nannotetrina* cf. *cristata* (Martini, 1958) Perch-Nielsen, 1971. Sample 15; **4**. *Discoaster* sp. Sample 24; **5**. *Discoaster distinctus* Martini, 1958. Sample 29; **6a, 6b**. *Discoaster lodoensis* Bramlette & Riedel, 1954. Sample 29; **7**. *Discoaster septemradiatus* (Klumpp 1953) Martini 1958. Sample 15; **8**. *Discoaster* cf. *sublodoensis* Bramlette & Sullivan, 1961. Sample 15; **9a, 9b**. *Discoaster barbadiensis*, Tan, 1927 and *Sphenolithus spiniger*, Bukry, 1971. Sample 15; **10a, 10b**. *Tribrachiatus orthostylus* Shamrai, 1963. Sample 15.

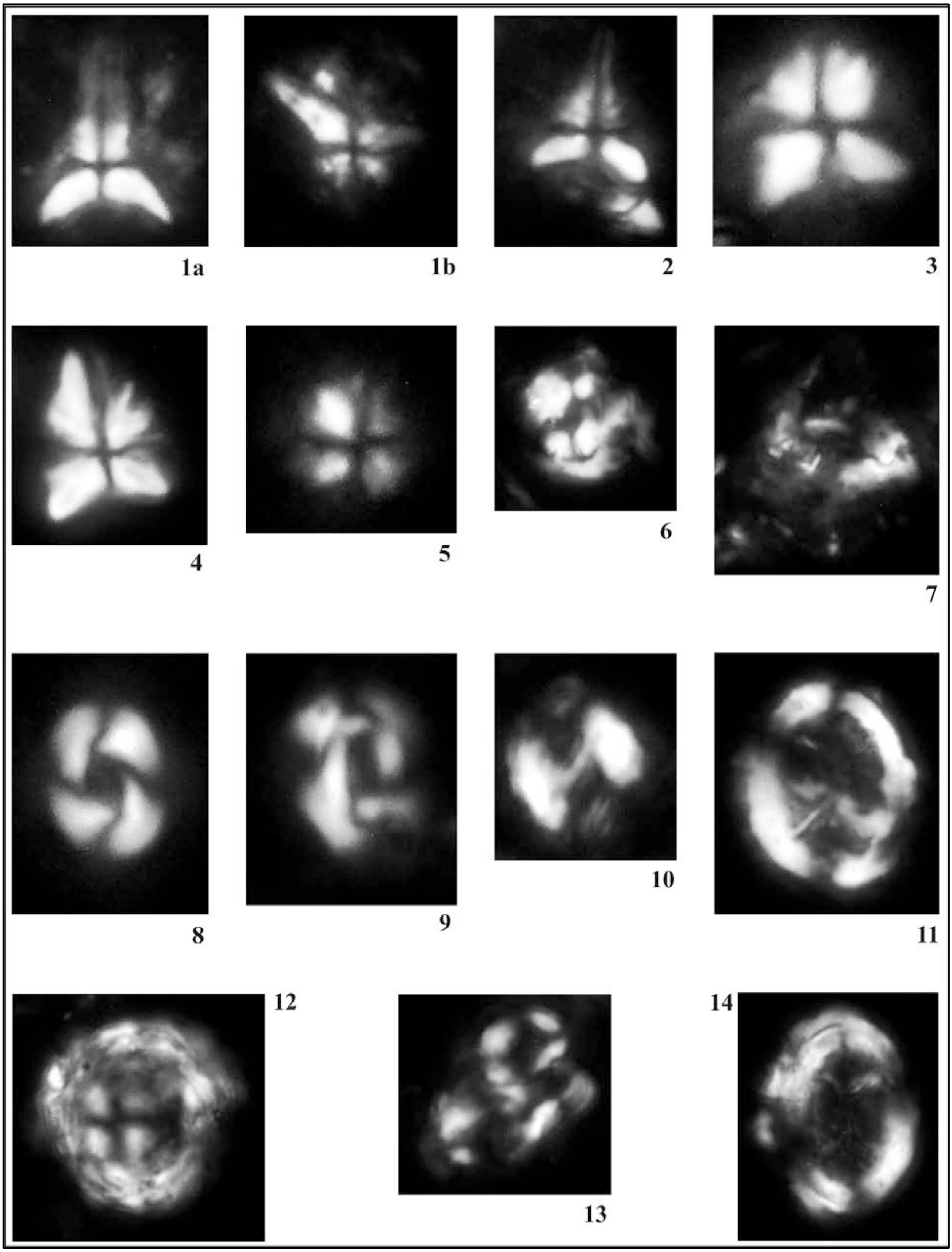

Plate 2. 1a, 1b, 2, 3, 4. *Sphenolithus radians* Delfandre *in* Grassé, 1952. Sample 24, 15; **5**. *Sphenolithus moriformis* (Bronnimann and Stradner, 1960) Bramlette and Wilcoxon, 1967. Sample 15; **6**. *Coccolithus crassus* Bramlette & Sullivan (1961). Sample 15; **7**. *Helicosphaera* cf. *papillata* (Bukry & Bramlette 1969) Jafar & Martini 1975. Sample 15; **8, 9**. *Reticulofenestra dyctioda* (Deflandre *in* Deflandre & Fert, 1954) Stradner *in* Stradner & Edwards, 1968. Sample 17, 16; **10**. *Pontosphaera pulchra* (Deflandre *in* Deflandre & Fert, 1954) Romein, 1979. Sample 24; **11**. *Chiasmolithus expansus* (Bramlette and Sullivan,1961) Gartner, 1970. Sample 15; **12**. Coccosphere of *Coccolithus* sp. Sample 2; **15**. Three coccoliths of *Toweius* cf. *callosus* Perch-Nielsen, 1971. Sample 13; **14**. *Chiasmolithus grandis* (Bramlette & Riedel, 1954) Radomski, 1968. Sample 15.

