GEOLOŠKI ANALI BALKANSKOGA POLUOSTRVA
Volume 80 (2), December 2019, 13–37
–
https://doi.org/10.2298/GABP1902013R
Original scientific paper
Оригинални научни рад

Facies analyses, biostratigraphy and radiometric dating of the Lower–Middle Miocene succession near Zaječar (Dacian basin, eastern Serbia)

Ljupko Rundić[1], Nebojša Vasić[1], Miodrag Banješević[2], Dejan Prelević[1], Violeta Gajić[1], Bojan Kostić[1] & Jelena Stefanović[1]

Abstract. Lower–Middle Miocene sedimentary succession and the conformable/unconformable relationships between the lacustrine-continental systems (i.e. DLS, SLS) and Badenian marine transgression represents one of the intrigue topics. Herein, we studied five exploration boreholes (eastern Serbia) and analyzed the main facies pattern, biostratigraphic characteristics of the Miocene succession, and applied the U-Pb radiometric dating of volcanic tuffs interstratified in the sedimentary series with coal layers (borehole NRKR-17002). The obtained concordia age of 16.9 ±0.2 Ma for all the analysed zircon grains without any inherited cores indicate a single magmatic event. We definite the freshwater series originated during Early Miocene Karpatian (= late Burdigalian). Consequently, for the first time, we demonstrated that age of a part of the Serbian Lake System (SLS) is much older than it was previous reported. In addition, sporadic findings of foraminifers, ostracods and molluscs documented the late Badenian marine transgression in eastern Serbia. If accept this fact the flooding occurred later than in the rest of Serbia (< 14.5 Ma). However, the lack of quality data and unclear stratigraphic position of some parts of the clastic succession (? Lower–Middle Badenian) makes this claim uncertain.

Key words:
Lower–Middle Miocene, lacustrine facies, marine transgression, U-Pb geochronology, eastern Serbia.

Апстракт. Седиментна сукцесија између доњег и средњег миоцена и складан тј. дискордантан однос између језерско-континенталних наслага (нпр. DLS, SLS) и баденских морских седимената представља једну од занимљивих тема. У овом раду смо проучавали пет истражних бушотина (источна Србија) и анализирали главни фацијални образац, биостратиграфске карактеристике миоценске сукцесије и применили U-Pb радиометријско датирање вулканских туфова интерстратификованих у седиментној серији са слојевима угља (бушотина NRKR-17002). Добијена је конкордија старост од 16,9 ± 0,2 милиона година за сва анализирана зрнца циркона без наследних језгара што говори да је у питању један магматски догађај. Прецизирали смо да је слатководна серија настала током раног миоцена – карпата (= млађи бурдигал). Сходно томе, по први пут смо показали да је старост једног дела Српског језерског система (SLS) много старија него што се раније мислило. Поред тога, спорадични

[1] University of Belgrade, Faculty of Mining and Geology, Đušina 7, 11000 Belgrade, Serbia. E-mails: ljupko.rundic@rgf.bg.ac.rs; nebojsa.vasic@rgf.bg.ac.rs; dejan.prelevic@rgf.bg.ac.rs; violeta.gajic@rgf.bg.ac.rs; bojan.kostic@rgf.bg.ac.rs; jelena.stefanovic@rgf.bg.ac.rs
[2] University of Belgrade, Technical Faculty in Bor, Vojske Jugoslavije 12, 19210 Bor, Serbia. E-mail: mbanjesevic@tfbor.bg.ac.rs

наласци фораминифера, остракода и мекушаца документују каснобаденску морску трансгресију у источној Србији. Ако прихватимо овај аргумент, онда се трансгресија догодила нешто касније него у остатку Србије (<14.5 милиона година). Међутим, недостатак квалитетних података и нејасан стратиграфски положај неких делова кластичне сукцесије (? доњи-средњи баден) чини ову тврдњу доста несигурном.

Кључне речи:
Доњи–средњи миоцен,
језерске фације,
морска трансгресија,
U-Pb геохронологија,
источна Србија.

Introduction

The Dacian Basin was a part of the large Paratethyan epicontinental sea (Laskarev, 1924). It covers approximately the domain of the Moesian Platform located in the foreland of the highly bended Carpatho-Balkanides (Vasiliev, 2006; Olteanu & Jipa, 2006; Jipa & Olariu, 2009; Ter Borgh, 2013). During the Neogene, the area of eastern Serbia (Timočka Krajina) belonged to the westernmost part of the Dacian Basin which leaned on the Carpathian foothills and the southern branches of the Carpathians and further eastward to Bulgaria and Romania (Marović et al., 1998; Ganić, 2005; Knežević & Ganić, 2013; Ter Borgh, 2013). The sedimentary facies in the Dacian Basin indicate an overall regressive pattern of complete basin fill, characterized by mass-progradation structures with near-shore facies, and large-scale deltaic environments observed in particular during middle-late Miocene and early Pliocene (Ganić, 2005; Vasiliev, 2006; Jipa & Olariu, 2009; Ter Borgh et al., 2014; Đajić et al., 2018). Based on the data from seismic sections and exploratory drillings, the total thickness of Neogene rocks reaches up to a few thousand meters (Ter Borgh, 2013). In the area of eastern Serbia, the Miocene formations unconformably overlie the lower Cretaceous (Valanginian to Albian) sandstones or upper Cretaceous (Cenomanian–Coniacian) carbonate and clastite rocks, andesite and their volcanoclastites (Veselinović et al., 1967, 1975; Đorđević & Banješević, 1997; Đorđević, 2005; Antonijević & Mijatović, 2014; Vasić et al., 2018; Rundić et al., 2018). In the framework of the Miocene succession, the middle Miocene Badenian marine deposits and Sarmatian marine-brackish sediments have a great distribution. A lot of authors reported on that (e.g. Laskarev, 1924, 1934; Džodžo-Tomić, 1963, 1970; Veselinović et al., 1967, 1975; Petrović, 1961, 1969, 1988; Popović, 1968; Popović & Gagić, 1969; Stevanović, 1958, 1964, 1967, 1977; Ganić, 2005; Marović et al., 2007). Additionaly, in the area of Zaječar, the Miocene freshwater sediments with coal layers were determined more than a century ago and was exploited in the Zvezdan coal mine since 1889 (e.g. Žujović, 1889; Radovanović & Pavlović, 1891; Živković, 1893; Pavlović, 1903). The scarce findings of bad preserved freshwater mollusks, ostracods and parts of fishes skeleton could not closely define the stratigraphic position of these deposits. Litostratigraphic analyses and correlation with similar sediments of the Intra-Carpathian basins indicated the middle Miocene age of that sediments (e.g. Dolić, 1977; Stevanović, 1977). All previous studies were based on the lithostratigraphic and biostratigraphic characteristics of the freshwater series. Fossil endemism, lithostratigraphic similarity, unconformable/conformable relationship to the overlaying rocks, lack of marker beds, etc., were not enough to precisely date the timing of the formation of these lake basins (Rundić, 2013; Rundić et al., 2013, 2018). In addition, independent age analyzes such as radiometry or magnetostratigraphy have never been done. The proposed model of the existence of a large lake system during the Miocene in the territory of Serbia (Serbian Lake System by Krstić et al., 2003) has opened numerous challenges of proving or doubting the time span, distribution and genesis of this large lake system (e.g. Dolić, 1998; Rundić et al., 2013; Simić et al., 2017; Sant et al., 2018; Mandic et al., 2019).

In this regard, besides the main facies analysis and biostratigraphic division of the Miocene succession, we applied the method of radiometric dating of volcanic tuff interstratified in the sedimentary series, and tried to define more precisely the age of the Miocene freshwater series with coal as well as the timing of Badenian marine transgression in this part of Serbia.

Geological background

The area of eastern Serbia belongs to the Carpatho-Balkanides as a large tectonic unit (e.g. Petković & Andjelković, 1958; Grubić & Antonijević, 1961/1962; Dimitrijević, 1997; Kräutner & Krstić, 2003; Schmid et al. 2008 and references therein). According to the last mentioned authors, they also include parts of the Serbo-Macedonian Massif (Dimitrijević, 1997) and to the west, follow the eastern margin of East Vardar Ophiolites. Inside this belt, the Timok Fault represents one of the main strike-slip structure which displace the Cretaceous nappe unit along the contact between the Dacia Mega Unit and the Moesian Platform (Schmid et al., 2008). This fault accommodated Oligocene to early Miocene dextral strike-slip motion with total movements up to a hundred kilometers (Schmid et al., 2008). Generally, from the end of the early Miocene up to the older part of the Middle Miocene, the Serbian part of Carpatho-Balkanides was subjected to extensional processes (Krstić et al., 1988; Krstić, 1991; Marović et al., 1998, 2002). It was a secondary effect of a much stronger activity established in the area of the Pannonian Basin which led to the formation of numerous basinal structures in these areas (Marović et al., 1998, 2002). Character of the Carpatho-Balkanides orogen was enabled by the general phase of uplifting manifested from the beginning of the Sarmatian to the recent time (Marović et al., 2002, 2007). During the middle Miocene, the Paratethys marine and brackish water was flooded area of the westernmost part of Carpathian foredeep in the territory of Serbia (Anđelković & Anđelković, 1997). It flooded different Mesozoic and Tertiary rocks depending on morphology of paleorelief (Ganić, 2005; Đajić et al., 2018; Rundić et al., 2018). Generally, different Mezosoic rocks (mostly Upper Cretaceous flysch, clastites, volcanoclastites and carbonates) as well as older Miocene continental-lacustrine sediments represent the basement rock for the mentioned transgressive sediments. These Upper Cretaceous rock formations are known as the carriers of mettalic raw materials (e.g. Đorđević & Banješević, 1997; Đorđević, 2005; Antonijević & Mijatović, 2014) (Fig. 1). In that sense, the studied boreholes were a part of exploration drilling which was performed by Tilva Co. during 2017.

Material and methods

This study presents results of detail mapping of five exploration boreholes (RTK-1501, RTK-1502A, RTK-1503, NRKR-17001 and NRKR-17002) located near Zaječar, eastern Serbia (Fig. 1). More than a hundred samples were taken for different analyses. Petrological and chemical analysis were performed in the laboratories of the Petrology and Geochemistry at the Faculty of Mining and Geology using standard procedure (grain-size analysis, calcimetry, thin-section, etc.). Tuff was used for age determination and chronostratigraphic position of the lowest positioned coal series as well as stratigraphic position other Miocene rocks. Fossil molluscs, foraminifers and ostracods were used for the biostratigraphic division of different Miocene units. Standard sam-

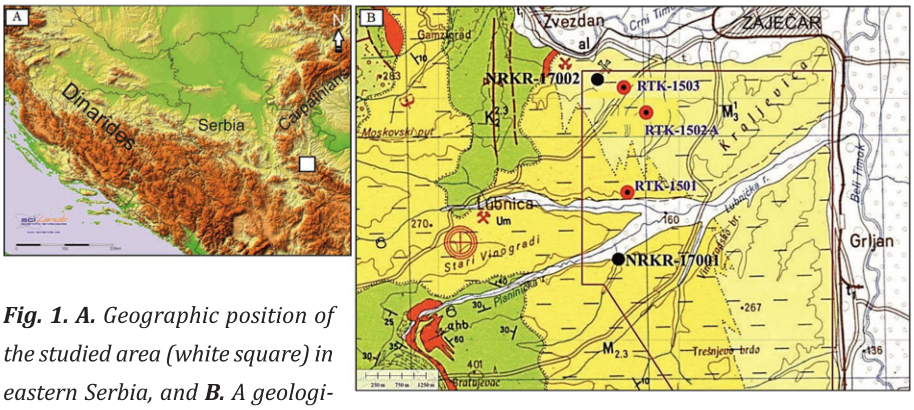

*Fig. 1. A. Geographic position of the studied area (white square) in eastern Serbia, and B. A geological map B. A geological map of the Zaječar area with the position of five explored boreholes (according to Veselinović et al., 1967, modified). Key: J_{1-3}, Jurassic; K_1, Lower Cretaceous (Valanginian to Albian); K_2 , Upper Cretaceous (Turonian-Coniacian); M_2 , Badenian-Early Sarmatian; M_2, Sarmatian; t_1, Quaternary terrace; **al,** Alluvial; **αhb,** volcanic rock.*

ple of ca. 300 g was disintegrated by breaking or using diluted hydrogen peroxide and sieved (2-0.063 mm) with water at room temperature at the Laboratory for Paleontology and Historical Geology, Faculty of Mining and Geology, Belgrade.

Zircon grains were separated from the tuff samples no. 93 and 94 (NRKR-17002) using standard mineral separation techniques. The rocks were crushed to coarse sand size with a tungsten carbide jaw crusher. Subsequently, zircons were concentrated by sieving, magnetic separation and heavy liquids. A representative batch of the zircon crystals with grain sizes of 150–300 μm was manually picked and mounted in Araldite 2020 resin.

After polishing, cathodoluminescence (CL) images were taken using a CL detector connected to Scanning Electron Microscope at University of Belgrade, Faculty of Mining and Geology. The CL investigations were carried out using a JEOL JSM-6610LV SEM (with a W-filament as a beam source), coupled with an X-Max EDS. The samples were coated with carbon using a BALTEC-SCD-005 sputter coating device. The results were recorded under high vacuum conditions with acceleration voltage was 20 kV.

