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Lower Triassic (Olenekian) microfauna from Jadar Block (Gučevo Mt., NW Serbia)

Milan N. Sudar[1], Yanlong Chen[2], Tea Kolar-Jurkovšek[3], Bogdan Jurkovšek[3], Divna Jovanović[4] & Marie-Beatrice Forel[5]

Abstract. Systematic study of microfossil associations on the Krivi Potok section (Gučevo Mt. area, NW Serbia) has been carried out to document and to refine the Lower Triassic stratigraphic correlations within Alpine-Mediterranean domain. Field investigation and laboratory process have enabled the identification of lowermost Olenekian (lower Smithian) conodonts, ostracodes and pyrite framboids. Two conodont zones are established in this region, in ascending order they are: *Pachycladina obliqua–Foliella gardenae* Assemblage Zone and *Neospathodus planus* Zone. A new ostracode species *Paracypris* ? *krivipotokensis* Forel n. sp. has been described, it co-occurs with conodont *Neospathodus planus* within the Zone of the same name. The pyrite framboids were formed within the ostracode carapaces after their death. The size distribution of pyrite framboids supports the former suggestion that large size (>6 μm in diameter) is not suitable for the reconstruction of seawater redox conditions.

Key words: Lower Triassic, Olenekian, conodonts, ostracodes, pyrite framboids, Jadar Block, Northwestern Serbia.

Апстракт. Систематско изучавање микрофосила профила Криви поток у области планине Гучево спроведено је ради документовања асоцијација и утврђивања детаљнијих доњотријаских стратиграфских односа у северозападној Србији, а у циљу корелација у оквиру Алпско-медитеранског региона. Након детаљног теренског рада и лабораторијских обрада узоркованог материјала, омогућена је идентификација старости конодоната, остракода и пиритских фрамбоида и добијен је најнижи олењок (доњи смит). У испитиваној области утврђене су две конодонтске зоне, *Pachycladina obliqua–Foliella gardenae* Assemblage Zone и *Neospathodus planus* Zone. Такође је описана нова остракодска врста *Paracypris* ? *krivipotokensis* Forel n. sp., која се појављује удружена са врстом *Neospathodus planus* у истоименој конодонтској зони. Присутни пиритски фрамбоиди су настали унутар остракодских љуштура после њиховог изумирања, а како су пречника већег од 6 μm потврђена је ранија сугестија да због тога нису били погодни за реконструкцију оксидо-редукционих услова у морској води.

Кључне речи: доњи тријас, олењок, конодонти, остракоди, пиритски фрамбоиди, Јадарски блок, северозападна Србија.

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Introduction

The Lower Triassic sediments are widespread in the Jadar Block of Northwestern Serbia. Together with the Upper Permian rocks and the Permian–Triassic boundary interval, they have been intensively studied especially because represent the only such formations of this age in Serbia. Generally, the Upper Permian sediments contain diverse macro- and microbiocenoses, whereas the Lower Triassic microfossil associations are rather poor.

Gučevo Mt. is situated in the north-western part of the Jadar Block, on the eastern side of the Drina River and southern of the Loznica town (Fig. 1). It is predominantly built of Lower Triassic sediments, which the Serbian authors mostly divided in the older „Seisian" and the younger „Campilian" beds. After repeated numerous field investigations of this area, authors of the paper intended to document new geological data to refine existing stratigraphic and lithostratigraphic definitions.

Therefore, the aim of this paper was to confirm the presence of different microfossils (conodonts, foraminifera, ostracodes, etc.) and biostratigraphic data within the Lower Triassic sediments of the Jadar Block, NW Serbia. It represents the continuation of the ongoing geological study, started in 2005 year with micropaleontological/sedimentological investigations in P–T boundary interval of NW Serbia (SUDAR *et al.* 2007, NESTELL *et al.* 2009, CRASQUIN *et al.* 2010).

Geological settings

Geographically, the Jadar Block, is located at the southern margin of the Pannonian Basin, and belongs to the central part of the Balkan Peninsula. It occupied great parts of the northwestern Serbia, southern Srem (Vojvodina) and extends partly westward over the Drina River into eastern Bosnia (Fig. 1).

This tectonostratigraphic unit is today an exotic block, which was placed into the Vardar Zone before the late Cretaceous. It is surrounded by the Vardar Zone Western Belt, except on the farthest south-eastern part where it is in direct contact with the Kopaonik Block and the Ridge Unit (Fig. 1). The Jadar Block differs from the Vardar Zone Western Belt in lacking post–Liassic sediments as well as in the absence of ultramafites, ophiolitic mélange, and Cretaceous flysch development (FILIPOVIĆ *et al.* 2003).

In this area, the deposition occurred during the Variscan and Early Alpine evolution with a predomination of Dinaridic features. The later tectonic stage is characterized by sedimentation of Upper Permian and lowermost Triassic shallow-water marine carbonates, dolomites of the Anisian age, „porphyrites" and pyroclastics of Ladinian age, platform-reefal limestones of Middle and Late Triassic age and their gradual transition into Lower Jurassic limestones.

In the Jadar Block the Upper Permian is represented by the „Bituminous Limestone" Formation and the Lower Triassic by the Svileuva and Obnica formations (FILIPOVIĆ *et al.* 2003).

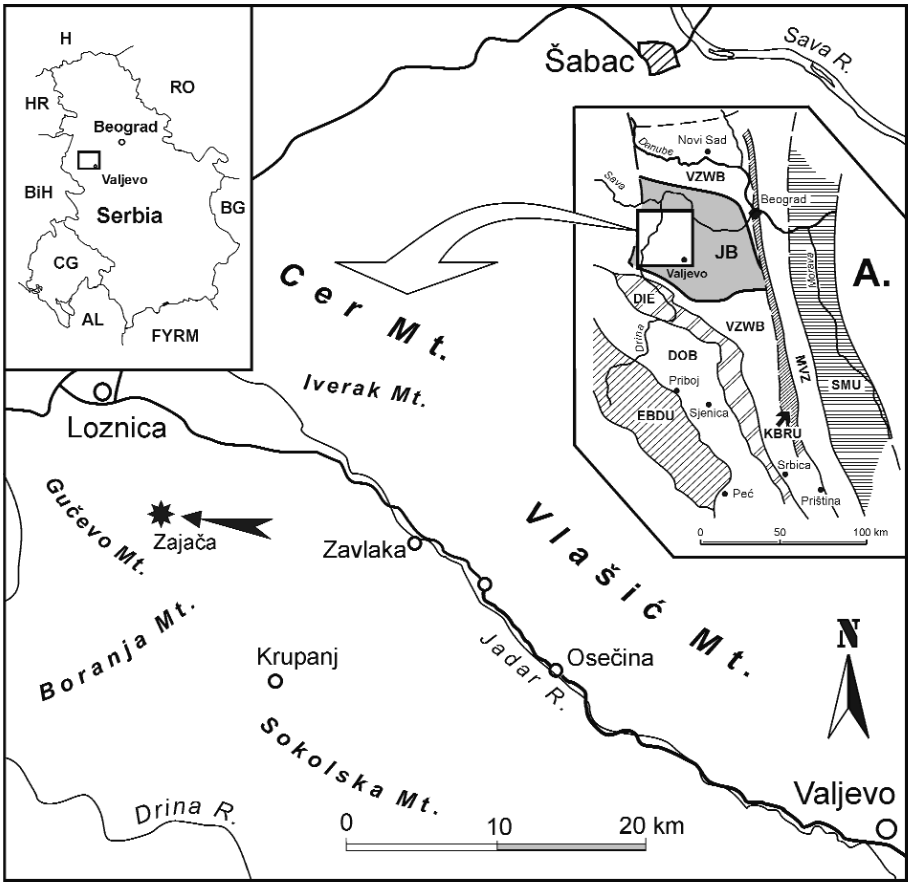

Fig. 1. Location map of the Krivi Potok section (asterisk) on the Gučevo Mt. (Jadar Block, NW Serbia) (modified after SUDAR *et al.* 2007). **A.** Terranes of a part of the Balkan Peninsula (KARAMATA *et al.* 2000; KARAMATA 2006): **SMU,** Serbian-Macedonian Unit; **MVZ,** Main Vardar Zone; **KBRU,** Kopaonik Block and the Ridge Unit; **VZWB,** Vardar Zone Western Belt; **JB,** Jadar Block; **DIE,** Drina–Ivanjica Element; **DOB,** Dinaridic Ophiolite Belt and **EBDU,** East Bosnian-Durmitor Unit.

Krivi Potok section

On the central parts and on the eastern slopes of the Gučevo Mt. there are mostly exposed

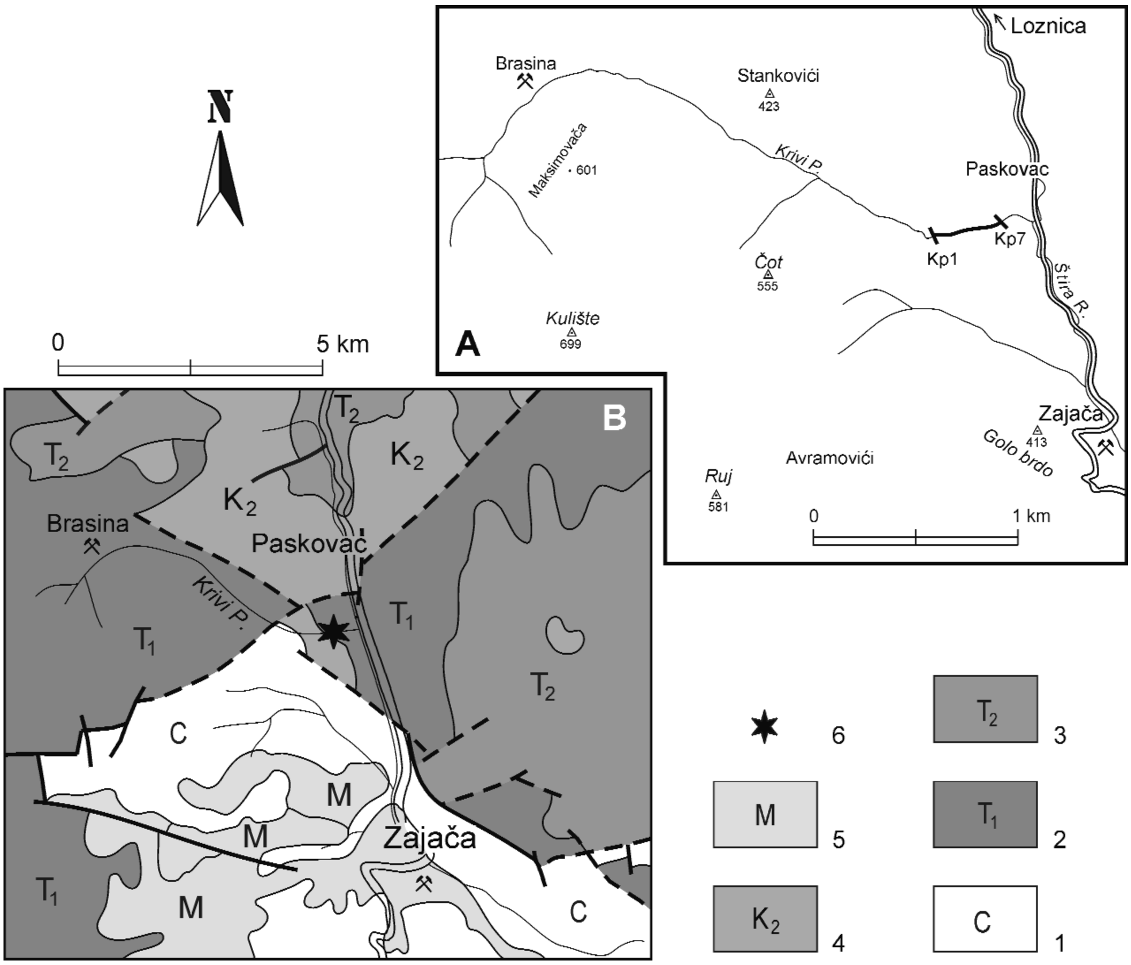

Fig. 2. Geographic position of the studied section on the eastern slopes of the Gučevo Mt. (**A**) simplified and modified geological map after Mojsilović *et al.* 1975 of the same areas (**B**). Legend: **1,** Carboniferous rocks; **2,** Lower Triassic sediments; **3,** Middle Triassic rocks; **4,** Upper Cretaceous sediments; **5,** Miocene dacites, andesites and pyroclastics; **6,** Location of the Krivi Potok section.

grey thin bedded to bedded limestones, in alteration with siltstones and sandstones of the upper Lower Triassic Obnica Formation (Filipović *et al.* 2003) generally thick about 200–350 m (Mojsilović *et al.* 1975). These sediments, especially in surroundings of the old mine Brasina and in the source part of the stream Krivi Potok, were frequently micropaleontologically and sedimentologically investigated in the previous years (Pantić 1971; Budurov & Pantić 1973, 1974; Urošević & Sudar 1980; Pantić-Prodanović & Radošević 1981; Sudar 1986, etc.).

In the Krivi Potok section, for the study presented herein, was investigated and sampled for microfauna only 11 m thick rock section near to the mouth of this stream in the rivulet Štira and on the northern side of the Loznica–Zajača road (N 19°14’13.8”, E 44°28’9.8”; figs. 1, 2). The field researches were undertaken in 2010 (samples SRB-1 and SRB-2) and 2012 (samples Kp1 – Kp7) years. The section (Fig. 3) consists of:

- Unit 1, bedded bioturbated limestones, 70 cm thick only with conodonts;
- Unit 2, bedded, sandy, ferruginous ooidal grainstone, 1 m thick, and only with conodonts;
- Unit 3, bioturbated micrites 30 cm thick with conodonts;
- Unit 4, *ca.* 5.5 m thick can be separated into the lower (4a) and upper part (4b) with covered part between. The lower part of this first entity of subunit 4a (*ca.* 3 m) is built of thick bedded limestones (beds are mostly 25 cm thick). Than, last 1 m is consisted of thin bedded laminated limestones (beds are less than 5 cm thick). Here in the subunit 4a are present abundant conodont and ostracode microfaunas, pyrite framboids (especially in sample SRB-1) and rare foraminifera.
  After covered 6 m, also to the same unit (subunit 4b) belongs 1.5 m thick part, mostly made of change of red and grey siltstones and sandstones, but in the upper part also contains sandy, ferruginous wackestone-packstone with one characteristic 20 cm thick bed of ooidal dolomitic limestones. Ooids are rare, sometimes filled with dolomite.

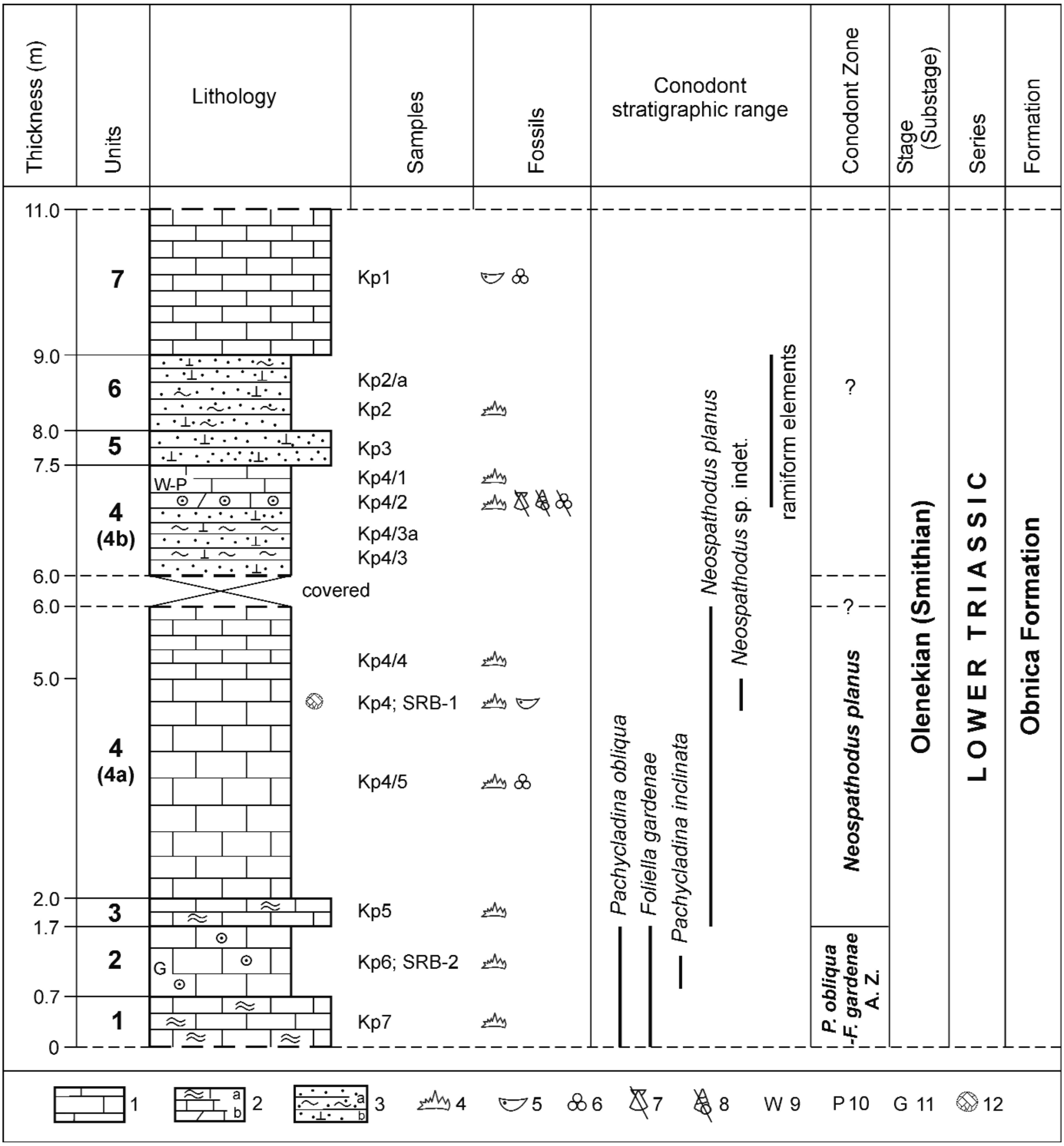

Fig. 3. Geological column, conodont stratigraphic ranges and zones of the Lower Triassic (Olenekian, Smithian) sediments in the Krivi Potok section on the Gučevo Mt. (Jadar Block, NW Serbia). Legend. **1,** thin to thick-bedded limestones; **2,** bioturbated (**a**) and dolomitic (**b**) limestones; **3,** bedded quartz sandstones, silty (**a**) and calcareous (**b**); **4,** conodonts; **5,** ostracodes; **6,** foraminifera; **7,** detritus of bivalves; **8,** detritus of gastropods; **9,** wackestone; **10,** packstone; **11,** grainstone; **12,** pyrite framboids.

Beside conodonts, detritus of bivalves, gastropods, and foraminifera, also fine quartz grains and dispersed ferruginous matter characterize bed.

- Unit 5, quartz sandstones thick 0.5 m;
- Unit 6, thin bedded micaceous quartz sandstones 1 m thick, and
- Unit 7, made of grey, thin bedded, 2 m thick limestones (thickness of beds is 2–15 cm) with ostracodes and rare pyritized foraminifera. This unit make the final part of the section.

The deposition of the fine carbonate mud, characteristic for low energy regime of the shallow water, relatively restricted environment, probably shallow subtidal (traces of bioturbations in lower part, fine laminated and thin bedded limestones in middle and upper part of the section) predominates in the section. Appearance of the bed with ooids in thin bioturbated micrites in lower part (Kp6; SRB-2) and also in 20 cm bed thick in subunit 4b (Kp4/2) with change of thin bedded siltstones and sandstones in lower part of subunit indicate high water energy. Possible explanation is existing of some topographic highs (normal relief or as a result of local tectonic uplift) were is water energy like in typical tidal regime, or occassionally influence of storm (wind) currents. In upper part of section (Kp3, Kp2, K2/a) is characteristic presence of siliciclastics imput, caused by some local tectonic event or change of climate (ferruginous pigments in sediments).

Conodont microfauna

Material and methods

Fourteen composite rock samples, each *ca*. 2.5 kg, are collected from the Krivi Potok section for conodont study, and same number of thin sections were also done from each level with the conodont samples for the petrographic purposes. The laboratory work was carried out at Geological Survey of Slovenia. All samples were prepared using standard laboratory techniques: dissolved in diluted formic and acetic acid, after dissolution, the residue was collected, sieved and dried. High density liquid (*ca*. 2.8 g/cm^3) is used for gravity enrichment; the density of conodont is larger than 2.8 g/cm^3, while the density of most of the other residues is smaller than 2.8 g/cm^3. The collected materials (samples, thin sections etc.) and collections of conodonts, ostracodes and pyrite framboids from investigated section are deposited in the Geological Survey of Slovenia under the catalogue numbers GeoZS 4768-4769 and 5104-5112, corresponding to numbers of the samples (SRB-1, SRB-2 and Kp1–Kp7) from the section. The illustrated pictures presented herein were taken with an Scanning Electron Microscope at the University of Graz, Nawi Graz, Institute of Earth Sciences.

Conodont dating

Six samples out of these fourteen yield conodonts which enable taxonomic identification: P_1 elements of *Neospathodus planus* Chen & Kolar-Jurkovšek, P_1 elements of *Neospathodus* sp. indet., P_2, S_1, S_2, S_3 or S_4 and M elements of multielement apparatus of *Neospathodus planus*, elements of the *Pachycladina–Foliella* conodont microfauna: *Pachycladina obliqua* Staesche, *Pachycladina inclinata* Staesche, *Foliella gardenae* (Staesche) and *Pachycladina* sp. (Fig. 3). Other three samples from the upper part of the section contain only ramiform elements and some undeterminated fragments of the conodonts (Fig. 3).

In the lower part of the presented Krivi Potok section, before the covered part of column, beside of stratigraphic ranges of determinated conodonts, two conodont zones can be recognized. They confirm the conodont sequence which has been proposed in the Idrija–Žiri area, Slovenia (Chen *et al*. in preparation). These zones are: *Pachycladina obliqua–Foliella gardenae* Assemblage Zone and *Neospathodus planus* Zone and both they are of the lowermost Olenekian (lower Smithian) in age (Fig. 3).

From the source part of the Krivi Potok, Sudar (1986) reported the results of the micropaleontological investigations of conodonts and foraminifera where it was determinated the *Parachirognathus––Furnishius* Z. in the Smithian and *triangularis–homeri*–C.R.Z. of the Spathian age.

Pachycladina obliqua–Foliella gardenae Assemblage Zone

Originally is introduced by Chen *et al*. (in preparation) in the type-section Žiri 29 of the Idrija–Žiri area, Slovenia as the *Pachycladina obliqua-Foliella gardenae* A. Z. in the interval between *Eurygnathodus costatus* and *Neospathodus planus* zones within the lower part of the Smithian (lowermost Olenekian).

In the Krivi potok locality the lower limit of this A. Z. lies on the beginning of the Unit 1 at the base of section. It is characterized by the first appearance of *Pachycladina obliqua* and *Foliella gardenae.* The upper limit of the Zone is marked with the first occurrence (FO) of *Neospathodus planus* in the Unit 3 at 1.7 m from the beginning of the section (Fig. 3).

In the investigated section of the Jadar Block the age of the Zone is the lower part of the Smithian in the lowermost Olenekian, and as associated conodont is present only *Pachycladina inclinata*.

This Assemblage Zone Chen *et al*. (in preparation) roughly correlate with the stratigraphic range within the lower part of Smithian belonging to the *Parachirognathus-Furnishius* conodont fauna by Sweet *et al*. (1971) and Budurov & Sudar (1995). They change only the name of the Zone according to the dominating presence of the species of the genera *Pachycladina* Staesche and *Foliella* Budurov & Pantić what is also obvious in the Krivi potok section.

The same interval, characterized by dominating *Pachycladina obliqua* joined with elements of *Hadrodontina* Staesche, was in External Dinarides attributed to the *Pachycladina obliqua* Zone (Kolar-Jurkovšek & Jurkovšek 1995, 1996, Aljinović *et al*. 2006, 2011) and correlated to the Lower Smithian Zone 7 (*Parachirognathus-Furnishius* Zone) of Sweet *et al*. (1971). In North Italy, *Pachycladina*

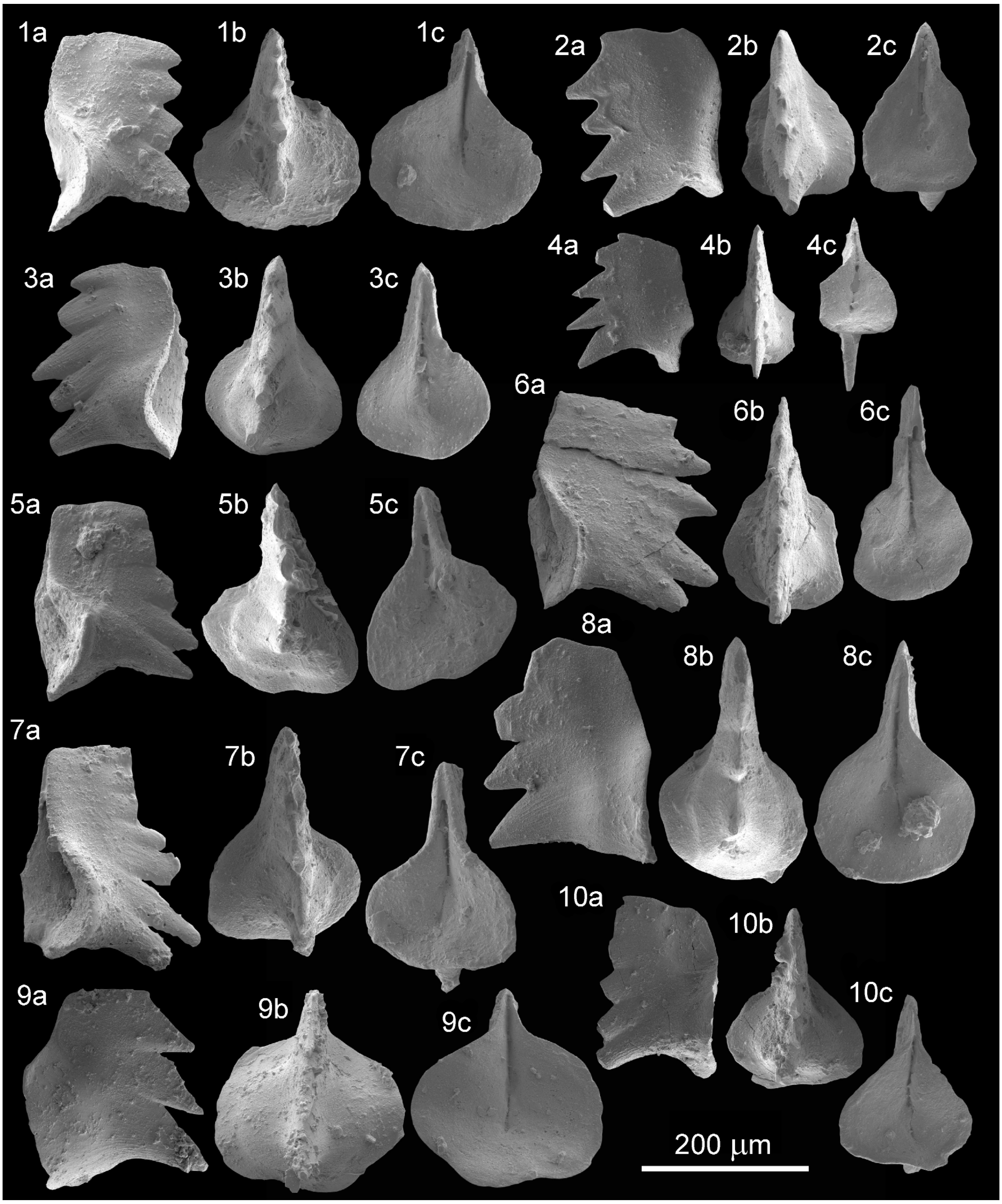

Fig. 4. Conodonts from the Krivi Potok Section, Gučevo Mt., Jadar Block, NW Serbia; middle part of the Obnica Formation, lowermost part of Olenekian (lower Smithian), *Neospathodus planus* Zone; a. lateral view; b. oral view; c. aboral view. **1–6.** P_1 elements of *Neospathodus planus* CHEN & KOLAR-JURKOVŠEK, sample SRB-1 (GeoZS 4768); **8–10.** P_1 elements of *Neospathodus planus* CHEN & KOLAR-JURKOVŠEK, sample KP4/4 (GeoZS 5108); **7.** P_1 elements of *Neospathodus* sp. indet., sample SRB-1 (GeoZS 4768).

obliqua Zone ranges within the almost whole Smithian and the Spathian (PERRI 1991).

In conodont zonation by BUDUROV & SUDAR (1995) exist the *Platyvillosus-Foliella* Beds with the range of both genera in the oldest parts of Spathian. ORCHARD (2007) indicated that species of the genera *Parachirognathus* CLARK*, Furnishius* CLARK*, Hadrodontina*, *Pachycladina* or *Foliella*, belonging to the family Ellisoniidae, are not present in the Spathian, but nearly only in the same time interval of the lower and middle Smithian. These facts were applied by CHEN *et al.* (in preparation) when define *Pachycladina obli-*

qua–Foliella gardenae Assemblage Zone in the lower part of the Smithian.

Neospathodus planus Zone

Neospathodus planus Zone was originally reported from the type-section Žiri 61 in the Idrija–Žiri region, Slovenia (Chen *et al.*, in preparation), where it lies between *Pachycladina obliqua–Foliella gardenae* A. Z. and *Neospathodus robustus* Zone. It is lower Smithian in age.

In the presented locality on the Gučevo Mt. their lower limit is marked with the first appearance of *Neospathodus planus* without elements of genus *Pachycladina* and *Foliella gardenae*, in the Unit 3 at 1.7 m above the base of the section. The upper limit is set at the end of the first part of the Unit 4 (subunit 4a), because the strata after covered part of 6 m, contain only ramiform conodonts without stratigraphic importance (Fig. 3).

In the Krivi Potok section this stratigraphic interval characterizes the lower part of the Smithian (lowermost Olenekian) only with the occurrence of the taxa *Neospathodus planus* and *Neospathodus* sp. indet.

Taxonomic notes

Neospathodus planus Chen & Kolar-Jurkovšek
Fig. 4.1–6, 8–10; Fig. 5.1, 2

P_1 elements of *Neospathodus planus* is characterized by 3–6 denticles and sometimes a large basal cavity that occupies almost the whole length of the unit (e.g., Fig. 4.9). The outer side of the basal cavity is always greatly expanded. It is similar to *Neospathodus robustus* Koike, but *Neospathodus robustus* commonly has more denticles, which are 6–10 (Koike 1982). *Neospathodus planus* can be differentiated from *Triassospathodus hungaricus* (Kozur & Mostler) by much wider and inflated basal cavity, and by relatively longer and stronger unit. So far, it is only recognized from Slovenia and Serbia, and it could be a species controlled by local environment.

Multielement apparatus of **_Neospathodus planus_**
Chen & Kolar-Jurkovšek
Fig. 4.1–6, 8–10; Fig. 5.1–8

The multielement apparatus of *Neospathodus planus* has also been discussed here, categories of conodont elements follow Sweet (1988), they are assigned to segminate, angulate, breviform, etc., and orientation of elements follows Purnell *et al.* (2000).

Multielement apparatuses of conodont play an important role in the conodont taxonomy system (e.g., Orchard 2005), thus it is expected that conodont workers illustrate these ramiform elements together with P_1 elements. Conodont clusters and nature assemblages have demonstrated that there are three types of apparatuses in the geological record of earth history, they comprise of 15, 17 and 19 elements respectively (Aldridge *et al.* 2013). Early Triassic conodont composed mainly three families: Gondolellidae, Anchignathodontidae, and Ellisoniidae (Orchard, 2007), nature assemblages or clusters have shown that apparatuses of all these three families consist of 15 elements (Rieber 1980; Orchard & Rieber 1999, Koike *et al.* 2004, Orchard 2005, Goudemand *et al.* 2012, Agematsu *et al.* 2014), paired P_1, P_2, S_1, S_2, S_3, S_4 and M; unpaired S_O. Orchard (2005) has reconstructed 26 Triassic apparatuses, including several Early Triassic species, and all his apparatuses consist of 15 elements, belong to the family Gondolellidea. Later, Goudemand *et al.* (2012) revise these S_1 and S_2 elements of Gondolellidea apparatuses as occupied S_2 and S_1 position, the S_3 and S_4 elements of subfamily Novispathodinae (family Gondolellidea) occupied S_4 and S_3 position.

The monospecies *Neospathoides planus* in Zone of the same name provides a chance for the reconstruction its apparatus. Apart from P_1 elements, P_2, S_1, S_2, $S_{3–4}$, and M elements are also identified, as they are shown in Fig. 5.3–8. However, S_O element has been found from neither Krivi Potok section, Serbia nor the Idrija–Žiri section, Slovenia (Chen *et al.*, in preparation).

Elements of *Neospathodus planus* are characterized as follow: P_2 element is angulate, relatively slender, has a cusp in the middle part of the unit. S_1 element is breviform digyrate, with well-developed rostral process, but lacks caudal-ventral process, the largest denticle located on the caudal end of the unit and caudally pointed. These characters of S_1 elements are similar to that of many Triassic conodont species which are illustrated by Orchard (2005). S_2 element is breviform digyrate, with a large rostral process but a very short caudal-lateral process which only bears 2 to 3 denticles. Only caudal part of the S_3 or S_4 element is found, as it is illustrated in Fig. 5.7, character of rostral part in not clear so far. M elements is also breviform digyrate, similar to S_1 element, however, it has a short ventral process which bears one denticle. Over all, elements of *Neospathodus planus* show high similarity with elements of *Triassospathodus homeri* (Bender) which are figured by Orchard (2005), especially for P_2 and S_1 elements. Since we lack well preserved S_3 and S_4 elements, their relationship can not be decided presently.

Neospathodus sp. indet.
Fig. 4.7

In the sample SRB-1 from the *Neospathodus planus* Zone in the Krivi potok section exists one speci-

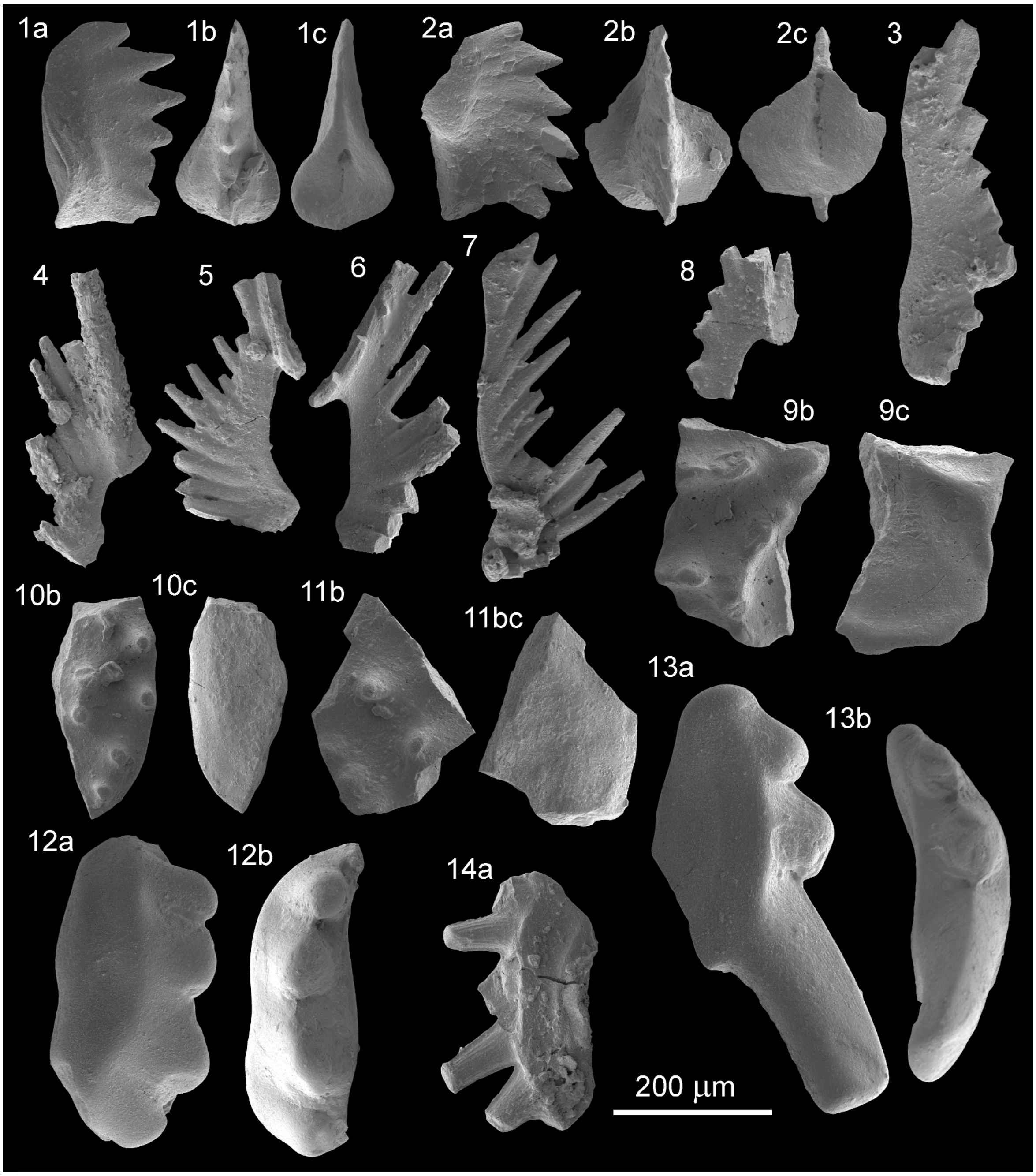

Fig. 5. Conodonts from the Krivi Potok Section, Gučevo Mt., Jadar Block, NW Serbia; middle part of the Obnica Formation, lowermost part of Olenekian (lower Smithian), *Neospathodus planus* Zone; a. lateral view; b. oral view; c. aboral view. **1, 2,** P_1 elements of *Neospathodus planus* CHEN & KOLAR-JURKOVŠEK, sample Kp4/5 (GeoZS 5109); **3-8,** P, M and S elements of *Neospathodus planus* CHEN & KOLAR-JURKOVŠEK, **3,** P_2 element, sample SRB-1 (GeoZS 4768). **4,** S_1 element, sample SRB-1, KP4/4 (GeoZS 4768, 5108). **5, 6,** S_2 elements, **5,** sample SRB-1 (GeoZS 4768), **6,** sample Kp4/4 (GeoZS 5108). **7.** distal part of S_3 or S_4 element, sample Kp4/4 (GeoZS 5108). **8,** M element, sample SRB-1 (GeoZS 4768). **9–14,** Elements of the *Pachycladina–Foliella* conodont microfauna from the *Pachycladina obliqua–Foliella gardenae* Assemblage Zone. **9-11,** *Foliella gardenae* (STAESCHE) (different fragments) sample SRB-2 (GeoZS 4769). **12,** *Pachycladina* sp., sample SRB-2 (GeoZS 4769). **13,** *Pachycladina obliqua* STAESCHE (fragment), sample SRB-2 (GeoZS 4769). **14,** *Pachycladina inclinata* STAESCHE, sample SRB-2 (GeoZS 4769).

men showing characters between *Neospathodus planus* and *Neospathodus robustus*. The ventral (anterior) part of the element lost some denticels, thus it is possible the specimen has seven or more denticles which probably should be identified as *Neospathodus robustus*. In this moment, because of the bad preservation of the fossil and since occur only one, ilustrated, specimen it is determinated in the open nomenclature like *Neospathodus* sp. indet.

Elements of the ***Pachycladina–Foliella*** conodont microfauna

The elements determinated within this conodont microfauna, *Pachycladina obliqua*, *Pachycladina inclinata* and *Foliella gardenae* were first reported from the middle to upper part of Campil Member in North Italy (STAESCHE 1964) with higher stratigraphic distributions than *Eurygnathodus costatus* STAESCHE.

Both, species of *Pachycladina*, were also reported from North Italy (PERRI & ANDRAGHETTI 1987, PERRI 1991), Slovenia (KOLAR-JURKOVŠEK 1990, KOLAR-JURKOVŠEK & JURKOVŠEK 1995, 1996, DOZET & KOLAR-JURKOVŠEK 2007, CHEN *et al.* in preparation), Croatia (ALJINOVIĆ *et al.* 2006), Bosnia (ALJINOVIĆ *et al.* 2011), NW Serbia (BUDUROV & PANTIĆ 1973, 1974; SUDAR 1986), and South China (WANG & CAO 1981, YANG *et al.* 1986).

Foliella gardenae was also reported from different localities in Slovenia (KOLAR-JURKOVŠEK 1990, KOLAR-JURKOVŠEK & JURKOVŠEK 1995, 1996, CHEN *et al.* in preparation), Croatia (ALJINOVIĆ *et al.* 2006), NW Serbia (BUDUROV & PANTIĆ 1973, 1974), and South Primorye, Eastern Russia (ZAKHAROV *et al.* 2009, IGO 2009).

Conodont Colour Alteration Index

The Conodont Colour Alteration Index (CAI values *sensu* EPSTEIN *et al.* 1977) of the conodonts from the presented Krivi Potok section are in the range of CAI from 5 to 6–7 (5, 5.5, 6, 6–7), with the tendency that conodonts from the middle parts of the section (*Neospathodus planus* Zone) have the highest values of CAI. It is in correspondance to the earleir data of CAI values from the Krivi Potok section which are 5.5 (unpublished information for the conodonts determinated by SUDAR 1986). All these mentioned data where CAI values are between 5 and 6–7 correspond to temperatures from 300–490 °C and characterize very low to low grade metamorphism (GAWLICK *et al.* 1994, SUDAR & KOVÁCS 2006).

Ostracode microfauna

From the fourtheen samples treated for conodonts extraction, two were productive with ostracodes (SRB-1 and Kp1; Fig. 3). A total of fifty-nine specimens have been recovered, illustrating a new species described below. Most of the specimens are represented by complete carapaces, testifying the absence or limitation of post-mortem transportation with low wave energy and/or rapid burial by high sedimentation ratio (OERTLI 1971).

During the earlier phases of micropaleontological investigations of the Lower Triassic and P-T boundary interval in the Jadar Block were published only few papers dealing with ostracodes: PANTIĆ-PRODANOVIĆ (1979), KRSTIĆ (1980) and CRASQUIN *et al.* (2010). In paper of PANTIĆ-PRODANOVIĆ (1979), only five species of ostracodes were cited (three in open nomenclature) from „Campilan" substage in the Valjevo area. In the southern and eastern slopes of the Gučevo Mt., KRSTIĆ (1980) in detail described and illustrated rich ostracode microfauna of the „Campilan" age: *Judahella tsorfatia*, „*Cultella*" cf. *laevis*, *Spinocypris nepalensis*, „*Bythocypris*" aff. *bijieensis*, *Bythocypris* cf. *pricei*, etc. Studying very abundant ostracode assemblages not found earlier in the P–T beds of this region, CRASQUIN *et al.* (2010) also introduced three new species. All together, were the first record of the youngest Upper Permian age microfaunas not only from NW Serbia, but also from the whole Serbia and the central part of the Balkan Peninsula.

In the present study, we follow the systematic classification of MOORE (1961) modified after LETHIERS (1981) and HORNE *et al.* (2002).

Abbreviations used in the text: AB, anterior border; DB, dorsal border; H, height; H_{max}, maximal height; L, length; L_{max}, maximal length; LV, left valve; PB, posterior border; RV, right valve; VB, ventral border.

Class Ostracoda LATREILLE, 1806
Subclass Podocopa MÜLLER, 1894
Order Podocopida MÜLLER, 1894
Suborder Podocopina SARS, 1866
Superfamily Cypridoidea BAIRD, 1845
Family Paracyprididae SARS, 1923

Genus ***Paracypris*** SARS, 1910

Type species. *Paracypris polita* SARS, 1866

Paracypris* ? *krivipotokensis FOREL n. sp.
Fig. 6.1–6

Derivation of name. From the type locality, Krivi Potok section.

Holotype. One complete carapace figured on Fig. 6.1, sample SRB-1, collection number GeoZS 4768.

Paratype. One complete carapace figured on Fig. 6.2, sample SRB-1, collection number GeoZS 4768.

Type locality. Krivi Potok section, Gučevo Mt., Jadar Block, Northwestern Serbia.

Type level. Unit 4 (4a), sample SRB-1, Obnica Formation of the Krivi Potok section, Upper Lower Triassic, lowermost part of Olenekian (lower Smithian), *Neospathodus planus* conodont Zone.

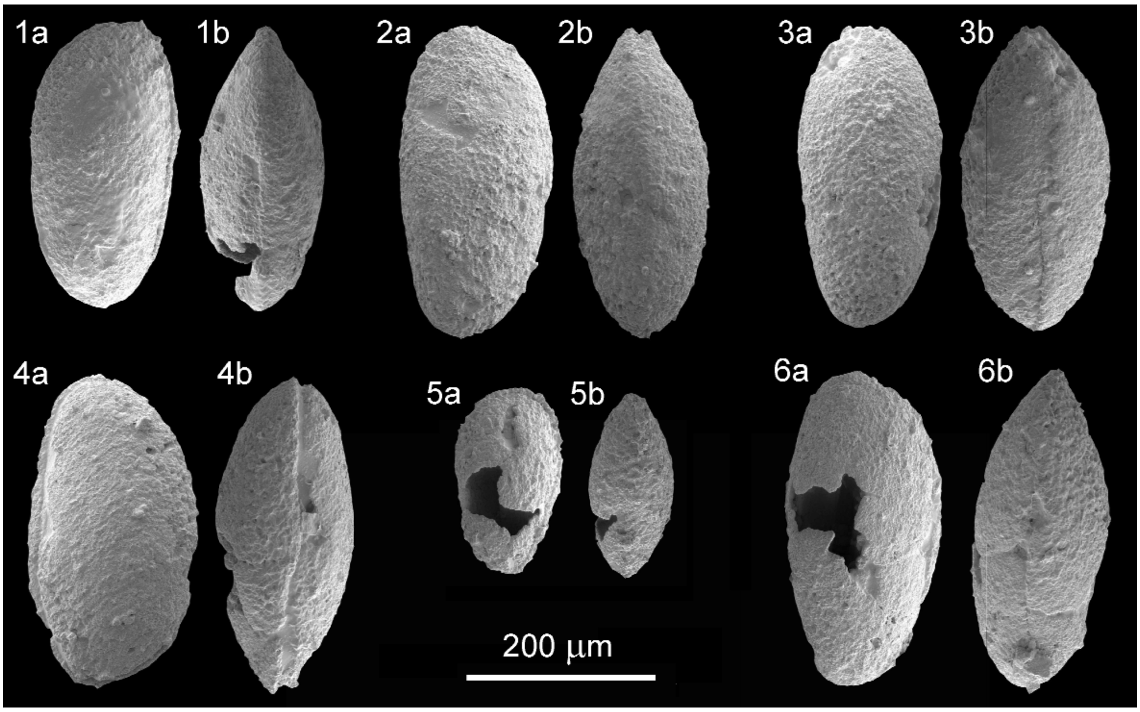

Fig. 6. Ostracodes from the Krivi Potok Section, Gučevo Mt., Jadar Block, NW Serbia; middle part of the Obnica Formation, lowermost part of Olenekian (lower Smithian), *Neospathodus planus* conodont Zone; a. lateral view; b. dorsal view of a complete carapace. All specimens belong to *Paracypris* ? *krivipotokensis* Forel n. sp. **1,** holotype, carapace, sample SRB-1 (GeoZS 4768). **2,** paratype, carapace, sample SRB-1 (GeoZS 4768). **3,** carapace, sample SRB-1 (GeoZS 4768). **4,** carapace, sample SRB-1 (GeoZS 4768). **5,** carapace, sample SRB-1 (GeoZS 4768). **6,** carapace, sample SRB-1 (GeoZS 4768).

Material. Fifty-nine complete carapaces and several fragments.

Diagnosis. A species attributed with doubt to the genus *Paracypris*, with AB and PB maximum of convexity symmetrically located in the lower 1/3rd of the carapace, upper portion of AB straight.

Description. Carapace elongate ($0.48 < H/L < 0.58$), surface smooth, LV slightly overlaps RV all around the carapace.

DB long (50–65% of L_{max}), regularly convex, smoothly sloping to PB; PB rounded with narrow radius of curvature, maximum located in the lower 1/3rd of H_{max}; posterior half of the carapace slightly wedge-shaped; VB flat to slightly concave at both valves; upper part of AB long and straight to slightly convex, resulting in a shouldering of the transition to VB larger than PB: anterior maximum of convexity located symmetrically to PB in the lower 1/3rd of H_{max}.

Remarks. The present species differs from *Paracypris gaetanii* Crasquin-Soleau from the Griesbachian? of the Guangxi Province, South China (Crasquin-Soleau *et al.* 2006) by its asymmetrical and shouldered AB with maximum of convexity located in the lower 1/3rd of H_{max} It differs from the species *Paracypris jinyaensis* Crasquin-Soleau from the Smithian-Spathian of the Guangxi Province, South China (Crasquin-Soleau *et al.* 2006) by its larger H/L ratio. The abundant specimens of *Paracypris gaetanii* Crasquin-Soleau from the Late Permian–Early Triassic of several localities worldwide recently allowed the recognition of five ontogenetic stages (Forel 2014). The specimens might correspond to at least two ontogenetic stages but more material is needed to confirm this hypothesis.

Until now, eleven Smithian ostracode species were known from South China (Crasquin-Soleau *et al.* 2006) and Tibet (Forel *et al.* 2011; Forel & Crasquin 2011). *Paracypris* ? *krivipotokensis* Forel n. sp. is the first record of Smithian ostracodes on the north-

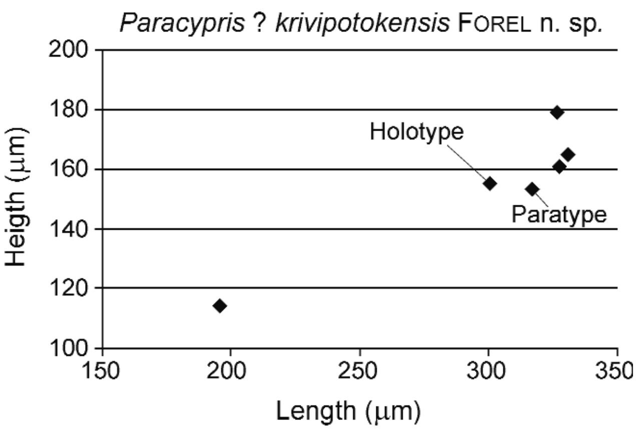

Fig. 7. Length/height scatter plot of *Paracypris* ? *krivipotokensis* Forel n. sp.

ern border of the Paleo-Tethys ocean. The absence of ostracodes from twelve of the fourteen samples can't be interpreted in terms of environmental/ecological forcing since diluted formic and acetic acids were used: acid attack of the carbonated carapaces of ostracods can't be ruled out. A traditional hot acetolysis (Lethiers & Crasquin-Soleau 1988; Crasquin-Soleau *et al.* 2005) processing of the samples might help have a more complete view of the Krivi Potok ostracode faunas and their implications in terms of environmental conditions.

Size. L=196–331 µm; H=114–179 µm; W=90–156 µm; H/L=0.48–0.58 (Fig. 7).

Occurrence. Lowermost part of Olenekian (lower Smithian) of the Krivi Potok section, Gučevo Mt., Jadar Block, Northwestern Serbia.

Pyrite framboids

Plentiful studies indicate that this kind of pyrite can be a proxy for redox conditions in the paleoseawater and sediments (e.g., Wilkin & Barnes 1996; Shen *et al*. 2007; Wignall *et al*. 2005; Tian *et al*. 2014). They form in dysoxic and sulfidic conditions which is close to the redox boundary (Wilkin & Barnes 1996). The diameters of pyrite framboids are very sensitive to the water depth between the redox boundary and the sediments, as they sink down rapidly after formation if they are formed in the water column and thus smaller (< 6 µm in diameter) and has a narrower size variation range (Wilkin & Barnes 1997; Wignall & Newton 1998; Wignall *et al*. 2005). However, larger sized and wider range of size variation of pyrite framboids indicate a formation within the sediments, as they have longer time and slower rate for their formation (Wilkin & Barnes 1996, 1997).

Pyrite framboids have been found in Unit 4 (subunit 4a, sample SRB-1) in the Krivi Potok section. This is the first discovery of pyrite framboids from the Lower Triassic of the Jadar Block and also from Serbia. They are attached on the ostracode shells and are mainly 12–21 µm in diameter, as shown in Fig. 8. These large amount of pyrite framboids found within octracode shells definitely formed in the sediments after the death of these ostracodes. Their size distribution (8–35 µm, Fig. 9) supports the former suggestion that the large pyrite framboids are not suitable for the diagnosis of the paleoseawater redox condition, but they only indicate a dysoxic and sulfidic micro-environment within the shells after the death of these ostracodes.

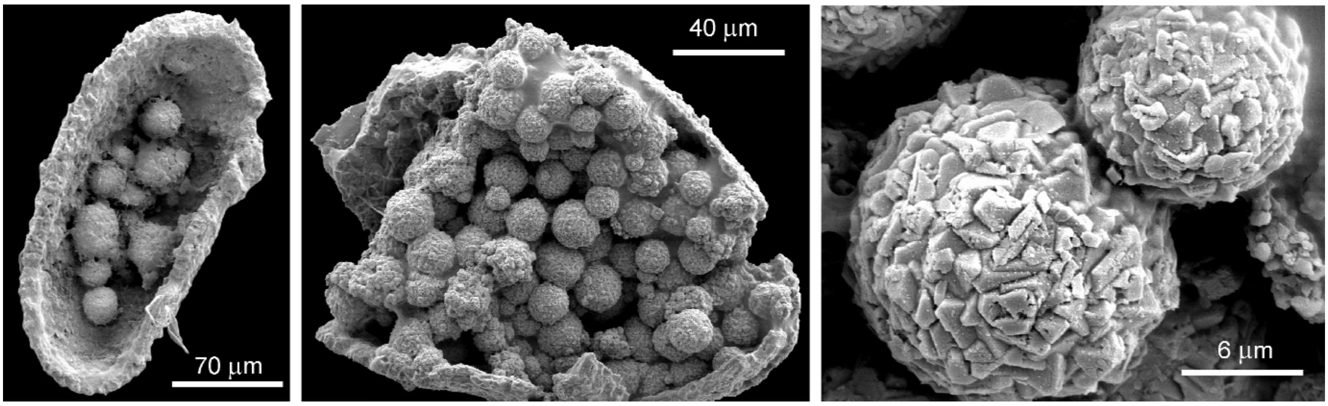

Fig. 8. Pyrite framboids from the Krivi Potok section, Gučevo Mt., Jadar Block, NW Serbia; middle part of the Obnica Formation, lowermost part of the Olenekian (lower Smithian), *Neospathodus planus* conodont Zone; sample SRB-1 (GeoZS 4768).

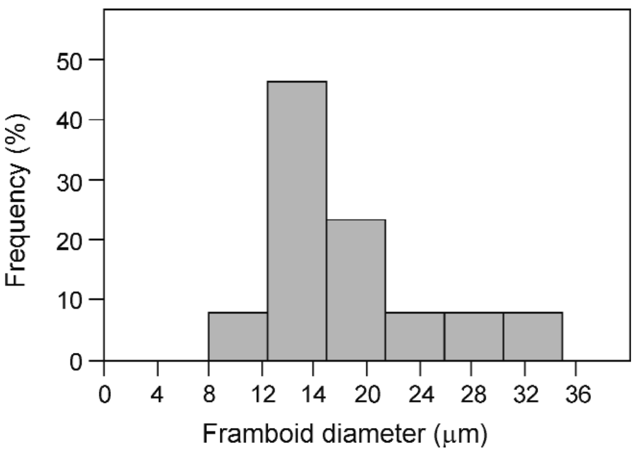

Fig. 9. Size distributions of pyrite framboids, sample SRB-1.

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References

AGEMATSU, S., SANO, H. & SASHIDA, K. 2014. Natural assemblages of *Hindeodus* conodonts from a Permian-Triassic boundary sequence, Japan. *Palaeontology,* doi: 10.1111/pala.12114.

ALDRIDGE, R.J., MURDOCK, D.E., GABBOTT, S.E. & THERON, J.N. 2013. A 17-element conodont apparatus from the Soom Shale Lagerstätte (Upper Ordovician), South Africa. *Palaeontology*, 56 (2): 261–276.

ALJINOVIĆ, D., KOLAR-JURKOVŠEK, T. & JURKOVŠEK, B., 2006. The lower Triassic shallow marine succession in Gorski Kotar region (External Dinarides, Croatia): Lithofacies and conodont dating. *Rivista Italiana di Paleontologia e Stratigrafia*, 112 (1): 35–53.

ALJINOVIĆ, D., KOLAR-JURKOVŠEK, T., JURKOVŠEK, B. & HRVATOVIĆ H. 2011. Conodont dating of the Lower Triassic sedimentary rocks in the external Dinarides (Croatia and Bosnia and Herzegovina). *Rivista Italiana di Paleontologia e Stratigrafia*, 117 (1): 135–148.

BUDUROV, K. & PANTIĆ, S. 1973. Conodonten aus den Campiller Schichten von Brassina (Westserbien) II. Systematischer teil. *Bulletin of the Geological Institute, Bulgarian Academy of Sciences, Series Paleontology*, 22: 49–64.

BUDUROV, K. & PANTIĆ, S. 1974. Conodonten aus den Campiller Schichten von Brassina (Westserbien) I. Stratigraphie und Conodonten-Zonen. *Bulletin of the Geological Institute, Bulgarian Academy of Sciences, Series Paleontology*, 23: 105–113.

BUDUROV, K. & SUDAR, M. 1995. Lower Triassic conodont stratigraphy. *Geologica Balcanica*, 25 (3–4): 97–109.

CRASQUIN, S., SUDAR, M.N., JOVANOVIĆ, D. & KOLAR-JURKOVŠEK T. 2010. Upper Permian ostracode assemblage from the Jadar Block (Vardar Zone, NW Serbia). *Geološki anali Balkanskoga poluostrva*, 71: 23–35.

CRASQUIN-SOLEAU, S., VASLET, D. & LE NINDRE, Y.M. 2005. Ostracods from Permian-Triassic boundary in Saudi Arabia (Khuff Formation). *Palaeontology*, 48: 853–868.

CRASQUIN-SOLEAU, S., GALFETTI, T., BUCHER, H. & BRAYARD, A. 2006. Early Triassic ostracods from Guangxi Province, South China. *Rivista Italiana di Palaeontologia e Stratigrafia*, 112: 55-75.

CHEN, Y.L., KOLAR-JURKOVŠEK, T., JURKOVŠEK B., RICHOZ, S. & ALJINOVIĆ. D. (in preparation). A unique Early Triassic conodont sequence from Idrija–Žiri area, Slovenia and its implications for conodont ecology.

DOZET, S. & KOLAR-JURKOVŠEK, T. 2007. Lower Triassic beds in the southeastern borderland of the Ljubljana depression, central Slovenia. *RMZ – Materials and Geoenvironment*, 54 (3): 361–386.

EPSTEIN, A.G., EPSTEIN, J.B. & HARRIS, L.D. 1977. Conodont Color Alteration – an Index to Organic Metamorphism. *U.S. Geological survey Professional Paper*, 995: 1-27.

FILIPOVIĆ, I., JOVANOVIĆ, D., SUDAR, M., PELIKAN, P., KOVÁCS, S., LESS, GY. & HIPS, K. 2003. Comparison of the Variscan – Early Alpine evolution of the Jadar Block (NW Serbia) and "Bükkium" (NE Hungary) terranes; some paleogeographic implications. *Slovak Geological Magazine*, 9, 1: 23–40.

FOREL, M.B. 2014. Heterochronic growth of ostracods (Crustacea) from microbial deposits in the aftermath of the end-Permian extinction. *Journal of Systematic Palaeontology* doi.org/10.1080/14772019.2014.902400.

FOREL, M.B. & CRASQUIN, S. 2011. In the aftermath of Permian-Triassic boundary mass extinction: ostracod new species and genus from South Tibet. *Geodiversitas*, 33 (2): 247–263.

FOREL, M.B., CRASQUIN, S., BRÜHWILER, T., GOUDEMAND, N., BUCHER, H. & BAUD, A. 2011. Ostracod recovery after Permian - Triassic boundary mass-extinction in South Tibet. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 308: 160–170.

GAWLICK, H.-J., KRYSTYN, L. & LEIN, R. 1994. Conodont colour alteration indices: Palaeotemperatures and metamorphism in the Northern Calacreous Alps – a general view. *Geologische Rundschau*, 83 (1): 660–664.

GOUDEMAND, N., ORCHARD, M.J., TAFFOREAU, P., URDY, S., BRÜHWILER, T., BRAYARD, A., GALFETTI, T. & BUCHER, H., 2012. Early Triassic conodont clusters from South China: Revision of the architecture of the 15 element apparatuses of the superfamily Gonolelloidea. *Palaeontology*. 55 (5): 1021–1034.

HORNE, D.J., COHEN, A. & MARTENS, K. 2002. Taxonomy, Morphology and Biology of Quaternary and living Ostracoda. *In*: HOLMES, J.A. & CHIVAS, A. (Eds.), The Ostracoda: applications in Quaternary Research. *Geophysical Monograph, American Geophysical Union*, Washington DC: 5–36.

IGO, H., 2009. Conodont succession. *In*: SHIGETA, Y., ZAKHARROV, Y., MAEDA, H. & POPOV, A.M. (Eds.), The Lower Triassic system in the Abrek Bay Area, South Primorye, Russia. *National Museum of Nature and Science*, Tokyo, 218 pp.

KARAMATA, S. 2006. The geological development of the Balkan Peninsula related to the approach, collision and compression of Gondwanan and Eurasian units. *In*: ROBERTSON, A.H.F. & MOUNTRAKIS, D., (Eds.), *Tectonic Development of the Eastern Mediterranean Region*, Geological Society, London, Special Publications, 260: 155–178.

KARAMATA, S., OLUJIĆ, J., PROTIĆ, LJ., MILOVANOVIĆ, D., VUJNOVIĆ, L., POPEVIĆ, A., MEMOVIĆ, E., RADOVANOVIĆ, Z. & RESIMIĆ-ŠARIĆ K. 2000. The Western Belt of the Vardar Zone - the remnant of a marginal sea. *In*: KARAMATA, S. & JANKOVIĆ, S. (Eds.), *Proceedings of the International Symposium "Geology and Metallogeny of the Dinarides and the Vardar Zone"*, Academy of Sciences and Arts of the Republic of Srpska, Collections and Monographs, I, Department of Natural, Mathematical and Technical Sciences, I: 131-135.

KOLAR-JURKOVŠEK, T. 1990. Smithian (Lower Triassic) conodonts from Slovenia, NW Yugoslavia. *Neues Jahrbuch für Geologie und Paläontologie, Monatshefte*, H.9: 536–546.

KOLAR-JURKOVŠEK, T. & JURKOVŠEK, B. 1995. Lower Triassic conodont fauna from Tržič (Karavanke Mts., Slovenia). *Eclogae geologicae Helvetiae,* 88 (3): 789–801.

KOLAR-JURKOVŠEK, T. & JURKOVŠEK, B. 1996. Contribution to the knowledge of the Lower Triassic conodont fauna in Slovenia. *Razprave IV. Razreda SAZU*, XXXVII (1): 3–21.

KOIKE, T. 1982. Triassic Conodont Biostratigraphy in Kedah West Malaysia. *In*: KOBAYASHI, T., TORIYAMA, R. & HASHIMOTO, W., (Eds.), *Geology and Paleontology of Southeast Asia* 1982, 23: 9–51, University of Tokyo Press.

KOIKE, T., YAMAKITA, S. & KADOTA, N. 2004. A natural assemblage of *Ellisonia* sp. cf. *E. triassica* Müller (Vertebrata: Conodonta) from the uppermost Permian in the Suzuka Mountains, central Japan. *Paleontological Research*, 8: 241–253.

KRSTIĆ, N. 1980. The Lower Triassic ostracodes of Gučevo. *Zapisnici Srpskog geološkog društva za 1979 godinu* (Vanredni zbor 24. I 1980), 203–208 (in Serbo-Croatian, English summary).

LETHIERS, F. 1981. Ostracodes du Dévonien terminal de l'Ouest du Canada: Systématique, biostratigraphie et paléoécologie. *Geobios*, 5: 1–234.

LETHIERS, F. & CRASQUIN-SOLEAU, S. 1988. Comment extraire des microfossiles à tests calcitiques de roches calcaires dures. *Revue de Micropaléontologie*, 31: 56–61.

