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Mathematical methods and terminology in geology 2020
(*Matematičke metode i nazivlje u geologiji 2020*)

Review scientific paper

Neogene deposits of the western slopes of the Psunj Mt., Croatia: an overview of historical background and actualisation of geological research

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Dedicated to Dr. Ivan Blašković, Full Professor,
Antovo, Crikvenica, 18. VII. 1935. – Zagreb, 30. VIII. 2008.
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Abstract

On the crystalline rocks of the western slopes of the Psunj Mt. disconformably lie Neogene sediments with recorded deposits from the Lower Miocene to the Quaternary period. The basal Neogene sediments are in the older papers defined as “Oligomiocene” or “preTortonian”, today corresponding to the Lower Miocene sediments. These freshwater and marine-brackish sediments are transgressively overlain by the marine middle Miocene sediments. Badenian deposits are distributed as a continuous belt along the western slopes of the Psunj Mt., east from Pakrac and Lipik, with various lithofacies diversity. In the wider area they are a part of the structure Bijela Stijena–Novska. Lower Sarmatian rhythmic sediments conformably lie on the Badenian sedimentary rocks. The brackish and freshwater development is marked by the continuation of the Upper Miocene sedimentation, and Pliocene sediments with complete “*Paludina* beds” development mark the end of the Neogene. Dominant is the anticlinal structure – structure nose with an axis Bijela Stijena–Novska. In the core of the structure are crystallinic rocks. Neogene sediments are periclinal and almost continued along the limbs and forehead of the structure.

Keywords: Neogene, stratigraphy, petroleum geology, Psunj Mt., Croatia

1. Introduction

Neogene sediments of the western slopes of the Psunj Mt. have been long-time studied by Professor Ivan Blašković and coauthors. They achieved significant results in geological research, giving the valuable overview of the geological development of the Psunj Mt. and Moslavačka gora Mt. during the Neogene, including the petroleum geology characteristics of adjacent parts of the Drava and Sava Depressions, especially the Ilova Subdepression as a marginal part between the Drava Depression toward the Sava Depression.

In this paper the authors presented an overview of the previous geological research of the Neogene deposits of the western part of the Psunj Mt., based on the dissertation of **Blašković (1975),** for which he received university award as the best composed and graphically prepared dissertation, and published papers afterwards. Contributions of Professor Blašković’s dissertation was recognized by the University of Zagreb, which gave him an award for the best graphically designed dissertation. Main goal of this review is to actualize research of the Neogene sediments in the area of the Psunj Mt. and to valorize results of the previous Blašković’s research. The further updates are proposed using examples of Middle Miocene outcrop analyzed in the area of Rogolji near the Psunj Mt. (**Figure 1**). That was compared to sections

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given in **Blašković (1975).** Their significance for the geology of this area is evaluated and compared with the recent knowledge of Neogene evolution in the Northern Croatia.

2. Historical background

Historical background of geological research of the Psunj Mt. is divided in two parts. The first part includes older papers, from the second half of the 19th and beginning of the 20th century, dealing with the geology of Psunj Mt. and the detailed descriptions and contributions from the dissertation of **Blašković (1975)**. Second part of historical background comprises research papers after **Blašković (1975)**.

There are several papers describing mineralogy and older, pre-Neogene rocks of the Psunj Mt., as well as non-available and non-published geological reports from a few geological institutions in Croatia. Here are included only the available and published papers about stratigraphy and paleontology of the Psunj Mt. during the Neogene period, as basic papers for the further research in selected area.

2.1. Research papers from the 1850's until 1975 (Blašković, 1975)

Geological records about the Slavonian Mountains, including the Psunj Mt. are described in **Stur (1861, 1862a,b)**. According to the author, the oldest Neogene deposits of the western slopes of the Psunj Mt. are located northern from Benkovac and Rogolji, and are comprised of "Lithothamnium limestone" (“*litavac*”; see more on topic “Lithothamnium limestone” and “litavac” and differences between them in e.g., **Basso et al., 2009**) and Badenian clay below, containing rich mollusc fauna, foraminifers and bryozoans.

Paul (1870, 1872, 1874) describes the younger Neogene deposits from Slavonia, including the Psunj Mt. area. He continues the stratigraphic research after Stur, and divides the deposits overlying the white marls on older “Congerian sediments”, and younger “*Paludina* clays” or freshwater facies.

Paper by **Neumayr and Paul (1875)** is of big importance for the stratigraphy and paleontology of younger Neogene deposits in Slavonia. The authors described in detail the Pliocene of Slavonia emphasizing the “*Paludina* beds” and dividing them into the lower, middle and upper “*Paludina* beds” based on the phylogeny of the gastropod genus *Viviparus* (before known as *Paludina*).

The first detailed geological maps (M 1:75 000) of the area of Daruvar and Pakrac – Jasenovac are given by **Koch (1908a,b; 1935)**. He described the Neogene sediments as a ring around the western Slavonian Mountains. According to him, the oldest Neogene deposits are the Badenian "Lithotamnium limestone" (sometimes called “*litavac*”) deposited in the shallow sea environments, and marls in the deep marine environments. The marls are older than the Badenian (“Tortonian”) conglomerates near Rogolji, Trnakovac and Benkovac, described in **Stur (1861, 1862a,b)**. Koch corrected Stur's comparison of Rajić marls with the Sarmatian deposits of Radoboj and compared them with the Badenian marls. He also considers the white limy marls of the Upper Sarmatian by **Stur (1862b)** as the freshwater deposits of the Lower Pliocene, with the congerian marls and sands and “*Paludina* beds” in the top.

In the early 1940's began the more intensified geological research on oil and gas in northern Croatia. One of the most significant papers regarding the geology of Neogene deposits of northern Croatia and corresponding oil geology is **Ožegović (1944)**, in which the author describes stratigraphic relations of younger Neogene (then “Tertiary”) deposits according to the data collected from the drilled cores. The research area to which belongs and here presented area, **Ožegović (1944)** describes as the valley of the river Ilova known as a “Tertiary” valley between the Moslavačka gora Mt. on the west, Psunj and Papuk Mts. on the east and Bilogora Mt. on north. Neogene basement was drilled in the wells of the Ilova River valley, i.e. the Ilova Subdepression (according to the petroleum geology division of the Croatian part of the Pannonian Basin System, abbr. CPBS), and the author concluded the existence of crystalline basement spread also in Moslavačka gora, Psunj and Papuk, Motajica and Prosara Mts. **Ožegović (1944)** mentioned Paleozoic and Mesozoic rocks of the Psunj Mt., which were most probably eroded from the crystalline basement of the drilled area, and gave the material for the Neogene sedimentation in the depressions.