Zircons were dated with the U/Pb method using Laser Ablation-Inductively Coupled Plasma-Mass Spectrometry (LA-ICP-MS). U, Th and Pb isotopes were measured at the Institute for Geosciences, University of Mainz using an Agilent 7500ce quadrupole ICP-MS system coupled to an ESINWR193 ArF excimer laser system with a 193 nm output wavelength. The laser system is equipped with a two volume sample chamber (10 cm × 10 cm). After pre-ablation, analyses were conducted using a spot size of 30 μm, 20 s warm up time, 30 s dwell time and 20 s washout time. The repetition rate was 10 Hz at pulse energy of 3.5 Jcm-2. The instrument was tuned for maximum sensitivity at low oxide formation rates of <0.5 %. The dwell times for individual masses are 10 ms for masses 232 and 238, and 30 ms for 202, 204 and 208. Dwell times of 40 and 60 ms were used for masses 206 and 207, respectively. For a first step data reduction, the time-resolved signal was processed using the program GLITTER (www.glittergemoc.com, Macquarie University, Sydney, Australia). Time-dependent laser and mass spectrometer induced inter-element fractionation (Pb/U), mass fractionation, as well as common lead, were corrected afterwards using an Excel spreadsheet of ComPbcorr (Andersen, 2002). The inter-element fractionation during ablation was corrected linearly. For this purpose, ablation conditions such as spot sizes and ablation times were kept constant during each session. The interference of ^{204}Hg on ^{204}Pb was corrected by measuring ^{202}Hg and calculating ^{204}Hg using the natural ^{204}Hg/^{202}Hg ratio of 0.2299. Ages, uncertainties and concordia diagrams were produced using Isoplot3 for Excel (Ludwig, 2003). Concordia ages are plotted with 2σ uncertainty ellipses and discordia intercept ages are given at 95% confidence. Analyses were calibrated using a GJ-1 (GEMOC) zircon (Slama et al., 2008). Reproducibility and accuracy were controlled by repeated analyses of Plesovice and 91500 reference zircons, from Jackson et al. (2004) and Wiedenbeck et al. (1995), respectively, treated as unknown samples; measured values deviate <2% from the published values.

Results

Facies analyses

All of the boreholes drilled the different Miocene units with total thickness up to 600 m (e.g. RTK-1501). Generally, Miocene succession is composed of clastic rocks. They unconformably overlies the various Cretaceous sediments and volcanoclastics. Older units include the Valanginian limestone, Albian glauconitic sandstone and siltstone, Cenomanian fine-grained clastics and the coarse-grained andesitic epiclastites of the upper Cretaceous, known as Metovnica Formation (Đorđević & Banješević, 1997; Antonijević & Mijatović, 2014). In vertical succession, the Miocene sediments were deposited in different environments: non-marine, marine and brackish ones (from the bottom to the top).

Non-marine facies (Lower-Middle Miocene)

Within the lower (non-marine, continetal-lacustrine) sedimentary succession, the following lithofacies are separated: a) Basal clastites, b) Colorful fine-grained clastites of muddy plain, c) Fine-grained clastites, d) Sediments of marsh, e) Marginal-lacustrine clastites and, f) Alluvial-lacustrine clastites.

The lacustrine succession starts with (a) basal clastites or coarse-grained clastites. Clasts are derived from the Valanginian limestones, re-deposited weathering crust of andesites and andesite epiclastites of Metovnica Fm. (U. Cretaceous) (Vasić et al., 2018). At the same time, a part of that could be clastites from the marginal parts with gravel and sand sequences. The thickness of the basal clastites is from several meters (RTK-1503 and NRKR-17002) up to 35 meters (RTK-1502A, Fig. 2). Fossils not observed.

b. Colorful fine-grained clastites of muddy plains

This lithofacies is made of finest clastics (silty clay and silt) with rapid color shifting in vertical direction (Figs. 2, 3). The colour can be marked by tones of red, grey, green, yellow with all the passes. The lithofacies thickness is variable and ranges from 10 to 65 m (Vasić et al., 2018). It suggests a shallow habitat with occasional subaeric conditions. As effect of this, thin levels of the paleosoil was developed (Fig. 2). Note that whole the Miocene series in the borehole RTK-1503 is located much more upward than in borehole RTK-1502A.

c. Lithofacies of gray fine-grained clastites

This lithofacies, from 5 to 40 m thick, represents the gradual transition from the lithofacies of varicolored fine-grained clastites into a marsh facies (Vasić et al., 2018). Regarding sedimentology, it suggests on the deepening of the lake basin. Regarding petrology the fine-grained clastites in shades of grey, brown, grayish-brown and green color prevail. They consider clayey silt, and silty clays with more or less sandy or calcareous component. If the content of calcite exceeds 35% the sediments transit into marlstones. These sediments contain carbonized floral detritus as well as the debris from fresh-water mollusk molds (e.g. RTK-1502A and RTK-1503 – Figs. 2, 3).

Interpretation: Marginal-basinal facies

d. Marsh facies

Sediments of marsh facies were identified in the northern part of the area of interest. This is, regarding petrology, the most complex unit due to rapid vertical and lateral changes of conditions in depositional environment. Generally, it consists of clastic sediments, coal, coal-bearing sediments, carbonate rocks and tuffs (Vasić et al., 2018). The succession discovered by drilling may contain from two to 10 levels of coal that are from 10 cm to 4 m thick such as in borehole NRKR-17002. Lithologically, marsh facies succession include homogeneous marls, a layer of coarse sand that has intraformation fragments of marl in the top (framed by a polygon), gray marls with small deformations, thin layered and laminated marls/marls with freshwater gastropods and coal (Figs. 3, 4). Generally, marl contains the assemblage of fossil fauna, particularly of gastropods and ostracods (RTK-1503, Fig. 3). A lot of thin, transparent ostracode specimens belongs the Candona group. It has been observed and rare large forms reaching over 1.8 mm. They have slightly perforated ornamentation resembling *Camptocypria*. There are also fragments of slightly accentuated sculpture such as ? *Dinarocythere, Ilyocypris* but the carapace is straighter. Rare, tiny suboval forms similar to Cypria have also been found. Fossil remains are found in carbonate rocks, commonly revealing the lamination. A peculiarity of this facies is the presence of a tuff layer which is exposed at the different position within the coal series. The observed thickness ranges of the marsh facies from 25 to 90 meters (NRKR-17002, Fig. 4).

e. Marginal-lacustrine facies

Marginal lacustrine (lake) facies is generally shallow-water facies. It was developed along the margins of the basin, and gradually towards the central parts of the lake, crossing the lake facies (Vasić et al., 2018). It is characterized by deposition of fine grained clastics and marl (e.g. RTK-1503, Fig. 3). If it is closer to the alluvial-lake facies, it occasionally contains medium-sized and coarse clastics.

f. Alluvial-lacustrine facies

Alluvial-lacustrine facies developed at place where river enters a lake exhibiting alluvial fans or deltas (Obradović & Vasić, 2007; Vasić et al., 2018). The most

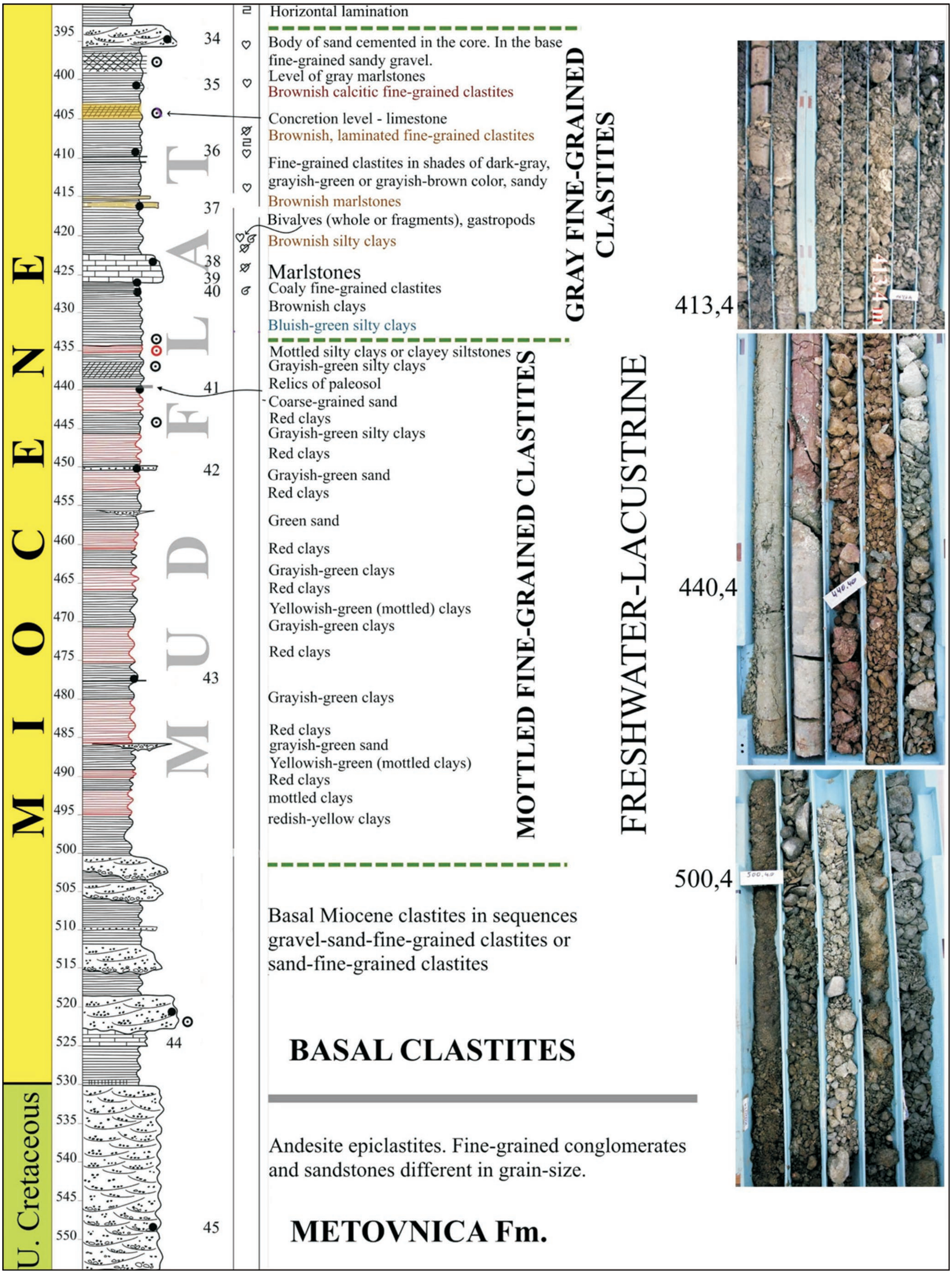

Fig. 2. *Lithostratigraphic column of the RTK-1502A borehole (depth interval 390–560 m). Numbers (34–45) indicate position of the samples. Symbols (thin column) mark sedimentological structures and fossils and explained within the text.*

Fig. 3. *Lithostratigraphic column of the Miocene sediments in the borehole RTK-1503. Sporadic findings of the marine sediment with foraminifers observed at the depth of 66 m. For the key, see previous figures.*

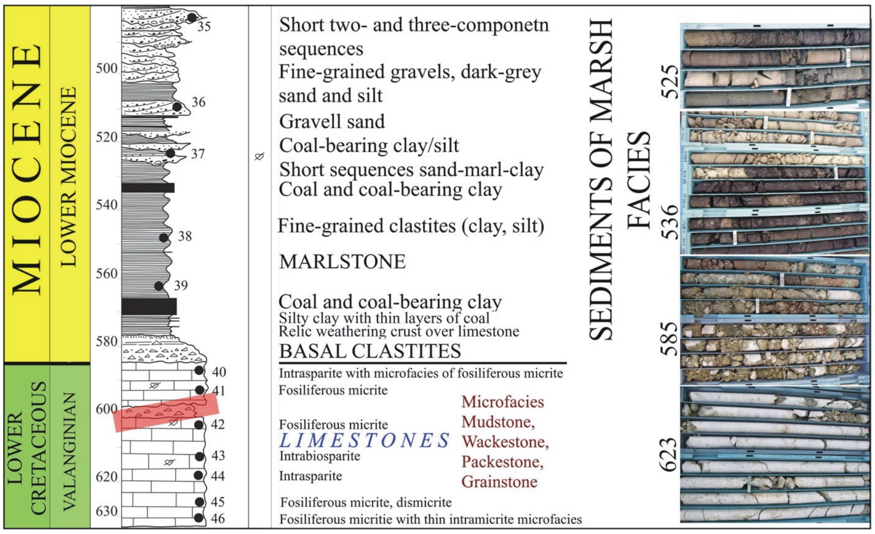

Fig. 4. *Lithostratigraphic column of borehole NRKR-17002. Sediments of marsh facies transgressivly overlying the Lower Cretaceous carbonates. For the key, see previous figures.*

abundant are coarse- and medium-grained clastites. Material was brought by alluvial flows from broader coastal area. Coarse-grained clastites were periodically brought into deeper and farther basin parts by torrential flows (flooding events) giving rise to marginal-lacustrine or basin facies. Marginal-lacustrine facies is generally a shallow-water. It is juxtaposed against basin margins and transits gradually towards the central lake parts into lacustrine facies.

