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# Badenian red algae and carbonate facies from Gârbova de Sus Formation (Transylvanian Basin)

## PHD THESIS RESUME

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# Introduction

The main purpose of this study is to bring new contributions to the knowledge of red algal assemblages from the Badenian calcareous deposits situated on the western border of the Transylvanian Basin, by creating an inventory of red algae species.

The red algae represent a dominant biogenic component of the Gârbova de Sus Formation. However, the taxonomic studies of Rhodophyta species from these deposits have been scarce. Following the identification of red algae species, made by using modern methods, it has been proposed their utilization in paleoenvironmental interpretations. After identifying and describing the microfacies types from the studied deposits, it has been proposed the interpretation of the depositional environment and the comparison with other Badenian deposits from the Central Paratethys.

The thesis is organized into seven chapters and the results of this study are presented in chapters 4-6. Chapter 4 includes the description of main microfacies types and microfossil assemblages from five localities (Moldovenești-Pietroasa, Pietroasa, Podeni, Lopadea Veche, Gârbova de Sus). Starting with a discussion about the diagnostic characters used in the identification process and a short history of the latest changes made to the red algae systematics, the systematic description of the red algae species is included in chapter 5. The stratigraphic distribution of these species is discussed in chapter 6, along with their palaeogeography, ecology and palaeoecology. Moreover, the depositional model is presented in the same chapter, after presenting the main facies types which were also described and compared to others from the Badenian deposits of the Central Paratethys.

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## 1. Previous research

The first geological studies on the deposits outcropping on the western border of the Transylvanian Basin were initiated during the second half of the 18th century. Beudant (1822) provided a brief geological description of this area and afterwards, Hauer & Stache (1863) described the geological succession of the Trascău Massif and the deposits outcropping around the massif.

Popescu (1970) defined the lower Badenian Dej Formation (“Tuful de Dej” Complex) and separated the Ciceu-Giurgești Member, represented by conglomerates, limestones, and marls. The limestones have been separated by Mészáros (1991) as the Podeni Limestones, after the Podeni village from Cluj county.

Later, Filipescu & Gîrbacea (1994) described Gârbova de Sus Formation, synchronous with the upper part of the Dej Formation and represented by the lower Badenian deposits outcropping on the western border of the Transylvanian Basin.

Bucur & Filipescu (1994) provide for the first time a detailed description of the Badenian red algae assemblages from the western part of the Transylvanian Basin. Previously, „*Lithothamnium ramosissimum*” was considered the most common red algae species from these deposits, known as “Lithothamniumkalke” type (Pávay-Vajna, 1910; Șuraru, 1992). While describing the “Dej Beds”, Popescu (1973) also reports the presence of *Lithophyllum* with nodular forms in the upper part of the succession.

Zágoršek et al. (2010) study in detail the Badenian deposits of the Gârbova de Sus Formation, outcropping in the Gârbova de Sus area. While the study is focused on the bryozoan assemblages and revision of the ones described previously by Ghiurcă (1964, 1972, 1974), the analysis of calcareous nannoplankton and foraminifera assemblages have been used in a palaeoenvironmental reconstruction.

Bucur et al. (2011) describe the carbonate deposits from the Podeni area and report for the first time the presence of green algae in the upper part of the Gârbova de Sus Formation.

In a relatively recent study regarding the rhodolith deposits from Lopadea Veche (Bucur & Filipescu, 2011), the red algae remain described at genus level. However, Chelaru & Bucur (2016) describe later 17 species from the Gârbova de Sus Formation (Lopadea Veche sedimentary succession).

# 2. Geological setting

The Transylvanian Basin corresponds to an intra-Carpathian sedimentary area that started its evolution during the upper Cretaceous. Its development took place especially during the upper Miocene and continued until the Pliocene (Krézsek & Filipescu, 2005). Moreover, the Transylvanian Basin represents a part of the Central Paratethys, alongside other intra-Carpathian basins: Vienna Basin, Pannonian Basin, Slovak Basin, Croatian Basin (Rögl et al., 1978; Popescu, 1987; Popov et al., 2004; Krézsek & Filipescu, 2005).

## *2.1 The Transylvanian Basin basement*

The basement of the Transylvanian Basin is formed by a stack of thrust sheets belonging to the Tisza, Dacia and Transilvanides domains (Schmid et al., 2008), assembled during the meso-Cretaceous tectonogenesis (Csontos & Vörös, 2004). The nappes are represented by Paleozoic crystalline units, Mesozoic ophiolites, island-arc volcanics and Triassic-Lower Cretaceous sedimentary deposits (Krézsek & Bally, 2006).

The evolution of the "Meliata-Maliac-Vardar Ocean" (Schimd et al., 2008) and its passive margins (Tisza and Dacia) had a direct influence on the adjustment of these units (Krézsek & Bally, 2006). The subduction of the oceanic domain started at the end of the Lower Cretaceous (meso-Cretaceous/Austrian tectonic events), subsequently causing the collision between its former passive margins (Tisza and Dacia units) (Krézsek & Bally, 2006; Schmid et al., 2008). The remains of this oceanic domain are represented by a Mesozoic ophiolitic belt obducted over the Tisza-Dacia units ("Transylvanian suture") and the sedimentary deposits of the Transylvanian nappes (Krézsek & Bally, 2006; Schmid et al., 2008). The Transylvanian Basin represents a post-Cenomanian, intra-Carpathian basin that formed on a thick basement represented by meso-Cretaceous geological units (Krézsek & Bally, 2006; Schmid et al., 2008).

## *2.2 The Transylvanian Basin sedimentary successions*

A series of tectonic events influenced the sedimentary evolution of the Transylvanian Basin and controlled and shaped the petrofacies architecture of its deposits.

The presence of major regional discontinuities in the stratigraphic succession of the basin has allowed the identification of four tectonostratigraphic megasequences during the Upper Cretaceous-Neogene period (Krézsek & Bally, 2006; Filipescu, 2011): (1) Upper Cretaceous megasequence (extensional collapse); (2) Paleogene megasequence (deformation and subsidence); (3) Lower Miocene flexural megasequence; (4) Middle-Upper Miocene, back-arc type megasequence.

### 2.2.1 Upper Cretaceous

The Upper Cretaceous (Santonian-Maastrichtian) deposits are represented by deep-marine pelagic deposits (marls), shallow water sediments (bioclastic limestones) and continental deposits that form a transgressive-regressive cycle (Proust & Hosu, 1996; Krézsek & Bally, 2006).

