New data concerning the Early Middle Miocene on the southern slopes of Fruška Gora (northern Serbia): a case study from the Mutalj Quarry

LJUPKO RUNDIĆ1, SLOBODAN KNEŽEVIĆ1, NEBOJŠA VASIĆ2, VESNA CVETKO3 & MILOVAN RAKIJAŠ4

Abstract. During the last few years, geological research at the southern slopes of Fruška Gora Mt. enabled the discovery of different Miocene units (undivided the Lower Miocene and Middle Miocene Badenian, predominantly). This is primarily thinking of the so-called Leitha limestone (Middle Miocene, Badenian), which is an important component in cement production (La Farge Co., Beočin). The high carbonate content (more than 98 %) allows it to be a very important raw material that is mixed with Pannonian marl in the process of cement manufacture. Continuous exploitation of this rock at the Mutalj Quarry enabled an insight into its structural, stratigraphic, sedimentological and hydrogeological features, as well as its relation to the other underlying/overlying units. Numerous fossils (i.e., red algae, mollusks, corals, bryozoans, and foraminifers) and their biostratigraphic range indicate to Middle Miocene Badenian age. Based on data from different boreholes, structural and sedimentological characteristics, spatial distribution, etc., a relatively large rock body was discovered (approx. 0.3 km²). Within these Leitha limestones, there are frequent cracks and caverns infilled with fine lateritic clays and alevrites. These clays were sampled for a paleomagnetic study. The carrier of the primary remanent magnetization (RM) is magnetite that has a primary origin. Lateritic clays are characterized by significant value of magnetic susceptibility. The degree of anisotropy of the magnetic susceptibility (AMS) is low with the dominant magnetic foliation.

Key words: Lower Middle Miocene, Badenian limestone, post-Badenian lateritic clays, paleomagnetism, Fruška Gora Mt.

Апстракт. Последњих неколико година, геолошка истраживања на јужним падинама Фрушке горе омогућила су увид у постојање различитих миоценских јединица (нерашчлањен доњи миоцен и првенствено, баденског ката средњег миоцена). Овде се говори пре свега о тзв. лајтовачким кречњацима (средњи миоцен, баден), важној компоненти у производњи цемента (Лафарж, Беочин). Висок садржај карбоната (више од 98%) омогућава им да буду врло значајна сировина, те се додају панонском ла- порцу у процесу производње цемента. Непрекидна експлоатација ових кречњака у каменолому Мутаљ, омогућила је увид у њихове структурне, стратиграфске, седиментолошке и хидрогеолошке каракте- ристике, као и њихов однос према другим, поднисним односно повлатним јединицама. Бројни фосилни (нпр. црвене алге, мекушци, корали, бриозе и фораминифери) и њихов биостратиграфски опсег упућују на млађу баденску старост. На основу података из различитих бушотина, структурних и седимен- толошкох карактеристика, као и просторне дистрибуције кречњака, утврђено је да се ради о релативно великој стенској маси (око 0,3 km²). Унутар те кречњачке масе, честе су пукотине и каверне запуњене финим латеритским глинама и алевритима које су биле и предмет палеомагнетних испитивања. Но-

1 Department of Geology, Faculty of Mining and Geology, University of Belgrade, Kamenička 6, 11000 Belgrade, Serbia. E-mail: rundic@rgf.bg.ac.rs; knezovic.slobodan@gmail.com
2 Department of Mineralogy, Crystallography, Petrology and Geochemistry, Faculty of Mining and Geology, University of Belgrade, Studentski Trg 1, 11000 Belgrade, Serbia. E-mail: vasic.nebojsa@rgf.bg.ac.rs
3 Department of Geophysics, Faculty of Mining and Geology, University of Belgrade, Đušina 7, 11000 Belgrade, Serbia. E-mail: cvetkov@rgf.bg.ac.rs
4 Hidro-Geo Rad, Brankova 23, Belgrade, Serbia. E-mail: smrakijas@yahoo.com
Introduction

The Pannonian Basin was formed as a result of continental collision and subduction of the European Plate under the African Plate during the Late Early to Late Miocene (Fodor et al. 2005). The Late Early Miocene subsidence and sedimentation was an effect of the sin-rift extension phase that resulted in the formation of various grabens filled by thin sin-rift marine and brackish deposits (Cloetingh et al. 2006; Horváth et al. 2006; Dombrádi et al. 2010). The tectonic events that formed the Pannonian Basin also affected the structure of the Neogene deposits of Fruška Gora (FG), which were deformed mainly by radial tectonics. Still, deformations that are more complex have been noted in the Upper Miocene and Pliocene near the Danube, in the influence zone of the regional fault that separated large blocks: the uplifted structures of the mountain. Precise stratigraphic position, a few limestone samples were examined as thin-sections. All the mentioned material is stored in the Faculty of Mining and Geology, Belgrade as well as the Hidro-Geo Rad, Belgrade. Paleomagnetic measurements were conducted on the lateritic clays on three occasions. The first two times were to determine the paleodirections and the last one was to determine the carrier of the remanent magnetization (RM) and the anisotropy of magnetic susceptibility (AMS).

