Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	74	9–23	Београд, децембар 2013 Belgrade, December 2013

DOI: 10.2298/GABP1374009R

Middle Miocene Badenian transgression: new evidences from the Vrdnik Coal Basin (Fruška Gora Mt., northern Serbia)

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Abstract. The latest field investigation of the Vrdnik Coal Basin as well as new data from numerous boreholes enabled the finding of an unconformity between the undivided continental-lacustrine Lower Miocene and the marine Middle Miocene Badenian. The different terrestrial-lacustrine sediments indicate a very mobile and dynamic environment (according to known drilling data, the total thickness of these deposits reaches up to 300 m). All these rocks belong to the Vrdnik series (Vrdnik Formation). The evolution of the Vrdnik series is distinguished by several stages (*e.g.* pre-lacustrine, lacustrine, peat-swamp, *etc*.). Each of these phases was proved by their sedimentologic and structural characteristics. On the other hand, among the fossils, only the swamp flora remains (*Sequoia, Laurus, Taxodium, Glyptostrobus, etc*.) and poor and fragmented ostracode valves (*Candona* sp.) were documented. Presently, the exact stratigraphic position of the Vrdnik series is unknown. Discordantly over the mentioned rocks, real marine sediments of the Paratethys Sea occur. To date, it was a completely unknown subsurface distribution of these sediments. Among a few types of rocks that have a small distribution, the so-called the Leitha limestones (Middle Miocene, Badenian) have great significance (up to 98% of $CaCO_3$). The total thickness of the limestones reaches up to 70 meters (borehole B-11). The findings of key foraminifer species (*Orbulina – Globigerinoides* Zone) indicate an early Badenian (Moravian) transgressive event (*ca*. 15 Ma). Lithologically, it is represented by gray, sandy marls and sandy clays, coarse-grained sands and microconglomerates in the base of the mentioned limestones (boreholes B-11, B-15, B-19, and B-21) with a total thickness of up to 15 meters.

Key words: Middle Miocene Badenian, marine transgression, Vrdnik Coal Basin, northern Serbia.

Апстракт. Најновија теренска истраживања Врдничког угљеног басена, као и нови подаци из бројних бушотина, допринели су да се укаже на дискордантан и трансгресиван однос између нерашчлањеног континентално - језерског доњег миоцена и морског средњег миоцена, бадена. Различити копнени и језерски седименти указују на врло мобилну и динамичну палеосредину (према познатим бушотинским подацима, укупна дебљина ових наслага достиже и до 300 m). Све те стене заједно припадају Врдничкој серији (Врдничкој формацији). Настанак и развој Врдничке серије одвијао се кроз неколико фаза (нпр. пре - језерска, језерска, тресетно-мочварна, итд). Свака од ових фаза је доказана на основу одређених седиментолошких и структурних карактеристика. С друге стране, од фосила једино су запажени остаци мочварне вегетације (*Sequoia, Laurus, Taxodium, Glyptostrobus*, итд) и ретки, фрагментирани капци остракода (*Candona* sp.). Због тога, тачно стратиграфско место Врдничке серије није познато. Дискордантно преко поменутих стена наталожени су прави морски седименти Паратетиса. До данас, било је потпуно непознато потповршинско распрострањење ових седимената. Међу неколико типова стена које имају мало распрострањење, тзв. лајтовачки кречњаци (средњи миоцен, баден) имају велики значај (имају до 98 % $CaCO_3$). Укупна дебљина кречњака достиже и до 70 метара (бушотина Б-11). Налазак руководећих фораминиферских врста *Orbulina – Globigerinoides* зоне, указује на старије баденски (моравиан) трансгресивни догађај (преко око 15 милиона година). Литолошки, ова зона је представљена сивим, песковитим лапорцима, песковитим глинама, грубозрним песковима и микроконгломератима који се налазе у бази поменутих кречњакаа (бушотине Б-11, Б-15, Б-19 и Б-21) и њена укупна дебљина достиже и до 15 метара.

Кључне речи: Средњи миоцен, баден, морска трансгресија, Врднички угљени басен, северна Србија.

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Introduction

During the Upper Oligocene and early Lower Miocene, young Alpine tectonics (so-called the Sava phase) created conditions for the development of continental–lacustrine sediments in a large area along the southern margin of the Pannonian Basin and within the Dinaride Lake System (KRSTIĆ *et al*. 2003, 2012; MANDIC *et al*. 2012; DE LEEUW *et al*. 2012). This more or less similar sedimentation regime lasted more than eight million years in the southern Pannonian domain (*ca*. 23–15 Ma). During the late Lower Miocene, subsidence and sedimentation were effects of the syn-rift extension phase that resulted in the formation of numerous grabens filled by thin syn-rift marine deposits (HORVÁTH *et al*., 2006). The Middle Miocene Badenian transgression is one of the most important events that occured within the Miocene. It left observable marks over the whole Central Paratethys, especially in the Pannonian Basin (ĆORIĆ & RÖGL 2004; ĆORIĆ *et al*. 2004, 2009; LATAL *et al*. 2006; KOVAČ *et al*. 2007; UTESCHER *et al*. 2007; HARZHAUSER & PILLER 2007; PILLER *et al*. 2007; HARZHAUSER *et al*. 2003, 2011; HOHENEGGER *et al*. 2009; MANDIC *et al*. 2012). A lot of evidence pointing to a sudden change in the sedimentation regime was described on the southern margin of the Pannonian Basin especially (BAKRAČ *et al*. 2010; KRSTIĆ *et al*. 2012; PEZELJ *et al*. 2013; TOLJIĆ *et al*. 2013). The event was tentatively synchronous and occurred at the beginning of Badenian age but, in fact, it was at different times affecting a large area of Paratethys (*ca*. 15 Ma). In Serbia, almost as a rule, different Badenian marine sediments unconformably and transgressively overlie the colorful series of the Lower Miocene clastics (ČIČULIĆ 1958; DOLIĆ 1961, 1998; ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1977; PETKOVIĆ *et al*. 1976; MAROVIĆ *et al*., 2007; RUNDIĆ *et al*., 2005, 2011, 2013, 2013a). All the mentioned authors noted the minor occurrence of the Middle Miocene at the southern flank of the mountain. An exception was the Vrdnik Coal Basin, where sediments of the Lower Miocene transgressively overlie the basement rocks (PETKOVIĆ *et al*. 1976). There are no other significant occurrences of Miocene rocks at the southern slope of the Fruška Gora Mt. Herein, for the first time, a significant subsurface distribution of the Middle Miocene rocks is shown.

This paper presents new stratigraphic and paleontological data from the Vrdnik Coal Basin, the largest Lower Miocene area on the southern slope of the Fruška Gora Mt. (Fig. 1). The studied area had had a long mining history (since 1804). However, after the last spectacular ground water flooding (1968), all the exploitation works were ceased forever. Soon afterwards, the mining activity was replaced by tourism and recently, it has become a very popular spa destination in Serbia.

