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DEPARTMENT OF GEOLOGY

BIOSTRATIGRAPHICAL AND PALEOECOLOGICAL STUDY OF THE SARMATIAN FORAMINIFERAL ASSOCIATIONS IN THE SOUTH-WEST AREA OF BOROD BASIN

Summary of the PhD Thesis

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Content of the PhD thesis

Content of the summary

KEY WORDS: foraminifers, Borod Basin, Vârciorog, Miocene, Sarmatian, Biostratigraphy, Paleoecology

NOTE: The figures and tables have the original labels, as in the PhD thesis.

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Chapter 1. INTRODUCTION

1.1. The aim and object of the study

Our thesis focuses on aspects related to foraminiferal associations in a complex perspective, in the view of providing information for biostratigraphic and paleoecological interpretations. The selected areal is represented by the south-western sedimentary area of the Borod Basin, as the westernmost extension of the Pannonian Basin. This choice was based on the richness and diversity of micropaleontological material, and the fact that the Sarmatian foraminiferal association were not studied before, from a detailed biostratigraphical and paleoecological perspective.

The aims of our study were:

- morphological description and taxonomic identification of foraminiferal associations separated from samples collected in lithological profiles in south Borod Basin where Miocene sediments crop out;

- analysis of the biostratigraphical significance of the foraminiferal associations and evaluation of the benthic foraminifers' potential as index species at basin and region level;

- qualitative and quantitative study of the Sarmatian benthic foraminifer communities in the view of paleoecological interpretation and paleoenvironmental reconstructions, as well as documenting the paleoenvironmental feedback to regional and/or global events.

1.2. Location

Geographically, the study area belongs to the Vad-Borod Depression in north-west Romania (Fig. 1.1), located on the north-western rim of the Apuseni Mountains. It is extended along the Crişul Repede Valley in the form of a graben between Pădurea Craiului Mountains in the south and Plopiş Mountains in the north (Fig. 1.1). The length of the depression between Oradea and Corniţel is about 57 km, with a width about 7-8 km, the depression representing a narrow gulf-type corridor within the system of the Apuseni Mountains (Petrescu et al., 1987).

The landscape consists of smooth crests with relatively low altitudes that cover most of the eastern part of the depression. Here, the only narrow lowland area is represented by the Borod Valley. Westwards, this area is gradually widening starting at the confluence of Borod and Crişul Repede Valleys, where hills mainly occupy the northern border of the depression. Their average altitudes vary between 200-450 m, with rare protuberances of over 450 m. Exceptionally, on the basin's eastern extremity there are hills over 500 m high, the averages being between 350-400 m high (Givulescu, 1957).

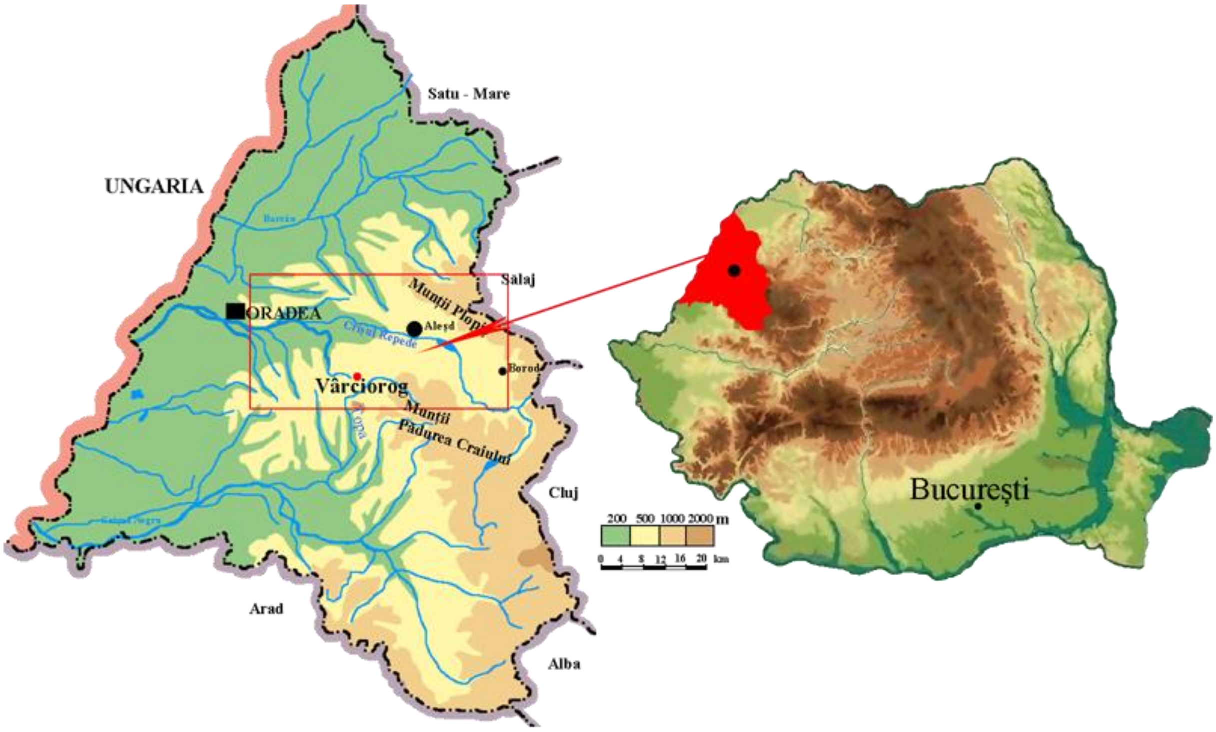


Fig. 1.1. Location of Borod Basin – within the territory of Romania, Bihor county (right) and in the western part of the Apuseni Mountains (red square) (left)
(modified after http://pe-harta.ro/judete/Bihor.jpg)

1.3. Previous geological research

Our research was based on all the significant previous geological contributions concerning the study region. Borod Basin was a topic of interest for many researchers who were interested in its lithology, tectonics and paleontology. In the case of some older publications, from the 19th century, which were not available to us, we have used newer, secondary sources (e.g., Givulescu, 1957).

In the Borod Basin, the basement consists of Permian-Mesozoic formations and the cover of Neogene and Quaternary ones. Among the authors of the most important contributions on the basin's basement, we have to mention: Szadeczky (1903), Szontagh, (1904, 1915), Pálfi (1916), Kräutner (1939, 1941), Givulescu (1943, 1950, 1954a,b), Șuraru & Șuraru (1973), Dragastan (1966), Dragastan et al. (1967), Istocescu (1970), Bleahu et al. (1971), Mureșan et al. (1974), Ianovici et al. (1976), Bucur (1981), Săndulescu (1984), Bucur et al. (1993) and Balintoni (1994, 1997).

Contributions on the Neogene sedimentary cover were signed by Boué (1833), Wolf (1863), Mártonfi (1882), Mátyásovszky (1883, 1884), Pantocsek (1886), Szádeczky (1903), Lázár (1910, 1912), Roth von Telegd (1913), Rotarides (1925), Protescu (1932), Voiteşti (1935), Kräutner (1938, 1939), Sümeghy (1939, 1943), or Hojnos (1942).

Starting with **1943-1944, Givulescu** published an impressive series of articles about this basin, summarizing its floral paleontology. In an article from **1950, Givulescu** describes from the area north from Crişul Repede River and south from Plopiş Mountains Lower Sarmatian and Pannonian deposits. They cover iregulary the basin's surface and contain characteristic fauna for each of these time intervals. **Givulescu (1954b)** signed a note on the Neogene deposits in Borod Basin, considering that they were cropping out in the area between Şes (Plopiş) Mountains and Pădurea Craiului Mountains, and partly along the Crişul Repede Valley. The presence of "Tortonian" (Badenian), Sarmatian and "Pliocene" was paleontologically demostrated by **Givulescu (1957)** in his geological monograph on Borod Basin. Based on his observations in the Cornițel-Aleşd area, **Givulescu (1964)** has placed the volcanic activity in this basin at the level of the Upper Pliocene.

Other important contributions to the fossil flora in the region were published by the same author in **1969, 1974a,b, 1976, 1994** and **1996.**

Other significant paleontological information for the area was publised by **Nicorici (1967, 1970)**, **Nicorici & Istocescu (1970)**, and **Nicorici et al.** (**1978)**. From Vârciorog, **Nicorici** (**1971)** has described a Sarmatian mollusk fauna associated with rests of foraminifers, algae, ostracodes and worms. **Nicorici (1980, 1981)** has also published stratigraphic correlations for the Neogene in the western basin of the Apuseni Mountains and in the Transylvanian Depression. Based on the study of drill core samples from Groşi-Aştileu-Copăcel that focused on the Sarmatian coal-bearing formations, **Nicorici et al. (1982)** have established a Lower Sarmatian age for the whole studied succession. **Nicorici** (**1988)** has also studied the malacological association in the south-western part of Vad-Borod Basin, pointing to its Lower Sarmatian age. In **1990**, the same author has compared the Pannonian mollusks from Vad-Borod Basin to those described from Vienna Basin.

Venczel (1990) published information on the Pleistocene and actual herpetofauna from Subpiatră.

Codrea & Czier (1991) have described the Pleistocene formations from Subpiatră, focusing on some dental and post-cranial elements of fossil rhinoceros.