The estimated thickness of alluvial-lacustrine facies is 170–190 m (RTK-1501, Fig. 5). Main lithology are gravel, sand, and their transitions. Vertical and lateral distribution is in sequences, which may be of two or three members. 40 sequences from 1–2 m to over 10 m thick were recognized vertically (Vasić et al., 2018). General characteristic of the all of sequences is the decreasing coarseness upward. Due to erosional contacts between sequences, a part of them may be shortened and lack of upper, sandy sequence part. Significant thickness of given facies and its gravelly pattern suggest on a relatively strong alluvial system that formed a deltaic model at river mouths (Obradović & Vasić, 2007; Vasić et al., 2018). Clastic material was re-deposited into other facies during extreme flooding events (Vasić et al., 2018). That was also the source area for the present marginal-lacustrine environment. In terms of lithology, the marginal-lacustrine facies is generally made by fine-grained clastites with bodies of sand and gravel (Fig. 6).

Marine and marine-brackish facies (Middle Miocene)

This sedimentary package consists of different size clastic roks and covers the previous mentioned lacustrine-continental sediments. Main criteria for the separation was the presence of marine-brackish fauna (Rundić et al., 2018). Lithologicaly, it can be divided onto three lithofacies: a) the lithofacies association of fine-grained clastites with sand and gravels, b) gravel and sand, and c) the upper lithofacies association of fine-grained clastites with sand and gravels (Vasić et al., 2018).

a. Lower lithofacies association of fine-grained clastites with sand and gravels

The measured thickness of the given lithofacies is within range of 60–160 m (e.g. RTK-1501, Fig. 7). Regarding sedimentology is the unit very similar with the succession of marginal-lacustrine facies as the fine-grained clastites are also dominating. The more emphasized frequency and thickness of sand and gravel bodies suggests on the proximity of the main source of clastic material, i.e. to a strong alluvial system. Fine-grained clastites were referred silty clays, clayey silts, sandy-clayey silts, clayey-silty sands, clayey-sandy silts. All sediments are generally calcite-poor, with the contents of 10–20% of $CaCO_3$ (Vasić et al., 2018). Sands vary in grain size from fine- to coarse-grained and their composition is inherited from gravel fraction. Gravels consist of pebbles that have been derived from andesite complex or from Metovnica Fm., from older limestones or clastic units (Vasić et al., 2018).

b. Lithofacies of gravel and sands

This unit is 60–120 m thick (RTK-1501, Fig. 7). Gravels and sands are the most abundant lithology.

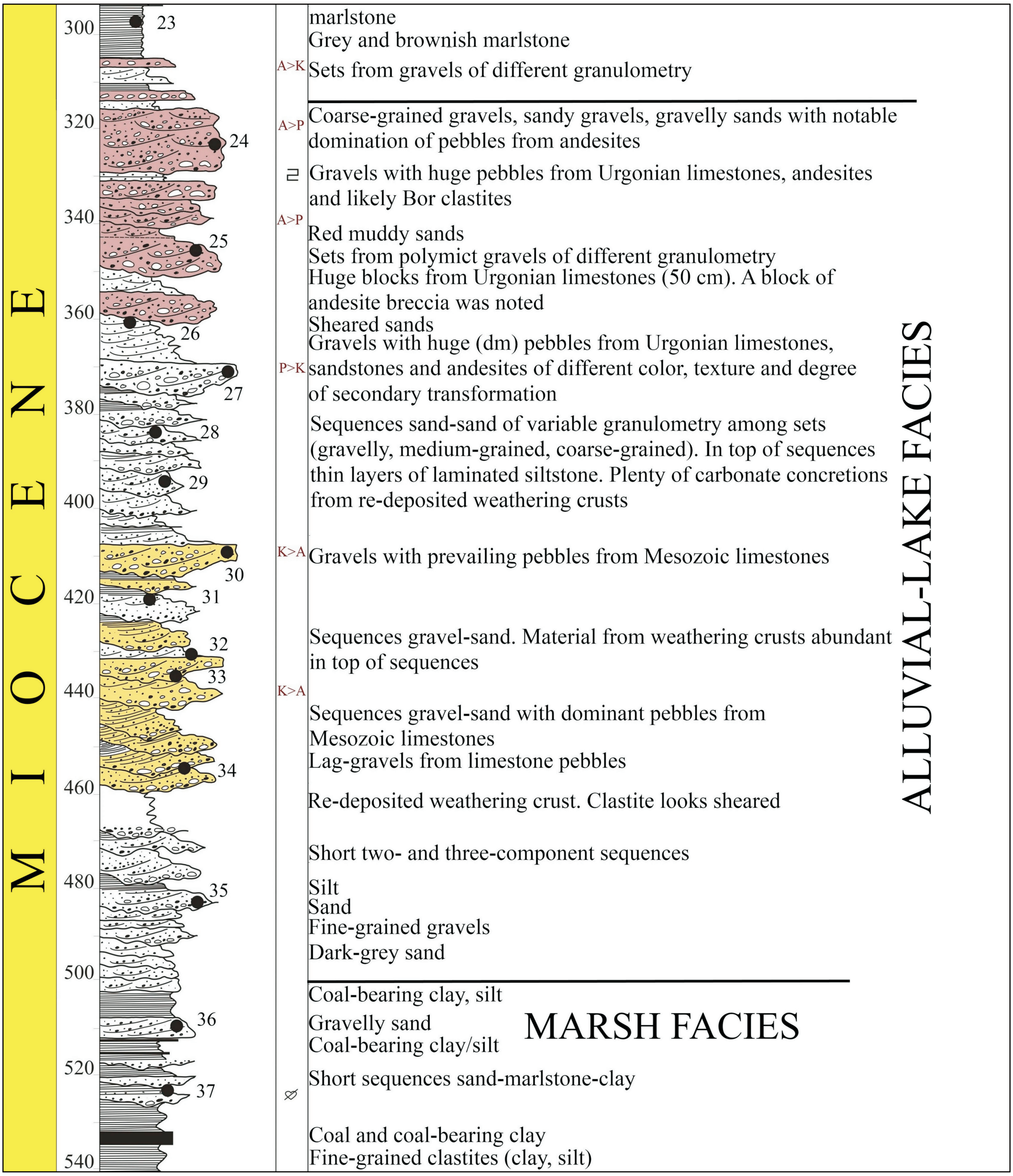

Fig. 5. *Lithological succession between the marsh and alluvial-lacustrine facies in borehole RTK-1501 (depth interval 300–540 m). Letters A, K, and P indicate quantitative relation between three dominant rock fragments: andesite-limestone-sandstone.*

Fig. 6. *Two sequences (2 and 3) from the alluvial-lacustrine facies (RTK-1502A);* ***2,*** *The top of this sequence is represented by fine-grained clastites with concretions of carbonates (white-bead bark of decomposition);* ***3,*** *Polymict gravel in the base of sequence.*

In terms of sedimentology, the unit is organized in clastic sequences whose thickness is up to 12 m (Fig. 8). Sequences are commonly from three members (gravel-sand-fine-grained clastites), less common of two members (gravel-sand). Gravelly sediments (lag gravels, gravels, sandy gravels and gravelly sands) occur in the base of sequences. They display the upward transition into sandy sediments (gravelly sands and sands of variable coarseness). The very top of sequences, which is the thinnest, build horizontally or cross laminated fine-grained sands and silts. General characteristic of the all of sequences is the upward decrease in coarseness. Their relations with basal sequences are constantly erosional (Vasić et al., 2018).

Interpretation: Alluvial facies.

c. Upper lithofacies association of fine-grained clastites with sand and gravels

The estimated thickness of this lithofacies is 80-90 m (e.g. RTK-1501, see Fig. 7). In this succession is the domination of fine-grained clastites striking, whereas the sands and gravels are subordinated. General characteristic of fine-grained clastites is that they represent two- or three-component systems from sand-silt-clay, silt-clay, clay-silt, and sand-silt. The content of calcite is very low, i.e. less than 10% (Vasić et al., 2018). Fine-grained clastites display textures that were governed by the system energy, which has been low. Consequently, horizontal and cross lamination developed. Fossil remains include tiny debris of mollusks (Vasić et al., 2018). Carbonized flora is occasionally present. Gravels and sands are quite the same as those in the lithofacies described above.

In the upper part of borehole RTK-1501 (up to 80 m), the assemblage of tiny gastropods and bivalves were found: *Granulolabium bicinctum* (Brocchi), *Acteocina lajonkaireana* Basterot, *Psamobia* cf. *laboidei sarmatica* Papp, *Mohrensternia* cf. *pseudoangulata* Jekelius, *Ervilia* cf. *dissita* (Eichwald), *Irus* cf. *gregarius* (Partsch), *Abra* sp., *Hydrobia* sp., *Cerithium* sp. and it suggests restricted marine environment. However, the foraminifer assemblage in same borehole at 270 m depth (see Fig. 7) suggests a marine environment. In the fine-grained calcite-poor and calcite-rich clastites the following taxa were recognized: *Ammonia* cf. *viennensis* (d'Orbigny), *Ammonia* ex gr. *beccarri* Linne, *Asterigerinata planorbis* (d'Orbigny), *Angulogerina* cf. *angulosa* (Williamson), *Bolivina* cf. *dilatata* Reuss, *Bulimina elongata* d'Orbigny, *Cancris auricularis* (Fichtel & Moll), *Cibicidoides ungerianus* (d'Orbigny), *Fursenkoina schreibersiana* Czjzek, *Globigerina* cf. *bulloides* d'Orbigny, *Globigerina* sp., *Cassidulina laevigata* d'Orbigny, *Hanzawaia boueana* (d'Orbigny), *Heterolepa dutemplei* (d'Orbigny), *Lenticulina calcar* (Linne), *Lenticulina inornata* (d'Orbigny), *Nonion commune* (d'Orbigny), *Quinqueloculina* cf. *triangularis* d'Orbigny, *Quinqueloculina* sp., *Stilostomella adolphina* (d'Orbigny), *Stilostomella* cf. *consonbrina* (d'Orbigny), etc. The ostracod identifications included: *Cytheridea* cf. *acuminata* (Bosquet), *Krithe papillosa* (Bosquet), *Olimfalunia* cf. *plicatula* (Reuss), *Cytheridea* sp. (cf. *C. acuminata* Bosquet), *Callistocythere* sp., *Leptocythere* sp.

At some samples located upward in the column, fossil remain resembles more brackish to freshwater forms (230 m).

Interpretation: Shallow-water facies with the occasional basinal influence.

Biostratigraphic framework

Based on the mentioned fossil content as well as superposition relationships of different Miocene fa-

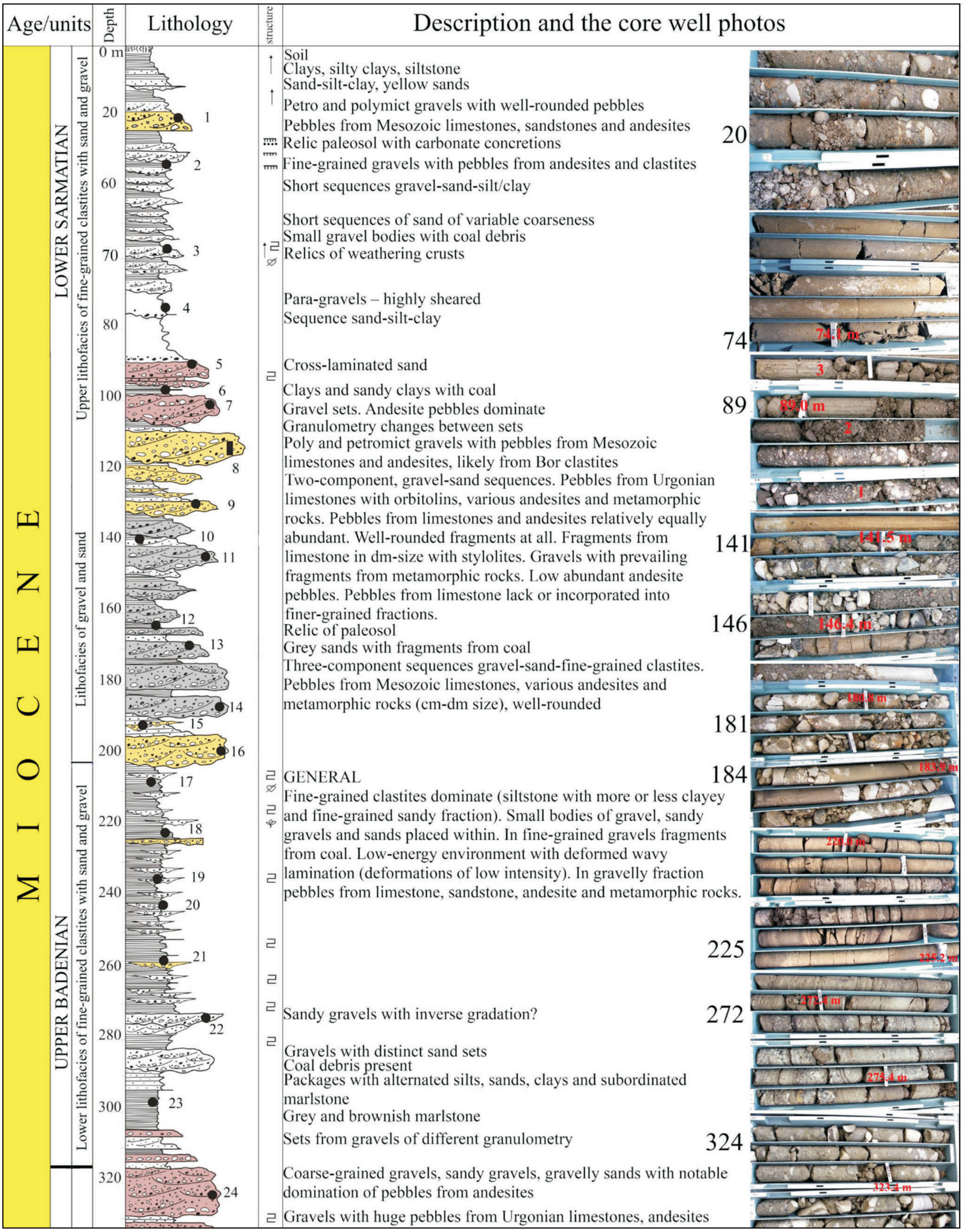

Fig. 7. *A thick series of predominantly fine-grained clastites with thin interbeds of gravel and sandy gravel (borehole RTK-1501). Upper part of the studied section corresponds to the Lower Sarmatian whereas the bottom part relates to the Upper Badenian (documented at 270 m).*