Materials and Methods

All the presented data were obtained on the surface at the Mutalj Quarry and from twelve boreholes (GB-1/10, GB-2/10, GB-3/10, B-16/05, BGMK-1/10, BGMK-3/10, IBMBK-1/10, IBMBK-2/10, IBMBK-4/10, IBMBK-5/10, IBMBK-6/10, IBMBK-7/10 – see Fig. 1; Table 1). Information was plotted on a geodetic plan on the scale 1:25 000, and three geological cross-sections drawn, to be reduced to the scale and prepared for print (Fig. 2).

A detailed sedimentological investigation was performed at the Mutalj Quarry during 2008. Additionally, different fossils were collected to date. For a more precise stratigraphic position, a few limestone samples were examined as thin-sections. All the mentioned material is stored in the Faculty of Mining and Geology, Belgrade as well as the Hidro-Geo Rad, Belgrade.
Technical University of Budapest). The demagnetization data were processed statistically following standard paleomagnetic procedures (KIRCHVINK 1980; FISHER 1953).

Geology of the Mutalj Quarry

The Mutalj Quarry belongs to the village of Bešenovo on the southern slope of FG (N 45°6'29.24"; E 19°41'40.46" – Fig. 1). It is the largest open pit in this part of FG (approx. 295 000 m²). Herein, Triassic and Jurassic rocks make the basement for the Neogene sediments that cover them on the southern side. Generally, the clastic–carbonate sediments of the Lower Triassic, the carbonate facies of the Middle Triassic and the igneous–sedimentary complex of the Middle and Upper Triassic represent the Triassic formations in FG. Tithonian–Berriasian sediments as well as an ophiolite complex represent the Jurassic age (Fig. 2, B–B'). The basement rocks form a very complex structural pattern with features of most diverse folding.

Fig. 1. Geographic position (A), satellite image of southern part of Fruška Gora Mt. (B) and satellite image of the Mutalj Quarry and its simplified geological map (C, D).
and radial deformation. In total, twelve exploration boreholes were investigated (Table 1).

Table 1. Geographic position of the investigated boreholes (WGS84).

<table>
<thead>
<tr>
<th>No.</th>
<th>Borehole</th>
<th>North</th>
<th>East</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IBMBK-1/10</td>
<td>45° 6’ 22.25&quot;</td>
<td>19° 42’ 6.75&quot;</td>
</tr>
<tr>
<td>2</td>
<td>IBMBK-2/10</td>
<td>45° 6’ 20.36&quot;</td>
<td>19° 42’ 16.94&quot;</td>
</tr>
<tr>
<td>3</td>
<td>IBMBK-4/10</td>
<td>45° 6’ 12.94&quot;</td>
<td>19° 42’ 16.61&quot;</td>
</tr>
<tr>
<td>4</td>
<td>IBMBK-5/10</td>
<td>45° 6’ 5.44&quot;</td>
<td>19° 42’ 6.72&quot;</td>
</tr>
<tr>
<td>5</td>
<td>IBMBK-6/10</td>
<td>45° 6’ 34.21&quot;</td>
<td>19° 42’ 15.22&quot;</td>
</tr>
<tr>
<td>6</td>
<td>IBMBK-7/10</td>
<td>45° 6’ 37.73&quot;</td>
<td>19° 42’ 5.99&quot;</td>
</tr>
<tr>
<td>7</td>
<td>BGMK - 1/10</td>
<td>45° 6’ 23.69&quot;</td>
<td>19° 41’ 19.82&quot;</td>
</tr>
<tr>
<td>8</td>
<td>BGOM-3/10</td>
<td>45° 6’ 38.45&quot;</td>
<td>19° 41’ 52.74&quot;</td>
</tr>
<tr>
<td>9</td>
<td>GB - 1/10</td>
<td>45° 6’ 54.77&quot;</td>
<td>19° 42’ 3.45&quot;</td>
</tr>
<tr>
<td>10</td>
<td>GB - 2/10</td>
<td>45° 6’ 45.38&quot;</td>
<td>19° 41’ 57.62&quot;</td>
</tr>
<tr>
<td>11</td>
<td>GB - 3/10</td>
<td>45° 6’ 20.59&quot;</td>
<td>19° 41’ 48.90&quot;</td>
</tr>
<tr>
<td>12</td>
<td>B-16/05</td>
<td>45° 6’ 29.25&quot;</td>
<td>19° 41’ 44.35&quot;</td>
</tr>
</tbody>
</table>