The Sarmatian calcareous algae from Luncşoara have been studied by **Bucur & Şuraru (1994).**

Popa et al. (1997) have evidenced the presence of associations of marine and brackish mollusks pointing to a Lower Miocene for the corresponding formations. **Popa (1998a,b)** has emphasized the biostratigraphical importance of the ostreids. This author has also performed a detailed paleontological and biostratigraphic study of the Neogene formations in the eastern part of Vad-Borod Basin. In **2000**, the same author provided new and significant contribution to the lithostratigraphy of the Miocene deposits in the eastern part of Borod Basin, while in **2001** she discussed the biostratigraphical significance of the mollusk associations. **Popa & Trîmbiţaş (2003)** pulished new information on the structure of the Miocene deposits in Borod Basin.

Filipescu & Popa (2001) have published a biostratigraphical and paleoecological analysis on the Badenian macro- and micropaleontological associations in the eastern part of the basin.

Codrea et al. (2007) have presented data on the Sarmatian diatomites and their associated fossil rests from the Zărand and Vad-Borod Borod.

A study concerning micromammals in sediments collected along Vișinilor Brook, Vârciorog has documented the Sarmatian age of these deposits (**Molnar, 2011)**.

Filipescu et al. (2014) have performed a complex biostratigraphical analysis based on micro- and macrofossils in a profile from Vârciorog (Vișinilor Brook), demonstrating the Sarmatian age of the corresponding formations.

Chapter 2. GEOLOGY OF BOROD BASIN

The Borod Depression represents an eastward extension of the Pannonian Basin (Fig. 2.1). It represents on the external Neogene basins formed on the western rim of the Apuseni Mountains (Istocescu & Istocescu, 1974; Györfi & Csontos, 1994; Papaianopol & Macaleţ, 1998a,b). The formation of the Borod Depression took place durig the Middle Miocene, as a consequence of an extensional tectonic regime, similar to the processes leading to the evolution of Şimleu, Beiuș and Zarand Depressions (Györfi & Csontos, 1994; Popa, 2000).

From a geotectonic perspective, the Borod Basin belongs to the Preapulian Craton (Balintoni, 1997). Its evolution was connected to that of the Pannonic Basin, showing an extensional tectonic regim. Other controlling factors were the tectonic processes located in the Carpathian – Pannonian area affecting the continental intra-Carpathian plates: ALCAPA plate and the Tisza-Dacia microplate. These have subsequently generated accommodation space for the Badenian and Post-Badenian sequences (Royden, 1988; Csontos, 1995; Balintoni & Puște, 2001). Being an estwards extension of the Pannonian Basin, the Borod Basin represents an NW-SE-oriented syncline consisting of sunken blocks of the basement along a fault with similar orientation (Istocescu et al., 1970). The basin filling deposits show undulating structures, due to differential compaction of the rocks and to vertical tectonic movements (Istocescu et al., 1970).

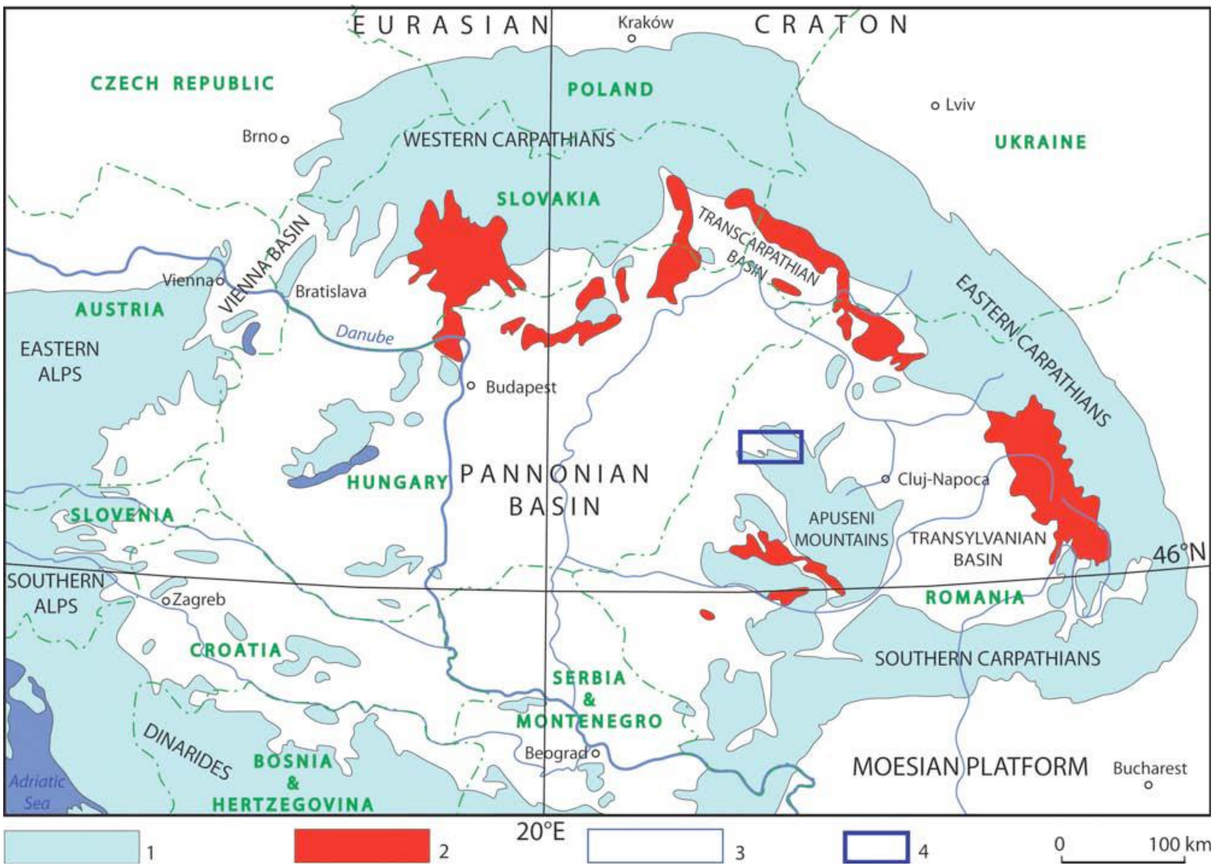


Fig. 2.1. Location of Borod Basin within the Carpathian-Pannonian area.
1. Mesozoic and Cenozoic mountain chains; 2. Neogene volcanics; 3. Neogene sedimentary filling; 4. Borod Basin (from Filipescu et al., 2014).

2.1. Basement

The basement of Borod Basin mainly consists of metamorphic rocks (medium- and high-metamorphozed) overlaid by a Permian-Mesozoic succesion of sedimentary and volcanic rocks (Istocescu et al., 1970; Popa, 2000). The crystalline schists (gneisses and micaschists) crop out on extended areas along the north-east border of the Borod Depression (Fig. 2.2). They were also identified in drill core samples (ex. in Borș; Istocescu & Ionescu, 1970).

2.2. Neogene sedimentary succession

The presence of **Lower Miocene** formations has been paleontologically argumented in numerous studies: Paucă, 1954; Givulescu, 1957; Şuraru & Şuraru, 1973; Nicorici et al**.**, 1978;

Petrescu & Nicorici, 1978; Şuraru et al., 1978; Moisescu, 1990a,b, 1991, 1992; Popa et al., 1997; Popa, 1998a,b, 2000; or Popa & Chira, 1999.

In Vad-Borod Basin, **Sarmatian** deposits are covering large areas (Fig. 2.2), showing dominantly terrigenous facies types with conglomerates, limestones, sandstones, marls, sands, tuffs, diatomites and coal interlayers.