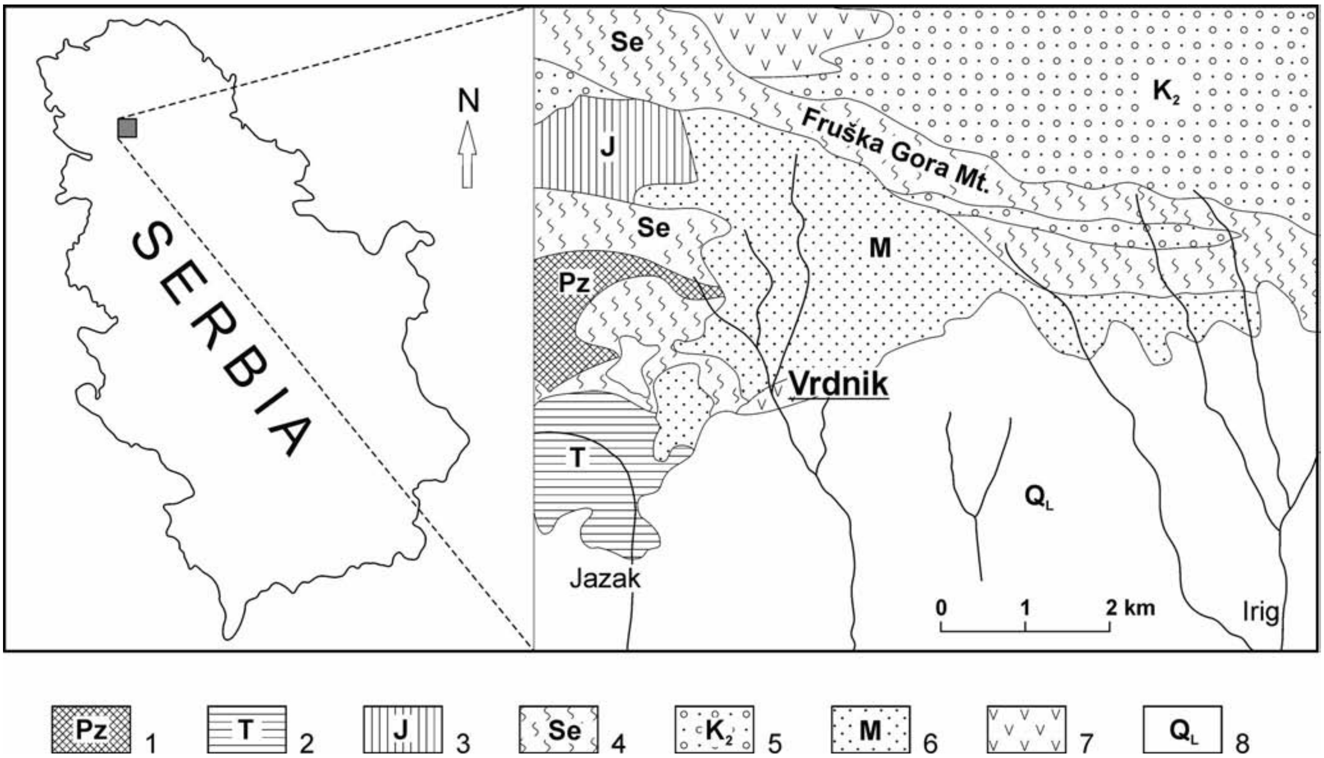


Fig. 1. Geographic position and the simplified geological map of the southern slope of Fruška Gora Mt. Key: **1,** Paleozoic; **2,** Triassic; **3,** Jurassic; **4,** Serpentinites; **5,** Upper Cretaceous; **6,** Miocene (general); **7,** Miocene volcanites; **8,** Quaternary (Loess).

A short review of the geology of the Vrdnik Coal Basin

The Vrdnik Coal Basin (VB) represents a relatively narrow, tectonic subsided structure between the Fruška Gora Mt. and Vrdnik where Miocene deposits occur along a discontinuous belt with E–W direction. Within the VB, Lower Miocene continental–lacustrine sediments, known as the Vrdnik Series (= Vrdnik Formation (VF)), represents the oldest Neogene unit (PETKOVIĆ *et al*. 1976; ČIČULIĆ & RAKIĆ 1976; RUNDIĆ *et al*. 2011, 2013). It discordantly overlies a Pre-Tertiary paleorelief (Triassic alevrolites and dolomitic limestones, serpentinites, Jurassic meta-sediments, Upper Cretaceous sandstones, *etc*., see Fig. 1) and is covered by Middle-Upper Miocene sediments at the higher parts of the mountain. Lithologically, these deposits consist of heterogeneous clastites (varicolored gravelly clay, gravel, sand, and conglomerate). On the northern slope of the Fruška Gora Mt., the VF discordantly overlies the various members of older, pre-Neogene units (ČIČULIĆ & RAKIĆ, 1976). In certain places, the contact with the older formations is tectonic (*e.g*. VF/serpentinites). The VF is better developed and studied on the southern slope of the Fruška Gora Mt. (environs of the Vrdnik spa especially), where deposits of brown coal and well-known fossil flora sites are situated. The Upper Oligocene (KOCH 1876) or Lower Miocene (PANTIĆ 1956) age of these rocks were considered. Based on their superposition, three litho-stratigraphic members are distinguished among them: 1) at the base, various breccia, conglomerate, and sandstone are present, 5–30 m thick; 2) above that, there is a coal–bearing horizon. It is composed of 4–6 coal layers, 0.6–2.5 m thick, represented by intercalated layers of montmorionite clay (bentonite, up to 1m thick); 3) the overburden of the coal layer is composed of lower and upper overburdens. In the lower overburden of the coal layers, there is some bituminous marl and clay, 10–12 m thick, containing remains of fossil flora, which is according to PANTIĆ (1956) dominated by the species: *Taxodium distichum*, *Glyptostrobus europeus*, *Sequoia langsdorfi*, *Castanea atavia*, *Quercus drimeja*, *Myrica lignitum*, *Zelkova ungeri*, *Laurus princes*, *Leguminosites gondini*, *etc*. In addition, the palynological analyses indicate the Lower Miocene age of these sediments. In the upper overburden of the coal horizon, there is a package of diverse sandstones, multicolored clays, sands, and rarely tuff. The layers of the upper overburden are characterized by greater thickness, which may be over 100 m. Based on earlier data from boreholes, the whole thickness of the VF is more than 250 m (PETKOVIĆ *et al*. 1976). However, the latest unofficial data from some boreholes in the area of the Vrdnik spa suggest a much greater thickness of the mentioned rocks. Recently, a similar observation was reported (RUNDIĆ *et al*. 2013a; TOLJIĆ *et al*. 2013).

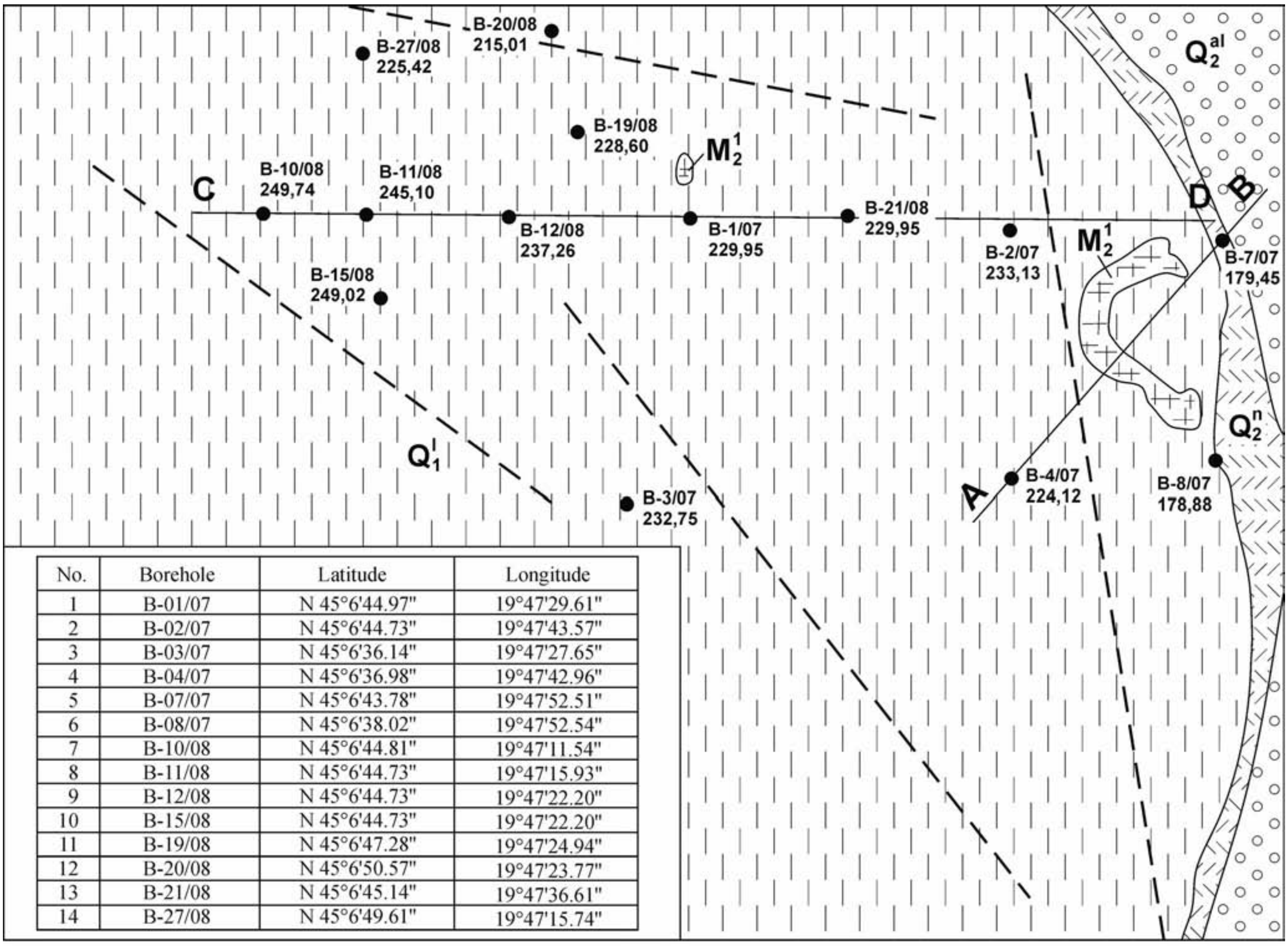
According to earlier data from the basic geological map, sheet Novi Sad, 1:100 000, the mentioned deposits lie below various Middle Miocene Badenian sands, conglomerates, sandy marls and clays, and different limestones and sandstones (ČIČULIĆ & RAKIĆ 1976). On the surface, marine Badenian deposits located at several places to the south of the Vrdnik spa have a very small distribution. On the other hand, their, to date, unknown subsurface spreading is very significant and their determination represents the main goal of this paper. Herein, the marine sedimentation was interrupted at the end of Badenian time and the deposition break lasted until the Upper Miocene. It was connected to the well-known marine regression at the beginning of the late Middle Miocene. Subsequently, a very small lacustrine phase during the Pannonian age (Lake Pannon) affected this area and resulted in the deposition of the so-called Beočin marls (RUNDIĆ & POTIĆ 2013). During the latest Middle Miocene, Pliocene, and Quaternary, because of the uplifting of the Fruška Gora Mt., different terrestrial sediments were formed (freshwater equivalents of the Upper Miocene –Pontian, the Pleistocene Srem series, the loess-paleosoil sequences, *etc*).