In the area of Bešenovo, the Miocene deposits are distributed along a narrow, discontinuous belt of E–W direction. The best exposure of these sediments is located at the Mutalj Quarry where Middle Miocene Badenian limestone appears. However, based on the exploratory drilling, it was determined that the basis of the Badenian sediments is composed of different rocks from an older Miocene continental series (Fig. 2. B–B’, C–C’). It consists of multi-colored pebbly clays, sands, quartzites, older rock fragments, and conglomerates. Stratigraphically, these rocks correspond to the undivided Lower Miocene (Fig. 2). These sediments were best studied on the southern slopes of FG, near Vrdnik (the Vrdnik Coal-Bearing Basin); hence, they are known as “the Vrdnik Series” or the Vrdnik Formation (PETKOVIĆ et al. 1976; RUNDIĆ et al. 2005). They are transgressive and discordant over the various members of the basement rocks (Fig. 2. B–B’). In certain places, the relationship with the different older fragmented and reworked rocks is probably sharp (Fig. 2, A–A). Based on earlier data (RUNDIĆ et al. 2005), three litho-stratigraphic members within the Vrdnik Series are distinguished: a) at the base, there are various breccias, conglomerates and sandstones, rarely clays, 5–30 m thick; b) above the basis, 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); c) the overburden of the coal layer is composed of a lower and upper overburden. However, based on the facts from the investigated boreholes, there are no coal seams at the Mutalj Quarry. Only a part of that lithological succession is determined. The varicolored terrigeneous series contains brown clay, reddish sandy clay, grayish sand, and pebbles of different rocks (serpentinites, quartzites, diabases, different schist, etc.). It has a great distribution and makes the base for the different younger rocks (see cross-sections in Fig. 2). According to this, it can be supposed that the Lower Miocene sediments have a thickness of more than 100 m.

The marine Badenian sediments have a relatively small distribution at the Mutalj Quarry. If compared to the northern parts of the mountain, there is a clear difference (PETKOVIĆ et al. 1976; RUNDIĆ et al. 2005). The Badenian sediments are present as an elongated, discontinuous rock body with E–W direction and they have much wider distribution on the northern slopes of FG. They are characterized by large diversity of the facies, which is a consequence of various conditions in the coastal area of the former island in the Parate-
thys Sea (conglomerates, sandstones, sandy marls and tuff-sandstones, clays and clayey marls, limestones, etc.). However, the Mutalj Quarry includes three lithostratigraphic members (Fig. 2. B–B’). Very rare grayish-green clay and sandy marl and the wider distributed biogenic limestones (the so-called Leitha limestone). They contain numerous fossils and several types of limestones could be distinguished: lithotamnian, amphistegin, bryozoan, etc. The limestone is massive, reefy, developed by the life activities of the red algae Lithotamnion, foraminifers and bryozoans, and including numerous fossil remains of mollusks, as well as scarce findings of sea urchins, corals and other organisms. Analyses of the sediment determined the dominance of algal and algal–foraminifer biomicrudite and biomicrudite (Figs. 3, 4). On the lateral sides, toward the E–NE periphery of the exploitation area, the limestones turn into marly limestones, sandy marl, and clay (Fig. 2. B–B’, C–C’). The Badenian sediments at Mutalj Quarry are overlaid by Pleistocene red beds. Finally, Pleistocene loess–paleosoil sequences cover both of them (Fig. 2. B–B’, C–C’).

Based on data from the above-mentioned boreholes and from field observations, it can be concluded that there is no rock connection between the active Mutalj Open Pit and the abandoned one (the Beli Kamen Open Pit). This means that there are two independent limestone bodies, which belong to a narrow belt on the southern slope of FG.

**Lithostratigraphy and sedimentology**

A lithostratigraphic column of the Badenian limestone with a total thickness of more than 30 meters (2009) was recorded in the Mutalj Quarry (N 45°06’21.1”, E 19°41’43.1’’). Including the Pleistocene sediments of the Srem Formation and the loess–paleosoil sequences, the overall thickness of the whole section reaches up to 48 meters (Figs. 3, 4). These are white biogenic limestones, very porous and poorly cemented. They have a general appearance of chalky carbonate and contain various fauna of mollusks (clams, snails), algae, and other reef builders. The thirty meters of the column appeared homogeneous without a clearly visible internal stratification or other structural features. At the top of the limestone, there are many emphasized cracks of meter dimensions that are filled by red clays and alevrites. The limestones are permeable and there is an accumulation in the deepest floor of the quarry (see Fig. 3A, B). The dark green water has a high content of carbonate. A typical example of Badenian biogenic limestone – biomicrudite is shown in Fig. 7.