The first part of the research era ends with the **Blašković (1975)** dissertation as a “path for the further research” of the Neogene sediments of the western slopes of the Psunj Mt. area. In his dissertation, **Blašković (1975)** gives special attention to the Ilova Subdepression as a connection between the Sava and Drava Depressions. He collects data on lithostratigraphic characteristics of the Neogene sediments, thickness of the deposits of the chronostratigraphic units and tectonic elements based on the field research, which he interprets together with the available geological, geophysical and deep drilling research data (**Blašković, 1975 and references therein**). **Blašković (1975)** also gives the reconstruction of the structural-tectonic and paleogeographical relations.

2.2. Research papers after 1975 (Blašković, 1975)

There are a few papers dealing with the Neogene sediments of the western slopes of the Psunj Mt. after the **Blašković (1975)** dissertation. The more detailed stratigraphic and paleoecological significance of the mentioned papers is given in Discussion chapter, and here are listed source selected as the most important for the further research in study area.

Blašković et al. (1975) described lithological and paleogeographical characteristics of the Miocene sediments at the western slopes of the Psunj Mt., between Kraguj and Šeovica, ranging from the Lower "Tortonian" (today Badenian) to the Upper Pannonian.

Kranjec and Blašković (1976) present the results of the detailed geological mapping of younger "Tertiary" (today Neogene) and Quaternary sediments from the western area of the Psunj Mt., i.e. Jagma – Popovac – Paklenica. The authors extended the knowledge of the stratigraphy, tectonics and structural-geomorphology of the investigated area, and emphasize the Upper Pontian (today Pannonian *sensu* **Pavelić and Kovačić, 2018** and references therein) and "*Paludina* beds" containing quartz-sands.

Blašković et al. (1981) described the Lower Sarmatian deposits from the southwestern slopes of the Psunj Mt., characterized by the regular rhythmic alternation distinguishing lithological sequences, and identifying the turbidity currents sedimentation caused by paleogeographic conditions between the Bijela Stijena–Novska paleostructure and Psunj Mt.

Different "Tortonian" (today Badenian) deposits from the area of Okučani, Pakrac and Novska, i.e. western slopes of the Psunj Mt., were described by **Blašković et al. (1982)**. The authors distinguished seven lithofacies, suggesting different depositional environments such as coastal, near-reef, reef, back-reef, turbidites and upper slope.

Blašković et al. (1984) summarize the results of the Miocene sediments research of the western slopes of the Psunj Mt., i.e., in the Lipik-Okučani-Novska region, and presented the lithofacies and sedimentological interpretation of the paleoenvironment and sedimentary conditions, particularly "pre-Tortonian" (pre-Badenian), "Tortonian" (Badenian) and Lower Sarmatian deposits.

Geology of the wider area of the western slopes of the Psunj Mt. is shown on the Basic Geological Map, sheets Nova Gradiška (**Šparica et al., 1984a**) and Daruvar (**Jamičić, 1989**), and described in the explanatory notes of the sheets (**Šparica et al., 1984b**; **Jamičić et al., 1989,** respectively).

Among the paleontological papers, **Kochansky-Devidé and Slišković (1978)** described dreisenid bivalves from the localities of the Miocene age in Croatia and Bosnia and Herzegovina, including the Rogolji locality.

Sokač (1987) described a new ostracod genus from the Bjelanovac section on the western slopes of the Psunj Mt., found in the pre-Badenian freshwater deposits, and indicating the Middle Miocene age.

From the recent papers, **Kruk et al. (2005)** described quartz sand deposit Jagma-6 near Lipik, explaining the paleoenvironmental conditions and genesis of the quartz sand in the Rhomboidea-beds of the upper Miocene.

Malvić (2003) described Neogene and Quaternary evolution of the Bjelovar Subdepression, which included also the Ilova Subdepression and western margins of the Psunj and Papuk Mts. The numerous data from deep wells are presented as well as regional structural and thickness maps using EK markers and borders, and lithostratigraphic formations or members in the Drava Depression. **Malvić (2011)** published separated and re-drawn set of such maps in the Bjelovar Subdepression.

3. Geological settings

The investigated area of Psunj Mt. during Neogene paleogeographically belonged to the Paratethys realm and later to consequent brackish and fresh water lakes (Pannon, Slavonia and smaller remnants) (e.g., **Rögl, 1998; Pavelić et al., 2003; Harzhauser and Piller, 2007; Kováč et al., 2007, 2017; Piller et al., 2007; Pavelić and Kovačić, 2018 and references therein; Vrsaljko et al., 2018 and references therein**). Paratethys started developing during the Oligocene, in the northern area of the former Tethys Ocean, and represented by a system of Paratethyan sedimentary basins distributed from Central Europe to Central Asia, due to tectonic changes. The connection of the Paratethys Sea with the Mediterranean and Indo-Pacific was unstable due to the constant paleogeographical changes controlled by geodynamic, climatic and glacio-eustatic fluctuations (e.g., **Rögl, 1998; Harzhauser and Piller, 2007; Piller et al., 2007; Kováč et al., 2017, 2018**), which reflected in opening and closing of the marine seaways. Due to the changes in fauna content between the Paratethys area/basins, three parts are recognized: Western, Central and Eastern Paratethys (e.g**., Rögl, 1998; Harzhauser and Piller, 2007; Kováč et al., 2007, 2017; Piller et al., 2007**). On the **Figure 1** is shown the location of the here presented area of Croatia, which belongs to the Central Paratethys area, and geotectonically to the Pannonian Basin System, bordered by the mountain chains of the Alps, Carpathians and Dinarides. The Central

