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Aulacogens, the Donets Basin (eastern Ukraine, southwestern Russia), and the new classification of rifts: towards a proper terminology

Dmitry A. Ruban[1]

Abstract. Some intra-cratonic basins are traditionally called “aulacogens”. This term has persisted in the geoscience literature since its invention by Soviet geologists in the mid-20th century before the triumph of the plate tectonics, but its meaning has evolved. Attempts to change its meaning from descriptive to genetic have led to a broad spectrum of opinions on the definition of aulacogens. Some specialists related them to continental rifts, while others have restricted aulacogens to the only particular rift systems or peculiar stages in the evolution of young cratons. The Donets Basin is a typical aulacogen stretching across the southern margin of the East European Craton. A brief review of present knowledge of this basin shows that its nature is rather incompatible with the present understanding of aulacogens. Instead, the new classification of rifts offers a more precise terminology for its exact characteristics. It is suggested that the term “aulacogen” should only be restricted to those basins for which it has been applied historically.

Key words: aulacogen, continental rift, craton, tectonic terminology, Donets Basin.

Апстракт. Неки интракратонски басени су традиционално називани “аулакогени”. Овај термин, прихваћен у геолошкој литератури, увели су совјетски геолози средином двадесетог века, пре тријумфа тектонике плоча. Пукушаји да се измени његов генетски значај водили су до широког спектра мишљења о дефиницији аулакогена. Неки аутори доводе га у везу са континенталним рифтовима, други су ограничавали аулакоген на један део рифтних система или на одређене стадијуме у еволуцији млађих кратона. Доњецки басен је типичан аулакоген који се пружа дуж јужног обода источноевропског кратона. Кратак преглед досадашњих сазнања о овом басену показују да његова природа није усаглашена са досадашњим схватањем аулакогена. Нова класификација рифтова даје прецизнију терминологију за његове одређене карактеристике. Предложено је да термин “аулакоген” буде прихваћен само за оне басене за које су и раније били примењивани.

Кључне речи: аулакоген, континентални рифт, кратон, тектонска терминологија, Доњетски басен.

Introduction

The term “aulacogen” was coined by the famous Russian geologist N.S. Shatskij and his followers in the midst of the 20th century (Kosygin & Parfjonov 1970; Paffengol’ts 1978). It has since been used by researchers outside the ex-USSR and Russia (e.g., Burke 1977; Perry & Pigott 1983; Hames *et al.* 1998). Although the number of publications mentioning aulacogens has not decreased until now (Fig. 1), the validity of this term has been questioned by some specialists in tectonics. For instance, according to the textbook by Frisch *et al.* (2011), “aulacogen” is a failed term to be replaced by “graben structure”. It should be also noted that many papers for international readership that employ this term have been written by Russian and Chinese authors.

In this brief note, I attempt to discuss whether “aulacogen” is a proper term to use within the context of modern tectonics. For this purpose, 1) its original and present meanings are examined and compared, and 2) the alternative usage of a new classification of rift structures (Merle 2011) to describe typical aulacogens (like the Donets Basin in Eastern Europe) is considered.

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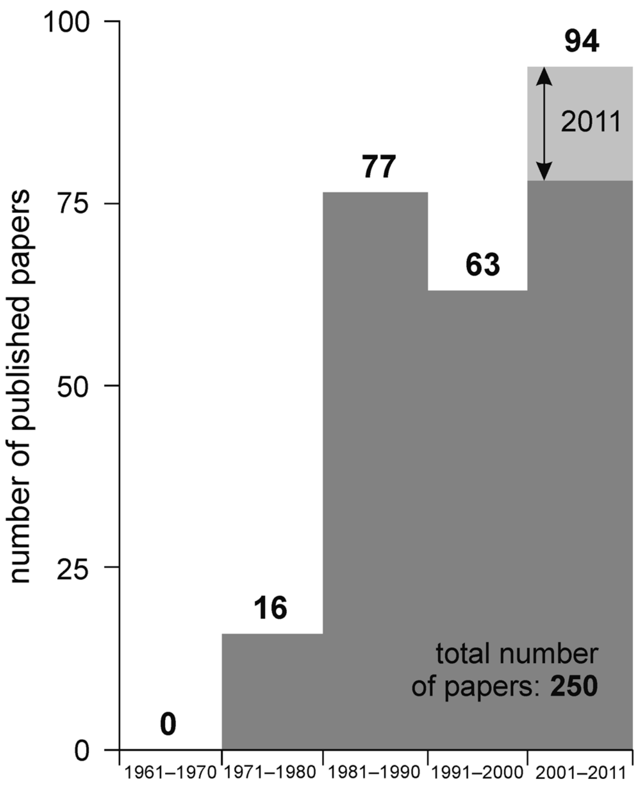

Fig. 1. Changes in the number of papers available for the international readership (based on a search of titles, abstracts, and key words in the bibliographical database scopus.com; accessed on April 9, 2012). The number of papers is indicated by columns; 16 papers were published in 2011.

What does the term "aulacogen" mean?

The term "aulacogen" was introduced by the Soviet geologist N.S. SHATSKIJ in 1964 (KOSYGIN & PARFJONOV 1970; PAFFENGOL'TS 1978). It originally meant nothing more than "a trench-like complex structure between similar zones of the platform" (KOSYGIN & PARFJONOV 1970, p. 148). Soviet geologists also emphasized thick, often folded, sedimentary cover (measured by thousands of meters) of aulacogens and controls of major faults on these basins (KOSYGIN & PARFJONOV 1970; PAFFENGOL'TS 1978). Several types of aulacogens were distinguished (e.g., KOSYGIN 1969). KOSYGIN (1969) pointed out that the original meaning of the term had already changed a few years after it was coined, and presented a broad spectrum aulacogen definitions (see also KOSYGIN & PARFJONOV 1970; PAFFENGOL'TS 1978). Interestingly, formation of aulacogens has been often attributed to a particular stage in the evolution of cratons, when young platforms experienced destructive deformations (KOSYGIN 1969; LAZ'KO 1975; POTAPOV, 1996). The East European Craton (= Russian Platform), which has been identified by Soviet geologists as an ideal object for cratonic studies, exhibited the formation of several aulacogens during the so-called Riphean (Meso- and Neoproterozoic – see RUBAN 2009 for more details), when this craton began to evolve into a "stable" tectonic block (LEJTES *et al.* 1970; BELOUSOV 1978; VALEEV 1978; POTAPOV 1996). This interpretation appeared so obvious that even elementary textbooks in general geology tended to relate the majority of aulacogens to the late Proterozoic evolution of young cratons (e.g., KORONOVSKIJ & JAKUSHOVA 1991).

It is important to note that ideas about aulacogens appeared before the wide acceptance of the plate tectonics as a universal tectonic theory (this is especially true for the Soviet geoscience community of 1960–70s). Aulacogens were treated in terms of fixism (or, more properly, the geosyncline concept) during the 1960s and the 1970s, when crucial information about them was accumulated (KOSYGIN & PARFJONOV 1970; PAFFENGOL'TS 1978). When the theory of plate tectonics became accepted and the attention of Soviet geologists turned to extensional structures (MILANOVSKIJ 1976), the term "aulacogen" started to become related to "continental rift" and "graben". However, some specialists expressed caution about a mix of these terms (BELOUSOV 1978). Moreover, it appears that the original definition of aulacogens (see above) does not require the formation of these structures within continental rifts (sometimes, compressed and folded after the main deposition phase), but also allows also their formation via large-scale epeirogenic deformation of cratons (often characterized in terms of dynamic topography). Nevertheless, continental rifting seems to be the most plausible explanation for the majority of aulacogens. Decades after the first definition of the term, the aulacogen stage in the evolution of young platforms was described in terms of continental rift development and the onset of extension (e.g., NIKISHIN *et al.* 1996). Thus, although the discussed term was originally only descriptive, it has "gained" a genetic sense as the tectonic knowledge of the geoscience community advanced.

The body of Soviet/Russian literature on aulacogens is huge, but what about the international publications? Below, I give some examples from books published recently. BOGGS (2006) provides several opinions on the nature of aulacogens. He notes, for instance, that these might have been failed rifts, later reactivated under a compressional regime. Following ŞENGÖR (1995), he also mentions the possible role of strike-slip displacements and tectonic block rotations in the origin of these structures. BOGGS (2006) also emphasizes the thick sedimentary cover of aulacogens and their occurrence at high angles relative to the continental margin. Does this mean that aulacogens can occur only in the peripheral parts of cratons?! This author also lists (as examples) aulacogens of a very different age (including late Paleozoic and Cretaceous structures). Reviewing knowledge of the intra-continental sedimentary basins, BAYER *et al.* (2008) note that aulacogens are old inverted stuck rifts. Frisch *et al*. (2011) reject the validity of the term "aulacogen", which, in their opinion, is a graben structure with thick sedimentary cover. It should be noted that these authors refer to a rather broad understanding of grabens. In his recent monumental review, Ingersoll (2012) treats aulacogens as fossil rifts evolved as a third arm in three-rift systems; according to this author, aulacogens are continental rifts that did not become oceans and were later compressed. Looking at recent research papers published in international journals (e.g., Aitken & Betts 2009; Dickinson *et al*. 2010; Teixeira *et al*. 2010; Duan & Duan 2011; Jin *et al*. 2011), it is easy to realize that the term "aulacogen" refers to basins related to continental extension and/or supercontinental break-up, and many of these basins are late Precambrian in age. It also appears (but this is a mere impression) that the term "aulacogen" is used historically for particular tectonic structures in some (if not many) cases.

The authors of the non-Soviet/Russian publications considered above tend to employ the term "aulacogen" with certain differences, and they always do so within the context of plate tectonics. This is far from the original understanding of aulacogens in the Soviet geoscience literature before the 1980s (see above), when this term was used within the geosyncline conceptual frame. Interestingly, none of the books or book chapters mentioned above (Boggs 2006; Bayer *et al*. 2088; Frisch *et al*. 2011; Ingersoll 2012) refer to aulacogen formation as a particular stage (often, late Precambrian) in the evolution of cratons, which has been a "classic" concept in the Soviet/Russian geoscience community.

The Donets Basin as aulacogen

The Donets Basin (*s. lato*) is an elongated tectonic structure stretching across the southern part of the East European Craton, on the territories of eastern Ukraine and southwestern Russia (Fig. 2). It consists of several segments, namely (from west to east) the Pripyat Trough (Depression), the Dniepr–Donets Basin (Depression), the Donbass (also spelled Donbas) Fold Belt (Donets Basin *s. str.*), and the Karpinsky Swell (Stephenson *et al*. 1996; Maystrenko *et al*. 2003; Ruban & Yoshioka 2005). The Donets Basin is a "classic" aulacogen (Paffengol'ts 1978; Potapov 1996; Stephenson *et al*. 1996; Natal'in & Þengör 2005; Boggs 2006), which was extended and subsided to allow deposition of thick late Paleozoic sedimentary deposits; then it was compressed with consequent folding and faulting (see brief review and references in Ruban & Yoshioka 2006; Sachsenhofer *et al*. 2012). However, Soviet geologists interpreted the same structure to be a geosyncline (see review in La'zko 1975). Modern views on the nature of the Donets Basin, which somewhat differ, are summarized by Stephenson *et al*. (1996), Maystrenko *et al*. (2003), Saintot *et al*. (2003a,b), Kostjutchenko *et al*. (2004), Natal'in & Şengör 2005; Ruban & Yoshioka (2005), Ruban (2007), Meijers *et al*. (2010), and Sachsenhofer *et al*. (2012).

According to the most recent synthesis of the available knowledge (Sachsenhofer *et al*. 2012), the opening of the Donets Basin occurred in the Late Devonian when the pre-existing Sarmatian Craton was divided into two parts, which are known today as the Ukrainian and Voronezh massives (Stephenson *et al*. 1996; Ruban & Yoshioka 2005). We can not exclude the possibility that emplacement of a mantle plume could trigger, or at least contribute to, the appearance of this basin (Wilson & Lyashkevich 1996; Racki 1998; Brink 2009; Sachsenhofer *et al*. 2012). The Donets basin, however, might have inherited some older structures (e.g., Potapov 1996). Strong post-rift subsidence occurred in the late Paleozoic, and was followed by an inversion and uplift (Sachsenhofer *et al*. 2012). The age of the compressional event(s) is still debated, but it ranges from the Permian to the Cretaceous (Saintot *et al*., 2003b; Natal'in & Þengör 2005; Ruban & Yoshioka 2005; see also brief review in Sachsenhofer *et al*. 2012). Ruban & Yoshioka (2005) and Ruban (2007) discussed the evolution of the Donets Basin in a broader context (similar views were also expressed independently by Natal'in & Şengör (2005)). These authors followed earlier ideas expressed by Arthaud & Matte (1977). According to these studies, the Donets Basin was formed as the result of strike-slip displacements in the Variscan and adjacent structures. It is possible that dextral displacements along the southern margin of the East European Craton detached from the Ukrainian block and opened the elongated basin between this new terrane and the rest of the craton in the late Paleozoic (Fig. 2). Changes in the direction of displacements along the major shear zone located along the southern margin of the East European Craton in the early Mesozoic resulted in compression of the thick sedimentary complexes that were accumulated in the above-mentioned basin. This scenario requires some refinement, but it relates the nature of the Donets Basin to forces that are much larger in scale than those responsible only for the evolution of the East European Craton. The noted major shear zone was an element of the global system of shear zones, which stretched across Gondwana and the northern Palaeo-Tethyan margin (Ruban 2007) (Fig. 2).

If the Donets Basin is an aulacogen, how does its nature, characterized above, fit the various definitions of aulacogen formation? If we take the only descriptive meaning of the term "aulacogen" from the Soviet literature of the mid-20th century (see above), there is no difficulty in applying this term to the Donets Basin. However, it is impossible to relate the term "aulacogen" to the Riphean stage in the evolution of the

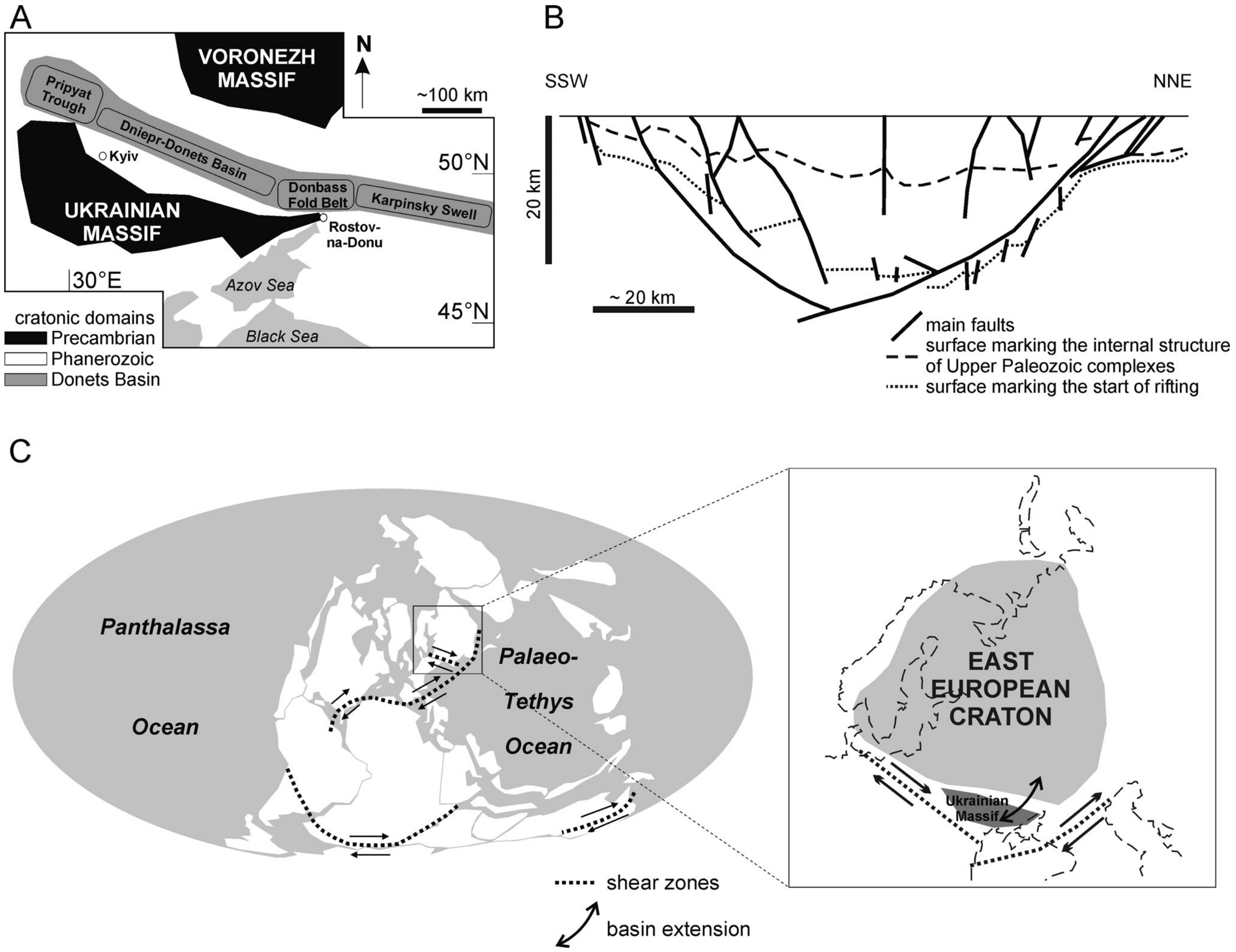

Fig. 2. Geological outline of the Donets Basin. **A**, Schematic location of the Donets Basin and its main segments (adapted and simplified from MAYSTRENKO *et al.* 2003 and RUBAN & YOSHIOKA 2005). **B**, Generalized profile across the Donbass Fold Belt (modified from MAYSTRENKO *et al.* 2003; SACHSENHOFER *et al.* 2012). **C**, Late Paleozoic development of the Donets Basin (after RUBAN & YOSHIOKA 2005; RUBAN 2007 with slight modifications; base plate tectonic reconstruction is simplified from SCOTESE 2004).

young East European Craton. If this basin inherited any Precambrian lineaments (e.g., POTAPOV 1996), then it was formed in the mid-Paleozoic, when the craton was already "old". Moreover, as said above, the forces responsible for the formation of the Donets Basin were different from those responsible for the evolution of the craton. From various definitions of aulacogens proposed in international publications, that of INGERSOLL (2012) differs especially from what occurred in the Donets Basin. In particular, there is no any clear evidence that the Donets Basin evolved as the third arm of a three-rift system.

Recently, a new classification of rift structures has been proposed; plume-related, subduction-related, mountain-related, and transform-related rifts are distinguished on the basis of the tectonic environments that were present at their formation (MERLE 2011). Is it possible to apply this classification to the Donets Basin? Features of two types of rifts can be found in the Donets Basin. First, we already suggested that the emplacement of a mantle plume could facilitate or even provoke the Donets rift formation in the Late Devonian (WILSON & LYASHKEVICH 1996; RACKI 1998; BRINK 2009; SACHSENHOFER *et al.* 2012), and the activity of mantle plumes might have contributed to the evolution of this rift at the later stages (ALEXANDRE *et al.* 2004). If so, this plume-related rift (*sensu* MERLE 2011) is to be compared with the East African continental rifts (CORTI 2009, 2012). Second, the Donets Basin developed in the strike-slip environment (NATAL'IN & ȘENGÖR 2005; RUBAN & YOSHIOKA 2005; RUBAN 2007). In this case, it bears features typical of transform-related rifts described by MERLE (2011). It is important to note that judging the Donets Basin as aulacogen does not clarify its nature. In contrast, the application of the new classification of rift structures

(MERLE 2011) permits us to indicate the mechanism of its formation exactly.

Discussion and conclusion

Undoubtedly, the geologic recognition of aulacogens, and the intense study of these formations by Soviet/Russian specialists, played a great role in deciphering the geologic history of cratons. Because of this, I do not tend to judge the results of *these* studies too critically, although when doing so it is important to also consider the alternative understandings of the term "aulacogen" (stressed already by KOSYGIN 1969), and the fact that aulacogen development is not necessarily associated with cratonic evolution (see about the nature of the Donets Basin). A greater problem is the "diffuse" meaning of the term "aulacogen" in the modern *international* geoscience literature. This meaning differs somewhat from the original definition, because it attempts to explain aulacogens genetically in terms of the plate tectonics. Moreover, the genetic treatment of aulacogens implies formational explanations that are not relevant for all possible aulacogens, including such typical aulacogens as the Donets Basin. Instead, the new tectonic nomenclature provides better causative descriptions of basins than "simply" judging them to be aulacogens. For example, the classification of rift structures proposed by MERLE (2011) provides a proper tectonic terminology from which we can infer the nature of the Donets Basin formation (combined plume- and transform-related).

Do the considerations presented above imply that the term "aulacogen" is improper or failed, as has been suggested by FRISCH *et al*. (2011). In my opinion, it is equally wrong to preserve one term that does not fit the present needs as it is to abandon it, especially if it remains relatively frequently used (Fig. 1). I propose the following solution to this dilemma: the term "aulacogen" may still be used, but for only those tectonic structures and sedimentary basins that were already judged aulacogens, e.g., the Donets Basin, the Pachelma Trough, and the Vyatka Aulacogen of the East European Craton (KOSYGIN 1969; BOGGS 2006). For these, "aulacogen" is the historically correct term. Moreover, the original Soviet meaning of the "aulacogen" is merely descriptive, which simplifies the preservation of the regional use of this term. Similarly, such terms "flysch" and "molasse" are used for particular sedimentary packages in the sedimentological, stratigraphic, and tectonic literature. As for other or future tectonic investigations, the term "aulacogen" should be avoided. The new classifications, such as those proposed by MERLE (2011), provide us with a proper tectonic terminology.

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Резиме

Аулакогени, Доњецки басен (источна Украјина, југозападна Русија), и нова класификација рифтова: према исправној терминологији

Термин "аулакоген" је увео познати руски геолог Н.С. Шатскиј средином двадесетог века. Од тада је овај термин прихваћен од стране истраживача ван граница бившег СССР и Русије. Међутим, оправданост овог термина оспоравали су неки тектоничари. Аутор покушава да одговори да ли је "аулакоген" подесан термин за употребу у контексту модерне тектонике. У том циљу: 1) његово оригинално, као и садашње значење, су испитивани и упоређивани, и 2) разматрана је алтернативна употреба нове класификације рифтних структура да опише типичне аулакогене (као Доњецки басен у источној Европи). Совјетски геолози су дефинисали термин "аулакоген" као издужену интракратонску структуру, често запуњену набраним дебелим седиментима. Занимљиво је да се формирање аулакогена често приписује одређеном стадијуму у еволуцији кратона, где су млађе платформе подвргнуте разорним деформацијама. Покушаји да се промени ово значење, од описног до генетског, довело је до широког спектра мишљења у дефинисању аулакогена. Неки истраживачи доводе их у везу са континенталним рифтовима или рововима. Аутори неких савремених несовјетских/руских публикација нагињу употреби термина "аулакоген" са извесним разликама, у контексту тектонике плоча.

Ни једна књига или пак поглавље књиге, који су коришћени овом приликом, не упућују на то да би аулакоген представљао посебну фазу (често касни прекамбријум) у еволуцији кратона, што је иначе било класично тумачење међу совјетским/руским геолозима. Насупрот томе, ако погледамо савремене радове публиковане у међународним часописима видећемо да се термин "аулакоген" односи на басене везане за континентална продужења и/или суперконтинентална издизања, и многи од ових басена су касне прекамбријске старости.

Доњетски басен у ширем смислу је једана издужена тектонска структура која се пружа дуж јужног дела источно европског кратона, на територији источне Украјине и југозападне Русије. Идући од запада ка истоку састоји се од неколико делова: Припјат трог (депресија), Дњепро-доњетски басен (депресија), Донбаски разломни појас, који су "класични" аулакогени. Ако је тако, како се његова природа, поменута горе, подудара са различитим дефиницијама формирања аулакогена? Ако узмемо само описно значење термина "аулакоген" из совјетске литературе средином двадесетог века, нема потешкоћа у примени овог термина за Доњетски басен. Мађутим, немогуће је довести термин "аулакоген" у везу са Рифејским стадијумом у еволуцији млађег источоевропског кратона. Ако је овај басен имао неке прекамбријске особине, тада је он формиран у средњем палеозоику, када је кратон већ био формиран. Шта више, силе одговорне за формирање Доњетског басена су различите од оних које су учествовале у еволуцији кратона. Важно је напоменути да тумачењем Доњетског басена као аулакогена не објашњава и његово порекло. Примена нове класификације рифтних структура дозвољава нам да прецизно укажемо на механизам његовог формирања. У Доњецком басену могу се уочити карактеристике два типа рифтова. Прво, положај плуме из омотача могао је да олакша или чак да проузрокује формирање Доњетског рифта у касном девону. У том случају, ови плуме рифтови могу се корелисати са источноафричким континенталним рифтовима. Друго, Доњетски басен се развијао у разломној средини. У том случају он има особине типичне за трансформне рифтове.

Аутор предлаже следеће решење овог питања: термин "аулакоген" може се још употрбљавати, али само за оне тектонске структуре и седиментационе басене које се већ сматрају аулакогеним, нпр. Доњетски басен, Печелма трог, Вијатка аулакоген источноевропског кратона, за. њих је "аулакоген" исправан термин.

Термини као "флиш" и "моласе" су у употреби за поједине седиментне пакете у седиментолошкој, стратиграфској и тектонској литератути. За будућа тектонска испитивања треба избегавати термин "аулакоген". Нове класификације крупних тектонских структура упућују нас на одговарајућу тектонску терминологију.

В.Р.

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The subsurface geology along the route of the new bridge at Ada Ciganlija Island (Belgrade, Serbia)

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Abstract. The largest single-pylon, cable-stayed bridge in the world was opened in Belgrade on January 1, 2012 and it passes over the tip of the Ada Ciganlija Island. Its monumentality, architectural design and construction innovations became a new symbol of Belgrade. Core samples from the boreholes drilled for the construction of the bridge revealed a relatively complex subsurface geological structure. An Upper Cretaceous–Paleogene flysch formation and Middle Miocene Sarmatian sediments were found near the surface on the right bank of the Sava River. However, at the tip of Ada Ciganlija, the Upper Cretaceous-Palaeogene flysch strata were found below several different Miocene and Quaternary units. In the deepest borehole DB-6, the flysch deposits were found at a depth of 80 meters. On the left bank of the Sava River in New Belgrade, only Upper Miocene Pannonian marls and Pleistocene and Holocene alluvial deposits were drilled. Based on a comparative analysis of the borehole sections and structural characteristics of the rocks, it could be concluded that the Pre-Quaternary units cascade subsided along sub-parallel faults towards N–NW.

Key words: Subsurface geology, blocks subsidence, Upper Cretaceous, Miocene, Quaternary, Belgrade.

Апстракт. Највећи мост на свету са једним носећим пилоном отворен је у Београду 1. јануара 2012., а пролази преко шпица острва Аде Циганлије. Његова монументалност, архитектонско решење и грађевинске иновације постали су нови симбол Београда. Анализирани узорци језгра бушотина изведених за потребе изградње моста, указали су на једну релативно комплексну подповршинску структуру. На десној обали реке Саве, горњокредно-палеогени флиш и средњомиоценски сарматски седименти су откривени близу површине терена. Међутим, на шпицу Аде Циганлије, утврђено је да флишне наслаге леже испод неколико различитих миоценских и квартарних јединица. У најдубљој бушотини DB-6, флишни седименти су откривени на дубини од 80 метара. На левој обали реке Саве, у Новом Београду, набушени су само горњомиоценски панонски лапорци и плеистоценске и холоценске алувијалне наслаге. На основу упоредне анализе профила бушотина и структурних карактеристика стена, може се закључити да су пре-квартарне јединице по систему субпаралелних раседа каскадно спуштене у правцу С–СЗ.

Кључне речи: Подповршинска геологија, тектонско спуштање, горња креда, миоцен, квартар, Београд.

Introduction

A new concrete-steel bridge over the Ada Ciganlija Island directly connects roads in Čukarica, on the right bank of the Sava River, and roads in New Belgrade, on the left bank of the river. It represents a part of the future Inner City Semi-Ring Road. Its total length is 996 meters and the width is exactly 45.06 m. The bridge is based on a large 200 m-high pylon that is located at the tip of the Ada Ciganlija Island. The distance between pylon and the left bank of the Sava River (main span) is 376 m, while the distance between the pylon and the supporting pillar on the right bank of Sava River is 250 m (see Plate 1). Exploration boreholes were drilled for the construction of a pylon at the tip of Ada Ciganlija and the pillars on the right and left bank of the Sava River (Fig. 1). On the right bank, in Čukarica near the famous restaurant "Stenjka", the boreholes DB-9 and DB-10–were drilled. Next to the pylon at the Ada Ciganlija tip, near

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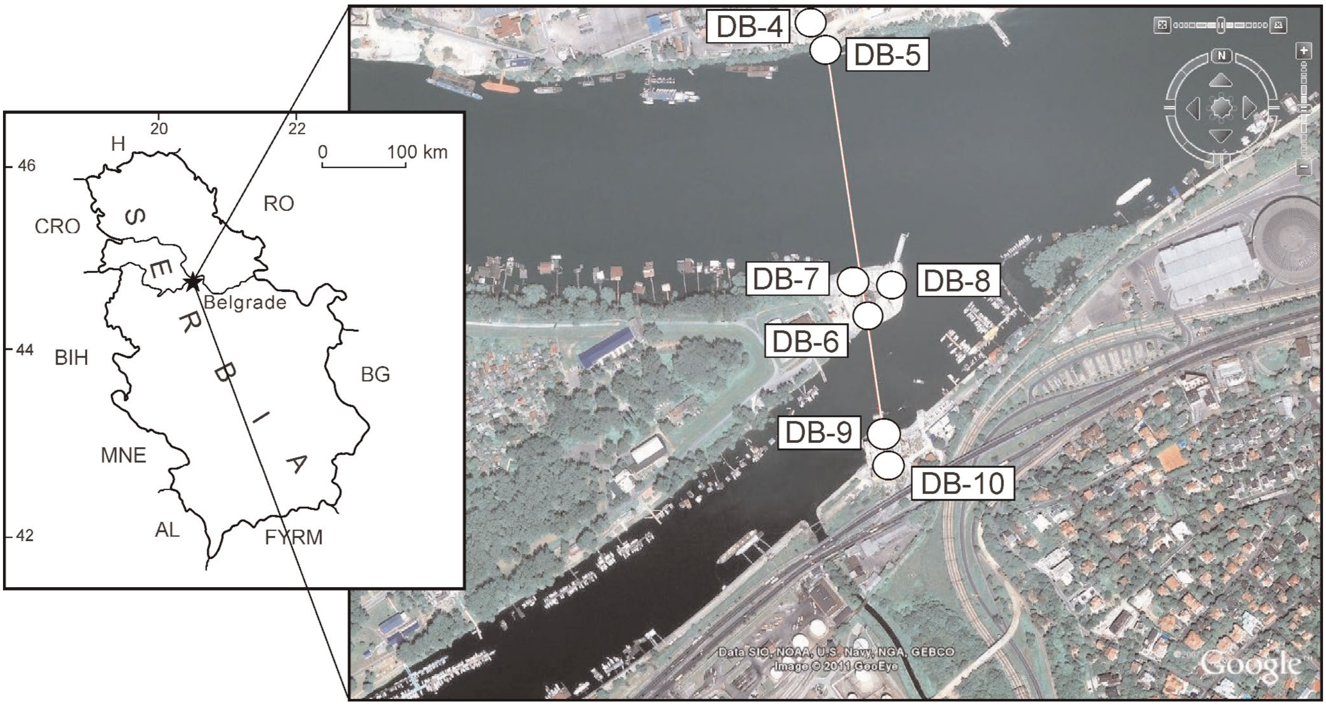

Fig. 1. The projected position of the new bridge over the Ada Ciganlija Island (Belgrade) and the locations of the investigated boreholes (Google Earth, 2011).

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

No.	Boreholes	Coordinates (WGS84)	
1.	DB-4	N 44° 47' 54.37"	E 20° 25' 30.44"
2.	DB-5	N 44° 47' 53.84"	E 20° 25' 32.53"
3.	DB-6	N 44° 47' 42.08"	E 20° 26' 02.23"
4.	DB-7	N 44° 47' 41.74"	E 20° 25' 34.10"
5.	DB-8	N 44° 47' 41.84"	E 20° 25' 35.87"
6.	DB-9	N 44° 47' 34.32"	E 20° 25' 36.39"
7.	DB-10	N 44° 47' 34.73"	E 20° 25' 36.65"

the rowing club "Partizan", the boreholes DB-6, DB-7 and DB-8 were drilled. The borehole DB-5 was drilled on the left bank of the Sava River, in the courtyard of Gemax Co., above the riverbank. The borehole DB-4 was drilled further away from the riverbank along the bridge route (Fig. 1, Table 1). The alignment of the bridge has a direction of NNW–SSE, and like other bridges on the Sava River in Belgrade, connects two geographic regions: the Balkan Peninsula and the Pannonian Plain.

Geological structure of this area has been interpreted based on the cores from the exploration boreholes. Results obtained in this study are valuable for understanding the geological evolution of Belgrade city area and geodynamic processes that occurred during the Neogene and Quaternary on the border between two realms: the Pannonian Plain and the Balkan Peninsula.

Material and methods

Samples were obtained from seven boreholes in the study area (Fig. 1, Table 1). Preliminary core analyses were realised in the field. Detailed stratigraphic and paleontological analyses of seventeen core samples were performed at the Faculty of Mining and Geology, University of Belgrade using classical methods of rock preparation (cleaning, washing and thin-sections).

Stratigraphy

The results obtained from the core samples revealed very interesting geological information concerning the subsurface terrain along the route of the new bridge. Upper Cretaceous–Paleogene flysch deposits represent the oldest unit, which make the basement rock for the overlying Miocene and Quaternary sediments.

Upper Cretaceous – Paleogene

The basement rocks of the terrain along the Sava River near the new bridge consist of beds with the so-called Ostružnica flysch. These beds comprise grey

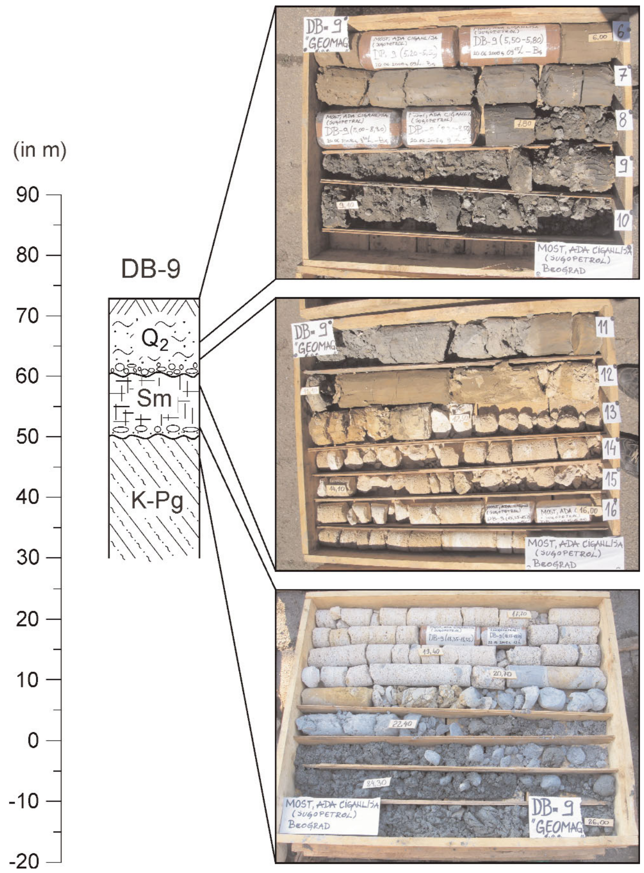

Fig. 2. The stratigraphic column and the core samples from the borehole DB-9. Key: **K-Pg,** Upper Cretaceous–Paleogene; **Sm,** Middle Miocene Sarmatian; **Pn,** Upper Miocene Pannonian; **Q_1,** Pleistocene, **Q_2,** Holocene.

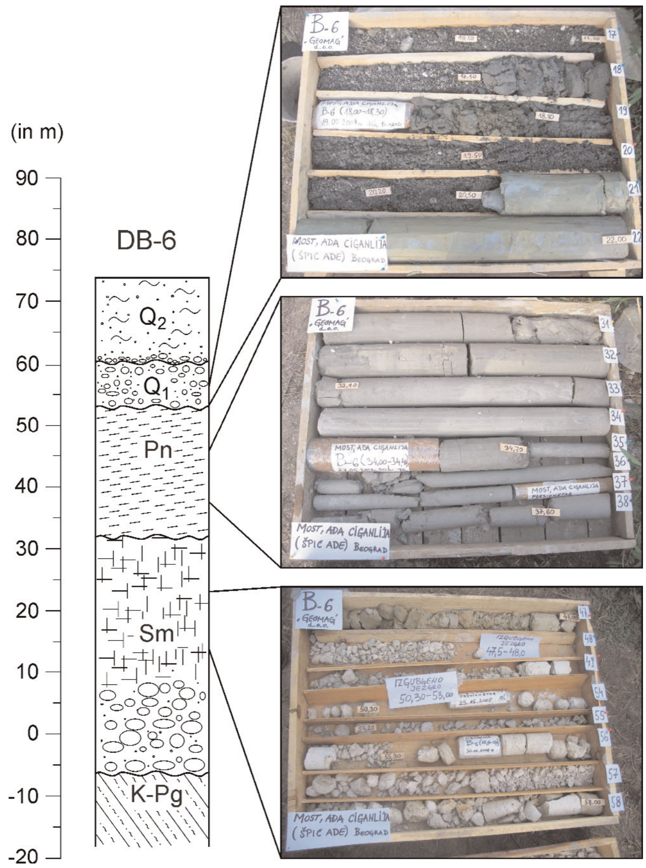

Fig. 3. The stratigraphic column and the core samples from the borehole DB-6. For the key, see Fig. 2.

and greyish-brown sandstones (micro-conglomerates occasionally) and clay interbeds. The youngest flysch formation in the vicinity of Belgrade is already known from the numerous wells in New Belgrade (near the Heating Station) and the Sava–Danube confluence (next to the Museum of Applied Arts and the famous shopping mall "Ušće"). The same formation was found at a small depth on the right bank of the Sava River (below 20 m, at Prince Marko Street No. 2 – Knežević & Ganić 2005). Therein, based on the presence of nannoplankton species, the Upper Cretaceous age was confirmed. According to Anđelković (1987), the flysch was formed at the end of the Upper Cretaceous and Early Paleogene.

The Ostružnica flysch strata were found on the right bank of the Sava River at Čukarica, as well as on the tip of Ada Ciganlija. On the right bank, the flysch strata were found in the boreholes DB-9 (from a depth of 22.3 m to its bottom at approximately 42 m – Fig. 2) and DB-10 (from 19 to 65 m). Thus, these layers were found in two out of three boreholes situated next to the pylon. In the deepest borehole DB-6, the flysch deposits were found from a depth of 80 m to its bottom at approximately 90 m (Fig. 3). In the second pylon borehole, which is only 20 m away from the above-mentioned boreholes, the Ostružnica flysch layers were found at a much smaller depth (less than 60 m).

Miocene

Miocene sediments were found in all wells along the route of the new bridge (Figs. 4–6). Stratigraphically, they correspond to the Middle Miocene Sarmatian and Upper Miocene Pannonian Stage (see Laskarev *et al*. 1932; Stevanović 1977; Knežević & Šumar 1993).

The Middle Miocene Sarmatian brackish-marine sediments lie uncomformably and transgressively over the mentioned flysch strata. They were discovered in the boreholes on the right bank of the Sava River at Čukarica and at the tip of Ada Ciganlija close to the position of the pylon. The older parts of the Sarmatian sediments consist of coarse-grained rocks, such as basal conglomerates and breccias. At the tip of the island, in the borehole DB-6, such deposits were discovered in the interval between 65 and 80 m depth, or between –7 m and +8 m altitude, with a total thickness of about 15 m (Figs. 3, 6). Moving toward the right bank of the Sava River, the horizon of clastites becomes thinner, until it reaches a total thickness of 0.5 m (between 22.3 and 21.7 m depth) in the borehole DB-9 (Fig. 6). Organogenic limestones are widely distributed and form the younger and thicker part of the Sarmatian sediments. Sometimes (*i.e.*, borehole DB-6 at a depth of 54.30–59.60 m), they are porous with molds and imprints of fossil gastropods (*Pirenella picta*, *P. disjuncta*, *Gibbula* sp., *Hydrobia* sp.) and bivalves (*Mactra vitaliana*, *Cerastoderma vindobonense*, *C. latisulcum*, *Irus gregarius etc.*). These fossils indicate the presence of the Lower/Middle Sarmatian boundary – the Mactra beds. Sarmatian limestones were found in all boreholes in Čukarica and at the tip of the island (Figs. 2, 3, 6). Their greatest thickness of about 24 m was found in the borehole DB-6, at the location of the pylon (Fig. 6). Hydrogeologically, the Sarmatian limestone unit is permeable rock and can represent an extremely good aquifer of groundwater, particularly in the tectonically folded terrain of the island and on the left bank of the Sava River (RUNDIĆ *et al*. 2005). On the right bank, similar carbonates were identified in the borehole DB-9 at a depth between 21.7 and 11.7 m (about 52–62 m above s.l.). On the other hand, within the boreholes located in the island, the Sarmatian limestones were found at much lower elevations, between 7 and 32 m altitude.

Upper Miocene Pannonian brackish ("caspibrackish") sediments have been found in the boreholes at the tip of the island of Ada Ciganlija and on the left bank of the Sava River in New Belgrade (Figs. 3–6). They were deposited over the Sarmatian limestones and make the basis for the Quaternary alluvial deposits. Lithologically, these sediments consist of grey marls and marly clays. On the island, near the location of the pylon, these sediments are located at an altitude between 30 and 53 m. Stratigraphically, they correspond to the lower part of the Pannonian (Slavonian Substage). Its lower and upper boundaries may vary slightly (the Pleistocene at the top and Sarmatian in the base). One or two interbeds with marly limestone up to 15 cm thick lay within these marls close to the Sarmatian limestones (i.e., in the borehole DB-7 at a depth of 44 m). A rare molluscs fauna, mainly bivalves (*Paradacna cekusi, Limnocardium praeponticum*), and small gastropods (*Gyraulus* cf. *praeponticus*, *Radix* cf *croatica*) was found. On the left bank of the Sava River in New Belgrade, similar sediments were found in the borehole DB-5, which is located above the riverbank, and in the borehole DB-4. In the borehole DB-5, Pannonian sediments were found from a depth of 29.5 m to its bottom at approximately 65 m (Fig. 4). In the borehole DB-4, the Pannonian deposits were found at a depth of 27.8 m. In contrast to the mentioned boreholes at the pylon, the layers with Upper Pannonian greyish marly clay

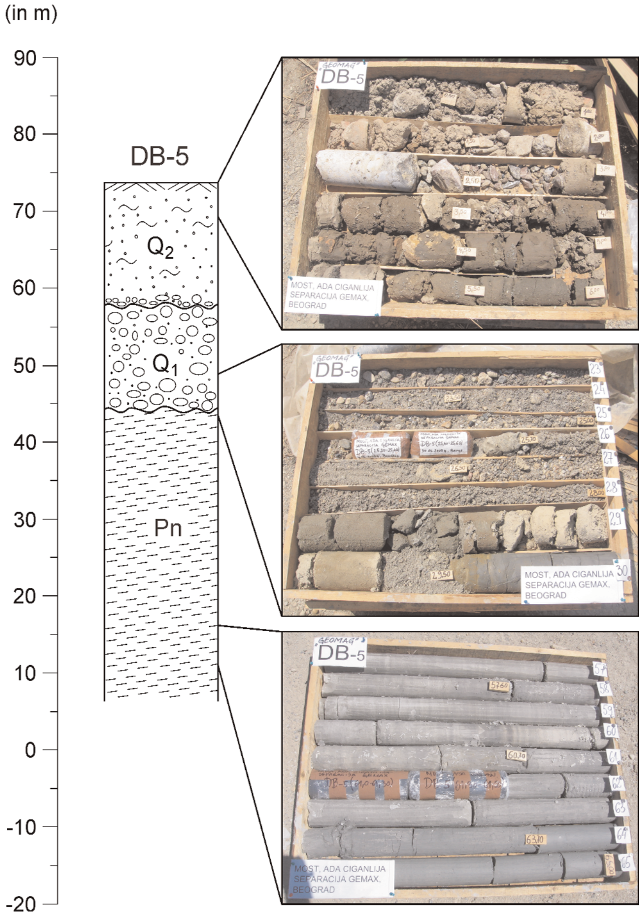

Fig. 4. The stratigraphic column and the core samples from the borehole DB-5. For the key, see Fig. 2.

with rare fossil remains, such as *Congeria banatica*, *Paradacna* cf. *syrmiense, Gyraulus praeponticus, etc*., were found (depth between 35.30–35.80 m)

Quaternary

Quaternary deposits are widely spread throughout the study area (Figs. 2–7). The dominant alluvial sediments can be divided into two distinct geological units based on superposition: 1) Pleistocene, polycyclic fluvial sediments and 2) Holocene, modern alluvial deposits of the Sava River and its tributaries.

Pleistocene - Polycyclic fluvial sediments

The older formation of alluvial deposits includes old, polycyclic river sediments, known from previous literature as "Makiš strata" or beds with "*Corbicula fluminalis*" (LASKAREV 1938). This formation consists mainly of sandy-gravel sediments deposited in the Early Pleistocene. It was formed during the stage of active tectonic movements, in the alternating phases of subsidence of the Sava River valley and rapid deposition of alluvial sediments. Within the lithological succession, there are alternations of riverbed sediments (gravel, gravelly sands and sands), floodplain sediments and oxbow-lake sediments (alevrites, and clays). Along with recent mollusc species, these sediments also contain fossil forms (*Corbicula cor, C. fluminalis, Viviparus boeckhi*). These beds occur in the Ada Ciganlija Island and on the left bank of the Sava River in New Belgrade. They contain large groundwater aquifers, which are exploited through wells for the water supply of Belgrade.

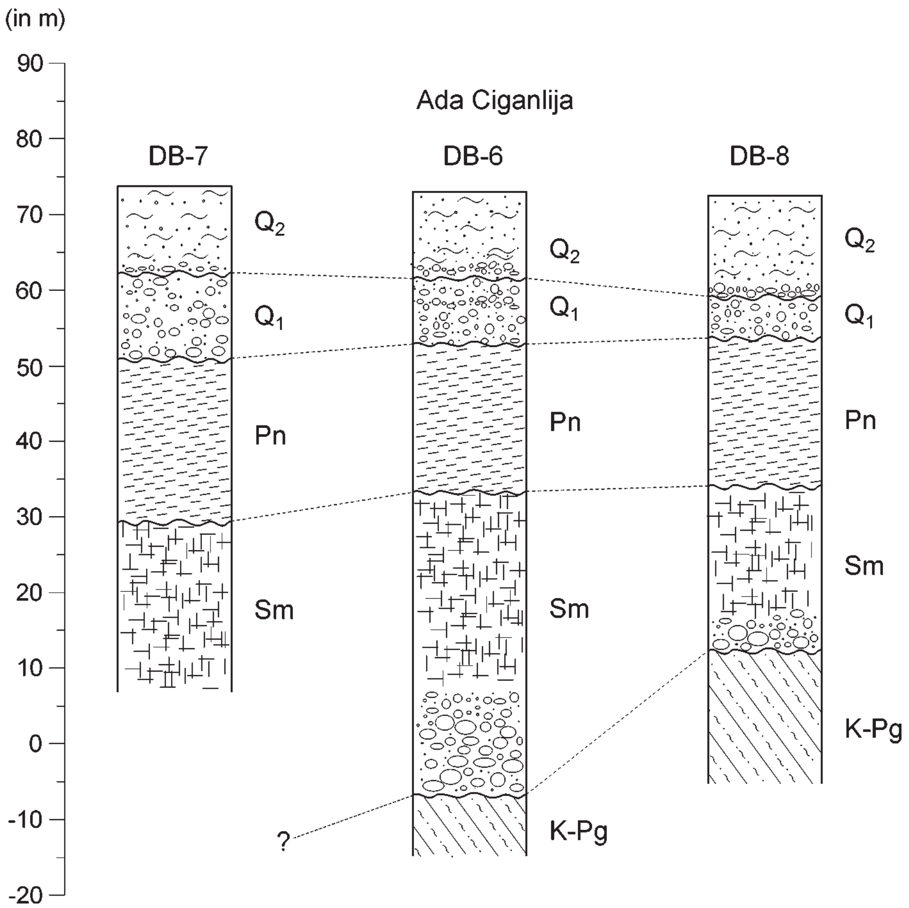

Fig. 5. Comparative stratigraphic sections of the boreholes at the tip of Ada Ciganlija. For the key, see Fig. 2.

Based on studies of the three boreholes at the tip of the Ada Ciganlija Island, it was determined that the thickness of the Pleistocene polycyclic fluvial sediments varies. In the borehole DB-7, the sediments reach a thickness of about 10 m, while in the other two boreholes, their thickness decreases to about 7 m (Fig. 5). On the left bank of the Sava River in New Belgrade, these sediments are thicker and their lower boundary is at a significantly lower depth comparing to those at the tip of the island. In the borehole DB-5 drilled above the left bank of the Sava River (Figs. 4, 6), they mark a lithological boundary to the Pannonian marls at a depth of 29.5 m (the whole thickness of the Pleistocene is about 13 m). In the borehole DB-4, situated about 150 meters away from the bank, this boundary is shallower and was identified at a depth of 27.8 m.

Holocene - modern alluvial sediments

The entire surface of the study area has been formed by recent alluvial sediments from the Sava River and its tributaries. The sediments are deposited discordantly over the Pleistocene alluvial deposits because the younger layers from the Pleistocene were previously eroded. On the right bank of the Sava River, at Čukarica, the recent alluvial sediments were deposited over the Sarmatian limestones. According to the superposition, as well as the genesis of these deposits, the recent alluvial sediments can be divided into riverbed sediments (sands, gravelly sand) and floodplain sediments (grey--yellow and brown alevrites, alevritic sands and sandy clays). Occasionally, there are oxbow-lake sediments and wetland deposits (greyish-dark clay and clayey alevrites rich in organic matter), especially in areas distant from the riverbank in New Belgrade. On the right bank of the Sava River at Čukarica, in both of the mentioned borehole, only floodplain sediments are presented that lie uncomformably over Sarmatian limestones.

An interesting observation was noticed at the borehole DB-4 in New Belgrade: the appearance of alternating replacements of riverbed sediments of the Sava River and its left tributary, called the Galovica Stream, both in the vertical and horizontal direction. Here, the former Sava riverbed sediments and small migrated riverbed sediments of its tributary are crossed. The Sava riverbed sediments comprise coarse-grained material, mostly quartz-micaceous sand, fine-grained gravel made of chert fragments, quartz and other rocks. The riverbed sediments of the Galovica Stream, which come from areas of the Srem Loess Plateau, contain many fine-grained alevrites with the cross-stratification tracks. Today, the Galovica Stream is displaced into the Galovica channel, and its mouth is located far upstream of the Sava River. However, the core of the mentioned borehole showed that the former riverbed sediments of the Galovica Stream in its natural confluence with the Sava River are preserved below the surface, under the route of the new bridge in New Belgrade. In addition, recent alluvial sediments from the Sava River are deposited, on the island Ada Ciganlija, forming an elongated river bar (lenticular sands, fine-grained sands and alevrites with distinct cross-stratification).

Holocene - anthropogenic or technogenic sediments

Anthropogenic deposits are present over a large surface area along the route of the bridge. These sediments consist of excavated sands, various dams, construction waste and other materials. Excavated sands are the most widespread, reaching a thickness of 5 meters on the left bank of the Sava River, in New Belgrade.

Discussion and interpretation

The basement rock consists of Upper Cretaceous––Paleogene deposits (the Ostružnica flysch). The overlying rocks comprise Miocene sediments of the Sarmatian and Pannonian Stage. Different Quaternary alluvial sediments represent the youngest deposits. This structural pattern is previously known from some other parts of the Belgrade City area (KNEŽEVIĆ *et al.* 1998; NENADIĆ *et al.* 2009; RUNDIĆ *et al.* 2011). Based on the samples from the boreholes along the route of the bridge (Figs. 6, 7), it was confirmed that the basement rocks and Miocene sediments subsided stepwise from the right bank of the Sava River to the left bank in the N–NW direction. This is consistent with previous studies in the area of the Sava–Danube confluence where a similar tectonic setting was observed (KNEŽEVIĆ & GANIĆ 2008, RUNDIĆ *et al.* 2011). On the right bank of Sava River in Čukarica, the Upper Cretaceous–Paleogene flysch deposits and Sarmatian sediments are located much shallower. No other rocks, except recent thin deposits occur on the surface. At the location of the bridge pylon, the same rocks are found at a much greater depth, which means that the boundary between the Ostružnica flysch and Sarmatian clastites is about 57 m lower than at Čukarica (Figs. 2, 3, 5). At the tip of the Ada Ciganlija Island and along the bank of the Sava River in New Belgrade, Pannonian strata and Pleistocene polycyclic fluvial sediments are present. On the left bank of the Sava River, the bore-holes reached Pannonian sediments and Pleistocene fluvial sediments of greater thickness. This indicates that the older stratigraphic units lie deep under the surface. This is consistent with other data from the area near the Sava–Danube confluence, where the Middle Miocene Badenian rocks have a higher vertical displacement and lie more than 70 m below the surface (RUNDIĆ *et al.* 2011). However, a more detailed analysis of the structural elements is necessary for a precise determination of the major faults and the structural features of the area.

Finally, it can be concluded that there are fault structures that run sub-parallel to the Sava River, which split all pre-Quaternary rock units into blocks. During the Mio-Pliocene, these blocks were differentially displaced along the faults and subsided from the right bank of the Sava River to the flat terrain of the Pannonian Plain on the left.

In terms of geomorphology, a part of the terrain along the route of the new bridge is

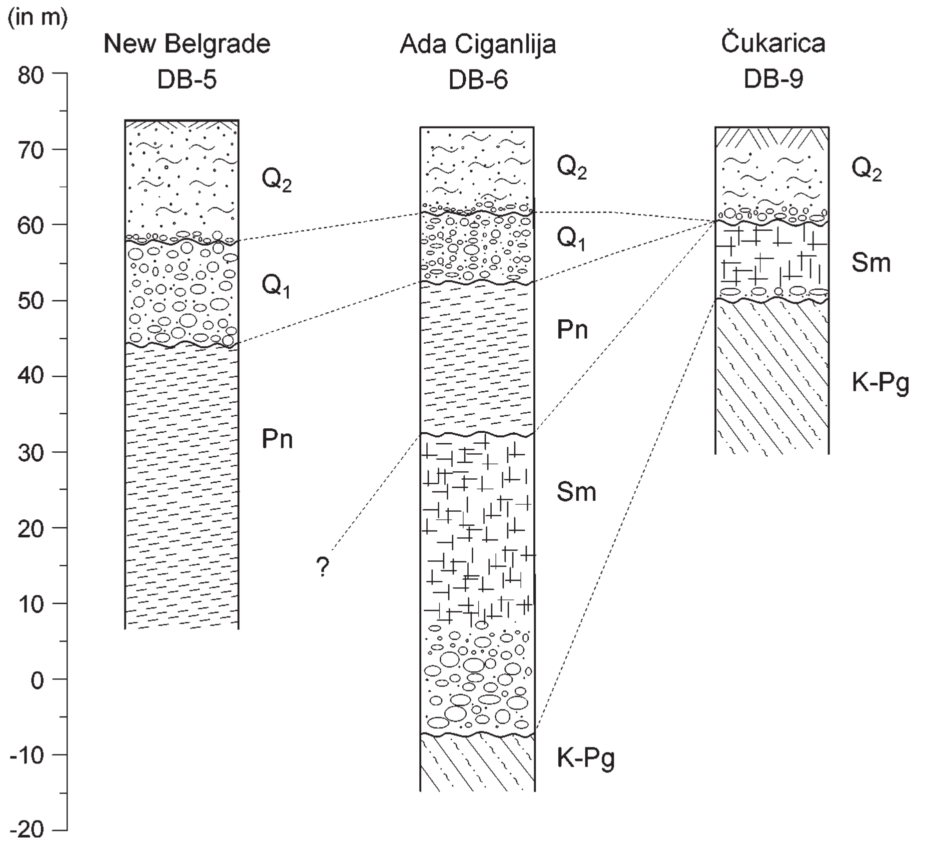

Fig. 6. Comparative stratigraphic sections of the boreholes along the route of the new bridge. For the key, see Fig. 2.

located in the border area between the Pannonian Plain and the foothills of the Balkan Peninsula. Additionally, from a morphostructural point of view, it represents the boundary between the Pannonian Basin and the Peri-Pannonian realm (MAROVIĆ *et al.* 2007). According to the neotectonic subdivision of the Belgrade City area, along the central part of the northern Šumadija there is a large structure called the Avala-Orešac Composite Structure in the NNW-SSE direction (MAROVIĆ *et al.* 2007). This structure separates the Velika Morava Graben to the east from the Kolubara–Tamnava Graben to the west (MAROVIĆ & KNEŽEVIĆ 1985, 1987). Consequently, several minor sub-blocks were generated, such as the complex Avala–Koviona Horst (MAROVIĆ *et al.* 2007). The core of the horst consists of the Palaeozoic–Mesozoic rocks of the Vardar Zone that make the so-called Šumadija Beam (STEVANOVIĆ 1980). During the Early Middle Miocene, the horst was uplifted and positioned as an isolated island in the Paratethys Sea, known as "the Avala land" (EREMIJA 1989). Later, during the Middle–Late Miocene, under the influence of tectonic movements, it was broken into tectonic blocks with local grabens within it and the sediments of the Paratethys Sea as well as of the Lake Pannon were deposited.

Along the route of the new bridge, the oldest formation consists of Upper Cretaceous–Paleogene deposits (the Ostružnica flysch). It is a part of the northern margin of the Mesozoic core of the Avala-Koviona Horst. Herein, the deposits of the Sarmatian and Pannonian stage (Late Middle and Early Late Miocene) are the products of sedimentation in local trenches and former bays. Comparing the Miocene sediments along the banks of the Sava River, it could be concluded that near the new bridge, there are no widespread Badenian deposits downstream close to the Sava–Danube confluence (KNEŽEVIĆ & ŠUMAR 1994, KNEŽEVIĆ & GANIĆ 2005, 2008; GANIĆ *et al.* 2011; RUNDIĆ *et al.* 2011). This means that here the process of the formation of coves and bays around the former Avala Land commenced later than at the mentioned confluence. In addition, some differences in the facial characteristics and distribution of Sarmatian sediments were also noticed. Near the Sava–Danube confluence and the Kalemegdan Fortress, these sediments are often absent. The thickness and lithology of these layers vary at different places. It is likely that Sarmatian sediments are spread everywhere along the route of the new bridge. Among them, younger strata represented by organogenic limestones are dominant. It seems that similar depositional conditions upstream and downstream of the Sava River were established during the Pannonian when the marly sediments were deposited almost everywhere.

The presence of faults and differential movement of the blocks separated by the faults along the bank at the Sava–Danube confluence was observed previously (KNEŽEVIĆ & GANIĆ 2005, 2008; GANIĆ *et al.* 2011; RUNDIĆ *et al.* 2011). Then, it was noticed that the terrains on the right bank of the Sava River are relatively elevated in comparison to the plain terrain on the left bank. By studying the subsurface geological setting in the new bridge area, it was found that here at least two faults occur along which subsidence of blocks was determined (Fig. 7). One fault is present in the small estuary of the Sava River between Ada Ciganlija Island and Čukarica. The entire rock units at the tip of Ada Ciganlija (at the position of a bridge pylon) have subsided with respect to the right bank of the Sava River. On the Čukarica block, the younger Pannonian sediments are eroded, while they are present at the tip of Ada Ciganlija. Sarmatian sediments and the flysch strata are deeply subsided with respect to the Čukarica block. On the left bank of the Sava River, at a relatively greater depth (below the absolute elevation of 0 meters), all the boreholes were realised

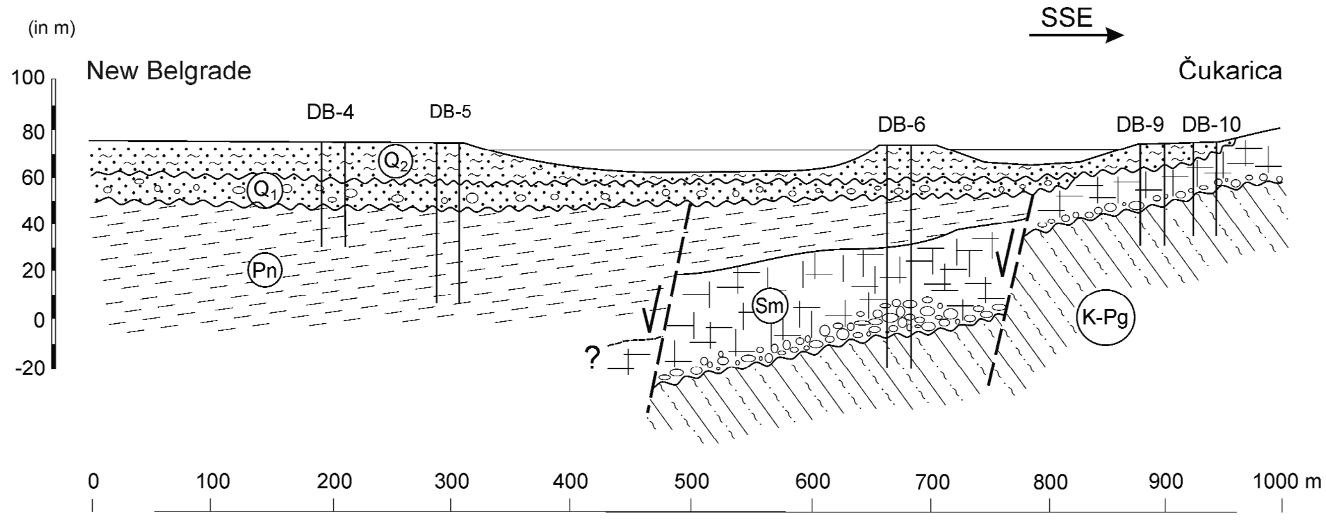

Fig. 7. A simplified geological cross-section along the route of the new bridge. Key: **K-Pg,** Upper Cretaceous-Paleogene; **Sm,** Middle Miocene Sarmatian; **Pn,** Upper Miocene Pannonian; **Q_1,** Pleistocene, **Q_2,** Holocene. √/ – Assumed fault.

in the Pannonian marls. This means that the older rocks are even deeper compared to Ada Ciganlija (Figs. 6, 7). Based on this, the presence of a second fault under the large estuary of the Sava River between the left bank and Ada Ciganlija Island can be assumed. These structural configurations were created under the influence of the neotectonic movements during the Pliocene and Early Quaternary. Exogenous processes later transformed the initial relief and the whole terrain along the route of the new bridge was levelled by a long-living deposition of alluvial sediment.