### 2.2.2 Paleogene

The Paleogene sedimentary deposits are placed over the Upper Cretaceous deposits and are characterized by a cyclic sedimentation that reflects sea-level fluctuations (Proust & Hosu, 1996; Krézsek & Bally, 2006). In the north-western part of the Transylvanian Basin, the Paleogene sedimentary succession has a stratigraphic thickness that exceeds 500 m (Filipescu, 2011).

### 2.2.3 Neogene

The palaeoenvironmental changes that took place during the Miocene in the Central Paratethys were also reflected in the Transylvanian Basin that shows a transition from brackish to lacustrine marine environment. The initiation of the Neogene calc-alkaline volcanism has also influenced the marine environment through the deposition of tuffs in the Transylvanian Basin and other neighboring intra-Carpathian basins (Szakács et al., 2012; Lexa at al. 2010).

The age of the upper Oligocene and lower Miocene deposits is difficult to estimate due to the presence of non-marine deposits and gaps in the sedimentary successions (Filipescu 2011). The lower Miocene deposits are outcropping mostly in the northern part of the Transylvanian Basin and are represented by turbidites and fan-delta sediments (Hida Formation) (Beldean et al., 2012). In the western, marginal area of the basin, the lower Miocene deposits represented by sandstones are characterizing a littoral facies (Coruș

Formation) and the ones represented by marls are suggesting an outer shelf environment (Chechiș Formation) (Krézsek & Bally, 2006).

The Miocene sedimentary succession is mainly represented by marine siliciclastic deposits (Krézsek & Bally, 2006; Filipescu et al., 2011). During the Middle Miocene, the global eustatic level decreased, and the Transylvanian Basin was isolated (Krézsek & Filipescu, 2005). Salt deposits were formed in the basin and were deposited during the well-known event "*Badenian Salt Crisis*" (Kováč et al, 2018). The Upper Badenian (Kossovian) is represented by deep water siliciclastic deposits (Kováč et al., 2007).

The Sarmatian deposits are represented by deltaic sediments representing a brackish to hypersaline environment (Krézsek & Filipescu, 2005). The Pannonian is characterized by a decrease in water salinity, causing the progressive transformation in an oligohaline lacustrine environment, favorable to some ostracods and agglutinated foraminifera (Filipescu, 1996).

### *2.3 The Badenian from the western border of the Transylvanian Basin*

During the Badenian (Langhian-Early Serravallian), the sedimentation on the western border of the Transylvanian Basin started with the deposition of the Gârbova de Sus Formation. The deposits of this formation are transgressively overlying the Mesozoic structures of the Trascău Mountains (Eastern Apuseni Mountains). The Mesozoic basement is represented by ophiolites, island-arc volcanics and sedimentary deposits of the Bedeleu Nappe (Štramberk-type limestones) or Râmeți Formation (Filipescu, 1996). The sedimentary deposits of the Paleogene and Early Miocene have been eroded in this area; therefore, they are absent on the western border of the Transylvanian Basin.

Sabkha-type gypsum deposits of the Cheia Formation (Wielician) are locally overlying the Gârbova de Sus Formation. However, above the formation is more often identified an unconformity that separates the deposits of Gârbova de Sus Formation from the Lopadea Formation, represented by shales and Pannonian sands. Between Pietroasa and Podeni villages and around Gârbova de Sus village, the sedimentary succession continues with the deposits of Pietroasa Formation (Late Badenian). These are finally overlain by the Sarmatian deposits of Măhăceni Formation represented by sandstones, sands, and volcanic tuffs (Filipescu, 1996).

### 2.3.1 Gârbova de Sus Formation

Gârbova de Sus Formation has a thickness of about 30-40m and it is expanding between Arieșului and Ampoiului valleys, bordering the western part of the Transylvanian Basin and the eastern part of the Trascău Mountains (Filipescu, 1996). The age of the formation was initially considered Early Badenian and it has been extended to the Middle Badenian upon the identification of Wielician foraminifera (Filipescu, 2001).

Gârbova de Sus Formation can be correlated with the upper part of the Dej Formation (Popescu, 1970), with the foraminiferal Zone M6 and the nannoplankton Zone NN5 (Filipescu, 1996). The foraminifera assemblage coincides with the "Upper Lagenid Zone" of the Central Paratethys and with the "*Orbulina suturalis* Zone" of planktonic foraminifera (Filipescu, 1996).

The formation is represented by algal bioclastic limestones formed in a shallow water environment and carbonate sands and sandstones. The upper part of the formation is characterized by the presence of algal limestones and the abundance of elphiids, "cibicids" and large benthic foraminifera (*Amphistegina*), suggesting a shallow water environment (20-50 m depth) (Filipescu & Gîrbacea, 1997). From the sedimentary successions outcropping in Moldovenești, Lopadea Veche and Gârbova de Sus, Bucur & Filipescu (1994) identified 13 species of red algae, therefore, creating the first inventory of red algae from these deposits.

Based on the identified red algal and foraminifera assemblages, Bucur & Filipescu (1994) conclude that the algal facies with rhodoliths formed in a shallow water environment, at depths of 30-50 m. Later, Bucur & Filipescu (2011) re-evaluate the environmental conditions from the rhodolith facies and conclude that was formed at depths of 50-80m and the algal-bryozoan facies formed at 30 m depth.

# 3. Methods and materials

## *3.1 Field stage*

In the field stage, the sampling was performed at 10-30 cm intervals, but only when the features of the sedimentary successions or the access has permitted. In general, the sampling was attempted at intervals as small as possible. A total of 360 samples were taken from the sedimentary successions outcropping in the Moldovenești-Pietroasa, Pietroasa, Podeni, Lopadea Veche and Gârbova de Sus (Pârâul Pietrii).The samples are represented by marly limestones, calcareous marls and bioclastic limestones (including large centimetric rhodoliths).

## *3.2 Laboratory stage*

The samples obtained in the field work/stage have been prepared for further analysis in the laboratory stage. The following steps were performed when preparing the micropaleontological material: cutting, polishing, gluing, cutting-out, roughing, and final polish. A total of about 500 thin sections of various dimensions have been prepared. The abbreviations used for marking the thin sections are the following: Pi (Moldovenești-Pietroasa), PT (Pietroasa), LV (Lopadea Veche, with LVC, LVB and LVC for rhodolith samples from the upper part of the succession), P (Podeni), Gârbova de Sus (G).

The microfacies and micropaleontological analysis were afterwards performed using a microscope. The microphotographs used for creating the figures/plates were made with a digital camera mounted on a polarized light microscope.