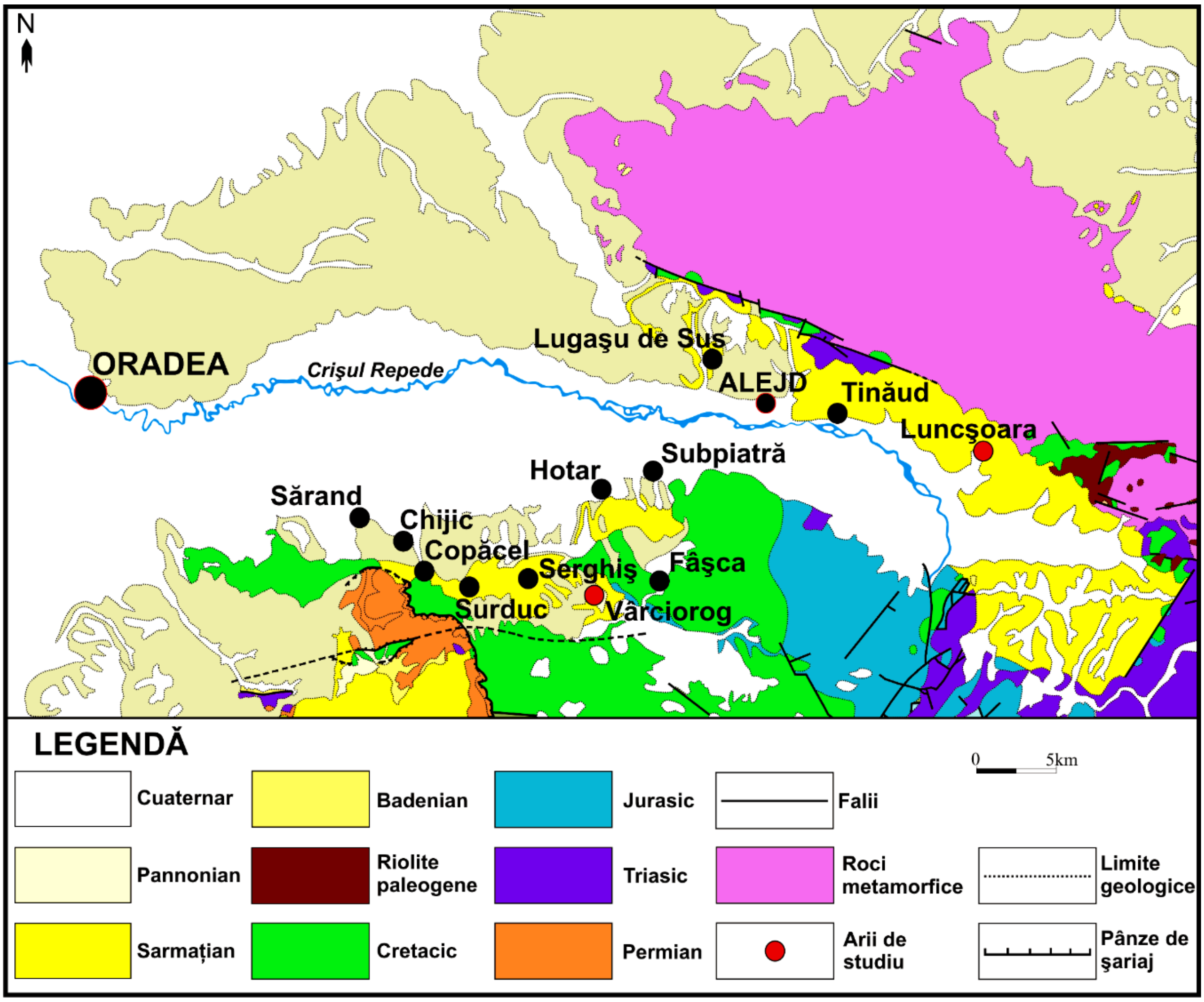


Fig. 2.2. Geological map of Borod Basin

(based on the Geological map of Romania, 1:200.000 scale, Sheet 9 - Şimleul Silvaniei).

In Vadului Basin, the Sarmatian formations show continental and brackish facies types. Isocescu et al. (1970) have separated a lower, domiantly marly unit with diatomites, bentonite and coal-containing clays overlaid by tuffites and limestones – all of Volhynian and Lower Bessarabian age. This is followed by an unconformity covering the Middle Bessarabian – Lower Pannonian (Istocescu & Istocescu, 1974).

The presence of **Pannonian** in the basin was a controversed topic. Roth von Telegd (1913) has mentioned Pannonian deposits in the Auşeu-Luncşoara area. Subsequent studies have either contradicted (Paucă et al., 1968; Paucă, 1969; Paucă, 1973a,b) or supported (Sümeghy, 1939; Nicorici, 1970; Givulescu, 1974b, 1991, 1994; Istocescu & Istocescu, 1974; Petrescu &

Nicorici, 1977; Petrescu et al., 1979; Popa, 2000) this observation. The main subject in this controvercy was the presence of genus *Orygoceras* (Paucă, 1954, 1969).

In the eastern past of the basin, three lithostratigraphic units were separated in the Badenian – Pannonian interval: Borod Formation, Corniţel Formation and Beznea Formation (Popa, 2000).

The Borod Formation (?Eggenburgian - Badenian) was defined based on studies performed in Valea Cetii area and consists of blackish siltic and marly clays with Cerites, with interlayers of siltites, sands, sandstones and thin coal levels. These deposits crop out only in the northern part of the basin, with thicknesses between 100-240 m. The characteristic fossil associations that were used for age determination consist of malacofauna, foraminifers, ostracods (Şuraru & Șuraru 1973; Moisescu, 1990a; Popa et al., 1997, 1998, 1999; Filipescu & Popa, 2001), spores and pollen (Petrescu & Nicorici, 1977), as well as calcareous nannoplankton (Popa et al., 1997; Popa & Chira, 1999).

The Corniţel Formation (Lower Sarmatian) covers the northern and eastern part of the basin and mainly consists of compacted marls, sandstones and greenish micro-conglomerates in the lower part. The two coal levels separated by tuffs were assigned to the **Borozel Member**. The thickness of the deposits varies from tens of meters to 250-300 m in the eastern part of the basin. Westwards, the average thickness increases to 600 m. The described fossil fauna contains only a few mollusk and foraminifers taxa. The age of the Corniţel Formation was established based on gastropods (Popa, 2000) and foraminifers (Filipescu et al., 2014). Calcareous algae associations were also described from these deposits (Bucur et al., 1993; Bucur & Șuraru, 1994).

The Beznea Formation (Pannonian) consists of whitish, strongly compacted marls with marly interlayers. It crops out on large areas within the basin, with thicknesses between 500 m in the east, and 700 m in the west. In the south-eastern part of the basin, these deposits directly overlay the Mesozoic formations of Pădurea Craiului Mountains, while in the north-western part the metamorphic rocks of Plopiş Mountains. The micro- and macropaleontological associations are relatively scarce, consisting of mollusks, foraminifers and ostracods (Givulescu, 1957; Nicorici et al., 1978).

The Quaternary sediments cover large areas of the basin (Fig. 2.2), mainly along the Crişul Repede Valley and all the terraces and alluvial meadows. They are more developed on the left bank of Crişul Repede Valley (Istocescu et al., 1970).

2.3. Tectonics

During the Neogene, the specific tectonic evlution of the Apuseni Mountains lead to the separation of three distinctive events, assigned to NW-SE (Paleogene-Lower Miocene), NE-SW

(Badenian-Sarmatian) and NV-SE (Upper Miocene - Pliocene) oriented fault systems (Györfi & Csontos, 1994; Csontos, 1995).

The fault system from Borod Basin was interpreted by Givulescu (1969) based on field observations corroborated with data from boreholes located in the eastern side of the basin. Istocescu et al. (1970) have seprated two major structures: a folded unit represented by the pre-Neogene deposits, and a post-tectonic unit. The northern sedimentary formations are delimited by a major fault system associated with volcanic rocks that build-up the transition towards the Plopiş Mountains, and separate the sedimentary unit from the basement.

2.4. Peculiar aspects in the studied areas

Our study focused on the Sarmatian deposits from two areas: Vârciorog area in the southern part of Vad-Borod Basin, and, respectivelly Luncșoara area in the east. In both areas the studied deposits are assigned to the Cornițel Formation (Popa, 2000). The Vârciorog area, and Vișinilor Brook in particular, hosts by far the richest paleontological associations.

Chapter 3. MATERIALS AND METHODS

3.1. Location of the studied sections

The studied material was collected between 2010 and 2015 from Vârciorog (Vișinilor Brook), respectively from 26 outcrops (the geographic coordinates are mentions for each of the studied profiles, below). We have realized lithological profiles and have systematically collected samples from each outcrop (in total, 526 samples).

In order to correlate this area with the neighboring ones, we have studied additional adjoining outcrops: we have collected 3 samples from Subpiatră area (47°0'15.30"N, 22°18'56.09"E; 47°0'16.17"N, 22°18'46.98"E and 47°0'21.96"N, 22°18'34.62"E), 2 from Luncșoara (47°2'33.20"N, 22°32'57.33"E and 47°2'33.21"N, 22°32'55.02"E), one from Surduc – 46°58'33.45"N, 22°12'6.18"E and one from Lugașul de Sus – 47°6'6.35"N, 22°20'52.17"E (in total 46 samples from outcrops).

The stages of my research were represented by: sampling and sample preparation following classical micropaleontological methods, quantitative and qualitative interpretation of the main association and morphogroups types in the view of evaluating their biostratigraphic and paleoecological potential, in the context of the sedimentary basin's evolution.

3.2. Sampling and preparation of micropaleontological material

The samples were collected along the whole length of the sections, at 2 to 30 cm distance. In the intervals where major litholigical variations, or a high micropaleontological potential were noticed, the sampling was performed at 2-15 cm-distance. We have collected about 1000 g for every sample, of which 250 g were processed and the rest was deposited at the Department of Geology of the ”Babeș-Bolyai” University.

3.3. Interpretation of the results

After the taxonomic interpretation was finalized, the specimens were grouped into 8 distinctive morphotypes for each profile. We have separated micropaleontological associations for which we have calculated diversity indices.

For each profile in the Vișinilor Brook we have drawn diagrams for interpreting biodiversity. Based on these interpretations, we have correlated the profiles based on their common features, and we have realized paleoenvironmental reconstructions based on the peculiar aspects of the associations.

For each species, we have calculated the abundance (%) and we have statistically presented these data in diagrams.

3.3.1. Diversity indices: Relative abundance, Dominance, Shannon-Wiener Index, Equitability, Fisher α, Simpson

For a given habitat, biodiversity may be quantified using various indices. These mathematical parameters of species diversity allow comparisons among the various structures in a community (Begon et al., 1996). We have calculated the diversity indices and performed the multivariant statistic analysis by using the programme PAST - PAlaeontological STatistics (Hammer et al., 2001).

3.3.2. Benthic foraminiferal oxygen index (BFOI) estimated based on the calcareous benthic foraminifers

BFOI (Benthic Foraminifera Oxygen Index) is an index illustrating the relationship between the calcareous benthic foraminifers and the amount of oxygen dissolved at the water-sediment interface. This index was established by analyzing the morphology of the tests of foraminifers in the present-day oceans; these observations are then extended to paleoenvironmental interpretation (Kaiho, 1991, 1994, 1999). However, the values for this oxygenation index proposed by Kaiho (1994, 1999) for quantifying the paleo-oxygenation of water masses were calculated for absolute oxygenation values and provide only a relative and limited estimation (Kouwenhoven & van der Zwaan, 2006).