In the Sava River valley, there are two previously known geological formations of alluvial sediments (LASKAREV 1938; KNEŽEVIĆ *et al*. 1998; NENADIĆ 2001; NENADIĆ *et al*. 2009). The older formation of the Lower Pleistocene polycyclic fluvial sediments is distributed in the Ada Ciganlija Island and the bank of New Belgrade, but not on the right bank of the Sava River. This formation was deposited in the initial phase of the formation of the Sava River valley, which was characterized by cyclic processes of tectonic subsidence of the terrain and alluvial sedimentation. At the tip of Ada Ciganlija, the old polycyclic fluvial sediments have a lower depth than on the terrain upstream on the same island and on the left bank of the Sava River (Fig. 7). The lower boundary to the Pannonian strata is at 18–19 m, *versus* the usual 25–26 m. The older horizons are missing, which could suggest that at a later stage of a fluvial process, part of the terrain entered the river bed.

Recent fluvial processes have led to major erosion of younger horizons of the old polycyclic fluvial sediments and creation of new alluvial sediments of the Sava River and its tributaries. Clastites from the Pleistocene polycyclic fluvial sediments were eroded and redeposited in the current riverbeds. On the left bank of the Sava River, along the route of the new bridge, the presence of the previous flow of the Galovica Stream was found. It is a left tributary of the Sava River that migrated during time. Its water flow comes from the Srem Loess Plateau and inflowed the river to the right of the studied area.

Conclusions

Belgrade's Ada Bridge that passes over the tip of the island of Ada Ciganlija has become one of the new symbols of Belgrade. It is the longest single-pylon, cable-stayed bridge in the world.

Data obtained from seven boreholes are presented for the first time herein.

The geological setting of the subsurface of the terrain was reconstructed based on lithological successions, stratigraphic sections and the basic structural elements. The following geologic units were found: Upper Cretaceous–Paleogene flysch formation (the Ostružnica flysch), Middle Miocene Sarmatian and Upper Miocene Pannonian sediments, different alluvial sediments of Quaternary age as well as modern anthropogenic sediments.

On the right bank of the Sava River, the older geological units were observed in the upper part of the sections. On the other hand, they had much greater depth at the location of the bridge pylon.

Pannonian marls have a different depth on the island Ada Ciganlija and on the left bank of the Sava River, where they reach up to 60 m in depth.

Among the Quaternary alluvial deposits, there are two different geological formations. The older one, presented by Pleistocene polycyclic sediments includes mostly gravels and sands. This one was never detected at the surface. However, it represents the major groundwater aquifer for the water supply of Belgrade. The younger one consists of Holocene modern alluvial sediments that have a wide distribution over the whole area.

The appearance of alternating replacements of riverbed sediments of the Sava River and its left tributary, named the Galovica Stream, was noticed.

There are faults that run sub-parallel to the Sava River and divide all the pre-Quaternary rock units into blocks. These blocks separated by faults are differentially displaced. They subsided stepwise from the right bank of the Sava River to the flat terrain of the Pannonian Plain.

Acknowledgments

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Резиме

Подповршинска геологија терена дуж трасе новог моста на Ади Циганлији (Београд, Србија)

Највећи бетонско-челични мост на свету са једним носећим пилоном отворен је у Београду 1. јануара 2012, а пролази преко шпица острва Аде Циганлије. Његова монументалност и архитектонско решење постали су нови симбол Београда. Нови мост директно повезује транспортне путеве на Чукарици и Новом Београду и представља део будућег унутрашњег магистралног полупрстена који ће значајно растеретити саобраћајне гужве у Београду. Укупна дужина моста је 996 метара, а ширина 45.06 m. Мост је заснован на великом, 200 m високом пилону који се налази на шпицу острва Аде Циганлије (фотографије на табли 1).

Анализирани су узорци језгра из седам бушотина (DB-4, DB-5, DB-6, DB-7, DB-8, DB-9, DB-10) изведених током изградње моста. Ти резултати су указали на постојање једне релативно комплексне подповршинске структуре. Обављеним истраживањима, утврђено је да су у дубинској геолошкој грађи терена заступљене следеће геолошке јединице: формација остружничког флиша горњокредно-палеогене старости, миоценски седименти сармата и панона, алувијални седименти квартара и савремени антропогени наноси.

На десној обали реке Саве, утврђени су горњокредно-палеогени флишни седименти на малој дубини (22 m), одмах испод танких средњомиоценских сарматских седимената и савремених квартарних наслага. На средини моста, на шпицу Аде Циганлије, утврђена је другачија ситуација. Тамо је преко флиша у сукцесији неколико различитих миоценских и квартарних јединица, а наслаге остружничког флиша су констатоване на различитим дубинама (у најдубљој бушотини DB-6, на око 80 m). На левој обали реке Саве, у Новом Београду, још више су потонуле старије формације и набушени су само горњомиоценски панонски лапорци и плеистоценске и холоценске алувијалне наслаге. У односу на шпиц Аде Циганлије, панонски лапорци су спуштени на много већу дубину (до 60 метара).

Плеистоценски полициклични речни седименти (тзв. Макишки слојеви) који представљају најважнији водени аквифер на подручју Новог Београда, нигде нису констатовани на површини терена дуж трасе моста, мада на ширем простору имају велико распрострањење. Млађу формацију квартарних алувијалних наслага представља савремени алувијални нанос реке Саве и њених притока, чији су седименти распрострањени на целој траси проучаваног терена. Њих чине седименти корита, поводња, повремено старача и мртваја, а на острву Ади Циганлији и седименти речног пруда.

Значајно је распрострањење на површини терена различитих типова техногених наслага међу којима се истичу наноси рефулираног песка на новобеоградској обали.

Стратиграфском корелацијом профила проучених бушотина уочено је да старије геолошке јединице каскадно тону идући од десне ка левој обали Саве. Може се претпоставити присуство раседа који су преквартарне творевине разбили на блокове. Раседима раздвојени блокови су диференцијално кретани по типу гравитационих раседа. Главни раседни правци иду субпаралелно са коритом реке Саве. Тектонски покрети који су довели до спуштања делова терена на левој обали Саве, обављени су током плиоцена и старијег квартара (нпр. у време таложења доњоплеистоценских полицикличних речних седимената).

PLATE 1

Figs. 1–5. Different construction stages and the views of the bridge during its building.
Fig. 6. The largest single-pylon, cable-stayed bridge in the world was opened in Belgrade on January 1, 2012 (a view from New Belgrade).


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Геолошки анали Балканскога полуострва Annales Géologiques de la Péninsule Balkanique	73	21–30	Београд, децембар 2012 Belgrade, December 2012

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New data on the geology of the archaeological site at Vinča (Belgrade, Serbia)

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Abstract. Landslides threaten Vinča, a world famous archaeological site of Neolithic culture. For this reason, a field investigation and geologic-geotechnical research of the cores of seven exploration boreholes were carried out. A very interesting structural setting was identified. The oldest stratigraphic unit consists of Middle Miocene Sarmatian sediments, which were discovered along the right bank of Danube River and within its riverbed about 300 m upstream from the archaeological site. These Sarmatian strata give evidence that the Danube River eroded the right bank. In addition, within its recent valley, there is a fault zone along which a block on the right bank was uplifted while a block on the left bank of the river that was subsided. All the boreholes passed through sediments of a previously unknown geological formation. It lies unconformably over Sarmatian strip marls and makes the base for Pleistocene loessoid sediments (approx. 10 m under the surface). These sediments were formed in a marsh-lake environment with a strong river influence. According to its superposition, the supposed age of this formation is the Plio-Pleistocene. Above the right bank of the Danube River, there are steep sections where Pleistocene swamp loessoid sediments were found. True loess deposits are not present here, but are in the hinterland of the right bank of the Danube River. The loess delluvium was deposited over the Pleistocene sediments. On the right bank of the Danube River, below the archaeological site, there are the anthropogenic water compacted sands that were previously incorrectly shown on geological maps as alluvial fans.

Key words: Stratigraphy, Sarmatian, Plio-Pleistocene, Quaternary, Vinča archaeological site.

Абстракт. Винча, светски познати археолошки локалитет неолитске културе, угрожен је клизиштима. Из тог разлога, урађена су геолошко-геотехничка истраживања језгра седам истражних бушотина као и непосредна теренска мерења. Том приликом је идентификован и врло занимљив структурно-тектонски склоп терена. Најстарија стратиграфска јединица су сарматски фино-ламинирани, тракасти лапорци који су откривени дуж десне обале Дунава као и у самом кориту реке, 300 m узводно од археолошког локалитета. Њихов просторни положај указује да данашњи Дунав еродира своју десну обалу. Осим тога, дуж савремене речне долине Дунава, постоји раседна зона дуж које је блок на десној обали издигнут насупрот блока на левој обали реке, који је спуштен. Свих седам бушотина је набушило седименте до сада, непознате геолошке формације. Они леже дискордантно преко сарматских тракастих лапораца, који нису набушени у овим бушотинама, а чине непосредну подлогу плеистоценским лесоидним наслагама (приближно 10 m испод површине терена). Ови седименти су формирани у барско-језерској средини са јаким утицајем реке. Према суперпозицији, старост ове формације би била у интервалу Плио-Плеистоцен. Изнад десне обале Дунава, постоје стрми одсеци на којима су такође пронађени плеистоценски барски лесоидни седименти. Прави лес није присутан овде, али га има даље у залеђу десне обале Дунава. Лесни делувијум је депонован изнад плеистоценских седимената. На десној обали Дунава, испод археолошког налазишта, присутни су антропогени наноси рефулираног песка који је раније погрешно приказан на геолошким картама као алувијални нанос.

Кључне речи: Стратиграфија, сармат, Плио-плеистоцен, квартар, археолошки локалитет Винча.

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Introduction

An archaeological site of the Neolithic culture of Belo Brdo (White Hill) is situated on the right bank of the Danube River in the village of Vinča (N 44°45’43”, E 20°37’23” – Fig. 1), 14 km downstream from Belgrade. It was first discovered in 1908 by the Serbian archaeologist Miloje Vasić (VASIĆ 1932). Since then, with several interruptions, numerous archaeological excavations have been carried out. The last campaign was finished a few years ago (1998–2009). Vinča-Belo Brdo was introduced into the treasury of world heritage as an object of prehistoric cultures. It is almost entirely made up of the remains of a human settlement and was occupied several times from the Early Neolithic (ca. 5000 BC) through to the medieval period (NIKOLIĆ & VUKOVIĆ 2008; SREJOVIĆ & TASIĆ 1990). There are many artefacts and, jewellery and objects made of precious and rare metals, vases, various materials, and real treasure that were procured from other parts of Europe (ANTONOVIĆ 2002; DIMITRIJEVIĆ & TRIPKOVIĆ 2006, DIMITRIJEVIĆ *et al.* 2010). The archaeological site is a very important part of the touristic offer of Belgrade. Currently, the entire Vinča archaeological site is closed for tourists and protected with thick layer of sand due to the landslide problems. For this reason, geological and geotechnical investigations were performed. Based on data from previous papers, it is surprising that during 104 years of archaeological excavations, neither geological explorations, drillings nor detailed geological research were performed. Some of the geological data cited in the literature are incorrect to date (for example, loess as the substrate for the anthropogenic-archaeological layers – IVKOVIĆ *et al.* 1966). Therefore, geological and geotechnical investigations presented herein represent the first serious study at the archaeological site. The results give a completely new view of the geological structure of the terrain.

Belo Brdo is of great importance for the pre-history of European civilization (VASIĆ 1932, 1936; SREJOVIĆ & TASIĆ 1990; NIKOLIĆ & VUKOVIĆ 2008; TASIĆ 2008). As such, the Serbian Government warranted it the highest level of state protection and classifies it as an archaeological site of exceptional importance. Today, Vinča has the status of Archaeological Park. Unfortunately, the site has received no appropriate treatment in practice. After so many years of excavation, the practice shows that little has been realised for it to become the most valuable object of the archaeological heritage of Serbia. It needs a lot of will, effort and financial support for the site to become one of the jewels of the geo-touristic offer of the City of Belgrade (RUNDIĆ 2010; RUNDIĆ *et al.* 2010).

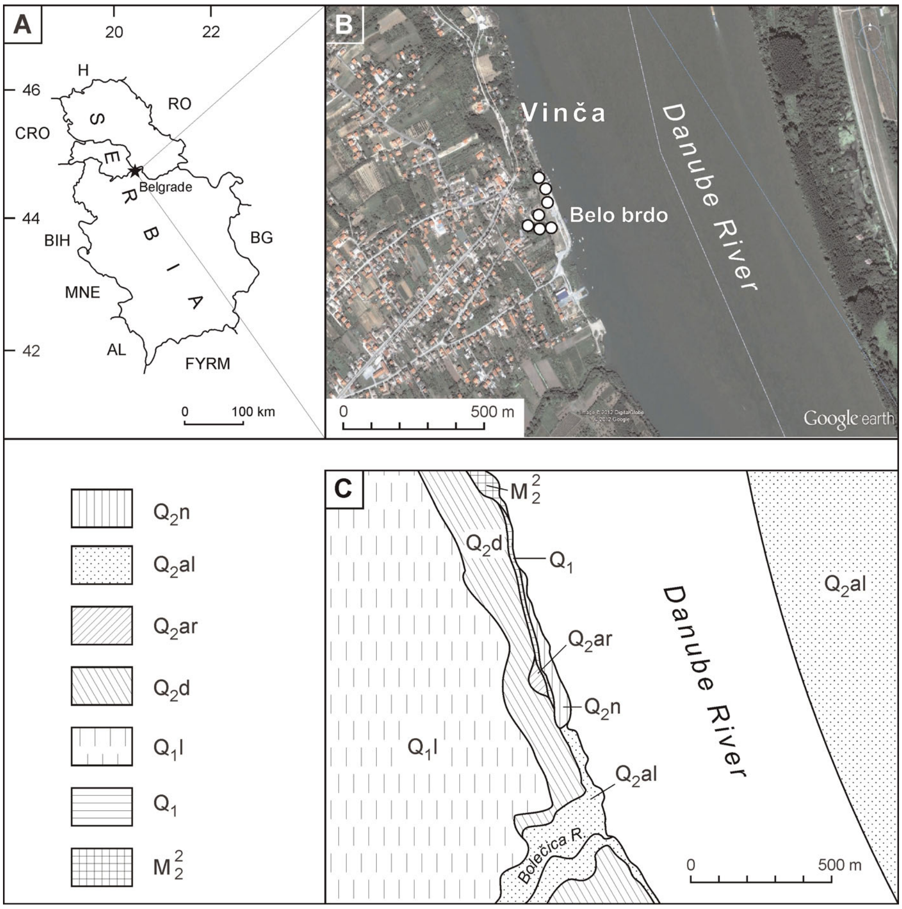

Fig. 1. **A)** The location, **B)** a satellite image of the Vinča archaeological site (Google Earth, 2012) and **C)** a simplified geological map of the investigated area. The white circles show the position of the boreholes. Key: $\mathbf{M_2^2}$, Sarmatian; $\mathbf{Q_1}$, Pleistocene (swamp loessoid); $\mathbf{Q_1L}$, Pleistocene (loess); $\mathbf{Q_2d}$, Holocene (delluvium); $\mathbf{Q_2al}$, Holocene (alluvial sediments); $\mathbf{Q_2ar}$, Holocene (archaeological layers); $\mathbf{Q_2n}$, Holocene (technogenic deposits).

Material and methods

Seven shallow boreholes were drilled in the courtyard of the Museum and the on the archaeological site and on the right bank of the Danube River (Fig. 1, Table 1). Twenty-five cores samples were analyzed and five samples from the Danube riverbed. Preliminary stratigraphic analyses were realised in the field. No fossils were detected in the mentioned cores. Five samples from the Danube riverbed were used for palaeontological studies. A detailed biostratigraphic and micropalaeontological analysis was made at the Chair of Historical Geology, Faculty of Mining and Geology, University of Belgrade. Classical methods of the preparation of soft rock, *i.e.* cleaning (6% of hydrogen peroxide) and washing were carried out (0.5–0.063 mm sieves). 100 g of each dried residue was observed under a stereomicroscope.

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

No.	Boreholes	Coordinates (WGS84)	
1.	V-1	N 44° 45' 42.83"	E 20° 37' 21.41"
2.	V-2	N 44° 45' 41.83"	E 20° 37' 22.23"
3.	V-3	N 44° 45' 44.12"	E 20° 37' 20.31"
4.	V-4	N 44° 45' 45.49"	E 20° 37' 23.85"
5.	V-5	N 44° 45' 44.33"	E 20° 37' 24.76"
6.	V-6	N 44° 45' 43.13"	E 20° 37' 25.22"
7.	V-7	N 44° 45' 44.97"	E 20° 37' 21.80"

Stratigraphic overview

The archaeological site at Belo Brdo is located above the right bank of the Danube River, on the outskirts of the village of Vinča. Downstream, the mouth of the Bolečka River flows into the Danube. The geological structure of the involved terrain consists of Middle Miocene Sarmatian sediments and Quaternary deposits (see the first geological map of this area – Laskarev *et al*. (1932). A few decades later, a similar stratigraphic conclusion was reached by Veljković-Zajec (1953), Ivković (1966) and Stevanović (1977, 1980). They concluded the Lower Sarmatian deposits represent the geological background for different type of Quaternary sediments. Besides Sarmatian stripped and laminated marls and sandstones, sandy limestones rich in microfauna were located on the hills above the Village Vinča. They contain lot of foraminifera, which indicates the younger level of the Sarmatian. Biostratigraphically, the finding of *Nubecularia novorosica,* which is a very characteristic species for the Middle Sarmatian of Russia is very important. It suggests a strong influence from the Carpathian domain on the Pannonian Basin (Veljković-Zajec 1953). Relatively recent stratigraphic studies in this area were performed by Šumar & Rundić (1992) and Knežević & Šumar (1993, 1994). As a conclusion, they confirmed the presence of Sarmatian striped and laminated sandy marls and alevrites belonging to the Lower Sarmatian. Biostratigraphically, based on the foraminifer biozonations, it represents the basal part of the Sarmatian, the *Elphidium reginum* Zone.

Results

Middle Miocene (Sarmatian - M_2^2)

The base of geological structure near the archaeological site consists of Sarmatian brackish-marine sediments of the Late Middle Miocene. However, these sediments were not found in all the prospecting boreholes. Probably, they lie much deeper than 65 m.a. s.l. (Figs. 3, 9). Sarmatian strata were discovered on the right bank of the Danube River (N 44°45'54", E 20°37'21") about 200–300 m upstream from the archaeological site (see Figs. 2A, B). They are made of striped and laminated sandy marls, alevrites and green clay. In the lithological succession, there are an alternation of light interlayers enriched with calcium carbonate and dark, grey-green laminas enriched with clay minerals. The layers have very steep declines oriented toward the N–NE (azimuth and dip angle of the surface layer is 63/27 – see Fig. 2C). Besides, the Sarmatian layers were found in the riverbed of the Danube River. They are observed in the shallows at low water levels, and they have steeper dip angles (more than 70° – Fig. 2D). However, there are strata that oriented toward the S–SW, which probably indicate a local anticlinal structure within the Sarmatian sediments. Fossil macrofauna in the Sarmatian sediments near the Vinča archaeological site as well as in its vicinity is very rare and it is assumed to belong to the lower part of the Sarmatian (the so-called the *Rissoa* layers). Among the rare gastropods, representatives of the genus Gibulla (*Gibulla* cf. *depressa*, *Gibulla* sp.) and *Cerithium* sp. dominate. Additionally, small bones of fish, otholites (*Gadus*? sp.) and fragments of organic matter were identified.

Microfossil assemblages from three samples of the striped alevrites were studied. A relatively poor foraminiferal-ostracod fauna was identified. In these associations, the species *Anomalidoides dividens*, *Ammonia* ex. gr *beccarii, Loxoconcha* cf. *kochi, Elphidium* sp., *Quinqueloculina* sp., *Xestoleberis* sp. are dominant. The fine-grained fraction of the samples shows more mineralization of pyrite, clay minerals, quartz grains, and faunal debris. In addition, small "balls" of the algae Diatomiacae were noticed.

Biostratigraphically, the above-mentioned sediments belong to the lower part of the Volhynian Substage of the Sarmatian age – the *Elphidium reginum* Zone (Šumar & Rundić 1992). Such findings are matched with previous studies of microfauna over a slightly wider area at Vinča and Ritopek (Veljković-Zajec 1953; Šumar & Rundić 1992) and the general

Fig. 2. Sarmatian sediments on the right bank of Danube River exposed during low water level. **A,** within the riverbed; **B, C,** on the right bank; and **D,** an abrupt dip angle of marls (more than 70°).

geological settings were given a long time ago by LASKAREV *et al*. (1932) and LASKAREV (1938).

Quaternary

The whole studied area except for a narrow strip along the Danube River is covered by Quaternary deposits. Stratigraphically, they are belonging to both Quaternary epochs: the Pleistocene and Holocene. Although the age of the newly discovered stratigraphic unit is not exactly known, because of the succession of layers observed in the field, they are here considered as the base of the Quaternary.

Pleistocene (Q_1)

Pleistocene sediments have a wide distribution. Among them, two packages can be divided by superposition: 1) older deposits of unknown age that are believed to belong to the Plio-Pleistocene (Pl/Q_1) and 2) younger Pleistocene sediments singled out here as the Pleistocene (Q_1)

Plio-Pleistocene as a lower level of the Quaternary was never detected on the surface. However, these sediments were observed in all the prospecting boreholes. They occur in the base of the Pleistocene sediments below an altitude of 77 m. The lower boundary was never established because all the exploration boreholes were completed within them. Lithologically, the older Quaternary deposits are made of greyish-yellow alevrites, grey alevrites and clays with interbeds of

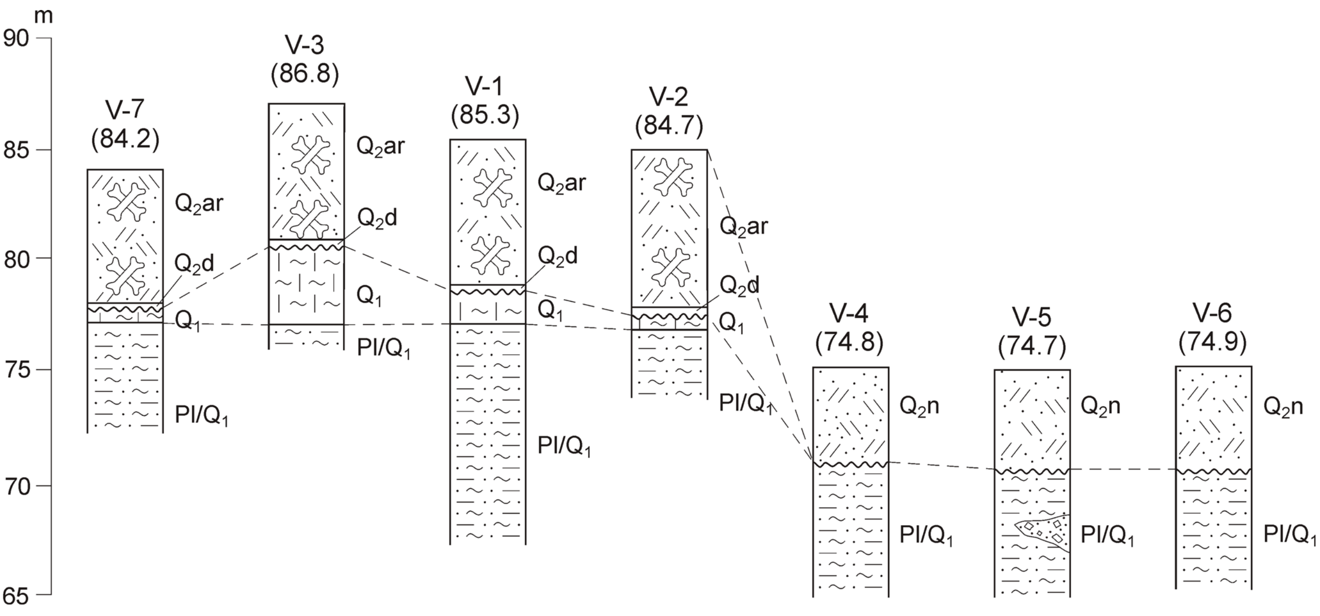

Fig. 3. Comparative lithostratigraphic sections of the investigated boreholes. Key: **Pl/Q_1,** Plio/Pleistocene; **Q_1,** Pleistocene (swamp loessoid); **Q_2d,** Holocene (delluvium); **Q_2ar,** Holocene (archaeological layers); **Q_2n,** Holocene (technogenic deposits).

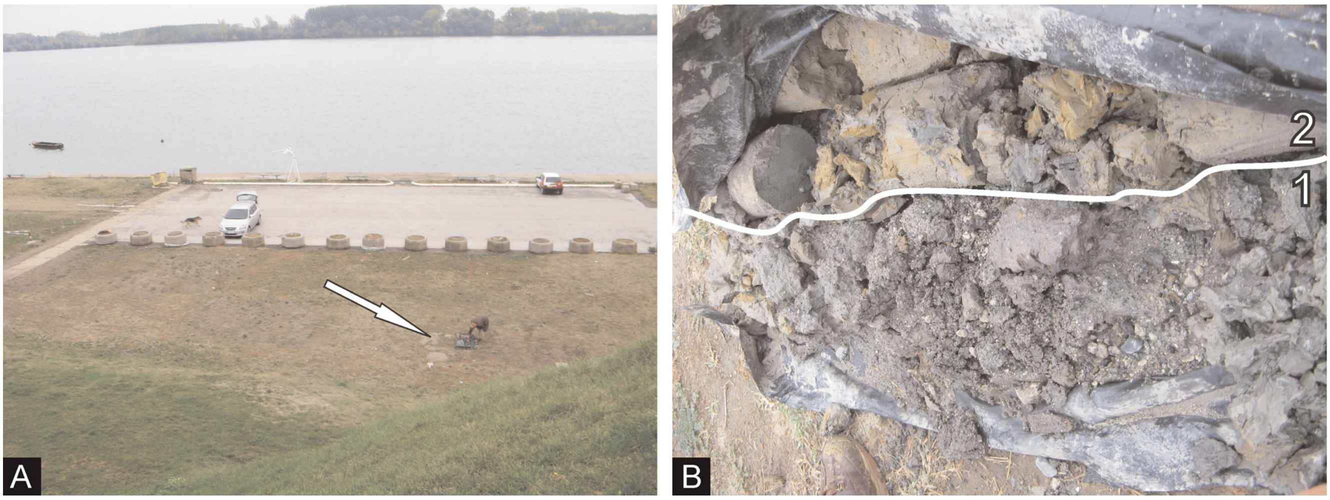

Fig. 4. Location of the borehole V-5 (A) and details of cores (B) with the redeposited Sarmatian limestone (1) and grayish alevrites and clays of Plio-Pleistocene (2).

fine-grained sands. More or less similar sediments were discovered in all the boreholes located on the right bank of the Danube River (boreholes V-4, V-5, V-6, and see Fig. 3). They are found at a depth of about 4 meters from surface (ca. 71 meters a.s.l.) and contain grey and yellowish marls, and fine-grained laminated sands. In some places, they contain organic matter. Fossils are completely missing. In the other boreholes (boreholes V-1, V-2, V-3, V-7) drilled in the courtyard of the Museum and the archaeological site, the greyish-yellow alevrites, grey alevrites and clays have a maximal thickness of more than 10 m (borehole V-1). Its lower boundary is unknown because the mentioned borehole was completed within this stratigraphic unit (Fig. 3). In the borehole V-5, drilled on the right bank of the Danube River below the archaeological site, a layer of sandy gravel at a depth of 6.8 to 8.3 m was determined. Redeposited pebbles of Middle Sarmatian sandy limestone with gastropod imprints were found within it (Figs. 3, 4).

Pleistocene deposits are widespread in the village of Vinča. They were detected in the notches along the steep bank of the Danube River and around roads and other buildings. Based on superposition, so-called swamp loessoid (Q_1) and loess (Q_1l) could be separated among them.

Lithologically, the swamp loessoid consists of grey and greyish-brown alevrites, locally stratified. They are weakly permeable to waterproof. They contain the remains of marsh-aquatic fauna (mostly representatives of the family *Planorbidae*) and terrestrial fauna with the genera *Succinea, Clausilia, Valonia*, etc. (Fig. 5). These sediments developed on the right bank of the Danube River. The loess's delluvial and anthropogenic deposits were deposited over them. In genetic terms, these sediments were performed from eolian dust and delluvial detritus in an aquatic, wetland-marsh environment.

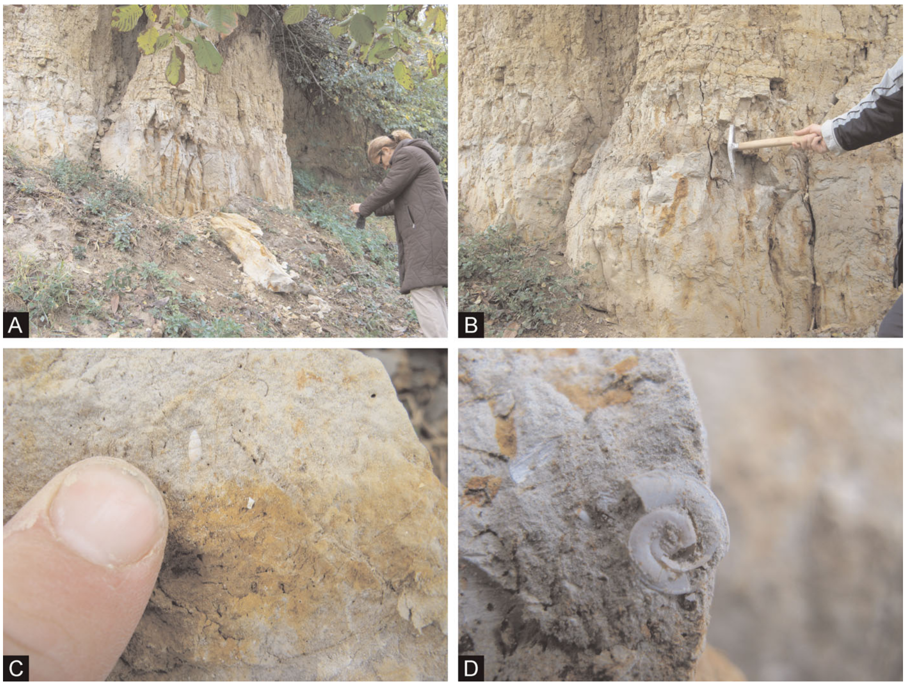

Fig. 5. The swamp loessoid at the base of steep banks of the Danube River (A, B). Terrestrial and swampy gastropods represented by the genera *Clausilia* (C) and *Planorbis* (D).

Loess (so-called the slope's loess) includes younger Pleistocene deposits formed by the deposition of eolian dust and mixed with delluvial deposits in the hilly terrain. It consists of greyish-yellow alevrites with pronounced vertical porosity. It has a massive structure and numerous vertical cracks and contains terrestrial fossil gastropods. It is not as widespread in the archaeological site area as at higher elevations further inland from the Danube River (Fig. 1). Based on analysis of the loess section in the brickyard at Vinča, the presence of the four loess horizons and three horizons of palaeosoil were identified. Actually, the oldest horizon of the loess deposits involves swamp loessoid sediments.

Holocene (Q_2)

The youngest Quaternary deposits have a relatively wide distribution on the surface of the studied area. A few different sediments could be separated: delluvial deposits (Q_2d), alluvial deposits (Q_2al), archaeological layers (Q_2ar) and technogenic deposits (Q_2n).

The delluvial deposits are widespread on the slopes above the right bank of the Danube River. Among them, the loess delluvial deposits are dominant (Fig. 6). They cover the swamp loessoid and make the base for the archaeological layers.

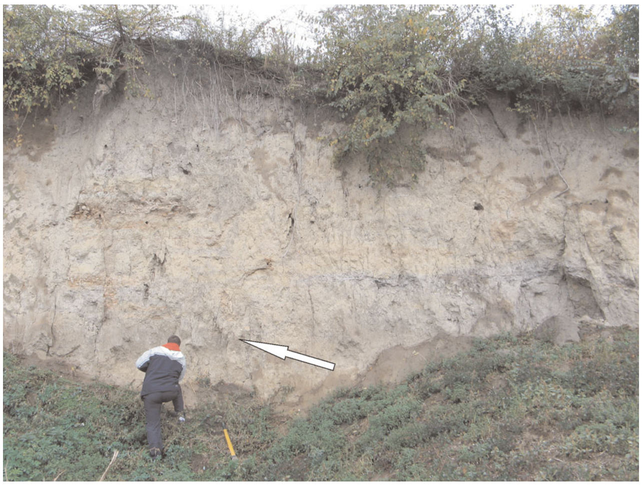

Fig. 6. Delluvial deposits as the base of the archaeological layers (in the front of the archaeological site).

The alluvial deposits occur along the Danube River. They have much narrower distribution than was shown on the existing geological map (IVKOVIĆ *et al.* 1966). Herein, they are represented by small alluvial deposits of sand and alevrites created during high water level. They cover partially exposed Sarmatian rocks or Pleistocene sediments. However, the alluvial deposits are much wider distributed near the confluence of the Bolečka and Danube River (Fig. 1), especially going upstream to the area of Veliko Selo.

The archaeological layers have been the subject of investigation for over 100 years. Their maximal thickness on the steep section to the Danube River is about 10.5 m. In the borehole V-2, drilled in the yard of the archaeological site and the Museum, the thickness of the archaeological layers is up to 7.8 m (Fig. 7). They lay over deposits of loess deluvium (humified in the upper part) the thickness of which reaches to 1.7 m. Much deeper in the borehole section, the Plio-Pleistocene unit was determined (Figs, 3, 7). Based on the review of the open section on the right bank of the Danube River and correlation of the boreholes, it could be concluded that the archaeological layers were formed in a depression within a swamp loessoid. Going towards the Danube, this depression expands and deepens, so the archaeological strata increase their thickness in that direction.

Fig. 7. A view on the archaeological layers (left) and the new the Plio-Pleistocene unit (right) in the borehole V-2 (courtyard of the archaeological site).

Among the anthropogenic sediments, the most important is a large communal dump of the City of Belgrade, upstream of the archaeological site. At the site, there are anthropogenic water compacted sand and archaeological layers. Water compacted sand is located on the right bank of the Danube River below the archaeological site and the access roads to the Danube. The thickness of these sediments in the boreholes reached up to 4.5 m (borehole V-6). On the existing geological map (IVKOVIĆ *et al.* 1966), these technogenic sediments were incorrectly marked as alluvial deposits of the Danube River.

Discussion

The geological study resulted in new knowledge about the geology of the terrain within the archaeological site of Vinča and its vicinity. The Sarmatian sediments on the right bank and the riverbed of the Danube River, showed that this part of the terrain belongs to a tectonic block that was uplifted in relation to the blocks on the left bank of the Danube River, in Banat and the Pannonian Plain. The Sarmatian sediments have a steep dip angle that increases towards the riverbed of the Danube River (Figs. 8, 9). This suggests the existence of a fault structure along the present riverbed of the Danube River along which there was differential movements of the blocks.

Fig. 8. The very abrupt dip angles of the Sarmatian strata within the Danube riverbed.

The absence of significant alluvial deposits and the presence of Miocene outcrops indicate that the right bank of the Danube River was eroded at the Vinča archaeological site. Historically, this process has been proceeding for a long time. Most likely that, since the existence of the Vinča culture up to the present, erosion of the Danube swept away part of the embankment with the archaeological layers that were closer to the Danube. In the wider region, the Danube River valley is a composite and very complex, with the river often meandering and changing the water flow direction. Here, there are alternations of the wide river valleys with extensive alluvial plains and river sand bars with a terrain where the alluvial plain is narrow or missing.

Based on this, it is safe to state that the changing of the flow direction and position of the riverbed of the Danube River as well as the occurrence of meanders occurred in the recent geological past (since the Early Neolithic to the present). It is possible that once the left bank of the Danube River was located much closer to the archaeological site of Starčevo (Early Neolithic Period). Later, the Danube River gradually shifted more towards the south, closer to the archaeological site of Vinča. Since the end of the Neolithic to the present, the Danube River has incised into the right bank with a part of the prehistoric settlement at Vinča. This certainly had a great influence and is a specific structural and lithological composition of the terrain. Similar investigations were performed along the Sava River, upstream from its confluence with the Danube. They also suggest large neotectonic mobility during the Late Miocene and Pliocene, and the creation of the differently subsided block structures (Marović & Knežević 1985; Marović *et al.* 2007). At that time, the creation of these great rivers valleys was initiated (Knežević & Ganić 2005, 2008; Ganić *et al*. 2011; Rundić *et al*. 2011). In the area of the archaeological site of Vinča, this study has shown the existence of a previously unknown geological formation that was discovered in the presented boreholes.

According to available data, the lower boundary of this formation was not determined but is known to lie unconformably over the Sarmatian and below the archaeological settlement (Fig. 9). According to superposition and facial characteristics, these younger sediments originated from a lake-river-marsh environment. A detailed age of this new formation and its facial features should be studied in future investigation. After the present study, it is possible to define only the approximate age that varies between Upper Pliocene–Lower Pleistocene. Thus, on the right bank of the Danube River, in the basis of archaeological layers, there is no loess deposits previously mentioned in the all archaeological papers and field guides. In fact, the swamp loessoid sediments lie below the loess deluvium. In a wide bay within a swamp, the loessoid sediments, were partially infilled by loess deluvium,

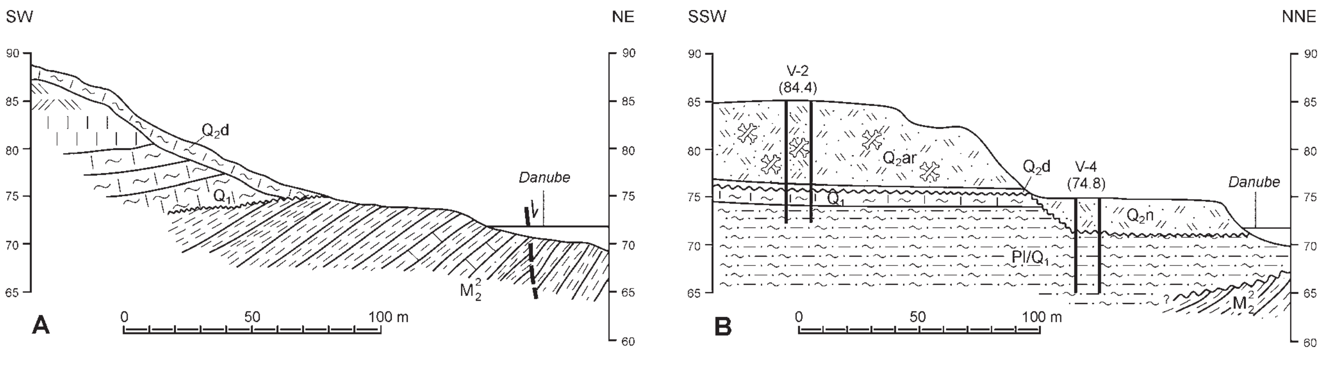

Fig. 9. Simplified geological cross-sections of the investigated area. **A,** upstream of the archaeological site; **B,** near the archaeological site. For the key see Figs. 1, 3. – Assumed fault.

there are archaeological remains of prehistoric settlement. In the borehole V-2, in the courtyard of the archaeological site, the thickness of anthropogenic layers is approximately 7.8 meter and increases toward the bank of the Danube River (up to 10.5 m – see Fig. 3.). In the boreholes that passed through anthropogenic sediments, many new artefacts were found that will be the subject of future archaeological research.

At the part of the area with the anthropogenic sediments, landslides occurred, which were the result of long-term excavations that caused the destabilization of the soil. This is a negative consequence of the geological composition of the terrain and especially unskilled construction and urbanization of the area surrounding the archaeological site. In particular, the intolerable fact must be emphasized that for more than 100 years there was no supervision by experts in geology and geotechnics in the area, which is known as a jewel of the natural, cultural, and historical heritage of Serbia and Europe.

Conclusion

Vinča, a world famous archaeological site of Neolithic culture, is threatened by landslides. For this reason, geological and geotechnical research of the cores of seven exploration boreholes was performed. This resulted in new knowledge concerning the geology of the investigated area.

The base of geological structure consists of Middle Miocene Sarmatian sediments, which were discovered along the right bank of the Danube River and in its riverbed. These Sarmatian strata testify that the Danube River eroded the coast and within its valley there is a fault zone along which the block on the right bank was uplifted with respect to the block on the left bank of the River which subsided.

In all the boreholes, sediments of a previously unknown geological formation. were identified. Lithologically, the formation contains grey alevrites and clay with layers of fine-grained sands. They unconformably overlap the Sarmatian strip marls and make a basis for the Pleistocene loessoid sediments. In genetic terms, the above-mentioned sediments were formed in a marsh-lake environment with a strong river influence. According to superposition, the supposed age of this formation is the Plio-Pleistocene.

Above the right bank of the Danube River, there are steep sections in which Pleistocene swamp loessoid sediments are found. True loess deposits are not present here, but in the hinterland of the coast at higher elevations of the terrain. The loess delluvium was deposited over Pleistocene sediments.

On the right banks of the Danube, below the archaeological site, there are the anthropogenic water-compacted sands that were previously incorrectly shown on geological maps as alluvial fans.

Archaeological layers are found within a swamp loessoid palaeodepression that was partially filled with loess deluvium. A part of the embankment with the archaeological layers was probably destroyed by erosion in the period from the late Neolithic to the present.

A future study of the archaeological site of Vinča should include geological studies that predict the development of deeper wells, and a detailed geological map with structural features.

Redeposited Sarmatian limestone ("pužarac" – a limestone with gastropod dominance) belongs to the younger sections of the Sarmatian, which were not developed near the Vinča archaeological site. Such material was transported by river and periodical flows from the remote hills compared to the current bank of the Danube River.

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Резиме

Нови подаци о геологији на археолошком локалитету Винча (Београд, Србија)

Први пут после 104 године ископавања на археолошком локалитету Винча-Бело брдо, урађена су геолошко-геотехничка истраживања терена и избушено је 7 истражних бушотина у циљу решавања проблема клизишта и одрона. Тим истраживањима је утврђено да су најстарији стратиграфски чланови средњомиоценски, сарматски фино-ламинирани и тракасти лапорци који су откривени дуж десне обале Дунава, као и у самом кориту реке (на котама 74–75 m изнад нивоа мора) око 300 m узводно од археолошког насеља. У њима је идентификована фосилна асоцијација која указује на старије нивое сармата (*Rissoa* слојеви и фораминиферска зона са елфидијумима). У свим бушотинама у дворишту археолошког локалитета и Музеја, као и испод њега, на десној обали Дунава, сарматски седименти нису лоцирани јер се налазе на нешто већим релативним дубинама. Свих 7 бушотина је набушило прашкасте седименте до сада, непознате геолошке формације која лежи дискордантно преко сарматских тракастих лапораца и чини непосредну подлогу плеистоценским лесоидним седиментима (приближно 10 m испод површине терена). Литолошки гледано, то су сиве, алевритске глине и алеврити са прослојцима финозрних пескова. Слабо су водопропусни и садрже остатке барске фауне (представници фамилије *Planorbidae*) и копнене фауне са родовима *Clausilia*, *Succinea* и *Valonia*. У генетском смислу, ови седименти су формирани у барско-језерској средини са јаким утицајем реке. Ове наслаге су присутне на десној обали Дунава. Изнад њих су наталожени седименти лесног делувијума и антропогени талози. Према суперпозицији, старост ове нове стратиграфске јединице би била у интервалу Плиоцен–

–Плеистоцен. Других доказа о ближој старости за сада нема. Изнад десне обале Дунава, постоје стрми одсеци на којима су плеистоценски, мочварни лесоидни седименти такође пронађени. Прави лес није присутан на самом локалитету, али га има даље у залеђу десне обале Дунава. Лесни делувијум је депонован изнад плеистоценских седимената. На десној обали Дунава, испод археолошког налазишта, присутни су антропогени наноси рефулираног песка који је раније погрешно приказан на геолошким картама као алувијални седимент.

Урађена геолошка истраживања указују да сарматски седименти на десној обали Дунава као и у самом кориту реке, припадају једном тектонском блоку који је издигнут у односу на блок(ове) на левој обали Дунава и у Банату. О томе сведоче врло оштри падни углови (преко 70°) и они су све стрмији идући од десне обале ка самом кориту реке. То даље указује на постојање једне разломне структуре дуж садашњег корита Дунава која је и условила различито кретање блокова.

Одсуство значајних алаувијалних наслага и присуство миоценских изданака на десној обали Дунава, указује на ерозију те обале коју врши сама река. Историјски гледано, овај процес је присутан већ дуже време. Врло је вероватно да је, од неолита до данас, Дунав еродовао и однео део обале са археолошким слојевима који су били ближе реци. Ако се зна да је у ширем подручју долина Дунава композитна, река често мења правац и постоје појаве меандрирања, онда је претходна претпоставка још реалнија.

Налазак комада сарматског кречњака (“пужарац”) у бушотини V-5, указује на млађе нивое сармата (средњи сармат) који је овде редепонован локално. Такав материјал је транспортован мањом реком или бујичним токовима из залеђа и удаљенијих виших подручја у односу на археолошки локалитет.

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Upper Cretaceous of the Čerevićki Potok, Fruška Gora Mt., Serbia: state of art

Rajka Radoičić[1] & Divna Jovanović[2]

Abstract. The paper is dealing with three interpretations of well known section Čerevićki Potok (Fruška Gora Mt., Serbia): 1. According to Koch, *in*: Pethö (1906), undisturbed succession of 23 lithologically different members, „Hipersenonian"; 2. According to Pašić (1974; unpublished text is used in monography of Petković *et al*. 1976), tectonically disturbed lithologically different Maastrichtian blocks; and 3. According to Čičulić-Trifunović & Rakić (1977), tectonically disturbed stratigraphic column, the Srem-Slavonian type of the Upper Cretaceous sediments, south of Srem dislocation, Maastrichtian.

Key words: Čerevićki Potok section, lithologically different members/blocks, stratigraphic column „Hipersenonian", Maastrichtian, chaotic complex, Fruška Gora, Serbia.

Апстракт. У раду су приказане три интерпретације познатог профила у Черевићком потоку (планина Фрушка гора, Србија): 1. Према Koch-у, *у*: Pethö (1906), 2. Према Пашић, 1974, у: Петковић *и др.* (1976), и 3. Према Чичулић-Трифуновић & Ракић (1977).

Кључне речи: профил у Черевићком потоку, литолошки различити чланови/блокови, мастрихт, хаотични комплекс, Фрушка гора, Србија.

Upper Cretaceous fossiliferous sediments of the Čerevićki Potok (Fruška Gora Mt.), were identified in 1864. by Koch. Later, Koch continued with investigations of geology of Fruška Gora and published numerous papers during period from 1867 to 1903. A macrofauna that collected over many years, was given to Pethö. They, in 1882, together visited the Čerevićki Potok to supllement the collection. Pethö's uncompleted study of this very rich and diversified macrofauna was posthumous published in 1906. The described collection contain 164 species, mainly gastropods and bivalvia, more than half of which new species. These extremely paleontologically rich sediments he determined stratigraphicaly as HIPERSENONIAN as youngest deposits of the Upper Cretaceous, younger than the Gossau Beds. The interest in the Cretaceous taken for Maastrichtian of the Čerevićki Potok, has not diminished up to the present time.

Comprehensive data on Upper Cretaceous of the Čerevićki Potok and adjacent area were published by Petković *et al.* (1976). The authors presented results published by Stepanović (1940), Papp (1954), Pašić (1951), Pašić & Maksimovć (1952), Pejović (1970) and Grubić (1972), which had contributed to the knowledge and the number of macro and microfaunal taxa from the Čerevićki Potok.

Hancock & Kennedy (1993) published first informations about the presence of Campanian sediments in the Čerevićki Potok based on revision of the ammonite species *Sonneratia cereviciana* Pethö, 1906, a younger synonym of the Upper Campanian species *Pseudokossmaticeras brandti* (Redtenbacher). Radulović & Motchurova-Dekova (2002) also documented Campanian age of brachiopods from the some of the Čerevićki Potok blocks.

The Čerevićki Potok section after Koch, *in*: Pethö (1906)

The Cretaceous of the Čerevićki Potok (Fig. 1) lies over the basement (1. Grundgesteine des Gebirge), covered by Neogene (2. Sarmatische Stufe). This is an undisturbed succession of the relatively equal north-

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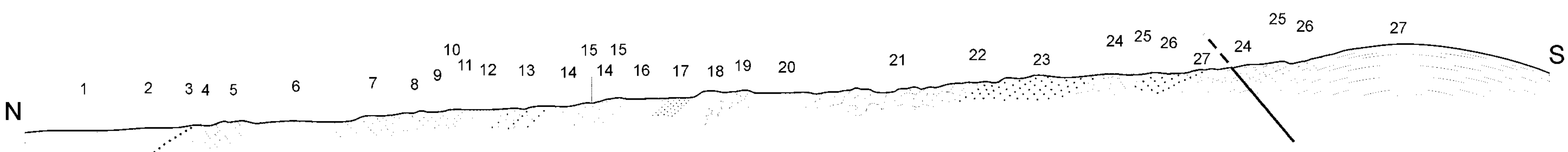

Fig. 1. Section Čerevićki Potok, Fruška Gora Mt. (according to KOCH, *in*: PETHÖ, 1906). **1,** Sarmatian beds; **2,** Porous, marly limestone (Leithakalk or *Amphisteginakalk*); **3,** Serpentinite breccias; **4,** Ferruginous greenish freckled claystones; **5,** Compact, hard limestones; **6,** Schisty greenish freckled beds; **7,** Black coloured clayey marlstones with numerous fossils (the richest collection; lately, new species and genus were found); **8,** Block (thick bed) with hippurids (10 m thick, according to Koch) with big and small hippurids of species *Hippurites (P.) polystylus, H. Cornuvaccinum (Hippurites sulcatus)*; **9,** Black-brownish clayey marlstone with serpentinite (*Sphaerulites* marlstone); **10,** Orbitoides limestones (and *Radiolites crateriformis*); **11,** Carbonate-serpentinite sandstone (*Sphaerulites solutus*); **12,** Reddish greenish freckled claystones (similar to beds of blocks 4 and 6); **13,** Change of schists and sandstones, conglomerates and dark schists; **14,** Reddish schisty claystones; **15,** Thick bedded to massive, hard, gray limestones with fine calcitic schists 1.5–40 m thick. Claystones and limestones are very fossiliferous; **16,** Blue-blackish clayey marlstones with *Inoceramus crispi* etc.; **17,** Green sandstones, Koch's „Brachiopodenführende Serpentinbreccie"; **18,** Lime marlstones without fossils; **19,** Schisty serpentinites 20 m thick; **20,** Clayey marlstone with *Gryphaea vesicularis*; **21,** Big masses of serpentinites; **22,** Grayish, earthy schists; **23,** Sandstones and conglomerates; **24,** Dark, earthy schists; **25,** Brown, platy limestones with fragments of rudists and molluscs; **26,** Change of schists, sandstones and breccias around 200 m along the stream; **27,** Clayey schists.

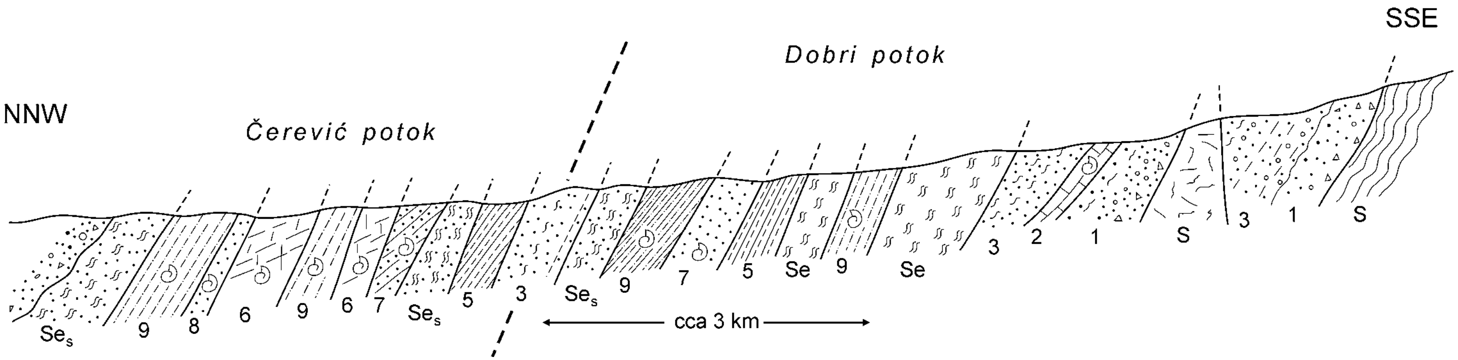

Fig. 2. Schematic section through Čerevićki–Dobri Potok, Fruška Gora Mt. (*in*: PETKOVIĆ *et al.* 1976). **Se,** serpentinites; **Se$_s$,** detritic serpentinites; **S,** schists in base; **1,** Conglomerates and breccias intercalated with coarse sandstones (basal part); **2,** Rudists limestones (*Hippurites cornucopiae*); **3,** Claystones, conglomerates, change of clayey marlstones and sandstones; **5,** Reddish marly limestones and gray marlstones; **6,** Debris limestones with rudists, corals and orbitoids (level with *Pironaea polystylos slavonica*; **7,** compact green and yellowish sandstones with small serpentinite grains (*Sphaerulites solutus*, brachiopods, ammonites etc.); **8,** Sandy compact gray limestones (orbitoids, corals, gastropods etc.); **9,** Gray, brown and black marlstones, micaceous and argillaceous and gray claystones (siltstones) with intercalations of yellowish sandstones of fine granulation (level with more fossils); **10,** Conglomerates of Neogene base.

ward dip, composed of 23 members (from younger to older), i.e. 3–5 some repeating members. The members are: serpentinite breccias, serpentinites (large mass), conglomerates, different sandstones (serpentinitic, ferruginous, carbonate and clayey), claystones, different clay-marly and marl-sandy sediments, limestones with orbitoids and rudists, hippuritid and marly limestones. Members 7, 8, 9, 10, 11, 16 and 17 are highly fossiliferous. Gastropods and bivalvia are dominant in the PETHÖ'S collection. Two members lithologically identical in diversified and numerous of fossils (127 species) are conspicuous members 7 („*Sphaerulites* mergel") and 9, also members 8 (*Hippurites/Pyronea/polystyla*) and 10 (*Orbitoides, Radiolites crateriformis*). These members are taken by PETHÖ to be the youngest Cretaceous sediments. Very interesting and rich in fossils serpentinitic sandstones of members 11 and 17, in addition to the abundance of rudist species *Sphaerulites solutus* and other molluscs, contain cephalopods and numerous brachiopods (member 17: KOCH'S „Brachiopodenführende Serpentinbreccie").

The KOCH-PETHÖ collection is deposited in the Hungarian Geological Institute in Budapest.

The section of the Čerevićki Potok according to PAŠIĆ, 1974, *in*: PETKOVIĆ *et al.* (1976)

„Pre-flysch Upper Cretaceous", distributed on northern slopes of western Fruška Gora, in middle and upper courses of the streams best exposed in the Čerevićki Potok section. On the geographic map the Čerevićki Potok source area designated as Dobri Potok and Orlovački Potok.

The authors emphasize that the section is schematic (Fig. 2), because the investigated area is tectonically much disturbed and largely covered by coluvial material. „The relationship of all horizons and their present-day place in the section and the description of some levels according to superposition from the lowermost are presented", they also noted that some blocks are tectonically moved to „different levels where is not their place superpositionally" (PETKOVIĆ *et al.* 1976).

In the fifties, studies of the Čerevićki Potok were recognized eight lithologically different blocks besides serpentinites and destroyed serpentinites (1–3, 5–9). Blocks 5 and 8 are not presented in Koch-Pethö's section. Some blocks are recurring:

Coarse basal breccia and conglomerates thick 40 m and more (block 1), in tectonic contact with serpentinite, appear in few tectonically separated parts. These composed of very coarse basal crystalline schists, serpentinites and quartz gravels in carbonate-ferruginous cement, which pass upward into fine-grained conglomerates with sandstone intercalations.

On the coarse basal sediments sporadically lies „lensoidal" limestone bearing rudists (block 2). This, 1.2 m thick limestone, contains numerous specimens of *Hippurites cornucopiae* (GRUBIĆ 1972).

Further, in the section, 6 blocks in tectonic contact (blocks 3, 5, 6, 7, 8 and 9) are described, which are repeatedly occuring, excluding 8 (sandstone with orbitoids, corals, gastropods):

*– two times basal member, serpentinite and blocks 5 (15 m redish marly limestones; in Dobri Potok about 30 m gray, platy marlstone), 6 (rudistid-orbitoides limestone corresponding to PETHÖ'S members 8 and 10 and, member 9 "*Sphaerulites *marlstone" between them) and 7 ("serpentinite sandstone" with* Sphaerulites solutus *another bivalvia and brachiopods, correspoding to PETHÖ'S members 11 and 17 with Sp. solutus, cephalopods and brachiopods, respectivelly KOCH'S "Brachiopodenführende Serpentinbreccie");*
– three times desintegrated serpentinite and block 3 (conglomerates, alternation of claystones, conglomerates, marlstone, sandstone and sporadically with intercalation of silicified limestone);
– four times block 9 (gray and black micaceous clayey marlstone and claystone with sandstone intercalations, which corresponds to PETHÖ'S members 7 and 9 abounding in chaotically mixed fossils). PAŠIĆ described from these two blocks 32 species not known from PETHÖ'S collection (some were new).

PETKOVIĆ *et al.* (1976) tried to interpret primary stratigraphic relationships to present the stratigraphic column, also nothing that tectonic movements disturbed the normal superpositional order. For construction the column they used data from the blocks everywhere in the Čerević area: Tancoš Maastrichtian limestone, blocks and/or km-blocks of basinal sediments of Srednje Brdo, Čitluk, Debeli Cer and flysch development north of the Srem dislocation.

Some species from Cretaceous of Čitluk Potok, like *Pironea polystylus slavonica* (HILBER) = in Pethö: *Hippurites (Pironea) polystilus* (PIRONA) emend. Pethö, some other rudist species and orbitoids were known as Maastrichtian markers (STEPANOVIĆ 1940; PAŠIĆ 1951; NEDELA-DEVIDE & POLŠAK 1961; MILOVANOVIĆ 1962; POLŠAK 1965; MILOVANOVIĆ & GRUBIĆ 1966; GRUBIĆ 1972). Consequently, for transgressive coarse clastics were accepted to be the Middle Maastrichtian and fossiliferous blocks the Upper Maastrichtian. The youngest Upper Cretaceous sediments, i.e. flysch, according to RADOŠEVIĆ & MARKOVIĆ (1967) also was ascribed to Maastrichtian.

RADOŠEVIĆ & MARKOVIĆ (1967) believed that the whole flysch series to be Upper Maastrichtian, and flysch sedimentation normally continued over fossiliferous sediments. They described three clearly different sedimentological parts (with *Inoceramus* in lower part). We would emphasize their opinion that the „upper part of the flysch, which really looks younger, resembles with the Ostružnica flysch in the Belgrade environment".

Fauna described by PAŠIĆ (1951) is preserved partially in the Paleontological collection of the Faculty of Mining and Geology, Belgrade.

Section of Čerevićki Potok, according to Basic Geological Map and Explanatory text, sheet Novi Sad, 1:100 000 (ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ, 1977)

Two structural-facial zones of the Upper Cretaceous on the Fruška Gora are identified: Bačka-Banat flysch development, north of Srem dislocation, and southern, Srem–Slavonia development, between Srem and Fruška Gora dislocations („Čerević Upper Cretaceous *s.l.*"; Fig. 3). The Cretaceous of the Srem–Slavonia zone is partially outcropping around 20 km east–west.

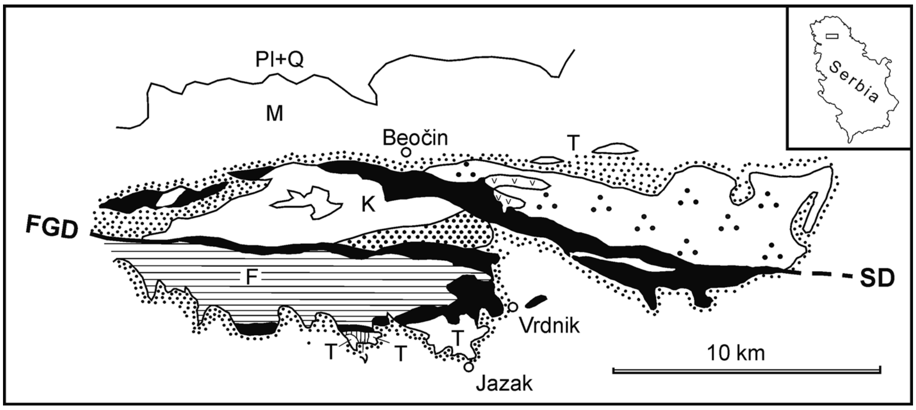

Fig. 3. Simplified and modified map of Fruška Gora area from Basic geological map of Novi Sad, 1:100 000. **SD,** Srem dislocation; **FGD,** Fruška Gora dislocation; **F,** Phyllitoids (metamorphosed Triassic?); **T,** nonmetamorphosed Triassic; **K,** Cretaceous; three dots – Cretaceous Flysch; **M,** Miocene; **Pl+Q,** Pliocene and Quaternary. (*in*: DIMITRIJEVIĆ 1997).

Transgressive position of Upper Cretaceous deposits over Jurassic schists is visible only in the middle of the zone, in the Ugljarski and Čitluk Potok vallies. The authors mentioned the difficulty of giving the stratigraphic column for the Srem–Slavonia development due to tectonic disturbance in the section Čerevićki Potok.