Materials and Methods

All the presented data were obtained from field investigations (2010, 2011) and from core-samples of twenty-seven boreholes drilled during 2007 and 2008. Many data were collected and more than a half of these boreholes are presented herein (Fig. 2). All the measured logs were performed in the field. Later, the logs were compared and more precise stratigraphic analyses were realized (Figs. 3–6). Different and relatively abundant marine fauna (mollusks, foraminifers, ostracodes, echinoids, corals, etc.) from forty core-samples were determined. Ten limestone samples were examined by thin-sections. Additionally, the four soft samples from the boreholes B-19 and B-20 were treated with 6 % hydrogen peroxide and later washed (0.5–0.063 mm sieves). Approximately 100 g of each dried residue was examined under a stereomicroscope. All the mentioned material is stored at the Hidro-Geo Rad Co., Belgrade and at the Chair of Historical Geology, Faculty of Mining and Geology, University of Belgrade. Some information was plotted on a geodetic plan on the scale 1:2500, and two simplified geological cross-sections were drawn (Figs. 10, 11).

Results

Quaternary deposits, mainly loess-paleosoil sequences, cover the area of the southern and southwestern part of the Vrdnik Coal Basin. The subsurface investigation of the wider area of Strmoglavnice and Velika



No.	Borehole	Latitude	Longitude
1	B-01/07	N 45°6'44.97"	19°47'29.61"
2	B-02/07	N 45°6'44.73"	19°47'43.57"
3	B-03/07	N 45°6'36.14"	19°47'27.65"
4	B-04/07	N 45°6'36.98"	19°47'42.96"
5	B-07/07	N 45°6'43.78"	19°47'52.51"
6	B-08/07	N 45°6'38.02"	19°47'52.54"
7	B-10/08	N 45°6'44.81"	19°47'11.54"
8	B-11/08	N 45°6'44.73"	19°47'15.93"
9	B-12/08	N 45°6'44.73"	19°47'22.20"
10	B-15/08	N 45°6'44.73"	19°47'22.20"
11	B-19/08	N 45°6'47.28"	19°47'24.94"
12	B-20/08	N 45°6'50.57"	19°47'23.77"
13	B-21/08	N 45°6'45.14"	19°47'36.61"
14	B-27/08	N 45°6'49.61"	19°47'15.74"

Fig. 2. A geological map of the investigated area and the positions of the boreholes (black circles and WGS84 coordinates), and the location of the geological cross-sections (A–B, C–D).

Pećina determined the geological structure and provided many previously unknown data. According to the BGM, sheet Novi Sad 1:100,000 (ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1977), on the surface were only a few small "patches" of marine Badenian sediments. They transgressively overlaid Lower Miocene freshwater deposits. On surface of the studied area, regardless of the package of quite thick Quaternary sediments, smaller outcrops of multicolored, gray-bluish, brown and reddish clay, and brown ferruginous sands (Fig. 3 A, B). They represent the final part of the lithological succession of the VF. A part of the continental-lacustrine series was discovered in some of the boreholes (*e.g.*, B-19 (72.80–76.90 m), B-20 (20.70–36.60 m), and B-27 (17.50–32.00 m – see Figs. 3C, 8). Generally, it consists of green, bentonite clays, and carbonaceous clay without fossil remains. Moreover, in almost all the other exploration wells, Middle Miocene Badenian deposits were registered. They overlie the Early Miocene clays and indicate the marine transgression in this area (Figs. 4–8).

The marine Badenian sediments have a relatively small distribution in the Vrdnik Coal Basin and they include only a few different facies. If compared with the synchronous rocks on the northern parts of the mountain, a clear difference is evident (PETKOVIĆ *et al*. 1976; RUNDIĆ *et al*. 2011). However, Badenian limestones appear much more than all the other synchronous rocks. Generally, these sediments are present as a split rock body with E–W direction. According to borehole data, there are sporadic occurrences of very rare grayish-green clays and sandy marls and wider distribution of biogenic limestones (the so-called Leitha limestone, in all the other boreholes). They contain abundant fossils and these limestones could be distinguished as separate biofacies (*e.g.*, the Lithotamnian, Amphistegin, Bryozoan, *etc*.). The limestone is massive, reefy, developed by the activities of corallinacean red algae, foraminifers and bryozoans, *etc*. In addition, it includes various fossil remains of mollusks, echinoids, corals and other organisms. Based on sediment analyses, a dominance of algal and algal-foraminifer biomicsparite and biomicrudite was determined (Fig. 9). Laterally, toward the E–NE margin of the Vrdnik Coal Basin, the limestones turn into marly limestones, sandy marls and clays. Biostrati-

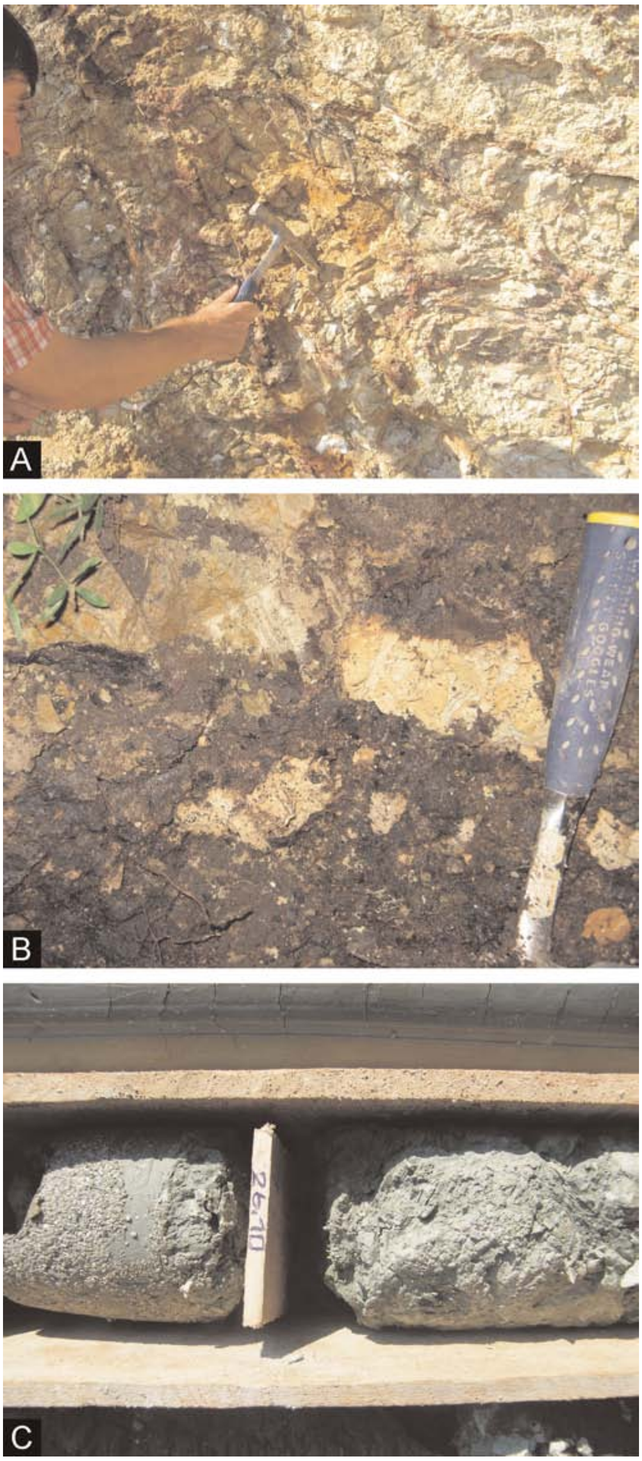


Fig. 3. The Lower Miocene Vrdnik series: **A, B,** Surface outcrops and **C,** A detail of green bentonite clay from the borehole B-20/08 (26.10 m).

graphically, the sediments of the Lower, Middle and Upper Badenian could be separated. Grayish sandy marls represent the oldest marine Badenian sediments. Occasionally, the Badenian sediments were overlaid by Upper Miocene (?Pontian) clastites or different Quaternary sediments (boreholes B-1, B-2, B-3 B-4, *etc*).