Based on specific morphological characters, the oxygenation level (Bernhard, 1986; Corliss, 1985; Corliss & Chen, 1988; Corliss & Fois, 1990) and the microhabitat (Corliss, 1985; Kitazato, 1984; Corliss & Emerson, 1990; Kaiho, 1991, 1994, 1999; Gebhardt, 1999), the benthic foraminifers were divided into three groups of fauna indices: oxic (O) (the amount of dissolved oxygen is > 1.5 ml/l), suboxic (S) (the amount of dissolved oxygen is 0.3-1.5 ml/l) and dysoxic (D) (the amount of dissolved oxygen = 0.1-0.3 ml/l) (Tab. 3.1).

Condiții de oxigenare	Oxigen, ml/L	BFOI	Foraminifera (indicatori)
Oxic ridicat	3.0 - 6.0	50 - 100	raport ridicat de indicatori oxici, disoxici, suboxici
Oxic scăzut	1.5 - 3.0	0 - 50	raport scăzut de indicatori oxici, disoxici, suboxici
Suboxic	0.3 - 1.5	-40 - 0	disoxici și raport ridicat de indicatori suboxici
Disoxic	0.1 - 0.3	-50 - -40	disoxici și raport scăzut/insuficient de indicatori suboxici
Anoxic	0.0 - 0.1	-55	forme calcaroase insuficiente

Table 3.1. Oxygenation conditions separated based on the features of benthic calcareous foraminifers (based on Kaiho, 1994)

3.3.3. Q-mode and R-mode factor analysis

Q-mode and R-mode factor analysis represent multivariant statistic quantitative models illustrating the correlations among ecosystems' components. They are achieved by processing a large number of experimental measurements in the frame of a complex monitoring program. When applied to biological or geological research topics, factor analysis reflects the relationships among a large number of measurable variables in the view of illustrating new, theoretical variables, *i.e.*, "factors".

In our study, Q-mode and R-mode factor analysis was performed on benthic foraminifer specimens' data, in order to distribute them into associations or samples that point to similar ecological conditions. The obtained dendrograms provide useful information and significantly reduce the data volume required for paleoecological interpretations based on benthonic foraminifers.

3.4. Analysis of the benthic foraminifer morphogroups

The shape and morphology of foraminiferal tests are important features in both benthic and planktonik foraminifers' description (Table 3.2). The term "morphogroup" refers to groups of foraminifers with similar shapes of growth patterns, with no input of taxonomic criteria (Murray et al., 2011). Thus, by using the morphogroups analysis the taxonomic factor is removed from the interpretation: thus, comparison between foraminiferal assemblages of different ages becomes possible.

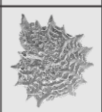
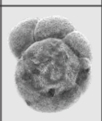
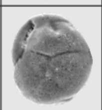
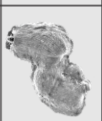
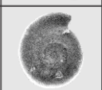
MORFOGRUP		FORMA TESTULUI		FAMILII DE FORAMINIFERE	MOD DE VIAȚĂ	MOD DE HRĂNIRE	NIVELUL DE OXIGEN	GENURI DE FORAMINIFERE (din această lucrare)
M1		Planspiral rotunjit		Elphidiidae Nonionidae	infaunal liber	ierbivore și detritivore	suboxic	*Cribroelphidium, Elphidiella, Elphidium (necarenat), Haynesina, Nonion, Nonionella, Porosononion*
M2		Planspiral carenat / aculeat		Elphidiidae	epifaunal	ierbivore	oxic	*Elphidium* (carenat/aculeat) *Parrelina*
M3		Planconvex / biconvex ușor trochospiral		Rotaliidae	infaunal liber	?ierbivore	oxic / suboxic	*Ammonia Aubignyna*
M4		Planconvex trochospiral		Rotaliidae	epifaunal atașat temporar / permanent	omnivore ierbivore	oxic / suboxic	*Anomalinoides, Asterigerinata, Cibicides, Lobatula, Neoconorbina, Rosalina, Rotaliella, Schackoinella*
M5	M5a	Conic alungit / aplatizat		Bolivinidae	infaunal-epifaunal liber	?detritivore	disoxic	*Bolivina*
	M5b	Conic cilindric bi-/triseriate trochospirale		Buliminidae	infaunal liber	?detritivore	suboxic / disoxic	*Bulimina Buliminella Caucasina Fursenkoina*
M6		Lenticular și/sau ovoid spre ovoid aplatizat		Rotaliidae	infaunal liber	detritivore	suboxic / oxic	*Cassidulina Globocassidulina*
M7		Sferice / pyriforme uniloculare		Lagenidae	infaunal liber	detritivore	suboxic	*Fissurina, Galwayella, Grigelis, Guttulina, Laryngosigma, Oolina Orthomorphina, Pseudopolymorphina*
M8	M8a	Miliolin parțial derulat		Miliolidae	epifaunal liber	ierbivore detritivore	oxic	*Articularia, Articulina, Dogielina, Ptychomiliola, Sarmatiella*
	M8b	Miliolin înrulat		Miliolidae	epifaunal liber	ierbivore detritivore	oxic / suboxic	*Affinetrina, Cycloforina, Edentostomina, Flintina, Massilina, Miliolinella, Nodobaculariella, Pseudolachlanella, Pseudotriloculina, Quinqueloculina, Spiroloculina, Triloculina, Varidentella*
	M8c	Planconvex și sinusoidal înrulat în faza inițială		Miliolidae	epifaunal sesil	ierbivore pasive ?hrănire din suspensie	oxic	*Meandroloculina Sinzowella*
	M8d	Planspiral înrulat		Miliolidae	infaunal	?	oxic	*Cornuspira*

Table 3.2. Benthic foraminifers morphogroups and morphotypes (adapted from Bernhard, 1986; Corliss & Chen, 1988; Corliss & Fois, 1990; Corlis, 1991; Kaiho, 1991, 1994, 1999; Murray, 1991; Intrieri & Valleri, 2007, Jones, 1994, 2014; Reolid et al., 2008; Tóth & Görög, 2008).

Chapter 4. RESULTS

During the field campaings between 2010 and 2015, 26 natural outcrops have been identified at Vârciorog (Vișinilor Brook), out of which 22 were sampled for the micropalaeontological study. The D12-D2 profiles are located along the main stream, from the lower part towards the the top, D0 and D1 crop out on the left affluent, while DF to DA are located on the left of the confluence where D7 is positioned (Fig. 4.1).

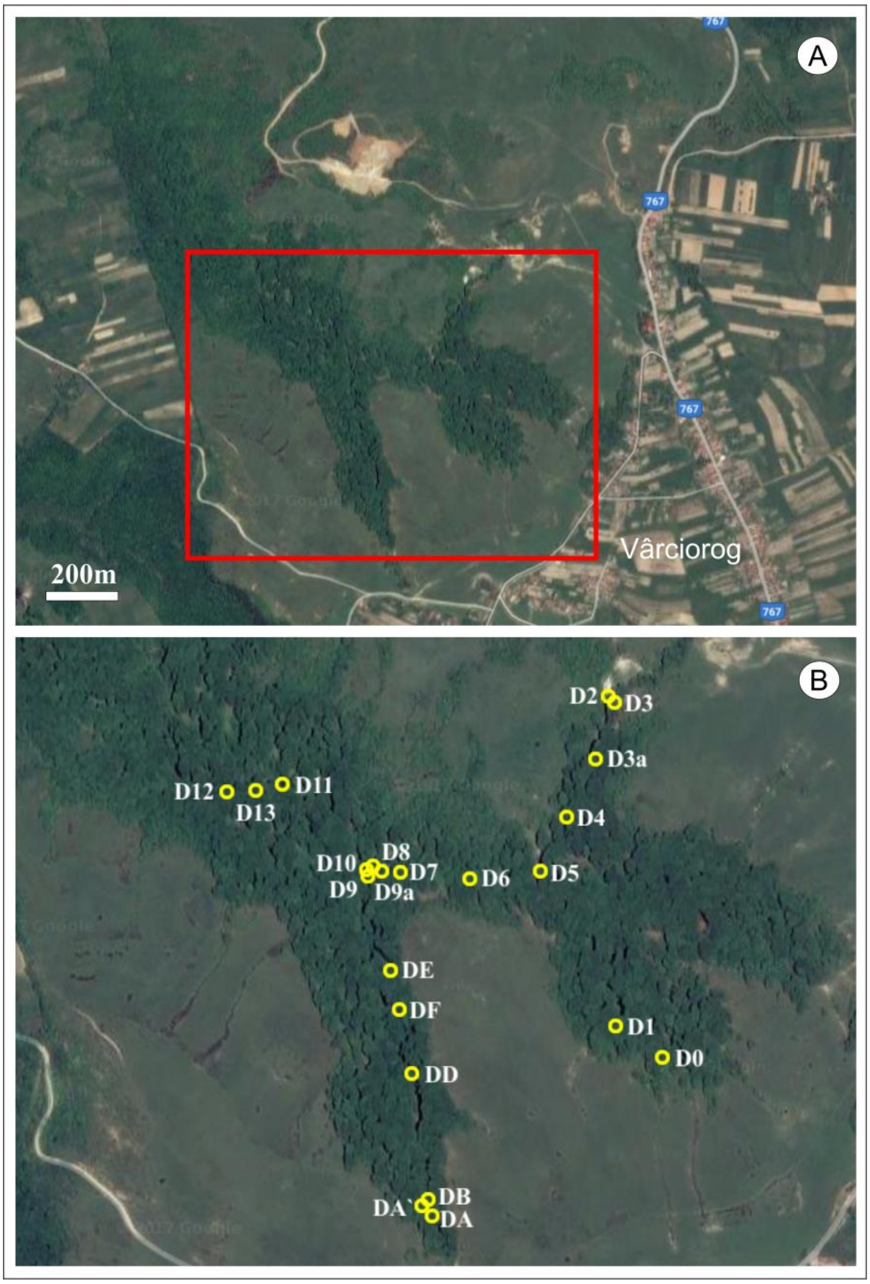


Fig. 4.1. Satellite photographs showing: A. the localization of the studied area in the Vârciorog zone (red square); B. Localization oif the investigated outcrops on the Vișinilor stream (https://www.google.com/earth).