Paratethys Sea persisted from the Oligocene to the Sarmatian with the open marine conditions and fully marine fauna (e.g., **Rögl, 1998; Harzhauser and Piller, 2007**; **Kováč et al., 2007; Piller et al., 2007**), and the major expansion (marine transgression) of the Central Paratethys is dated as the Middle Miocene and known as the Badenian marine flooding (e.g., **Rögl, 1998; Harzhauser and Piller, 2007**; **Kováč et al., 2007; Piller et al., 2007; Ćorić et al., 2009**; **Malvić, 2012**). During the Badenian marine connections were possibly open to the Mediterranean via the "Transtethyan Trench Corridor" (Slovenian gateway), but there is still strong debate going on about the existence of open marine connections between Paratethys and neighbouring marine areas during the Badenian stage (e.g., **Rögl, 1998; Studencka et al., 1998; Piller et al., 2007; Bartol et al., 2014**). There was also eastern connection toward Black Sea and Indopacific paleobasins. Open marine conditions persisted until ~12.6 Ma when the gradual extinction of the fully marine biota and disappearing of marine environments marks the regional Sarmatian age, being replaced by brackish, lacustrine, fluvial and terrestrial environments and living creatures (e.g., **Pavelić and Kovačić and references therein; Vrsaljko et al., 2018 and references therein**).

Here we present the general outline of the Neogene paleoenvironments of the Croatian part of the Pannonian Basin System (CPBS). The Pannonian Basin System formed in the Early Miocene due to the continental collision and subduction of the Euroasian plate beneath the Pannonian crustal fragment. CPBS is a rift-type basin. The extensional tectonics started during the Early Miocene and generated forming of the four half-grabens as the elongated subbasins as the main depocentres: Drava Depression, including the Bjelovar Subdepression, Sava Depression, including the Karlovac Subdepression, Mura Depression and Slavonija-Srijem Depression (e.g., **Pavelić and Kovačić, 2018 and references therein**; which also similar area described as the North Croatian Basins). The evolution of the basin is divided into two or four phases, synrift and postrift, during which the basin was marked by transgressive-regressive cycles (e.g., **Kováč et al., 2007, 2018; Pavelić and Kovačić and references therein**). Synrift phase lasted from the Early Miocene – Ottnangian, until the Middle Miocene – Middle Badenian, and was characterized by the continental environments changed to the marine environments. The postrift lasted from the Middle Miocene – Late Badenian to the Quaternary and was characterized by the marine environments replaced by continental environments. In later work it was improved in model with two transtensional and two transpressional phases (e.g., **Malvić and Velić, 2011**).

After the development of the Paratethys sea during the Eocene – Oligocene boundary, sedimentation continued during the Oligocene only in north-western Croatia (**Pavelić and Kovačić, 2018**; **Vrsaljko et al., 2018 and references therein**). The deposition in the CPBS started in the Ottnangian, with the formation of continental environments, with the oldest deposits being the alluvial deposits. **Pavelić and Kovačić (2018 and references therein)** assumed the existence of one large lake in the Early Badenian. Marine environments were introduced in the CPBS by one of the Middle Miocene – Badenian transgression (e.g., **Rögl, 1998**; **Kováč et al., 2007**; **Piller et al., 2007**; **Ćorić et al., 2009 and references therein**). Marine transgressions in the Paratethys area during the Early Miocene did not affect the CPBS, and the basement was unconformably overlain by deposits of different age. The full marine conditions lasted until the Sarmatian, during which the shallowing of the Central Paratethys started, and there was only a connection to the Eastern Paratethys by a narrow marine connection into the Indopacific/Black Sea (e.g., **Rögl, 1998**; **Piller et al., 2007**). The end of Sarmatian is marked by the regression caused by eustatic sea-level fall. The final isolation of the Central Paratethys Sea commenced around 11.6 Ma ago when Lake Pannon formed (e.g., **Magyar et al., 1999**; **Harzhauser and Piller, 2007**; **Piller et al., 2007**). Decreased salinity generated evolution of endemic, brackish-water fauna. The Pannonian lithology indicates that the river floodplains and delta systems already existed in CPBS by the early Pannonian and reached its eastern part in the latest Pannonian (**Pavelić and Kovačić, 2018 and references therein**). According to the recent studies (e.g., **Mandic et al., 2015**), the boundary between the Miocene and Pliocene is placed at about 4.5 Ma, marking the beginning of the Lake Slavonia. Described paleogeographical changes in the Central Paratethys resulted in the style of the development of the basin different from the Mediterranean, and evolution of endemic species, therefore the Neogene regional stages for the Central Paratethys have been introduced (**Figure 2**), which are, for the investigated area, described in the Discussion of this paper.

Blašković (1975) describes two geological complexes of the Ilova Subdepression area; (a) the magmatic-metamorphic complex with partially sedimentary complex of the Paleozoic and Mesozoic age, recorded on the surfaces of Papuk, Psunj and Moslavačka gora Mts., and also as the pre-Neogene basement of the wider area by drilled cores, and (b) sedimentary complex of the Neogene and Quaternary period (further in the text). The Paleozoic and Mesozoic rocks are considered the basement of the Neogene and Quaternary deposits and represent the terrestrial environments which gave the local material for the deposition of the younger sediments.

Here presented area of the western slopes of the Psunj Mt. is a part of the tectonic anticline structure, a structural nose. The axis of the nose stretches from the Bijela Stijena locality to the town of Novska (**Figure 2**) (e.g., **Blašković, 1975; Blašković et al, 1982, 1984**). Crystalline rocks are in the core of the structure, and the Neogene deposits surround the core marking the limbs and the forehead of the structure nose.

The investigated locality is located near the Rogolji locality (**Figure 2**), in the north-western part of the Bijela Stijena structure, where Middle Miocene – Badenian ("Helvetian" by **Jamičić et al., (1989)**) sediments are recorded (e.g, **Blašković, 1975; Blašković et al., 1982, 1984**).