The stratigraphic column, described and given on the geological map starts with the trasnsgressive deposits of shallow-water coastal facies which consist of breccias, conglomerates, sandstones, brecciated limestones, reefal and massive limestones and sandy reefal limestone. Upward, prevailing are claystone, siltstone and fine-grained clayey sandstone which gradually pass into marlstones and marly limestones that close the Upper Cretaceous lithostratigraphic column of this formational zone. The latter, distributed in western area in Debeli Cer, Čitluk Potok and Srednje Brdo are not mentioned in the Čerevićki Potok by PETHÖ. Although paleontological evidence was not discovered in sediment of PAŠIĆ's block 5, they being lithologically similar, were compared to sediments of the mentioned localities (PETKOVIĆ *et al.* 1976).

Authors considered that fauna of shallow-water sediments, without exception, and basinal marly limestones of Čitluk Potok and Srednje Brdo are Maastrichtian. DANILOVA (1960) described an association of planktonic foraminifers from Čitluk Potok with species prevailing the Maastrichtian. DANILOVA (acc. to mem. of R. RADOIČIĆ) corrected this stratigraphic conclusion in some of the internal reports and limestones of Čitluk Potok asigned to the Campanian.

In the Srednje Brdo quarry very tectonically disturbed basinal sediments with planktonics are outcropped (see in: PETKOVIĆ *et al.* 1976). Marly reddisch limestones from a part of the quarry are Lower Campanian – *Globotruncanita elevata* zone (DE CAPOA *et al.* 2002). ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ (1976), the Srednje Brdo sediments dated Maastrichtian, based on the presence of *Inoceramus balticus*.

Inoceramus balticus was found by Pašić in the Pethö's member 7. According to KÜHN (PAŠIĆ 1951) the species was wrongly ascribed by many authors to *Inoceramus cripsi* MANTELL *Inoceramus balticus*, respectivelly *Cetaceramus balticus* (BOEHM) WALASZCZYK, COBBAN & HARRIES, 2001, is the species characterizing Lower and Middle Campanian.

Fossils collected during geological mapping of the sheet Novi Sad, which were deposited in Geological Institute in Belgrade, have not been preserved.

Comment

Sediments in some Čerevićki Potok blocks contain an abundance of mixed fauna not only of different fossil groups, but also different environments (including brackish and paralian, according PAŠIĆ 1951), of different preservation and different ages. Some specimens from the same block are very well preserved and undamaged (well preserved sculptures of gastropods, sculptures and hinge apparatus of bivalvia). Many specimens collected undamaged were washed away from soft sediments of stream slopes. Well preserved numerous rudists and other molluscs will be good material for Sr-isotope measurement. Sr-isotope stratigraphy has recently been used in the revision of stratigraphic range for some rudist species previously considered Maastrichtian.

The sediments older than Upper Senonian have not documented so far; the youngest known are Maastrichtian limestones with orbitoids, siderolites, loftusias and Pironea. An open question is whether sediments of the some blocks without paleontological evidence are younger than Cretaceous.

It should be mentioned that in the part of Fruška Gora flysch Oligocene sediments are documented on the base of nannofossils (CP19=NP25 biozone, DE CAPOA *et al.* 2002), what implies that the main tectonic events are not older than Chatian.

The observation of RADOŠEVIĆ & MARKOVIĆ (1967) on the similarity of the upper part of Fruška Gora and Ostružnica flysch is confirmed by the finding also Oligocene nannofossils (CP19=NP25, DE CAPOA *et al.* 2002) in sediments of a part of Ostružnica Maastrichtian flysch.

Upper Cretaceous beds of the Čerevićki Potok were deposited in different shallow-water (and bathyal?) and different sedimentary environments. Some blocks of „pre-flysch Upper Cretaceous", i.e. „Srem–Slavonia structural-facial zone"of Fruška Gora indicate on a multiple preceding tectonic activity. Based on available data, Srednje Brdo block was also deformed by late Campanian tectonic events.

Cretaceous sediments, occuring in blocks between two tectonic lineaments – Srem and Fruška Gora dislocation, in fact are blocks of a chaotic complex including serpentinites, which are nowadays in a stratigraphic column incorrectly presented, as an undisturbed Upper Cretaceous succession.

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Резиме

Осврт на познавање горње креде Черевићког потока (Фрушка гора, Србија)

Богату и веома разноврсну фауну у седиментима Черевићког потока открио је KOCH 1864. године и уступио је Pethö-у на проучавање. Koch и Pethö, приликом заједничког обиласка овог локалитета 1882. године, допунили су збирку која је приписана најмлађем сенону, Хиперсенону. Њихови резултати су објављени у обимној студији након Pethö-ове смрти 1906. године.

Први публиковани податак о присуству кампанских седимената у Черевићком потоку дали су HANCOCK & KENNEDY (1993) на основу ревизије амонитске врсте *Sonneratia cereviciana* PETHÖ, 1906, која је млађи синоним горњокампанске врсте *Pseudokossmaticeras brandti* (REDTENBACHER, 1873). Кампанску старост једног од блокова Черевићког потока документовали су на основу брахиопода и RADULOVIĆ & MOTCHUROVA-DEKOVA (2002).

У овом тексту приказане су три интерпретације горњокредног профила у Черевићком потоку, према:

– KOCH у: PETHÖ (1906): непоремећена сукцесија 25 детаљно описаних, литолошки различитих, чланова најмлађег сенона – хиперсенона. Из појединих чланова сакупљена је богата, веома разноврсна фауна (преко 160 врста, а више од половине нових).

– ПАШИЋ 1974 (*у*: ПЕТКОВИЋ *и др*. 1976): у веома поремећеној горњој креди, између Сремске и Фрушкогорске дислокације, осим серпентинита и здробљних серпентинита, описано је, у тектонском контакту, 8 литолошки различитих блокова; неки од њих понављају се два, три или четири пута; иако је, на профилу јасно приказан тектонски склоп Черевићког потока, аутори су, укључивши блокове знатно ширег подручја Черевића, као и флишне седименте северно од Сремске дислокације, реконструисали стуб са претпостављеним стратиграфским редоследом. Горња креда Фрушке горе приписана је средњем и горњем мастрихту.

– ЧИЧУЛИЋ-ТРИФУНОВИЋ И РАКИЋ (1977): структурно-фацијална зона горње креде, јужно од Сремске дислокације, издвојена је као посебан Сремско-славонски тип горње креде мастрихтске старости. Аутори такође истичу велику поремећеност и тектонску расцепканост због чега је тешко дати детаљан литостратиграфски стуб. Стратиграфски стуб горње креде ове формационе зоне, приказан уз геолошку карту и описан, односи се на читаво подручје поменуте зоне, а завршава се лапорцима и лапоровитим кречњацима. Макро и микрофауна, која се у овим слојевима помиње као мастрихтска, уствари је кампанска (планктонски фораминифери, као и доњо-средњокампански *Inoceramus balticus*, одн. *Cetaceramus balticus*).

Коментар

Седименти неких блокова Черевићког потока садрже обиље измешане фауне, не само различитих фосилних група, него и различитих седиментационих средина (укључујући бочатне и паралске, према Пашић). Фосили су различитог степена очуваности и различите старости. Примерци фауне неких блокова су веома добро очувани и неоштећени (добро очуване скулптуре гастропода, скулптуре и бравни апарати бивалвија). Бројни рудисти и друге молуске могли би да буду веома добар материјал за Sr-изотопска мерења, с обзиром да је примена Sr-изотопске стратиграфије допринела ревизији стратиграфског положаја неких рудистних врста које су сматране мастрихтским маркерима.

Седименти старији од сенона до сада нису документовани; најмлађи мастрихтски кречњаци садрже фауну крупних фораминифера и пиронеа. Отворено је питање да ли су млађи од креде неки блокови у којима нису нађени макрофосили, а микропалеонтолошке анализе нису рађене. Такође треба поменути да су у делу Фрушкогорског флиша на основу нанофосила документовани седименти горњег олигоцена (као и у седиментима једног дела Остружничког флиша у околини Београда), што упућује на закључак о непосредној постолигоценској старости главних тектонских збивања.

Горњокредни седименти Черевићког потока депоновани су у различитим плитководним (и батијалним?) седиментима и различитим седиментационим јединицама. Неки блокови "префлишне горње креде", одн. „Сремско-славонске структурно-фацијалне зоне" Фрушке горе указују на ранију вишекратну тектонску активност. Блок Средњег брда, према расположивих подацима, тектонски је био деформисан у кампану.

Кредне седименте, који се појављују у блоковима између Сремске и Фрушкогорске дислокације, а који су у ствари блокови хаотичног комплекса који укључује и серпентините, данас није прихватљиво приказивати у стратиграфском стубу као непоремећену горњокредну сукцесију.

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The Neogene Lakes on the Balkan Land

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Abstract. Palaeogeographic maps of the lacustrine Miocene and Pliocene have been constructed according to all the known geological data. The Lakes of the Balkan Land, depending on the tectonics, migrated due to causes from the deep subsurface. There are several phases of the Miocene lakes: the lowermost Miocene transiting from marine Oligocene, Lower, Middle, Upper Miocene covering, in patches, the main part of the Land. The Pliocene lakes spread mostly to the north of the Balkan Land and covered only its marginal parts. Other lake-like sediments, in fact freshened parts of the Black Sea Kuialnician (Upper Pliocene), stretched along the middle and southern portions of the Balkan Peninsula (to the south of the Balkan Mt.). Subsequently, the Balkan Peninsula was formed.

Key words: Neogene, south-eastern Europe, lacustrine environments.

Апстракт. Палеогеографске карте језерског миоцена и плиоцена начињена су на основу свих геолошких података сакупљеним до данас. Распоред језера Балканског копна зависио је од тектонике, а мигрирала су сагласно са узроцима насталим дубоко под земљом. Може се разликовати неколико фаза настанка миоценских језера: најнижи миоцен на преласку из морског олигоцена, доњи, средњи и горњи миоцен који су местимично покривали велике делове копна. Плиоценска језера налазила су се углавном на северу од Балканског копна и захватала су његове маргиналне делове. Друга врста седимената, слична језерским, у ствари ослађене биофације делова црноморског кујалника (горњи плиоцен) пружале су се дуж средњег дела Балканског полуострва (јужно од планине Балкан). После тога је било формирано Балканско полуострво.

Кључне речи: неоген, југоисточна Европа, језерска средина.

Introduction

The lacustrine Miocene and Pliocene sediments of the Balkan Peninsula have been known since the late 19th century. Later studies were performed in the first half of the 20th century and culminated during its second half in the preparation of the Basic Geological Map (BGM) 1:100 000 of Yugoslavia (Coll. authors 1968–1995 for Serbia) and all the Balkan and neighbouring countries. The second phase of 1:50 000 mapping included specialist studies of phenomena characteristic for certain areas, resulting in the publication of monographs solving some of problems raised by the BGM. The third phase was important as UNESCO started international cooperation through their IGCP projects, including the Neogene and post-Neogene of the area through the following Projects: 25, 155, and 329 (Coll. authors 1974–1997), as well as through bilateral and multilateral cooperation based on these projects. All these studies enabled the preparation of palaeogeographic maps (Hamor 2001; Krstić *et al.* 2003; Popov *et al.* 2004; *etc.*), including both marine and lacustrine biofacies, as they were often in immediate contact.

Study area

The present-day Balkan Peninsula includes the area to the south of the Sava and the Danube. The Balkan Land, together with its lakes, in certain phases of the Neogene development also spread to areas that are presently included not only in the Lower but also in the Middle Danube Plains.

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The Balkan Land originated from the coalescence of an eastern part, making the edge of stable Europe (Carpatho-Balkanides), and a western island, which in the Upper Cretaceous was a part of Africa (Dinaric Alps). A strait existed between them until the very end of the Oligocene (DE CAPOA & RADOIČIĆ 2002). At the turn of the Palaeogene to the Neogene, the two islands merged into the Balkan Land. The complicated tectonic movements, only occasionally precisely defined (KRSTIĆ *et al.* 1999), matched with appropriate climatic conditions, caused the appearance and diversity of a series of Miocene and Pliocene lakes, positioned in various parts of the Balkan Land (ZAGORČEV 2001, *etc*.). In other words, the shape changes of the Balkan Land were caused by tectonics (PRELEVIĆ *et al.* 2005).

The transgressing and retreating of the mostly epicontinental seas enables a correlation of the lacustrine formations of the Balkan Land with the stratigraphic scale of a World Ocean. Unfortunately, the direction of these connections has still not been unambiguously determined, although the Central Paratethys was during the Miocene connected with the Mediterranean towards the West (RÖGL 1998; HAMOR 2001). However, this view is challenged by the presence of Lower Miocene lacustrine formations on the Adriatic islands Rab and Pag (KOCHANSKY & SLIŠKOVIĆ 1978; KRSTIĆ 2000, BULIĆ & JURIŠIĆ-POLŠAK 2009). During the Pliocene, this connection certainly existed towards the Adriatic (KRSTIĆ 2006) and in the area of the present-day Aegean Sea (KRSTIĆ *et al.* 1999; GEORGIADES-DIKEOULIA *et al.* 2002, *etc*.).

Material and methods

It was possible to study in great detail the sediments of the Neogene lakes at outcrops and in shallow bore holes during studies of the drillings made for coal research, sources of underground water, the preparation of the BG Maps and, additionally, other works (such as the choice of a site for a nuclear power plant), all of which are included in this review. The systematic drillings (of 20 and 200 m in depth) made for the purpose of the BG Mapping were performed in the lowlands, mostly to the north of the Sava and Danube, and the number of such drillings was over 80 per sheet 1:100 000 (a sheet area is 1500 km^2, while the surface of the Balkan Peninsula is about 500 000 km^2).

In addition to ostracodes, which are the most useful as they are very abundant in lacustrine sediments, the results of other palaeontological methods were also employed. In the first place were the autochthonous fossils: well-studied molluscs and sufficiently known diatoms. The presence or absence of Charophyta gyrogonits are important for in-depth enciphering. The allochthonous fossils include mammals, macroflora (leaves and fruits) and palynomorphs; also fish fossilized under thermocline. All the recorded fossils enabled the determination of the biostratigraphic age, as isotope studies were rarely performed.

Fossil position in sediments and their characteristics indicate the properties of a basin and its shape. For this, the sediment type is very important.

Miocene lakes

The origin of the Miocene lakes may be connected with tectonic movements, from the northwards movement of the Adriatic Plate to the curvature of the Carpatho-Balkan Mountain Range. Both these factors caused alternating shifts of dilatations and compressions, which produced depressions (filled with Neogene formations) followed by faulting and overthrusting (KRSTIĆ *et al.* 1988; RADOIČIĆ *et al.* 1989; MIKES *et al.* 2008; *etc*).

Various Early Miocene lakes

Several smaller lakes originated from the closure of the limans situated around the Late Oligocene Strait in the axis of the present Balkan Peninsula. Other such lakes were set against the Aegean Sea. The limans might have been the habitat for marine fishes of the family Mugilidae, which spawned exclusively in the sea (GAUDANT 2002). After the strait became closed due to the appearance of the Balkan Land, the limans became closed lakes, which existed in the place of the limans for a short period of time, which were mostly inhabited by *Botriococcus* algae, and oil shale sediments formed (VASS *et al.* 2006).

Šumadijan Lake

The Šumadijan Lake (Š in Fig. 1) is one of these lakes (KRSTIĆ *et al.* 2003). Unfortunately, it lacked organisms with a calcium carbonate shell, as the lake water had to be acidic due to influence of some volcanic apparatus surrounding the lake from all sides, dated about 23 Ma and less (CVETKOVIC *et al.* 2000). Hence, it is possible that the Lake origin follows the collapse of the magma chamber. The Šumadijan Lake also contains oil shale sediments–a few drillings were made for oil research (KNEŽEVIĆ 1997).

The Buštranje–Poljanica Lake (B in Fig. 1) is the second lake, with a number of layers of oil shale and palynomorphs, which indicate the Oligocene (VASS *et al.* 2006). According to geotectonics, palaeoclimatic indicators and spectrums of palynomorphs, this lake should be of the same age as the Šumadijan Lake.

In Bulgaria, SW of Sofia, the Pernik Coal Mine (P in Fig. 1) has a probable late Oligocene to early Aquitanian age, according to the palynomorphs and some fishes (VATSEV 2004).

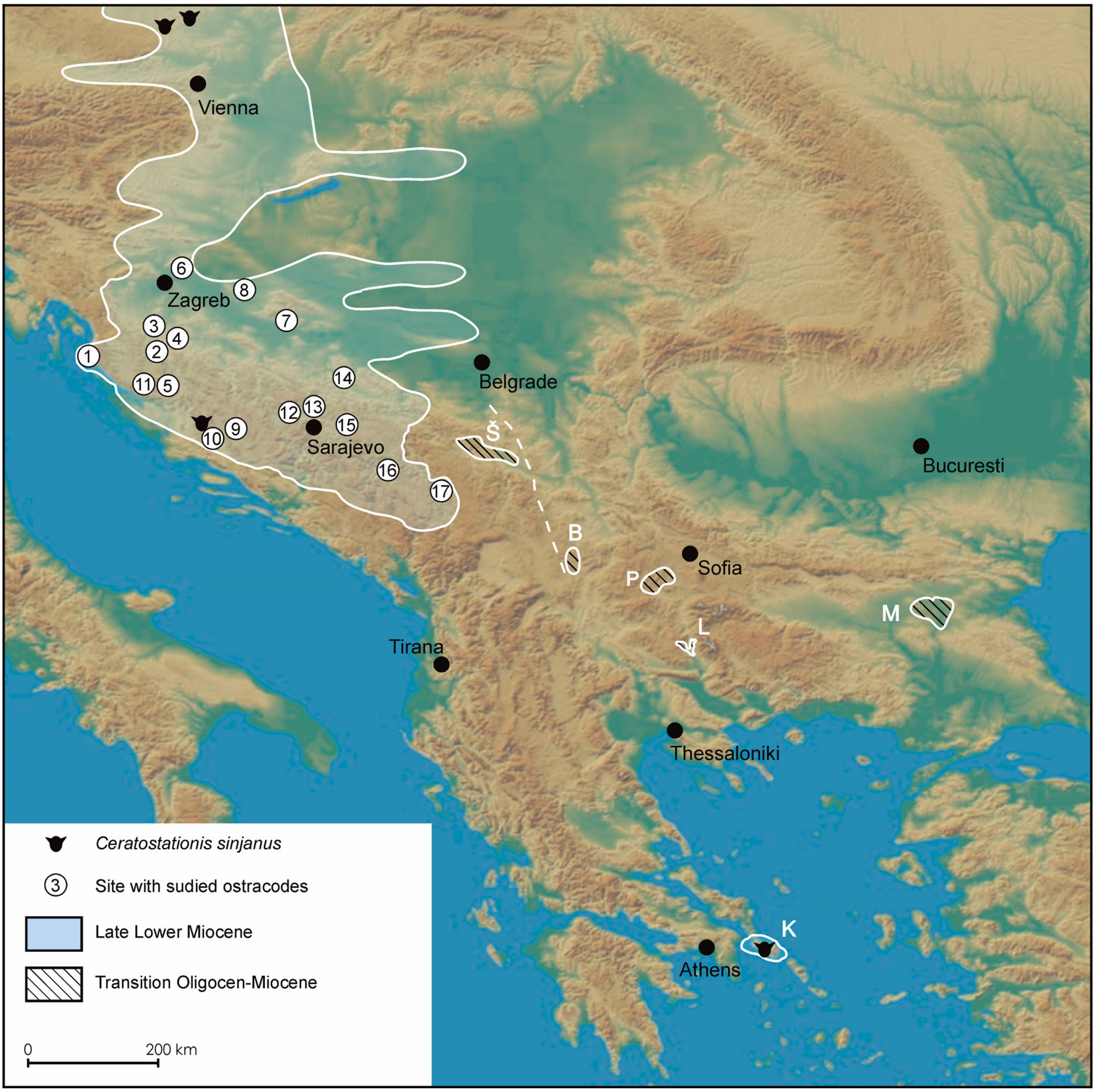

Fig. 1. Approximate distribution of the early Miocene lakes on the Balkan Land. Legend: Oblique lines - water basins existing in the Late Oligocene and the very start of the Miocene: **Š,** Šumadijan Lake; **B,** Buštranje–Poljanica area; **P,** Pernik mine area; **M,** basins of Plovdiv and western Maritsa; **L,** Luleva Fm. of the Brežani area under Pirin Mt. (Juranov *et al*. 1993), **K,** Kymi on Eubea. Horizontal lines – Dinaric system of lakes and its probable extension northwards into Hungary, Austria, Slovakia and beyond. Horned dots – sites with fruits of *Ceratostationis sinjanus*. Empty circles - sites with ostracodes (Sokač & Krstić 1987): **1,** Rab; **2,** Žagar; **3,** Gata; **4,** Cazin; **5,** Dugo Selo; **6,** Medvednica; **7,** Psunj; **8,** Bunjani; **9,** Livanjsko Polje; **10,** Sinj; **11,** Krbava; **12,** Busovača; **13,** Breza; **14,** Korenita; **15,** Romanija; **16,** Pljevlja; **17,** Sjenica.

Also in Bulgaria, the lowlands around the lower reaches of the Maritsa River (M in Fig. 1), with possible connection toward Plovdiv, are of Chattian to Aquitanian age. The Merichleri Limestone Formation includes exclusively marine molluscs of the Chattian. For the next, the Maritsa Formation, Vatsev claimed, “age probably Chattian–Early Miocene... b) member of shale with lower coal bearing unit; age probably Early Miocene”, contains only the fossil fish *Drapalis macrurus*. The ostracodes are drawn only aside the marine column part (Vatsev 2004).

Westwards, in the graben of Brežani under Pirin Mt., the lowermost Miocene, Luleva Formation of Rakitna Village, contain *Paleoleuciscus elegans* Gaudant and remnants of an Anoures (frog), *Paleobatrachus?* (Gaudant & Vatsev 2003). The genus *Paleoleuciscus* was not known previously to the Miocene. In two formation below appear freshwater molluscs, Oligocene palynomorphs and *Protothymallus pirinensis* Gaudant, the genus known from the Oligocene and Lower Miocene. The species *P. pirinensis* and the coal below it, may be Rupelian in age, while the Gaudant species is very similar to *P. elongatus* (Kramberger). The formation between the two, a fluviatile one, contain only badly preserved freshwater gastropods.

Dinaride System of Lakes

In the area of the Dinarides, but also further towards the northwest (Krstić *et al.* 2003), all the way to Lower Austria, there are well-developed, karst-subtropical types of lakes, in the intramontane depressions. In the winter half of the year, the lakes coalesced. This situation matches the present day example of the Scodra Lake, rising by 6 m during the wet half of the year (Karaman & Beeton 1981).

Preserved Neogene sediments were tilted during and, even more, after the sedimentation. The coal beds deepened as a result of faults, mostly along the NE of the valleys. These movements affected the bedrocks by the same amount, *i.e.*, by 1500 m, thus forming all the mountains (Milojević 1966).

Two column parts are easy distinguishable; a lower one without congeria and an upper one with halofile organisms, mainly dreissenids. While in the lower column part freshwater genera predominate (Krstić *et al.* 2009), in the upper one, different aberrant bentic creatures made an endemic biofacies. The source of these highly developed taxons, transported from distant eastern saline lakes, could be China, with several unknown adequate refugiums in between.

The lithology is quite diverse. Marl is the type of sediment with the widest distribution, forming mostly the upper part of the column. At the base, there are some well-sorted, unconsolidated, white chalky layers, indicating shallow lake water as in Kupres (Krstić *et al.* 2010b) and submersed plants of the *Potamogeton* type. In other places, there are some poorly sorted siliciclastics, indicating fluvial transport as in Maoče Bay (Krstić *et al.* 2010a). Above the marl, there are sand and conglomerate of prograding deltas filing up the lake basins. At the lower part of the column, there are many layers of coal and thick packages of bentonite, indicating a remote volcanic activity at the time, as there are no autochthonous synchronous igneous rocks (Vujnović *et al.* 2000). The main coal seams lie between the lower (freshwater) and the upper (saline) part of the column.

All these sediment types alternate at short distances, indicating a very long twisting shoreline of the lacustrine system of the Dinaric Alps (Krstić *et al.* 2003, text-fig. 3; Čičić & Milojević 1977; Mandić *et al.* 2009; Bulić & Jurišić-Polšak 2009). The marginal areas were covered with characin meadows, and in some remote gulfs, such as Maoče (Krstić *et al.* 2010a), bentic organisms could show a lower degree of salinity due to freshwater tributaries.

These sediments were disturbed by a number of gravitational faults. The faults are post-sedimentation ones and, in the northern half, they seem to be exclusively situated along the northern edge of the valleys (Pljevlja), while even somewhat reverse faulted towards the south (Krstić *et al.* 1994). In the south-western half of the Dinaric System of lakes, the faults are situated along the south-western edges of the valleys, adjusting the nape structures (Ilić & Neubauer 2005; Mikes *et al.* 2008). The napes were produce by northward movements of the Adriatic plates on both sides of the Adrian (cf. Cipollari *et al.* 1999). The collision zone of the Adriatic and Dinaric segment is caracterized by late-orogenic (Oligocene to Miocene) thick-skinnned compressional uplift (exhumation), related gravity gliding, and still active escape tectonics renching (Corbar 2009).

There are numerous sites with endemic molluscs (Brusina 1897, 1902, *etc*.), but it is difficult to attribute them to a definite part of the column as the exact positions are lacking. The lacustrine molluscs belong to “endemic” forms mostly congerias (Kochansky & Slišković 1978 etc). The endemicity level is extremely high (98 %) (Harzhauser & Mandic 2008). These large creatures are known from the Paratethys province, its estuaries, gulfs and similar biotopes (Popov *et al.* 2004). The gastropods *Clivunella, Orygoceras, Fossarulus,* as well as endemic species from *Prososthenia, Melanopsis, Emmericia*, are often ornamented with ridges and tubercles. However, there is not a single representative of the genus *Viviparus* (Brusina 1884), a freshwater to halotolerant genus. At some lacustrine costal sites, there is admixture of terrestrial snails (Prysjazhnjuk 2008).

The ostracode fauna was studied only at a smaller number of localities (Fig. 1). Below the coal seams and close to them, the ostracodes are freshwater types; in the marly sediments their shells may be partly or highly absorbed (Štavalj Coal Mine on the Sjenica Plateau). In the silty beds of the higher column parts, the ostracodes are well preserved and represented by elongated aberrant forms of Candoninae, bimucronate representatives of the genus *Amplocypris* and ornamented representatives of the genus *Potamocypris*, while there are several species of Cytherideidae from the genera *Clonocythere* (earlier as *Amnicythere*), *Guangbeinia*, *Sinometacypris* (Krstić 1987a, b, 2000; Youtang *et al.* 2002) – the Chinese forms. The above-listed and some others indicate a salty lacustrine environment.

Charophyta indicate shallow water. They appear abundantly below the coal seams, represented by large gyrogonits, of a genus close to *Harrisichara,* and a great number of small ones belonging to *Chara, Sphaerochara*, *etc*. (KRSTIĆ *et al.* 2009). Above the main coal seam appear large gyrogonits *Nitellopsis merianii*, in some levels "tuberculate", and small ones *Chara molassica notata, Rhabdochara langeri* and others (KRSTIĆ *et al.* 2010a).

Fruit of the water nut *Cerastoderma sinjana* is not abundantly present but was recorded from Austria and Slovakia through Sinj to the area Kymi at the southern part of Eubea in Greece (VELIZTELOS & GREGOR 1990), hence, in a stratigraphic-time sense, it connects these distant regions.

Age. Studying the congeria fauna, KOCHANSKY & SLIŠKOVIĆ (1978) anticipated the Ottnangian age of the Dinaric Alps lakes. The Pag succession as deposited between 17,41 and 16,7 Ma and that it corresponds to the Burdigalian Stage of the Central Paratethys (JIMENEZ-MORENO *et al*. 2009). According to terrestrial snails (PRYSJAZHNJUK *et al.* 2000; PRYSJAZHNJUK 2008), the Sjenica Lake should be regarded as somewhat younger than the mammal Zone MN3b, or Ottnangian–Karpatian. A fossiliferous bed in Sjenica is overlain by a basalt (analcimite) flow, dated 22.95±1.25 (but its prolongation on Koritnik /leucitite/ yielded 9.12±0.35) Ma (CVETKOVIĆ *et al.* 2004) – this indicate late Eggerian (and the second one, a subsequent basaltic outflow on the same fault line in the Upper Miocene equivalent of the MN10 Zone !). In Sinj, recent measurements of the upper column part yielded an age of 17.92±0.18 Ma (LEEUW *et al.*, 2010).

The larger mammals *Antracotherium minus* and *Chalicotherium grande* are known in different places and less indicative are several findings (from BULIĆ & JURIŠIĆ-POLŠAK 2009) of *Gomphotherrium angustidens* and *Prodeinotherium bavaricum,* which give the age of the MN4 Zone (Ottnangian) to these sediments.

Serbian Lake

Lacustrine sediments are widely distributed throughout Serbia (Fig. 2) as they originated by post-collision spreading, not only in the area where the Dinaric and Carpatho-Balkan islands collided, but also deep into both sides. To the east, they are compressed due to the later curvature of the Carpathian Mountain Range (KRSTIĆ *et al.* 1988), while in the Western Island they sank due to post-compressional extension (CVETKOVIĆ & PECSKAY 1999).

The sediments of the Serbian Lake are composed of sand, silt, clayey silt, marl and marlstone, as well as of sandy limestone, rarely lacustrine chalk and different limestone types. This today highly populated hilly area acquires its drinking water mostly from Neogene sands. Coal is present in many of the depressions, but underground exploitation in most mines is no longer economically viable. The areas with marly clays are susceptible to sliding, causing great damage during heavy rains (*e.g.*, in the spring of 2006 and all of 2010).

The sedimentological features were given by OBRADOVIĆ & VASIĆ (2007). The sediments of deep depressions (lacustrine profundal) are of a meromictic character containing the autogenic minerals: sirlesite in Kremna, magnezite in Baljevac on the Ibar River, zeolite in Zlatkop near Vranje and many other sites of similar origin but with a smaller content of them; in shallow lake parts, dolomitic limestone could be present. The lacustrine profundal often bear oil shales, richest in Bela Stena near Valjevo and Subotinac near Aleksinac (VASS *et al.* 2006).

The very large Serbian Lake, dotted with many islands, was for the first time comprehended by CVIJIĆ in 1924 based on the contours of the Mačkat fluviodenundation Plain. The age was defined by STEVANOVIĆ *et al.* (1977b) as Middle Miocene, according to records of the reverse-spiralled Lymnaeide snail *Kosovia* (PAVLOVIĆ, 1903, 1931). The lacustrine basin was recognized as unique by DOLIĆ (1983), according to molluscs in oxygen-rich, shallow parts of the lake. This large lake, which used to stretch throughout Serbia from Belgrade to Macedonia and through SW Bulgaria (OGNJANOVA-RUMENOVA 2000; KRSTIĆ *et al.* 2003) to Serrai in Greece, was named the Serbian Lake by KRSTIĆ & KOMARNICKY (1996). It is not clear whether the small Čukurovo Basin to the SE of Sofia, having plant remnants only (VATSEV 2004), was linked to the Serbian Lake or was only a satellite.

The diatom microflora of the Serbian Lake was studied in the Lubnica near Zaječar, and in the Simitli Basin of SW Bulgaria. *Aulacoseira, Ellerbeckia, Melosira* and *Actinocyclus* developed there during the Middle Miocene time. "This period is marked mainly by the coarsely ornamented forms of *Aulacoseira granulata* and *A. islandica* and different lacustrine *Actinocyclus* species" (OGNJANOVA-RUMENOVA 2000).

Allochtonous, macroflora is represented by forests stretching along the river margins, called riparian or galerian flora. It has its climatic value, but changes in short cycles and depends on the exposure. A large study of Serbian flora by PANTIĆ (1956) was completed by MIHAJLOVIĆ (1978), which placed Serbian sites not far from the Morava Valley, but to the east (Melnica, Rakova Bara, Popovac, Misača), and Slanci near Belgrade into subtropical Helvetian (early Middle Miocene). Palynological analyze of silt from the Ribnica River in Mionica gave again a subtropical climate (VASS *et al.* 2006). Only one site in the Levač County of central Serbia, in village Kaludra, contained macroflora of Lower Miocene age, equivalent to the Upper Ottnangian-Karpatian (MIHAJLOVIĆ 1988).

The sediments with lacustrine ostracodes at the locality Slanci near Belgrade lie concordantly below the marine Middle Badenian (as below the Lower Badenian – ĆORIĆ, *et al.* 2009 – in the northern lying trough). The species *Mediocypris nisseana* was collect-

Fig. 2. Approximate spreading of the Middle Miocene lakes on the Balkan Land. Ostracode sites of the Serbian Lake: **1,** Slanci; **2,** Koceljeva; **6,** Petrovac; **7,** Melnica; **8,** Kragujevac-Sabanta; **9,** Levač; **10,** Dragačevo; **11,** Kraljevo – Dragčić; **12,** Paraćin – Mutnica; **13,** Ražanj – Madjari; **14,** Sokobanja – Resnik & others; **15,** Knjaževac – Gradište; **16,** Svrljig; **17,** Niš – Komren; **18,** Mali Jastrebac – Azbresnica; **19,** Metohija-Rudnik; **20,** Vladičin Han; **21,** Skopje – marl pit. Diatomacea sites: **Z,** Zaječar (Lubnica); **S,** Simitli; (OGNJANOVA-RUMENOVA 2000), Higher plants: **Č,** Čukorovo. Early Sarmatian (early Volhinian) Lake of Bukulja, ostracode sites: **3,** Vračević; **4,** Brajkovac; **5,** Jelovik.

ed not only at Slanci and Niš but also at other localities with silty layers (compare KRSTIĆ *et al.* 1988). In the sand and sandy silt of Mutnica near Paraćin and nearby sites, the rich ostracode assemblage contains *Ilyocypris pannonica, Cypridopsis pannonica, Potamocypris bouei*, *Dinarocythere costata*, *etc*. In marly-dolomitic layers all over the central and western parts of the Serbian Lake, the most common ostracode species are 'halofile' "*Reticulatocandona" baljkovacensis* and *Ohridiella sabantae*. At the eastern part of the Serbian Lake, between Carpathian/Balkan ridges, freshwater genera predominate in Žagubica, Lubnica near Zaječar, Čitluk near Sokobanja, *etc*. Rarely they are replaced by halofile ones, like in Melnica from where the endemic genus *Septocypris* (European equivalent of the Chinese genus *Megacypris*) was described (KRSTIĆ 1987a). The second such, remote outcrop of white chalky unconsolidate sediment lies where Žukovska Reka reaches the Timok trench (on the road to the Gradište village): white chalk yealded a candonid from *lampadis* group and in Žagubica (commentary of Selište) another candonid of the *chasei* group both are corroborating unusual water chemistry.

The mollusc macrofauna association differs largely from that of the Dinaride System of lakes, despite some dreissena being successor of their very well known Lower Miocene predecessors. According to Knežević 1996 and Jovanović & Krstić 2010, these are *Mytilopsis cvitanovici servica*, *M. antecroatica sumadica* and others differing more, such as *M. nisseana, M. dactyloides* descriebed by Pavlović 1931. Gastropods are more numerous and very diversified– *Ancylus serbicus*, *A. dimici*, *Planorbis pavlovici*, *Prososthenia serbica* they were described by Brusina (1894) and *P. fuchsi*, *Melanopsis petkovici* by Pavlović (1903) Later Pavlović (1931) presented snails from the Peć Fm.: *Hydrobia santrici*, *Bythinella cvijici*, *Micromelania proni*, *M. metohiana*, *Kosovia praepontica*, *Gyraulus decani*. Some of these species (*Radix cobeltiformis*, *R. levasi*, *Fossarulus praepontícus* and *Marticia macarii*) spreads northwards along the Ibar River (Stevanović, 1985) making them Ibar biofacies.

Among the proboscideans, most findings belong to *Deinotherium giganteum*, *Anancus avernensis* and a transition form from *Gomphotherrium angustidens* to *G. Longirostris* (Krstić *et al.* 2007). Several localities rich in diverse bones and teeth of micromammals belong to the MN5 Zone (Marković 2008), hence to the Karpatian–Badenian according to Steininger (1999).

The age of the Serbian Lake sediments are older than the marine Middle Badenian, while laying concordantly below it. Combining macroflora and micromammals with the Borač eruptive complex (Cvetković & Pecskay 1999), late Karpatian–early Badenian was determined, even though the intercalated dacite tuff (near Mionica and in Popovac) was not measured.

In Popovac, the marl quarry consists of feldspar, quartzite and biotite as the main constituents (Pešić & Koprivica 1996), hence the material is quite good for radiometric age measurement.

Southern margin of the Badenian Sea

Along the River Sava, from Belgrade to Zagreb, the lacustrine formation is overlain mostly by marine Badenian.

Near Belgrade, the Badenian rises slowly from the lacustrine Slanci Formation, starting as brachyhaline sediments, changing fast into fully marine ones (Krstić 1978). F. Rögl (personal communication) recognised in them a Middle Badenian relative of *Uvigerina pygmaea*. The marine Lower Badenian drilled to the north of the Danube, in southern Banat, included numerous plankton foraminifers of the Zone *Praeorbulina-Orbulina suturalis* (determination of F. Rögl, in personal communication). On the Papuk Mt. and near Zagreb, the initial marine sediments "contain the nanoplankton assemblages characterising the NN5 Zone" (Ćorić *et al.* 2009) covering the whole Badenian. The foraminifera assemblage "belongs to the Early Badenian, corresponding with the Lower Lagenide Zone*"* (*ibid*). Thus, this is a southward transgression, going step by step from one to another trough. In all cases, it was a "sudden but continuous transition from a freshwater lake into a marine environment" (*ibid*) in the whole southern part of the Pannonian Plain.

Two remote bays of the Badenian Sea penetrated into the Balkan Land, along extremely tectonically disturbed areas. One of them, called Timok Bay, penetrated along the Timok strikeslip fault, which was reactivated before the start of the Middle Badenian (Kräutner & Krstić 2003). The other larger one, Morava Bay, stretched along the contact between the Dinaric and the Carpatho-Balkanic Islands; at the time, the contact was still not sufficiently stabilized, as still is, as its bottom is still subsiding now.

Age. The Badenian comprises the upper part of the MN5, the MN6 and the lower part of the MN7+8 Zones (Steininger 1999).

Timok Bay

Timok Bay was not at all elongated. In the Middle Badenian, marine facies reached to the town of Zaječar. In the Upper Badenian, some interbeds have a sarmatoid character; hence, it was classified within the "Buglovka Layers" (Džodžo-Tomić 1963). However, the Badenian Sea, of Vienna type, mainly comes through SW Romania to the north-western part of Bulgaria.

Mlava Bay

In the small Mlava Bay, near Petrovac, there are several interbeds of freshwater sediments following thin coal seams in the gulf facies most influenced by freshwater. The ostracodes within the coal-bearing level are less numerous than charophyta gyrogonites, indicating transparent shallow water (to a depth of 7 m, approximately). Biofacies, transiting to marine, lie on the edge of the Bay at the Danube (Jovanović & Tomić 1997; Krstić *et al.* 2003).

Morava Bay

The Morava Bay stretched far towards the south, gradually spreading the marine and then the brackish biofacies of the Middle Badenian all the way to Kruševac (STEVANOVIĆ *et al.* 1977; DOLIĆ 1978). New data on fossils from Tavnik (near Kruševac, wrongly attributed to Upper Miocene by KRSTIC *et al.* 2007), such as the new micrommamal species *Miodyromys wesselsi* (dormouse) and other small mammals, must have oriental origin. The environment was a shallow calm pond according to charophyta (gyrogonits of *Nitellopsis merianii*) and higher plants, such as *Trapa* and *Nysa* (depth around 6–7 m), then frogs, tritons, emids and even small species crocodile remnants. Among the molluscs, there are some hydrobioids, unionacea and other pelecipiods and a ceritihid *Terebralia lignitarum* along with a large *Planorbarius.* The last two indicate a swamp and the proximity of coal forming facies. The only high energy indicator is a roughly ornamented *Theodoxus* and the sandy interbeds embedding all these thermophile fossils.

Towards the west, a sign of the Badenian impact was recorded along Bosna River, to Doboj, but no freshwater dilution of the marine Badenian has been recorded to date.

Sarmatian Bukulja Lake

The relatively small Valjevo–Mionica–Belanovica Lake, hidden by the Bukulja Mt. and Blizanjski Visovi, was only sometimes affected by the influence of Paratethys biofacies.

Lying discordantly above the sediments of the Serbian Lake, with a long gap, it was largely drilled for uranium in Jelovik Village, where the Gornji Breg Hill contained some of uranium in coaly interbeds (KRSTIĆ, *et al.* 2011). To the East, the Lake stretches along the Jasenica Valley, westwards through Kačer (STEVANOVIĆ *et al.* 1977a) and into the Mionica–Valjevo Depression (STEVANOVIĆ 1977). The contact with the Serbian Lake sediments in Tabanović should be at a depth of 82 m (JOVANOVIĆ *et al.*, 1994), just above a kind of hardground made of zeolitised tuff, as in the Zmajevac Brook (JOVANOVIĆ & DOLIĆ 1994).

The shallow water part of Jasenica–Kačer contains mainly freshwater lacustrine organisms. Among the molluscs in Jelovik (site 5 in Fig. 2), there are many dreissenids larval valves covering the bedding planes; adult dreissena are restricted to some beds, while *Prososthenia, Hydrobia, Planorbis, Theodoxus* and *Planorbarius* are usually poorly preserved (PRYSJAZHNJUK & RUDJUK 2005, KRSTIĆ *et al.*, 2011). Some of the Jelovik ostracode fauna is similar to that in the Serbian Lake, but there are numerous large *Eucandona* also found in Brajkovac (site 4 in Fig. 2) together with vertebrates, including *Bunolistriodon meidamon, Giraffokeryx punjabiensis, Pseudoeotragus seegrabensis* and micromammals; "there are also some very well preserved bird remains" including eggs, first found long ago (1959) by STEVANOVIĆ.

In the Valjevo–Mionica costal area, at the ancient watering place of Vračević (point 3 in Fig. 2), many micromammals were collected – *Eomyops oppligeri, Keramidomys mohleri, Anomalomys gaudryi, Bysantinia bayraktepensis, Collimys longidens, Eumyorion latior* and *Microdyromys koenigswaldi*–indicating that these sediments belong to the MN7+8 Zone (MARKOVIĆ & PAVIĆ 2004), actually supporting the Sarmatian age that was determined by STEVANOVIĆ. The profundal of this lake was situated between today's villages Radobić and Šušeoka, the sediments of which had a meromictic character. There, thick seams of oil shales (ERCEGOVAC *et al.* 2003; VASS *et al.* 2006) with imprints of fish carcasses (GAUDANT 2002) and other rare fossils (insects – bee, *etc*.) were collected. These sediments contain authigenic minerals, zeolites, searlesite and even shortite and trona, suggesting a salty lacustrine environment (OBRADOVIĆ *et al.* 1997; OBRADOVIĆ & VASIĆ 2007).

Age. Their stratigraphic position between the Serbian Lake sediments delimited by discordance and the transgressively lying Middle Volhinian (Lower Sarmatian) place them into the lowermost Sarmatian. Many micromammals from Vračević indicate that these sediments belong to the MN 7+8 Zone (MARKOVIĆ 2003; MARKOVIĆ & PAVIĆ 2004), actually supporting the Sarmatian age determined by STEVANOVIĆ.

In the late Volhinian and afterwards, the northern part of the Valjevo–Mionica Depression was periodically flooded by Paratethys water. In a structural borehole in Tabanović (above and eastwards of Radobićka Bela Stena) containing freshwater meiofauna (riverine *Potamocypris* mostly), there are some interbeds with Sarmatian molluscs (JOVANOVIĆ & DOLIĆ 1994) and one meter of the Pannonian on the very top.

Upper Miocene lakes

The Paratethys became fully separated from the Mediterranean and the World Ocean at the beginning of the Upper Miocene (PAPP *et al.* 1974), after the brackish Sarmatian phase of the late Middle Miocene, as some kind of remote gulf sediments.

Transitional lagoons

On the north-western edge of the Middle Danube Plain, there are two small ostracode sites of Upper Miocene age. One is the lowland of Turiec (PIPIK 2001) and the other a lagoon near Graz (GROSS 2005). The Turiec site contains the endemic mollusc *Kosovia stromphostomopsis* and a nanogastropod, possibly *Lithoglyphus nannus*, (collection of the late Miloš Rakuš). Another Turiec sample of the Martin site (PIPIK 2001, GROSS *et al*. 2009) contains sarmatoid fossils (GOZHYK, personal communication). Both the Gratkorn near Graz and the Turiec indicate a faunal succession near the Middle/Late Miocene transition.

The Maeothian in the Lower Danube Plain, the equivalent of the Upper Pannonian of Middle Danubian one, was influenced by sea water in its lower half, with a venerid *Dosinia maeotica*. The upper half has nearly lacustrine fauna; together with ostracodes some Unionacea *Teyserrinaia* and *Anodonta* occur (see: GOZHYK 2006), as many different gastropods sometimes in great accumulations (*Lithoglyphus nannus*).

Caspibrackisch sea- lakes

The specific (Caspian-like) type of sediments of the Paratethys sea-lakes overlaps the northern parts of the Balkan Land from the Middle and Lower Danube plains southwards (Fig. 3, upper case). Large books on the Pannonian (PAPP *et al.* 1985) and the Pontian (eds. STEVANOVIĆ *et al.* 1989) present the geology, palaeogeography, lithology and their fossil content of both huge lakes. Therefore, no details are given in the schematic sketch in Fig. 3. The evolution of the basin was studied by ROYDEN & HORVATH (1988).

Pannonian Sea-Lake

The Pannonian Sea-Lake is restricted to the Middle Danube Plain filled by deltaic sediments from the north-west (KORPÁS-HODI *et al.* 1992, *etc*.). The paleogeographic evolution of Lake Pannon within the Pannonian basin is reconstruced with eight maps, ranging from Middle Miocene to the Early Pliocene. The maps are based on the distribution of selected biozones and specific fossils, and on sedimentological and seismic information (MAGYAR 1999). Outside it, only in the Besarabian (Middle Sarmatian) of Moldavia (Black Sea Basin) are there a few levels with Pannonian fauna (PAPP *et al.* 1985, *etc*.). According to STEININGER (1999), the Pannonian started already in the late Astaracian, the MN7+8 Zone and finished before the upper third of the MN12 Zone.

The Upper Pannonian equivalent in the Dacian Plain is the Maeotian. The Maeotian penetrated the Lower Danube Plain as a deep highly freshened marine gulf.

Pontian Sea-Lake

The caspibrackish Pontian Lake was the largest one ever on the Earth. It overlaps the Balkan Land not only from the North but also from the South, less from the East and the least from the West.

In the Serrai (Strimon) Valley, the Pontian lies over beds of the Turolian (the supposed continental Maeotian of STEVANOVIĆ 1964).

The Pontian and the Maeotian also appear in the west, as their ostracodes were recorded in the Peri-adriatic Depression (PAD) of Albania (PRILO & HASANAJ 2002).

The Lower Pontian is present in the vicinity of Athens, on the island Aegina.

A contact of the caspibrackish Pontian of the northern Aegean (the Katherina, Halkidiki and Strimon Depression) and the Central Macedonian Lake is not sufficiently clear. It is possible that there were some mountain ridges with very narrow and often closed straits or a threshold of subdued eustatic or tectonic twisting. In a meridional trench covering the Pelagonia-Florina-Ptolemais-Servia Valleys, the Late Miocene was proved below the Pliocene.

The time span of the Pontian was not large. According to STEININGER (1999), it started before the upper third of the MN12 Zone and lasted until the end of the MN13 Zone. The absolute age values are not mentioned here, as their data are not coherent in different publications. According to CHUMAKOV (1993), based on fission track analyses, the Pontian started at 7.00 Ma and ended, in the Black Sea area, *ca*. 5.5 Ma ago, but in Caspian one, it lasted longer until 5.19±0.89 Ma.

Central Macedonian Lake

Between the Paratethys and the Mediterranean, there were several Upper Miocene salty lakes (Fig. 3). The largest among them was the Central Macedonian Lake (DUMURDŽANOV 1997).

The Central Macedonian Lake stretches from the city of Vranje southwards to Athens. Its width is difficult to calculate: lacustrine sediments crop out at Bureli in Albania and in the opposite direction, through Bulgarian Srednegorie, with gaps, reach Elhovo (VATSEV 2004; KRSTIĆ *et al.* 2008). Its column consists of a lower coarse-grained part and an upper fine-grained one.

The sediments of the lower part of the Central Macedonian Lake are exhibited in the uplifting region. They are often badly sorted due to a high erosion rate. None of the autochthonous bentic fossils were found but an accumulations of vertebrate bones were widely spread and sometimes very numerous. In the Axios Valley, lacustrine (?) sediments of the Turolian (lying below the Pontian), contain bones of Hominoidea (DE BONIS *et al.* 1986; KOUFOS & DE BONIS 2004).

In the upper column part, the sediments of the Central Macedonian Lake contain diatomitic beds. The diatom assemblage consists of coarsely ornamented benthic forms of genus *Aulacoseira,* in the Vranje and Prespa Basins. Similar rough species *Aulacoseira (A. granulata, A. ambigua)* are dominant in SW Bulgaria in the diatomaceous sediments of Gotse Delchev, Satovcha, Kostenets and Elhovo Ba-

Fig. 3. The Upper Miocene Lakes: in the North, in the Paratethys realm, these are the Pannonian and Pontian, in the middle of the Balkan land, it is the Central Macedonian Lake. The whole array of basins of the Pelagonia–Florina–Ptolemais–Servia hosted a kind of freshened Late Pontian. Diatomite sites according TEMNISKOVA-TOPALOVA & OGNJANOVA-RUMENOVA 1997, OGNJANOVA-RUMENOVA 2006: **E,** Elhovo, **GD,** Gotse Delchev, **Ko,** Kolubara, **Ks,** Kostenets, **M,** Mariovo, **Pr,** Prespa, **Pt,**Ptolemaida, **Sa,** Satovcha, **Sr,** Srednegorie, **Vr,** Vranje. Lacustrine mollusc sites: **B**, Bureli (Unionidae); **Pt,** Ptolemaida (*Theodoxus*); **S,** Strimon depression; **K,** Katherina. Ostracode sites containing also molluscs of the upper part of the Central Macedonian Lake sediments: **1,** Veternik; **2,** fortress of Skopje. Main sites of mammal bones: **A,** Axios, **K,** Kalimanci; **P,** Pikermi; **V,** Veles.

sins. Their age was determined after the identical microflora recorded in the Upper Pontian sediments of the Serbian coal mine Kolubara (OGNJANOVA-RUMENOVA & KRSTIĆ 2007). In Kostenets, they contain some extinct species which can be considered key fossils for the Pontian. In the Satovcha Basin of SW Bulgaria, the Upper Miocene diatom microflora contains “the Miocene index-species *Eunotia japonica* and *Fragilaria miocenica*” (OGNJANOVA-RUMENOVA 2003). The Late Miocene indicates to eutrophic freshwater lakes, only slightly alkaline, under moderate temperatures (TEMNISKOVA & OGNJANOVA 1997).

The benthic macrofossils of lacustrine upper part of the column were found around Skopje and Bureli. The mollusc fauna is represented mainly by Unionidae, both in Skopje and Bureli, together with *Melanopsis affinis* (Kumati *et al.* 1997). At Veternik, to the north from Skopje, one lens included a few well-preserved mollusc shells: *Theodoxus doricus*, *T.* cf. *neumayri*, decorated with ribs and tubercles, and *Aphanothilus* as well as several ornamented species of *Prososthenia* (Dumurdžanov & Krstić 1999).

Ostracodes are very abundant and diverse in the silt below the Skopje Fortress. There from, a new genus *Macedocandona* with reverse valves (RV larger and overlaps LV), yielded a species flock containing four taxa. This new genus shows similarity to the Chinese *Potamocyprella*. There are also other taxa, unknown yet, maybe also oriental. Aberrant ostracodes lived next to the less numerous halotolerant *Fabaeformiscandona*, *Cypria*, *Cypridopsis* and *Plesiocypridopsis*. One marine *Callistocythere* (*Clonocythere?*) representative was, probably, brought from the Mediterranean area (Krstić & Guan 2000). These ostracodes have peculiar features and could only be compared with some taxa from the Chinese Eocene and Oligocene stages.

Age. The mammals of the Veles and other sites in the Central Macedonian Lake belong to the Pikermian fauna, *i.e*., to the Turolian. The closeness of the Pontian at the Strimon Valley and Katherina, but also on Aegina, near Athens, where Pikermy itself is situated, indicates that they are superimposed. The conditions that caused mass dying of mammals during the Turolian are probably the repeated droughts which occurred during the MN11 Zone. The palynomorphs of the upper part of the Central Macedonian Lake, at Bitola in Pelagonia, indicate a climate change into a humid warm-temperate one (Ivanov 2002) by the end of the Miocene.

Eordeian Trench

A different evolution proceeded in a meridional trench covering the Pelagonia–Florina–Ptolemais––Servia Depressions. For one of them, Cvijić (1911) used the ancient name Eordeian. Here, this name is applied to the whole trench.

There, only youngest Miocene sediments are present; most of the sediment fill belongs to the Pliocene.

The coal-bearing outcrops are made of the Komnina Formation, belonging to the Late Miocene (Bornovas & Rondogianni-Tsimbaou 1983; Pavlides & Mountrakis 1987). According to orbital signatures, it mostly matches the Pontian age. In the Lava Section, this is from 6.9 to 6.2 Ma (Steenbrink *et al.* 2000). The 6 m of the Ptolemaida Section, above coal (observed during the Pindosexcursion of the 10th Intern. Congress, Geol. Soc. Greèce, 2004) consists of diatomite-containing, mostly, broken Unionidae, in its lower part and above them, alternate greater or smaller amounts of snails of different sizes (*Theodoxus macedonicus*, *Valvata piscinalis*, *Lymnaea stagnalis*). Two *Neglecandona* sp. juv. valves come out from a shell of *T. macedonicus*, together with a finest ochre red limonitic sandy fill. All this indicate redeposition in water of low energy, diminishing upwards.

Attique

Several localities with aberrant lacustrine molluscs of Attika were shown by Kühn (1963) and Papp (1979). Kühn determined museum material according the papers of Brusina on the Dinarides. Later Papp corrected the checklist having his own collection. The gastropod species are highly endemic: *Theodoxus atticus*, *Th. morulus*, *Th. milessii*, *Melanostteira milessii*, *Melanopsis (Canthidomus) longa*, *M. (C.) oroposi*, *M. (C.) freydbergi.*

The Athens area is now heavily urbanized and fossils have not been collected recently. An important finding there was during the digging for a swimming pool at the Pirgos Vasilissis site, also known for molluscs. There were found different mammals, along with *Graecopithecus* (de Bonis *et al.* 1986): *Mastodon pentelici, Dicerorhinus orientalis, Hipparion mediterraneum, Tragoceras amalheus, Gasella gaudryi, Helladitherium divernoi* and *Giraffa attica*. The age is late Miocene, like the famous Pikermia mammal site, lying in the close vicinity of Athens.

The paleogeography of the marine and continental Miocene of Greece was reconstructed by Guernet (1978).

Pliocene lakes

The Pliocene lakes (Fig. 4) developed through different mechanism of origin. The two lakes forming the northern boundaries of the Balkan Land belonged to the area of the Paratethys. These are the Paludinian and Dacian–Romanian lakes. Their sediments are connected to and gradually grow out of previously laid formations of the caspibrackish Pontian Lake, as the Paratethys area continued to subside during the Pliocene.

From the east, the Balkan Land was flooded by waters of the Black Sea and from the south by water of the Levantine Aquatorium. The subsidence was due to the obduction of Asia Minor over the Balkans, causing detachment of a "thin skin" (Krstić *et al.* 1999). The "thin skin" even reached the centre of the present-day Balkan Peninsula, being there combined with strong crustal extension (Marović *et al.* 1999). Cvijić (1911) named the southern aquatorium the Aegean Lake.

Fig. 4. Approximate spreading of the two types of Upper Pliocene lakes on the Balkan Peninsula: horizontal lines – the nearly freshwater Paludinian and the Dacian – Romanian Lakes; vertical lines – the slightly salty Aegean Lake being in connection with the oblique lines – Kuialnician Sea – Lake in the East (in the Black Sea realm). Diatomite sites (Sofia, Palakaria, Karlovo, Pilep, Bitola, Servia) according OGNJANOVA-RUMENOVA (2006) and JENKO & GJUSELKOVSKI (1957–1958 for Prilep). **1,** Moslavina, Kutina ZP-8, ZP-9; **2,** Slavonia, Strizivojna V-4; **3,** Posavina, Prevlaka OS-1; **4,** Erdut P-2; **5,** Baranja Hill P-10 (all from SOKAČ, 1978); **6,** Bajmok Sb-5, Sb-6, Sb-7; **7,** Čoka K-11 and others; **8,** Mol K-59 and others; **9,** Crnja Ž-11 and others; **10,** Lazarevo JT-1 and others; **11,** Gložanj G-3 and others; **12,** Srbobran SRB-2; **13,** Mačva: Crna Bara and Pričinović; **14,** brickyard at Krivci; **15,** Ugrinovci KG-33 and Zemun B-12.13 (from KRSTIĆ, 2006); **16,** Baraolt; **17,** Silistra; **18,** Mazgoš – Stanjinci, **19,** Metohija; **20,** Joanina; **21,** Eubea; **22,** Megara; **23,** northern Peloponnesus; **24,** Megalopolis; **25,** Sparta; **26,** Kos (starting with No 16 - by different authors).

Paludinian Lake

The Paludinian Beds obtained their name from a synonym of the gastropod genus *Viviparus*. The Paludinian Lake of the Middle Danube lowland was probably the deepest, among the Pliocene lakes of the Balkans, lasting for the longest period. At the boundary, "caspibrackish sediments alternate with limnic ones on the border between the 'Pontian' and the 'Paludinian Beds', therefore making the border diachronous" (STEVANOVIĆ *et al.* 1989).

The Early Pliocene of northern Europe had mostly an arid and regressive character, especially during its latter half. At that time, all the lakes in southeastern Europe decreased in size, and their interconnections were occasionally interrupted (KRSTIĆ 2006).

Molluscs appeared in shallow water, along the coast or on the shore. The Paludinian molluscs cited by KNEŽEVIĆ (PAPAIANOPOL *et al.* 2003) are distributed according to *Viviparidae* stratigraphy. In the Lower Paludinian, along with the smooth key species *V. neumayri*, ornamented Unionidae appear as *Rytia bielzi, Cuneopsidea partschi* and many *Melanopsis* species. In the Middle Paludinian, the key fossil is *Viviparus bifarcinatus* followed by other ribbed, smooth and ornamented unionids, a few *Melanopsis* species and different extinct gastropod taxa. The Upper Paludinian is marked by the key species *V. dezmanianus* and other knotted, but also some smooth viviparids along with different *Unionacea* and some extinct *Theodoxus, Hydrobia* and *Valvata* as several species of *Melanopsis*. To the Pliocene belong *Viviparus boeckhi* Beds still having ornamented Unionidae: *Potomida sturi, P. wilchelmi, Wenziella, Rugunio* as the first *Unio* cf. *pictorum*, then *Pisidium rugosum, Hydrobia syrmica*, *etc*. Some recent species, such as *Dreissena polymorpha*, *Fagotia esperi, Theodoxus transversalis* and many others are known since the Middle Paludinian.

The ostracode meiofauna, as well as planktonic microflora, was evenly distributed by wetland birds, which carried it over large distances. The numerous records of ostracodes enable a quite precise recognition of the arid phases which were present with variable intensity and quantity, depending on the particular basin. For the Middle Danube Plain, the key fossils are *Cypris subglobosa mandelstami*, *Zonocypris membranae*, *Stenocypris* cf. *boileki*, *Cyprideis torosa*, and various taxa of Limnocytheridae (KRSTIĆ 2006). Representatives of Leptocytheridae are rare (SOKAČ & KRSTIĆ 1987).

The Upper Paludinian Beds have a transgressive character. The lakes increased in size and in the Upper Pliocene, they were widely connected with each other (KRSTIĆ, *et al.* 2005). Only once did evaporation prevail, indicated by *Scordiscia*, making distinctive subzone in the lower part of the Upper Paludinian Beds.

The most important species of ostracodes in the Upper Paludinian Beds is *Ilyocypris malezi*. Most of the other taxa are known from extant biotopes, but the Paludinian Lake contains exclusively halotolerant forms, probably those that also thrived in alkaline environments. Subspecies of recent species are common (only a few of them were occasionally described, therefore most are indicated by "cf."). These subspecies lasted until the Mindel / Riss interglacial (300–100 KAa): *Ilyocypris* cf. *monstrifica*, *Cyclocypris* cf. *serena*, *C.* cf. *impressopunctata*, *Laevicypris laevis ducatensis*, *Trajancypris* cf. *laevis*, as well as the species *Ilyocypris sokacae.* The subspecies *Scottia browniana kubanica* and *Ilyocypris getica crnjanskii* became the main species below the Pliocene–Pleistocene boundary. Both subspecies of the species *Scottia browniana*, indicate an environment of high water energy, while they are abundant in more or less sandy sediments (KRSTIĆ 2006).

In the Dinaric realm, Viviparids and large mammals are known from the Vinodol–Ilirska Bistrica graben. An erosional remnant in a supposed Pliocene lake strait, on the way to Adrian, in Srb, along with Hydrobiids just a single *Erpetocypris* was recorded (JURIŠIĆ-POLŠAK *et al.* 1997). In Istria, STACHE (1889) collected also *Viviparus* snails.

A curiosum is that Pliocene ostracode communities of the same type as in the Pannonian Lake appear as far as Thüringia (KRSTIĆ 2006).

Dacian–Romanian Lake

The Dacian–Romanian Lake lies on the Platform Moesian, covering mostly the Romanian plain and only small part crosses the Danube towards the south covering a little of Bulgarian territory.

At the Miocene–Pliocene transition, the Paratethys water retreated and connection between the Pannonian and Dacian Basins "was reduced to a system of channels and straits" (ENCIU 2007). Its water chemistry changed and in the Dacian Basin, along with different Lymnocardiidae (*Pachidacna*, *Dacicardium*, *Pseudocatillus*, *Stylodacna*), the "first species of *Psilunio (Psilunio)*, *Jaskoa* and numerous gastropods of paludal facies (*Valvata, Planorbis*)" appear. "The internal change of lithology, architecture of sedimentary rhythms and thickness depended on the slow tectonic movement of the Moesian" Plate. The Early Pliocene was named Dacian, the late Romanian; they continue one after other making a single Dacian–Romanian Lake.