MOJSILOVIĆ, S., FILIPOVIĆ, I., RODIN, V., NAVALA, M., BAKLAIĆ, D., DJOKOVIĆ. I., JOVANOVIĆ, Č., ŽIVANOVIĆ, D., EREMIJA, M. & CVETKOVIĆ, B. 1975. Basic Geological Map of SFRY, 1:100,000, Sheet Zvornik (L 34-123), *Savezni geološki zavod,* Beograd (*Zavod za geološka i geofizička istraživanja,* Beograd, 1960-1968; *Institut za geološka istraživanja,* Sarajevo, 1967).

MOORE, R.C. (Ed.) 1961. *Treatise on Invertebrate Paleontology. Arthropoda 3, Crustacea, Ostracoda*. Geological Society of America and University of Kansas Press, Boulder and Lawrence, 442 pp.

NESTELL, G.P., SUDAR, M., JOVANOVIĆ, D. & KOLAR-JURKOVŠEK, T. 2009. Latest Permian foraminifers from the Vlašić Mountain area, northwestern Serbia. *Micropaleontology*, 55 (5): 495–513.

OERTLI, H.J. 1971. The aspect of Ostracode fauna – a possible new tool in petroleum sedimentology. *In*: OERTLI, H.J., (Eds.), *Paléoécologie des Ostracodes*. *Bulletin du Centre de Recherche* SNPA 1981, 5 (Supplement): 137–151.

ORCHARD, M.J. 2005. Multielement conodont apparatuses of Triassic Gondolelloidea, *In*: PURNELL, M.A. & DONOGHUE, P.C.J. (Eds.), *Special Papers in Palaeontology*, 73: 73–101.

ORCHARD, M.J. 2007. Conodont diversity and evolution through the latest Permian and Early Triassic upheavals. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 252: 93–117.

ORCHARD, M.J. & RIEBER, H. 1999. Multielement *Neogondolella* (Conodonta, upper Permian – middle Triassic). *Bolletino della Societa Paleontologica Italiana*, 37 (2–3): 475–488.

PANTIĆ, S. 1971. Conodontes Triasiques d'une partie des Dinarides et des Carpates Yougoslaves. *Acta Geologica Academiae Scientiarium Hungaricae*, 15: 231–242.

PANTIĆ-PRODANOVIĆ, S. 1979. Triassic of the Valjevo area. *Excursion quide, VII International Symposium on Ostracodes, Serbian Geological Society,* 13–15, Belgrade.

PANTIĆ-PRODANOVIĆ, S. & RADOŠEVIĆ, B. 1981. Biostratigraphic and sedimentologic characteristics of Upper permian and Lower Triassic sediments in the Gučevo Mt. area, Yugoslavia. *Acta Geologica Academiae Scientiarium Hungaricae*, 24 (1): 99–115.

PERRI, M.C. 1991. Conodont biostratigraphy of the Werfen Formation (Lower Triassic), Southern Alps, Italy. *Bollettino della Societa Paleontologica Italiana*, 30 (1): 23–46.

PERRI, M.C. & ANDRAGHETTI, M. 1987. Permian-Triassic boundary and Early Triassic conodonts from the southern Apls, Italy. *Rivista Italiana di Paleontologia e Stratigrafia,* 93 (3): 291–328.

PURNELL, M.A., DONOGHUE, P.C.J. & ALDRIDGE, R.J. 2000. Orientation and anatomical notation in conodonts. *Journal of Paleontology*, 74: 113–122.

RIEBER, H. 1980. Ein conodonten-cluster aus der Grenzbitumenzone (Mittlere Trias) des Monte San Giorgio (Kt. Tessin/Schweiz). *Annalen des Naturhistorischen Museums in Wien***,** 83: 256–274.

SHEN, W., LIN, Y., XU, L., LI, J., WU, Y. & SUN, Y. 2007. Pyrite framboids in the Permian-Triassic boundary section at Meishan, China: Evidence for dysoxic deposition. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 253: 323–331.

STAESCHE, U. 1964. Conodonten aus dem Skyth von Südtirol. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, 119, 3: 247-306.

SUDAR, M.N. 1986. Triassic microfossils and biostratigraphy of the Inner Dinarides between Gučevo and Ljubišnja Mts., Yugoslavia. *Geološki anali Balkanskoga poluostrva*, 50: 151–394 (in Serbo-Croatian, English summary).

SUDAR, M., JOVANOVIĆ, D. & KOLAR-JURKOVŠEK, T. 2007. Late Permian conodonts from Jadar Block (Vardar Zone, northwestern Serbia). *Geologica Carpathica*, 58 (2): 145–152.

SUDAR, M.N. & KOVÁCS, S. 2006. Metamorphosed and Ductilely Deformed Conodonts from Triassic Limestones Situated Beneath Ophiolite Complexes: Kopaonik Mt., Serbia and Bükk Mts., NE Hungary. A Preliminary Comparison. *Geologica Carpathica*, 57 (3): 157–176.

SWEET, W.C., MOSHER, L.C., CLARK, D.L., COLLINSON, J.W. & HASENMUELLER, W.A. 1971. Conodont Biostratigraphy of the Triassic. *In*: SWEET, W.C. & BERGSTROM, S.M., *Symposium on Conodont Biostratigraphy. The Geological Society of America*, *Memoir*, 127 (1970): 441–465, Boulder, Colorado.

SWEET, W.C. 1988. The Conodonta: Morphology, Taxonomy, Paleoecology and Evolutionary History of a Long Extinct Animal Phylum. *Oxford Monographs in Geology and Geophysics,* 10: 1–212, Oxford University Press, New York, Oxford.

TIAN, L., TONG, J.N., ALGEO, T.J., SONG, H.J., SONG, H.Y., CHU, D.L., SHI, L. & BOTTJER, D.J. 2014. Reconstruction of Early Triassic ocean redox conditions based on framboidal pyrite from the Nanpanjiang Basin, South China. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 412: 68–79.

UROŠEVIĆ. D. & SUDAR, M. 1980. Triassic microfossils in the area of the Mountain Gučevo. *U:* ANĐELKOVIĆ, M. (ur.), *Simpozijum iz regionalne geologije i paleontologije (Beograd, 16, 17 XII 1980), Zavod za regionalnu geologiju i paleontologiju, Rudarsko-geološki fakultet, Univerzitet u Beogradu*, 491–507, Beograd (in Serbo-Croatian, English summary).

WANG, Z.H. & CAO, Y.Y. 1981. Early Triassic conodonts from Lichuan, Western Hubei. *Acta Micropalaeontologica Sinica*, 20 (4): 363–375.

WILKIN, R.T. & BARNES, H.L. 1996. Pyrite formation by reactions of iron monosulfides with dissolved inorganic and organic sulfur species. *Geochimica et Cosmochimica Acta*, 60 (21): 4167–4179.

WILKIN, R.T. & BARNES, H.L. 1997. Formation processes of framboidal pyrite. *Geochimica et Cosmochimica Acta*, 61 (2): 323–339.

WIGNALL, P.B. & NEWTON, R. 1998. Pyrite framboid diameter as a measure of oxygen deficiency in ancient mudrocks. *American Journal of Science*, 298: 537–552.

WIGNALL, P.B., NEWTON, R. & BROOKFIELD, M.E. 2005. Pyrite framboid evidence for oxygen-poor deposition during the Permian–Triassic crisis in Kashmir. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 216: 183–188.

YANG, S.R., WANG, X. & HAO W.C. 1986. Early and Middle Triassic conodonts sequence in Western Guangxi. *Acta Scientiarum Naturalium Universitatis Pekinensis*, 4: 90–106.

ZAKHAROV, Y.D., SHIGETA, Y. & IGO, Y. 2009. Correlation of the Induan-Olenekian boundary beds in the Tethys and Boreal realm: evidence from conodont and ammonoid fossils. *Albertiana*, 37: 20–27.

Резиме

Микрофауна доњег тријаса (олењок) Јадарског блока (планина Гучево, СЗ Србија)

Област планине Гучево (Јадарски блок, северозападна Србија) је прилично палеонтолошки неистражена, нарочито кад су у питању стене доњотријаске старости, раније третиране као „сајски“ и „кампилски“ кластити и карбонати. Комплекснија истраживања на овим просторима вршена су тек последњих година и то у седиментима на граници горњи перм–доњи тријас (SUDAR *et al.* 2007, NESTELL *et al.* 2009, CRASQUIN *et al.* 2010), али су настављена и на седименте доњотријаске старости Формације Обнице.

У региону планине Гучева, на локалитету Криви поток који се налази у доњем делу истоименог потока, у седиментима доњег тријаса снимљен је стуб дебљине 11 m. Опробовање је вршено у два маха (2010. и 2012. године). Стуб се састоји из седам пакета, у прва три пакета изграђена од танко слојевитих микритских кречњака је присутан ооидни кречњак дебљине 1 m (Кр6, SRB-2). Четврти пакет је делом покривен, па је подељен у два дела. У целом доњем делу (4а) обилује конодонтима, а остракоди и пиритски фрамбоиди су нарочито присутни у дебело банковитим кречњацима (Кр4, SRB-1). У горњем делу пакета у слоју дебљине 0,2 m такође су нађени ооиди. Пакете 5 и 6 изграђују кварцни пешчари, а преко њих је пакет 7 изграђен од слојевитих кречњака различите дебљине. Депозиција се углавном одвијала у плитком субтајдалу, у ниско енергетском режиму, али присуство ооида, карактеристично за плимни режим, указује на постојање топографских узвишица на терену што је узроковано нормалним рељефом или локалним издизањима. Повремено је долазило и до прилива силицикластичног материјала, услед локалне тектонике или климатских промена.

На стубу је узето четрнаест композитних проба за конодонте, а урађени су и петрографски препарати. Шест узорака садржи конодонте који су омогућили таксономску идентификацију: P_1 елементе *Neospathodus planus* CHEN & KOLAR-JURKOVŠEK, P_1 елеменат недетерминисаног конодонта *Neospathodus* sp., P_2, S_1, S_2, S_3 или S_4 и M елементе од мултиелементарног апарата *Neospathodus planus*, елементе од *Pachycladina–Foliella* конодонтске микрофауне: *Pachycladina obliqua* STAESCHE, *Pachycladina inclinata* STAESCHE, *Foliella gardenae* (STAESCHE) и *Pachycladina* sp. Остала три узорка из горњег дела стуба садрже само рамиформне (гранате) елементе и неодредљиве фрагменте конодоната. У делу пакета 4 пре покривеног дела стуба препознате су две конодонтске зоне: *Pachycladina obliqua–Foliella gardenae* Assemblage

Zone и *Neospathodus planus* Zone и обе су по старости најнижи олењок (доњи смит). Иначе, CAI вредности испитиваних конодоната из Кривог потока су од 5 до 6–7 (5, 5,5, 6, 6–7), са тенденцијом да конодонти из средњег дела стуба (*Neospathodus planus* Zone) имају више вредности. Ове CAI вредности одговарају температурама од 300–490 °C карактеристичним за веома низак до низак степен метаморфизма (GAWLICK *et al*. 1994, SUDAR & KOVÁCS 2006).

Од четрнаест проба третираних за екстракцију конодоната, две садрже и остракоде (SRB-1 и Кр1). Од укупно педесет девет примерака одређена је и нова остракодска врста *Paracypris* ? *krivipotokensis* FOREL n. sp., која се појављује заједно са врстом *Neospathodus planus* у истоименој конодонтској зони. Већина узорака је представљена са целим љуштурама, указујући на одсуство или постмортални транспорт при ниској енергији и/или брзо затрпавање услед високог режима седиментације (OERTLI 1971).

У пакету 4 (део 4а, узорак SRB-1) нађени су пиритски фрамбоиди, који су по први пут констатовани у доњотријаским стенама како Јадарског блока, тако и Србије. Већи део фрамбоида је нађен унутар остракодских љуштура (капака) где су дефинитивно настали у седиментима након умирања остракода. Неуједначеност у величини њиховог пречника (8–35 µm) потврђује раније сугестије да нису погодни за дијагнозу палео оксидоредукционог потенцијала морске воде, и да само индицирају диоксичну и сулфидну микросредину унутар љуштура остракода након њихове смрти.

Приказана микрофауна конодоната и остракода, дефинисано конодонтско зонирање, као и пиритски фрамбоиди су скоро у целости по први пут утврђени у просторима Јадарског блока северозападне Србије. Зато су ови наласци врло значајни за овај део Алпско-медитеранског региона јер представљају микропалеонтолошки добро документоване доказе доњотријаске старости – најнижи олењок (доњи смит).

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Taxonomic diversity dynamics of Early Cretaceous brachiopods and gastropods in the Azerbaijanian domains of the Lesser Caucasus (Neo-Tethys Ocean)

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Abstract. Palaeontological data available from the Azerbaijanian domains (Somkhit-Agdam, Sevan-Karabakh, and Miskhan-Kafan tectonic zones) of the Lesser Caucasus permit reconstruction of the regional taxonomic diversity dynamics of two groups of Early Cretaceous marine benthic invertebrates. Stratigraphical ranges of 31 species and 14 genera of brachiopods and 40 species and 31 genera of gastropods are considered. The total number of species and genera of brachiopods was low in the Berriasian–Valanginian and then rose to peak in the Barremian. Then, the diversity declined in the Aptian, and brachiopods are not known regionally from the Albian. Gastropods appeared in the Hauterivian and experienced a strong radiation in the Barremian. The diversity of species and genera declined in the Aptian (with a minor radiation in the Middle Aptian), and no gastropods are reported from the Albian. Globally, the number of brachiopod genera remained stable through the Early Cretaceous, and the number of gastropod genera increased stepwise with the maximum in the Albian. The regional and global patterns of the diversity dynamics differed for the both groups of marine benthic invertebrates. The Barremian maximum of the taxonomic diversity coincided with the regional flourishing of reefal ecosystems. The taxonomic diversity dynamics of brachiopods in the Azerbaijanian domains of the Lesser Caucasus is very similar to those of the Northern Caucasus, which is an evidence of proximity of these regions during the Early Cretaceous.

Key words: brachiopods, gastropods, taxonomic diversity, transgression, Early Cretaceous, Lesser Caucasus, Azerbaijan, Neo-Tethys Ocean.

Апстракт. Палеонтолошки доступни подаци из Азербејџански домена (Сомкхит-Агдам, Севан-Карабаху, и Мискхан-Кафан тектонске зоне) Малог Кавказа дозвољавају реконструкцију динамике регионалних таксономских разноликости две групе доњокредних морских бентоских бескичмењака. Разматран је стратиграфски опсег 31 врсте и 14 рододова брахиопода и 40 врста и 31 род гастропода. Укупан број брахиоподских врста и родова је био низак у беријас-валендину, а врх разноликости достигао у барему. Затим, разноликост опада у апту, а од алба брахиоподи нису регионално познати. Гастроподе су се појавиле у отриву и доживела јаку експанзију у барему. Разноликост врста и родова опада у апту (са мањом експанзијом у средњем апту), а ниједан гастропод се не појављује од алба. Глобално, број брахиоподских родова остао је стабилан током доње креде, а број гастроподских родова је постепено повећаван, са максимумом у албу. Регионални и глобални обрасци динамике различитости разликовала су се за обе групе морских бентоских бескичмењака. Баремски максимум таксономске разноликости поклопио са регионалним процватом гребенског екосистема. Динамика таксономске разноликости брахиопода у азербејџанским деловима Малог Кавказа је веома слична онима на северном Кавказу, што је доказ близине ових региона током ране креде.

Кључне речи: брахиоподи, гастроподи, таксономска разноврсност, трансгресија, рана креда, Мали Кавказ, Азербејџан, Неотетис.

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Introduction

Reconstructions of regional changes in taxonomic diversity of marine organisms are highly important for understanding spatial differences of biodiversity changes registered with the available global palaeontological data (Sepkoski 1993, 2002; Alroy *et al.* 2008; Purdy 2008; Alroy 2010). Particularly, the fossil record of the Caucasus, a large region stretching between the Black Sea and the Caspian Sea, is useful for analysis of the Cretaceous biotic evolution (Ruban *et al.* 2011). Representative palaeontological data from this region were already compiled and published, but still unemployed for the analysis of diversity dynamics.

The present paper focuses on the Azerbaijanian domains of the Lesser Caucasus (Fig. 1). Two groups of marine benthic macroinvertebrates, namely brachiopods and gastropods, are common in the Lower Cretaceous deposits of the study area (Akopjan & Khalilov 1986; Ali-zadeh 1988). These groups seem to be suitable for the analysis of the regional taxonomic diversity dynamics and its further comparison with the global patterns. This study is a part of the palaeobiological re-evaluation of the information about Cretaceous marine invertebrates from the Caucasus (see also Ruban 2006, 2011a; Ruban *et al.* 2011).

Fig. 1. Geographical location of the study area. Spatial distribution of the Lower Cretaceous deposits in the Lesser Caucasus is shown schematically after Khalilov & Aliyev (1972), Akopjan & Khalilov (1986), and Ali-zadeh (1988). Plate tectonic reconstruction for 120 Ma is simplified from Scotese (2004). Approximate position of the Lesser Caucasus is shown according to Golonka (2004).

Geological setting

The Lesser Caucasus comprises a large southern portion of the Caucasus (Fig. 1). It occupies Armenia and parts of Azerbaijan and Georgia, as well as the neighbouring parts of Turkey and Iran. According to Shikhalibeyli (1972), the Azerbaijanian domains of the Lesser Caucasus include the Somkhit-Agdam, Sevan-Karabakh, and Miskhan-Kafan tectonic zones (the names are given in Russian transliteration). The exact Mesozoic plate tectonic setting of the Lesser Caucasus, which is a Gondwana-derived terrane (Ruban *et al.* 2007), has been debated (Lordkipanidze *et al.* 1984; Gamkrelidze 1986; Golonka 2004; Ismail-Zadeh 2007; Adamia *et al.* 2011). This terrane was located either in the midst of the Neo-Tethys Ocean or near its northern periphery (e.g., Stampfli & Borel 2002; Golonka 2004) (Fig. 1). The Lesser Caucasus was affected by active tectonic processes in the Early Cretaceous, including hot-spot activity (Azizbekov *et al.* 1972; Ismail-Zadeh 2007; Adamia *et al.* 2011; Rolland *et al.* 2009, 2011).

The regional Lower Cretaceous stratigraphy has been developed, particularly, by Khalilov & Aliyev (1972, 2007), Akopjan & Khalilov (1986), Ali-zadeh (1988), and Aliyev & Khalilov (2007). Generally, Lower Cretaceous deposits constitute the carbonate- and volcaniclastic-dominated successions with a total thickness of ~1500 m and more (Khalilov & Aliyev 1972, 2007; Akopjan & Khalilov 1986; Ali-zadeh 1988; Aliyev & Khalilov 2007) (Figs. 2, 3). The Urgonian limestones and reefs are abundant in the Barremian (Jasamanov 1978; Akopjan & Khalilov 1986; Ali-zadeh 1988; Akhmedov *et al.* 2003; Aliyev & Khalilov 2007; Khalilov & Aliyev 2007) (Fig. 3). Clastic lithofacies are common in the upper part of the regional Lower Cretaceous succession (Fig. 2). The Lower Cretaceous deposits of the study area were accumulated in a shallow-marine open basin; the seawater was warm with normal salinity (Jasamanov 1978; Ali-zadeh *et al.* 1982). The sea was populated by different marine organisms, including ammonites, belemnites, bivalves, brachiopods, and gastropods (Khalilov & Aliyev 1972, 2007; Akopjan & Khalilov 1986; Ali-zadeh 1988; Aliyev & Khalilov 2007). Palaeobiogeographically, the fossil assemblages belonged to the Mediterran–Caucasian Subrealm (Westermann, 2000).

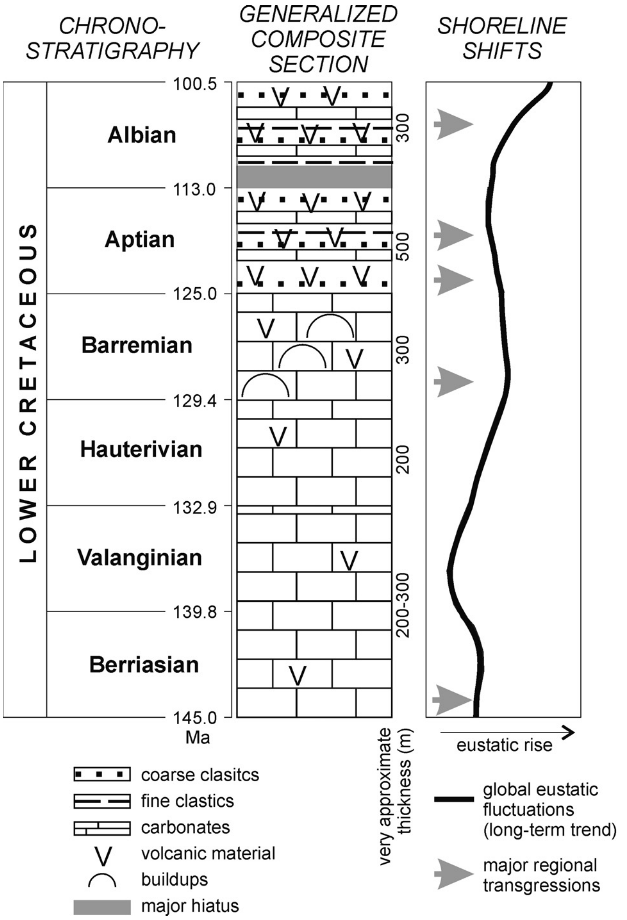

Fig. 2. The stratigraphical outline of the Lower Cretaceous deposits of Azerbaijan. Lithology and regional transgressions are based on information summarized by Khalilov & Aliyev (1972, 2007), Akopjan & Khalilov (1986), Ali-zadeh (1988), and Aliyev & Khalilov (2007); chronostratigraphy after Gradstein *et al.* (2012) (see the updated time scale on-line: stratigraphy.org); global eustatic fluctuations after Haq (2014). Regional transgressions should be distinguished from global eustatic changes, because the latter did not necessarily appear regionally.

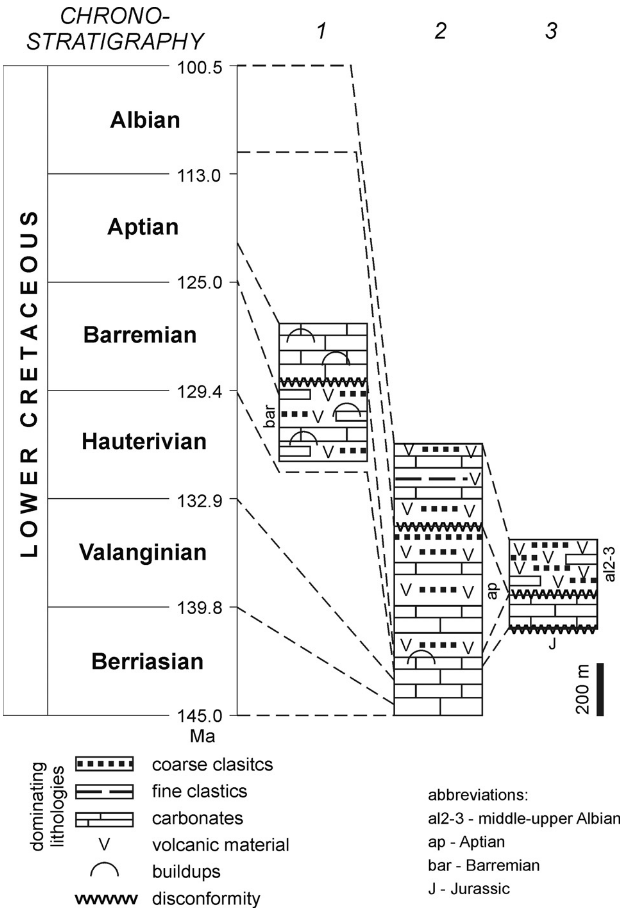

Fig. 3. Correlation of three Lower Cretaceous reference sections (1 – Dashalty, 2 – Dolanlar, 3 – Dashushen) in the Azerbaijanian domains of the Lesser Caucasus (based on the information from Aliyev & Khalilov 2007). These sections are given as examples; many other sections and outcrops are also known in the study area, and they were investigated by Khalilov & Aliyev (1972, 2007), Akopjan & Khalilov (1986), Ali-zadeh (1988), and Aliyev & Khalilov (2007). Formal lithostratigraphical units are yet to be established for the study area. Chronostratigraphy follows Gradstein *et al.* (2012) (see the updated time scale on-line: stratigraphy.org).

The available stratigraphical information (Khalilov & Aliyev 1972, 2007; Akopjan & Khalilov 1986; Ali-zadeh 1988; Aliyev & Khalilov 2007) permits to indicate five regional transgressions (Fig. 2). These are interpreted on the basis of consideration of relative spatial distribution of marine deposits, erosional surfaces, and transgression surfaces. For instance, the limited occurrence of the pre-Barremian deposits in the Azerbaijanian domains of the Lesser Caucasus relatively to the distribution of the Barremian desposits implies landward shoreline shift, i.e., transgression (sensu Catuneanu 2006), peaked in the Barremian. The largest was the Albian transgression (Jasamanov 1978; Khalilov & Aliyev 2007), which coincided with the global long-term sea-level rise (Haq 2014) and was, probably, triggered by the latter. Deposits of this age are the most widely distributed among the Lower Cretaceous sedimentary packages (Ali-zadeh 1988; Aliyev & Khalilov 2007; Khalilov & Aliyev 2007). This transgression took place in the Middle Albian, and it is documented locally by transgressive surface between the Middle Albian and underlying deposits (Aliyev & Khalilov 2007; Khalilov & Aliyev 2007).

Materials and methods

This study employs regional and global stratigraphical ranges of Early Cretaceous brachiopods and gastropods. The regional data on brachiopods (Appendix 1) were taken from Akopjan & Khalilov (1986) and Ali-zadeh (1988) with certain updates (e.g., *Cyrtothyris pseudosella* (Lobatscheva) and *Praelogithyris pseudosella* Lobatscheva given as two distinct species in the original data source seem to be synonyms; *Cyclothyris gillieroni* Pictet, *C. picteti* Burri, and *C. renauxiana* d' Orbidny can be attributed to the genus *Lamellaerhynchia*). The work by Akopjan & Khalilov (1986) synthesizes the information on the regional stratigraphy, and, among others, it lists common brachiopod taxa. The chapter by Zeyniyev & Lobatscheva in Ali-zadeh (1988) is the first comprehensive taxonomic review of Cretaceous brachiopods from Azerbaijan, which remains essential source of the relevant information up to nowadays. These data are the result of regional sampling of many Early Cretaceous fossil localities in the Azerbaijanian domains of the Lesser Caucasus. The global generic diversity of brachiopods was established by Curry & Brunton (2007). The regional data on gastropods (Appendix 1) were extracted from Ali-zadeh (1988). Aliyev in Ali-zadeh (1988) reviewed all available information about Early Cretaceous taxa reported from Azerbaijan, including those described earlier by Aliyev (1963). As in the case of brachiopods, the above-mentioned data were collected during sampling of many localities, and it is regionally representative. The global data on gastropods were taken from the compilation of Sepkoski (2002; see database on-line: http://strata.geology.wisc.edu/jack/start.php).

For the purposes of this quantitative analysis, two regional datasets were composed (Appendix 1). The first of them comprises stratigraphical ranges of 31 species of brachiopods belonging to 14 genera. The second dataset shows the stratigraphical distribution of 40 species of gastropods belonging to 31 genera. The presence of taxa is recorded at the scale of stages, but the distribution of Early Hauterivian–Middle Aptian gastropods (Late Aptian taxa were not reported at all) is also recorded at the level of substages (Appendix 1). All regional data were collected from numerous localities within the study area. As the data are given in the original sources, they characterise the entire region (not individual sections or outcrops), which is typical for palaeontological syntheses from the former USSR. Such information is very suitable for palaeobiological studies (see Ruban (2011b) for discussions).

The present quantitative analysis of the regional taxonomic diversity dynamics of brachiopods and gastropods includes evaluation of the total diversity (=total number of taxa), the number of appearances, and the number of disappearances by stages of the Early Cretaceous. Appearances and disappearances are preferred to originations and extinctions respectively, because the formers could be only temporal in regional records (see Ruban & van Loon 2008). This analysis is done for both species and genera. For further comparisons of diversity patterns, the global changes in the total number of brachiopod and gastropod genera are also considered (no data on the global number of species are available). The taxonomic diversity dynamics are described herein at the level of stages. This resolution enables direct comparisons with the global diversity trends. Uncertainties related to different understandings of substages are avoided (cf. Ruban & van Loon 2008). Also, a major part of the original data is attached to stages only. However, the available information on gastropods allows a tentative reconstruction of their diversity dynamics on the level of substages.

This study is based on the Early Cretaceous chronostratigraphical framework established by the International Commission on Stratigraphy (Gradstein *et al.* 2012; see the updated time scale on-line: stratigraphy.org). Some cautions are necessary when using data from the older palaeontological literature (Ruban 2011b). Particularly, there may be some differences between the regionally established Lower Cretaceous stages (Khalilov & Aliyev 1972, 2007; Akopjan & Khalilov 1986; Ali-zadeh 1988; Aliyev & Khalilov 2007) and the actual global stages (Gradstein *et al.* 2012; see the updated time scale on-line: stratigraphy.org). A brief examination of the regional biostratigraphy (Khalilov & Aliyev 1972, 2007; Akopjan & Khalilov 1986; Ali-zadeh 1988; Aliyev & Khalilov 2007) suggests that some stage boundaries may be replaced downwards or upwards by about a triple of the stage length, but their exact position can be fixed only after detailed special investigations, and this is not the purpose of the present paper. However, the possible influence of the noted problem is considered in the interpretations of the results of this study (e.g., minor diversity changes are supposed to be within the error, and, thus, they are ignored). It should be also noted that the stratigraphical ranges employed for the purposes of the present study are based on generally consistent chrono- and biostratigraphical frameworks used in the original sources (Akopjan & Khalilov 1986, Ali-zadeh 1988), and no major errors linked to differences in stage understanding in different works are expected.

Results

The number of brachiopod taxa changed significantly in the Azerbaijanian domains of the Lesser Caucasus during the Early Cretaceous (Fig. 4). Few brachiopods are reported from the Berriasian and Valanginian deposits. However, the total brachiopod diversity increased in the Hauterivian and duplicated in the Barremian. The Aptian brachiopod assemblages were poor again, and the Albian brachiopods are unknown. The number of appearances tended to remain below

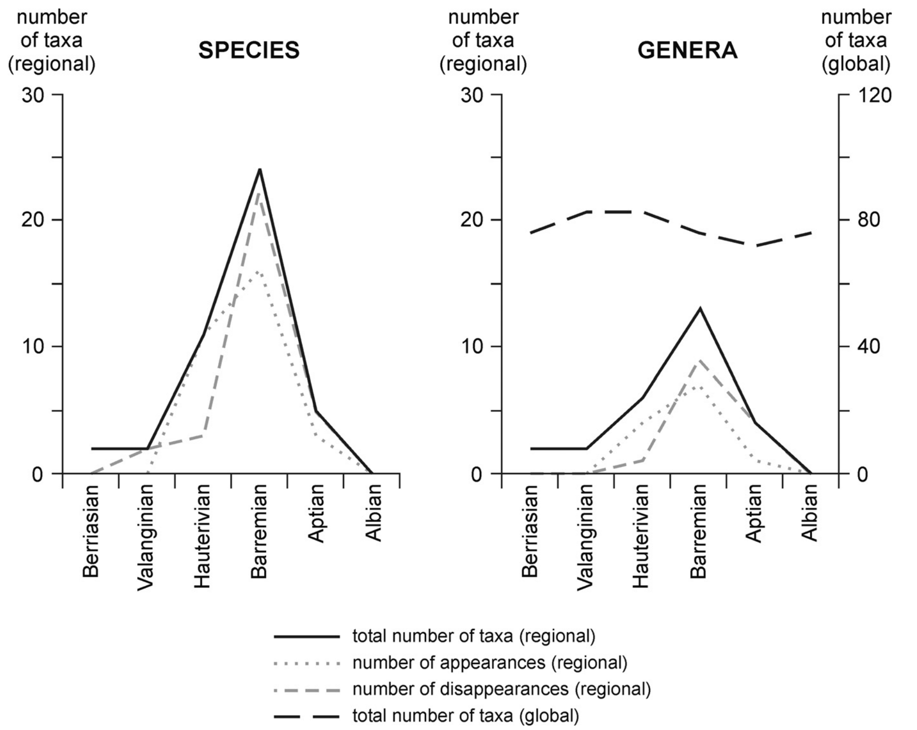

Fig. 4. Regional taxonomic diversity dynamics of Early Cretaceous brachiopods in the Azerbaijanian domains of the Lesser Caucasus. Changes in the global number of brachiopod genera (after CURRY & BRUNTON 2007) are given for reference.

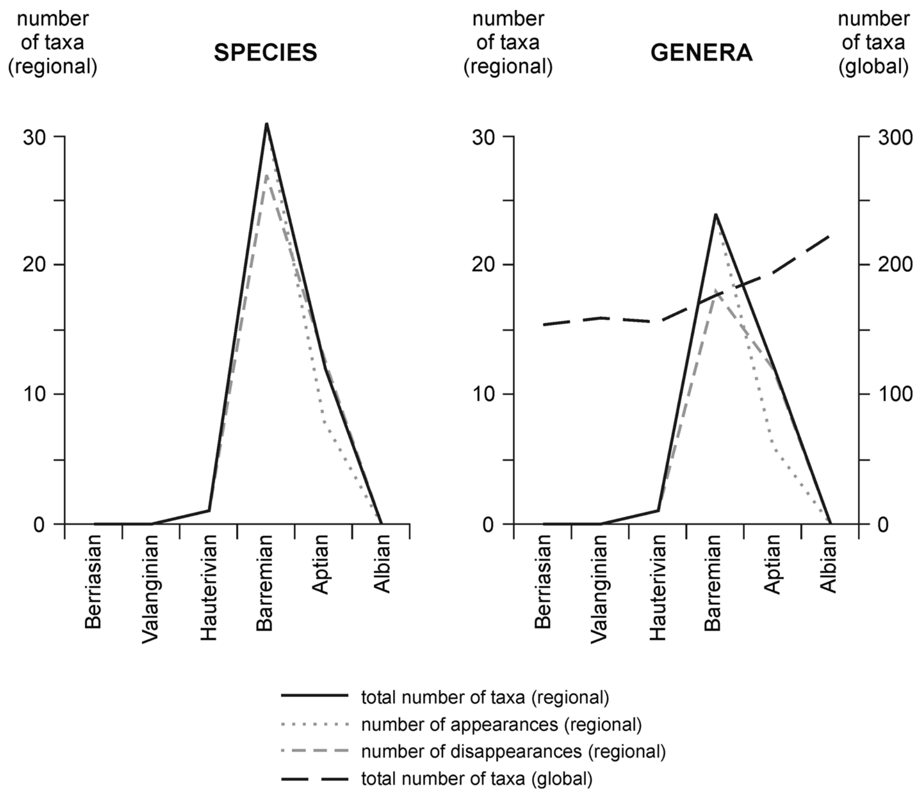

Fig. 5. Regional taxonomic diversity dynamics of Early Cretaceous gastropods in the Azerbaijanian domains of the Lesser Caucasus. Changes in the global number of gastropod genera (on the basis of data from SEPKOSKI 2002) are given for reference.

the number of disappearances (except for the Hauterivian). The Barremian total diversity maximum is a result of 16 species appearances in this stage and only 3 species disappearances in the Hauterivian. Very similar patterns of the generic diversity dynamics are registered (Fig. 4).

The number of gastropod taxa also varied during the Early Cretaceous (Fig. 5). The first gastropod taxon appeared regionally in the Hauterivian. The Barremian stage is characterised by a strong radiation of gastropods. The total diversity declined by about a half in the Aptian, but they remained relatively diverse in this stage. No gastropods are reported from the Albian deposits of the study area. The Barremian diversity maximum was a result of striking increase in the number of appearances in this stage. 27 species disappearances in the Barremian and only 8 species appearances in the Aptian reduced the gastropod diversity in the latter stage. As in the case of brachiopods, very similar patterns of the generic diversity dynamics are registered (Fig. 5). Consideration of the total diversity dynamics at a higher resolution demonstrates that gastropods radiated gradually through the Barremian, and their diversity increased slightly in the Middle Aptian to be followed by the total disappearance of gastropods already in the late Aptian (Fig. 6).

The comparison of the regional taxonomic diversity dynamics of the two groups of marine benthic invertebrates (Figs. 4, 5) implies that the both reached the maximum in their total species and generic diversity in the Barremian. However, the brachiopod assemblages were more diverse in the Hauterivian than in the Aptian, whereas gastropods were relatively diverse in the Aptian and much less diverse in the Hauterivian. In other words, brachiopods experienced a gradual radiation and less gradual decline (Fig. 4), whereas gastropods experienced a strong radiation and gradual decline (Figs. 5, 6).

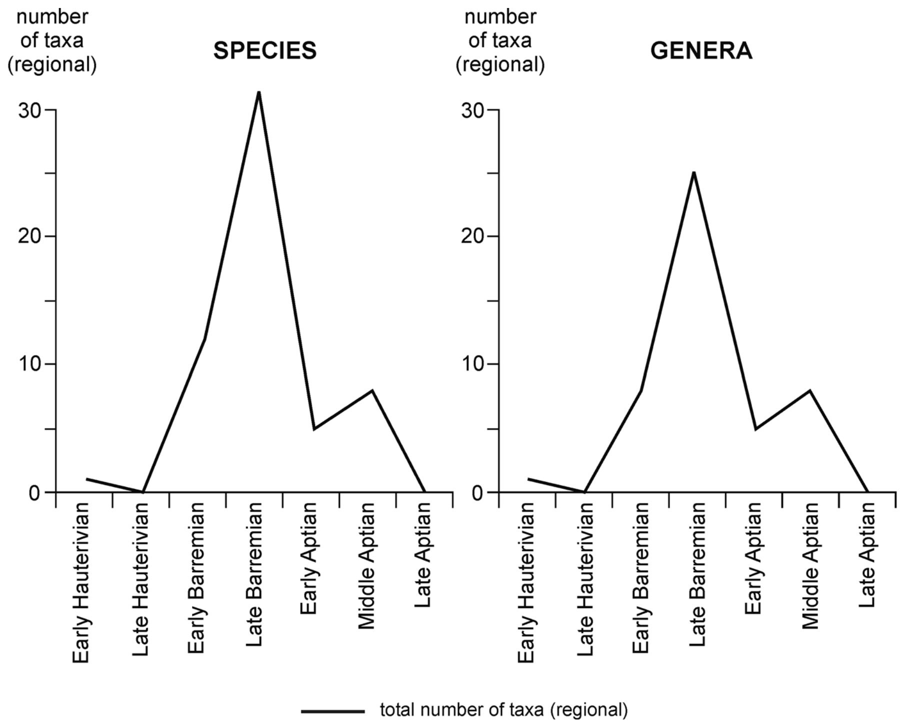

Fig. 6. Regional taxonomic diversity dynamics of Hauterivian–Aptian gastropods in the Azerbaijanian domains of the Lesser Caucasus calculated per substages. The names of the regional sub-stages are not capitalized, because these units are provisional.

Discussion

Globally, the total generic diversity of brachiopods remained stable in the Early Cretaceous, which is different from the regional pattern (Fig. 4). The maximum in the total diversity that occurred in the Azerbaijanian domains of the Lesser Caucasus is not established globally. And, vice versa, brachiopod communities were poor or absent regionally, when this group diversified globally. Gastropods experienced a stepwise diversification on a global scale, which contrasts with the regional changes in the number of genera (Fig. 5). The only Barremian regional diversity maximum coincided with the onset of the late Early Cretaceous diversification, but the latter was not as striking global feature as the above-mentioned regional strong radiation of gastropods. Moreover, the global diversity of these fossils peaked in the Albian, whereas no gastropods of this age are reported from the Azerbaijanian domains of the Lesser Caucasus.

This comparison suggests that there was a fundamental difference between the regional and global diversity dynamics of both brachiopods and gastropods. Moreover, these fossils were more similar by changes in the total number of genera on a regional scale than on a global scale. Therefore, it is unlikely that the regional taxonomic diversity dynamics was controlled by the global changes in the number of taxa. Of course, this conclusion is valid if no bias is significant. For instance, the restricted distribution of pre-Barremian strata (ALIYEV & KHALILOV 2007; KHALILOV & ALIYEV 2007) may explain the low number of brachiopods and gastropods reported from them. The investigations that provided data for the compilations of AKOPJAN & KHALILOV (1986) and ALI-ZADEH (1988) were regional in scale essentially. As shown in their works, each interval was studied with an equal attention. Thus, it is unlikely that sampling bias affect the taxonomic diversity reconstructions presented in this paper. As for the preservation bias, carbonate rocks, which are favourable for fossil preservation, are frequent in the entire Lower Cretaceous successions of the study territory (KHALILOV & ALIYEV 1972, 2007; AKOPJAN & KHALILOV 1986; ALI-ZADEH 1988; ALIYEV & KHALILOV 2007) (Fig. 2).

Some regional palaeoenvironmental controls on diversity should be considered. The geological information summarized by KHALILOV & ALIYEV (1972, 2007), AKOPJAN & KHALILOV (1986), ALI-ZADEH (1988), and ALIYEV & KHALILOV (2007) allows to outline several landward shoreline shifts that occurred in the Azerbaijanian domains of the Lesser Caucasus and either coincided with or differed from the global eustatic changes (HAQ 2014) (Fig. 2). It is unlikely that these transgressions (Fig. 2) were an ultimate control on the regional taxonomic diversity dynamics of either brachiopods or gastropods because of their different correspondence to the diversity changes (Figs. 4, 5). However, it cannot be excluded that the transgression peaked in the Barremian facilitated (or, at least, did not preclude) the rapid diversification of marine benthic macroinvertebrates, and the Aptian transgressions were, probably, responsible for the minor radiation of gastropods (Fig. 6). Interestingly, the global dibersity of brachiopods (Fig. 4) and gastropods (Fig. 5) also did not correspond to the long-term eustatic changes reconstructed by HAQ (2014) (Fig. 2).

Another possible palaeoenvironmental control on the reconstructed diversity dynamics was seawater temperature. It was evaluated regionally on the basis of isotope studies of benthic molluscs and belemnites. Results from such studies should be used with caution because of certain difficulties with isotopic data interpretation (e.g., LONGINELLI 1996, pers. comm.). The investigation by Jasamanov (1978) showed some cooling druing the late Early Cretaceous. The seawater temperature dropped by 4–5 °C down to ~18 °C. Still, the water remained warm, and the basin was situated in or near the tropical climatic belt (JASAMANOV 1978). The palaeotemperature analysis by ALI-ZADEH *et al.* (1982) showed cooling in the marine basin of Eastern Azerbaijan from ~22 °C to ~16 °C during the Valanginian–Barremian and then warming to ~22 °C in the Albian. The above-mentioned data from JASAMANOV (1978) do not permit to judge about direct influences of seawater temperature on the fossil diversity. The results of ALI-ZADEH *et al.* (1982) imply that the diversity maximum was reached when the seawater was the coldest. If the latter is true, this is an unusual coincidence (one would expect fauna flourishing in warm-water conditions), and further investigations are necessary to confirm and to explain this.

The Barremian deposits of the Azerbaijanian domains of the Lesser Caucasus bear reefs with diverse corals (AKOPJAN & KHALILOV 1986; ALI-ZADEH 1988; AKHMEDOV *et al.* 2003) (Appendix 2). It is broadly accepted that coral ecosystems sustained high taxonomic diversity in the geological past (KIESSLING *et al.* 2010). The Urgonian facies with reefs are established in the study area (JASAMANOV 1978; AKOPJAN & KHALILOV 1986; ALI-ZADEH 1988; ALIYEV & KHALILOV 2007; KHALILOV & ALIYEV 2007). These are also typical for many European regions (CSÁSZÁR 2002; IDAKIEVA & IVANOV 2002; MASSE *et al.* 2003, 2009; BODIN *et al.* 2006; GODET *et al.* 2010; MILLAN *et al.* 2011; STEIN *et al.* 2012; CAREVIC *et al.* 2013; GODET 2013; HUCK *et al.* 2013; MASSE & FENERCI-MASSE 2013), where they were formed in environments favourable for diversification of benthic invertebrates. The development of reefal ecosystems in the Barremian provides a plausible explanation of the strong diversification of brachiopods and gastropods relatively to Hauterivian and Aptian intervals. Anyway, the low diversity of these benthic macroinvertebrates in the Berriasian and the Valanginian, we well as their absence in the Albian remain enigmatic, because the regional palaeoenvironments (relatively shallow-water and warm seas with carbonate sedimentation) do not appear restrictive for diverse fossil communities (Fig. 2).

Globally, the Barremian is not known as a stage with the highest global distribution of reefs. Their quantity rose gradually through the Early Cretaceous, but the peak (not as pronounced as that of the Late Jurassic) was reached near the end of this epoch (KIESSLING *et al.* 1999; see also BOGGS 2006). The global generic diversity of Barremian corals (LÖSER 1996, 2005) was high, but not as exceptionally high (relatively to older and younger stages) as it was regionally (ALI-ZADEH 1988). Probably, the regional growth of reefal ecosystems in the only Barremian explains why the diversity maximum of marine benthic invertebrates is registered in the Azerbaijanian domains of the Lesser Caucasus, but not globally in this stage.

The quantitative analysis by RUBAN (2011a) permitted to register the taxonomic diversity dynamics of brachiopods in the Northern Caucasus, i.e., the northern part of the Greater Caucasus Basin. This dynamics can be compared with the diversity patterns established by the present study. The two regions are now located in the proximity of each others, but their relative position during the Early Cretaceous remains quite uncertain because of debates on the exact plate tectonic location of the Lesser Caucasus (LORDKIPANIDZE *et al.* 1984; GAMKRELIDZE 1986; GOLONKA 2004; ISMAIL-ZADEH 2007; ADAMIA *et al.* 2011). However, it is clear that the Lesser Caucasus was located to the south of the Greater Caucasus and within the same tectonic sector of the Neo-Tethys Ocean.

The total brachiopod species diversity in the Azerbaijanian domains of the Lesser Caucasus was lower than that in the Northern Caucasus in the Berriasian, the Valanginian, and the Albian (Fig. 7). However, the total species number changed very similarly in these regions, and the Barremian diversity maximum was reached synchronously (Fig. 7). The total brachiopod generic diversity in the Azerbaijanian domains of the Lesser Caucasus was lower than that in the Northern Caucasus during the Early Cretaceous, except for the Barremian and the Aptian. The only difference in the generic diversity dynamics between the two compared regions is the peak that was reached in the Barremian in the Azerbaijanian domains of the Lesser Caucasus and in the Hauterivian in the Northern Caucasus. Such a similarity of the brachiopod taxonomic diversity dynamics between the two regions can be treated as an indirect evidence of their proximity in the Early Cretaceous. This matches the scenario, where both regions were situated at the northern margin of the Neo-Tethys Ocean. The comparison of assemblage composition between the Azerbaijanian domains of the Lesser Caucasus and the Northern Caucasus (RUBAN 2011a) indicates certain number of common species and genera, which supports the conclusion about their proximity.

Conclusions

The quantitative analysis of the Early Cretaceous taxonomic diversity dynamics of two groups of marine benthic invertebrates, namely brachiopods and gastropods, allows some conclusions:

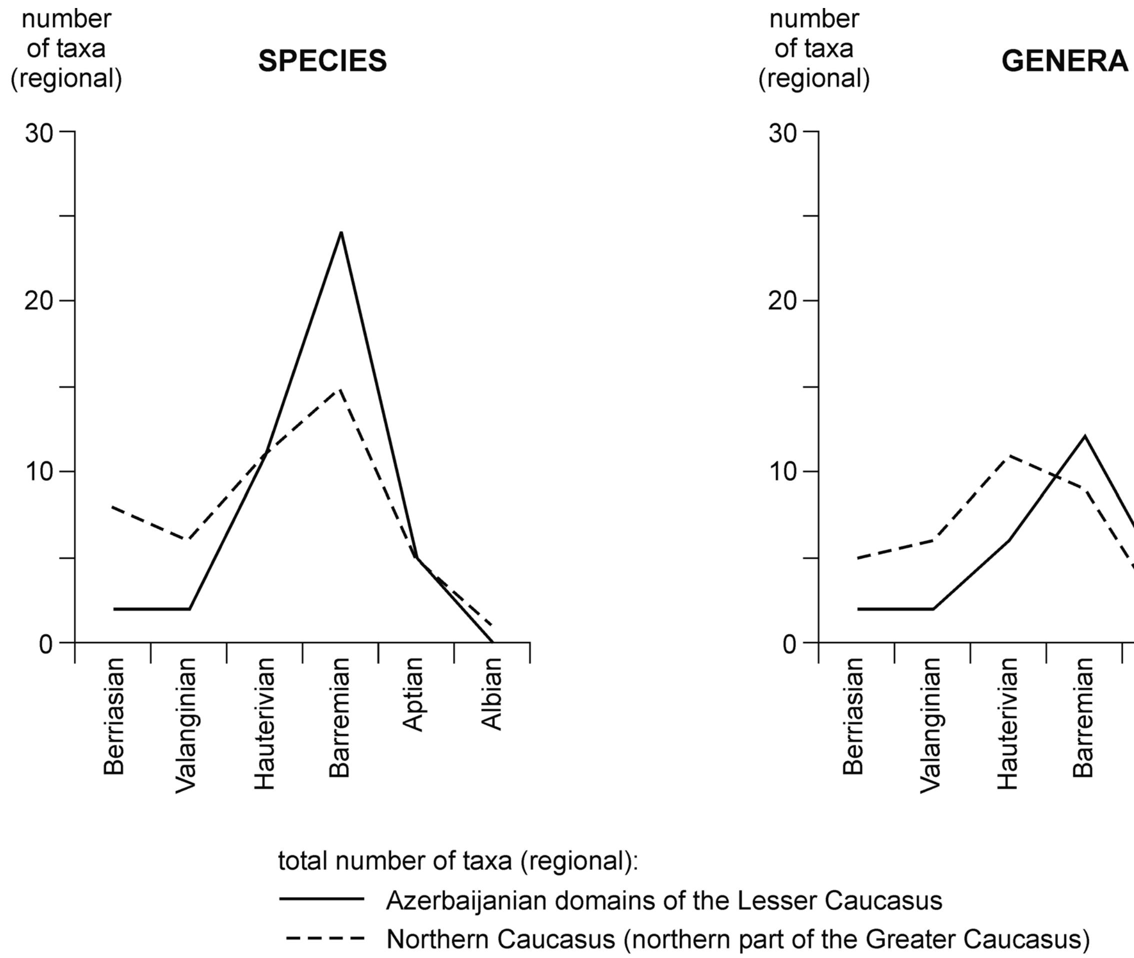

Fig. 7. Regional changes in the total number of species and genera of brachiopods in the Azerbaijanian domains of the Lesser Caucasus and the Northern Caucasus (after RUBAN 2011a).

- the number of species and genera of brachiopods increased in the Hauterivian, peaked in the Barremian, and dropped rapidly in the Aptian;
- the number of species and genera of gastropods increased in an strongly in the Barremian and then declined in the Aptian;
- the regional and global changes in the total generic diversity differed for each fossil group;
- the regional development of reefal ecosystems in the Barremian was likely responsible for the regional diversity maximum of marine benthic macroinvertebrates;
- the patterns of the taxonomic diversity dynamics of brachiopods were similar between the study area and the Northern Caucasus.

Further investigations should be aimed at evaluation of the Early Cretaceous diversity dynamics of such fossil groups as ammonites and belemnites. Sequence stratigraphical architecture and palaeoenvironmental changes also need accurate reconstruction to judge about the possible extrinsic controls on the fossil diversity.

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References

ADAMIA, S., ZAKARIADZE, G., CHKHOTUA, T., SADRADZE, N., TSERETELI, N., CHABUKIANI, A. & GVENTSADZE, A. 2011. Geology of the Caucasus: A Review. *Turkish Journal of Earth Sciences*, 20: 489–544.

Akhmedov, A.K., Babayev, R.G. & Mamedov, I.I. 2003. O rasprostranenii nazemnykh i pogrebjonnykh mezozojskikh organogennykh postroek v Azerbajdzhane (On distribution of surficial and fossil Mesozoic organogenous buildups in Azerbaijan). *Azerbaijan National Academy of Sciences. Proceedings. The sciences of Earth*, 1: 71–77. (in Russian)

Akopjan, V.T. & Khalilov, A.G. 1986. Malyj Kavkaz i Adzharo-Trialety (The Lesser Caucasus and the Adzharo-Trialety). *In:* Moskvin, M.M. (ed). *Stratigrafija SSSR. Melovaja sistema. Polutom 1. (Stratigraphy of the USSR. Cretaceous System. Half-vol. 1)*, 183–189. Nedra, Moskva. (in Russian)

Ali-zadeh, Ak.A. (ed) 1988. *Melovaja fauna Azerbaidzhana (Cretaceous fauna of Azerbaijan)*. Elm, Baku, 648 pp. (in Russian)

Ali-zadeh, Ak.A., Aliyev, S.A., Mamedalizadeh, A.M. & Gamzayev, G.A. 1982. Izotopnye temperatury melovykh bassejnov Vistotchnogo Azerbajdzhana (Isotopic temperatures of the Cretaceous basins of Eastern Azerbaijan). *Geokhimija*, 9: 1370–1373. (in Russian)

Aliyev, G.A. 1963. *Brjukhonogie molljuski melovykh otlozhenij azerbaidzhanskoj tchasti Malogo Kavkaza i ikh stratigrafitcheskoe znatchenie (Gastropods from the Cretaceous deposits of the Azerbaijanian part of the Lesser Caucasus)*. Izdatel'stvo AN AzSSR, Baku, 156 pp. (in Russian)

Aliyev, G.A. & Khalilov, A.G. 2007. Malyj Kavkaz. Nizhnij mel. Melovaja sistema (The Lesser Caucasus. Lower Cretaceous. Cretaceous System). *In:* Alizadeh, Ak.A. (ed). *Geologija Azerbajdzhana. Tom I. Straigrafija. Tchast' II. Mezozoj i kajnozoj (Geology of Azerbaijan. Vol. 1. Stratigraphy. Pt. II. Mesozoic and Cenozoic)*, 124–149. Nafta-Press, Baku (in Russian)

Alroy, J. 2010. The Shifting Balance of Diversity Among Major Marine Animal Groups. *Science*, 329: 1191–1194.

Alroy, J., Aberhan, M., Bottjer, D.J., Foote, M., Fürsich, F.T., Harries, P.J., Hendy, A.J.W., Holland, S.M., Ivany, L.C., Kiessling, W., Kosnik, M.A., Marshall, C.R., McGowan, A.J., Miller, A.I., Olszewski, T.D., Patzkowsky, M.E., Peters, S.E., Viller, L., Wagner, P.J., Bonuso, N., Borkow, P.S., Brenneis, B., Clapham, M.E., Fall, L.M., Ferguson, C.A., Hanson, V.L., Krug, A.Z., Layou, K.M., Leckey, E.H., Nürnberg, S., Powers, C.M., Sessa, J.A., Simpson, C., Tomašových, A. & Visaggi, C.C. 2008. Phanerozoic Trends in the Global Diversity of Marine Invertebrates. *Science*, 321: 97–100.

Azizbekov, Sh.A., Agabekov, M.G., Grigor'jants, B.V., Shikhalibeyli, E.Sh. & Mamedov, A.V. 1972. Istorija geologitcheskogo razvitija (History of geological development). *In:* Azizbekov, Sh.A. (ed). *Geologija SSSR. Tom XLVII. Azerbajdzhanskaja SSR. Geologitcheskoe opisanie (Geology of the USSR. Vol. XLVII. Azerbaijanian SSR. Geological description)*, 441–502. Nedra, Moskva. (in Russian)

Bodin, S., Vermeulen, J., Godet, A. & Föllmi, K. 2006. New data on the age of the installation of Urgonian-type carbonates along the northern Tethyan margin: biostratigraphy of the Chopf Member (Helvetic Alps, eastern Switzerland). *Comptes Rendus Geosciences*, 338: 727–733.

Boggs, S. 2006. *Principles of Sedimentology and Stratigraphy*. Pearson Prentice Hall, Upper Saddle River, 662 pp.

Carevic, I., Abad, M.T.K., Ljubovic-Obradovic, D., Vaziri, S.H., Mirkovic, M., Aryaei, A.A., Stejic, P. & Ashouri, A.R. 2013. Comparisons between the Urgonian platform carbonates from eastern Serbia (Carpatho-Balkanides) and northeast Iran (Kopet-Dagh Basin): Depositional facies, microfacies, biostratigraphy, palaeoenvironments and palaeoecology. *Cretaceous Research*, 40: 110–130.

Catuneanu, O. 2006. *Principles of Sequence Stratigraphy*. Elsevier, Amsterdam, 375 pp.

Császár, G. 2002. Urgon formations in Hungary with special reference to the Eastern Alps, the Western Carpathians and the Apuseni Mountains. *Geologica Hungarica, ser. Geologica*, 25: 1–209.

Curry, G.B. & Brunton, C.H.C. 2007. Stratigraphic distribution of brachiopods. *In:* Selden, P.A. (ed). *Treatise on Invertebrate Paleontology. Part H. Brachiopoda. Revised. Vol. 6. Geological Society of America*, 2901–3081. University of Kansas, Boulder and Lawrence.

Gamkrelidze, I.P. 1986. Geodynamic evolution of the Caucasus and adjacent areas in Alpine time. *Tectonophysics*, 127: 261–277.

Godet, A., Föllmi, K. B., Bodin, S., De Kaenel, E., Matera, V. & Adatte, T. 2010. Stratigraphic, sedimentological and palaeoenvironmental constraints on the rise of the Urgonian platform in the western Swiss Jura. *Sedimentology*, 57: 1088–1125.

Godet, A. 2013. Drowning unconformities: Palaeoenvironmental significance and involvement of global processes. *Sedimentary Geology*, 293: 45–66.

Golonka, J. 2004. Plate tectonic evolution of the southern margin of Eurasia in the Mesozoic and Cenozoic. *Tectonophysics*, 381: 235–273.

Gradstein, F.M., Ogg, J.G., Schmitz, M. & Ogg, G. (eds) 2012. *The Geologic Time Scale 2012*. Vols. 1-2. Elsevier, Oxford, 1176 pp.

Haq, B.U. 2014. Cretaceous eustasy revisited. *Global and Planetary Change*, 113: 44–58.

Huck, S., Heimhofer, U., Immenhauser, A. & Weissert, H. 2013. Carbon-isotope stratigraphy of Early Cretaceous (Urgonian) shoal-water deposits: Diachronous changes in carbonate-platform production in the north-western Tethys. *Sedimentary Geology*, 290: 157–174.

Idakieva, V. & Ivanov, M. 2002. Koralovi postrojki v Smotchanskata svita (Urgonski kompleks, Dolna Kreda) okolo gr. Lovetch (tsentralna severna B'lgarija) (Coral buildups in the Smotchanska Formation (Urgonian complex, Lower Cretaceous)). *Godishnik na Sofijskija universitet, Geologo-geografski fakultet, kniga 1 - geologija*, 95: 31–45. (in Bulgarian)

Ismail-Zadeh, A.D. 2007. *Gabbo-giperbazity i problema ofiolitov Malogo Kavkaza*. Nafta-Press, Baku, 262 pp. (in Russian)

JASAMANOV, N.A. 1978. *Landshaftno-klimatitcheskie uslovija jury, mela i paleogena Juga SSSR (Landscape-climatic conditions of the Jurassic, the the Cretaceous, and the Paleogene in the South of the USSR)*. Nedra, Moskva, 224 pp. (in Russian)

KHALILOV, A.G. & ALIYEV, G.A. 1972. Nizhnij mel (Lower Cretaceous). *In:* AZIZBEKOV, SH.A. (ed). *Geologija SSSR. Tom XLVII. Azebajdzhanskaja SSR. Geologitcheskoe opisanie (Geology of the USSR. Vol. XLVII. Azerbaijanian SSR. Geological description)*, 101–109. Nedra, Moskva. (in Russian)

KHALILOV, A.G. & ALIYEV, G.A. 2007. Nizhnij mel. Malyj Kavkaz. Obosnovanie stratigrafitcheskikh podrazdelenij i regional'nye stratigrafitcheskie shkemy nizhnego mela. Melovaja sistema (Lower Crecaeous. The Lesser Caucasus. Arguing stratigraphic units and regional stratigraphic scales of the Lower Cretaceous. Cretaceous System). *In:* ALIZADEH, AK.A. (ed). *Geologija Azerbajdzhana. Tom I. Straigrafija, Tchast' II. Mezozoj i kajnozoj (Geology of Azerbaijan. Vol. I. Stratigraphy. Pt. II. Mesozoic and Cenozoic)*, 154–161. Nafta-Press, Baku. (in Russian)

KIESSLING, W., FLÜGEL, E. & GOLONKA, J. 1999. Paleoreef maps: Evaluation of a comprehensive database on Phanerozoic reefs. *American Association of Petroleum Geologists Bulletin*, 83: 1552–1587.

KIESSLING, W., SIMPSON, C. & FOOTE, M. 2010. Reefs as Cradles of Evolution and Sources of Biodiversity in the Phanerozoic. *Science*, 327: 196–198.

LONGINELLI, A. 1996. Pre-Quaternary isotope palaeoclimatological and palaeoenvironmental studies: science or artifact? *Chemical Geology*, 129: 163–166.

LORDKIPANIDZE, M.B., ADAMIA, SH.A. & ASANIDZE, B.Z. 1984. Evoljutsija aktivnykh okrain okeana Tetis (Evolution of the active margins of the Tethys Ocean). *In:* LISITZIN, A.P. (ed). *Paleookeanologija. Doklady 27 Mezhdunarodnogo geologitcheskogo kongressa (Palaeoceanology. Reports, 27th Internationlal Geological Congress)*, 72–83. Nauka, Moskva. (in Russian)

LÖSER, H. 1996. Cretaceous corals - state of knowledge and current research. *Zentralblatt für Geologie und Paläontologie, Teil I*, 11/12: 1475–1485.

LÖSER, H. 2005. Stratigraphy of Cretaceous coral genera. *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, 238: 231–277.

MASSE, J.-P. & FENERCI-MASSE, M. 2013. Bioevents and palaeoenvironmental changes in carbonate platforms: The record of Barremian "Urgonian" limestones of SE France. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 386: 637–651.

MASSE, J.P., FENERCI, M. & PERNARCIC, E. 2003. Late Barremian, Urgonian, sequences of Provence (SE France). *Palaeogeography, Palaeoclimatology, Palaeoecology*, 200: 65–81.

MASSE, J.-P., TÜYSÜZ, O., FENERCI-MASSE, M., ÖZER, S. & SARI, B. 2009. Stratigraphic organisation, spatial distribution, palaeoenvironmental reconstruction, and demise of Lower Cretaceous (Barremian-lower Aptian) carbonate platforms of the Western Pontides (Black Sea region, Turkey). *Cretaceous Research*, 30: 1170–1180.

MILLAN, M.I., WEISSERT, H.J., OWEN, H., FERNANDEZ-MENDIOLA, P.A. & GARCIA-MONDEJAR, J. 2011. The Madotz Urgonian platform (Aralar, northern Spain): Paleoecological changes in response to Early Aptian global environmental events. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 312: 167–180.

PURDY, E.G. 2008. Comparison of taxonomic diversity, strontium isotope and sea-level patterns. *International Journal of Earth Sciences*, 97: 651–664.

ROLLAND, Y., GALOYAN, G., BOSCH, D., SOSSON, M., CORSINI, M., FORNARI, M. & VERATI, C. 2009. Jurassic back-arc and Cretaceous hot-spot series in the Armenian ophiolites – Implications for the obduction process. *Lithos*, 112: 163–187.

ROLLAND, Y., SOSSON, M., ADAMIA, SH. & SADRADZE, N. 2011. Prolonged Variscan to Alpine history of an active Eurasian margin (Georgia, Armenia) revealed by $^{40}Ar/^{39}Ar$ dating. *Gondwana Research*, 20: 798–815.

RUBAN, D.A. 2006. Diversity changes of the Brachiopods in the Northern Caucasus: a brief overview. *Acta Geologica Hungarica*, 49: 57–71.

RUBAN, D.A. 2011a. Diversity dynamics of Callovian-Albian brachiopods in the Northern Caucasus (northern Neo-Tethys) and a Jurassic/Cretaceous mass extinction. *Paleontological Research*, 15: 154–167.

RUBAN, D.A. 2011b. Do outdated palaeontological data produce just a noise? An assessment of the Middle Devonian-Mississippian biodiversity dynamics in central Asia on the basis of Soviet-time compilations. *Geologos*, 17: 29–47.

RUBAN, D.A. & VAN LOON, A.J. 2008. Possible pitfalls in the procedure for paleobiodiversity-dynamics analysis. *Geologos*, 14: 37–50.