The rhodoliths were measured (short, intermediate, and long axes) before being cutting and polishing them. After cutting and polishing their surfaces, they were scanned. Ternary diagrams (Sneed & Folk, 1958 model) and the TRI-PLOT calculus paper (Microsoft Excel) created by de Graham & Midgley (2000) were used for determining the rhodolith sphericity and shapes. For every rhodolith, the dimension, form, structure, growth stages, type of nucleus (when present), red algal assemblage and thallus growth-type were described. Rhodolith classification and description (form and structure, including the density grades of branching rhodoliths) followed the model proposed by Bosence (1983a).

## *3.3 Thin section analysis*

### 3.3.1. Microfacies analysis

The microfacies analysis has been performed on thin sections and polished slabs with the purpose of determining the main microfacies types, facies types and determine the depositional environment of the studies deposits. In this study, Dunham's (1962) classification of carbonate rocks has been used, along with the additional description of Embry & Klovan (1972).

### 3.3.2. Micropalaeontological analysis

The identification at genus and species level of non-geniculate red algae was performed by following the identification guide presented by Harvey & Woelkerling (2007) and by checking their systematic position after Guiry & Guiry (2020). The thallus type of the specimens was identified following Woelkerling et al. (1993). The biometric measurements made on each specimen was performed by using the ImageJ software (Abràmof et al., 2004) and according to Basso et al. (1996) and Rasser & Piller (1999).

All the measurements presented in the Systematic Paleontology chapter (including tables) below mostly to one specimen that presents all the characteristic features or to multiple specimens of the same species. The abundance of red algae was calculated by counting the number of thin sections in which each species is present. Moreover, the presence of the identified species was marked in tables (Appendix), reflecting the section and the corresponding microfacies type.

# 4. Profile description

## *4.1 Moldovenești-Pietroasa Section*

The studied sedimentary succession situated between Moldovenești and Pietroasa (Cluj County) is approximately 11m thick and is represented in the lower part by bioclastic limestones with ichnofossils and in the upper part is represented by coarse bioclastic limestone in which coralline red algae and bryozoans are dominating.

## *4.2 Pietroasa Section*

The studied deposits from the Pietroasa section are outcropping at the entry in the Pietroasa Village (Cluj County, Moldovenești Township). This sedimentary succession is approximately 26 m thick and is mainly represented by bioclastic limestones dominated by coralline red algae. Moreover, the occasional abundance of serpulid tubes and large benthic foraminifera (*Amphistegina* and *Planostegina*) is also observed.

The lower part of the succession is represented by a level about 1.7 m thick of clays/marls covered by a level of bioclastic limestones, about 4.7 m thick, dominated by small rhodoliths and clasts of various dimensions. The upper part of the succession is represented mostly by coarse bioclastic limestones. Five distinct levels of limestones are observed in the succession, each with a thickness that varies between 80 cm and 6m and separated by erosional surfaces. Each level starts with fine bioclastic limestones, about 70 cm thick, or sands/gravels dominated by dark clasts and rich in large benthic foraminifera.

## *4.3 Podeni Section*

The sedimentary succession studied from Podeni can be tracked in the Podeni Quarry (Podeni Village, Moldovenești Township, Cluj County) and the deposits outcropping on the hill behind it (western direction). The lower part of the succession is represented by the bioclastic limestones, about 10 m thick, in which small rhodoliths (diameter up to 2 cm) can be observed. Above this level, it was identified a level of limestones rich in bivalves, about 50 cm thick. Forward in the succession, the median part is represented by a rhodolithic level (in the upper part of the quarry) represented by large (up to 19 cm in diameter) rhodoliths dispersed in a fine marly matrix. The upper part of the succession is represented by limestone levels, up to 1 m thick, outcropping on the hill next to the quarry in the form of small bioherms.

### *4.4 Lopadea Veche Section*

The sedimentary succession from Lopadea Veche is situated on the Buhii Valley, at the western exit from Lopadea Veche Village (Alba Iulia County, Mirăslău Township). The lower and median part of the succession have a thickness of about 27 m and are represented by bioclastic limestones rich in coralline algae and with marly-sandy intercalations. The profile starts with a level of marly limestones in which only fragments and small coralline thalli can be observed. About 100 m south of the sampled deposits, this level is overlying the Mesozoic basement of Apuseni Mountains (ophiolites) and is represented by bioclastic limestones rich in bivalves and centimetric rhodoliths that formed around large clasts from this basement. In the median part of the succession, the red algae are represented by free and branched thalli, encrusting forms or centimetric rhodoliths. The rhodoliths in the median part of this profile are formed around bryozoan colonies or are lacking a nucleus. Centimetric bryoids are also observed occasionally in some levels. The upper part of the succession is represented by a distinct level about 3 m thick, formed by centimetric rhodoliths dispersed in a marly matrix. The rhodoliths in this level are forming a densely packed rhodolith bed.

### *4.5 Gârbova de Sus*

The sedimentary succession from Gârbova de Sus (Aiud Municipality, Alba County) can be observed on the Pietrii’s Creek Valley. The outcrop is found at the exit from the village, in the north-western direction.

The lower and median part of the succession is represented by layers of sands and sandstones and gravels. The microfacies analysis was performed on the limestones from the upper part of the successions. The limestones are rich in coralline algae and are intercalated in a sandy matrix in which coralline fragments can also be observed. The uppermost part of the successions is represented by a 30 cm thick level of massive bioclastic limestones.

# 5. Red Algae – Systematic Paleontology

## *5.1 Red algae – diagnostic features and remarks*

Fossilized coralline algae present a series of morphological features which have been used by biologists for identifying modern species (Rösler et al., 2015; Chelaru & Bucur, 2016; Coletti et al., 2020). Although many of these features can be tracked in fossil material, it is important to highlight the fact that the content of the reproductive structures cannot be accurately determined. Therefore, different phase of the sexual life cycle of coralline algae and more difficult to identify in fossil material. Thereby, for the most part, the studies carried through the 20th century excluded the possibility of identifying fossil coralline plants in gametangial or carposporangial reproductive phases, with a few exceptions (Conti, 1943; Mastrorilli, 1968, Basso et al., 1996).

Coralline red algae (Ord. Corallinales, Hapalidiales, Sporolithales) present the following reproductive structures: uniporate conceptacles, multiporate conceptacles and bi/tetrasporangial compartments. These reproductive structures are usually containing tetraspores (in tetrasporangial conceptacles or in tetrasporangial compartments), representing sporangial plants in an asexuate reproductive phase. Carposporangial plants, and also gametangial plants that represent the sexuate reproductive phase, contain only uniporate conceptacles. These contain carpospores (carposporophyte stage = fertilized female plant) and spermatangia or carpogonia (male or female gametophytes in a sexual life cycle stage). Thus, the uniporate conceptacle are present in both the tetrasporophytic plants (asexual phase) of order Corallinales and in all other corallines from the Rhodophyta phylum that are found in carposporangial or gametangial reproductive phases.