The allochem contains primarily large algal remains. The fragments are rudites. Large pelagic and benthic foraminifers make a small percent of the allochem. Biogenic detritus is minimized. Ortochem is a micrite calcite. The Leitha limestone has an intergranular and intra-granular porosity. The pores sporadically contain a sparite calcite. Non-carbonate ingredients are clay minerals that are either adhered to algal fragments or mixed with micrite. The total content of calcite (CaCO₃) is about 98%.

Over the Badenian bioclastic limestone, there are breccias up to 2 meters thick (Fig. 3). One local phenomenon was noted, even in the realm of the quarry, which, regardless of their limited occurrence, we think consider very interesting. The phenomenon is constructed of a variety, both in size and form, of fragments that originated from the Badenian rocks (Fig. 5). The fragments can be observed macroscopically and they contain algal debris and large foraminifers (Fig. 7D). In some parts of the breccias, there was a significant transport of fragments, while in other parts, there was none at all. It is evident that there are polyphases of its making (Fig. 5). Vertically as well as laterally, there is black scree of black pebbles with centimeter dimensions. The cement of the breccias is carbonate, without fossil remains, painted in different shades of red. Given that, these breccias lie over “karstified” Badenian limestone and under the Srem Formation, their stratigraphic position for the time being, outstanding issues. A sample of the carbonate breccias (No. 33, Fig. 3), which overlies the Badenian biogenic limestone, is built from various, primarily in size, angular fragments. Smaller fragments may have rounded and dark brown to black membranes. These fragments may correspond to grain-type black pebbles. The Badenian algal limestone represents the source rock for the fragments. Each fragment represents the different microfacies. Most of the rudites contain algal fragments and other biogenic allochem similar to that of the Badenian limestone. In addition, as smaller fragments, independent algal grains are embedded in the matrix. The cement is a micrite pigmented with iron oxides. The terrigenous component is evenly distributed throughout the rock. Its content is up to 5%. These are mainly angular quartz grains and fragments of metamorphic rocks. Present in the micrite matrix, there are an irregular cavities filled by sparite calcite which, together with micrite, correspond to a type of dismicrite.

A slightly different example is a sample of limestone breccias (No. 34, Fig. 3). A feature of the fragments is that they all have brown, ferrous membranes (black grains). The fragments do not touch; they are embedded in the matrix. The cement is a micrite pigmented with iron oxides. Within it, the terrigenous component reaches up to 2–3%. The total content of calcite (CaCO₃) is about 97%.

An important characteristic of the Leitha limestone is its high CaCO₃ content, which in certain samples reaches over 98%. Therefore, it is used to enrich the main raw material (Pannonian marl) with carbonates.
Fig. 3. Lithostratigraphic succession at the Mutalj Quarry and the main sedimentological features. The numbers from 25 to 45 show the position of the taken samples.

- Brown to yellow sands and sandy dust of loess-paleosol sequences
- Red colored heterogeneous clastics in triangular diagram gravel-sand-silt. Gravel as a fill of small alluvial channels. (Pleistocene - The Srem Formation)
- Calcareous breccia built of the angular fragments of Badenian limestones. The cement is calcite colored by iron oxides. Local occurrence.
- Black pebbles
- Biomicrudites
- Vertical fissure system filled by fine-grained red material (lateritic clay - paleomagnetic samples)
- White organogenic limestones - Biomicrudite. Organic alchem made of algal remains (Lithotamnion sp.), fragments and the whole remains of shells of mollusks and reef builders, large foraminifers. The content of carbonate between 95.8-99.2%.
during cement production. In the paleogeographical sense, they were deposited during the Badenian, along the southern shore of the former Fruška Gora Island. Due to good insulation, the conditions needed for the development of red algae and other reef-forming organisms were more suitable here than on the northern coast; hence, the Badenian limestones on the southern slopes are richer in $\text{CaCO}_3$.

During the first phase of the limestone exploitation at the Mutalj Quarry, their total thickness was more than 100 meters.

**Fossils in the Leitha limestone**

The fossil macrofauna often contains large forms, such as: *Pecten aduncus*, *P. haueri*, *Chlamys latissimus*, *Glycimeris pilosus*, *Panopea menardi*, *Ostrea lamelosa*, *O. digitalis*, *Isocardia cor*, *Conus mercati*, etc. (Fig. 6). Foraminifers, ostracodes, as well as different algae and bryozoans, have also been recorded. Among the foraminifers, the genus *Amphistegina* is of particular importance and makes the microfacies specific. Following species were recognized: *Amphistegina haueri*, *Globigerina bulloides*, *G. bilobata*, *Asterigerina planorbis*, *Cibicides lobatulus*, *Ammonia* ex gr. *beccari*, *Elphidium crispum*, *Elphidium* sp., *Bolivina* sp., *Lithotamnion* sp. and *Lithophyllum* sp. Similarly, there are other types of these rocks based on the prevailing microfossils (Fig. 7). All the mentioned fossil species suggest the Upper Badenian, which is consistent with field observations and the position of similar sediments on the northern slope of the FG. However, a precise biostratigraphic determination will be realized later.