In volume, Dacian (MARINESCU & PAPAIANOPOL 1995) in a description of the Getian substage Lake was figured as large and spread over the whole of the southern plain of Romania, ending in the south at Lom in Bulgaria. Bivalvia Lymnocardiids are diverse and numerous, giving the name *Pachidacna* – Beds to Getian, but there are enough *Dreissena polymorpha*, *Viviparus rumanus* and other molluscs in it. Thick coal beds spread over western and northern part of the Dacian Basin.

During the late Dacian, the Paskovian substage, the Lake shrank considerably, retreating from the west and north, where the coal areas were situated; now coal appears in the middle of this smaller Lake, but also in its NE portion were there was nearly none regression, as opposed to the southwards ingression in the middle and eastern Lake portions. The main fossils are Lymnocardiidae: *Limnodacna*, *Pseudocatillus*, *Horiodacna*, *Dacicardium*, *Prosodacnomya* and some gastropods, such as, *Lithoglyphus*. Among the ostracodes in Bulgaria, halophilous species prevail, such as *Cyprideis torosa*, *Paracyprinotus salinus* and the extinct *Zonocypris membranae*, also the halotolerant: *Pseudocandona compressa*, *Laevicypris laevis* and *Neglecandona*. In the Roþitori borehole, *Romanocastor filipescui* was determined to the MN14 Zone belong Bereþti site rich in micromammals and Ciupreceni with large mammals.

The Upper Pliocene, Romanian spread its aquatorium even larger than it was at the beginning of the Pliocene. The Romanian stage of Moesian Plate was delimited towards the Black Sea, the Kuialnician biofacies, by a threshold laying to the south of the Buzau River. It was not a barrier while the two sea-lakes communicated over it (PAPAIANOPOL *et al.* 2003). This could be used to explain Pliocene remnants in Baraolt-Brasov intramontane depression containing aberrant ostracodes, molluscs and mammals.

The Romanian has its tripartite biostratigraphic subdivision supported on molluscs: while Lymnocardiidae vanished, Unionacea flourished. The Lower Romanian contains smooth unionids accompanied by *Viviparus bifarcinatus*, *Jaskoa sturdze*, *Psilunio sibinensis* and *Melanopsis rumana*. The Middle Romanian is rich in ornamented unionidae, corroborating a higher temperature when $CaCO_3$ intake was faster; it is possible to distinguish three contemporaneous zones: a) *Rugunio lenticularis*, *Rytia slavonica*; b). *Pristinunio davilai* with *Viviparus stricturatus* and c) *Bulimus vukotinovici* with *Canthidomus lanceolata*. In the Upper Romanian, climatic variations are observed according to lacustrine, palustrine and terrestrial facies, the zone with *Ebersiniana milcovensis* and subzone *Unio kujalnicensis*. In the Romanian stage are present: *Ilyocypris angulata*, *I. lanceolata*, *Zonocypris membranae*, *Berocypris*, *Kowalevskiella*, *Scordiscia jiriceki* (taxonomy corrected according to KRSTIĆ 2006) and others. Mammals are recorded in two areas of the Romanian Plain: the ten outcrops at the slope of Carpathians along the Olt and neighbouring rivers belong to the Gilbert and early Gauss (4.3–3.1 Ma) and Slatina 1, 2, 3, as the Tetoiu to the Matuyama (2.6–1.9 and 1.75 Ma) (PAPAIANOPOL *et al*. 2003).

The mentioned Baraolt–Brasov Depression could be a remote bay of the Black Sea. Kuialnician penetration into the Carpathian Mountains and having higher salinity (due to evaporation and the narrow strait), *Paradacna abichi*, *Lymnocardium zagrabiense* and even *Budmania,* being there in a refugium, were therefore determined (MARINESCU & PAPAIANOPOL 1995). From the Baraolt Basin in the Carpathians, the first recorded species was *"Candona" kinkelini*. Eight ostracode taxa are identical for both Baraolt and Metohija (in southern Serbia), and one of them is shown on the drawing–*Carpathocandona bataniica* (from Metohija). The last belongs to the most distinctive find at Baraolt–a species flock of bimucronate Candoninae, there together with *Cyprideis jekeliusi* and a few Leptocytheridae species of the Pontian type (PAPAIANOPOL *et al*. 2003). In Baraolt-Brašov, one mammal-bearing column started at 3.7 and ended at 3.5 Ma; the remaining three columns started at 3.5 and ended at 3.1 Ma, hence they belong completely to the Early Gauss, in other words, to the middle and the first one partially to the Lower Romanian.

Aegean Lake

The ancient Aegean Lake covered the southern Balkan Peninsula, Aegean Sea and parts of Asia Minor. Its water chemistry was similar to seawater but much diluted, while it comes from the Black Sea Kuialnician biofacies. It is fossil-bearing from Kosovo and Metohija to the Peloponnesus. At the same time, the southern part of the Balkan Peninsula communicated with the Mediterranean Sea. This can be observed in a column of Megara near Athens, where *Melanopsis* layers and *Cardium* layers alternate (GEORGIADES-DIKEOULIA *et al.* 2002).

The largest area with fossiliferous Pliocene sediments lies approximately in the middle of the Balkan Peninsula. It is Kosovo and Metohija where mollusc fauna (mostly congerias and *Viviparus*) in places litters the sediment (PAVLOVIC, 1903). The ostracode fauna of the area is rich and diverse-three groups of ostracodes are distinguishable (KRSTIĆ *et al.* 1988). The species which are the same as recent freshwater ones are: *Fabaeformiscandona krstici*, *Cypria karamani*, *C. sketi*, *Paralimnocythere ohridensis*, *P. geogevitschi*, with some others, such as *Candona candida pliocenica,* which are related to them. On the other hand, there are species of the Kuialnician type, such as *Graviacypris*, *Zalaniella*, *Ohridiella*, *Reticulocandona* as the very rare *Amnicythere* and *Cyprideis*; also extinct species *Ilyocypris malezi*, *Scottia browniana kubanica*. Bimucronate Candoninae belongs to an intermediary group.

West of Sofia, at the very border of the state of Serbia, the erosion remnants of Pliocene sediments are present at the open coal pits in Mazgoš and Stanjinci. In Mazgoš (Serbian mine), the halophilous ostracodes *Paracyprinotus salinus* and *Neglecandona angulata decimai* were recorded together with halotolerant ones, such as *Peudocandona compressa* and others. The mollusc fauna present in Mazgoš includes the ubiquitous pond species *Planorbarius corneus* and *Galba palustris* as well as a slightly smaller and *Planorbarius*–shaped, African snail (JOVANOVIĆ *et al.* 2005). This intramontane area was slightly influenced by Kuialnician water, in the same manner as Metohija.

Towards the south, sediments of the same Upper Pliocene age with numerous fossil ostracodes and molluscs, such as *Viviparus brusinai*, are recorded in the basins of Joanina (GUERNET *et al.* 1977), also at northern Eubea (MOSTAFAWI 1994), in the open pit of Megara near Athens (GEORGIADES-DIKEOULIA *et al.* 2002), on the north of Peloponnesus (MOSTAFAWI 1994), as well as the central part of Peloponnesus at Sparta (GUERNET 1979; KRSTIĆ & VELITZELOS 2002) having the same community in Megalopolis (LÜTTIG & MARINOS 1962).

There are similar interesting associations away from the Balkan Peninsula mainland on the island Kos (GUERNET *et al.* 1976; MOSTAFAWI 1988). All this means that Paratethys water during the Upper Pliocene poured into the nearly dry Mediterranean depression, yet recorded only close to Barcelona (GILLET 1965) and curiously in the upper Ebro Basin (RODRIGUEZ-LAZARO & MARTIN-RUBIO 2005).

Implications

For the precise determination of the biostratigraphic placement of lake fossils, the ostracode communities have to be used for various purposes. The ecology and distribution of certain species, clear enough in the younger levels, indicate the evolution of climate. The correlation with other similar or different palaeobiological units enables an understanding of the evolution of the Balkan lakes in Neogene time and space. These conclusions mirror the geodynamic evolution–the distribution of equivalent time sediments indicates the tectonic mechanism that preceded them. The obtained data are actually proof for the existing tectonic models (CIPOLLARI *et al.* 1999; MIKES *et al.* 2008). However, certain explanations are still lacking.

The transition from the latest Oligocene limans into early Miocene lakes is connected to compressive closing of the strait between the Western (Dinaric) and the Eastern (Carpatho-Balkanic) Islands. The origin of the water basins also assumes transcurrent movements along the straits in the direction North–South, with perpendicular faulting at their sides, causing the appearance of depressions in the West–East direction.

The origin mechanism of Dinaride System of Lakes slowly becomes apparent, aside it spreading across the Middle Danube Plain until behind the Alps. The explanation by De CAPOA and RADOIČIĆ (2002) is that tectogenesis of the External Dinarides "actually occurred during the Early Late Miocene", so the early extensional movements could commence in the mid Lower Miocene, while the faulting occurred later. A detailed study of palaeostress in the Central Dinarides "indicates, a NE–SW contraction, as well as a subordinate NW–SE extension, which is related to the early Miocene shortening of the Dinaric orogenic wedge" (ILIĆ & NEUBAUER 2005). These pressures caused isoclinal folds of the Dinarides along the Adriatic, where de CAPOA & RADOIČIĆ (2002) recorded a continuity of sediments from the Eocene to the Seravalian. Whether the Eubean Kymi site (VELITZELOS & GREGOR 1990) is a part of this folding is difficult to say. The last research prolonged the marine Miocene northwards until Istria (Triesete–Kopar and Pazin Basin) all along the Outer Dinaride (MIKES *et al.* 2008) "Upper Oligocene palynomorphs, nanofossils and larger foraminifera in the Pićan flysh" (Istria) "have been dated herein to be not older than the Late Burdigalian" according to nanofossils which "tolerate reduced salinity". For the islands Rab and Pag (BULIĆ & JURIŠIĆ-POLŠAK 2009), with their freshwater ostracode genera and congerian fauna, the conclusion should be the same, namely, there was a large lacustrine aquatorium of the Ottnangian Stage.

The Chinese biota had to travel a long way to the Dinaride Lake, from one refugium to another, carried by birds, in order to appear in south-eastern Europe in the Lower Miocene. Some such refugiums are presented on the Palaeogeographic Maps of SE Europe–SW Asia (POPOV *et al.* 2004). A large Dneper–Donets Basin, from Donets High over Kiev and into Poland contains congeria fauna in its gulfs and estuaries of already freshened sea.

For the Middle Danube Area, HAMOR (2001) declared that "the marginal sediments of the Ottnangian transgression are the 'Oncophora-bearing sandstones'" and that it was "detected in the NN3 Zone, the 'Rzehakia layers' ... in the Vienna Basin", in northern Hungary and in Czech Moravia. HAMOR drew quite narrow river valleys on his map of the Lower Miocene (Upper Eggerian–Eggenburgian–Ottnangian), where fluvial channel line facies and fluvial floodplain facies separated. According to the distribution of the lacustrine pre-Badenian in the Serbian part of the Middle Danube Plain (COLL. AUTH. 1968–1995), the equivalent sediments are widely distributed but preserved only as remnants of erosion processes.

For the Serbian Lake, there is a hypothesis of post-collision spreading (CVETKOVIĆ *et al.* 2000, 2004) and later compression (PRELEVIĆ *et al.* 2005), explaining the great elongation of this "narrow" lake. However, the original width of the lake was much larger than shown in Fig. 2. Its eastern half is compressed between the many stripes of the Carpatho-Balkanides and often deeply buried Neogene (KRSTIĆ *et al.* 1988). The time of these movements approximately corresponds to the boundary between the Lower and Middle Miocene, but it cannot be precisely determined as the coal-bearing "lower Badenian" part of the lacustrine sediments is folded and faulted, while the upper part remained almost horizontal. In the Serbian Lake, the depth zones are already recognizable: the almost unconsolidated lake chalk with "*Candona*" cf. *similil-ampadis* at Knjaževac, compressed between the gabro massif of Zaglavak at the East and Mesozoic rocks in the West; the right transcurrent Timok dislocation transversely cuts through Jurassic limestone and an over - laying succession of lower Cretaceous stratigraphic units (KRSTIĆ *et al.* 1970; KRÄUTNER & KRSTIĆ 2003).

The spacious valleys of the mid-southern Balkan (including the Pelagonia–to Servia trench–PAVLIDES & MOUNTRAKIS, 1987; STEENBRINK 2001), where the Upper Miocene continental and lacustrine sediments were laid, could be connected with the collapse of the present-day Aegean Sea (MAROVIĆ *et al.* 1999). This extension follows the closing of the Middle Miocene Serbian Lake in the North, due to a compression of the actual bending of the Carpathian-Balkan Arc.

Upper Miocene sediments have their widest distribution in Macedonia and a somewhat smaller area along the southern flank of the Balkan Mt. and nearly the whole of southern Bulgaria (OGNJANOVA-RUMENOVA 2001, 2003, 2007). Towards the west, the Bureli surroundings in the middle of Albania (KUMATI *et al.* 1997) could be an extremely freshened distal part of an Adriatic bay containing Unionacea. A small erosion remnant, rich in ornamented *Theodoxus*, is situated in the town of Athens (KÜHN 1963; PAPP 1979).

The Pliocene tectonics is quite different, being connected with the obduction of Asia Minor over the Balkan Land. The obduction caused the detachment of a "thin skin" layer over a wide area from Sofia and Metohija southwards, with very visible bow-shaped boundaries near Skopje (COLL. AUTH., 1968–1995). The obduction reflexes might be found all the way to Čačak and Rtanj (KRSTIĆ, 2006), and towards the west to the Adriatic Coast in Albania, as well as in its Peshkopi Trench (KRSTIĆ *et al.* 1999). The Montenegro–Adriatic fault caused great earthquakes.

Due to such a great impact of tectonics on the present distribution of the Neogene lacustrine sediments, a palaeogeographc reconstruction is difficult. Each individual lake or any of its parts would have to be studied in greater detail–that would be one of palaeolimnology important tasks. The problem is an insufficient number of observation points and an even smaller number of detailed studies of fossil associations in the Miocene part of the Balkan Peninsula Neogene. The number of samples from the Pliocene is already considerably larger, especially in the Middle Danube Plain, and their fauna is similar enough to the extant one that a palaeogeographic map could be constructed (KRSTIĆ 2006). For the Pliocene spreading all over southern Europe and SW Asia, a reconstruction was performed (KRSTIĆ *et al.* 2005).

The chemistry of the lacustrine water could be deduced based on a number of "endemics"-the aberrant taxa-and the ornamentations on their shells. There is a surprising diversity in the ornamentation of ostracode genera that in freshwater environments are either smooth or only insignificantly punctuated, such as the various systematic categories of Candoninae, except *Pseudocandona.* The genus *Potamocypris* has tubercles or spines, some Limnocytheridae taxa (the one transported from China and Russia) may be heavily ornamented with ridges and tubercles along with a denticulate hinge, *etc*. The chemistry of the water sometimes caused reversion of the shells, when the left ostracode valve acquires the characteristics of the right one and *vice versa*. *Theodoxus* ornamentation was also noticed. Even the lack of ostracodes and other organisms that bear a calcium carbonate shell can indicate the acidity of the lake water. This characteristic is due to intensive volcanic action in the Šumadijan Lake.

The energy of the water is represented through the presence or absence of certain groups. In addition to the gastropods *Fagotia, Theodoxus* and *Lithoglyphus,* ostracodes may also be reophilous, for example *Scottia browniana*.

Changes in climatic belts cause the presence or absence of certain ostracode species. While in the Pannonian Plain, the Pliocene taxon *Scottia browniana kubanica* is very abundant and at Metohija, it is rarely represented but still recorded, it is completely missing in Peloponnesus and southwards. The representatives of the species *Ilyocypris malezi* are smaller in the Aegean than in the Paludinian Lake, probably due to the warmer climate in the southern areas.

A climate reconstruction is possible for the late Pliocene and for the lacustrine Pleistocene. By the end of the Pliocene, colder winters are recorded while in the same sample may be found both–summer and winter generations of a particular species (cold winters and warm summers)–hence, a climatic cooling may be directly recorded. In the older lacustrine sediments, reconstruction of the climate is more or less connected with the reconstruction of the water chemistry, when it is affected by the climate. Thus, warm temperatures cause an increase in evaporation and, therefore, also a diminishing of the tributaries. Both increased the mineralization of the water. However, it is more complicated–when a lake decreases in size, due to aridity, it looses not only its influx but also its outflow, hence the balance in the water chemistry is affected.

Ostracode meiofossils are the best support for studies of lacustrine sediments as they are much more abundant than molluscs, they are also autochthonous benthic organisms and since studies of diatoms, dinoflagelata and endemic calcareous nanoplankton, which were often transported still alive, are less significant.

The main means of meiofauna and microflora unification, when the environment is appropriate, is dissemination by birds. Old ideas of their evolution in restricted geographic region were born due to the slow evolution of the environment chemistry in the Paratethys and similar areas. Understanding that bird transport was the main agent of ostracode dissemination providing the meiofauna of the Central Macedonian Lake (KRSTIĆ & GUAN 2000) explains why the ostracodes have no similarity with those of the neighbouring Paratethys parts but with the Kainozoic lacustrine ostracodes of China. The same comprehension was a little later placed for the microflora–diatoms and dinoflagelata (personal communication by OGNJANOVA–RUMENOVA) and afterwards for larval stages of gastropods, maybe all molluscs (personal communication by Bandel, Hamburg). It is not known how many ancient refugia existed between China and southeastern Europe. Some of them, since Lower Miocene, contain congerian and other fauna, still insufficiently correlated between themselves. The recent molluscs and ostracodes of western and central Europe are identical in every of lake and pond due to the circulation of wild geese. However, there are different recent species in the southeastern part, especially on the Balkans, due to the different climate and bird migration, which come from SW Siberia and have their feather change on the Caspian. In general, today and in the past, bird migration had the same direction, from east toward west, due to the rotation of the Earth. Hence, the appearance of the community from Chinese early Eocene is the same as in the early Pliocene of the Middle Danube Lowland; the same species *Ilyocypris angulata* Sars lives today in the H'nka Lake near Vladivostok with its subspecies found in the Middle Paludinian Beds (KRSTIĆ 2006) and so on.

Meiofauna indirectly provide data on ancient water chemistry, even by their absence due to lake water acidity. When the obtained proxies are combined with studies of palynomorphs and macroflora, there is a possibility for conclusions about the climate in the whole Neogene past. Matched with sedimentological and other geological studies, they provide data for palaeogeography and tectonics, which can protects us from geological hazards.

Conclusions

The time of the appearance and the distribution of lacustrine basins on the Balkan Peninsula were caused by numerous processes at the boundary of the asthenosphere and the lithosphere, combined with movements of tectonic plates.

The water of the Šumadijan Lake used to have high acidity, judging by the absence of autochthonous carbonate fossils. It may be assumed that the lake was formed by the collapse of a magma chamber, from which the numerous magmatic bodies have already erupted, including the massifs of Borač and Kotlenik.

The Dinaric system of lakes was formed by pulsating indentation of Adriatic plates towards the north. The Dinaric mountain system was formed by underthrusting and uplifting, leading to greater elevation of younger sediments and the altitudinal difference of about 2000 m between the same levels, for example Livanjsko Polje and the freshwater biofacies of Kupres. The measured absolute age of the younger Neogene of Sinj, deposited in mineralized water inhabited by dreissena, is 17.92 ± 0.18 Ma.

The Serbian Lake originated by the postcollision spreading of western and eastern Balkan Islands. At the East, the nape of the Carpatho-Balkanides has covered the older Lake, coal-bearing sediments with Mesozoic and other older sediments in the meridional direction. In the younger subhorizontal part, there are coarse-grained coastal limestones with *Kosovia* and fine-grained siliciclastic rocks rich in benthos fauna in lentic areas. The fauna shows a slight indication of mineralization. The profundal in the deeper parts of the Lake is highly mineralized with well-preserved remains of fish. According to the diatomic association, it may be concluded that the Lake stretched southwards to the Simitli Valley in SW Bulgaria.

The marine Badenian later gradually penetrated from the North into the Serbian Lake, and the furthest attained area was in the Morava Bay: the Middle Badenian, of Sarmatoid biofacies, reached the town of Kruševac. The other bays were shorter and shallower: at the Mlava Bay, the meiofauna close to the coal was of the freshwater type - with abundant characean gyrogonites. The marine Middle-Badenian fauna penetrated to Doboj down the River Bosna Valley. The Viennese type of Badenian reached Bulgaria and eastern Serbia through Romania, along the River Olt .

Generally speaking, the northern boundary of the Serbian Lake sediments, predisposed by faults in the W–E direction, moved slowly southwards. Therefore, in southern Banat, the Papuk belt, the marine Lower Badenian continuously ascended from the lacustrine pre-Badenian. The belt passing through Belgrade included the Middle Badenian only, while to the south from Bukulja and in Valjevo–Mionica Depression, the lacustrine-riverine Lower Volinian with *Potamocypris* was concordantly covered with brackish *Mactra* limestone of the Middle Volinian.

The deep gulfs at the northern and western edge of the Pannonian Plain were inhabited by endemic fauna. The one close to Graz was determined as Sarmatian (due to vertebrate bones), while the other in Hungary is the equivalent of freshened Badenian and includes Black Sea biofacies.

The two Upper Miocene lacustrine phases, the "Pannonian Sea" and its much greater Pontian descendant, have entered over the Balkan Land to the south to only a small extent. However, the Pontian part also approached the Balkan Land from the South, *via* the Aegean, and from the West in the Periadriatic Depression of Albania.

The Aegean collapse reached northward to Vranje. It was widespread in central Macedonia and SW Bulgaria. The Central Macedonian Lake was a tectonically mobile area; hence, the older coarse clastic sediments with mammalian remains (Veles, Kalimanci, *etc.*) were preserved over a wider area than the younger fine-grained lacustrine sediments with endemic macro and meiofauna and rich microflora. The Central Macedonian Lake was bordered by a threshold from the Pontian of the Aegean Lake in the South. In Greèce, besides the Eordean Rift, there are numerous valleys stretching from Athens southwards and across the sea to Rhodes and the Anatolian Xanthos Rift.

The Pliocene lakes from the North entered the Southern areas along the coasts of the Balkan Land. These are the Paludinian and the Dacian–Romanian Lakes. In the Middle Danube Valley, the gradual decrease in salinity influenced the formation of ornaments in species of the genus *Viviparus* and numerous taxa of Unionacea. In the ostracodes, there are some almost exclusively halotolerant species, with the exception of rare layers with halophiles. In the Lower Danube Valley, a great regression is observed during the Dacian stage, as well as the transgression during the Romanian stage.

The Kujalnitian of the Black Sea reached to the Buzãu River; hence, the Brašov-Baraolt Depression in the Carpathians was narrowly connected to the Black Sea, having more saline biofacies. To the south from Stara Planina, the waters of the Black Sea flooded the SE part of the Balkan Land, as a consequence of the obduction of Asia Minor over the Balkans.

In the southern parts of Greece, the lacustrine Pliocene was alternating with marine biofacies in short intervals. This was the area of contact between the water bodies of the Paratethys and the Mediterranean.

The occasional records of Pliocene formations with *Viviparus* and meiofauna, reaching westwards into Spain and northwards into Thuringia, pose a question about the uniformity of the lacustrine biotopes of the Late Pliocene and the transport of smaller organisms (including mollusc larvae) inside the plumage of migratory birds.

This concludes the present-day knowledge on the origin, development and disappearance of the Miocene and Pliocene lakes on the Balkan Land.

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Резиме

Неогена језера на Балканском копну

Време настанка и распоред језерских басена на Балканском полуострву последица су кретања тектонских плоча и других процеса који су се дешавали на граници астеносфере и литосфере.

Вода Шумадијског језера је била доста кисела јер у њему нису нађени аутохтони карбонатни фосили. Може се претпоставити да је језеро настало урушавањем магматске коморе из које су се већ избила бројна магматска тела, укључујући масиве Борач и Котленик.

Динаридски систем језера је продукт пулсационе индентације Јадранских плоча ка северу. Динаридски планински систем је настао подвлачењем, што је изазивало постепено издизање млађих седимената и висинску разлику од око две хиљаде метара између истих слојева, као на пример између Ливањског поља и слатководних биофацијa Купреса. Апсолутна старост млађег „конгеријског" дела Сињског неогена, таложеног у минерализованој води, износи 17,92 ± 0,18 Ма.

Пространо Српско језеро настало је услед постколизионог одбијања западног и источног Балканског острва. У његовом источном делу, повијањем Карпато-Балканида дошло је до покривања старијих седимената са мезозојским и другим старијим седиментима меридионалног правца. У млађем субхоризонталном делу могу се разликовати приобалске кречњачке творевине са *Kosovia* и ситнозрни силицикластити богатих бентоском фауном са малим индикацијама минерализације. Профундал дубљих делова језера високо је минерализован са добро сачуваним остацима риба. На основу дијатомеја може се закључити да се према југу језеро пружало до Симитли потолине у ЈЗ Бугарској.

Морски баден је касније са севера продро у Српско језеро, најдаље у Моравском заливу; средњи баден, у сарматоидној биофацији се простире се код Крушевца. Други заливи су били краћи и плићи: у Млавском заливу је меиофауна слатководног типа, а гирогонити харацеа су бројни. Морска средњобаденска фауна је продрла дуж реке Босне до Добоја, а у Бугарску и источну Србију је бечки тип бадена стигао преко Румуније, дуж реке Олт.

Уопште посматрано северна граница седимената Српског језера, приближно правца З–И полако се померала према југу, па у појасу јужни Банат–Папук морски доњи баден постепено је израстао из језерског пребадена. У појасу који пролази кроз Београд заступљен је само средњи баден, а јужно од Букуље и у Ваљевско-мионичкој потолини језерско-речни доњи волин са *Potamocypris* и конкордантно је прекривен бракичним кречњаком средњег волина са *Mactra*.

На северном и западном ободу Панонске низије дубоки заливи су били настањени ендемичном фауном. Нека је одређена као сармат (кости кичмењака), друге су у Мађарској еквиваленти бадена и садрже црноморске биофације.

Две горњомиоценске језерске фазе Паратетиса – "Панонско море" и његов много пространији понтијски наследник – само малим делом залазе према југу на простор Балканског копна.

Егејски колапс је достигао на север до Врања. Дејство колапса се осећало у простору средње Македоније као и ЈЗ Бугарске. Централно Македонско језеро је било тектонски мобилни простор, отуда старији грубокластични талози са остацима сисара (Велес, Калиманци и др.) захватају шире подручје него млађи финозрни језерски талози са ендемичном макро и меиофауном и богатом микрофлором. Централно Македонско језеро је на југу делимично одвојено од понта Егејског језера на југу. Осим Еордејског рова захвата још и бројне потолине, а простире се јужно од Атине и преко мора до Родоса и анадолског Ксантос грабена.

Плиоценска језера на северу незнатно залазе ка југу дуж обала Балканског копна. То су Палудинско и Дакијско-романијско језеро. У средњедунавској низији постепено снижење слaности воде одразило се на скулптуру врста рода *Viviparus* и бројност таксона Unionacea. Остракоде су заступљене скоро само халотолерантним врстама, мада има и ретких слојева са халофилима. У низији доњег Дунава јасно се препознају исушивања настала током дакијског ката као и водом богати романијски кат.

Унутар Карпата, депресија Брашов–Бараолт била је повезана са црноморским кујалником што је допирао до реке Бузау. Слична веза је постојала и јужно од Старе Планине јер су воде Црног мора преплавиле ЈИ део Балканског копна као последица обдукције Мале Азије на Балкан.

На југу Грчке, језерски плиоцен се у кратким интервалима наизменично смењује са морским биофацијама. То је био простор контакта вода Паратетиса и Медитерана. Местимични налази плиоценских творевина са *Viviparus* и меиофауном, према западу до Шпаније и према северу до Тирингије, отварају питања истоветности језерских биотопа касног плиоцена и транспорта ситнијих организама (укључујући ларве мекушаца) у перју птица селица.

Овај закључак представља досадашње познавање настанка, развоја и нестанка миоценских и плиоценских језера на Балканском копну.

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Correlation of metabasic rocks from metamorphic soles of the Dinaridic and the Western Vardar zone ophiolites (Serbia): three contrasting pressure-temperature-time paths

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Abstract. The field, petrological-mineralogical, geochemical and geochronological data of the metamorphic sole rocks recorded beneath the Fruška Gora, Povlen (Tejići), Stolovi and Banjska ophiolites in the Western Vardar Zone (WVZ) and beneath the Zlatibor, Bistrica, Sjenički Ozren and Brezovica ophiolites in the Dinaridic ophiolite belt (DOB) in Serbia are compared. The focus has been made on metabasic rocks formed in contact with the oceanic crust members: cumulate gabbro and basalts of SSZ-type with E-MORB and OIB-signature and more evolved tholeiitic basalts of MOR-affinity.

Amphibole, the major phase formed from the mafic sole components, depending on pressure-temperature conditions exhibits compositional variations. According to mineral assemblages, estimated P–T conditions and ages, the potential P–T paths are given: *high pressure – low temperature blueschist facies* assemblage (7–9 kbar and ~400°C and <300–350°C and 4–8 kbar), recorded only in the metamorphic sole at the Fruška Gora (WVZ); *high pressure – high temperature amphibolite to granulite facies* (8–10 kbar and >700–850°C), recorded in both domains, the WVZ (Banjska) and the DOB (Bistrica, Sjenički Ozren, Brezovica) and *medium pressure – medium temperature amphibolite facies assemblages* (~3.5–7 kbar and >350–650°C) recognized in the WZV (Tejići, Devovići) and the DOB (Zlatibor). The peak metamorphic conditions point to depths of the oceanic lithosphere detachment and its initial cooling at 10–30 km, but the ages and tectonic setting of ophiolites remain poorly constrained. The summarized data may be used as an important key in geodynamic evolution of the Mesozoic Tethyan ophiolites.

Key words: Serbia, Western Vardar Zone, Dinarides, ophiolites, metamorphic sole, metabasic rocks, amphibole, PT conditions, correlation.

Апстракт. Постојећи теренски, петролошко-минералошки, геохемијски и геохронолошки подаци о метаморфним стенама развијеним у подини офиолитског појаса Западне Вардарске Зоне (Фрушка гора, Повлен, Столови и Бањска) и Динарида (Златибор, Бистрица, Сјенички Озрен и Брезовица) у Србији корелисани су и допуњени новим минералошким подацима о амфиболитима Бистрице. Разматрани су само метабазити формирани метаморфизмом стена океанске коре тј. кумулатних габрова и базалта из супра-субдукционих зона са геохемијскит афинитетом обогаћеног MORB-а и OIB-а или више диференцираних толеитских базалта средњоокеанских гребена.

Разлике у саставу амфибола, главне минералне фаза метабазита, последица су услова метаморфизма и карактера протолита. На основу минералног састава, P–T услова и старости метаморфизма, издвојена су три потенцијална P–T–t метаморфна градијента:

– *високих притисака–ниских температура: асоцијација блушист фације* (7–9 kbar, T ~400°C и <300–350°C, P 4–8 kbar; 123 ± 5 Ma); забележена је једино у метаморфном ореолу Фрушке Горе (Западна Вардарска зона);

– *високих притисака и температура: гранулитска до амфиболитска фација* (8–10 kbar и >700–850°C; 146 ± 4.9 Ma – 174 ± 14 Ma); асоцијација забележена у метаморфном ореолу Бањске (Западна Вардарска зона), Бистрице, Сјеничког Озрена и Брезовице (Динаридски офиолитски појас).

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– *средње високих притисака и средњих температура:* амфиболитска фација (~3.5–7 kbar и >350–650°C; 160–178.3 ± 6.7 Ma), забележена у Тејићима и Девовићима (Западна Вардарска зона) и на Златибору (Динаридски офиолитски појас).

P–T услови метаморфизма указују на „одвајање“ океанске литосфере и почетак хлађења на дубини од 10–30 km, али су тектонске средине и старост метаморфизма за поједине локалности и даље недовољно проучене. Приказани подаци су важни за тумачење геолошке еволуције Мезозојских офиолита Тетиса.

Кључне речи: Србија, Западна Вардарска зона, Динариди, офиолити, метаморфне стене, метабазити, амфиболи, P–T услови, корелација.

Introduction

Numerous ultramafic sequences worldwide comprise high to medium and low grade metamorphic sole rocks formed during the overthrusting of hot lithospheric fragments in intra-oceanic settings or within orogenic belts. Their presence is the clue in clarifying the nature of emplacement processes during intra-oceanic subduction and post-obduction tectonic events. The creation of metamorphic sole is among the earliest event at the end of magmatic construction when tectonic processes take part in ophiolite evolution instead of igneous (JAMIESON 1986; GARFUNKEL 2006). The size of metamorphic sole, its age, thermal evolution and peak metamorphic condition can enable a better insight into the age and thermal properties of the ophiolite sequences during their emplacement. Moreover, it is of key importance in proceedings related to the ocean-realm evolution.

Well to slightly evolved metamorphic sole rocks occur beneath most of the Jurassic Tethyan-type ophiolites in the Western Vardar Zone (WVZ) and in the Dinaridic belt (DOB) in Serbia. The best preserved metamorphic sole rocks crop out within the DOB in association with the Zlatibor, Bistrica, Sjenički Ozren and the Brezovica ophiolites, and in the WVZ in association with the Fruška Gora (FG), Maljen, Povlen (Tejići), Stolovi and the Banjska ophiolites (Fig. 1). The majority of them comprise approximately 100–250 m thick assemblage of metasediments associated with high to medium grade metabasites.

The goal of this contribution is to make correlation sole amphibolites evolved beneath two ophiolite belts i.e. the DOB and the WVZ, on the basis of available geological, geochemical and geochronological data contributed with some new data related to the garnet amphibolites of Bistrica.

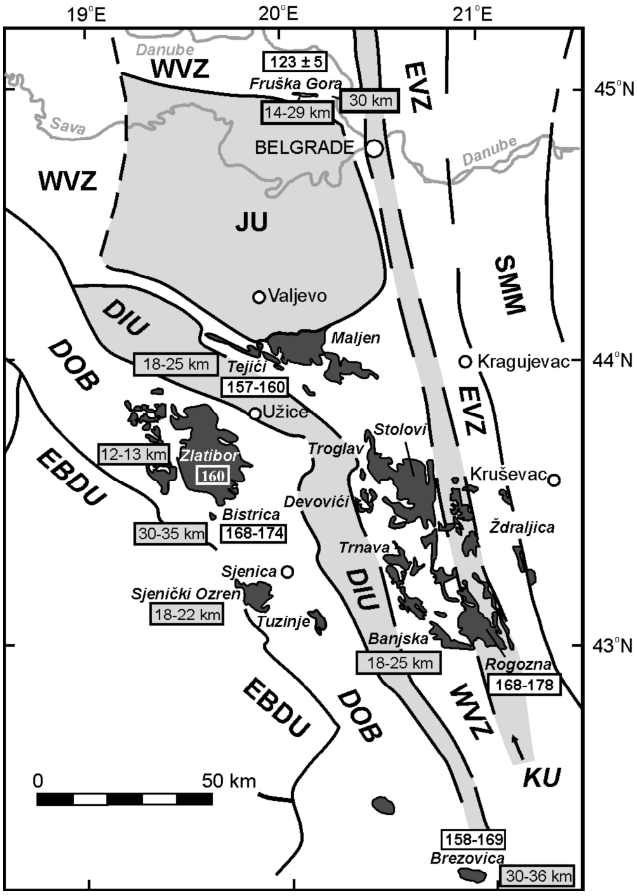

Fig. 1. The ultramafic massifs of Serbia in the geotectonic framework of KARAMATA (2006) with K–Ar radiometric ages of their metamorphic sole rocks and depths realized according to P-T condition of metamorphism. Abbreviation: **EBDU**, East Bosnian Durmitor Unit; **DOB,** Dinaride Ophiolite Belt; **DIU,** Drina Ivanjica Unit; **WVZ,** Western Vardar Zone ophiolite belt; **JU,** Jadar Unit; **KU,** Kopaonik Unit; **EVZ,** Eastern Vardar Zone ophiolite belt; **SMM,** Serbo-Macedonian Massif.

Geological setting

The closure of the Tethyan oceanic realm in the Central Balkan Peninsula since Early Jurassic time was followed by subduction of the oceanic lithosphere along convergent continental margins or within supra-subduction oceanic environments (KARAMATA 2006; ROBERTSON *et al*. 2009, and references there in).

The NNW–SSE trending WVZ represents a large "suture zone" exposed between the Drina–Ivanjica, Kopaonik and the Jadar Units, which continues further northwest (close to Zagreb, Sava Zone of PAMIĆ 2002) and crops out in isolated mountains (Fruška Gora, Požeška Gora and Prosara) northwest of Belgrade. To the south it extends between the Pelagonian and the Paikon Unit. The WVZ is made of various dismembered ultramafic masses generally harzburgitic (± spinel) in composition with 160 to 123 Ma aged metamorphic sole at their base – mainly amphibolites and subordinated blueschists, gneisses, mica schists and greenschists (KARAMATA *et al*. 2000; MILOVANOVIĆ *et al*. 1995; SREĆKOVIĆ-BATOĆANIN *et al*. 2006; BAZYLEV *et al*. 2009; KORIKOVSKY *et al*. 2000a).

The NW–SE trending DOB is bordered by the Drina–Ivanjica Unit to the east and the WVZ to the northeast and extends to the Dinaridic Carbonate platform to the west and related units to the southwest (Fig. 1). Southwards it enters Metohija Depression and continues to Albania and Greece. The dismembered ultramafic bodies are interpreted as fragments of subcontinental mantle or as supra-subduction (back arc) type. The former is mostly lherzolitic (± garnet) and the latter is lherzolitic (± spinel)-harzburgitic in composition (BAZYLEV *et al*. 2006a, 2009). The metamorphic sole at their base comprises high to medium grade amphibolites (rarely granulite) of 168 ± 1 Ma age (LANPHERE *et al*. 1975).

Material and Methods

Samples of amphibolites (with ± garnet) from Bistrica were investigated under the microscope and afterwards the freshest samples were selected for further study. Morphologies and chemical composition of mineral phases were identified using a JEOL JSM-6610LV Scanning Electron Microscope that was connected to an X-Max large Area Analytical Silicon drift in the Faculty of Mining and Geology in Belgrade. Quantitative mineral analyses were performed under high vacuum conditions, acceleration voltages 20 kV, step sequence 10 mm and external set of standards characteristic for each element. Mineral abbreviation used in text is done after KRETZ (1983).

Metamorphic soles of the WZV and DOB: an overview

In the Vardar Zone Ophiolite Belt the metamorphic sole rocks were noted at its northernmost (Mt. Fruška Gora, MILOVANOVIĆ *et al*. 1995), western (Massif Povlen, the village Tejići; SREĆKOVIĆ-BATOĆANIN *et al*. 2002), central (Massif Stolovi, the village Devovići; POPEVIĆ 1973) and southern parts (Massif Banjska, KORIKOVSKY *et al*. 2000a; Rogozna Massif, PALINKAŠ *et al*. 2008).

The metamorphic soles within the Serbian part of the DOB are evolved in contact with ultramafics at the Mt Zlatibor (ĆIRIĆ, 1968; KORIKOVSKY *et al*. 2000b; BAZYLEV *et al*. 2009), Bistrica (MAJER, 1972; POPEVIĆ & PAMIĆ 1973; POPEVIĆ & KARAMATA 1993; MILOVANOVIĆ, 1988; MILOVANOVIĆ *et al*. 2008; BAZYLEV *et al*. 2006a) and Brezovica (KARAMATA 1968; KARAMATA & MILOVANOVIĆ 1990; KARAMATA *et al*. 2000).

The metamorphic sole rocks beneath the WVZ ultramafics

Mt. Fruška Gora. The metamorphic sole rocks crop out on the southern slope of the mountain inside the mélange composed of large blocks and fragments of sedimentary, igneous and volcaniclastic rocks set in a very low to low grade metamorphosed clayey-sandy matrix. Their age ranges from Triassic to Jurassic––Cretaceous (pre-Maastrichtian). Elongated dismembered ultramafic bodies, spinel harzburgitic (rarely lherzolitic) in composition, form the southern slopes of the mountain in the area Bešenovo–Jazak–Grgurevac. The smaller bodies of serpentinized harzburgite and dunite crop out at the northern slopes in the area between Beočin and Sremski Karlovci, also. Blocks and fragments of terrigenous and volcaniclastic rocks as well as basalts and rarely carbonate rocks from mélange were exposed to various metamorphic grade and transformed into phyllites, sericite-chlorite schists, green schists, metabasalts, metadolerite, calcschists, rarely marbles and blueschists (ALEKSIĆ & ČUČULIĆ-TRIFUNOVIĆ 1972; MILOVANOVIĆ *et al*. 1995; KORIKOVSKY & KARAMATA 2011). The actual size of these blocks cannot be estimated due to insufficient exposure of ultramafics and mélange.

Subduction related high pressure-low temperature metamorphic sole rocks were determined as crossiteschists by MILOVANOVIĆ *et al*. (1995) and later as glaucophane-riebeckite-pumpellyite-actinolite-epidote schists by KORIKOVSKY & KARAMATA (2011). They occur as large blocks on the northeastern slope of Mt. (stream Selište, ~2 km northern of the town Sremski Karlovci,) and on the western slope within the Upper Jurassic–Lower Cretaceous olistostrome mélange (KORIKOVSKY & KARAMATA 2011) as well as pebbles within the Maastrichtian basal conglomerates (e.g. Čitluk stream). The amphibole in the first occurrence is classified as crossite according to the classification of LEAKE *et al.* (1978). MILOVANOVIĆ *et al.* (1995) considered the mineral assemblage epidote + sodic amphibole + quartz to be formed under the epidote-blueschist subfacies or high-T epidote bearing segment of blueschist facies (see EVANS 1990) i.e. at the temperature of approximately 400°C and pressure 7–9 kbar. This pressure corresponds to metamorphism at a depth of about 30 km.

This study reveals the subduction of the oceanic crust of the Vardar Ocean during the Early Cretaceous time (Barremian–Aptian; 123 ± 5 Ma), probably beneath the continental crust situated northeast, which argues the existence of an eastward dipping subduction zone. The second occurrence contains zonal Na-amphibole of the glaucophane–riebeckite series, actinolite, pumpellyite, epidote, chlorite, and rarely quartz. KORIKOVSKY & KARAMATA (2011) suggested that the mélange rocks along with the high-Ti subalkaline basalts and associated K-rich quartz–mica arkoses were buried to depths of 14–29 km by cold subduction. The same authors assumed that at pressure of 4–8 kbar and temperature below 340–350°C the mentioned rocks were transformed into glaucophane (riebeckite)–pumpellyite–actinolite–epidote–chlorite metasandstones and phyllites with high-pressure Mg–Si phengite.

Mt. Povlen (Tejići). The metamorphic sole rocks occur within an olistostrome mélange as fragments or large blocks beneath the ophiolite slab, which is exposed as a narrow, approximately 200 m wide and 800 m long zone. The ophiolite sequence, mainly composed of harzburgite (minor lherzolite) with typical tectonite fabric, gabbro, diabase and pillow-basalt associated with volcanic breccias and tuffaceous rocks, is tectonically emplaced to its present position during the late Upper Jurassic.

The metamorphic sole comprises greenschist to amphibolite facies mineral assemblages created by metamorphism of basic igneous rocks and their volcaniclastics along with sandy-silty (argillaceous) sediments. The low-grade metamorphic rocks are various greenschists, while higher-grade metamorphic rocks (garnet bearing amphibolite, amphibolite sensu stricto and epidote-bearing amphibolite) are exposed at the base of the ultramafic sequence (mostly harzburgite). Amphiboles within higher-grade metamorphic rocks are tschermakite, rarely magnesio-hornblende; primary plagioclase is almost completely replaced by epidote and prehnite whereas garnet porphyroblasts are almandine-rich. Biotite, chlorite, and actinolite are formed at the expense of amphibole due to retrograde metamorphic conditions. Amphibolitic rocks are followed by large blocks or fragments of augen gneisses and garnet mica schists metamorphosed under P–T condition of 435–550°C and 4.5 ± 0.5 kbar (SREĆKOVIĆ-BATOĆANIN & VASKOVIĆ 2000). The P–T conditions of amphibolites estimated for a Grt-Hbl pair using the method of GRAHAM & POWELL (1984), POWELL & HOLLAND (1985) and PERCHUK & LAVRENTEVA (1985) reveal a temperature range of 630 to 680°C and pressure of 6 ± 1.5 kbar (SREĆKOVIĆ-BATOĆANIN *et al*. 2002). The K–Ar age of sole rocks of 160–150 Ma (Tithonian/Callovian) reveals the time when protoliths were overthrusted by the hot ultramafic slab, and the beginning of the closure of the ocean basin (SREĆKOVIĆ-BATOĆANIN *et al*. 2002, 2010). The presence of metaclastic rocks assembled with metabasic rocks reveals the site of emplacement close to a major landmass. The presence of amygdales in pillow basalts and lack of deep water sediments additionally confirm this statement.

Devovići (Ušće). On the southwestern slope of the large Ibar ultramafic mass (Massif Radočelo), 5 km distant from Ušće, the metamorphic sole appears in a narrow tectonic zone (0.3–0.4 km wide and ~1 km long) within the serpentinized spinel harzburgite. A dense alternation of various low and medium to high grade metamorphic rocks derived from rocks of the diabase-chert formation were identified (POPEVIĆ 1973). Based on mineral assemblages in amphibolites next to ultramafics a temperature of about 600°C is suggested. The whole sequence subsequently underwent retrograde metamorphism. Data related to whole rock- and mineral chemistry are lacking.

Banjska. The Banjska Massif (20 × 8 km) is a relatively large body composed of clinopyroxene-poor spinel lherzolite (BAZYLEV *et al*. 2009). The metamorphic sole is developed as a zone of almost 20 m wide and 2 km long. It comprises high grade metamorphic rocks: clinopyroxene and/or hornblende (± clinozoisite) amphibolites with thin bands of garnet-cordierite-sillimanite gneiss (MAJER *et al.* 1979; KORIKOVSKY *et al*. 2000a). Most of them underwent retrograde metamorphism and Fe–Mg–Ca metasomatic processes (KORIKOVSKY *et al*. 2000a). The high-temperature amphibole from amphibolites with up to 1.9% TiO_2 is classified as pargasite-tschermakite-hastingsite. Due to retrograde greenschist facies overprint it is mostly replaced by actinolite ± epidote. Replacements by chlorite ± sericite in garnet and cordierite, and plagioclase by saussurite or prehnite and pumpellyite have been noted. According to the garnet-biotite and garnet-cordierite thermometer of PERCHUCK (1989) and garnet-cordierite-sillimanite-quartz barometer of ARANOVICH & PODLESSKII (1989) gneisses formed within the temperature range of 650°C to 760–780°C at pressure of 6.7–6.9 kbar (KORIKOVSKY *et al*. 2000a). Pressure estimates are compatible with the arrangement of jadeite isopleths in clinopyroxene in the clinopyroxene-plagioclase-quartz assemblage after HOLLAND (1980) indicating the depth of the initial cooling and the onset of tectonic stabilization of the ultramafic mass at 24–25 km.

Troglav. The Troglav Massif mainly consists of spinel harzburgite. Dunite and spinel lherzolite are subordinated. POPEVIĆ (1978) assumed that the Stolovi (east of the Troglav) and the Troglav represent parts of one large massif separated by the Ibar River valley. The metamorphic sole at its base has not yet been studied.

Rogozna. Metamorphic sole at the Rogozna Massif formed from basic igneous and sedimentary rocks mostly comprises schistose amphibolites and greenschists. Rare occurrences of mica schists and marbles are also noted. Rocks are highly hydrothermally altered during the Oligocene Pb–Zn–Ag mineralization processes. Amphibolite samples collected near the Crnac Pb–Zn–Ag mine and along the road section Jošanička creek – Leposavić consist of hornblende (replaced by secondary chlorite and fibrous actinolite) and plagioclase, partly replaced by epidote and prehnite (PALINKAŠ *et al.* 2008). The Ar–Ar ages determined on amphibole and actinolite vary from 168.8 ± 3.9 Ma to 178.3 ± 6.7 Ma; the age of the hydrothermally altered amphibolite is 150.4 ± 10.2 Ma. This age implies the onset of intra-oceanic subduction-obduction processes (Lower to Middle Jurrasic i.e. Toarcian to Bajocian time) synchronous with the formation of Dinaridic and Albanian metamorphic soles (PALINKAŠ *et al.*, loc.cit.).

The metamorphic sole rocks beneath the DOB

Mt. Zlatibor. Metamorphic sole rocks related to the Zlatibor ultramafic mass (20 × 30 km) are found in a few localities: Braneško Polje, Čajetina–Rudine and Rožanstvo. The weakly to moderately serpentinized lherzolitic body of the Zlatibor massif comprises cumulate gabbros at the top of the section (Rzav River), mantle tectonite and subordinated dunite, while the southern and southwestern parts are harzburgitic in composition (POPEVIĆ *et al.* 1996a; PAMIĆ & DESMONS, 1989; BAZYLEV *et al.* 2006a, 2009).

An inverted metamorphic sole (150–200 m thick), mostly composed of metabasic rocks with subordinated gneisses and phyllites is exposed beneath the central part of the Zlatibor massif along the road section Čajetina–Rudine. Three temperature zones are recognized within it: I. hornblende–clinopyroxene–plagioclase, II. hornblende–chlorite–albite and III. actinolite–prehnite–pumpellyite (KORIKOVSKY *et al.* 2000b). Amphibole from metabasic rocks is tschermakite. According to the Grt-Pl thermometer of BLUNDY & HOLLAND (1990) the temperature range of 550–650°C is calculated for the first zone. In the second zone the temperature is estimated at 400–500°C based on the Grt-Phn thermometer of GREEN & HELLMAN (1982). For the third zone a temperature range of 300–350°C is assumed according to the petrogenetic grid for metabasic rocks within an accepted pressure of 3 to 3.5 kbar (after LIOU *et al.* 1987). The roughly estimated pressure according to Jd- concentration in clinopyroxene (after HOLLAND, 1980) is 3–3.5 kbar, too. It seems that this massif was tectonically stabilized and started to cool at much shallower depths (12–13 km) than the other Serbian ultramafic massifs (KORKOVSKY *et al.* 2000b).

Bistrica. A small isometric tectonic block exposed to the south of Zlatibor Mt. is mainly composed of massive coarse-grained spinel lherzolite (northern part), and lherzolites with layers and veins of porphyroblastic harzburgite (southern part). Veins of garnet clinopyroxenite and spinel hornblendite are also common. Ultramafic and underlying metamorphic sole rocks are predominant lithologies. This massif is assumed to be of subcontinental mantle origin (POPEVIĆ & KARAMATA 1993; BAZYLEV *et al.* 2003, 2009). Various high to medium grade metamorphic rocks crop out along the road section Priboj–Prijepolje: garnet bearing mafic granulites, garnet ± clinopyroxene amphibolite, corundum-plagioclase-pargasite amphibolite, and massive to schistose amphibolites sensu stricto (Fig. 2). A number of studies were carried out on these rocks: MARIĆ (1933), PAMIĆ & KAPELER (1970), POPEVIĆ (1970), MAJER (1972), POPEVIĆ & PAMIĆ (1973), LANPHERE *at al.* (1975), MARKOVIĆ & TAKAČ (1985), MILOVANOVIĆ (1988). Recently, CHIARI *et al.* (2011) reported some new data related to the fabric of amphibolite varieties and the chemistry of amphibole, garnet, and clinopyroxene. Garnet-pyroxene amphibolites underwent metamorphism within a temperature range of 828–879°C and pressure of about 10 kbar (MILOVANOVIĆ 1988), while FED'KIN *et al.* (1996) calculated temperatures of 740 to 830°C and pressure of 8 to 10 kbar using the Cpx-Grt equilibrium. MILOVANOVIĆ *et al.* (2008) reported edenitic hornblende from the corundum- bearing amphibolite and cumulate gabbro protoliths (P–T conditions are estimated at >0.8 GPa and >800°C), while CHIARI *et al.* (2011) classified amphibole in the same rocks as pargasite/edenite. BAZYLEV *et al.* (2006b) reported an age of 146.8 ± 4.9 (Nd-Sm isochron age) for a garnet-plagioclase clinopyroxenite (Jurassic–Cretaceous boundary). The K–Ar age of 178 ± 14 Ma is obtained for garnet pyroxene amphibolites and corundum pargasite amphibolites (LANPHERE *et al.* 1975; MAJER & KARAMATA 1979).

Sjenički Ozren. This ultramafic massif (10 × 15 km) consists of spinel and plagioclase lherzolites in a nearly equal amount. The former comprises dunite, depleted spinel lherzolite and harzburgite; while within the latter a small gabbro bodies and thin veins occur (POPEVIĆ 1985; POPEVIĆ *et al.* 1996b; BAZYLEV *et al.* 2006b). The metamorphic sole up to 200 m thick is exposed in a few localities at the mountain's NNE and SE margin: Krajinovići, Brdo, Zmajevac, Gonje and Marina Ravan. Its contact with the ultramafics is tectonic and often followed by blastomylonitization, which led to the formation of low temperature minerals at the expense of primary minerals. In the contact aureole four zones were distinguished (POPEVIĆ, 1985; POPEVIĆ *et al.* 1996b; KORIKOVSKY *et al.* 1996). The fourth zone, next to the contact, is made up of garnet-clinopyroxene amphibolites, while further amphibolites sensu stricto, gabbro-amphibolites and greenschists occur. According to Grt–Cpx geothermometer of AI (1994) amphibolites of the fourth zone formed in the temperature range of 750–830°C at pressure of about 5–6 kbar, corresponding to depths from 18 to 22 km (KORIKOVSKY *et al.* 1996). The peak metamorphic conditions imply the emplacement of the Sjenički Ozren ultramafic mass in a solid-subsolid state (over 1000°C).

Brezovica. The Brezovica massif represents an accretionary complex interpreted as a sub-ophiolitic block-in-matrix type sedimentary mélange or an ophiolitic rock-bearing olistostrome with a peridotite tec-

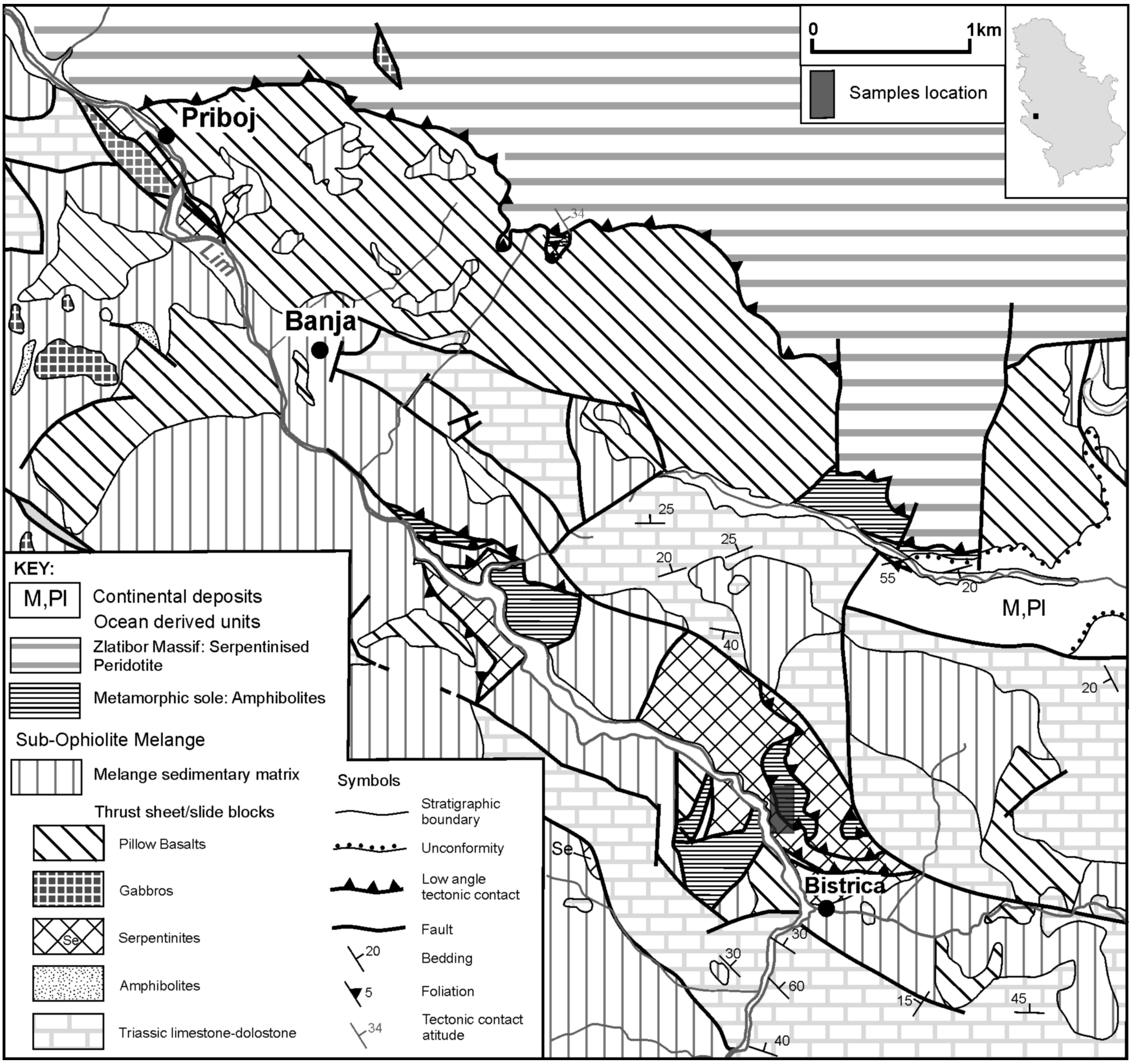

Fig. 2. Geological map of Bistrica–Priboj area: according to Basic Geological Map of former Yugoslavia, scale 1: 100 000 – Sheet Prijepolje (ĆIRIĆ *et al*. 1980) and CHIARI *et al*. (2011).

tonic sheet set up over it (KARAMATA 1968, 1985; KARAMATA *et al.* 1991, 2000; BAZYLEV *et al*. 2003). Blocks and fragments of sediments and basic igneous rocks placed in silty-shaly matrix compose the mélange, up to 1000 m thick. Ultramafics are generally spinel harzburgites, while dunites (± spinel) and layered cumulate rocks are subordinated. A well evolved metamorphic sole (200–500 m wide) occurs beneath. The local study of some of these rocks and minerals dates back to the works of many authors (e.g. MAJER 1956, 1978; KARAMATA 1974, 1979, 1985; SCHREYER & ABRAHAM 1977; ABRAHAM & SCHREYER 1976; MAJER & KARAMATA 1979; KARAMATA & MILOVANOVIĆ 1990; ĆIRIĆ & ERIĆ, 1996).

Within the metamorphic sole KARAMATA *et al.* (2000c) distinguished three zones. The *first zone* (30–50 m wide), next to peridotite, consists of garnet (± clinopyroxene) amphibolites and garnet-kyanite gneisses. Amphiboles in garnet amphibolites are classified as pargasite, hornblende, hastingsite and tschermakite following the classification of LEAKE *et al.* (1997). Using the Grt–Cpx, Grt–Pl and Grt–Bt thermometers (see Table 3 for references) temperatures of 700–750°C and 600–670°C and pressure of 8–9 kbar (employing maximum concentration of jadeite component in clinopyroxene) were estimated. The *second zone* (50–200 m) includes various schistose metamorphic rocks: metabasite with pargasite, tschermakite and edenite; Na-rich pargasite or barroisite garbenschiefer with almandine-rich garnet and phengite (maximum Si content of 3.5 apfu at Mg + Fe = 0.9) which points to pressure of 8–9 kbar; magnetite-bearing metacherts with riebeckite (acmite) needles, chlorite and paragonite; gneisses; talc + phengite metapelites (white schists of ABRAHAM & SCHREYER 1976) an indicator of high pressure (7–9 kbar). Based on the Grt-Hbl, Grt-Phn and Grt-Bt thermometers a temperature of 500–600 °C is estimated (see Table 3 for references). The rocks of this zone underwent retrograde metamorphic imprint reflected in replacement of Bt → Ms + Chl, Grt → Chl, St → Ser, Ky → Ser and by rims of secondary riebeckite around amphibole grains. The *third zone* mostly consists of low temperature metabasites having actinolite (edenite), hornblende or pargasite (winchite)-barroisite amphiboles; metagreywackes and garbenschiefers with Si-rich phengite assembled with barroisite ± pargasite and metacherts with Na-clinopyroxene (acmite-augite-jadeite). Temperatures of 350–500°C were estimated according to Grt–Chl, Grt–Phn, and Grt–Hbl thermometers, while pressure of 7–9 kbar was predicted based on the presence of high-Si phengite (see Table 3 for references). The country rock outside the aureole underwent a very low temperature- high pressure (300–350°C and 7–10 kbar) regional metamorphism before the emplacement of the hot ultramafic slab.

Discussion

The formation of metamorphic soles is directly related to the emplacement of ultramafics implying the overthrusting of hot oceanic lithosphere within intra-oceanic setting or orogenic belts. According to tectonic setting, relationships with adjacent geological units and main tectonic structures, a few models of sole formation have been recently proposed. Some of them for example are low-angle shearing and overthrusting of oceanic lithosphere in an intra-oceanic environment, overlapping mid-ocean ridge crest, obduction caused by roll-back subduction, transform-activated obduction and shearing superimpose onto an older contact aureole (e.g. KARAMATA 1968, 1988, 2006; KARAMATA & LOVRIĆ 1978; WOODCOCK & ROBERTSON 1977; ROBERTSON & KARAMATA 1994; SPRAY 1984; ROBERTSON & DIXON 1985; JONES *et al*. 1991; PARLAK & DELALOYE 1999; ROBERTSON & SHALLO 2000; WAKABAYASHI & DILEK, 2000; ROBERTSON *et al.* 2009). The field, petrological-mineralogical, geochemical and geochronological (K–Ar, Ar–Ar, U–Pb, Sm–Nd) studies of the evolved metamorphic sole rocks reveal valuable data on thermal conditions during intra-oceanic thrusting or during obduction onto passive continental margin.

Comparison of metamorphic sole rocks recorded in the WVZ and the DOB in Serbia offer data on the nature and emplacement of Mesozoic Tethyan ophiolites. However, each metamorphic sole as noted above relies on its own tectonic, structural and metamorphic characteristics. The focus of our comparison has been made only on mafic precursors from which various types of high to medium grade metamorphic rocks were formed.