Failing to determine the reproductive phase of the studied coralline algae leads to the misidentification of carposporangial or gametangial plants, most commonly being identified as tetrasporangial plants of the order Corallinales. Starting with the 21st century, many of the taxonomic studies of corallines focused on the revision of collections formed in the previous century.

In this study, I focused on using modern identification criteria that are used also on modern plants, and on recognizing different reproductive phases in which the studied red algae are found.

The carposporangial and gametangial plants were generally identified in the same thin section with the tetrasporangial plants. Both the growth type and the vegetative anatomy of coralline algae are similar in all the reproductive stages of the species. Therefore, all the specimens with uniporate conceptacles and similar biometric measurements, found in the same thin section, were studied with the aim of identifying their asexuate or sexuate reproductive phase. Twelve out of 39 species were identified in gametangial/carposporangial phase. Their identification was easily made in the following cases: the vegetative features of the gametangial plant were already documented for the species (*Sporolithon praeerythraeum*, *Sporolithon ptychoides*, *Lithophyllum racemus*, *Neogoniolithon* cf. *propinqum*, *Mesophyllum alternans*, *Mesophyllum crassiusculum*); the bi/tetrasporangial plant is in fusion with the carposporangial/gametangial plant (*Spongites fruticulosus*, *Lithothamnion* sp. 2, *L.* sp. 3, *L.* sp. 6) or it is encrusting it (*Sporolithon irinae*). The gametangial plant of *Sporolithon* sp. 1 is encrusting *Lithothamnion* sp. 1, but it was found in the same thin section with the plant in the asexuate phase.

### 5.1.1 The identification of geniculate red algae (articulated)

Geniculate coralline algae can belong to either Corallinoideae subfamily (*Jania*, *Corallina*, *Arthrocardia*), if cell fusions are present, or Lithophylloideae subfamily (*Amphiroa*), if secondary-pit connections are present. The geniculate specimens with cell fusions can be associate with the *Arthocardia* genus if more than 20 tiers of cells can be observed in the ventral filaments of the intergenicula (Guiry & Guiry, 2020). The intergenicula of *Jania* and *Corallina* are formed by 20 or less tiers of cells (Guiry & Guiry, 2020), but in the identification process it must be taken into consideration that the fossilized material is generally represented by incomplete intergenicula fragments. The revised description of (Kim et al., 2020) mentions the presence of 90-130 µm long medullar cells. However, *Jania*, the only genus from the tribe Janieae Johansen & Silva, 1978 (Kim et al., 2020), can be separated from the species of tribe Corallineae Areschoug, 1852 based only on the basis of differences in the reproductive cells (feature that cannot be studied in fossil material) and the conceptacle structures. Therefore, *Jania* and *Corallina* cannot be separated based on different morphological features, in the absence of conceptacles and they are generally rare in fossilized material.

The intergenicula fragments identified in the studied sedimentary successions from Gârbova de Sus Formation present secondary-pit connections between the ventral cells and they were all associated with *Amphiroa* sp. 1.

### 5.1.2 The identification of non-geniculate red algae

In the order Sporolithales, the identification of *Sporolithon* species was made by using the following morphological features: the presence/absence of a layer of elongated cells under the sporangial compartments, cell and sporangial compartments measurements and the number of cells in the paraphyses (Bahia et al., 2011; Henriques et al., 2014). However, even why trying to identify modern species, applying these diagnostic features is debateble.

Leão & Bahia described *Sporolithon franciscanum* Leão et al. (2020) a new species identified in modern rhodoliths from Brazil, based on molecular studies. This species can be identified only by confirming a specific DNA sequence, but from a morphological point of view, it is similar to other five modern *Sporolithon* species. This study emphasizes the fact that the diversity of this genus is actually much greater in modern marine environments.

Taking into consideration the morphological features presented, six *Sporolithon* species have been identified in the studied sedimentary successions from Gârbova de Sus Formation. *Sporolithon praeerythraeum* and *Sporolithon ptychoides* present a layer of elongated cells below the sporangial compartments and they were separated by taking into consideration the dimensions of the compartments. The other four species were separated according to the different biometric measurements of cells and sporangial compartments and also by taking into consideration different number of cells that form the paraphyses.

In the order Corallinales, the species bear uniporate conceptacles and are separated in families and subfamilies (Hydrolithoideae, Lithophylloideae, Mastophoroideae, Neogoniolithoideae) according to characteristic morphological features (dimerous/monomerous thalli, the presence/absence of palisade cells, coaxial/non-coaxial ventral cells, presence/absence of cell fusions or secondary-pit connections, pore canals lined by cells parallel/perpendicular to the conceptacle roof) and the species were separated and identified based on the thallus growth-type and different biometric measurements. All the species of this order were also evaluated with the aim to avoid misidentifications, in case of presence of carposporangial/gametangial specimens of the orders Sporolithales or Hapalidiales. Not only carposporangial and gametangial thalli of *Sporolithon* but also tetrasporangial thalli of *Lithophyllum* present uniporate conceptacles, non-coaxial ventral filaments, and secondary-pit connections. Both genera were identified together only in one thin section (G2, Gârbova de Sus profile). However, their biometric measurements are not similar (*L. racemus* and *S. lvovicum*), therefore, excluding the possibility of the identification of gametangial thalli of *Sporolithon*. Furthermore, the carposporangial or gametangial thalli of *Mesophyllum* can be erroneously identified as tetrasporangial thalli of *Neogoniolithon*, the thalli presenting in both cases a coaxial ventral core and cell fusions. It is not excluded that further research may reveal that both identified species of *Neogoniolithon* (*N.* sp. 1 and *N.* cf. *propinqum*) are actually carposporangial or gametangial thalli of *Mesophyllum*. However, these two species present all the characteristic features of *Neogoniolithon* tetrasporangial thalli and no similarities were found with any other *Mesophyllum* species from the coralline assemblage (or thin section). Moreover, one of the species is similar to the gametangial plant of *Neogoniolithon propinqum* described from modern environments (*N.* cf. *propinqum*) and the other one is similar to *Lithophyllum bassanense*, an extinct species that requires a revision. Likewise, the species identified in this study and associated with the subfamily Mastophoroideae (*Karpathia* and *Lithoporella*) also require revisions.