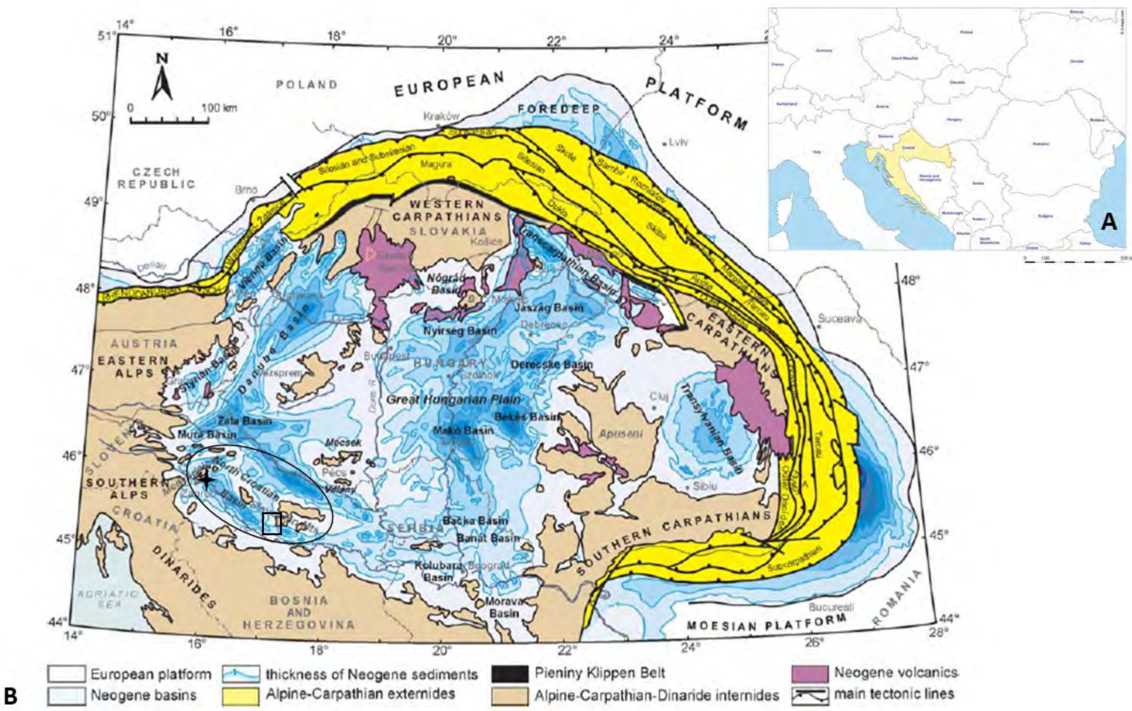

Figure 1: Pannonian Basin System (after **Kováč et al., 2007**). A) Geographical position of Croatia, coloured in yellow (after **https://d-maps.com/carte.php?num_car=2242&lang=en**). B) Pannonian Basin System. Marked area is the location of the Croatian part of the Pannonian Basin System. Four-point star marks the location of Zagreb, capital of Croatia. Rectangular marks the investigated area of the western slopes of the Psunj Mt.

4. Results

The schematic lithological column of the investigated outcrop on the Bijela Stijena structure is shown on **Figure 3**. The height of the outcrop is more than 8 meters and it is made of two sequences of the Badenian sediments. They overlay the Paleozoic Basement ("Temeljno gorje" in Croatian). The Neogene basement, in wider area, is composed of Paleozoic and Mesozoic rocks, but in both cases the top is represented by transgressive fluvial-lacustrine or marine Neogene sediments. The thickness can vary widely and sometimes cannot be determined (**Blašković, 1975**), but is measured on the here presented outcrop. The first sequence recognized at the outcrop is made of the fine-grained laminated sandstones with the thickness 3 meters or more (**Figure 3**). The sandstones contain biogenic detritus, with fragments of corals, molluscs (bivalves ostreids and pectinids), echinoid spines and possible algae, indicating the fully marine conditions with prevailing fossil echinoid spines. The second sequence of sandstones is around 5 meters or more thick. The sandstones are characterized with coarsening upward sequence and are consisted of fragments of fine-grained sandstones in a dominant conglomeratic sandstone (**Figure 3**). Fossil findings are similar as in the first sandstone sequence, but more crushed, and again with echinoid spines as the most numerous fossil findings.

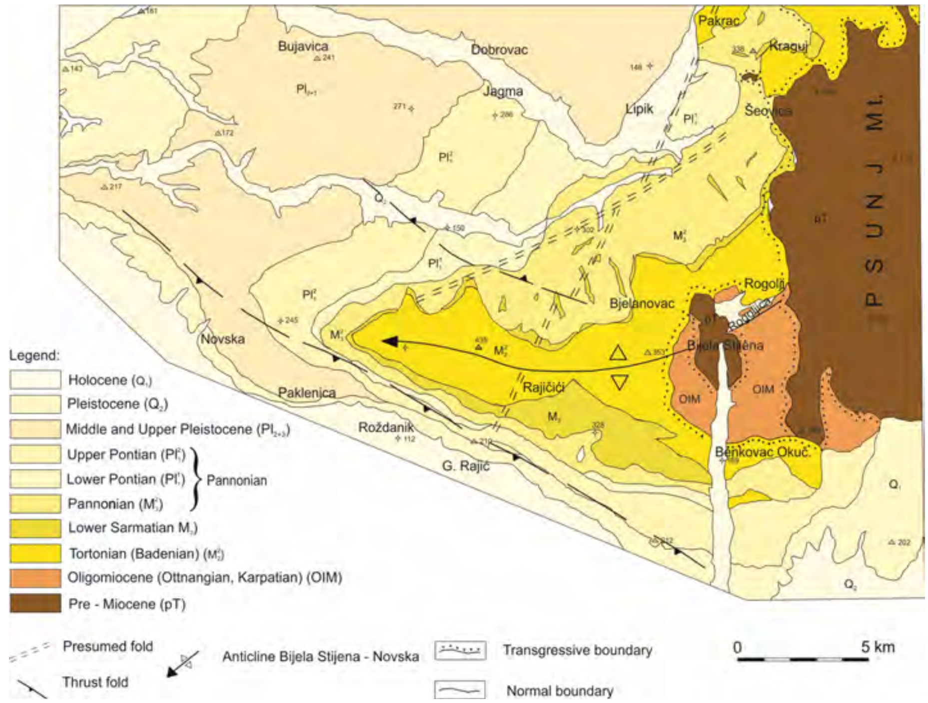

Figure 2. Neogene regional stages for the Central Paratethys compared to the stratigraphic units in **Blašković (1975)** and **Blašković et al. (1982, 1984)** for the area of the western slopes of the Psunj Mt. shown on the schematic geologic map (after **Blašković, 1975**). *after International Commission on Stratigraphy 2020 (**www.stratigraphy.org**); ** after **Pavelić and Kovačić (2018)** and references therein; ***after **Blašković (1975)** and **Blašković et al., (1982, 1984)**