**Hydrogeological features**

From the hydrogeological point of view, the Middle Miocene Badenian limestones provide a good environment for the formation of karst aquifers. This was confirmed by geological exploration drilling and installation of piezometers, as well as other hydrogeological studies.

Analyses of hydrogeological mapping in the wider area of the Mutalj Open Pit, the bored cores and the infiltration tests determined the large permeability potential of this limestone as well as the overlying beds composed of loess sequences and different pebbly and sandy clay deposits of so-called the Srem Formation (Pleistocene). The results of the infiltration tests (*in situ*) showed that the coefficient of filtration in the Mutalj Open Pit limestone is about $K = 10^{-2}$ cm/s.
According to these results, they belong to the highly permeable sediments. The coefficient of filtration for the overlying sediments is less than $K = 10^{-4}$ cm/s and they belong to the middle-permeable sediments. Based on these results, it can be concluded that the infiltration of atmospheric precipitation into the underground occurred very quickly and recharged the karst aquifer formed in the Badenian limestones. Drainage of the karst aquifer is towards the southwest, which is compatible with the dip direction of the Vrdnik Formation. This was concluded from the results of numerous measurements that were performed in the network of piezometers formed around the Mutalj Open Pit. During 2005, the limestone exploitation reached the groundwater level at an elevation of from 175 m to 177 m and opened the karst aquifer within it.

The hydrogeological conditions and the relation between the Mutalj Open Pit and the abandoned neighboring limestone of the Beli Kamen Open Pit were the objects of detailed investigations during 2010. Main goal of these studies was to explain the geological conditions as well as their hydrogeological relations. Namely, during the past decades, it was not possible to determine whether there is a unique aquifer between these limestone quarries. In addition, there was doubt whether the karst aquifer in the Beli Kamen limestone and the artificial lake formed therein could affect the aquifer recharge in the Mutalj Open Pit. Finally, it could lead to an increased inflow of groundwater from this direction. However, further exploitation of the limestone from the Mutalj Open Pit, as well as its continual dewatering resulted in a lowering of the ground water level; the mirror of the water at level is now at 158.76 m (Table 2).

Table 2. Recent measurements of the elevation of the water mirror.

<table>
<thead>
<tr>
<th>Open pit</th>
<th>Elevation</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutalj</td>
<td>158.76 m</td>
<td>19.11.2010</td>
</tr>
<tr>
<td>Beli Kamen</td>
<td>173.10 m</td>
<td>17.01.2011</td>
</tr>
</tbody>
</table>
All the mentioned geological and hydrogeological data obtained during 2010 show that the space between the pits is not constructed of marine limestone rock. It consists of Lower Miocene lacustrine deposits, dark, grayish-green siltstones, reworked blocks and fragments of diabases and schists, minor pebbles of carbonates, etc. (IBMBK-6/10, IBMBK/7/10). The exploration borehole BGMO-3/10, which was drilled with the purpose of determining of the absence of limestone, showed that there is a diabases block below the mentioned lacustrine sediments. From the hydrogeological point of view, the diabases are impermeable. These formations alternate with low-permeable sediments, such as gray–yellow marly clay, marly sandstone, poorly consolidated sandstone, gravel with lenses of sand, etc. These sediments represent a lateral facies of Badenian limestone (IBMBK-1/10, IBMBK-2/10). Similar geological successions were observed in boreholes IBMBK-4 and IBMBK-5. Different loess and paleosoil sequences form the cover of the mentioned Miocene sediments.

**Paleomagnetic data**

All samples in the NRM domain have measured values of initial magnetic susceptibility in the range $1.9 \text{--} 3.4 \times 10^{-3}$ SI and remanent magnetization in the range $29.1 \text{--} 78.4$ mA/m. The degree of AMS is low with the dominant magnetic foliation indicating remanent magnetization formed during compaction (Fig. 8). Correction for tectonics caused a slight change in the position of the anisotropy axis of the magnetic susceptibility (Fig. 9). Based on the acquisition of iso-thermal remanent magnetization experiment by the method of step-by-step thermal demagnetization three-component IRM (LOWRIE 1990) and the CISOWSKI test (1981), it was found that the primary carrier of natural remanent magnetization is magnetite (Fig. 10). To avoid cracking and loss of the samples during heating, it is planned to perform alternating field demagnetization. However, the presence of a “resistant” RM to the effect of an alternating field (AF) would require the use of thermal demagnetization (Fig. 11). The direction of the high-stability PRM component was determined by principal-component analysis (KIRSCHVINK 1980) and Fisher statistics (FISHER 1953). The isolated paleomagnetic directions are consistent not only within a cavern, but also between the cavities (Fig. 12).