In the order Hapalidiales, *Mesophyllum* presents a coaxial ventral core and rounted or flattened epithallial cells (not flared), and *Lithothamnion* and *Phymatolithon* present non-coaaxial ventral filaments. Unlike *Phymatolithon*, *Lithothamnion* present flattened and flared epithallial cells and the subepithallial cells are as long or longer than the ones below them (Guiry & Guiry, 2020). These morphological features were successfully used in separating these 3 genera both in modern Maneveldt et al., 2016), and fossil plants (Aguirre et al., 2012; Hrabovský et al. 2015; Chelaru & Bucur, 2016). However, a large part of the collections formed in the 20th century require revisions. After the revision of *Lithothamnion, Phymatolithon* and *Mesophyllum* species from Maslov's collections (Braga et al., 2015), it has been concluded that only one out of eleven type species present morphological features representative for the genus, and all the other could not be accurately associated with any of these three genera.

*Lithothamnion* sp. 5, one of the most abundant species identified in the studied deposits of Gârbova de Sus Formation, is similar to ?*L. praefruticulosum* Maslov, a species revised by Braga et al. (2015). The holotype of ?*L. praefruticulosum* does not present epithallial cells (Braga et al., 2015), therefore it could not be associated with any of the three genera of the order Hapalidiales. Before the revision of this species, it has been identified in the Oligocene-Upper Miocene deposits from Italy (Fravega et al., 1993), Middle Miocene from Polonia (Pisera & Studencki, 1989) and Romania (Bucur & Filipescu, 1994), Upper Miocene from Malta (Bosence, 1983b) and Pleistocene from India (Kishore et al., 2012). However, *Lithothamnion* sp. 5 presents flared epithallial cells, characteristic to the genus, and its association with ?*L. praefruticulosum* remains uncertain, thus, obstructing possible paleoecological or paleogeographical interpretations.

The red algal species identified in this study were most efficiently compared with the species described completely and in detail, from modern or fossil material. Out of the identified gametangial thalli, *Lithothamnion* sp. 3 is distinguished by its similarity (cells and conceptacles) to *Lithophyllum heteromorphum* Mastrorilli. However, the revision of the type material of *L. heteromorphum* is necessary for determining the presence/absence of cell fusions and other morphological features and afterwards, the possibility of transferring the species to the *Lithothamnion* genus could be taking into consideration.

## ***5.2. Systematic description of red algae***

Order **Sporolithales** Le Gall, Payri, Bittner & Saunders, 2009
Family **Sporolithaceae** Verheij, 1993
Subfamily **Sporolithoideae** Setchell, 1943
Genus ***Sporolithon*** Heydrich, 1897
**Type species.** *Sporolithon ptychoides* Heydrich, 1897, Actual, Sinai Peninsula, Egypt.

***Sporolithon irinae*** (Maslov, 1956) Bassi et al., 2007
***Sporolithon lvovicum*** (Maslov, 1956) Bassi et al., 2007
***Sporolithon praeerythraeum*** (Airoldi, 1932) Vannucci et al., 2000
***Sporolithon ptychoides*** Heydrich, 1897
***Sporolithon* sp. 1**
***Sporolithon* sp. 2**

Order **Corallinales** Silva & Johansen, 1986
Family **Hydrolithaceae** Towndsend & Huisman, 2018
Subfamily **Hydrolithoideae** Kato & Baba in Kato et al. 2011
Genus ***Hydrolithon*** (Foslie) Foslie, 1909
**Type species**. *Hydrolithon reinboldii* (Weber-van Bosse & Foslie) Foslie, 1909, Actual, Muras Reef, East Kalimantan, Indonesia.

***Hydrolithon corculumis*** (Maslov, 1962) Braga, Bassi, Zakrevskaya & Petrovna-Radionova, 2005
***Hydrolithon lemoinei*** (Miranda, 1935) Aguirre, Braga & Bassi, 2011
***Hydrolithon* sp. 1**

Family **Lithophyllaceae** Athanasiadis, 2016

Subfamily **Lithophylloideae** Setchell, 1943

Tribe **Amphiroeae** Cabioch, 1972

Genus **Amphiroa** Lamouroux, 1812

**Type species**. *Amphiroa Tribeulus* (Ellis & Solander) Lamouroux, 1816, Actual, Indiile de Vest, North Atlantic Ocean, Leeward Islands.

***Amphiroa*** sp. 1

Tribe **Lithophylleae** Zanardini, 1844

Genus ***Lithophyllum*** Philippi, 1837

**Type species** *Lithophyllum incrustans* Philippi, 1837, Actual, Sicily, Mediterranean Sea, Italy.

***Lithophyllum racemus*** (Lamarck) Foslie, 1901

***Lithophyllum* sp. 1**

***Lithophyllum* sp. 2**

Family **Mastophoraceae** (Setchell) Townsend & Huisman, 2018

Subfamily **Mastophoroideae** Setchell, 1943

Genus ***Karpathia*** Maslov, 1962

**Type species** *Karpathia sphaerocellulosa* Maslov, 1962, Paleocen, Starîi Sambir, Ukraine.

***Karpathia sphaerocellulosa*** Maslov, 1962

Genus ***Lithoporella*** (Foslie, 1902) Foslie, 1909

**Type species**. *Lithophorella melobesioides* (Foslie, 1903) Foslie 1909, Actual, South Nilandu Island, Maldive Islands.

***Lithoporella melobesioides*** (Foslie) Foslie, 1909

***Lithoporella* sp. 1**

Family **Spongitaceae** Kützing, 1843

Subfamily **Neogoniolithoideae** (Kato & Baba, in Kato et al., 2011) emended Rösler, Perfectti, Peña & Braga, in Rösler et al., 2016