The investigated sedimentary succesion on the Vișinilor Brook includes benthic foraminifera assemblages and other micro and macrofossils, which have a high potential for the reconstruction of the palaeoenvironmental conditions durind the Sarmatian.

For each studied outcrop from the Vișinilor Brook, statistical analyses, relative abundence charts of the main taxonomical groups, palaeoecological indices, the ratio and frequency of the morphogroups and R-mode and Q-mode cluster analyses were involved.

Folowing the investigation of the benthic foraminifera assemblages, the index species were identified in order to establish biozones, the sedimentary profiles being grouped based on the Sarmatian biozonation from the Central Paratethys.

Chapter 5. OTHER IDENTIFIED MICROFOSSIL ASSOCIATIONS

The benthic foraminifers are ofted accompanied by other micro- and macrofossil groups (molluscs, ostracods, bryozoa assemblages and otholiths), which were partially studied throught collaboration with Dr. Mathias Harzhauser (molluscs), Dr. Martin Gross (ostracods), Dr. Kamil Zágoršek (bryozoa) (e.g. D9 outcrop from Vișinilor Brook - Filipescu et al., 2014). These fossil groups were used to constrain the biostratigraphical and palaeoecological conclusions as resulted from the foraminifers' studies.

18 families and 25 mollusc species were identified from the analysed samples up to date, including a new species for Romania - *Tectura* aff. *zboroviensis* Friedberg, 1928 (sp. nov.), 17 ostracod species, 6 bryozoa species and numerous otholiths (Harzhauser in Filipescu et al., 2014).

The mollusc fauna from the D9 outcrop is typical to the Lower Sarmatian, respectively the *Mohrensternia* Zone and it correlates with the foraminifera and ostracod assemblages.

From the terrestrial gastropods (*Clausiliidae*, *Helicidae*), the helicids point out a continental influence, with humid and forested areas. *Agapilia picta*, *Granulolabium* or *Loripes niveus* forms indicate marine coastal conditions. Muddy coastal sediments have been populated by *Agapilia picta*, *Granulolabium bicinctum* and *Cerithium rubiginosum*, whilst *Mohrensternia angulata* and *Clavatula doderleini* probably preffered the brackish sublittoral tranzition zone (Harzhauser in Filipescu et al., 2014).

The ostracod assemblage has also constrained a Lower Sarmatian age and has been included in the *Cytheridea hungarica* - *Aurila mehesi* Zone (NO 11 - Jiříček & Riha, 1991).

Miocryprids and Hemicryprids are colonizing the environments with salinity variation. These taxas are dominating the near-shore environments, sand deposits or brackish waters (Cernajsek, 1972). The *Aurila* genus prefers epinerithic zones, infralittoral to circalittoral, oxic waters with depths up to 80 m (Hartman, 1975; Tóth et al., 2010). Xestoleberids live in near-shore, brackish environments, on a muddy substrate with algae (Puri et al., 1969; Bonaduce et al., 1976; Lachenal, 1989, Tóth, 2009). The occurance of rare freshwater ostracods (*Ilyocypris, Heterocypris*) documents the existence of some fluvial environments, while *Cytherella* or *Tenedocythere* often populate deeper depositional environments with warm waters from the euphotic zone (Gross in Filipescu et al., 2014). Species which belong to the *Loxoconcha* are adapted to marine-litoral waters that are rich in algae, being characteristic to the Sarmatian deposits (Tóth, 2009).

The bryozoa assemblages show a lowered diversity, with opportunistic ciclostomate species such as *Tubulipora*, *Cryptosula* or *Schizoporella*, species which also document the Sarmatian age of the deposits (Ghiurcă & Stancu, 1974; Vávra, 1977; Zágoršek, 2007; Zágoršek in Filipescu et al., 2014). The *Schizoporella* genus was reported in almost every brackish environment, having a high adaptive capacity to variation of the environmental conditions (Holcová & Zágoršek, 2008).

In the Borod Basin, at Lugașu de Jos, the Lower Sarmatian centric and pennate diatoms occur on small areas, together with vertebrates such as fish, reptiles or mammals (Codrea et al., 2007). The micro- and macrofossil assemblages indicate wooded environments with brackish waters and freshwater episodes. In the upper part of the Vișinilor Brook, the diatoms from the tuffitic levels, together with other fossil groups, record similar depositional environments.

The bolboforms are marine microfossils with a still unclear lineage, which come from cold/temperate waters from medium/high latitude and present a biostratigraphical and palaeoceanographical potential due to a high resistance to the dissolving processes from sediments (Cooke et al., 2002; Spezzaferri & Rögl, 2004: Spiegler & Spezzaferri, 2005). The bolboform fragments identified at Vârciorog are similar to those from the Bessarabian of the Moldavian Platform (Brânzilă, 2013) and are reported for the first time in the Borod Basin. The foraminifera assemblages identified from the *Bolboforma* sp. level indicate colder waters from brackish water environments.

The Myssid biozone is characteristics for the Sarmatian (Upper Volhynian - Lower Bessarabian) in Paratethys (Voicu, 1981, 1984, 1992). The Myssids identified in the upper part of Vișinilor stream, from Vârciorog, together with nubeculariids, suggest the Bessarabian age of the deposits.

The dasyclad algae in the D9 profile from the Vișinilor Brook, but also those from Luncşoara, are characteristic to the Sarmatian, as constrained by the *Halicoryne moreletti* species (Bucur et al, 1993; Bucur & Șuraru, 1994; Bucur, pers. com.).

The Vârciorog otholiths are similar to the Paratethys species, belonging to the Mugilidae, Gobiidae, Clupeidae etc., which populated the slightly salted, brackish waters (<50 m) (Bratishko et al., 2015). Other vertebrate fragments have also been collected from the Vișinilor stream outcrops such as cranial fragments, vertebrae, fish teeth and microvertebrates.

In Molnar's Bachelor thesis (2011), under prof. Vlad Codrea's supervision (Babes-Bolyai University of Cluj Napoca), microvertebrate fragments from the Vișinilor Brook area were identified for the first time. They belong to Muridae, Gliridae and Erinaceida and prove the Lower Sarmatian age (Volhynian) of the deposits.

Fresh water crab fragments (*Potamidae* chelae - Klaus, pers. com.) were identified in some of the investigated outcrops, indicating tranzitional environments (marsh - lacustrine environments) (Klaus et al., 2011).

Chapter 6. SYNTHESIS OF RESULTS AND DISCUSSIONS

Following the investigation of the outcrops from the Vișinilor Brook, it was concluded that the sediments from the south-west of the Borod Basin cover a large area and include a consistent part of the Sarmatian succession. The deposits consist of a large lithological variety: clay, coaly clay, silt, sand, gravel, sandstone and limestone, and, some clay and silt layers have a lumaschellic appearance. The facies are very different laterally due to the neighbouring the marine and continental domains, which sometimes made the outcrops less relatable.

From the bottom towards the top, the following lithologies have been noticed:

- sands, with gravel intercalations in the lower part,
- silts and clays, transitioning into sandstones in the upper part,
- tuffs, which sometimes contain coaly clay intercalations,
- limestone and silt alternations with shell concentrations,
- siltic sands.

From palaeontological point of view, the outcrops from the Vișinilor stream preserve extremely rich foraminifera assemblages, together with other micro and macrofossils, all characterstic of Sarmatian age.

The abundance of the foraminifera species was studied and statistically represented. The synthetic cluster (Fig. 6.1) was obtained transposing all the foraminifera species that participated with a minimum of 3%, for 355 investigated samples. The same data was used for the principal components analysis (PCA - Fig. 6.2). From both analyses, the relative abundances of 12 species and 7 genera turned out to be significant.

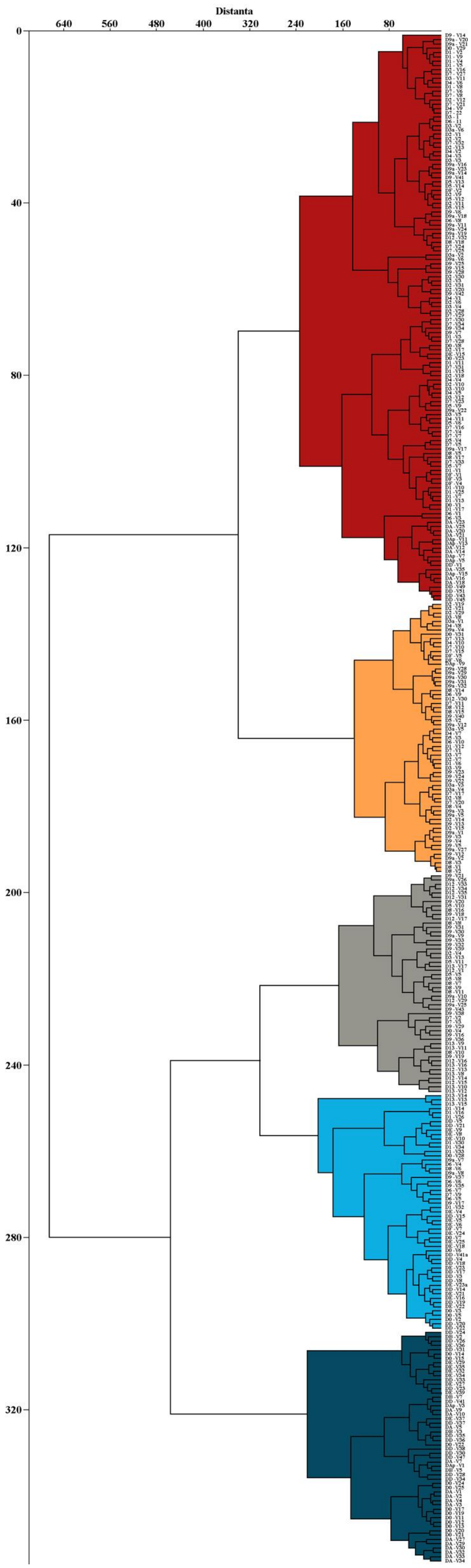


Fig. 6.1. Synthetic cluster based on the abundance of the species with at least 3% presence, on the Vișinilor Brook