Comparison of petrography and mineral composition

It can be recognized from the previous section that different species of amphibole are the major phase formed at the expense of the mafic sole components (Fig. 3). Depending on the conditions attained during the ophiolite emplacement a variety of metamorphic rocks were formed close to the contact (e.g. garnet and amphibole bearing granulite, clinopyroxene ± garnet amphibolite, corundum-bearing amphibolite, amphibolite sensu stricto and blueschist). Further from the contact a number of medium to low grade metabasic rocks have formed. Foliation within the last is defined by an arrangement of idiomorphic to sub-idiomorphic amphiboles. At the contact with ultramafics some amphibolite outcrops exhibit an alternation of amphibole- and plagioclase-rich bands (e.g. Tejići, Zlatibor, Bistrica, Brezovica). Generally, grain size ranges from 1–3 mm, although it can be below 0.5 mm. According to the available data the amphibole chemistry shows compositional variations with increasing temperature and pressure, ranging from actinolite to magnesiohornblende, tschermakite to edenite and magnesiohastingsite (Fig. 3), following the classification of LEAKE *et al.* (1997). Exceptions are blueschists from Mt. Fruška Gora - there amphibole corresponds to ferroglaucophane and magnesioriebeckite or to zonal Na-amphibole (glaucophane-riebeckite formed at the expense of older riebeckite), and corundum amphibolites from Bistrica where amphibole is edenite to magnesio-hastingsite and pargasite in (Fig. 3). The individual amphibole grains are commonly compositionally homogeneous.

The insignificant prograde core-rim variations are observed in amphiboles from Fruška Gora, Tejići, Zlatibor, Sjenički Ozren and Brezovica (KORIKOVSKY & KARAMATA 2011; SREĆKOVIĆ-BATOĆANIN *et al*. 2002; KORIKOVSKY *et al*. 1996, 2000b; CHIARI *et al*. 2011).

In the Fruška Gora area the replacement of riebeckite by glaucophane is characterized by an increase in Al, Mg, and Mg/(Mg + Fe^{2+}) ratio due to partial reduction of Fe^{2+} through the prograde reaction *Rbk* + *Chl* + *Ab*→ *Gln* + O_2. According to their composition the Na-amphiboles from those blueschists belong to a single genetic group (KORIKOVSKY & KARAMATA 2011).

The increase of Fe^{3+} values and decrease in Al_{tot} in some zoned amphiboles from the Tejići, Mt. Zlatibor, and Brezovica amphibolites could be related to

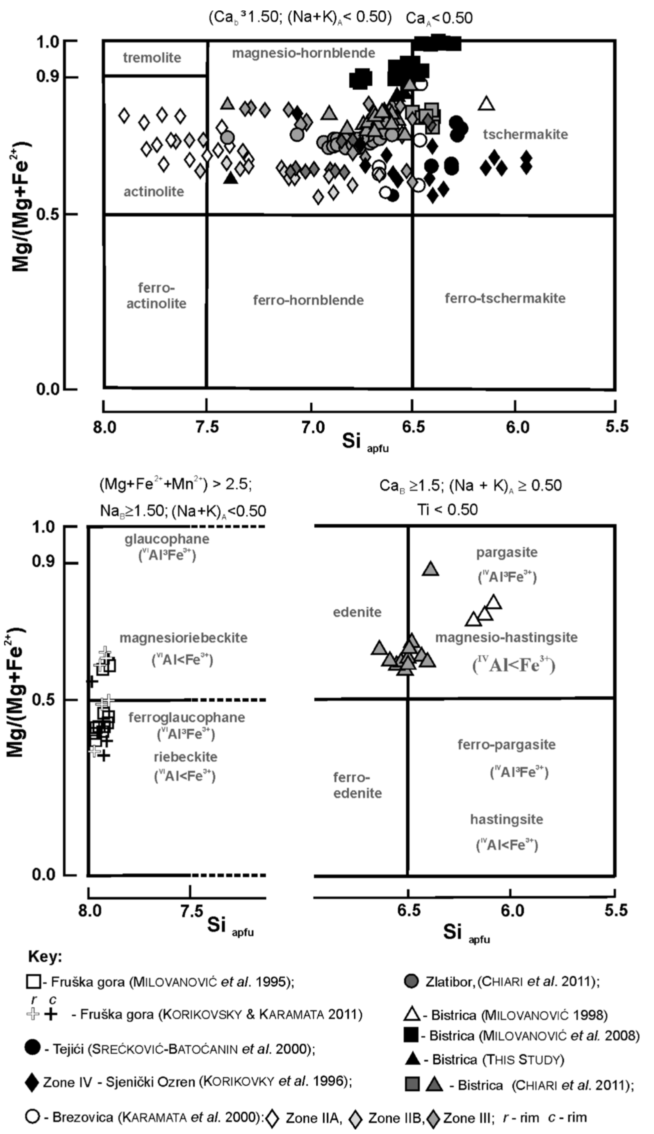

Fig. 3. Classification of amphiboles from the metabasic sole rocks of WVZ and DOB after LEAKE *et al.* (1997).

changes in fO_2 (see SPEAR 1981) during metamorphism. However, the Fe^{3+} content should be taken with caution due to limitation of EPMA to measure Fe^{3+} (see DROOP 1987). The appearance of amphibole within the peripheral parts of the symplectite coronas (cpx + pl) evolved around garnets is noted for the first time in the Bistrica garnet amphibolites (Fig. 4). It is probably related to increase of total Fe content along with decrease of silica as can be seen from the data obtained from the spectrum 3 (Fig. 5). The chemistry of analyzed amphiboles (Table 1) coincides with the data of CHIARI *et al.* (2011): the Si content ranges between 6.52 and 6.72 apfu and $Mg/(Mg+Fe^{2+})$ ratio ranges from 0.782 to 0.793. It must be stressed out that the analyzed amphiboles are compositionally homogenous. The chemistry of amphiboles from the Bistrica garnet amphibolite, presented by MILOVANOVIĆ

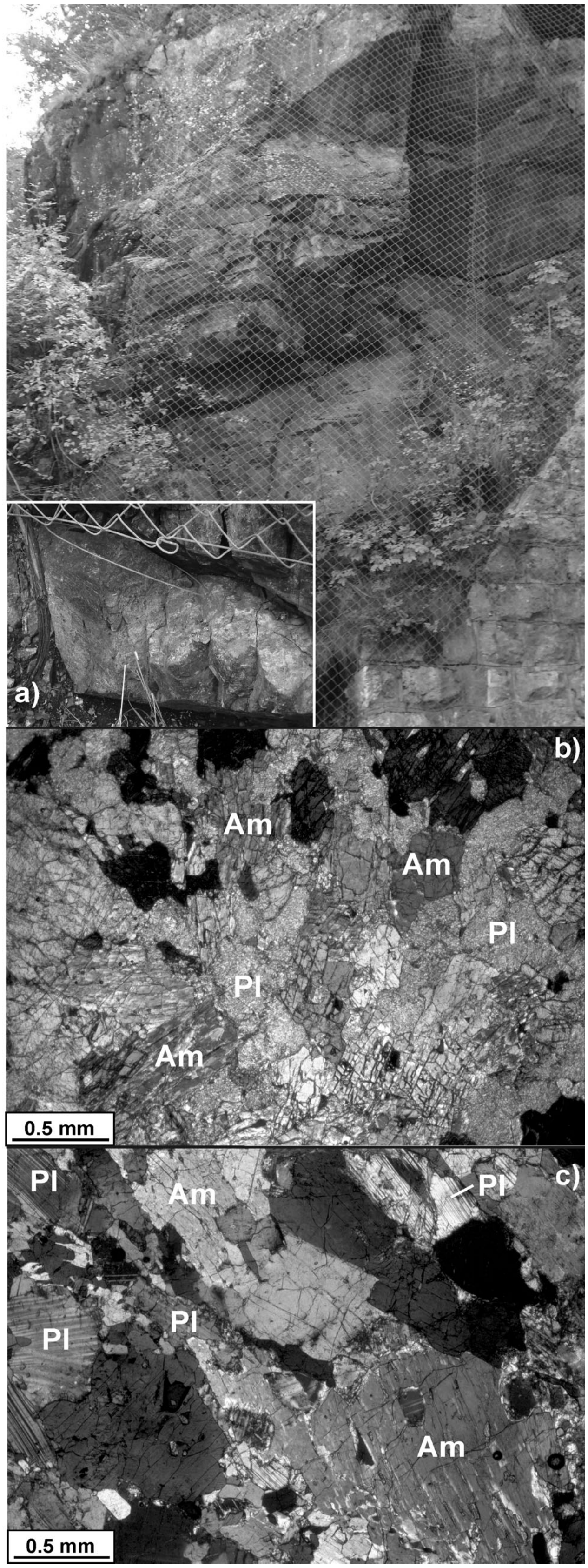

Fig. 4. Outcrop of granulitic amphibolite and garnet amphibolite on the right side of the road, just behind the tunnel (43°28'10.2" N; 19°39'11.4" E) (a); photomicrographs of altered amphibolite having highly saussiritized (b) and fresh plagioclase (c).

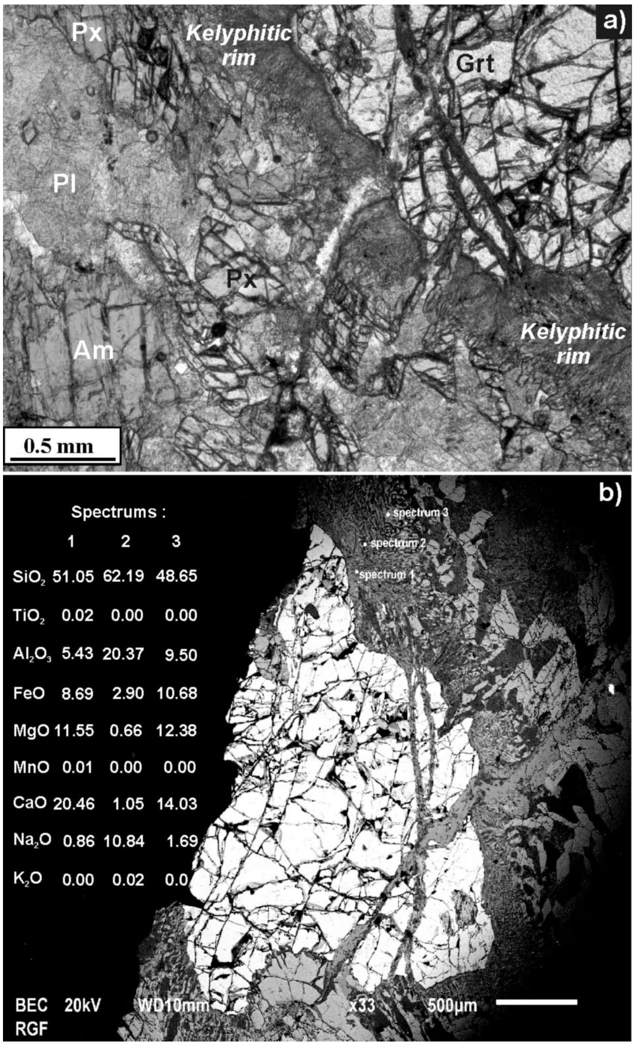

Fig. 5. Microphotograph of the amphibole (Am) with simplectite coronas, clinopyroxene (Px) and garnet (Grt) in granulitic amphibolite from Bistrica (a); Back-scattered image with chemical composition and measured spectrums (1, 2 and 3) within simplectite (b).

(1988), deviates from new obtained data. Only one amphibole has homogenous tschermakitic composition, while the others correspond to magnesio-hastingsite and are characterized by lower Si content per formula unit (6.05–6.14) and higher Al^{VI} (1.88–1.95 apfu), Ti (0.24–0.27 apfu), and Na_A (0.33–0.80 apfu) relative to the previously mentioned ones (Fig. 3). The amphibole grains from the garnet granulitic amphibolites of CHIARI *et al*. (2011) show identical Ti per formula unit (0.22–0.27). The garnet bearing amphibolites have lower Ti concentrations (0.10–0.13 apfu) that correspond to upper amphibolite to lower granulite facies conditions. Amphiboles from the studied amphibolite sensu stricto lack Ti as well as some from garnet clinopyroxene amphibolites of MILOVANOVIĆ (1988). Due to lack of available published data it is not possible to get a real insight into the Bistrica amphibole chemistry. However, an overall impression is that the compositional changes in amphibole are controlled by temperature while the relatively high Al^{IV}/Al^{VI} ratio implies on moderate increase of pressure during metamorphism.

The occurrence of garnet in amphibolites is confined to the upper sections of the metamorphic soles in both ophiolite belts, with the exceptions of garnet-free amphibolites from the metamorphic soles of Rogozna, Devovići, Zlatibor, and Fruška Gora Mt.

The composition of garnet, its distribution and appearance in amphibolites is generally controlled by protolith bulk composition (i.e. Ca content) and by metamorphic conditions. The syn-kinematic and mostly cracked garnet porphyroblasts (<0.5 cm to 1–2 cm across) are commonly assembled with amphibole and often next to plagioclase accumulations or bands (Fig. 4). The appearance of the thin symplectite reaction rim (kelyphitic) in the Bistrica amphibolite taken on the right side of the road section, just behind the tunnel is reported for the first time (Figs. 2, 4, 5). The garnets from Tejići and Bistrica show variable composition ranging between $Alm_{50.5–54.3}Pyr_{18.1–23.3}Grs_{9.2–15}Sps_{10.4–12.1}$ in Tejići to $Alm_{31.5–50}Pyr_{21.5–50.7}Grs_{15.4–24}Sps_{0.9–5}$ in Bistrica (Table 1). The data for garnet chemistry in sole rocks of Sjenički, Ozren and Brezovica are lacking. According to KORIKOVSKY *et al.* (1996) and KARAMATA *et al.* (2000) it is almandine, rich in pyrope component (up to >40 %). All analyzed garnet grains from Tejići are weakly zoned (rims are slightly poorer in pyrope component, 2–4 %) and occasionally occur as inclusions in amphibole. In the Bistrica amphibolites two types of garnet can be recognized: homogenous i.e. unzoned (MILOVANOVIĆ 1988; CHIARI *et al.* 2011), reflecting the compositional equilibration, and zonal with notable increase of pyrope and decrease of almandine and grossularite components from core to rim (FED'KIN *et al.* 1996). The amphibole, clinopyroxene, and plagioclase are found as inclusions in the Bistrica garnets. The observed symplectite coronas around the Bistrica garnets consist of very tiny clinopyroxene, albite and amphibole grains (Fig. 5). The mineral relationships suggest that the garnet mostly grew at the expense of these minerals (higher contents of grossularite).

The clinopyroxene found in the upper part of the metamorphic sole of the Bistrica is diopside, salite and augite following the classification of MORIMOTO *et al.* (1988). It occurs in relic unzoned sub-idiomorphic to xenomorphic grains up to 2–3 mm in size (Fig. 5). Its composition ranges from $En_{37.5–39.9}Fs_{15.2–18.3}Wo_{44.6–47.1}$ to $En_{41.4–42.2}Fs_{7.1–7.9}Wo_{47.4–49.6}$ and $En_{51.7–56.6}Fs_{15.6–19.3}Wo_{27.8–29.0}$ (Fig. 6a; Table 1). The Al_2O_3 content is highly variable, ranging from 3.12 to 6.23 wt.% if we take into consideration the data of MILOVANOVIĆ (1988) and CHIARI *et al.* (2011). The clinopyroxene from analyzed garnet-bearing granulitic amphibolite samples is richer in alumina (7.84 wt.%), but the average of 4.21 wt.% Al_2O_3 (MILOVANOVIĆ 1988) is similar to the value we have obtained in the same rock type (4.83 wt.%).

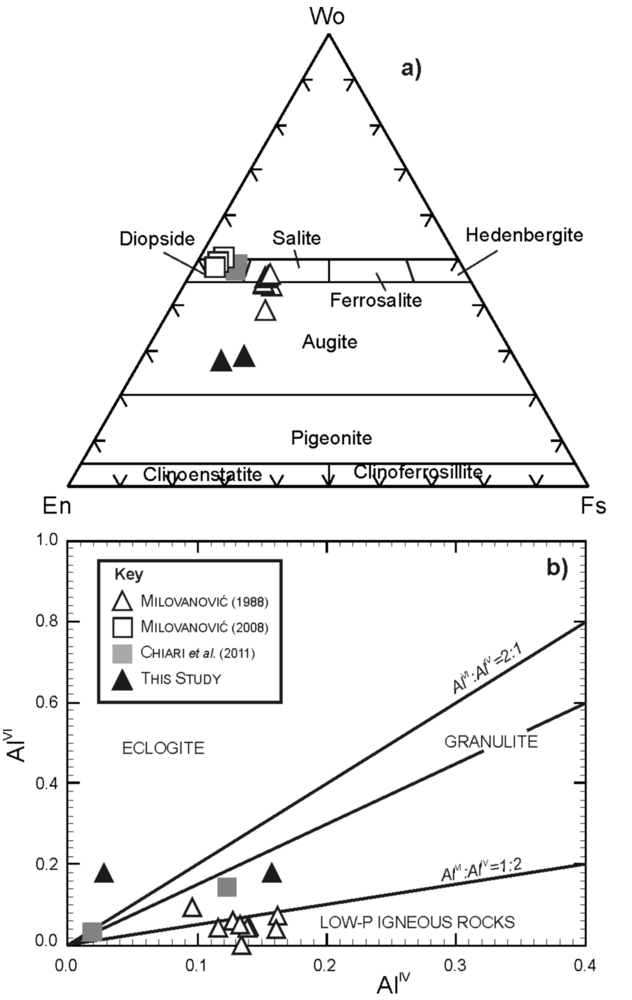

Fig. 6. Composition of clinopyroxenes from garnet bearing granulitic amphibolite and clinopyroxene amphibolite. (a) En-Fs-Wo classification diagram (MORIMOTO *et al.* 1988) and (b) Al^{IV} vs Al^{VI} diagram (MUKHOPADHYAY, 1991).

These differences are probably in close relation with the protolith composition and proximity of the contact zone as can be confirmed by the ratio Al^{IV}/Al^{VI}. This ratio reflects moderate recrystallization of primary clinopyroxene grains within the granulite facies and resulted in Al^{VI} enrichment, i.e. Tschermak component (Fig. 6b). The Jadeite component varies between 9.57 and 8.88 % in average in clinopyroxenes from garnet amphibolites studied by MILOVANOVIĆ (1988). Similar values are found in clinopyroxenes from garnet bearing granulitic amphibolite (9.96 %) while a lower value (6.43 %) is reported by CHIARI *et al.* (2011). MILOVANOVIĆ (1988) has reported also matrix metamorphic clinopyroxene with much lower Al_2O_3 (0.11 wt.%). It should be emphasized that differences in clinopyroxene composition within the Bistrica metamorphic sole could be the result of nonsystematic sampling and use of different analytical techniques. The chemistry of clinopyroxene (associated with garnet) from the Sjenički Ozren amphibolites is similar to the above mentioned – rich in the Tschermak component (i.e. alumina). However, the Al_2O_3 content is higher ranging from 5.8–6.0 wt.% and contain up to 1.3 wt.% Na_2O (KORIKOVSKY *et al.* 1996). The clinopyroxene in the Banjska amphibolite is poorer in Al_2O_3 (1.7–2.1 wt.%) and richer in Jadeite component (6–7 %). The clinopyroxenes in the Brezovica amphibolites are compositionally homogeneous and correspond to high temperature augite with < 8–10 % of Jadeite component (KARAMATA *et al.* 2000). The data of clinopyroxene chemistry for Sjenički Ozren, Banjska, Zlatibor, and Brezovica are not published.

The clinopyroxene is generally associated with plagioclase, amphibole and garnet at the immediate contact with ultramafics and are absent from amphibolite sensu stricto. Therefore, its presence and distribution is a function of bulk rock chemistry and particularly of metamorphic grade. The presence of clinopyroxene in garnet-free assemblages of Zlatibor and Bistrica is probably controlled by protolith Ca abundance. Plagioclase from amphibolites is mostly altered and replaced by prehnite or saussurite (Fig. 4). Albite (0–2 mol.% An), a common constituent of the Tejići garnet amphibolites, is probably formed as a low temperature retrograde phase. Rare unaltered plagioclase found in the Bistrica garnet amphibolite and amphibolite sensu stricto ranges in composition from 58.5–60.2 mol.% An (Fig. 4). MILOVANOVIĆ (1998) reported almost pure anorthite in garnet pyroxene amphibolites, which has been recently classified as garnet bearing mafic granulites (MILOVANOVIĆ *et al.* 2004). FED'KIN *et al.* (1996) found that plagioclase enclosed in garnet has a composition of 30–33 mol.% An while matrix plagioclase is anorthite poor (An 3–4 mol.%) in the garnet clinopyroxene amphibolites. The composition of the plagioclase from the Zlatibor garnet-free amphibolite is 45–50 mol.% An in the contact zone, and 12–15 mol.% An in the mid zone. The plagioclase of the Sjenički Ozren clinopyroxene amphibolite ranges in composition from 50–80 mol.% An (KORIKOVSKY *et al.* 1996). Further from the contact plagioclase is strongly zoned and poorer in An (15–25 mol.%). Generally, in the majority of metabasic rocks occurred further from the contact, the plagioclase have <10–30 mol.% An what enables the determination of P–T conditions.

Correlation of P–T conditions and age of metamorphism

The P–T conditions during metamorphic events are closely related to the thermal properties of the ophiolite sequences and to the rigidity of protoliths. The pressure is directly proportional to the depth. There-

Table 1. Representative mineral chemistry of the Bistrica amphibolites used in thermobarometry.

Amphibole	1	2	3	4	5	6
SiO_2	46.16	46.88	44.21	46.21	46.78	45.98
TiO_2	1.13	1.16	0.00	0.89	0.96	1.05
Al_2O_3	10.88	10.33	11.53	10.95	10.86	11.08
FeO	11.37	11.08	12.71	11.25	11.05	11.65
MnO	0.25	0.00	0.58	0.12	0.21	0.08
MgO	14.66	14.80	13.49	14.58	14.36	14.79
CaO	11.70	11.81	10.73	11.25	11.39	11.38
Na_2O	1.82	1.72	1.86	1.76	1.82	1.77
K_2O	0.19	0.15	0.00	0.08	0.00	0.11
Total	98.16	97.93	95.11	97.09	97.43	97.89
Recalculated on the basis of 23(O)						
Si	6.613	6.719	6.526	6.659	6.720	6.579
Al^{IV}	1.387	1.281	1.474	1.341	1.280	1.421
Sum_T	8.000	8.000	8.000	8.000	8.000	8.000
Al^{VI}	0.450	0.464	0.532	0.519	0.559	0.448
Ti	0.122	0.125	0.000	0.096	0.104	0.113
Fe^{3+}	0.370	0.277	0.731	0.411	0.318	0.507
Mg	3.131	3.162	2.969	3.132	3.075	3.155
Fe^{2+}	0.927	0.972	0.769	0.841	0.944	0.777
Sum_C	5.000	5.000	5.000	5.000	5.000	5.000
Fe^{2+}	0.065	0.079	0.070	0.104	0.066	0.110
Mn	0.030	0.000	0.073	0.015	0.026	0.010
Ca	1.796	1.814	1.697	1.737	1.753	1.745
Na	0.109	0.107	0.161	0.145	0.156	0.136
Sum_B	2.000	2.000	2.000	2.000	2.000	2.000
Na	0.397	0.371	0.372	0.347	0.351	0.355
K	0.035	0.027	0.000	0.015	0.000	0.020
Sum_A	0.432	0.398	0.372	0.362	0.351	0.376
Mg/Mg+Fe	0.76	0.75	0.78	0.77	0.74	0.78

Clinopyroxene	1	2
SiO_2	50.27	54.09
TiO_2	0.87	0.00
Al_2O_3	7.84	4.83
Cr_2O_3	0.18	0.00
FeO	10.71	8.79
MnO	0.00	0.32
MgO	16.04	18.61
CaO	12.53	12.71
Na_2O	1.32	0.49
Total	99.76	99.84
Recalculated on the basis of 6(O)		
Si	1.842	1.953
Al^{IV}	0.158	0.047
Al^{VI}	0.171	0.159
Ti	0.024	
Fe^{3+}	0.018	0.000
Mg (M1)	0.772	0.841
Mg (M2)	0.104	0.160
Fe^{2+}(M2)	0.310	0.265
Mn	0.000	0.010
Ca	0.492	0.492
Na	0.094	0.034
End members		
En	51.7	56.6
Fs	19.3	15.6
Wo	29.0	27.8

Garnet	1	2	3
SiO_2	39.75	38.71	38.65
TiO_2	0.00	0.23	0.00
Al_2O_3	21.70	21.75	21.20
FeO	19.48	19.27	19.08
MnO	1.22	1.32	1.25
MgO	9.66	9.26	6.71
CaO	8.36	8.40	8.34
Total	100.17	98.94	95.23
Recalculated on the basis of 12(O)			
Si	3.000	2.962	3.105
Al^{IV}	0.000	0.038	0.000
Sum_T	3.000	2.962	3.105
Al^{VI}	1.929	1.923	2.006
Ti	0.000	0.013	0.000
Fe^{3+}	0.065	0.083	0.000
Sum_A	1.994	2.018	2.006
Fe^{2+}	1.165	1.151	1.282
Mg	1.087	1.056	0.804
Mn	0.078	0.086	0.085
Ca	0.676	0.689	0.718
Sum_B	3.006	2.982	2.889
End members			
Alm	38.76	38.60	44.38
Andr	3.25	4.00	0.00
Grs	19.25	19.00	24.86
Pyr	36.15	35.43	27.82
Sps	2.59	2.87	2.94

Plagioclase	1	2	3	4
SiO_2	53.49	53.10	52.66	53.01
Al_2O_3	29.92	29.36	30.34	29.96
FeO	0.12	0.25	0.00	0.00
CaO	12.46	12.10	12.27	12.32
Na_2O	4.64	4.74	4.59	4.50
Total	100.63	99.55	99.86	99.83
Recalculated on the basis of 8(O)				
Si	2.406	2.414	2.386	2.401
Al	1.587	1.573	1.620	1.600
Fe	0.005	0.010	0.000	0.001
Ca	0,600	0.589	0.596	0.598
Na	0.405	0.418	0.403	0.395
End members				
Ab	40.3	41.5	40.4	39.8
An	59.7	58.5	59.6	60.2

Explanations:

Amphibole: site assignment and ferric iron contents were calculated using the scheme of SCHUMACHER in LEAKE *et al.* (1997).

Garnet: Fe is recalculated on Fe^{2+} and Fe^{3+} after KNOWLES (1987); End members after DEER *et al.* (1992); End members mineral abbreviation after KRETZ (1983).

Clinopyroxene: site assignment and ferric iron contents were calculated using the scheme of MORIMOTO *et al.* (1988). End members mineral abbreviation after KRETZ (1983).

fore various pressures can indicate various depths of detachment of the oceanic lithosphere as well as the depth of initial cooling. A gradual increase of P–T conditions with advancing movement of the ophiolite slab was recorded in some minerals through changes in their chemistry (e.g. Tejići, Bistrica, Fruška Gora). WAKABAYASHI & DILEK (2000) assumed considerable thinning of ophiolites after the sole formation, in cases when the estimated depths greatly exceed the thickness of ophiolites.

Based on P–T estimates for mineral assemblages in metabasic rocks of the WVZ and the DOB three types of metabasic soles can be distinguished (Fig. 7a, Table 2, 3):

a) high pressure – low temperature blueschist facies assemblage, only recorded in the metamorphic sole at the Fruška Gora (WVZ). A temperature of approximately < 300–350°C and ~400°C and pressure of 4–8 kbar and 7–9 kbar respectively, corresponding to depths of about 14–29 km and 30 km, are estimated. These estimations are based on the petrogenetic grid for low-temperature metabasic rocks of moderate and high pressures of LIOU *et al.* (1987) for the glaucophane-riebeckite + pumpellyite assemblage. This assemblage is controlled by the reactions: *Pmp + Chl + Qtz = Czo + Act* + H_2O and *Pmp + Gln +Qtz = Czo + Act + Ab*+H_2O (see NAKAJIMA *et al.* 1977) and by the stability field of natural glaucophane (MARESH 1977), which is in the upper limit range of 6–9 kbar and 400–450°C. The stability field for Na-amphibole is well constrained at pressure range of 5–9 kbar for the temperature range of 300–600°C (e. g. HOLLAND & POWELL 1988; HOLLAND 1988; HOFFMAN 1972; MARUYAMA *et al.* 1986; BROWN 1974, 1977; BROWN & FORBES, 1986). Generally, in this stability field the composition of Na-amphibole is pressure dependent. Accordingly, the estimation of MILOVANOVIĆ *et al.* (1995) for the assemblage ferroglaucophane (former crossite) + phengite + epidote can be considered realistic. Crossite is pressure dependent and very useful as it divides low-P riebeckite from high-P ferroglaucophane. Although the term crossite is not used anymore for the amphibole nomenclature of LEAKE *et al.* (1997) it was used due to its above described nature.

The K–Ar age of 123 ± 5 Ma for the blueschist implies the Early Cretaceous subduction of the oceanic crust beneath the northeastern continental crust (MILOVANOVIĆ *et al.* 1995).

b) high pressure – high temperature granulite to amphibolite facies characterize the metamorphic soles in both, the WVZ (Banjska) and the DOB (Bistrica, Sjenički Ozren and Brezovica) domains.

At the Banjska domain the chemistry of amphiboles from the metabasic members, (belong to the pargasite-tschermakite-hastingsite series, with up to 1.9 wt.% TiO_2) imply temperature conditions which coincide with the maximum temperature of 760–780°C calculated for the garnet-cordierite-sillimanite gneisses,

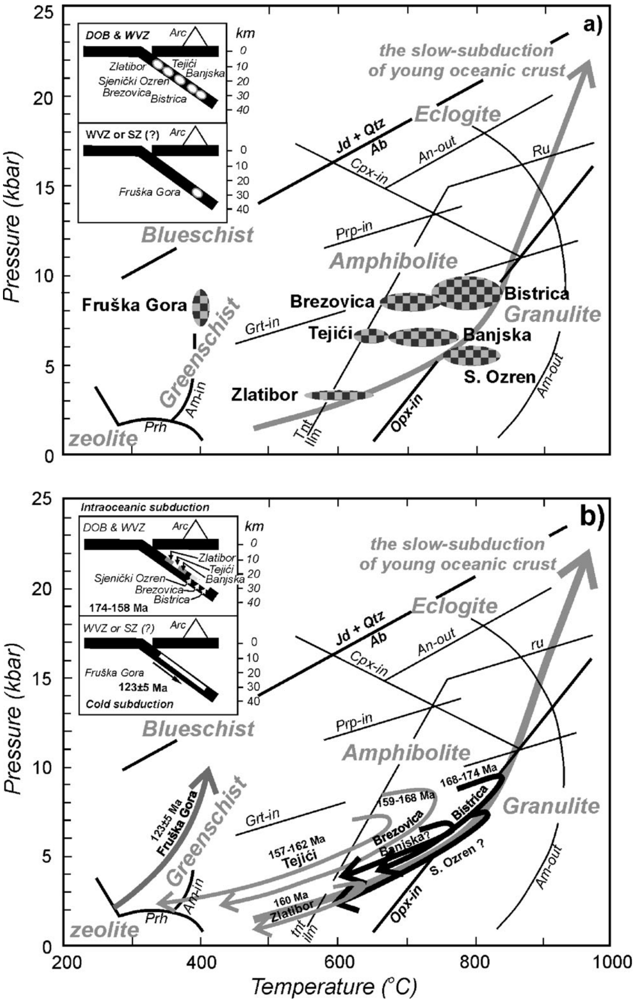

Fig. 7. a) P-T ranges of the metabasic rocks from the WVZ and DOB metamorphic sole. Reaction curves: Am-in, Am-out and Grt-in (ERNEST & LIOU 1998); Prp-in, Jd+Qtz and An-out (GREEN & RINGWOOD 1967); Cpx-in, Opx-in (MUKHOPADHYAY & BOSE 1994); titanite-ilmenite and rutile (LIOU *et al.* 1996); Prh (FREY *et al.* 1991); b) Assumed P-T-t paths for the DOB and WVZ metamorphic sole rocks operated during the intra-oceanic subduction and cold subduction within the northern part of the WVZ or Sava Zone (SZ) – Fruška Gora. Inlet in the upper left corner shows the depth of metamorphism (a) and (b) begining of subduction related to scrutinized domains with different rock types. The P–T–t path of slow-subduction of young oceanic lithosphere is after PEACOCK *et al.* (1994).

which occur as thin layers within the immediate contact with ultramafics (KORIKOVSKY *et al.* 2000a). The pressure of 6–7 kbar, estimated according to the jadeite isopleths in clinopyroxene from the clinopyroxene + plagioclase + quartz assemblages is also in accordance with the pressure calculated for the gneisses using the Grt-Crd-Sil-Qtz geobarometer of ARANOVICH & PODLESSKII (1989). This pressure corresponds to a depth of 24–25 km.

Table 2. Overview of P–T conditions for the metabasic rocks of the WVZ metamorphic soles in Serbia

Location	Rock Type	P kbar	T °C	Geothermometar Geobarometar	Depth km	K-Ar Age (Ma)	Reference
Fruška Gora	Blueschist	7–9 4–9	400 <300–350	PT stability of Na-Am and pumpelyite*	~30 14–29	123 ± 5	MILOVANOVIĆ *et al.* (1985) KORIKOVSKY & KARAMATA (2011)
Tejići	Grt Amphibolite	5.5 ± 1	620–670	T: Grt-Pl (HB) P: Al-in Hbl (HZ)	18–25	160 ± 6.2 157.6 ± 10 160.3 ± 8	SREĆKOVIĆ-BATOĆANIN *et al.* (2002)
Devovići	Amphibolite	no data	600	no data		no data	POPEVIĆ (1973)
Banjska	Cpx amphibolite,	6–7	650–780	P: Jdin Cpx (H) T: Grt-P l(HB);	18–25	no data	KORIKOVSKY *et al.* (2000a)
	Grt-Crd gneiss	6.7–6.9	760–780	T: Grt-Crd & Grt-Bt (P) P: Grt-Crd-Sil-Qtz (AP)			
Troglav	no data						
Rogozna	Amphibolite s.s. Greenschist	no data				168 ± 3.9 178 ± 6.7	PALINKAŠ *et al.* (2008)

Abbreviations: HB – HOLLAND & BLUNDY (1994); A – AI (1994); HZ – HAMARSTROM & ZEN (1986); J – JAQUES (1982); KS – KOHN & SPEAR (1990); P – PERCHUK (1989); 1990; AP – ARANOVICH & PODLESSKII (1989); H – HOLLAND (1980). * – LIOU *et al.* (1987); MARESH (1977); NAKAJIMA *et al.* (1977).

The amphibolites from the Bistrica domain (DOB) were the subject of a few researches. The P–T estimates for garnet-clinopyroxene granulitic amphibolite, garnet amphibolites and corundum-bearing amphibolites are almost consistent and range from 740 to 830°C and 8–10 kbar. The amphibolites sensu stricto are metamorphosed under T–P of 600–650°C and 3.5 to 7 kbar. FED'KIN *et al.* (1996) pointed out that the retrograde stage of the thermal evolution of the Am+Cpx+Pl amphibolite was probably periodically interrupted by tectonic movements caused by the rapid ascent of the Bistrica complex. According to the Am–Cpx–Pl geothermobarometry and estimated P–T changes four phases or depth levels are distinguished. The peak metamorphic condition for the Bistrica garnet-bearing granulitic amphibolite, garnet clinopyroxene amphibolite, and amphibolite sensu stricto is estimated according to the amphibole – plagioclase geothermometer of HOLLAND & BLUNDY (1994). The temperature was calculated for the assumed pressures of 6 to 12 kbar and the pressure estimates were based on the Grt–Am–Pl–Qtz geobarometer of KOHN & SPEAR (1990) for the temperature range of 600 to 900°C. The average P–T value resulted from the intersection of lines for calculated temperatures and pressures (taking into consideration the average error of the applied method). The obtained temperature of 808°C ± 40°C and pressure of 9.5 ± 0.9 kbar corresponds to the lower part of the granulite facies (Fig. 7a). These results are in accordance with the data of MILOVANOVIĆ (1988) and FED'KIN *et al.* (1996).

The K–Ar age of the Bistrica amphibolite ranges from 168 to 174 ± 14 Ma (Table 3). The high PT conditions of the Bistrica garnet pyroxenite and its age of 146 ± 4.9 Ma (Nd–Sm) imply the subduction of oceanic crust ensued by exhumation and cooling in a subduction channel (BAZYLEV *et al.* 2006a): the exhumation can arise during SSZ-spreading and rollback of the subducting oceanic slabs and culminate in tectonic emplacement over a continental margin prior to the Tithonian–Berriasian time (see ROBERTSON *et al.* 2009).

The P–T conditions of the amphibolites comprising Cpx+Am+Pl (up to 80 % An) assemblage from the Sjenički Ozren (DOB) were calculated following the Hbl-Pl thermometer of JAQUES *et al.* (1982). The estimated peak metamorphic conditions of 750–830°C and 5–6 kbar (according to Al-in Hbl geobarometer and high pyrope content in garnet) imply a depth of 18–22 km (Table 3). The age of those amphibolites and of the Banjska metamorphic sole remains unknown.

The inverted zonal metamorphic sole at the subduction-accretion complex of Brezovica (DOB) is characterized by metamorphic imprint of igneous basic rocks to amphibole schists and amphibolite varieties in the temperature range from 350–500°C in the third zone to 500–600°C in the second zone. The maximum metamorphic peak of 600–670°C is attained in the first A zone to 700–750°C in the first B zone at almost isobaric condition (7–9 kbar). On the basis of P–T calculations two subdomains are recognized: the southwestern part with upper amphibolite facies (Borov Vrh, Malo Borče and Jezerina) and the northeastern part with greenschist to medium amphibolite facies conditions (locality Krst). Both show evidence of localized retrogressive reactions related to the subsequent uplift, cooling and thrusting of ultramafics: clinopyroxene and hornblende → actinolite and epidote; garnet → chlorite and epidote; plagioclase → saussurite.

The difference in the temperature imprint of these two subdomains, originally metamorphosed at almost the same depth, suggests that the ultramafic part of a single harzburgite mass had a different temperature. It should be stressed out that garnet, the usual source of information about prograde metamorphism, shows

Table 3. Overview of P-T conditions for the metabasic rocks of the DOB metamorphic soles in Serbia.

Location	Rock Type	P kbar	T °C	Geothermometar Geobarometar	Depth km	K-Ar Age (Ma)	Reference
Zlatibor	Zone I: Cpx Amphibolite	3–3.5	550–650	**T**: Grt–Pl (HB) **P**: Jd-in Cpx (H, G)	12–13	[1]160	KORIKOVSKY *et al*. (2000) [1]KARAMATA & LOVRIĆ (unpublished)
	Zone II: Amphibolite s.s		400–500	**T**: Grt–Phn (GH)			
	Zone III: Greenschist, Act-Prn-Pmp schist		300–350	According to LIOU *et al.* (1987) and SPRINGER *et al.* (1992)			
Bistrica	Grt-Cpx Amphibolite	10	800–1000	**T**: Grt–Hbl (GP; P**); Am–Cpx (P**) **P**: Grt–Cpx (P*)	30–35		MILOVANOVIĆ (1988)
	Grt-Cpx Granulitic amphibolite; Grt Amphibolite	8–10	740–830	**P**: Am–Grt–Pl (KS); Cpx–Pl (P) **T**: Grt–Cpx (A); Am–Pl (HB); Am–Grt (LP)		[1]174±14 170±11 168±8.2 [2]146±4.9 (Nd-Sm)	[1]LANPHERE *et al*. (1975); FED'KIN *et al*. (1996) [2]BAZYLEV *et al*. (2006)
	Amphibolite	3.5–7	600–650				
	Grt-Cpx Granulitic amphibolite	9.5±0.9	808±40	**T**: Hbl–Pl (BH) **P**: Grt–Am–Pl (KS)			this study
	Corund bearing Amphiibolite	> 8	> 800	not specified			MILOVANOVIĆ *et al*. (2008)
Sjenički Ozren	Cpx Amphibolite Amfibolite s.s. Greenschists	5–6	750–830 400–430	**T**: Grt–Px (A) **P**: Al in Hbl (HZ)	18–22		KORIKOVSKY *et al*. (1996)
Brezovica	Zone IB:Grt-Cpx Amphibolite	8–9	750	**T**: Grt–Hbl (J); Grt–Phn (GH), Grt–Bt (FS); **P**: Jd-in Cpx (H)	30–36	[1]169.0±3.2 162.6±3.4 161.5±1.6 162.8±1.9	[1]OKRUSCH *et al*. (1978)
	Zone IA: Grt Amphibolite; amphibolite, garbenschiefer		600–670				
	Zone II: metabasat, amphibolite		500–600	**T**: Grt– Hbl (J) Grt–Phn (GH), Grt–Bt (FS)			
	Zone III: metabasalt, greenschist	7–9	350–500	**T**: Grt–Chl (DH); Grt–Phn (GH); Grt–Hbl (GP; P**); **P**: Si–Phn		[2]158–168	[2]KARAMATA *et al*. (2000)
	Zone IV: Blueschist-metabasite	7–10	300–350				

Abbreviation: HB - HOLLAND & BLUNDY (1994); A – AI (1994); HZ – HAMARSTROM & ZEN (1986); J – JAQUES (1982); KS – KOHN & SPEAR (1990); P** – PERCHUK (1967, 1969, 1970); P – PERCHUK (1989, 1990); AP – ARANOVICH & PODLESSKII (1989); H – HOLLAND (1980), G – GASPARIK (1985); GH – GREEN & HELLMAN (1982); GP – GRAHAM & POWELL (1984); P* - POWELL (1985); DH – DICKENSON & HEWITT (1986) MODIFIED BY LAIRD (1989); FS – FERRY & SPEAR (1978); **T** – geothermometer; **P** – geobarometer.

evidence of prograde zoning growth. It is reflected in an increase of Mg and decrease in Ca component from core to rim. It is almandine rich with up to 24 % of pyrope component in the outer shells in the second to nearly 40 % in the first distinguished zone. Textural and chemical evidence suggest that garnet grew at medium to high temperature and continuously re-equilibrated up to peak conditions.

The K–Ar age measured on the Brezovica amphibolites gave 159–168 Ma (KARAMATA & LOVRIĆ, 1978) and 162–169 Ma (OKRUSH *et al.* 1978).

c) medium pressure – medium temperature amphibolite facies assemblages is found in WVZ (Tejići, Devovići) and DOB (Zlatibor).

At the Tejići domain (WVZ) the Am-Grt geothermometer (Table 2) gave an average temperature range of 620–670°C at an assumed pressure of 5.5 ± 1 kbar. This P–T range is similar to that obtained for the garnet-free clinopyroxene amphibolites in DOB (Table 3). The garnet mica schist displays lower P–T range (500 ± 50°C at 3–5 kbar) and could be assigned to uplift of hot ultramafic body (SREĆKOVIĆ-BATOĆANIN & VASKOVIĆ 2000).

The K–Ar age measured on amphibole and mica ranges from 157.6 ± 10 to 160.1 ± 7.1.

Based on mineral assemblages in amphibolites next to the ultramafic body at the Devovići domain a temperature of about 600°C is reported by POPEVIĆ (1973).

An inverted contact metamorphic aureole underneath the large Zlatibor ultramafic mass comprises three metamorphic zones. A temperature range of 300–350°C and pressure of 3–3.5 kbar for the third marginal zone (actinolite + pumpellyte + prehnite) is assumed using the petrogenetic grid for low temperature metabasites of LIOU *et al.* (1987). The remarkable progressive change in mineral assemblages within metabasites is realized in the transition to the second zone. It is characterized by the break down of pumpellyite and prehnite, replacement of actinolite rim by tschermakite, appearance of phengite (Si up to 3.38–3.41 apfu, MgO up to 3.3 wt.%, FeO up to 2.9 wt.%), and an increase of anorthite component in plagioclase (7–15 %). The presence of rare intercalations of phyllites and paragneisses in metabasic members with mica and garnet (4–16 % of pyrope component from core to rim and decrease of grossular from 21–8 % and spessartine component from 15–7 %) allowed the Grt – Phn thermometer of GREEN & HELLMAN (1982) to be used. A temperature range of 400–500°C was estimated (KORIKOVSKY *et al.* 2000b). The first zone with almost homogenous magnesiohornblende and tschermakite having a slightly elevated Ti concentration, plagioclase (20–50 % An) and rare augite with less than 2–3 % of jadeite component implies shallower depths when compared to the Brezovica aureole. The Grt-Pl thermometer of BLUNDY & HOLLAND (1990) gave temperatures of 550–650°C. The low concentration of jadeite component in clinopyroxene enabled rough estimation of pressure of 3–3.5 kbar at a temperature of ~650°C (Table 3). According to all these estimations KORIKOVSKY *et al.* (2000b) summarized that the Zlatibor massif was tectonically stabilized and started to cool isobarically at depths of approximately 12–13 km.

The K–Ar age of the Zlatibor metabasites is 160 Ma (KARAMATA & LOVRIĆ, personal communication) what is consistent with the ages obtained for the Tejići and the Brezovica metamorphic sole.

Based on mineral assemblages, estimated P–T conditions, zoning in mineral phases and obtained ages, the potential *P–T*–t paths are given for metabasic rocks from the WVZ and the DOB metamorphic sole (Fig. 7b). The retrograde assemblages indicating the overprint of high- to medium grade metabasites are low-temperature mineral phases of greenschist facies.

The tectonic settings that could be parental to the Serbian southwestern part of DOB (e. g. Bistrica) are assigned to the ocean thrusting and subsequent intra-oceanic subduction. At the beginning the metamorphism operated at a depth ≥30 km (≥10 kbar and ~800 ± 50 °C). The appearance of corona texture and medium-PT mineral phases imply a short-lived high-PT event and subsequent fast exhumation of the ophiolitic sequence; at another domain the intra-oceanic subduction of SSZ-type, operating in various depths, was responsible for the development of metamorphic soles. Thus, the garnet clinopyroxene bearing metabasites of the Bistrica represent the deepest subducted slab (~30 km). Further northwest, the peak metamorphic condition of various types of amphibolites imply the shallower burial of subducted slabs – ranging from 18–25 km (Sjenički Ozren and Banjska) over 18–15 km (Tejići) until 12–13 km (Zlatibor).

Composition and Correlation of protoliths and tectonic implication

Generally, the ocean units of the Dinaridic and the Western Vardar Zone belt comprise sub-ophiolite mélange thrust by an ophiolite unit with a metamorphic sole at its base. Within them the different types of basaltic rock and rarely gabbros were metamorphosed under various metamorphic conditions.

The blueschists of the Fruška Gora are considered to be a relic of the subducted oceanic unit (MILOVANOVIĆ *et al.* 1995). Recalculation of data reflects on prevailing of basaltic trachyandesitic composition instead of trachybasaltic (Fig. 8b). The ratios of incompatible elements (Ti, Zr, Y) suggest an MORB- and CAB-affinity (Fig. 8a). The latter was reported by MILOVANOVIĆ *et al.* (1995) as VAB-affinity (due to lack of data for Nb it is not possible to discriminate between Nb–Zr–Y). The Zr/Y ratio ranges from 4.01 to 5.95. The REE patterns normalized to chondrite values after SUN & MCDONOUGH (1989) show medium

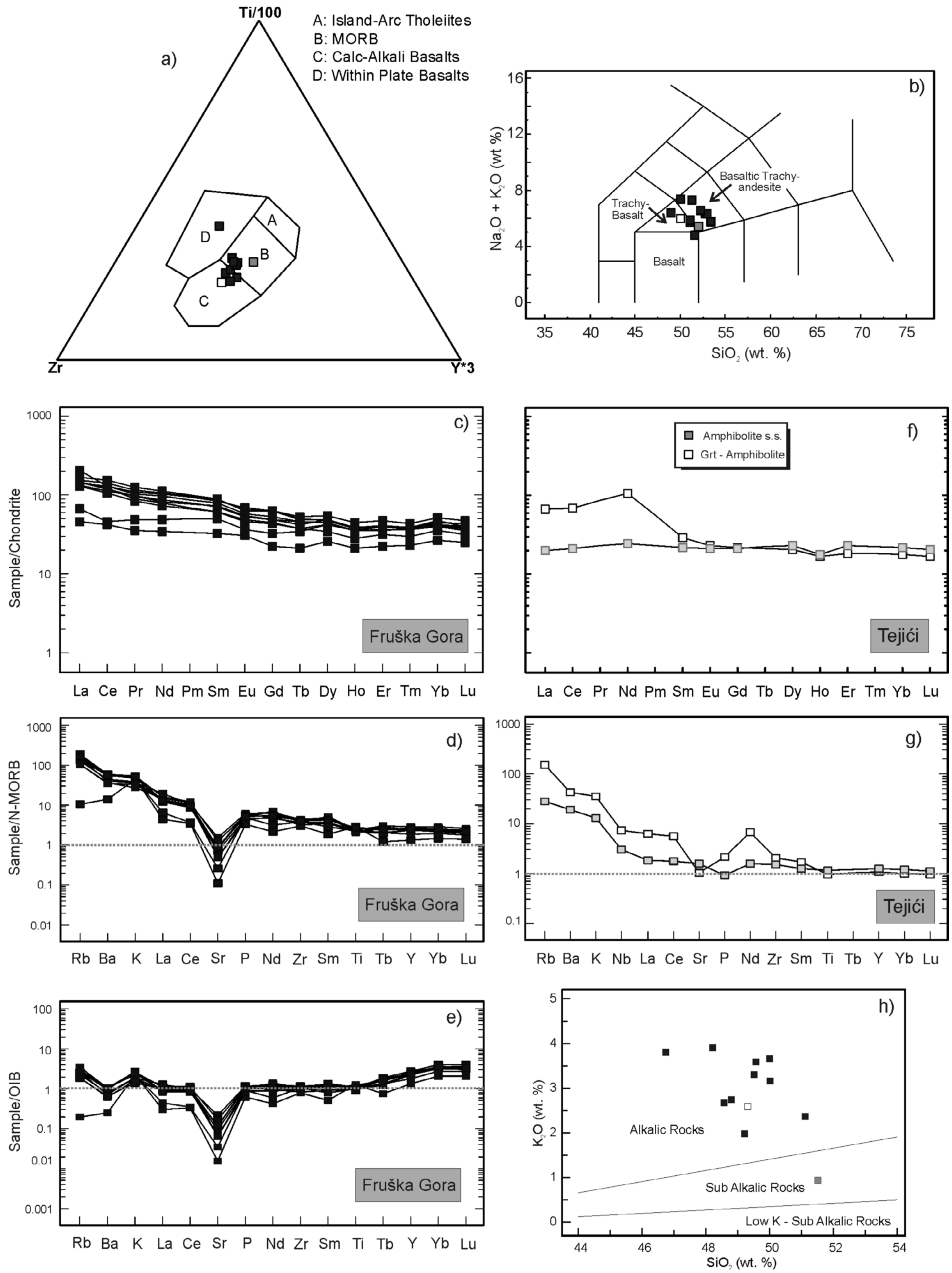

Fig. 8. Geochemistry of the Fruška Gora blueschists and Tejići amphibolites according to recalculated data of MILOVANOVIĆ *et al*. (1995) and SREĆKOVIĆ-BATOĆANIN *et al*. (2002): a) Ti-Zr-Y discrimination diagram (after PEARCE & CANN, 1973); b) SiO_2–Na_2O+K_2O classification diagram (after LEBAS *et al*. 1986); c) Fruška Gora chondrite – normalized REE patterns, d) N-MORB normalized and e) OIB normalized trace element spider diagrams of the Fruška Gora blueschists, f) Chondrite – normalized REE and g) N-MORB normalized trace element spider diagrams of the Tejići amphibolites; g) SiO_2 vs K_2O classification diagram (after MIDDLEMOST 1975); normalizing values are after SUN & MCDONAUGH (1989).

LREE enrichment (La_N/Yb_N = 1.41–3.43), no marked Eu-anomaly (Eu/Eu* = 0.84–1.13) and high SREE content (187.7–253.3) with two exceptions (85.8 and 116.6). All analyzed rocks are high-TiO_2, Zr and Y type basaltic rocks enriched in alkalis (Fig. 8b, h). The relations between compatible and incompatible elements presented on spider diagrams normalized to the average N-MORB and average OIB (Fig. 8e) indicate a very strong negative Sr-anomaly relative to adjacent elements. In respect to the average N-MORB they are much more enriched in LILE and slightly in HFSE as compared with the average OIB (Fig. 8d). Actually, the reexamination of blueschist geochemistry has shown characteristics very similar to OIB (Fig. 8d; Fig. 8e). The strong negative Sr-anomaly as has been many times encountered in MORB and OIB environments (see HOFMAN 1997) could be a result of seawater- basic magma interaction i.e. alteration prior to subduction. During the high-P low-T metamorphism the LILE elements behave as immobile (e.g. BEBOUT 1995, 2007; BEBOUT *et al.* 1999). Therefore, the blueschists probably originate from rocks whose composition is similar to OIB.

The metabasic rocks from the Tejići show the tholeiitic trachybasaltic to basaltic trachyandesitic composition (Fig. 8b). According to the ratio of Ti, Zr and Y they plot within MORB and CAB field (Fig. 8a). The Zr/Nb ratios (5.59–1.91) are lower than in the typical N-MORB (~32). The chondrite normalized REE patterns for garnet amphibolite (GA) and amphibolite sensu stricto (A) differ in LREE abundance (Fig. 8f). The former is much more enriched in LREE (70–100× chondrite values; La_N/Sm_N = 1.93) than the latter (~10× chondrite values; La_N/Sm_N = 0.77) with almost flat REE. The Eu-anomaly is absent (Eu/Eu* = 0.91–1). The La_N/Yb_N is 3.15 (GA) and 0.77 (A). The slight to moderate enrichment in LREE could be assigned to pre-metamorphic basalt-seawater interaction. The N-MORB normalized trace element patterns (Fig. 8g) are characterized by a negative slope from Rb to Sr and nearly smooth pattern from Zr–Y: the more mobile elements i.e. LILE are variably enriched; whereas, the HFSE have an N-MORB abundance. The $(Nb/La)_{PM}$ ratio (1.04–1.45) precludes sediment contribution. The Nb/Y is 0.46 (GA) and 0.19 (A). The Zr/Nb of 5.59 for the GA and 1.51 for the A and Ce/Y of 1.38 (GA) and 0.36 (A) ratios and Ti/Y vs. Zr/Y relation (see PEARCE & GALE 1977) indicate an E-MORB affinity as summarized also by SREĆKOVIĆ-BATOĆANIN *et al.* (2002).

The texture, mineral chemistry and geochemical composition (high Mg#, low SiO_2/Al_2O_3 values, REE pattern, and positive Eu anomalies) of the Bistrica metabasic sole rocks are consistent with a cumulate gabbro and evolved tholeiitic basalts originated in MOR-type setting (BAZYLEV *et al.* 2003, 2009; MILOVANOVIĆ *et al.* 2008). The geochemical data of the Bistrica and the Zlatibor metabasic sole rocks are not published.

According to data of CHIARI *et al.* (2011) three types of basaltic rocks are recognized in the Zlatibor aureole. The first two have N-MORB, E-MORB or P-MORB affinities and their origin is assigned to partial melts derived from depleted mantle that was variably influenced by an OIB-component erupted in seamount or off-axis tectonic settings. The third one of CAB affinity originates in an island or a continental arc orogenic setting – the enrichments in Th and Yb are recognized as indicators of the SSZ-imprint.

The protoliths of the sole metabasic rocks of the Brezovica are identified as moderate to high-Mg, low-Ti and moderate to high-Ti low-K tholeiitic basalts (KARAMATA *et al.* 2000). Among them three sub-types are distinguished: strongly LREE depleted ($La_N/Sm_N = 0.44 \pm 0.22$), moderately LREE depleted ($La_N/Sm_N = 0.73 \pm 0.13$) and LREE enriched ($La_N/Sm_N = 1.51 \pm 0.36$). The first two sub-types have geochemical feature similar or close to N-MORB while the third is transitional between enriched MORB (T-type) and OIB. Following their age (Table 3) the N-MORB basalts are recognized as products of an early oceanic stage or later paleo-oceanic products, whereas the third (T-MORB–OIB), the oldest one closely linked to the initiation of oceanic basin and continental fragmentation, is SSZ-type. They show similar features with those within the northwest and southern continuation of DOB (Krivaja–Konjuh, Borja, Mirdita–Pindos) concerning their LREE abundance, TiO_2, P_2O_5 as well as with metabasalts of E-MORB affinity in WVZ (e.g. Tejići).

Conclusions

The correlation of data collected from the available literature related to the metabasic sole rocks developed at the base of the ophiolites of DOB and WVZ with contribution of new data for the Bistrica metabasic rocks allow to summarize and conclude that:

1. Spatial relation and comparison of mineralogical, petrological and geochemical data as well as P–T conditions of metabasic sole rocks between the WVZ and the DOB ophiolites, with the exception of Fruška Gora, confirmed their common origin;

2. The different types of metabasic sole rocks occur at the base of obducted ophiolites as thrust or collided sheets, large blocks and fragments within the sub-ophiolitic mélange;

3. Metamorphic structures (i.e. foliation) of the majority of metabasites are parallel to basal thrust faults beneath the overlying peridotites; the same feature is confirmed in the metasediment interlayers occurring within;

4. The zonal composition of amphiboles and garnets from some metamorphic soles (e.g. Tejići, Zlatibor, Sjenički Ozren and Brezovica) are controlled by temperature; the relatively high Al^{IV}/Al^{VI} ratios in amphiboles imply mostly the moderate increase of

pressure during metamorphism; due to pressure drop and a subsequent short thermal increase the garnet from the Bistrica granulitic amphibolite show corona textures;

5. The metamorphic peak conditions recognized based on mineral assemblages and chemistry of minerals, determined: a) a high-P – low-T epidote-blueschist facies at 4–8 kbar and <300–350°C to 7–9 kbar and ~400°C (Fruška Gora); b) a high-PT amphibolite-granulite to amphibolite facies at 8–10 kbar and >700–850°C (Banjska, Bistrica, Sjenički Ozren and Brezovica); c) a greenschist to medium-PT amphibolite facies at ~3.5–7 kbar and >350–650°C (Tejići, Devovići and Zlatibor).

6. Major, trace and rare earth element distribution and elemental ratios within metabasic rocks bear geochemical affinities of cumulate gabbro and basalts of SSZ-type (E-MORB and OIB signature) or more evolved tholeiitic basalts of MOR-affinity (e.g. Bistrica); the E-MORB – OIB affinity can be linked to the rifting in an oceanic spreading center, partially affected by a plume-mantle component in both domains (WVZ and DOB); the east-dipping intra-oceanic subduction (SCHMID *et al*. 2008; CHIARI *et al*. 2011) was responsible for the evolution of the metabasic sole rocks at different metamorphic grades; according to available data it probably started at the end of Early Jurassic (178 Ma) leading to development of back-arc SSZ oceanic basins in the Middle–Late Jurassic;

7. The depth of metamorphism, i.e. the depth of detachment varies from 10 to 30 km.

8. The still hot overlying ultramafics were responsible for the creation of an inverted metamorphic sole during intra-oceanic obduction (KARAMATA *et al*. 2000; ROBERTSON *et al*. 2009 and reference therein);

9. At the Fruška Gora domain the different rock-types from the olistostrome mélange including subalkaline basalts were buried to the depths of 14–30 km by cold subduction. The generated blueschists are represented by two different mineral assemblages: glaucophane(riebeckite) + pumpellyite + actinolite + epidote at its west slope and ferro-glaucophane (earlier crossite) + riebeckite + albite + epidote + phengite at its eastern slope;

10. The reported K–Ar age range is between 174 and 146 Ma and spans almost 30 Ma.

11. The estimated P–T conditions and mineral assemblages depicted in metabasic sole rocks in the Serbian Dinaridic and the Western Vardar ophiolites are mostly in accordance with the majority of metamorphic sole metabasites developed in their northwestern and western continuation in Bosnia (e.g. Krivaja–Konjuh, Borja, Ozren, Kozara) and Croatia ("Sava Zone" or WVZ) where blueschist facies metabasic rock occur as remnant of cold subduction within the sub-ophiolitic mélange (Medvednica & Motajica, see BELAK & TIBIJAŠ 1998) along with its eastern occurrence at Mt. Fruška Gora. Additionally, the metabasic sole rocks are spatially related with those exposed further south in Albania (Mirdita zone) and in Greece (Pindos zone).

This correlation reveals the need to further clarify various aspects of metamorphic sole formation, particularly for those which have not yet been studied and whose age remains uncertain.

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Резиме

Корелација метабазита из метаморфних серија у подини офиолита Динарида и Западне Вардарске Зоне (Србија): три различита P–T–t градијента

Метаморфне стене у подини офиолита указују на време метаморфизма који је изазван још загрејаном ултрамафитском масом на самом почетку затварања океанског простора. У Србији су откривене на Фрушкој Гори, Маљену, Повлену (Тејићи), Столовима и Бањској у Западној Вардарској зони (WVZ), односно на Златибору, Бистрици, Сјеничком Озрену и Брезовици, у Динаридском офиолитском појасу (DOB). На основу минералног састава, P–T услова и старости метаморфизма, издвојена су три различита P–T– t градијента.

Постојећи теренски, петролошко-минералошки, геохемијски и геохронолошки подаци о метаморфним стенама у подини офиолита WVZ и DOB-а допуњени су новим минералошким подацима о амфиболитима Бистрице. У раду су разматране само метабазичне стене чији протолити су стене океанске коре: кумулатни габрови и базалти из супра-субдукционих зона (SSZ) са одликама обогаћеног MORB-а, OIB-а или више диференцираних толеитских базалта средњоокеанских гребена. Овакве стене се редовно налазе на самом контакту са ултрамафитима. Ултрамафитски масиви, претежно лерзолитског (± гранат) састава су дефинисани као фрагменти субконтиненталног омотача (Бистрица, Сјенички Озрен) док су лерзолити (± спинел)-харцбургити Златибора и Брезовице сврстани у офиолите супра-субдукционих зона (басени иза лука). У њиховој подини су, зависно од

услова метаморфизма и карактера протолита, образоване метаморфне стене веома различитог састава: гранатски и амфиболски гранулити, гранат-клинопироксенски амфиболити, клинопироксенски амфиболити, амфиболити са корундом, амфиболити и блушисти. Већина је претрпела накнадне ретроградне измене при чему су образоване различите асоцијације нискотемпературних минерала.