Genus **Neogoniolithon** Setchell & Manson, 1943

**Type species**. *Neogoniolithon fosliei* (Heydrich) Setchell and Manson 1943, Actual, El Tor, Sinai Peninsula, Egypt.

***Neogoniolithon* cf. *propinqum*** (Foslie) Lemoine, 1966

***Neogoniolithon* sp. 1**

Genus ***Spongites*** Kützing, 1841

**Type species**. *Spongites fruticulosus* Kützing 1841, Actual, Mediterranean Sea.

***Spongites fruticulosus*** Kützing, 1841

***Spongites* sp. 1**

***Spongites* sp. 2**

Ordin **Hapalidiales** Nelson, Sutherland, Farr & Yoon, in Nelson et al., 2015

Family **Lithothamniaceae** Haas, 1886

Tribe **Phymatolitheae** Adey & Johansen, 1972

Genus ***Phymatolithon*** Foslie, 1898

**Type species.** *Phymatolithon calcareum* (Pallas, 1766) Adey & McKibbin, 1970, Actual, Falmouth Harbour, England.

***Phymatolithon calcareum*** (Pallas) Adey & McKibbin ex Woelkerling & Irvine, 1986

Tribe **Lithothamnieae** Foslie, 1908

Genus ***Lithothamnion*** Heydrich, 1897

**Type species**. *Lithothamnion muelleri* Lenormand ex Rosanoff, 1866, Actual, Western Port Bay, Victoria.

***Lithothamnion crispatum*** Hauck, 1878

***Lithothamnion ramosissimum*** (Reuss) Piller, 1994

***Lithothamnion roveretoi*** Airoldi, 1932

***Lithothamnion valens*** Foslie, 1909

***Lithothamnion* sp. 1**

***Lithothamnion* sp. 2**

***Lithothamnion* sp. 3**

***Lithothamnion* sp. 4**

***Lithothamnion* sp. 5**

***Lithothamnion* sp. 6**

Family **Mesophyllumaceae** Schneider & Wynne, 2019

Genus ***Mesophyllum*** Lemoine, 1928

**Type species.** *Mesophyllum lichenoides* Lemoine, 1928, Actual, Cornwall, England.

***Mesophyllum alternans*** (Foslie, 1907) Cabioch & Mendoza, 1998

***Mesophyllum crassiusculum*** (Foslie, 1902) Lebednik, 2004

***Mesophyllum curtum*** Lemoine, 1939

***Mesophyllum* cf. *incisum*** (Foslie) Adey, 1970

***Mesophyllum* cf. *obsitum*** Airoldi, 1932

***Mesophyllum* cf. *sancti-dionysii*** Lemoine, 1939

***Mesophyllum* sp. 1**

# 6. Palaeogeography and palaeoecology of red algae

## *6.1 Palaeogeography*

From the 39 identified species, eleven of them are also present in modern marine environments, in the Mediterranean Sea, Adriatic Sea, Red Sea, Atlantic Ocean, Pacific Ocean or Indian Ocean. Six out of eleven species appeared only in the Paratethys or in the Mediterranean during the Paleocene (*K. sphaerocellulosa*), Eocene (*Lithothamnion roveretoi*) and Oligocene (*S. preerythraeum, H. lemoinei*, *Lithophyllum bassanense* – *Neogoniolithon* sp. 1, *M. obsitum*), when these domains were in connection via the "Slovenian corridor" (Popov et al., 2004) and either disappeared after the Wielician Salinity Crisis (Mid Badenian) or survived until present (*Lithoporella melobesioides, Spongites fruticulosus, Phymatolithon calcareum*). *Lithophyllum racemus* appeared during the Early Miocene (Aquitanian) in the Western Paratethys, was abundant during the Middle Miocene (Early Badenian) and survived until the Pliocene in the Mediterranean domain and present Mediterranean Sea. A total of six species appeared during the Badenian of the Central Paratethys (*Sporolithon irinae*, *S. lvovicum*, *H. corculumis*, ?*Lithophyllum perrandoi* – *Spongites* sp. 1, *Lithothamnion rammosissimum, Mesophyllum curtum, M. sancti-dionysii*) and did not survived the Badenian Salinity Crisis. *S. ptychoides* migrated to the Mediterranean domain during the Pliocene and Pleistocene and survived until present and other six species (*N.* cf. *propinqum, Lithothamnion valens*, *L. crispatum, Mesophyllum alternans, M. crassiusculum, M. incisum*). However, fossil specimens were identified only in Badenian deposits.

The coralline red algal assemblages identified in Gârbova de Sus Formation is similar especially to the ones described from Poland, hence, indicating similar marine conditions and a similar depositional model throughout the Badenian, highlighted also by similar facies.

## *6.2 General elements of ecology and palaeoecology*

Coralline red algae are representing one of the most important carbonate sediment producers from the Lower Cretaceous (Tomás et al., 2007; Simone et al., 2012; Pleș et al., 2017), but dominated in a rhodalgal facies especially during the Miocene (Aguirre et al., 2000). In modern environments, coralline red algae are main biogenic components especially in rhodolith/maërl beds (Tâmega et al., 2014), identified from all around the world, from the Equator to the Arctic Circle and from the intertidal zone down to depths of 120 m (Amado-Filho et al., 2012). Their capacity to adapt to various marine conditions (with low luminosity, at great depths or in low temperatures even in the polar regions) contributed to their survival and evolution of this group of algae (Aguirre et al., 2000). Both red algae (modern or fossil) and the rhodoliths formed by them have been successfully used in paleoecological interpretations, offering details about the temperature, water energy, bathymetry or luminosity, hence, being very good indicators of paleoenvironment conditions (Bracchi et al., 2014; Brandano et al., 2016; Colleti et al., 2018).

### *6.3 Facies types and red algae assemblages*

In the scientific literature, the free-living thalli of red algae identified in the sediment have been described by using various terms. The most common terms are „rhodolith” and „maërl”, which are considered synonyms, along other 10 terms found in literature: „boxwork rhodolith”, „coating”, „coralline algal nodules”, „nucleated rhodoliths”, „nodules”, „prâlines”, „oncolith/onkoid”, „rhodoid”, „rubble”, „unattached branches” (Riosmena-Rodríguez, 2017).

Free structures formed mostly by non-geniculate coralline algae that accumulate on extended surfaces are generally described from modern environments as „rhodolith beds” or „maërl beds”. The sedimentary structures dominated by rhodoliths have been described by using different terms: rhodolith beds (Foster, 2001), rhodolith pavements (Bassi et al., 2009; Bassi & Nebelsick, 2010), maërls (Basso et al., 2008), rhodolith banks (Wilson, 2013), algal gravels (Freiwald et al., 1991), biostrome (Bosence, 1983a), rhodolith facies (Hetzinger et al., 2006), rhodolith rudstones/floatstones (Basso et al., 2012; Martinuš et al., 2013).

The non-geniculate red algae identified in the studied sedimentary successions present thalli with different forms found also in modern environments: thalli fragments, encrusting thalli, free-living branches and rhodoliths with or without nucleus, formed by one or multiple red algal species.

According to the microfacies analysis, the lower part of the sedimentary successions from Moldovenești-Pietroasa, Podeni and Lopadea Veche (M-TPM1, P-TPM1, and LV-TPM1) are dominated by red algal debris, characterizing the **coralline algal debris facies** (AMF1; Tab. 1). In the lower part of the sedimentary successions from Moldovenești-Pietroasa (M-TPM2) and Pietroasa (Pt-TPM2), serpulid tubes and large benthic foraminifera are also dominating. This level represents the **facies with serpulid and large benthic foraminifera** (AMF2; Tab. 1).