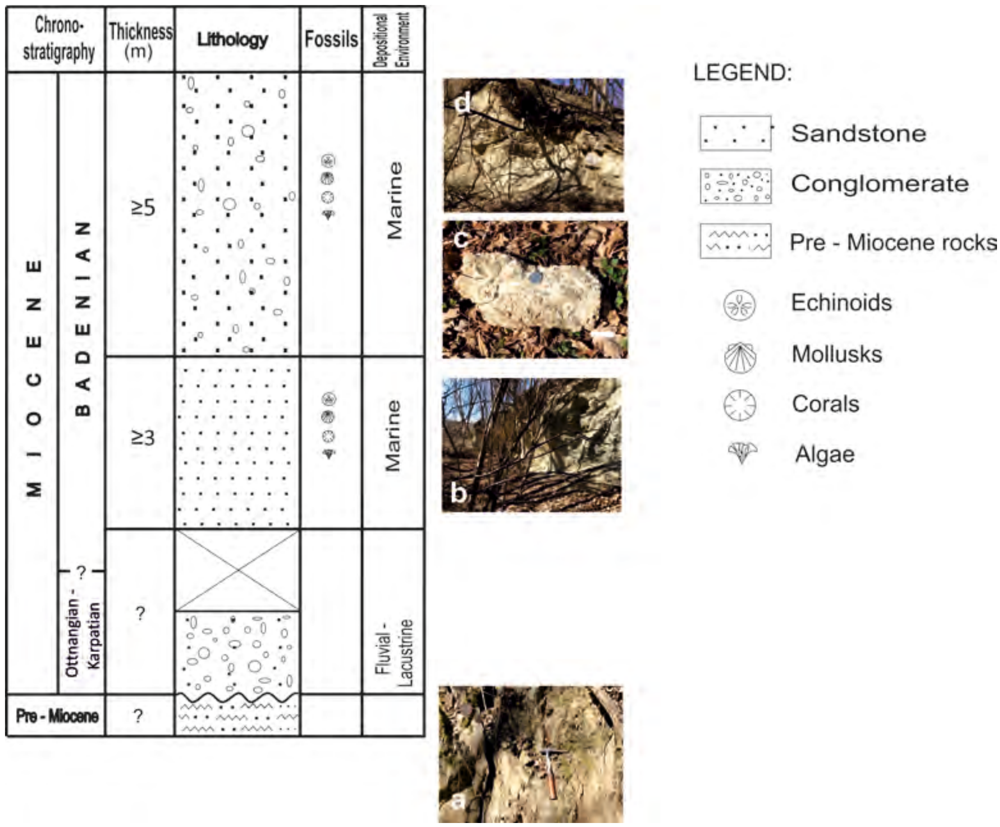

Figure 3. Schematic geological column of the investigated outcrop Bijela Stijena near Rogolji. a) Pre-Miocene rocks, in the wider area of Rogolji locality); b) First Badenian sandstone sequence; c and d) Second Badenian conglomeratic sandstone sequence.

5. Discussion and Conclusions

As can be seen in the research papers of the Neogene sediments of the western slopes of the Psunj Mt. and wider area, the Neogene deposits recognized at the area are divided in the chronostratigraphic units according to the "old chronostratigraphic unit" of the CPBS shown on the **Figure 2**. The old units are compared to the "new chronostratigraphic division" of the Central Paratethys and described in this chapter.

5.1. Neogene stratigraphic units of the western slopes of the Psunj Mt.

5.1.1. Lower Miocene – Ottnangian – "Oligomiocene"

The oldest deposits disconformably covering the pre-Miocene basement are of the "Oligomiocene" age after **Blašković (1975)** or "Pretortonian" after **Blašković et al. (1984)**, corresponding to the recent division to the Lower Miocene – Ottnangian (**Figure 2**). In the general lithology of the stratigraphic unit, dominate marls with subordinately present sands, conglomerates and gravels (**Blašković, 1975; Blašković et al., 1984**) recorded at the Rogolji and Bjelanovac locality (silty marls) and Okučanski Benkovac I, Dobrovac and Rogoljica (conglomerates, gravels, sands/sandstones) (**Figure 2**). **Blašković et al. (1984)** report fragments of bryozoans, bivalves, echinoids and planktic foraminifers found in the sandstones, and redeposited from the coastal area.

In the Lower Miocene deposits, **Blašković et al. (1984)** differentiate four lithofacies: A) low energy shallow sea or marly lithofacies; B) near coast, chaotic coarse-grained clastic sediments; C) delta fans D) fine-grained clastic-carbonate (basin) deposits.

From the investigated localities in the literature, freshwater and marine-brackish developments are distinguished. The freshwater development is present at the Rogolji and Bjelanovac localities, corresponding to the above mentioned lithofacies A (**Figure 2 after Blašković, 1975**), supported by the present dreienids and ostracods (**Blašković, 1975**; **Blašković et al., 1984**), and **Kochansky-Devidé and Slišković (1978)** defined Rogolji locality as the Ottnangian in age according to the dreisenid fauna. Profile in the area of Okučanski Benkovac after **Blašković (1975)** (**Figure 2**) comprises marine-brackish sediments deposited in the marine environment with weak freshwater influx.

The Lower Miocene deposits of the western slopes of the Psunj Mt. were deposited in the alluvial environment in the time span from the beginning of the Ottnangian to the end of the Karpatian (e.g., **Pavelić and Kovačić, 2018 and references therein**).

5.1.2. Middle Miocene – Badenian– "Tortonian"

Middle Miocene, "Tortonian" (= Badenian) deposits are recorded in the area east of the Pakrac and Lipik cities (**Figure 2**). They are marked by the lithological diversity as a result of varied environmental and depositional conditions, paleorelief, and by the regularity in the lateral and vertical changes (e.g., **Blašković et al., 1982 and references therein**). The Badenian deposits of the western slopes of the Psunj Mt. are made of conglomerates, conglomeratic sands / sandstones, sands / sandstones, biocalcrudites and biocalcarenites, sandy and silty marls and clayey limestones (**Blašković, 1975; Blašković et al., 1982**).