Метаморфити високих притисака и ниских температура, везани за субдукцију, налазе се на Фрушкој Гори: асоцијација глаукофан-рибекит-пумпелит-актинолит-епидот образована је у условима епидот-блушист субфације температурама од ~400°C и притисцима 7–9 kbar тј. на дубинама од око 30 km. Сматра се да је ту океанска кора некадашњег Вардарског океана субдукована под континенталну кору на североистоку почетком креде (барем-апт; 123 ± 5 Ma). Други тип метаморфита на Фрушкој Гори, односно другачија минерална парагенеза, образована је на температурама испод 340–350°C и притисцима од 4–8 kbar. Њихови протолити су стене из меланжа, које су процесом хладне субдукције потиснуте на дубину 14–29 km где су метаморфисане у глаукофан (рибекит)–пумпелит–актинолит–епидот–хлоритске метапешчаре и филите са фенгитом.

Метаморфити Тејића обухватају различите стене образоване у условима амфиболитске и гриншист фације. Протолити су базичне магматске стене и њихови вулканокластити, као и песковито-алевритски (пелитски) седименти. Стене вишег ступња метаморфизма (амфиболити са и без граната и епидотски амфиболити) налазе се у подини ултрамафита (претежно харцбургити из омотача). Чести су и фрагменти или блокови окцастих гнајсева и микашиста са гранатом који су образовани на температурама од 435–550°C до 630–680°C и притисцима од 4.5 ± 0.5 kbar до 6 ± 1.5 kbar. Титон/Келовејска старост метаморфита Тејића (160–150 мил. год.) утврђена је K-Ar методом. Присуство метакластита у асоцијацији са метабазитима може указати на близину копна што је потврђено појавом мандоласте текстуре у „pillow"-базалтима и одсуством дубоководних седимената.

Амфиболити на контакту са ултрамафтима у селу Девовићи (југозападни обронци Ибарског ултрамафитског масива) су формирани на температурама око 600°C од стена дијабаз-рожначке формације, односно меланжа.

Амфиболити из подине ултрамафитске масе Бањске, метаморфисани у температурном интервалу од 650°C до 760–780°C и притисцима од 6.7–6.9 kbar, указују да се почетак хлађења и тектонске стабилизације ултрамафитске масе дешавао на дубинама од 24–25 km.

Метаморфити Рогозне су углавном представљени амфиболитима и зеленим шкриљцима (микашисти и мермери су мање заступљени). Старост мерена на зрнима амфибола из свежих стена је између 168.8 ± 3.9 и 178.3 ± 6.7 милиона година, а старост хидротермално алтерисаних амфиболита 150.4 ± 10.2 милиона година (Ar–Ar метода). Добијене вредности времена почетка интраокеанске субдукције/обдукције (доња до средња јура; тоарски и бајески кат) су у складу са вредностима добијеним за метаморфите из подине офиолита Динарида и Албаније.

Метабазити развијени око Златиборског ултрамафитског масива (550–650°C и 3–3.5 kbar) показују да се тектонска стабилизација и почетак хлађења овог масива дешавао на знатно мањој дубини (12–13 km) у поређењу са другим масивима Србије. Тектонски блок Бистрице на јужном ободу Златиборског масива састоји се углавном од спинел лерзолита и лерзолита са жицама и слојевима порфиробластичних харцбургита, гранатских клинопироксенита и спинелских хорнблендита, које указују на порекло из субконтиненталног омотача. Метаморфне стене у подини ултрамафита су образоване у условима амфиболит-гранулитске, амфиболитске и гриншист фације. Гранат-пироксенски амфиболити настали су на температурама између 828–879°C и 740–830°C при притисцима од 8–10 kbar. Старост гранат-пироксенских амфиболита и корунд-паргаситских амфиболита од 178 ± 14 милиона година утврђена је K–Ar методом.

Опсег услова метаморфизма гранат-пироксенских амфиболита Сјеничког Озрена јесте 750–830°C при притисцима 5–6 kbar што је еквивалентно дубинама од 18 до 22 km. Амфиболити, габро амфиболити и зелени шкриљци, који се налазе даље од контакта са ултрамафитима, метаморфисани су на температури између 400–430°C. Максималне израчунате вредности метаморфизма указују да је масив Сјеничког Озрена смештен у данашњи положај као већ очврсла или делимично очврсла маса (изнад 1000°C).

У контактном ореолу Брезовице издвојене су три зоне. У првој зони, на самом контакту са перидотитима, налазе се гранат (± клинопироксен) амфиболити и гранат –дистенски гнајсеви, образовани на температурама између 700–750°C и 600–670°C и притисцима од 8–9 kbar.

У свим испитиваним метаморфним стенама амфибол је главна минерална фаза. Образује се од мафитске компоненте из протолита, а варијације у хемизму су последица промене P–T услова. У већини напред приказаних типова стена они по саставу одговарају Mg – хорнбленди, едениту, магнезијском хастингситу и актинолиту. Изузетак су блушисти Фрушке Горе у којима је то феро–глаукофан и Mg–рибекит или зонарни Na–амфибол глаукофан рибекитског типа, као и амфиболити Бистрице са еденитом и Mg–хастингситом и паргаситом.

Гранати су запажени у амфиболитима развијеним на самом контакту са ултрамафитима и то у оба офиолитска појаса. Амфиболити Рогозне, Девовића, Златибора и Фрушке Горе не садрже гранат. Симплектитски, реакциони руб, запажен први пут око зрна граната у гранатским амфиболитима Бистрице, изграђен је од врло ситних зрна клинопироскена, албита и амфибола, што говори да је гранат углавном и растао на рачун ова три минерала.

Температурни услови метаморфизма и карактер новостворених фаза су тесно везани за топлотни капацитет офиолита и карактер протолита. Притисак је директно пропорционалан дубини, па његове различите вредности указују на различите дубине одвајања океанске литосфере и дубину иницијалног хлађења. Метаморфити у подини офиолита Србије су образовани на притисцима којима одговарају дубине од 10 до 30 km. Постепен пораст притиска са напредовањем океанске плоче је у неким случајевима забележен кроз промене хемизма минерала (на пр. Тејићи, Бистрица, Фрушка Гора).

На основу минералног састава, израчунатих P–T услова метаморфизма, зонарности минерала и старости метаморфизма, издвојена су три потенцијална *P–T–t* градијента:

– висок-P – ниска-T – 123 ± 5 мил.год. (7–9 kbar, T ~400°C и <300–350°C, P 4–8 kbar). Ова асоцијација метаморфних минерала је забележена једино у метаморфном ореолу Фрушке Горе (WVZ);

– висок-P – висок-T – 146 ± 4.9 и 174 ± 14 мил. год. (8–10 kbar, >700–850°C) утврђена у Бањској (WVZ) и у Бистрици, Сјеничком Озрену и Брезовици (DOB) и

– средњи- P – средњи-T – 160–178.3 ± 6.7 мил. год. (3.5–7 kbar и >350–650°C), утврђена у оба појаса: Тејићи и Девовићи (WVZ) и Златибор (DOB).

Тектонска средина која би одговарала делу DOB у Србији (на пр. Бистрица) одговара подручју обдукције океанске плоче и касније изазване унутар океанске субдукције. Метаморфизам се у почетку одвијао на великим дубинама ≥30 km (P≥10 kbar и T ~800 ± 50°C). Појава реакционих рубова и минералних фаза средњих P–T указују да су овакви услови кратко трајали и да је дошло до брзе ексхумације офиолитске секвенце.

У другим деловима океанског подручја се унутар-океанска субдукција SSZ-типа одвијала на различитим дубинама и дала различите метаморфне стене. Продукт најдубље субдукованог офиолитског блока (~30–36 km) су гранат–клинопироксенски метабазити Бистрице. Одатле ка северозападу постепено опадају вредности P–T, односно дубине субдукције на 18–25 km (Сјенички Озрен и Бањска) и 18–15 km (Тејићи). Минимална вредност, од 12–13 km је забележена на Златибору.

Просторни распоред и поређење минералошко-петролошких и геохемијских података, као и P–T услова у којима су образоване метабазичне стене у бази офиолита ЗВЗ и ДОП са изузетком метаморфита Фрушке Горе, указују на образовање у сличном тектонском режиму, на шта су указали и SCHMID *et al*. (2008) и CHIARI *et al*. (2011).

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Salpingoporella nicolacarrasi spec. nov., a dasycladalean alga from Santonian of southwestern Serbia (Novi Pazar, Mirdita Zone)

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Abstract. A dasycladalean alga, *Salpingoporella nicolacarrasi* spec. nov., is described from Santonian limestones of the Mur Formation outcropping in Novi Pazar, Mirdita Zone belt, SW Serbia. The alga, the main axis of which bears tightly packed whorls of numerous laterals, resembles the Triassic *Salpingoporella sturi*. Calcareous sparry calcite skeleton, likely first aragonitic, is more or less heavily destroyed by a special process of bio-erosion, described under the name of Mur1.

Key words: Dasycladales, new taxon, bio-erosion, diagenesis, Upper Cretaceous, Santonian, SW Serbia, Mirdita Zone.

Абстракт. Нова врста *Salpingoporrlla nicolacarrasi* описана је из сантонских кречњака Бајевица формације у локалитету Мур, јужно од Новог Пазара.

Кључне ријечи: Dasycladales, зелене алге, нова врста, биоерозија, горња креда, сантон, ЈЗ Србија, Мирдита зона.

Introduction

Salpingoporella nicolacarrasi spec. nov., was first informally described and illustrated by Radoičić (1984) under the name of *Dasycladacea* gen. ind., in a paper primarily introducing *Drimella*, a subgenus of *Neomeris*. As mentioned at that time (*ibid.* p. 24), the skeleton of this alga is compact around the primary laterals, and the possible presence of secondary laterals is dimly suggested by one specimen only (ibid., pl. 5, fig. 1), *Dasycladacea* gen. ind., consequently and tentatively corresponding to the internal part of a *Drimella* type skeleton. *Salpingoporella nicolacarrasi* spec. nov. was found in the Novi Pazar area, in an outcrop of Late Cretaceous limestones belonging to the NW Rogozna–Novi Pazar–S Golija Mt. belt (in short Novi Pazar belt, Mirdita Zone, Fig. 1), also called the western belt of the Vardar Zone by some authors.

Geological setting

Sample location is in the Novi Pazar–Golija Mt., Mirdita Zone belt, also called the western belt of the Vardar Zone, i.e. Dinarides by some authors. In this area, the Late Cretaceous succession transgressively rests on the Paleozoic, showing a transition from shallow-water to basinal environments. As shown by Polavder (2002), in the south Novi Pazar suburb, two formations are visible on outcrop: (1) the Bajevica Formation (Santonian to lowermost Campanian), with a basal, transgressive member of quartzite and sandstone, and a shallow water carbonate upper member, and (2) the Mur Formation (Campanian to lowermost Maastrichtian), with a lower member of hemipelagic-bioclastic deposits and an upper hemipelagic-pelagic member. The lower member of the Mur Formation consists of silty-marly deposits containing limestone blocks and clasts originating from a fractured, perireefal area. This episode ended with thick-bedded limestones corresponding to the influx of finer bioclastic debris. Limestone blocks are present as a lateral development of the upper Bajevica, nearly in situ in slope deposits. Some blocks bear numerous, large *Vaccinites* and *Hippurites*, smaller forms of *Radiolitidae*, rudist fragments, debris of colonial corals, calcisponges and more or less frequent foraminifera with an association comprising *Idalina antiqua* (Polavder 2002, p. 82, figs. 3–5 p.p.). Our new *Salpingoporella* originates from one of these blocks.

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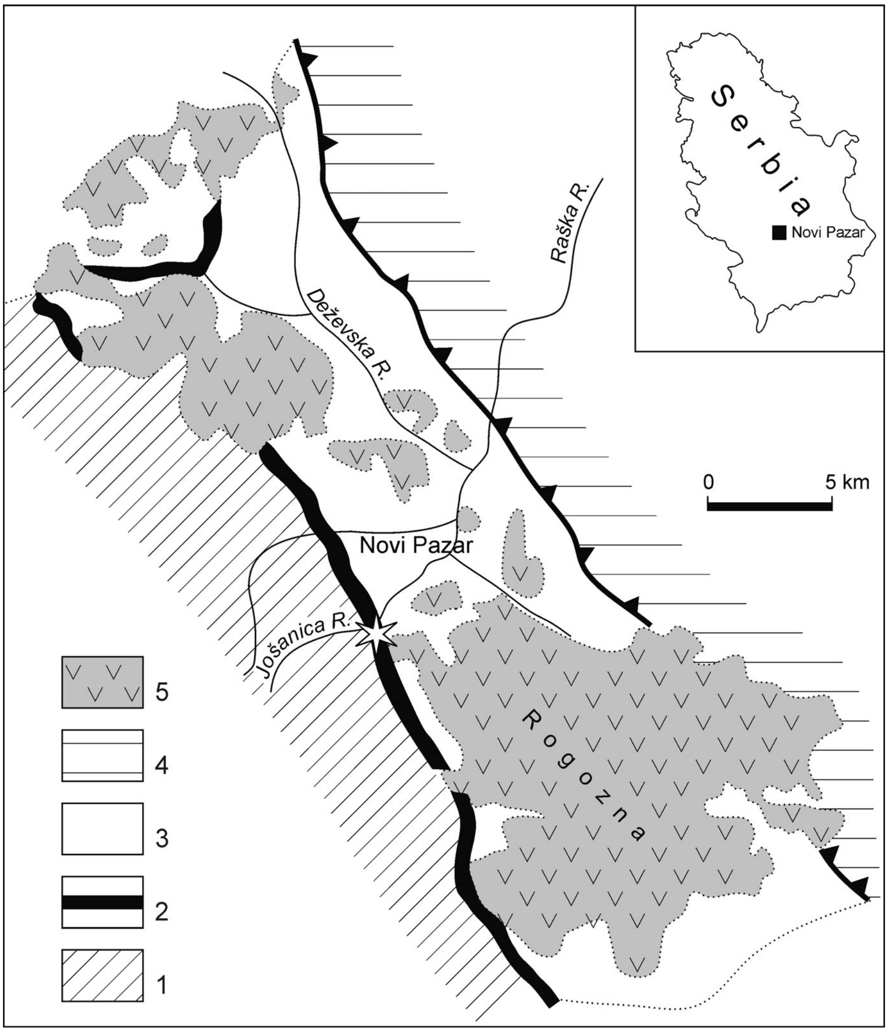

Fig. 1. Geological sketch map of the Novi Pazar area, redrawn after MILOVANOVIĆ & ĆIRIĆ (1968) and UROŠEVIĆ *et al.* (1970), simplified. Legend: **1,** Paleozoic; **2,** Basal terrigenous deposits, lower member of the Bajevica Formation; **3,** Shallow-water, hemipelagic and bioclastic carbonates (upper member of the Bajevica and Mur Formation); **4,** Senonian flysch; **5,** Ophiolites; **6,** Quartz latites. Based on calcareous nannoplankton, the part of ''Senonian flysch'' exposed north of Mur along the road in the Novi Pazar city, is Eocene (DE CAPOA *et al.* 1998).

Systematic taxonomy

Order *Dasycladales* PASCHER, 1931
Family *Triploporellaceae* (PIA, 1920) BERGER & KAEVER, 1992
Tribus *Salpingoporellaceae* BASSOULLET *et al.*, 1979
Subtribus *Salpingoporellinae* BASSOULLET *et al.*, 1979
Genus *Salpingoporella* PIA in TRAUTH, 1918

Salpingoporella nicolacarrasi spec. nov.
Figs. 2, 3; Pls. 1–3

1984 *Dasycladacea* gen. ind. – RADOIČIĆ, pl. 5, figs. 1–5., locality Mur, Novi Pazar, Santonian.

Origin of name. The specie is dedicated to our friend Dr. NICOLAOS CARRAS (IGME, Athens), as a tribute to our long friendship, collaboration and fruitful contribution to the knowledge of the Jurassic and Cretaceous calcareous algae.

Holotype. The transverse section illustrated in Fig. 2 and Pl. 1, Fig. 1, with 35 laterals per whorl. Thin section RR2299, R. RADOIČIĆ collection housed in the Geological Institute of Serbia, Beograd.

Isotypes. Numerous specimens, some of which are illustrated in Pls. 1–3, cut in different sections, contained in 18 thin sections labeled RR2293 to RR2310 (hand sample 013614).

Type locality and age. Mur, at the southern periphery of Novi Pazar, immediately south of the bridge on the Jošanica river, in a block of bioclastic limestone, part of the upper member of the Bajevica Formation. Latest Santonian to Early Campanian. Coordinates: x 7458000, y 4773450.

Diagnosis. Large, elongated cylindrical thallus with a large main stem (d/D of skeleton 47–57 %, occasionally 52–55 %) and tightly packed whorls of numerous (25–35) horizontal, occasionally slightly tilted laterals forming quincunxes. Laterals phloiophorous, first very narrow with a short proximal tapering, then funnel-like, slightly widening out except at tip, where rapidly expanding, forming a bulge corresponding to the uncalcified cortex typical of *Salpingoporella*. Calcareous skeleton made of sparry calcite.

Measurements. *Salpingoporella nicolacarrasi* is among the largest species of the genus. Only the Triassic *Salpingoporella sturi* has equivalent values for the thallus width. The skeleton of our new species varies in size, with an external diameter (excluding two small forms) ranging from 1.58 to 2.74 mm, and the main stem from 0.840 to 1.55 mm. Thickness of skeleton (length of laterals) from 0.37 to 0.59 mm. The longest observed specimen is 9.2 mm. The space between two contiguous whorls varies from 0.148 to 0.197 mm, and the width of the laterals at periphery of the skeleton may reach 0.247 mm.

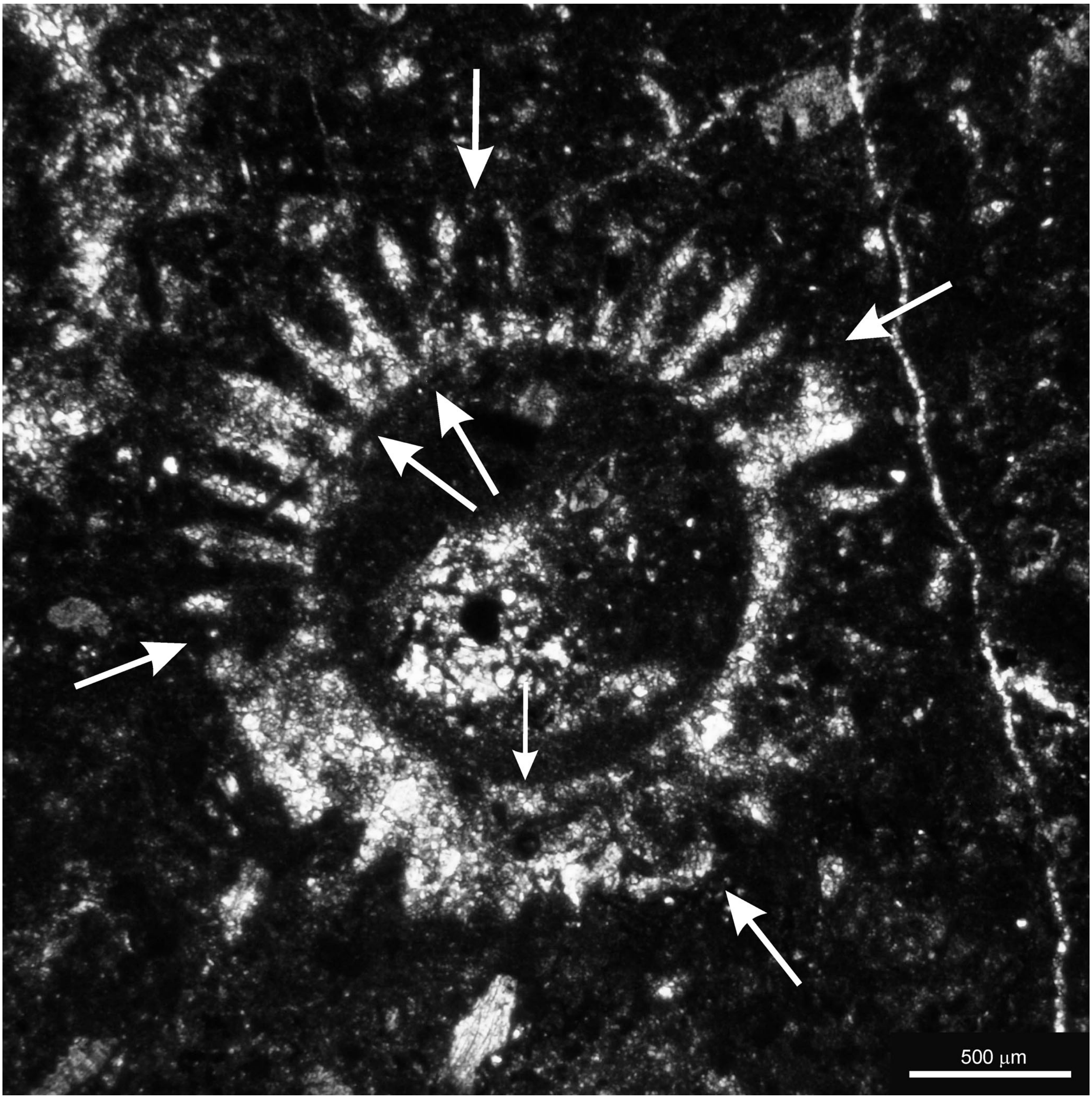

Fig. 2. *Salpingoporella nicolacarrasi* spec. nov., the holotype, transverse section, thin section RR2299 (= Pl. 1, Fig. 1). In the upper half of the section, pores corresponding to the laterals are relatively well preserved. Some of them (two arrows) indicate the characteristic "palisade"-like structure of the skeleton. In lower half of the section, various stages of preservation of the skeleton are visible, ranging from simply recrystallized pores (lower-left) to different grades of alteration. Thin arrow: a small, circular Mur1 cavity. Other arrows: some Mur1 cavities located in the pores (laterals), and also in the partly altered skeleton. To the right, a more advanced process of disintegration is visible; on the right, only the proximal part of the skeleton being preserved.

Calcification and preservation. When relatively unaltered, the final product of calcification forms a sleeve enclosing the slender proximal part of the laterals and the proximal portion of the distal bulge (Fig. 1; Pl. 1, Fig. 1). Distally, the laterals are still uncompressed, circular or subcircular in section, but because of their alternating setting among contiguous whorls, the surface of sleeve typically forms a hexagonal pattern (Pl. 3, Figs. 4, 5). The well preserved, smooth inner skeleton surface was the more resistant area, lingering disintegration processes and corresponding to the past presence of a membrane coating the cyto-

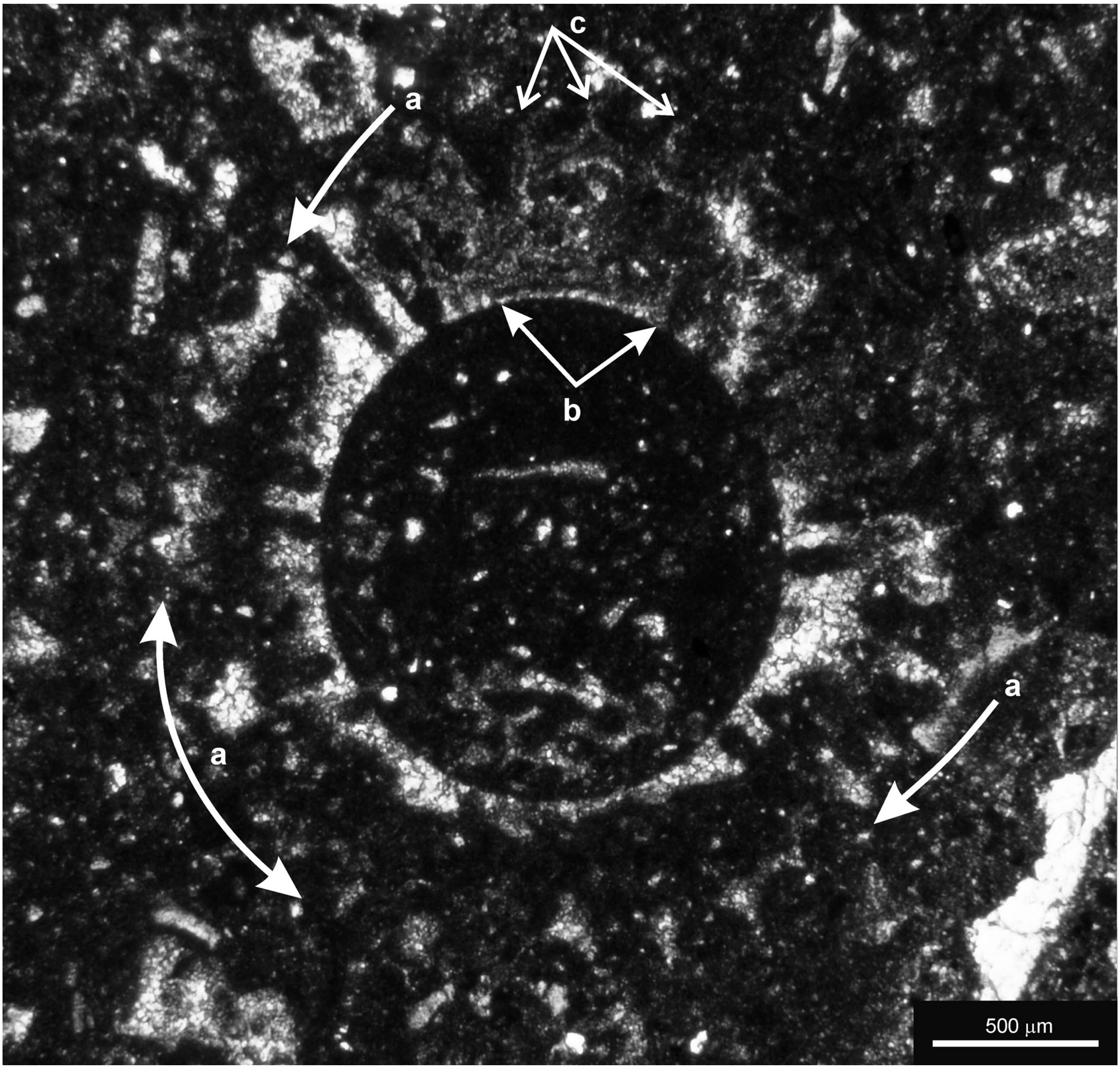

Fig. 3. *Salpingoporella nicolacarrasi* spec. nov., thin section RR2295 (= Pl. 1, Fig. 6). Transverse section of the skeleton largely affected by the microbial cryptoendolith Mur1, in addition to a slightly ochraceous, pervasive, diffuse Mur2 (?biological, ?chemical), alteration-disintegration. The late, but not latest phase, Mur1 bioerosional activity results in the disintegration of the middle part of the skeleton wall, half way from the proximal and distal parts of the laterals. Arrows **a** (from the upper left to the lower-right in the figure) indicate the remnants of the skeleton surface network. Arrows **b**: several Mur1 circular cavities are assembled in the part of the skeleton altered by Mur2, leaving a very thin calcite line corresponding to the innermost remainder of the calcified main stem membrane. Arrows **c**: Altered thin surface network of the skeleton.

plasm (Pl. 2, Fig. 5). In several cases, a very thin calcite line occurs corresponding to the innermost remainder of the membrane (Pl. 1, Figs. 6, 8, 9; Pl. 3, Fig. 1).

In most specimens the skeleton is affected by a peculiar biological process of boring here informally called Mur1, and another process of pervasive, diffuse Mur2 (?biological, ?chemical), alteration-disintegration. Mur1 chiefly develops in the middle part of the pores (laterals), half way from the proximal attachment and the skeleton surface (Pl. 1, Figs. 1, 3, 4, 5; Pl. 2, Fig. 8). In its incipient stage of development, it consists of well delineated, sub-circular holes, isolated or in groups of two-three, initially of small size (Pl. 1, Fig. 8). Then, these holes expand, producing in some cases large circular cavities (Pl.1, Figs. 9, 10), or coalescing to produce, as final result, some sort of undulated tubular strings (Pl. 1, Figs. 3, 6). Tentatively, the Mur1 feature was carried out by seemingly microbial cryptoendoliths. It is especially visible in transverse sections (Pl. 1, Figs. 1, 3–8) showing the various stages of the process.

Relationships. At first glance, *Salpingoporella nicolacarrasi* bears a resemblance to the Triassic *Salpingoporella sturi* (BYSTRICKY) (see CARRAS *et al.* 2006 for a review). In our new species however, in the distal part of the laterals, the distance between two adjacent laterals of the same whorl is clearly smaller than the distance between two adjacent whorls, while in *S. sturi* it is clearly the opposite. Consequently, in both species the pattern of the laterals in tangential section forms polygons which are equilateral in *S. nicolacarrasi* and horizontally elongated in *S. sturi*.

Accompanying biota. Rotalids are prevailing in the foraminiferal association with numerous *Pararotalia minimalis* HOFKER and similar small forms; *Idalina antiqua* MUNIER-CHALMAS, *Hemicyclammina chalmasi* (SCHLUMBERGER), *Moncharmontia apenninica* (DE CASTRO) and *Rotalia reicheli* HOTTINGER, are uncommon. Other biota includes radiolitids, corals, calcispongia fragments and fine metazoan debris.

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Резиме

Salpingoporella nicolacarassi spec. nov., дазикладалеанска алга из сантона југозападне Србије (Нови Пазар, Мирдита зона)

Нова врста *Salpingoporrlla nicolacarrasi* описана је ин сантонских кречњака Бајевица формације у локалитету Мур, јужно од Новог Пазара.

Salpingoporella nicolacarrasi spec. nov
Figs. 2, 3, Pls. 1–3

1984 *Dasycladacea* gen. ind. - RADOIČIĆ, Таб. 5, сл. 1–5, локалитет Мур, Нови Пазар, сантон.

Дијагноза. Крупан издужен цилиндрични талус са пространом главном осом и густо сложеним пршљеновима са бројним огранцима (25–35), наизмјенично распоређеним у сусједним пршљеновима. Огранци су љевкастог облика са дужим благо проширеним проксималним и нагло проширеним дисталним дијелом који на површини талуса одговара некалцифицираном кортексу типичном за салпингопореле. Кречњачки омотач спари-калцитски.

Опис. Кречњачки омотач обухвата већи дио огранака укључујући доњи дио дисталног проширења дајући мрежасту хексагоналну слику површини омотача. Карактеристично је да је унутрашња површина омотача глатка и веома отпорна на процес разарања. У неким случајевима као посљедњи остатак разореног омотача очувана је танка калцитска линија, у ствари посљедњи остатак првобитно отпорније мембране главне осе.

У већини кречњачких омотача ове врсте уочава се дјеловање особеног биоерозионог процеса који је неформално именован Мур1, и другог, Мур2 процеса (?биолошког, ?хемијског) који се огледа у смеђе измијењеном и мање или више разореном омотачу. Мур1 развија се у средњем дијелу пора, односно кречњачког зида, остављајући кружне шупљине, у почетку ситнијих димензија, изоловане или у групама (веома лијепо видљиве особито у попречним пресјецима на табли 1). У даљем дјеловању обим ових шупљина се повећава (табла 1; сл. 9, 10) или повезује стварајући цјеловиту шупљину неравног обриса кроз средњи дио зида као на сл. 3 и 6, на табли 1.

Salpingoporella nicolacarrasi спада у накрупније салпингопореле, а на први поглед подсјећа на тријаску врсту *Salpingoporella sturi* (BYSTRIICKY).

PLATE 1

Salpingoporella nicolacarrasi spec. nov., transverse and quasi transverse sections showing different kinds of conservation of the skeleton. Magnifications: see Fig. 1.

Fig. 1. The holotype (see also Fig. 1 in the text). Thin section RR2299.

Fig. 2. Lower part: the smallest specimen. To a certain extent the skeleton is dissolved, with the exception of the calcified membrane corresponding to the stem and part of the laterals. Thin section RR2310.

Fig. 3. The middle part of the skeleton wall is largely destroyed by the cryptoendolith Mur1. Arrow: a circular cavity is visible at the end of the coalescing holes. Thin section RR2301.

Fig. 4. Rather ill-preserved skeleton. Arrow: group of Mur1 cavities. Thin section RR2305.

Fig. 5. Fragment, recrystallized and affected by Mur1. Arrow: distal opening of a pore and, in mid-part of the skeleton, circular cavity of Mur1. Thin section RR2305.

Fig. 6. The skeleton is largely destroyed by the Mur1 activity and partly altered, or destroyed by another secondary process. (See also Fig. 3 in the text). Thin section RR2295.

Fig. 7. The skeleton is quite recrystallized and Mur1 coalescing cavities are visible. Thin section RR2308.

Fig. 8. Most of the skeleton is altered by Mur1 (the relatively small holes between the arrows) and other destructive processes. Thin section RR2294.

Fig. 9. The left part is affected by an advanced stage of Mur1, leaving a very thin line of calcite corresponding to the main stem membrane. Thin section RR2294.

Fig. 10. The skeleton is largely disintegrated by an advanced stage of Mur1. Some better preserved laterals are visible in the upper part of the section. Thin section RR2295.

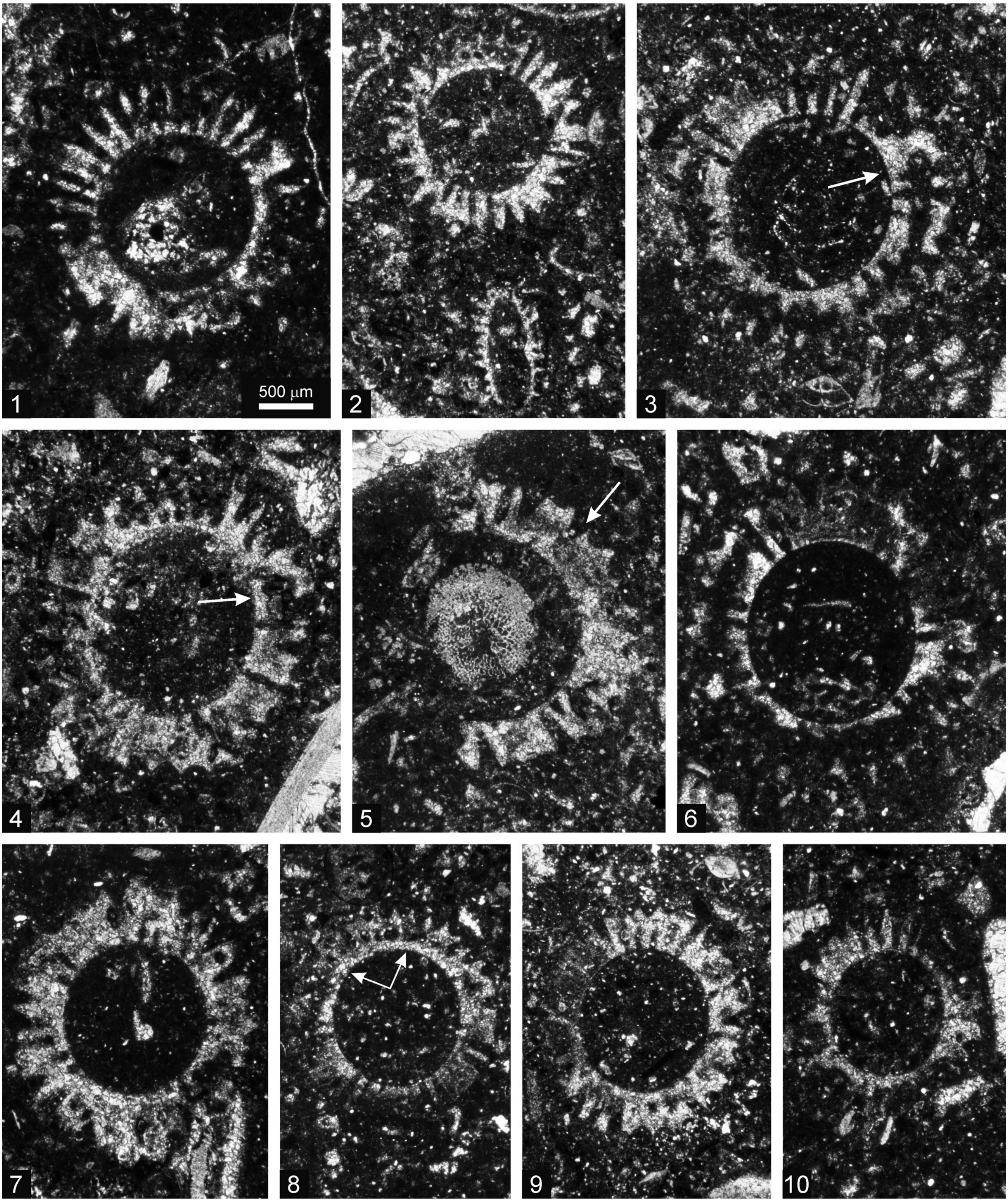
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Plate 2

Salpingoporella nicolacarrasi spec. nov., oblique, oblique-longitudinal and tangential sections.
Magnifications: see Fig. 1.

Fig. 1. Sections of large, middle and small-sized skeletons with about 25 laterals per whorl. The specimen in the upper left is more disintegrated. The skeleton of the large section is affected by the very small irregular tubular euendolith (not clearly visible). Thin section RR2300.

Figs. 2,3. Sections of medium-sized skeletons. Thin sections RR2299 and RR2307.

Fig. 4. Partly disintegrated skeleton. In the lower right part of the section, the skeleton is partly disintegrated, probably by both Mur1 and Mur 2 activity. Thin section RR2308.

Fig. 5. Most of the skeleton is dissolved, leaving the well preserved, calcified membrane of the main stem, and part of the membrane coating the laterals. Thin section RR2305.

Fig. 6. Only the proximal-middle part of the skeleton is preserved. Thin section RR2301

Fig. 7. Tangential-longitudinal section, of a slightly deformed specimen. Thin section RR2296.

Fig. 8. Rather well preserved skeleton showing laterals alternating in the successive whorls. *Mur1* activity is visible on the left side, producing coalescing cavities in the middle part of the wall. Thin section RR 2293.

Fig. 9. Tangential-longitudinal section.The piece of skeleton is strongly altered, except in the axis area. Thin section RR2296.

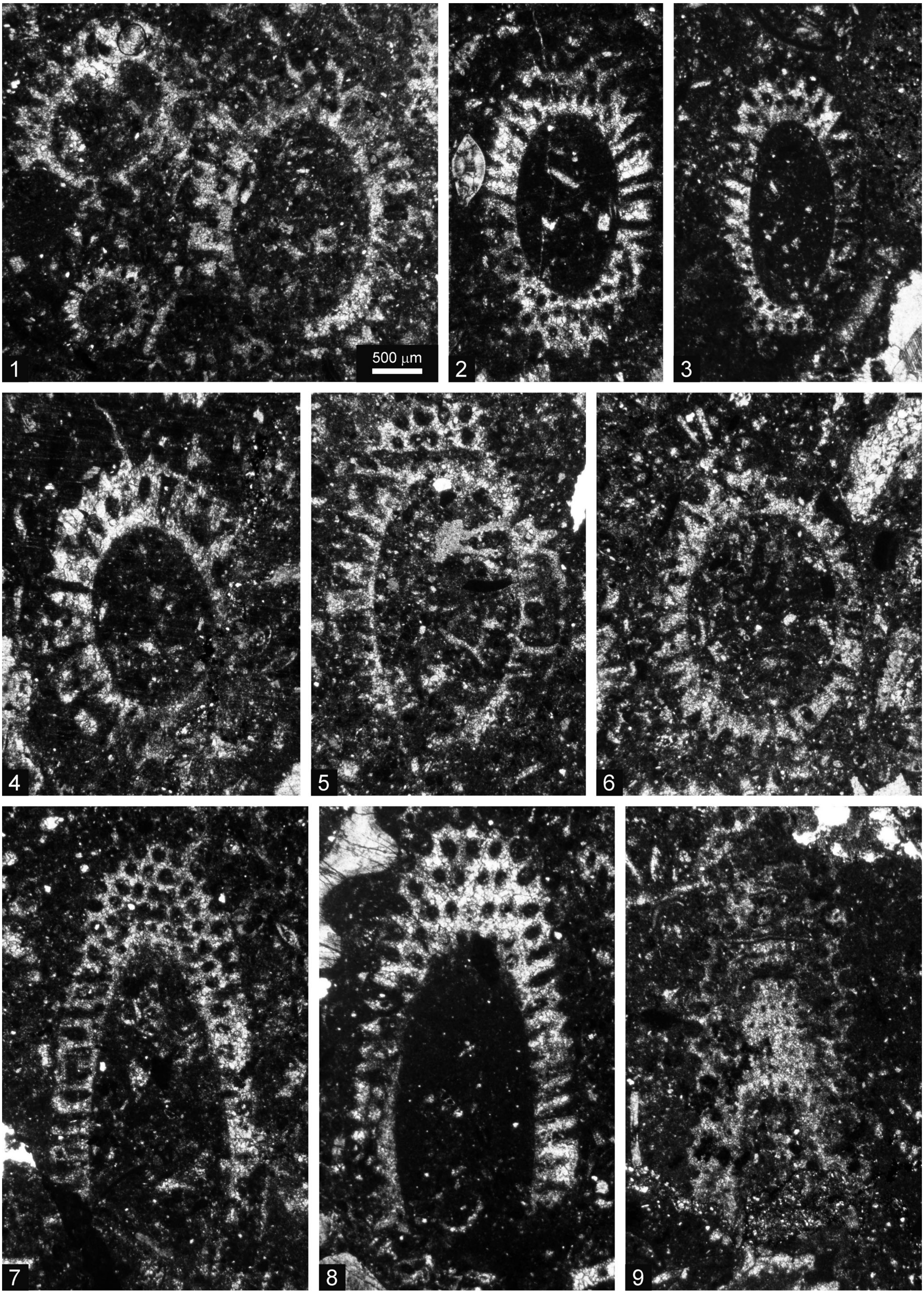
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PLATE 3

Salpingoporella nicolacarrasi spec. nov. Magnifications: see Fig. 1, except Fig. 5.

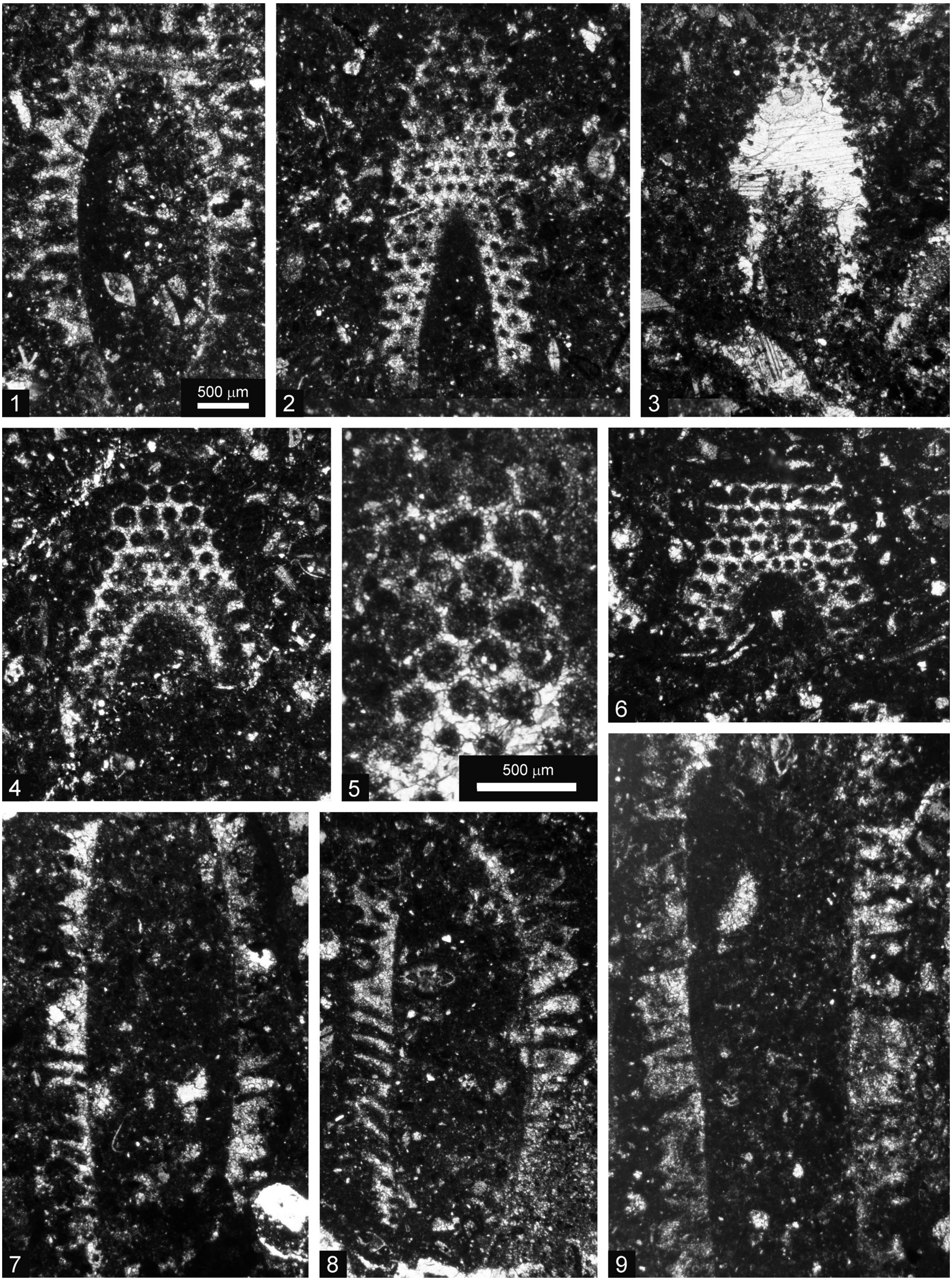
Fig. 1. Oblique section,showing the disintegrating Mur1 activity. Note the clear-cut calcification of the axial membrane. Thin section RR2305.

Fig. 2. Tangential-oblique section showing laterals regularly alternating in consecutive whorls. Upper part in the section: borings due to the Mur1 process are characteristically located in the middle part of the wall. Thin section RR2307.

Fig. 3. Tangential-oblique section.In this case, most of the skeleton is replaced by late calcite cement. Thin section RR2300.

Figs. 4–6. Tangential sections showing the hexagonal network at surface of the skeleton. Note in Fig. 4 the coalescing Mur1 cavities in middle part of the wall. Thin sections RR2297, 2306, 2297.

Figs. 7–9. Longitudinal and quasi-longitudinal sections of slightly deformed specimens. Fig. 9 shows part of a 9.2 mm-long section. Thin sections RR2300, 2299, 2299.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New paleomagnetic results for Tertiary magmatic rocks of Fruška Gora, Serbia

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Abstract. Fruška Gora Mountain is a large scale antiform located at the southeast part of the Pannonian Basin between the Danube and Sava Rivers. It is built of Paleozoic and Mesozoic rocks with Neogene sediments on all sides and at the flanks. The Paleozoic and Mesozoic rocks are largely metamorphosed (age of the metamorphism is early Cretaceous) and they are intruded by Eocene/Oligocene latites and rhyodacites and Badenian basaltic trachyandesite. On Fruška Gora two major structural units are observed, the northern and southern structural units which are divided by the Srem dislocation striking NNW–SSE.

The Tertiary magmatic rocks located on both sides of this dislocation were the subject of paleomagnetic analysis. Tectonically meaningful paleomagnetic directions are obtained from latites and rhyodacites, while basaltic trachyandesite has a secondary remanent magnetization. The obtained overall-mean paleomagnetic direction, after applying the correction for the general tilt of the Lower Miocene sediments, suggests a clockwise rotation (D = 210°, I = –45°, k = 21, α_{95} = 14°) of 30° with respect to the present North of blocks on both sides of the Srem dislocation. The fact that close to the end of Miocene–Early Pliocene Fruška Gora rotated in a counterclockwise direction for 40° with respect to the present North means that all of Fruška Gora rotated in a clockwise direction for 70° with the respect to the present North in a short time after the intrusion of Eocene/Oligocene magmatic rocks and before Middle Miocene.

Key words: Tertiary, magmatic rocks, Srem dislocation, paleomagnetic measurements, paleorotation, Fruška Gora Mt.

Апстракт. Фрушка гора је велика антиформа у јужном Панонском басену, између Дунава и Саве. Изграђена је од палеозојских и мезозојских стена док су јој стране прекривене неогеним седиментима. Већина палеозојских и мезозојских стена су метаморфисане (током ранокредног метаморфизма), а најзначајније постметаморфне стене су еоценско-олигоценски латити и риодацити, и баденски базалтни трахиандезити. У структурном плану на Фрушкој гори истиче се Сремска дислокација, пружања ССЗ–ЈЈИ, која Фрушку гору дели на северну и јужну структурну јединицу. Терцијарни магматити са обе стране ове дислокације били су предмет детаљних палеомагнетских испитивања. Тектонски значајни палеомагнетски правци утврђени су код латита и риодацита, док је код базалтних трахиандезита издвојена секундарна реманентна магнетизација. Добијени општи–средњи правац, након тектонске корекције генералним елементима пада доњомиценских седимената, указује на ротацију у смеру кретања казаљке на сату (D = 210°, I = –45°, k = 21, α_{95} = 14°) од 30° у односу на савремен правац севера блокова са обе стране Сремске дислокације. С обзиром да је крајем миоцена–раног плиоцена Фрушка гора ротирала 40° у смеру супротном од кретања казаљке на сату у односу на савремен положај севера, може се закључити да је цела Фрушка гора ротирала 70° у смеру кретања казаљке на сату у односу на савремен правац севера у веома кратком периоду, после интрузије еоценско/олигоценских магматита а пре средњег миоцена.

Кључне речи: Терцијар, магматити, сремска дислокација, палеомагнетска мерења, палеоротација, Фрушка гора.

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Introduction

Magmatic rocks of Paleogene to Early Miocene have a wide spatial distribution in the Pannonian Basin. These rocks are mostly covered by Neogene sediments, very rarely exposed on the surface. They built up a relatively huge zone which strikes parallel to major tectonic lines i.e. along the Balaton (BF), Mid-Hungarian (MHF), Sava (SF) and Drava (DF) fault (see KOVÁCS *et al*. 2007, Fig. 1). The Neogene sedimentary cover was deposited during back-arc collapse associated with the subduction and roll-back recorded in the external Carpathians (KOVÁCS *et al*. 2007).

Previous paleomagnetic research of Fruška Gora (LESIĆ *et al.* 2007; CVETKOV *et al.* 2004) has shown that the Upper Cretaceous flysch (with an overprint component) and the Rakovac latites which intrude them have rotated in a clockwise direction (D = 220°, I = –43°, k = 25, α_{95} = 16°). Because this observation is made only on paleomagnetic data obtained for the block north of the Srem dislocation located in the northern Fruška Gora structural unit, an additional paleomagnetic investigation was carried out to show whether the clockwise (CW) rotation obtained for the period after the intrusion of latites during Oligocene–Early Miocene was a consequence of regional movement or relative movement of the block with respect to the rest of Fruška Gora. The investigation was carried out on magmatic rocks situated south of the Srem dislocation (the southern FG structural unit) and north of the Srem dislocation beneath the Petrovaradin fortress. Also, magmatic rocks exposed in the far east

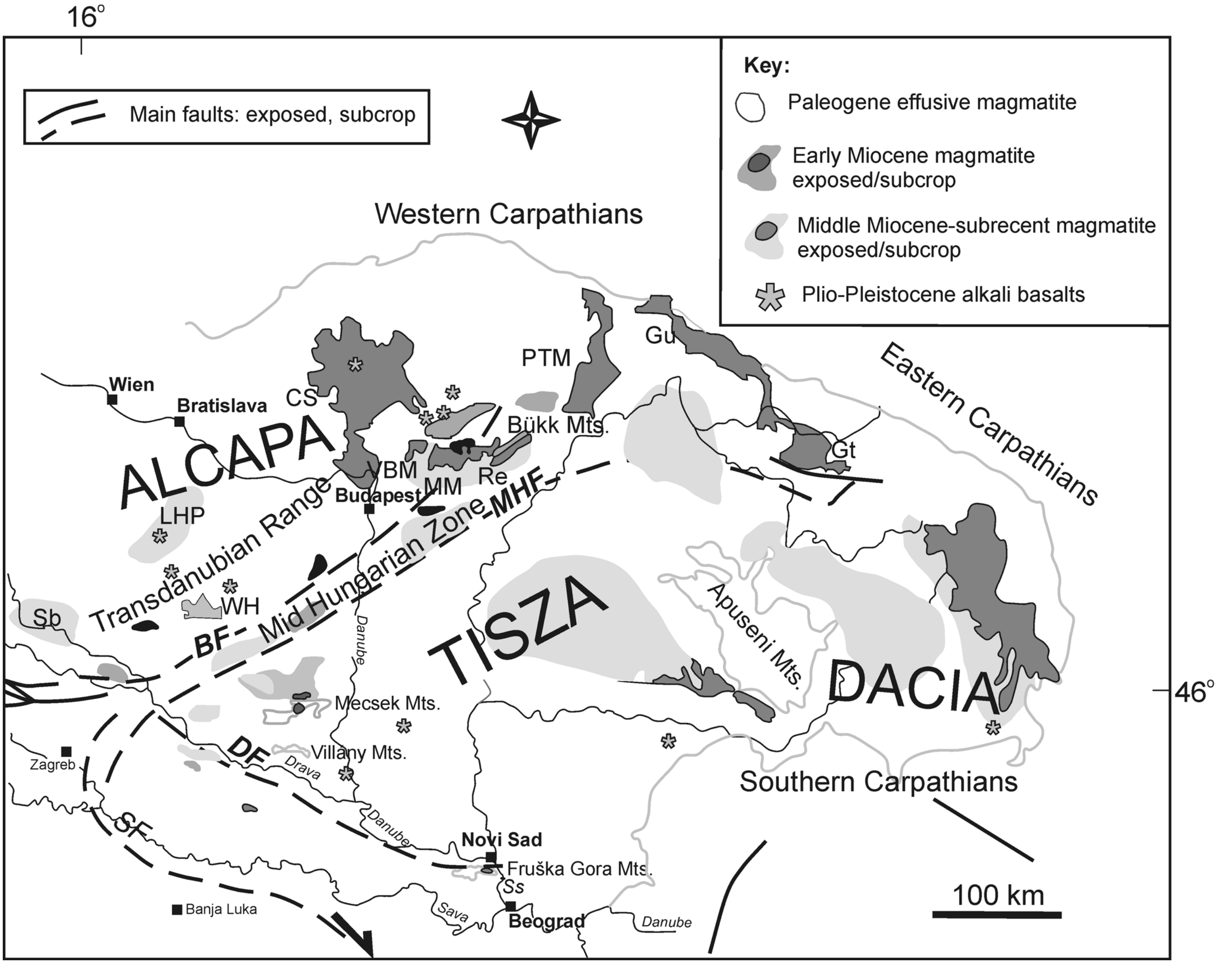

Fig. 1. Major tectonic units and spatial distribution of Paleogene to mid-Miocene magmatic rocks of the Pannonian Basin (after KOVÁCS *et al.* 2007).

Eocene/Oligocene-Miocene magmatic rocks formed during postcollisional setting in the Serbian part of the South Pannonian Basin are accessible for paleomagnetic investigation on Fruška Gora (FG). The main aim is the reconstruction of the amount and the direction of the paleorotation after the intrusion (Fig. 2).

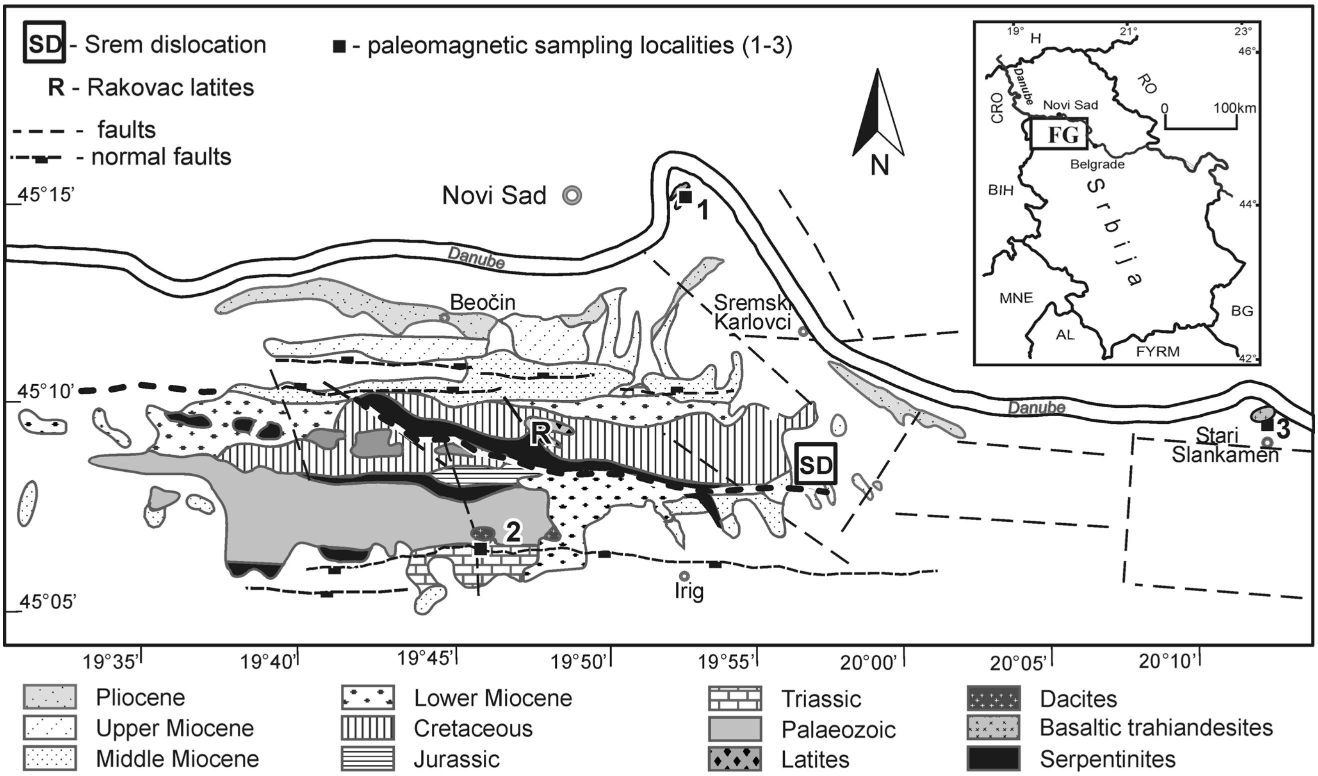

Fig. 2. Geological sketch map of Fruška Gora (FG) (after ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1971, 1984; PETKOVIĆ *et al*. 1976; DIMITRIJEVIĆ 1997) with paleomagnetic sampling localities.

of the FG on the right bank of the Danube River were investigated. According to MAROVIĆ *et al.* (1996 based on the position of the Neoalpine structures in the area of Vojvodina – the Serbian part of the South Pannonian Basin (Fig. 2)), they belong to Fruška Gora.

Geological background

Magmatic rocks of the Fruška Gora have been the subject of geological investigation since the second half of the 19th century, when the first geological maps of Fruška Gora were made (LENZ 1874, KOCH 1876) and the massive eruptive rocks were separated. Petrological characteristics and the origin of these volcanics classified as trachyte, latite or trachyandesite are described by KIŠPATIĆ (1882), TUĆAN (1907) and KNEŽEVIĆ *et al*. (1991). There, on a relatively small area (80 km long and only 15 km wide), so far two volcanic phases during Tertiary time have been distinguished. The first one is related to the extrusions of latites, dacito-andesite and rhyodacites in Oligocene (31.6–36 Ma), and the second to the extrusion of basaltic trachyandesite in Miocene i.e. in Badenian time (KNEŽEVIĆ *et al*. 1991, MATOVIĆ & MILOVANOVIĆ 1998; VASKOVIĆ *et al*. 2010). These volcanics are linked, spatially and temporally, with the same rock types evolved during Paleogene–Early Miocene within the Pannonian basin (KOVÁCS *et al*. 2007).

The main feature of this tectonic phase is opposite rotations of Alcapa and Tisza-Dacia microplates within the Carpathian–Pannonian area (MÁRTON, 1987; CSONTOS *et al*. 2002). The paleomagnetic data recorded in Paleogene–early Miocene rocks (MÁRTON, 1987) imply that these microcontinents were detached from the Dinarides and pushed/rotated into the Carpathian embayment (KOVÁCS *et al*. 2007).

There is still no agreement about the geotectonic affiliation of Fruška Gora. The reported structural relationships of the pre-Tertiary formations, their lithological and petrological features, age and paleontological data imply the existence of several opinions about its geotectonic evolution. The FG is exposed on the most northern part of the Western Vardar Zone (KARAMATA & KRSTIĆ 1996; DIMITRIJEVIĆ 1997) where the closure of the Vardar Ocean started in Early Cretaceous (123 ± 5 Ma) by the subduction of the oceanic crust towards the NE (MILOVANOVIĆ *et al*. 1995) and ended by the obduction with the northern vergence just above the Periadriatic suture (GRUBIĆ *et al.* 1998). According to PAMIĆ (2000), the FG belongs to the Sava Zone recorded as a Late Cretaceous-Early Paleogene back-arc basin open till Middle Miocene, formed by the collision of the Internal Dinarides and Tiszia. Recently, the increasingly accepted point of view is of SCHMID *et al*. (2008) who also consider the FG ophiolites as a part of the internal Sava Zone, a tectonic unit formed by the collision of Tiszia and the Dacides with the internal Dinarides.

East–west extending Mt. Fruška Gora is bound by the Danube River on the north and Telek hill on the west. At the easternmost side, at the village Stari Slankamen, it is bordered by the right bank of the Danube. Its northern and southern sides are bound by regional normal faults (Fig. 2). Upper Cretaceous and older rocks are strongly tectonised (DIMITRIJEVIĆ 1997). The Tertiary tectonic movements caused breaking of the FG into sub-blocks which are overlain by Neogene sediments.

The FG is made of Paleozoic, Mesozoic and Tertiary lithological units. The oldest, Paleozoic metamorphic rocks are in tectonic contact with Triassic sediments (Fig. 2). Triassic sediments are mainly developed on the southern slopes. Upper Triassic through mid-Jurassic is not exposed. In the central part the Upper Jurassic basic magmatic rocks and serpentinised peridotites (ophiolites) occur in three zones. Two types of Cretaceous development are found in the tectonic units separated by Srem dislocation (Fig. 2). The first (south of SD) comprises shallow water clastics and reef limestones, the second (north of SD) deep-water flysch deposits. During the Eocene–Miocene latites (KNEŽEVIĆ *et al*. 1991) and dacito-andesites are extruded. Their pyroclastics can be found on the northern slopes of Fruška Gora (PETKOVIĆ *et al.* 1976).

