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Early Cretaceous glauconite formation and Late Cretaceous magmatism and metallogeny of the East Serbian part of the Carpatho-Balkanides

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1. Introduction

Serbia is located between four mountain chains, the Dinaric Alps to the west, the Eastern Carpathians to the east, the Balkan Mountains to the southeast and the Rhodopes to the south. This region is one of the most complex geological areas on the Central Balkan Peninsula, *i.e.* the Alpine–Carpathian–Balkan–Dinaride orogen (ACBD) formed through a long history of multiple deformations (Fig. 1).

The ACBD, one of the most intricate regions within Europe, has still not been completely researched, especially as regards Tethyan tectonics. There are noticeable differences in significance and interpretation of many tectonic units and a number of ideas relating to their evolution. These discrepancies undoubtedly require the compilation of locally obtained data and, naturally, scientific debate. In this course, we suggest exploration of some Lower Cretaceous sediments and Upper Cretaceous magmatites and related copper ore deposits in the Timok magmatic complex in East Serbia as part of the southwest Carpathian arc so that geologists may acquaint themselves with their features.

1.1 Geological and tectonic setting

There are several opinions about the geotectonic framework of Serbia and the adjacent regions, where some differences in detail may be noticed (Karamata & Krstić, 1996; Karamata, 2006; Dimitrijević, 1997, 2001; Schmid *et al.*, 2008; Robertson *et al.*, 2009). Briefly, the following units may be distinguished from east to west: (1) the East Serbian Carpatho-Balkanides; (2) the Serbo-Macedonian Massif; (3) the Ophiolite Suture(s) Complex with the Vardar zone mélange, the Jadar, Kopaonik and Drina-Ivanjica basement units and the Dinaride mélange; (4) units of the External Dinarides (Fig. 2). This field trip goes through the East Serbian Carpatho-Balkanide geotectonic unit.

The geodynamic evolution of the Central Balkan Peninsula is very complex. In order to understand it, we should start with a brief overview of the geological map of Serbia where a complex NNW–SSE stretching zone of ophiolites is immediately noticed (Fig. 1). This suture zone (or zones) comprises relics of an obducted oceanic lithosphere, numerous tectonic blocks (olistoliths) and sediments of various age (Karamata, 2006; Robertson *et al.*, 2009 and references therein). In simple

Fig. 1. Geological map (1 : 500 000) and geographical position of Serbia (a, b).

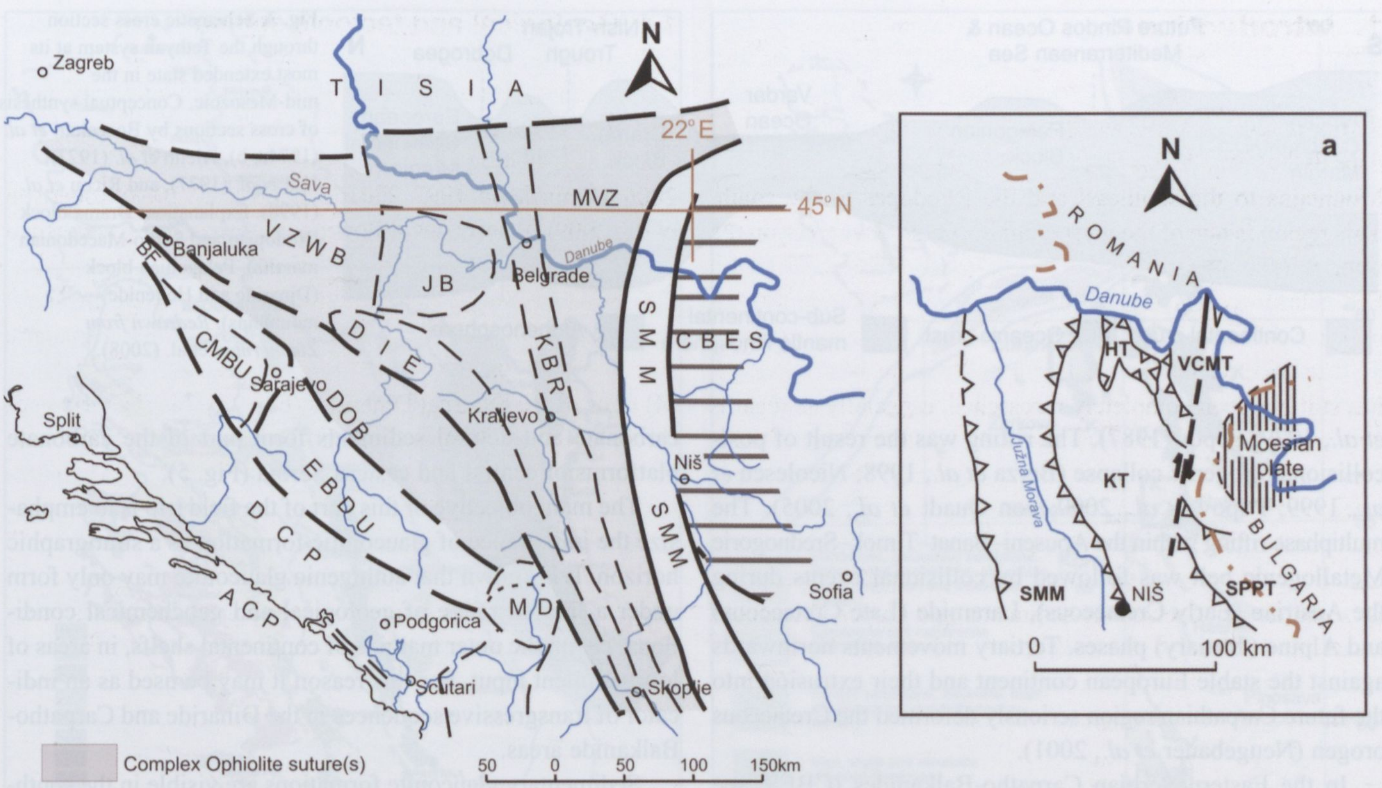

Fig. 2. Outline geotectonic framework of Serbia and adjacent regions. Key: CBES: East-Serbian Carpatho-Balkanides; SMM: Serbo-Macedonian Massif; MVZ: Main Vardar Zone; VZWB: Vardar Zone Western Belt; JB: Jadar Block; DIE: Drina–Ivanjica Element; DOB: Dinaride Ophiolite Belt; EBDU: East Bosnian–Durmitor Unit; BF: Bosnian Flysch; VF: Vrbas Fault; CBM: Central Bosnian Mountain Unit; DCP: Dinaride Carbonate Platform; ACP: Adriatic Carbonate Platform; a) Terranes of the CBES: VCMT: – Vrška Čuka–Miroč Terrane; HT – Homolje Terrane, SPPT – Stara Planina–Poreč Terrane, KT – Kučaj Terrane (data according to Karamata & Krstić, 1996; Karamata, 2006; Robertson *et al.*, 2009).

terms, two continental units are divided by a complex dismembered ophiolite belt (Figs. 1, 2). These continental units were part of the southern/southwestern margin of Europe (Eurasia) and northern/northeastern margin of Africa (Gondwana) which, before the end of the Mesozoic period, were separated by the Tethys Ocean. After the final closure of the Tethys Ocean, probably close to the end of the Cretaceous period, these continental margins shared a common geological history. Certainly, before the beginning of Cenozoic period, the areas situated eastwards and westwards of the ophiolites underwent a different evolution. We shall focus on the eastern area, *i.e.* the East Serbian Carpatho-Balkanides and neighbouring Serbo-Macedonian Massif comprising a number of smaller east-vergent tectonic units. According to some authors, these units represent accreted Paleozoic terrains to the stable south/southwestern European margin, *i.e.* to the Moesian platform, before the Permian age (Fig. 2a). Due to post-accretion compressive tectonics and the deposition of younger sediments (so-called overstep sequences) the original border between them is mostly obscured (Karamata & Krstić, 1996; Karamata, 2006).

Generally speaking, the ACBD is generated by the interaction of several microplates that existed between the African and Eurasian continents during closure of the Tethys Ocean (Willingshofer, 2000; Neugebauer *et al.*, 2001; Neubauer, 2002; Neubauer & Heinrich, 2003). The complexity of the tectomagmatic and metallogenetic evolution of the Apuseni–Banat–Timok–Srednogorie Metallogenic belt is illustrated by a variety of geodynamic models, in which a slab rollback and a slab tear model dominate. Both of them are based on processes related to Cenozoic consumption of the Penninic Ocean (Csontos *et al.*, 1992; Linzer, 1996; Wortel & Spakman 2000; Lips, 2002; Neubauer, 2002; Von Quadt *et al.*, 2005; Zimmerman, 2006). Recent work by Zimmerman *et al.* (2008) proposed a slab rollback metallogenetic–tectonic model for the evolution of the Apuseni–Banat–Timok–Srednogorie Metallogenic belt which coincides with the assumption of orogenic collapse (Berza *et al.*, 1998; Bojar *et al.*, 1998; Neubauer, 2002).