Fig. 8. *Close-up view on the two clastic sequences (A, B).* ***1,*** *Gravel;,* ***2,*** *Sand (RTK-1501, 108-110 m).*

cies, three different stratigraphic units could be separated: late Lower Miocene (Karpatian), early Middle Miocene (Badenian) and late Middle Miocene (Sarmatian). The oldest one unit is marked by poor and endemic assemblages of fossil mollusks, ostracods, fish remains and very scarce charophyta gyrogonites within the marsh facies with coal (e.g. borehole NRKR-17002, RTK-1501, RTK-1502A, and RTK-1503). Small and often fragmented planispiral forms such as *Gyraulus* sp., *Planorbarius* sp. and *Planorbis* sp. (Fig. 9) represent typical freshwater fauna. Only few findings of *Prososthenia* sp. and *Fossarulus* sp. were noted (NRKR-17002). Very often along the thin layers there are the "coquina" with operculums of freshwater gastropods (Fig. 9). Similarly, poorly preserved ostracods such as *Candona* sp., *Fabaeformiscandona* sp., *Ilyocypris* sp., ?*Dinarocythere* sp., *Candonopsis* sp., ?*Cypria* sp. were observed in so-called the ostracod marls (Rundić et al., 2018). Somewhere, very rare and few fragments of charophyta could be seen. Based on these fossils, it is impossible to give a precise stratigraphic designation of the mentioned series. However, the marsh facies contains tuff layers, which are exposed across the whole facies (at the base of coal series, inside it as well as in its covering part, too). Radiometric dating of zircon grains from the vitroclastic tuff was obtained (borehole NRKR-17002). This is the first evidence concerning the age of the coal series (freshwater equivalents of Karpatian, Lower Miocene, 16.9 Ma) in this part of SLS. The total thickness of continental-lacustrine Miocene reaches from 110 to 260 m (Vasić et al., 2018; Rundić et al., 2018).

Fig. 9. *Characteristic small planispiral gastropods (left, RTK-1502A, 374.80 m) and a "coquina" containing operculums (right, RTK-1503, 110 m).*

Middle Miocene Badenian regional stage was determined by well-preserved foraminifera and mollusk remains (e.g. borehole RTK-1502A, Fig. 10). However, this conclusion is based on only a few samples with marine taxa (RTK-1501, 1502A and 1503). So, there are no good biostratigraphic markers across the borehole sections. Among the foraminifers, dominance of the species such as *Ammonia* cf. *viennensis*, *Ammonia* ex gr. *beccarri*, *Asterigerinata planorbis, Bolivina* cf. *dilatata*, *Bulimina elongata*, *Cassidulina laevigata*, *Fursenkoina schreibersiana*, *Globigerina* cf. *bulloides* suggest to the Upper Badenian *Bolivina- Bulimina* Zone (Pezelj et al., 2016). Non-systematic biostratigraphic sampling and lack of fossiliferous samples make this statement questionable. The mentioned fauna confirms the previous reports concerning Badenian marine clastic facies in the studied area (e.g. Džodžo-Tomić, 1963, 1970; Popović & Gagić, 1969; Dolić, 1977; Stevanović, 1977).

Middle Miocene Sarmatian regional stage (Volhynian, Rissoid/Hydrobian strata) is documented by the assemblage of small gastropods and bivalves: *Granulolabium bicinctum* (Brocchi), *Acteocina lajonkaireana* Basterot, *Psamobia* cf. *laboidei sarmatica* Papp *Mohrensternia* cf. *pseudoangulata* Jekelius, *Ervilia* cf. *dissita*

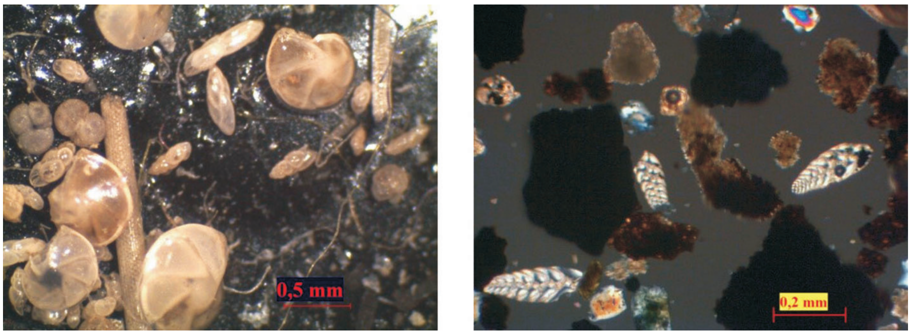

Fig. 10. *Badenian large foraminifer Lenticulina inornata* (d'Orbigny) *- left, and small specimens of Bolivina cf. dilatata* (Reuss) *- right. (RTK-1502A, 268.4 m).*

(Eichwald), *Irus* cf. *gregarius* (Partsch), *Abra* sp., *Hydrobia* sp., *Cerithium* sp. They are identified in boreholes NRKR-17001, RTK-1501, RTK-1502A, and RTK-1503 (Fig. 11). Besides, the scarce finding of foraminifers and ostracods indicate Lower Sarmatian association of small *Anomalinoides* sp. and *Ammonia* ex gr. *beccarri (*RTK-1502A, 210 m).

Fig. 11. *Lower Sarmatian mollusks Psamobia cf. laboidei sarmatica* Papp *(left) and Granulolabium bicinctum* (Brocchi) *(right). Borehole RTK-1503 (44.50 m).*

Zircon U/Pb dating by LA-ICP-MS

The zircons from the volcanic tuff from borehole NRKR-17002 that is positioned on the top of coal series (Fig. 12) were dated. We analysed around 20 zircon grains, each grains are analysed in the core and in the rim (Fig. 13). Results from the zircon U/Pb are presented in Table 1 and corresponding concordia plots and age results are presented in Fig. 14. We obtained concordia age of 16.9 ± 0.2 Ma for all analysed grains without any inherited cores, meaning that we were able to document a single magmatic event. This age in general corresponds to similar ages obtained the Central Pannonian basin (Seghedi et al., 2013, Lukács et al., 2018) when a voluminous magmatism was synchronous with the development of main sedimentary basins during the main Miocene–Quaternary tectonic events in Carpathian-Pannonian Region. Therefore, we interpret this to represent their crystallization age and therefore as the age of emplacement of this tuff.

Discussion and interpretation

During the Early to Middle Miocene large parts of Central Europe were covered by the Paratethys Sea that had phases of good and partial connectivity to the Mediterranean. Paratethys reduced and expanded through time by a complex combination of climate variability, sea level change, and geodynamic processes of Alpine tectonics (e.g. Rögl, 1998; Ter Borgh et al., 2014; Sant et al., 2017). In the latest Early Miocene, the Central Paratethys mainly occupied the northwestern part of the Pannonian Basin in Slovenia, Austria, Slovakia and Hungary. During the early Middle Miocene this sea extended to the southeastern Pannonian Basin in Croatia, Bosnia and Herzegovina and Serbia, to the Transylvanian Basin in Romania, and to the Carpathian foredeep (e. g. Ćorić et al., 2009; Pezelj et al., 2013; Ter Borgh et al., 2014; Sant et al., 2017, 2018; Jovanović et al., 2019, 2019a; Mandic et al., 2019). During this marine water expansion, there were a few corridors between Central and Eastern Paratethys Sea (Neubauer et al., 2015). Similar scenario was observed in eastern Serbia and so-called the Trans-Carpathian seaways across the Djerdap, Tekija and Borska Slatina were recognized (Popović, 1968; Dolić, 1977; Stevanović, 1977). In the same time span a series of

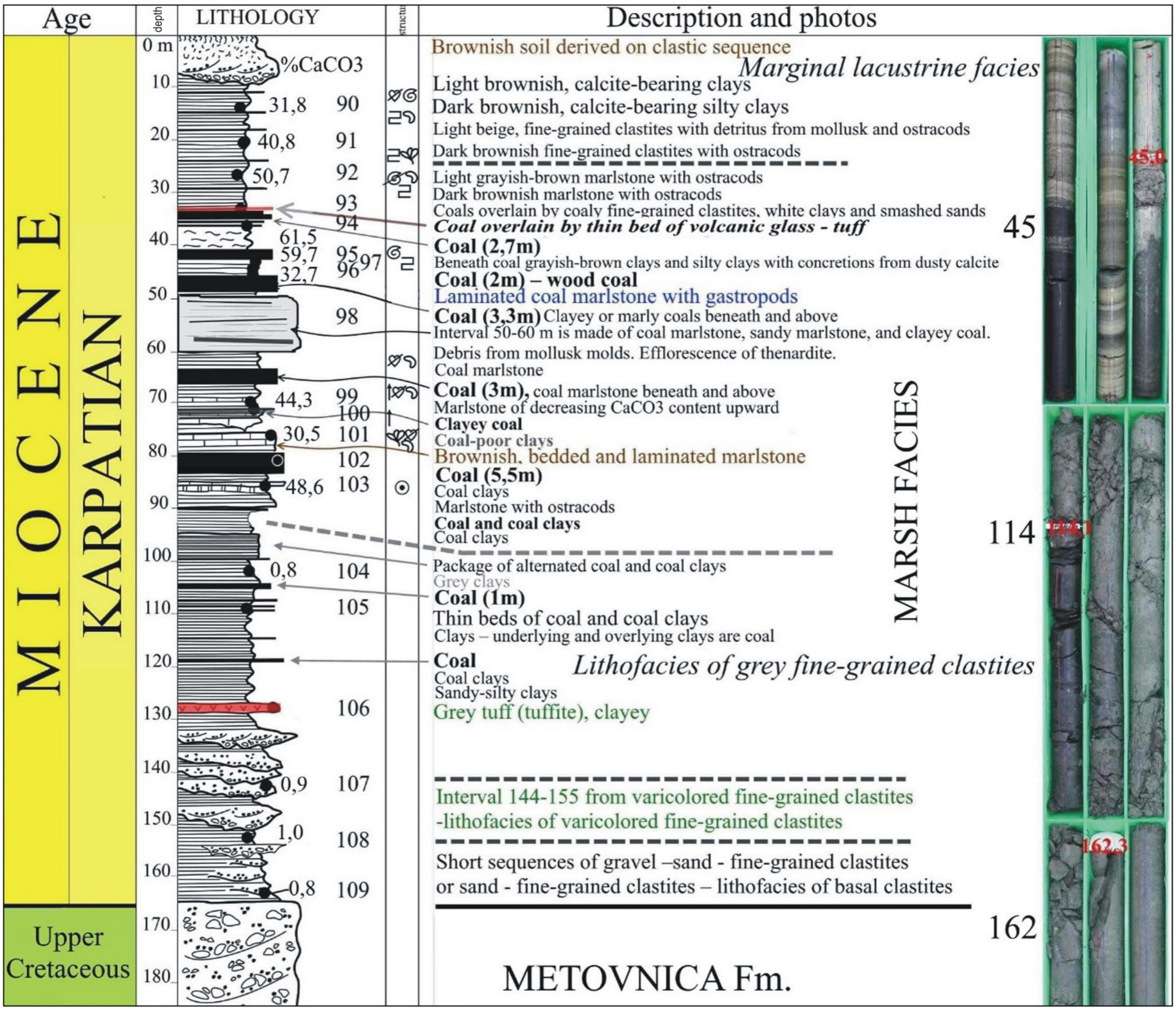

Fig. 12. *Lithostratigraphic column of the Lower Miocene coal series in the borehole NRKR-17002 and position of the sampled tuff interbed (grey arrow, samples 93 and 94). For the symbols, see previous figures.*