**Interpretation and Discussion**

The Miocene epoch on the southern slope of FG is relatively unknown. Poor data were derived from the BGM 1: 100 000 sheet Novi Sad (ČICULIĆ-TRIFUNOVIĆ & RAKIĆ 1971). Therein, only a few “patches” indicate the presence of Miocene rocks. However, continual investment in the cement industry and the demand for good raw material resulted in numerous drilling in this area. Consequently, a completely different distribution pattern of the Miocene on the southern slope of FG to that on the northern slopes was established.

Lower Miocene undivided heterogeneous rocks have a relatively small distribution. Practically, they are confirmed only in the studied boreholes (Fig. 2). However, based on core data, there is a clear signal for the continental development of the Lower Miocene there. The main characteristics of these deposits are as follows: variegated beds, lack of fauna, domination of coarse-grained clastics, very fast vertical and lateral alternation of facies, noticeable variations in grain size, etc. According to the early known facts regarding the geology of the Vrdnik coal-bearing basin (PETKOVIĆ et al. 1976; RUNDIĆ et al. 2005), these rocks correspond to the upper part of the Lower Miocene Vrdnik Formation. Up to the present, the age of these sediments is not clear. Comparable data comes from the neighboring Požeska Mt. (northern Croatia), where Lower Miocene alluvial deposits were discovered (PAVELIĆ & KOVAČIĆ 1999).
A well-known fact is that the beginning of the Badenian age (Early Langhian, ca. 16.3 Ma) coincides with a marine transgression in the domain of the Central Paratethys (Ćorić & Rögl 2004; Ćorić et al. 2004, 2009; Harzhauer & Piller 2007; Hohenegger et al. 2009; Piller et al. 2007; Rögl et al. 2008). Such records, coupled with different tectonic, seismic and sequence stratigraphy data, indicate to a very powerful and important event (Hováth et al. 2006; Kovač et al. 2007; Schmid et al. 2008). Generally, the Lower Badenian deposits discordantly overlie the older Miocene strata or the pre-Tertiary basement (e.g., the Vienna Basin, the Styrian Basin, the southern margin of the Pannonian Basin in Croatia, Bosnia, Bulgaria, and Serbia).
Serbia – see ĆORIĆ et al. 2009). All the collected facts from the Vojvodina Province and Fruška Gora Mt. indicate to a similar time event (PETKOVIĆ et al. 1976; RADIVOJEVIĆ et al. 2010). It is considered that the marine transgression engulfed the Fruška Gora Island surrounded by the Central Paratethys Sea. On the southern flank of FG, there are no Lower Badenian rocks on the surface. The only evidence for them was found in borehole B-16/05, where sandy marl was drilled at a depth of 53 meters under the surface (see Fig. 2, B–B’). On the other hand, Lower Badenian marine deposits on the northern slopes of FG have a wider distribution (PETKOVIĆ et al. 1976). Nevertheless, younger Badenian sediments have a much wider distribution on FG. During the Late Badenian (Early Serravallian, ca. 13.6–12.7 Ma), algal–bryozoans, and coralline reefs built a distinct belt along both sides of the mountain (Erdelj, Ležimir, Mutalj, etc.). The main sedimentological feature is the enhanced carbonate production controlled by strong volcanism (tuffs, dacites, andesites, etc.). These Badenian limestones are not only high-quality raw materials, but also contain extremely fine association of fossil mollusks, algae, coral, bryozoans, foraminifers, ostracodes and other fauna. For example, warm-temperature pectinids and oysters suggest a shallow-marine, sublittoral to littoral environment (SCHMID et al. 2001). The mentioned biomicrudites with abundant reef-builders could be a part of a small carbonate platform that is existed in the area of FG. Similar records come from northern Croatia and Austria (SCHMID et al. 2001; VRSAJKO et al. 2006). Temperature estimates for the Central Paratethys Miocene mostly rely on a comparison of the biota characteristic for a certain time interval with their present-day relatives. Additionally, a number of isotope and trace element studies are also available for the period considered (BALDI 2006; KOVÁČOVÁ et al. 2009). However, a direct interpretation of these records in terms of paleo-temperature without a consistent control based on faunal records is unsafe (LATAL et al. 2006). The reason is that relatively small epicontinental seas, such as the Paratethys, can be strongly influenced by regional differences in

Fig. 11. Typical demagnetization curves for clay. Key: Zijderveld diagrams and intensity/susceptibility versus temperature curves. During thermal demagnetization, the remaining intensity of the NRM was measured after heating the specimen to a given temperature and cooling back to ambient. In the Zijderveld diagrams full/open circle: projection of the NRM in the horizontal/vertical plane; in the others susceptibility: dots, NRM intensity: circles. In0 - initial intensity of the NRM, k0 - initial susceptibility.