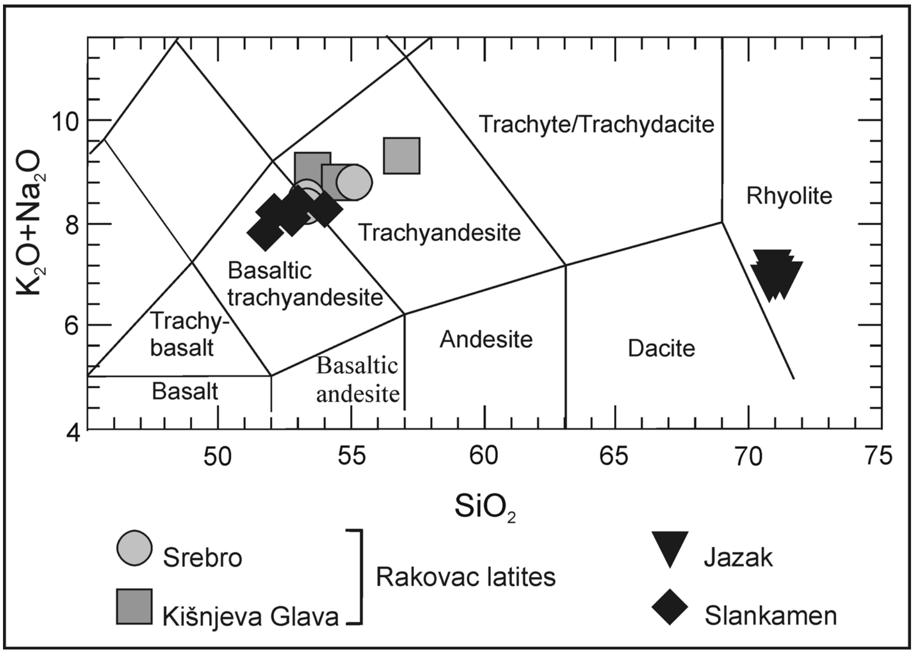

Fig. 3. Classification of the volcanics from the Mt. Fruška Gora according to SiO_2 vs. ($Na_2O + K_2O$) diagram (LA MAITRE *et. al*. 1989).

The latites of Rakovac occur in the central part of Fruška Gora, in the form of elongated bodies striking E–W, or as small intrusions below the Petrovaradin fortress. They are intruded into Triassic limestones, Upper Jurrasic serpentinites and Upper Cretaceous flysch. Based on data obtained from boreholes SIMIĆ & SIMIĆ (2002) reported the occurrence of Rakovac latites in the form of clustered dikes which form conjugate pairs in the deeper levels and make up a larger body. The latites occurring as nearly vertical dykes below the Petrovaradin fortress have the same features as the previously (PETKOVIĆ *et al.* 1976; VASKOVIĆ *et al.* 2010). ČIČULIĆ & RAKIĆ (1971) determined Tertiary magmatic rocks south of the Srem dislocation as dacites and andesites. Later on VASKOVIĆ *et al.* (2010) classified them as rhyodacites (Fig. 3). These rocks occur along the regional fault zone striking E–W, which spreads from Hopovo to the valley of the Beli potok in the area of Jazak village (ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1971). According to the position of these magmatic rocks with the respect to the Paleozoic, Triassic and Lower Miocene rocks as well as the presence of accessory minerals in bentonites of the Vrdnik coal-bearing Miocene series, the extrusion of dacito-andesite (i.e. rhyodacite after VASKOVIĆ *et al.* 2010) occurred in several phases during Oligocene–Mid Miocene (ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1971; PETKOVIĆ *et al*. 1976). Recently, VASKOVIĆ *et al*. (2010) have limited their age to Oligocene, although additional isotopic age data is required, e.g. K–Ar.

The magmatic rocks on the right bank of the Danube River in the vicinity of Stari Slankamen, not mapped on the basic geological map of SFRJ, sheet "Inđija" 1:100000 (ČIČULIĆ-TRIFUNOVIĆ *et al*. 1984), are classified as basaltic trachyandesites (VASKOVIĆ *et al*. 2010) probably of Miocene age (Fig. 3).

Lacustrine sediments of Lower Miocene age and Badenian to Pontian sediments occur at the marginal parts and in the base of FG. Pliocene is represented by lacustrine Paludian beds.

Based on the difference in the development of geological formations, their position and characteristics of tectonic correlations, PETKOVIĆ *et al.* (1976) and DIMITRIJEVIĆ (1997) distinguish two major structural units (blocks) on the Fruška Gora: the northern Fruška Gora structural unit north of the Srem dislocation (SD) and the southern Fruška Gora structural unit south of SD (Fig. 2).

Materials and Methods

Tertiary magmatic rocks, which are the subject of our investigation, were sampled from the northern side of FG, latitic dykes (locality 1) below the Petrovaradin fortress, rhyodacites (locality 2) near Jazak from the south side of FG, and on the east basaltic trachyandesites (locality 3) near village Stari Slankamen (Fig. 2).

For measuring the magnetic susceptibility, MFK1-A kappabridge (AGICO instrument) was used. The JR-5 spinner magnetometer (AGICO instrument) was used to measure the natural remanent magnetization before demagnetization (NRM) and remanent magnetization (RM) after each step of demagnetization. The intensity and the direction of the RM (shown by the angle of declination (D) and inclination (I)) was measured after each step of demagnetization. For demagnetization an alternating field demagnetizer (AFD300, Magnon instrument) was used.

First the NRM of each specimen was measured, followed by the measurement of magnetic susceptibility. Then, pilot specimens from each locality were subjected to detailed stepwise alternating field (AF) demagnetization until the RM signal was lost. Based on the behavior of pilot specimens, steps for AF demagnetization of the remaining specimens were chosen.

It was important during demagnetization to remove any secondary magnetization and identify the characteristic remanent magnetization (ChRM, remanence preserved in the sample). The demagnetization curves were analyzed using principle component analysis (Kirschvink 1980) to determine the ChRM and then subjected to statistical evaluation (Fisher 1953) to determine the mean paleomagnetic direction on locality level and the overall-mean paleomagnetic direction for all localities.

Paleomagnetic sampling, measurements and results

We drilled 33 cores from 3 localities using a portable drilling machine and oriented the cores with the magnetic and sun compasses in the field (Fig. 2). Latites (locality 1) were sampled from two dykes (since the distance between them was a few meters they are regarded as one locality with two sampling sites). From the first dyke, which was visually fresher, 7 cores were drilled and from the second dyke 3 cores were drilled. The value of magnetic susceptibility varies from 34450–53420 × 10^{-6} SI and the intensity of NRM from 300–600 mA/m. The maximum field used for demagnetization of specimens from the first dyke is 70 mT, while for the second dyke it was 210 mT.

After AF demagnetization, contrary to our expectation only the specimens from the second dyke had ChRM (Fig. 4).

Specimens from the first dyke had a secondary remanent magnetization which overprinted the primary one. Inclinations of four specimens were too shallow, while the other three had declinations and inclinations which coincide with the local geomagnetic field (Fig. 4).

The microscopic inspection of latite thin sections shows that the samples from the first dyke are hydrothermally altered and that their central part is highly calcitised (80 vol.%). Phenocrysts of amphibole and pyroxene are generally partly to completely chloritised and comprise secondary magnetite. The latite samples from the second dyke were much fresher under the microscope. The remanent magnetization is of normal polarity (Table 1).

Three good results of ten indicate that the mean paleo-

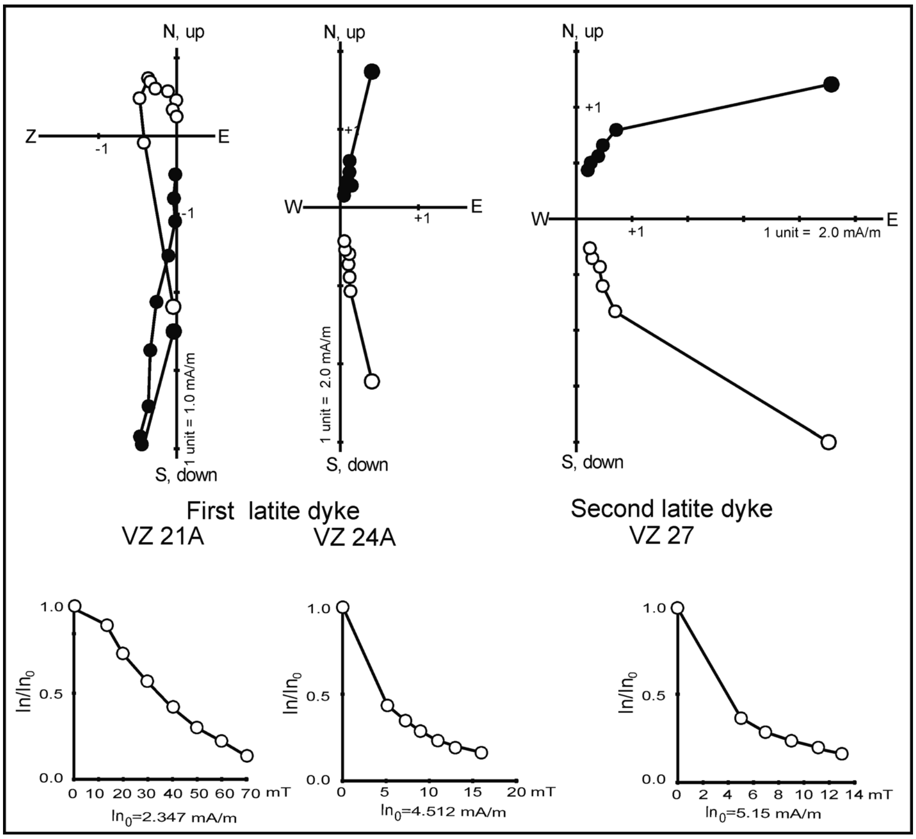

Fig. 4. Fruška Gora, latites. Typical demagnetization curves. Key: Upper row – Zijderveld diagrams (full/open circles: projection of the NRM in the horizontal/vertical plane). Lower row – Normalized NRM intesity as a function of demagnetizing field. In_0 - initial intesity of the NRM.

Table 1. Summary of locality mean palaeomagnetic directions, based on the results of principal component analysis (KIRSCHVINK 1980). Key: n/n_0 - number used/collected (the samples are independently oriented cores); *D*, *I* - declination, inclination; *k* and α_{95} - stastistical parameters (FISHER 1953); * directions are used in paleomagnetic interpretation.

	Locality	Lat. N Lon. E	n/n_0	$D°$	$I°$	k	α_{95}
1	*Petrovaradin fortress latites VZ 20-29	45°14'49" 19°52'16"	3/10	36	+60	87	13
2	*Jazak rhyodacites VZ 82-96	45°16'59" 20°21'19"	12/15	243	-73	74	6
3	Slankamen basaltic trachyandesites VZ 167-174	45°07'19" 19°45'49"	8/8	18	+71	97	6

magnetic direction is of low confidence (MÁRTON 1993), but if we take into account that the defined ChRM for specimens from the second dyke coincide with the primary remanent magnetization of Rakovac latites (LESIĆ *et al.* 2007) then it is justified to use the mean paleomagnetic direction for latites (locality 1) for defining the overall mean paleomagnetic direction for magmatic rocks of Fruška Gora.

Rhyodacites (locality 2) were sampled from the middle part of the Beli potok stream. Although the rocks looked altered on the surface, the crushed surface is fresh which was proven by petrological analysis. The traces of alteration are recorded only on plagioclase phenocrysts in the form of micron-sized flakes of sericite. The position of the dyke in the field could not be precisely defined due to thick cover - for that reason we sampled only four sites along the stream and drilled all together 15 cores. The value of magnetic susceptibility varies from 50.76–67.68 × 10^{-6} SI and the initial intensity of NRM from 1.99–5.71 mA/m. The maximum field used for demagnetization is 100 mT. During demagnetization, the demagnetization path in all specimens decayed towards the origin of Zijderveld diagram (Fig. 5). The remanent magnetization is of reversal polarity (Table 1).

The outcrop of basaltic trachyandesites (locality 3) is around 15 m long and 10 m high. Mainly it is covered with young loess sediments. On the crushed surface, rocks are fresh and dark gray in color. Eight cores from three sites were drilled. The value of magnetic susceptibility varies from 39770–45310 × 10^{-6} SI and the initial intensity of NRM from 947–1148 mA/m. The maximum field used for demagnetization is 15 mT. During demagnetization, the demagnetization path in all specimens did not decay towards the origin, which pointed to a magnetization probably acquired due to weathering and alteration. Also, the direction of the

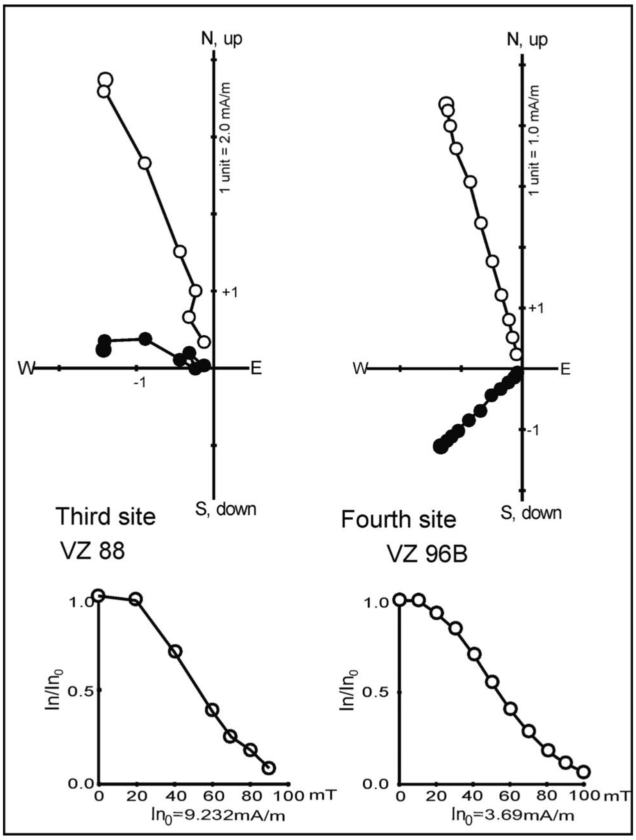

Fig. 5. Fruška Gora, rhyodacites. Typical demagnetization curves. Key as for Fig 4.

RM coincides with a N–S direction which supports the premise that the overprint was acquired in the magnetic field of present day Earth (Fig. 6, Table 1).

Discussion and conclusions

The new results of paleomagnetic investigation of Tertiary magmatic rocks from Fruška Gora can be divided into two groups. The first group comprises the results obtained from basaltic trachyandesites (locality 3) near Stari Slankamen – it is characterized by the remanent magnetization with high positive inclination and declination slightly deviated from the North, most probably acquired in the present day geomagnetic field during weathering. The second group comprises results obtained from latites (locality 1) below the Petrovaradin fortress from the north side and the rhyodacites (locality 2) from the south side of the crest of Fruška Gora – it is characterized by a stable remanent magnetization which is parallel with the vector of primary remanent magnetization of Rakovac latites (quarries Srebro, Kišnjeva Glava and Gradac) and the Upper Cretaceous flysch (with an overprint component) intruded by the Rakovac latites (CVETKOV *et al.* 2004; LESIĆ *et al.* 2007).

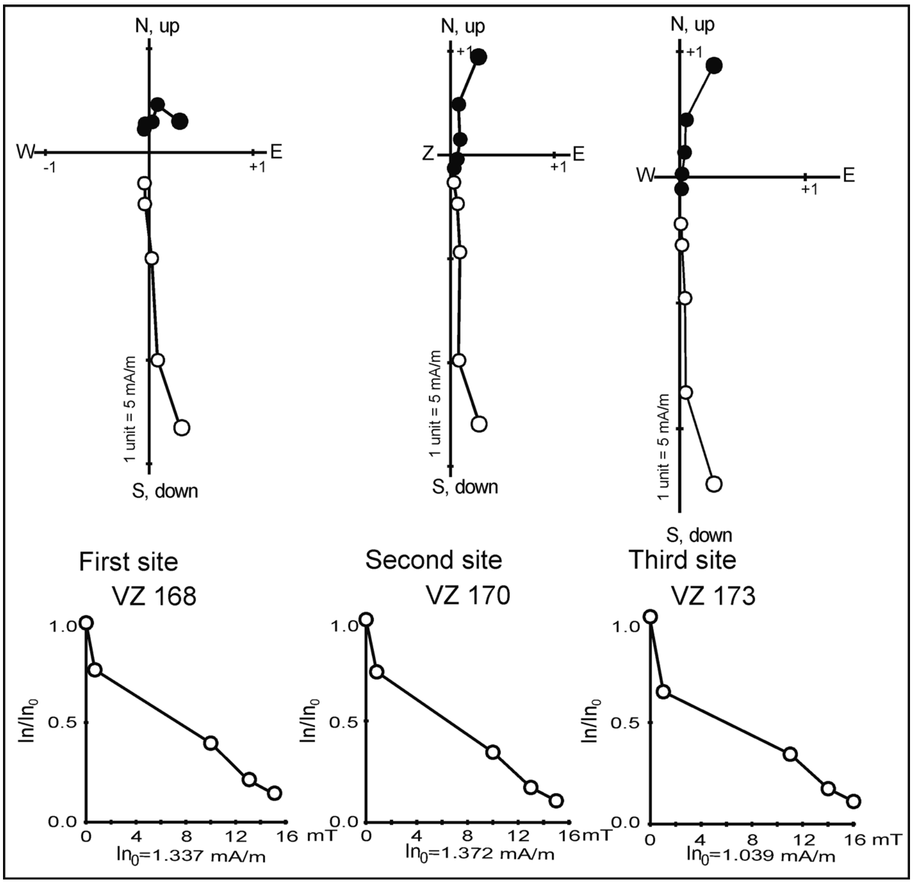

Fig. 6. Fruška Gora, basaltic trachyandesites. Typical demagnetization curves. Key as for Fig 4.

Latites below the Petrovaradin fortress have easterly oriented declination like the rhyodacites and the main latitic mass of the Rakovac but the polarity of the ChRM is positive (Table 1). According to the mineralogical-petrological and isotopic K/Ar data (KNEŽEVIĆ *et al.* 1991; VASKOVIĆ *et al.* 2010) and also the position of the studied localities on magnetostratigraphic scale (C12-R, C13, C15 and C16-NR1, OGG *et al.* 2008) it can be concluded that latites from Mt. Fruška Gora came from the same magmatic source and that they extruded during the same tectonic activity, at one of the three mentioned changes of the polarity of the Earth's magnetic field. The difference in the polarity of the primary remanent magnetization of latite dykes below the Petrovaradin fortress and the considerably bigger latite mass of Rakovac is most probably due to the faster cooling down of the former from the latter.

The overall-mean paleomagnetic direction of magmatic rocks from Fruška Gora with respect to the North suggests a considerable CW rotation of about 91° (Fig. 7). Considering that the Lower Miocene sediments are tilted and assuming that the magmatic rocks were affected by the same tectonic event, a tilt correction can be applied on the obtained direction for magmatic rocks. The tilt correction for the structural elements of Lower Miocene sediments (tilt angle of 41° towards 3° N) was statistically calculated from the data read from the basic geological map of SFRJ, sheet Novi Sad 1:100 000 (ČIČULIĆ-TRIFUNOVIĆ 1984). After applying the tilt correction, the overall mean paleomagnetic direction for magmatic rocks (D = 210°, I = –45°, k = 21, α_{95} = 14°) exhibits a more moderate CW rotation of 30° with respect to the North. The fact that close to the end of Miocene-Early Pliocene Mt. Fruška Gora rotated in a counterclockwise direction for 40° with the respect to the present North (LESIĆ *et al.* 2007) suggests a total of 70° of clockwise rotation for the period after the intrusion of magmatic rocks and before mid-Miocene.

The latest Miocene–pre-middle-Pliocene counterclockwise rotation of Mt. Fruška Gora which affected the Miocene and Mesozoic sediments is not recorded by the magmatic rocks. The reason for this most probably lies in the magnetic characteristics of the NRM of the studied magmatic rocks.

Since the paleomagnetic investigations were carried out on both sides of the Srem dislocation, both in the northern and southern Mt. Fruška Gora structural units, the obtained CW rotation is of regional significance and is connected to the period of the end of Eocene–beginning of Oligocene till the beginning of mid-Miocene. Then the CCW rotation of Mt. Fruška Gora begins, most probably induced by the influence of the Adriatic microplate (MÁRTON 2005; MÁRTON *et al.* 2011).

When analyzing the extensional structures in the territory of Vojvodina (Serbian part of the South Pannonian Basin) MAROVIĆ *et al.* (1996, 2007) concluded that the beginning of bending and movement of the pre-Neogene basement south of the Trans–Banat–Bačka dislocation is a consequence of the incorporation of Tiszia in the southern part of the future Pannonian Basin system during Upper Paleogene–Lower Miocene. The eastward movement of Tiszia and the CW rotation led to the transportation of southeastern Pannonian units towards NE with progressive eastward and southeastward movement which, ac-

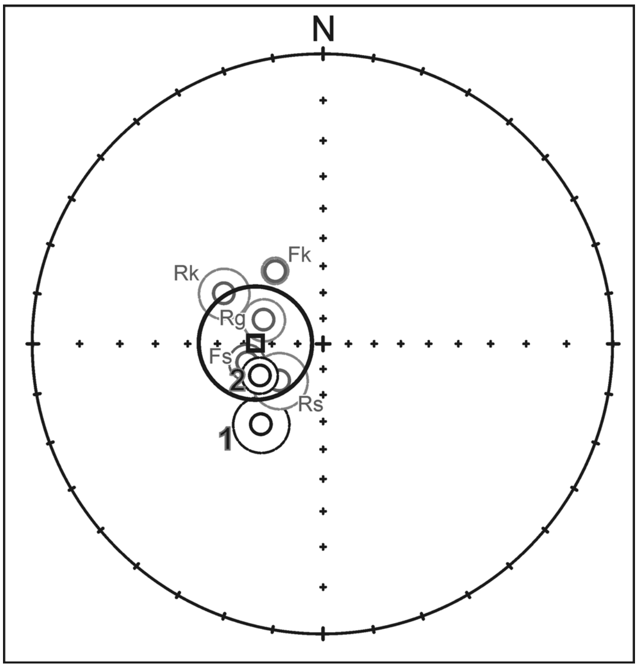

Fig. 7. Fruška Gora, magmatic rocks of Eocene/Oligocene age and Upper Cretaceous flysch. Locality mean paleomagnetic directions with α_{95} for: latite beneath the Petrovaradin fortress (1) originally of reversed polarity and rhyodacites (2) – present study; Rakovac latites: quarries Srebro (Rs), Kišnjeva Glava (Rk), Gradac (Rg) and Upper Cretacous intruded flysch: quarries Srebro (Fs) and Kišnjeva Glava (Fk) after LESIĆ *et al.* (2007). The overall-mean paleomagnetic direction (square) with α_{95} is also ploted. Key: open circles: negative inclination. Stereographic projection.

cording to the authors, represents in fact a clockwise rotation.

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Резиме

Нови палеомагнетски подаци из терцијарних магматита Фрушке горе, Србија

Само на неколико места у јужном Панонском басену, као што је на Фрушкој гори, терцијарни магматити нису покривени неогеним седиментима и доступни су за палеомагнетска испитивања са циљем реконструкције њихове кинематичке еволуције. Фрушка гора је једна велика антиформа, пружања И–З, која је са севера ограничена Дунавом, западну границу чини брдо Телек, а источну десна обала Дунава код Старог Сланкамена. На основу разлика у развићу геолошких формација, њиховог распореда и карактеристика тектонских односа, Петковић *и др.* (1976) и Dimitrijević (1997) издвајају две главне структурне целине (блока) – северпофрушкогорску структурну јединицу северно од сремске дислокације и јужнофрушкогорску структурну јединицу јужно од сремске дислокације. Током еоцена–олигоцена у палеозојске–мезозојске творевине екструдовани су вулканити латитског (Knežević *et al.* 1991) и риодацитског (Vasković *et al.* 2010) типа који су уједно и најстарије вулканске стене у јужном делу Панонског басена (Matović & Milovanović 1998). У близини села Стари Сланкамен јављају се базалтни трахиандезити миоценске старости (Vasković *et al*. 2010).

Током ранијих палеомагнетских истраживања (Cvetkov *et al.* 2004; Lesić *et al.* 2007) испитана је главна латитска маса тзв. Раковачки латити (каменоломи Сребро, Кишњева Глава и Градац и кредни седименти у њиховој околини на које су латити извршили магнетски "*overprint*") северно од Сремске дислокације. Нова палеомагнетска испитивања, представљена у овом раду, обављена су на локалитетима знато удаљеним од главне латитске масе и на вулканитима са јужне стране Сремске дислокације. Узорковани су латити испод Петроварадинске тврђаве који се јављају у виду скоро вертикалних дајкова који пресецају базичне магматске стене горњотријаске или јурске старости, базалтни трахиандезити код Старог Сланкамена и риодацити код Јаска који су утиснути дуж регионалне раседне зоне пружања И–З.

Укупно је избушено 33 оријентисана језгра која су подвргнута стандардним лабораторијским испитивањина: мерење иницијалне вредности магнетске сусцептибилности, интензитета реманентне магнетизације у домену тоталне природне реманентне магнетизације као и након сваког корака демагнетизације у наизменичном магнетском пољу.

Добијени резултати се могу поделити у две групе. У првој групи су подаци из базалтних трахиандезита Сланкамена који се одликују високом позитивном инклинацијом и деклинацијом незна-

тно отклоњеном од севера, највероватније стеченом у савременом геомагнетском пољу приликом површинског распадања стена. У другој групи су резултати, добијени из латита испод Петроварадинске трђаве и риодацита Јаска, коришћени у тектонској интерпретацији. Положај стабилне реманентне магнетизације друге групе колинеаран је са вектором примарне реманентне магнетизације Раковачких латита (CVETKOV *et al*. 2004; LESIĆ *et al.* 2007), с том разликом што латити испод Петроварадинске тврђаве поседују позитиван поларитет примарне реманентне магнетизације. На основу минералошко-петролошких (VASKOVIĆ *et al.* 2010) и изотопских (К/Ар метода, KNEŽEVIĆ *et al.* 1991) испитивања и положаја испитиваних локалитета на магнетостратиграфској скали (C12-R, C13, C15 и C16-NR1; OGG *et al.* 2008) може се закључити да фрушкогорски латити потичу из истог магматског извора, да су утиснути током исте тектонске активности, на граници једне од три промене поларитета магнетског поља Земље, при чему се жична појава латита испод Петроварадинске тврђаве највероватније брже охладила од знатно веће Раковачке масе, што је произвело разлику у поларитету примарне реманентне магнетизације.

Општи средњи правац вулканита Фрушке горе у односу на савремен правац севера указује на знатну ротацију, од 91° у смеру кретања казаљке на сату. С обзиром да су доњомиоценски седименти деформисани и ако претпоставимо да су магматске стене захваћене истом тектонском фазом, може се применити корекција за тектонику добијена статистичком анализом елемената склопа доњомиоценских седимената очитаних са ОГК лист Нови Сад 1: 100 000 (ČIČULIĆ-TRIFUNOVIĆ & RAKIĆ 1971). Елементи за ову корекцију су падни угао од 41° и правац пада од 3° северно. Након примењене корекције, добијена је умеренија ротација општег средњег правца вулканита ($D = 210°$, $I = –45$, $k = 21$, $\alpha_{95} = 14°$) од 30° у смеру казаљке на сату, што указује на укупну ротацију од око 70° у смеру казаљке на сату, за период после екструдовања вулканита и пре средњег миоцена, с обзиром да је Фрушка гора претрпела хоризонталну ротацију од 40° у смеру супротном од кретања казаљке на сату крајем миоцена почетком плиоцена (LESIĆ *et al*. 2007).

Палеомагнетска испитивања су обављена са обе стране сремске дислокације а добијена ротација у правцу казањке на сату је од регионалног значаја и везује се за крај еоцена/почетак олигоцена до почетка миоцена, када доминанту улогу преузима ротација у смеру супротном од кретања казаљке на сату услед утицаја Јадранске микроплоче (MÁRTON 2005).

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The impact of geology on the migration of fluorides in mineral waters of the Bukulja and Brajkovac pluton area, Serbia

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Abstract. One of the hydrogeochemical parameters that classify groundwater as mineral water is the content of fluoride ions. Their concentration is both important and limited for bottled mineral waters. Hydrochemical research of mineral waters in the surrounding area of Bukulja and Brajkovac pluton, in central Serbia, was conducted in order to define the chemical composition and genesis of these waters. They are carbonated waters, with content of fluoride ranging from 0.2 up to 6.6 mg/L. Since hydrochemical analyses showed variations in the major water chemistry, it was obvious that, apart from hydrochemical research, some explorations of the structure of the regional terrain would be inevitable. For these purposes, some additional geological research was performed, creating an adequate basis for the interpretation of the genesis of these carbonated mineral waters. The results confirmed the significance of the application of hydrochemical methods in the research of mineral waters. The work tended to emphasize that "technological treatment" for decreasing the concentration of fluoride in mineral waters occurs in nature, indicating the existence of natural defluoridization.

Key words: fluorides, hydrogeochemistry, mineral waters, Bukulja and Brajkovac granitoid pluton, defluoridization.

Апстракт. Један од хидрогеохемијских параметара за издвајање подземне воде као минералне је и садржај флуоридног јона. Садржај овог јона је изузетно важан и ограничавајући код флашираних минералних вода. Хидрохемијска истраживања минералних вода у околини плутона Букуље и Брајковца, у централној Србији, су спроведена ради дефинисања хемијског састава и одређивања порекла испитиваних вода. Оне су угљокиселе, са садржајем флуоридног јона од 0,2 до 6,6 mg/l. Пошто су хидрохемијске анализе показале разлику у хемијском саставу макро компоненти, било је јасно да је неопходно спровести и истраживања регионалне грађе. За ове потребе, нека додатна геолошка истраживања су спроведена, стварајући неопходну основу за интерпретацију порекла испитиваних угљокиселих минералних вода. Резултати су потврдили велики значај примене хидрохемијских метода у истраживању минералних вода. „Технолошки третмани" смањења концентрација флуоридног јона у минералним водама се одвијају и у природним условима, указујући на природну дефлуоридизацију.

Кључне речи: флуориди, хидрогеохемија, минералне воде, гранитоидни плутон Букуље и Брајковца, дефлуоридизација.

Introduction

Research of mineral waters is of great importance due to the wide variety of their utilization and consumption. Some of them are used for balneotherapeutic purposes, others as medicinal waters, or in the form of bottled mineral water. It is significant to know the content of trace elements. Set of norms and regulations on natural mineral waters define the minimum as well as the maximum allowed values of the content. Fluoride ions have an important place among trace elements; low values cause dental caries, while high values produce dental fluorosis or even skeletal fluorosis. The optimal values are between 0.5 and 1.5 mg/L (Fordyce

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2011). The impact of fluorides on the physiological functions of the human body is manifold. Fluorides affect normal endocrine function, as well as the function of the central nervous system and the immune system (Committee on Fluoride in Drinking Water, US National Research Council 2006). The overall assumption is that the fluoride content in some mineral waters is important because of hyperactivity the ion in the biological balance of elements in the human body. As was already mentioned, the emphasis is put on the content of fluoride ions in waters which can be used as bottled mineral waters. In this case, hydrogeochemical methods play an important role within hydrogeological investigations. Namely, defining hydrogeological conditions favorable for migrations of these ions aids greatly in the recognition the hydrogeological conditions required for the formation of mineral waters with the optimal content of fluoride. Lithology is definitely regarded as one of key factors for defining the presence of a certain element. This kind of approach allows for the recognition of the main issues of hydrochemistry and hydrogeology, for example mineral water genesis, to establish the conditions and forms of migration of fluoride in groundwater, *etc*. Based on previous investigations, the basic principles have been defined in reference to the migrations of this important trace element in the mineral waters of Serbia (Papić 1994), and in later hydrochemical investigations, attention was paid to the interdependence of lithology and the presence of fluoride in mineral water. Different fluoride containing minerals are the main sources of fluorides in soil and groundwater (Tirumalesh 2006; Shaji 2007) and there is a strong correlation between the lithology of aquifers and the fluoride concentration in groundwater (Seelig 2010). Relevant fluoride minerals are: amphibole, mica, fluorite (CaF_2), apatite ($Ca_5(PO_4)_3(F,OH,Cl)$), topaz ($Al_2SiO_4(F,OH)_2$) and cryolite (Na_3AlF_6). Granite and pegmatite are especially rich in fluoride minerals (Bailey 1977; Hitchon 1999; Reddy 2010) and Rankama & Sahama (1950) mention that rocks rich in alkali metals and volcanic glass contain more fluoride than other magmatic rocks. The fluoride concentration in groundwater is controlled by many geochemical factors. Elevated concentrations of fluoride are associated with high *TDS* values (Total Dissolved Solids), high Na^+ and low Ca^{2+} contents, ion exchange processes, *etc*. (Rafique 2009). High fluoride concentrations occur in groundwaters with low concentrations of calcium, therefore the cation exchange processes, resulting in Ca^{2+} removal from water, provides favorable conditions for fluoride enrichment of groundwaters (Furi 2011). The positive correlation between fluoride content in groundwaters and pH is explained by the fact that the ionic radius of $OH^–$ is nearly identical with that of $F^–$, allowing them to undergo exchange processes in the crystal structure of minerals. Clay minerals, *e.g*., kaolinite, have the ability to bind $F^–$ ions on its surface, but if the pH increases, $OH^–$ ions tend to replace $F^–$ ions, whereby $F^–$ ions are consequently released into the groundwater (Sreedevi 2006). Relatively high fluoride concentrations also occur in groundwater that circulates deep down fault structures (Kim 2005). All of this makes it easier to locate new high-quality groundwater aquifers that satisfy the current requirements and regulations on bottled mineral waters.

Methods

Samples of mineral waters were collected during the investigation period in 2010–2011. Water samples were taken from eight representative localities in the area of Bukulja and Brajkovac granitoid pluton and 16 physico-chemical parameters were determined in these samples, following standard and official methods of analysis. The groundwater samples were filtered through 0.4 μm membrane on site. Unstable hydrochemical parameters were measured on site, immediately after collection of the sample by potentiometry (pH-meter, WTW) and conductometry (EC, WTW). The major anions and fluoride were measured by ion chromatography (IC Dionex ICS 3000 DC). The major cations were determined by inductively coupled plasma – optical emission spectroscopy (ICP–OES, Varian).

The Schlumberger water quality analysis software AquaChem and USGS software Phreeqc were used for processing the hydrogeochemical data. The packages were used for the determination of the mineral saturation indexes and for the construction of charts.

Results

In the following text, eight characteristic localities of mineral waters, with different fluoride contents, are described. They are located in the area of Bukulja Mountain and Brajkovac Village in central Serbia, 60 km south of Belgrade (Fig. 1).

Geology

The region of Bukulja is dominated by a horst structure, which is in the form of an elongated block that stretches ESE–WNW and can be clearly discerned. It is composed of Paleozoic psamite-pelite sediments, which due to regional and contact metamorphism, first transformed into sericite schists and phyllite, and then into micaschists and finally into sericite schists and gneisses which form a contact aureole of Tertiary pluton bodies. The immediate cover of the Bukulja crystalline rock is composed of Cretaceous basal clastic limestones and flysch sediments, which in the course of intrusion of the Bukulja granite monzonite and the Brajkovac granodiorite, underwent some contact metamorphic changes. These are

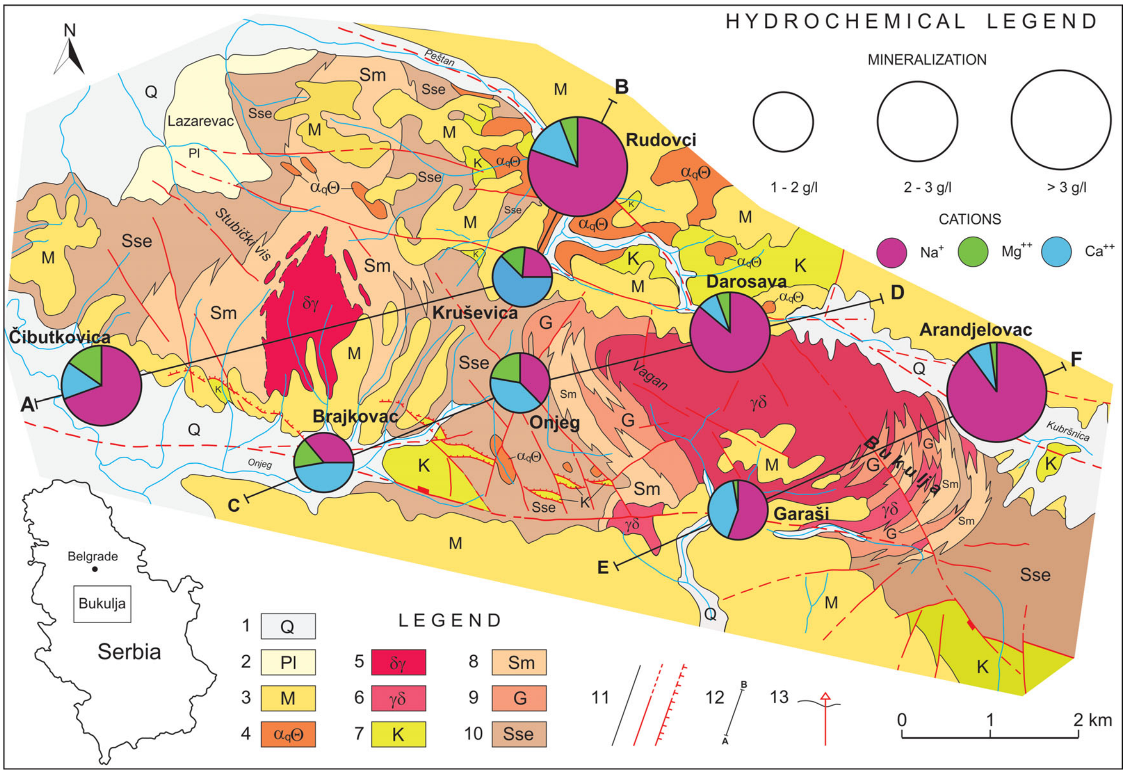

Fig. 1. Hydrochemical and geological map of the granitoid massif of Bukulja and Brajkovac, modified by I. Djoković and P. Papić, after: Basic geologic map, scale 1:100 000, sheets: Obrenovac (FILIPOVIĆ *et al.* 1979), Smederevo (PAVLOVIĆ *et al.* 1979), Gornji Milanovac (FILIPOVIĆ *et al.* 1967) and Kragujevac (BRKOVIĆ *et al.* 1979). Legend: **1,** Quaternary sediments; **2,** Pliocene clastic sediments; **3,** Miocene conglomerate, sandstone and claystone; **4,** dacites, andesites and pyroclastic rocks; **5,** granitoid of Brajkovac; **6,** granitoid of Bukulja; **7,** Cretaceous flysch and limestones; **8,** mica schists; **9,** gneiss; **10,** sericite schists; **11,** contact and fault lines; **12,** geological cross section; **13,** borehole.

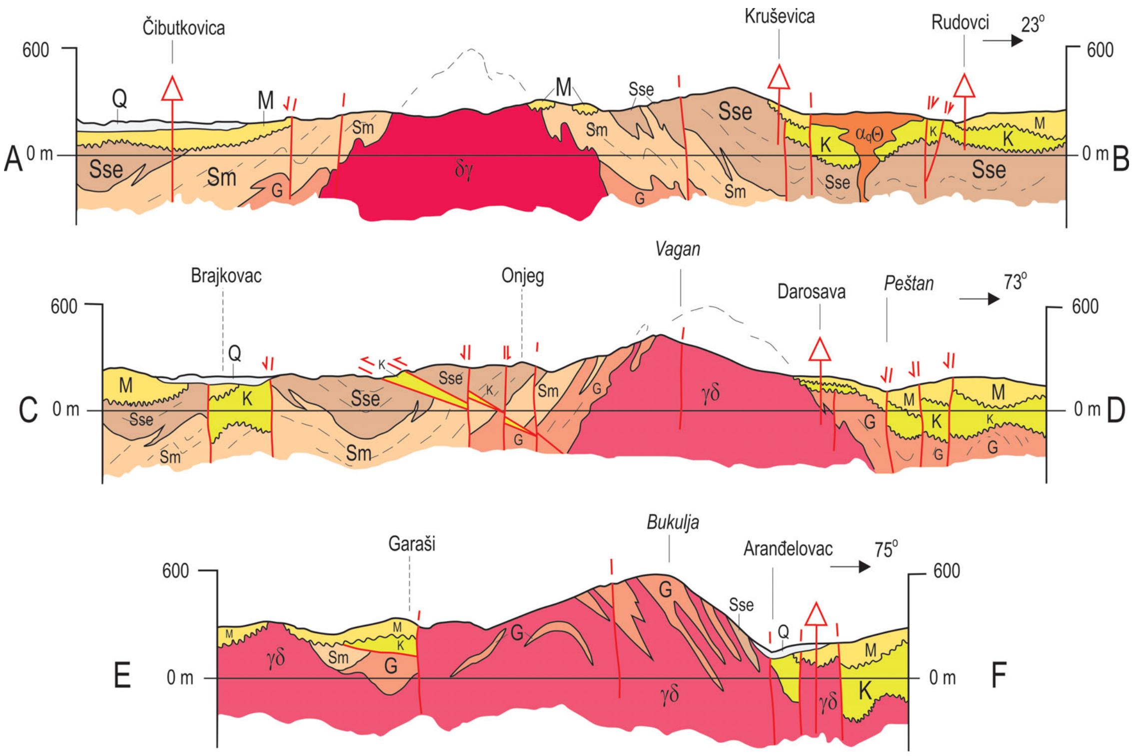

Fig. 2. Geological cross sections of the Bukulja and Brajkovac granitoid massifs (Legend is the same as for Fig. 1).

Table 1. Description of representative localities of carbonated mineral waters in the investigated area.

	Locality	*T* (°C)	Type of water source and depth of wells (m)	Flow rate (l/s)	Lithology
1	Čibutkovica	22.3	well (1002.8)	0.5	Paleozoic schist
2	Rudovci	18	well (119)	0.4	Paleozoic schist
3	Darosava	17.5	well (~50)	0.08	Granite
4	Arandjelovac	35.4	well (477)	2.2	Granite
5	Brajkovac	18.6	spring	0.03	Contact of Paleozoic schist and Cretaceous sediments
6	Onjeg	23	spring	0.02	Paleozoic schist and limestone
7	Garaši	16	spring	0.01	Paleozoic schist and Cretaceous sediments
8	Kruševica	22.1	well (65.5)	0.52	Sandy Tertiary sediments

particularly conspicuous in the vicinity of the investigated area (especially in the Venčac Mountain area) where masses of Cretaceous limestones were converted into marbles. The crystalline block base and its Cretaceous cover are overspread by Middle Miocene clastic rocks and pyroclastic rocks formed during the Miocene volcanic phases. Their intrusive and extrusive varieties in the form of dacite-andesites, phenoandesites and latites are widely spread in the northern part of the Bukulja block (along the Darosava–Rudovci–Kruševica–Lazarevac line), whereas in its southern part, they occur sporadically, near the headwater of the Onjeg River and in the form of erosion debris (DJOKOVIĆ & MARKOVIĆ 1986; DJOKOVIĆ & MARKOVIĆ 1985; KARAMATA 1994).

In the tectonic sense, the Bukulja block underwent a polyphase formation, which occurred during the Variscan and Alpine tectogenetic phases. Traces of Variscan folding are to be seen in rarely preserved portions of axial lines of folds and regionally developed axial-plane cleavage. During the Alpine tectogenenesis, the early structure of the Bukulja block was overfolded and it gained a different appearance. It is made of a large longitudinal antiform structure that resulted from overfolding of the Variscan cleavage. In their core, the pluton bodies of Bukulja and Brajkovac were embossed, which, by dome upfolding of the overlying rocks, partly altered the original fold form. The Alpine tectogenesis formed fault and joint structural fabrics, among which regional fractures are of crucial importance since they represent deep-seated faults in the Bukulja horst (TRIVIĆ 1998).

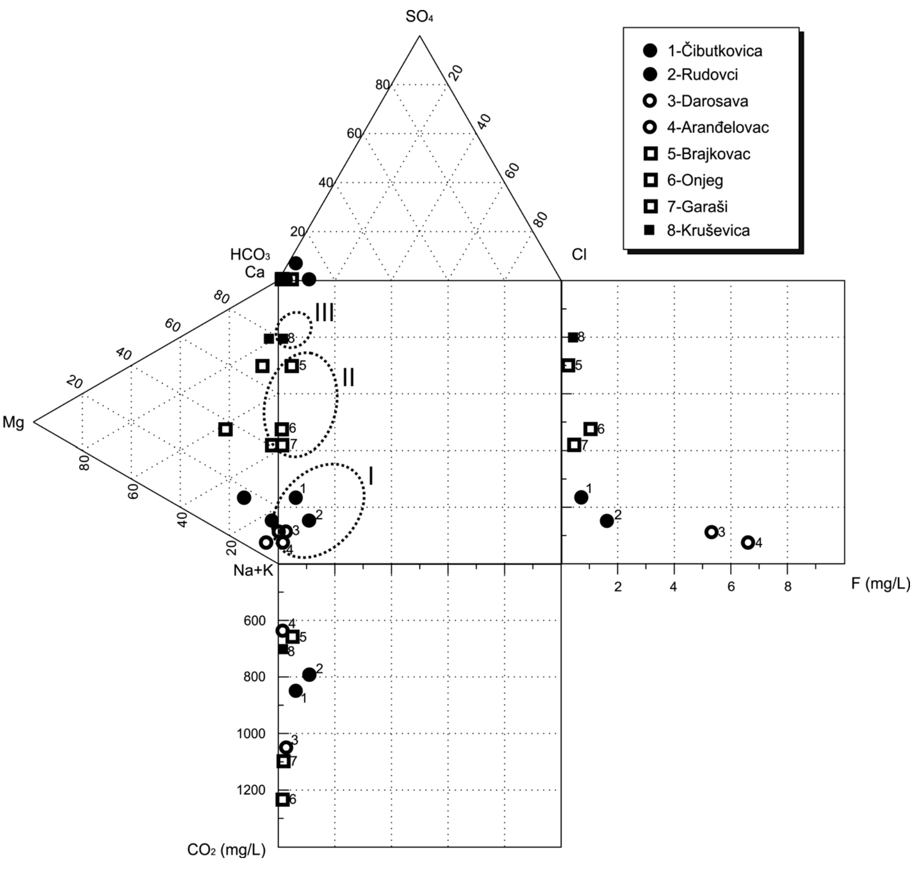

Fig. 3. Expanded Durov diagram with CO_2 and fluoride concentration (I, II and III – hydrochemical types of mineral waters).

Hydrogeochemistry

From the hydrochemical viewpoint, there are three types of mineral waters, as indicated on the Durov diagram (Fig. 3 I, II and III).

The first type is sodium hydrogencarbonate water (Čibutkovica, Rudovci, Darosava, Arandjelovac). They are mineral waters (*TDS* 1.7–3.8 g/L) with a carbon-dioxide content of 0.6–1.05 g/L. They have rather high contents of stron-

Table 2. Representative localities of carbonated mineral waters in the investigated area – macro and micro components.

	Locality	pH	CO_2 (mg/L)	*TDS* (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	HCO_3 (mg/L)	SO_4 (mg/L)	SiO_2 (mg/L)	F (mg/L)	B (mg/L)	Li (mg/L)	Sr (mg/L)
1	Čibutkovica	6.27	853.6	1761.19	90.18	49.86	452	71	24.11	1568	89	57.8	0.7	1.14	2.39	2.83
2	Rudovci	6.53	792	3796.84	204.41	29.18	1443	78.6	283.6	4227	1	12.6	1.64	6.93	3.4	0.266
3	Darosava	6.27	1056	1713.82	70.14	0.73	641	46.8	26.23	1931.99	0.9	84	5.31	0.761	2.98	0.369
4	Arandjelovac	6.64	633.6	3524.5	60.12	41.34	1313	87.8	28.36	4046.74	3	84.1	6.62	1.02	6.05	1.27
5	Brajkovac	6.49	660	1582.39	400.8	26.75	188	11.5	44.67	1827.56	0.8	76.5	0.2	0.59	0.984	5.06
6	Onjeg	6.4	1230	3030	248.1	93	330	46.8	7.1	2165.5	0.5	120	1.0	0.2	2.88	2.65
7	Garaši	6.4	1100	2610	240.2	12.2	391	15.6	7.1	1836.1	2	100	0.4	0.5	2.85	2.1
8	Kruševica	6.32	704	1558.71	460.92	14.59	130	8.48	15.6	1853.67	0.9	112	0.36	0.08	0.746	2.19

tium, lithium, silicon and fluoride. The fluoride content ranges from 0.7 to 6.6 mg/L. Among other macrocomponents, it is worth mentioning the contents of calcium ions, which range from 60 to 204 mg/L. The values of the genetic coefficient, *r*Na/(*r*Ca+*r*Mg) (*r* is reacting concentration in % eqv.) range from 2.3 to 10. The mineral waters are genetically confined to Paleozoic schists and granite gneisses. The favorable migration of fluorides is affected by the slightly acid environment (pH around 6.5), carbon dioxide in gas composition, sodium hydrogencarbonate content and the relatively low calcium ion values (Table 2).

The second hydrochemical type of mineral waters are the sodium hydrogencarbonate-calcium waters (Garaši, Brajkovac and Onjeg), with high contents of strontium, lithium and silicon. The fluoride content ranges from 0.2 to 1 mg/L. Among macrocomponents in their chemical composition, the high calcium ion content, which range from 240 to 400 mg/L, is worth mentioning. The genetic coefficient values *r*Na/*r*Ca+*r*Mg range from 0.4 to 1.3. These mineral waters occur at the contacts of Paleozoic schists with Cretaceous sediments. As a result of the extremely high calcium values, the fluoride ion contents are an order of magnitude lower compared to the previous type of mineral water.

Third type of mineral water is calcium hydrogencarbonate water (Kruševica). The mineralization is about 1.55 g/L with a carbon dioxide content of about 0.7 g/L. This type has higher strontium and silica contents, but the contents of the other micro components are not elevated. The value of genetic coefficient *r*Na/Ca+Mg is about 0.3. The calcium content is extremely high and reaches 460 mg/L, consequently the fluoride ion contents are as low as 0.36 mg/L.

Discussion and conclusions

Correlation diagrams (Fig. 4) show positive correlation between the fluoride content and *TDS*, as well as between fluoride and the sodium content. It is also obvious from these diagrams that high concentrations of fluoride are present in waters with high values of the genetic coefficient (*r*Na/*r*Ca+*r*Mg). This was generally expected considering that decomposition processes of silicate and aluminosilicate minerals occur in the majority of these waters (in the presence of CO_2), resulting in a carbonated, sodium hydrogencarbonate composition of the water (Fig. 3).

Calcium ions are negatively correlated with fluoride ions, because the content of fluoride in water is limited by the solubility product of calcium fluoride (the more calcium, the less fluoride in water). It is obvious from the Fig. 4 that low fluoride concentrations (< 0.5 mg/L) appear in waters where the concentration of calcium ions are elevated (> 200 mg/L).

Saturation indexes (*SI*) of fluorite and calcite were calculated using chemical thermodynamics, and obtained values indicated mainly mineral waters unsaturated with respect to fluorite and oversaturated with respect to calcite (Table 3 and Fig. 4). There are two exceptions: the mineral water from Darosava, which is mildly saturated with respect to fluorite, and the mineral water from Arandjelovac, which is in equilibrium with fluorite. The fact that these two mineral waters differ from the rest of the analyzed waters could be observed on every correlation diagram – number 3 (Darosava) and number 4 (Arandjelovac) are always significantly separated from the rest of the symbols, *i.e.*, mineral waters, on the diagrams.

The fact that the majority of analyzed waters are unsaturated with respect to fluorite is explained by the elevated concentrations of calcium (and consequently low concentrations of fluoride). The conclusion is that precipitation of fluorite is not possible under these hydrochemical conditions.

By comparing geological and tectonic characteristics and results of hydrochemical research, it was established that there is an evident connection between geological structure of the Bukulja substrate and the hydrocarbonate mineral water genesis. It was concluded that, apart from lithology, joint fabrics and larger dislocation structures are of crucial importance for the water chemistry in the studied region. In addition, it should be stated that smaller ruptures determine the type of porosity that enables the accumulation of groundwater in the rock mass and its chemical transformation, while larger dislocation forms determine the stream flows of the regional water circulation. For better perception of the correlation between certain spring

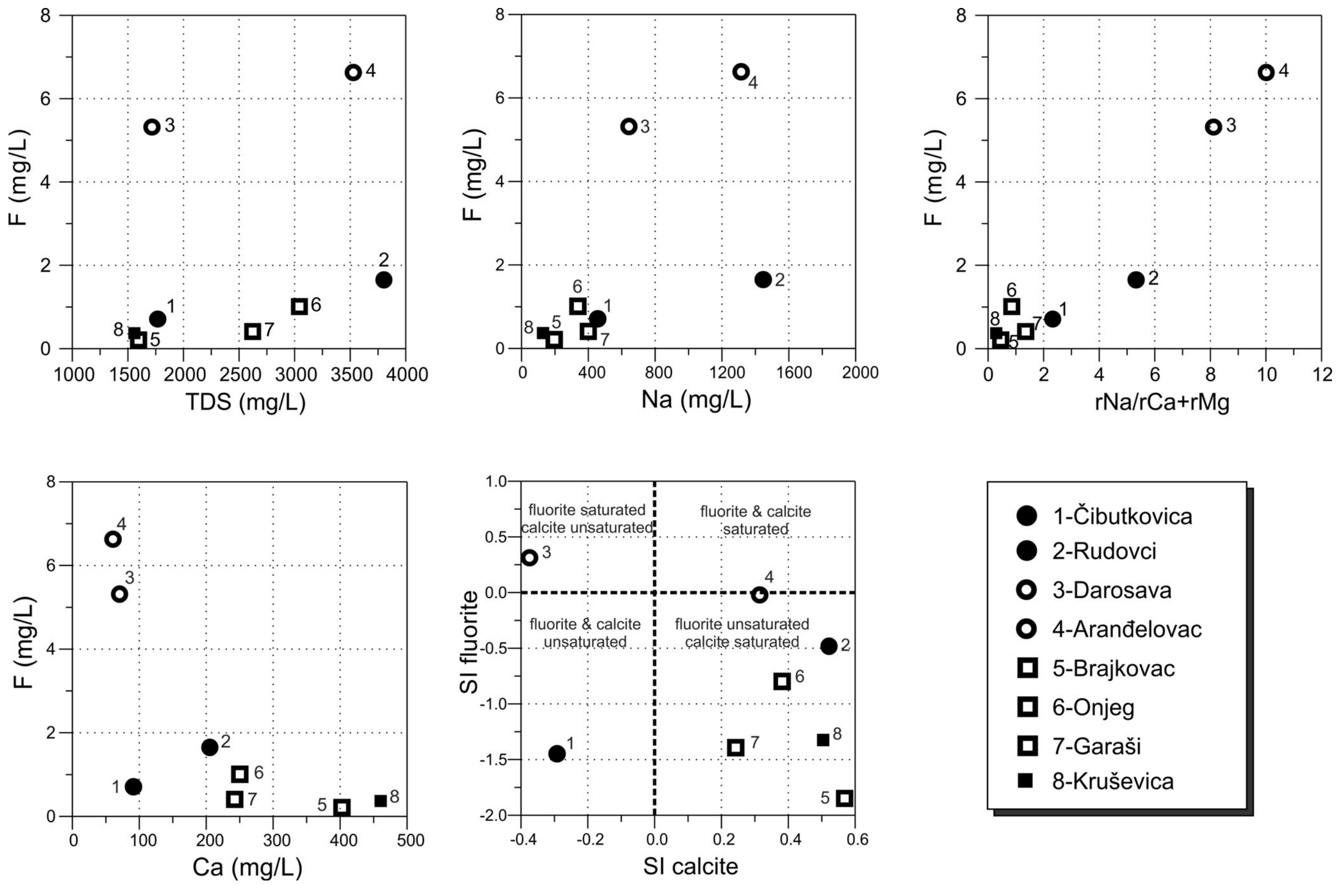

Fig. 4. Correlation diagrams for selected hydrochemical parameters.

Table 3. Representative localities of carbonated mineral waters in the investigated area – water type, genetic coefficients and saturation indexes (*SI*).

	Locality	Water type	*r*Na/*r*Ca+*r*Mg (r, %eqv)	*SI* calcite	*SI* fluorite
1	Čibutkovica	HCO_3-Na	2.3	-0.29	-1.45
2	Rudovci	HCO_3-Na	5.3	+0.52	-0.49
3	Darosava	HCO_3-Na,	8.1	-0.38	+0.31
4	Arandjelovac	HCO_3-Na,	10.0	+0.31	-0.02
5	Brajkovac	HCO_3- Na, Ca	0.4	+0.56	-1.85
6	Onjeg	HCO_3-Ca, Na,Mg	0.8	+0.38	-0.80
7	Garaši	HCO_3-Ca, Na	1.3	+0.24	-1.40
8	Kruševica	HCO_3-Ca	0.3	+0.51	-1.33

areas, a hydrochemical map was constructed with major geological structures along with hydrochemical properties of the spring locations (Fig. 1).

In order to present clearly the correlation between geological and hydrochemical parameters, transversal and diagonal cross sections were drawn, displaying the basic structures and lithologic properties of the rocks (Fig. 2). Associated with them are the following spring areas:

– Čibutkovica–Kruševica–Rudovci
– Brajkovac–Onjeg–Darosava and
– Garaši–Arandjelovac

In accordance with previous conclusions, it was established that the main spring areas of sodium hydrogencarbonate mineral waters (having dominant sodium content) occur along the complex regional fault which borders the Bukulja block on its north-eastern side, whereas mineral waters with dominant calcium content appear along the dislocation which borders its northern side.

It is obvious that the north-eastern dislocation (which connects Arandjelovac, Darosava and Rudovci) and the sets of joints that accompany it cut muscovite granite, gneiss, igneous and clastic flysch rocks, which in turn influence the formation of sodium waters.

In the spring area of Čibutkovica, the hydrogencarbonate mineral waters have distinctly sodium characteristics, which prove that the southern dislocation does not act as a groundwater recharge. Recharge is most probably realized in the metamorphic complex that forms the northern hinterland of the spring area.

In contrast, along the southern dislocation, Bukulja crystalline rocks are at many places in contact with

Upper Cretaceous clastic-carbonate flysch, which increases the amount of calcium in the spring areas of Garaši and Brajkovac. The Onjeg locality belongs to this group, its water having a higher content of calcium due to the dissolution of the limestone thick layers that form a tectonic block between the two reverse faults.

The water of Kruševica spring is characterized by a high content of calcium, but the contents of the micro components are not elevated, except for strontium and silica. This is due to a shallower zone of groundwater formation in the sandy Tertiary sediments.

It should be emphasized that the two mineral waters belonging to the first type are bottled as the mineral water "Knjaz Miloš" from Arandjelovac (Bukovička spa) and "Dar voda" from Darosava. The fluoride concentrations in these waters are higher than 1 mg/L; hence, they are called fluoride waters. Due to the biological activity of fluoride, its content is limited to 5 mg/L for bottled mineral waters. If the level is higher than 1.5 mg/L, the term "contains more than 1.5 mg/L of fluoride: not suitable for regular consumption by infants and children under 7 years of age" should appear on the label in close proximity to the name of the product. The European Directive on the exploitation and marketing of natural mineral waters and spring waters sets standards for excluding harmful elements such as fluoride ions, iron, manganese, sulfur and arsenic. It is obvious from the obtained results that some mineral waters in Serbia should be subjected to water treatment, which seems to be difficult in practice, and sometimes nature itself plays the role of a "technologist". Two possibilities are offered here: the right choice of locations for abstraction of mineral water with satisfactory chemical composition, which is a hydrogeologist's task, and the application of artificial defluoridization by means of aluminum oxide, lime, ion exchange resins or similar methods, which is a technologist's task. It is important to emphasize the impact and application of hydrochemical methods throughout hydrogeological research, which includes defining the conditions and factors of migrations of fluoride ions in mineral waters, the defining of the basic hydrochemical types of waters with high and low levels of ions and of gas composition, as well as the thermodynamic conditions in aquifers with accumulated mineral waters.

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Резиме

Утицај геологије на миграцију флуорида у минералним водама околине плутона Букуље и Брајковца, Србија

Хидрохемијска истраживања вода ширег подручја Букуљског и Брајковачког плутона су обављена ради утврђивања њихових хемизама и генетских својстава. Испитивањима је обухваћено осам најважнијих изворишних локалитета, од којих се Аранђеловац, Даросава и Рудовци налазе на североисточном, Гараши, Брајковац и Чибутковица у југозападном, а Оњег и Крушевица у централном делу изучаваног простора. Пошто су хидрохемијске анализе указале да је у наведеним извориштима присутно варирање хемизма вода, било је очигледно да су за разјашњавање њихове генезе, поред хидрохемијских истраживања, неопходна и изучавања регионалне грађе. Ради тога су извршени и додатани геолошки радови, што је у целини створило основу за тумачење генезе хидрокарбонатних вода.У тектонском смислу букуљски блок је претрпео полифазна обликовања, која су се одиграла током варисцијске и алпске тектонске фазе. Трагови варисцијског набирања се манифестују кроз ретко сачуване делове набора и регионално развијен кливаж аксијалне површине. Током алпске тектогенезе ранија структура букуљског блока је пренабирана, при чему је стекла другачији изглед. Њу чини крупна лонгитудинална антиформна структура, настала пренабирањем варисцијског кливажа. У њен језгрени део су утиснута плутонска тела Букуље у Брајковца, која су куполастим задизањем кровине донекле изменила основну наборну форму. Алпским обликовањима су формирани раседни и пукотински склопови, од којих посебан значај имају регионални разломи који представљају кључне граничне структуре букуљског хорста.

Следећи претходне закључке, утврђено је да се главна изворишта хидрокарбонатно-натријумских вода (са доминантном натријумском компонентом) јављају на сложеном регионалном раседу који ограничава букуљски блок са североисточне стране, а да се на дислокацији која га ограничава са југа јављају воде са доминантним јоном калцијума. Очигледно је да североисточна дислокација (која повезује изворишта Аранђеловца, Даросаве и Рудоваца) и пукотински системи који се налазе уз њу, у највећој мери пресецају гранит-монцонитске, гнајсне, вулканске и кластичне флишне стене, које својим саставом утичу на формирање натријумског типа воде.