For example, in the borehole B-1/07 (N 45°6'44.97"; E 19°47'29.61" – Fig. 4) under different Pleistocene sediments and thin interbeds of ?Pontian gray alevrites (the first 17 meters of the core section), there is a relatively thick series of Badenian limestone (17.70–74.80 m). At higher levels, the limestone is more whitish, massive and has typical structural characteristics such as those documented in other areas of the Fruška Gora Mt. It is the well-known Leitha limestone (name after the Leitha Mountains, Austria). A sample from a depth of 38.50 m has a system of ca-

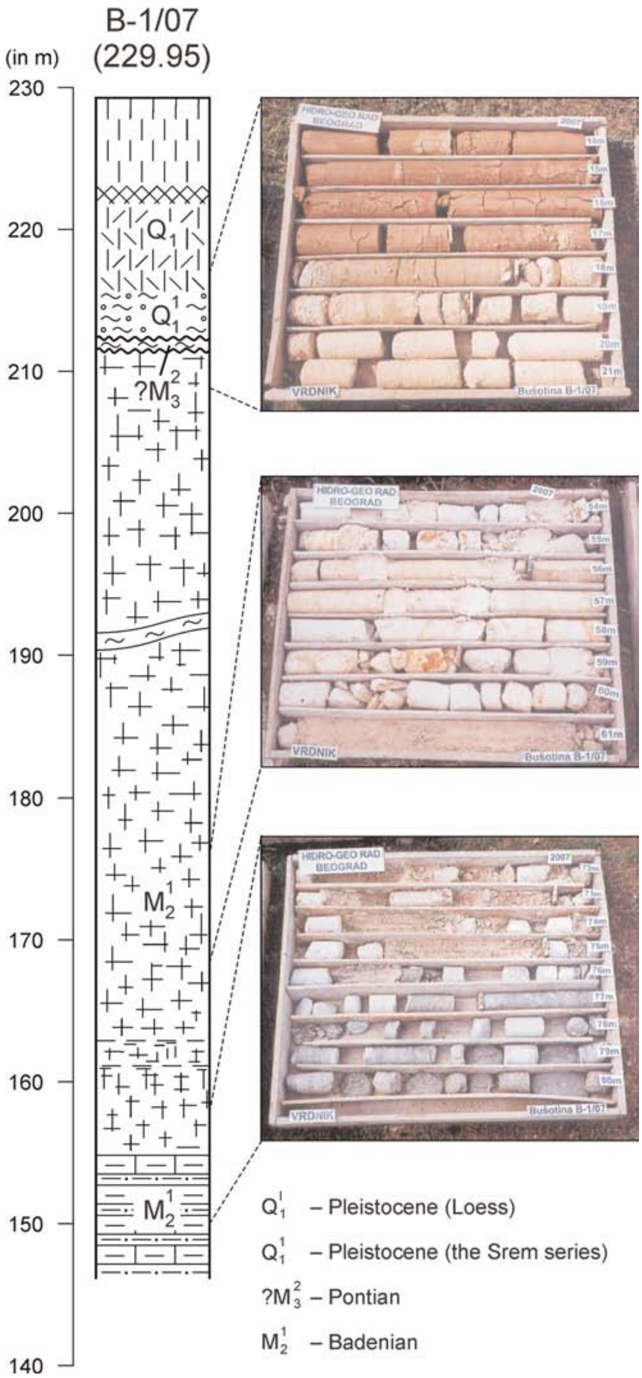


Fig. 4. The stratigraphic section and some core-samples from the borehole B-1/07.

verns, which are filled by reddish-brown alevrites and clays. This is a very common occurrence in these sediments (RUNDIĆ *et al*. 2011). These limestones alternate with gray and partly marly limestones in the deeper parts of the borehole (63.00–74.80 m). According to its structural properties and fossil association involved, it corresponds to the real bioclastic limestones (corallinaceans, bryozoans, foraminifers, echinoderms, bivalve remains, *etc*.). Although the red algae are not as dominant, the textural pattern is predominantly composed of unattached coralline algal branches, rhodoliths, and their detritus. FREIWALD *et al*. (1991) described a similar modern environment from Norway.

Based on the analyzes of thin-sections from core-samples, the facies comprises packstones, rudstones, and floatstones consisting of angular and subrounded corallinacean clasts. The corallinaceans are represented by *Lithothamnion, Mesophyllum*, and ?*Lithophyllum*. Sporadically, rhodoliths of corallinacean red algae are present (Fig. 9). Bivalves and gastropods occur in variable quantities (*Ostrea* sp., *Aequipecten* sp., and *Conus* sp.), as well as regular and irregular echinoids and bryozoans (64.50–65.00 m) which are represented by branching forms. Elsewhere, rotaliids forms, such as Amphistegina and ?Planostegina (37.00–37.50 m), scarce cibicidoids and miliolids represent the abundant foraminifers. In the deepest core interval (74.80–83.50 m), this bioclastic limestone is more fine-grained and alternates to sandy marl. From time to time, the genus Amphistegina has mass occurrence and can then make a separate biofacies – Amphistegina limestone (Fig. 9).

In the borehole B-11/08 (N 45°6’44.73”, E 19°47’15.93” – Figs. 5, 11), under a thicker package of ?Pontian and Quaternary sediments (total thickness of approximately 33.50 m), two different facies of Middle Miocene Badenian were determined (RUNDIĆ *et al*. 2013a). Leitha bioclastic limestone with a very diverse fauna of corallinacean algae, bryozoa, foraminifers, mollusks, and echinoderms was determined at depth of 33.50–104.00 m. In all the boreholes in this area, it is the thickest package of limestones that has been specified (thickness almost 70 m). The limestones are not the same everywhere; there are few differences in texture, fossils and color (whitish to light yellow in shallow samples, and more grayish in the deeper samples of the borehole (80.50–104.00 m). In the sample from depth of 35.00–35.80 m, foraminifer species *Amphistegina mammilla* is dominate, while elphidiums and rotalids are individually present. Besides corallinacean algae and bryozoa that are macroscopically observable, very numerous bivalves were found in a sample from a depth of 82.50–83.00 m (Fig. 6): *Glycymeris pilosus, Flabellipecten besseri,* ?*Gigantopecten sp., Chlamys latissima, Cardiocardita partschi, Panopea menardi,* and *Ostrea* sp.(cf. *Ostrea lamellosa*), and significantly less gastropods

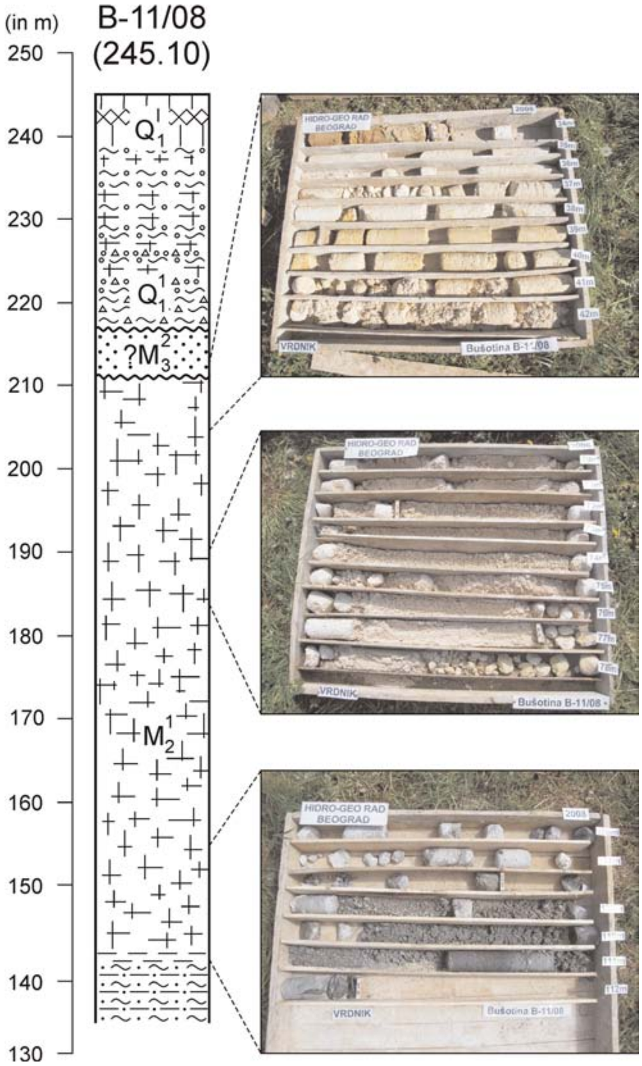


Fig. 5. The stratigraphic section and some core-samples from the borehole B-11/08. For key, see Fig. 4.