There are seven Badenian lithofacies recognized at several localities in the western part of the Psunj Mt. according to **Blašković et al. (1982)**:

(A) coarse-grained clastic coastal (littoral) lithofacies
(B) biohermal lithofacies
(C) biocalcarenitic fore-reef lithofacies
(D) lithofacies of back-reef shoals
(E) sandy-marly lithofacies
(F) lithofacies of transitional slope
(G) turbidite lithofacies

Blašković et al. (1982) describe in detail the lithofacies recognized at the area of Bijela Stijena structure (localities Rogolji, Bjelanovac, Bijela Stijena), northern from the Bijela Stijena structure, in the area east from Pakrac (localities Šeovica, Omanovac, Sigovac) and west and south from the Bijela Stijena structure (localities Rajičići, Dobrovac, Okučanski Benkovac, Luka stream, Roždanik) (**Figure 2**). At the area of Bijela Stijena structure authors recognized lithofacies A, C and E, and eastern from Pakrac city the lithofacies B and D are present. Lithofacies E is present in the area of Bijela Stijena structure and eastern from Pakrac (**Figure 2**). To the west and south from the Bijela Stijena structure, lithofacies F and G are recognized.

Lithofacies (A) is recognized at the Rogolji, Bjelanovac and Bijela Stijena localities (**Figure 2**), and is comprised of transgressive conglomerates of the coastal environments lying on the pre-Badenian marls or directly on the crystalline rocks (**Blašković, 1975; Blašković et al., 1982**). There are differences in the fossil record between these localities: in Rogolji prevail fragments of lithothamnions (coralline algae), bivalves and bryozoans, and at the Bjelanovac and Bijela Stijena area the most numerous are fragments of echinoids and bivalves (**Blašković et al., 1982**).

The area east of Pakrac city (**Figure 2**) is covered by "Lithothamnium limestones" of *lithofacies (B)*, covering the Badenian transgressive contact with the crystalline basement (Šeovica, Omanovac, Sigovac) as described in **Blašković et al. (1982)**. Together with numerous coralline algae, there are recorded pectinid and ostreid bivalves, gastropods and bryozoans.

Lithofacies (C) is present at the Rogolji locality (**Figure 2**), with uniform development of biocalcarenites with well sorted fragments of lithothamnions, echinoids, bryozoans, bivalves and scarce benthic foraminifera (**Blašković et al., 1982**).

Lithofacies (D) is marked by the Badenian transgressive sediments with bivalve coquinas (pectinids, ostreids) in a clayey-carbonate (marly) matrix, and smaller pectinids, brachiopods and echinoid spines. At the investigated localities Sigovac and Šeovica (east from Pakrac city, **Figure 2**), the Badenian sediments are directly overlying the crystalline basement (**Blašković et al., 1982**). The authors recorded lateral transition of lithofacies (D) into lithofacies (B), covered by the sediments of the lithofacies (E).

Blašković et al. (1982) describe *lithofacies (E)* in the area of Bijela Stijena structure and at the localities east from the Pakrac city (**Figure 2**), as a sequence with mostly vertical exchange of sandy-marly sediments. The most numerous fossils are fragments of bryozoans, bivalves and echinoids, and less lithothamnion fragments and benthic foraminifera.

The authors also recorded bentonite layers at the Bjelanovac locality (**Figure 2**), which could indicate altered tuff and/or tuffites.

From the Bijela Stijena structure to the west, **Blašković et al. (1982)** describe the transition from the lithofacies (A), (C) to (E) and *lithofacies (F)*, which is marked by the frequent change of sand layers, sandy-silty marls and marls. Lithofacies (F) is changing to the *lithofacies (G)* in the deeper parts of the sedimentary basins, marking the turbiditic lithofacies. Lithofacies (G) is recorded also in the southern part of the Bijela Stijena structure and marked by the regular rhythmic change of sequences made of conglomeratic sand / sandstones, middle- to fine-grained sands / sandstones, sandy-silty marls, marls and sometimes marls rich in carbonate and /or clayey limestones.

The analysed outcrop near Bijela Stijena structure shown on **Figure 3**, corresponds to the lithofacies (A). The sandstone sequence with conglomerates points to the transgressive rocks of the coastal environments, and the zone of high wave energy. Fossil fragments of red algae and echinoids point to the shallow environments and reef structures. Crushing of the shells in the high energy water produced fossil detritus deposited in the interspace of coarser pebbles.

According to **Pavelić and Kovačić (2018),** Early Badenian of the Croatian part of the Pannonian Basin System is marked by the lacustrine development, with gradual replacement by the marine environments due to the marine transgression and flooding during the Middle Badenian. The end of the Badenian is also marked by the widespread transgression in the Late Badenian, which was of regional character. The marine deposits of the "Tortonian" age described in older papers correspond to the Middle and Late Badenian sediments.

5.1.3. Middle Miocene – Sarmatian– Lower Sarmatian

Lower Sarmatian deposits conformably overlie the Badenian sediments (**Blašković, 1975**). **Blašković et al. (1984)** describe Lower Sarmatian deposits as similar to turbiditic lithofacies (G) of the "Tortonian" (Badenian), with main characteristic of frequent and regular rhythmic change between sandy-marly-clayey-carbonate sediments, described also in **Blašković et al. (1982)**. From the investigated Lower Sarmatian profiles, **Blašković (1975)** describes redeposition of Badenian fossils in the Sarmatian, with exception of fauna adapted to the brackish Sarmatian conditions.

Pavelić and Kovačić (2018) describe Sarmatian deposits as overlying the Badenian in a continuous depositional succession with a transgressive-regressive cycle. The latest Badenian was marked by the sea-level fall, and the deposition of Sarmatian sediments was in a restricted marine environment of reduced salinity, with the shallowing trend in the latest Sarmatian, marking the beginning of closure of the CPBS.

5.1.4. Upper Miocene – Pannonian

The boundary between the Sarmatian and Pannonian is marked by a major drop in a sea-level base. During the Pannonian, area of the CPBS was isolated from the sea, forming the brackish Lake Pannon with a consequent adaptation and speciation of endemic molluscs (**Pavelić and Kovačić, 2018 and references therein; Vrsaljko et al., 2018 and references therein**). Pannonian is divided into four zones based on the present molluscs (the oldest *Croatica*, *Banatica*, *Abichi* and the youngest *Rhomboidea* beds). The *Croatica*-beds were deposited during the low-stand, as a consequence of the regression in the latest Sarmatian. *Banatica*- and *Abichi*-beds were deposited in the deeper lake environments. *Rhomboidea*-beds are characterized by delta front due to a final infilling and closing of the lake.