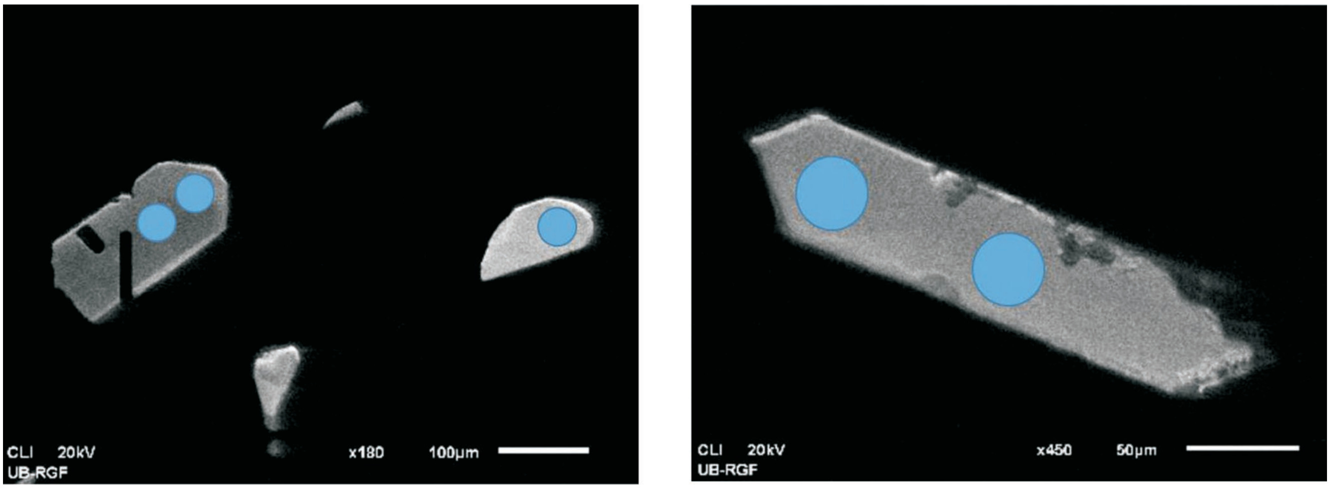

Fig. 13. *Cathodoluminescence (CL) images of the zircon grains.*

Table 1. U-Pb data measurements and isotope ratio.

NV93	$^{207}Pb/^{206}Pb$	1σ	$^{206}Pb/^{238}U$	1σ	$^{207}Pb/^{235}U$	1σ	Age $^{206}Pb/^{238}U$	1σ	Age $^{207}Pb/^{235}U$	1σ
NV93_1	0.045	0.0032	0.002628	0.000071	0.0166	0.0012	16.92	0.46	16.7	1.2
NV93_2	0.0485	0.0031	0.002647	0.00008	0.0173	0.0011	17.04	0.52	17.4	1.1
NV93_3	0.0468	0.0037	0.002632	0.000063	0.0168	0.0013	16.94	0.41	16.9	1.3
NV93_4	0.0507	0.0075	0.0027	0.00013	0.0193	0.0023	17.37	0.84	19.4	2.3
NV93_5	0.0525	0.0076	0.002542	0.000085	0.0181	0.0024	16.37	0.55	18.2	2.4
NV93_6	0.0501	0.0063	0.00265	0.000092	0.0183	0.0022	17.06	0.59	18.4	2.2
NV93_7	0.0499	0.0062	0.00266	0.00012	0.0183	0.0021	17.15	0.78	18.4	2.1
NV93_8	0.047	0.0025	0.002741	0.000074	0.01795	0.00093	17.65	0.48	18.06	0.92
NV93_9	0.0454	0.0012	0.002616	0.00003	0.01644	0.00038	16.84	0.19	16.55	0.38
NV93_10	0.0474	0.0038	0.002803	0.000095	0.0186	0.0017	18.04	0.61	18.7	1.7
NV93_11	0.049	0.0032	0.002531	0.00009	0.0175	0.0011	16.29	0.58	17.6	1.1

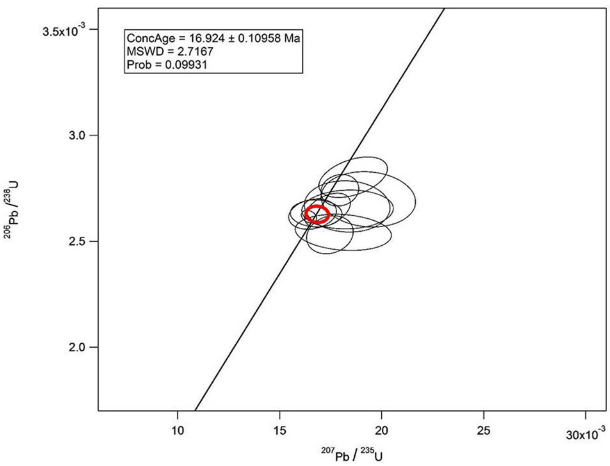

Fig. 14. *U-Pb concordia diagram and weighted mean ages (16.9 Ma).*

basins, filled with lacustrine deposits, developed in the Dinarides, northern Croatia and Serbia (e.g. Neubauer et al. 2015, Figs. 15, 16). These dominantly intramountain basins were disconnected from both Mediterranean and Paratethys which gave rise to the development of regional bioprovinces with their own specific endemic fauna (Harzhauser & Mandic, 2008; Krstić et al., 2012; Neubauer et al. 2015; Sant et al., 2017, 2018; Bradić-Milinović et al., 2019).

The endemic fauna, together with the lack of magnetostratigraphic and radioisotopic data, led of misunderstanding of the age and evolution of the Serbian basins (Sant et al., 2018; Rundić et al., 2018).

Miocene sediments of eastern Serbia were a subject of interest from long time ago. The first observation on Timok tertiary basin and determination of some mollusks taxa (Venus, Cerithium) comes from Ami Boué, the founder of geology of Balkan Peninsula, during his trip in Serbia between 1836-1837 (Živković, 1893). A half century later, Jovan Žujović, the founder of geology of Kingdom of Serbia informed that during the Miocene the Mediterranean Sea flooding the Timok valley in eastern Serbia (Žujović, 1889). His conclusion was based on analysis of five fossiliferous localities (including Zvezdan near Zaječar). Since that time, the Miocene freshwater sediments with coal layers were already known from the Zvezdan coal mine which was opened in 1889. Very soon, Radovanović & Pavlović (1891) and Živković (1893) gave very important contributions concerning the Neogene of Timok basin and, especially its geological relationships as well as systematics and taxonomy of Tertiary fossils. The last one author mentioned very interesting geological realtionship between freshwater Tertiary sediments with coal and marine deposits near Zvezdan (Živković, 1893). He found a very abundant assemblage of freshwater taxa (*Melania serbica, Melanopsis sandbergeri*, *Prososthenia suessi*, etc.). A

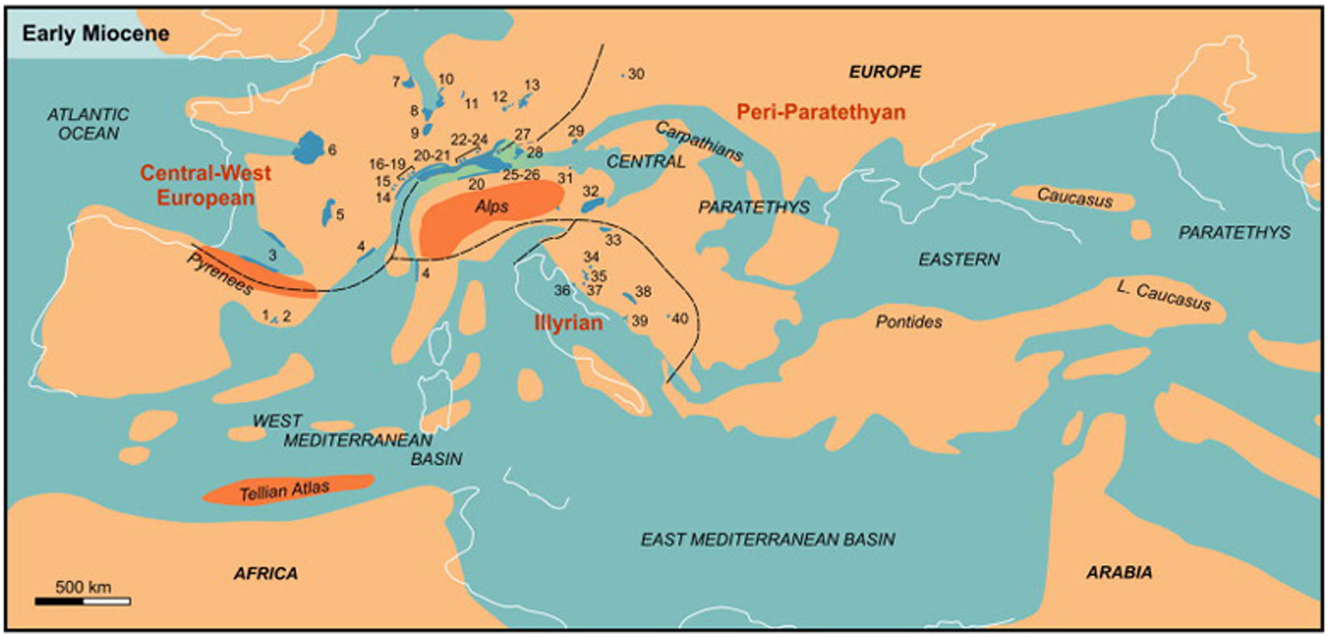

Fig. 15. *Palinspastic maps of Europe freshwater system during the Early Miocene with indication of palaeobiogeographic units (red color) (Neubauer et al., 2015). Note that during the Early Miocene there are no data from the Serbian territory except the no.40 – Trijebine (Illyrian province).*

Fig. 16. *Palinspastic maps of Europe freshwater system during the Middle Miocene (Neubauer et al. 2015). Note the Balkan lacustrine province existed: 39 – Vračević, 40 – Serbia, 41 – Timok, 43 – Metohia and, 44 – Skopje. White ellipse marks the studied area of eastern Serbia.*

decade later, Brusina (1902) and Pavlović (1903) informed about freshwater mollusks, ostracods and parts of fishes skeleton of the Miocene age. For example, Brusina (1902) determined and drawn a few freshwater mollusks from the Zvezdan and Zvezdanski Ključ sites. He determined the tiny specimens (*Planorbis pavlovici*, *Emmericia zivkovici*, *Nematurella? nikolajevici, Prososthenia serbica, Amphime-*

lania macedonica, *Ancylus serbicus*, etc.) from the samples which Žujović gave him for identification. Much more later, the great field campaign in frame of the basic geological mapping of eastern Serbia (Veselinović et al., 1967) shows that a close stratigraphic position of these Miocene freshwater series is impossible and there are no good biostratigraphic markers. Similar studies by Dolić (1977, 1998) and Stevanović (1977) confirmed that the mentioned freshwater fossils have the early-middle Miocene age.

However, based on lithostratigraphic correlation, biostratigraphy and radiometric measurements, our study confirms that the freshwater fossiliferous series from the studied boreholes (NRKR-17002, RTK-1501, RTK-1502A, RTK-1503) corresponding to the late Early Miocene equivalents of the Karpatian regional stage (= late Burdigalian). Fossil material that was found within the marsh facies with coal layers has been deposited during the lacustrine phase of the late Early Miocene (SLS). The tiny, planispiral forms of *Gyraulus*-type gastropods, the rare tower-shaped and sculptured forms like *Fossarulus* and *Prososthenia*, and the numerous operculums (mostly *Bithynia*) show no orderliness in terms of orientation. In addition, there are many ostracods, especially many molds of elongated forms that are difficult to determine (most belong to the genus *Candona*). Their carapaces do not show orderliness i.e. no dominant orientation indicating *in situ* association. This lake (Lubnica Lake) was an endemic lake settled by various, more or less endemic biota. Sculptured gastropods (*Fossarulus, Prososthenia*) as well as ornamented ostracods (*Ilyocypris,?Dinarocythere*) indicate shallow-water, but more dynamic water regime. Contrary, tiny, transparent ostracod carapaces (*Candona, Cypria, Fabaeformiscandona*, etc.) live in a quiet, low turbulence depositional conditions in sheltered or profundal part of lake (Sant et al., 2018). This environmental depended life pattern is more or less recognized within all freshwater lakes during the Miocene time. For that reason, the clear stratigraphic range of the mentioned lake based on fossil content couldn't be defined. However, for the first time, our radiometric age dating (16.9 Ma) of tuff located above the coal series give the precise stratigraphic position of these sediments. On other words, the famous freshwater series from the Zvezdan and Lubnica coal mines that underlie the Badenian marine sediments was deposited during the Karpatian (= late Burdigalian). Chronologically, it could be correlated with Pag, Livno and Sinj basins within the Dinaridic Lake System (DLS) which are originated during the Miocene Climatic Optimum (De Leew et al., 2012). Age of the tuff can be correlated with well-known Miocene syn-extensional volcanism across the Pannonian and Dacian basin (Cvetković & Pecskay, 1999; Cvetković et al., 2004; Lukács et al., 2018; Marković et al., 2018). Our results prove that SLS was developed much early than the latest study reported (Krstić et al., 2012, Sant et al., 2018). Based on ostracods and diatoms taxa (Ognjanova-Rumenova, 2006; Ognjanova-Rumenova & Krstić, 2007) as well as some mollusks comparison, Krstić et al. (2012) concluded that majority of the freshwater basins in Serbia (SLS) were developed during the early Middle Miocene (including Popovac and Zaječar basins). Similarly, in the palinspastic map of Balkan area during the Early Miocene there are no data about lacustrine basins in Serbia (Neubauer et al., 2015). Only exception is the Levač basin (central Serbia), which according to the flora remains was developed during the very Early Miocene (Krstić et al., 2012). However, recent study from Popovac basin in central Serbia (Sant et al., 2018) and obtained radiometric age of 14.4 Ma (Ar/Ar dating of tuff from lacustrine marls) show that all the mentioned basins are significantly different age. All the conventional methods (lithostratigraphy, biostratigraphy, etc.) are not enough for a precise age determination of these lakes. Fossil fauna have endemic character and it haven't biostratigraphic potential (Rundić et al., 2013, 2018). It needs more independent age control methods (magnetostratigraphy, radiometric age dating) which can obtain real data concerning timing of SLS (Rundić et al., 2013, 2018; Sant et al., 2018). Otherwise, its relationship towards the younger Badenian marine transgressive sediments is subject of debate (e.g. Mandic et al., 2019). Somewhere, this relation can be more or less obvious (e.g. Sant et al., 2018). Some authors reported that the age of the SLS is older than the marine Middle Badenian but there is concordant relation between them (Krstić et al., 2012).