(*Conus* sp. and *Turritella* sp.). In the gray, sandy limestone (87.50–88.00 m) algal and bryozoans sections dominated (Fig. 9). The algal-zoogenic biomicrudite/floatstone is real. Within the rock, algal and zoogenic fragments are visible (> 2 mm). The deepest sample (109.5–110.00 m) taken from gray, sandy, and sandy-marl clay represented a completely different facies of the Badenian Stage. Based on fossil associations with the predominant forms of planktonic foraminifera (*Orbulina suturalis*, *Globigerinoides* cf. *trilobus*, and *Uvigerin*a sp.) and mollusks such as *Ammusium cristatum* and *Dentalium* sp., and other smaller forms of bivalves, it could be assumed that these sediments belong to the Lower Badenian Lagenidae Zone. At moment, the precise biostratigraphic position of these layers (?Lower or Upper Lagenidae Zone) is unknown and requires detailed quantitative and qualitative analyses of the mentioned foraminifers and calcareous nannoplankton (ĆORIĆ *et al*. 2009; HOHENEGGER *et al*. 2009; PEZELJ *et al*. 2013) as well

Fig. 6. The bioclastic limestone: **A,** Remains of bivalves (? *Chlamys* sp.) and gastropods (*Conus* sp.) from the borehole B-11/08 (82.50–83.00 m), and **B,** the core sample with rhodoliths – corallinacean limestone (B-12/08, 79.20 m).

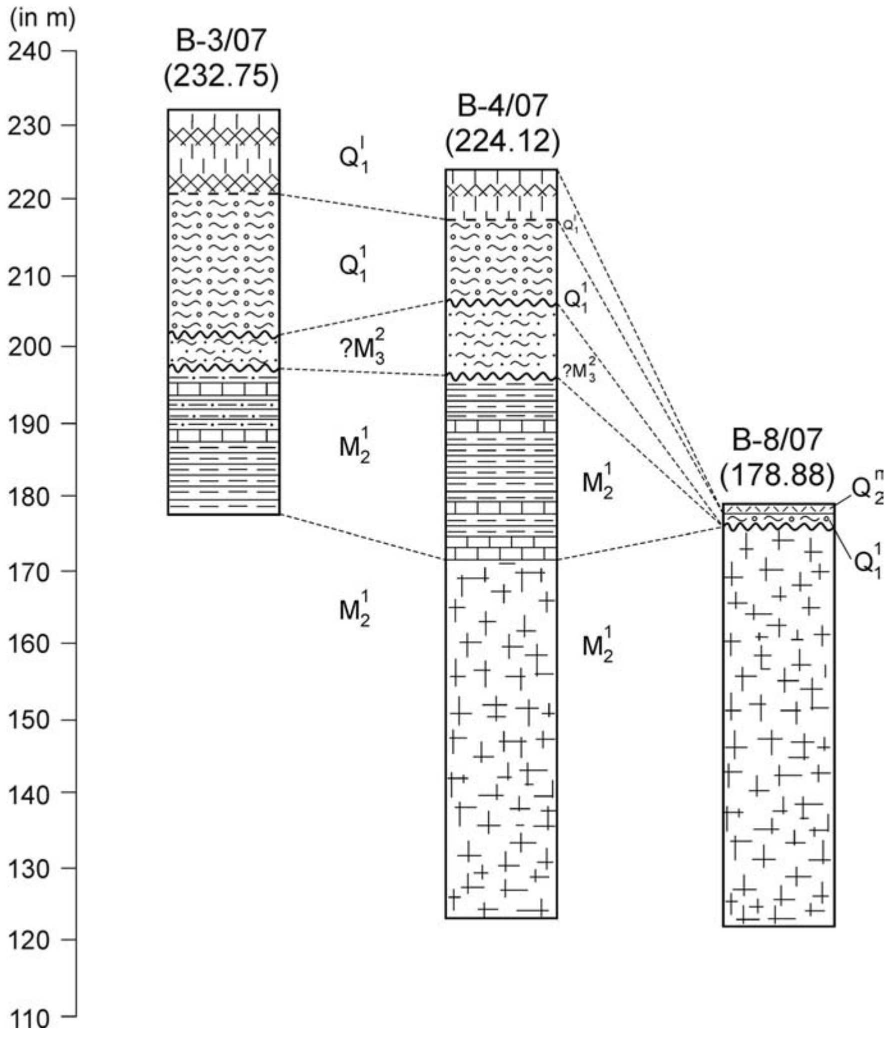


Fig. 7. Comparative stratigraphic logs of boreholes B-3/07. B-4/07, and B-8/07.

as provision of the initial time of marine flooding in this area (Mandic *et al*. 2012).

In the other boreholes, the lithological pattern is similar (Figs. 7, 8). The Badenian deposits are largely presented by bioclastic limestones (B-2/07, B-3/07, B-4/07, B-7/07, B-8/07, B-9/08, B-10 / 08, B-12/08, B-19/08, B-20/08, B-21/08 and B-27/08 – see Fig. 3). Exceptionally, other different facies of the Badenian stage were observed (*e.g*., B-11/08, B-19/08). Lithologically, these are represented by sandy marls and sandy clays, coarse-grained sands, gravel and microconglomerates. The very scarce fossil remains (mostly planktonic foraminifers such as Globigerinoides and Orbulina) enable the oldest Badenian age to be suggested. In boreholes B-11/08, B-15/08, and B-19/08, these sediments make the basis of the mentioned bioclastic limestones. Sometimes, they consist of well-rounded but poorly sorted polymict gravel (1–5 cm) composed of metamorphic and carbonate rocks (Čičulić & Rakić 1976). They are supported by fine-grained quartz sand reaching 60–80% and occasionally clay up to 20 %. (Fig. 8, see B-19/08). Quartz fine-sand layers or dispersed fine-sand lenses of variable thickness (cm to dm) are intercalated within the

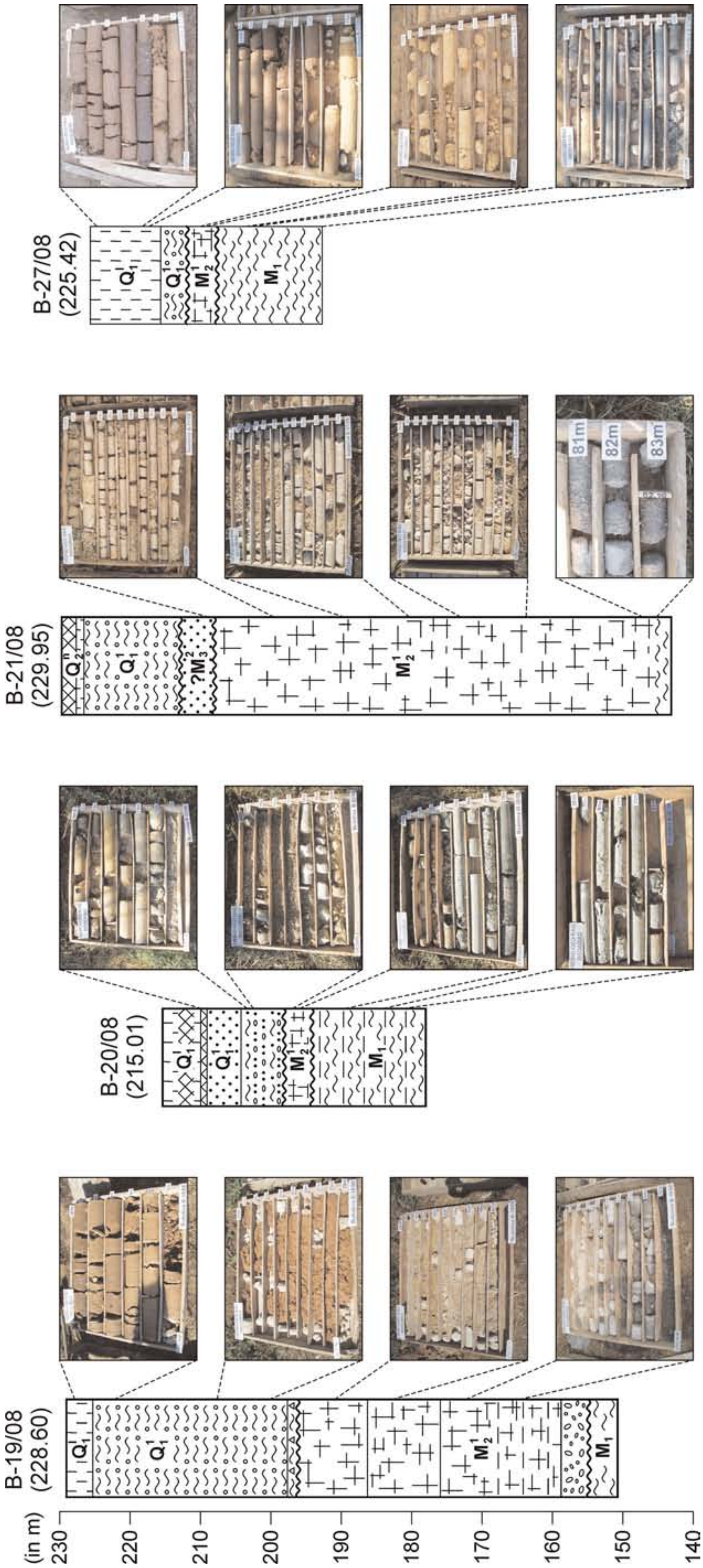


Fig. 8. Comparative stratigraphic logs of boreholes B-19/08. B-20/08, B-21/08 and B-27/08.

gravels. However, in the boreholes B-3/07 in the depth interval between 34.90–54.60 m and B-4/07 (28.00–50.50 m) very similar gray sandy marls overlie bioclastic limestones. They contain marine foraminifers and ostracodes (predominantly rotalids forms of foraminifers), which probably belong to the Upper Badenian age.