The species were statistically grouped in the following major biofacies (Fig. 6.1):

- the *Ammonia tepida* biofacies (red color) - is represented by opportunistic, dominant euryhaline species, with tolerance for fluctuant environment;
- the *Ammonia beccarii* biofacies (yellow color) - the massive presence of species with the same name indicates the marginal environments with consistent inputs of fresh water;
- the *Elphidium crispum, E, grilli, E. reginum, E. hauerinum* biofacies (grey color) - is characteristic for shallow water, stable environments, with a phytal substrate;
- the *Elphidium aculeatum* biofacies (light blue color) - epifaunal *Elphidium* species, together with the miliolids, constrain normal salinity to hypersaline episodes in oxic conditions;
- the *Cribroelphidium excavatum* biofacies (dark blue color) defines limiting depositional environments, with suboxic episodes and varying quantities of organic matter.

The PCA chart (Fig 6.2) reduces, to a bidimensional level, the grouping of individual sampling (the colored dots) based on the taxons which define the assemblages (colored segments), highlighting the similarity between the samples and the linear link of the variables. The PCA shows the importance of some ecological parameters and searches for sets of samples which correlate, in order to define some environments which includes species with the same palaeoecological preferences. The results of the analysis allow us to verify of some results deducted from the palaeoecological interpretations of the assemblages.

The PCA (Fig 6.2) resulted in grouping of the following assemblages:

- the *Ammonia beccarii* assemblage, represented by yellow dots, which marks the environments with the lowest salinity and a slighly reduced oxygen level;
- transitional assemblages (with *Ammonia*, *Elphidium*, *Porosononion*, *Lobatula* etc. species), represented by red dots, usually present in the lower to midle part of the sedimentary succession, characterised by a certain tolerance to the environmental conditions;
- assemblages characteristic to environments with high salinity and a relatively good oxygenation (with dominating miliolids and some rotaliids), represented by light blue dots;
- assemblages specific for environments with the salinity close to normal values and the highest oxygenation level (with dominating rotaliids and miliolids), represented by grey dots;

- assemblages which suggest an environment that is rich in nutrients, with reduced oxygenation values, but normal salinity (dominated by buliminids species), represented by dark blue dots.

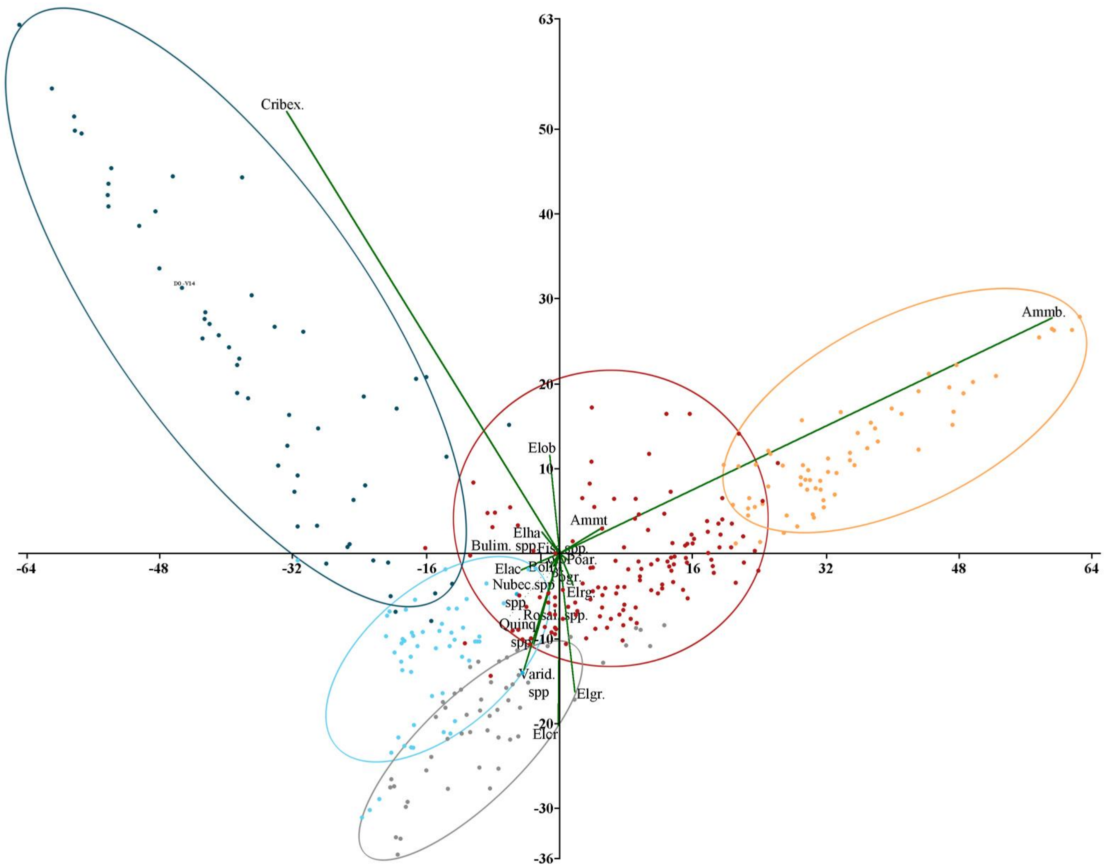


Fig. 6.2. The grouping representation of the main identified assemblages on the Vișinilor stream, using factorial analysis (PCA)

The green segments represent proportionally the degree of conformity of the species to the environmental conditions typical for the assemblages defined by them or from the vicinity.

Even if the values of the axis from the chart are not directly related to the values of some environmental parameters, following the graphic grouping of the dots that are characteristic to the major assemblages, it is noticed that the salinity increase from right to left, while the oxygenation value decreases from the bottom to the top.

The outcrop correlation from the Vișinilor Brook (Fig. 6.3) was possible through representation of the assemblages (in the left column, with the colors from fig. 6.1) and biofacies that resulted from the factorial analysis (shown in the column from the right and explained in the legend), together with the identified biozones through biostratigraphic analysis on the individual lithological profiles. As it can be observed in the figure, the multiple data use allows a better resolution in positioning the individual outcrops in each biozone, which highlights the utility of the statistical methods.