The ACBD *sensu lato* comprises several tectonic units (Fig. 3; for detail see Zimmerman *et al.*, 2008). This bent orogen is created in two independent stages of continent-continent collision during the Mid to Late Cretaceous and Late Eocene-Oligocene periods *i.e.* the final collision of the stable European/Moesian platform and the Adriatic plate (Fig. 4, Neubauer & Heinrich, 2003). In general, these processes are related to northward/northeastward subduction in front of the southern margin of European plate, convergent movement between Africa and Eurasia with consumption of the Vardar ocean in the Hellenic trench-arc, and extension after the closure of the Vardar Ocean during a pre-orogenic stage of Balkan-Dinaride evolution (e. g. Boccaletti *et al.*, 1974a, 1974b; Antonijević *et al.*, 1974; Ivanov

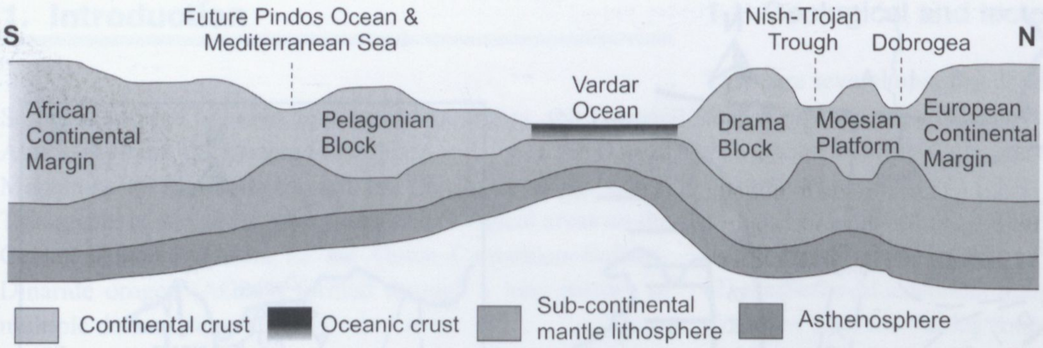

Fig. 3. Schematic cross section through the Tethyan system at its most extended state in the mid-Mesozoic. Conceptual synthesis of cross sections by Boccaletti *et al.* (1974a, b), Aiello *et al.* (1977), Hsü *et al.* (1977), and Ricou *et al.* (1998). Explanation: Drama block (Rodopian and Serbo-Macedonian massifs), Pelagonian block (Dinaride and Hellenide mountains). *Redrawn from Zimmerman* et al. (2008).

et al., 1979; Popov, 1987). The rifting was the result of post-collisional orogenic collapse (Berza *et al.*, 1998; Nicolescu *et al.*, 1999; Popov *et al.*, 2000; von Quadt *et al.*, 2005). The multiphase rifting within the Apuseni–Banat–Timok–Srednogorie Metallogenic belt was followed by collisional events during the Austrian (Early Cretaceous), Laramide (Late Cretaceous) and Alpine (Tertiary) phases. Tertiary movements northwards against the stable European continent and their extrusion into the future Carpathian region seriously deformed the Cretaceous orogen (Neugebauer *et al.*, 2001).

In the Eastern Serbian Carpatho-Balkanides (CBES, see Fig. 2), the later phases of Vardar Ocean closure at the end of Cretaceous period caused strong calc-alkaline magmatic activity (mostly andesitic), which was probably related to active margin tectonic processes, *i.e.* to eastward subduction. The magmatism in the area of the CBES lasted from the Early Turonian to Paleogene periods. In the Timok area, taking into consideration existing data (89–70 Ma), magmatism undoubtedly shows systematic younging (displacement of magmatic pulses) from southeast to northwest (trenchward?) and specific changes in composition. The worldclass Cu–Au ore deposits in East Serbia, *i.e.* the Timok Magmatic Complex (TMC), are related to this magmatism.

2. The Lower Cretaceous glauconitic formations of Serbia

The Mesozoic sedimentary cover in the Serbian part of the central Balkan Peninsula, including the southeastern Carpathians, mostly overly the Paleozoic rocks. Evolved sedimentary facies are mainly composed of carbonate rocks and clastites implying shelf-, reef- and pelagic-type deposition from the Middle Triassic to late Early Cretaceous ages. The most widespread are shallow-water clastic and carbonate facies. Pelagic deep-water facies are related to the Middle Triassic period in Western Serbia (the Valjevo basin) and the Jurassic and Early Cretaceous periods in East and Central (Šumadija) Serbia. Sedimentation was followed by intermittent submarine volcanic activity and the deposition of volcano-sedimentary facies. Lower Cretaceous carbonate and detrital sediments form part of the carbonate platforms of central and eastern Serbia (Fig. 5).

The main objective of this part of the field trip is to emphasize the importance of glauconitic formation as a stratigraphic horizon. It is known that authigenic glauconite may only form under a limited range of geological and geochemical conditions, *i.e.* on the outer margins of continental shelfs, in areas of low sediment input. For this reason it may be used as an indicator of transgressive sequences in the Dinaride and Carpatho-Balkanide areas.

Sedimentary glauconite formations are visible in the southwestern part of the Carpatho-Balkanide or Carpathian paleogeographic area and the northeastern margin of the Dinarides and eastern margin of the Main Vardar Zone known as the Šumadija paleogeographic area according to Anđelković (1975a, Fig. 6). The Lower Cretaceous formations range in age from the Berriasian to Albian periods. The localities we should visit have been selected to present the best geological picture given their accessibility and the time available. The order of observation dictates the order of the field trip itinerary. Outcrops of Lower Cretaceous sediments commonly show beds of only one

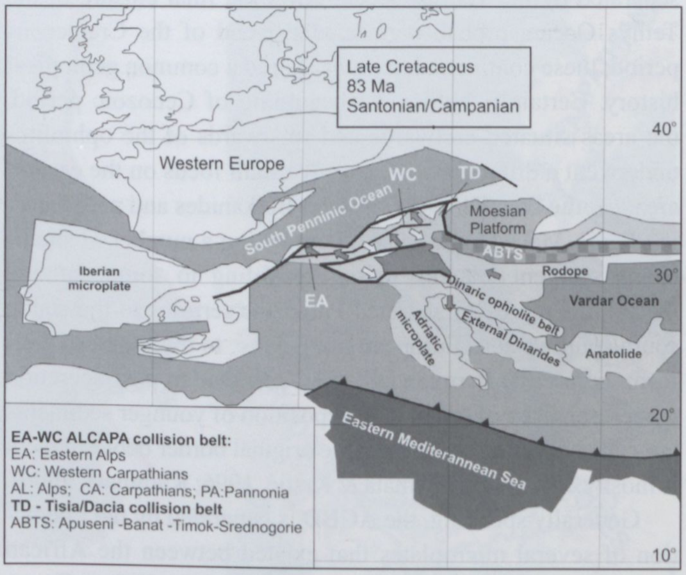

Fig. 4. Palaeogeographic reconstruction of the ABTS belt during Late Cretaceous time according to Neugebauer *et al.* (2001) and Neubauer (2002). *Redrawn from von Quadt* et al. *(2005).*

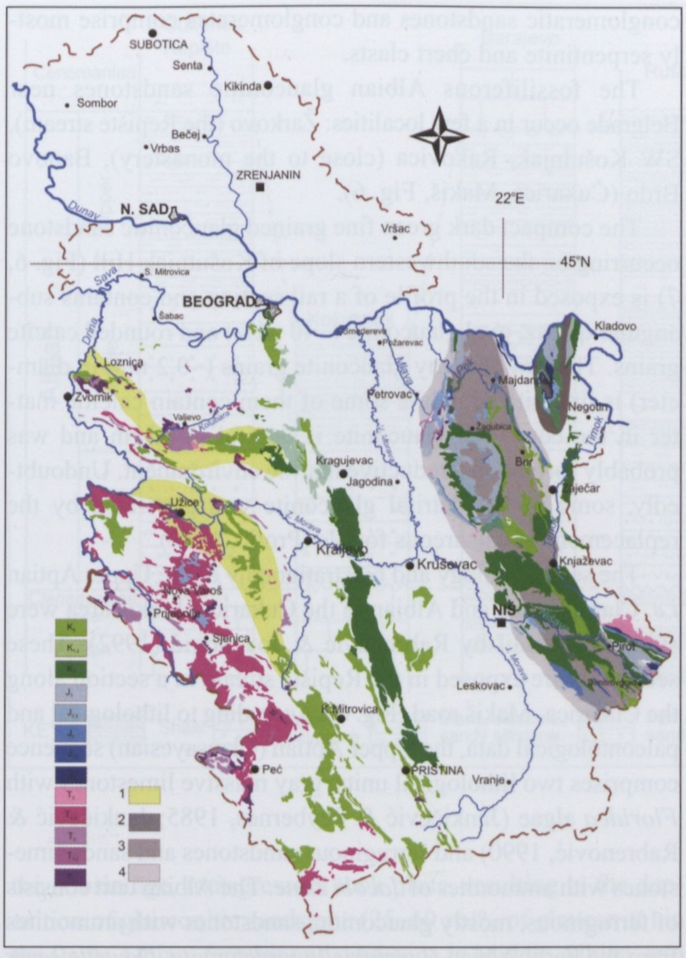

Fig. 5. Mesozoic cover and position of carbonate platfroms of Serbia (based on the1 : 500 000 geological map of Serbia) and paleogeographic areas. *Legend: 1 – Jadar carbonate platform and Carbonate platform of SW Serbia (Radoičić, 1982; Dimitrijević & Dimitrijević, 1991, Dimitrijević et al., 1996); 2 – Miroč carbonate para-platform; 3 – Central part of Kučaj–Tupižnica carbonate platform; 4 – Western margin of Kučaj–Tupižnica platform (Grubić & Jankičević, 1973).*