RUBAN, D.A., AL-HUSSEINI, M.I. & IWASAKI, Y. 2007. Review of Middle East Paleozoic Plate Tectonics. *GeoArabia*, 12: 35–56.

RUBAN, D.A., FORSTER, A. & DESMARES, D. 2011. Late Cretaceous marine biodiversity dynamics in the Eastern Caucasus, northern Neo-Tethys Ocean: regional imprints of global events. *Geološki anali Balkanskoga poluostrva*, 72: 29–46.

SCOTESE, C.R. 2004. A Continental Drift Flipbook. *Journal of Geology*, 112: 729–741.

SEPKOSKI, J.J. 1993. Ten years in the library: New data confirm paleontological patterns. *Paleobiology*, 19: 43–51.

SEPKOSKI, J.J. 2002. A compendium of fossil marine animal genera. *Bulletins of American Paleontology*, 363: 1–560.

SHIKHALIBEYLI, E.SH. 1972. Polozhenie Azerbajdzhana v obtschej strukture Kavkaza i sopredel'nykh skladtchatykh oblastej (Position of Azerbaijan in the general structure of the Caucasus and adjacent regions). *In:* AZIZBEKOV, SH.A. (ed), *Geologija SSSR. Tom XLVII. Azebajdzhanskaja SSR. Geologitcheskoe opisanie (Geology of the USSR. Vol. XLVII. Azerbaijanian SSR. Geological description)*, 286–290. Nedra, Moskva. (in Russian)

STAMPFLI, G.M. & BOREL, G.D. 2002. A plate tectonic model for the Paleozoic and Mesozoic constrained by dynamic plate boundaries and restored synthetic oceanic isochrons. *Earth and Planetary Science Letters*, 196: 17–33.

STEIN, M., WESTERMANN, S., ADATTE, T., MATERA, V., FLEITMANN, D., SPANGENBERG, J.E. & FÖLLMI, K.E. 2013. Late Barremian–Early Aptian palaeoenvironmental change: The Cassis-La Bedoule section, southeast France. *Cretaceous Research*, 37: 209–222.

WESTERMANN, G.E.G. 2000. Marine faunal realms of the Mesozoic: review and revision under the new guidelines for biogeographic classification and nomenclature. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 163: 49–68.

Резиме

Динамика таксономске разноврсности доњокредних брахиопода и пужева у Азербејџанским областима Малог Кавказа (Нео-Тетис)

Фосилни налази Кавказа, велике области која се протеже између Црног мора и Каспијског мора, је користан за анализу биотичке еволуције креде. Брахиоподи и пужеви су чести у доњокредним наслагама у Азербејџанским областима Малог Кавказа. Ове фосилне групе су погодне за анализу регионалне динамике таксономске разноврсности као и за њено даље поређењу на глобалним нивоу. Азербејџанске области Малог Кавказа обухватају Сомхит-Агдам, Севан-Карабах и Мисхан-Кафан тектонске зоне. Седименте доње креде чине карбонати и вулканокластити, који доминирају у сукцесијама укупне дебљине од ~ 1500 m и више. У овој студији коришћени су подаци који се односе на регионално и стратиграфско распрострањење доњокредних брахиопода и пужева. Сачињене су две регионалне базе података. Прва обухвата стратиграфско распрострањење 31 брахиоподске врсте, који припадају 14 родова. Друга база података приказује стратиграфско распрострањење 40 врста пужева који припадају 31 роду. Квантитативна анализа обухватила је процену укупне разноврсности таксона, као број њиховог појављивања и ишчезавања током доње креде. Број брахиоподских таксона значајно се променио у Азербејџанској областима Малог Кавказ за време доње креде. Из берјаских и валандинских седимената познато је само неколико брахиоподских таксона. Међутим, укупна разноврсност брахиопода повећава се у отриву, а дуплира у барему. Током апта брахиоподске заједнице поново постају сиромашне, а у албу су потпуно непознате. Број гастроподских таксона такође варира током доње креде. Први гастроподски таксон у проучаваном простору појавио се у отриву. Баремски век се карактерише значајном радијацијом пужева. Током апта њихова укупна разноврсност опада и упола је мања, мада су ипак и даље релативно разноврсни. Наласци гасторопода нису потврђени из албских наслага проучаваног подручја. У албским седиментима проучаваног подручја пужви потпуно изостају. Поређење динамике регионалне таксономске разноврсности ове две групе морских бентоских бескичмењака указује на то да су обе групе достигле максимум у укупном броју врста и генеричке разноврсности у брему. Међутим, код брахиопода је дошло до постепене радијације и бржег опадања разноврсности, док је код пужева радијација била израженија и било је присутно постепено опадање разноврсности таксона. Постојала је фундаментална разлика између регионалне и глобалне динамике диверзитета како код брахиопода тако и код пужева. Штавише, ови фосили показују већу сличност у променама укупног броја родова на регионалном нивоу него што је то био случај на глобалном нивоу. Мало је вероватно да су регионалне трансгресије биле главни фактор који је контролисао динамику регионалне разноврсности брахиопода и јежева. Занимљиво је да глобални диверзитет брахиопода и пужева такође не одговарај дугорочним променама нива мора. Развој спрудних екосистема у барему би могао да буде објашњење за велику разноврсност брахиопода и пужева у односу на отривске и аптске интервале. На глобалном нивоу барем није познат као век са највећим распрострањењем спрудова. Њихова бројност је постепено расла током доње креде, али су врхунац достигли тек крајем ове епохе. Вероватно да регионални раст спрудних екосистема у барему објашњава због чега је максимум разноврсности морских бентоских бескичмењака забележен у Азербејџанским областима Малог Кавказа али не и глобално у овом беку. Вјероватно, регионални раст спрудних екосистема само у Барему објашњава зашто максимална разноврсност морских бескичмењака бентосним је регистрована у Азербејџанским доменима Мали Кавказ, али не глобално у овом кату. Сличност у динамици разноврсности брахиоподских таксона између Азербејџанских области Малог Кавказа и Северног Кавказа је индиректан доказ њихове близине током доње креде. Даља истраживања би требало да имају за циљ процену доњокредне динамике диверзитета фосилних група као што су амонити и белемнити. Структура секвентне стратиграфије као и промене палеосредине такође захтевају прецизну реконструкцију како би могло да се суди о могућој спољашњој контроли фосилног диверзитета.

Appendix 1. Stratigraphical distribution of Early Cretaceous brachiopods and gastropods in the Azerbaijanian domains of the Lesser Caucasus. Based on data from AKOPJAN & KHALILOV (1986) and ALI-ZADEH (1988) with improvements. See text for more explanations.

BRACHIOPODS

Taxa	Stages					
	Berriasian	Valanginian	Hauterivian	Barremian	Aptian	Albian
Cruralina cruralinica SMIRNOVA				×		
Cyclothyris ardescica (JACOB et FALLOT)			×	×		
Cyclothyris castellanensis (JACOB et FALLOT)			×	×		
Cyclothyris contractoides JACOB et FALLOT			×			
Cyclothyris irregularis (PICTET)			×	×		
Cyclothyris kiparisovae (MOISSEEV in LOBATSCHEVA)			×			
Cyclothyris larwoodi (OWEN)				×		
Cyclothyris lata (D'ORBIGNY)			×	×	×	
Cyclothyris tenuicostata LOBATSCHEVA				×		
Cyrtothyris kentugajensis (MOISSEEV)				×		
Cyrtothyris middlemissi Calzada					×	
Cyrtothyris minor (LOBATSCHEVA)				×		
Cyrtothyris pseudosella (LOBATSCHEVA)				×		
Dzirulina marianovkaensis (MOISSEEV in SMIRNOVA)				×		
Fortunella decipiens (D'ORBIGNY)				×		
Lacunosella cherennensis (JACOB et FALLOT)			×	×		
Lacunosella malbosi (PICTET)	×	×		×		
Lamellaerhynchia gillieroni (PICTET)				×		
Lamellaerhynchia picteti BURRI				×		
Lamellaerhynchia renauxiana (D'ORBIGNY)				×		
Loriolithyris russillensis (DE LORIOL)			×	×		
Moutonithyris karakaschi MOISSEEV				×		
Moutonithyris moutoniana ('DORBIGNY)				×		
Nucleata cf. *strombecki* (SCHLOENBACH)				×		
Sellithyris campichei (PICTET)	×	×				
Sellithyris sella (SOWERBY)			×	×	×	
Terebrirostra? aff. *neocomiensis* D'ORBIGNY			×	×		
Terebrirostra taurica (MOISSEEV)				×		
Torquirhynchia astierana (D'ORBIGNY)					×	
Torquirhynchia aurea (ELLIOTT)					×	
Tropeothyris salevensis (DE LORIOL)			×			

GASTROPODS (listed per stages)

Taxa	Stages					
	Berriasian	Valanginian	Hauterivian	Barremian	Aptian	Albian
Ampullospira kurdistanica (ALIEV)					×	
Ampullospira subupensis ALIEV				×		
Archimedea archimedi (ORBIGNY)				×		
Balkanella garthisensis (ALIEV)					×	
Campichia azerbaijanensis ALIEV et LYSSENKO				×		
Campichia margaritae ALIEV et LYSSENKO				×		
Columbellina maxima LOR.				×		
Confusiscala sp.					×	
Contortella cylindrica ALIEV				×		
Contortella tuberculata ALIEV				×		
Culindrobulina geuialensis ALIEV					×	
Cylindroptyxis pellati (COSSMANN)				×		
Dalmatea bicarinata ALIEV				×		
Diozoptyxis coquandi (ORBIGNY)				×	×	
Diozoptyxis renauxi (ORBIGNY)				×		
Diozoptyxis traversensis PICT. et CAMP.				×		
Diptyxiella transcaucaucasica ALIEV et LYSSENKO				×	×	
Diptyxis subdistincta ALIEV				×		
Funiptyxis pcelincevi ALIEV				×		
Harpogodes pelagi (BRONG.)				×	×	
Helicaulax caucasicum ALIEV				×		
Lissochilus subantonii (ALIEV)					×	
Lyosoma capduri COSSMANN				×		
Microchiza nickchici PCELINCEV				×		
Neoptyxis formosa PCELINCEV				×		
Nerinella algarbiensis CHOFF.				×	×	
Oonia pseudoovalis ALIEV				×		
Phaneroptyxis arnaudi (MATH.)				×		
Phaneroptyxis balkanensis (PCELINCEV)				×		
Pleurotomaria subjaccardi PCELINCEV			×			
Proacirsa provencali COSSMANN					×	
Purpuroidea pcelincevi ALIEV					×	
Salinea alizadei (ALIEV)					×	
Salinea pseudobella (DVALI)				×		
Sculpturea fogdtiana (MORT.)				×		
Trochonatica bruguierii (MATH.)				×		
Tylostoma depressum PIC. et CAMP.				×		
Tylostoma paranaticoide ALIEV				×		
Tylostoma rochatianum PIC. et CAMP.				×		
Umbanea favrei ALIEV				×		

GASTROPODS (listed per substages)

Taxa	Substages					
	Early Hauterivian	Late Hauterivian	Early Barremian	Late Barremian	Early Aptian	Middle Aptian
Ampullospira kurdistanica (ALIEV)						×
Ampullospira subupensis ALIEV				×		
Archimedea archimedi (ORBIGNY)				×		
Balkanella garthisensis (ALIEV)						×
Campichia azerbaijanensis ALIEV et LYSSENKO			×	×		
Campichia margaritae ALIEV et LYSSENKO			×	×		
Columbellina maxima LOR.				×		
Confusiscala sp.						×
Contortella cylindrica ALIEV				×		
Contortella tuberculata ALIEV				×		
Culindrobulina geuialensis ALIEV						×
Cylindroptyxis pellati (COSSMANN)			×	×		
Dalmatea bicarinata ALIEV				×		
Diozoptyxis coquandi (ORBIGNY)			×	×	×	
Diozoptyxis renauxi (ORBIGNY)			×	×		
Diozoptyxis traversensis PICT. et CAMP.			×	×		
Diptyxiella transcaucaucasica ALIEV et LYSSENKO				×	×	
Diptyxis subdistincta ALIEV				×		
Funiptyxis pcelincevi ALIEV				×		
Harpogodes pelagi (BRONG.)				×	×	
Helicaulax caucasicum ALIEV				×		
Lissochilus subantonii (ALIEV)						×
Lyosoma capduri COSSMANN			×	×		
Microchiza nickchici PCELINCEV				×		
Neoptyxis formosa PCELINCEV				×		
Nerinella algarbiensis CHOFF.				×	×	
Oonia pseudoovalis ALIEV				×		
Phaneroptyxis arnaudi (MATH.)				×		
Phaneroptyxis balkanensis (PCELINCEV)				×		
Pleurotomaria subjaccardi PCELINCEV	×		×			
Proacirsa provencali COSSMANN					×	×
Purpuroidea pcelincevi ALIEV						×
Salinea alizadei (ALIEV)						×
Salinea pseudobella (DVALI)			×	×		
Sculpturea fogdtiana (MORT.)			×	×		
Trochonatica bruguierii (MATH.)			×	×		
Tylostoma depressum PIC. et CAMP.			×	×		
Tylostoma paranaticoide ALIEV				×		
Tylostoma rochatianum PIC. et CAMP.			×	×		
Umbanea favrei ALIEV				×		

Appendix 2. Stratigraphical distribution of Early Cretaceous coral genera in the Azerbaijanian domains of the Lesser Caucasus. Only Barremian and Aptian taxa were reported from this region. Based on data from ALI-ZADEH (1988) with improvements.

Taxa	Stages	
	Barremian	Aptian
Actinastrea	×	
Clausastrea	×	
Cryptocoenia	×	
Dimorphocoenia	×	
Eohydnophora	×	
Eugyra	×	
Holocystis	×	×
Hydnophoromeandraraea	×	
Mesomorpha	×	
Metaulastraea	×	
Microsolena	×	
Placocolumastrea	×	
Polyphylloseris	×	
Pseudopolytremacis	×	
Rhipidomeandra	×	
Stelidioseris	×	
Thecosmilia	×	

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Original meaning of the notion and term "Formation" in geology

Aleksandar Grubić[1]

Abstract. The notion of (geological) formation has gradually developed through mostly German terms: from *ein Gebirge*, which was used by Saxon miners for several centuries (Agricola), then *Schichten*, *Bergart* (Lehmann) and *serie montana* (Fuchsel) to *Gebirgsart* (Werner). The term 'formation' was introduced by Werner in 1791 and its meaning was clearly defined around 1800. He included the notion of "formation" into his system of "geognostic structures": mineral; rock (layer); formation; Earth's crust. Therefore, it was an equivocal term from the start. It implied a geological body of certain composition, genesis and superposition (*i.e.* time of origination). After Werner, the term 'formation' was used in different ways, mostly as a synonym for a 'system', until 1881 when such use was forbidden. The original Wernerian sense of the term 'formation' (as a unit in geological levels of organisation: mineral–rock–formation–geosphere–planet) with an intentionally equivocal meaning was not restored until the second half of the twentieth century.

Key words: formation, Gebirge, Gebirgsart, serie montana, Fuchsel, Werner.

Апстракт. У раду се третирају појам и термин (геолошка) формација према ономе шта су о томе писали Агрикола, Леман, Фухсел и Вернер. Појам се развијао постепено из вишевековне праксе саксонских рудара („en Gebirge") а термин „формација" је увео немачки геолог Вернер (A.G. Werner) 1791. године. Око 1800. године исти аутор је унео формацију у свој систем „геогностичких структура": „минерал – стена (слој) – формација – земљина кора". На тај начин термин формација је постао вишезначан. Подразумевао је геолошко тело одређеног састава, постанка и суперпозиционог положаја (односно старости). То је скоро потпуно игнорисано током целог XIX века. Шездесетих година XX века руски геолог Драгунов (1965) дошао је до истог фундаменталног става који је открио Вернер. Писац ових редова се залаже за повратак изворној примени појма и термина формација јер се управо тако превазилазе сва многобројна схватања око којих се деценијама сукобљавају разне школе.

Кључне речи: формација, Gebirge, Gebirgsart, serie montana, Fuchsel, Werner.

Introduction

The *International Guide to Stratigraphic Classification and Terminology* defined the term 'formation' as follows:

> The Formation is the fundamental formal unit of lithostratigraphic classification ... and is the only formal unit which is used for completely dividing the whole stratigraphic column all over the world into named units on the basis of lithostratigraphic character (Hedberg 1972, p. 20).

Its hierarchic position within the lithostratigraphic sequence (layer–member–formation–group) was then precisely specified. However, the original meaning of the term 'geological formation' or simply 'formation' was not restricted to this definition. It was just one of its aspects, which had reference to geological mapping.

According to its original sense in the eighteenth century (Werner 1791), but also in the discussions and usage during the second half of the twentieth century, this notion of 'formation' acquired a much deeper, broader and more significant sense. Thanks to fruitful discussions among different conflicting schools of geology, it became clear that the term 'formation' has a precisely defined position in the 'geological levels of organisation of matter', between 'rock' and 'geosphere' (Dragunov 1968; Krut

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1968). This fact paved the way for an awareness that establishing of 'formational geology', *i.e.* of a group of geological disciplines essentially based on the study, identification and use of formations was taking place (GRUBIĆ 1985).

In modern geology, 'formation' is one of the fundamental geological notions, because it lies at the base of the whole of applied geology as well as a large part of theoretical geology. It is particularly important to emphasise that knowledge of geological formations is of vital importance for the exploration of mineral ore deposits, engineering geology, hydrogeology, and environmental protection.

Moreover, the application of 'formational analysis' in the production of 'geologic' maps of the Moon and Mars by means of remote sensing showed that formations, as well as minerals and rocks, are not only terrestrial but also cosmic entities, causally related to the evolution of terrestrial-type planets.

Such significance of the notion and term 'formation' in the family of Earth Sciences suggests a need to study, reconstruct and precisely define its historical roots, since there are inconsistent citations and usages in the literature.

Saxon miners and Georg Agricola

German miners started quite early to use the geographical term *Gebirge* (mountains) for the geological space "below the surface of the Earth, [regardless of whether] whether the surface [wa]s mountainous or plain" (OSPOVAT 1999, p. 14). In other words, the term was the close to the modern concept of 'the underground' in its material sense. Since during their complicated and arduous work Saxon miners ran into alternations of rocks in which they used different tools and techniques, they began to distinguish thick and thin sequences of rocks with similar characteristics. For thick sequences, they used the term *Gebirge*, which was always related to a characteristic feature of an actual rock sequence (*e.g. das blaue Kohlen-Gebirge*: LEHMAN 1756, p. 167). Sequences of medium and small thickness were called *Lage(r)* and *Schicht* respectively. The term *Floetz* was used for a 'layer' in a narrower sense. All these were important elements of mining organisation.

Such professional terminology in the mines of Thuringia was recorded by AGRICOLA (1521, p. 96) in his description of "the roof of the copper schists of Mansfield". Among the other rocks, he referred to the following *Gesteinsschichten* (rock layers): "First, 20 to 35 *Lachter* of dark red *Gebirge* ... ; Second, 1 *Lachter* of gray-clay *Floetz* ...; ash-gray rock with 3 *Lachter* of ... ash and 5 *Lachter* of rock fragments". (*Lachter*: an old German unit of length, used in mining industries. It varied somewhat from one region to the next but was approximately two metres in length).

At the time when Agricola obtained the above mentioned data from mine workers, they were still distinguishing rock sequences according to their color and work techniques they used. This lasted for two more centuries.

In the eighteenth century, miners in Thuringia already knew different rock types, thus they could identify different rock sequences and name them according to the main rock. Color of the rock became a secondary characteristic, but superposition of each sequence became very important. This was based on the fact that the order of thin and thick sequences of layers in almost undisturbed sediments of Thuringia was constant and well known to the miners. This is also the answer to the question: why the Saxon miners in Thuringia were the first to clearly distinguish alternations of sequences made up of different rocks in vertical succession.

Johann Gottlob Lehmann

The oral tradition of Saxon miners was accepted by J. G. LEHMANN, a mining inspector with an excellent mining and geological education and experience and a good knowledge of geological literature. With his mining experience, Lehmann knew that there was a succession of different rocks in the Earth's crust and that it was constant in Thuringia. He also used his experience of studying the surface outcrops of the rock layers of the region. He knew, however, that this idea had not been developed and described in detail. So he decided to take this task as his 'minor' contribution (LEHMANN 1756, 'Preface').

In his well-known monograph about the area between Ilfeld and Mansfield counties in Saxony, LEHMANN (1756) described the rock succession in detail and represented it in a well-known cross-section (LEHMANN 1756, Table 7, p. 162). He distinguished thirty-one units: ten thicker and the rest thinner. Each unit received a precisely defined position in the vertical succession, as well as the specific characteristics and name used in mining terminology. He used a general term *Schichten* for all these units (p. 162). In general, Lehmann did not use the term *Gebirge* (because of its very specific meaning, referring to the underground) in his name for each unit. However, he included *Gebirge* in the names of three of the units – in sequences 19, (*felsige Gebirge*), 23 (*leberfarbene Gebirge*), and 24 (*blaue Kohlen-Gebirge*). He used the term *Floetz* for actual layers. It is interesting that he used that term only once for a whole unit (No. 29), but he also used it for all sedimentary rocks of Thuringia: *Floetz-Gebirgen* (p. 157). Thus Lehmann often used the term *Schichten*, but only rarely *Gebirge*, for recognisable sequence made up of identical or similar rocks. He also used also the term *Bergart* on one occasion for the rocks in Unit 28 (p. 168). This was another mining term that would later be used by WERNER.

Several important conclusions can be drawn from Lehmann’s book. In the first place, he introduced into the professional literature an idea from mining practice in Thuringia—that there are recognisable large geological bodies in the Earth’s crust made up of the same rocks and minerals. Lehmann also assigned a particular (mining) name to each of the established rock units. Furthermore, he occasionally used the old mining term for ‘underground’ (*Gebirge*), but did not use it consistently in the names of these bodies because he knew it had a specific meaning in mining terminology. Finally, he mostly used term *Schichten* (*i.e.* ‘layers’) for the bodies that he mentioned. He used the name *ein Floetz* (*i.e*. ‘one layer’) for only one of his units (No. 29, p. 168), in order to make a distinction between the larger and smaller units within the named unit.

In this way, the practical mining terms for distinguishing and naming large subsurface geological bodies recognizable by their composition, was also applied in Lehmann’s book to the surface outcrops and thereby was introduced into the geological scientific theory and literature. But a specific term was not assigned to these bodies. He used the terms *Schichten*, *Gebirge* and *Bergart* instead.

Georg Christian Fuchsel

Several years after the Lehmann’s book, GEORG CHRISTIAN FUCHSEL (1761) published his famous *Historia terrae et maris ex historia Thuringiae, per montium descriptionem* in Latin. (Füchsel published his book under his Latinised name, which is therefore used here, rather than the more usual spelling.) Fuchsel was a well-educated doctor, an outstanding naturalist and connoisseur of the specialised literature of his time, as is confirmed by the variety of subjects on which he wrote extensively. Besides having an intimate knowledge of Lehmann’s wotk, he was also a skilled field observer and Lehmann’s book encouraged him to publish everything that he discovered during his several years of field investigations and sampling in the area of Thuringia southwest of Jena. His original idea of delineating the superficial extent of geological units–which had otherwise been known only to miners and Lehmann–on a rough sketch of the region was particularly important. This was how this very early geologic map in the world originated (FUCHSEL 1761, Tab. V). The author needed a more precise identification of large geological bodies with distinctive characteristics. This demanded several years of systematic, persistent and thorough fieldwork, an inventive mind and original solutions in synthesizing the large amount of collected data, because Fuchsel had no pattern to follow.

Fuchsel’s text was comprised of two parts (*sectio*). The first, shorter part had eighty-one pages of theoretical discussion and a short description of the units that he established, while the his interpretation of the geological history of Thuringia was presented in about hundred pages in Part 2. The whole was accompanied by tables and illustrations.

Following the mining practice, Fuchsel theoretically separated and precisely defined three types of units (pp. 46–48): *stratis (Schichten)*; *serie montana (ein Gebirge)*; and *serie statuminis (*ein *Unterlager).* Unlike Lehmann, he followed the mining terminology strictly, but in order to avoid possible confusion, he chose not to use the word *Floetz* (layer) as much as possible.

Fuchsel’s text was published in Latin, but he kept the corresponding German names in brackets for all the important terms. This is important for a proper understanding of Fuchsel’s procedures and the terminology that he applied. If he had not done it that way, one would have hardly realised that the old German term *ein Gebirge* was hidden behind *serie montana*! One should pay attention to the fact that the author did not simply use the word *Gebirge* for a geological body. Rather, he wrote *ein Gebirge* thus emphasising that it was just “one part of the underground”.

We may leave aside here the term *stratus*, because it simply meant a single material layer. But it is necessary to discuss the terms *serie montana* and *serie statuminis.*

Fuchsel gave two complementary definitions of *vero series montanas* (p. 50) or simply *serie*. In the first definition (Paragraph 4, p. 48), he wrote: “Mountains made up of identical deposits (*situs*), with the same composition (*massa*) and of the same origin (*modo constructos*) c[an] be named *serie montana* (*ein Gebirge*)”. In the second definition in Paragraph 45 (p. 9), he wrote: “*Serie montana* are thick layers composed of numerous thinner layers”. According to these definitions and the attached map–a kind of block diagram for the area studied–it is clear that when Fuchsel used the phrase *serie montana* he was referring to geological bodies of large dimensions, large enough to be distinguished, separated and represented on his map. Therefore, the idea ‘mapped unit’–a fundamental concept in contemporary geological mapping–was born.

Fuchsel did not give a strict definition of the term *serie statuminis*. However, according to the description in Paragraph 5 (p. 48) and the corresponding German word (*ein Unterlager*), it appears that it can be construed as “a sequence of thin layers” that mutually alternate (*Wechsel*). These layers lie between two *serie montana* from which they differ, connecting them and separating them, with the lower one making the footwall of the upper one.

Applying these notions, Fuchsel separated and described nine *serie montana* that always had the mining suffix -*gebirge* in the German names (*e.g.*, *oberste Kalchgebirge*, *rothe Schalgebirge, etc*.) and six *statu-*

minis that contained *Lager* in their names (*rothe tode Lager*, *etc*.) in the area that he studied southwest of Jena. The word *Floetz* was used only once (Unit 17e, *Sandfloetz*, p. 62). All these units were designated by numbers (10 to 25) on the map and by letters (A to K) on the diagrams.

Because of the need to graphically present the extent of each *serie montana*, Fuchsel understood that the positions of lithologic units in the vertical sequence of rocks and in geographical space are very important for its occurrence on the surface. This was further emphasised by the presentation of the established units on a primitive block diagram (in the accompanying tables). Thus, he made every effort to explain the terms: *situs (Lager*) and *positus* (*Stand*). The first term related to the superpositional relationships between any given unit and the other units, while the other term referred to the position of a unit in the geographical space.

By this work, Fuchsel set the foundations for future formational analysis. In his area of study, he defined, separated and mapped geological bodies that we accept as distinct formations today. He emphasised the importance of 'mass' (composition), position, distinctiveness and fossil content for their distinguishing and separation. He thought that each such body should be given a particular name (p. 48). And he clearly distinguished *vero series montanas* from *serie statuminis*, which means 'formations' and 'layers' as particular, objectively separable lithostratigraphic units in their contemporary sense.

All this was really unexpectedly much work for an author from the eighteenth century. Therefore it is unsurprising that Fuchsel's work is still regularly cited today. The problem is, however, that despite numerous citations, only a small number of experts have had Fuchsel's work in their hands, which is perhaps why different things have been attributed to him. He did much and introduced several important notions into geological science. But he never used the term 'formation', though numerous authors still say otherwise in their texts, starting from KEFERSTEIN (1840, pp. 56–57) and particularly after ZITTEL (1899, p. 51).

Abraham Gottlob Werner

The term 'formation' was introduced into the geological literature by ABRAHAM GOTTLOB WERNER (1791)–the well-known mining inspector and professor of mineralogy and geognosy at the Freiberg Mining Academy. In order to explain mining to future mining engineers, Werner based his lectures on established mining practices, referring among other things to Lehmann's book and Fuchsel's work. The principal terms in these sources were: *Gebirge*, *Schicht*, *Lager*, *Floetze*, and *Bergart*. Werner accepted them, as research subjects, and established the basis for a new science, which he adumbrated in 1778 and introduced in a new set of lectures under the name *Gebirgslehre* (GUNTAU 1984, p. 67). In addition to the aforementioned terms, Werner used a new one, *Gebirgsart* ('mountain rock', as translated by JAMESON: 1812, p. 192), which had not been used previously in the published literature. Actually, Werner used the terms *Bergart* and *Gebirgsart* as synonyms, which can be described in free translation as "a type of underground solid rock" (WERNER, 1817/1818, p. 10, Articles 20 and 22). A trace of all this is to be found in WERNER'S famous work on the classification of *Gebirgsarten* (1787).

Werner considered the terms *Gebirge* and *Gebirgsart* to be of crucial importance at that time. That is why it is interesting to discuss how he used these terms.

At first sight, when reading Werner's texts informatively, one gets an impression that he used terms *Gebirge* and *Gebirgsart* inconsistently: from using *Gebirge* as a term for the whole underground (or the Earth's crust), similarly to Saxon miners (OSPOVAT 1999, pp. 14 and 15); and then using both terms as synonyms for *Gestein* (rock) and *Gesteinsart* (rock type) (see GUNTAU 1984, pp. 40 and 80), in cases where a part of the *Gebirge* is made up one or several *Gebirgsarten* (WERNER 1787, p. 5).

This, however, is just a superficial impression. Werner's system, to which he held consistently, was quite simple. The Earth crust (*Gebirge*) is made up of actual *Gebirges* that could be simple or composite. The simple *Gebirges* are made up of a single *Gebirgsart*, while the complex ones are composed of two or several *Gebirgsarten*. Moreover, a *Gebirgsart* (*i.e. Bergart*) itself could be simple or composite. A simple *Gebirgsart* is made up of a single *Gesteinsart* while two or more of them make a composite *Gebirgsart*. That is all. Such a system allows for a simple *Gebirgsart*, for instance, or even one *Gesteinsart* to be synonyms for simple actual *Gebirge.* This explains an apparent inconsistency in the Werner's lectures. It is important, however, to understand what he wanted to achieve by using the term *Gebirgsart*. Apparently, the answer to that question is: *Gebirge* is a general term for underground that could be made up of one or several different *Gebirgsarten*.

Miners had three criteria according to which they identified different *Gebirgsarten* in a *Gebirge*: technical work methods in a rock unit, its dimensions (particularly thickness) and its position, *i.e.* its place in the order of superposition (OSPOVAT 1999, p. 15). Besides, Werner had in mind the same criteria but he significantly extended the scope of 'methods of work' and replaced them by petrographic characteristics of rocks in the *Gebirgsart*. He clearly emphasised this in his idea that a *Gebirgsart* comprises one or more *Gesteinsarten* (1787, p. 6). According to all this, the term *Gebirgsart* in Werner's texts referred to a solid geological body of large dimensions, and with a certain order of superposition and petrographic composition. According to its content, therefore, *Gebirgsart* came close to the future meaning of *Formazion*.

During the first fifteen years of his professorship, Werner, as one conversant with mining, principally focused on mining terminology. However, he did not wholly understand Fuchsel, even though he had his work in his hands. This is confirmed by the fact that Fuchsel’s text still exists in the Werner’s private library in Freiberg, as well as by his adopting Fuchsel’s term ‘geognosy’ in 1786.

In his system, WERNER (1787) distinguished *Hauptgebirgsarten* (p. 26), including *Hauptarten* (p. 6) and *untergeordnete Bergarten* (p. 11). He systematized the related *Gebirgsarten* into *Gattungen Gebirgsarten* (pp. 16, 21 and 26) and, finally, he divided all deposits that originated during the Earth’s history into the following four: *Hauptabtheilungen: uranfangliche-*, *Floetz-*, *vulkanische-*, *und aufgeschwemmte Gebirgsarten* (p. 5).

Therefore, during the first fifteen years of his academic career, Werner used the term *Gebirgsart* for the notions that Lehmann named *Schichten* and *Gebirge*, while Fuchsel used the expressions *serie montana* or *eine Gebirge.* However, Werner used this term in a precisely defined way and incorporated it into the foundation of his classification of geological bodies.

A new period in the development of these issues began with publishing of Werner’s famous book on the origination of veins in 1791, in which he used the term *Formazion* (formation) for the first time in print. It had been used before among geologists, but without have any particular geognostic meaning.

In this book, Werner wrote: “I call all the veins of common origin, which might occur together or close to each other in an area, or are far from each other in the different countries, a *Gang-Formazion* or in brief a *Formazion* (1791, pp. 5–6). And he added: “the identity or equivalence of *Gang-Formazionen* ... is recognised and confirmed by comparison of ore types in veins; thus the veins that contain the same types of ore and particularly these composed of several ore types of the same age can be considered as belonging to the same *Formazion*” (1791, p. 54). At the same time, and right from the start, Werner distinguished the *Haupt-Formazionen* of ores and rocks (*sic*) from *Spezielle Gang-Formazionen*. The first term referred to the formations that originate over a long period of time by renewal, while the others are just parts of the *Haupt-Gang Formazionen* of some specific age.

The whole idea of *Gang-Formazionen* is still somewhat unclear, because there are only a few notes that clarify what Werner meant under the term ‘formation’. Thus right from the beginning we find: veins of the same origin (p. 5), of the same composition (p. 32), and of the same age (p. 32), for veins filling former fractures.

Thus the term ‘formation’ was introduced into geological literature for a notion that had already been known in Germany as: *Schichten*, *seriae montana* and *eine Gebirge*. It seems that this also applied to the terms *Bergart* and *Gebirgsart.* This is not specifically mentioned anywhere, but the two words were almost completely abandoned after the use of the term ‘formation’ began. (But Werner used them again in one of his last texts 1817/1818.)

The next step in introducing the term ‘formation’ was made by Werner in his manuscript ‘Plan of study for geognosy from 11 March 1794’, held at the archives of Freiberg University. In chapters on different types of *Gebirge*, there are two conspicuous units that refer to *Gebirgsformazionen* and *Metallformazionen* in the Chapter 13 on the distribution of mineral ore deposits (=*Fossilien*) (from SCHMIDT 1999, p. 156). It means that the term ‘formation’ was still not completely distinguished from *Gebirge* in 1794. This happened, however, during the next few years because, after 1800, Werner’s students published books and articles with quotations of his precise definitions and comprehensive knowledge of formations.

Werner’s ideas about formations after 1784 can only be traced in the preserved concepts of his lectures and in the published students’ notes (GUNTAU 1984, p. 69). He gave his lectures at the Academy according to his current beliefs so that with his constant effort to express himself as precisely as possible there were continuous changes in and development of his lectures. Werner was aware that his terminology was unstable at that time, so he did not publish anything about geognosy at that time, because he knew that anything he wrote would become obsolete. Just in case, however, he systematically corrected his students’ notes, thereby actually authorising the reproduction of his lectures in accordance with his contemporary views. He expected that his students would publish their notes after graduation—and he was right. Many did publish the acquired knowledge in their papers and books, though always referring to their professor. When using these texts, however, it is necessary to keep in mind that the authors might have changed the original notes to a greater or lesser extent, so that they do not always fully correspond to the Werner’s ideas. That is why one should rely on the authors who specifically stated that they tried to be faithful to what Werner had said in his lectures.

Sudden improvements of knowledge or ideas about formations were not completely accidental. Werner quickly realised the advantages of the term *Formazion* over older terms that were burdened by traditional and deep-rooted mining notions. Earlier and previously imprecise or ambiguous meanings of the new term could have been modified according to the new geognostic needs of the time. Besides, preparations for the systematic geological mapping of Saxony began in 1791. For that reason, Werner had to prepare a special instruction manual for fieldwork, which was the main agenda for his students and the other numerous participants in this project between 1798 and 1811. This could not have been carried out without a thorough knowledge of the Fuchsel's work. At that time, Werner's was the only instruction manual that contained extensive practical information for the extensive cartographic work. Through that important preparatory work for geological mapping, methodical studying of Fuchsel's results, and the practical experiences of the first geological mappers, Werner came to realise the vital importance of the term 'formation' for *Geognosia.* Therefore, he decided to replace the term *Gebirgsart* by *Formazion.* He tried to define it as precisely as possible and, finally, to develop a theoretical base for its application.

While discussing the terms *Formazion* and *Gebirge*, Werner wrote that they "relate[d] to each other as a genus to an individual. A *Gebirge* [wa]s a local occurrence of a large rock mass with great horizontal and vertical extent, with uniform characteristics of composition and stratification. All the existing *Gebirgen* with identical characteristics ma[d]e up a *Formazion*" (from GUNTAU 1984, p. 80).

Werner used also the term *Gebirgsformazion* in that phase of his work. According to OSPOVAT (1999, p. 15), he regarded it as: "a determinate assemblage of similar or dissimilar rock masses, which are characterised by external and internal relations as an independent whole, that is, as a unit in a series of rock formations ... and which are recognisable by the characters which each period and mode of formation has impressed upon it". An identical definition was given by ROBERT JAMESON (1808, p. 59) from one of Werner's lectures in 1801, and by FRIEDRICH MOHS in 1842 (PUSCH 1826, p. 524). A similar, but somewhat shorter, definition was published by J. F. AUBUISSON DE VOISINS (1828, p. 268), from a lecture of 1805. Therefore, it is undoubtedly Werner's definition.

According to the published notes of JAMESON (1808, 1813), AUBUISSON DE VOISINS (1828) and others, Werner had a well-developed theory of geological formations after 1800. The theory contained the following general synthesised concepts and solutions.

Werner determined the precise position of a formation in the sequence of the objects that constitute the subject of geognosy: minerals, rocks, layers, formations, and the Earth's crust. At the same time, he distinguished four levels of 'geognostic structures': the structure of rocks (*Gebirgsgestein*); of masses or mineral layers (*Gebirgsmasse*); of formations (*Gebirge*); and of the Earth itself (*Structur der Erde*) (AUBUISSON DE VOISINS 1828, pp. 267–269). But Werner's explanation became completely forgotten and was only discovered again in the sixties of the twentieth century, during the developing of the modern concept of the "geological levels of the organisation of matter" (DRAGUNOV 1965, p. 64; KRUT 1968).

The internal structure of formations could be either simple or compound. A formation is simple when it is comprised of identical material, while a compound formation is made up of different *Lagern*, *couches*, or *rock-masses.* According to their participation in a formation, these could be: principal, subordinate, common (*habituelles*) or accidental (*accidentelles*) (JAMESON 1808, pp. 59–60; AUBUISSON DE VOISINS 1828, pp. 317–318).

Werner thought that formations could occur not only in sedimentary, but also in crystalline rocks (JAMESON 1812, p. 60; PUSCH 1826, p. 514). This was an important point: there are still disagreements among geologists regarding this issue.

But Werner used the term *Formazion* ambiguously. He knew that the notion of 'formation', as with terms for all other natural bodies (mineral, rock, layers, Earth, *etc*.), involved several different aspects. There were three main aspects of each such natural body: its material composition, as well as the manner and time of its origin. Werner had this in mind from the start (PUSCH 1826, pp. 512–513). But owing to the incomplete knowledge of, misunderstandings of, and unilateral interpretations of Werner's ideas, this important fact has become a source of much discussion and division among researchers and commentators.

Relying on his Neptunist doctrine of the Earth's history, Werner thought that all formations originated by deposition from water. Changes in the water's properties over time resulted in changes in the conditions of deposition, and hence in the conditions for the origin of formations. Formations, therefore, differed in the nature, texture, and generality and also the nature of their petrifactions. Crystalline formations are the oldest. Sedimentary formations are in the middle. The youngest are of mechanical origin. (For this paragraph, see: AUBUISSON DE VOISINS (1828, pp. 326, 352, 357).)

According to their material composition, Werner divided formations into: schistose, calcareous, traps, porphyritic, gypseous, coaly, talky, topaz-bearing and schorl. All these formations were classified into four *Hauptgruppen* or *Formazionszeit-raum* (time-space) groups that occur naturally in the form of: *Urgebirge*, *Uebergangsgebirge*, *Floetzgebirge*, *Aufgeschwemte Gebirge* and *Vulkanische Gebirge* (STEFFENS [1801], according to REUSS (1805 pp. 169–184 and *Tabelle* by KARSTEN, p. 185).

Two main categories of formations were distinguished: *universal* or general, which occur on the whole Earth or over its large parts of it; and partial, anomalous or local, which are of limited extent (JAMESON 1812, p. 63; AUBUISSON DE VOISINS 1828, pp. 320–322).

Werner emphasised that formations and their parts contain different fossils. He wrote that: "It is important that different layers in *Floetzkalkgebirgen* contain different petrifactions (GUNTAU 1984, p. 89). In his last published work, WERNER (1817/1818, p. 10) emphasized that even different petrifactions form certain *Gebirgsschichten*, which enable us to recognize "a certain order in geological deposits".

Werner noticed that similar *Gestein-Massen* occurred quite often at different times. Each individual occurrence was a particular formation and the whole was named a *Formazions-Suite* (MOHS 1805, from PUSCH 1826, p. 524). There were said to be two types of *Suiten*: continuous and discontinuous. The first were characterized by the fact that "deposits from different epochs ... change into each other gradually; thus there are no clear boundaries between them". The others occur in the form of separate and independent bodies. Two distinctive examples were: the 'schist suite' and 'limestone suite' (AUBUISSON DE VOISINS 1828, pp. 380–383).

Finally, the following formations were distinguished in the Earth's crust according to the frequency of occurrence: *Hauppt-Formazionen* (principal), *Formazion Suiten*—or independent formations and subordinate formations (JAMESON 1808, pp. 60–61; MOHS 1805, from PUSCH 1826, p. 525).

That is how Werner slowly and gradually developed, improved and established a comprehensive knowledge and explanation of geological formations, devoting himself to the tasks of improvement and clarification. One must acknowledge that this work was done most successfully—even masterfully. It is completely understandable, and justifiable, that professor Werner enjoyed a great reputation in his day.

After Werner

At the age of fifty, Werner was still active when his former students started to publish notes from his lectures. In addition, according to KEFERSTEIN (1840, p. 68):

> The notebooks in which Werner's students were keeping notes at his lectures on geognosy have reached many hands; these notebooks were quickly published, either original, abridged or extended, thus numerous textbooks and manuals appeared and Werner's doctrine has become more popular in years.

The notes were also published by geologists who did not attending Werner's lectures directly. And such books became the only published sources of information on *Gebirgs-Formazionen.*

However, the authors of these books soon began to differ in their ideas about formations. This happened in part because Werner himself kept changing and supplementing his lectures and partly because the authors developed different views according to their own ideas and practical experience. Thus some deviations from Werner's ideas developed, though they were often insignificant. For example, when Werner was still using the term *Gebirgsarten* it was used in the same way by HUMBOLDT (1792) and BOEHMER (1794). But they were also using the term *Formazion* for all rocks of the same petrographic composition (FRANKE 1962, p. 209).

HEIM (1798) was one of the first to draw attention to the ambiguity of Werner's term 'formation'. Heim believed that the word should *not* be understood to imply time of origin or relative age. And there were others who had similar ideas about how the expression *Gebirgs-formazion* should be construed–such as MOHS (1805), REUSS (1805), STEFFENS (1810), REICHETZER (1812), and others. On the other hand, KEFERSTEIN (1821), and later HUMBOLDT (1823), AUBUISSON DE VOISINS (1828) and others, maintained that the term 'formation' should only refer to the time of a rock or stratum's origin (FRANKE 1962, pp. 209–210).

The most important and famous among the various critical reviews of Werner's ideas was that systematically written by GEORG GOTTLIEB PUSCH (1826), who was a student of WERNER in 1806. Pusch correctly noted that Werner's term *Formazion* meant at the same time rock type, manner of origin, and time of formation (pp. 512–513). In addition, Pusch critically analysed papers written by various authors with different views as to the meaning of this term (Steffens, Mohs, Humbolt, Heim, Breislack, Raumer). Finally, he concluded (pp. 519 and 580) that the term *Formazion* could simply imply time of origination, *i.e.* age. Pusch gave reasons for his conclusion and asserted that this "correct idea" was advocated by the majority of French and German geologists at that time.

Therefore, owing to the fact that geologists, even those who were Werner's students, did not understand that the term *Formazion*, as used by Werner himself, was *intentionally* ambiguous. So the term deviated from its original meaning during the course of the nineteenth century and it was used more and more in chronostratigraphy as a synonym for 'system'.

However, it is important to note that, in his *Manuel of Elementary Geology* LYELL (1855, p. 3) advocated the Wernerian notion of 'formations' as: "any assemblage of rocks which have some character in common, whether of origin, age, or composition. Thus we speak of stratified and unstratified, freshwater and marine, aqueous and volcanic, ancient and modern, metalliferous and non-metalliferous formations". This statement was repeated in Lyell's *Student's Elements of Geology* (1874). But despite his authority, Lyell was not followed on this point. For example, this part of Lyell's text was omitted by John Judd's account of Lyell's thinking in *The Student's Lyell* (1896).

After significant disagreements and discussions among the different conflicting geological schools, the original meaning of this fundamental term was only revived in the second half of the twentieth century, based on the concepts of the "elementarity of natural objects" and "levels of organisation of matter" (DRAGUNOV 1965 p. 64).

Conclusions

1. The notion of (geological) 'formation' developed from an old German mining term *ein Gebirge* (AGRICOLA 1556), through *Schichten* and *Bergart* (LEHMAN 1756), *serie montana* (FUCHSEL 1761), and *Gebirgsart* (WERNER 1787).

2. The term 'formation' was introduced into geological literature by WERNER in 1791 to refer to a particular concept.

3. Werner defined a 'formation' as "a determinate assemblage of similar or dissimilar rock masses, which are characterised by external and internal relations as an independent whole, that is, as a unit in a series of rock formations ... which are recognisable by the characters which each period and mode of formation has impressed upon it" (OSPOVAT 1999, p. 15). He distinguished formations according to their composition, extent, and frequency of occurrence.

4. Werner considered the term 'formation' to refer to a body in the sequence of natural 'geognostic structures': mineral–rock (layer)–formation–Earth's crust. Therefore, the term 'formation' in reference to a natural body could have, and *should* have, been ambiguous from the beginning. It embraced: petrographic composition, mode, and time of origin.

5. Werner's students and followers mostly did not understand the *intentional* ambiguity of the term 'formation'. They thought that there had been a serious mistake, criticised it, and took different positions in relation to the issue.

6. The interpretation that 'formation' could have only one—what we would today call chronostratigraphic—meaning prevailed during the nineteenth century. The term 'formation' thus became in effect a synonym for 'system'. It was widely used in this way until the II International Geological Congress in Bologna in 1881. But despite the 'prohibition' on this use of the term 'formation', it continued to be used instead of 'system' in certain geological schools well into the twentieth century.

7. It is interesting that LYELL (1885, 1874) supported Werner's idea, even when almost everyone else abandoned it.

8. In the second half of the twentieth century, after all these vicissitudes, the term 'formation' regained its original Wernerian sense with the original ambiguity and status of an elementary unit in geological levels of organisation of matter: mineral–rock–formation–geosphere–planet (DRAGUNOV, 1965). Each preceding unit in this sequence is elementary relative to the following one of higher level in this organisation. The term 'formation' is nowadays the main subject of research in 'Formational Geology'.

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References

AGRICOLA, G. 1521. *Bergwerck Buch darinnen nicht allein alle Empter, Instrument, Gezeug, und alles, so zu disem Handel gehörig, mit Figuren vorgebildet und klärlich beschrieben: Sondern auch wie ein rechtverständiger Bergmann seyn soll und die Gäng ausszurichten seyen ...* Basel: Verlag Ludwig Koenigs.

AUBUISSON DE VOISINS, J.F. 1828. Traité de géognosie, 2nd edn, Vol. 1, Paris.

DRAGUNOV, V.I. 1965. Geology and the study of elements, structure and levels of organisation of matter. *Extended Abstracts of the Meeting on General Principles of Geological Phenomena*. Leningrad: A. P. Karpinsky Russian Geological Research Institute (VSEGEI), 55–67 (in Russian).

DRAGUNOV, V.I. 1968. Fundamental meaning of geological formations. *Extended Abstracts of the Meeting on Geological Formations.* Leningrad: A. P. Karpinsky Russian Geological Research Institute (VSEGEI), 21–27 (in Russian).

FRANKE, D. 1962. Zu Frage geologischer Terminologie und Klassifikation (I). Der Begriff Formation. *Zeitschrift fuer angewendte Geologie*, 4: 208–214.

FUCHSEL, G.C. 1761. Historia terrae et maris ex historia Thuringiae, per montium descriptionem. *Actorum Academiae Electoralis Moguntinae scientarium utilum, Erfurt*, 2: 44–208.

GRUBIĆ, A. 1985. Formational geology. *Comptes rendus, Société Serbe de Géologie* (for 1984), 151–158.

GUNTAU, M. 1984. Abraham Gottlob Werner. *Biographien hervorragender Naturwissenchaftler, Techniker und Mediziner*, 75: 1–112.

HEDBERG, H.D. (ed.). 1972. Introduction to an *International Guide to Stratigraphic Classification, Terminology and Usage*. *Leithea*, 5: 283–295.

JAMESON, R. 1808. *Elements of Geognosy: System of Mineralogy*. Vol. 3. Edinburgh: William Blackwood.

JAMESON, R. 1813. On Formations. *Thomson Ann. Philosophy*, Vol. 1 (for 1812), 191–206.
JUDD, J.W. 1890. *The Student's Lyell: A Manual of Elementary Geology*. London: John Murray.
KEFERSTEIN, C. 1840. *Geschichte der Geognosie*: Halle: Johan Friedrich Lippert.
KRUT, I.V. 1968. The position of geological formations in geological space. *Enlarged Abstracts to the Meeting on Geological Formations.* Leningrad: A. P. Karpinsky Russian Geological Research Institute (VSEGEI), pp. 36–38 (in Russian).
LEHMANN, J.G. 1756. *Versuch einer Geschichte von Floetz-Gebuergen*. Berlin: Kluetrischen Buchhandlung.
LYELL, C. 1855. *A Manual of Elementary Geology: Or, The Ancient Changes of the Earth and its Inhabitants as Illustrated by Geological Monuments*. London: John Murray. Fifth edition.
LYELL, C. 1874. *The Student's Elements of Geology*. London: John Murray. Second edition revised and corrected.
OSPOVAT, A.M. 1999. *German Text, with English Translation and Introduction of A. G. Werner: General Observations about the Earth, 1817/18*: International Commission on the History of Geological Sciences, printed at The University of New South Wales.
PUSCH, G.G. 1826. Ueber den Begriff Gebirges-Formation und den bisher so schwankenden Gebrauch dieses Ausdrucks in der Geognosie: *Zeitschrift fuer Mineralogie*, Frankfurt am Main, 1826, 1: 511–529, 2: 68–80.
REUSS, F.A. 1805. *Lehrbuch der Geognosie: Lehrbuch der Mineralogie*, Vol. 2, and O. B. Karsten: *Tabellen zu Seite* 185. Leipzig: Verlag F. G. Jacobaer.
SCHMIDT, P. 1997–1998. Abraham Gottlob Werners Vorlesungen „Oriktognosie" und „Geognosie" 1775–1795, und sein dazugehoerige handschriftlicher Plan von 1794. *Nachrichtenblatt zur Geschichte der Geowissenschaften*, 7–8: 147–161.
WERNER, A.G. 1787. *Kurze Klassifikation und Beschreibung der verschiedenen Gebirgsarten*. Dresden: Walterische Hofbuchhandlung.
WERNER, A.G. 1791. *Neue Theorie von der Entsthehung der Gaenge mit Anwendung auf den Bergbau*. Freiberg: Gerlachischen Buchdrukerei.
WERNER, A.G. 1817/18. *Allgemeine Betrachtungen ueber den fersen Erdkoerper* edited by A. M. Ospovat, 1999. International Commission on the History of Geological Sciences, printed at The University of New South Wales.
ZITTEL, K.A. 1899. *Geschichte der Geologie und Palaeontologie bis Ende des 19. Jahrhunderts*. Munich and Leipzig: Verlag R. Oldenburg.

Glossary

Aufgeschwemmten Gebirge – loose detrital rocks; the fourth unit of Neptunist general stratigraphy.
Bergart – synonym of *Gebirgsart* and *ein Gebirge*; (= formation).
Blaue Kohlen-Gebirge – blue (mountain ranges) beds with coal; the twenty-fourth unit in Lehman's cross section of the layered mountain range of Thuringia.
Ein Gebirge – one part of (mountain ranges) rocks (= formation).
Festige Gebirge – solid (mountain ranges) rocks.
Floetz – layer of, or with, non-metallic mineral content.
Floetz Gebirge – bedded (mountain ranges) rocks with non-metallic content; the third unit of Neptunist general stratigraphy; the bedded mountain range of Thuringia
Formazion Suiten – continual and discontinual recurrences of formations in vertical succession.
Formazionszeit–raum – the unity of space and time during the creation of a formation.
Gang – Fomazion – (ore) veins of similar composition, origin and age, from one or different areas.
Gattungen Gebirgsarten – (mountain ranges) rocks classified in genera according to the prevailing rocks (for example, the genus or real volcanic and genus of pseudo-volcanic mountain ranges rocks).
Gebirge – before 1798: mountains; mountain ranges; a general name for all underground rocks; the whole solid crust of the Earth. After 1798: the local development of a larger formation.
Gebirgsart – sufficiently large and clearly distinctive (mountain ranges or rock bodies; (= formation).
Gebirgsformazion – synonym of 'formation'.
Gebirgslehre – knowledge of the Earth: rocks, different bodies, mineral deposits, dynamics and history; (= geognosy).
Gebirgsgeschichten – mountain ranges strata.
Gebirgsgestein – rock made up simple *Gebirgsart*.
Gebirgsmasse – general term for any (mountain ranges) rock mass.
Gestein – rock.
Gesteinsart – rock species.
Gesteinsschichten – rock beds, strata.
Hauptarten – synonym of *Hauptabteilungen Gebirgsarten*.
Hauptabteilungen Gebirgsarten – name of the units of general Neptunist stratigraphy.
Haupt Gang Formazionen – vein formations that are long term repeating in succession.
Hauptgruppen – synonym of *Hauptabteilungen Gebirgsarten*.
Hauptgebirgsarten – universal or principal (mountain ranges) rocks wide spread in the world.
Hauptformazionen – synonym of *Hauptgebirgsarten*.
Lage(r) – layer.
Leberfarbene Gebirge – liver-coloured (mountain ranges) beds; twenty-fourth unit in Lehman' s cross-section of the bedded mountain range of Thuringia.
Lehre von Gebirgen – synonym of *Gebirgslehre*.
Metallformazionen – metalliferous formations.
Oberste Kalckgebirge – upper limestone (mountain ranges) beds; youngest *serie* in Fuchsel's stratigraphy of Thuringia (= *Muschelkalk*).
Rothe Schalgebirge – red laminated (mountain ranges) beds; sixth *serie* in Fuchsel's stratigraphy of Thuringia.

Rothe Tode Lager – literally ‘red dead layer’; thirtieth unit in Lehmann’s cross-section of the Bedded mountain range of Thuringia.

Sandfloetz – sand layer; interlayer under fourth *serie* in Fuchel’ s stratigraphy of Thuringia.

Schichten – beds, strata.

Spezielle Gang-Formazionen – special vein formations; veins in universal formations.

Stand – position (for example, some mountains in relation to others).

Uebergangsgebirge – Transition (mountain ranges) rocks; the second unit of Neptunist general stratigraphy.

Urgebirge – primitive (mountain ranges) rocks; the first unit of Neptunist general stratigraphy.

Uranfaengliche Gebirge – synonym of *Urgebirge*.

Untergeordnete Bergarten – subordinate (mountain ranges) rocks (= formations).

Unterlager – interlayer between two *serie montana* (= formations).

Wechsel – change.

Резиме

Оригинално значење појма и термина „формација“ у геологији

Појам (геолошка) формација постепено је уобличаван под разним претежно немачким називима: од „ein Gebirge“ из вишевековне праксе саксонских рудара (Agricola, 1521, стр. 167), преко „Schichten“ и „Bergart“ (Lehman, 1756, стр. 162 и 168) до „Gebirgsart“ (Werner, стр. 5). Термин „формација“ (Formazion) увео је Werner 1791. (стр. 5–6).

Werner је око 1800. године појам и термин „формација“ дефинисао као „одређену заједницу сличних или различитих стенских маса које се карактеришу као једна независна целина по својим спољашњим и унутрашњим односима, т.ј. као јединица у низу стенских творевина,...препознаје се по особинама, које су сваки период и начин формирања оставили као траг у њој“ (по Ospovat-у, 1999, стр. 15). При томе, аутор је разликовао формације по њиховом материјалном саставу, распрострањењу и суперпозицији.

Веома значајно је што је Werner појам „формација“ увео у свој систем „геогностичких структура“ у низу: минерал – стена (слој) – формација – земљина кора (по Aubuisson de Voisins-у, 1828, стр. 267–269). Због тога је термин „формација“ добио вишезначан смисао. Подразумевао је у исто време геолошко тело одређеног састава, постанка и суперпозиционог положаја (односно времена када је настало).

Werner-ови ђаци и следбеници већином нису разумели зашто је он формацији одредио вишезначност. Мислили су да је то озбиљна грешка, критиковали су то и заузимали различите ставове у погледу коришћења тог термина.

Занимљиво је да је Lyel (1855, стр. 3, 1874), доста усамљено заступао оригинално Werner-ово схватање формације, чак и онда када су га готово сви напустили и заборавили.

Током XIX столећа преовладао је став да формација може да има само једно, и то – хроностратиграфско значење. Тако је овај термин сведен на синоним за „систем“. На тај начин слободно и широко је био у употреби до II Међународног геолошког конгреса у Болоњи 1881. године, када је то изричито забрањено. Упркос забрани, међутим, погрешна употреба термина формација настављена је у неким школама и у XX веку.

Између 1930. и 1980. године, посебно после 1945., појам и термин „формација“ и њихово практично коришћење били су предмет повећаних расправа између различитих геолошких школа. (Највише их је било у СССР-у.) У дефинисању и издвајању формација коришћени су литостратиграфски, парагенетски, разни генетски и комплексни принципи. То је довело до успостављања различите праксе формационе анализе. На основу целокупшног тог искуства Драгунов (1965) је дефинисао формацију као „елементарно природно тело које заузима ниво између стене и геосфере у хијерархији организације материје“. Тако је овај аутор дошао до истог фундаменталног става који открио и промовисао Werner.

Формација, као назив за елементарно природно тело, као и термини за сва друга таква тела, мора и може да буде само вишезначна јер је то иманента особина сих тих назива. Због тога се формација другојачије дефинише и издваја, и примењује на специфичан начин у разним геолошким дисциплинама; баш исто као што је то случај са минералом, стеном геосфером и планетом. Формација није термин слободне употребе, да би се користио без икаквог правила, већ је то термин „вишезначан“. То значи, када се наведе, онда тачно мора да се зна како и зашто је тако употребљен (н.пр. у стратиграфији, геолошком картирању, металогенији, хидрогеологији итд.)

После свих авантура, у другој половини XX века враћен је „формацији“ њен изворни вернеријански смисао: „вишезначност“ термина и појам „елементарне јединице у геолошким нивоима организације материје: минерал – стена – формација – геосфера – планета. У овом низу свака претходна јединица је елементарна према следећој, која припада вишем нивоу поменуте организације. Укратко – „формација“ је данас основни објекат проучавања „Формационе геологије“, односно скупа геолошких дисциплина у којима се она испитује и користи.

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Quaternary tectonic and depositional evolution of eastern Srem (northwest Serbia)

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Abstract: The area of eastern Srem is situated in the southern periphery of the Pannonian basin. Its depositional evolution during the Neogene and the Quaternary has been controlled by tectonic processes. Miocene extensional subsidence was followed by the Pliocene-Quaternary inversion of the basin. The latter was accomplished as the result of replacement of the tensile by the compressive stress field. Since the Late Neogene, the regional tectonic activity has been controlled by compressive stress produced by the north-northeastern propagation of the Adria microplate. In the compressive NE–SW-oriented stress field, the recent structural plan of the Pannonian basin and its wider environment, including its southern periphery, was reactivated. The youngest tectonic deformations are characterized by positive and negative vertical motions of large intrabasinal segments and basinal periphery, resulting in the final inversion of the basin. The effects of the basinal inversion can be recognized in genetic features of Quaternary sediments and geomorphological characteristics of the relief. Sources of data used for the interpretation of the Quaternary tectonic activity in the area of eastern Srem are of geological, geomorphological, thermochronological, and geophysical character. The positions of prominent fault structures have been ascertained by remote sensing, interpretations of available geophysical cross-sections, and using the field data.

Key words: tectonic activity, Pannonian basin, northwest Serbia, subsidence, basin inversion, eastern Srem, Quaternary.

Апстракт: Подручје источног Срема налази се у јужном ободном делу Панонског басена. Његова депозициона еволуција током неогена и квартара била је контролисана тектонским процесима. Миоценску екстензиону субсиденцију, прати плиоценско-квартарна инверзија басена. Инверзија басена је изведена као последица смене тензионог напонског поља са компресионим. Касно-неогена и рецентна тектонска мобилност контролисана је компресионим стресом, генерисаним север-североисточном пропагацијом адријске микроплоче. Рецентни структурни план читавог Панонског басена и његовог ширег окружења, укључујући и јужни обод, реактивиран је у домену компресионог напонског поља, оријентисаном по правцу североисток–југозапад. Најмлађе тектонске деформације карактерише позитивна и негативна вертикална мобилност значајних унутарбасенских сегмената као и периферије басена, што је резултирало финалном инверзијом басена. Ефекти басенске инверзије препознају се у генетским карактеристикама квартарних седимената, као и у геоморфолошким карактеристикама рељефа. Извори података који су коришћени за интерпретацију квартарне тектонске активности у подручју источног Срема су геолошког, геоморфолошког, термохронолошког и геофизичког карактера. Позиције значајнијих раседних структура утврђене су даљинском детекцијом, интерпретацијом расположивих геофизичких профила и на основу теренских података.

Кључне речи: тектонска мобилност, Панонски басен, северозападна Србија, субсиденција, басенска инверзија, источни Срем, квартар.

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Introduction

In the area of eastern Srem during Quaternary period tectonic activity has been manifested as a significant control factor of deposition and final shaping of modern relief (MAROVIĆ *et al.* 2007). However, tectonic evolution of the Pannonian basin has started much earlier, hence all tectonic structures that have been active in Quaternary, are actually a part of previously existing structural pattern and they belong to the category of inherited structures. Furthermore, sedimentation as a dominant process of final phases of filling of an inverted depositional basin, took place in previously tectonically defined domains (MAROVIĆ *et al.* 2002, and other references therein).

During the younger stages of Pliocene and earlier part of Quaternary, after the retreat of Paratethys, the area of the southern rim of the Pannonian basin in whole passed through the terrestrial phase of development (NENADIĆ *et al*. 2010, 2011). In that interval tectonic shaping of low intensity has been carried out, by which regional morphostructural forms were finally shaped. Also, tectonically controlled mobility within basinal segments caused the absence of some stratigraphical substages of Pliocene, and change of facies and thickness of the youngest lithostratigraphical units (MAROVIĆ *et al.* 1996, 1998; RAKIĆ *et al*. 2005).

In the southern parts of the Pannonian basin, Pliocene-Quaternary tectonic activity was manifested in gradual, continuous descending of extensional areas in Posavina toward the interior parts of the Pannonian basin and in uplift of the area of the Fruška Gora massif, Belgrade promontory and some parts of Šumadija (MAROVIĆ *et al.* 2007). This vertical mobility brought significant changes in relief and initiated the development of exogenic denudation-accumulation processes.

The postbasinal structural complex, formed in a post-Neogene phase, is represented by a relatively thick sequence of sediments within which two parts, differing in superposition and origin, can be distinguished (NENADIĆ *et al*. 2003, 2009).

– *older*, fluvial and fluvio-lacustrine, with relics of basinal frame, generated by movements on the boundary between Pliocene and Quaternary, which were manifested in a poly-phase lowering of the former basin bed and formation of complex alluvial plains of the pre-Danube and pre-Sava.

– *younger*, which corresponds to the fluvio-denudation system s.s., and which comprises morphological structures made in the Late Pleistocene and Holocene.

Geological settings

The Pannonian basin is an intracontinental entity situated between the Dinarides, the Alps, and the Carpathians. It is filled with Neogene and Quaternary deposits. The basement of the basin is formed by the tectonic units of both Adriatic and European continental affinity: the Dinarides (as a part of Adria), Tisza and Dacia (as parts of Europe), and also tectono-stratigraphic contents that belong to the Sava zone (as a suture between Adria and Europe, SCHMID *et al*. 2008). The territory of Serbia includes the southernmost parts of the Pannonian subsidence area represented by basinal and peribasinal structures, and deeply penetrated towards the south between Dinaric and Carpatho-Balkan morphostructures (MAROVIĆ *et al.* 2007). Neotectonic movements formed some interesting structural, depositional, and morphological features that are different from those in the other parts of the Pannonian basin.