Discussion and interpretation

All the mentioned data derived from the borehole sections and surface outcrops clearly suggest a relatively wide subsurface distribution of the Middle Miocene marine sediments. More or less, these sediments represent a part of the well-known carbonate ramp, which was formed during the Middle Miocene (Langhian/Badenian) Climatic Optimum (SCHMID *et al.* 2001; BÖHME, M. 2003; HARZHAUSER & PILLER 2007; RÖGL *et al.* 2008). According to the first evaluation, the dominant reef limestone occupies a relatively narrow strip of the east-west direction with a total length of about 1,200 m. The potential width of the limestone reservoir is about 250 m. The most prevailing limestone components are coralline red algae but bryozoans and rare corals locally formed small patch reefs (RUNDIĆ *et al.* 2011). Except these, other marine facies occur but they have a minor distribution. Stratigraphically, all of these marine sediments transgressively overlie Pre-Tertiary units or undivided Lower Miocene continental sediments.

From the lithological point of view, the basal part of the marine Badenian succession was made of gravels and sandy gravels (borehole B-19/08), which originated from different older tectonic units (ČIČULIĆ 1958; DOLIĆ 1961, 1998; ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1976, 1977; PETKOVIĆ *et al.* 1976; RUNDIĆ *et al.* 2013a). They are relatively poorly sorted but well-rounded with a medium fine-sand content. The medium/high degree of roundness indicates relatively long transport and/or following coastal reworking. The exact provenience of the gravels is still unclear; the source area could be the basement rocks of the Fruška Gora Mt. (PETKOVIĆ *et al.* 1976; RUNDIĆ *et al.* 2005, 2011). WIEDL *et al.* (2012) have discussed river transport but also marine reworking by coastal breakers in a deltaic system. However, the sporadically presence of the coarse-grained sediments, gravels and microconglomerates within only one of the investigated boreholes is insufficient for a more precise reconstruction.

During the Miocene time, the southern part of the Pannonian Basin (*i.e.* the Vrdnik Coal Basin) was strongly affected by the Alpine orogeny (PETKOVIĆ *et al.* 1976; KOVAČ *et al.* 2007; TOLJIĆ *et al.* 2013). The Middle Miocene Badenian was the peak of the Miocene carbonate production in the Central Paratethys (SCHMID *et al.* 2001; HARZHAUSER & PILLER 2007; RÖGL *et al.* 2008; BASSO *et al.* 2008; PEZELJ *et al.* 2013; WIEDL *et al.* 2012, 2013). The Middle Miocene Climatic Optimum (MCO) led to an extension of the tropical belt and favored the wide distribution of coral reefs throughout the Mediterranean and Central Paratethys during the Langhian age (BÖHME 2003; HARZHAUSER & PILLER 2007; BASSO *et al* 2008). Coral reefs are found along the Mediterranean and the Central Paratethys up to the southern Vienna and Transylvanian Basins (WIEDL *et al.* 2012). From this distribution pattern of the circum-Mediterranean region, a subdivision into two biogeographic areas during the Langhian time is possible (WIEDL *et al.* 2012). Coral reefs (*sensu strictu*) characterize the southern area. Its northern boundary could be drawn from the Aquitaine Basin to the Vienna and Transylvanian Basins (WIEDL *et al.* 2012, 2013). Further to the north, the coral occurrences are characterized by coral carpets/assemblages. In this context, the Leitha limestone, which is positioned at the edge of the coral reef belt, indicates the transition zone between coral reefs to non-reefal coral communities (WIEDL *et al.* 2013). The distribution of corals in the Central Paratethys is linked with the Middle Miocene Climatic Optimum, which supported the northward shift of tropical elements (HARZHAUSER *et al.* 2003, 2011; WIEDL *et al.* 2013).

In the southwestern part of the Vrdnik Coal Basin, within the Badenian shallow-water carbonates (the Leitha Limestone), a few (bio) facies types could be recognized according to the abundance of some biogenic characteristics (*e.g.* Amphistegina, Bryozoan, Lithothamnion, *etc)*. Similarly, recent sediments up to 40 m of water depth were reported by RASSER (2000) from the Mediterranean Sea and HALFAR *et al.* (2000, 2012) from the Gulf of California. Generally, the Amphistegin's limestone is the youngest biofacies and corresponds to the Upper Badenian mostly. Other biofacies have stratigraphic range the Middle–Upper Badenian.

The Amphistegina limestone (Amphistegina biofacies) is characterized by the very common occurrence of the foraminer genus Amphistegina (Fig. 9A). Recent Amphistegina inhabit the tropical to subtropical belt in shallow waters down to 70–80 m where they are primarily attached to macrophytes with high densities. Their presence implies a minimum water temperature of 17°C (WIEDL *et al.* 2012). In summary, the Amphistegina subfacies was formed in a shallow, sublittoral environment with a depth range of *ca.* 20–30 m between the bryozoan subfacies and the mollusc subfacies. A typical bivalve of this facies is the deep-burrowing *Panopea menardi.* Modern representatives of Panopea live in sandy and muddy substrates preferring shallow subtidal habitats down to 20 m, burrowing between 0.6 and 2 m deep into the sediment (WIEDL *et al.* 2012). Besides, during the MCO, the optimal conditions resulted in extraordinary growth rates of oysters (*Crassostrea gryphoides*). Marine waters during the MCO in Central Europe displayed a seasonal temperature range of *ca*. 9–11°C. The absolute water temperatures ranged from 17–19°C during cool seasons and up to 28°C in the warm seasons (HARZHAUSER *et al*. 2011). The findings of bivalve species (?*Gigantopecten* sp., *Chlamys latissima*, *Glycymeris* sp., *Cardites partschi*, *Panopea menardi*, and *Ostrea* sp. (cf. *Ostrea lamellosa*) could support this paleotemperature pattern. A similar facies is present in the Badenian corallinacean limestones of Bosnia and Herzegovina, Croatia and Austria (ĆORIĆ & RÖGL 2004; ĆORIĆ *et al*. 2004, 2009; HOHENEGGER *et al*. 2009; PEZELJ *et al*., 2013). In addition, the other foraminifers that were found in the Badenian sediments indicate more or less similar conditions. Thus, the relatively scarce finding of *Globigerina* sp. as well a *Globigerinoides* sp. may indicate short-time climatic oscillations of cooler climate during the MCO, which could be characterized as fairly uniform for the Badenian climate of the Central Paratethys realm (BÖHME 2003; BÁLDI 2006; KOVÁČOVÁ *et al*. 2009; KOPECKA 2012; WIEDL *et al*. 2012, 2013).

Modern Rhodolith-dominated carbonate systems are known worldwide (BASSO 1998; BASSO *et al* 2008; HALFAR *et al.* 2012 and references therein). The rhodolith biofacies (Fig. 9A) is represented by coralline algal rudstones with packstone matrix comprising spheroidal thin-branched rhodoliths (up to 6 cm). It also contains foraminiferal macroids with diameters of 0.3–2 cm. Interspaces between the rhodoliths and macroids are filled with coralline algal debris. Foraminifers are represented by rotalids (*Amphistegina* and *Ammonia*), and rare miliolids (*Borelis* sp.). Bryozoans are rare and commonly encrusted by coralline algae. A relatively similar rhodolith biofacies from the Leitha Mountains, Austria was well-described (WIEDL *et al.* 2012). For the mentioned facies types, these authors indicated water depths of 10–20 m. Consequently, a similar water depth could be suggests for this subfacies in the southwestern part of the Vrdnik Coal Basin.

The Bryozoan biofacies is very similar to the algal facies and in some places contain a rich bivalve fauna. Modern analogues are found on the Apulian shelf (Italia) along the seashore between 10–30 m of water depth (WIEDL *et al*. 2013). In addition, the bryozoan subfacies is associated with the Amphistegina subfacies (Fig.9B). A similar bryozoan facies was reported from the Mannersdorf Quarry, Austria. Therein, the facies is overlain by a coral facies. The co-occurrence of coral and bryozoan-bearing assemblages was explained by differences in the productivity of surface waters (WIEDL *et al*. 2012, 2013).