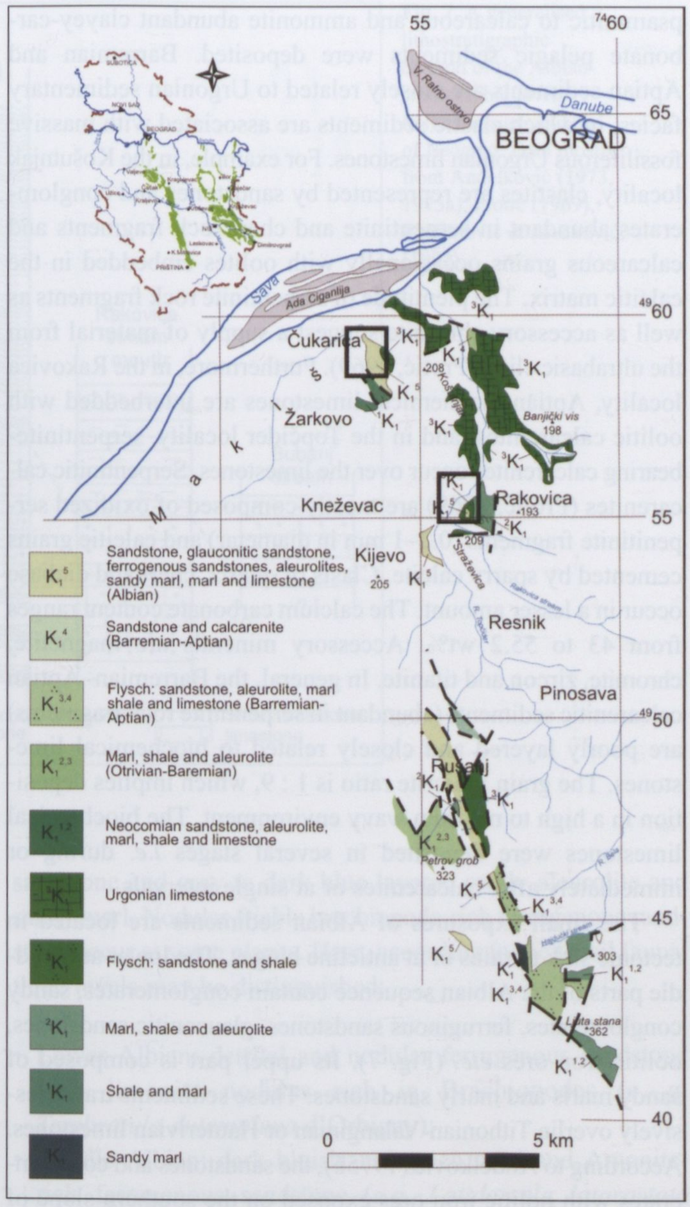

Fig. 6. Lower Cretaceous sediments of the surroundings of Beograd (based on the Beograd and Obrenovac sheets of the 1 : 100 000 geological map of Serbia) and location of the visiting areas (rectangle).

formation, most of them are only a few to 10 m, rarely 100 m thick. All the localities are fossiliferous.

The Lower Cretaceous glauconitic formation in Šumadija area and the Carpathian area (Fig. 6) has not been studied in detail according to available geological data (Protić, 1969; Anđelković & Antonijević, 1975; Rabrenović & Jovanović, 1992).

The Serbian part of the northeastern Dinarides extends from Belgrade via Kragujevac to Mt. Kopaonik to the south (the Šumadija paleogeographic area, Anđelković, 1975a). It comprises local Neocomian terrigenous or terrigenous-carbonate sediments with effusions of small basaltic lava flows or pillow-lavas and diabases, Barremian–Aptian terrigenous sediments are rich in fossil fauna and ammonites, with abundant Albian shallow-marine shelf carbonates and limited terrigenous sediments.

Within the Carpathian region two basins have developed: the Lower Neocomian terrigenous flysch of Lužnica overlapped by post-flysch marly psammitic sediments to the west and the Krajina Basin to the east with Lower Neocomian carbonate-terrigenous flysch known as "Timok Strata" and Barremian–Aptian terrigenous flysch. The southeastern parts comprise Lower Cretaceous deep-water fossiliferous clayey carbonate sediments.

The best exposures of glauconitic sandstones occur in the vicinity of Belgrade and southwest of Zaječar (Fig. 5).

2.1 Belgrade area

Lower Cretaceous sediments built up the western (Straževica, Kijevo) and southern (Topčider, Banovo Brdo, Košutnjak, Dedinje) hills of Belgrade (Fig. 6). These sediments are widespread in the Žarkovo–Čukarica–Rakovica–Resnik zone, southwest of the river Topčider (Fig. 6). Due to deepening of the sea basin that began in the Late Jurassic period and continued into the Barremian (Early Cretaceous), shallow-marine marly-psammitic to calcareous and ammonite abundant clayey-carbonate pelagic sediments were deposited. Barremian and Aptian sediments are closely related to Urgonian sedimentary facies, in which clastic sediments are associated with massive fossiliferous Urgonian limestones. For example, in the Košutnjak locality, clastites are represented by sandstones and conglomerates abundant in serpentinite and chert rock fragments and calcareous grains occasionally with oolites embedded in the calcitic matrix. The plentitude of serpentinite rock fragments as well as accessory chromite suggest a supply of material from the ultrabasic cliffs (Protić, 1969). Furthermore, in the Rakovica locality, Aptian biochemical limestones are interbedded with oolitic calcarenites, and in the Topčider locality, serpentinite-bearing calcarenites occur over the limestones. Serpentinitic calcarenites (Protić, 1969) are mostly composed of oxidized serpenitinite fragments (0.2–1 mm in diametar) and calcitic grains cemented by sparry calcite. Clasts of quartz, chert and diabase occur in a lesser amount. The calcium carbonate content ranges from 43 to 55.2 wt%. Accessory minerals are magnetite, chromite, zircon and titanite. In general, the Barremian–Aptian calcarenitic sediments (abundant in serpentinite rock fragments) are poorly layered and closely related to biochemical limestones. The grain : micrite ratio is 1 : 9, which implies deposition in a high to medium wavy environment. The biochemical limestones were deposited in several stages *i.e.* during or immediately after calcarenites or at single intervals.

The small exposures of Albian sediments are located in tectonic sink terrains or at anticline hinges. The lower and middle parts of the Albian sequence contain conglomerates, sandy conglomerates, ferruginous sandstones, glauconitic sandstones, oolitic iron ores *etc.* (Fig. 7). Its upper part is composed of sandy marls and marly sandstones. These sediments transgressively overlie Tithonian-Valanginian or Hauterivian limestones. According to Anđelković (1975b), the sandstones and conglomerates with oolitic iron ores exposed on the southern slope of Košutnjak Hill are somewhat older than the Lower and Middle Albian fossiliferous ferruginous sandstones. Comparison of ferruginous sediments with oolitic iron ores within the Šumadija area, including Belgrade, suggests that their stratigraphic position has not been clearly defined up to now. According to available data they lie over serpentinites or transgressively overlie Urgonian limestones and older sediments. Furthermore, intercalation with Urgonian limestones have also been noted as well as their appearance at different levels of the Albian sediments.

The ferruginous sandstones and pelitic sediments with oolitic iron occur in the Žarkovo district, close to the settlement and quarry called Zmajevac. Here, poorly cemented clayey sediments with chert and serpentinite pebbles contain clusters of oolitic and pisolitic grains mostly composed of hematite, maghemite, magnetite, limonite and chlorite.

The southeastern part of Košutnjak Hill (Fig. 6) comprises coarse grained ferruginous sediments and oolitic (pisolitic) iron ores (hematite, magnetite, limonite and Fe silicate). Its southern slope is tectonically deformed and crumbling; the conglomeratic sandstones and conglomerates comprise mostly serpentinite and chert clasts.

The fossiliferous Albian glauconitic sandstones near Belgrade occur in a few localities: Žarkovo (the Repište stream), SW Košutnjak, Rakovica (close to the monastery), Banovo Brdo (Čukarica–Makiš, Fig. 6).

The compact dark green fine grained glauconitic sandstone occurring on the southwestern slope of Košutnjak Hill (Fig. 6, 7) is exposed in the profile of a rail section and contains subangular quartz, oval glauconite (~40 wt%) and rounded calcite grains. The rim of many glauconite grains (~0.2 mm in diameter) is limonitized, while some of them contain calcitic matter in the core. The glauconite is detrital in origin and was probably formed in a reductive marine environment. Undoubtedly, some of the detrital glauconite was generated by the replacement of calcareous fossils (Protić, 1969).