In the recent literature, there are interpretations that the southern boundary of the Pannonian basin in Serbia is formed by the rivers Danube and Sava, while the areas south of them, made of Neogene deposits of similar or same composition as those in the Pannonian basin, belong to the peri-Pannonian area. Although this boundary has a certain geographical and geomorphological sense, from the geological point of view it is difficult to place it here, since the basin boundary is situated further south of the Sava and Danube. Locally, the investigated area belongs to eastern Srem, limited by the Danube and Sava from the north, east and south, and by the line Sremska Mitrovica–Neštin from the west (Fig. 1A).

Identification of structures in the investigated part of the area, as well as monitoring of their activity during the youngest tectonic phase, was carried out on the basis of palaeogeographical, structural, thermochronological, and geophysical, characteristics of this area. When reconstructing the tectonic evolution, beside the remote sensing analysis, the data from the exploration wells and field data have been used as well as reinterpretation of available seismic sections.

Material and methods

The positions of prominent fault structures in the investigated area have been ascertained by remote sensing, interpretations of available geophysical cross-sections, and using the field data. The field data were obtained by the analysis of numerous borehole cores situated in the investigated area. The mineralogical and petrological composition of these samples has been preliminary analyzed. Remains of molluscs and ostracodes have been picked out under a binocular microscope and determined to the level of species when it was possible, using the qualitative methods. When no fossils were available, the age of deposits has been estimated by the so-called superposition principle.

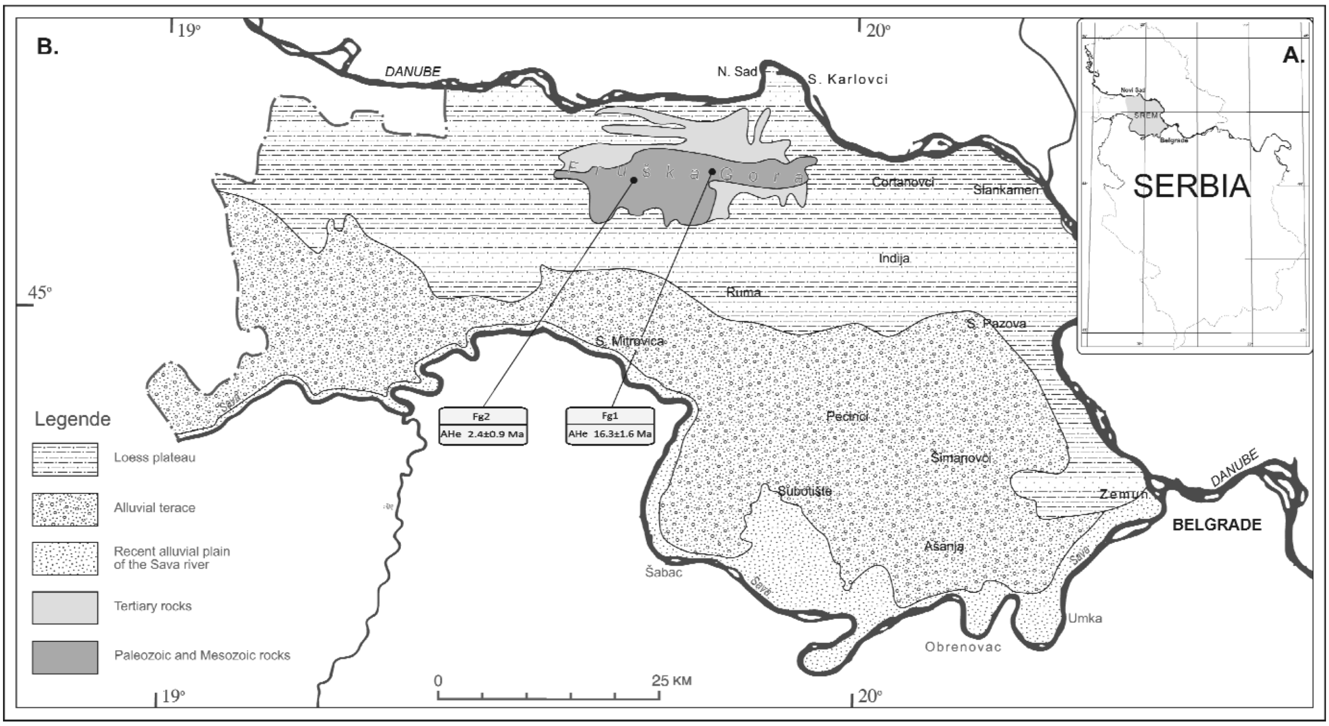

Fig. 1. **A,** Geographic position; **B,** Simplified geological map of the study area with localities where samples for new (U-Th)/He apatite thermochronology ages (AHe) werecollected.

Results and discussion

Quaternary tectonic mobility

Quaternary tectonic activity of the southern parts of the Pannonian basin has been perceived in context of the regional Miocene extensional evolution of the entire basinal area and its Pliocene-Quaternary inversion (e.g. HORVATH *et al.* 2006; MAROVIĆ *et al.* 2002; MAROVIĆ *et al.* 2007; MATENCO & RADIVOJEVIĆ 2012 and other references therein). Miocene extension, produced by rollback of European lithosphere in the Carpathians, was accompanied by rifting, thinning of the lithosphere and subsidence in the domain of the Pannonian basin. A long-term Middle and Late Miocene post-rift subsidence, controlled by thermal sag cooling (HORWATH & CLOETINGH 1996; CLOETINGH *et al.* 2006), was followed by the Pliocene–Quaternary basin inversion, performed in compressive stress field. The extensive stress field was replaced by compression, which was activated as a result of the final break off of the subducted European lithosphere in the domain of the Carpathians, on one side, and the north-northeastern progression of the Adria plate, on the other side (BADA *et al.* 2007). During Pliocene and Quaternary, both the Dinaric-Carpathian orogen and intracontinental Pannonian basin were exposed to constant compression, generally oriented towards NE–SW in this region (BADA *et al.* 2007). Under these conditions the lithologically heterogeneous lithosphere in the basement of the Pannonian basin, wrinkled in kilometer-scale folds, was thinned (CLOETINGH *et al.* 2006). The regional folding of lithosphere was accompanied by vertical mobility of segments of the lithosphere, of different direction and intensity, which finally resulted in a relatively rapid uplift and denudation of the peripheral parts of the basin and further subsidence and deposition of the central domains of the basin. At the same time the existing tectonic pattern was reactivated by local redistribution of compressive stress. This pattern was responsible for the control of tectonic mobility within basinal entities, such is the area south of Fruška Gora (TOLJIĆ *et al.* 2013). Regionally, in the Pannonian area, to the north of the Danube and Sava slow subsidence has been continuing throughout Quaternary, but with smaller velocity than in Neogene and with a constant tendency of weakening until recent time. In contrast to this sinking, peripheral part of the Pannonian basin and intrabasinally situated morphostructure of Fruška Gora have been raised.

Quaternary tectonic activity can be identified by studying the origin and thickness of sediments. Of particular significance here are pre-loess fluvial polycyclic deposits in the southern and deluvial-proluvial sediments in the northern part of the area. Geomorphological data, such as hypsometric relationship, position of fluvial terraces, process of erosion, etc., also point to tectonic changes. Also, information on geodetic measurement and seismic activity are of special interest. Furthermore, thermochronology can yield information on the exact timing of the tectonic activity.

Basic geophysical characteristics of the investigated area

Seismicity represents one of the most relevant factors in detecting recent fault activity in the Pannonian and peri-Pannonian region (MAROVIĆ *et al.* 2002). On the basis of existing data it can be concluded that the Serbian part of the Pannonian basin shows very low seismicity, with exception of the Fruška Gora massif and the area of eastern Banat. Particularly, these areas are characterized by quakes of magnitudes which do not exceed M=4.5, except the area of Fruška Gora (M=4.5–5) and a part of eastern Banat. In the Serbian part of the Pannonian basin the most seismically active faults are of direction NW–SE, representing structures across which there have been transcurrent left movements, with a pronounced reverse component (MAROVIĆ *et al.* 2002). Southern periphery of the Pannonian basin belongs to a seismic active region in Serbia, with maximum magnitude M=5,5–6. Southern periphery of the Pannonian basin and its immediate hinterland are characterized by seismically active, transcurrent right faults of direction NE–SW (ENE–WSW). These two systems of conjugated faults are further active in the compressive stress field which has an axis of maximum compression oriented in general direction NE–SW.

Recent mobility of the Earth's crust in the area of the Pannonian basin has been confirmed by geodetic measurements (JOVANOVIĆ 1971, FGS 1972). The general model of vertical mobility of the Earth crust in the domain of the southern parts of the Pannonian basin suggests that the northern periphery of the investigated area (the area of Fruška Gora) has been raised by the rate up to +2 mm/year (MAROVIĆ *et al.* 2002; MAROVIĆ *et al.* 2007). The peripheral northeastern parts of the Dinarides show a similar trend. Recent subsidence (by the rate of approximately 1 mm/year) has been ascertained in the area of Srem (Map of recent vertical movements of the Earth's crust in the area of SFRJ, FGS 1972, MAROVIĆ *et al.* 2002, MAROVIĆ *et al.* 2007). The most recent geodetic study of the Earth's crust mobility in the southern parts of the Pannonian basin shows a low level of mobility in the area of Srem (SUŠIĆ 2013). Isolines map is (Fig. 2) showing rates of vertical tectonic movement in the area of Srem.

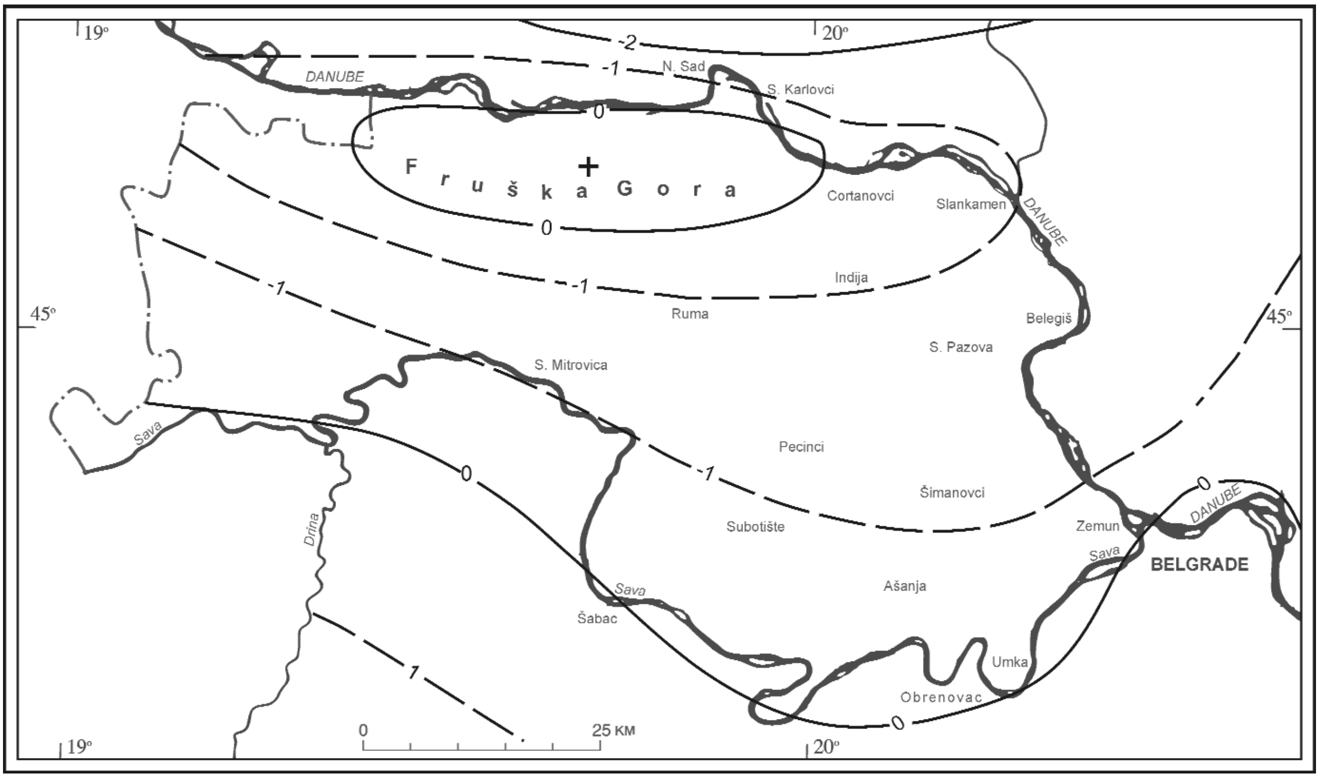

Fig. 2. Map of velocities of the recent tectonic movements in the area of Srem (modified after MAROVIĆ *et al,* 2002).

In the sections of seismic profiles in the area of Fruška Gora (MATENKO & RADIVOJEVIĆ 2012) in the south of the mountain an association of faults that form the Vrdnik fault could be recognized (TOLJIĆ *et al.* 2013). The southern block was primarily gravitationally downthrown across this structure, so the thickness of Pliocene-Quaternary sediments to the south of the fault exceeds 500 m. The synthesis of the data obtained by seismic profiling and deep exploration drilling in this area, also indicates the significant thickness of Pliocene-Quaternary sediments (MARTINOVIĆ *et al*. 2010). The greatest thickness is observed between Stara Pazova and Šabac, in the depression whose axis lies in the E–W (ENE–WSW) direction. While the Vrdnik fault is situated in the northern periphery of the depression, central parts of the area are controlled by an association of horsts and grabens defined by the faults across which the central part of the Sefkerin depression was downthrown (MATENCO & RADIVOJEVIĆ 2012). The southern periphery of the investigated area in seismic section shows a complicated tectonic nature of a transitional region between the Pannonian basin and its uplifted southern hinterland. The Kalemegdan fault (as association of faults) stands out as a dominant structure. It is a syndepositionally active fault(s), across which subsidence of the NW domain has continued to take place in Quaternary, as suggested by the significant thickness of the youngest sediments. This scenario is also indicated by a relatively small thickness of Pliocene-Quaternary sediments to the east of this fault. In a planar view, the association of faults which constitute the Kalemegdan fault consists of echeloned faults with the NE–SW direction that may be followed from Kalemegdan across Obrenovac and further to SW (Fig. 4).

Geomorphological analysis

Effects of Quaternary tectonic movements can be considered by studying morphogenetic characteristics of the area and sedimentological features of deposits. The former include forms of relief, dynamics and origin of river valleys, sharp de?ection of river valleys etc., while the later can be obtained by analysis of thickness of facies and types of sedimentation.

In the investigated area, three units can be clearly distinguished by the shape of relief: 1) hilly northern part, which belongs to the positive morphostructure of Fruška Gora showing constant uplift trend, 2) transitional part, which corresponds to the higher fluvial terraces of Pleistocene age, and 3) the lowland part of the Sava valley with lower terraces, which are undoubtedly situated in the area of significant, tectonically controlled, subsidence.

Fruška Gora represents a horst whose tectogenesis began as early as Early Miocene, but it was generally formed in Early Quaternary, and has been permanently modified until recent time (TOLJIĆ *et al.* 2013). Significant part of primary shaping of morphostructures in this massif took place in the Miocene, and it can be recognized in gravitational shear across the faults of the E–W direction. During Pliocene and the earlier parts of Quaternary some of these faults were reversely reactivated, by which an antiform and positive structural build of Fruška Gora was additionally highlighted. This was accompanied by a rapid erosion of the uplifted parts and an equally rapid accumulation in the neighbouring lowered domains. Consequently, recent morphostructural and morphosculptural appearance of this massive is a reflection of causality and interaction of numerous processes, of both endogenic and exogenic origin, so the recent geomorphological features represent the result of complex morphogenesis of this mountain.

In the Early Miocene, the metamorphic core of the mountain was primary exhumed from the ductile domain across the zone of decolman shear, situated at the boundary of metamorphic and underlying Mesozoic non-metamorphosed tectono-stratigraphical contents. Further extensional deformations in the brittle domain were performed in Middle and Late Miocene across the gravitational faults, which are now situated in the northern and southern slopes of the mountain (TOLJIĆ *et al.,* 2013). Finally, in the Pliocene and the Quaternary, the Dinaric-Carpathian system entered into compression while the Pannonian basin was progressively inverted and filled by Plio-Quaternary terrestrial sediments. Differential vertical motions of block structures led to intensification of erosional processes and final modelling of an asymmetrical horst structure surrounded by Quaternary deposits of Srem and Bačka plains.

The uplift that began at the end of Pontian reached its maximum at the Pliocene/Pleistocene boundary, when across the existing E–W directed faults remobilization occurred, characterized by asymmetrical rotation of the Fruška Gora block. This is recognized in stronger uplift of the southern edge of the massif, resulting in high hypsometrical position of the mountain range.

Throughout the Quaternary time, the activities along these faults continued in the peripheral parts of the recently formed Fruška Gora horst, particularly mobile being the zones of the Vrdnik fault, Karlovac dislocation and Čortanovci transverse fault. The Danube fault, whose trace coincides with the riverbed of the Danube, along with the above mentioned faults, played a key role in the formation of the Fruška Gora horst, around which very specific genetic categories of Quaternary sediments were deposited.

After the intensified uplift of Fruška Gora, accompanied by subsequent subsidence of the southern foothills, a relatively shallow basin was formed, with axial parts oriented in accordance with the orientation of tectonically active structures (i.e. E–W). Also, it can be considered that these movements were causally related to climatic changes at the Pliocene-Pleistocene boundary, so that the proluvial sediments formed in that time have a regional distribution and represent landmark for the drawing of the lower boundary of Quaternary in this part of the area.

The neotectonic uplift of the Fruška Gora horst caused the intensive, but uneven cutting of the Fruška

Gora watercourses, which on both slopes belong to a parallel drainage system, developed at the right angle to the direction of the peripheral structures and parallel to the generally N–S oriented structures. Thus formed river valleys are composite, mainly transverse and consequent. The watercourses that belong to the Sava drainage system have deeply cut and narrow valleys only in their source parts. In lower parts, because of gentler slopes and a gradual transition into the plain, river valleys are wider, watercourses are often ephemeral, and form an alluvial fan, often with waterlogging phenomena. At the northern slopes of the mountain, rivers are deeply cut, of small width, with steep valley sides in their upper and middle parts, while in the lower parts they expand and form narrow floodplains.

Unlike the areas with a steady trend of rising, in the lowered regions relatively thick deposits of different origin were formed. Among them are products of fluvial, swamp, deluvial, and in Late Pleistocene also aeolian type of sedimentation. In the areas more lowered by tectonic agents, the watercourses of the Danube and Sava have been developed. Vast meanders, sharp de?ection of river valleys and apparent asymmetry of their valleys represent distinctive characteristics of watercourses under the influence of neotectonic and recent tectonic processes.

The intermontane valley of the river Sava has been sinking during Quaternary, while the horst of Fruška Gora and the northernmost parts of Šumadija have been rising. As a result of this trend of movement, within the young trough a wide river valley was formed, whose origin was connected to the tectonically controlled, slow but continuous subsidence. Throughout the Early and Middle Pleistocene the tectonic trough of the Sava river was constantly descending, which was reflected in the increased thickness of the deposits and their polycyclic character. Of particular importance were gravitational movements across the Kalemegdan fault, which controlled the development of the asymmetrical Sava trough. The depression axis migrated over time, from NW to SE, which was followed by migration of the Sava riverbed. From morphological point of view, the valley of this river belongs to the asymmetrical type of river valleys – its right side is in constant motion toward SE, while the left one is quite poorly distinguished and covered by deluvial deposits. The longer axis of the river valley is generally parallel to the extension of the recent depression, with the width amounting to up to 25 km.

Looking at the broader area, a distinctive double sharp de?ection valleys of this river can be observed on the line Sremska Mitrovica–Šabac. Namely, under the influence of a great floodplain of the Drina, this river has been shifted towards Sremska Mitrovica, so outside the zone of its influence it turns abruptly towards Šabac, from where it spreads (occasionally meandering) to Belgrade, following mainly the Kalemegdan fault along the Pannonian part of the section. Its valley in this part also has an asymmetrical character, because the loess and alluvial terrace are much more developed on the left, than on the right side of this watercourse.

The dynamic stage of the longitudinal profile of the Sava river, especially in its lower part to its confluence with the Danube, is characterized by permanent sinking, which is manifested in the morphology of the river valley, as well as in polycyclic character of sedimentation. Beside the extreme meandering of the course of this river, numerous deserted meanders are present, from completely dry, over occasionally to permanently active. Permanent lowering within the Sava trough is also indicated by a significant increase of the thickness of fluvial deposits with thick alluvial deposits of Late Pleistocene and Holocene overlying them. The younger part of these deposits was formed in conditions of relative rest in this area.

Also, from the regional point of view the Danube near Vukovar turns from the meridional direction at the angle of almost 90° towards the east, following the faults along the northern foothill of Fruška Gora, all the way to Stari Slankamen where the watercourse changes its direction and flows to the south. The river valley in this area is pronouncedly asymmetrical with the morphologically low left valley side and the right side marked by a steep section. This can be explained by the recent lowering of the area to the north of the fault, followed by migration of the riverbed to Fruška Gora.

From Stari Slankamen to Belgrade the Danube turns twice. The first turning (Stari Slankamen) is controlled by the mobility of the faults present on the eastern slopes of Fruška Gora, the activity of which led to the separation of the Titel loess plateau from the Srem loess plateau. Both of them were parts of the same entity before the deposition of the penultimate loess level (GORJANOVIĆ–KRAMBERGER 1921), when they were separated by a fault near Stari Slankamen, which controlled the turning of the Danube and formation of the recent valley. Another turning is in the area of Stara Pazova. It has a distinctive elbow character, so it may be related to the fault structures that control the area of uplift to the south of Stari Banovci (MARTINOVIĆ *et al*. 2010). At the same time, this is an area of the contact of the Fruška Gora and Zemun parts of the Srem loess plateau. The valley in this part also has a pronouncedly asymmetrical character, wherein its left side makes a vast loess and alluvial terrace (Pančevački rit), while the right side forms a very steep loess section, permanently eroded by the river.

Lithofacial analysis

Throughout Quaternary in the Serbian part of the Pannonian basin, and to a much lesser extent in its periphery, a relatively thick succession of genetically different types of sediments was deposited. Of special interest are pre-loess deposits, whose thickness and great distribution indicate that in the wider area of southern part of the Pannonian basin intensive sinking of the terrain was taking place throughout Pleistocene. This is particularly indicated by the presence of fluvial-lacustrine sediments, whose thickness in some places exceeds 200 m. However, despite the great thickness of deposits it can be concluded that subsidences were of low intensity compared to those in the central parts of this basinal system, such as the Great Hungarian depression, where the thickness of Quaternary deposits exceeds 700 m (RONAI 1974). As opposed to the deposits formed in the subsided regions, deluvial-proluvial sediments („Srem series“, „Kličevac Series“, etc.) that have been formed on the slopes occasionally aquatic (swampy) areas, which were eroded from the adjacent uplifted structures (Belgrade Promontory). These parts of the area were subsided across the cascade systems of faults, indicated by an increased thickness of older Pleistocene deposits.

Deposits of Plio-Pleistocene age (marsh-lacustrine deposits) were found by deep drilling in the area of Zemun and Novi Beograd, where their upper boundary is situated at an altitude of about 30,0 m, and lower at –60,0 m; while in some boreholes which are even deeper, their lower boundary is not reached, so presumably it could descent to a much greater depth. Taking into consideration that in the area of the Kvantaš pijaca (meaning Green market) in Zemun the Neogene basement was not reached even at the depth of 260 m, it can be concluded that these deposits have a great thickness (Fig. 3).

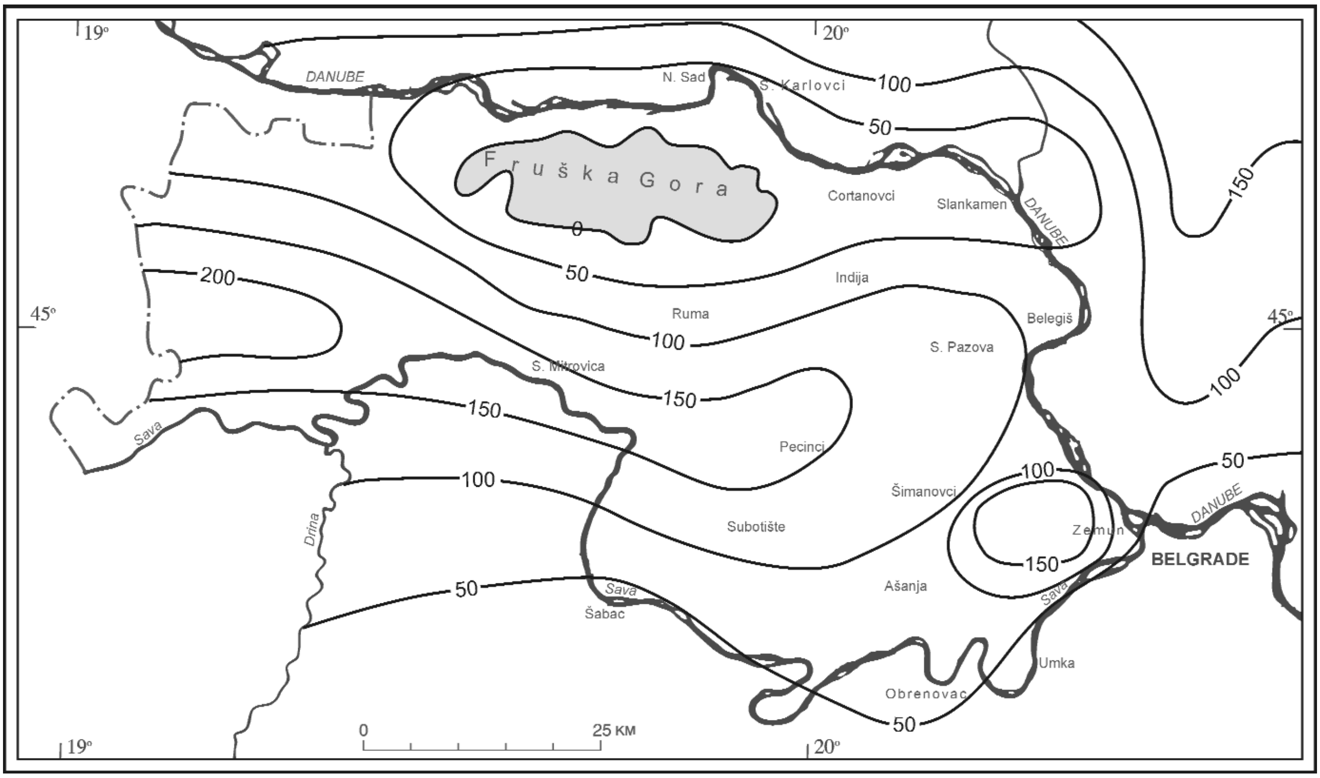

Fig. 3. Map of thicknesses of the pre-loess Pleistocene deposits in the area of Srem (amended after MAROVIĆ *et al.* 2002).

of Fruška Gora and in the peripheral belt of the Pannonian basin, especially in its eastern part towards the Carpathians (RAKIĆ, 1977), indicate the environment of inflicted areas between elevated regions.

According to the thickness of Quaternary deposits, in particular Pleistocene pre-loess deposits, it can be assumed that in the extreme SE part of Srem (today's territory of Novi Beograd and Zemun) the differentiation of relief under the influence of vertical tectonic movements occurred in Early Pleistocene (KNEŽEVIĆ *et al.* 1998; NENADIĆ 1997, 2003; NENADIĆ *et al.* 2009, 2010, 2011). The lowered parts were then quickly buried by rapid accumulation of slope deposits in

A very distinct and relatively extended subsidence in the area of Zemun and Bežanija is indicated also by a great thickness of fluvial polycyclic deposits of Early Pleistocene, which largely overlie the Plio-Pleistocene deposits. The faults that caused cascade subsidence in this part of the area, are covered with these sediments and other overlying Quaternary deposits. NE–SW directed structures can be followed from Kalemegdan to Obrenovac, from where further on, in a planar view, they form a system of echeloned faults of similar orientation.

The deposits of the Early Pleistocene age are situated in the hilly areas to the south of the Danube and

Sava rivers (area of the Belgrade Promontory and around it) on the significant height which is variable and ranges from an altitude of 170–179 m on Zvezdara, 135–156 m on Mirijevo, 113–130 m on Čubura, 69–78 m on Kalemegdan etc.

The hypsometric position of the fluvial polycyclic deposits to the north of the Danube and Sava is significantly lower. In the area of Novi Beograd their lower boundary begins on an altitude of 35–48 m, and the upper on approximately 55 m, sometimes over 66 m, so that some recent mollusk shells are found in these deposits together with the washed shells of the genus *Corbicula*. The most extensive subsidence was noticed in the area of Zemun, where the lower boundary of these deposits descends in some places to an altitude of 25 m.

A significantly decreased thickness of pre-loess Quaternary sediments in the riparian parts of the Sava river indicates that subsidence in this region took place a little later, in relation to northern parts of the territory. Locally, on the right bank of the river, a morphologically prominent fault system has been developed. Across these structures the NW block has been subsided, which brought to development of the Makiš depression. It can be concluded from the mentioned data that during Quaternary the overall subsidence in the area of the hanging-wall of the Kalemegdan fault was approximately 160 m.

Opposite to the areas of subsidence, the uplifted area of the Belgrade promontory and the Fruška Gora massif were in the stage of intensive erosion and accumulation of eroded material, which was transported by colluvial-deluvial processes and then deposited in the environments that were gradually sinking.

In the northern part of the territory (on the slopes of the Fruška Gora massif) the earlier Pleistocene proluvial-deluvial deposits were formed by a stronger hypsometric denivelation of the area on the boundary between Neogene and Quaternary, i.e. by a prominent tectonic activity manifested in the uplift of the core of this massif and subsidence of the outlying foothill areas. In the process of accommodation of the newly formed inflicted areas between the uplifted and subsided morphostructures, there was active erosion, denudation and filling of these areas with proluvial-deluvial deposits.

According to the stratigraphic-lithological characteristics of Quaternary deposits in the area of eastern Srem, it can be concluded that palustrine-lacustrine and fluvial polycyclic sediments mark the areas of subsidence, and proluvial-deluvial – inflicted areas beside the uplifted structures (RAKIĆ 1977; NENADIĆ 2003; NENADIĆ *et al*. 2011; NENADIĆ & GAUDENYI 2013).

During Late Pleistocene great areas of the Pannonian basin were covered by loess and loess-like deposits. Loess deposits cannot be an indicator of tectonic activities, because they could be primarily deposited at any height, but their thickness can immediately point to the existent palaeorelief, as well as to the intensity of erosional processes which occurred in the areas where these deposits were sedimented. Considering the number of palaeosols and loess horizons and their disturbances, ZEREMSKI (1960, 1961) established three phases of tectonic movements of epeirogenic character on the section of the loess plateau above the Danube. The oldest movements were finished before the accumulation of loess; the movements of the second phase took place during deposition of these sediments, while the third phase took place after the accumulation of the last loess horizon, in younger Neolithic. Movements of two older phases were manifested only in some parts across the profile line Stari Slankamen–Zemun, i.e. they have local character, while the younger ones were manifested on the whole profile of the loess plateau.

An example of tectonic activity can be seen near Slankamen (locality Surduk), where beneath two upper horizons of loes, which are horizontal, a package of deluvial-proluvial deposits is situated, tilted at the angle of 8° together with paleosols. On the contact of these two units there are slope debris and pebbles of hard Neogene and Mesozoic rocks. These were probably formed by the action of proluvial process on the slopes of the Fruška Gora mountain, in the course of which the base across which the water mass was moving was leveled. In this way, on the horizontal surface formed in such way the upper loess complex was deposited in the undisturbed position. This unconformity between lower and upper horizons, with colluvial gravels, was probably formed at the boundary between Middle and Late Pleistocene. In the other parts of the loess plateau similar elements that would point to the presence of tectonic activity have not been observed, since all loess horizons (as well as paleosols) are horizontal, which was also noted across the visible profiles from Surčin to Stari Slankamen.

According to the lithostratigraphic characteristics of deposits it can be concluded that tectonic activity in Holocene has a similar character as in Pleistocene, i.e. areas of subsidence were marked by fluvial, palustrine and swamp deposits, while deluvial and more rarely deluvial-proluvial deposits were linked to the inflicted areas toward the uplifted structures.

Thermochronological data

(U-Th)/He dating of apatite minerals (AHe) represents a low-temperature thermochronological technique, which is used for documenting the latest stages of cooling of rocks as they pass the uppermost levels of the crust, corresponding to the temperatures of ~75 °C (closure temperature Tc of AHe system, WOLF *et al*. 1996). Therefore, this method is frequently used to quantify the time of vertical movements in the uppermost ~1–2 km and correlate these movements with the associated tectonic phases. Two (U-Th)/He single grain ages were determined on the two rock samples collected in greenschist facies metamorphic core, located in the southern part of the Fruška Gora (Fig. 1B.). The ages were obtained following standard analytical procedures available at the VU University Amsterdam (see STOJADINOVIĆ *et al*. 2013).

The AHe single grain age of the sericite schist sample Fg1 is 16.3±1.6 Ma, while the AHe age of chlorite-sericite schist sample Fg2 is 2.4±0.9 Ma (Table 1). The older age of 16.3±1.6 Ma recorded in sample Fg1 reflects a Middle Miocene phase of cooling in the Fruška Gora metamorphic core. It represents the result of contemporaneous uplift caused by extensional deformations in the brittle domain that occurred along the gravitational faults along the southern slope of the mountain (TOLJIĆ *et al.* 2013). Hence, temporally it can be well correlated with the main phase of Pannonian extension (HORVATH *et al*. 2006). The younger, lowermost Quaternary, cooling age of sample Fg2 is 2.4±0.9 Ma, and it is associated with the most recent phase of regional tectonic activity. The obtained age corresponds well with strong uplift at Pliocene/Pleistocene boundary that was recorded in the southern parts of the mountain and was associated reverse reactivation of previously existing E–W oriented gravitational faults. It represents direct evidence of continuous uplift in the Pliocene and Quaternary, followed by intensive, tectonically induced erosion of the source area in the Fruška Gora and the fast deposition of proluvial-deluvial sediments in surrounding domains. This uplift is, again, associated with the contemporaneous phase of compression that affected the entire region (MAROVIĆ *et al*. 2002, 2007).

deposits (especially deposits of Plio-Pleistocene age) so they are usually not morphologically prominent but they represent significant control elements of subsurface geological structure. In the peripheral parts of the investigated area there are faults which directly affect the morphology of the terrain (for example, the faults by the rim of Makiš, along the Fruška Gora massif, etc.). Across the traces of these faults colluvial movements of rock masses are common.

Undoubtedly, the most striking structures are situated along the northern and southern periphery of the Fruška Gora massif, and they actually formed this asymmetrical horst surrounded by Quaternary deposits. The northern Danubian fault, whose trace generally coincides with the Danube riverbed, is covered by a thick package of Quaternary sediments but it is morphologically very distinct because of a pronounced asymmetry of the river valley. In the investigated area, on the southern slopes of the Fruška Gora, Vrdnik fault is situated (TOLJIĆ *et al*. 2013). Its trace is locally observed in the area of Vrdnik, while laterally it is mostly hidden by loess and pre-loess Quaternary sediments. In the eastern periphery this massif is laterally limited by the Karlovac and Čortanovci transverse structures. In the south of the investigated area especially striking is the Kalemegdan fault, developed along the Pannonian part of the section, extending from the SW part of the investigated area across Ostružnica, Železnik and Žarkovo to the confluence of the Sava. Across this complex fault its NW block was downthrown, which was accompanied by deposition of a thick package of sediments of Neogene–Quaternary age. The central parts of the area are covered by thick Quaternary deposits, hence fault structures are rarely visible on the surface. However, on the

Table 1. Apatite (U-Th)/He (AHe) Analytical Data. Bold numbers represent corrected final AHe single grain ages obtained in this study. *Ft is fraction of alphas retained, "corrected ages" are corrected for this effect.

Sample name	Rock type	4He (atms)	4He error (atms)	238U/233U	238U (atms)	238U error (atms)	235U (atms)	235U error (atms)
Fg1	sericite schists	8.762E+09	1.820E+08	2.220	1.712E+11	9.293E+09	1.272E+09	6.740E+07
Fg2	chlorite-sericite schist	1.447E+08	4.513E+06	1.004	6.485E+10	3.521E+09	4.703E+08	2.554E+07

Sample name	Rock type	232Th (atms)	232Th error (atms)	Th/U	uncorrected He age (Ma)	Error	Ft factor*	corrected He age (Ma)
Fg1	sericite schists	1.368E+12	7.403E+10	7.99	14.0	1.3	0.86	16.3
Fg2	chlorite-sericite schist	–1.850E+09	–6.51E+14	–0.03	1.7	0.6	0.73	2.4

Quaternary active faults and structures

The faults across which movements were performed represent inherited structures, primarily formed in the Miocene, as previously interpreted by TOLJIĆ *et al.* (2013). They are mostly covered by Pleistocene

available seismic sections (MATENKO & RADIVOJEVIĆ 2012) syn-depositionally active faults are recognized, across which the axial parts of the Srem depression were deeply downthrown.

By the analysis of satellite image (1:250 000) information on spatial position of larger and morphologi-

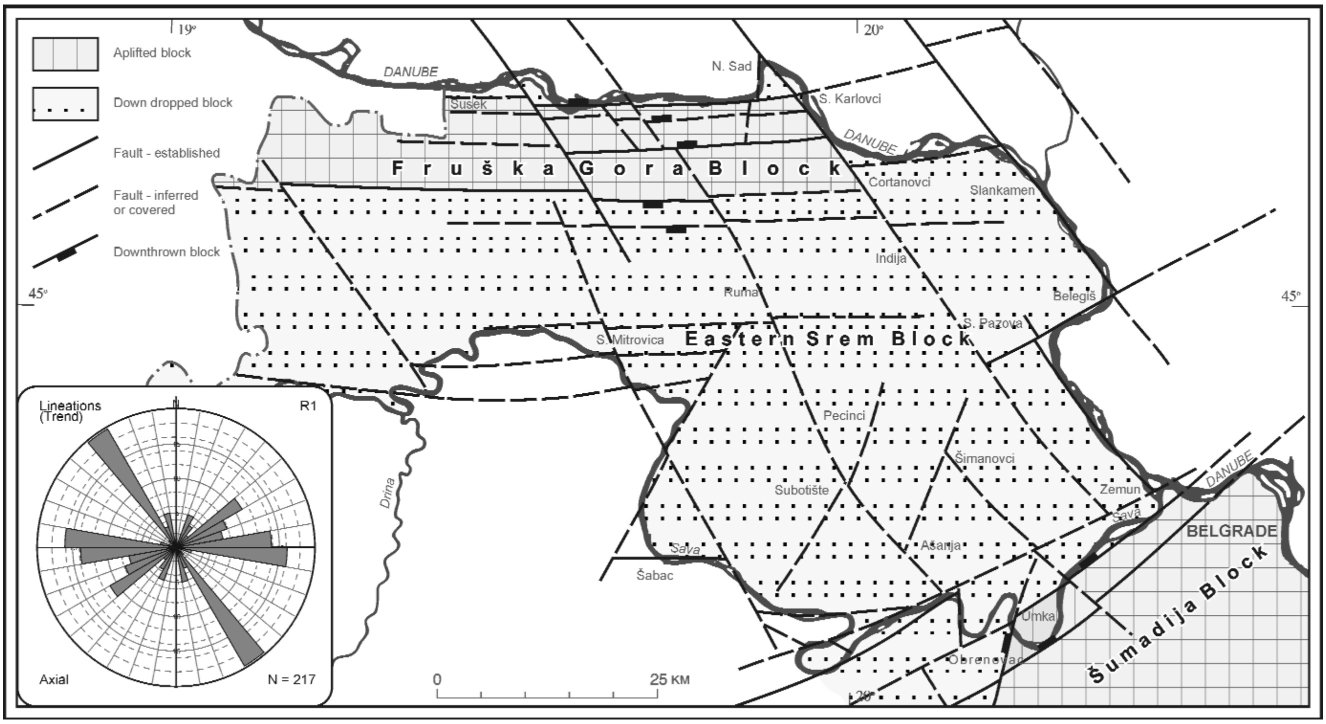

Fig. 4. Map of the regional fault setting of the eastern Srem with simplified review of the tectonic blocks structure.

cally prominent faults in the area of the eastern Srem has been obtained (Fig. 4). The basic feature of this structure is the existence of several fault systems. In the area of Fruška Gora the most significant faults are aligned with the strike of the plicative structures. These longitudinal structures are oriented in the E–W (ENE–WSW) direction and associated with the NW–SE directed faults. Longitudinal structures are large regional ruptures of deca-kilometre dimensions, among which the Vrdnik fault and Kalemegdan fault are particularly prominent. Across them the downthrow of central parts of the eastern Srem was performed (Eastern Srem Block), opposite to the uplift of the Fruška Gora Block in the north and Šumadija Block to the south of the investigated area (Fig. 4).

According to the determined positions of large faults, difference in spatial distribution of internal structures, as well as the lithofacial characteristics of the investigated deposits, 3 structural-depositional environments can be singled out in this area: Fruška Gora block, Eastern Srem Block and Šumadija block (Šumadija–Belgrade hills, Fig. 4).

Fruška Gora block

It represents an area limited by the Danube fault on the north and the Vrdnik fault on the south. By statistical data processing on spatial positions of the faults of this block, a maximum has been obtained with the direction 90–270 (diagram R1, Fig. 4). The majority of ruptures developed in this block generally belong to this system, which represent the faults that form the periphery of the positive Fruška Gora morphostructure. On the diagram in the form of a submaximum a system of faults with a statistical direction 150–330 is also observed. The NW–SE directed faults are often detected in the central and eastern parts of Fruška Gora.

Geodetic measurements confirm that the Fruška Gora block has been uplifted in recent times at the velocity of 0–1 mm/year (MAROVIĆ *et al.* 2002).

Eastern Srem block

On the north it is limited by the Vrdnik fault, and on the south by the Kalemegdan fault. This block is completely covered by Quaternary sediments, which hampered geometrical analysis of fault structures. Still, careful analysis of the satellite image made it possible to define spatial position of a part of dislocations developed in this area. The data on the fault structures were measured, statistically processed and shown on the diagram R1 (Fig. 4). On the rosetta a conspicuous maximum marks ruptures with a medium strike direction of 150–330. These structures are found on the eastern periphery and in center of the block. The submaximum with a medium direction 30–210 corresponds to the faults detected in the SW part of the block. Part of the fault setting developed in the domain of this block is also comprised of faults with the direction 90–270, which are situated in the area between Sremska Mitrovica and Pazova.

The available geodetic measurements indicate that the block of the central Srem subsided at the velocity up to –2 mm/year (MAROVIĆ *et al.* 2002).

Šumadija Block (Šumadija–Belgrade hills)

The northwestern boundary of this block makes the complex Kalemegdan fault, while the southern one is poorly defined and beyond the investigated area. The results of analysis of the faults are represented on the rosetta R1 (Fig. 4). Detected structures are uniformly oriented. On the diagram the faults that belong to the complex Kalemegdan fault have a statistical strike direction of 60–240. These faults are developed in the domain of the Sava river and they could be followed from Zemun on NE to Obrenovac and Debrec on SW.

Geodetic information confirms that this area has been slowly uplifted at the velocity of 1 mm/year (MAROVIĆ *et al.* 2002), whereas more to the south the velocity of uplift is increased up to 4 mm/year.

Generally speaking, by the analysis of obtained data it can be observed that in the blocks of Fruška Gora and Šumadija Block, as well as at their periphery, the E–W (ENE–WSW) directed faults dominate, while in the Eastern Srem Block the NW–SE faults prevail. The reasons for such discrepancies probably lie in the fact that the central block is covered by relatively thick Quaternary deposits, which masked older structures of this area, so their remote sensing is disabled in that way.

Conclusion

Quaternary tectonic activity in southern parts of the Pannonian basin genetically corresponds to the stress field, established earlier, at the end of Miocene (TOLJIĆ *et al.* 2013). As a consequence of the northward movement of the Adria microplate and final abruption of a segment of the subducted lithosphere in the Carpathian domain (MATENKO & RADIVOJEVIĆ 2012), the whole Pannonian basin was exposed to permanent compression. In the border area between the Dinarides and Pannonian basin, the axis of maximum compression is NE–SW oriented (BADA *et al.* 2007). In this stress field lithologically and structurally complex and thinned lithosphere of the basement of the Pannonian basin was folded in regional fold structures of low amplitudes. Folding has been accompanied by vertical mobility of blocks limited by the existing fault pattern.

By the analysis of spatial position of faults, their kinematic features and origin and mutual relationship of deposits formed in Quaternary, the data were obtained for the purpose of reconstruction of Quaternary tectonic mobility in the area of Srem. The peripheral southern parts of the Pannonian basin have similar evolution as the internal parts of the basinal area. In these parts there are also domains characterized by permanent late Neogene and Quaternary subsidence. Intensity of the subsidence is lower compared to the central parts of the Pannonian basin. Relatively highly hypsometrically uplifted blocks of Fruška Gora and northern parts of Šumadija have been developed on the periphery of the downthrown areas, in the area of Srem, during Late Neogene and Quaternary.

Simultaneous existence of neighboring domains, which are uplifted and subsided in a compression stress field, can be explained by flexion banding of the lithosphere (CLOETINGH *et al.* 2005; DOMBRÁDI *et al.* 2010), followed by reactivation of the large existing faults which are in the same time boundaries between the segments with a different character of vertical movement. Different character and intensity of vertical mobility of the lithosphere in the southern parts of the Pannonian basin have been, throughout Quaternary, the control factors of the origin and thickness of deposited sediments. A significant control factor of the Quaternary depositional environment were the faults on the southern slopes of Fruška Gora and to the southeast of the Sava river. The internal mobility and outline of the depressions are controlled on the east by the faults (from Sremski Karlovci, across Slankamen and Belegiš to Zemun), while the basin is open towards the west.

The central parts of the investigated area are generally characterized by a slow, permanent tectonically controlled subsidence, distinctive also in the recent time. The peripheral parts of the Šumadija-Belgrade hills and Fruška Gora horst have been in younger Neogene and Quaternary permanently and relatively slowly, uplifted. The (U-Th)/He cooling age obtained in the metamorphic core of the Fruška Gora horst, provides a direct evidence for the continuous uplift at the transition from Pliocene to Quaternary, which is the result of the ongoing compression. As a result of accommodation of uplift and following erosion of the uplifted blocks, in the domain of active faults relatively thick deposits of proluvial-deluvial character have been formed. In the subsided areas, thick deposits of different genetic origin have been formed. Among them the most prominent are lacustrine, alluvial, palustrine, and in younger Pleistocene aeolian deposits. In all tectonically subsided parts the flows of major rivers (Danube and Sava) have been developed. Their river valleys are situated in areas of faults in which during Quaternary gravitational movements of high intensity have been performed. These faults in the same time represent main tectonic boundaries of the morphostructural entities developed in this part of the Pannonian basin.

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References

BADA, G., HORVÁTH, F., DÖVÉNYI, P., SZAFIÁN, P., WINDHOFFER, G. & CLOETINGH, S. 2007. Presentday stress field and tectonic inversion in the Pannonian basin. Global and Planetary Change, 58: 165–180.

CLOETINGH, S., MATENCO, L., BADA, G., DINU, C. & MOCANU, V. 2005. The evolution of the Carpathians–Pannonian system: interaction between neotectonics, deep structure, poly-phase orogeny and sedimentary basins in a source to sink natural laboratory. *Tectonophysics*, 410: 1–14.

CLOETINGH, S., BADA,G., MATENCO, L., LANKREIJER, A., HORVÁTH, F. & DINU, C. 2006. Modes of basin (de)formation, lithospheric strength and vertical motions in the Pannonian–Carpathian system: inferences from thermomechanical modelling. *In*: GEE, D.G. & STEPHENSON, R.A. (Eds.), *European Lithosphere Dynamics*, Memoirs, 32: 207–221, Geological Society, London.

DOMBRÁDI, E., SOKOUTIS, D., BADA, G., CLOETINGH, S. & HORVÁTH, F. 2010. Modelling recent deformation of the Pannonian lithosphere: Lithospheric folding and tectonic topography. *Tectonophysics*, 484: 103–118.

FEDERAL GEODESY SURVEY (FGS), 1972. The Map of the Recent Vertical Displacements of Earth's Crust in Yugoslavia 1:2 500 000, Belgrade.

GORJANOVIĆ–KRAMBERGER, D. 1921. Morfološke i hidrografske prilike srijemskog lesa. *Glasnik geografskog društva*, 5: 17–53, Beograd.

HORWATH, F. & CLOETINGH, S. 1996. Stress–induced latestage subsidence anomalies in the Pannonian basin. *Tectonophysics*, 146: 183–201. [not cited in the text!]

HORVATH, F., BADA, G., SZAFIAN, P., TARI, G., ADAM, A. & CLOETING, S., 2006. Formation and deformation of the Pannonian Basin: constraints from observational data. Geological Society, London, Memoirs 32 (1): 191–206.

JOVANOVIĆ, P. 1971. Recent vertical crustal movements in Yugoslavia. IUGG, XV International Assembly MITS, Moskva, Beograd, 10 pp.

KNEŽEVIĆ, S., NENADIĆ, D. & STEJIĆ, P. 1998. Prelesni Preloess Qaternary and PliceneDeposits of Yemun and Novi Beograd. *Geološki anali Balkanskoga poluostrva*, 62: 57–73 (in Serbian and English).

MAROVIĆ, M., ĐOKOVIĆ, I. & MILIĆEVIĆ, V. 1996. Structural Geometry and Kinematics of Neoalpine Litospheric Extension in Vojvodina Part of Pannonian. *Geološki anali Balkanskoga poluostrva*, 60 (2): 79–97 (in Serbian and English).

MAROVIĆ, M., ĐOKOVIĆ, I., PEŠIĆ, L., TOLJIĆ, M., VOJVODIĆ, V. & GERZINA, N. 1998. Pliocensko–kvartarna tektonska aktivnost terena Srbije: seizmološke implikacije. Zbornik 1. Kongresa geofizičara Jugoslavije, 446–455, Beograd.

MAROVIĆ, M., DJOKOVIĆ, I., PEŠIĆ, L., RADOVANOVIĆ, S., TOLJIĆ, M. & GERZINA, N. 2002. Neotectonics and seismicity of the southern margin of the Pannonian basin in Serbia. EGU Special Publication, 277–295.

MAROVIĆ, M., TOLJIĆ, M., RUNDIĆ, L. & MILIVOJEVIĆ, J. 2007. *Neoalpine Tectonics of Serbia*. Serbian Geological Survey, Belgrade, 87 pp.

MARTINOVIĆ, M., ZLOKOLICA MANDIĆ, M. & VUKIĆEVIĆ Z. 2010. Geotermalni atlas Vojvodine, Pokrajinski sekretarijat za energetiku i mineralne sirovine, Novi Sad, 18 pp.

MATENCO, L. & RADIVOJEVIĆ, D. 2012. On the formation and evolution of the Pannonian Basin: Constraints derived from the structure of the junction area between the Carpathians and Dinarides. *Tectonics*, 31, TC6007, 18–49. doi:10.1029/2012TC003206.

NENADIĆ, D. 1997. Paleogeographic and Tectonic characteristics of Quarternary of Belgrade and the surrounding area. MSc. Thesis (unpublished in manuscript), University of Belgrade, Faculty of Mining and Geology, Belgrade, 71 pp. (in Serbian, English abstract).

NENADIĆ, D. 2003. Pleistocene deposits of eastern Srem. *Unpublished Doctoral thesis*. 224 pp. Beograd (in Serbian, English abstract).

NENADIĆ, D., KNEŽEVIĆ, S. & BOGIĆEVIĆ, K. 2009. Stratigraphical and Paleogeographical characteristics of Pleistocene series in the Sava riparian area at Belgrade (Serbia). *Bulletin of the Natural History Museum in Belgrade*, 2: 63–83.

NENADIĆ, D., BOGIĆEVIĆ, K., LAZAREVIĆ, Z. & MILIVOJEVIĆ, J. 2010. Lower and Middle Pleistocene sediments of Eastern Srem (northern Serbia), Paleogeographical Reconstruction. *Bulletin of the Natural History Museum in Belgrade*, 3: 7–25.

NENADIĆ, D., GAUDENYI, T., BOGIĆEVIĆ, K. & GULAN, Z. 2011. The lower boundary of Quaternary in the area of the southeastern Srem (north Serbia). *Bulletin of the Natural History Museum in Belgrade*, 4: 23–36.

NENADIĆ, D. & GAUDENYI, T. 2013. Stratigraphical position of Pleistocene fluvial polycyclic deposits of Serbia. Neogene and Quaternary stratigraphy, actual terminology and nomenclature. Serbian Geological Society, 44–47, Beograd.

RAKIĆ, M. 1977. Pleistocen Srema i Banata. *Geologija Srbije* II–3, Stratigrafija (Kenozoik), Univerzitet u Beogradu, Beograd, 2 (3): 399–405.

RAKIĆ, M. & STEJIĆ, P. 2005. Tectonic of south eastern part of Pannonian Basin during upper Pliocena and Qaternary. *14. Kongres geologa Srbije i Crne gore*, Novi Sad, 107–108 (in Serbian and English).

RONAI, A. 1974. Quaternary movements in Hungary's area. *Acta Geologica Academiae Scientiarium Hungaricae*, 18: 39–44.

SCHMID, S.M., BERNOULLI, D., FÜGENSCHUH, 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 J. Geosci., 101: 139–183.

STOJADINOVIĆ, U., MATENCO, L., ANDRIESSEN, P.A.M., TOLJIĆ, M. & FOKEN, J.P.T. 2013. The balance between orogenic building and subsequent extension during the Tertiary evolution of the NE Dinarides: Constraints from low-temperature thermochronology. Global and Planetary Change, 103: 19–38.

SUŠIĆ, Z. 2013. Geodinamička analiza pomeranja zemljine kore regionalnog karaktera, Doktorska disertacija, Univerzitet u Novom Sadu, Fakultet tehničkih nauka, Geodezija i geomatika, 196 pp., Novi Sad.

TOLJIĆ, M., MATENCO, L., DUCEA, M., STOJADINOVIĆ, U., MILIVOJEVIĆ, J. & ĐERIĆ, N. 2013. The evolution of a key segment in the Europe – Adria collision: the Fruška Gora of northern Serbia. Global and Planetary Change, 103: 39–62.

WOLF, R.A., FARLEY, K.A., SILVER, L.T. 1996. Helium diffusion and low temperature thermochronometry of apatite, Geochim. Cosmochim. Acta, 60: 4231–4240.

ZEREMSKI, M. 1960. Reljef Beogradske i Zemunske posavine. *Zbornik radova Prirodno–matematičkog fakulteta*, Geografski institut, 7: 56–98.

ZEREMSKI, M. 1961. Još jedan prilog holocenskim epirogenim pokretima na istočnom delu odseka sremske lesne zaravni. *Zbornik Matice srpske*, serijal prirodnih nauka, 20: 16 p..

Резиме

Квартарна тектонска и депозициона еволуција источног Срема (северозападна Србија)

Током квартара на подручју источног Срема, саставног дела Панонског басена, испољила се тектонска активност као битан контролни фактор депозиције и финалних уобличавања савременог рељефа. Тектонска еволуција Панонског басена је почела знатно раније, тако да су све током квартара тектонски активне структуре део раније постојећег предцртежа и спадају у категорију наслеђених и реактивираних структура. Седиментација, као доминантан процес финалних фаза запуњавања инвертованог депозиционог басена, вршила се у раније тектонски дефинисаним доменима.

Током млађих одељака плиоцена и старијег квартара, након повлачења Паратетиса, област јужног обода Панонског басена у целини пролази кроз копнену фазу развоја. У том интервалу обављена су тектонска обликовања ниског интензитета, којима су финално уобличени регионални морфоструктурни облици. Такође, тектонски контролисана мобилност унутар басенских сегмената проузроковала је недостатак неких стратиграфских подкатова плиоцена, промену фација и дебљина најмлађих литостратиграфских целина (MAROVIĆ *i dr*. 1996, 1998).

Постбасенски седименти, депоновани током квартара, представљени су релативно дебелим пакетом седимената у оквиру кога се суперпозиционо и генетски могу разликовати два дела:

- *старији*, речни и речно-језерски, са реликтима басенског склопа, генерисан покретима влашке или валахијске тектонске фазе, манифестујући се вишекратним спуштањем некадашњег басенског дна и стварањем сложених алувијалних равни пра-Дунава и пра-Саве, и
- *млађи*, који одговара флувиоденудационом систему у ужем смислу, а који обухвата морфолошке облике стваране током горњег плеистоцена и холоцена.

Квартарну тектонску активност јужних делова Панонског басена је сагледана у контексту регионалне миоценске екстензионе еволуције басенског простора и његове плиоценско-квартарне инверзије. Миоценска екстензија, продуцирана rollback-ом европске литосфере у Карпатима, била је праћена рифтингом, истањењем литосфере и субсиденцијом у домену Панонског басена (HORVATH *et al.* 2006). Дуготрајну средње и горњомиоценску пострифтну субсиденцију, контролисану са поступним хлађењем литосфере у домену Панонског басена (thermal sag cooling, CLOETINGH *et al.* 2006), пратила је плиоценско-квартарна басенска инверзија, изведена у компресионом напонском пољу. Екстензионо напонско поље је смењено компресијом, активираном као последица финалног откидања (break off) субдуковане европске литосфере у домену Карпата, с једне стране, и север-североисточне прогресије Адријске плоче, с друге стране. Током плиоцена и квартара, Динарско-Карпатски ороген и интраконтинентални Панонски басен су изложени константној компресији, за ове просторе генерално оријентисаној по правцу СИ–ЈЗ (BADA *et al.* 2007). У овим условима је истањена и литолошки хетерогена литосфера у подини Панонског басена, убрана у наборе километарских размера (CLOETINGH *et al.* 2005, 2006). Регионална литосферна убирања су била праћена вертикалном мобилношћу сегмената литосфере, различитог смера и интензитета, што је као финалну последицу имало релативно брз аплифт и денудацију периферијских делова басена и даљу субсиденцију и депозицију централних басенских домена. При томе је локалном редистрибуцијом компресионог стреса реактивиран постојећи тектонски предцртеж, који је био у функцији контроле тектонске мобилности унутар басенских ентитета, какав је био простор јужно од Фрушке Горе.

На секцијама сеизмичких профила Фрушке Горе (MATENKO & RADIVOJEVIĆ 2012) може препознати асоцијација раседа који чине Врднички расед (TOLJIĆ *et al*. 2013). По овој структури је примарно гравитационо спуштен јужни блок, при чему је дебљина плиоценско-квартарних седимената јужно од раседа и преко 500 m. Такође синтеза података сеизмичког профилирања и дубоких истражних бушења изведених у овом подручју, упућује да је дебљина плиоценско-квартарних седимената значајна (Martinović *i dr.* 2010). Највећа дебљина седимената је између Старе Пазове и Шапца, у депресији чија оса се пружа правцем И–З (ИСИ–ЗЈЗ). На северној периферији депресије се налази Врднички расед, централне делове подручја контролише асоцијација хорстова и ровова дефинисаних раседима по којима је дубоко спуштен централни део Сефкеринске депресије (Matenco & Radivojević, 2012). Јужна периферија проучаваног простора на сеизмичким секцијама показује сложену тектонску природу прелазног подручја између Панонског басена и његовог издигнутог јужног залеђа. Као доминантна структура се препознаје Калемегдански расед, синдепозиционо активни расед, по коме је субсиденција северозадног домена била активна и током квартара, на што упућује значајна дебљина најмлађих седимената. На овакав сценарио указује и релативно мала дебљина плиоценско-квартарних седимената источно од овог раседа. Посматрано у плану, асоцијацију раседа који чине Калемегдански расед, чини низ ешалонираних раседа пружања СИ–ЈЗ који се могу пратити од Калемегдана до Обреновца и даље ка југозападу (Сл. 4).

Фрушка Гора представља хорст чија тектогенеза је отпочела још у доњем миоцену, генерално уобличен током раног квартара, перманентно модификован до у рецентно време. За примарно морфоструктурно обликовање овог масива значајна су миоценска обликовања која се могу препознати у гравитационим смицањима дуж раседа пружања И–З. Током плиоцена и старијег квартара део ових раседа је реверсно реактивиран, чиме је додатно истакнута антиформна, позитивна стурктурна грађа Фрушке Горе, што је било праћено рапидном ерозијом аплифтираних делова и исто тако рапидном акумулацијом у околним спуштеним доменима.

После интензивнијег издизања Фрушке Горе, праћеног субсеквентном субсиденцијом јужног предгорја, долази до формирања релативно плитког басена са аксијалним деловима оријентисани сагласно оријентацији тектонски активних структура пружања И–З. Такође, може се сматрати да су ови покрети каузално били повезани са климатским променама на граници плиоцена и плеистоцена, те да тада настали пролувијални седименти имају регионално распрострањење и представљају репер за извлачење доње границе квартара на овом делу терена.

Интрапланински ситуирана долина реке Саве током квартара тоне, док се хорст Фрушке Горе и најсевернији делови Шумадије издижу. Као последица оваквог тренда кретања, у оквиру младог рова формирана је широка долина реке, чија се еволуција може везати за тектонски контролисану спору, али континуирану субсиденцију. У току старијег и средњег плеистоцена тектонски ров Саве налазио се у константном спуштању, што се и одразило на повећану дебљину наслага и њихов полициклични карактер. При томе су посебно од значаја била гравитациона кретања по Калемегданском раседу, која су контролисала развој асиметричног Савског рова. Оса депресије је временом мигрирала, од северозапада ка југоистоку, што је било праћено и миграцијом речног корита реке Саве.

Током квартара у српском делу Панонског басена, а у знатно мањој мери на његовом ободу, наталожена је релативно дебела сукцесија генетски различитих типова наслага. Посебан значај при том су имале прелесне наслаге, чија дебљина и велико распрострањење упућује да су се на ширем подручју јужног дела Панонског басена током плеистоцена одвијала интензивна спуштања. На то нарочито указују седименти речно-језерског карактера чија дебљина местимично прелази и преко 200 m. Насупрот наслагама формираним у спуштеним областима, делувијално–пролувијални седименти („сремска серија“, „кличевачка серија“, итд.) који су формирани на падинама Фрушке Горе и на ободном појасу Панонског басена, посебно у источном делу према Карпатима (Rakić 1977), указују на превојна подручја према издигнутим структурама.

На основу дебљине квартарних, посебно прелесних плеистоценских наслага, може се претпоставити да је на крајњем ЈИ делу Срема (данашњем простору Новог Београда и Земуна) долазило до диференцијације рељефа под утицајем вертикалних тектонских покрета током старијег плеистоцена (Knežević *i dr.* 1998; Nenadić 1997, 2003; Nenadić *i dr.* 2009, 2010, 2011). При томе су спуштени делови затрпавани брзом акумулацијом падинских наслага у повремено акватичним (забареним) срединама, еродованих са околних издигнутих структура (београдског рта). Ови делови терена су дуж каскадних система раседа спуштани наниже, о чему нарочито сведочи повећана дебљина старијеплеистоценских наслага.

Творевине плио-плеистоцена (барско-језерске наслаге) су констатоване дубинским бушењем на подручју Земуна и Новог Београда, где им је одређена горња граница на око 30,0 mnv, а доња на –60,0 mnv, док поједине бушотине и преко те дубине нису стигле до његове подине, па је за претпоставити да се доња граница ових наслага местимично спушта доста ниже од горе наведене. Узимајући у обзир да се на простору Кванташке пијаце у Земуну није набушена неогена подлога ни на дубини од 260 m, за претпоставити је да ове наслаге местимично имају јако велику дебљину (Сл. 3).

Интересантни су и подаци добијени применом термохронолошке методе. Као што је познато, одређивање старости хлађења апатита коришћењем (U-Th)/He термохронолошке методе, представља технику која се често употребљава за дефинисање времена одвијања вертикалних тектонских покрета у најплићим нивоима земљине коре. Ово је омогућено тиме што је температура затварања (U-Th)/He система у апатитима ~75 °C (WOLF *et al.* 1996), што би одговарало хлађењу стена при њиховом вертикалном кретању кроз приповршинске нивое земљине коре (~1–2 km). Две старости хлађења добијене су анализом два узорка из метаморфног језгра Фрушке горе (Табела 1 и Сл. 1Б., Fg1 16.3±1.6 Ma и Fg2 2.4±0.9 Ma). Старост узорка Fg1 od 16.3±1.6 Ma, представља резултат хлађења изазваног издизањем метаморфног језгра Фрушке горе током миоценских екстензионих деформација дуж гравитационих раседа лоцираних на јужном ободу планине (TOLJIĆ *et al.* 2013). Старост узорка Fg2 od 2.4±0.9 Ma се, међутим, може корелисати са хлађењем ових стена током снажног издизања на граници плиоцена и плеистоцена, а која је асоцирана са реверсном реактивацијом већ постојећих гравитационих раседа оријентисаних по правцу исток–запад. Старост узорка Fg2 представља директан доказ континуираног издизања метаморфног језгра Фрушке горе током плиоцена и квартара, што представља последицу компресије која диктира рецентни тектонски режим читавог региона (MAROVIĆ *et al.* 2002, 2007).