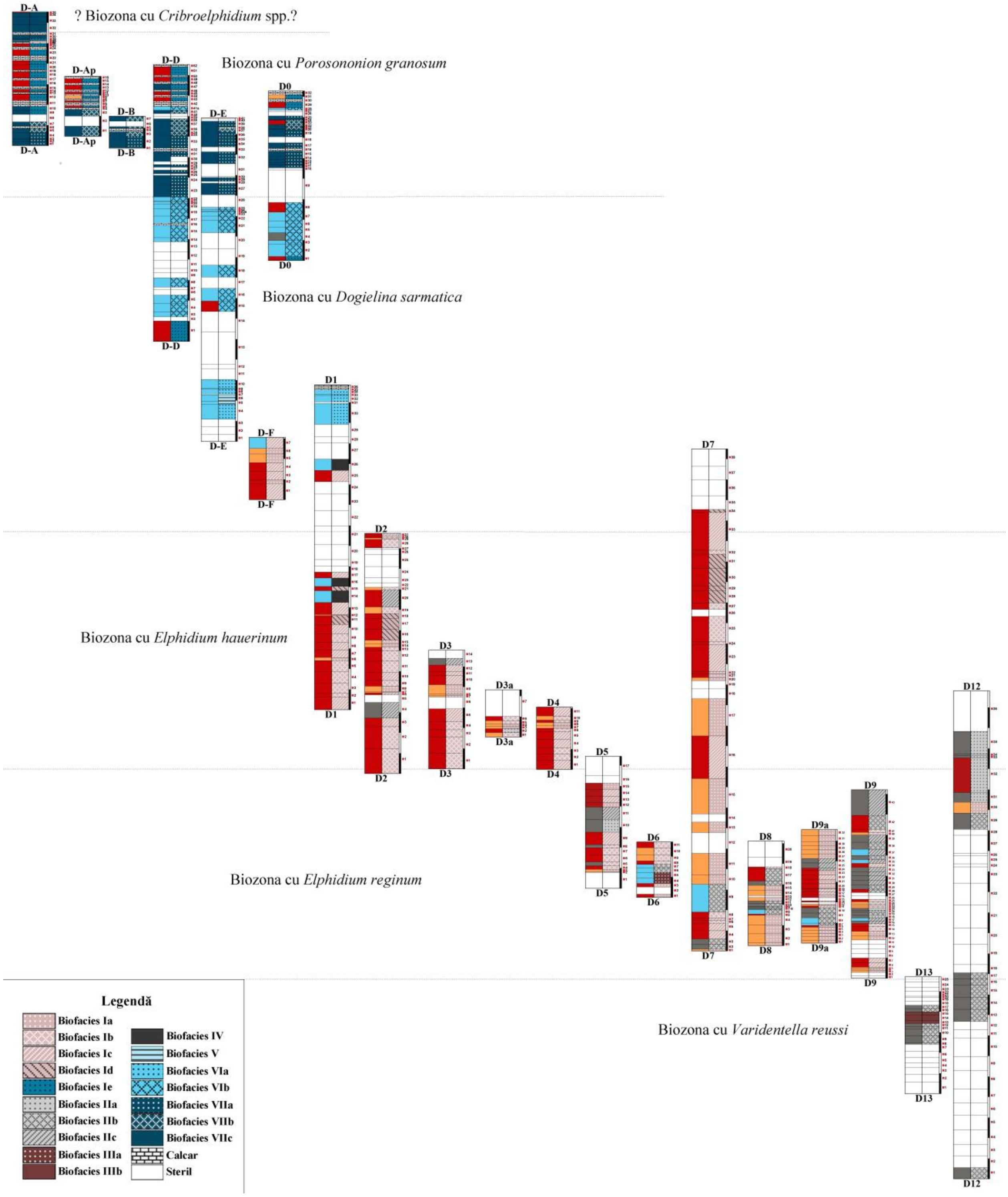


Fig. 6.3. The correlation of the studied outcrops from the Vișinilor stream

Chapter 7. CONCLUSIONS

The topic of this study was to investigate the Sarmatian foraminifera assemblages from the south-west part of the Borod Basin, to detail the biostratigraphy and to reconstruct the palaeoenvironmental context and the evolution in time and space of the depositional environments.

Out of the 22 outcrops that have been investigated on the Vișinilor Brook, diverse benthic foraminifera assemblages have been separated (137 species, 54 genera), some of which were mentined for the first time in Romania (ex. *Elphidium* aff. *tongaense*, *Galwayella trigonomarginata*). The assemblages were characterized using taxonomical, biostratigraphical and abundance analyses, while defining and interpreting of the characteristic morphogroups, assemblages and biofacies were used to reconstruct the palaeoecological features.

7.1. Characteristic morphogroups of benthonic foraminifers

The morphogroups highlight the relationship between the foramifera test and bathymetry, the quality of the substrate, salinity, hydrodynamics, oxygenation level and nutrient intake. In the Vișinilor stream section, the following morphogroups have been separated:

- **M1** is represented by elphidiids and nonionids with rounded planspiral test, with a free infaunal mode of life, which describe depositional environments that are rich in organic matter, from the internal shelf zone until the upper-bathyal zone, in waters with salinity values slightly lower to hypersaline, although without sustaining high variations of salinity (Boltowskoy & Wright, 1976; Jorissen, 1987; Langer, 1993; Poignant et al., 2000; Debenay et al., 2005; Murray, 1991, 2006, Darling et al., 2016).
- **M2** includes *Elphidium* species which are keeled, aculeate, epifaunal and epiphytic with a suspensivore feeding mechanism, preferring a gravel/sandy substrate in oxygenated waters, with an abundance in the litoral and sublittoral zones (Langer et al., 1989; Murray, 2006; Darling et al., 2016). In actual environments, keeled elphidiis indicate temperate - warm waters (Murray, 1991).
- **M3** with infaunal species with a planconvex/biconvex test that is slightly trochospiral, with preferences for a muddy and/or sandy fluvial environments, estuary, brackish marine zones from the oxic-suboxic zone, with high variations of salinity and temperature or a wide value range in terms of organic matter (Bradshaw, 1957, 1961; Jorissen, 1987; Walton & Sloan, 1990; Almogi-Labin et al., 1992, 1995; Debenay et al., 1998; Alve & Murray, 1999; Hayward et al., 2004).

- **M4** reunites epifaunal/epiphyte rotaliids genera with a trohospiral planconvex test, with the spiral part flattened from a lateral view and rounded to sharpened outline. They are temporarily or permanently attached, with preferences for coarse sand or gravelous substrate, in zones with high hydrodynamics, in brackish waters with normal salinity values and well oxygenated (Corliss & Fois, 1990; Murray, 1991, 2006; Langer, 1993; Schönfeld, 2002).
- **M5** is split in two morphotypes:
  - M5a contains taxons with a flattened, conical-shaped test, with a free mode of life in fine sediments, in deep marine environments with relatively low energy and normal salinity, capable of tolerating suboxic depositional environments to anaerobe conditions (Bernhard, 1986). These infaunal and detritivore forms (*Bolivina*) are found on the internal shelf and in the lower part of the bathyal zone, with a high amount of vegetal detritus (Corliss & Chen, 1988; Kaiho, 1991, 1994; Bernhard & Sen Gupta, 1999; Murray, 2003, 2006).
  - M5b groups infaunal species with a rounded bi-triserial conical-cylindrical test (buliminids) which are opportunistic forms with a tolerance for zones with reduced oxygenation to dysaerobic levels in normal salinity conditions, in brackish water, neritic zones to deep waters with relatively low energy, species diversity being directly proportional with the depth (Intrieri & Valleri, 2007; Jones 1994, 2014).
- **M6** is represented by species with a lenticular to flattened-ovoidal test, with biconvex morphology. They are infaunal, detritivore taxons which live freely in fine sediments from brackish waters with normal salinity, in conditions of low oxygenation and relatively low energy (Kaiho, 1991, 1994; Intrieri & Valleri, 2007).
- **M7** includes infaunal spherical/pyriform unilocular species, with a detritivore feeding mode, with preferences for fine sediments in brackish suboxic waters with low energy, normal salinity and moderate flux of organic matter (Mendes et al., 2004; Murray, 2006; Intrieri & Valleri, 2007).
- **M8** is represented by milioliids and has four morphotypes:
  - M8a which groups partially uncoiled milioliids which live freely in relatively coarse sediments and their presence in the assemblage suggests near-shore zones, with brackish waters (<30m), well oxygenated and less agitated (Łuczkowska, 1974).
  - M8b contains epifaunal forms with a coiled milioline test, free or attached on substrate or plants, with preferences for normal marine conditions to hypersaline,e

in temperate-warm waters, in oxic/suboxic conditions, lagoons, internal shelf zone (0-40 m) (Murray, 1991, 2006; Peryt & Gedl, 2010).

- M8c includes milioliids with a planconvex test and sinusoidaly coiled in the initial stage. They are epifaunal forms with a sessile mode of life, being found in oxygenated, brackish marine environments that are unstable at the water-sediment interface on the vegetal substrate. These species suggest marine environments from the near-shore, with high energy zones, warm brackish waters with higher salinity conditions (Blanc-Vernet, 1969; Łuczkowska, 1974; Murray, 1991; Amstrong & Brasier, 2005; Tóth & Görög, 2008).
- M8d includes small milioliids that are associated with the brackish marine environments from the internal continental platform zone, which can tolerate salinity variations, in oxygenated waters, with a diversity that is proportionally inverse to the depth (Jones 1994, 2014).

7.2. Types of benthic foraminifers assemblages

The foraminifera assemblages were name according to the species with the highest percentage in the cluster. The palaeoecological conditions have been described considering the species groups or even singular species if they had different preferences compared to the rest of the assemblage. In the outcrops from the Vișinilor Brook, 14 types of benthic foraminifera assemblages were identified, statistically named and grouped according to the species frequency:

- **A1** - *The Ammonia Assemblage* is specific to the dominantly brackish environments, with high ecological parameter fluctuations, such as salinity, temperature, oxygen or nutrient quantity (Boltovskoy & Wright, 1976; Murray, 1991, 2006; Sen Gupta, 2002; Carboni et al., 2009). The preference of the species for a certain microhabitat can change depending on the food availability or the environmental conditions (Jorissen, 1988; Corliss & Emerson, 1990; Debenay et al., 1998).
- **B1** - The *Elphidium crispum assemblage*, together with infaunal species, characterizes the brackish depositional environments, golfs or protected lagoons, without any active currents, in oligothrophic environmental conditions up to normal ecological marine values, on predominantly muddy/sandy sediment.
- **B2** - The *Elphidium grilli assemblage*, together with epiphyte species, is characteristic for the oxygenated, brackish environments with a sandy, vegetal substrate from the infralittoral-circalittoral zone with normal salinity values (Langer, 1993; Tóth & Görög, 2008; Sadri et al., 2011).

- **B3 -** *The Elphidium reginum assemblage* describes a medium with rich vegetation of arborescent algae, with a short life span, with clay-sandy sediments from the infralittoral-circalittoral zone (Langer, 1993; Tóth & Görög, 2008; Sadri et al., 2011).
- **B4 -** *The Elphidium hauerinum assemblage* is typical to oxic/suboxic brackish and fluctuant salinity depositional environments, but close to the normal values on muddy/sandy sediments
- **B5 -** *The Elphidium aculeatum assemblage* describes depositional environments with a substrate that is rich in vegetation, in brackish marine environments, near-shore with high hydrodynamics areas and normal to slightly high salinities.
- **B6 -** *The Cribroelphidium excavatum assemblage* is characteristic to the brackish marine conditions with oxic/suboxic conditions, with preferences for sandy/clay substrate, in sediments that are rich in organic matter.
- **C1 -** *The Quinqueloculina assemblage* indicates environments with normal to hypersaline salinities, with high abundance in warm regions, in brackish waters, lagoons or golfs, with well oxygenated waters and moderate primary productivity.
- **C2 -** *The Varidentella sarmatica assemblage* describes oxic, brackish marine environments, with a vegetal substrate, lagoon environments with normal to hypersaline salinity in unstable environmental conditions.
- **C3 -** *The Sinzowella assemblage* represents a particular assemblage with the presence of nubeculariids as a dominant species. Such assemblages suggest near-shore marine environments in brackish warm water zones, with a vegetal substrate and a higher salinity.
- **D -** *The Bolivina-Buliminella assemblage* describes suboxic depositional environments on muddy/clay sediments, and with important quantities of organic matter.
- **E -** *The Porosononion granosum assemblage* characterizes sediments that are rich in organic matter, a muddy/sandy substrate from the internal shelf to the upper-bathyal zone, in waters with salinity values slightly lowered to normal marine conditions.
- **F -** *The Lobatula* assemblage shows a detritical sedimentation and waters with a high energy regime in unstable environments.