The sedimentology and biostratigraphy of the Upper Aptian *i.e.* Clansayesian and Albian in the Čukarica–Makiš area were studied in detail by Rabrenović & Jovanović (1992). These sediments are exposed in the Repište stream in a section along the Čukarica–Makiš road (Fig. 6). According to lithological and paleontological data, the Upper Aptian (Clansayesian) sequence comprises two lithological units: gray massive limestones with *Floridea* algae (Jankičević & Peybernes, 1985; Jankičević & Rabrenović, 1990) and ferruginous sandstones and sandy limestones with ammonites of *Jacobi Zone*. The Albian unit consists of ferruginous, mostly glauconitic, sandstones with ammonites from the Early Albian *(Laymeriella tardefurcata, Douvilleiceras nammillatum)* and Middle Albian *(Puzoisia, Inaceramus)* ages. The Upper Albian gray siltstone, shale and sandy limestone enclose *Mortoniceras (Pervinquierian) inflatum Zone* (*Puzosia mayoriana* d'Orbigny – shell > 25 cm in diameter, *P. mayoriana Africana* Kilian, *Hamites* cf. *simplex* (d'Orbigny).

In the Belgrade area, according to present ammonite fauna, three stratigraphic levels are distinguished (Fig. 7):

- the lowest Clansayesian transitional level between Aptian and Lower Albian (Repište)
- the Lower and Middle Albian horizon (Košutnjak, Rakovica, Čukarica-Repište) with up to 3–13 m thick ferruginous and glauconitic sandstone containing ammonitic fauna (so-called stratigraphic condensation)
- the Upper Albian level with transition to Cenomanian (Košutnjak, Repište, Rakovica): sandy marl and marly to clayey sandstone overlie ferruginous (glauconitic) sandstones. Marls and marly sandstone from the northeast side of Košunjak Hill show transition from Albian to Cenomanian.

2.2 Carpathian area

Within the Carpathian region of Serbia, occurrences of glauconite are also related to Albian sandstone (Fig. 8). At the end of the Aptian period, this region underwent regression. During

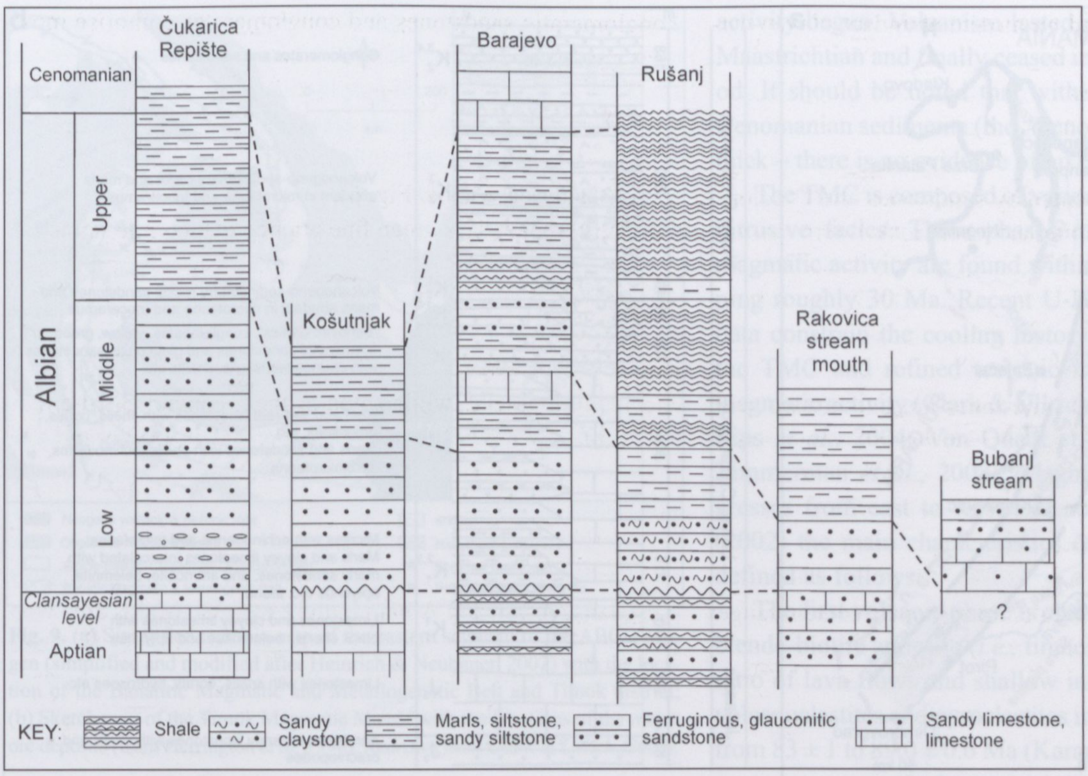

Fig. 7. A generalised lithostratigraphic column of the Albian stratigraphic levels in the the surroundings of Beograd. Data mostly from Anđelković (1973, 1975a), Protić (1969), Rabrenović & Jovanović (1992).

the Albian age, transgression took place, resulting in the deposition of glauconitic sandstone (25–60 vol% of glauconite) in the Early Albian, ferruginous sandstone in Middle Albian, and fossilifeous sandy marl and clayey sadstone with ammonites, shells and belemnites in the Late Albian to the Cenomanian period. This shallow-marine "Lenovac Strata" (Anđelković & Nikolić, 1974) or "Lenovac Clastics" (Đorđević & Banješević, 1997) transgressively overlie Baremian limestones and Aptian sanstones and marls.

Sediments of Late Albian and Albian–Cenomanian origin are the most widespread. They lie over Middle Albian sandstone or are transgressively deposited on older rocks. The best outcrops are located in the Golubac, Kučaj, Svrljig, Suva Planina, Belava, Crni Vrh, Ozren, Device, Stara Planina and Tupižnica mountains (Fig. 8).

The Lower Albian belt consists of green and red ferrugenous sandstones with ammonites (*Kossmatella agassiziana* Pict., *Latidorsela latidorstata* Mich., *Tetragonites timotheanus* Mayg., *Hamites virgulatis* d'Orbigny, *Actinoceramus concentricus* Park., *Inoceraus salomoni* d'Orbigny) and echinoderme (*Discoidea conica* Des.). The lower levels of the Upper Albian and Albian–Cenomanian area consist of fine grained green sandstones and marly sandstone with transition to ammonite-rich shales (*Puzosia mayoriana* d'Orbigny, *Puzosia planulata* Sow., *etc.*).

The "Lenovac Clastics" (up to 100 m thick) at Mount Tupižnica (Lenovac, Brzakovica, Pčela, Gornja Bela river, and Grlište) are made of dark green massive to stratified coarse grained to conglomeratic glauconitic or ferrugenous sandstone and gray to dark blue layered sandy aleurolite and sandy marl. Nodular friable brachiopode-rich ferrugenous sandstone occur at some places. Here, according to the fossil fauna, three levels may be distinguished:

- Lower Albian: detrital and nodular ferrugenous sandstone with limonite nodules rich in Brachiopodes (e. g. *Terebratula dutemplena* d'Orbigny);
- Middle Albian: dark bluish and green marl and Amonite-rich ferrugenous sandstone (*e.g. Latidorsela latorastata* Mich., *Beudanticeras beudanti* Brong., *etc.*); marls
- Upper Albian and Albian–Cenomanian: greenish coarse to fine grained detrital sandstone and Amonite-rich ferrugenous sandstone (*e.g. Anisoceras armatum* Sow., *Puzosia mayoriana* d'Orbigny, *etc.*).

Close to Gamzigrad, these Upper Albian sediments overlie the Urgonian limestone. The gradual transition to Cenomanian stratified clayey sandstone and siltstone is noted in the upper level.

To the north from Mt. Tupižnica the "Lenovac Clastics" are widespread in the Veliki Krš and Majdanpek-Krivelj localities. There the "Lenovac Clastics" comprise green to brown clayey glauconitic sandstone with Upper Albian fauna (*Puzosia mayoriana* d'Orbigny, *Anisoceras armatum* Pict., *etc*). On the eastern side of the Golubac Mountains glauconitic limestone and sandstone are preserved in a tectonically narrowed zone. To the south from Tupižnica (the Knjaževac area) clayey glauconitic sandstone and sandy marl with ferruginous cephalopodic limestone are widespread (Fig. 8).