На основу утврђених позиција крупних раседа, разлика у просторној дистрибуцији интерних структура, као и на основу литофацијалних карактеристика проучаваних депоната, на истраживаном подручју могуће је издвојити 3 структурно-депозиционе целине: *Блок Фрушке Горе*, *Блок источног Срема* и *Шумадијски блок (шумадијско–београдско побрђе)* (Сл. 4). Блок Фрушке Горе представља подручје ограничено Дунавским раседом на северу и Врдничким раседом на југу. Блок источног Срема је са севера ограничен Врдничким раседом, а са југа Калемегданским раседом. Шумадијски Блок као северозападну границу има сложени Калемегдански расед, док је јужна недефинисана и изван подручја истраживања.

Квартарна тектонска активност у јужним деловима Панонског басена генетски кореспондира са напонским пољем успостављеним раније, крајем миоцена. Као последица кретања Адријске микроплоче ка северу и финалног откидања сегмента субдуковане литосфере у карпатском домену, цео Панонски басен је изложен перманентној компресији. У граничном подручју између Динарида и Панонског басена, оса максималне компресије је оријентисана правцем СИ–ЈЗ. У овом напонском пољу је литолошки и структурно сложена и истањена литосфера подине Панонског басена, убрана у регионалне наборне структуре ниске амплитуде. Убирања су праћена вертикалном мобилношћу блокова лимитираних постојећим раседним предцртежом.

Истовремено егзистирање суседних домена који се издижу и тону у компресионом напонском пољу, могу се објаснити флексионим савијањем литосфере, праћено реактивирањем крупних, постојећих раседа који су уједно и границе сегмената са различитим карактером вертикалног кретања. Различит карактер и интензитет вертикалне мобилности литосфере у јужним деловима Панонског басена су током квартара били контролни фактори генезе и дебљине депонованих седимената. Као важан контролни фактор квартарног депозициног простора препознати су раседи на јужним падинама Фрушке Горе (Врднички расед) и југоисточно од реке Саве (сложени Калемегдански расед).

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The copper deposits of Bor, eastern Serbia: Geology and Origin of the Deposits

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Abstract. The copper deposits of Bor, volcanic activities in the area and relationship of minerals through time are presented by formations within the Cenomanian–Turonian range. Geology and age of the deposits are given in the geological-time order based on superposition of the Timok mineral-ore Formation and the underlying (Cenomanian) and fossiliferous overlying (Senonian) strata. The concept of dating Bor deposits the Turonian is discussed in this context. Bor deposits lie between the Cenomanian Krivelj Formation and the Senonian epiclastic Metovnica Formation. Embedded between the two formations is the Timok volcanogenic Formation. Described in this paper are principal members of the Timok Formation strata: volcanogenic and subvolcanogenic-intrusive rocks, a zone of hydrothermally altered rocks and main types of the Bor ore deposits: (a) Deposits of massive sulphide coppers; (b) Vein and stockwork-disseminated type of mineralisation; (c) Porphyry mineralisation; and (d) Reworked ore-clasts of copper sulphides of the Novo Okno deposit. Identified deposits, according to the Bor Geological Service records and published works, are systematized and summarized into three geographic units: (1) Group of deposits Severozapad (Brezanik); (2) Central Bor Deposits (Tilva Roš, Čoka Dulkan, Tilva Mika, Borska Reka, and Veliki Krivelj) and many ore bodies; (3) Copper deposits Jugoistok (ore bodies X and J) and olistostrome deposit Novo Okno. Information given in this paper, the discussion on relative geologic age of the Bor deposit's floor and roof in particular, support our concept that the process ceased before the Upper Turonian, and that age of the primary copper mineralization is Turonian.

Key words: Turonian, volcanism, copper deposits, Bor, floor (Cenomanian), roof (Senonian), formation, superposition, deposit age.

Апстракт. Борска лежишта бакра, вулканизам и временски односи настанка рудне минерализације приказани су формационо у хроностратиграфском дијапазону ценоман-турона. Геологија и старост лежишта изложени су геохронолоски на основу суперпозиције Тимочке рудонос-формације и фосилоносних наслага подине (ценоман) и повлате (сенон) ове формације. У том контексту формулисана је концепција о туронској позицији борских лежишта. Подину тих лежишта изграђује ценоманска Кривељска формација, а повлату сенонска епикластична Метовничка формација. Између тих основних стенских маса (формација) смештена је главна рудоносна јединица борских лешишта Тимочка вулканогена формација. У оквиру ове (Тимочке) формације приказане су главне асоцијације вулканогених и субвулканогено-интрузивних стена, зоне хидротермалне алтерације и важнији типови лежиста односно рудне минерализације у Бору: а. Лежиста бакра масивних сулфида, б. Жиличасто-штокверкни импрегнациони тип, ц. Порфирска рудна минерализација и д. Редепоновани рудокласти масивних сулфида бакра, лежишта "Ново Окно". Према документацији Борске геолошке службе и објављеним радовима, лежишта су систематизована и сажето изложена у оквиру три географске целине: 1. Група лежишта Северозапад (Брезаник), 2. Централна лежишта Бора (Тилва Рош, Чока Дулкан, Тилва Мика, Борска река, Велики Кривељ) и бројна рудна тела, 3. Лежишта бакра Југоисток (рудна тела "X" и "1") и Олистостромско лежиште "Ново Окно". Приказани резултати у овој студији посебно дискусија о релативној геолошкој старости подине и повлате борских лежишта, потврђују нашу концепцију да је све завршено још пре горњег турона и да је старост лежишта бакра примарне борске минерализације туронска.

Кључне речи: Турон, вулканизам, лежишта бакра, Бор, подина (ценоман), повлата (сенон), формације, суперпозиција, старост лежишта.

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Introduction

Bor area has been explored for copper deposits over hundred years. New large porphyry deposits were found and worked parallel with the earlier opened ones and the known copper ore of massive sulphides. Some of porphyry bodies (e.g. Borska Reka) are expected to be economic, both in reserve and recovery, more than all the deposits known so far in Bor area.

History of exploration (1902–2005) and geological-economic evaluation of the excavated and potential deposits, ore reserves, average Cu, Au, Ag, et al. metal concentrations are reported in monographs by JANKOVIĆ (1990, 2002) and DROVENIK (2005). Many geological-metallogenic studies, analyses and monographs on metallogeny of the Bor deposits, paragenetic sequences and types of mineralization have been published but have not yet finally solved the original relation (age, porphyry mineralization, massive sulphide copper deposits, the Novo Okno ore clast deposit, etc.).

Formational approach last few years to the issue helped an accurate geological presentation of the time-stratigraphic relationship of ore minerals, origin and development of the Bor deposits. Considered in this context are processes of the Upper Cretaceous (Turonian) volcanism and mineralization in the area, relationship between the fossiliferous Cenomanian floor and the Senonian roof of the Bor ore-bearing rocks in particular.

Interpretation of the likely Turonian age of the Bor deposits and the abandoned Laramian concept of Paleogene metallogeny are supported by a more recent fundamental scenario and published geological and metallogenic data, viz.:

- Location of the ore-clast deposit Novo Okno at the Upper Turonian–Lower Senonian boundary, a turning point in dating the Bor deposit and its geology;
- Metallogenic zone Bor, Bor copper deposit, Novo Okno and other bodies;
- Pyroclastics and epiclastics from the first phase of the Timok Magmatic Complex;
- Copper and gold Bor deposits – hundred years of exploration;
- Volcanogenic Turonian and epiclastic Senonian in the Timok Magmatic Complex;
- Origin of the Bor and other copper deposits;
- Formational base of the Bor copper-gold deposits;
- Novo Okno copper deposit of olistostrome origin; etc.

Further treatment of the Bor copper deposits, besides the mentioned and adopted information, includes some conventional prospecting methods used in his geological dating:

a. Superposition in the Timok volcanogenic complex;

b. Time-stratigraphic relationship between the under- and over-lying strata of the Timok complex and deposits;

c. Reworked ore-clasts of the primary Bor deposits and epi-clasts of the Upper Turonian and Lower Senonian, an olistostrome-like deposit;

d. Discordances, transgressions and the like.

Investigation data on geology, origin and age of the Bor copper deposits are presented within the above given frame.

Geology

Geology of the Bor copper deposits is described by superposition of strata in a model of homogeneous lithogene units, formations, underlying and overlying the mineral deposit (Tab. 1):

- underlying Krivelj Formation,
- Timok ore-bearing Formation,
- overlying Metovnica Formation, and
- Bor conglomerates and pelite.

The Underlying Krivelj Formation

Geological basement of the deposits northeast of Bor consists of clastic-pelitomorphic rocks of the Krivelj Formation (Cenomanian/Lower Turonian). The formation is transgressive and unconformable over Urgonian limestone of the Veliki Krš monocline (Veliki Krivelj–Kvarnana).

The Krivelj Formation began to form in the Middle Cretaceous (Vraconian) with rifting and volcanic events, uplifting and stretching of the east-Serbian paraplatform and strong Albian-Cenomanian transgression (ANTONIJEVIĆ 2010).

Strata of the underlain Krivelj Formation were found in 1958 (Krivelj–Kvarnana, Fig. 1) at the base of the Veliki Krivelj porphyry copper deposit, beginning with Albian-Cenomanian glauconitic ferruginous sediments and conglomerates and grading upwards into Cenomanian pelitomorphic fossiliferous sediments equivalent to the Lenovac Beds of Tupižnica south of Veliki Krš and Bor.

In the east of Veliki Krivelj area, the Krivelj Formation penetrates deep into the floor, where metamorphised in contact with quartz diorite and partly transformed into skarn (ALEKSIĆ 1979). An exotic block of Krivelj limestone, with Albian-Cenomanian rocks, is also metamorphic and partly transformed into skarn. Hydrothermally altered andesite and quartz diorite with porphyry copper mineral identical to that of Veliki Krivelj were found deep in the block on the Veliki Krivelj side.

In the local geological columns, three members were differentiated of about 125 metres total thickness. How deep is the intrusion of the upper metamor-

Table 1. Formational model of the Bor copper deposits

FORMATION			ENVIROMENT	COMPOSITION		MINERAL	EPOCH
Volcanogenic-sedimentary	DUBRAVE F. Conglomerate Pelite - tuff	superline	Marine volcanogenic-sedimentary	Conglomerate, sandstone, pelite-tuff		/	Upper Senonian
Clastic	METOVNICA	overlying	Submarine	Breccia, conglomerate, clastics		Ore-clastics from Novo Okno **olistostrome**	Lower Senonian-Upper Turonian
Ore-bearing	pyroclastic TIMOK subvolcanic associations	intermediate	Volcanogenic (subaerial) intrusive hypabyssal	Pyroclastics hornblende andesite diorite quartz diorite	Hydrothermally altered	**Massive Cu sulphides: stockwork-impegnated** mineral at Bor; **porphyry** at Borska Reka, Krivelj	Middle Turonian Turonian
Sedimentary	KRIVELJ	underlying	Marine pelitomorphic clastic	Pelite, glauconite, siltstone, conglomerate		Glauconite	Turonian, Cenomanian, Vraconian Beds

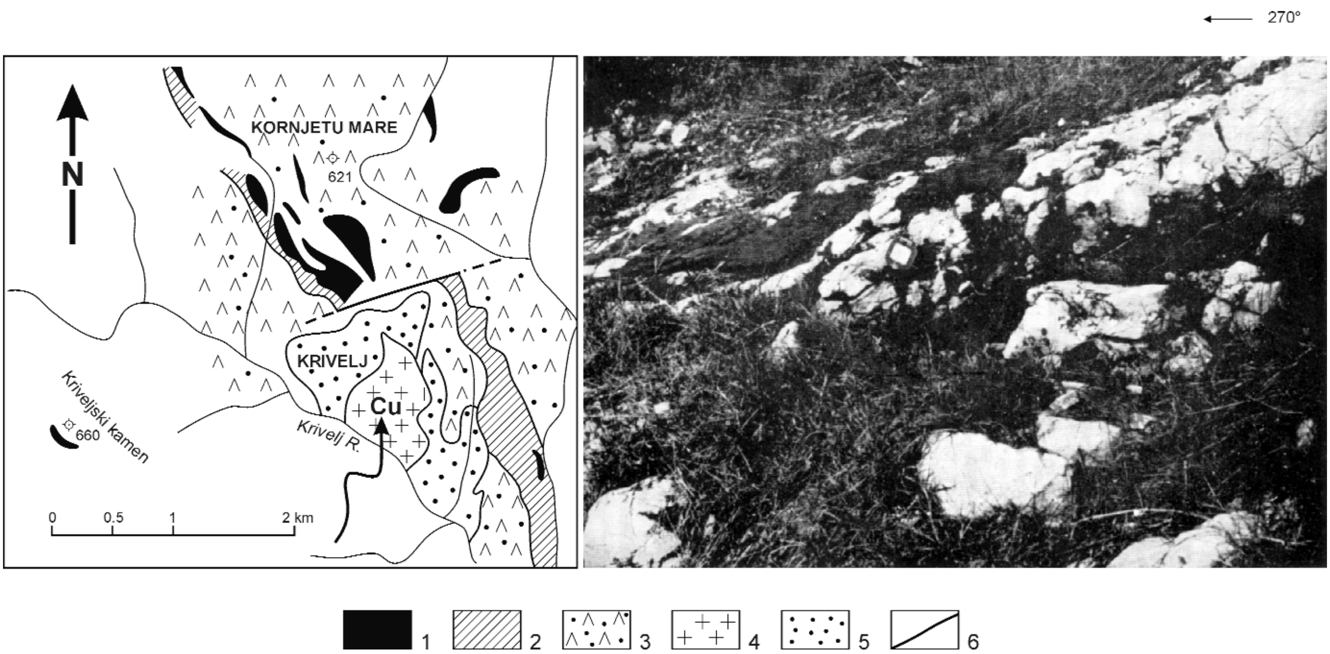

Fig. 1. Krivelj Formation and Veliki Krivelj copper deposit. Map left: **1,** Albian–Cenomanian (Vraconian); **2,** Cenomanian–Turonian; **3,** Volcanogenic Turonian; **4,** Veliki Krivelj deposit; **5,** Hydrothermally altered rocks (3, 4, 5 the Timok Formation); and **6,** Fault. Photo right: Dark Albian–Cenomanian, Light Urgonian.

phic member (pelite) of the Formation upwards into the volcanogenic Turonian and the Krivelj deposit is conjectural; the contact is probably discordant (ANTONIJEVIĆ 2010, p. 3).

The Timok Ore-Bearing Formation

Basic lithologic unit in the volcanic Bor structure is the volcanogenic, ore-bearing Timok Formation hundreds of metres thick. It is largely subaerial, with notable amounts of hornblende-biotite andesite (Timozite) and pyroclastics, and locally with subvolcanic intrusive deep-seated rocks (dykes). Hydrothermally altered rocks and metasomatic copper deposits also are extensive. The Formation controls main copper deposits of massive sulphides and porphyry copper mineralisation of Bor (volcanogenic Turonian, in ĐORĐEVIĆ 2005).

Rock associations or members identified in relation to the complexity of the Timok Formation, processes of volcanism and hydrothermal alteration, and the types of ores and deposits are the following:

1. Hornblende-biotite andesite association;
2. Diorite and quartz diorite; and
3. Hydrothermally altered rock zones, deposits or ore occurrences.

Hornblende-biotite andesite association includes hornblende-biotite dacite and other volcanic rocks such as hornblende andesite pyroclastics subaerially consolidated. These are products probably of the earliest volcanic phase, the so-called Timozite rock association in Bor (DROVENIK 1968). ĐORĐEVIĆ (1994) notes essential differences in the association, resulting from the composition, complexity and formational environment of rocks, and divides it into the groups of epiclastic and pyroclastic rocks. This classification reduces the proportion of true volcanic rocks (Timozite and pyroclastics) in the first volcanic phase products.

Volcanic products of the Timok Formation build up the entire Bor structure. They are located largely in the eastern marginal area and less in the rest of the Bor complex, because most rocks, previously taken for pyroclastic material (Timozite), are in fact reworked epiclasts of the Metovnica Formation (ĐORĐEVIĆ 1994).

The entire complex of the Timok rock association is discordant over the Krivelj Formation, bounded by the reversed Brestovac dislocation and Senonian andesite basalt in the west and by Bor conglomerate and Bor fault in the east (Fig. 2).

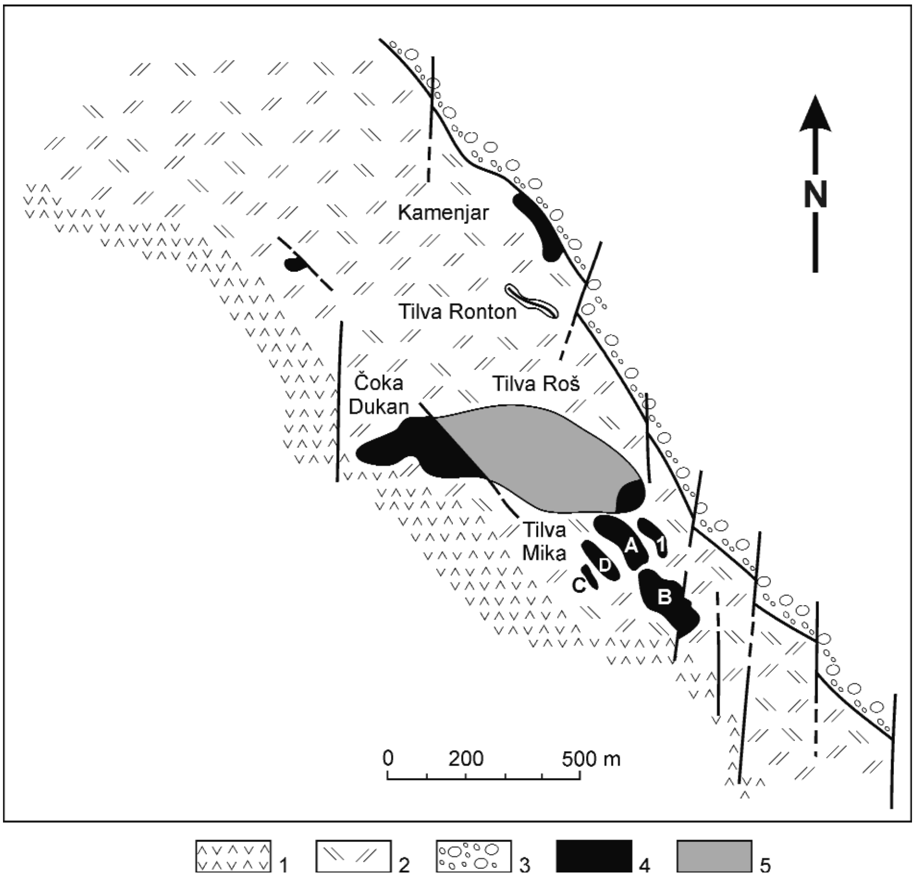

Fig. 2. Sketch geological map of Central Bor ore bodies. **1,** Timok volcanogenic Formation (Timozite); **2,** Hydrothermally altered Timozite; **3,** Bor conglomerates; **4,** Massive copper sulhide minerals (pyrite ore bodies); **5,** Impregnated ore bodies (DROVENIK F. & DROVENIK M. 1956, modified).

Diorite, quartz diorite association includes biotite, hornblende, dacite, etc. (hypabyssal rock association) and porphyry copper of the Borska Reka and Veliki Krivelj. It is related in time and petrochemistry to the above described association of volcanic rocks (MARIĆ 1975). The association occurs in small dykes and vein bodies in pyroclastics (Bor, Krivelj).

Petrology and relationship of the Upper Cretaceous igneous rocks in the Bor area are studied by MARIĆ (1957), DROVENIK (1961, 1968), ĐORĐEVIĆ G. (1985, 1995), ĐORĐEVIĆ M. (1994, 2005), BANJEŠEVIĆ (2010), et al.

Hydrothermally altered rocks and deposits, provisionally members or subunits, within volcanic and subvolcanic-intrusive rock association of the Timok Formation are potential environments and important prospecting criteria for prediction, exploration and monitoring copper ore mineralization in the Bor mineral ore field.

Large ore bodies of massive sulphide coppers and porphyry are associated with hydrothermal alteration zones, major dislocations and igneous structures and related to pyritisation, silicification, sericitisation, argillisation, and similar low-temperature alterations, as well as to chloritisation, carbonization, etc. in the lower part of deposits (Đorđević 1997).

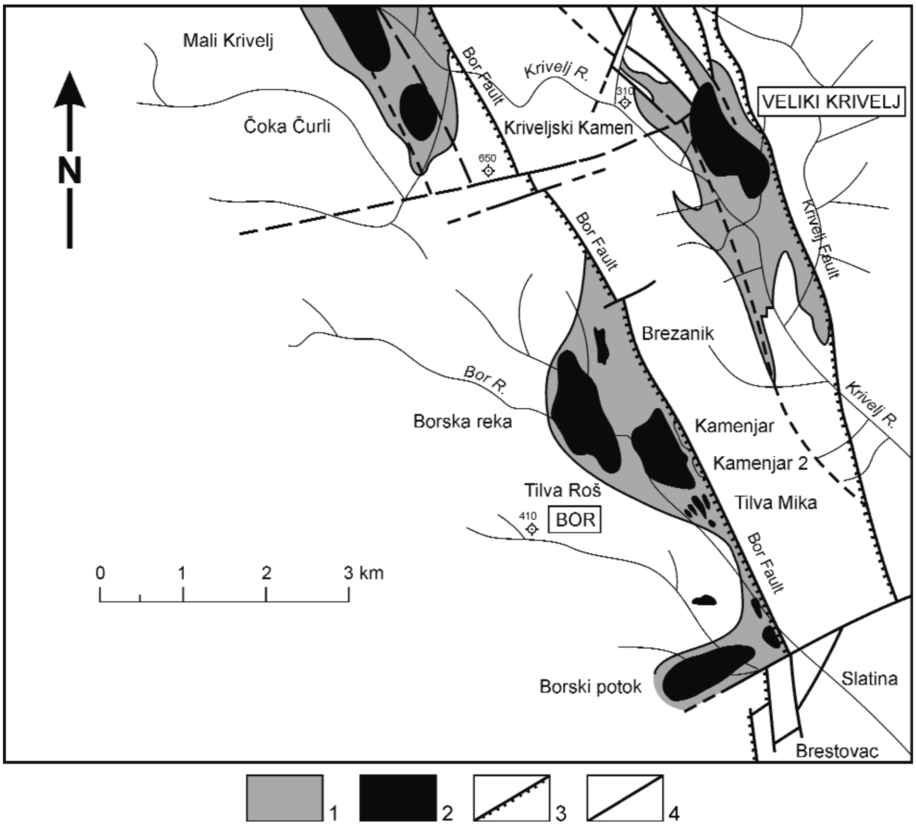

Fig. 3. Sketch tectonic map of Bor province: fault system and three hydrothermally altered zones with copper deposits Bor, Mali Krivelj and Veliki Krivelj. **1,** Hydrothermally altered zone; **2,** Ore bodies with different pyrite and copper sulphide proportions; **3,** Thrust; **4,** Fault (Drovenik F. & Drovenik M. 1956, modified).

Drovenik focuses on the hydrothermal alteration and identifies three notable alteration zones in the main massive sulphide copper deposits of central Bor (Fig. 3). The alterations are obviously related with dykes and dislocations (e.g. Bor fault) extending NNW to SSE (Drovenik 2005, p. 19).

The Overlying (Metovnica) Formation

Senonian epiclastic unit (Đorđević 1994) overlies the Timok Formation and copper deposit transgessively lain with conglomerate and breccia of hornblende-biotite andesite, reworked tuff and fragments of the underlying rocks locally including Cenomanian glauconite sandstone and ore-clasts of massive sulphide coppers. In the Jugoistok orebody, south of Bor, the sedimentary Novo Okno copper deposit of olistostrome derivation (Antonijević 2011) formed at the depth of 270 metres.

Discordantly laid over the volcanic Turonian, including zones of hydrothermal alteration and massive sulphide copper deposits (e.g. Tilva Roš), this unit resembles in composition the parent Timok pyroclastic association of rocks. It is a unit of Senonian reworked epiclastics. In stratigraphy and formation it is equivalent to the Metovnica Formation south of Bor, where the petrology and formation are well studied and described (Đorđević 1997).

Epiclasts and pyroclasts in the eastern Timok Magmatic Complex were undistinguished for a long time, taken for a unified association of volcanogenic rocks and even in Bor treated and mapped as (Timozite) the first volcanic phase.

Rocks of the Bor Complex formed and were eroded in the Turonian and later under the submarine conditions. The final product is a very thick Senonian epiclastic unit, composed of different reworked pyroclastics, which was not interpreted to be epiclastic in the Bor area. Erosional remnants of this unit in the roof of the Tilva Roš ore body, however, were proposed (Spasov 1972) and confirmed (Đorđević 2005, p. 69).

Additional mapping and map revision must separate epiclastics and pyroclastics as it has been done for the Novo Okno olistostrome copper deposit (Antonijević 2010).

The Superlain Formation

Pelite, Tuff and Bor Conglomerates

The superlain units in geology of the Bor mineral area are obviously young and not directly relevant to the interpretation and to the Turonian position of the Bor mineral deposits.

Pelite associated with tuff at Bor is generally referred to as the alternating volcanogenic-sedimentary rock association of Campanian age. This group of rocks overlay discordantly the ore-bearing Timok Formation and Senonian epiclastics. The upper units of the group form a succession of pelite and tuff alternating with fine pyroclastics dominantly of andesite-basalt phreatic tuff. ĐORĐEVIĆ *et al.* (1997, p. 87) treat Bor pelite and tuff as members of the andesite-basalt Dumbrava Formation, west of Bor.

Bor Conglomerates is the newest (Maastrichtian) formational unit of the Bor deposits, which is discordant on the Senonian (epiclastic) Metovnica Formation and over other orebody units. It is inversed in relation to the Turonian ore-bearing formation and to almost all copper bodies of Central Bor along the eastern reverse contact (Fig. 2).

Conglomerates formed during shallowing and likely regression of the Senonian sea; they contain fragments of older surrounding rocks, mainly from crystalline bedrock, and of ore ("secondary quartz derived from the Bor mineral resource area, formed through hydrothermal mineral alteration", in ĐORĐEVIĆ 1997, p. 126).

Lower units of the Conglomerates bear Middle Maastrichtian foraminiferal fauna (ĐORĐEVIĆ *et al.* 1997, p. 126).

Types of Ore Mineralisation

Geological Service records of Bor list four types of copper mineralisation: (1) Massive sulphide copper mineralisation; (2) Hydrothermal-filiform mineralisation, (3) Porphyry mineralisation, and (4) Ore-clasts of massive sulphide copper mineralisation.

Mineralisation of each type is auriferous, especially the massive sulphide copper mineral, with commercial concentrations of Cu, Au, Ag, etc. The mineral types were controlled by hydrothermal alterations and subvolcanic intrusive rocks produced by Turonian volcanic events, all but the reworked massive sulphide copper ore-clasts.

JANKOVIĆ (1990) mentions frequent occurrence of "two-mineral" ores: massive sulphide copper in the upper and stockwork-impregnated mineral in the lower or lateral deposit units.

Massive sulphide copper Mineralisation

This is the commonest widespread type of mineral in Bor, a metasomatic product in the hydrothermally altered rocks, dominantly hornblende andesite and hornblende-biotite andesite (Timozite) of the Timok Formation. Occurrences of the mineral are noted on the periphery of similar hydrothermally altered deep-seated rocks (diorite, quartz diorite, and the like).

DROVENIK (2005, p. 19) draws attention to the structural control of massive sulphide copper mineralization in most deposits (Bor fault, for example). Massive sulphide concentrations usually occur in the upper volcano-tectonic structures in NNW to SSE strike direction and in volcanic vents and fissures (Fig. 3).

Ore bodies are oblong, mainly columnar, containing metasomatic massive or stockwork-impregnated ('reticulate') copper mineral (JANKOVIĆ 1990).

Massive sulphide mineral is composed dominantly of pyrite and different copper sulphides (enargite, bornite, covellite or chalcocite) sulphides and accessory chalcopyrite, neodigenite, etc.

This type of mineralisation is prevailing in almost all copper ore bodies of Central Bor (Čoka Dulkan, Tilva Mika, Tilva Roš, etc.) and the Jugoistok deposit.

Hydrothermal-Vein Type Copper Mineralisation

This type of mineralization evolved dominantly in faults and systems of parallel fractures and fissures. Mineral bodies vary in thickness from a few cm to half a metre and from 300 to 340 metres in length (DROVENIK 1956; GRUJIČIĆ 1979; JANKOVIĆ 1990). Mineralisation occurs mainly in veins, locally in minor nests and lenses of massive sulphide (Fig. 4). Ore bodies of this type are Tilva Ronton and Brezanik and the orebody L of the Severozapad deposit.

Mineral occurrences resembling veinlets are Kraku Bugaresku and local impregnations diffused in massive sulphide rock of the Tilva Roš, Central Bor (JANKOVIĆ 1990).

Porphyry Copper Mineralisation

Lower units of the massive sulphide deposits and stockwork-impregnated ore bodies contain appreciable copper concentrations of porphyry ore (e.g. Borska Reka). They also occur in the structures that control mineralization of massive sulphides and hydrothermally altered andesite and pyroclastics.

The grade of mineral concentration in the mentioned deposits is controlled by the presence of intrusive dyke diorite, quartz diorite porphyry and related hypabyssal rocks.

Porphyry mineralisation includes large porphyry copper deposits of Veliki Krivelj and Bor (Borska Reka etc.).

Interrelation of the shallow-seated porphyry ore mineral and the massive sulphide deposits, and of the volcanic rocks similar with intrusive dykes, is not yet completely explained (JANKOVIĆ *et al.* 2002). Minor lens like concentrations of massive sulphides occur in some layers of the Borska Reka porphyry mineral.

Ore-Clasts of Massive Sulphide Mineralisation

Ore mineralization of the olistostrome derivation in Bor is a type apart; it forms chaotic mechanical assemblages of ore and non-ore fragments, ore-clasts, in continental or olistoliths in marine environment. Ore-clasts are formed by explosive destruction of the primary massive sulphide copper deposits of Bor, their ejection onto the surface and gravity slide down the volcanic land-slopes ("slumping phenomenon") into a sea basin (Antonijević 2011).

Given the high grade of the ore mineral concentrations in olistoliths, size of ore blocks up to 50 cubic metres, this type of copper mineral was found to be valuable.

A unified mineral deposit of this type is Novo Okno; its ore reserve is 2.250,000 tons, average copper concentration 4.85% (Janković 2002, p. 119). There are also some occurrences of ore-clasts near Metovnica and north of Bor town (Čoka Bare, Ujova).

Geological basement under all these deposits is made up of identical hydrothermally altered and mineralized andesites and hornblende-biotite pyroclastics and locally minor dykes of intrusive rocks.

Copper Deposit Severozapad

Brezanik is one of the Severozapad deposits. It consists of two ore bodies of notable veinlet-fissure and lens like mineralization on which it was classified as a "separate" morphogenetic type (Fig. 4).

The deposit Brezanik is geologically well explored. Its formational environment, hydrothermal alterations and paragenetic ore sequences are described by Miličić & Grujičić (1979), Janković *et al.* (2002), Drovenik (2005).

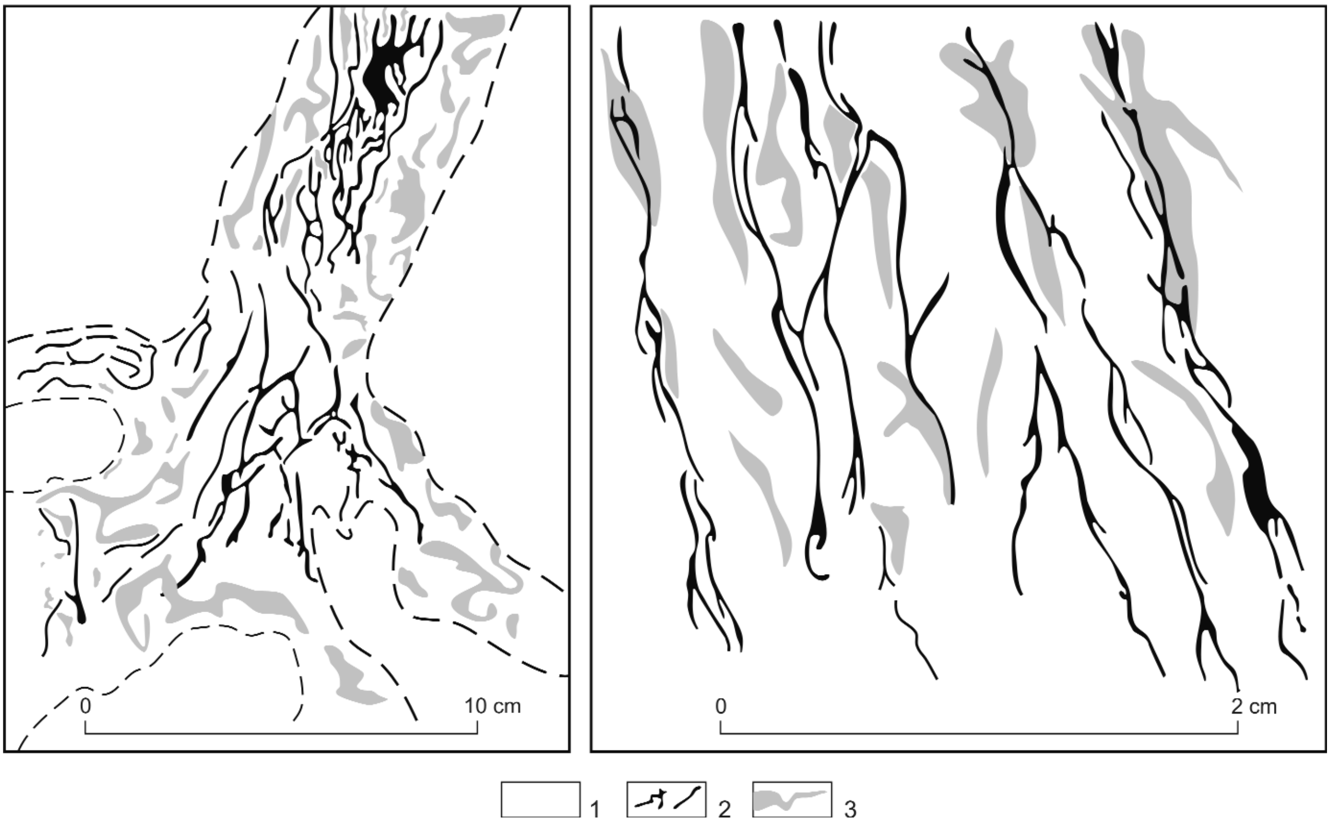

Fig. 4. Types of vein mineralization in the Brezanik deposit. **1,** Hydrothermally altered andesite; **2,** Sulphide mineralization (pyrite-chalcopyrite); **3,** Adjacent impregnations (Miličić & Grujičić 1979).

Geological Overview of Deposits

The overview of the Bor mineral deposits outlines three geographic entities based on published works, particularly the conclusive geological studies of Janković (1990), Janković *et al*. (2002), and Drovenik (2005). These are:

– Severozapad copper deposits,
– Central Bor deposits, and
– Jugoistok copper deposits.

Mineral occurs in minor massive sulphide nests and lenses and impregnations. Main rocks of the deposit are hydrothermally altered andesite and pyroclastics of the hornblende-biotite andesite (Timozite), with local occurrence of quartz diorite porphyry.

Drovenik (2005, p. 26) mentions erosional remnants of pelite and pyroclastics at the top of Brezanik deposit, which, by analogy with Tilva Roš, seems to represent parts of the similar, epiclastic Senonian rocks from the roof.

JANKOVIĆ *et al.* (2002) describe several ore minerals, of which pyrite-covellite is of economic interest. Pyrite is the dominant Fe sulphide in all types of the ore minerals.

In the Brezanik ore, Cu grade is 1.23%, and the excavated volume about 500,000 tons (JANKOVIĆ *et al.* 2002, pp. 119, 174).

Central Bor Deposits

Most of copper deposits are ore bodies (twenty) of all types and classes, and the largest volume of extracted and potential ore is located in the Central Bor (Tilva Roš, Čoka Dulkan, Tilva Mika, Borska Reka, Veliki Krivelj).

Near in distance and origin to volcanic vents and dislocations, the deposits formed in the zones of hydrothermal alteration where the formational conditions and environments were similar to those of the overlying Timok Formation.

Geological-economic value of the deposits, hundreds of millions of tons in volume, which bear commercial Cu, Au, Ag, and some other metals, in general, and the types of ore minerals and main copper deposits of massive sulphides and porphyry in particular, give the Central Bor deposits a broader metallogenetic importance.

Massive Sulphide Copper Deposits

Tilva Roš the largest copper deposit of massive sulphide: about 100 million tons mined ore with 0.66% average copper content (JANKOVIĆ *et al.* 2002, p. 119, Tab. 8). It is mentioned as the richest copper ore body in Bor.

The deposit formed along the principal volcanic structure, Bor dislocation, in NNW to SSE strike direction, in a length of 2 km. It has been mined in the same direction to a depth of 800 metres (JANKOVIĆ 1990).

Mineral is located in hydrothermally altered hornblende-biotite andesite (Timozite) like in other deposits of the Central Bor. It passes with the depth into stockwork-impregnated or porphyry type of mineralisation.

Interesting geological information on the Tilva Roš deposit *about its Upper Cretaceous age* (our italics) is given in SPASOV *et al.* (1972); it states that the overlying rocks include erosional remnants with ore breccia and clasts of the destroyed primary copper deposits. ĐORĐEVIĆ (2005, p. 69) accentuates this information and explains that ore breccia, in tuffogene cement, are remains of Senonian epiclastics reworked with ore-clasts and laid transgressively over Turonian volcanic rocks of the Tilva Roš deposit. A similar occurrence is reported by DROVENIK (2005) at the Brezanik deposit.

Published information by SPASOV (1972) and ĐORĐEVIĆ (2005) and the tuffite occurrence over the Brezanik deposit (DROVENIK 2005) add supportive evidence to the Upper Cretaceous Turonian age of the Bor copper deposits.

Čoka Dulkan is a major copper ore body of 13 million tons extracted ore, with average Cu 3.80%, mentioned as the best known massive sulphide copper ore in Bor (JANKOVIĆ *et al.*, 2002, p. 124). Types of minerals uncovered in the Čoka Dulkan, according to JANKOVIĆ *et al.* (2002, p. 128), are the following:

a. Siliceous 'cap' at the top of mineral rocks;
b. Cementation zone, under the 'cap', (zone of secondary or supergene sulphide enrichment);
c. Massive sulphides in the upper part of the orebody;
d. Stockwork-impregnated type of mineral; and
e. Hydrothermal ore veins.

Tilva Mika system is a group of small ore bodies (A, B, C, D. J, L) in the hydrothermally altered hornblende-biotite andesite and the surrounding ore bodies of the southeastern Bor.

Vertical and horizontal 'regularity' in the distribution of some facies of mineralization and alteration is observable in this deposit as well. Massive sulphide mineralisation is prevailing, and ordinarily stockwork-impregnated mineral lower in the deposit (Fig. 4).

Orebody C, smallest in the Tilva Mika group, is a mineral of the stockwork-impregnated type.

Mineral reserve of all the Tilva Mika bodies is a comparatively modest amount; the largest and richest is orebody A of 11 million tons excavated ore with average Cu 3.03% (JANKOVIĆ *et al.* 2002, p. 130).

Other ore bodies of massive sulphide coppers and disseminated stockwork-impregnated deposits in Central Bor (Šistek, Tilva Ronton, Kamenjar, Krpe, et al.) are described in the Geological Service records of Bor and in monographs by JANKOVIĆ (1990, 2002) and some other publications.

Porphyry Copper Deposits

Two almost identical porphyry copper deposits in the Bor mineral resources, Borska Reka and Veliki Krivelj, (differ slightly in size, gold content, skarn, etc.). Principal deposits, especially Veliki Krivelj, have been studied for the origin of mineralization and the Turonian position of copper deposits.

Paragenetic sequence of the porphyry copper mineralisation is simple, like most deposits of this type. Pyrite and chalcopyrite form the major proportion of the mineral, and the minor proportion consists of bornite, enargite, chalcocite and covelite (JANKOVIĆ 1990, p. 306).

Borska reka is the largest deposit of the Bor copper district, a volume of about 557 million tons and average Cu 0.6%. At a copper metal recovery of 3.6 million tons, this deposit is expected to produce more than the total amount of the copper ore extracted so far from all the mined ore bodies in Bor (DROVENIK 2005, p. 29)!

This deposit falls (by size) into the group of porphyry bodies with elevated copper and gold. It formed in somewhat different geochemical environment from those of the massive sulphides (JANKOVIĆ *et al.* 2002, p. 160).

It is localized in rocks underlying sulphide ore bodies and in stockwork-impregnated ores, in the same volcanic structure as the Bor mineral resource. The mineral and the accessory hydrothermally altered hornblende-biotite andesite low in the deposit are associated with intrusive diorite, quartz diorite porphyry dykes (Fig. 5B). Some units of the Borska Reka porphyry mineral include minor lenses and massive sulphides, elevated copper, and locally skarn (JANKOVIĆ 2002).

JANKOVIĆ (1990, p. 306) mentions impregnated-metasomatic veinlets and nests of copper mineral in the Borska Reka deposit.

The deposit is currently being prepared for exploitation. More details on the paragenetic sequence, metallogenetic and geological evaluation of the Borska Reka porphyry deposit can be obtained by referring to the Bor Mine Works records and publications by MILIČIĆ & GRUJIČIĆ (1979), BRAJKOVIĆ & PAVLOVIĆ (1989), JANKOVIĆ (1990, 2002), DROVENIK (2005), etc.

Veliki Krivelj is the second largest porphyry copper deposit of the Bor ore field; its reserve is about 465 million tons, average Cu rate 0.34% and much lower gold than in the Borska Reka. It is located some 3.5 km north of the Central Bor (The Veliki Krivelj deposit is not part of the Central Bor proper, but belongs to the Bor mineral resource; it is presented in this paper together with the porphyry deposit of the Borska Reka.).

The deposit lies within the zone of hydrothermally altered hornblende-andesite and pyroclastics, associated with intrusive diorite and quartz diorite dykes and skarn in the Krivelj dislocation.

Absolute age of the deposit varies within the range from 77 to 91 million years (Tab. 2, in: JANKOVIĆ *et al.* 2002).

Explorations in the deposit were carried out from 1965 to 1979 (OGNJENOVIĆ 1976; ALEKSIĆ 1979; ĐORĐEVIĆ 1980; etc.). It is intensively worked at present (Monograph by Janković (1990, p. 316) in the chapter Ore Deposits of Serbia (Bor Copper Deposits) gives a complete description of the Veliki Krivelj deposit.).

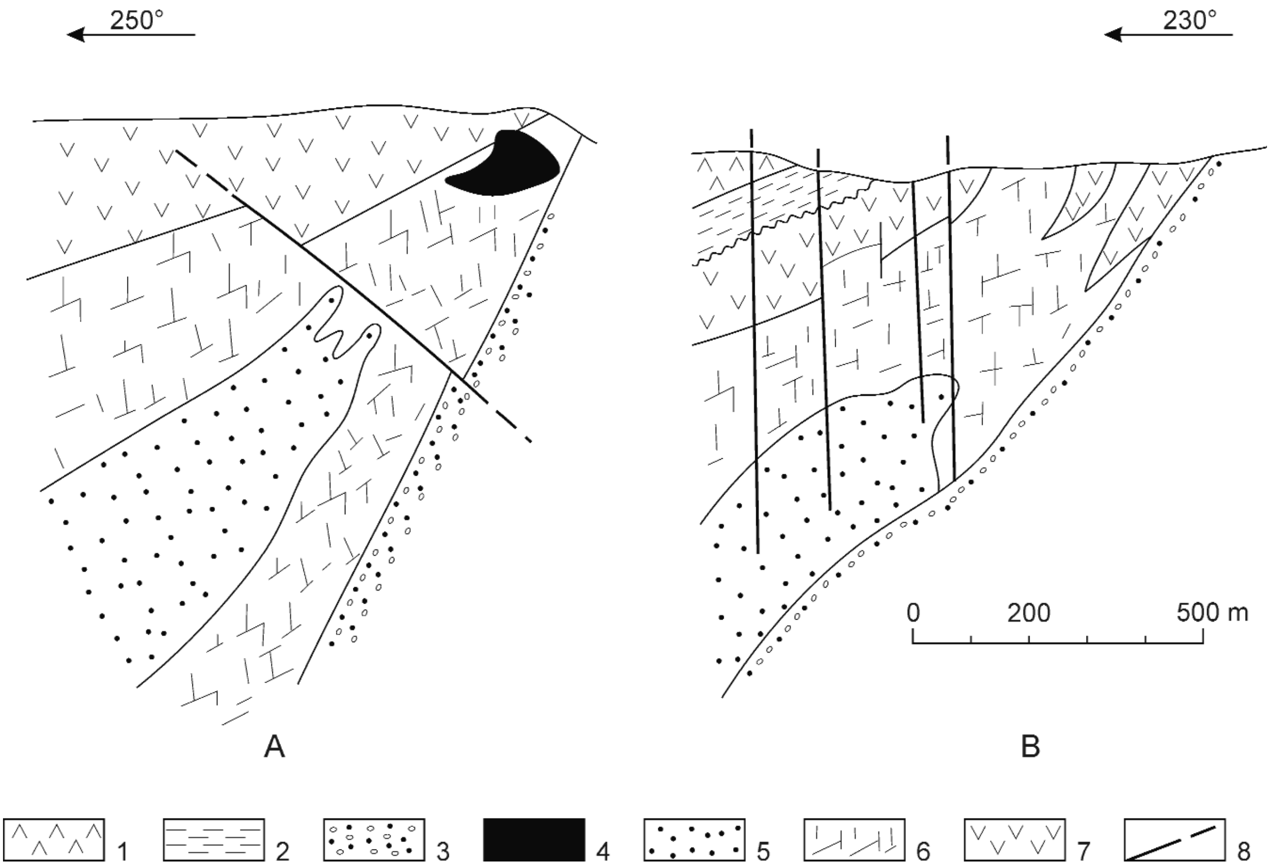

Fig. 5. Porphyry copper deposits Borski Potok (A) and Borska Reka (B). **1,** Pyroxene andesite; **2,** Bor pelite and tuff, (1–2) Dumbrava Formation; **3,** Bor Conglomerate; **4,** Massive sulphide copper (orebody X); **5,** Porphyry copper mineral; **6,** Hydrothermally altered minerals; **7,** Hornblende andesite, (4–7) Timok Formation; **8,** Fault [Schematic presentations by MILIČIĆ & GRUJIČIĆ (1979) and by BRAJKOVIĆ & PAVLOVIĆ (1989) from DROVENIK 2005, modified].

The deposit Veliki Krivelj (east) rests on Cenomanian/Turonian Krivelj Formation (ANTONIJEVIĆ 1957, 1973) underlain by glauconite sandstone and fossliferous siltstone. A part of the Formation is widely affected by Timok andesites and quartz diorite dykes, locally metamorphosed and transformed into skarn and skarnoids. Similarly mineralized is the block of Urgonian limestone, 'The Krivelj Stone'. The whole group of the Veliki Krivelj porphyry deposit units, its Cenomanin floor, intrusive dykes and skarn, are southwest inclined (Fig. 7).

Aleksić, Drovenik et al. have long believed and wrote without evidence that metamorphic sedimentary rocks underlying the Krivelj deposit were Senonian; consequently, mineralisation with skarn is post-Senonian, Paleogene. On the basis of this dating and the previous prevailing opinion the copper deposits of the entire Bor metallogenetic zone is interpreted to be Laramian or Paleogene (DROVENIK 1956–2005).

DROVENIK (2005, p. 44) finally concluded: "As far as I know, the Veliki Krivelj copper deposit is typical deposit of the whole Timok igneous complex, where the linkage of copper mineralization with the Laramian thrust fault and with dykes, especially the quartz diorite porphyry dykes, is best expressed."

Jugoistok Copper Deposit

The Jugoistok group of deposits extending from Central Bor includes copper bodies X and J, occurrences (I.M.N.), and Novo Okno olistostrome copper deposit. The group also includes the before mentioned Borska Reka porphyry deposit.

Ore Bodies X and J, studied in detail by MILIČIĆ & GRUJIČIĆ (1979), MIŠKOVIĆ (1995), and JANKOVIĆ (2002), are localized in the same rocks as the hydrothermally altered hornblende-biotite andesite of Bor.

Products of pyritisation and silicification, and less of sericitisation and kaolinitisation, according to JANKOVIĆ (2002, pp. 186–188) are extensive within the zone of hydrothermal alteration in Jugoistok. Pyrite, with copper minerals, is massive in the upper, and porphyry minerals (Borski Potok) in the lower part of the orebody X (Fig. 5a).

Copper mineralization in the orebody X was a staged process; the two principal stages, according to MILIČIĆ & GRUJIČIĆ (1979), being: older, dominantly pyrite-enargite bornite mineralization, and younger, including chalcopyrite-pyrite veinlets and gold.

Porphyry mineralization in the lower part of the orebody X is of stockwork-impregnated type in thin veinlets and "specific products of hydrothermally altered" surrounding rocks. Copper content is variable, between 0.3% and 1% (JANKOVIĆ, 1992, p. 15), whereas chalcopyrite is the commonest copper mineral in the orebody X.

Orebody J is composed of a few minor lens-like massive sulphide concentrations, marginally stockwork-impregnated, and a lower proportion o copper. The question: Was the 'deeper' part of this orebody affected by disseminated mineralization of the stockwork-impregnated type X? (JANKOVIĆ 1990, p. 316) is left open.

Geological explorations in the Jugoistok and eventual location of new mineral occurrences similar to those of the ore bodies X and J may be expected in the rift structure of the Veliki Krš and Stol monocline sunken to southeast.

Ore-clast deposit Novo okno is a new genetic type of olistostrome derivation in the Bor Metallogenetic Zone. It was uncovered in the seventies of the last century south of Bor in Turonian-Senonian epiclastics of the Metovnica Formation.

The olistostrome-derivation of the deposit was first reported at the 15th Congress of Serbian Geologists, 2010, and described later (ANTONIJEVIĆ 2011) in the Geological Annals of Balkan Peninsula, vol. 72.

Morphogenetic characteristic of an olistostrome body is a chaotic mass of mechanically mixed ore-clasts, olistoliths, Classes A and B, in a sedimentary deposit of a basin. Ore-clasts of massive sulphide coppers, from 0.5 to 50 m^3 in size, associated with amphibole andesite pyroclastics and fragments in matrix from the country rock are the main lithological member of the Novo Okno olistostrome or deposit (Fig. 7).

The olistostrome mass of the Novo Okno indicates two specific phases of formation:

(1) Turonian (pre-olistostrome) volcanic and

(2) Senonian (olistostrome) submarine phases.

The volcanic phase includes volcanic explosion of the Central Bor structure, breaking the primary ore bodies and volcanic rocks into blocks and fragments, their partial ejection to the surface and deposition on land (ore-clasts).

The submarine phase at the boundary Upper Turonian/Lower Senonian includes slumping of a semi-consolidated mass in the form of a unified gravity slide (olistostrome 320×140×30 m) down volcanic slopes into normal sediments of the basin and mechanical accumulation of ore and non-ore clasts, olistoliths (ANTONIJEVIĆ 2011, p. 103).

Mining, drilling and detail laboratory data and the paragenetic sequence of ore-clasts, the Novo Okno olistolite, indicate three mineral associations:

– Pyrite-covellite-chalcocite (Olistolith Class A from 0.5 to 50 m^3);
– Chalcopyrite-bornite (Olistolith Class B from 0.5 to 10 m^3); and
– Pyrite-chalcopyrite (ore-clasts and small rock fragments);

and rocks overlying the olistostrome sequences Classes A and B.

Ore-clasts of the Novo Okno deposit and their olistostrome derivation strongly indicate an older age of the primary massive sulphide copper deposits, most likely Middle Turonian, because the Novo Okno

Table 2. Absolute age of magmatic rocks in the Bor mineral resource (from JANKOVIĆ 2002, p. 29).

Location	Rock	Analysed	Age m.y.	Method	Source
Veliki Krivelj	H-B andesite	Amphibole	91±4	K–Ar	JANKOVIĆ *et al*. 2002
Veliki Krš	H-B andesite	Amphibole	77±3	K–Ar	JANKOVIĆ *et al*. 2002
Put Bor–Krivelj	H-B andesite	Biotite	88	Rb–Sr	JANKOVIĆ *et al*. 2002
Kriveljska reka	Andesite breccia	Amphibole	84,16	K–Ar	LOVRIĆ 1986
Kriveljska reka	Timozite breccia	Amphibole	80,56	K–Ar	LOVRIĆ 1986
Bor village	Dacite	Amphibole	65,70	K–Ar	LOVRIĆ 1986
Bor village B-2	Dacite	Amphibole	70,04	K–Ar	JANKOVIĆ *et al*. 2002
Bor river	H-B andesite	Rock	78±4	K–Ar	JANKOVIĆ *et al*. 2002
Tilva Mika pit	H-B andesite	Biotite	74	Rb–Sr	JANKOVIĆ *et al*. 2002
Bor, Bor river	H-B andesite	Rock	66,85	K–Ar	JANKOVIĆ , unpbl
Bor, Bor river	H-B andesite	Rock	66±56	K–Ar	JANKOVIĆ , unpbl
Bor pit	H-B andesite	Amphibole	89	K–Ar	BANJEŠEVIĆ *in* ĐORĐEVIĆ 2005
"Novo Okno"	H-B andesite	Amphibole	±90	K–Ar	MIŠKOVIĆ 1989
Todorov potok–Krivelj	Diorite	Rock	75.33	K–Ar	
Veliki Krivelj	Diorite-Porphyry	Rock	77±76	K–Ar	JANKOVIĆ *et al*. 2002

deposit was formed in the Upper Turonian/Lower Senonian epiclastics (ANTONIJEVIĆ 2011, p. 108).

The interpretation of MIŠKOVIĆ (1995) of the "distal" Novo Okno copper deposit in the Jugoistok massive sulphide mineral (ore bodies X and J) is therefore untenable.

Discussion of the Deposit Formation and Origin

Absolute age of the Bor mineral deposit was determined mainly using the K-Ar method on a relatively small number of rock and mineral samples. The process of mineralization, interpreted by Janković (2002, p. 30), evolved within the range from 91 m.y. to 66 m.y. Translated into the language of relative age, Bor volcanic rocks (first phase volcanism) and their hypabyssal equivalents (diorite, quartz diorite, etc.) may be taken for pre-Senonian, formed in the interval Turonian-Senonian.

Porphyry copper deposit of Veliki Krivelj formed in the hornblende-biotite andesite environment, from 88 m.y. to 91. m.y. absolute age, and partly in its pyroclastics and quartz diorite (JANKOVIĆ 1990, p. 316).

Some intrusions, however, such as the Todorov Potok diorite, are 76 m.y. K-Ar dated.

ĐORĐEVIĆ (2005, p. 87) mentions the age of ±90 m.y. using Banješević' (K-Ar) data for two hornblende grains from pyroclasics of the Bor Mine (Tab. 2).

Absolute age of hornblende andesite from under the Novo Okno olistostrome, south of Bor, also was ±90 m.y. by K-Ar method (MIŠKOVIĆ 1989).

Summarizing the research results and the new determinations of the absolute age of volcanogenic intrusive rocks in the Timok region, Banješević writes: "Volcanism in the Timok Magmatic Complex has a long history of ten million years. It began at the Turonian/Senonian boundary. The oldest rocks are dated Upper Turonian; shallow-seated rocks formed up to the Upper Senonian. Copper porphyry ore minerals in Bor and Krivelj are Santonian." (BANJEŠEVIĆ 2010, p.3).

JANKOVIĆ *et al*. (2002, p. 30) discuss further the absolute age of the Bor complex and conclude:

"The determined age of magmatic rocks varies within a wide range even of one and the same type. Any result that deviates much from the relative rock age cannot be taken into consideration.

"Age determination of the Bor magmatic rocks therefore should be taken for preliminary; further systematic examination is needed, especially of the stratigaphic relationship between porphyry ore minerals in the lower and massive sulphide minerals in the upper parts of the deposits."

It needs to be noted, however, that none of the subvolcanic-intrusive rocks of the Bor Complex analysed so far were identified as Laramian or the Paleogene absolute age.

Relative age. Without reliable evidence of the geologic age of magmatic rocks in the Bor Complex, conventional prospecting methods were used, some of which, in our opinion, are crucial in addressing the age issue. These are:

– Superposition,
– Biostratigraphy, and
– Reworked ore-clasts.

Superposition. Recent investigations have confirmed that the ore-bearing volcanogenic rocks of the Bor Complex rest on the Krivelj Formation (Cenomanian–Lower Turonian) and under the Metovnica Formation of epiclastics (Upper Turonian–Lower Senonian) (ANTONIJEVIĆ 2010).

The Krivelj Formation, for example, is characterized by fossiliferous pelitomorphic rocks and the associated glauconitic sandstone and conglomerate at the base. It is transgressively underlain by the Veliki Krš carbonate monocline (Vlaole, Veliki Krivelj, Kvarnana) and the Krivelj Stone (Fig. 6). The upward extent and relationship of this deposit (Cenomanian––Lower Turonian) into and with the volcanogenic Turonian is a conjucture.

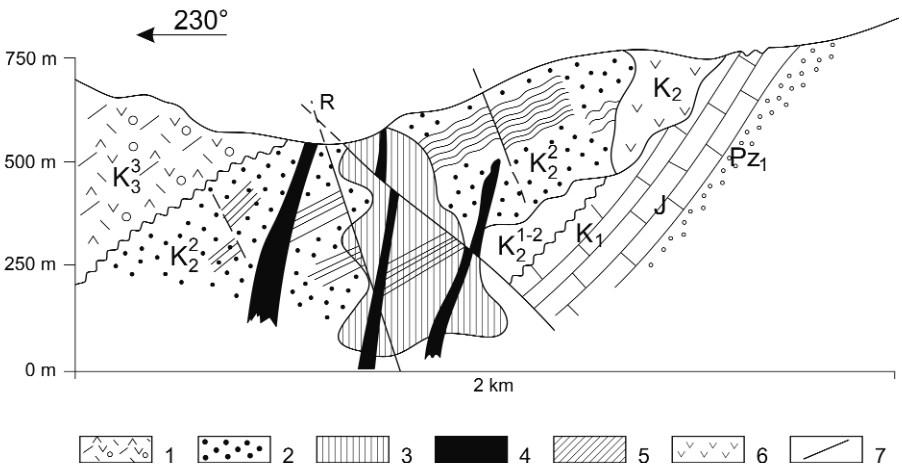

Fig. 6. Compiled section of the Veliki Krivelj porphyry copper ore bodies (ANTONIJEVIĆ 1953, 1973, OGNJANOVIĆ 1976, ALEKSIĆ 1979). **1,** Epiclastics of the Metovnica Formation; **2,** Hydrothermal alteration zone; **3,** Copper deposit; **4,** Diorite, Quartz diorite porphyry; **5,** Skarn; **6,** Hornblende andesite (K_2^{1-2} Cenomanian–Turonian, K_1–J Jurassic–Cretaceous, P_zl Paleosoic); **7,** Fault.

In the Veliki Krivelj porphyry copper deposit, at the contact with volcanic rocks and quartz diorite, the underlying rocks, dominantly pelite, are locally metamorphic and transformed into skarn, and together with the deposit are generally westward inclined (ALEKSIĆ 1979, Fig. 6).

The superjacent epiclstics (Upper Turonian–Lower Senonian), variable in thickness and well stratified, are transgressive over the volcanogenic Turonian and Bor mineral deposits (Tilva Roš for one). Epiclastics are composed of the older subjacent rock fragments, mainly amphibole andesite clasts including Cenomanian sandstone pebbles and ore-clasts of the primary massive sulphide deposits.

The described stratigraphic relationship has been located long before even in Bor, at the top of the Tilva Roš deposit (SPASOV *et al.* 1972), and explicitly confirmed in field (ĐORĐEVIĆ, 2005, p. 69). In a controversial argument with DROVENIK (1973) Đorđević mentions stratigraphic position and age of the later uncovered Novo Okno deposit as evidence of the Upper Cretaceous Bor mineralization.

Biostratigraphy. Relative ages of the Bor mineral resource subjacent and superjacent rocks are determined using the non-abundant but characteristic fossils of macro- and micro-fauna.

Rocks, for example those underlying the Krivelj deposit, are dated Vraconian (Albian–Cenomanian) on zonal cephalopods *Turrilites bergeri, Montoniceras inflatum*, etc., and the rocks over the Vraconian Beds bearing *Montoniceras rostratum, Anisoceras, Guadryceras*, etc. are dated Lower and Middle Cenomanian (ANTONIJEVIĆ 1973, 2010).

Rocks overlying the Bor deposits are dated Upper Turonian–Lower Senonian on the microfossil globotruncanid association of *Marginotruncana coronata, Globotruncana lineinana*, etc. (SLADIĆ & GAKOVIĆ, 1988) in pelites of the Metovnica Formation. Fossiliferous pelites rest on Turonian andesite (Timozite) immediately under the Novo Okno olistostrome (Fig. 7).

Copper deposits of the Bor mineral resource are taken, through evidence of superposition and biostratigraphy, to be older than the epiclastic Metovnica Formation (Upper Turonian–Lower Senonian) and the Novo Okno deposit.

Reworked Ore-Clasts in Bor are angular fragments/blocks of hornblende-biotite andesite and pyroclastics, in similar bodies, reworked with other redeposited material from the Cenomanian–Turonian subjacent unit, which indicate a younger age than the Bor deposits. The lowermost parts of the deposits and the olistostrome Novo Okno include some fossiliferous rocks from the Upper Turonian and Lower Senonian as mentioned before.

Erosion remnants of epiclastics with ore clasts over the Tilva Roš are mentioned particularly as a contribution to the discussion of SPASOV (1972) on the Upper Cretaceous pre-Senonian age of the Bor mineral resource.

The age of hornblende andesite from under the Novo Okno, K-Ar determined ±90 m.y. (MIŠKOVIĆ 1989), is overlain immediately with the Novo Okno deposit and epiclasics of the Senonian Metovnica Formation, which is additional evidence of the stratigrahic relationship of rocks and of the origin of Bor mineral deposits.