Forward in the sedimentary successions, a level with small rhodoliths (maximum of 2 mm in diameter) is remarked. The rhodoliths are nucleus free and represented by nodular thalli, protuberances, or branched thalli. These free-living red algal thalli are found in association with bryozoans, which dominated only locally the habitat. This level was identified only in the Moldovenești-Pietroasa (M-TPM3) and Podeni (P-TPM2) profiles and marks the initiation of the **rhodolith facies** (AMF3; Tab. 1). The rhodolith facies dominates the median and the upper parts of the sedimentary successions and is characterized by the dominance of rhodoliths with various forms and dimensions, their diameter varying from 2 mm to 19 cm.

| **Main microfacies assemblages** | **AMF1** | **AMF2** | **AMF3** | | | | **AMF4** |
|---|---|---|---|---|---|---|---|
| | | | **I** | **II** | **III** | **IV** | |
| **Facies type** | **Coralline algal debris facies** | **Facies with serpulid and large benthic foraminifera** | **Rhodolith facies** | | | | **Algal facies** |
| **Main microfacies types** | M-TPM1, P-TPM1, LV-TPM1 | M-TPM2, Pt-TPM2 | M-TPM3, P-TPM2 | M-TPM4, Pt-TPM1, P-TPM3, LV-TPM5, G-TPM2 | LV-TPM2, LV-TPM3, LV-TPM4, G-TPM1 | P-TPM4, LV-TPM6 | Pt-TPM3, P-TPM5 |

**Tab. 1**. Facies types identified in the studied deposits from the Gârbova de Sus Formation and the corresponding main microfacies types.

The rhodolith facies AMF3(I) is represented by rhodoliths without a nucleus, formed by a single coralline species and that have a diameter of maximum 2 mm. The rhodoliths with a diameter of maximum 5 cm, lacking a nucleus and formed mostly by free-living branches, rarely encrusted by other organisms, are representing the rhodolith facies AMF3(II) that is similar to the modern maërl facies. The rhodolith facies AMF3(III) is represented by rhodoliths with a diameter of maximum 10 cm. AMF3(IV) rhodolith facies is represented by the largest rhodoliths, their diameter reaching up to 19 cm, that are generally presenting a nucleus and other organisms also participate in their formation. These rhodoliths are forming densely packed rhodolith beds.

In the uppermost part of the Podeni and Pietroasa successions, the **algal facies** has been identified (AMF4; Tab. 1). This facies is characterized by the presence of halimedacean green algae in association with coralline algae and other organisms.

A total of 39 species belonging to 11 genera have been identified in the coralline algal assemblage from Gârbova de Sus Formation. The red algae are representing the orders Sporolithales (*Sporolithon*), Corallinales (*Hydrolithon*, *Amphiroa*, *Lithophyllum*, *Karpathia*, *Lithoporella*, *Neogoniolithon*, *Spongites*) and Hapalidiales (*Phymatolithon*, *Lithothamnion*, *Mesophyllum*). The most abundant red algae are genera are *Spongites*, *Lithothamnion* and *Mesophyllum*, followed by *Sporolithon*, *Phymatolithon* and *Hydrolithon* (Fig. 1). The least abundant genera are *Amphiroa*, *Lithophyllum*, *Lithoporella*, *Neogoniolithon* and *Karpathia*. *Sporolithon*, *Spongites* and *Lithothamnion* were identified in all the studied successions (Fig. 2). *Hydrolithon* and *Mesophyllum* were not identified in the Moldovenești-Pietroasa succession. *Amphiroa*, *Lithoporella*, *Neogoniolithon* and *Phymatolithon* were identified only in the Pietroasa, Lopadea Veche and Podeni profiles and *Lithophyllum* was identified only in the Pietroasa, Lopadea Veche and Gârbova de Sus successions. *Karpathia* was identified only in the Lopadea Veche profile.

The red algal assemblage is the most abundant and diversified in the Lopadea Veche succession (Fig. 2), 36 species being identified from this profile. The most dominant species in Gârbova de Sus Formation are: *Spongites fruticulosus*, *Mesophyllum alternans*, *Phymatolithon calcareum*, *Lithothamnion valens* and *Lithothamnion* sp. 5 (Fig. 3).

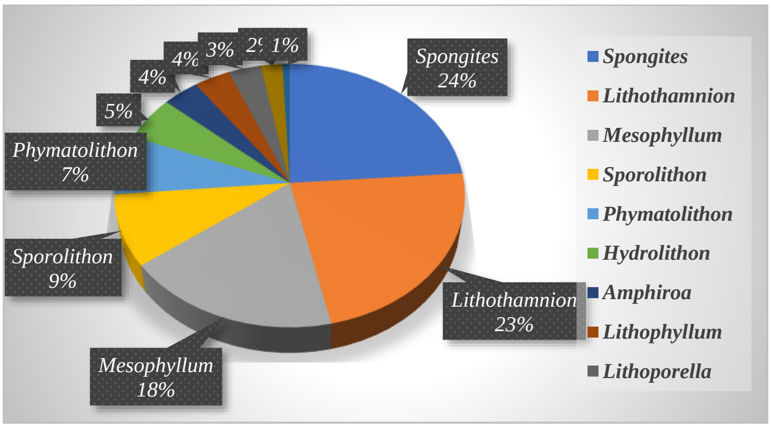

**Fig. 1**. The abundance of red algae (genus level) in the studied sedimentary successions from Gârbova de Sus Formation. *Spongites*, *Lithothamnion* and *Mesophyllum* are the most abundant.

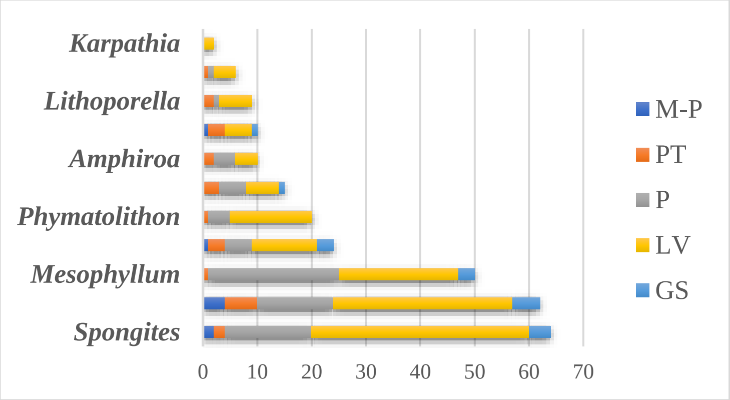

**Fig. 2**. The abundance of red algae (genus level) in the studied sedimentary successions. The most abundant is *Spongites*, identified in 64 thin sections, wherefrom 40 are representing the Lopadea Veche section; M-P, Moldovenești-Pietroasa; PT, Pietroasa; P, Podeni; LV, Lopadea Veche; GS, Gârbova de Sus.