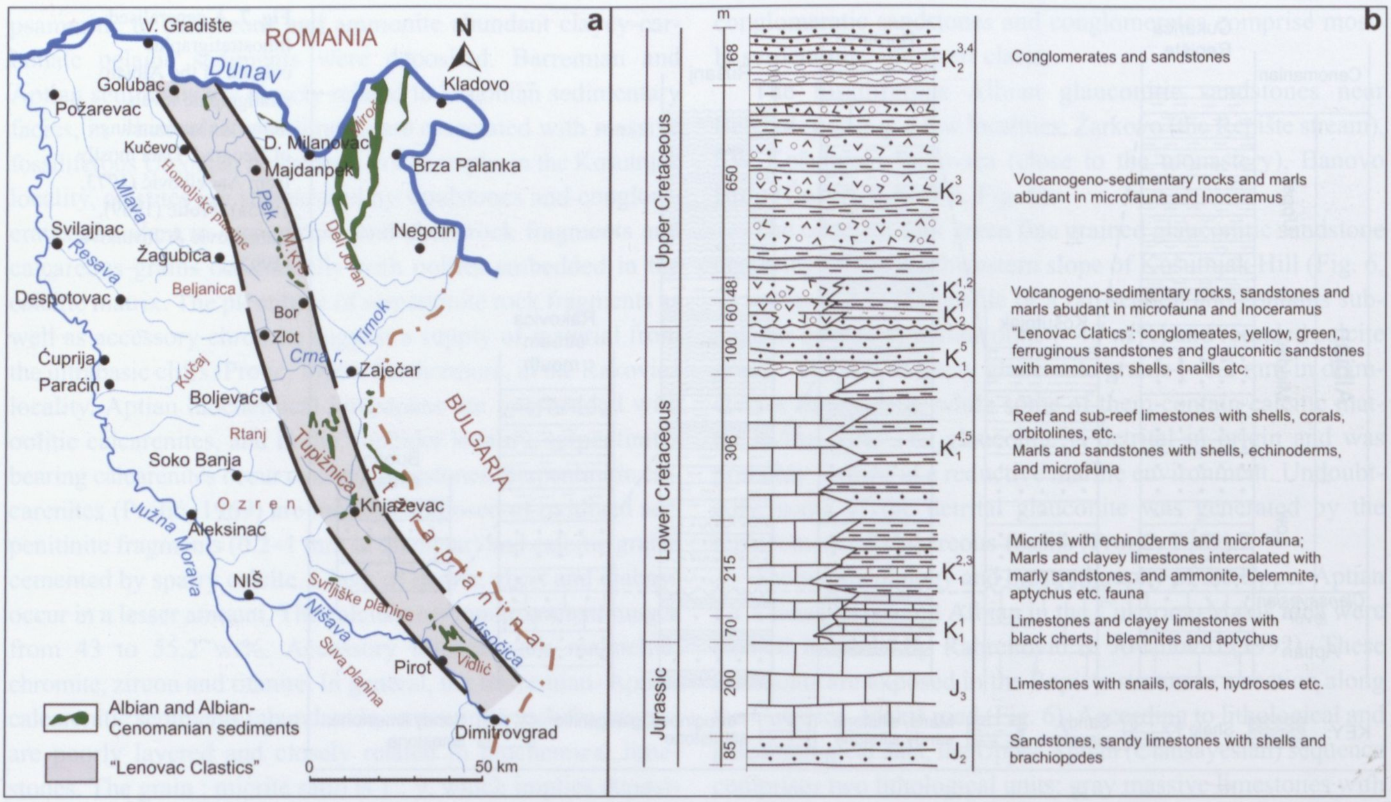

Fig. 8. (a) Outline map of Albian and Albian–Cenomanian sediments in the Carpathian area of Serbia; (b) Lithostratigraphic column of the area Dobro polje-Grlište according to Anđelković (1975b).

3. Late Cretaceous magmatism and metallogeny of the East Serbian Carpatho-Balkanides

3.1 The Timok magmatic complex

The eastern Serbian Timok Magmatic complex (TMC) forms part of the "Tethyan Eurasian Metallogenic Belt" (TEMB; Janković, 1977*)* within the Carpatho-Balkanides (CB). This is a particularly interesting area due to its complex Mesozoic–Tertiary geological evolution and occurrences of porphyry copper, high sulphidation type epithermal and skarn mineralization. This area (*sensu stricto*) belongs to the Apuseni–Banat–Timok–Srednogorie Metallogenic Belt (ABTS; Popov *et al.*, 2000), also known as the Banatitic Magmatic and Metallogenic belt (BMM; Berza *et al.*, 1998).

The ABTS is approximatelly 1500 km long and 70 km wide and extends from SW Romania (the Apuseni Mountains) to the river Danube and continues southwards via Eastern Serbia (the Timok Massif) to Srednogorie in Bulgaria (Fig. 9a). The ABTS comprises Cu–Au–Mo(–PGE) porphyry deposits, Mo–Fe–Pb–Zn skarn and Cu–Au–Ag epithermal deposits. Several world-class copper ore deposits (Moldova Nouă and Băița Bihor in Romania, Majdanpek and Bor in Serbia, Chelopech and Elatsite in Bulgaria) are still mined in this belt.

The East Serbian part of the Timok area shows rift-like extensional features with occurrences of major ore deposits along deep normal faults adjacent to the Early Cretaceous thrust as well as the Srednogorie zone in Bulgaria.

In East Serbia, products of Late Cretaceous magmatism occur in the following areas: the Timok Magmatic Complex (TMC) to the east and Ridanj–Krepoljin Zone (RKZ) to the west (Fig.10)

The TMC appears between the Getic and Danubian nappe (Figs. 9b, 10a). Skarn and porphyry mineralization crop out along their boundaries. The Majdanpek area is characterized by skarn and porphyry mineralization (Janković *et al.*, 1998), similar to the Banat region in Romania (Janković & Jelenković, 1997), and the Bor area by porphyry and epithermal mineralization, similar to the Panagyurishte ore field in the Srednogorie zone of Bulgaria (see Lips *et al.* 2004).

In the southwest Carpathians and their extension towards the Balkanides, the TMC is one of the largest exposures of andesite and subordinate basaltic andesite (rarely dacite and latite). These rocks mostly occur as volcanoclastics with subordinate lavas and feeder dykes. They also contain intrusives and dykes of monzonite, diorite and quartz diorite. Syenite and granodiorite are less abundant.

The TMC is formed on a basement consisting of Jurassic and Lower Cretaceous sediments. Accoriding to Đorđević & Banješević (1997), evolution of the Timok basin (*sensu stricto*) started in a marine environment by deposition of Albian conglomerates and sandstone and continued through their widening and deepening till the end of Cenomanian when volcanic

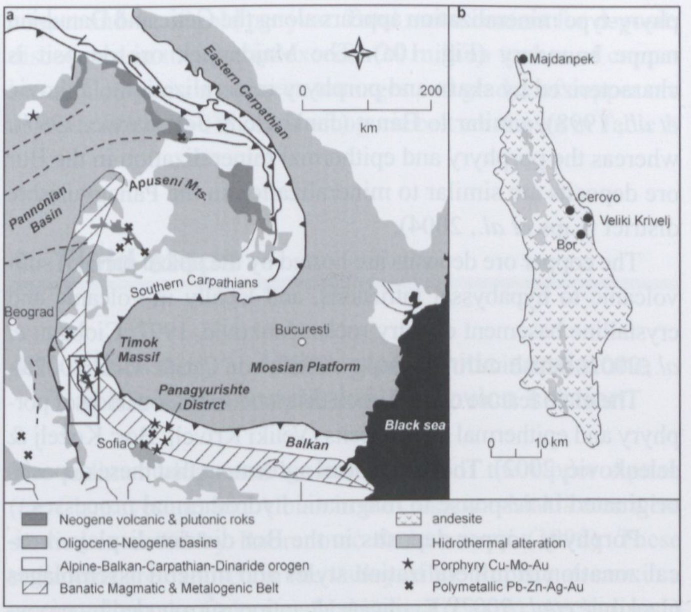

Fig. 9. (a) Simplified tectonic map of the eastern segment of the ABCD orogen (simplified and modified after Heinrich & Neubauer, 2002) with the location of the Banatitic Magmatic and Metallogenetic Belt and Timok district; (b) Sketch map of the Timok Magmatic Massif with the locations of the major ore deposits (from Herrington *et al.* 1998). *Redrawn from Clark & Urlich (2004).*

activity begun. Volcanism lasted intermittently to the Middle Maastrichtian and finally ceased in the late Maastrichtian period. It should be noted that within the Lower Cretaceous to Cenomanian sediments (the "Lenovac Clastics") – up to 100m thick – there is no evidence of no evidence of volcanic activity.