The Mollusk biofacies is equivalent to the bioclastic algal-mollusk facies and to the branching algal facies (BASSO *et al*. 2008) with its diversified molluskan assemblage. The mollusk biofacies consist of rudstones and floatstones that are characterized by high amounts of various mollusks. ZUSCHIN & HOHENEGGER (1998) described comparable mollusk assemblages from the modern Red Sea (Egypt). There, Turritellids are widely distributed on soft and hard substrates, muddy sediments, and on the reef slope down to 40 m; Cerithiids show distinct habitat preferences and occur in water depths up to 40 m with common occurrences between 5 and 30 m. The genus Glycymeris was described from sands between coral patches in depth of ca. 10 m (ZUSCHIN & HOHENEGGER 1998). Glycymerids are also reported from present-day sand bottoms at 10–30 m depth from the Florida Keys (see WIEDL *et al*. 2012). The mollusk biofacies is often associated with the rhodolith biofacies. The mollusk biofacies probably represents a shallow tran-

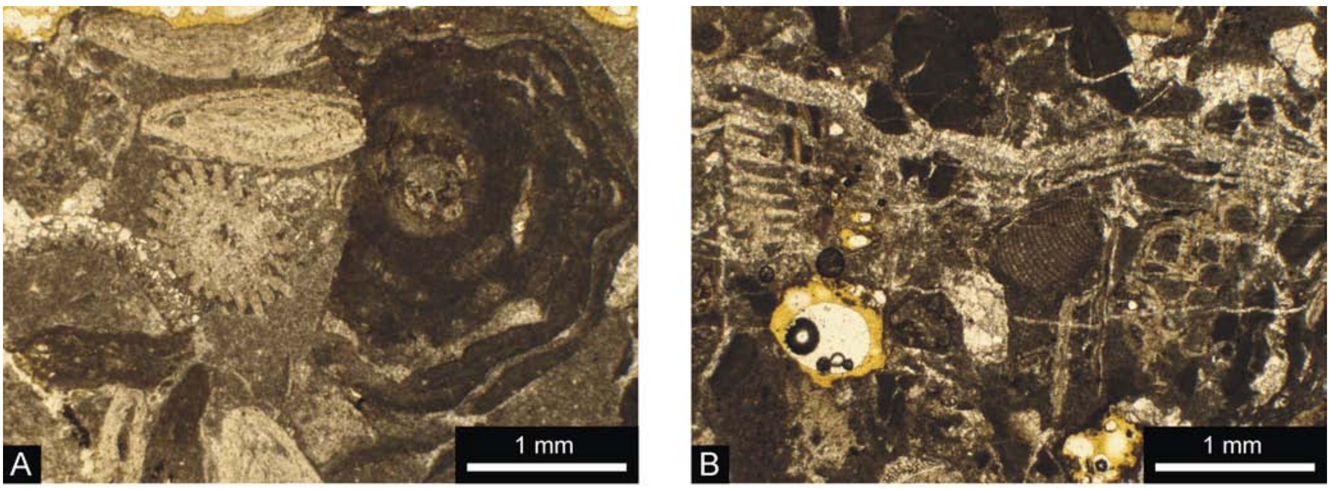


Fig. 9. **A,** Amphistegina biofacies with the rhodoliths, bryozoans and an echinoids section (B-1/07, 72.80–73.00 m); **B,** Algal-bryozoans biofacies (B-11/08, 87.50–88.00 m).

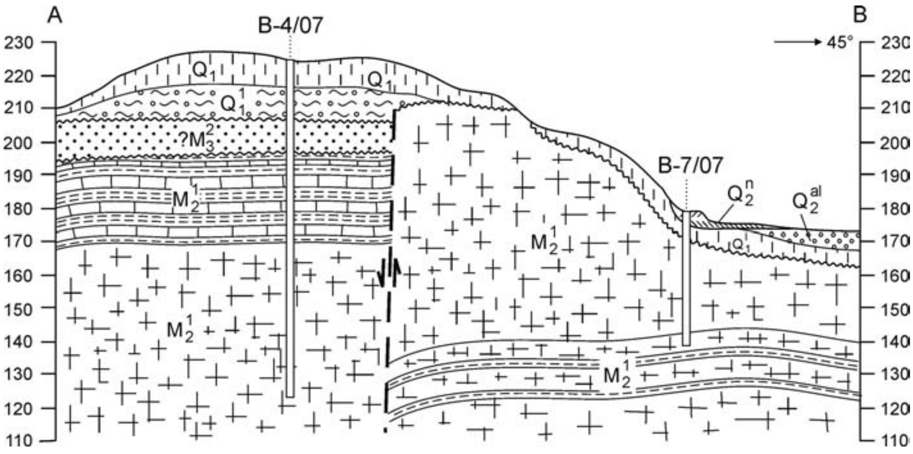


Fig. 10. A simplified geological cross-section (A–B) from the eastern part of the studied area.

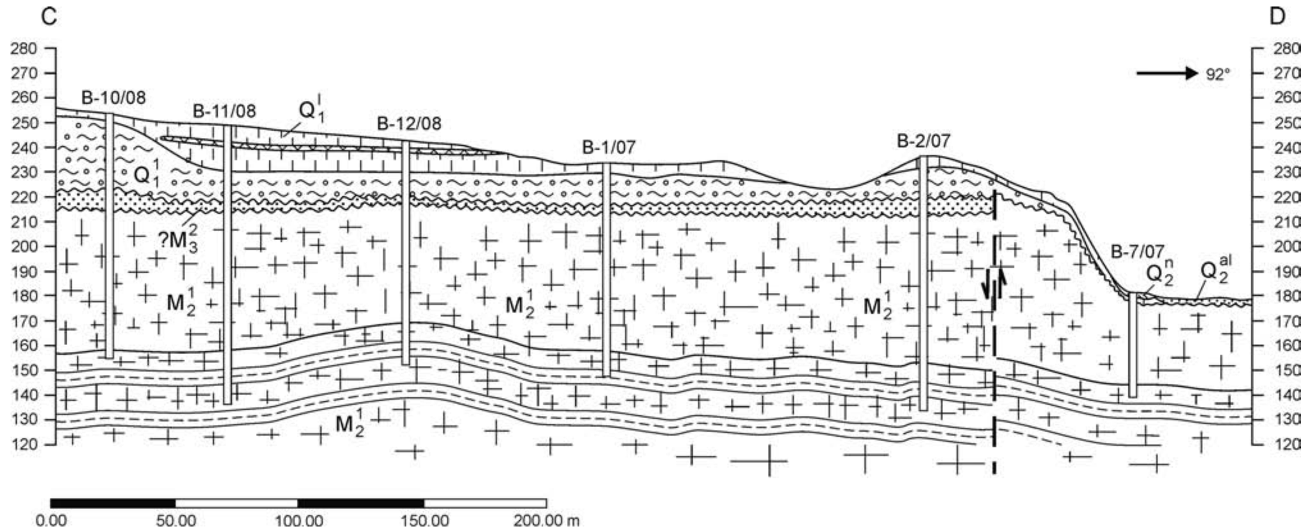


Fig. 11. A simplified geological cross-section (C–D) from the central part of the studied area.

sition zone between the rhodolith subfacies and relatively deeper water with the bryozoan biofacies.

Based on preliminary analyses of all the investigated boreholes as well as the surface distribution of the bioclastic limestones, the existence of the marine carbonate ramp in the southwestern part of the Vrdnik Coal Basin could be supposed. Additionally, an earlier study of similar sediments from the southern slope of the Fruška Gora Mt. (Rundić *et al*. 2011), indicated an elongated carbonate belt with E-W direction around the mountain (Fig. 11). The main part of it is yet undiscovered and our studies indicate to small, tectonically dislocated blocks. Based on the boreholes data, these carbonates underwent significant radial stress and were dislocated by fault tectonics after the Middle Miocene (Figs. 10, 11). This is in agreement with previously documented results from Bešenovo and Ležimir (more towards the west), where similar blocks of a shallow-water carbonate ramp occur (Rundić *et al*. 2011, 2013). In some places, they are displayed below different Quaternary sediments and they belong to small uplifted blocks where erosion processes were expressed (B-7/07, Fig. 10). On the other hands, there are relatively sunken blocks (B-4/07, Fig. 10) on whom, above the mentioned Badenian carbonates, much more younger stratigraphic units are present. A similar tectonic pattern was observed on the northern slope of the Fruška Gora Mt. (Čičulić-Trifunović & Rakić 1977; Petković *et al*. 1976; Rundić *et al.* 2005). However, therein there are no sedimentation breaks within the late Middle Miocene and there is a complete Neogene succession.