Until recently, Upper Miocene sediments of the CPBS were divided into the Pannonian and Pontian horizons, with the subdivision on the zones based upon molluscs: Croatica (lower Pannonian, based on the gastropod *Radix croatica*), Banatica (upper Pannonian, based on the bivalve *Congeria banatica*), Abichi (lower Pontian, based on the bivalve *Paradacna abichi*) and Rhomboidea (upper Pontian, based on the bivalve *Congeria rhomboidea*). According to the new division of the Upper Miocene in the CPBS (**Figure 2**), there is only the Pannonian stage in the Upper Miocene, and the four marker zones are considered to be of the early Pannonian (Croatica- and Banatica-beds) age and of the late Pannonian (Abichi- and Rhomboidea-beds) age (**Pavelić and Kovačić, 2018 and references therein**). The authors also mention the possibility that the upper Rhomboidea-beds were deposited during the Pliocene Epoch (Early Pliocene = Zanclean).

a) Lower Pannonian (Croatica beds)

Pannonian sediments *sensu stricto* are, in the wider area of Bijela Stijena structure, mostly represented by the marly limestones, calcareous marls and marls. They overlie the Lower Sarmatian, Badenian or pre-Miocene deposits (**Blašković, 1975; Blašković et al., 1975**).

The dominant member of the *Croatica* beds are the clayey limestones ("white marls"), with marls, silty and sandy marls and mostly thin layers of sand, that is, sandstones (**Blašković et al., 1984**).

Kranjec and Blašković (1976) describe the Upper Miocene deposits of the area between Jagma, Popovac and Paklenica (**Figure 2**). The authors describe Croatica-beds in two sequences: lower part is composed of hard, thick and thin platy white and light grey marly limestone, while in the upper part marly limestones and limy marls prevail. Fossils recorded in the *Croatica*-beds are characteristic for the Pannonian ("Lower Pannonian") deposits and comprise freshwater molluscs: gastropods *Radix croatica* (Gorjanović-Kramberger, 1890), *Radix extensa* (Gorjanović-Kramberger, 1890) (old name *Lymnaea extensa* Gorjanović-Kramberger, 1890), *Gyraulus vrapceanus* Neubauer, Harzhauser, Kroh, Georgopoulou & Mandic, 2014 (old name *Planorbis dubius* Gorjanović-Kramberger, 1890), *Gyraulus* (*Gyraulus*) *praeponticus* (Gorjanović-Kramberger, 1890), then bivalves limnocardiids, dreisenids, ostracods and fish remains (**Blašković, 1975; Kranjec and Blašković, 1976**).

*b) Upper Pannonian (*Banatica *beds)*

Banatica-beds overlie the *Croatica*-beds (**Figure 2**), and are lithologically similar to them, represented by the mostly grey and light grey marls with freshwater mollusc fauna (e.g., bivalve *Congeria banatica* R. Hörnes, gastropod *Gyraulus tenuistriatus* (Gorjanović-Kramberger, 1899) (old name *Planorbis tenuistriatus* Gorjanović-Kramberger, 1899) and fossil flora remains (**Blašković, 1975; Kranjec and Blašković, 1976**).

*c) Lower Pontian (*Abichi *beds)*

Abichi-beds (**Figure 2**) overlie the marly sediments of the *Banatica*-beds, and are represented by the light and dark grey greyish to brownish marls and clayey marls rich in macrofossils: bivalves *Paradacna abichi* R. Hörnes, *Paradacna* sp., *Congeria zagrabiensis* Brusina and gastropods *Gyraulus tenuistriatus* (Gorjanović-Kramberger, 1899) (old name *Planorbis tenuistriatus* Gorjanović-Kramberger, 1899), *Lymnaea* sp., Valenciennius reussi Neumayr in Neumayr & Paul, 1875 (old name *Valenciennesia reussi* Neumayr in Neumayr and Paul, 1875), *Valenciennesius* sp. (**Blašković, 1975; Kranjec and Blašković, 1976**).

*d) Upper Pontian (*Rhomboidea *beds)*

Rhomboidea-beds represented by marls, clay and sands concordantly come on the Abichi-beds and make the continued belt around the Bijela Stijena structure–Novska area (**Figure 2**). **Blašković (1975)** and **Kranjec and Blašković (1976)** describe two parts of the Rhomboidea-beds: marly sediments in the lower part, and sandy-clayey sediments with limy concretions in the upper part. The authors list rich fossil findings in *Rhomboidea*-beds: bivalves (e.g., *Congeria rhomboidea* M. Hörnes, *C. zagrabiensis* Brusina, *C. croatica* Brusina, *Limnocardium* (*Arpadicardium*) *mayeri* Hörnes, *Limnocardium* sp., *Paradacna okrugici* (Brusina)), gastropods (e.g., Valenciennius reussi Neumayr in Neumayr & Paul, 1875 (old name *Valenciennesia reussi* Neumayr in Neumayr & Paul, 1875), *Planorbis* sp., *Unio* sp., *Melanopsis lepavinensis* Brusina, 1897, *M. sabolici* Brusina, 1902, *Goniochilus croaticus* (Brusina, 1892) (old name *Micromelania croatica* (Brusina, 1892)), *Zagrabica ampullacea* Brusina, 1884, etc.), ostracods, redeposited foraminifers, fish remains, and freshwater gastropods viviparids in the latest Rhomboidea-beds, marking the transition to the Pliocene.

*5.1.5. Pliocene – "*Paludina *beds"*

Pliocene sediments are well distributed in the western part of the Psunj Mt. (**Figure 2**). As described by **Blašković (1975)** and **Kranjec and Blašković (1976)**, they are well defined based on the fossil content, mostly on the freshwater gastropods Viviparidae and divided into the lower, middle and upper "*Paludina* beds" (*Paludina* is the old genus name for *Viviparus*). "*Paludina* beds" are made of regular repeating of the mostly clayey and less sandy sediments, continuing on the upper part of the *Rhomboidea* beds.