The TMC is composed of various calc-alkaline volcanic and intrusive facies. Three phases of Late Cretaceous–Tertiary magmatic activity are found within the TMC (Fig. 10a), spanning roughly 30 Ma. Recent U-Pb, $^{40}Ar/^{39}Ar$ and Re-Os age data constrain the cooling history and temporal evolution of the TMC and refined tectonic models linked to resolvable magmatic activity (Clark & Ullrich, 2004; Handler *et al.*, 2004; Lips *et al.*, 2004; Von Quadt *et al.*, 2002a, b; 2004, 2005; Zimmerman *et al.*, 2008). Magmatic activity generally progresses from east to west and according to Karamata *et al.* (2002) the main characteristics of each magmatic phase are defined as follows:

The first volcanic phase is characterized by biotite to hornblende-biotite andesite (*i.e.*, timacite), mostly as a high aspect ratio of lava flows and shallow intrusions in association with volcanoclastites and pyroclastites in a minor amount. K-Ar ages from 83 ± 1 to 89.0 ± 0.6 Ma (Karamata *et al.* 1997, Banješević,

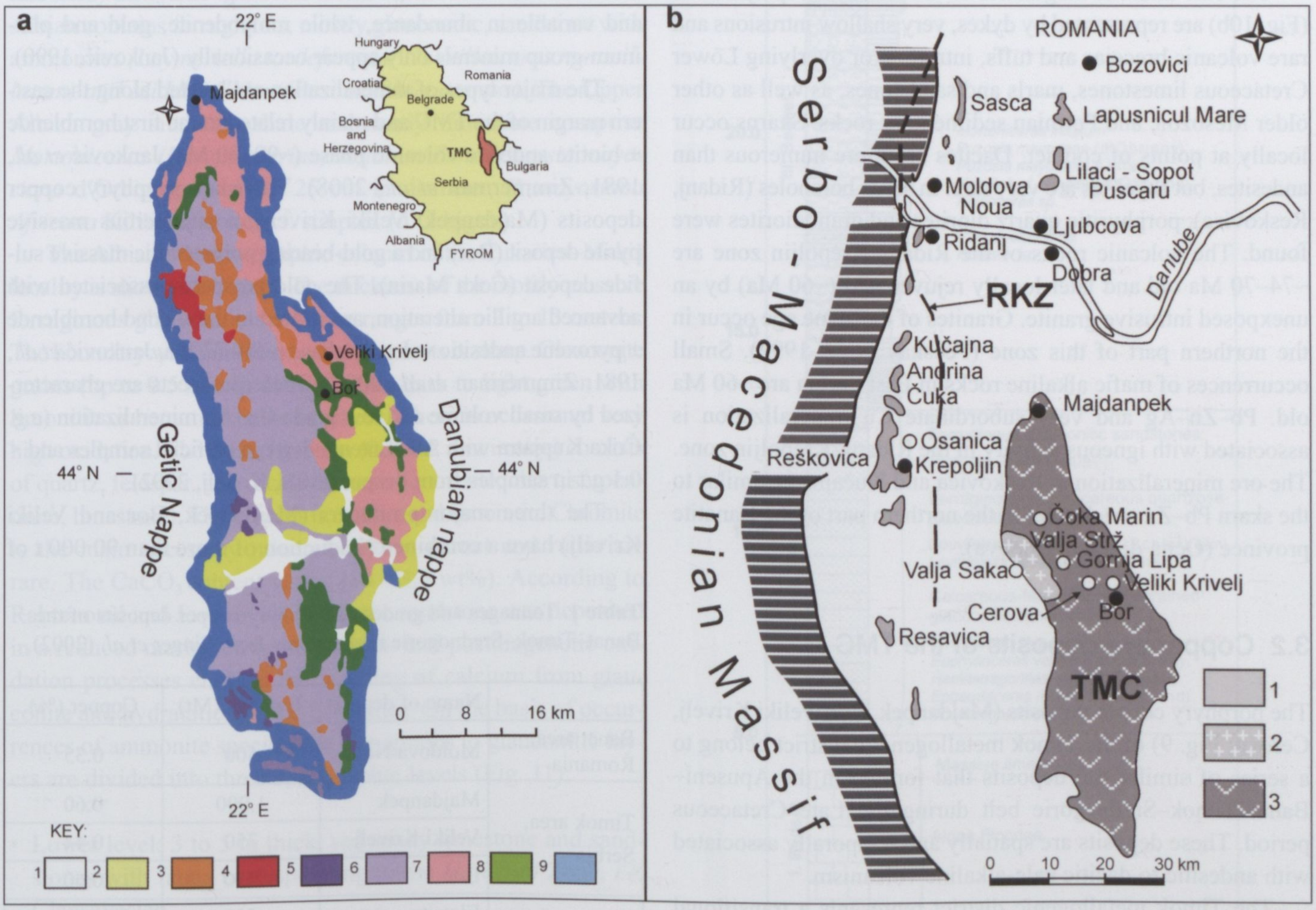

Fig. 10. (a) Geological map of the Timok Magmatic Complex and (b) position of Ridanj–Krepoljin Zone - RKZ. Key: (a) 1 – Alluvium; 2 – Quarternary sediments; 3 – Hydrothermally altered volcanic rocks; 4 – Upper Cretaceous plutons; 5 – Upper Cretaceous volcanics (3rd phase); 6 – Upper Cretaceous volcanics (2nd phase); 7 – Upper Cretaceous volcanics (1st phase); 8 – Upper Cretaceous sedimentary rocks; 9 – Mesozoic arc zone. *Redrawn from Zimmerman* at al. *(2008) and from Karamata* et al. *(1997)*; (b) 1 – Dacites and andesites of the RKZ; 2 – Quartz diorite; 3 – Andesites and their volcanoclastites.

2001; Banješević *et al.*, 2003; Banješević *et al.*, 2004) implying, respectively, Turonian–Coniacian and Santonian eruption ages. Shallow to hypoabyssal intrusions of diorite and quartz diorite were contemporaneously emplaced. Some of them are associated with porphyry-style mineralization. The porphyry and epithermal Cu–Au–Mo deposit of Bor as well as Cu–Mo porphyry deposit of Veliki Krivelj were formed during this phase (Fig. 10a). The Re-Os molibdenite ages gave 83.6 ± 0.4 Ma for the Majdanpek Cu–Au–Mo porphyry deposit, 87.88 ± 0.5 for the Veliki Krivelj Cu–Mo porphyry deposit and 89.6 ± 0.45 for the Bor Cu–Au–Mo deposit (Zimmerman *et al.*, 2008).

The second volcanic phase (Senonian, <83 Ma), the most voluminous and widespread, comprises mostly pyroxene (± hornblende) andesite (predominantly as subaquatic extrusive facies and related volcanoclastics) with subordinate andesitic basalt and the intrusion of monzonite, granodiorite and diorite. The large Valja Strž monzonite complex and associated Dumitru Potok Cu porphyry deposit are 80.7 ± 0.45 Ma old (mean value of Re-Os molibdenite age, Zimmerman *et al.*, 2008).

The third volcanic phase was limited in extent and only produced small latite–quartz latite bodies and quartz diorite to tonalite dikes.

The calc-alkaline magmatics of the Ridanj–Krepoljin zone (Fig. 10b) are represented by dykes, very shallow intrusions and rare volcanic breccias and tuffs, intruding or overlying Lower Cretaceous limestones, marls and sandstones, as well as other older Mesozoic and Permian sedimentary rocks. Skarns occur locally at points of contact. Dacites are more numerous than andesites, but rhyolites are very rare. In some boreholes (Ridanj, Reskovica), porphyritic quartz diorites and granodiorites were found. The volcanic rocks of the Ridanj–Krepoljin zone are ~74–70 Ma old and later locally rejuvenated (~60 Ma) by an unexposed intrusive granite. Granites of the same age occur in the northern part of this zone (Pécskay *et al.* 1992). Small occurrences of mafic alkaline rocks in East Serbia are ~60 Ma old. Pb–Zn–Ag and very subordinate Cu mineralization is associated with igneous activity in the Ridanj–Krepoljin zone. The ore mineralization at Reškovica and Kučajna is similar to the skarn Pb–Zn ore deposit in the northern part of the Banatite province (Ocna de Fier, Tincova).

3.2 Copper ore deposits of the TMC

The porphyry copper deposits (Majdanpek, Bor, Veliki Krivelj, Cerovo; Fig. 9) of the Timok metallogenetic district belong to a series of similar ore deposits that formed in the Apuseni–Banat–Timok–Srednegorie belt during the Late Cretaceous period. These deposits are spatially and temporally associated with andesitic to dacitic calc-alkaline volcanism.

The Timok metallogenic district represents a transitional zone between the thrust nappe-dominated Apuseni–Banat districts in Romania and the extension-dominated setting of the Panagyurishte district in Bulgaria (Fig. 9, 10). Skarn- and porphyry-type mineralization appears along the Getic and Danubian nappe boundary (Fig. 10a). The Majdanpek ore deposit is characterized by skarn and porphyry mineralization (Janković *et al.*, 1998), similar to Banat (Janković & Jelenković, 1997), whereas the porphyry and epithermal mineralization in the Bor ore deposits are similar to mineralization in the Panagyurishte district (Lips *et al.*, 2004).

The copper ore deposits are hosted by the apical parts of subvolcanic to hypabyssal intrusions, and locally in volcanic and crystalline basement country rocks (Janković, 1997; Ciobanu *et al.*, 2002; Strashimirov & Popov, 2000; von Quadt *et al.*, 2002a).

The main feature of the Timok district is the association of porphyry and epithermal ore deposits (Veliki Krivelj, Bor; Koželj & Jelenković, 2002). There is general agreement that these deposits originated in response to magmatic hydrothermal processes.

Porphyry copper deposits in the Bor district display vertical zonation of mineralization styles and mineral assemblages (Janković *et al.*, 2002). K-silicate alteration, surrounded by propylitic alteration, is recognized in the early hydrothermal stages of most porphyry copper deposits, with local overprints by sericite alteration, and advanced argillic alteration at some localities (*e.g.*, Borska Reka; Janković, 1990). Pyrite and chalcopyrite are the most common minerals; bornite and magnetite are subordinate and variable in abundance, while molybdenite, gold and platinum-group minerals only appear occasionally (Janković, 1990).