Accordingly, the mentioned investigation data in general and the relative geologic age (based on super-

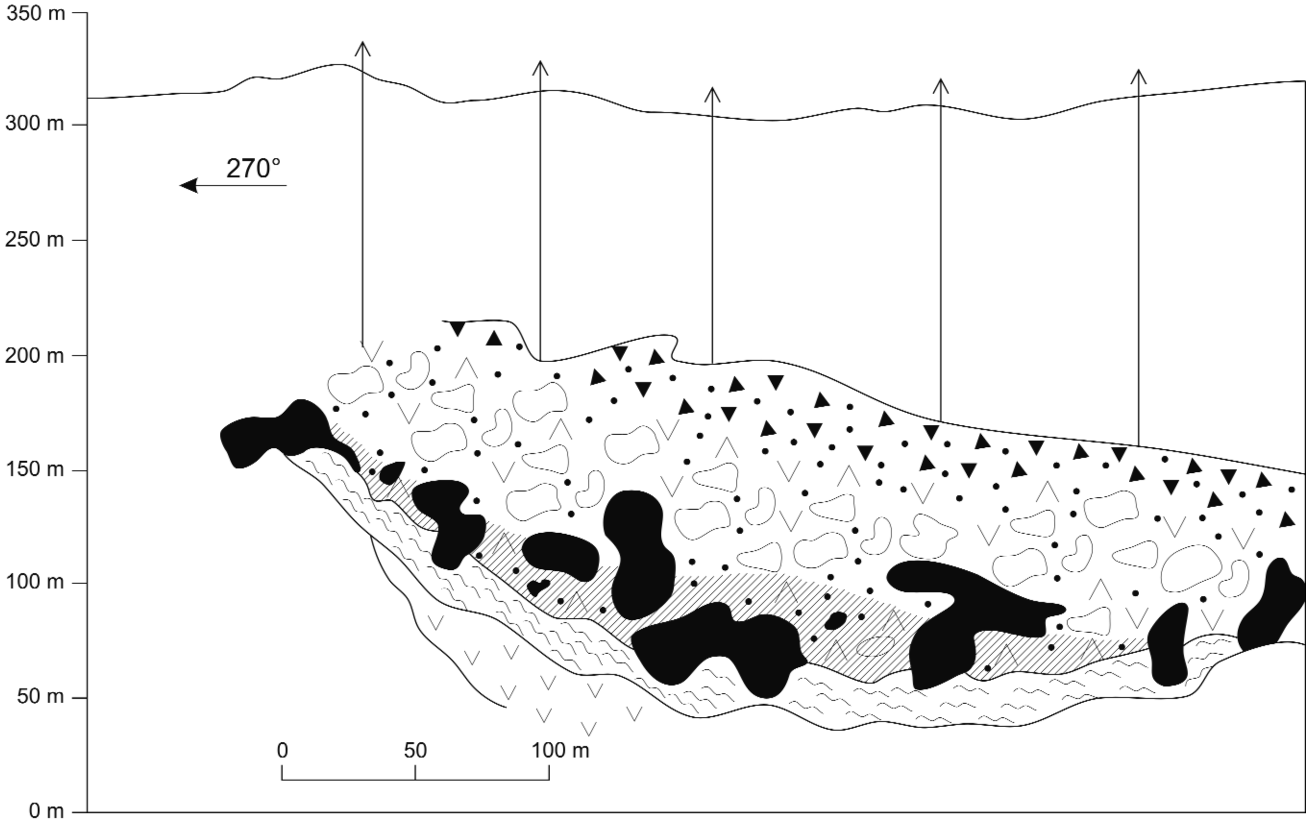

Fig. 7. Ore-clast deposit Novo Okno, K_2^{2-3} (schematic). **1,** Olistoliths Class A; **2,** Olistoliths Class B; **3,** Matrix; **4,** Subjacent pelite; **5,** Hornblende-biotite andesite; **6,** Superjacent epiclastics.

position, biostratigraphy, Cenomanian subjacent and Senonian superjacent rocks, reworked ore-clasts) in particular, support the argument of SPASOV (1972), ĐORĐEVIĆ (1994, 1997, 2005) and our studies (2010, 2011) that mineralization ceased before the Upper Turonian and that the Bor mineral resources are probably Middle Turonian.

Summary

Bor copper mineralization is dated Cenomanian––Turonian on evidence of the ore-bearing Timok Formation and its subjacent Cenomanian and superjacent Senonian units. Relative age of ore minerals in the Formation are considered here for the first time Turonian.

Reworked ore-clasts of the primary Bor copper minerals and their derivation from olistostrome in the Novo Okno orebody (Upper Turonian–Lower Senonian) are an even stronger argument that the Laramian model of the Paleogene copper metallogeny in Bor is no longer tenable.

Bor mineral ores are underlain by the fossiliferous (Cenomanian) Krivelj Formation (Veliki Krivelj, Bučje, Kvarnana) and overlain with (Turonian–Lower Senonian) epiclastics and ore-clasts of the Metovnica Formation (Tilva Roš, Novo Okno, et al.).

The Krivelj Formation is transgressive over Lower Aptian carbonate rocks (Veliki Krš) NE of Bor. This is the oldest formational unit that underlies volcanogenic Turonian and Bor ore minerals. Within the Veliki Krivelj porphyry extent, it is intruded deeply at the base, metamorphised and partly transformed into skarn.

Volcanogenic Turonian of the Timok Formation is a complex intermediate subaerial unit, locally composed of calc-alkalic, mainly volcanic rocks and pyroclastics (Timozite), hydrothermal alterations and subvolcanic-intrusive deep-seated dykes (diorite, quartz diorite porphyry, etc,).

Rocks of the Timok Formation generate ore mineralization and formation of massive sulphide and porphyry copper minerals in Bor and Veliki Krivelj.

Senonian superjacent unit (epiclastics of the Metovnica Formation), transgressive over the ore-bearing Timok Formation (volcanogenic Turonian) and Bor mineral deposits (Tilva Roš), includes fragments of almost all reworked subjacent rocks and locally reworked ore-clasts of the primary massive sulphide copper rocks.

The Novo Okno ore-clast body of olistostrome derivation (Upper Turonian–Lower Senonian) formed in deepest pelite of the Metovnica Formation, the Jugoistok deposit south of Bor.

Erosional remnants of epiclastics and mineralized tuff breccia and clasts of the destroyed primary massive sulphide copper rocks over the copper bodies (Tilva Roš, Brezanik et al.) clearly indicate stratigraphic relationship and pre-Senonian, Turonian age of the Bor copper deposits.

Copper ore minerals of Bor are products of several types of mineralization: Massive sulphide coppers, hydrothermal veinlets (stockwork-impregnated), Porphyry, and Ore-Clasts olistostrome.

Each type of ore mineral is auriferous, massive sulphide coppers more than the others. Amounts of the contained Cu, Au, Ag and other minerals have commercial value. The process of mineralization was controlled in time and space by volcanic and subvolcanic intrusive rocks and products of hydrothermal alteration of Turonian volcanic rocks. An exception is Novo Okno, a younger copper deposit reworked from olistostrome.

Copper deposits of the Bor metallogenetic ore field are divided into three 'geographic' units: Severozapad (Brezanik), Central Bor deposits and ore bodies (20), and Jugoistok (ore bodies X, J, Novo Okno, et al.). The porphyry orebody Veliki Krivelj, NW in the province, is treated within Central Bor, with the Borska Reka deposit.

Most deposits and ore bodies of massive sulphide coppers are uncovered and mined in the Central Bor (Tilva Roš, Čoka Dulkan, Tilva Mika, et al.). They formed in similar geological settings and were closely related to volcanic structures and dislocations (Bor and Krvelj faults, for example), and to hydrothermally altered hornblende-biotite andesite and minor dykes of deep-seated, hypabyssal intrusive rocks.

Largest porphyry copper deposits, Borska Reka and Veliki Krivelj, located in the Central Bor area, are studied for the period of mineralization and for Turonian position of minerals. These deposits are found by drilling low in massive sulphide rocks and in stockwork-impregnated mineral ore, in the same structures but in somewhat different geochemical environment (e.g. Borska Reka) in relation to massive sulphide mineralization.

Veliki Krivelj is the second largest copper deposit in Bor, localized in a zone of hydrothermally altered hornblende-biotite andesite and pyroclastics, 88–91 m.y. K–Ar absolute ages, in association with intrusive Turonian quartz diorite dykes and skarn. Stratigraphy of Turonian volcanic and similar deep-seated rocks (diorite, quartz diorite, etc.) of the Krivelj deposit is yet to be studied. Copper deposits Jugoistok (massive sulphide ore bodies X and J) are almost identical with the Central Bor deposits. The only open question is: Did the porphyry stockwork-impregnated mineralization of the orebody X type evolve in the lower part of the orebody J?

The Jugoistok group includes the Novo Okno copper orebody of a different derivation, from an olistostrome. Morphogenetic characteristics of the orebody and its position in Upper Cretaceous sedimentary deposits indicate a particular composition, a clastic, mechanical accumulation of ore-clasts, olistoliths, from 0.5 m^3 to 50 m^3 in size Classes A and B, slumped in sea basin (Upper Turonian–Lower Senonian).

All the reported research results about Bor mineral deposits, their origin and relationship with the subjacent and superjacent units, and interpretation of the Novo Okno deposit formation, are supporting the discussed Turonian age of the Bor mineral source.

None of the analysed rocks or rock deposits in the Bor complex was of (absolute or relative) age that corresponds to the Laramian, Paleogene metallogeny.

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References

ALEKSIĆ, D. 1979. The Deposit Veliki Krivelj. International Symposium: The European Copper Deposits, Field Trip Guide Book, 39–51, Bor.

ANTONIJEVIĆ, I. 1958. Lower Cretaceous between Krivelj and Bučje. *Geološki vesnik*, 16: 5–27 (in Serbian, German summary).

ANTONIJEVIĆ, I. 1973. Stratigraphy and Tectonics of Veliki Krš and Stol in eastern Serbia. *Memoirs du service Geologique et Geophysique*, Unpublished PhD Dissertation, 10: 1–111 (in Serbian, English summary).

ANTONIJEVIĆ, I., GRUBIĆ, A. & ĐORĐEVIĆ, M. 1974. The Upper Cretaceous Paleorift in Eastern Serbia. Metallogeny and Concepts of the Geotectonic Development of Yugoslavia. Faculty of Mining and Geology, 1974: 315–339, Belgrade.

ANTONJEVIĆ, I. 2010. Formational Base of the Bor Copper Deposit. Proceedings of the 15th Congress of Geologists of Serbia, 177–180, Belgrade (in Serbian).

ANTONIJEVIĆ, I. 2011. The Novo Okno Copper Deposit of Olistostrome Origin, Bor, Eastern Serbia. *Geološki anali Balkanskoga poluostrva*, 72: 101–109.

BANJEŠEVIĆ, M. 2011. Volcanological Characteristics of the Timok Magmatic Complex. *Proceedings of the 15th Congress of Geologists of Serbia*, 1–6, Belgrade (in Serbian).

BRAJKOVIĆ, M. & PAVOVIĆ, Đ. 1989. The Borska Reka Orebody Investigation Results. *XXI Conference of Miners and Metallurgists*, 5–16. Bor (in Serbian).

DROVENIK, F. & DROVENIK, M. 1956. Current Findings of Ore Mineralization in the Timok Andesites. *1st Yugosla-*

vian Geological Congress, Bled, 267–292 (in Serbian, English summary).

DROVENIK, M. 1961. Geological-Petrological Study of Bor Greater, Eastern Serbia. Unpublished Doctoral Thesis, Ljubljana, 1–344 (in Serbian, English summary).

DROVENIK, M. 1968. Development of Igneous and Pyroclastic Rocks in the Bor Copper Mine Zone. *Geology, Rasprave in poročila*, 111–127 (in Slovenian, English summary).

DROVENIK, M. 1973. On the Upper Cretaceous Age of the Bor Deposits (Comments on Spasov et al., 1972). *Zbornik radova Rudarsko-geološkog fakulteta i Institut za bakar u Boru*, 14: 33–40 (in Serbian, English summary).

DROVENIK, M. 1993. Contribution to the Study of Ore-Clasts from the Novo Okno Orebody in the Bor Copper Deposit. *Geology, Rasprave in poročila*, 35: 287–318 (in Slovenian, English summary).

DROVENIK, M. 2005. Origin of the Bor and Other Copper Deposits in the Region, Eastern Serbia. *Rasprave IV razreda SAZU*, 46: 5–81 (in Slovenian).

ĐORĐEVIĆ, G. 1980. Quartz Diorite Porphyry of Veliki Krivelj, Its Alteration and Association with Mineralization. Magisterial Thesis. Rudarsko-geološki fakultet, Beograd (in Serbian).

ĐORĐEVIĆ, M., 1989. Formational Geological Explorations for Mineral Occurrences in the Timok Eruptive Area. Oktobarsko savetovanje rudara i metalurga, Saopštenja, 7–12. Tehnički fakultet, Bor. Institut za bakar (in Serbian, Summary in English).

ĐORĐEVIĆ, M., Pyroclastics and Epiclastics of the First Volcanic Phase in the Timok Eruptive Area. *Geološki vesnik*, Serija A, B, Geology 46: 291–311 (in Serbian, Summary in English).

ĐORĐEVIĆ, M. & BANJEŠEVIĆ, M, 1997. Geology of the south part of the Timok Eruptive area. Savezno ministarstvo za privredu, 171 pp. Beograd (in Serbian, English summary).

ĐORĐEVIĆ, M. 2005. Volcanogenic Turonian and Epiclastic Senonian in the Timok Magmatic Complex between Bor and Tupižnica Mountain, Eastern Serbia. *Geološki anali Balkanskoga poluostrva*, 66: 63–71.

JANKOVIĆ, S. 1990. Ore Deposits of Serbia. a. Metallogenetic Zone Bor; b. Bor Mineral Resources. Monograph, 1–760. Fond za geološka istraživanja i Zajednica nauke Srbije, Beograd (in Serbian, English summary).

JANKOVIĆ, S., JELENKOVIĆ, R. & KOŽELJ, D. 2002. The Bor Copper and Gold Deposits. 298 pp. Mining and Smelting Basin Bor (RTB Bor), Copper Institute Bor (CIB), Bor.

LAZAREVIĆ, M., 1909. Die Enargit-Covellin der Čoka Dulkan bei Bor in Ostserbien, Ibid. 20: 337–370, Wien.

LAZAREVIĆ, M. 1912. Neue Beobahtungen über die Enargit-Covellin Legestätten von Bor und verwandte Vorkommen. Zt. f. prakt. Geol. 17: 177–179.

Lovrić, M. 1972. Upper Cretaceous Tertiary Magmatic Formations in the Timok-Srednjogorje Region and Their Absolute Age. *III Savetovanje o istraživaju bakronosne mineralizacije na teritoriji SFRJ*. RTB Bor. 17–50 (in Serbian).

MARIĆ, L. 1957. Igneous Rocks in the Bor Mine Area Proper, Eastern Serbia. *Pos. izd. SANU* CCXVI, Odel. prir. Nauka, 17: 1–71 (in Serbian).

MILIČIĆ, M. 1978. Geological Evaluation of the Bor Copper Ore Bodies H and J. *"Bakar"* Bor, 23: 26–50 (in Serbian).

MILIČIĆ, M. & GRUJIČIĆ, B. 1979. Metallogenetic Features of the Bor Province. International Symposium on the European Copper Deposits. Field Trip Guide Book. 82–104, Bor.

MIŠKOVIĆ, V. 1989. Genesis of the Copper Deposit Novo Okno and Metallogenetic Correlation with Ore-Clasts in the Bor Province, Eastern Serbia. Unpublished. 189 pp., Faculty of Mining and Geology, Belgrade (in Serbian).

MIŠKOVIĆ, V. 1995. Distal Copper Deposit Novo Okno, a Special Type of Massive Sulphide Mineral in the Carpatho-Balkan Metallogenetic Belt. *Carpatho-Balkan Geological Association*, 4 (2): 789–793, Athens.

OGNJANOVIĆ, S. 1976. Deformative Fabric of the Veliki Krivelj Orebody. Unpublished. Institut za bakar. Odeljenje za geologiju, Bor (in Serbian).

SLADIĆ, M. & GAKOVIĆ, M. 1988. Paleontological Identification of Materials from Bor Area. Unpublished Internal Report, Institut za bakar Bor (in Serbian).

SPASOV, T., STEVANOVIĆ, O., MILIVOJEVIĆ, S. & MILIČIĆ, M. 1972. Available and New Information on Copper Mineralization in Eastern Serbia. III Savetovanje o istraživanju bakrove mineralizacije na teritoriji SFRJ, RTB, Bor: 1–24 (in Serbian).

Резиме

Борска лежишта бакра: геологија, постанак и старост лежишта

Геологија борских лежишта, процеси вулканизма и временски односи рудне минерализације (старост лежишта), приказани су формационо у дијапазону ценоман–турон. На основу суперпозиције Тимочке рудоносне формације и геолошких односа њене ценоманске подине и сенонске повлате, релативна старост борских лежишта и ове формације први пут се приказују као туронска.

Редепоновани рудокласти примарних борских лежишта и олистостромска интерпретација тих рудокласта у лежишту бакра "Ново Окно" (горњи турон–доњи сенон), посебно указују да није више одрзив ларамијски концепт о палеогеној металогенији бакра у рудном пољу Бор.

Геолошку основу тимочке формације и борских лежишта изграђује фосилоносна Кривељска формација (ценоман) (Велики Кривељ, Бучје, Кварнана), а повлату епикластити са рудокластима метовничке формације (турон–доњи сенон; Тилва Рош, "Ново Окно" и др.).

Кривељска формација лежи трансгресивно преко карбонатних стена доњег апта (Велики Крш) североисточно од Бора. То је најстарија формаци-

она јединица, подина вулканогеног турона и борских лежишта. У домену порфирског лежишта Велики Кривељ дубоко залази у основе лежишта где је метаморфисана и делом претворена у скарнове.

Вулканогени турон Тимочке формације представља сложену рудоносну јединицу у вулканској структури Бора, интермедијару субаерску са веома израженим калкоалкалним стенама, нарочито вулканитима и пирокластитима (тимоцити), хидротермалним алтерацијама субвулканско-интрузивним дајковима дубље консолидације (диорити, кварцдиоритпорфирити и др.).

Стене Тимочке формације генеришу рудну минерализацију и настанак лежишта масивних сулфида и порфирских лежиста бакра у Бору и Великом Кривељу.

Повлатна сенонска јединица лежишта (епикластити Метовничке формације) лежи трансгресивно преко рудоносне Тимочке формације (вулканогени турон) и борских лежишта (Тилва Рош). У епикластитима повлате (сенон) налазе се фрагменти скоро свих старијих преталожених стена подине, укључујући локално редепоноване рудокласте масивних суфида бакра примарних лежишта.

На потезу лежишта "Југоисток", јужно од Бора, у најдубљим пелитским наслагама Метовничке формације, са глоботрунканама, формирано је лежиште рудокласта "Ново Окно" олистостромске генезе (горњи турон–доњи сенон).

Сачувани ерозиони остаци епилкастита, са рудним туфозним бречама и кластима разорених масивних сулфида примарних лежишта бакра, у повлати борских рудних тела (Тилва Рош, Брезаник и др.), јасно указују на међусобне односе и пресенонску туронску старост лежишта бакра у рудном пољу Бор.

Међу лежиштима бакра у Бору познато је неколико типова рудне минерализације: лежишта бакра масивних сулфида, хидротермално-жиличасти тип (стокверкно-импрегнациони), порфирски тип и рудокласти олистостромске генезе.

Сви типови рудне минерализације су златоносни, нарочито лежишта бакра масивних сулфида, са комерцијалним садржајима Cu, Au, Ag и других метала. Строго су генетски и просторно контролисани вулканским и субвулканско-интрузивним стенама и продуктима хидротермалне алтерације туронског вулканизма. Изузетак је младо редепоновано, лежиште бакра "Ново Окно", олистостромске генезе.

Лежишта бакра у рудном пољу Бор груписана су у три "географске" целине: лежиста бакра Северозапад (Брезаник), Централна лежишта Бора и рудна тела (± 20) и лежишта бакра "Југоисток" (рудна тела "X" и "J" "Ново Окно" и др.). Порфирско лежиште Велики Кривељ, на северозападу, приказано је у групи лежишта Централног Бора, са порфирским лежиштем Борска Река.

Највећи број лежишта и рудних тела бакра масивних сулфида откривен је и откопаван у централном делу Бора (Тилва Рош, Чока Дулкан, Тилва Мика и др.). Настала су у сличним геолошким срединама и тесној генетској вези са структурама вулканског апарата и дислокацијама (борски и кривељски расед, на пример), у хидротермално алтерисаним зонама хорнбленда-биотит андезита и мањих дајкова интрузивних стена хипоабисалне консолидације.

У централној зони Бора налазе се и највећа порфирска лежишта бакра: Борска Река и Велики Кривељ. Кључна лежишта, посебно Велики Кривељ, за решавање временске проблематике борске минерализације и туронску позицију лежишта.

Откривена су бушењем у нижим деловима лежишта масивних сулфида и стокверкно-импрегнационих руда, у истим структурама али у нешто другачијим геохемијским срединама (Борска река, на пример) у односу на минерализацију масивних сулфида.

Порфирско рудиште Велики Кривељ друго је по величини лежиште бакра у рудном пољу Бор. Налази се нешто северније у зони хидротермално промењених хорнбленда-биотит андезита и пирокластита, апсолутне старости 88–91 милион година (Ka/Ar), у асоцијацији са интрузивним туронским дајковима кварцдиорита и скарновима. Међусобни односи туронских вулканита и материјално сличних стена дубље консолидације (диорити, кварцдиорити и др.), Кривељског лежишта и др., предмет су посебних, даљих истраживања.

Лежишта бакра Југоисток (рудна тела масивних сулфида "X" и "J") потпуно су индентична лежиштима Централног Бора. Отворено је, међутим, питање да ли је и у нижим деловима рудног тела "J" дошло до стварања порфирске штокверкно-импрегнационе минерализације типа рудног тела "X" (7).

Групи лежишта Југоисток у Бору припада и "Ново Окно", посебан тип лежишта бакра олистостромске генезе. Морфогенетске одлике лежишта и његов положај у седиментним горњокредним наслагама, указују на специфицну геолошку грађу и механичку хаотичну акумулацију рудокласта - олистолита (Slumping phenomenon), величине 0,5 до 50 m^3, "A" и "Б" класе, у морски басен (горњи турон–доњи сенон).

Сви приказани резултати истраживања борских лежишта, посебно дискусија о њиховој старости и међдусобним односима подине и повлате лежишта и генетска олистостромска интерпретација лежишта "Ново Окно" потврђују изложену концепцију да су лежиста бакра у рудном пољу Бор туорнске старости.

Ни у једној до сада анализираној средини није утврђена старост борских стена и лежишта (апсолутна и релативна), која би одговарала ларамијској односно палеогеној металогенији.

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Ceramic clays from the western part of the Tamnava Tertiary Basin, Serbia: deposits and clay types

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Abstract. Based on geological, mineralogical, physical, chemical and technological investigations in the Tamnava Tertiary Basin near Šabac town (western Serbia), deposits of ceramic clays were studied. These ceramic clays are composed of kaolin–illite with a variable content of quartz, feldspars, mica, iron oxides and hydroxides, and organic matter. Four main types of commercial clays were identified: i) red–yellow sandy–gravely (brick clays); ii) grey–white poor sandy (ceramic clays); iii) dark-carbonaceous (ceramic clays); and iv) lamellar ("interspersed") fatty, poor sandy (highly aluminous and ferrous clays). Ceramic clays are defined as medium to high plastic with different ranges of sintering temperatures, which makes them suitable for the production of various kinds of materials in the ceramic industry.

Key words: ceramic clays, deposits and clay types, Tamnava Basin, western Serbia.

Апстракт. На основу геолошких, минералошких, физичких, хемијских и технолошких испитивања дати су резултати испитивања керамичких глина лежишта тамнавског терцијарног басена (западна Србија). Ове керамичке глине су углавном састављене од каолин-илита, са променљивим садржајем кварца, фелдспата, лискуна, оксида гвожђа и органске материје. Постоје четири главна типа комерцијалних глина: i) црвено-жута песковито-шљунковито опекарска глина, ii) сиво-бела слабо песковита керамичка и делом ватростална глина, iii) тамна-угљевита керамичка глина, iv) прошарана (ламеларна) слабо песковита, масна високо алуминозна и гвожђевита глина. Анализиране глине су средње до високо пластичне са различитим температурама синтеровања, што их чини погодним за производњу различитих производа у керамичкој индустрији.

Кључне речи: керамичке глине, лежишта и типови глина, тамнавски басен, западна Србија.

Introduction

Ceramic clay deposits, situated in Mio–Pliocene sediments of the western part of the Tamnava Tertiary Basin (western Serbia), were discovered in the middle of the last century. Most parts of these deposits are located in the areas of the villages Donje and Gornje Crniljevo (approximately 65 km to the South of Šabac, Fig. 1) with active open pits of grey–white clays Bele Vode and Zbegovi (the Jovanovića Brdo open-pit only produces brick clay and dark-carbonaceous clay). Besides these, Stare Kuće, Latkovac, Kisela Voda, Ramnava, and Brezaci are newly discovered deposits situated in the wider area (Radosavljević *et al.* 1994). The production of grey–white ceramic clay is about 100,000 tons per annum, and the total reserves are estimated at over 50 million tons (Radosavljević *et al.* 1986).

Generally, there are four main clay types (macroscopic description): a) red–yellow sandy–gravely (brick clays), b) grey–white (ceramic and partially refractory

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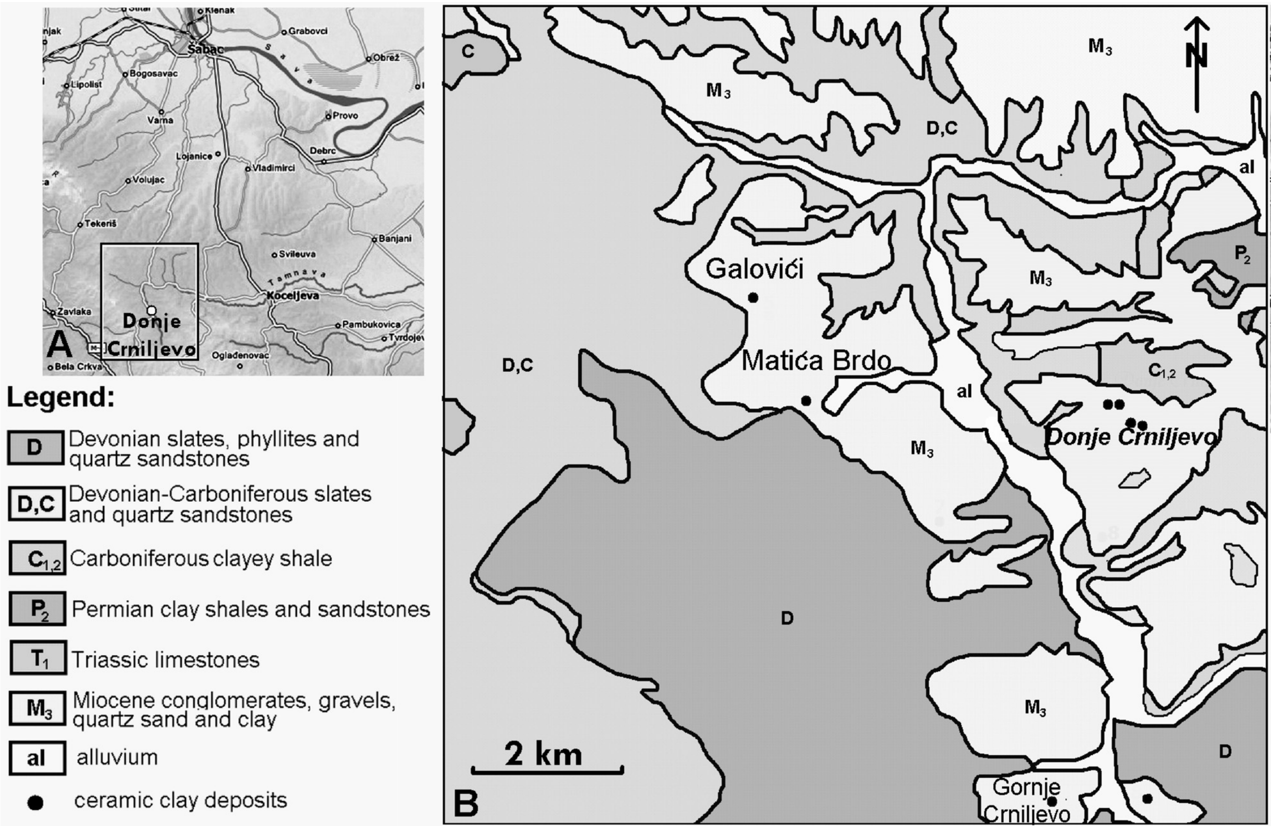

Fig. 1. Location and geological map of the Tamnava Tertiary Basin (modified according to Basic Geological Map of Serbia 1:100,000, Vladimirci sheet). **A,** Position of the Tamnava Tertiary Basin; **B,** Geological settings of the Tamnava Tertiary Basin.

clays - composite 1), c) dark-carbonaceous (ceramic clays - composite 2) and d) lamellar, fatty and poor sandy (highly aluminous and ferrous clays - composite 3). Brick clays are for local use only, and are therefore not the subject of this study (DESPOTOVIĆ *et al.* 2006). All these are sediments composed of clay minerals (kaolinite, smectite clay, illite/hydromica) with variable contents of aggregates (phyllites, and slates), clastic grains (quartz, feldspars, mica, Fe-, and heavy minerals), and organic matter (coal) (RADOSAVLJEVIĆ *et al.* 1994).

Modern plants for preparation and technological homogenization of different ceramic clay, for crushing and micronization, and façade brick factory are located in the Donje Crniljevo open-pit (“Zorka-Opeka”), while the production of wall and floor ceramic tiles is situated in Šabac (“Zorka-Keramika”). All open-pits plants and factories operate within the Alas-Holding ad, from Novi Sad.

The decision for new investments in research in this part of the Tamnava Tertiary Basin was, first of all, good clay quality, reliable reserves, existing infrastructure and processing, as well as the ability to export raw materials of the highest quality and finished products. Accordingly, the geological characteristics of active deposits of ceramic clays, as well as mineralogical, physical, chemical and technological features of the investigated clay types (grey–white, dark-carbonaceous, and interspersed-lamellar aluminous and ferrous clays) were investigated in detail in this study.

Location and geology

The Savinian-Tamnava Tertiary Basin covers a wide area between the River Sava to the North, the Vlašić Mountain to the South–West and the Tamnava River to the South–East. The Tamnava Tertiary Basin, in the narrow sense, occupies the valley of the Tamnava River and the Savinian-Tamnava watershed area. The oldest sediments represent a foot wall to the younger sediments and simultaneously create the frame of the Basin, represented by the Palaeozoic sediments Devonian–Carboniferous–Permian, Fig. 1).

These are most often found at the North–East slopes of the Vlašić Mountain in numerous erosive trenches. According to VESELINOVIĆ (1955), residual fossil flora is found in the small-grained mica sandstones, indicating their Devonian–Carboniferous–Permian age. In this series of flysch character, the Permian and Triassic formations in the form of smaller erosive portions were discovered, composed of bituminized and marlous limestones.

Tertiary formations of the Tamnava Basin are represented by Miocene–Tortonian, Sarmat and various Mio–Pliocene sediments. These sedimentary bodies are widely spread in very thick layers. They are located in areas of the villages: Galović, Donje Crniljevo, Šabačka Kamenica, Kaona, *etc*. (Fig. 1), and represented by heterogeneous lithological members where various gravels, sands, and clays are dominant.

The clays of this Basin do not have defined stratigraphic positions, but they appear on different levels of the Mio–Pliocene series, with frequent and gradual transitions from fatty clays over clayey sands to quartz sands. Economically interesting occurrences and deposits of ceramic clays appear from 2 to 35 m in depth, while productive Mio–Pliocene series finishes with various sands, gravels and conglomerates.

There are no greater disturbances of clay masses in the tectonics of the Mio–Pliocene sediments of this area. Landslides, *i.e.*, gravity movements of various intensities, are rather frequent.

Lenticular occurrences of clays in different levels throughout the Mio–Pliocene series could be explained by frequent oscillations of Mio–Pliocene waters, lifting and deepening of the Basin bed and precipitation of clastic sediments or fine pelitic clay materials. Erosion factors significantly contributed to the formation of today's outlook deposits in the Tamnava Tertiary Basin. Deposits of ceramic and brick clays were discovered in these sediments (Jovanović Brdo, Bele Vode, Stare Kuće, Burovica, Latkovac, Zbegovi, Kisela Voda, Brezaci, and Ramnava).

Ceramic clay deposits

The Jovanovića Brdo deposit is the largest, with characteristic grey–white ceramic clay, is mostly excavated. It is situated in the North–East slopes of the Vlašić Mountain at an elevation from 210 to 240 m. Within this deposit, exploitation of brick clays for local use only, as well as periodical exploitation of white-sandy, dark, and aluminous and ferrous ceramic clays, remains. Dark-carbonaceous clays interwoven with thin layers of coal (lignite, peat) were found only in this deposit (Đurišić *et al.* 1986; Radosavljević & Milićević 1991; Nikolić 1998; Filipović-Petrović *et al.* 2008).

Above this deposit are quality brick clays, dark, and yellow–grey clays from 3 to 16 m in thickness. Depending on the configuration of the terrain, ceramic clays appear from 3 to 17 m in depth. Immediately beneath the ceramic clays, aluminous and ferrous clays with fine grained clayey sands are situated, representing below to the productive series. In the Bele Vode deposit, the layers are horizontal to sub-horizontal. Thus, in addition to other factors such as the spatial position of the deposit, hydrogeological characteristics, reserves and quality of clays provide all the conditions for a longer economic production of ceramic and brick clays. This deposit is the backbone of the current production for domestic and other producers of ceramic products.

The Stare Kuće deposit continues in the North part, as a logical extension of the already described Bele Vode deposit.

This deposit is composed of one lenticular layer gently sloping to the South–West. The deposit itself has the form of a horseshoe, of which the two legs end in the North, and the central part in the South. Above the ceramic clays are brick clays to a lesser extent, whereby most of it is gravely and sandy clays, unsuitable for façade bricks. Below the ceramic clays are quartz sands of different colours. Quality ceramic clays appear at a depth of 6–30 m, with a thickness of 1–10 m.

The Zbegovi deposit is lenticular, characterized by a somewhat longer strike axis and a shorter dip axis (Fig. 2). The central part is divided into two productive layers. In between these layers, clays with a similar mineral composition, but with an increased content of an iron component occur. Above, the clays are commonly gravely and sandy dark-red clays not suitable for the production of brick clays. Below the clays are yellow–red and grey–white clayey quartz sands, which without technological processing do not have the utility value for now. The thickness of the basic layer of grey–white ceramic clays ranges from 2 to 15 m at a depth of 0.5–20 m. There are no greater disturbances of horizontal layers in this deposit, which is characteristic for almost all deposits of the Tamnava Tertiary Basin.

Fig. 2. A view on the Zbegovi open pit, Donje Crniljevo (taken from the internal magazine "Alas Holding", No 3, 2007).

The localities Kisela Voda, Ramnava, and Brezaci are situated on the left bank of the Tamnava River to the South–East of Gornje Crniljevo village. According to up to date research data, it could be concluded that these deposits contain very interesting raw materials with an increased SiO_2 component in comparison to Al_2O_3 (Despotović *et al.* 2006). Grey–white poor sandy clays appear beneath a thin layer of humus, and above, brick clays are at a depth from 2 to 35 m. Unlike the clays from Donje Crniljevo, they are characterised by an increased thickness (1–15 m) of grey–white sandy clays. These clays represent the raw material of the future for the ceramic industry (white façade bricks). The analyses of the obtained data of the chemical, physical, and mineralogical composition of the ceramic clays of the Tamnava Tertiary Basin clearly showed that these clays are of similar composition, as well as that the newly discovered deposits approach the standard quality of grey–white ceramic clays from the Jovanovića Brdo deposit.

Finally, all the ceramic clay deposits were discovered in the Mio–Pliocene sediments of the Tamnava Tertiary Basin along the easterly slopes of the Vlašić Mountain. These materials as transformational forms yielded different assortments of ceramics, bricks, and other clays, quartz sands, as well as all transitions between them (VELDE & MEUNIER 2008). During the ingression of Mio–Pliocene waters, feldspars and mica were transformed into clay minerals and precipitated into depressions along with gravely–sandy materials. Frequent uplifting and deepening of the basin bottom favoured the formation of characteristic lenticular bodies of ceramic clays.

Materials and methods of analysis

Three composite samples of raw materials from the active open pit mines Jovanovića Brdo, Bele Vode and Zbegovi were obtained. The composites were as follows: 1. grey–white poor sandy clays (Bele Vode and Zbegovi deposits); 2. dark-carbonaceous clays (Jovanovića Brdo deposit) 3. lamellar aluminous–ferrous clays (Jovanovića Brdo, Bele Vode and Zbegovi deposits). Composites of equal amounts from each deposit were taken by spot sampling.

Binocular studies were obtained using a Leitz Wetzlar stereo microscope, while microscopic analyses were realised on a Carl Zeiss, Jena, model JENAPOL-U polarisation microscope in transmitted light by the immersion method using xylene as an immersion liquid.

Chemical analyses were obtained by classical wet analytical methods: SiO_2, humidity and loss on ignition were determined gravimetrically; TiO_2, K_2O and Na_2O were determined by the AAS method after acid dissolution; Al_2O_3, Fe_2O_3, CaO and MgO were determined using AAS (AAS instrument Analyst 300) after acid dissolution and melting, (FILIPOVIĆ-PETROVIĆ *et al.* 2007).

Electron Probe Microanalyses (EPMA) and the observation of clay samples were performed on a JEOL JSM-6610LV scanning electron microscope (SEM) connected with an INCA energy-dispersion X-ray analysis unit; EDX analytical system (Faculty of Mining and Geology, University of Belgrade). An acceleration voltage of 20 kV was used. The samples were coated with gold (15 nm layer, density g/cm^3 19.32). The following standards and analytical lines were used: MgO (Mg K_α series), wollastonite (Ca K_α series), Al_2O_3 (Al K_α series), SiO_2 (Si K_α series), MAD-10 feldspar (K K_α series), Ti (Ti K_α series), Fe (Fe K_α series). The EDX detection limit amounts to $2\sigma \approx 0.3$ wt. %.

The XRD method was used to determine the mineral composition. The XRD patterns were obtained on a Philips PW-1710 automated diffractometer using a Cu tube operated at 40 kV and 30 mA. The instrument was equipped with a diffracted beam curved graphite monochromator and a Xe-filled proportional counter. The diffraction data were collected in 2θ Bragg angle range from 4 to 65°, counting for 1 s (qualitative identification) at every 0.02° step. The divergence and receiving slits were fixed at 1 and 0.1, respectively. All XRD measurements were performed at room temperature in a stationary sample holder.

Infrared (IR) absorption spectra were recorded on a Perkin-Elmer, model 377 spectrophotometer, using the KBr pellets technique in the wavelength range from 4000 to 400 cm^{-1}.

Thermal analysis (DTA/TGA) was performed under air atmosphere using a Netzsch STA-409EP instrument at heating rate of 10 C°/min. The cation exchange capacity (*CEC*) was determined by titration using Methylene Blue (FILIPOVIĆ-PETROVIĆ *et al.* 2008).

The ceramic-technological testing (basic technological parameters of raw materials) was obtained according to FILIPOVIĆ-PETROVIĆ *et al.* (2007).

Results and discussion

Raw ceramic clay composites had high SiO_2 contents, moderate Al_2O_3 contents, and low contents of other oxides (Table 1). The Fe_2O_3 contents varied; in the grey–white and dark composite clays, they were below 2 wt. %. EPMA of sample 3 (lamellar clay) were performed on red and white–yellow lamellae

Table 1. The comparative chemical analyses of the studied ceramic clay composites from the Tamnava Tertiary Basin (in wt%). Note: - not analyzed; 3a - red lamellae; 3b - yellow-white lamellae; * - average EDS analyses; n.d. not detected (< 0.40 wt%).

Ceramic clay composites	1	2	3	3a*	3b*
SiO_2	58.86	61.87	58.76	64.56	66.64
TiO_2	1.18	1.01	1.18	0.68	0.63
Al_2O_3	26.86	21.63	26.04	26.50	25.63
Fe_2O_3	1.69	1.17	2.47	2.71	2.17
CaO	0.61	1.05	0.65	n.d.	n.d.
MgO	0.61	0.46	0.61	1.01	0.86
Na_2O	0.12	0.07	0.11	n.d.	n.d.
K_2O	3.97	2.05	4.30	5.12	4.56
L.O.I.	6.08	10.67	5.85	–	–
Total	99.98	99.98	99.97		

(field analysis, 1.24 mm^2). The Fe_2O_3 content ranged from 2.53 to 2.92 (three analyses) in the red lamellae, while in the white–yellow lamellae, it was slightly lower, ranging from 1.99 to 2.37 wt. %. Minor deviations were noticed in the SiO_2, MgO and K_2O contents, while CaO and Na_2O were not detected (Table 1).

The grain size values were generally unique, and according to the distribution, the ceramic clays from the active deposits belong to poor sandy-powder clays. A results of a comparative analyses of grain size distribution of the three main ceramic clay composites, sand (<2–0.063 mm), powder (<0.063–0.011 mm) and clay (<0.011 mm), are shown in Figure 3.

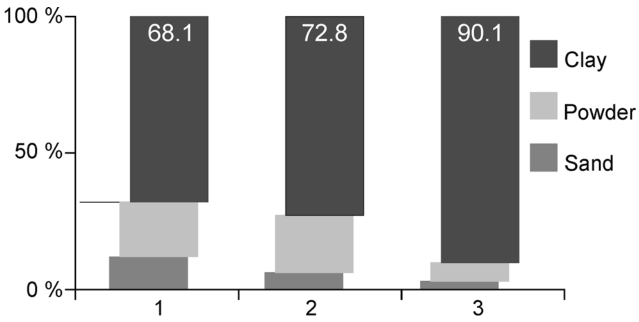

Fig. 3. The comparative grain size distribution of the main clay composites from the Tamnava Tertiary Basin (in wt%).

The mineralogical studies were concerned with the testing of the composite samples and fractions of sand, powder and clay using combined methods, *i.e.*, optical microscopy, XRD, IR, DTA/TGA and SEM.

According to the XRD method, the mineralogical composition was as follows: kaolinite, illite/hydromica, mica, quartz and feldspar. Illite/hydromica, mica and feldspars were not determined in the dark-carbonaceous ceramic clays (composite 2) because their contents were below the detection threshold. The presence of these minerals varies because small amounts were detected in previous research (Filipović-Petrović *et al.* 2008). Feldspars are connected to ceramic clays with lower amounts of kaolinite and higher amounts of illite/hydromica. The XRD patterns of raw ceramic clay composites are presented in Figure 4.

Comparing the three IR spectra in the range 3700–3600 cm^{-1}, no significant differences were observed incurred as a result of water in the layers. The IR-spectra show characteristic forms for kaolinite, which are in good agreement with literature data (Kato *et al.* 1981). Weak H_2O stretching vibrations near 3630 and 3640 cm^{-1} in composite 2 could correspond to montmorillonite (Worral 1986), but it was not enough to exclude other minerals with identical vibrations. These absorptions were assigned to water bound directly to cations and surface-bonded H_2O. The IR-spectra for the raw ceramic clay composites are shown in Figure 5.

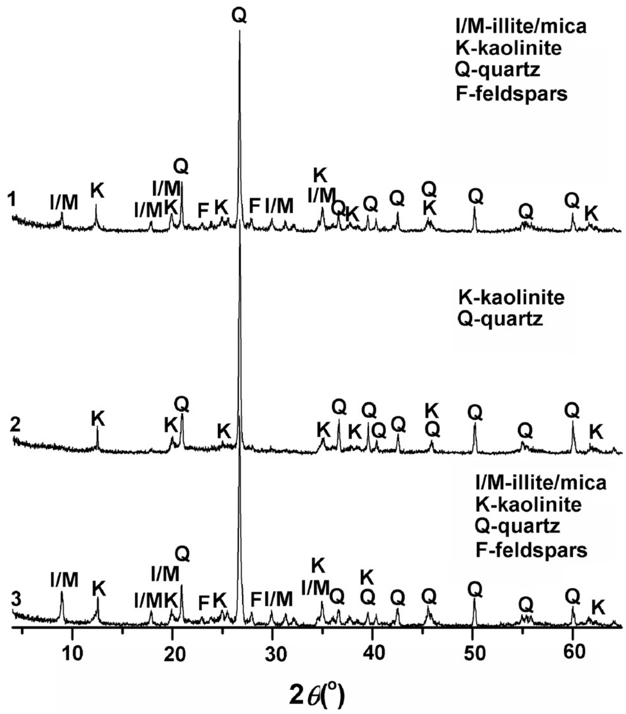

Fig. 4. The comparative XRD analyses of the main clay composites from the Tamnava Tertiary Basin.

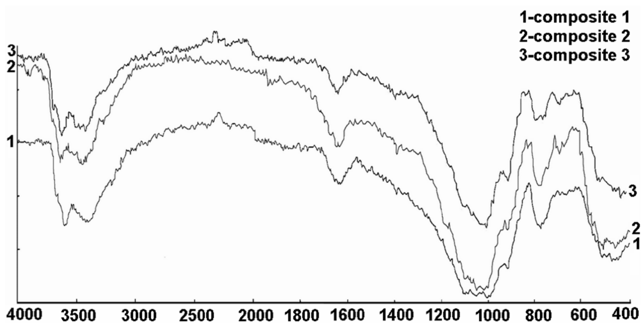

Fig. 5. The comparative IR spectra of the main clay composites from the Tamnava Tertiary Basin.

The DTA/TGA endothermic effects in the ranges of 83–106, 145–178, 535–540, and 886–924 °C correspond to clay minerals (illite/hydromica, kaolinite and smectite clays) accompanied by appropriate body losses. The first and second effects are related to loss of inter-layer water (dehydration) and the effect is caused by loss of structural water in form of OH$^-$ group-constitution water (dehydroxylation). The fourth endo-effect is caused by the formation of the layer structure of clay minerals. The morphology of the first two peaks indicates to smectite clays (montmorillonite). The exothermic effects at 353 °C and 424 °C arise due to the combustion of organic matters at various temperatures (composite 2, Fig. 6). The exothermic effects in the range between 966 and 982 °C correspond to total decomposition of the clay minerals (kaolinite, illite/hydromica) and the beginning of a mullitization process (Worral 1986). The DTA/TGA results for the raw ceramic clay composites are presented in Figure 6.

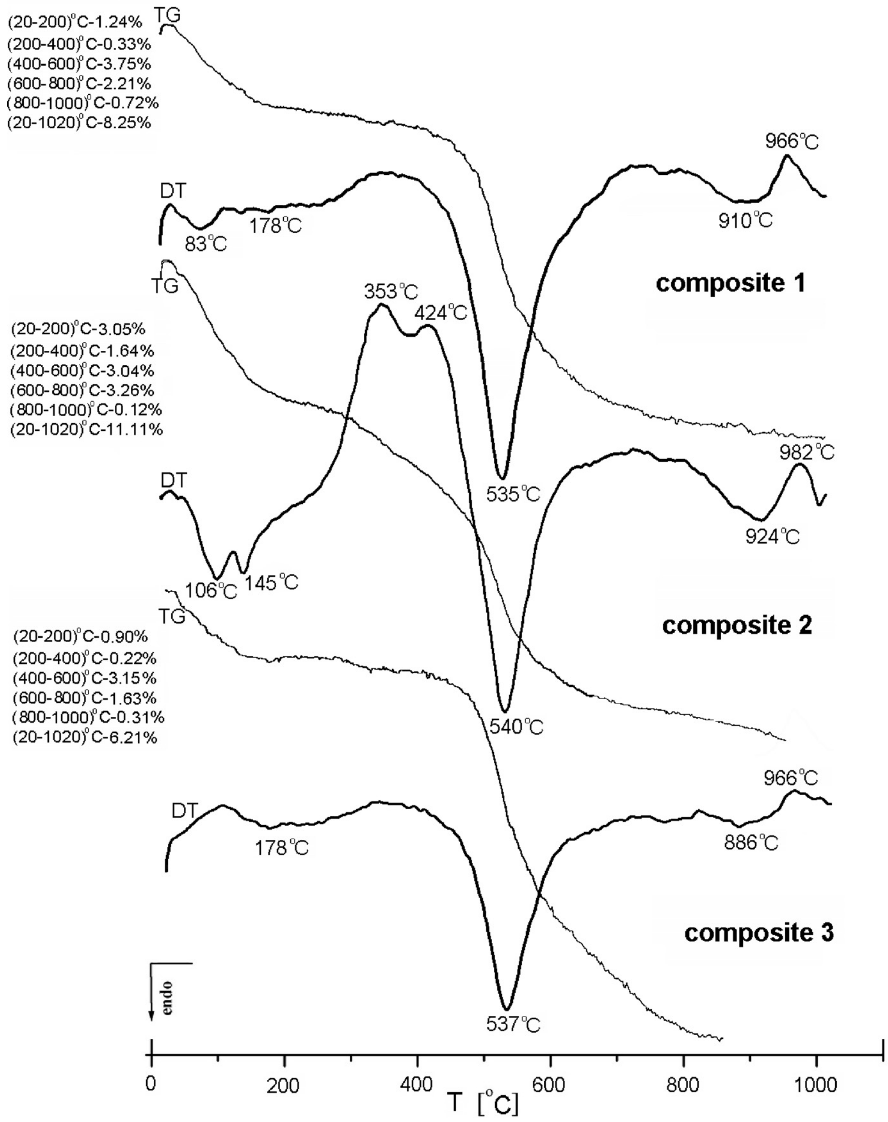

Fig. 6. The comparative DTA/TGA of the main clay composites from the Tamnava Tertiary Basin.

Optical photographs and SEM secondary electron images (SEI) of the ceramic clays composite samples are presented in Figure 7. The macroscopic appearances of all three composites are shown in Figures 7a–c, while SEI of the red and white–yellow lamellae of composite 3 are shown in Figures 7d–f and 7g–i, respectively.

Macroscopically, the grey–white poor sandy clays (composite 1) are compact-plastic semi-cohesive sediments, the textural appearances of which are monolithic (Fig. 7a). They are rather abrasive; hence, a large number of scratches caused by coarse grains could be observed on a glass surface.

Macroscopically, the dark-carbonaceous fatty clays (composite 2) are compact-plastic semi-cohesive sediments characterised by a layered or pseudo-breccia texture. They are composed of rhythmical light-grey, grey, dark to black layers with irregularly spaced inclusions of organic matter (Fig. 7b). Clay and coal lenticular layers are alternately replaced in the deposits, but their contact still remains unclear.

The lamellar aluminous–ferrous clays (composite 3) are highly plastic semi-cohesive sediments. Their textures are finely stratified with pseudo-paallel white, yellow, and red lamellae, which are alternately replaced without any regularity (Fig. 7c).

Mineralogical qualitative and semi-quantitative analyses were obtained using a stereo microscope, a polarised microscope and the XRD method. The samples were sieved in order to separate the grain size fractions. The >63 μm (sand) fractions were examined using stereo, and polarised microscopy, while –63+10 μm (powder), and –10+0 μm (clay) fractions were prepared for XRD analysis. Heavy minerals are separated from the light mineral fraction (<2.8 g/cm^3) by passing the >63 μm fractions through a separation column containing a heavy liquid (Morton 1985). A fraction of the heavy mineral residue is mounted in Canada balsam and minerals identified using standard stereo and polarising microscopy.

Quartz, which was bright to milky white, rarely yellowish or black, was the most abundant mineral in the sand fraction in all three composites (up to 90 wt. %). Of other minerals, kaolinized feldspars, quartz–sericite sandstone aggregates, cherts, muscovite and sericite were also found in small amounts. Tourmaline, Ti-minerals, corundum, cordierite, and apatite were among the most frequent heavy minerals. This fraction rarely contained liberated Fe-minerals, but they quite often appeared as limonite–goethite coatings on quartz. Besides the clastic minerals, coal inclusions regularly appeared in the dark-carbonaceous clays.

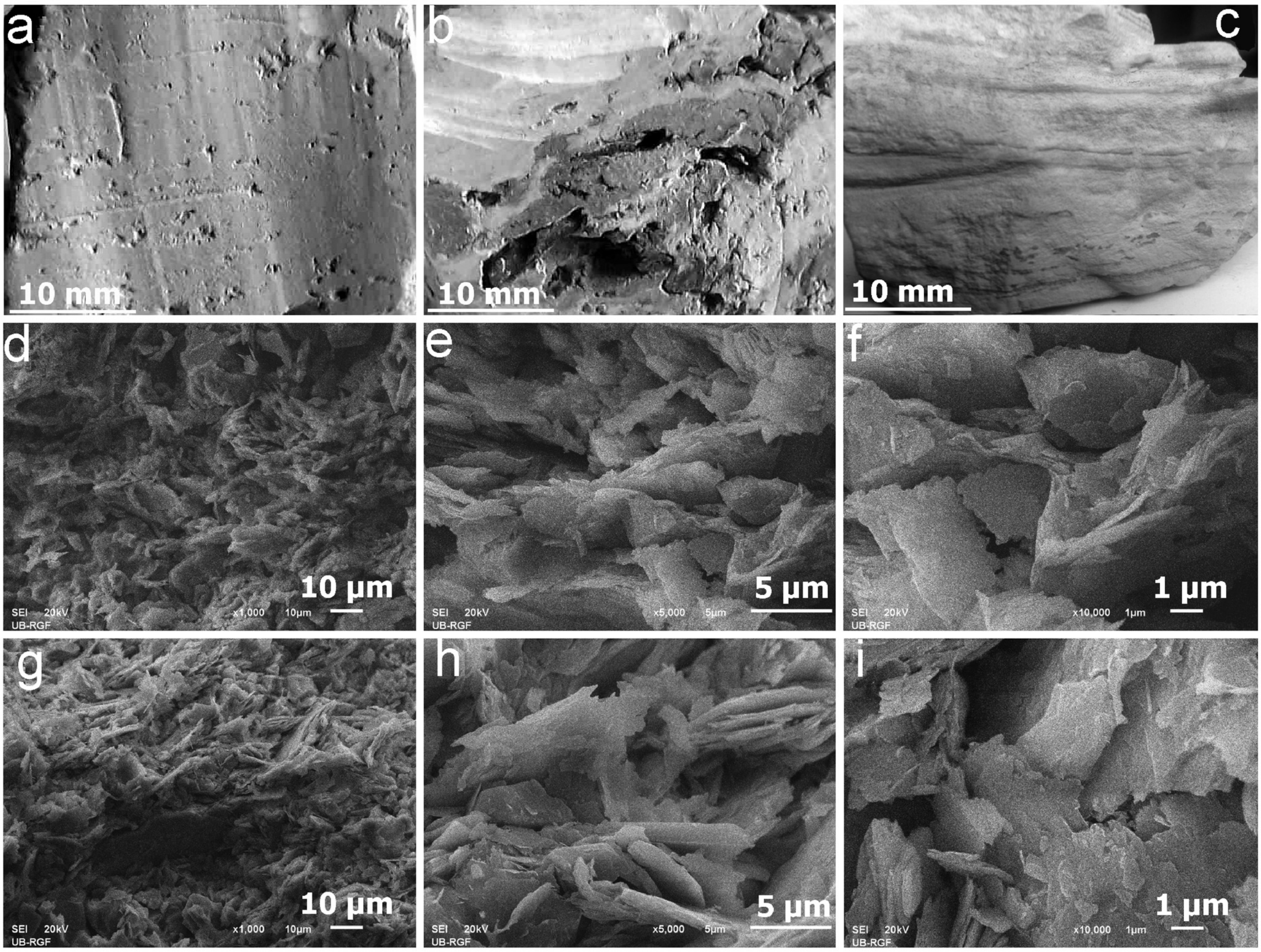

Fig. 7. The comparative optical microscopy microphotographs and SEI of studied clay composites: **a,** Macroscopic appearance of the grey-white poor sandy ceramic clay; **b,** Macroscopic appearance of the dark-carbonaceous ceramic clay; **c,** Macroscopic appearance of the lamellar aluminous and ferrous ceramic clay; **d-f,** Different magnifications of crystal aggregates of clay minerals in red lamellae (the sample in Figure 7c); **g-i,** Different magnifications of crystal aggregates of clay minerals in white-yellow lamellae (the sample in Figure 7c).

The mineralogical composition of the powder fraction was very similar to the previous fraction, differing in the abundance of sericite and illite/hydromica (up to ≈40 wt. %) compared to quartz.

Clay minerals appear habitually in “jaggy” plate-like forms without geometric regularity up to 30 μm^2. According to the SEM analyses, it is more than obvious that there were no differences in the clay habit between the white–yellow and red lamellae (Figs. 7d–f and 7g–i). In addition, liberated quartz grains were not observed in SEI, even though EMPA showed an increased content of SiO_2 compared to the classical quantitative chemical analysis (Table 1). Based on this phenomenon, it is possible to assume that most of the SiO_2 is in a form of submicronic silica dispersed with kaolinite–illite/hydromica flakes.

The kaolinite/illite ratio, which is generally around 1:1, varied, which could affect small differences in the basic technological parameters. Clay minerals are usually accompanied by quartz, amorphous silica and Fe-hydroxides. Depending on their content, Fe-hydroxides impart a yellow, ochre, red, or brown colour on the clay fraction. In the dark-carbonaceous clays, kaolinite is also the most abundant mineral, but the variable presence of smectite clays and illite/hydromica were also determined (FILIPOVIĆ-PETROVIĆ *et al.* 2008).

Ultimately, the general mineralogical composition of the raw composite sample was as follows: clay minerals (kaolinite, illite/hydromica and smectite clays), quartz, muscovite/sericite, altered alkali feldspars, heavy minerals (tourmaline, Ti-minerals, corundum, cordierite, and apatite) ± organic matter. This study confirmed that the ceramic clays from the active deposits belong to the kaolinite–illite/hydromica type, and are identical to the standard clay from the Jo-

Table 2. The comparative values of basic technological parameters of the main clay composites from the Tamnava Tertiary Basin.

Ceramic clay composites		1	2	3
Water for plastic processing, wt%		31.39	46.25	39.95
Plasticity index according to Pfefferkorn, wt%		35.32	47.15	41.55
Shrinkage drying, wt%		4.97	6.24	5.40
flexural strength, N/cm^2		242	373	170
Sintering area, ºC		1079–1125	1045–1090	1014–1040
Refractoriness, SK		26	26/27	26
CEC **methylene blue, mmolM$^+$/100 g**		35	45	55
Characterization of firing process, ºC	900	yellowish-creamy	grayish-white	reddish
	1.000	creamy	yellowish-creamy	dark red
	1.100	dark pink-creamy	dark yellow-creamy	**brownish-red**

vanovića Brdo deposit. Moreover, other deposits and occurrences from the Tamnava Tertiary Basin are of the same mineralogical composition.

According to the basic technological parameters, it could be concluded that the clays from the active deposits according to their characteristics belong to medium plastic clays with prolonged sintering time, which makes them suitable for the production of all types of ceramic tiles. The lamellar aluminous–ferrous clays could be used in part for the engobing of roof tiles (ERIĆ *et al.* 1989). The high ceramic clay refractory from the Tamnava Tertiary Basin is due to an increased content of quartz. According to the values of their refractoriness, these clays could be used in the production of some refractory products. Furthermore, the values obtained for the cation exchange capacity (*CEC*) suggest that these raw materials are suitable for further processing in activation processes. Their basic technological parameters are given in Table 2.

Conclusions

In the area of the western Tamnava Tertiary Basin, a large number of economically interesting ceramic clay deposits at a depth of 2–35 m were determined. The productive Miocene series finite with various sands, gravels, and conglomerates. The clays of this Basin do not have a specific stratigraphic place, but they occur in different levels of the Mio–Pliocene series with frequent gradual transitions from fatty clays over clayey sands to quartz sands. Kaolinite, illite/hydromica, and sometimes smectite clays are the most abundant clay minerals in the clay fraction.

According to the mineralogical, physical, chemical, and technological quality testing of the raw ceramic clay composites from the active deposits at Jovanovića Brdo, Bele Vode and Zbegovi, four types of clays were evidenced, i.e., red–yellow sandy–gravely (brick clays), grey–white poor sandy (ceramic and partly refractory clays), dark-carbonaceous (ceramic clays) and lamellar fatty, poor sandy (highly aluminous and ferrous clay).

The most important from the economic point of view are the grey–white (composite 1) clays, while the dark-carbonaceous (composite 2), and lamellar (composite 3) clays could be used independently or as a mixture of raw clays. According to analyses of the mineralogical composition data of the ceramic clays, it can be concluded that they differ from each other in grain size distribution (different ratios of sand, powder, and clay fractions) and in the contents of other minerals (quartz, smectite clays, Fe-minerals and organic matter). Finally, as all three types of ceramic clays from the Tamnava Tertiary Basin could be utilized for a wide range of non-metal materials, these deposits provide a full contribution for the further economic development of this part of SE Europe.

Acknowledgments

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References

DESPOTOVIĆ, S., BABIČ, D., FILIPOVIĆ-PETROVIĆ, L. & ERIĆ-ANTONIJEVIĆ, S. 2006. Some characteristics of mineralogical composition of clay Zorka. *Proceeding of 20th International Symposium on Mineral Processing*, 150-156, SokoBanja, Serbia.

ĐURIŠIĆ, M., TOMAŠEVIĆ-ČANOVIĆ, M., PAVLOVIĆ, LJ. & RADOSAVLJEVIĆ, S. 1986. Comparison of physico-chemical characteristics of dark clay Jovanovića Brdo. *Proceedings of 5th Counseling of Ceramic of Yugoslavia*, book 1, Kupari, Yugoslavia: 41–50 (In Serbian with English abstract).

ERIĆ, I., RADOSAVLJEVIĆ, S. & ALMAŽI, E. 1989. Tiles engobe on the basis of Tamnava Clays. *Proceedings of 5th Counseling of Ceramic of Yugoslavia*, book 1, Kupari, Yugoslavia: 342 (in Serbian with English abstract).

FILIPOVIĆ-PETROVIĆ, L., ERIĆ-ANTONIĆ, S., DESPOTOVIĆ, S., VUJIĆ, V., PAVLOVIĆ LJ, 2007. Physical-chemical and ceramical-technological properties of some clays of Podrinje-Kolubara region. *39th International October Conference on Mining and Metallurgy,* 402–408, Soko Banja, Serbia.

FILIPOVIĆ-PETROVIĆ, L., MILADINOVIĆ, M., VUJIĆ, V., DESPOTOVIĆ, S. & SAVIĆ, 2008. S. Chemical-mineralogical and ceramic characteristics dark clay „Jovanovića Brdo“. *Proceeding of 21st International Symposium on Mineral Processing*, 96–100, Bor, Serbia.

KATO, E., KANOKA, S. & INAGOKI, S. 1981. Infrared spectra of kaolin minerals in hydroxyl vibration region. In: III. Classification of the infrared spectra kaolinite and halloysite. Nagoya Kogio Gijutsu Shikensho Hokoku, 29: 215–221.

Morton, A.C. 1985. Heavy minerals in provenance studies. *Proceedings of the NATO Advanced Study Institute on Reading Provenance from Arenites,* Vol. 148: 249–277.

NIKOLIĆ, M. 1998. Potential domestic resources of nonmetallic minerals. In: Domestic nonmetallic mineral raw materials for commercial use. Institut za tehnologiju nuklearnih i drugih mineralnih sirovina, Belgrade: 61–82 (in Serbian with English abstract).

RADOSAVLJEVIĆ, S., MILIĆEVIĆ, R. & PANIĆ, B. 1986. Ceramic Clays of Tamnava Tertiary Basin – West Serbia. *Proceedings of 11th Congress of Geologists of Yugoslavia*, book 4: 357–369 (in Serbian with English abstract).

RADOSAVLJEVIĆ, S. & MILIĆEVIĆ, R. 1991. New appearance of ceramic clay in the Tertiary Basin Tamnava. Građevinar, Belgrade: 32–39 (In Serbian with English abstract).

RADOSAVLJEVIĆ, S., STOJANOVIĆ, M. & Branković A. 1994. Ceramic clays of Tamnava Tertiary Basin (West Serbia). Industial Ceramics, 14 (4): 155–158.

VELDE, B. & MEUNIER, A. 2008. *The Origin of Clays Minerals in Soils and Weathered Rocks*. 403 pp. Springer-Verlag, Berlin Heidelberg.

VESELINOVIĆ, M. 1955. The results the geological observations in the region of Gornje Crniljevo and Šabačka Kamenica (West Serbia). *Proceedings of Geological Institute “Jovan Žujović”*, book 8: 355–373 (in Serbian with English abstract).

WORRAL, W.E. 1986. *Clays and ceramic raw materials*. 203 pp. Elsevir Applied Scence Publishers, 2nd edition.

Резиме

Керамичке глине западног дела тамнавског терцијарног басена, Србија: лежишта и типови глина

На подручју западног тамнавског терцијарног басена, утврђен је већи број лежишта керамичких глина у економски интересантним количинама, која се појављују на дубини од 2–35 m. Продуктивна миоценска серија завршава се различитим песковима, шљунковима и конгломератима. Глине овог басена немају одређено стратиграфско место већ се јављују у различитим нивоима миоплиоценске серије, са честим поступним прелазима од масних глина ка глиновитим песковима до кварцних пескова. Сочивасто појављивање глина у различитим нивоима миоценске серије може се објаснити, честим осцилацијама миоплиоценских вода, издизањем и продубљивањем дна басена, односно таложењем кластичних седимената.

На основу минералошких, физичких, хемијских и технолошких испитивања квалитета композита ровних керамичких глина са активних лежишта Јовановића Брдо, Беле Воде и Збегови издвојена су четири комерцијална типа глина: а) црвено-жуте песковито-шљунковите (опекарске глине); б) сиво-беле слабо песковите (керамичке и делом ватростално глине); ц) тамне угљевите (керамичке глине); д) прошаране (ламеларне), масне и слабо песковите (високо алуминозне и гвожђевите глине). Опекарске глине су за интерну употребу, а најважнија је сиво-песковите керамичка глина (композит 1). Тамне-угљевите масне (композит 2) и прошаране високо алуминозно-гвожђевите керамичке глине (композит 3), могу да се користе самостално или као део композитних ровних глина.