A few of the studied boreholes documented the Badenian marine transgression (e.g. RTK-1501, RTK-1502A). There is good comparison between our results and previous researches (Petrović, 1961, 1969; Džodžo-Tomić, 1963, 1970; Veselinović et al., 1969, 1975; Popović, 1968; Popović & Gagić, 1969; Dolić, 1977; Stevanović, 1977; Ganić, 2005). The transgression occurred accross the Timok bay which was developed along the Timok strike-slip fault reactivated at the beginning of Middle Miocene (Kräutner & Krstić, 2003; Krstić et al., 2012). In eastern Serbia, the area of Zaječar was the southernmost prolongation of the Paratethys Sea (Stevanović, 1977; Ganić, 2005). During the Middle Badenian, marine facies reached to the town of Zaječar (Krstić et al., 2012). However, in the Upper Badenian (= Konkian, regional stage in eastern Paratethys), the topmost part of succession have a Sarmatoid character and classified as the "Buglovian layers" (Laskarev, 1934; Džodžo-Tomić, 1963) or "Veselyankian horizon" (Kókay, 1984, p. 41). Based on these studies, the topmost Badenian and transitional Badenian/Sarmatian sediments have Eastern Parathetian affinity. However, it is not easy to reconstruct marine gateways between Central and Eastern Paratethys (Kókay, 1984; Ter Borgh et al., 2014).. The existence of small oases of Badenian rocks within so-called the Trans-Carpathian corridor (Serbian part of Carpathians) could be a connection route (Dolić, 1977; Stevanović, 1977). Contrary, other authors mentioned that the Badenian Sea of so-called the Vienna type, mainly comes through SW Romania to the north-western part of Bulgaria (Krstić et al., 2012). Recently, similar paleogeographic reconstructions based on biochronology and Ar/Ar radiometric age of tuffs from the NW Transylvanian basin and SE Carpathian Foredeep indicate that the marine transgression of the Paratethys occurred during Middle Badenian between 14.9–14.4 Ma (Sant et al., 2019).

Our results from a few samples contain microfauna confirm existence of late Badenian to early Sarmatian phases of evolution of the Paratethys Sea in the studied area. Based on foraminifer and ostracod assemblages and scarce molluscan remains found in these samples as well as lithological succession (e.g. RTK-1501, RTK-1502A) there is an indication about the late Badenian transgressive event. It could be correlative with global 3rd order cycle TB 2.5 of sea-level fluctation that is already known form Central Paratethys (Ćorić et al., 2009; Pezelj et al., 2016). Species such as *Ammonia* ex gr. *beccarri*, *A.* cf *.viennensis*, *Bolivina* cf. *dilatata*, *Bulimina elongata, Hanzawaia boueana*, *Heterolepa dutemplei, Cassidulina laevigata* etc*.* indicate full marine conditions (Popović, 1968; Popović & Gagić, 1969; Petrović, 1969, 1988). However, large portion of clastites within all the studied boreholes indicate a regressive trend and transition towards the restricted marine and brackish environment (Stevanović, 1977; Schwarzhans et al., 2015; Vasić et al., 2018; Rundić et al., 2018). Indeed, fossil fauna such as *Granulolabium bicinctum*, *Acteocina lajonkaireana*, *Mohrensternia* cf. *pseudoangulata*, *Ervilia* cf. *dissita, Irus* cf. *gregarious, Abra* sp., *Hydrobia* sp., *and Cerithium* sp. suggest that changes. Additionally, small foraminifers such as rare Anomalinoides and Ammonia with small-size shell as well as scarce ostracod species indicate the shift from the marine to shallow-water brackish environment (Laskarev, 1934; Džodžo-Tomić,1963, 1970; Popović & Gagić, 1969; Ganić, 2005). Afterwards, we recognized a faunistic sterile package of clastites between the freshwater lacustrine sediments and marine-brackish sediments on the top of some boreholes (RTK-1501, RTK-1502A, and RTK-1503 - Fig. 17). It represents the transitional part between these units and it is impossible to give it more precise stratigraphic age. So, it could correspond to time interval from late Karpatian to late Badenian. Based on the mentioned results and spatial and temporal relation between the studied boreholes RTK-1501 and RTK-1502A, the next stratigraphic range within the marine and marine-brackish succession could be determined (Fig. 18).

Finally, based on all the collected data from the studied area, we sketched a hypothetical model of development of the lateral alluvial-lacustrine and marginal-lacustrine facies during the early Miocene (Fig. 18). Vertical alteration of the facies in the studied wells and their basic sedimentological and paleontological properties give some elements to the sketch and suggest about the mode of deposition in such a system. The arrangement of individual facies (marginal-lacustrine, lacustrine, prodelta, etc.) and their distribution over the surface indicate to the depositional mode. The thickness of the clastic sediments from the alluvial facies (AL) decreases to basin wards. Generally, this model of facies distribution indicates the direction of transport from north to south. Two of transparent arrows mark the direction of the redeposited clastic material to the marginal facies.

On the other hand, there is clear evidence that during the middle Miocene marine water of Paratethys flooded this area. It is clearly observed in the boreholes RTK-1501 and RTK-1502A. However, these sporadic evidences of the late Badenian transgressive event (no evidence on older Badenian flooding) and more or less uniform pattern of distribution of the clastic sediments across the basin make too difficult to create another one sketch map of facies distribution during the Badenian and Sarmatian time. So, we

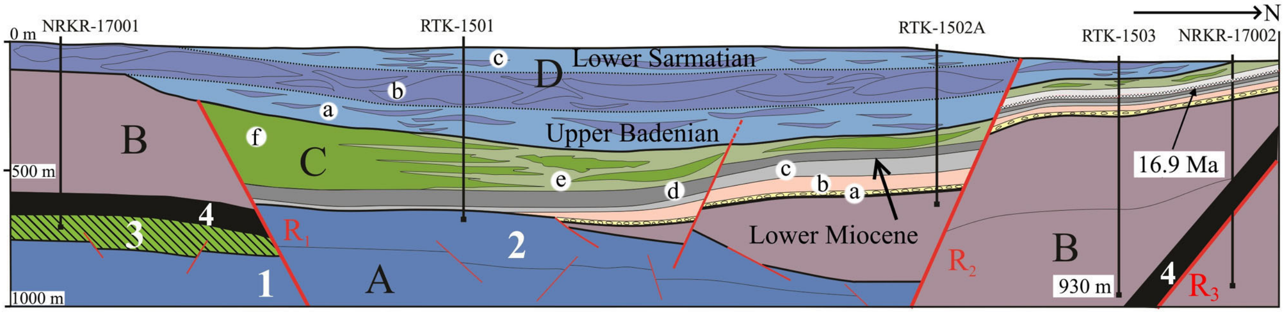

Fig. 17. A simplified geological cross-section based on data from the studied boreholes (Vasić et al., 2018). Stratigraphic units: ***A****. Paleorelief (older than Metovnica Fm.):* ***1,*** *Berrias?carbonates;* ***2,*** *Valanginian limestones;* ***3,*** *Albian glauconitic sandstones and;* ***4,*** *Cenomanian fine-grained clastites.* ***R1*** *– Pre-Miocene and Miocene fault.* ***R2 i R3*** *–Post-Miocene, reverse faults;* ***B.*** *Cr-Paleogene Metovnica Fm.;* ***C.****Lower Miocene terrestrial-lacustrine clastites;, and* ***D.*** *Middle Miocene marine and brackish clastites. Small letters within the unit C indicate six main non-marine lithofacies mentioned in the text. Letters for the unit D mark three main marine and marine-brackish lithofacies. These unstandardized colors and textures should to point out main lithological differences and lithofacies distribution.*

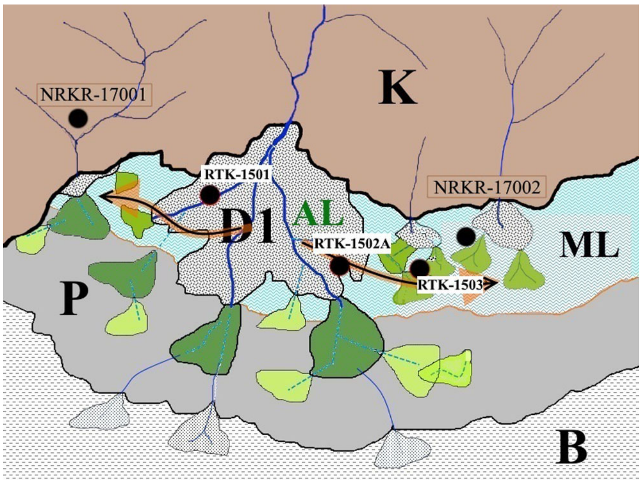

Fig. 18. A hypothetical model of development of the lateral alluvial-lacustrine and marginal-lacustrine facies during the early Miocene (with the positions of wells). Key: ***K,*** *land with an alluvial network;* ***ML,*** *Marginal-lacustrine facies;* ***B,*** *Basin (lacustrine facies);* ***P,*** *Prodelta;* ***AL,*** *Alluvial-lacustrine facies with diverse delta (D1) (Vasić et al., 2018, modified).*

think that more detailed analyses of the mentioned core-wells as well as the future nearby boreholes can better support this attempt to reconstruct the direction of the marine Badenian flooding as well as following regressive trend during Sarmatian.

Conclusions

This study is obtained the first exact data regarding the stratigraphic position of freshwater Miocene clastic sediments and pyroclastites in the Zaječar area. The oldest Miocene unit corresponds to the continental-lacustrine series of so-called the Serbian Lake system (SLS) that was originated during the late early Miocene whereas overlying marine and restricted marine sediments belong to the middle Miocene (Badenian and Sarmatian).

Six different major lithofacies within the continental-lacustrine deposition (SLS) and three major marine and restricted marine facies (marine-brackish Paratethys) indicate rapid evolution of the area during the early and middle Miocene.

Stratigraphically, the continental-lacustrine sediments (basal clastites and marsh facies especially) belong to the Lower Miocene (freshwater equivalents of Karpatian i.e. late Burdigalian).

U-Pb radiometric analyses of zircon grains from the tuff located above the coal series (borehole NRKR-17002) indicates a mean radiometric age of 16.9 Ma. It is the first data that precisely indicate the Lower Miocene age of coal series in eastern Serbia. Previously, it understood as the Lower–Middle Miocene.

Analyses of mollusk and foraminifer assemblages from the different clastic sediments which overlay the mentioned freshwater series indicate a marine and marine-brackish development that corresponds to the time interval from late Badenian to early Sarmatian.

Based on data from the studied boreholes, it is impossible to date the timing of marine Badenian transgression in this westernmost part of Dacian basin. Namely, biostratigraphic analyses of the studied material show that the older biostratigraphic zones within Badenian could not be determined. Only upper Badenian Bolivina-Bulimina Zone is recognized. No determined stratigraphic range for different clastites which separate the lower, freshwater series of clastites with coal (Lower Miocene) from the upper Badenian and Lower Sarmatian sediments on the top of Miocene succession. They have a potential stratigraphic range from the Karpatian to Upper Badenian.

Comparative lithostratigraphic analysis as well as a geological model of the studied area, point that Badenian flooding sediments or Sarmatian restricted marine clastites cover different older geological units (e.g. Lower Miocene, Lower or Upper Cretaceous, etc.) depending of the morphological characteristics of paleorelief.

Acknowledgements

These studies represent results of a few projects (No. 176015, 176019) funded by Ministry of Science and Technological Development (Republic of Serbia). Our thanks go to the reviewers N. Ognjanova-Rumenova (Sofia) and S. Ćorić (Wien) for useful suggestions and constructive comments which improved the first version of the manuscript. The results of this researches which performed during 2017 have been published courtesy by the Tilva Co., Belgrade.