The major types of mineralization are located along the eastern margin of the TMC and mainly related to the first hornblende ± biotite andesite volcanic phase (~90–80 Ma, Janković *et al.*, 1981, Zimmerman *et al.*, 2008). There are porphyry copper deposits (Majdanpek, Veliki Krivelj), a cupriferous massive pyrite deposit (Bor) and a gold-bearing polymetallic massive sulfide deposit (Čoka Marin). The gold prospects, associated with advanced argillic alteration, are related to the second hornblende ± pyroxene andesitic volcanic phase (~80–72 Ma, Janković *et al.*, 1981; Zimmerman *et al.*, 2008). These prospects are characterized by small volume and low grade Cu–Au mineralization (*e.g.* Čoka Kupjatra with Au content ~1 g/t in surficial samples and < 0.1 g/t in samples from deeper levels, Koželj, 2002).

The three major producers (Majdanpek, Bor and Veliki Krivelj) have a combined production of more than 90 000 t of

Table 1. Tonnages and grades of porphyry copper deposits of the Banat–Timok–Srednogorie region. Data from Singer *et al.* (2002).

	Name of deposit	Tonnage (Mt)	Copper (%)
Banat area, Romania	Moldova Nouă	500	0.35
Timok area, Serbia	Majdanpek	1,000	0.60
	Veliki Krivelj	750	0.44
	Bor	450	0.60
Srednogorie area, Bulgaria	Elatsite	550	0.32
	Assarel	360	0.44
	Medet	260	0.37

copper and 4 t of gold per year. Total metal content for deposits discovered in the district exceeds 20 million tonnes of copper metal. Comparison between tonnages and grades of copper ore deposits in Banat–Timok–Srednogorie belt are shown in Table 1.

4. Field stops

4.1. Field stop 1: Albian glauconitic sandstone at the Čukarica–Makiš–Rakovica section.

The sedimentology and biostratigraphy of the Upper Aptian (*i.e.* Clansayesian) and Albian in the Čukarica–Makiš area were studied in detail by Rabrenović & Jovanović (1992). These sediments are exposed in the valley of the Repište stream in a section along the Čukarica–Makiš road (Fig. 6). According to lithological and paleontological data, the Upper Aptian (Clansayesian) comprises two lithological units: gray massive limestone with *Floridea algae* (Jankičević & Peybernes, 1985; Jankičević & Rabrenović, 1990) and ferruginous sandstone and sandy limestone with ammonites of *Jacobi Zone*. The Lower Albian contains ferruginous, mostly glauconitic, sandstone with ammonites *(Laymeriella tardefurcata, Douvilleiceras nammillatum) and Middle Albian (Puzoisia, Inaceramus)*. The Upper Albian gray siltstone, shale and sandy limestone comprise *Mortoniceras (Pervinquierian) inflatum Zone* (*Puzosia mayoriana* d'Orbigny – shell > 25 cm in diameter, *P. mayoriana Africana* Kilian, Hamites cf. simplex (d'Orbigny).

The Albian lithostratigraphic column of the Čukarica–Makiš locality is shown on Fig. 11. The thickness of the mostly massive ferruginous glauconitic sandstone ranges from 2 to 13 meters. The boundary with under and overlying units is sharp. Glauconite grains (up to 0.5 mm in diameter) are dark to light green with limonitic or hematitic halos in places. There is occasional very high oxidation. The clastic fraction (0.1–0.2 mm in size) consists of quartz, feldspar, and rock fragments (quartzite, chert, serpentinite, limestone). The cement is calcitic and limonitic. Chromite is the main accessory mineral; zircon, garnet and rutile are rare. The $CaCO_3$ content varies (10–33.5 wt%). According to Rabrenović and Jovanović (1992), the sandstone was deposited in a reduced marine enviroment; syn- and postdiagenetic oxidation processes enabled the leaching of calcium from glauconite and hydratation of the Fe-oxides. On the basis of occurrences of ammonite species, the ferruginous to glauconitic layers are divided into three stratigraphic levels (Fig. 11):

- Lower level: 3 to 5 m thick, red sandy limestone and sandstones with fauna corresponding to the *H. jacobi* Zone, *i.e.* Clansayesian
- Middle level: up to 2 m thick, ferruginous glauconitic sandstone with Lower and Middle Albian fauna
- Upper level: 4–6 m thick, ferruginous and glauconitic sandstone with *Puzosia*, *Inoceramus* and *Leylliceras lyelli* (Leymerie) corresponding to a Middle Albian subzone.

The laminated gray calcareous clayey to sandy clayey siltstone, sandstone, calcareous silty shale and sandy limestone of the third level are formed in a deeper marine environment with a continuous supply of siliciclastic and carbonate material. These sediments with the ammonite zone *Mortoniceras (Pervinquierian) inflatum* date from the Upper Albian age.

The compact dark green to dark brown glauconitic sandstone from the Rakovica locality is interbedded with limestone (Fig. 7). The sandstone consists of subangular well-sorted quartz and oval glauconite grains (up to 50 wt%) from 0.2–0.5 mm in size. These grains contain limonite-coated calcite in the core. The glauconite at this locality is not entirely detrital in origin (Protić, 1969).

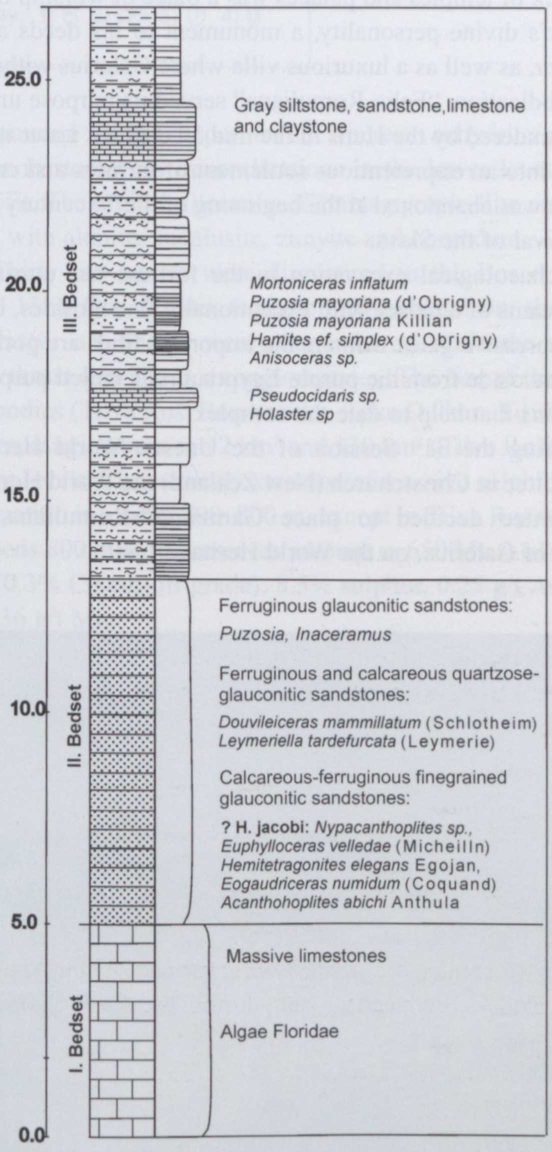

Fig. 11. Lithostratigrafic column of the Čukarica–Makiš locallity (data from Rabrenović & Jovanović, 1992)

4.2. Field stop 2: Gamzigrad, the "Felix Romuliana" archaeological site

Gamzigrad is a small village spa located south of the river Danube near Zaječar (Fig. 12). In its vicinity there are ruins of a Roman complex called "Felix Romuliana", one of the most important late Roman sites in Europe. At first it was believed that the ancient ruins represented a Roman military camp because of their size and numerous towers. However, systematic archaeological excavation since 1953 has shown them to be an imperial palace. "Felix Romuliana" is thought to have been one of the residences of the Roman Emperor Gaius Galerius Valerius Maximianus, in the late 3rd and early 4th century. The imperial palace got the name "Felix Romuliana" in memory of his mother, Queen Romula, a priestess of a pagan cult.

The tetrarchs, Galerius, the adopted son and son-in-law of the great Diocletian started to build the palace in 289, after a victory over the Persians, to mark the place of his birth. This complex of temples and palaces was a place of worship of his mother's divine personality, a monument to his deeds as an emperor, as well as a luxurious villa where Galerius withdrew after abdication. "Felix Romuliana" served its purpose until it was plundered by the Huns in the mid 5th century. Later it was turned into an unpretentious settlement of farmers and craftsmen. It was abandoned at the beginning of the 7th century with the arrival of the Slavs.

Archaeological excavation in the fortress has unearthed the remains of a palace with exceptionally fine mosaics, baths and impressive gates. Among the important finds are portraits of rulers made from the purple Egyptian rock called porphyry and coins that help to date the complex.