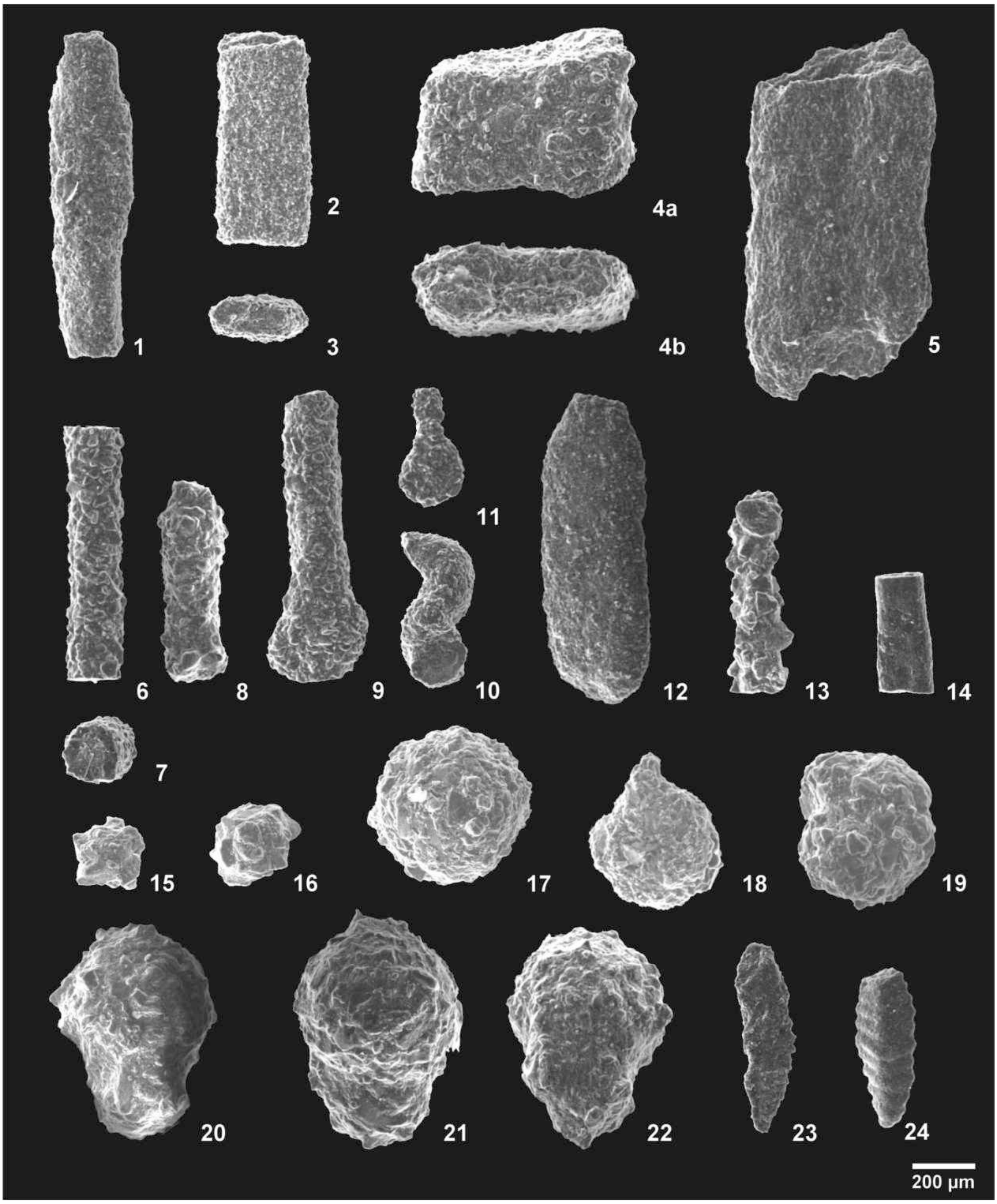

Plate 3. M1 - 1. *Bathysiphon sp.,* sample 17; **2, 3**. *Nothia excelsa* (Grzybowski), sample 13; **4a-b**. *Nothia robusta* (Grzybowski), sample 21; **5**. *Nothia latissima* (Grzibowski), sample 15; **6, 7**. *Psammosiphonella cylindrical* (Glaessner), sample 15; **8**. *Psammosiphonella discret*e (Brady), sample 28; **9**. *Rhabdammina linearis* Brady, sample 18; **10**. *Rhizammina indivisa* Brady, sample 13; **11**. *Hyperammina elongata* Brady, sample 15; **12**. *Hyperammina subnodosiformis* Grzybowski, sample 13; **13**. *Hyperammina rugosa* Vardenius and Van Hinte, sample 15; **14**. *Kalamopsis grzyboeski* (Dylazanka), sample 21; **M2a -15, 16**. *Psammosphaera fusca* Schultze, sample 25; **17**. *Psammosphaera irregularis* (Grzybowski), sample 18; **18**. *Saccammina grzybowskii* (Schubert), sample 17; **M2b** - **19**. *Recurvoides anormis* Mjatliuk, sample 13; **20, 21, 22**. *Saccamminoides carpathicus* Geroch, sample 21; **M2c** - **23, 24**. *Spiroplectammina spectabilis* (Grzybowski), sample 18.

Within this range, the abundance of the morphogroups M1 and M4b displays a negative correlation, with a minimum for M1 and a maximum for M4b in sample 22, which confirms the fact that the eustatic variation at the Yp/Lu transition affected the Eastern Carpathian foreland basin, as well (Figs. 4, 5).

The $CaCO_3$ content of the silto-lutitic sediments of the aforementioned range vary up to

30‰, with minimum values at the Yp/Lu boundary. A similar description (with minimum values at the Yp/Lu boundary) was provided by Pekar et al., (2005) for the variation of $CaCO_3$ across Eocene sub-Antarctic areas.