Анализом добијених података о минералошком саставу испитиванах керамичких глина лежишта тамнавског басена, може се закључити да су оне међусобно разликују у гранулометријском саставу (различити односи фракције песка, праха и глине) и садржавају примесе других минерала (кварц, смектитске глине, минерали гвожђа, органска материја). Сиво-беле слабо песковите керамичке глине са активних копова и нових налазишта су истоветне са стандардним квалитетом глина лежишта Јовановића Брдо. На крају, сва три типа керамичких глина из тамнавског терцијерног басена може се употребити за ширу прерађивачку индустрију неметала, те да ова лежишта пружају свој пуни допринос за даљи економски развој овог дела ЈИ Европе.

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Tertiary plutonic rocks of southern Serbia Vardar Zone as dimension stone

Lidja Kurešević[1] & Vladimir Simić[2]

Abstract. Three granitoid plutons of south-Serbian part of the Vardar Zone, of Tertiary age were studied in order to establish their potential for utilization as dimension stone. These rocks vary in composition from quartzmonconite to quartzdiorite. Field study aimed at establishing the geological factors – presence of fractures, harmful minerals, alterations, jointing type and fabric homogeneity in order to determine the possibility of obtaining large size blocks of stone from the plutons. Laboratory examinations comprised petrological analyses and testing of technical properties. Stone from these plutons has shown favourable results in both field and laboratory examinations. Evaluation of the rock based on obtained laboratory testing results is performed according to technical requirements of the Serbian standard B.B3.200. It has shown that rocks from these plutons can be used as dimension stone for the production of slabs for the exterior and interior paving and cladding.

Key words: dimension stone, Vardar Zone, Tertiary granitoids, southern Serbia.

Апстракт. Истражена су три гранитоидна плутона терцијарне старости у јужносрбијанском делу Вардарске зоне, са циљем да се утврди њихова потенцијалност са аспекта архитектонског грађевинског камена. Састав стена у овим плутонима варира од кварцмонцонита до кварцдиорита. Циљ теренских истраживања је био да се утврде геолошки фактори – присуство раседа и пратећих пукотинско-прслинских система, штетних минерала, алтерација, типа лучења и хомогеност склопа стена, како би се установила могућност добијања стенских блокова комерцијалних димензија из плутона. Лабораторијска испитивања су обухватила минералошко-петролошке анализе стена и испитивање физичко-механичких својстава стенске масе. Стенска маса из ових плутона је показала задовољавајуће резултате теренских и лабораторијских испитивања. Оцена употребљивости стенске масе на основу лабораторијских испитивања је извршена према техничким захтевима Српског стандарда Б.Б3.200. Закључено је да се стенска маса из ових плутона може користити као архитектонски грађевински камен за добијање плоча за хоризонтално и вертикално облагање површина у екстеријеру и ентеријеру грађевинских објеката.

Кључне речи: архитектонски грађевински камен, Вардарска зона, терцијарни гранитоиди, јужна Србија.

Introduction

Until 1990, Serbia had a stone production that covered almost all the domestic needs. Over the last 23 years, it has turned into an importer of significant amounts of dimension stone (table 1). Efforts made at the state level to start the recovery of the national stone industry are founded on reassessment of the domestic resources of decorative stone raw materials basis. Kurešević (2013a) comprised various types of exploration methods of Tertiary magmatic complexes in the Vardar Zone of Serbia (Fig. 1) at the level of reconnaissance survey. The Tertiary volcanic complexes of the Vardar zone have proved to be more compliable for use as crushed stone (especially as aggregate in road-building), while plutonic complexes have significant potential as dimension stone. This paper presents the properties of three plutonic com-

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Table 1. Relationship between dimension stone commerce and production in 1990 and 2000 in Serbia (according to the National statistics institute data).

year	Commerce				Production		
	blocks		slabs and tiles		blocks	slabs	tiles
	import	export	import	export			
1990	209 t	0	1388 t	0	777 m^3 (2100 t)	29591 m^2	1613 m^2*
2000	40602 t	150 t	326 t	0	5 m^3 (13.5 t)	2018 m^2	467 m^2

*the missing data is replaced by the data from the first following year where it appears, 1992.

plexes situated in the southern part of the Vardar Zone in Serbia, Kremići, Drenje and Željin that are important for their evaluation as potential sources of dimension stone (Fig. 1, plutons within the rectangular frame). The Kopaonik pluton, which is also situated in this part of the Vardar Zone, is within the territory of the National park and is therefore excluded from any further exploration and mining plans. The properties of the Tertiary plutons of the northern and western Serbian part of the Vardar Zone (Cer, Boranja, Kosmaj, Brajkovac, Bukulja) are presented in KUREŠEVIĆ (2013b).

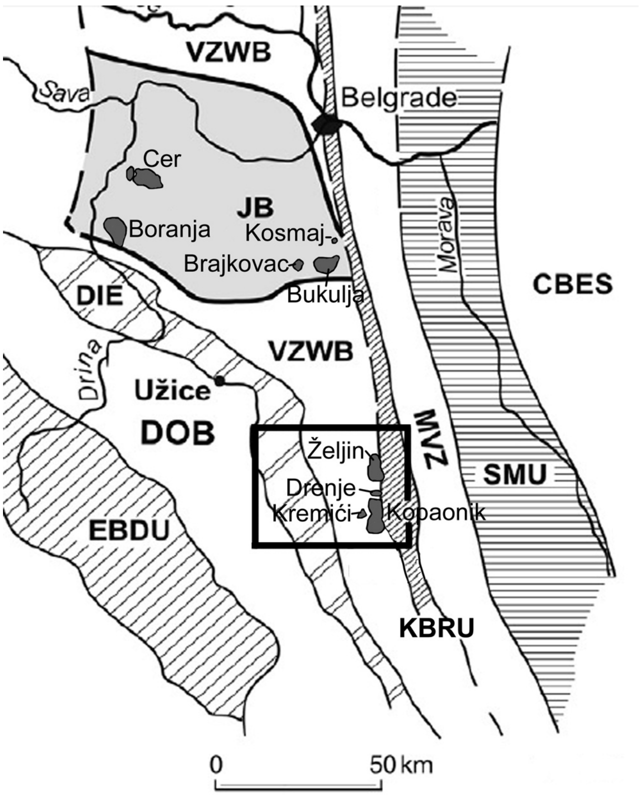

Fig. 1. Location of studied Tertiary plutons (within rectangular frame) in the Vardar Zone (tectonic units according to KARAMATA, 2006 and ROBERTSON *et al*., 2009); **CBES,** Carpato-Balcanides of Eastern Serbia; **SMU,** Serbian-Macedonian Unit; **MVZ,** Main Vardar Zone; **KBRU,** Kopaonik Block and Ridge Unit; **VZWB,** Vardar Zone Western Belt; **JB,** Jadar Block; **DIE,** Drina–Ivanjica Element; **DOB,** Dinaric Ophiolitic Belt; **EBDU,** Eastern Bosnian-Durmitor Unit).

The formation of Tertiary magmatic complexes of the Vardar Zone is connected with geotectonic evolution as a part of the Tethys ocean – the opening of oceanic subdomains, their closure, subduction and collision (SCHEFER *et al.* 2011). According to CVETKOVIĆ *et al.* (2000), the examined plutons belong to the Tertiary igneous formation of the Dinarides, Vardar Zone and adjacent regions, group of Late Paleogene-Early Neogene granitoid formation, subgroup Dinaridic granitoid suite. These rocks are of calcalkaline I-type of magmatic arcs, formed from subcrustal melts generated by partial melting of the Upper mantle and significantly contaminated by crustal material. Magma is formed by melting of thickened continental crust which sank deep into the Upper mantle. Basic data on the examined plutons are summarised in Table 2.

Material and methods

Field study has been performed as part of reconnaissance survey, aiming at establishing the geological factors – presence of fractures, harmful minerals, alterations, jointing type and fabric homogeneity, in order to determine the possibility of obtaining large size blocks of stone from the plutons. Laboratory examinations comprised petrological analyses and testing of technical properties. Microscopic study was performed on polarizing microscope for transmitted light type Leica DMLSP with a digital camera. Laboratory testing of stone technical properties was performed according to technical requirements of the Serbian standard B.B3.200, in the Stone and aggregate laboratory of the Institute for materials testing in Belgrade.

Table 2. Summarised basic data on studied plutons (KUREŠEVIĆ 2013a), and their ages.

Pluton	Open surface (km^2)	Petrologic determination	Age (Ma)
Kremići	5	quartzdiorite-granodiorite, < quartzmonconite	31.9 (KARAMATA *et al*., 1992)
Drenje	4	granodiorite, < quartzdiorite	31.7–31.2 (SCHEFER *et al*., 2011)
Željin	56	granodiorite-quartzmonconite, < quartzdiorite	31.8–31.4 (SCHEFER *et al*., 2011)

Results

Kremići pluton

This pluton is situated around 180 km south of Serbia's capital, Belgrade. Its shape is an irregular dyke with an open surface of 5 km^2. It intrudes into Ibar ultramafic complex (UROŠEVIĆ *et al*. 1973a, b). The tectonic framework is presented mostly by faults striking NW–SE, NE–SW, E–W and N–S. Mineral composition (quartz, andesine, K-feldspar (orthoclase to microcline), hornblende, biotite; Fig. 2A), mostly corresponds to quartzdiorite and granodiorite (amphibole-biotite, rarely amphibole varieties). Quartzmonconite occurs in central parts of the pluton. The rock texture is hipidiomorphic granular. The major part of the pluton open by erosion is today covered with soil and thick woods. Therefore, only small marginal parts of the pluton are available for observation. Here, jointing is tabular, prismatic and irregular (Fig. 2B). Slight hydrothermal alterations are found along the NW pluton margins; otherwise the rock is fresh and sound.

As a dimension stone, this rock has both favourable properties (durability, soundness, favourable texture) and unfavourable (inhomogeneous appearance, xenoliths, sporadic occurrence of slight magmatic layering, unfavourable jointing types and small dimensions of natural blocks). However, only a small part of the pluton is open and available for examination and it is quite certain that deeper parts of the plutonic mass have more favourable properties from the aspect of dimension stone.

According to the laboratory testing of technical properties and evaluation of the rock by the Serbian standard B.B3.200, as dimension stone it can be used for the production of slabs for the interior and exterior paving and cladding with no restrictions.

Drenje pluton

This pluton is situated around 170 km south of Belgrade. Its open surface is 4 km^2. It intrudes into Triassic metamorphic complex of the Kopaonik Block and Ridge Unit (UROŠEVIĆ *et al*. 1973a). The tectonic framework comprises faults striking NW–SE and N–S. Mineral composition (andesine, quartz, K-feldspar (orthoclase to microcline), biotite, hornblende; Fig. 2C) mostly corresponds to granodiorite, and quartzdiorite along the pluton margins. Rock texture is hipidiomorphic granular. Magmatic layering is clearly displayed, especially along pluton margins. Jointing is tabular in peripheral parts of the magmatic body and prismatic to massive in central parts (Fig. 2D). Hydrothermal alterations have been observed along the SE margin of the pluton.

As a dimension stone, this rock has both favourable properties (durability, soundness, favourable jointing and possibility of obtaining large stone blocks) and unfavourable (inhomogeneous appearance due to magmatic layering). There are also pegmatite-aplite veins and xenoliths throughout the pluton.

According to the laboratory testing of technical properties, the stone can be used for the production of slabs for all the interior paving and cladding with no restrictions, but due to a somewhat lower compressive and flexural strengths for exterior cladding only up to 30 m in height and for the paving of surfaces with intensive and medium intensive pedestrian traffic.

Željin granitoid

This pluton is situated around 155 km south of Belgrade and has exposed open surface of 56 km^2. It intrudes into Triassic metamorphic complex of the Kopaonik Block and Ridge Unit. The tectonic framework is presented mostly by faults striking NNW–SSE and NE–SW to ENE–WSW. Mineral composition (quartz, andesine, K-feldspar (orthoclase to microcline), biotite, hornblende, epidote up to 10 %; Fig. 2E), mostly corresponds to granodiorite and quartzmonconite in central parts of the pluton and to quartzdiorite along its rims. Rock texture is hipidiomorphic granular. Magmatic layering is clearly displayed along pluton margins. Jointing is tabular in peripheral parts of the pluton and irregular to massive in its central parts (Fig. 2F). Hydrothermal alterations have not been observed.

As a dimension stone, this rock has both favourable properties (durability, soundness, favourable texture in central parts of magmatic body and possibility of obtaining stone blocks over 10 m in length) and unfavourable (inhomogeneous appearance due to magmatic layering, in addition to pegmatite veins in the marginal parts of the pluton; they are rarer in central parts of the pluton).

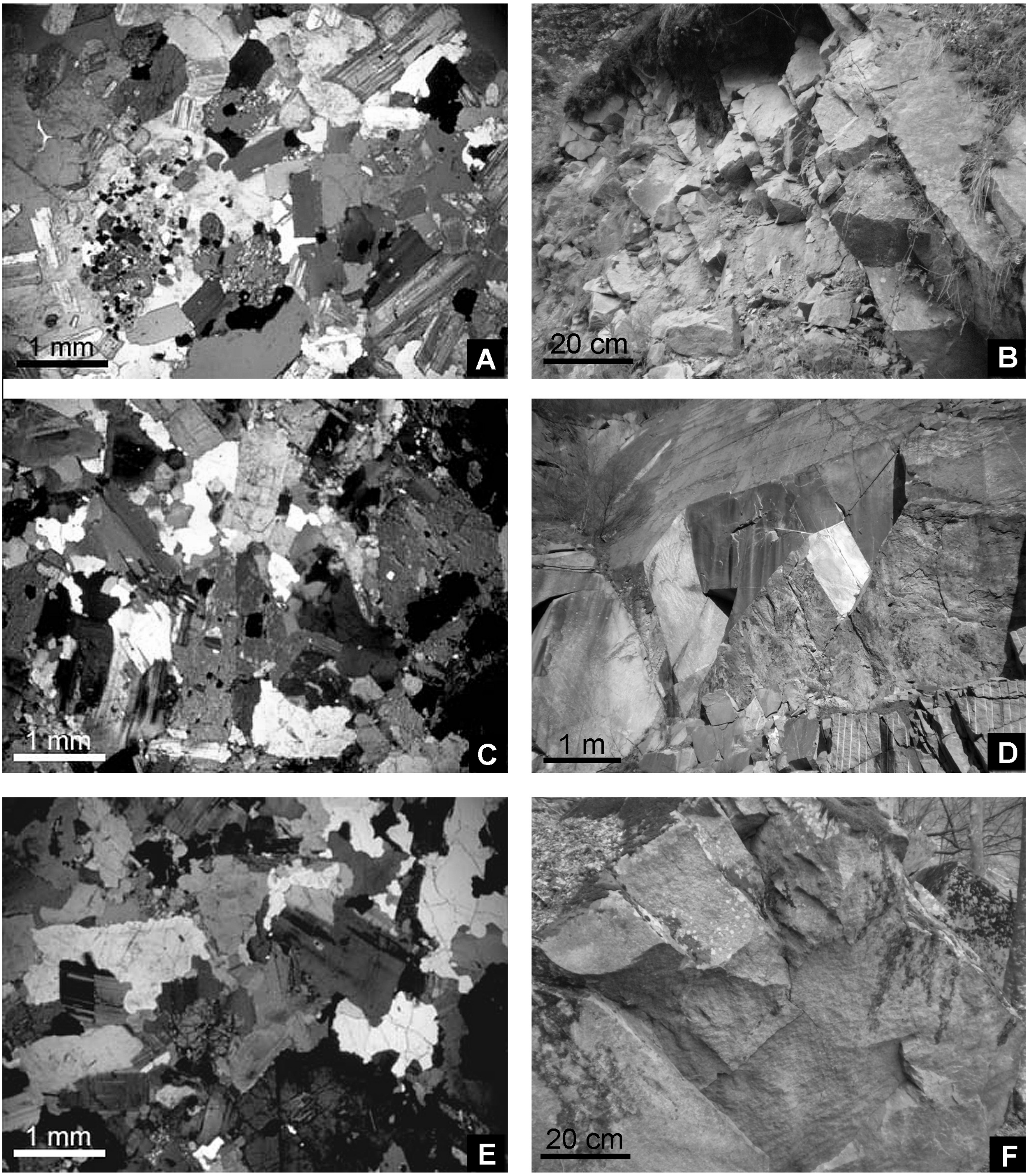

Fig. 2. **A**, Photomicrograph of the Kremići granodiorite thin section. Crossed polars; **B**, Field photograph showing the jointing in the Kremići pluton marginal parts; **C**, Photomicrograph of the Drenje granodiorite thin section. Crossed polars; **D**, Field photograph showing the jointing in central parts of the Drenje pluton; **E**, Photomicrograph of the Željin granodiorite thin section. Crossed polars; **F**, Field photograph showing the jointing in the Željin pluton.

Laboratory testing of technical properties has shown that the stone can be used for the production of slabs for all the interior paving and cladding with no restrictions, but due to a lower flexural strength, for exterior cladding only up to 30 m in height and for the paving of surfaces with intensive and medium intensive pedestrian traffic.

Common properties of examined plutons

Throughout the rock mass of each pluton, there is a moderately pronounced variation of mineral-petrological composition and technical properties, which is typical for a natural rock. The degree of jointing and fracturing is higher in plutons' marginal parts compared to their central parts. With the increasing depth, the intensity of fracturing and jointing is decreasing. Therefore, the dimensions of natural blocks of rock mass are increasing too, enabling the production of commercial size stone blocks.

Technical properties of the stone are favourable (Table 3). Samples for lab testing have been taken from the field surface, and the experience suggests that the samples from the fresh-open rock parts from greater depth would yield even better testing results. All samples are resistant to frost impact and crystallization of Na_2SO_4.

Decorative properties of stone from these plutons are average, as grey colour predominates, and textures are granular with small grain sizes (Fig. 3). In some parts of Željin pluton, increased incidence of epidote grains up to 3 mm in size has been observed. This property gives the stone from these parts of pluton a higher decorative value. The presence of harmful minerals has not been observed in the examined plutons.

Discussion

Examined plutons display differences in size and jointing type. Their other properties relevant for use as dimension stone – mineral composition, fabric, intensity of faulting, fracturing and alteration, decorative properties, technical properties and their variation throughout the rock are rather uniform. There is an increased incidence of pegmatite-aplite veins, xeno-

Table 3. Results of technical properties testing (Kurešević 2013a). Note: reference values from the technical requirements of the Serbian standard SRPS B.B3.200 can be found on the web page www.lymak.com/bb3200.aspx.

Stone property	Units	Standard SRPS	Testing results, average value		
			Kremići	**Drenje**	**Željin**
Uniaxial compressive strength: - dry	Mpa	B.B8.012	169	158	189
- water-saturated			136	154	145
- after 25 freeze-thaw cycles			134	145	145
Abrasion resistance	$cm^3/50\ cm^2$	B.B8.015	10.01	9.79	11.00
Flexural strength	MPa	B.B8.017	31.97	17.67	15.62
Porosity	%	B.B8.032	0.9	1.0	1.7
Water absorption	%	B.B8.010	0.40	0.31	0.29
Apparent density	g/cm^3	B.B8.032	2.678	2.710	2.701
Particle density	g/cm^3	B.B8.032	2.703	2.737	2.752
Thermal expansion	mm/m	ISO 10545-8	0.499	0.656	0.620

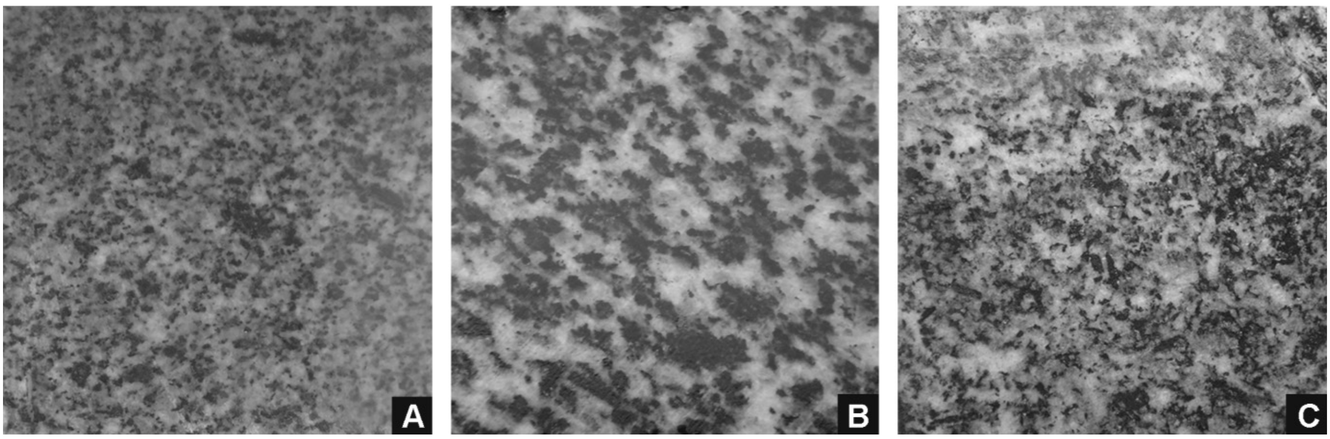

Fig. 3. Macroscopic appearance of the straight cut stone surface; **A**, Kremići; **B**, Drenje; **C**, Željin.

Table 4. Possible use of tested stone according to Serbian standard SRPS B.B3.200. **UH-1** Very intensive pedestrian traffic (hospitals, hotels, company buildings, industrial plants, theatres, cinemas etc.); **UH-2** Intensive pedestrian traffic (shops, residential buildings, museums, restaurants, schools etc.); **UH-3** Moderate pedestrian traffic (libraries, archives, book-shops, waiting-rooms etc.); **SH-1** Very intensive pedestrian and sometimes even vehicle traffic (public squares, city pedestrian zones, streets, shopping molls); **SH-2** Intensive pedestrian traffic (parks, esplanades, less known city pedestrian zones etc.); **SH-3** Moderate pedestrian traffic; **UV** Interior walls cladding; **SV-1** Buildings high over 30 m above ground level; **SV-2** Buildings high from 10 to 30 m above ground level; **SV-3** Buildings high up to 10 m above ground level.

Pluton	Interior				Exterior					
	paving			cladding	paving			cladding		
	UH-1	UH-2	UH-3	UV	SH-1	SH-2	SH-3	SV-1	SV-2	SV-3
Kremići	+	+	+	+	+	+	+	+	+	+
Drenje	+	+	+	+	–	+	+	–	+	+
Željin	+	+	+	+	–	+	+	–	+	+

liths, magmatic layering, unfavourable jointing and hydrothermal alterations presence in marginal parts compared to central parts of the magmatic body in each pluton.

All samples are taken from the existing outcrops, so the weathering degree is rather uniform for all and can be correlated and compared. The results of technical properties testing (Tables 3 and 4) show that the stone from the Kremići pluton can be used for the production of slabs for all the interior and exterior paving and cladding with no limitations, according to the technical requirements of Serbian standard SRPS B.B3.200. Stone from the other two plutons has unlimited possibility for use as dimension stone for production of slabs for the interior paving and cladding while the exterior paving span is limited to areas with intensive (SH-2) and moderate (SH-3) pedestrian traffic, and exterior cladding is limited to categories up to 30 m above ground level (SV-2 and SV-3).

Conclusion

All laboratory testing and field studies of the examined plutons have shown satisfactory results from the aspect of dimension stone. Željin, as a larger pluton, has higher potential because fault-free zones can be located more easily. All tested rock samples satisfy the requirements of the Serbian standard SRPS B.B3.200 and their use for the production of slabs for the exterior and interior paving and cladding is possible. It is reasonable to assume that samples taken from the fresh-open deeper parts of rock mass, which have not been subjected to long-lasting weathering, would have had even better testing results. However, even with the results obtained here, their use is possible. The dimensions of naturally jointed blocks of rock significantly increase with depth. All three examined plutons display rock fabric heterogeneity. Therefore, the stone from these plutons can not comply if there is a demand for large number of slabs of uniform appearance. As these investigations have been performed at the reconnaissance survey level, the results should be used in directing the further phases of the geological exploration process. In Željin pluton, central parts have the highest potential for dimension stone. The entire Drenje pluton has inhomogeneous fabric. Only a small part of the Kremići pluton is open and available for exploration and it is not possible to give a reliable assessment of its potential at this exploration stage.

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References

CVETKOVIĆ, V., KNEŽEVIĆ, V. & PÉCSKAY, Z. 2000. Tertiary igneous formations of the Dinarides, Vardar Zone and adjacent regions: from recognition to petrogenetic implications. *In*: KARAMATA, S. & JANKOVIĆ, S. (eds.), *Geology and Metallogeny of the Dinarides and the Vardar Zone*, 245–252. The Academy of Sciences and Arts of the Republic of Srpska, Banja Luka-Serbian Sarajevo.

KARAMATA, S. 2006. The geological development of the Balkan peninsula related to the approach, collision and compression of Gondwanan and Eurasian units. *In*: ROBERTSON, A.H.F. & MOUNTRAKIS, D. (eds.), *Tectonic development of the Eastern Mediterranean region*, Geological society special publications, 155–178. London.

KARAMATA, S., DELALOY, M., LOVRIĆ, A. & KNEŽEVIĆ, V. 1992. Two genetic groups of Tertiary granitic rocks of

Central and Western Serbia. *Geološki anali Balkanskoga poluostrva*, 56 (1): 263–283.
KUREŠEVIĆ, L. 2013a. Potentiality of Tertiary magmatic complexes of the Vardar Zone in Serbia from the aspect of dimension stone. Unpublished PhD thesis, 254 pp., Faculty of Mining and Geology, University of Belgrade.
KUREŠEVIĆ, L. 2013b. Tertiary plutonic rocks of central and western Serbia Vardar Zone as dimension stone. *Acta Montanistica Slovaca*, 18 (3): 180–187.
ROBERTSON, A., KARAMATA, S. & ŠARIĆ, K. 2009. Overview of ophiolites and related units in the Late Plaeozoic-Early Cenozoic magmatic and tectonic development of Tethys in the northern part of the Balkan region. *Lithos*, 108 (1–4): 1–36.
SCHEFER, S., CVETKOVIĆ, V., FÜGENSCHUH, B., KOUNOV, A., OVTCHAROVA, M., SCHALTEGGER, U. & SCHMID, S. 2011. Cenozoic granitoids in the Dinarides of southern Serbia: age of intrusion, isotope geochemistry, exhumation history and significance for the geodynamic evolution of the Balkan Peninsula. *International Journal of Earth Sciences*, 100 (5): 1181–1206.
UROŠEVIĆ, M., PAVLOVIĆ, Z., KLISIĆ, M., MALEŠEVIĆ, M., STEFANOVIĆ, M., MARKOVIĆ, O. & TRIFUNOVIĆ, S. 1973a. *Basic geologic map 1:100 000 explanatory booklet*, sheet Vrnjci, K 34-18. Zavod za geološka i geofizička ispitivanja, 69 pp., Belgrade.
UROŠEVIĆ, M., PAVLOVIĆ, Z., KLISIĆ, M., KARAMATA. S., MALEŠEVIĆ, M., STEFANOVIĆ, M., MARKOVIĆ, O. & TRIFUNOVIĆ, S. 1973b. *Basic geologic map 1:100 000 explanatory booklet*, sheet Novi Pazar, K34-3. Zavod za geološka i geofizička ispitivanja, 77 pp., Belgrade.

Резиме

Терцијарни плутони јужног дела Вардарске зоне Србије са аспекта архитектонског грађевинског камена

Истражена су три гранитоидна плутона терцијарне старости у јужном делу Вардарске зоне Србије, са циљем да се утврди њихова потенцијалност за коришћење као архитектонски грађевински камен: жељински, кремићки и дрењски. Теренска проучавања су имала за циљ утврђивање геолошких фактора оцене потенцијалности – присуство дисјунктивних структура, штетних минерала, алтерација, типа лучења и хомогености склопа, како би се утврдила могућност добијања крупних стенских блокова из плутона. Лабораторијска испитивања су обухватила минералошко-петролошке анализе стена и испитивање физичко-механичких карактеристика стенске масе.

Плутон Кремића се налази око 180 km јужно од Београда. Има облик неправилног дајка, отворене површине од око 5 km². Интрудован је у Ибарски ултрамафитски комплекс. Минералошки састав (кварц, андезин, калијски фелдспати (ортоклас до микроклин), хорнбленда, биотит), углавном одговара кварцдиориту до гранодиориту (амфиол-биотитски, ретко амфиболски варијетети). Кварцмонцонит је заступљен у централним деловима плутона. Структура стене је хипидиоморфно зрнаста. Највећи део ерозијом откривене површине плутона данас је покривен земљиштем и густом шумом. Теренском проучавању су доступни само мали, ободни делови плутона. У њима је лучење плочасто, призматично и неправилно. Утврђено је присуство слабих алтерација уз северозападни обод плутона. У осталим деловима плутона, стенска маса је свежа и чврста.

Као архитектонски грађевински камен, стенска маса из кремићког плутона има повољна својства (чврстоћу, једрину, повољну структуру), али и неповољна (нехомоген изглед, присуство ксенолита, местимична појава магматског литажа, неповољни типови лучења и мале димензије природно лучених блокова). Лабораторијска испитивања су показала да се стенска маса може користити за производњу плоча за хоризонтално и вертикално облагање у екстеријеру и ентеријеру без ограничења.

Плутон Дрења налази се око 170 km јужно од Београда. Његова ерозијом отворена површина је око 4 km². Интрудован је у метаморфни комплекс Копаоничког блока, тријаске старости. Минералошки састав (андезин, кварц, калијски фелдспати (ортоклас до микроклин), биотит, хорнбленда) углавном одговара гранодиориту, и кварцдиориту дуж обода плутона. Структура стене је хипидиоморфно зрнаста. Магматски литаж је јасно изражен, нарочито у ободним деловима плутона. Лучење је плочасто у ободним деловима плутона, и призматично до масивно у централним. Хидротермалне алтерације су примећене дуж југоисточног обода плутона.

Као архитектонски грађевински камен, стенска маса из дрењског плутона има повољна својства (чврстоћу, једрину, повољан тип лучења и могућност добијања крупних блокова стенске масе), али и неповољна (нехомоген изглед, присуство ксенолита и аплитско-пегматитских жица, местимична појава магматског литажа). Лабораторијска испитивања су показала да се може користити за производњу плоча за хоризонтално и вертикално облагање у ентеријеру без ограничења, а због нешто ниже притисне и савојне чврстоће у екстеријеру ограничено.

Жељински плутон се налази око 155 km јужно од Београда. Његова ерозијом отворена површина је око 56 km². Интрудован је у метаморфни комплекс Копаоничког блока, тријаске старости. Минералошки састав (кварц, андезин, калијски фелдспати (ортоклас до микроклин), биотит, хорнбленда, епидот) углавном одговара гранодиориту и кварцмонцониту у централним деловима плутона и кварцдиориту дуж обода плутона. Структура

стене је хипидиоморфно зрнаста. Магматски литаж је јасно изражен у ободним деловима плутона. Лучење је плочасто у ободним деловима плутона, и неправилно до масивно у централним. Хидротермалне алтерације нису констатоване.

Као архитектонски грађевински камен, стенска маса из жељинског плутона има повољна својства (чврстоћу, једрину, повољну структуру и тип лучења у централним деловима плутона, и могућност добијања крупних блокова стенске масе, дужине преко 10 m), али и неповољна (нехомоген изглед због магматског литажа, и присуство аплитско-пегматитских жица, нарочито у ободним деловима плутона). Лабораторијска испитивања су показала да се може користити за производњу плоча за хоризонтално и вертикално облагање у ентеријеру без ограничења, а због нешто ниже савојне чврстоће у екстеријеру ограничено.

Плутони показују нека заједничка својства. Склоп стена, као и изглед камена су хетерогени, услед присуства магматског литажа. Из овог разлога, стенска маса из ових плутона се не може користити у случајевима када се захтева камен униформног изгледа.

Димензије природно лучених блокова стена повећавају се са дубином. Жељински плутон због својих димензија има највећу потенцијалност због лакшег лоцирања зона без структурних деформација. Цео дрењски плутон има нехомоген склоп. На данашњем нивоу еродованости, само мали део плутона Кремића је отворен и доступан за истраживање, те стога није могуће дати поуздану оцену његове потенцијалности у овој фази истраживања.

Оцена могућности примене на основу добијених резултата лабораторијских испитивања врши се у складу са техничким захтевима Српског стандарда Б.Б3.200, и показала је да се камен из ових плутона може користити као архитектонски грађевински камен за вертикално и хоризонтално облагање грађевинских објеката у ентеријеру и екстеријеру. Можемо предпоставити да би узорци узети из свежих, дубљих делова стенске масе, који нису били изложени дуготрајном утицају атмосферилија, имали још боље резултате испитивања. Међутим, чак и са овим резултатима, оцена њихове употребљивости је позитивна.

Камен из ових плутона је показао повољне резултате теренских и лабораторијских испитивања. С обзиром да су ова истраживања спроведена на нивоу регионалне проспекције, њихове резултате треба користити као смернице у наредној фази процеса геолошког истраживања.

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Assessment of the discharge regime and water budget of Belo Vrelo (source of the Tolišnica River, central Serbia)

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Abstract. A sufficiently long spring discharge regime monitoring data set allows for a large number of analyses, to better understand the process of transformation of precipitation into a discharge hydrograph. It is also possible to determine dynamic groundwater volumes in a karst spring catchment area, the water budget equation parameters and the like. It should be noted that a sufficiently long data set is deemed to be a continuous spring discharge time series of more than 30 years. Such time series are rare in Serbia. They are generally much shorter (less than 15 years), and the respective catchment areas therefore fall into the "ungauged" category. In order to extend existing karst spring discharge time series, we developed a model whose outputs, apart from mean monthly spring discharges, include daily real evapotranspiration rates, catchment size and dynamic volume variation during the analytical period. So far the model has solely been used to assess the discharge regime and water budget of karst springs. The present paper aims to demonstrate that the model also yields good results in the case of springs that drain aquifers developed in marbles. Belo Vrelo ("White Spring", source of the Tolišnica River), which drains marbles and marbleized limestones and dolomites of Čemerno Mountain, was selected for the present case study.

Key words: groundwater regime, catchment area, real evapotranspiration, dynamic volume, water budget, Belo Vrelo, Serbia.

Апстракт: Довољно дуг низ осматрања режима истицања неког врела омогућује примену великог броја анализа које могу помоћи да се процес трансформације падавина у хидрограм истицања боље разуме. Такође омогућајаву да се одреде: динамичке запремине подземних вода слива карстног врела, параметри билансне једначине, итд. Овде треба напоменути да довољно дуги низ подразумева чињеницу да је неопходно имати непрекидну серију осматрања режима истицања неког врела у временском интервалу дужем од 30 година, што је редак случај у Србији. Најчешће су серије осматрања истицања на врелима знатно краће (испод 15 година) што их на жалост сврстава у категорију хидролошки неизучених сливова. За потребе продужавања постојећих низова истицања карстних врела развијен је модел који, као излаз, поред серије средње месечних протицаја неког врела, даје и дневне вредности реалне евапотранспирације, површину слива и промену динамичке запремине у рачунском периоду. Модел је до сада примењиван искључиво за потребе анализе режима и биланса карстних врела. Сврха овог рада је да покаже да развијени модел даје добре резултате када су у питању и врела која дренирају издани формиране у мермерима. У конкретном случају је изабрано Бело врело (врело Толишнице) које дренира мермере и мермерисане кречњаке планине Чемерно.

Кључне речи: режим подземних вода, површина слива, реална евапотранспирација, динамичка запремина подземних вода, биланс вода, Бело врело.

Introduction

One the key prerequisites for efficient groundwater use for any purpose is knowledge of the hydrogeological characteristics of the area, the qualitative and quantitative characteristics of the groundwater, and the variations in these parameters over time. The aquifer regime is governed by a series of factors, pri-

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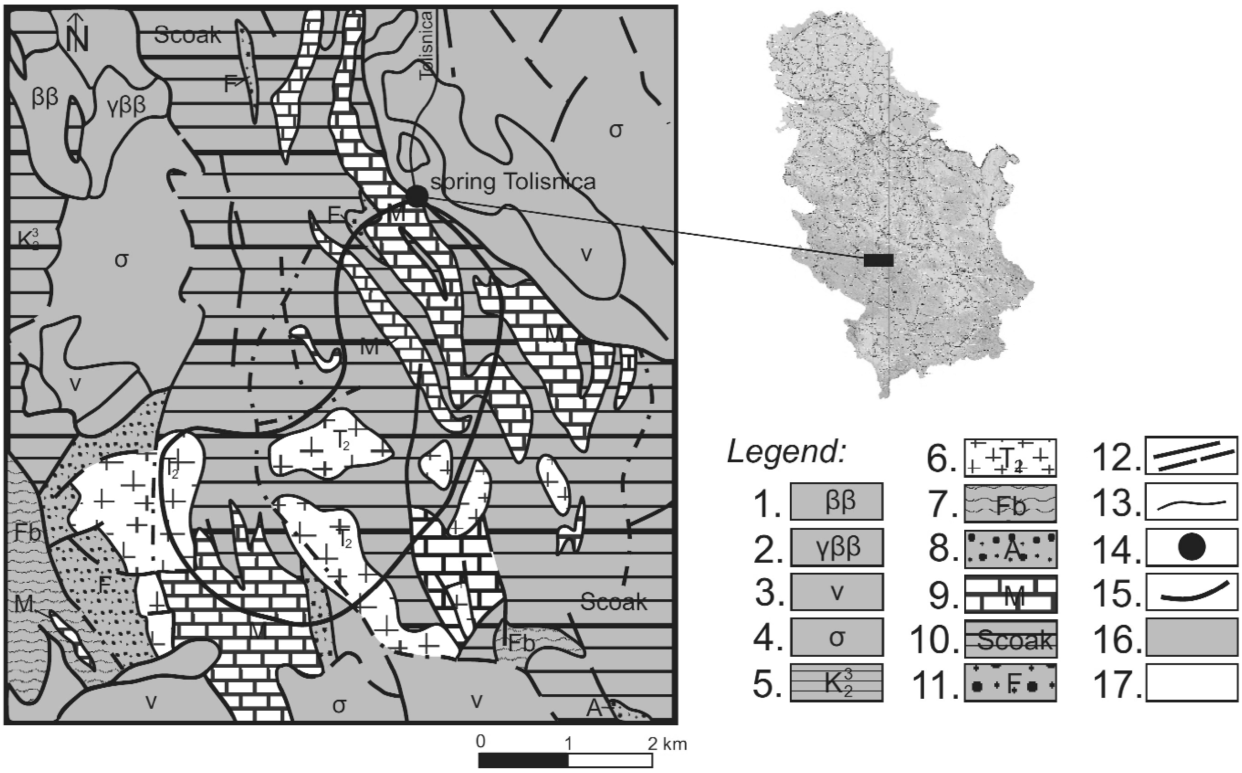

Fig. 1. Location and hydrogeological map of the Belo Vrelo (Tolisnica Spring) catchment (after BRKOVIĆ *et al.* 1977). Legend: **1,** diabases; **2,** gabbro-diabases; **3,** gabbros; **4,** harzburgites, siltstones, schistose mudstones and cherts; **5,** arenites, alevrolytes, schistose slays and cherts; **6,** massive dolomitic marbleized limestones; **7,** schists and biotitic phyllites; **8,** amphiboles; **9,** marbleized limestones; **10,** chlorite-epidote-actinolite rocks; **11,** phyllites; **12,** fault; **13,** surface stream; **14,** spring; **15,** water divide; **16,** fractured aquifer; **17,** karst aquifer.

marily the geological setting and the geomorphological, hydrogeological and climate conditions.

A catchment area is deemed to be gauged if the regime of relevant quantitative parameters has been monitored for at least 30 years. A catchment area is partially gauged if monitoring lasted for 15 to 30 years, and ungauged if the monitoring period was shorter than 15 years (PROHASKA 2003). From this perspective, gauged catchment areas of karst springs in Serbia are extremely rare. There are only two such cases at present: a karst spring near the Village of Žagubica, which is the source of the Mlava River, and Sveta Petka Spring near the City of Paraćin (STEVANOVIĆ *et al.* 2014).

The time series of all the other karst springs are either much shorter (from one to ten years) or there has been no monitoring at all, the latter being more often the case. Assessments of the discharge regime and water budget of ungauged springs, or those that have not been studied in hydrological and hydrogeological terms, can be misleading. To prevent potentially erroneous assessments of the water budget equation parameters in such cases, or to at least ensure reasonable departures from real values, the Department of Hydrogeology of the Faculty of Mining and Geology at the University of Belgrade developed a model that extends relatively short (less than 15 years) time series of karst spring discharges. Apart from extending the length of existing time series, the model provides the catchment size, real evapotranspiration rates and variations in karst spring dynamic volume in the analytical period for which gaps in the existing time series of average monthly discharges have been filled. To date, the model has been tested and applied to about 20 karst springs in Serbia (RISTIĆ 2007; RISTIĆ VAKANJAC *et al.* 2010, 2013, 2014a, 2014b; STEVANOVIĆ *et al.* 2010). The difference between the catchment size computed by the model and the real catchment size of the karst spring resulting from detailed hydrogeological research is up to 10%.

Described below is the outcome of an application of the model, in this case to Belo Vrelo (source of the Tolišnica River), which drains marbles, marbleized limestones and dolomites of Čemerno Mountain.

Geological and hydrogeological characteristics of the extended area of Belo Vrelo

The karst spring of Belo Vrelo is situated in central Serbia, in Ivanjica Municipality (Fig. 1). The drainage area of the spring belongs to the catchment area of the

Fig. 2. Belo Vrelo.

Tolišnica River, which in turn belongs to the wider Lopatnica River Basin on the slopes of Čemerno Mountain**.** The upper part of the Lopatnica River Basin features several springs, the largest being: Belo Vrelo (Fig. 2), Konjsko Vrelo (Horse's Spring) and Mala Sokolina cluster of springs (Fig. 1). The altitude of most of the basin varies from 600 to 1000 m, while the edges of the basin in the south are as high as 1581 m a.s.l. (Fig. 3) (at Smrdljuš Summit of Čemerno Mountain).

The area is largely made up of Paleozoic deposits that hold a fractured aquifer. The sediments include phyllites, metamorphic quartz conglomerates, gneisses and schists, as well as marbleized limestones which are highly relevant to this research. In addition to Paleozoic sediments, there are also massive Middle Triassic dolomitic and marbleized limestones, but to a lesser extent. They occur as erosion remnants – peneplains, whose size is about 1.5 km^2. They constitute the margin of a large Triassic belt of Jelica Mountain, with which they are in contact. There are also Upper Cretaceous (Senonian) siltstones and schistose mudstones, overthrust on Senonian-Upper Cretaceous flysch (limestones, marls, sandstones and mudstones). The faults (the most pronounced of which are found in the Rudno–Propljenica zone) are nearly parallel to the plane of overthrust, roughly running in the NNW–SSE direction. Flaking is also evident in the

Fig. 3. Smrdljuš Summit of Čemerno Mountain.

middle of this zone, where Triassic sediments are developed. Young transverse faults are quite common throughout the area (Brković *et al.* 1977).

Limestones, marbleized limestones and dolomites determine to a large extent the hydrogeology of the study area because of their fracture porosity resulting primarily from local tectonic movements. The aquifer stores a considerable amount of groundwater. Towards the surface, these rocks act as hydrogeological collector-conduits, while in the deeper reaches they serve as collector-reservoirs, discharged at the point of contact with semi-permeable and impermeable rocks via springs formed in places where local faults occur, like in the case of Belo Vrelo. The study of the hydrogeological characteristics of the terrain included an analysis of spring discharges, whose minimum-to-maximum ratio was less than 10 and the number of karst features less than one per km^2.

Recharge comes from precipitation and sinking of small surface streams. In the case of fracture porosity, groundwater pathways are determined by the geological formation, extent of fracturing and local hydrogeological conditions. At Belo Vrelo, groundwater circulates within faults, fractures and fissures. Groundwater drainage, or discharge, is gravity-driven and takes place via springs exposed on the ground surface, whose discharge rates vary. Belo Vrelo features the highest discharge rates; the lowest rate ever recorded was 40 l/s in December 1978, while the highest rate was more than 300 l/s. Konjsko Vrelo (Horse's Spring) discharges some 5 l/s and Mala Sokolina springs 2 to 3 l/s. Belo Vrelo emerges on the ground surface below a bend called Tisovski Prevoj, on the northern slopes of Čemerno Mountain, at an altitude of 770 m. The spring is located at a distance of about 3 km from the Village of Tolišnica. The spring discharges through a steep slope at the point of contact between marbleized limestones and impermeable rocks. In the spring area, visible blocks of while marbleized limestones, 3–5 m wide, suggest the existence of a fault that follows the gradient of the terrain (about 30°).

Hydrological monitoring of Belo Vrelo

In 1994, the National Hydrometeorological Service established hydrological stations at several karst springs, including Belo Vrelo. Hydrometric surveys and water level monitoring began on 1 January 1995 and continued through the end of 2002. Table 1 shows mean monthly and annual discharges of Belo Vrelo during the period of monitoring. Generally speaking, maximum discharge rates are usually attributable to snowmelt and spring rains.

and the lowest only 67 l/s, recorded several times in 1995, 1996 and 2001. The 1995–2002 ratio of minimum-to-maximum discharges was 1:6, indicative of a relatively uniform discharge regime of Belo Vrelo. Figure 4 shows the 1996 hydrograph of this spring. The hydrograph includes one prolonged spring maximum (possibly two), and one minimum. The discharge peaks are generally attributable to snowmelt, which started in March/April, and spring rains (April/May/June). If snowmelt and spring rains occurred simultaneously, the hydrograph showed a prolonged peak. If the two events did not coincide, there were two or more lower peaks in the first half of the year. Conversely, the lowest discharge rates were noted in the summer months, when the discharge rates of Belo Vrelo were the lowest.

Table 1. Mean monthly and annual discharges of Belo Vrelo (m^3/s).

	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec	Annual
1995	0.124	0.135	0.140	0.150	0.150	0.147	0.111	0.086	0.081	0.070	0.080	0.079	**0.113**
1996	0.078	0.079	0.080	0.109	0.147	0.147	0.117	0.086	0.106	0.115	0.106	0.106	**0.106**
1997	0.104	0.090	0.087	0.129	0.156	0.144	0.143	0.142	0.128	0.120	0.117	0.115	**0.123**
1998	0.115	0.131	0.115	0.127	0.115	0.108	0.103	0.086	0.087	0.100	0.105	0.100	**0.114**
1999	0.102	0.097	0.113	0.110	0.102	0.090	0.085	0.089	0.092	0.098	0.098	0.117	**0.099**
2000	0.123	0.114	0.125	0.109	0.098	0.088	0.081	0.079	0.093	0.089	0.089	0.088	**0.098**
2001	0.071	0.075	0.080	0.094	0.115	0.125	0.127	0.127	0.170	0.205	0.187	0.175	**0.129**
2002	0.247	0.241	0.232	0.264	0.188	0.178	0.172	0.208	0.253	0.266	0.330	0.214	**0.232**
Qav	**0.121**	**0.120**	**0.122**	**0.136**	**0.134**	**0.128**	**0.117**	**0.113**	**0.126**	**0.133**	**0.139**	**0.124**	**0.127**
σ	**0.05**	**0.05**	**0.05**	**0.05**	**0.03**	**0.03**	**0.03**	**0.04**	**0.06**	**0.07**	**0.08**	**0.05**	**0.04**
Cv	**0.45**	**0.45**	**0.41**	**0.40**	**0.24**	**0.25**	**0.26**	**0.40**	**0.47**	**0.51**	**0.60**	**0.37**	**0.35**
Cs	**2.12**	**1.91**	**1.83**	**2.31**	**0.51**	**0.05**	**0.67**	**1.66**	**1.75**	**1.46**	**2.13**	**1.33**	**2.50**
Max	**0.247**	**0.241**	**0.232**	**0.264**	**0.188**	**0.178**	**0.172**	**0.208**	**0.253**	**0.266**	**0.330**	**0.214**	**0.232**
Min	**0.071**	**0.075**	**0.080**	**0.094**	**0.098**	**0.088**	**0.081**	**0.079**	**0.081**	**0.070**	**0.080**	**0.079**	**0.098**

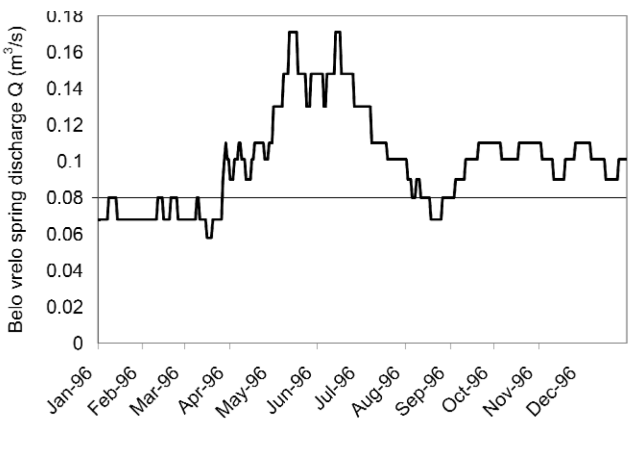

Fig. 4. 1996 hydrograph of Belo Vrelo.

Based on recorded daily discharges, the long-term average discharge for the period 1995–2002 was 0.127 m^3/s. The maximum mean monthly discharge rate was 0.330 m^3/s, registered in November 2002. The minimum mean monthly discharge was 0.070 m^3/s, in October 1995. With regard to absolute daily discharge rates, the highest was 410 l/s on 24/25 December 2002

Autocorrelation and cross-correlation analyses of Belo Vrelo

Correlation analyses of the effect of annual precipitation totals on discharge rates of Belo Vrelo were undertaken to substantiate the above conclusion, or, in other words, to corroborate the correlation between precipitation and discharge. At a calendar year level, the coefficients of correlation were extremely low ($r = 0.275$ for the station at Ivanjica and $r = 0.073$ at Kraljevo). However, when the hydrological year was assessed, the coefficients of correlation were much higher, amounting to $r = 0.465$ at Ivanjica and as much as $r = 0.667$ at Kraljevo. This was a result of the fact that winter (November, December and January) precipitation remained in the catchment area and caused runoff/discharge during the next calendar year, after snowmelt. As a result, this type of analysis generally requires parameter averaging with regard to the hydrological year (1 October to 30 September). Then a cross-correlation analysis was undertaken to examine the effect of daily precipitation totals on discharge rates of Belo Vrelo. Figure 5 shows a cross-correlogram with a 100-day time lag. It is apparent that the strongest correlation between precipitation and discharge was noted after one day, but that there was a pronounced peak after 32 days, which was certainly due to snowmelt.

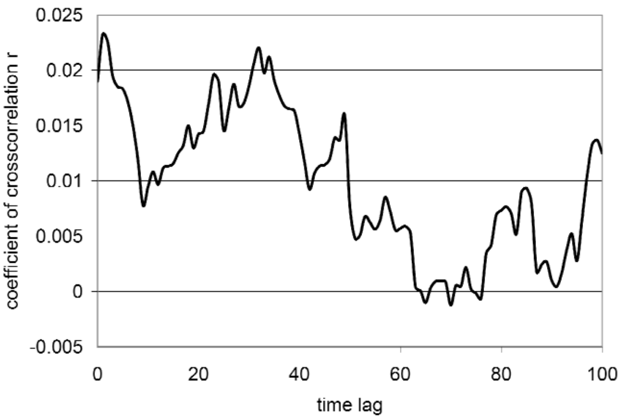

Fig. 5. Cross-correlogram (Čokorilo Ilić *et al.* 2014).

Apart from the cross-correlation analysis of Belo Vrelo, an autocorrelation analysis was undertaken for a time lag of 100 days (Fig. 6). The autocorrelogram showed a strong correlation even after 100 days, corroborating the earlier claim that the discharge regime of Belo Vrelo is relatively uniform (or that the memory is long, 100 days or more).

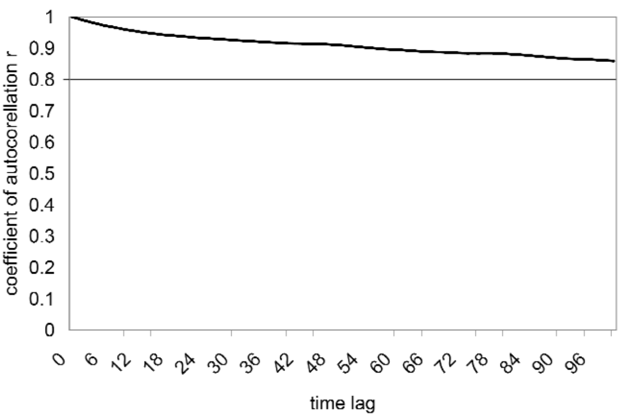

Fig 6. Auto-correlogram.

Recession curve analysis

Groundwater reserves of Belo Vrelo were assessed by recession curve analysis. A proper analysis of the retardation capacity of an aquifer requires a period of at least 90 days after heavy rainfall, with constant drainage and no recharge (aquifer recession). The discharge regime monitoring data revealed that these criteria were fulfilled in 1995, from 8 June to 2 November (a total of 148 days), and in 2000, from 23 March to 21 August (156 days). It should be noted that there was some rainfall during the period, but it had no significant effect on the spring discharge regime, as clearly shown in Figs. 7 and 8. Namely, during that period the rainfall was either torrential in nature, such that a part of the atmospheric precipitation was lost to surface runoff or evapotranspiration, or the precipitation totals did not cause any signification variation in the dynamic volume and thus had no effect on the discharge hydrograph.

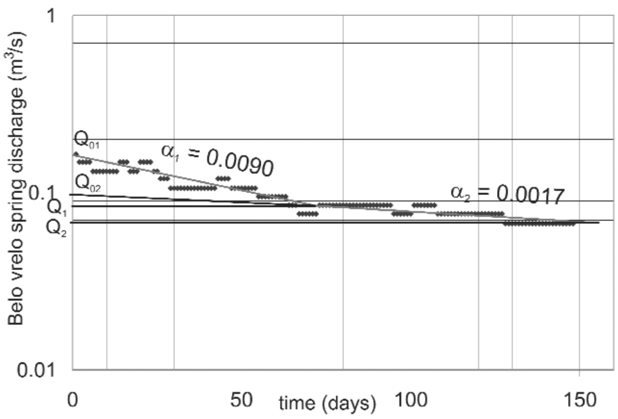

Fig. 7. Analyzed part of the regression stage of the hydrograph, 8 June to 2 November 1995.

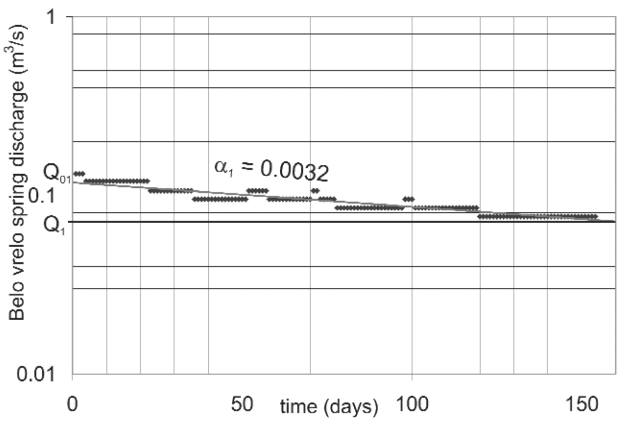

Fig. 8. Analyzed part of the regression stage of the hydrograph, 23 March to 21 August 2000.

Analysis of the regression stage of the hydrograph (Fig. 7) revealed two discharge microregimes, whose characteristics were nearly identical. Maillet's equation (Maillet 1905; Krešić & Bonacci 2009) was used to compute the drainage coefficient:

$$\alpha = \frac{\log Q_0 - \log Q_t}{0.4343 \cdot (t - t_0)} \tag{1}$$

It follows from Eq. 1 that during the 1995 recession period (Fig. 7):

$$\alpha_1 = \frac{\log Q_{01} - \log Q_1}{0.4343 \cdot (t_1 - t_0)} = \frac{\log 0.155 - \log 0.081}{0.4343 \cdot 72} = 0.009013$$

$$\alpha_2 = \frac{\log Q_{02} - \log Q_2}{0.4343 \cdot (t_2 - t_0)} = \frac{\log 0.095 - \log 0.072}{0.4343 \cdot 156} = 0.001777$$

Similar results were obtained for the 2000 recession curve (Fig. 8):

$$\alpha_1 = \frac{\log Q_{01} - \log Q_1}{0.4343 \cdot (t_1 - t_0)} = \frac{\log 0.12 - \log 0.072}{0.4343 \cdot 160} = 0.003193$$

The drainage coefficients were of the same order of magnitude and demonstrated average-to-good recession characteristics of the aquifer. These parameters were used to determine the summary volume of the discharged water. In the first case (1995), the summary volume was:

$$V = V_1 + V_2 = \frac{Q_{01} - Q_{02}}{\alpha_1} \cdot 86400 + \frac{Q_{02} - 0}{\alpha_2} \cdot 86400$$

$$V = \frac{0.155 - 0.095}{0.009013} \cdot 86400 + \frac{0.095}{0.001777} \cdot 86400 =$$

$$= 575141 + 4619100 = 5194241 \text{ m}^3$$

and in the second case (2000):

$$V = V_1 = \frac{Q_{01} - 0}{\alpha_1} \cdot 86400 = \frac{0.12 - 0}{0.003193} \cdot 86400 = 3247490 \text{ m}^3$$

Application of the model to fill gaps in average monthly discharge time series

A model developed at the University of Belgrade, Faculty of Mining and Geology, Department of Hydrogeology was used to identify the parameters of the water budget equation, primarily the catchment area of Belo Vrelo. The model comprises several levels; in the present case:

1. Generation of a long-term time series of Belo Vrelo discharges using a mathematical model of multiple nonlinear correlation (MNC) for spatial transfer of hydrometeorological data (PROHASKA *et al.* 1977, 1979, 1995). Here the MNC model was used to extend the time series of average monthly discharges of Belo Vrelo for the period 1960–2009. Figure 9 shows the intra-annual distribution of derived average monthly discharges of Belo Vrelo during the analytical period.
2. Determination of potential evapotranspiration (PET) by means of a modified Thornthwaite equation (RISTIĆ 2007; RISTIĆ VAKANJAC *et al.* 2013).

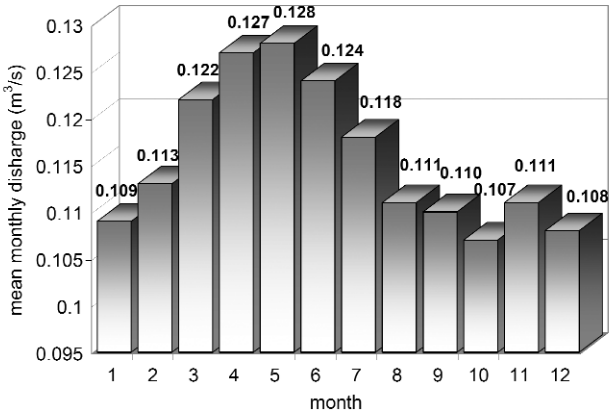

Fig. 9. Intra-annual distribution Belo Vrelo discharge (ČOKORILO ILIĆ *et al.* 2014).

3. Determination of real evapotranspiration (RET), catchment size and water budget of the considered aquifer as follows: for rainy days PET = RET, and for days following rainfall RET was obtained from the exponential equation RET = PET $\Theta^{2\tau}$, where Θ is a dimensionless parameter and τ is the time step (1, 2, 3 ...). For the parameter values Θ = 0, 0.1, 0.2, ..., 0.8, 0.9 and 0.95, the water budget equation was established by calibrating the potential catchment size such that the condition $V_0 \cong V_K$ was fulfilled. Then the function $\Theta = f$ (F) was constructed, where the vertex represented the real catchment area (Fig. 10) (RISTIĆ VAKANJAC *et al.* 2013).

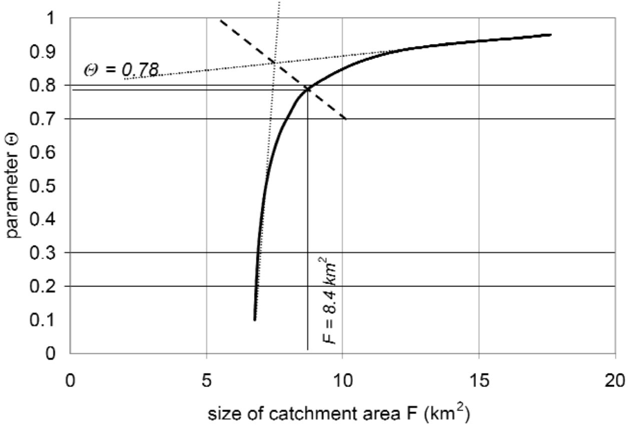

Fig. 10. Function $\Theta = f$ (F) of the Belo Vrelo catchment. (ČOKORILO ILIĆ *et al.* 2014).

The resulting catchment size could be used to compute the parameters of the water budget equation (Table 2). Table 2 shows: the catchment size F (km²), the long-term average discharge Q (m³/s), the discharged volume of water W (10⁶ m³), the long-term average runoff modulus q (l/s/km²), the runoff layer h (mm), the average annual precipitation P (mm), the average annual evapotranspiration E (mm), and the long-term average runoff coefficient φ. To clarify some of the parameters, following are the equations that were applied in the analysis.

- Discharged volume W (10^6 m^3)

$$W = Q \cdot T \tag{2}$$

- Runoff layer h (mm)

$$h = \frac{W}{F} \tag{3}$$

- Runoff modulus q (l/s/km^2)

$$q = \frac{Q}{F} \tag{4}$$

- Average annual evapotranspiration E (mm)

$$E = P - h \tag{5}$$

- Runoff coefficient φ

$$\varphi = \frac{h}{P} \tag{6}$$

where: Q is the average annual discharge in m^3/s, T is a one-year period in seconds, W is the average annual discharge volume (m^3), F is the catchment area in m^2, P is the precipitation in mm, and h is the runoff layer in mm.

Table 2. Summary of Belo Vrelo water budget, 1960–2009.

F	P	E	h	Qav	q	W	φ
km^2	mm	mm	mm	m^3/s	l/s/km^2	10^6 m^3	°
8.6	866.5	445.6	421.0	0.116	13.5	3.62	0.48

Assessment of the dynamic volume of Belo Vrelo

The basic water budget equation for a karst aquifer, with a monthly time step, is:

$$\varphi = \frac{h}{P} \tag{7}$$

where:
P_{ij} - monthly precipitation totals of the karst catchment;
h_{ij} - total monthly karst spring discharge layer;
E_{ij} - monthly sums of actual (real) evapotranspiration in the karst catchment;
V_{ij} - water volume of the considered karst aquifer in the j-th month; and
Δ_{ij} - variation in stored karst groundwater, in the j-th month.

Given that monthly precipitation totals are known quantities and the average monthly runoff layer and monthly sums of real evapotranspiration were generated by the model, Eq. 7 is generally used to compute variations in dynamic volume during the analytical period. Such volume variations in a karst groundwater reservoir, derived in the above manner, are shown in Fig. 11. It is apparent that the total dynamic volume of Belo Vrelo, based on monthly values of all water budget components during the analytical period from 1960 to 2009, amounted to approximately 10^7 m^3.

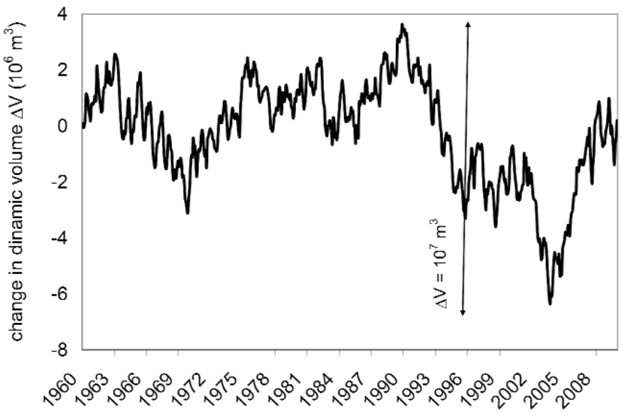

Fig. 11. Variation in dynamic volume of Belo Vrelo.

Conclusion

The general conclusion was that the annual average discharge rate of Belo Vrelo was Q = 0.116 m^3/s. Given that the catchment size of this spring is 8.6 km^2, the long-term average discharge layer during the analytical period was h=421.0 mm. With regard to water abundance, the specific yield of the Belo Vrelo drainage area was found to be 13.5 l/s/km^2, while the derived runoff coefficient suggested that 48% of all precipitation was infiltrated and then discharged via springs. The quality of this bacteriologically safe water is extremely high, such that it can be used for domestic water supply, agriculture and fish farming.

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References

BRKOVIĆ T., MALEŠEVIĆ M., UROŠEVIĆ M., TRIFUNOVIĆ S. & RADOVANOVIĆ Z., 1976. Geological map of the Ivanjica sheet K34-17, scale 1:100.000, Federal Institute of Geology, Belgrade, Yugoslavia.