Fig. 12. Mutalj Open Pit, limestone with paleokarst. Paleomagnetic directions (open circles), locality mean paleomagnetic directions (squares) with statistical parameters a95 (interrupted line). Stereographic projection. Key: open circles - negative inclination.
Atlantic Ocean, and the Paratethys (Karami et al. 2011). They applied an oceanic 4-box model to determine the temperature, salinity and exchange flows for the Paratethys and the Mediterranean Sea before and after closure of the Indian Ocean gateways. They concluded that closure of the gateways connecting Paratethys and the Mediterranean to the Indian Ocean had a great impact on the temperature of the basin’s temperature as well as on its salinity. Following this model, it seems that the Badenian predominantly algal and bryozoan limestone suggests warm-temperature conditions (17–21°C) in this period (Kovác et al. 2007).

Based on the lithological succession, the geological and hydrogeological cross-sections and the results of the infiltration tests, it can be asserted with confidence that there is no hydraulic connection between the Mutalj and Beli Kamen Quarries that could have a significant impact on aquifer recharge.

The paleomagnetic study of the post-Badenian latereitic clays shows that biogenic limestones and their products should not be rejected a priori as unsuitable for paleomagnetism but should be viewed as potential carriers of the primary RM. The carrier of remanent magnetization in these clays is magnetite, which occurs in significant concentrations and probably has a primary origin. In relation to the Badenian sediments on the northern slope of FG, which have a positive RM polarity, they have the opposite RM polarity and, practically, same values of inclination (Cvetkov 2010; Lesić et al. 2007). The declination of the RM is counter-clockwise rotated, which is typical for Badenian deposits on FG (Lesić et al. 2007), as well as for other rock masses of the southern part of the Pannonian Basin (Marton 2005). On the other hand, the extracted paleodirection is limited by the Late Pliocene rotation and the Badenian limestone underlying the Pontian sediments, hence, it can be concluded that the mentioned clays formed during the Middle–Late Miocene. This is contrary to common opinion that they belong to the Pleistocene (the Srem Formation, see Petković et al. 1976).

Core data, structural and stratigraphic measurements show that the whole limestone deposit on the southern belt of Middle Miocene Badenian sediments with E–W extension. In the Mutalj Quarry, the limestone has the largest distribution and transgressively lies over the Lower Miocene Vrdnik Formation (up to date, there is no confident data regarding the precise stratigraphic position of these rocks). There are no other Miocene units there. This means that the Middle Miocene Sarmatian and the whole Upper Miocene are completely missing. Different Pleistocene sediments including the red continental beds (the Srem Formation) and the loess–paleosoil sequences form the cover of this limestone.

Sedimentological analyses as well as fossil remains from the limestone indicate to favorable conditions needed for development of marine, shallow-water assemblages (mollusks, foraminifers) and reef-forming organisms, such as red algae, bryozoans, corals, etc. This indicates to the Badenian marine transgression in this part of the Central Paratethys. The mostly algal and bryozoan limestone suggests warm-temperature conditions (17–21°C). This biogenic, shallow-water carbonate unit on the Mutalj Open Pit represents the best section of Leitha limestone on the investigated area. After the Badenian, a continental regime replaced this marine one. Due to the drier climate, red latereitic beds were formed upwards. Additionally, numerous cracks and caverns within the limestone were formed. Later, fine-grained prolluvial sediments filled them.

The Middle Miocene Badenian limestone provides a good environment for the formation of karst aquifers. Analyses of hydrogeological mapping in the wider area of the Mutalj Open Pit, and data from boreholes and infiltration tests determined the large permeability potential of this limestone. The coefficient of filtration is about \( K = 10^{-2} \text{ cm/s} \), thus they belong to the highly permeable sediments.

Based on paleomagnetic investigations, it was determined that the magnetite-bearing sediments deposited during the post-Badenian time mainly do not carry a coherent. In relation to the Badenian sediments on the northern slope of the FG that have a positive RM polarity, they have the opposite RM polarity. The declination of the RM is counter-clockwise rotated, which is a characteristic for Badenian Age (Lesić et al. 2007). However, the extracted paleodirection is limited by the well known the Late Pliocene rotation. Therefore, it can be concluded that the mentioned clays probably formed during the Middle–Late Miocene.