References

Andersen, T. 2002. Correction of common lead in U–Pb analyses that do not report ^{204}Pb. *Chemical geology*, 192 (1-2): 59–79.

Anđelković, M. & Anđelković, J. 1997. Badenski ciklusi u Srbiji [Badenian cycles of Serbia – in Serbian and English]. *Geološki anali Balkanskoga poluostrva*, 62: 25–45.

Antonijević, I. & Mijatović, P. 2014. The copper deposits of Bor, eastern Serbia: Geology and Origin of the Deposits. *Geološki anali Balkanskoga poluostrva*, 75: 59–74.

Bradić-Milinović, K., Ahnelt, H., Rundić, Lj. & Schwarzhans, W. 2019. The lost freshwater goby fish fauna (Teleostei, Gobiidae) from the early Miocene of Klinci (Serbia). *Swiss Journal of Paleontology*, 138: 285–315.

Brusina, S. 1902. Iconographia Molluscorum Fossilium in tellure tertiaria Hungariae, Croatiae, Slavoniae, Dalmatiae, Bosniae, Herzegovinae, Serbiae and Bulgariae inventorum. Officina Soc. Typographicae, Agram

Cvetković, V. & Pecskay, Z. 1999. The Early Miocene eruptive complex of Borač (Central Serbia): Volcanic facies and evolution over time. *Geologica Carpathica*, 50: 91–93.

Cvetković, V., Prelević, D., Downes, H., Jovanović, M., Vaseli, O. & Pecskay, Z. 2004. Origin and geodynamic significance of Tertiary postcollisional basaltic magmatism in Serbia (Central Balkan Peninsula). *Lithos*, 73: 161–186.

Ćorić, S., Pavelić, D., Rőgl F., Mandić, O., Vrabac, S., Avanić, R., Jerković, L. & Vranjković, A. 2009. Revised Middle Miocene datum for initial marine flooding of North Croatian Basins (Pannonian Basin System, Central Paratethys). *Geologia Croatica*, 62 (1): 31–43.

De Leew, A., Mandic, O., Krijgsman, W., Kuiper, K. & Hrvatović, H. 2012. Paleomagnetic and geochronologic constraints on the geodynamic evolution of the Central Dinarides. *Tectonophysics,* 530–531 (2012): 286–298.

Dimitrijević, M. 1997. *Geology of Yugoslavia*. Geological Institute GEMINI Special Publication, Belgrade, 187 pp.

Dolić, D. 1977. O problemima stratigrafskog raščlanjavanja slatkovodnog neogena Srbije [On problems of stratigraphic division of freshwater Neogene of Serbia – in Serbian, German summary]. *Zapisnici Srpskog geološkog društva za 1975*, 93–103.

Dolić, D. 1998. Odnos nasleđa Paratetisa i miocenskih jezerskih formacija u Srbiji [The relationship of Paratethyan and Miocene lake deposits of Serbia – in Serbian]. *XIII kongres geologa Jugoslavije*, 2: 373–382.

Džodžo-Tomić, R. 1963. Mikrofauna buglovskog horizonta Timočke krajine s naročitim osvrtom na njegovo stratigrafsko mesto (Microfauna of Buglovian horizont from Timočka krajina with the special regard to its stratigrafical position - in Serbian, English summary. *Vesnik Geozavoda*, 21 (A): 11–132.

Džodžo-Tomić, R. 1970. Sarmatsko razvice Dakijskog basena u istočnoj Srbiji sa aspekta mikrofaune i njegova zonalna biostratigrafska podela [Sarmatic evolution of the Dacian Basin in eastern Serbia from the aspect of microfauna and its zonal biostratigraphic division – in Serbian, English abstract]. *Vesnik*, 28 (A): 201–212.

Đajić, S., Tanasković, Lj. & Petrović, S. 2018. Paleopalinološke asocijacije srednjeg miocena istočne Srbije (šira okolina Negotina) [Palaeopalynological middle Miocene associations of east Serbia (broader vicinity of Negotin) – in Serbian and English]. *Zapisnici Srpskog geološkog društva za 2018*, 1–20.

Đorđević, M. 2005. Volcanogenic Turonian and epiclastic Senonian in the Timok Magmatic Complex between Bor and Tupiznica Mountain, eastern Serbia. *Geološki anali Balkanskoga poluostrva*, 66: 63–71.

Đorđević, M. & Banješević, M. 1997. *Geology of the southern part of the Timok Eruptive area* (in Serbian, English summary). Savezno ministarstvo za privredu, Beograd, 171pp.

Ganić, M. 2005. Morsko-brakični miocen Dakijskog basena, istočna Srbija [*Marine-brackish Miocene of the Dacian Basin, Eastern Serbia* – in Serbian]. Unpublished PhD thesis, Faculty of Mining and Geology. University of Belgrade, 185 pp.

Grubić, A. & Antonijević, I. 1961/1962. Nova shvatanja o tektonskom sklopu istočne Srbije. [News on the structural properties of east Serbia – in Serbian, English abstract]. *Zbornik radova RGF*, 8: 177–187.

Harzhauser, M. & Mandic, O. 2008. Neogene lake systems of Central and South-Eastern Europe: Faunal diversity, gradients and interrelations. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 260: 417–434.

Jackson, S., Pearson, J., Griffin, L. & Belausova, A. 2004. The application of laser ablation-inductively coupled plasma-mass spectrometry to in situ U–Pb zircon geochronology. *Chemical Geology*, 211: 47–69.

Jovanović, G., Ćorić, S. & Vrabac, S. 2019. The First evidence of marine Badenian transgression near Koceljeva (Central Paratethys, western Serbia). *Geološki anali Balkanskoga poluostrva*, 80 (1): 1–15.

Jovanović, G., Trif, N., Codrea, V. & Đurić, D. 2019a. Middle Miocene shark teeth from the southern margin of the Pannonian Basin System (Serbia, Central Paratethys). *Geološki anali Balkanskoga poluostrva*, 80 (1): 29–43.

Jipa, D.C. & Olariu, C. 2009. Dacian Basin - Depositional architecture and sedimentary history of a Paratethys Sea. *Geo-Eco-Marina special publication*, 3: 264 pp.

Knežević, S. & Ganić, M. 2013. Intracarpathian connection between the Pannonian and Dacian basins. In: Rundić, Lj., Gaudenyi, T. & Jovanović, M. (Eds.). *Neogene and Quaternary stratigraphy - Actual terminology and nomenclature*. Serbian Geological Society, 34–35.

Kókay, J. 1984. Central and Eastern Paratethyan Interrelations in the light of Late Badenian salinity conditions. *Geologica Hungarica, series palaeontologica,* 48: 61 pp.

Krstić, N. 1991. Posledica štajerskih pokreta u jugoslovenskim Karpato-Balkanidima [Styrian orogeny effect in the Yugoslavian Carpatho-Balkanides – in Serbian, English abstract]. *Radovi Geoinstituta*, 25: 21–30.

Krstić, N., Savić, Lj., Jovanović, G. & Bodor, E. 2003. Lower Miocene lakes of the Balkan Land. *Acta Geologica Hungarica*, 46 (3): 291–299.

Krstić, N., Sikošek, B. & Krstić, N. 1988. The Neogene tectonics of the Yugoslav Carpathian–Balkanides. *Proceedings of Geoinstitute*, 22: 77–85 (in Serbian, English summary).

Krstić, N., Savić, Lj. & Jovanović, G. 2012. The Neogene Lakes on the Balkan Land. *Geološki anali Balkanskoga poluostrva,* 73: 37–60.

Kräutner, H.G. & Krstić, B. 2003. Geological map of the Carpatho-Balkanides between Mehadia, Oravita, Niš and Sofia, at scale 1: 300 000. Geoinstitute, Belgrade.

Laskarev, V. 1924. Sur les equivalents du Sarmatien Superieur en Serbie. *Recueil de Travaux offert á Jovan Cvijić*. Državna štamparija Beograd, 73–85.

Laskarev, V. 1934. O buglovskim slojevima duž spoljneg oboda Karpata [Sur les couches Bougloviennes le long du bord exterieur des Carpathes – in Serbian, French resume]. *Geoloski anali Balkanskoga poluostrva*, 12 (1): 1–17.

Ludwig, K.R. 2003. User's manual for Isoplot 3.00. A Geochronological Toolkit for Microsoft Excel. Berkeley Geochronology Center, *Special Publication*, 4: 1–74.

Lukács, R., Harangi, S., Guillong, M., Bachmann, O., Fodor, L., Buret, Y., Dunkl, I., Sliwinski, J., Quadt, A., Peytcheva, I. & Zimmerer, M. 2018. Early to Mid-Miocene syn-extensional massive silicic volcanism in the Pannonian Basin (East-Central Europe): Eruption chronology, correlation potential and geodynamic implications. *Earth-Science Reviews* 179: 1–19.

Mandic, O., Rundić, Lj., Ćorić, S., Pezelj, D., Theobalt, D., Sant, K. & Krijgsman, W. 2019. Age and mode of the Middle Miocene marine flooding of the Pannonian Basin - constraints from Central Serbia. *Palaios*, 34 (2): 71–95.

Marković, F., Kovačić, M., Ćorić, S., Tibljaš, D., Pezelj, Đ., Hajek-Tadesse, V., Hernitz-Kučenjak, M. & Bakrač, K. 2018. Miocenski tufovi Sjevernohrvatskoga bazena [*Miocene tuffs from the North Croatian basin* – in Croatian, English abstract]. 17. Kongres geologa Srbije, Srpsko geološko društvo, Abstract book, 164–168.

Marović, M., Đoković I. & Toljić, M. 1998. Genesis of the Neotectonic Structures of Serbia. *Geoloski anali Balkanskoga poluostrva*, 62: 25–45.

Marović, M., Đoković, I., Milićević, V., Toljić, M. & Gerzina, N. 2002. Paleomagnetism of the late Paleogene and Neogene rocks of the Serbian Carpatho-Balkanides: tectonic implications. *Geoloski anali Balkanskoga poluostrva*, 51: 329–334.

Marović, M., Toljić, M., Rundić, Lj. & Milivojević, J. 2007. *Neoalpine tectonics of Serbia*. Serbian Geological Society, Belgrade, 87 pp.

Neubauer, T., Harzhauser, M., Kroh, A., Georgopoulou, E. & Mandic, O. 2015. A gastropod-based biogeographic scheme for the European Neogene freshwater systems. *Earth-Science Reviews*, 143: 98–116.

Obradović, J. & Vasić, N. 2007. *Neogene lacustrine basins of Serbia*. Serbian Academy of Sciences and Arts, Monographs 662, Department of Mathematics, Physics and Geo- Sciences, 3: 310 pp. (In Serbian, English summary).

Ognjanova-Rumenova, N. 2006. Some aspects and problems concerning diatom biochronology for the Neogene in the region of the Balkan Peninsula. In: Witkowski, A. (Ed.). *Proceeding of 18th International Diatom Symposium, Bristol*, 337–345.

Ognjanova-Rumenova, N. & Krstić, N. 2007. Neogene diatom assemblages from lacustrine sediments of Serbia and their distribution in the correlative formations in South-West Bulgaria and Republic of Macedonia. In: Kusber, H-W. & Jahn, R. (Eds.), *Proceeding of 1st Central-European Diatom Meeting 2007, Berlin*, 121–124.

Olteanu, R. & Jipa, D.C. 2006. Dacian Basin environmental evolution during Upper Neogene within the Paratethys domain. *Geo-Eco-Marina,* 12: 91–105.

Pavlović, P. 1903. Zwei neue Arten aus Zvezdan und Madjare. *Geološki anali Balkanskoga poluostrva*, 6 (1): 324–325.

Petković, K. & Andjelković, M. 1958. Neki novi podaci o vremenu epirogenih i orogenih zbivanja i pratećim pojavama u severoistocnoj Srbiji [Neue Daten Über den zeitlichen Verlauf epirogener und orogener Vorgänge und detren Begleiterscheinungen in Ostserbien – in Serbian, German summary]. *Geološki anali Balkanskoga poluostrva*, 25: 1–16.

Petrović, M. 1961. Prilog poznavanju mikrofaune okoline Stubika, Velikog Izvora i Vojilova. [Contribution to the knowledge of the microfauna of Štubik, Veliki izvor and Vojilovo – in Serbian, English summary]. *Glasnik Prirodnjačkog muzeja*, 22 (A): 14–15.

Petrović, M. 1969. Tortonski foraminiferi Štubika (ist. Srbija) i njihov biostratigrafski znacaj [Tortonian foraminifers of Štubik, eastern Serbia – in Serbian, English summary]. *Vesnik zavoda za geološka i geofizička istraživanja*, 27 (A): 231–254.

Petrović, M. 1988. Novine u biostratigrafiji badenskog kata Štubičko-timočkog rova, Velikog Izvora i Vojilova [The new in the Badenian biostratigraphy of Štubik-Timok trough – in Serbian, English summary]. *Geološki anali Balkanskoga poluostrva*, 51: 329–334.

Pezelj, Đ., Mandic, O. & Ćorić, S. 2013. Paleoenvironmental dynamics in the southern Pannonian Basin during initial Middle Miocene marine flooding. *Geologica Carpathica*, 64 (1): 81–100.