7.3. Biofacies types

Seven types of biofacies were identified in the studied outcrops, statistically grouped based on ecological parameters responsible for the distribution of the foraminifera species in the investigated samples:

The **Biofacies I,** with its sub-biofacies, is dominated by *Ammonia* and corresponds to unstable areas, with brackish waters, in various substrate and nutrient intake conditions;

The **Biofacies II**, dominated by *Elphidium*, corresponds to more stable environmental conditions, with a coarser or more vegetated substrate, variable oxygenation level and nutrient intake, which allows the epifaunal and infaunal, herbivore and detritivore species to live, in conditions of salinity that are close to the normal values;

The **Biofacies III**, dominated by milioliids, which are epifaunal, detritivore and/or herbivore forms, characterizes brackish water with normal saline or hypersaline conditions;

The **Biofacies IV**, with *Lobatula lobatula*, which documents the existence of a coarser or vegetated substrate, with high hydrodynamics;

The **Biofacies V**, separated after the occurence of new species as compared to the rest of the succession (*Dogielina sarmatica, Sinzowella, Affinetrina*), in the transitional zone to Bessarabian;

The **Biofacies VI**, dominated by the particular nubeculariid assemblages, is described by a fine substrate with reduced hydrodynamics and normal or hypersaline conditions;

The **BiofaciesVII**, dominated by the explosive occurence of the *Cribroelphidium, Elphidium* and *Porosononion* genus, which characterize salinities that are close to normal values, lower depths, muddy or sandy substrate with organic matter intake.

7.4. Morphological anomalies of the benthic foraminifers tests

Another approach in the palaeoecological study was represented by the investigation of morphological anomalies of the foraminifers’ tests, which was focused on the assemblages from the D9 sample. The observations were made on the test of the benthic species from the *Ammonia* and *Elphidium* genera, even though test malformations were noticed în case of other species. After the qualitative and quantitative analysis, the abnormal forms were separated following the model proposed by Polovodova & Schönfeld (2008) in 4 types (chambers, aperture, architecture and test abnormalities) and 14 subtypes of malformations. The most frequent types of abnormalities were associated with the instability of the environment, caused mainly by the fluctuating values of salinity and oxygenation level.

7.5. Biostratigraphy

Following the evolution of the micropalaeontological assemblages from the investigated outcrops, known biozones at a regional level for the Sarmatian age were identified (Fig. 7.1):

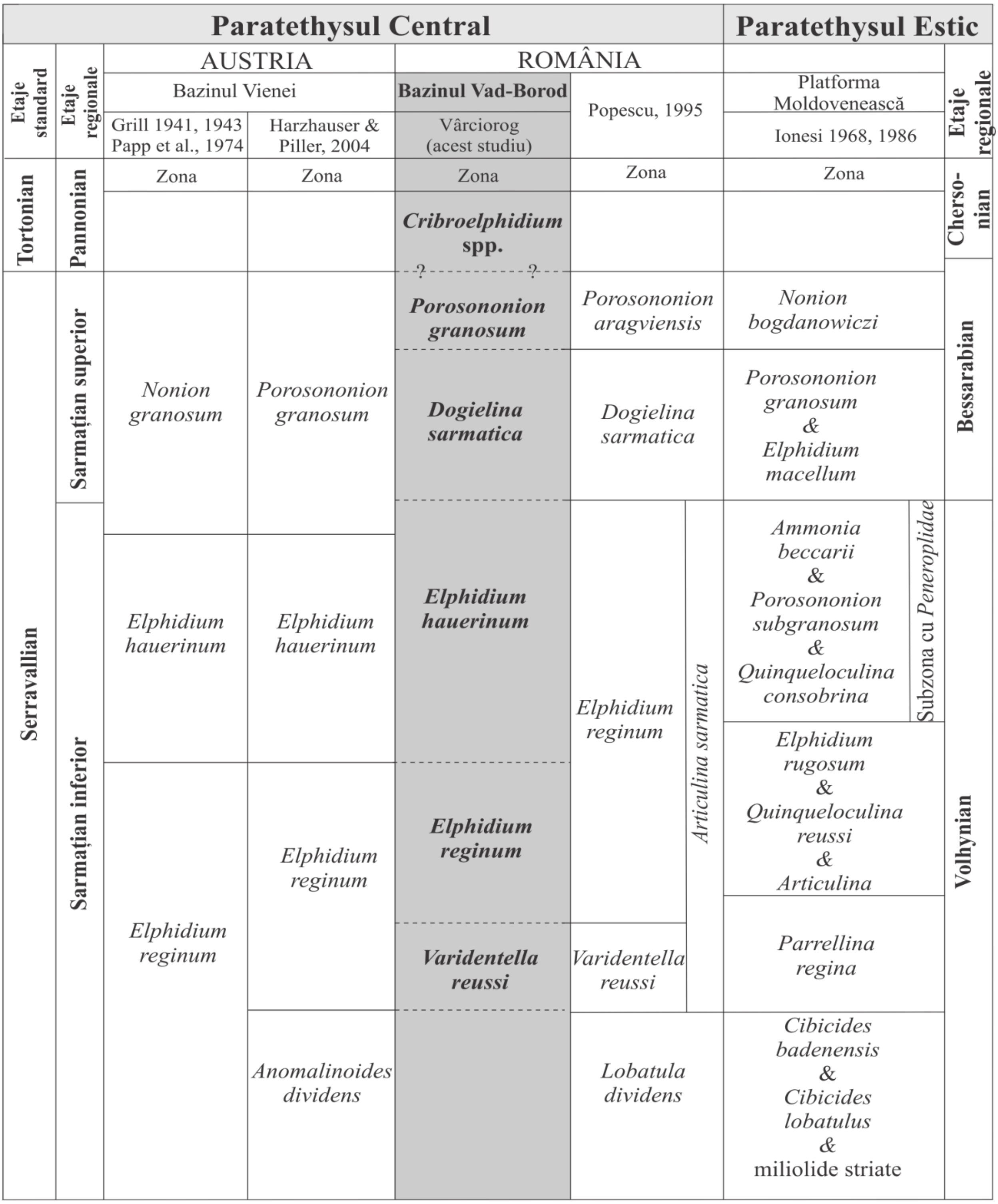


Fig. 7.1. The Sarmatian biozone correlation based on benthic foraminifera
(based on Grill, 1941, 1943; Ionesi, 1968, 1986; Papp et al., 1974; Popescu, 1995; Harzhauser & Piller, 2004).

- The *Varidentella reussi* biozone (Sarmatian / Volhynian) – characterized by the proliferation of the *Varidentella* genus (Popescu, 1995).
- The *Elphidium reginum* biozone (Sarmatian / Volhynian) - characterized by a large spreading of the *Elphidium (E. reginum, E. aculeatum)* species, along with the species of

Porosononion and *Nonion*. The common species in the upper part of this biozone are *Glabratella imperatoria, Elphidium koberi* and *Spiroloculina okrajantzi* (Popescu, 1995).

- The *Elphidium hauerinum* biozone (Sarmatian / Volhynian) – (Grill, 1941) was separated based on the high abundance of the index species. The absence of stenohaline taxa and the occurence of some new species - ex. *Elphidium alvarezianum serrulatum* (Cushman, 1930) are among other particularities of the biozone.
- The *Dogielina sarmatica* biozone (Sarmatian / Bessarabian) – has the lower limit traced at the occurence of the *Dogielina* genus, together with other milioliids species (*Sinzowella, Affinetrina* etc. – Popescu, 1995).
- The *Porosonion granosum* biozone (Sarmatian / Bessarabian) – (Grill, 1941) was separated based on the high frequency of the index taxon, after the total disappearance of the nubeculariids (The *Dogielina sarmatica* biozone).
- The *Cribroelphidium* biozone – characteristic to the upper part of the stratigraphical succession, marked by the abundant apparition of the *Cribroelphidium excavatum* species and a reduced diversity of the assemblages. This biozone is difficult to be correlated to other regional biozones.

7.6. The importance of the Vârciorog section

The investigated section preserved brackish micropalaeontological assemblages which have evolved in fluctuant conditions due to the continental and transitional environment proximity, which migrated under the influence of marine level oscillation.

The Vişinilor stream section offers the possibility of a good correlation between the micropalaeontological assemblages and the depositional environments.

The different methods of analysis used in the study evidenced the potential of the correlation criteria based on lithology (similar lithology levels), biostratigraphy (the presence of the biozones), sequential stratigraphy (flooded surfaces and regressions), events with correlation potential (the deposition of volcanic tuffs) and statistical methods. The correlation of the investigated outcrops can be seen in Chapter 6 – Fig. 6.4.

The section from Vârciorog is a representative interval for the Sarmatian age from the Borod Basin, which contains the majority of the biozones described up to present in Romania and the Central Paratethys. The characteristic biozone of the Lower Sarmatian age was the only one not identified in the studied section.

All the involved analysis methods, interpretations and the results have allowed clarifying the spatial and temporal distribution of the assemblages, which led to the reconstruction of a part in the evolution history of the Borod Basin and the eastern extremity of the Pannonic Basin.

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