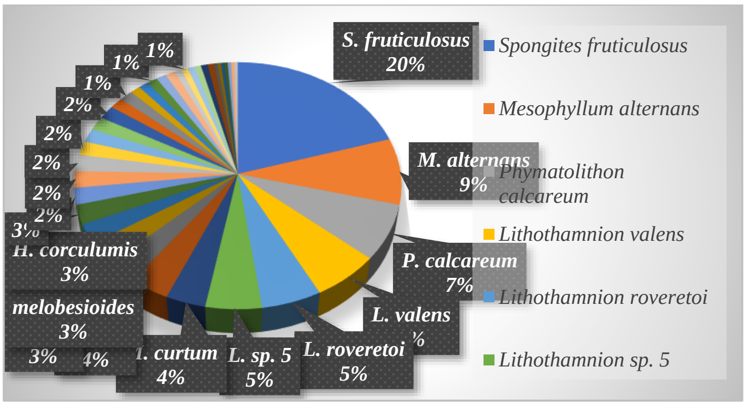

**Fig. 3**. The abundance of red algae (species level) in the studied sedimentary successions. *Spongites fruticulosus*, *Mesophyllum alternans*, *Phymatolithon calcareum* and *Lithothamnion valens* are the most abundant red algae species from the Gârbova de Sus Formation.

### *6.4 Depositional model*

The carbonate facies identified in Gârbova de Sus Formation represent a middle carbonate ramp. The lower part of the middle ramp is represented by the coralline algal debris facies (AMF1), identified in all the studied successions and by the facies with serpulid and large benthic foraminifera (AMF2) identified only in the northern part of the formation (Moldovenești-Pietroasa). These two facies are suggesting a high siliciclastic input in this level, most probably correlated with the beginning of the upper carbonate sequence and the second transgression episode in Gârbova de Sus Formation, described by Filipescu & Gîrbacea (1997).

Rhodolith facies AMF3(I) marks the first phase in the development of the non-geniculate coralline algal dominated bioconstructions. The red algal assemblage from the rhodolith facies AMF3(II) (maërl-type facies) indicates a 50-80m water depth, marking the end of the transgressive episode and suggesting its correlation with the second maximum flood surface described by Filipescu & Gîrbacea (1997). The rhodolith facies AMF3(III), identified in the Lopadea Veche and Gârbova de Sus successions, presents mixed red algal assemblages that suggest 3-40m and 30-60 m water-depths, marking a decrease of the sea-level. This facies also revealed three levels in which the water energy oscillated from low-moderate to high, indicating the position of the facies between normal wave-base and storm wave-base. The rhodolith facies AMF3(IV) (rhodolith pavement or densely packed rhodolith bed) formed most probably in a depression from the upper part of the median ramp at depths of maximum 40 m, under moderate water-energy.

Finally, the algal facies (AMF4) from the upper part of the Pietroasa and Podeni successions is marking the uppermost part of the median ramp, the bioconstructions being formed in a subtropical environment with low to moderate water-energy and a depth of maximum 40 m in the proximity of the inner carbonate ramp.

Based on the morphological features of the red algal thalli, of the red algal species and their abundance in the separated facies, it can be concluded that the carbonate sequence, that represents the upper part of Gârbova de Sus Formation, starts with a transgressive trend that advantaged the formation of levels with millimetric rhodoliths and the ones rich in large benthic foraminifera and serpulid tubes [AMF1, AMF2, AMF3(I), AMF3(II)] and continues with the formation of the large and well developed rhodoliths (AMF3(III), AMF3(IV) and the bioconstructions with vermetid worms and green algae (AMF4), advantaged by a regressive trend.

# 7. Conclusions

The results of this study are providing multiple contributions to the knowledge of the red algae assemblages and the paleoenvironmental conditions during the deposition of the carbonate sequence of Gârbova de Sus Formation from the Transylvanian Basin.

Following the taxonomic study of red algae, in which the most recent diagnostic criteria used for identifying both fossil and modern red specimens, 39 species were identified, representing 11 genera belonging to orders Sporolithales, Corallinales and Hapalidiales. Only six species have been previously reported (Bucur & Filipescu, 1994) from Gârbova de Sus Formation.

*Sporolithon praeerythraeum, Neogoniolithon* cf. *propinqum* and *Mesophyllum* cf. *incisum* are for the first time reported from the Central Paratethys area. The gametangial thalli of *Sporolithon praeerythraeum* are described for the second time, while their first description was made from the type material. The species was previously described only from Eocene and Oligocene deposits. Therefore, the identification of this species in the studied deposits permitted the extension of its stratigraphic interval to Badenian (Chelaru & Bucur, 2016). *N.* cf. *propinqum* and *M.* cf. *incisum* are for the first time described from fossil material. Moreover, *Sporolithon ptychoides* is the second time reported from the Central Paratethys area, with the first report made from the Badenian deposits from the north-western part of the Transylvanian Basin (Chelaru et al., 2019).

As a result of using modern criteria of identification, fossil red algal thalli in carposporangial and gametangial reproductive phases have been identified and described for the first time from Romania. Twelve species have been identified and described in a carposporangial/gametangial phase. Carposporangial/gametangial thalli of *Sporolithon irinae, Sporolithon ptychoides, Neogoniolithon* cf. *propinqum, Spongites fruticulosus* and *Mesophyllum alternans* are for the first time described from fossil material. Following the identification and description of both male and female gametangial thalli of *Spongites fruticulosus, Lithophyllum platticarpum* has been synonymized with *S. fruticulosus* (Chelaru & Bucur, 2016). Following a revision of the type material of *Neogoniolithon* sp. 1 and *Spongites* sp. 1, these species could be associated with *Lithophyllum bassanense,* respectively *Lithophyllum perrandoi*.

Microfacies and micropaleontological analysis have been performed on five sedimentary successions (Moldovenești-Pietroasa, Pietroasa, Podeni, Lopadea Veche, Gârbova de Sus) from the Gârbova de Sus Formation. Upon their correlation, four facies types have been established: algal debris facies, large benthic foraminifera and serpulid facies, rhodolith facies and algal facies.

From the 39 described species, eleven are also known from modern environments (Mediterranean Sea, Adriatic Sea, Red Sea, Atlantic Ocean, Pacific Ocean, or Indian Ocean). Their ecological features, especially the bathymetric ones, have been successfully used in the interpretation of palaeoenvironmental conditions in the rhodolith and algal facies.

The studied deposits formed during the Badenian on the middle carbonate ramp extended on the western border of the Transylvanian Basin. Following a comparison with Badenian deposits described from the Central Paratethys, it has been concluded that both the red algal assemblages and the facies identified in the studied deposits resemble mostly the ones described from Poland (Studencki 1988a, 1988b; 1999; Pisera & Studencki, 1989; Pisera, 1996).

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