The studied boreholes showed subsurface features of Lower and Middle Miocene sediments, which were unknown before (presence/absence of stratigraphic units and their thickness, facial diversity, dip angle, unconformity, *etc*.). A preliminary analysis of fault structures in the Vrdnik Coal Basin is confirmed its complex structure and the character of a tectonic trench that was formed during the Miocene and inverted in the youngest stages of the Pliocene and Quaternary.

Conclusions

The data collected from surface researches and numerous boreholes in the southwestern part of the Vrdnik Coal Basin enabled the following conclusions:

• Based on lithological successions, stratigraphic logs and basic structural elements, the subsurface geological setting of the southwestern part of Vrdnik Coal Basin has been reconstructed. The following stratigraphic units were documented: the Lower Miocene, the Middle Miocene Badenian, the Upper Miocene ?Pontian, as well as different terrestrial sediments of Pleistocene age, including the loess-paleosoil sequences on surface.

• From a stratigraphic point of view, marine Badenian sediments transgressively and discordantly overlie older rock units (usually above the freshwater Lower Miocene Vrdnik series). They indicate the well-known regional transgression, which occurs in the Central Paratethys during the early Middle Miocene.

• There is a much larger subsurface distribution of Badenian sediments than previously supposed. Generally, they belong to an elongated carbonate belt that was generated during the Middle Miocene Climatic Optimum. Stratigraphically, this ?Upper Badenian carbonate ramp has a significantly wider distribution than a similar one formed during the Middle Badenian.

• Within the Badenian shallow-water carbonates, the so-called Leitha limestones have a dominant position and distribution (thickness over 70 m). They indicate a shallow reef environment (up to 40 m of water depth), relatively warm, clear water and favorable bionomical conditions nearby the Fruška Gora Island of the Central Paratethys. Among them, a few (bio) facies types could be recognized according to the abundance of some biogenic and textural characteristics (e.g. Amphistegina, Bryozoans, Lithothamnion, *etc*).

• Sandy marl, which generally lies below the Leitha limestone, has a relatively smaller distribution. In places, there is a lateral link to the limestone. However, it is of the great stratigraphic importance because a preliminarily study of a foraminiferal association indicated older levels of the Badenian Stage (the Lower Badenian Lagenidae Zone).

• Future biostratigraphic analyses of foraminifers and calcareous nannoplankton will clearly indicate the presence of Lower Badenian biozones (Lower or Upper Lagenidae Zone) and closely define the time of the marine transgression in this area. Besides, the precise biostratigraphic position of the Badenian limestone should be given.

Acknowledgements

The Ministry of Education, Science and Technological Development of the Republic of Serbia, Project No. 176015 (grant to Lj. R.) supported this work. Special thanks go to LYNNE KATSIKAS for the English revision of the manuscript. In addition, NENAD MALEŠEVIĆ (Faculty of Mining and Geology, Belgrade) is thanked for technical support and the final preparation of illustrations. Finally, the authors are very thankful to the reviewers, Prof. Dr. SEJFUDIN VRABAC (University of Tuzla, Bosnia and Herzegovina) as well as anonymous reviewer for their constructive remarks and useful suggestions.

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Резиме

Средње миоценска баденска трансгресија: нови докази са простора Врдничког угљеног басена (Фрушка гора, северна Србија)

Средње миоценска баденска трансгресија је један од најважнијих догађаја у миоцену који је оставио видљиве трагове на простору некадашњег Паратетиса. С тим у вези, много је доказа који указују на изненадне промене у режиму седиментације и по јужном ободу Панонског басена (BAKRAČ *et al*. 2010; KRSTIĆ *et al*. 2012; PEZELJ *et al*. 2013). Почетком средњег миоцена, као последица екстензионих фаза, створени су бројни грабени и ровови који су били испуњени морским синрифтним наслагама. Догађај је био условно синхрон на једној великој територији. Међутим, логично је веровати да је трансгресија захватила поједине делове Паратетиса у различито време (у распону од стотину хиљада година). У Србији, готово по правилу, кластични морски седименти бадена, дискордантно и трансгресивно леже преко старије подлоге, а врло често преко једне хетерогене, шарене серије старијег миоцена (има и другачијих мишљења – види KRSTIĆ *et al*. 2012). Слична ситуација је и раније констатована на простору Фрушке горе (ČIČULIĆ 1958; DOLIĆ 1961, 1998; ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1976; PETKOVIĆ *et al*. 1976; RUNDIĆ *et al.* 2013). За разлику од северне стране планине, где је много лакше истражити те односе на самој површини, у околини Врдника су такви примери врло оскудни. Због тога су и урађена додатна теренска осматрања која су, уз подршку плитких бушотина у југозападном делу Врдничког угљеног басена, пружила нове доказе о присуству морске трансгресије на овом простору. Посебно је важно то што је по први пут документовано значајно подповршинско распрострањење морских седимената за које се раније није ни знало. На основу тога, дошло се до нових сазнања о геологији овог младог басена, тектонског рова формираног током миоцена и даље обликованог за време старијег плиоцена. Најважнији резултати су:

- На основу података добијених теренским истраживањима и анализом 14 плитких бушотина, извршена је реконструкција подповршинских односа на потезу Стрмоглавице–Велика Пећина, јужно од бање Врдник.
- У суперпозиционом поретку, присутне су следеће стратиграфске јединице: континентално-језерски доњи миоцен, морски средњи миоцен баден, горњи миоцен ?понт, те различите плеистоценске наслаге (првенствено тзв. сремска серија и лесно-палеоземљишне секвенце). Међутим, сматра се да велики део баденских наслага још увек није откривен. Нашим истраживањима је констатовано присуство више тектонских блокова који су резултат горње миоценске радијалне тектонике. Тим покретима је баденска карбонатна платформа издељена на блокове који су, у млађим фазама током плиоцена, додатно кретани и дислоцирани. Тако на неким издигнутим блоковима (бушотина Б-7), директно преко бадена належу квартарни седименти, што указује да знатан степен ерозије. Супротно томе, постоје и релативно спуштени

блокови где су осим бадена утврђене и друге неогене јединице (бушотина Б-4).

• У стратиграфском смислу, постоји трансгресиван и дискордантан однос морских наслага бадена преко старијих јединица (на нашим примерима само преко континентално-језерске Врдничке серије). Такав однос упућује на присуство напред наведене морске трансгресије и на овом простору.

• Анализом бушотина, утврђено је да постоји значајно подповршинско присуство морских наслага бадена у различитим фацијама, али је доминантно плитко, карбонатно развиће које указује на присутво једне релативно уске и издужене карбонатне платформе правца пружања исток–запад (процењена дужина од преко 1200 m а ширина до 250 m). У појединим бушотинама, дебљина карбоната достиже 70 m (Б-11).

• На основу прелиминарне палеонтолошке анализе (црвене алге, бриозое, мекушци, фораминифере и др.), може се рећи да је карбонатна платформа (рампа) више присутна у млађем бадену, него за време старијег и средњег бадена. Депоновање оваквих наслага (до 98 % $CaCO_3$) везано је за тзв. средње миоценски климатски оптимум који је омогућио стварање сличних седимената на широком простору Паратетиса али и Медитерана (Böhme, M. 2003; Harzhauser & Piller 2007; Rögl *et al*. 2008).

• Међу овим наслагама, доминантни су тзв. лајтовачки кречњаци који, у зависности од доминантне фосилне компоненте, могу би подељени на неколико биофација (алгални, бриозојски, амфистегински, и др.). У палеоеколошком смислу, сви они указују на плитку, спрудну и субспрудну морску средину са релативно топлом, чистом водом и дубином од 5 до 40 m (Zuschin & Hohenegger 1998; Wiedl *et al*. 2012, 2013).

• Мање партије песковитих лапораца и неких кластита које су откривене у бушотинама Б-11, Б-15, Б-19 и Б-21 а испод лајтовачких кречњака, имају мало опсервирано распрострањење. Међутим, извесно је да оне имају ванредно важну стратиграфску позицију. Наиме, прелиминарне одредбе присутне микрофауне фораминифера (*Orbulina suturalis*, *Globigerinoides trilobus, Lagena* и др. тј. асоцијација која одговара доњобаденској лагенидној зони) указују да се ради о најстаријим нивоима бадена и управо ти седименти леже трансгресивно преко шарених кластита Врдничке серије. О прецизнијој биостратиграфској детерминацији ових слојева није могуће говорити у овом тренутку (? доња или горња лагенидна зона) без детаљније квалитативне и квантитативне анализе поменутих фораминифера и кречњачког нанопланктона. На тај начин ће бити могуће и утврдити право време када се трансгресија и десила (оквирно пре 15 милиона година), слично ономе како је учињено и у неким другим подручјима по јужном ободу Панонског басена (Ćorić *et al*. 2009; Hohenegger *et al*. 2009; Pezelj *et al.* 2013).