Насупрот томе, јужна гранична дислокација на више места гради контакт између букуљског кристалина и горњокредног кластично-карбонатног флиша, што доприноси повећању калцијума у изворишним подручијима Гараши и Брајковац. У ову групу изворишта треба сврстати и локалност Оњег, чија вода има повећан садржај калцијума, што је највероватније последица растварања кречњачких пакета, који граде тектонске пласа, укљештене између два реверсна раседа. У изворишна подручја Чибутковице хидрокарбонатне воде имају изразито натријумски карактер, што показује да у овом изворишту јужна гранична дислокација нема функцију прихрањивања. Подручје се вероватно прихрањује из метаморфног комплекса који чини северну залеђину изворишта. Изворишна област Крушевице представља хидрогеолошки загонетну појаву. У њеним водама изразито доминира калцијум, мада се сам локалитет налази у зони гнајсних стена. Изгледа да се у северној околини изворишта, испод миоценских седимената налази остатак трансгресивних, флишних седимената, а у њима се често јављају банци песковитих кречњака. Могуће је да су они дали калцијумску компоненту води.

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Factors contributing to the formation of carbonated mineral water systems in Serbia

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Abstract. There are more than 65 occurrences of carbonated mineral water (CMW) within the territory of Serbia. More than 93 % of these systems are found in the geotectonic unit referred to as the Vardar Zone and on the fringes of nearby units. To the east, west and north of the Vardar Zone, CMWs are either rare or non-existent. The area featuring CMWs is characterized by Tertiary magmatism, a complex geology and deep neotectonic structures. Based on $\delta^{13}C$ values of CO_2 and HCO_3^- in several CMWs in Serbia, and also in carbonates and CO_2 from liquid inclusions in several hydrothermal deposits around the world, it was concluded that CO_2 in the lithosphere of Serbia could originate from hydrothermal carbonates, and carbonates from sedimentary, metamorphic and magmatic rocks. The findings clearly showed that the main generators of CO_2 are located in the Vardar Zone and that CO_2 degasification is accomplished through temperature metamorphosis of carbonates (dolomite, calcite). Based on the carbonate transformation temperatures and the temperature conditions in the lithosphere of Serbia, the CO_2 might be the result of temperature-induced carbonate transformation below a depth of 3 km. Therefore, the conclusion of the study of CMWs in Serbia is that the formation of CMW systems in the lithosphere depends on the geochemical, temperature, and the magmatic and structural-neotectonic conditions.

Key words: CO_2, mineral waters, magmatism, geochemistry, neotectonic structures, Serbia.

Апстракт. На територији Србије је регистровано 65 појава угљокиселих минералних вода (УМВ). Од овог броја је чак 93% формираних система УМВ везано за познату геотектонску јединицу Вардарска зона и маргине суседних јединица према овој зони. Са удаљавањем од Вардарске зоне, источно, западно и северно, појаве УМВ су ретке или их уопште нема. Исто подручје доминантног распрострањења појава УМВ се карактерише и терцијарним магматизмом, сложеном геолошко-структурном грађом и дубоким неотектоонским структурама. На основу вредности $\delta^{13}C$ у слободном угљен диоксиду и хидрокарбонатима и карбонатима и угљен диоксиду у течним инклузимјама, констатовано је да у литосфери Србије угљеник може да води порекло из карбоната хидротермалних процеса, карбоната седиментних и метаморфних стена и карбоната магматских стена. Постигнути резултати су јасно показали да се у домену Вардарске зоне налазе главни генератори угљен-диоксида и да се дегазација одвија кроз процесе температурне метаморфозе карбоната (калцита, доломита). На основу познатих температура трансформације карбоната, при којима се ослобађа угљен-диоксид и геотемпературних услова у литосфери Србије, закључено је да угљен-диоксид у домену Вардарске зоне може да се генерише испод 3 km дубине. Тако је у резултату истраживања УМВ Србије закључено да формирање система УМВ зависи, пре свега, од геохемијских, геотемпературних, магматских и структурно-неотектонских услова.

Кључне речи: угљен-диоксид, минералне воде, магматизам, геохемија, неотектонске структуре.

Introduction

In Serbia, most of the registered occurrences of carbonated mineral water (CMW) are found in the central part of southern Serbia. Several isolated occurrences have been registered away from this area, but there are no such occurrences in the northern, eastern and south-eastern parts of Serbia. Within the territory

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of Serbia, CMWs are grouped such that they reflect the different regional geological structures (anticlines, fault zones, and the like). There are only a few published papers which consider these mineral waters in Serbia. PROTIĆ (1995) addressed all the mineral waters in Serbia and grouped most of the CMWs according to their genetic link with metamorphites, and a small number based on their contact with volcanism and sedimentary basins. The same author briefly described the geological makeup of the near surrounding of the occurrences, presented the physical and chemical properties, the gas compositions and the radioactivity of the CMWs, and described major documented investigations.

The goal of the research reported in this paper was to determine the main factors contributing to CMW formation and thus identify the laws of nature which govern their extent and depth in Serbia's lithosphere. The study of these factors included the results of modeled geotemperature conditions in Serbia's lithosphere, the outcomes of CMW $\delta^{13}C$ tests and the results of isotope tests of the infiltration origin of the CMW (MILIVOJEVIĆ 1989). To define the depth of favorable geotemperature conditions for geochemical oxidizable carbonate transformation processes and the release of CO_2, the results of investigations by *in-situ* methods conducted at boreholes in the Yellowstone Park in the USA (PATRICK & WHITE 1968) were used.

A spatial link of Serbia's CMW systems was established with the geostructural unit of the Vardar Zone, Tertiary magmatism and regional neotectonic structures. It was then determined that the origin of carbon is primarily associated with oxidizable forms of carbonates in Proterozoic, Paleozoic and Mesozoic sedimentary and metamorphic rocks, and that CO_2 is generated in the Vardar Zone below a depth of 3 km or, in other words, at depths where favorable geotemperature conditions exist for geochemical processes of temperature-induced metamorphosis of carbonates and the release of CO_2. The findings led to the conclusion that the main contributors to the formation of CMW systems in Serbia's lithosphere are geochemical, geotemperature, magmatic and structural-neotectonic factors.

Results and discussion

Extent of CMW systems in geostructural terms

A CMW system is a unit of geological inter-connected porous water-bearing structural elements in the lithosphere, between the recharge zone, the blending zone of infiltrated water and CO_2, and the CMW drainage zone.

The extent of the CMW systems relative to known geological tectonic units within the territory of Serbia (DIMITRIJEVIĆ 1995) is shown in Figs. 1 and 2. Based on the number of occurrences in geological tectonic units, 57 % of them are found in the Vardar Zone (VZ), 26 % in the Gneiss Complex (GNC) of the Serbo–Macedonian Massif (SMM), 11 % in the zone of the Drina–Ivanjica Element (DIE), 4 % in the Ophiolitic Belt (OB), and 1.5 % in both the East Durmitor Block (EDB) and the Carpathian–Balkan Region (CB). If follows from the above, as shown in Fig. 2A, that 93 % of the occurrences are within the VZ and on the fringes of nearby units.

This means that CO_2 is generated in the deeper reaches of Serbia's lithosphere within the VZ and that, while migrating toward the surface, the CO_2 is distributed to neighboring tectonic units *via* younger tectonic zones. This is analogous to the observation of WEINLICH *et al.* (2003) in connection with the Western Eger Rift, namely that CO_2 from the deeper reaches of the lithosphere migrates to the surface along so-called Y-structures. In the present case, the CMW systems are rooted in the deeper reaches of the lithosphere within the VZ. For these reasons, the majority of the CMW occurrences in Serbia are found in the VZ and the border zones with adjacent geotectonic units. The directions of the younger tectonic structures that distribute the CO_2 away from the VZ are quite distinct within the belt between the VZ and the SMM (Figs 1 and 2B).

A schematic representation of the noted linear directions of the CMWs is presented in Fig. 2B. It is a well-known fact that most tectonic faults are characterized by limited permeability or virtual impermeability. The greatest fault permeability is found in the moving zones of the Earth's crust, particularly in its stretching parts (STEPANOV 1989). Consequently, considering all relevant aspects, it follows that the linear directions in Serbia's lithosphere are the directions of neotectonic movements. These are also the privileged pathways of CO_2 distribution from the deeper reaches of the lithosphere to the surface and open structures for the easy infiltration of meteoric and surface waters for CMW recharge. According to the schematic representation in Fig. 2B, the directions of these neotectonic structures vary but are approximately northwest–southeast, east–west and northeast–southwest. It is also apparent in Fig. 2B that many of the CMW occurrences are grouped along the southern edge of the Pannonian Basin. This suggests a connection between these occurrences and the tectonic structures formed by the cascading descent of the Pannonian Basin and the parallel ascent of the Vlašić–Bukulja Anticlinorium and other structures south of the Pannonian Basin.

Based on the present observations, it is important to emphasize that the considered mineral water occurrences are associated not only with magmatic massifs, but also with younger tectonic structures, as is clearly shown by their linear distribution (Figs. 1 and 2). With regard to chemical types of the CMWs, there is only

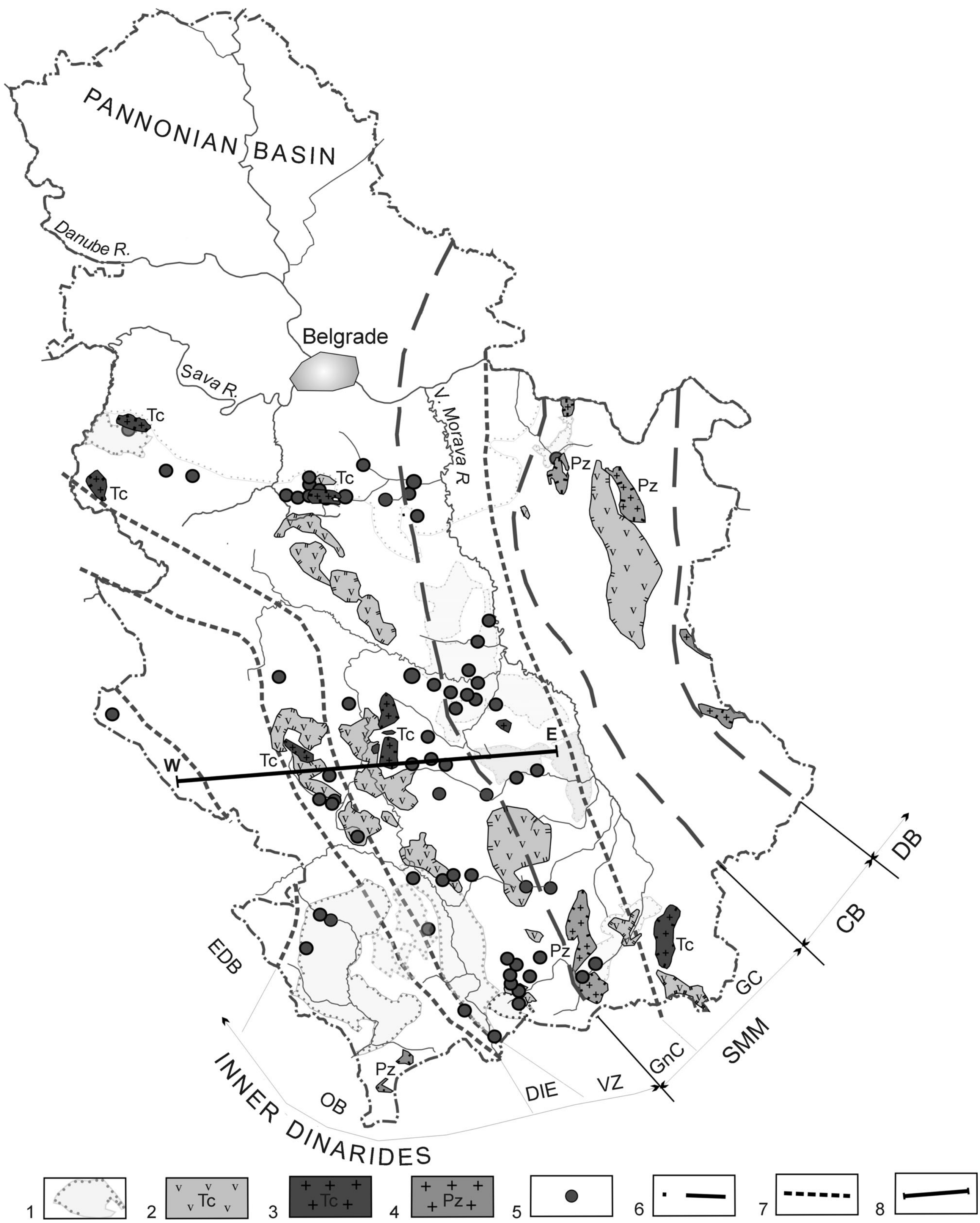

Fig. 1. CMW occurrences in Serbia in respect to granitoid intrusions (Tertiary and Paleozoic) and igneous rocks (Tertiary) of the Serbian lithosphere. **1,** Tertiary sedimentation basin; **2,** Tertiary igneous rocks; **3**, Tertiary granitoid intrusion; **4,** Paleozoic granitoid intrusion; **5,** CMW occurrence; **6,** Geological-structural unit boundary; **7,** Geological-structural subunit boundary; **8,** Geological cross-section (Geology reprinted from the Geological Map of Yugoslavia, Scale 1:500.000; produced by Federal Geological Institute, Belgrade, 1970). Geological-structural units: **CB,** Carpathian-Balkan Region; **SMM,** Serbian-Macedonian Massif; **GnC,** Gneiss complex; **GC,** Greenrock complex; **VZ,** Vardar Zone; **DIE,** Drina–Ivanjica Element; **OB,** Ophiolite Belt; **EDB,** East-Durmitor Block.

one occurrence of the SO_2–CaMg type, while all the other registered occurrences are of the HCO_3-type based on their anion composition, and with regard to their cation composition, they are mostly of the Na-type, rarely of the C-type and very seldom of the Mg-type.

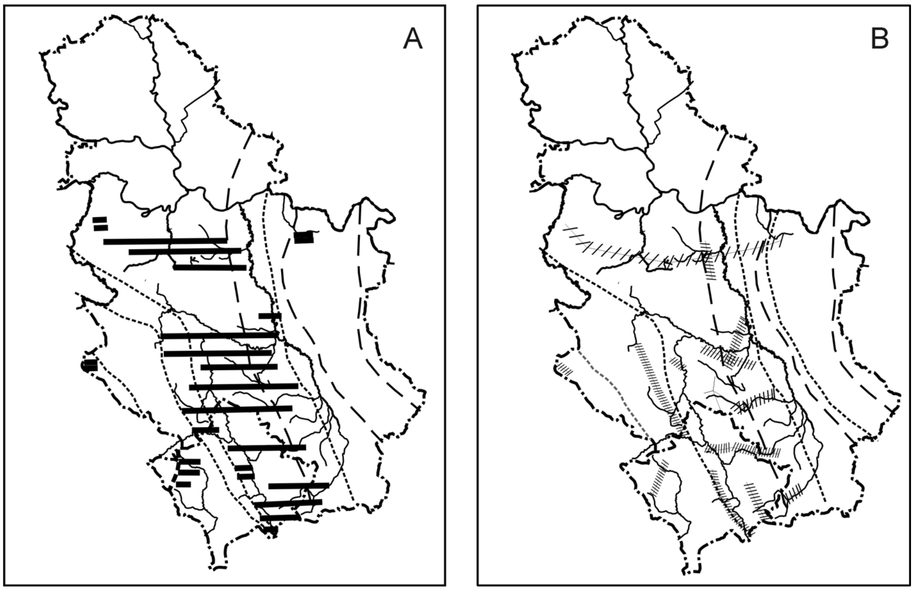

Fig. 2. Schematic representation of (A) the region of CMW occurrences and (B) noted linear distributions of the occurrences as potential directions of deep tectonic structures.

Based on the above, it is safe to assume that the VZ, characterized by a complex geological and tectonic makeup and Tertiary magmatism, holds the main CO_2 generators and that the distribution of CO_2 and the infiltration of surface water occur along regional neotectonic discontinuities which are rather pervious. Neotectonic vertical movements cause an enormous mass of carbonate-rich rock to become gradually exposed to elevated geotemperatures and, as a result, there is ongoing exposure of new masses to thermometamorphic geochemical processes. Consequently, the neotectonic units both predispose porous tectonic zones to CO_2 migration and expose new masses of the substrates of this gas to favorable geotemperatures for the transformation and release of CO_2.

Origin of carbon in carbonated mineral waters

For a number of CMW occurrences in Serbia, the values of the $\delta^{13}C$ isotope in free CO_2 were found to be in the range from –8.5 to –2.5 ‰, that is –10.03 to +1.78 ‰ in HCO_3^- (MILIVOJEVIĆ 1989). If this range of values detected in Serbia is compared with the values of the $\delta^{13}C$ isotope in the carbonates and CO_2 of liquid inclusions determined at several hydrothermal sites in the world (Fig. 3), a very good match is apparent. This supports the assumption that some CMWs in Serbia are traceable to carbonates *via* hydrothermal processes (either ended or still active, but in the "quenching" stage). Oxidizable forms of carbon in hydrothermal fluids can originate from magmatic sources, but can also be formed as a result of oxidation of reducible forms of carbon and leaching of sedimentary carbonates (OMOTO & RYE 1982).

Investigations involving the $\delta^{13}C$ isotope have shown that in granites and mafic and ultramafic rocks its values vary over a much broader range than in carbonates, and that the $\delta^{13}C$ values of carbonates in such rocks are generally from +2 to –10 ‰, and those of reducible forms of carbon from –15 to –30 ‰ (OMOTO & RYE 1982). Based on the above and the values of the $\delta^{13}C$ isotope in free CO_2 and HCO_3^- in Serbia's CMWs, it is safe to assume that the carbon in Serbia's CMWs may originate from carbonates of Proterozoic, Paleozoic and Mesozoic sedimentary and metamorphic rocks, carbonates of magmatic rocks created through assimilation of carbonates from sedimentary and metamorphic rocks, and carbonates from hydrothermal processes which could have leached from sedimentary, metamorphic and magmatic rocks. It is also safe to conclude that carbon from reducible forms cannot be a major contributor to Serbia's CMWs.

Supporting the above assumptions are estimates that about 93 % of all carbon in the Earth's crust is attributed to sedimentary and metamorphic rocks and only 7 % to magmatic rocks, while as little as 0.01 % is the sum of carbon in the atmosphere, hydrosphere and biosphere (OMOTO & RYE 1982). In Serbia's lithosphere, as schematically represented in Fig. 4, such a large proportion of carbon (in excess of 90 %), can only be found up to a depth of 5–8 km, or the depth of the complex of Proterozoic, Paleozoic and Mesozoic sedimentary and metamorphic rocks, interspersed with Tertiary magmatites. Below these depths, up to 15–20 km, in the "granitoid metamorphic layer", a carbon content of up to 7 % may be expected.

The depths of the CMW systems in Serbia are consistent with the configuration of the VZ (Fig. 4). In this part of the lithosphere, Tertiary magmatites intersperse the entire complex of sedimentary and meta-

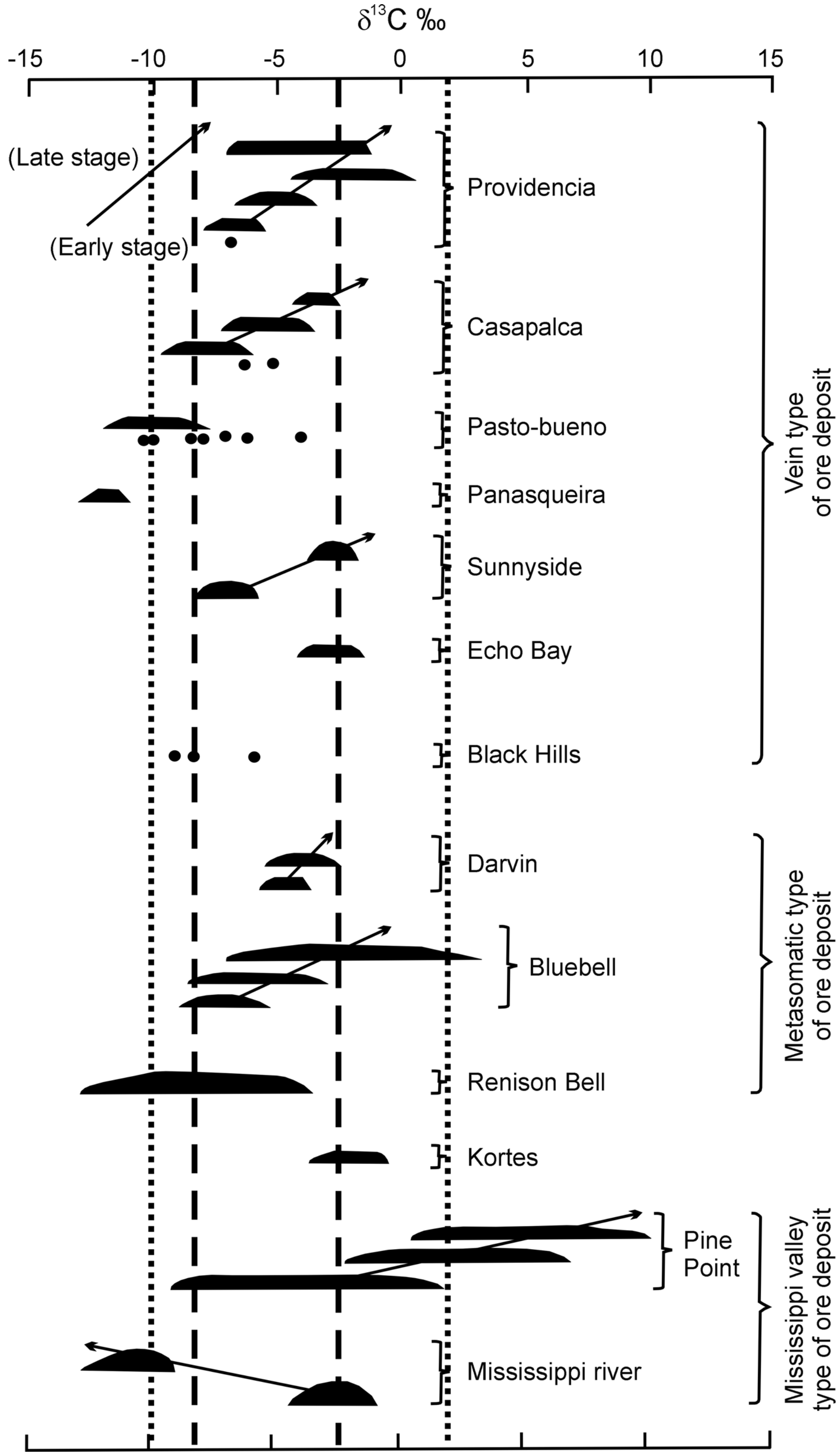

Fig. 3. Schematic representation of carbon isotope compositions of several hydrothermal ore deposits (OMOTO & RYE 1982), along with $\delta^{13}C$ ranges of free CO_2 (dashed line) and HCO_3^- (dotted line) at several CMW sites in Serbia.

morphic rocks rich in carbonates. While penetrating the complex of these rocks, the magmatites assimilated considerable amounts of carbon, which partly led to CO_2-generating thermometamorphic processes and, in the VZ, generally brought about elevated geotemperatures. As such, the connection between the

CMW systems and the VZ is logical, since it holds the main supply channels of Tertiary vulcanites and granitoid intrusions, from the deeper reaches of Serbia's lithosphere to the surface.

CO_2 generation processes in the Vardar Zone

In general, gases in the lithosphere can be generated by biochemical, metamorphic (chemical) and radioactive processes (KARTSEV & SHUGRIN 1964). As stated above, based on the $\delta^{13}C$ values, the carbon in Serbia's CMWs cannot be traced to reducible forms, or to carbon from organic compounds and graphite. Consequently, biochemical processes are not the dominant generators of CO_2 in the CMWs. Although CO_2 is not generated as a result of radioactive processes, elevated concentrations of radioactive elements and Rn gas in the CMWs allow for a conclusion to be drawn about their joint origin associated with granitoid intrusions.

Elevated concentrations of F, Pb, As and other heavy metals suggest a connection with volcanic processes. As such, it may be concluded that the CO_2 in the CMWs within the VZ is generated through the chemical processes of temperature-induced metamorphism. Among the chemical processes that lead to the release of CO_2, the most important are deep processes associated with intrusive and regional metamorphism (KOROTKOV 1983). It follows that an important factor for the CO_2-generating processes is the geotemperature of Serbia's lithosphere which, in the VZ, is governed by Tertiary volcanism and intrusive magmatism, with hydrothermal processes being the final stages of the magmatism.

According to PROTIĆ (1995), fluoride concentrations in Serbia's CMWs range from 0.1 to 14.25 mg/L (about 60 % above 1.0 mg/L), U concentrations range from 0.1 to 8.0 μg/L, Ra from 0.06 to 1.4 Bq/L, and Rn from 7.4 to 2035 Bq/L, whereby more than 75% of the CMWs exhibit elevated concentrations of U, Ra or Rn. Based on the good match of the $\delta^{13}C$ range of the CMWs and hydrothermal deposits (Fig. 3) and the elevated F concentrations in the majority of the CMWs, it is safe to conclude that there is a connection between the CMW CO_2 and hydrothermal processes. Considering the elevated concentrations of radioactive elements, there is a link between the CMWs and the granitoid intrusions. The oxidizable forms of carbon in the hydrothermal fluids (CO_2, H_2CO_3, HCO_3^-, and CO_3^{2-}) may be traced to magmatic sources and leaching of sedimentary carbonates (OMOTO & RYE 1982). It follows from all the above that the CO_2 gas in Serbia's lithosphere can be generated by temperature-induced transformation, from carbonates of Tertiary hydrothermal processes, magmatic rocks, and Proterozoic, Paleozoic and Mesozoic sedimentary and metamorphic rocks. However, given that the carbonates from the Tertiary hydrothermal processes are actually leached carbonates from sedimentary and metamorphic rocks and/or magmatic rocks, and that carbon is assimilated by magmatites from the same rocks, it follows that the Proterozoic, Paleozoic and Mesozoic sedimentary and metamorphic rocks in the lithosphere up to a depth of some 10 km can be considered as the parent substrates of the CO_2.

If the registered minimum temperatures (150 and 320 °C) are taken into account, at which dolomite and calcite are transformed and CO_2 released (PATRICK & WHITE 1968), as well as the geotemperature conditions in Serbia's lithosphere (MILIVOJEVIĆ 1989) and the results of regional geological investigations of the make-up of Serbia's lithosphere (Fig. 4), it follows that temperature-induced transformations of carbonates in the VZ may be expected below a depth of 3–8 km. As apparent in Fig. 4, this is the transition zone between the "granitoid metamorphic layer" and the Prote-

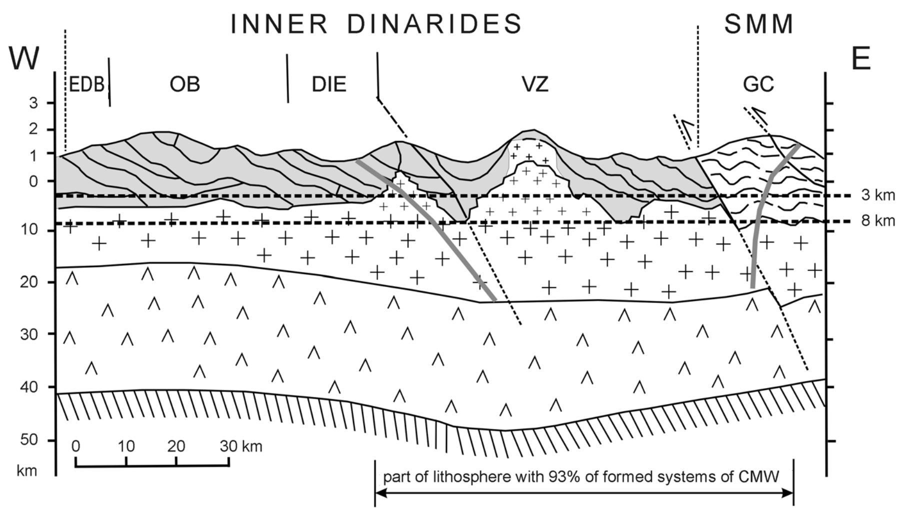

Fig. 4. Geological cross section of Serbia's lithosphere, part of the Inner Dinarides geological tectonic unit (ANĐELKOVIĆ 1988, modified). Legend: **1,** Pz–Mz sedimentary and metamorphic rock complex with magmatic intrusions; **2,** Ptz metamorphic rocks; **3,** granite–metamorphic layer; **4,** basalt layer; **5,** minimum depths for optimal geological and temperature conditions for geochemical processes of CO_2 production from dolomite (3 km) and calcite (8 km). Geological-structural units: **CB,** Carpathian–Balkan Region; **SMM,** Serbian–Macedonian Massif; **GnC,** Gneiss Complex; **GC,** Greenrock Complex; **VZ,** Vardar Zone; **DIE,** Drina–Ivanjica Element; **OB,** Ophiolite Belt; **EDB,** East-Durmitor Block.

rozoic, Paleozoic and Mesozoic complex of sedimentary and metamorphic rocks, interspersed with vulcanite and granitoid intrusions.

With regard to the previously-identified potential connection between the CMWs and hydrothermal processes, the CMW CO_2 could be traced to carbonates from completed hydrothermal processes and/or contemporary hydrothermal processes in the final stages of "quenching" of volcanic activity. In hydrothermal solutions, CO_2 from carbonates may be generated as a result of dissolving reactions (*e.g.*, $CaCO_3 + 2H^+ \rightarrow H_2CO_3 + H_2O$) and decarbonization reactions (*e.g.*, 3 dolomites + 4 quartzites + $H_2O \rightarrow$ talc + 3 calcites + $3CO_2$) (OMOTO & RYE 1982). The first reaction is dominant under surface conditions, while at high temperature, both reactions play significant roles. The carbonate dissolution reaction leads to the formation of HCO_3^- under surface conditions and CO_2 at high temperatures.

Conclusions

CMW systems in Serbia's lithosphere were formed in dependence on complex interactions between geochemical, geotemperature, magmatic and structural-neotectonic factors. The parent CO_2 substrates in Serbia's lithosphere are carbonates from Proterozoic, Paleozoic and Mesozoic sedimentary and metamorphic rocks, up to a depth of some 10 km. The depth of CO_2 generation of about 3 km is characterized by favorable geotemperature conditions for carbonate transformation. From a geotectonic perspective, more than 93 % of the CMW systems were formed within the Vardar Zone and on the fringes of nearby units, or in the part of the lithosphere which features Tertiary magmatite intrusions and eruptions. The linear distribution of the CMWs, the fact that the CMWs are by necessity associated with deep tectonic structures, and the faults in the mobile (and particularly stretching) parts of the Earth's crust featuring the highest permeability clearly indicate that the CMW systems are predisposed by neotectonic structures.

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Резиме

Фактори формирања система угљокиселих минералних вода Србије

Највећи број регистрованих појава угљокиселих минералних вода (УМВ) распрострањен је у подручју централног јужног дела територије Србије. Ван тог централног дела регистрован је мањи број усамљених појава, а у северном, источном и југоисточном делу Србије нису регистроване. На територији Србије појаве УМВ су груписане тако да маркирају различите регионалне геолошке структуре (антиклинале, разломне зоне и др.). Систем УМВ подразумева целину повезаних порозних водоносних геолошко-структурних елемената у простору литосфере између области храњења, зоне мешања инфилтрационих вода и CO_2 и зоне дренирања УМВ. За системе УМВ Србије утврђена је њихова просторна веза са геоструктурном јединицом Вардарске зоне (ВЗ), Тс магматизмом и регионалним неотектонским структурама. Затим је утврђено, да је порекло угљеника примарно везано за оксидационе форме карбоната у Ptz, Pz и Mz седиментним и метаморфним стенама и да се CO_2 генерише у домену ВЗ на дубини испод 3 km. Односно, на дубинама где владају повољни геотемпературни услови за геохемијске процесе температурне метаморфозе карбоната и ослобађање CO_2. Постигнути резултати су омогућили да се закључи да су основни фактори формирања система УМВ у литосфери Србије геохемијски, геотемпературни, магматски и структурно-неотектонски.

Са доста поузданости се може закључити да се у домену ВЗ, која се карактерише сложеном геолошко-тектонском грађом и Тс магматизмом, налазе главни генератори CO_2 и да се дистрибуција CO_2 и инфилтрација вода са површине врши регионалним неотектонским дисконтинуитетима који се издвајају добром пропусношћу. Системи УМВ Србије залежу сагласно залегању ВЗ. У том делу литосфере терцијарни магматити прожимају цео комплекс седиментих и метаморфних стена богатих карбонатима. Према томе, веза система УМВ са ВЗ сасвим је логична, с обзиром да кроз њу воде главни доводни канали Тс вулканита и грантоидних интрузива, из дубоких делова литосфере Србије до површине. Повишени садржаји F, As Pb, и других тешких метала, указују на њихову везу са вулканским процесима. По подацима ПАПИЋ и СТОЈКОВИЋ (2012) и ПРОТИЋ (1995) у УМВ Србије садржај F је 0,1–14,25 mg/l (око 60 % изнад садржаја 1,0 mg/l), садржај U у границама 0,1–8,0 μg/l, Ra 0,06–1,4 Bq/l и Rn 7,4–2035 Bq/l. Готово у више од 75 % УМВ утврђен је повишен садржај U, Ra или Rn. На основу доброг поклапања опсега вредности изотопа $\delta^{13}C$ у УМВ у хидротермалним лежиштима, и повишеног садржаја F у већем броју УМВ, може се са доста поузданости закључити да постоји веза CO_2 УМВ са хидротермалним процесима. На основу повишених садржаја радиоактивних елемената постоји веза УМВ са гранитоидним интрузивима, па произилази да се као матични супстрати CO_2 могу сматрати Ptz, Pz и Mz седиментне и метаморфне стене у литосфери, до дубине око 10 km. Дубина генерисања CO_2 од око 3 km, дефинисана је повољним геотемпературним условима за трансформацију карбоната. У геотектонском погледу више од 93 % система УМВ је формирано у домену Вардарске зоне и на маргинама суседних јединица, односно у делу литосфере који се карактерише пробојима и изливима терцијарних магматита. Линијски распоред појава УМВ, чињеница да УМВ морају бити везане за дубоке тектонске структуре и да су највеће водопропусности разломи у мобилним деловима Земљине коре и посебно у деловима њеног растезања, јасно намећу закључак да су системи УМВ предиспонирани неотектонским структурама.

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Groundwater pollution with heavy metals in the Ibar alluvium near Raška (Serbia)

Branko Miladinović[1], Petar Papić[2] & Marina Mandić[3]

Abstract. As a result of the operation of an ore flotation facility at Donja Rudnica near Raška, Serbia, during the period from 1972 to 2002, flotation tailings and wastewater of highly complex chemical compositions were deposited in the alluvial plain of the Ibar River. Due to the excellent groundwater flow characteristics of the alluvial formations underlying the tailings dump, the groundwater and soil over an extended area were continually polluted. High concentrations of heavy metals (Fe = 7.38 mg/L. Zn = 4.04 mg/L, Pb = 2.17 mg/L) in the soil and concentrations of sulfate as high as 3709 mg/L, and pH levels of 4.2 in the groundwater have been recorded at some locations. This paper draws attention to the potential risk this site poses for the conservation of biodiversity over the extended area.

Key words: flotation tailings dump, alluvium, groundwater pollution, Serbia.

Апстракт. Као резултат рада постројења за флотацију руде у Доњој Рудници код Рашке, у периоду од 1972. до 2002. године, депонована је у алувијоној равници реке Ибар, флотацијска јаловина и отпадне флотацијске воде веома сложеног хемијског састава. Услед добрих филтрационих својстава алувијалних творевина које се налазе у подини јаловишта, врши се стално загађење подземних вода и земљишта на ширем подручју. У земљишту су одређене високе концентрације тешких метала (Fe = 7.38 mg/L, Zn = 4.04 mg/L, Pb = 2.17 mg/L) а у подземним водама и високе концентрације сулфата (достижу 3709 mg/L), као и pH вредности у неким водама од 4,2. Овим радом се указује на потенцијалне ризике које овај простор може имати на очување биодиверзитета шире околине.

Кључне речи: загађење подземних вода, алувијон, флотацијско јаловиште, Србија.

Introduction

The Ibar is one of the most important rivers in southwest Serbia. In geological terms, a portion of its catchment area, from Donja Rudnica (or from the administrative border between Serbia and Kosovo) to the downstream location of Biljanovac (along the road to Kraljevo), belongs to the so-called “Raška” Ore-bearing Area.

The ore-bearing capacity of this area was known back in the Middle Ages but intensive mining took place only in the latter half of the past century. In 1972, a magnetite separation and copper flotation plant was built in Donja Rudnica. This plant processed a total of 2858100 tons of ore until the year 1986.

Following the opening of new lead and zinc mines at Sastavci and Kiževak on the western slopes of Mt. Kopaonik, the Donja Rudnica plant began floating these ores as well in 1986. Until the year 2002, when the flotation plant was decommissioned, a total of 2064956 tons of Pb/Zn ores had been processed.

During the period of operation of the flotation plant from 1972 to 1986, flotation tailings were deposited at several sites along the Ibar River. The most significant flotation tailings dump was formed in the alluvial plain of the Ibar, at Veliko Polje near Donja Rudnica.

The development of a new flotation tailings dump in the Kukanjica Creek upstream from the Donja Rudnica plant began in mid-1991. By the year 2002, some one million tons of tailings had been deposited at this site (from 1991 to 1996, a portion of the tailings were disposed of at the Veliko Polje site).

In addition to flotation tailings, flotation wastewater was also disposed of at these landfills. The che-

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mical composition of the wastewater was highly complex, given that the flotation reagents NaCN, $ZnSO_4$, $CuSO_4$, $FeSO_4$, $NaSO_3$, *etc*. were used in the ore flotation process. For example, the plant used 170 tons of sodium cyanide (NaCN) from 1986 to 2001. The soil and groundwater over an extended area were polluted through infiltration of this wastewater from the flotation tailings dump. Additionally, flotation wastewater was occasionally discharged directly into the Ibar River *via* tailings dump collectors.

Given that the Village of Donja Rudnica does not have a public water supply system, its inhabitants withdraw groundwater from shallow dug wells for their daily needs, and that there is active farming at Veliko Polje immediately adjacent to the flotation tailings dump, pilot tests of environmental substrates were conducted from 2002 to 2004. The objective of this paper is to present the results of the tests performed in the Veliko Polje Plain, in view of the fact that they showed that there was considerable environmental pollution, with the Ibar River potentially spreading the pollution over a much greater area. The exposure of the local population to health risks is highlighted.

General geological and hydrogeological characteristics of the extended area of Donja Rudnica

The extended area of Donja Rudnica is made up of Tertiary volcanics that are found over a large area, from Ušće in the north to Leposavić in the south. The volcanic rocks are underlain by Paleozoic shales (the oldest rocks), ophiolitic rocks (peridotites and a diabase–chert formation), Kopaonik granodiorites and other rocks.

Tertiary volcanism began in the Lower Miocene, lasted through the Neogene (albeit with certain interruptions) and began to cease at the end of the Pliocene. Its nature was distinctly explosive and it underwent several stages and pulsations (UROŠEVIĆ *et al.* 1973).

The volcanic rocks are made up of dacite–andesites (αqα), quartzlatite, basaltoids (to a lesser extent), as well as volcanic pyroclastics (Θαqα) represented by volcanic breccias, tuffs and agglomerates (Fig. 1). The thickness of the volcanic rocks varies but is about 300 m on average, depending on the paleorelief morphology, the nature of the volcanic activity and the proximity of supply channels.

The youngest formations are Quaternary and are represented by alluvials (al), which are found along the course of the Ibar. They are made up of sands, gravels and clays the total thickness of which occasionally exceeds 10 m, as is the case in the alluvial plain at Veliko Polje near Donja Rudnica (Fig. 1).

From a structural perspective, the terrain is heavily tectonically faulted and deformed. There are many faults of different sizes and orientations. Aerial photographs east of Raška also show circular (ring-like) structures. In the andesites, the faults feature a better continuity and longer dip elements than those of the poorly consolidated pyroclastites.

In hydrogeological terms, the volcanic rocks are characterized by fracture veins and a fractured rock aquifer formed within them (Fig. 1). Given that the fractures are heavily squeezed and packed with secondary fillings, the permeability of the volcanic rocks is poor and they hold relatively modest amounts of groundwater.

A confined aquifer was formed in the alluvial formations, due to their intergranular porosity. The largest extent of these formations is found in the alluvial plain at Veliko Polje. The groundwater flow characteristics of the alluvial formations is good, with permeability coefficients of $k = 2.5\times10^{-3}$ m/s (KB-1), Fig. 2, and $k = 8.1\times10^{-4}$ m/s (KB-8), MILADINOVIĆ (2005).

The fluctuations of the groundwater level in the alluvial formation were continuously monitored in 2004, and the mean of these measurements are shown in Fig. 3. Evident jumps of groundwater levels were observed in the spring after snow melt and heavy rains. The difference

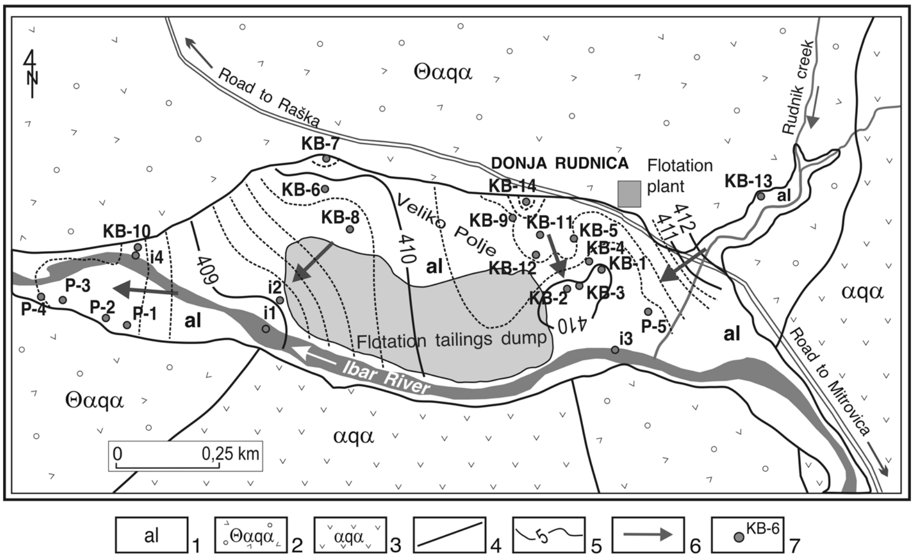

Fig. 1. Hydrogeological map of the extended are-a of Veliko Polje near Donja Rudnica. **1,** Alluvial sands, gravels and clays (intergranular aquifer); **2,** dacite–andesite pyroclastites (fractured rock aquifer); **3,** dacite–andesites (fractured rock aquifer); **4,** geological boundary; **5,** water-table contour lines of confined aquifer (as of 20 December 2004); **6,** direction of groundwater flow; **7,** dug well.

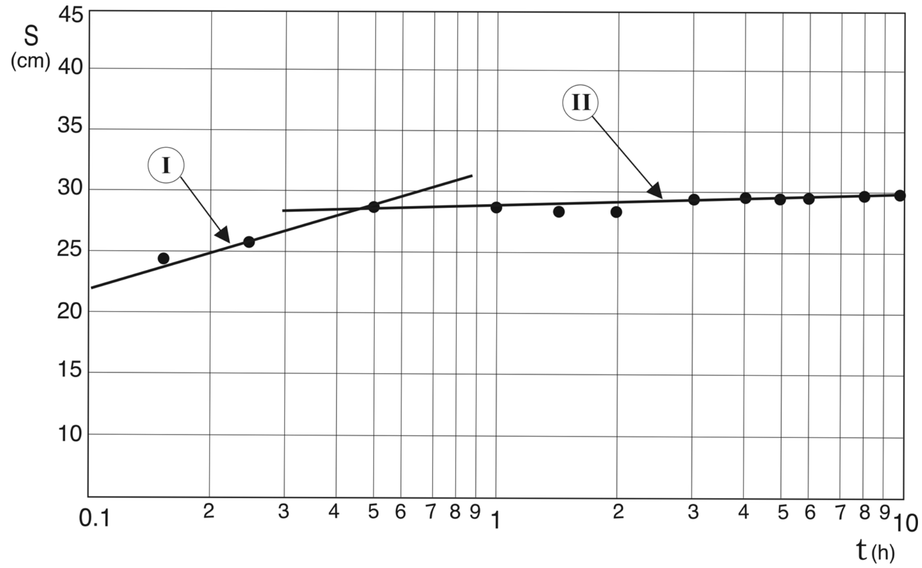

Fig. 2. Dynamic groundwater level of the confined aquifer in the Ibar alluvium during a pumping test at the dug well KB-1 in Veliko Polje.

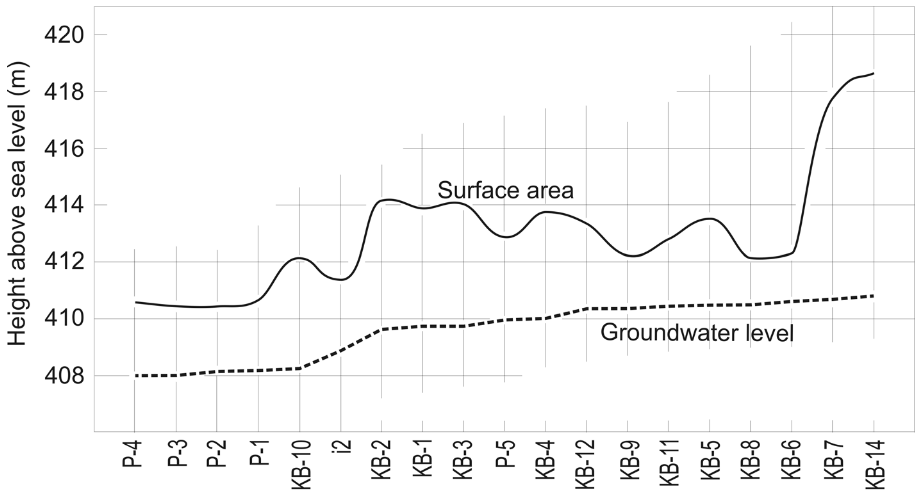

Fig. 3. Diagram of the groundwater levels in the alluvial formations near Donja Rudnica (the mean fluctuation levels for 2004).

between the minimum and maximum levels varied according to location; the lowest was registered at the locations of P-1, P-2, P-3 and P-4 (1.58 to 1.72 m) and the largest at KB-7 (3.46 m) and KB-14 (3.95 m).The aquifer is in good hydraulic contact with the Ibar River, which flows along the southern edge of the Veliko Polje alluvial plain (Fig. 1).

The direction of groundwater flow in the alluvial formations of Veliko Polje are directly dependent on the stages of the Ibar River, but it is generally from the northern edges to the central portions of the alluvial plain, or to the most downstream profiles of the Ibar at Veliko Polje (Miladinović 2005).

At low water stages of the Ibar, the confined aquifer is discharged directly into the River and is partly drained by groundwater abstraction from the wells dug by the local population. The confined aquifer is recharged by precipitation and from surface streams, but only at high water stages of the Rudnik Creek and the Ibar River relative to the groundwater level.

Methods

In order to determine the impact of the flotation tailing in Veliko Polje on the surrounding soil and groundwater, laboratory tests of the substrate environment were conducted.

Sampling of the loose soil was performed by taking samples that consisted of three individual samples with a surface area of 2 m^2 at a depth of 10 cm. The collected samples were air-dried and milled to a particle size < 2 mm.

The soil samples were prepared for metals analysis by measuring 1 g a dry sample and digestion by the addition of portions of concentrated HNO_3 and HCl and 30% H_2O_2. The determinations were performed by flame atomic absorption spectroscopy (AAS) using a Varian Spectra AA200 instrument, and hydride AAS using a Varian Spectra AA20+ instrument, according to the manufacturer's instructions (Institute of Public Health of Belgrade).

Groundwater was sampled from privately dug wells, the levels of which are shown in Fig. 3. The samples were taken at the end of autumn when the level of the Ibar River was lower than the groundwater level, shown in Fig. 1

Samples from the River were taken from the middle part of the flow at a depth of 0.5 m and samples were taken from the same depth from the excavation site by the flotation tailings. All water samples were acidified with HNO_3 to pH < 2.

Water samples with turbidity <1 NTU were analyzed directly. The other samples were prepared by the addition of HNO_3 and HCl, reduction of the volume and refluxing, and subsequent dilution to the start volume. The determinations were realized by AAS.

A standard QA/QC protocol was adopted throughout this research. For example, in the analysis of each metal, the slope of the calibration curve was verified by analyzing every fourth concentration of the calibration standards used for the construction of the curve after the analysis of every 20th sample and by analyzing QC standards with concentrations in the middle of the calibrated range immediately after completion of the analysis of each batch of samples. In addition, duplicate samples of both field and laboratory blank samples were included in each analytical batch.

Results

Environmental substrates

Laboratory tests of environmental substrates in the Donja Rudnica area revealed considerable pollution of the alluvial soil and groundwater (DALMACIJA 2000).

As a result of particles from the tailings dump being carried by winds into the neighboring areas, as well as due to the infiltration of floatation tailings leachate into the permeable alluvial formations (Fig. 4), heavy metals were detected in the soils at Veliko Polje in concentrations which were several times higher than the regulation standards.

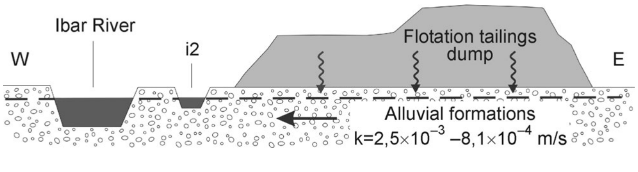

Fig. 4. Schematic view of the impact of flotation tailings on groundwater pollution in the alluvial formations.

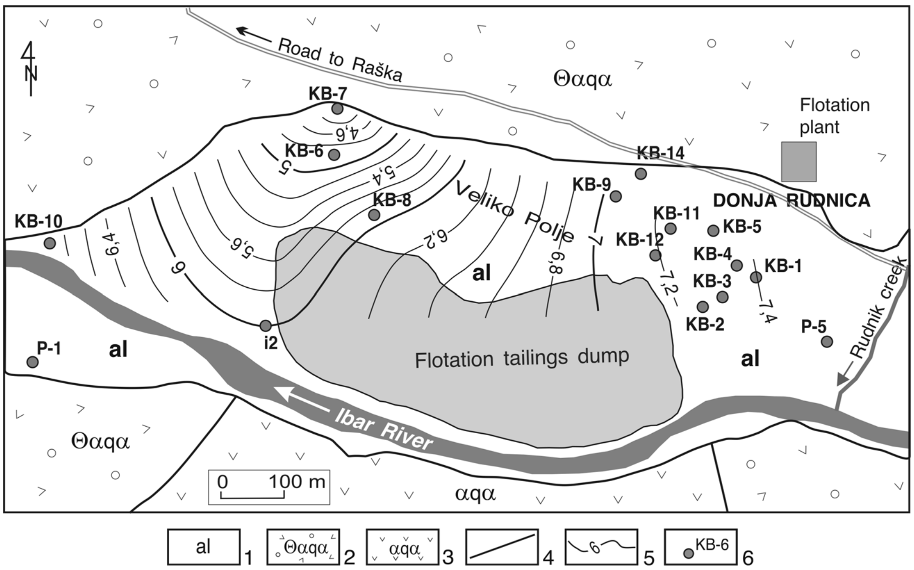

Fig. 5. Contour chart of the pH values in the groundwater in the Ibar alluvium near Donja Rudnica. **1,** Alluvial formations; **2,** dacite–andesite pyroclastites; **3,** dacite–andesites; **4,** geological boundary; **5,** pH values contour lines; **6,** dug well.

The results of the analysis of the groundwater from the private wells were compared with maximum allowed concentration (*MAC*) values defined in the Regulations on the Hygiene of Drinking Water (Official Gazette of the FRY 42/98). The obtained values for the surface water were compared with the Ordinance on Hazardous Substances in Water / Official Gazette SRS 31/82, and the results for the soil samples were compared with the *MAC* values given in Regulations on Permitted Amounts of Hazardous and Harmful Substances in Soil and Water for Irrigation and Methods of their Testing (Official Gazette of RS 23/94).

Significant deviation from the allowed values were found for the content of heavy metal in the soils west of the tailings (Fig. 1 and Fig. 4), primarily lead (Pb = 335.5 mg/kg, *MAC* – 100 mg/kg), arsenic (As = 44.3 mg/kg, *MAC* – 25 mg/kg), chromium (Cr = 104.7 mg/kg, *MAC* – 100 mg/kg) and nickel (Ni = 79.7 mg/kg, *MAC* – 50 mg/kg). The zinc concentrations were similar to the reference value (Zn = 249.7 mg/kg, *MAC* – 300 mg/kg).

This research devoted special attention to groundwater pollution in the alluvial formations of Veliko Polje, or the so-called "first" aquifer. Laboratory tests of the groundwater were conducted using samples collected from six dug wells (KB-1, KB-6, KB-7, KB-8, KB-10 and KB-11), as well as from a gravel excavation site located on the western edge of the tailings dump (i2), Fig. 1. These tests revealed elevated concentrations of both major ions and micro-components in the groundwater.

The concentration of sulfate (SO_4) in four samples exceeded the drinking water standard and ranged from 579.6 mg/l to as much as 3709 mg/l (*MAC* – 250 mg/L, REGULATION ON HYGIENIC STANDARDS OF WATER 1998).

The maximum allowable concentration (*MAC*) values of heavy metals in the tested groundwater of samples from the dug wells were exceeded in the central and northern parts of Veliko Polje: lead (Pb = 2.17 mg/L, *MAC* – 0.010 mg/L), cadmium (Cd = 0.1 mg/L, *MAC* – 0.003 mg/L), zinc (Zn = 4.04 mg/L, *MAC* – 3.0 mg/L), aluminum (Al = 2.5 mg/L, *MAC* – 0.2 mg/L), total iron (Fe = 7.38 mg/L, *MAC* – 0.3 mg/L) and manganese (Mn = 2.04 mg/L, *MAC* – 0.05 mg/L). The lowest pH values were found in wells KB-7 (4.2), KB-6 (4.9) and KB-8 (5.9), Fig. 5.

The most important groundwater pollution was recorded

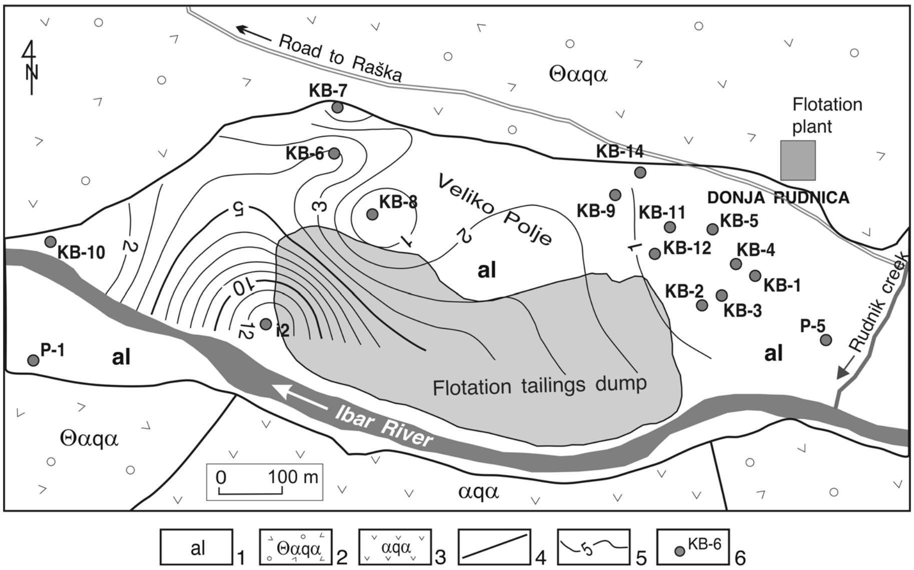

Fig. 6. Contour chart of the zinc (Zn) concentrations in the groundwater of the Ibar alluvium near Donja Rudnica. **1,** Alluvial formations; **2,** dacite–andesite pyroclastites; **3,** dacite–andesites; **4,** geological boundary; **5,** zinc concentration (mg/L) contour lines; **6,** dug well.

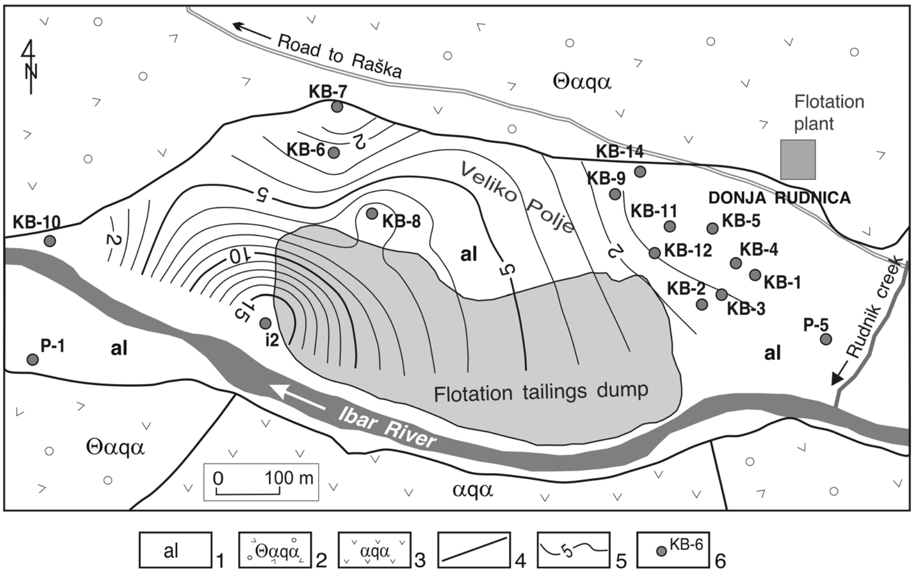

Fig. 7. Contour chart of the iron (Fe) concentrations in the groundwater in the Ibar alluvium near Donja Rudnica. **1,** Alluvial formations; **2,** dacite–andesite pyroclastites; **3,** dacite–andesites; **4,** geological boundary; **5,** total iron concentration (mg/L) contour lines; **6,** dug well.

in the south-western part of Veliko Polje, immediately adjacent to the western perimeter of the tailings dump (i2), primarily as a result of the direction of groundwater flow (or the prevailing direction of the plume) from the tailings dump source at Veliko Polje to the downstream profiles of the Ibar in the western part of Veliko Polje. Samples of this groundwater had the maximum concentrations of zinc Zn = 12.7 mg/L (Fig. 6), nickel Ni = 0.6 mg/L, manganese Mn = 10.6 mg/L and iron Fe = 16.0 mg/L (Fig. 7). The total dissolved solids (*TDS*) value was 8010 mg/L and the pH level was 6.0 (Fig. 5).

Discussion

Before the construction of the ore separation plant in 1972, the residents of Donja Rudnica used only groundwater drawn from wells dug for their daily needs. Even after 30 years of heavy environmental pollution in this area, the inhabitants of Donja Rudnica customarily continue to use groundwater for their household needs and, in some cases, to even drink this water.

The use of groundwater from the wells dug in Donja Rudnica, based on the evidenced by the determined concentrations and their deviations from standards, constitutes a major health risk if used not only as drinking water, but also other household needs and water for domestic animals, given that over a protracted period of time, some of the inorganic pollutants are likely to enter the food chain (WHO 2008).

A sulfate ion (SO_4) concentration higher than the *MAC* value for drinking water results in a tart taste and can also have a laxative effect on sensitive individuals if the sulfate concentrations exceed 500 mg/L.

Manganese (Mn) concentrations in excess of the *MAC* value alter the taste of water, leave stains and deposits, and foster the growth of manganese bacteria. Prolonged use of drinking water with high manganese concentrations leads to poisoning, the symptoms of which are related to the central nervous system, where manganese psychosis is typical but not lethal.

The use of water from well KB-7, featuring a high lead (Pb) concentration (2.17 mg/L) would pose a considerable health risk, particularly for children who absorb 50 % of lead ingested with water, compared to adults whose absorption rate is 10–15 %. Lead has an adverse effect on nearly all body systems, but in accumulates in the central nervous system and, in children, affects intelligence, growth and development.

Conclusion

The environment of the Village of Donja Rudnica near Raška has been considerably polluted by an ore processing industry. The local population is exposed to health risks, given that environmental substrates (soil and groundwater) were found to be polluted.

Measures should be undertaken without delay to seek out alternative sources of healthy water supply from neighboring areas for Donja Rudnica, as well as to remediate the soils of Donja Rudnica, which were found to be polluted by a tailings dump, in order that environmentally acceptable conditions be restored for life in this area.

Acknowledgments

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Резиме

Загађење подземних вода тешким металима у алувијону Ибра, близу Рашке (Србија)

До изградње постројења за сепарацију, мештани Доње Руднице, Рашка, користили су искључиво подземне воде из својих копаних бунара за основне животне потребе. После 30 година интензивног загађења животне средине на овом простору, становништво и даље користи ове воде за потребе својих домаћинстава, а неки и за пиће. Коришћење подземних вода из копаних бунара, представља велики ризик по здравље људи, не само ако се користе за пиће, већ и за друге потребе. Ово може довести до уласка неких загађујућих супстанци неорганског порекла у ланац исхране. Концентрација сулфатних јона која прелази максимално дозвољену вредност утиче на горак укус, а у већим концентрацијама од 500 mg/l, могу деловати и лексативно. Узорци подземних вода имају максималне концентрације цинка од 12,7 mg/l, никла од 0,6 mg/l, мангана од 10,6 mg/l и гвожђа од чак 16 mg/l. Укупно растворене материје су чак 8 g/l, а вредност pH индекса је 6. Коришћење воде из бунара КВ-7, која садржи олово у концентрацији од 2,17 mg/l, представља велики ризик по здравље, нарочито за децу која апсорбују 50% олова из воде, у поређењу са одраслима који апсорбују само 10–15% олова из воде за пиће. Овај метал има негативно дејство на све системе у људском организму. Водоснабдевање становника Доње Руднице, захтева неодложне мере за изналажење алтернативних изворишта из околних подручја, како би се обезбедиле здравствено исправне воде за пиће. Такође, неопходно је одредити и ремедијационе поступке за довођење животне средине у предходно стање квалитета, које је угрожено флотацијским јаловиштем.

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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. *Paleontologičeskii Žurnal*, 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.

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ГЕОЛОШКИ АНАЛИ БАЛКАНСКОГА ПОЛУОСТРВА
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