BRKOVIĆ T., MALEŠEVIĆ M., UROŠEVIĆ M., TRIFUNOVIĆ S., RADOVANOVIĆ Z., DIMITRIJEVIĆ M. & DIMITRIJEVIĆ M. N., 1977. Explanatory book for Geological map of the Ivanjica sheet K34-17, scale 1:100.000, Federal Institute of Geology, Belgrade, Yugoslavia.

ČOKORILO ILIĆ, M., RISTIĆ VAKANJAC, V., OUDECH, S., POLOMČIĆ, D. & BAJIĆ, D. 2014. Hydrogeological characteristics, discharge regime and water balance of Belo Vrelo (source of the Tolišnica River, Serbia). *Proceedings of the 16th Conference of Serbian Geologists,* 346–352, Donji Milanovac (in Serbian).

KREŠIĆ, N. & BONACCI, O. 2009. Spring discharge hydrograph. *In*: KREŠIĆ, N. & STEVANOVIĆ, Z. (Eds.), *Ground Hydrology of Springs*, 129–230, Elsevier.

MAILLET, E. (ED.) 1905. Essais d'hydraulique souterraine et fluviale. Herman, Paris.

PROHASKA, S., PETKOVIĆ, T. & SIMONOVIĆ, S. 1977. Application of multiple nonlinear standardized correlation in calculating correlations. *Collection of papers of the Jaroslav Černi Institute for the Development of Water Resources*, 58: 25–34..

PROHASKA, S., PETKOVIĆ T. & SIMONOVIĆ S. 1979. Mathematical model for spatial transfer and interpolation of hydro-meteorological data. *Collection of papers of the Jaroslav Černi Institute for the Development of Water Resources*, 64.

PROHASKA, S., RISTIĆ V., SRNA P. & MARČETIĆ I. 1995. The use of Mathematical VMC Model in Defining Karst Spring Flows Over the Years. *15th Conference of the Carpatho-Balkan Geological Association*, 4 (3): 915–919, Athens.

PROHASKA, S., 2003. Hydrology, Part I. University of Belgrade, Faculty of Mining and Geology. pp. 556, Belgrade

RISTIĆ, V. 2007. Development of a Simulation Model of Daily Karst Spring Discharges. Unpublished, Doctoral Thesis. University of Belgrade, Faculty of Mining and Geology, pp. 319, Belgrade.

RISTIĆ VAKANJAC V., POLOMČIĆ D ., BLAGOJEVIĆ B., ČOKORILO M. & VAKANJAC B., 2012. Simulation of Karst Spring Daily Discharges, *Proceeding of the Conference BALWOIS 2012,* Ohrid, Macedonia, pp. 1–10.

RISTIĆ VAKANJAC V., PROHASKA S. & POLOMČIĆ D., 2010. Definition of the Size of the Krupac Spring Drainage Area (Carpatho-Balkanide Arch, Southern Serbia) for a Karst Aquifer Water Balance Assessment. *Proceeding of the Conference BALWOIS 2010,* Ohrid, Macedonia, pp. 1–10.

RISTIĆ VAKANJAC, V., PROHASKA S., POLOMČIĆ D., BLAGOJEVIĆ B. & VAKANJAC B. 2013. Karst aquifer average catchment area assessment through monthly water balance equation with limited meteorological data set, application to Grza Spring in Eastern Serbia. *Acta Carstologica*, 42 (1): 109–119.

RISTIĆ VAKANJAC, V., STEVANOVIĆ, Z., MARAN, A., VAKANJAC, B. & ČOKORILO ILIĆ M., 2014. An example of karst catchment delineation for prioritizing the protection of an intact natural area, Environmental Earth Sciences, Vol. 1, Hydrogeological and Environmental Investigations in Karst Systems, Malaga, Spain, 387–396

RISTIĆ VAKANJAC V., STEVANOVIĆ Z. & ČOKORILO ILIĆ M. 2014. Underground piracy of Raska spring (southwestern Serbia) and concept for the delineation of catchment area and estimation of karst groundwater budget elements, *Proceedings of the international conference and field seminar "Karst without Boundaries"*, Trebinje, Bosnia and Herzegovina, pp. 207–212

RISTIĆ VAKANJAC V., STEVANOVIĆ Z. & MILANOVIĆ S., 2012. WP4-Availability of Water Resources. *In*: Stevanović Z., Ristić Vakanjac V., Milanović S. (Eds.), *Climate Change and Impacts on Water Supply*, 133–176. Monograph, University of Belgrade, Faculty of Mining and Geology, Serbia.

STEVANOVIĆ Z., MILANOVIĆ S. & RISTIĆ VAKANJAC V., 2010. Supportive Methods for Assessing Effective Porosity and Regulating Karst Aquifers. *Acta Carstologica*, Slovenia, 39 (2): 313–329.

STEVANOVIĆ, Z., RISTIĆ VAKANJAC V. & MILANOVIĆ S. 2014. On the need to set up a new national groundwater monitoring network in Serbia. *Proceedings of the 16th Conference of Serbian Geologists,* Donji Milanovac, 317–319.

Резиме

Процена режима истицања и биланса вода Белог врела (извор реке Толишнице, централна Србија)

Хидролошка изученост неког слива подразумева да су осматрања режима квантитативних параметара вршена у интервалу од минималних 30 година. Карстна врела на жалост имају знатно краће низове осматрања (од 1 до 10 година) или, углавном, осматрања до сада уопште нису вршена на њима. Анализе режима истицања и прорачун параметара биланса код ових врела које можемо сврстати у групу хидролошки/хидрогеолошки неизучених сливова, могу понекад довести до погрешних закључака. Да би се потенцијалне грешке одређивања параметара билансне једначине елиминисале код ових случајева, или свеле на разумна одступања од реалних вредности развијен је модел за потребе продужавања постојећих низова релативно кратких серија осматрања истицања из карстних врела (испод 15 година). Једно од врела које нема довољно дуги низ осматрања је и Бело врело (врело Толишнице). Врело није каптирано, налази се у централном делу Србије, територи-

јално припада општини Ивањице (слика 1) и дренира падине планине Чемерно.

У широј зони Белог врела, поред палезојских седимената присутни су у мањем обиму масивни доломитични и мермерисани кречњаци средњег тријаса. Јављају се у виду ерозионих остатака - крпа величине око 1.5 km^2 и чине незнатан огранак великог тријаског појаса планине Јелице са којима су у контакту. Присутни су и алевролити и шкриљави глинци горње креде (сенон), навучени преко сенонско горњекредног флиша (кречњаци, лапорци, пешчари, глинци). Кречњаци, мермерисани кречњаци и доломити имају велики хидрогеолошки значај на испитиваном терену јер имају значајну пукотинску порозност насталу на првом месту као последица локалних тектонских покрета. Ове стене у површинским деловима представљају хидрогеолошке колекторе - спроводнике, док у дубљим деловима представљају колекторе - резервоаре из којих се на контакту са слабо водоносним и водонепропусним стенама врши њихово пражњење путем врела која су формирана у зонама локалних раседа, што је случај и са Белим врелом.

Током 1994. године РХМЗ је успоставио хидролошке станице на више карстних врела међу којима је било и Бело врело. Осматрања водостаја и мерења протицаја су трајала до краја 2002. године. На основу добијених дневних вредности протицаја Белог врела може се констатовати да је средњи вишегодишњи протицај за период од 1995–2002. године износио 0.127 m^3/s (табела 1). Максимални средње месечни протицај се јавио током новембра 2002. године и износио је 0.330 m^3/s. Минимални средње месечни протицај регистрован је у октобру 1995. године и износио је 0.070 m^3/s. Што се тиче апсолутних дневних протицаја, максимални дневни протицај јавио се 24. односно 25. децембра 2002. године и износио је 410 l/s, док је апсолутно минимални протицај у износу од свега 67 l/s регистрован више пута током 1995., 1996., и 2001. године. Однос регистрованих максималних и минималних протицаја за поменути осматрачки период је 1:6 што указује на релативно уједначен режим истицања овог врела.

Ради потврђивања постојеће везе падавине – истицање урађене су корелационе анализе утицаја годишњих сума падавина на истицање Белог врела. Уколико се разматра ова веза на календарском нивоу коефицијенти кореалције су изузетно ниски ($p = 0.275$ – к.с. Ивањица, $p=-0.073$ – м.с. Краљево). Са друге стране ако се анализира веза падавине – протицај врела на нивоу хидролошке године, коефицијенти корелације су знатно значајнији и износе за к.с. Ивањица $p = 0.465$ и за м.с. Краљево чак $p = 0.667$. Ово је последица чињенице да падавине у току зимских месеци (новембар и децембар) се задржавају у сливу и изазивају отицај/истицање у наредној години када долази до њиховог отапања. Тако да при овој врсти анализа неопходно је вршити осредњавање параметара на нивоу хидролошке године (1. октобар – 30. септембар). Ово потврђује и кроскорелациона анализа (слика 5) на којој се види да је најчвршћа веза утицаја падавина на истицање врела након једног дана, с тим да је изражен пик и након 32 дана што је свакако последица отапања снега.

Прорачун резерви подземних вода извора реке Толишнице извршен је и применом методе анализе ретардационе криве. За валидну анализу ретардационих способности издани потребан је период од завршетка изражених падавина са константним пражњењем без прилива у трајању од најмање 90 дана (рецесија издани). Анализом резултата режимских осматрања може се увидети да је овај услов испуњен током 1995. године, период од 8. јуна до 2. новембра (укупно 148 дана) и током 2000. године, период од 23. марта до 21 августа (укупно 156 дана), када је долазило до константног пражњења врела. Добијени коефицијенти пражњења су истог реда величине, и указују на средња до добра рецесиона својства формиране издани. Ови параметри рецесионих својстава искоришћени су за утврђивање збирне запремине отекле воде.

За потребе дефинисања параметара билансне једначине а на првом месту сливне површине Белог врела коришћен је поменути модел развијен на Рударско-геолошком факултету, Департману за хидрогеологију. Примењен модел се састоји из више нивоа. Коришћењем нивоа 1 осматрачки низ средње месечних протицаја је продужен на период од 1960–2009. године. Средње вишегодишњи протицај овако дефинисаног рачунског низа износи 0.116 m^3/s. Као излаз из нивоа 3 добијена је реална површина слива у износу од 8,6 km^2 (слика 10). Затим су добијене реалне вредности дневних евапотранспирација и промене динамичке запремине на месечном новоу за рачунски период (слика 11). Параметри билансне једначине подземних вода Белог врела срачунати су коришћењем адекватних једанчина (јед. 2, 3, 4, 5 и 6) а њихове вредности су приказане у табели 2.

Генерално може се закључити да са сливног подручја Белог врела просечно годишње истекне укупно 116 l/s Како сливна површина врела Толишница износи 8.6 km^2, средње вишегодишњи слој истицања за рачунски период износи $h = 421.0$ mm. Са гледишта водности подручја, може се констатовати да специфична издашност слива Белог врела износи 13.5 $l/s/km^2$, док на основу срачунатог коефицијента отицаја може се закључити да се 48% од укупно пале воде (падавина) инфилтрира и касније истиче кроз врела. Ова бактериолошки чиста вода и изузетног квалитета може се користити за потребе водоснабдевања локалних домаћинстава, за потребе пољопривреде или пак за потребе рибогојства.

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Fuzzy optimization in hydrodynamic analysis of groundwater control systems: Case study of the pumping station “Bezdan 1”, Serbia

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Abstract. A groundwater control system was designed to lower the water table and allow the pumping station “Bezdan 1” to be built. Based on a hydrodynamic analysis that suggested three alternative solutions, multicriteria optimization was applied to select the best alternative. The fuzzy analytic hierarchy process method was used, based on triangular fuzzy numbers. An assessment of the various factors that influenced the selection of the best alternative, as well as fuzzy optimization calculations, yielded the “weights” of the alternatives and the best alternative was selected for groundwater control at the site of the pumping station “Bezdan 1”.

Key words: groundwater lowering, groundwater management scenario, fuzzy analytic hierarchy process, expert knowledge, triangular fuzzy numbers, linguistic variables.

Апстракт. За обарање нивоа подземних вода како би се изградила црпна станица „Бездан 1” пројектован је систем одбране од подземних вода. На основу хидродинамичке анализе којом су дефинисане три алтернативе решења система, приступило се методом вишекритеријумске оптимизације како би се одабрала оптимална алтернатива. За те потребе коришћена је метода фази аналитичко хијерархијског процеса, базирана на троугластим фази бројевима. Анализом различитих фактора који утичу на избор алтернативе и фази оптимизационим прорачунима, добијене су „тежине” алтернатива и донета је одлука о оптималној алтернативи решења система одбране од подземних вода на подручју црпне станице „Бездан 1”.

Кључне речи: обарање нивоа подземних вода, варијанте система одбране од подземних вода, фази аналитичко хијерархијски процес, знање експерта, троугаони fuzzy број, лингвистичка варијабла.

Introduction

The best way engineers or scientists can express their opinions is in fact everyday verbal communication. It is a significant source of uncertainty, because of the transfer of both information and knowledge coupled with various uncertainty and imprecision (Kosko 1993). This is the reason why fuzzy logic systems are distinguished, given that their essence is to handle knowledge that can be highly imprecise and expressed verbally. In fuzzy logic systems this “knowledge” is represented by production (expert) rules, which are a suitable verbal means of expressing the knowledge of each individual. Consequently, fuzzy logic is the codification of common sense (Graham 1991; Lai & Hwang 1996). Expert knowledge is used instead of differential equations to describe a system. The knowledge is conveyed in a natural way, by linguistic variables, such that fuzzy logic is “computing with words” (Zadeh 1965; Zadeh 1975).

As indicated above, the basic unit that represents knowledge in fuzzy logic is a linguistic variable, with its linguistic values that make up fuzzy sets. Combinations of variables and their values produce linguistic statements (expressions), which constitute a bridge between numerical representation of information on a computer and human thinking. Zadeh (1975) introduced the “linguistic (fuzzy) variable”, which is the value of an uncertainty described by a linguistic statement. The linguistic or fuzzy variable is

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defined as the variable whose permissible values are words of natural language, and not numbers. Apart from their symbolic linguistic form, linguistic variables also have a quantified analytical form-membership function, such that they are of a dual nature. This dual identity makes linguistic variables suitable for qualitative-symbolic and quantitative-numerical calculations. A correlation is thereby established between the natural language used by man and the numerical data used by a computer.

In recent years there has been a rapid increase in the number and types of applications of systems based on the fuzzy theory. While it was originally used to analyze data that allow for partial set membership, to avoid the approach where there is either full or no such membership, today fuzzy logic is a management method which, despite its early stage, is increasingly used in all fields of science, including hydrogeology - groundwater management, water quality management, dewatering and groundwater control, etc. (AZARNIVAND *et al.* 2004; SINGH *et al.* 2007; UDDAMERI *et al.* 2014; KARNIB 2014).

One branch of fuzzy logic applied in hydrogeology is fuzzy optimization. The present paper describes an application of multicriteria fuzzy optimization - the so-called fuzzy analytic hierarchy process (FAHP), to select the optimal groundwater management scenario (groundwater control system) for the pumping station "Bezdan 1" ("Bezdan 1" PS), out of three alternatives derived from the hydrodynamic analysis reported by POLOMČIĆ & BAJIĆ (2014).

There are many FAHP approaches suggested by different authors in the literature. LAARHOVEN & PEDRCYZ (1983) initiated the first studies that applied fuzzy logic and the analytic hierarchy process. They used triangular fuzzy numbers to express the evaluation by the decision maker (expert) of alternatives against each of the given criteria, while BUCKLEY (1985) used trapezoidal fuzzy numbers for the same purpose. CHANG (1996) introduced a new approach to FAHP, using triangular fuzzy numbers, FAHP scale and extent analysis to compare pairs of criteria in a matrix. Going into more detail, CHAN & KUMAR (2007) added risk factors to the extent analysis in FAHP, which included uncertain information used in decision making. DENG (1999) proposed a fuzzy approach to solving the problem of qualitative multicriteria analysis - using FAHP for multicriteria decision making. ZHU *et al.* (1999) presented the fundamental theories of fuzzy triangular numbers, contributed an improved approach to their comparison, and demonstrated a practical application to an oil field. CHOU & LIANG (2001) proposed a fuzzy multicriteria decision-making concept that integrated the fuzzy theory with the analytic hierarchic process. Additionally, CHANG *et al.* (2003) introduced statistical methods to FAHP, for selecting the criterion that affected the end result (i.e. selection of alternative). Among the FAHP approaches mentioned above, the one devised by CHANG (1996) was used to arrive at the best alternative for the groundwater control system of the "Bezdan 1" PS.

Study Area

To prevent an environmental disaster in the Bačka District (Serbia), as well as avoid suspensions of navigation and different types of water supply, it is necessary to expand the Bačka section of the Danube–Tisa–Danube Water Scheme. To resolve one of the functional issues of the multipurpose Danube–Tisa–Danube system, new pumping stations (total capacity 35 m^3/s) will have to be built at the locations of previous pumping stations, which have been out of commission for some time. Apart from dealing with the issues mentioned above, this project will regulate the Bezdan–Vrbas Canal, the Baračka Canal and a number of smaller canals. The present research addresses the "Bezdan 1" PS, located in the Town of Bezdan in northwestern Bačka. Figure 1 shows the geographical position and microlocation of the study area.

Predictive Hydrodynamic Analysis

The site of the future "Bezdan 1" PS features high groundwater levels, which directly affect the feasibility of construction. Three-dimensional (3D) hydrodynamic modeling, in this case to define a groundwater control system for the "Bezdan 1" PS, is a common approach in modern hydrogeology. The hydrogeological setting was schematized, the input parameters defined and a model based on finite differences constructed to develop a predictive hydrodynamic analysis after matching natural and modeled hydrogeological parameters through calibration. As a result, POLOMČIĆ & BAJIĆ (2014) proposed a groundwater control system for the "Bezdan 1" PS, whose function is to lower the water table to below the design elevation, so that the pumping station can be built. Three alternatives were considered, to ensure protection against groundwater intrusion and provide for unhindered construction of the "Bezdan 1" PS. Figure 2 shows the lowering of the water table of the analyzed alternatives. For each alternative, the characteristics of the groundwater control system: the number of wells and their spatial distribution, and the time needed to achieve maximal lowering of the water table below the excavation for the "Bezdan 1" PS, were defined as follows:

- Alternative 1 (A_1): Long-term average stages of the canals within the study area (Baračka Canal 82.80 m above sea level and Bezdan–Vrbas Canal 84.80 m.a.s.l.) were used in the predictive hydrodynamic analysis. The groundwater control sys-

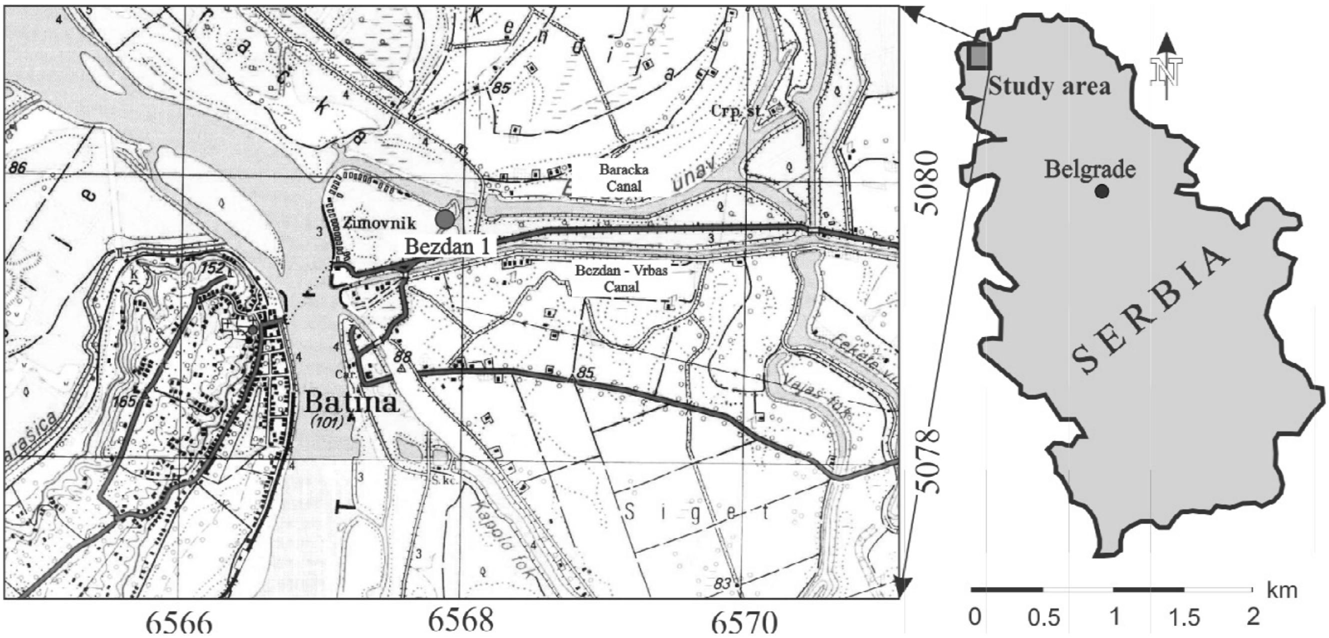

Fig. 1. Study area and "Bezdan 1" pumping station.

tem is comprised of 12 wells, whose capacity is 40 l/s each. The time needed to lower the water table to below the design elevation and allow for the construction work to proceed is 5 days.

- Alternative 2 (A_2): Long-term average maximum stages of the canals within the study area (Baračka Canal 86.61 m.a.s.l. and Bezdan–Vrbas Canal 85.16 m.a.s.l.) were used in the predictive hydrodynamic analysis. The groundwater control system is comprised of 12 wells, whose capacity is 40 l/s each. The water table "stabilizes" after 7 days of operation of the system.
- Alternative 3 (A_3): In this case, lowering of the water table was simulated using maximum elevations of the designed cofferdams for the following canal stages: Baračka Canal 87 m.a.s.l. and Bezdan–Vrbas Canal 86.5 m.a.s.l. The groundwater control system is comprised of 17 wells, whose capacity is 40 l/s each. The time needed to lower the water table to below the design elevation is 8.5 days.

Based on the predictive analysis and the three identified alternatives for the groundwater control system, as described in POLOMČIĆ & BAJIĆ (2014), the selection of the best alternative applying the FAHP approach is discussed below.

Fuzzy Optimization Method

Apart from the several approaches to fuzzy optimization and the use of the FAHP approach described

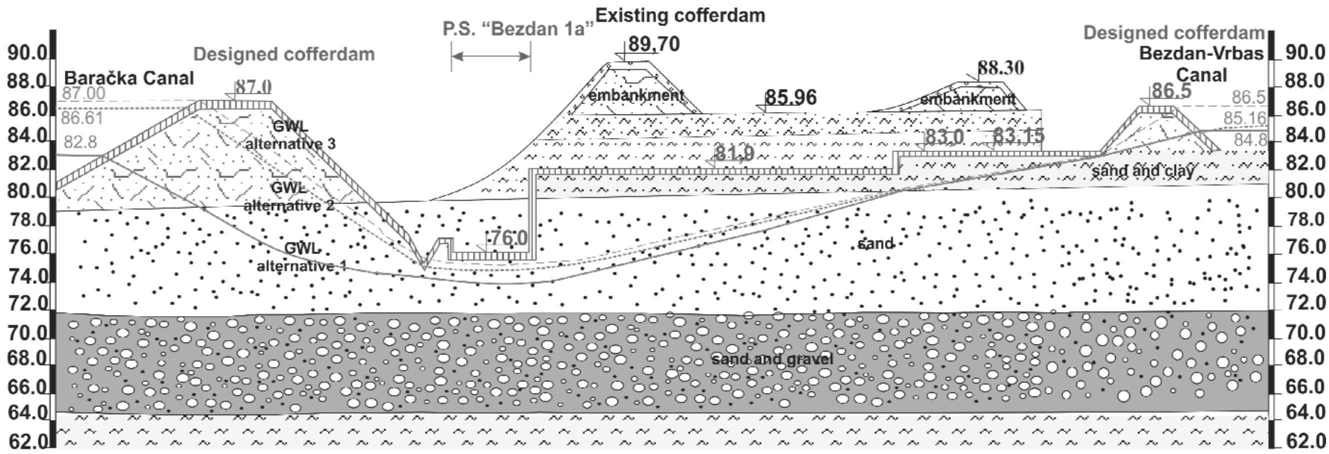

Fig. 2. Lowering of the water table, alternatives 1, 2 and 3, as a result of control system operation.

above, the solution produced by hydrodynamic calculations was optimized by means of fuzzy extent analysis, an FAHP approach proposed by (CHANG 1996). This method is based on triangular fuzzy numbers and Saaty's pairwise comparison scale (SAATY 1980). The main features of this method are presented below in several steps.

The basic concept of the FAHP approach is the triangular fuzzy number. If this number is denoted by $M(l,s,d)$, as illustrated in Fig. 3, it is defined by its membership function as follows:

$$\mu_M(x) = \begin{cases} \dfrac{x}{s-l} - \dfrac{l}{s-l}, & x \in [l, s] \\ \dfrac{x}{s-d} - \dfrac{l}{s-d}, & x \in [s, d] \quad \text{where is } l \le s \le d \\ 0, & x \notin [l, d] \end{cases}$$

The correlation between the numerical values of triangular fuzzy numbers and linguistic variables is represented by fuzzified Saaty's scale (CHANG 1996; DENG 1999; TOLGA 2005). One such correlation is shown in Table 1.

Table 1. Fuzzified Saaty's scale for pairwise comparisons (DENG 1999)

Linguistic variable (judgment definition)	Saaty's crisp value	FAHP scale Triangular fuzzy numbers ($0.5 \le \alpha \le 0.5$)
Equal importance	1	(1, 1, 1+α)
Weak dominance	3	(3–α, 3, 3+α)
Strong dominance	5	(5–α, 5, 5+α)
Demonstrated dominance	7	(7–α, 7, 7+α)
Absolute dominance	9	(9–α, 9, 9)
Intermediate values	2, 4, 6, 8	(x–1, x, x+1) x=2, 4, 6 ,8

Step 1. Taking the pre-defined factors that affect the selection of one among several alternatives, a matrix of criterion X is constructed with triangular fuzzy numbers assigned by the decision maker (expert), using the FAHP scale.

Step 2. Taking the generated matrix, an extent analysis of all the elements of the matrix is conducted, resulting in m values of step analyses for each element of the set X:

$$M_{g_i}^1, M_{g_i}^2, \ldots, M_{g_i}^m, \; i = 1, 2, \ldots, n,$$

where all $M_{g_i}^{\,j}$, $j = 1, 2, \ldots, m$ are triangular fuzzy numbers.

Then, taking into account the membership function of the triangular fuzzy numbers, the value of the fuzzy synthetic extent is computed using the expression:

$$S_i = \sum_{j=1}^{m} M_{g_i}^{j} \otimes \left[\sum_{i=1}^{n} \sum_{j=1}^{m} M_{g_i}^{j} \right]^{-1} =$$

$$= \left(\sum_{j=1}^{m} l_j, \sum_{j=1}^{m} s_j, \sum_{j=1}^{m} d_j \right) \otimes \left(\frac{1}{\sum_{i=1}^{n} d_j}, \frac{1}{\sum_{i=1}^{n} s_j}, \frac{1}{\sum_{i=1}^{n} l_j} \right)$$

Step 3. In this step the degree of possibility of two triangular fuzzy numbers (Fig. 3) $M_1 = (l_1, s_1, d_1)$ and $M_2 = (l_2, s_2, d_2)$, is determined applying the fuzzy number comparison principle:

$$V(M_1 \ge M_2) = \sup_{x \ge y} \left[\min \left(\mu_{M_1}(x), \mu_{M_2}(y) \right) \right]$$

If there are pairs (x, y) such that $x \ge y$ and $\mu_{M_1}(x) = \mu_{M_2}(y) = 1$, then $V(M_1 \ge M_2) = 1$. Since M_1 and M_2 are convex triangular fuzzy numbers, it follows that:

$V(M_1 \ge M_2) = 1 \; \mathit{if} \; s_1 \ge s_2$

$$V(M_2 \ge M_1) = hgt(M_1 \cap M_2) = \mu_{M_1}(c) \begin{cases} 1, & \text{if } s_2 \ge s_1 \\ 0 & \text{if } l_1 \ge d_2 \\ \dfrac{l_1 \quad d_2}{(s_2 - d_2) - (s_1 - l_1)}, & \mathit{other} \end{cases}$$

where c is the ordinate of the highest intersection at point C between the membership functions μ_{M_1} and μ_{M_2}

To compare the triangular fuzzy numbers M_1 and M_2, both values, $V(M_1 \ge M_2)$ and $V(M_2 \ge M_1)$ are needed.

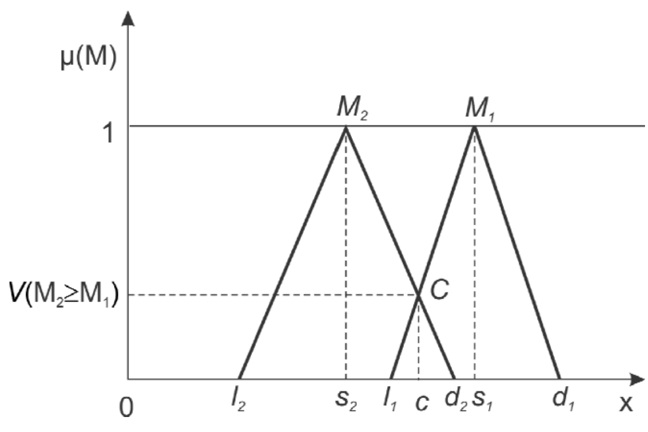

Fig. 3. Triangular fuzzy number.

The degree of possibility of a convex fuzzy number to be greater than k, the convex fuzzy numbers M_i can be defined by i=1,2,…,k:

$$V(M \geq M_1, M_2, ...M_k) = V[(M \geq M_1) \wedge ... \wedge (M \geq M_k)] =$$
$$= \min V(M \geq M_i)$$

Then, summing everything up, it follows that: $c'(A_i)=\min V(S_i \geq S_k)$, $k=1,2,\ldots, n$; $k \neq i$

Step 4. Continuing from the previous step, the weight priority vectors are defined as follows:

$$W' = \left(c'(A_1), c'(A_2), ..., c'(A_n)\right)^T$$ where A_i ($i=1,2,\ldots,n$)

Step 5. The ultimate values of the weights are obtained applying one of the normalization methods:

- The additive normalization method (SAATY 1980), or
- The weighted least squares method (CHU *et al.* 1979), the logarithmic least squares method (CRAWFORD & WILLIAMS 1985), the fuzzy preference programming method (MIKHAILOV 2000), the direct least squares method (CHU *et al.* 1979), which often yields multiple solutions, or the logarithmic goal programming method (BRYSON 1995).

This results in a normalized weight vector in the form of a classical non-fuzzy number, whose maximum value is 1:

$$W = \left(c(A_1), c(A_2), ..., c(A_n)\right)^T$$

Step 6. In this step the alternatives are compared for each criterion separately. Matrices are produced and then the weight vectors determined following Steps 1 through 5.

Step 7. Here the ultimate weights of the alternatives are determined. They are obtained by multiplying the weight vectors derived from the criterion matrix by the weight vectors from Step 6. The alternative with the greatest weight vector value is the best alternative.

Results and Discussion

The fuzzy extent analysis and the analytic hierarchic process described above were applied to develop a decision-making model and select the best alternative for the groundwater control system of the "Bezdan 1" PS. Fuzzy optimization calculations included assessments of the various factors/criteria that affected the selection of the best possible solution to the problem. In general, it is difficult to produce an alternative that will instantaneously satisfy all the applicable criteria, but an acceptable trade-off can be found. The following criteria were considered in connection with the present groundwater control system:

- *Time (K_1),* which is the time needed for the water table to be lowered to the design level. To assess this criterion, it was not assumed that the best time was the shortest time. Instead, the time was related to the analyzed conditions and the elevation of the water table for each alternative.
- *Characteristics of the groundwater control system (K_2),* which included the number of components of the groundwater control system, where the system was analyzed and its cost-effectiveness and flexibility assessed. In the present study, as the number of wells increased, so did capital expenditure and operating and maintenance costs. However, it should be noted that in some cases the construction of wells is more economical than the pumping time. Flexibility included the ability of the system to adapt to possible changes to its characteristics. Consequently, when the time comes to lower the water table, if the groundwater levels are below those used in the hydrodynamic analysis of the selected alternative, not all the wells need to be constructed or operated.
- *Safety factor (K_3)*, which represents an analysis of possible water table conditions at the time of lowering for the purposes of constructing the "Bezdan 1" PS. This analysis was used to assess the status of boundary conditions in the hydrodynamic analysis of different canal stages in the study area.

Shown below are the calculations for the selection of the best alternative in accordance with the above-described steps (the FAHP approach discussed in the previous section).

The criteria matrix was produced by evaluating the criteria according to the fuzzified scale (TOLGA 2005):

$$X = \begin{bmatrix} & K_1 & K_2 & K_3 \\ K_1 & 1,1,1 & \frac{2}{3},1,2 & \frac{1}{2},1,\frac{3}{2} \\ K_2 & \frac{1}{2},1,\frac{3}{2} & 1,1,1 & 1,\frac{3}{2},2 \\ K_3 & \frac{2}{3},1,2 & \frac{1}{2},\frac{2}{3},1 & 1,1,1 \end{bmatrix}$$

Using a specially developed application, according to Step 2, the calculated values of the fuzzy synthetic extent were as follows:

$$S_1 = (2.16, 3, 4.5) \otimes \left(\frac{1}{13}, \frac{1}{9.16}, \frac{1}{6.82}\right) = (0.17, 0.33, 0.66)$$

$$S_2 = (2.5, 3.5, 4.5) \otimes \left(\frac{1}{13}, \frac{1}{9.16}, \frac{1}{6.82}\right) = (0.19, 0.38, 0.66)$$

$$S_3 = (2.16, 2.66, 4) \otimes \left(\frac{1}{13}, \frac{1}{9.16}, \frac{1}{6.82}\right) = (0.17, 0.29, 0.59)$$

According to Step 3, the fuzzy numbers were compared and the degree of possibility of two triangular fuzzy numbers (i.e. their values of fuzzy synthetic extent) was determined as follows:

$$V\left(S_1 \geq S_2\right) = \frac{0.19 - 0.66}{\left(0.33 - 0.66\right) - \left(0.38 - 0.19\right)} = 0.9$$

$$V\left(S_1 \geq S_3\right) = 1$$

$$V\left(S_2 \geq S_1\right) = 1$$

$$V\left(S_2 \geq S_3\right) = 1$$

$$V\left(S_3 \geq S_1\right) = \frac{0.17 - 0.59}{\left(0.29 - 0.59\right) - \left(0.33 - 0.17\right)} = 0.91$$

$$V\left(S_3 \geq S_1\right) = \frac{0.19 - 0.59}{\left(0.29 - 0.59\right) - \left(0.38 - 0.19\right)} = 0.81$$

Then the minimum value was selected, as described in Step 3, and the weight vectors obtained as:

$W' = (0.9,1,0.81)$

Finally, the ultimate criterion weights were obtained through normalization:

$W = (0.33,\ 037,\ 0.3)$

Shown below are the criterion - based evaluation of alternatives (where three matrices were generated) and the ultimate weight vectors for each comparison.

Criterion 1 (matrix, the value of fuzzy synthetic extent, the degree of possibility, the weight priority vectors and the ultimate values of the weights):

$$X_{K_1} = \left[\begin{array}{c|ccc} K_1 & A_1 & A_2 & A_3 \\ \hline A_1 & 1,1,1 & 4,5,6 & \frac{1}{5},\frac{1}{4},\frac{1}{3} \\ A_2 & \frac{1}{6},\frac{1}{5},\frac{1}{4} & 1,1,1 & 6,7,8 \\ A_3 & 3,4,5 & \frac{1}{8},\frac{1}{7},\frac{1}{6} & 1,1,1 \end{array}\right]$$

$$S_{1K_1} = \left(5.2, 6.25, 7.33\right) \otimes \left(\frac{1}{22.74}, \frac{1}{19.59}, \frac{1}{16.48}\right) = \left(0.23, 0.32, 0.44\right)$$

$$S_{2K_1} = \left(7.16, 8.2, 9.25\right) \otimes \left(\frac{1}{22.74}, \frac{1}{19.59}, \frac{1}{16.48}\right) = \left(0.31, 0.42, 0.56\right)$$

$$S_{3K_1} = \left(4.12, 5.14, 6.16\right) \otimes \left(\frac{1}{22.74}, \frac{1}{19.59}, \frac{1}{16.48}\right) = \left(0.18, 0.26, 0.37\right)$$

$V_{K_1}\left(S_1 \geq S_2\right) = 0.56 \quad V_{K_1}\left(S_1 \geq S_3\right) = 1$

$V_{K_1}\left(S_2 \geq S_1\right) = 1 \quad V_{K_1}\left(S_2 \geq S_3\right) = 1$

$V_{K_1}\left(S_3 \geq S_1\right) = 0.7 \quad V_{K_1}\left(S_3 \geq S_2\right) = 0.01$

$W' = (0.56,1,0.01)$
$W = (0.36,0.64,0.01)$

Criterion 2 (matrix, the value of fuzzy synthetic extent, the degree of possibility, the weight priority vectors and the ultimate values of the weights):

$$X_{K_2} = \left[\begin{array}{c|ccc} K_2 & A_1 & A_2 & A_3 \\ \hline A_1 & 1,1,1 & 5,6,7 & \frac{1}{8},\frac{1}{7},\frac{1}{6} \\ A_2 & \frac{1}{7},\frac{1}{6},\frac{1}{5} & 1,1,1 & 7,8,9 \\ A_3 & 6,7,8 & \frac{1}{9},\frac{1}{8},\frac{1}{7} & 1,1,1 \end{array}\right]$$

$$S_{1K_2} = \left(6.12, 7.14, 8.16\right) \otimes \left(\frac{1}{27.5}, \frac{1}{24.42}, \frac{1}{21.37}\right) = \left(0.22, 0.29, 0.38\right)$$

$$S_{2K_2} = \left(8.14, 9.16, 10.2\right) \otimes \left(\frac{1}{27.5}, \frac{1}{24.42}, \frac{1}{21.37}\right) = \left(0.3, 0.38, 0.48\right)$$

$$S_{3K_2} = \left(7.11, 8.12, 9.14\right) \otimes \left(\frac{1}{27.5}, \frac{1}{24.42}, \frac{1}{21.37}\right) = \left(0.26, 0.33, 0.43\right)$$

$V_{K_2}\left(S_1 \geq S_2\right) = 0.06 \quad V_{K_2}\left(S_1 \geq S_3\right) = 1$

$V_{K_2}\left(S_2 \geq S_1\right) = 1 \quad V_{K_2}\left(S_2 \geq S_3\right) = 1$

$V_{K_2}\left(S_3 \geq S_1\right) = 1 \quad V_{K_2}\left(S_3 \geq S_2\right) = 0.72$

$W' = (0.06,1,0.72)$
$W = (0/03,0.56,0.4)$

Criterion 3 (matrix, the value of fuzzy synthetic extent, the degree of possibility, the weight priority vectors and the ultimate values of the weights):

$$X_{K_3} = \left[\begin{array}{c|ccc} K_3 & A_1 & A_2 & A_3 \\ \hline A_1 & 1,1,1 & 6,7,8 & \frac{1}{9},\frac{1}{9},\frac{1}{8} \\ A_2 & \frac{1}{8},\frac{1}{7},\frac{1}{6} & 1,1,1 & 4,5,6 \\ A_3 & 8,9,9 & \frac{1}{6},\frac{1}{5},\frac{1}{4} & 1,1,1 \end{array}\right]$$

$$S_{1K_3} = \left(7.11, 8.11, 9.12\right) \otimes \left(\frac{1}{26.53}, \frac{1}{24.45}, \frac{1}{21.39}\right) = \left(0.27, 0.33, 0.43\right)$$

$$S_{2K_3} = \left(5.12, 6.14, 7.16\right) \otimes \left(\frac{1}{26.53}, \frac{1}{24.45}, \frac{1}{21.39}\right) = \left(0.19, 0.25, 0.33\right)$$

$$S_{3K_3} = \left(9.16, 10.2, 10.25\right) \otimes \left(\frac{1}{26.53}, \frac{1}{24.45}, \frac{1}{21.39}\right) = \left(0.35, 0.42, 0.48\right)$$

$V_{K_3}\left(S_1 \geq S_2\right) = 1 \quad V_{K_3}\left(S_1 \geq S_3\right) = 0.47$

$V_{K_3}\left(S_2 \geq S_1\right) = 0.42 \quad V_{K_3}\left(S_2 \geq S_3\right) = 0.13$

$V_{K_3}\left(S_3 \geq S_1\right) = 1 \quad V_{K_3}\left(S_3 \geq S_2\right) = 1$

$W' = (0.47,0.13,1)$
$W = (0.29,0.08,0.63)$

Based on these calculations, the ultimate evaluation of the alternatives is shown in Table 2.

The criteria-based assessment showed that the best solution for the groundwater control system of the "Bezdan 1" PS was Alternative 2. Here the control system is comprised of 12 wells. It takes seven days to lower the water table to below the design elevation and establish quasi-steady groundwater flow. As pointed out in connection with the evaluation of criteria, in this alternative, if the canal stages should be

Table 2. Ultimate evaluation of alternatives.

Criterion	Criterion weight	Alternative 1	Alternative 2	Alternative 3
1	0.33	0.36	0.64	0.01
2	0.37	0.03	0.56	0.4
3	0.3	0.29	0.08	0.63
Final score:		0.22	0.44	0.34

below the long-term average maximum levels, some of the wells can be shut down, as needed.

Conclusion

Human beings are often uncertain in assigning evaluation scores by conventional methods, so decision making frequently involves uncertainties. FAHP can cope with that difficulty. The method has the ability to capture the vagueness of human thinking and effectively solve multicriteria decision-making problems. In the present study, the FAHP approach was applied to assess the factors that affect the selection of the optimal groundwater control system at the location of the future pumping station “Bezdan 1”, whose construction is hindered by high groundwater levels. Applying this multicriteria approach, three alternatives, previously identified by hydrodynamic modeling, were assessed. According to the results of the FAHP analysis, each of the alternatives was evaluated and Alternative 2 was found to be the “best”. It scored 0.44/1. As a result, Alternative 2 was proposed for the groundwater control system associated with the “Bezdan 1” PS, whose general and spatial characteristics are: 12 wells with individual capacity of 40 l/s and seven days to lower the water table.

In some cases, the FAHP analysis can eliminate certain criteria, assigning them weights close to zero. Such clustering may help managers make decisions based on the most important criteria, especially in cases where more precise information can be expensive to obtain. Proposed for future study are other multicriteria optimization methods and decision-making approaches, to compare several different methods and present the results in parallel. The FAHP analysis used in the present study can be recommended for other fields of science and technology, where optimization is required and the best-possible decision needed.

Acknowledgement

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References

Azarnivand, A., Hashemi-Madani, F.A. & Banihabib, M.E. (2014). Extended fuzzy analytic hierarchy process approach in water and environmental management (case study: Lake Urmia Basin, Iran). *Environmental Earth Science*, DOI 10.1007/s12665-014-3391-6.

Bryson, N. 1995. A goal programming method for generating priorities vectors. *Journal of Operational Research Society*, 46: 641–648.

Buckley, J.J. 1985. Fuzzy hierarchical analysis. *Fuzzy Sets and Systems*, 17: 233–247.

Chan, F.T.S. & Kumar, N. 2007. Global supplier development considering risk factors using fuzzy extended AHP-based approach. *Omega International Journal of Management Science*, 35: 417–431.

Chang, D.Y. 1996. Applications of the extent analysis method on fuzzy AHP. *European Journal of Operational Research*, 95: 649–655.

Chang, Y.H., Cheng, C.H. & Wang, T.C. 2003. Performance evaluation of international airports in the region of East Asia. *Proceedings of the Eastern Asia Society for Transportation Studies*, 4: 213–230.

Chou, T.Y. & Liang, G.S. 2001. Application of a fuzzy multi-criteria decision making model for shipping company performance evaluation. *Maritime Policy and Management*, 28 (4): 375–392.

Chu, A., Kalaba, R. & Springam, K. 1979. A comparison of two methods for determining the weights of belonging to fuzzy sets. *Journal of Optimization Theory and Applications*, l27: 531–541.

Crawford, G. & Williams, C. 1985. A note on the analysis of subjective judgement matrices. *Journal of Mathematical Psychology*, 29: 387–405.

Deng, H. 1999. Multicriteria analysis with fuzzy pair-wise comparison. *International Journal of Approximate Reasoning*, 21: 215–231.

Graham, I. 1991. *Uncertainty and expert systems*. University of Bristol, Bristol, 363 pp.

Karnib, A. (2004) An approach to elaborate priority preorders of water resources projects based on multicriteria

evaluation and fuzzy sets analysis. *Water Resource Management*, 18: 13–33.
KOSKO, B. 1993. *Fuzzy thinking: The new science of fuzzy logic*. Hyperion, New York, 336 pp.
LAI, Y.J. & HWANG, C.L. 1996. *Fuzzy multiple objective decision making*. Springer, Berlin, 591 pp.
MIKHAILOV, L. 2000. A fuzzy programming method for deriving priorities in the analytic hierarchy process. *Journal of Operational Research Society*, 51: 341–349.
POLOMČIĆ, D. & BAJIĆ, D. 2014. Application of hydrodynamic predictive modeling on the example of the pumping station "Bezdan 1". *Tehnika*, 65 (6): 956–962 (in Serbian, English summary).
SINGH A.P., GHOSH S.K., SHARMA P. (2007). Water quality management of a stretch of river Yamuna: aninteractive fuzzy multi-objective approach. *Water Resource Management*, 21: 515–532.
UDDAMERI V., HERNANDEZ, A.E. & ESTRADA, F. (2014). A fuzzy simulation-optimization approach for optimal estimation of groundwater availability under decision maker uncertainty. *Environmental Earth Science*, 71 (6): 2559–2572.
VAN LAARHOVEN, P.J.M. & PEDRCYZ, W. 1983. A fuzzy extension of Saaty's priority theory. *Fuzzy Sets and Systems*, 11: 229–241.
ZADEH, L.A. 1965. Fuzzy Sets, *Information and Control*, 8 (3): 338–353.
ZADEH, L.A. 1975. The concept of a linguistic variable and its application to approximate reasoning. *Information sciences*, 8: 199–249.
ZHU, K., JING, Y., & CHANG, D. 1999. A discussion on extent analysis method and applications of fuzzy AHP. *European Journal of Operational Research*, 116: 450–456.

Резиме

Примена fuzzy оптимизације у хидродинамичкој анализи за потребе избора система одбране од подземних вода: пример црпне станице "Бездан 1", Р. Србија

На основу предходних прогнозних хидродинамичких прорачуна, како би се оборио ниво подземних вода, дефинисане су три варијанте (алтернативе) решења система одбране од подземних вода и његове карактеристике којим се штити подручје будуће црпне станице „Бездан 1" како би се она могла изградити.

Коришћењем fuzzy оптимизације - методе fuzzy аналитичко хијерархијског процеса, базиране на троугаоним fuzzy бројевима и анализом различитих фактора као што су време које је потребно да се ниво подземних вода спусти на проектовани ниво, затим карактеристике система одбране од подземних вода и фактор сигурности, дате су различите оцене које утичу на избор оптималне алтернативе.

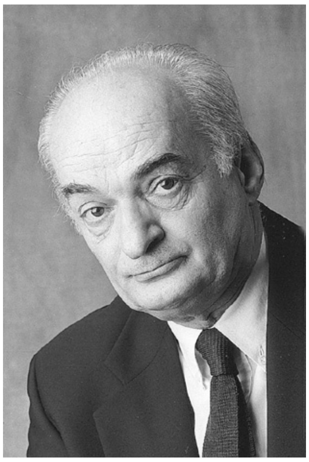
Према прорачунима ове методе вишекритеријумске оптимизације, анализиране су три алтернативе решења система одбране од подземних вода, које су утврђене раније, хидродинамичким моделирањем. На основу добијених резултата фази аналитичко хијерархијских прорачуна, добијене су оцене за сваку алтернативу, где се показало да је „најбоља" алтернатива број два, са оценом 0.44/1.

Као крајње решење постављеног проблема, од три понуђене алтернативе дефинисане хидродинамичким прорачунима, одабран је оптималан систем одбране од подземних вода црпне станице „Бездан 1", тзв. „Алтернатива 2" која укључује у систем одбране 12 бунара појединачних капацитета од 40 l/s, где је потребно 7 дана да се обори ниво подземних вода.

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	75	111–112	Београд, децембар 2013 Belgrade, December 2013

In memoriam

Академик Марко Ерцеговац
(1937–2012)



Дана 15. фебруара 2012. године, преминуо је Марко Ерцеговац, редовни члан Српске академије наука и уметности, омиљени професор, уважени колега и изнад свега угледни и у светским размерама признати геолог и палеонтолог. Савладан болешћу, напустио нас је тихо али је иза себе оставио немерљив траг по коме ће га памтити генерације садашњих и будућих геолога.

Професор Марко Ерцеговац рођен је 12. априла 1937. године у Нишу. Основну школу и нижу гимназију похађао је у Новом Саду и Земуну, а матурирао је у Београду 1956. године. Исте године уписао је Геолошко-палеонтолошку групу Природно-математичког факултета у Београду, где је дипломирао 1959. године. Убрзо после дипломирања, као један од најбољих студената, 1960. године изабран је за асистента на истом факултету, а 1963. године изабран је у исто звање на новоформираном Рударско-геолошком факултету Универзитета у Београду. На поменутом факултету 1964. године завршио је магистарске, а 1967. и докторске студије. Као изузетно вредан и успешан стручњак прошао је кроз сва звања. Доцент је постао 1970., а ванредни професор 1975. године. У звање редовног професора изабран је 1981. у својој 44. години, што је одлика само најбољих.

Професор Марко Ерцеговац је изузетно одговорно учествовао у извођењу наставе. Као млади асистент држао је вежбе из више предмета, а као професор предавао је Микропалеонтологију, Упоредну морфологију фосилних организама, Геологију каустобиолита и Лежишта и истраживање нафте и гаса. Преносећи врло успешно своје знање и искуство на студенте и млађе сараднике стекао је углед професора кога су сви изузетно веолели и ценили, а као доказ томе је чињеница да су га врло често предлагали за ментора својих радова. Поред великог броја дипломских радова, професор Ерцеговац је водио 15 магистариских теза и 12 доктората, од којих су 4 одбрањена на Факултету за рударство, геологију и металургију у Ахену (Немачка).

У оквиру научне активности проф. Ерцеговац је своје напоре усмеравао у правцу палинолошких, фитостратиграфских и регионално-геолошких истраживања фанерозојских седимената, проучавању генезе и петрографског састава угља и уљних шкриљаца, као и органско-петрографским и геохемијским проучавањима керогена и битумена. Неоспоран је и његов допринос развоју методике свих ових дисциплина. То се пре свега односи на квантитативно моделовање геолошких, геотермичких и геохемијских процеса, а тиме и моделовање геотермичке еволуције седиментних басена у нафтногеолошким истраживањима. Са својим сарадницима израдио је први домаћи модел SimpleMat. Професор Ерцеговац је такође заслужан за формирање првих лабораторија и стручњака за органску петрологију и геохемију (ИНА-Нафтаплин, Загреб и Нафтагас, Нови Сад).

Током своје каријере проф. Ерцеговац се стално усавршавао. Боравио је 1963. године у Геолошком институту и на Универзитету у Бечу. Касније је, као стипендиста фондације Александар фон Хумболт, у више наврата боравио у Немачкој (Ахен, Крефелд, Хановер и Есен). По позиву је учествовао у настави на Катедри за геологију, геохемију и лежишта угља и нафте на Универзитету у Ахену

(1988, 1999, 2001), а на студијском боравку у САД (Chevron Oil., University of Los Angeles и др.) и Канади (University of Toronto, University of Ottawa и др.) био је 1979. године.

Професор Ерцеговац је сам или у коауторству објавио преко 190 радова и то у водећим међународним и домаћим часописима. Израдио је први уџбеник из Микропалеонтологије, који је имао два издања (1981, 1999) и који се и данас користи, како код нас, тако и у Хрватској, Македонији, Словенији и Бугарској. Професор Ерцеговац је написао и прву монографију о геологији уљних шкриљаца (1990), која је прихваћена и ван наше земље. Универзитетски уџбеник „Геологија нафте“ објавио је 2002. године. Објављени уџбеници и монографија су усаглашени са најсавременијим светским сазнањима и као такви, још увек представљају основну литературу многих курсева на основним, мастер и докторским студијама већине универзитета у окружењу, а и шире. Поред тога, професор Ерцеговац је био аутор бројних радова по позиву, а исто тако је учествовао са бројним рефератима на међународним и домаћим скуповима. По позиву одржао је више предавања у иностранству (Москва, 1984; Загреб, 1987; Ахен, 1988, 1999, 2003; Софија 1989; Атина 1995).

Као стални члан Међународног комитета за петрологију угља и керогена Марко Ерцеговац је био коаутор Петролошког речника који је објављен у Паризу 1971. и 1975. и који је незаобилазна литература у петрологији органске материје, а чија се цитираност у светским часописима мери у хиљадама.

Професор Марко Ерцеговац је је био изузетно активан и у оквиру друштвених активности. Био је члан Међународног комитета за петрологију угља и органску петрологију, а касније и почасни члан истог комитета, члан Комисије за микрофлору и Америчке асоцијације за органску петрологију. Такође, био је експерт Савезног министарства за науку, технологију и развој у области геологије, геохемије и каустобиолита, научни саветник Рударског института у Земуну, члан Знанственог савјета за нафту Југословенске академије знаности и умјетности у Загребу, члан експертског тима за област енергетске технологије и рударства (2001) и Савезне комисије за геологију (2002), секретар Националног комитета Карпато-балканске геолошке асоцијације, редовни члан Академије инжењерских наука Србије и председник Хумболтовог клуба Србије. Био је члан уређивачких одбора часописа „Геолошки анали Балканскога полуострва“, „Coal Geology“ из Амстердама, „Глас“ и „Билтен“ Српске академије наука и уметности. На матичном факултету је обављао дужности од шефа катедре до шефа Геолошког одсека.

Као председник Организационог одбора и Научног савета учествовао је у организовању међународног скупа посвећеног академику Милутину Миланковићу (2004). Следеће године објављена је књига са овог скупа, а један од уредника био је и Марко Ерцеговац. Активно је учествовао у раду Српског геолошког друштва и представљао друштво на међународним и домаћим конгресима и скуповима. Био је председник Научног одбора 14. Конгреса геолога Србије и Црне Горе са међународним учешћем, као и секретар 18. Конгреса Карпато-балканске геолошке асоцијације. Поред свега, био је и активан члан секције за угљоводонике Српског хемијског друштва.

Овако богат и плодан рад обележен је наградама и признањима. За научна остварења у области палеонтологије и регионалне геологије професор Ерцеговац је добитник награде “Јован Жујовић“ за 1986. годину. Повеља Српског геолошког друштва за допринос развоју геологије и рад у друштву додељена му је 1991. године поводом обележавања стогодишњице Друштва. За почасног члана Друштва за органску петрологију САД изабран је 2003. године.

Врхунац овако блиставе научне каријере је био избор за дописног члана Српске академије наука и уметности 2000. године, а за редовног 2006. године. Професор Ерцеговац је био председник Одбора за палеофлору и палеофауну и члан Одбора за геохемију и Одбора за геодинамику САНУ. За заменика секретара Одељења за математику, физику и гео-науке изабран је 2003. године, а смрт га је затекла на месту секретара истог одељења.

О професору Ерцеговцу је речено и написано много тога лепога, мада он није волео хвалоспеве и помпезне говоре. Поштујући ту његову особину, довољно га је описати са само неколико речи. Професор Марко Ерцеговац је био велики човек у правом смислу те речи. Помисао да сте таквог човека имали за учитеља, колегу и пријатеља изазива осећање части и поноса.

Слава му и хвала!

Ненад Малешевић

Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	75	113–114	Београд, децембар 2013 Belgrade, December 2013

Note:

The XXth Congress of the Carpathian-Balkan Geological Association

The XXth Congress of the "Carpathian-Balkan Geological Association" was held in Tirana (Albania) from September 24 to September 26, 2014. This Jubilee Congress that took place for the first time in Albania was organized by the Geological Society of Albania in cooperation with the most important and traditional Albanian educational and research institutions: Polytechnic University of Tirana, Geological Survey of Albania, Faculty of Geology and Mining, Institute of Geosciences, Water, Energy and Environment and the Academy of Sciences of Albania. The board members of the Organizing Committee were Prof. Dr. Arjan Beqiraj as Chairperson, Dr. Viktor Doda as Vice-chairperson, Dr. Arben Pambuku as General Secretary and Msc Andreea Uta as Executive Secretary.

The Welcoming Ceremony was opened by the President of the "CBGA 2014", Prof. Dr. Arjan Beqiraj and was greeted by the Rector of the Polytechnic University of Tirana, Acad. Jorgaq Kaçani, the CBGA councilor, Prof. Dr. Corina Ionescu – NR of Romania and the Minister of Energy and Industry of Albania, Mr. Damian Gjiknuri. The participants enjoyed a short video and photo retrospective featuring the research works performed by the Albanian and foreign geologists during the last 70 years.

The XXth CBGA Congress offered a wide and rich program comprising a number of 18 Special Sessions, 8 General Sessions, 3 Workshops and 5 Field Trips organized in different regions of Albania. Per total, 470 short and extended abstracts have been accepted, of which 220 were oral presentations and 250 posters. The abstracts are published in two volumes, as special issues of the Albanian Journal "Buletini i Shkencave Gjeologjike". In addition, a number of 5 field trip guide books was published and distributed to about 150 participants. The contribution of more than 550 participants coming from different countries all over the world made this congress to be an event of high scientific success. By bringing together scientists not only from the CBGA-countries (Albania, Austria, Bosnia and Herzegovina, Bulgaria, Czech Republic, Croatia, FYR of Macedonia, Greece, Hungary, Montenegro, Poland, Romania, Serbia, Slovakia, Slovenia, Ukraine) but also from european and worldwide countries as Algeria, Australia, Canada, China, Cyprus, Egypt, England, France, Georgia, Germany, Iran, Italy, Jordan, Kosovo*, Luxembourg, Moldavia, New Zealand, Norway, Portugal, Russia, South Korea, Spain, Sweden, Switzerland, Turkey, USA, the congress was an excellent opportunity for presentation of outstanding scientific achievements and for a real exchange between scientists passionate by the world of geology and related sciences.

In particular, the participation of young geoscientists in the "CBGA 2014" was strongly encouraged. The Organizing Committee is pleased to confirm that as a result of this policy, about 100 young researchers have submitted abstracts and presented their contributions in the different scientific sessions of the congress.

The CBGA Council meeting held on September 23, 2014, was mostly focused on three topics: i) Expanding of CBGA with other member countries. With the arrival of Croatia and Bosnia and Herzegovina, CBGA counts now 16 member countries; ii) Preparations of "CBGA 2014". All the councilors present in the meeting have appreciated the serious and consistent work made by the local organizing Committee for the preparation of the "CBGA 2014"; iii) Nomination of the "CBGA 2018" organizer. The council unanimously agreed that the next congress (XXIst) of the CBGA will be held in Salzburg (Austria). The President of the Organizing Committee will be Prof. Dr. Franz Neubauer and he will constitute its Organizing Committee and will check for other geological events in order to decide the time when the "CBGA 2018" will be held. The councilors also agreed with the proposal of the The NR of Bulgaria, Prof. Peycheva, who

* This designation is without prejudice to positions on status, and is in line with UNSC 1244 and the ICJ Opinion on the Kosovo declaration of independence.

announced that Bulgaria is going to organize the "CBGA 2022".

The Council meeting charged the new President, Prof. Neubauer to be involved with CBGA status improvements, to update the agreements between the CBGA and its official journals, "Geologica Carpathica" and "Geologica Balcanica" and to maintain regular reports with IUGS.

Several participants of CBGA 2014 congratulated us for the organization of the congress during the days of the scientific sessions and the closing ceremony. Other colleagues sent us their positive impressions concerning the organization of the congress and field trips. The Organizing Committee is really pleased that reached to organize such a successful congress of CBGA, thus saving its long-term tradition as one of the best geoscience events in Europe.

Arjan Beqiraj
Andreea Uta

Instructions for authors

Geološki anali Balkanskoga poluostrva is issued annally and publishes original scientific contributions over a wide range of topics in any field of the geological sciences. The journal accepts papers in English of moderate length, not exceeding 50 double spaced manuscript pages, including illustrations.

Authors are asked to submit an electronic version of the manuscript. Leave adequate margins of 3 cm, on all sides, and the right margin unjustified with no automatic hyphenation. Do not send large files (e.g. photographic illustrations) as e-mail attachments, but submit them on a CD-ROM sent by air-mail.

Material being described must be registered as part of a formal collection housed in some recognised Institution so that it is accessible and available for study by other workers.

Paper should be arranged as follows: title, name and surname (in full) of author or authors, abstract, key words, adresses (foot note on the 1st page) with a mention of the parent organisation and e-mail address, text, acknowledgements, references, summary, figures, tables, and plate captions.

The title of the paper should be short, but expressing the principal aim of the paper.

The abstract must be concise, not more than 200–250 words, and should be informative, stating the results presented in the article rather than describing its contents. Inclusion of references in the abstract is not recommended.

After the abstract, list 5–8 **keywords** which describe the subject matter of the work. They should be arranged from general to more specific ones.

The text should be written as clear and understandable as possible. Use up to threee levels of headings. Their hierarchy should be indicated in the left-hand margin of the text. Italics are used only for the name of genera and species, or if a word is italicized in the original title. References should be cited in the text as follows: DAMBORANEA (2002) or (DANBORANEA 2002) for a single author; FÜRSICH & HEINZE (1998) or (FÜRSICH & HEINZE 1998), for two authors; RICCARDI *et al*. (1991) or (RICCARDI *et al*. 1991) for multiple-author works.

References should be classified alphabetically according to the author's names. Include only published papers mentioned in the text, unpublished reports will be accepted only in exeptional cases. Do not abbreviate the titles of journals and give the names of symposium volumes and edited books. For books it is necessary to give the publisher's name and place of publication. References in Cyrillic alphabet must be transliterated to the Latin alphabet. The titles of the paper in a non-Latin alphabet should be translated into English with an indication of the original language in parenthases, while the name of the journal must be transliterated into Latin alphabet. Examples are as follows:

AGER, D.V. 1963. *Principles of Paleoecology*. 318 pp. McGraw-Hill, New York.

OWEN, E.F. 1962. The brachiopod genus Cyclothyris. *Bulletin of the British Museum (Natural History)*, *Geology*, 7 (2): 2–63.

RABRENOVIĆ, D. & JANKIČEVIĆ, J. 1984. Contribution to the study of Albian near Topola. *Geološki anali Balkanskoga poluostrva*, 48: 69–74 (in Serbian, English summary).

SMIRNOVA, T.N. 1960. About a new subfamily of the Lower Cretaceous dallinoid. *Paleontologicheskii Zhurnal*, 2: 116–120 (in Russian).

SULSER, H. 1996. Notes on the taxonomy of Mesozoic Rhynchonellida. *In*: COOPER, P. & JIN, J. (eds.), *Brachiopods*, 265–268. Balkema Press, Rotterdam.

Acknowledgments should be as short and concise as possible.

A **summary** (up to 15% of the paper) is published in Serbian and should contain the essence of all new data and the conclusions.

Illustrations can be submitted as conventional hardcopies or in electronic form. The preferred formats for graphics is CDR (600 dpi) and for photographs and plates JPG or TIFF (600 dpi). The illustrations should have a width of 8.4, 12 or 17.5 cm, the final limit is the size of type area (17.5 × 24.5). Lines and letters must be suitable for reduction. It is also recommended to send copies reduced to the size for publication; after reduction, the smallest lettering should be not less then 1 mm and not greater than 4 mm in height (in the Arial font). The aproxiamte position of figures and tables should be indicated in the manuscript margin. Do not incorporate illustrations in the text of the paper. Figure, table and plate captions should be listed on separate sheets. The author's name and figure number should be indicated at the foot of the illustration. The figure numbers can be writen by hand on a paper copy of the plate or on a transparent overlay, not on the plate itself. The cost of printing colour figures must be paid in full by the author.

Authors will receive one and if necessary two **proofs**. These must be returned within the time limit indicated. If this does not happen, the publication of the paper will be postponed automatically to a later date.

25 **reprints** per article will be provided free of charge for the author (in the case of multi-authored papers, the senior author will receive the reprints).

All **correspondence**, enquires and manuscript submissions should be directed to the Editor-in-Chief of *Geološki anali Balkanskoga poluostrva*.

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ГЕОЛОШКИ АНАЛИ БАЛКАНСКОГА ПОЛУОСТРВА
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