Pezelj, Đ., Sremac, J. & Bermanec, V. 2016. Shallow-water benthic foraminiferal assemblages and their response to the palaeoenvironmental changes – example from the Middle Miocene of Medvednica Mt. (Croatia, Central Paratethys). *Geologica Carpathica*, 67 (4): 329–345.

Popović , R. 1968. O starosti sedimenata Slatinskog basena u istočnoj Srbiji [About age of the sediments of Slatina basin, eastern Serbia – in Serbian]. *Vesnik zavoda za geološka i geofizička istraživanja*, 26: 101–110.

Popović, R. & Gagić, N. 1969. Novi podaci o tortonu srednjeg dela Timočkog basena (ist. Srbija) [New data about Tortonian of the middle part of Timok basin, east Serbia – in Serbian]. *Vesnik zavoda za geološka i geofizička istraživanja*, 27, A, 83–104.

Radovanović, S. & Pavlović, P. 1891. O tercijaru Timočke krajine [On Tertiary of the Timok Krajina – in Serbian]. *Glas Srpske kraljevske akademije*, 29: 1–113.

Rögl, F., 1999. Mediterranean and Paratethys. Facts and Hypotheses of an Oligocene to Miocene Paleogeography (Short overview). *Geologica Carpathica*, 50: 339–349.

Rundić, Lj. 2013. Stratigraphy of Neogene – Status and perspectives in Serbia. In: Rundić, Lj., Gaudeny T. & Jovanović M. (Eds.). *Neogene and Quaternary stratigraphy / Actual terminology and nomenclature*. Abstract book, Serbian Geological Society, Belgrade, 9–11.

Rundić, Lj., Knežević, S. & Rakijaš, M. 2013. Badenian marine transgression: new evidence from the Vrdnik coal basin (northern Serbia). *Geološki anali Balkanskoga poluostrva*, 74: 9–23.

Rundić, Lj.,Vasić, N., Banješević, M., Prelević, D., Gajić, V., Jovanović, M., Pantelić, N. & Stefanović, J. 2018. New biostratigraphic, sedimentological, and radiometric data from Lower - Middle Miocene of the Zaječar area (westernmost part of Dacian basin, eastern Serbia). *Abstracts of the XXI Congress of the CBGA, Salzburg, Austria (September 10-13, 2018), Geologica Balcanica*, 99.

Sant, K., Palcu, D., Mandic, O. & Krijgsman, W. 2017. Changing seas in the Early - Middle Miocene of Central Europe: a Mediterranean approach to Paratethyan stratigraphy. *Terra Nova*, 29 (5): 273–281.

Sant, K., Mandic, O., Rundić, Lj., Kuiper, K. & Krijgsman, W. 2018. Age and evolution of the Serbian Lake System: integrated results from Middle Miocene Lake Popovac. *Newsletter on Stratigraphy*, 51 (1), 117–143.

Sant, K., Palcu, D., Turco, E., Di Stefano, A., Baldassini, N., Kouwenhoven, T., Kuiper, K. & Krijgsman, W. 2019. The mid-Langhian flooding in the eastern Central Paratethys: integrated stratigraphic data from the Transylvanian Basin and SE Carpathian Foredeep. *International Journalof Earth Sciences*, 108 (7): 2209–2232.

Schmid, S.M., Bernoulli, D., Fugenschuh, B, Matenco, L., Schefer, S., Schuster, R., Tischler, M. & Ustaszewski, K. 2008. The Alpine-Carpathian-Dinaridic orogenic system: correlation and evolution of tectonic units. *Swiss Journal of Geoscience*, 101: 139–183.

Schwarzhans, W., Bradić, K. & Rundić, Lj. 2015. Fish-otoliths from the marine-brackish water transition from the Middle Miocene of the Belgrade area, Serbia. *Paläontologische Zeitschrift*, 89 (4): 815–837.

Seghedi, I., Ersoy, Y. E. & Helvaci, C. 2013. Miocene–Quaternary volcanism and geodynamic evolution in the Pannonian Basin and the Menderes Massif: A comparative study. *Lithos,* 180-181: 25–42.

Simić, V., Životić, D., Andrić, N. & Rundić, Lj. 2017. *Evolution of Neogene Intramontane Basins in Serbia - Field Trip Guide*. Émile Argand Conference - 13th Workshop on Alpine Geological Studies September 7th - 18th 2017 Zlatibor Mts. (Serbia). University of Belgrade – Faculty of Mining and Geology, 58 pp.

Slama, J., Košler, J., Condon, D., Crowley, J., Gerdes, A., Hanchar, J., Horstwood, M., Morris, G., Nasdala, L., Norberg, N., Schaltegger, U., Schoene, B., Tubrett, M. & Whitehouse, M. 2008. Plešovice zircon - A new natural reference material for U-Pb and Hf isotopic microanalysis. *Chemical Geology,* 249 (1-2): 1–35.

Stevanović, P. 1958. Marinski miocen (torton, sarmat i meot) između sela Sipa, i Kladušnice na izlazu iz Đerdapske klisure [Torton, Sarmat in Mäot ostlich des eisernen Tores am rechten Donauufer zwischen Sip und Kladušnica – in Serbian, German summary]. *Geološki anali Balkanskoga poluostrva*, 25: 17–28.

Stevanović, P. 1964. Marinsko-brakični miocen karpatskog predgorja u istočnoj Srbiji. [Marine-brackish Miocene of the Carpathian Foredeep of eastern Serbia – in Serbian]. *Glas SANU*, 25: 83–101.

Stevanović, P. 1967. Geological review of the Carpatho-Balkanides of Eastern Serbia (stratigraphy, tectonics and magmatism). *Proceedings of VIII Congress of Carpathian-Balkan Geological Association,* 160 pp.

Stevanović, P. 1977. Istočna Srbija, Miocen (Miocene of Eastern Serbia – in Serbian). In: Petković, K. (Ed.). *Geology of Serbia, II–3, Stratigraphy of Serbia*. University of Belgrade, 31–65.

Ter Borgh, M. 2013. *Connections between sedimentary basins during continental collision - how tectonic, surface and sedimentary processes shaped the Paratethys*. PhD Thesis, Universiteit Utrecht, 204 pp.

Ter Borgh, M., Stoica, M., Donselaar, M. E., Matenco, L. & Krijgsman, W. 2014. Miocene connectivity between the

Central and Eastern Paratethys: Constraints from the western Dacian Basin. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 412: 45–67.

Vasiliev, I. 2006. *A new chronology for the Dacian Basin (Romania): consequences for the kinematic and paleoenvironmental evolution of the Paratethys region*. PhD Thesis, Universiteit Utrecht, 193 pp.

Vasić, N., Banješević, M., Rundić, Lj., Gajić, V., Jovanović, M., Prelević, D. & Pantelić, N. 2018. Sedimentologija i biostratigrafija miocena Kraljevice (istočna Srbija) [Miocene sedimentology and biostratigraphy in the Kraljevica area (east Serbia) – in Serbian and English]. *Zbornik apstrakata 17. Kongresa geologa Srbije*, vol. 1: 102–108.

Veselinović, M., Divljan, M., Đorđević, M., Kalenić, M., Milošaković, R., Rajčević, D., Popović, R. & Rudolf, Lj. 1967. Osnovna geološka karta SFRJ 1: 100 000 - list Zaječar [*Basic Geological map of Former Yugoslavia 1:100 000, sheet Zaječar* – in Serbian]. Savezni geološki zavod, Beograd.

Veselinović. M., Antonijević, I., Lončarević, Č., Kalenić, M., Rajčević, D., Krstić, B., Banković, V. & Rakić, B. 1975. Tumač za list Zaječar [*Basic Geological Map of Former Yugoslavia 1: 100 000. Explanatory booklet for the Sheet Zaječar* – in Serbian]. Savezni Geološki Zavod, Beograd.

Wiedenbeck, M., Alle, P., Corfu, F., Griffin, W.L., Meier, M., Oberli, F., Von Quadt, A., Roddick, J.C. & Spiegel, W, 1995. Three natural zircon standards for U-Th-Pb, Lu-Hf, trace element and REE analyses. *Geostandards and Geoanalytical Research*, 19: 1–23.

Živković, M. 1893. Tercijer srednjeg dela Timočkog basena [Tertiary of the middle part of the Timok basin – in Serbian]. *Geološki anali Balkanskoga poluostrva*, 4: 37–117.

Žujović, J. 1889. Osnovi za geologiju Kraljevine Srbije. *Geološki anali Balkanskoga poluostrva*, 1: 1–131.

Резиме

Анализа фација, биостратиграфија и радиометријско датирање доње и средње миоценске сукцесије код Зајечара (Дакијски басен, источна Србија)

Дакијски басен је у неогену био део великог епиконтиненталног мора Паратетиса (Laskarev, 1924). За време миоцена, подручје источне Србије (Тимочка крајина) припадало је најзападнијем делу Дакијског басена који се ослањао на карпатско предгорје, југоисточне огранке Карпата и даље на исток према Бугарској и Румунији (Marović et al., 1998; Ganić, 2005; Ter Borgh, 2013). Седиментне фације у Дакијском басену указују на један регресивни образац запуне басена који карактерише присуство проградационих структура с приобалским фацијама и великим делтама које су нарочито присутне током средњег и млађег миоцена и раног плиоцена (Ganić, 2005; Vasiliev, 2006; Jipa & Olariu, 2009; Ter Borgh et al., 2014; Đajić et al., 2018). На основу детаљне петрографске односно седиментолошке анализе пет истражних бушотина у околини Зајечара (RTK-1501, RTK-1502A, RTK-1503, NRKR-17001 и NRKR-17002), у оквиру миоценске стенске сукцесије велике дебљине (негде и преко 500 m), издвојено је шест главних литофација унутар старије миоценских континентално-језерских наслага и три литофације које одговарају наслагама морског и морско-бракичног мора Паратетиса (Vasić et al., 2018). Релативно брза смена грубокластичних стена и финозрних кластита указује на динамичан развој овог подручја током старијег и средњег миоцена (нпр. Veselinović et al., 1967, 1975; Popović, 1968; Popović & Gagić, 1969; Stevanović, 1958, 1964, 1967, 1977). Поред детаљних седиментолошких анализа, појединачни наласци фосилног материјала и радиометријско датирање прослојака туфа унутар седиментне серије, омогућили су стратиграфско расчлањавање миоценске серије и добијање првих егзактних података о стратиграфском положају слатководних миоценских кластита и вулканита. Најстарија миоценска јединица одговара континентално-језерској серији такозваног Српског језерског система (SLS) а посебно базални кластити и мочварне фације са угљем. U-Pb радиометријске анализе зрна циркона из интерстратификованог туфа у повлати лубничке угљене серије (бушотина NRKR-17002, дубина 34 m) указују на старост туфа од 16,9 милиона година (доњи миоцен – Карпат). Ово су први подаци који прецизно указују на старије миоценску старост угљене серије са угљем у Лубници односно Звездану. Тиме је утврђено да овај језерски басен по времену стварања одговара тзв. Динарском језерском систему (De Leew et al., 2012) и да је знатно старији од неких језерских басена у оквиру Српског језерског система (Sant et al., 2018). Пронађена асоцијација мекушаца, фораминифера и остракода (RTK-1501, RTK-1502A, RTK-1503) из различитих нивоа кластита који трансгресивно леже преко поменуте слатководне серије, указује на развој мора тј. бракичног мора (Паратетис) на овом простору у периоду с краја бадена и почетка сармата (средњи миоцен). На основу доступних података из проучаваних бушотина, није могуће датирати време баденске трансгресије на овом, најзападнијем делу Дакијског басена (констатована је само горњобаденска *Bolivina- Bulimina* зона). На жалост, због оскудних налазака фосилног материјала, није утврђен стратиграфски положај за различите кластите који раздвајају доњу, слатководну серију са угљем (доњи миоцен) од горње баденских и доње сарматских седимента на врху миоценске сукцесије. Узимајући те чињенице у обзир, ова истраживања би могла указати да је поменута баденска трансгресија дошла мало касније на ове просторе (горњи баден) за разлику од јужног дела Панонског басена где је утврђена на око 14,5 милиона година (доњи баден) (нпр. Ćorić et al., 2009; Pezelj et al., 2013; Sant et al., 2018; Mandic et al., 2019). На граници старији/средњи миоцен, екстензиони процеси и син-рифтна наглашена спуштања у домену басенских структура на ширем простору, утицали су и на обликовање локалних морфоструктурних депресија (нпр. Тимочки ров). Све то је праћено значајним вулканизмом на ширем простору (Cvetković et al., 2004; Lukács et al., 2018). Тако су стварани предуслови да надолазећа морска трансгресија у средњем миоцену прекрије велики простор централне Европе. Међутим, управо је тектоника била главни контролни фактор који је условио да трансгресија није била синхрона на читавом простору некадашњег Паратетиса (Sant et al., 2019). О томе где су били морски коридори (тзв. транс-карпатски мореуз у Србији или Трансилванија) и како је та „поплава" стигла на просторе источне Србије за сада нема довољно егзактних података.

Manuscript received October 15, 2019
Revised manuscript accepted December 03, 2019