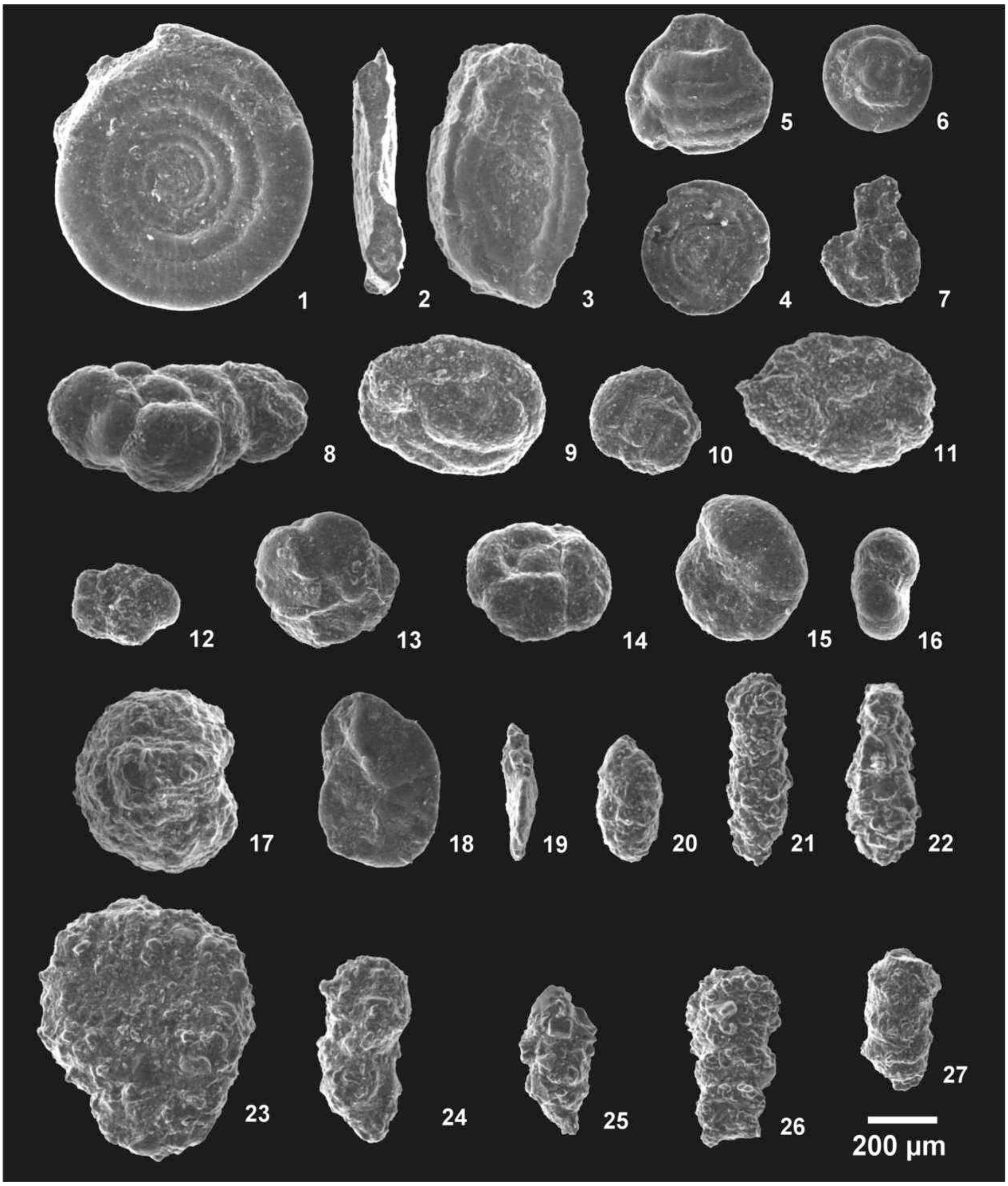

Plate 4. M3a – 1, 2. *Ammodiscus tenuissimus* Grzybowski, sample 20; **3**. *Ammodiscus peruvianus* Berry, sample 24; **4**. *Ammodisus* sp., sample 24; **5**. *Glomospira charoides* (Jones & Parker), sample 20; **6**. *Glomospira gordialis* (Jones & Parker), sample 10; **7**. *Lituotuba lituiformis* (Brady), sample 13; **8**. *Conglophragmium irregularis* (White), sample 15; **9**. *Paratrochamminoides gorayskii* (Grzybowski), sample 4; **10**. *Paratrochamminoides olszewskii* (Grzybowski), sample 13; **11**. *Trochamminoides proteus* (Karrer), sample 13; **12**. *Paratrochamminoides* sp., sample 13; **13**. *Trochamminoides subcoronatus* (Grzybowski), sample 20; **14**. *Trochamminoides variolarius* (Grzybowski), sample 13; **M4a** – **15**. *Haplophragmoides eggeri* Cushman, sample 22; **16**. *Haplophragmoides eggeri* Cushman, sample 13; **17**. *Haplophragmoides suborbicularis* (Grzybowski), sample 13; **18**. *Haplophragmoides walteri* (Grzybowski), sample 22; **19**. *Haplophragmoides walteri* (Grzybowski), sample 29; **M4b** – **20**. *Karrerulina coniformis* (Grzybowski), sample 15; **21**. *Karrerulina conversa* (Grzybowski), sample 15; **22**. *Karrerulina horrida* (Mjatliuk), sample 15; **23**. *Reophax pilulifer* Brady, sample 21; **24**. *Reophax globosus* Sliter, *sample* 21; **25**. *Reophax subnodosiformis* Earland, sample 18; **26**. *Subreophax pseudoscalaris* (Samuel), sample 15; **27**. *Subreophax scalaris* Grzybowski, sample 18.

In the case of the profile analyzed in the present study, there is a positive correlation between the $CaCO_3$ curve and the $^{88}Sr/^{85}Rb$ ratio, while the relative abundance of agglutinated foraminifera exhibits a negative correlation. This data, along with the absence of calcareous foraminifera throughout the profile and the poor conservation of calcareous nannoplankton, could point to an increase in the solubilization capacity of the marine environment due to the cooling of the water and the decrease in carbonate compensation depth (CCD).

Tectonic events. The transition from the depositional environment specific to the Straja Formation, with input of fine bioclastic material from the shelf (the upper part of the continental slope) (Miclăuş et al., 2009), to that specific to the heterochronous formations Suceviţa and Scorbura (the domain of largely sandy cones), is partially due to the paleoclimatic events that occurred at the Yp/Lu