5.2. Neogene paleogeography and paleoenvironments of the western slopes of the Psunj Mt.

Neogene stratigraphic units recorded on the western slopes of the Psunj Mt. are listed in the chapter 5.1. and described in detail in cited papers. Based on the investigated localities, **Blašković (1975), Blašković et al. (1975, 1982,**

1984) and **Kranjec and Blašković (1976)** gave an overview of the paleonvironmental development of the western part of the Psunj Mt. area during the Miocene.

Pre-Miocene deposits are described from the localities Rogolji and Okučanski Benkovac in the area of Bijela Stijena structure (e.g., **Blašković, 1975; Blašković et al., 1984**). Locality Rogolji is determined as a freshwater development, and Okučanski Benkovac as a brackish-marine development (**Figure 2**), indicating the existence of a land mass, that is an anticline Bijela Stijena–Novska, as a shallow barrier which divided these two areas (**Blašković, 1975**).

As described in **Blašković (1975)** and **Blašković et al. (1982)** due to the Badenian marine transgression over the pronounced paleorelief and tectonic changes in the basin, Badenian sediments ("Tortonian") in the area between Okučani, Novska and Pakrac (**Figure 2**) show different lithofacies characteristics as described in the previous chapter, pointing to the different depositional conditions and environments. Psunj Mt. crystalline massif with the Bijela Stijena structure, as the submarine reef, played the main role in the lithofacies development. Psunj Mt. represented the coastal area during the Badenian marine transgression and was a source of material for the filling of the basin due to the constant eustatic changes. Also, the rugged coast enabled the evolution of various environments and fauna. Conglomerates were developed in the coastal area due to the abrasion of the coast and influx of the eroded material in the zone of high energy waves and represent the above mentioned Badenian lithofacies (A) (coarse-grained coastal lithofacies). In the coastal area with less pronounced terrigenous influx, lithofacies (B; biohermal lithofacies) is developed. Sediments of lithofacies (E; sandy-marly lithofacies) are developed in time of more intensive terrigenous particles input. Fossil detritus produced by crushing the biogenic reefs is deposited in the near-reef environments as lithofacies (C, biocalcarenitic lithofacies), or it is deposited in the deeper part of the basin as a turbiditic lithofacies (G). Lithofacies comprised of coquinas (D) is developed in the back-reef environments with favorable ecologic conditions for molluscs, brachiopods and echinoids.

Blašković et al. (1975) assume the existence of land mass in the area of Lipik during the Badenian and Lower Sarmatian, which was possibly connected to the land mass of the crystalline rocks in Omanovac as a barrier of the basin south of Kraguj to the open sea (**Figure 2**). Although the Lower Sarmatian is marked by the transgression, it is of local character, and Sarmatian sediments are generally deposited in the regressive conditions (**Blašković, 1975**). The sedimentary basin is starting to close, the fossil fauna is redeposited from the Badenian and the water salinity is decreasing influencing the development of the brackish fauna. Material is in the basin transported as a turbiditic sequence as described in (e.g., **Blašković, 1975; Blašković et al., 1984**).

The beginning of the Upper Miocene is marked by the regional transgression. The deposition of the Upper Miocene sediments is similar in lithology, with marl as a dominant member with less strong tectonic activity. The transition to the Pliocene is gradual but short, and indicated by the regressive tendencies, tectonic movements, and climatic changes (e.g., **Blašković, 1975**).

5.3. Further actualization of Prof. Blašković's work

The analysed outcrop is only a small fragment selected to revive the researching of the Psunj Mt. area, as a heritage of perennial and fruitful work of the Dr. Ivan Blašković, Full Prof. Authors here describe all main Neogene sequences important for the regional geology of the Psunj Mt. and wider reconstruction of the Paratethys period in the CPBS. They could be correlated with lithological composition, stratigraphic position and petrophysical properties of the Neogene-Quaternary sediments and basement rocks, especially on the west, in the Bjelovar Subdepression and specially the Ilova Subdepression. Badenian deposits (the Mosti Member) are proven as a promising reservoir rocks in the northern, northeastern and central part of the subdepression.

Structural interpretation could be done using regional EK markers and borders and lithostratigraphic units, but on particular localities, like presented, the smaller units can be selected and mapped. However, regionally it was the most promising to map EK border Tg/Pt (basement/Neogene), EK marker Rs7 (Sarmatian/Pannonian) and Rs5 (Lower Pannonian/Upper Pannonian), i.e. Mosti and Križevci Members (as part of the Moslavačka gora Formation). It is sure that one of two main fault systems in the Bjelovar Subdepression play crucial tectonic role on the western margins of the Psunj Mt. It strikes approximately west/northwest-east/southeast (approximately longitudinal). Fault activity, as well as the weathering, especially of the Paleogene rocks, caused strong disintegration of the upper part of the basement rocks and sedimentation of coarse-grained deposits, mostly in the alluvial-fan environments, which are characterized by a strong and abrupt transport.

6. References

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SAŽETAK

Neogenske naslage zapadnih padina Psunja, Hrvatska: pregled dosadašnjih istraživanja i aktualizacija geoloških istraživanja

Na kristalinskoj podlozi zapadnih padina Psunja diskordantno slijede neogenske naslage starosti od donjeg miocena do kvartara. Stariji neogenski sedimenti se u ranijim radovima nazivaju "oligomiocenski" ili "predtortonski", što danas odgovara donjomiocenskim sedimentima. Preko tih slatkovodnih i morsko-bočatih sedimenata transgresivno slijede morske srednjomiocenske naslage. Badenski talozi čine kontinuirani pojas oko zapadnih padina Psunja, istočno od Pakraca i Lipika, s raznolikim litofacijesima. U širem području strukture Bijela Stijena-Novska, donjosarmatski sedimenti su diskordantni na badenske. Bočati i slatkovodni okoliši obilježeni su kontinuiranim taloženjem gornjomiocenskih sedimenata, a pliocenski sedimenti s kompletnim razvojem "paludinskih naslaga" obilježavaju kraj neogena. Dominantna je antiklinalna struktura – strukturni nos s osi Bijela Stijena-Novska. Jezgru strukture čine kristalinske stijene, a neogenski sedimenti slijede periklinalno duž krila i čela strukture.

Ključne riječi: neogen, stratigrafija, naftna geologija, Psunj, Hrvatska.

Acknowledgments

Authors are grateful to the University Support „Mathematical methods in geology V“ (leader: Tomislav Malvić).

Author's contribution

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