Conclusions

The Mutalj Quarry is located on the southern slope of Fruška Gora. It is the largest Miocene quarry in this part of the mountain. It occupies 0.3 square kilometer of a more or less rectangular area and the mean thickness is more than 40 meters (recent data). The high content of carbonate (more than 98 %) in the limestones allows them to be very important raw materials for cement production (La Farge Cement Factory, Beočin).

Core data, structural and stratigraphic measurements show that the whole limestone deposit on the southern belt of Middle Miocene Badenian sediments with E–W extension. In the Mutalj Quarry, the limestone has the largest distribution and transgressively lies over the Lower Miocene Vrdnik Formation (up to date, there is no confident data regarding the precise stratigraphic position of these rocks). There are no other Miocene units there. This means that the Middle Miocene Sarmatian and the whole Upper Miocene are completely missing. Different Pleistocene sediments including the red continental beds (the Srem Formation) and the loess–paleosoil sequences form the cover of this limestone.

Sedimentological analyses as well as fossil remains from the limestone indicate to favorable conditions needed for development of marine, shallow-water assemblages (mollusks, foraminifers) and reef-forming organisms, such as red algae, bryozoans, corals, etc. This indicates to the Badenian marine transgression in this part of the Central Paratethys. The mostly algal and bryozoan limestone suggests warm-temperature conditions (17–21°C). This biogenic, shallow-water carbonate unit on the Mutalj Open Pit represents the best section of Leitha limestone on the investigated area. After the Badenian, a continental regime replaced this marine one. Due to the drier climate, red latereitic beds were formed upwards. Additionally, numerous cracks and caverns within the limestone were formed. Later, fine-grained prolluvial sediments filled them.

The Middle Miocene Badenian limestone provides a good environment for the formation of karst aquifers. Analyses of hydrogeological mapping in the wider area of the Mutalj Open Pit, and data from boreholes and infiltration tests determined the large permeability potential of this limestone. The coefficient of filtration is about \( K = 10^{-2} \text{ cm/s} \), thus they belong to the highly permeable sediments.

Based on paleomagnetic investigations, it was determined that the magnetite-bearing sediments deposited during the post-Badenian time mainly do not carry a coherent. In relation to the Badenian sediments on the northern slope of the FG that have a positive RM polarity, they have the opposite RM polarity. The declination of the RM is counter-clockwise rotated, which is a characteristic for Badenian Age (Lesić et al. 2007). However, the extracted paleodirection is limited by the well known the Late Pliocene rotation. Therefore, it can be concluded that the mentioned clays probably formed during the Middle–Late Miocene.

Acknowledgements

We would like to express gratitude to the La Farge Co. (Beočin, Serbia) for allowing access to their quarries. The
authors wish to thank Stjepan Ćorić (Geological Survey, Vienna) for useful comments that significantly improved the paper. In addition, thanks go to Violeta Gajić (RGF, Belgrade) and Marija Dedović (Hidro-Geo Rad, Belgrade) for technical support. The Ministry of Education and Science of the Republic of Serbia, Project No. 176015, supported this study.

Reference


Kovačová, P., Emmanuel, L., Hudácková, N. & Renard, M. 2009. Central Paratethys paleoenvironment during the Badenian (Middle Miocene): evidence from foraminifera and stable isotope ($\delta^{13}$C and $\delta^{18}$O) study in the


љиве седименте (K=10⁻² cm/s). Новим истраживањима (2010) је утврђено да не постоји хидраулична веза (нема јединствене карстне издани) између Мутала и напуштеног оближњег каменолома Бели Камен. Висинска разлика између кота водених огледала на та два копа износи око 15 m. Палеомагнетна истраживања пост-баденских латеритских глина показују да се биогени кречњаци не смеју априори одбацити као неподобне стене за палеомагнетна мерења, и треба их посматрати као потенцијалне носиоце примарне магнетизације. Носилац реманентне магнетизације у овим глина је магнетит, који се јавља у великим концентрацијама и вероватно има примарно порекло. У односу на баденске седименте на северним па-динама Фрушке Горе који имају позитиван поларитет реманентне магнетизације, ове глине на Мутаљу имају супротан поларитет и практично, исте вредности инклинације (Lesić et al. 2007; Cvetkov 2010). Деклинација реманентне магнетизације показује ротацију у смеру супротно кретању казаљке на сату што је типично за баден Фрушке горе (Lesić et al. 2007) као и за остале стене у јужном делу Панонског басена (Marton 2005). С друге стране, издвојени палеоправца је ограничен млађе плиоценском ротацијом те се може закључити да су поменуте глине формирane у периоду средњегорњег миоцена.