transition. However, these climatic changes cannot fully account for the sedimentological dynamics of the depositional environment. From a sedimentological point of view, the profile analyzed is characterized by an alternation of debris flows (sandstone petrofacies) – turbiditic flows with Bouma sequences (greso-lutitic and heterolithic petrofacies) – debris flows (sandstone petrofacies). The relatively rapid changes in basin depth at the Yp/Lu boundary, along with the triggering of debris flows, could be explained by a context of pronounced tectonic instability, while the cause behind the forced eustatic variation is, apart from cooling, tectonic subsidence.

The tectonic events assumed in the present study are in agreement with the geotectonic model suggested by Guerrera et al., (2012) for the evolution of the Cretaceous-Miocene sedimentary basins from the central part of the Outer Moldavides (the Vrancea Nappe from the Bistriţa Semiwindow and the Tarcău Nappe). Authors point to 4 intervals of tectonic instability, the second of which is represented by the boundary between the end of the Ypresian and the Lutetian. Payros et al., (2006) provided the same explanation (that of tectonic instability) for the alternation of debris flows (megabreccias) / turbiditic flows in the Eocene foreland basins of the Western Pyrenees (Basque and Pamplona).

5. CONCLUSIONS

The present study aimed to identify certain biostratigraphic, paleoclimatic, paleomedial and paleoenvironmental events that occurred in the old Eastern-Carpathian foreland basin of Bucovina. Within the Pietroasa section, the sedimentary sequence at the Yp/Lu transition is constantly exposed, and, therefore, a reference point for the delineation of the Yp/Lu boundary in the isochronous formations of the outer flysch of Bucovina.

Acknowledgements

The authors wish to express their gratitude toward the Department of Geography of the Faculty of Geography and Geology of the "Alexandru Ioan Cuza" University of Iaşi, as well as to the Enviromatics Laboratory – CERNESIM Platform of the same university, for the assistance provided in the present study and Department of Geology of the UBB Cluj-Napoca.

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***BS 7755-3.10:**1995. *Soil quality. Chemical methods. Determination of carbonate content. Volumetric method.*

Received at: 11. 05. 2015
Revised at: 14. 10. 2015
Accepted for publication at: 26. 10. 2015
Published online at: 03. 11. 2015