During the 31st Session of the Unesco World Heritage Committee in Christchurch (New Zealand) the World Heritage Committee decided to place Gamzigrad-Romuliana, the Palace of Galerius, on the World Heritage List.

Boljevac – Rtanj Ethno Center at Balašević (Mount Rtanj) – overnight accommodation. The Balašević Ethno-Center is a luxury motel designed in rustic style, located on the Paraćin–Zaječar regional road close to the village of Boljevac. The motel lies amid beautiful scenery with a view of Mt. Rtanj.

4.3 Field stop 3: The village of Lenovac – the "Lenovac Clastics": glauconitic sandstone along the road cut by Lenovac and the Gornja River

Near the village of Lenovac glauconitic sandstone and marly sandstone occur in a few localities. The best outcrop is exposed by the road about 500 m from the village (Figs. 13, 14). Dark green coarse grained to conglomeratic glauconitic sandstone alternating with partly disintegrated ferruginous (sometimes nodular) sandstone and marly sandstone and marl occur along a length of more than 200 m. They appear as interstratified masses, rarely as beds, and abound in fossil fauna.

Three levels of Albian are distinguished according to the fossil fauna:

- Lower Albian: detrital nodular ferruginous sandstone with brachiopods
- Middle Albian: marl and marly sandstone with ammonites
- Upper Albian and Albian–Cenomanian: greenish coarse to fine grained detrital sandstone and ferruginous red sandstone with ammonites (*e.g. Anisoceras armatum živkovići, etc.*).

4.4 Field stop 4: Bor Cu–Au ore deposit

The Bor Cu–Au ore field is located in the eastern part of the TMC in the Upper Cretaceous hornblende ± biotite andesite and vol-

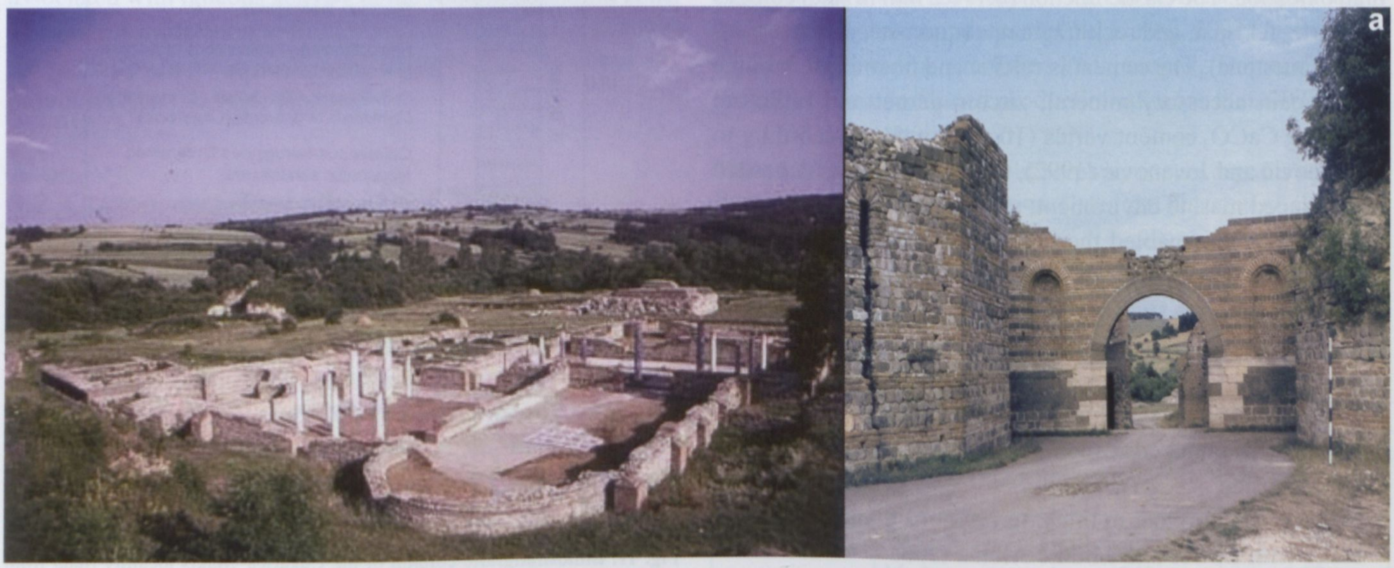

Fig. 12. Archaeological site "Felix Romuliana" and the West Gate (a).

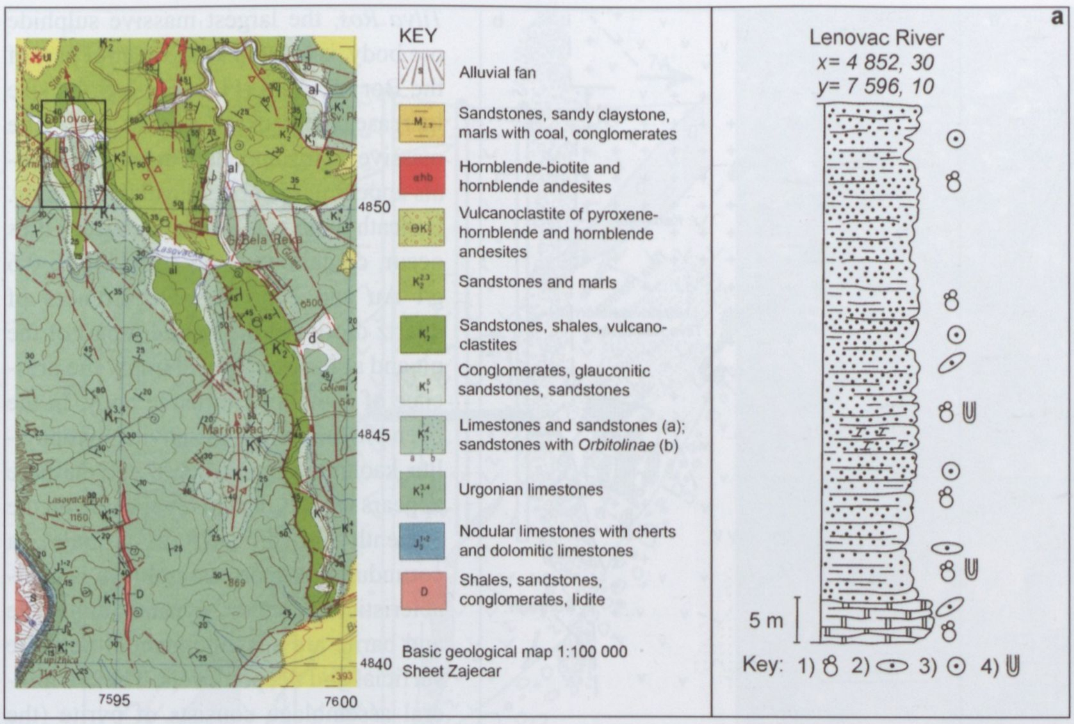

Fig. 13. Geological map of the surroundigs of Lenovac and geological column of the visited area (a) – *Redrawn from Đorđević & Banješević (1997)*. Key: 1 – Pelagic foraminifera; 2 – Nodules; 3 – Glauconite; 4 – Fucoides.

canoclastite series of the first volcanic phase. It extends in a NW–SE direction and slopes SW at an angle of 45–50°. The ore field is 5 km long and ~1.2 km wide (Fig. 15a). Its eastern part consists of conglomerate and sandstone containing andesite, Upper Jurassic to Lower Cretaceous limestone and Proterozoic gneiss, mica schist and amphibolite fragments. These sediments are divided from the hydrothermally altered volcanic rocks by the NW–SE fractured "Bor fault" (Fig. 15b). The western side of the open pit is built up by so-called "Bor Pelites" consisting of various types of volcanoclastic rocks and marl (*i.e.* Senonian epiclastites, Đorđević, 2005).

Generally, the Bor mineralization is characterized by massive cigar-shaped and pipe-like bodies related to fracture zones and volcanic breccias. The massive ore contains up to 70 vol% of fine-grained pyrite with chalcocite, covellite and enargite. Barite is common in the upper level, whereas anhydrite/gypsum occur in stockwork mineralizations in the lower level of the deposit. The argillic alteration contains pyrophyllite and diaspore with alunite, andalusite, zunyite and corundum.

Thirty ore bodies were discovered in the Bor ore field (Fig. 15b). Due to later tectonic movements from the west, the larger ore bodies were dismembered while the smaller ones thrust over the Bor conglomerates. The size of the major ore bodies (Tilva Roš, Borska reka, Čoka Dulkan, Tilva Mika) varies, ranging between 2 km^2 and 130 km^2 (Tilva Roš) at different levels. The vertical extension of massive sulphide mineralization is mostly 200–800 m, except in Tilva Roš where it exceeds 800 m. Total reserves amount to 650 Mt: 0.61% copper (0.3% Cu cut-off grade), 8.5% sulphur, 0.25 g/t Au, 2 g/t Ag, 36 g/t Mo.

Fig. 14. Glauconitic sandstone outcrop at the road section south of Lenovac village; (a) detail: glauconite grains are <1 to 5 mm in diameter.

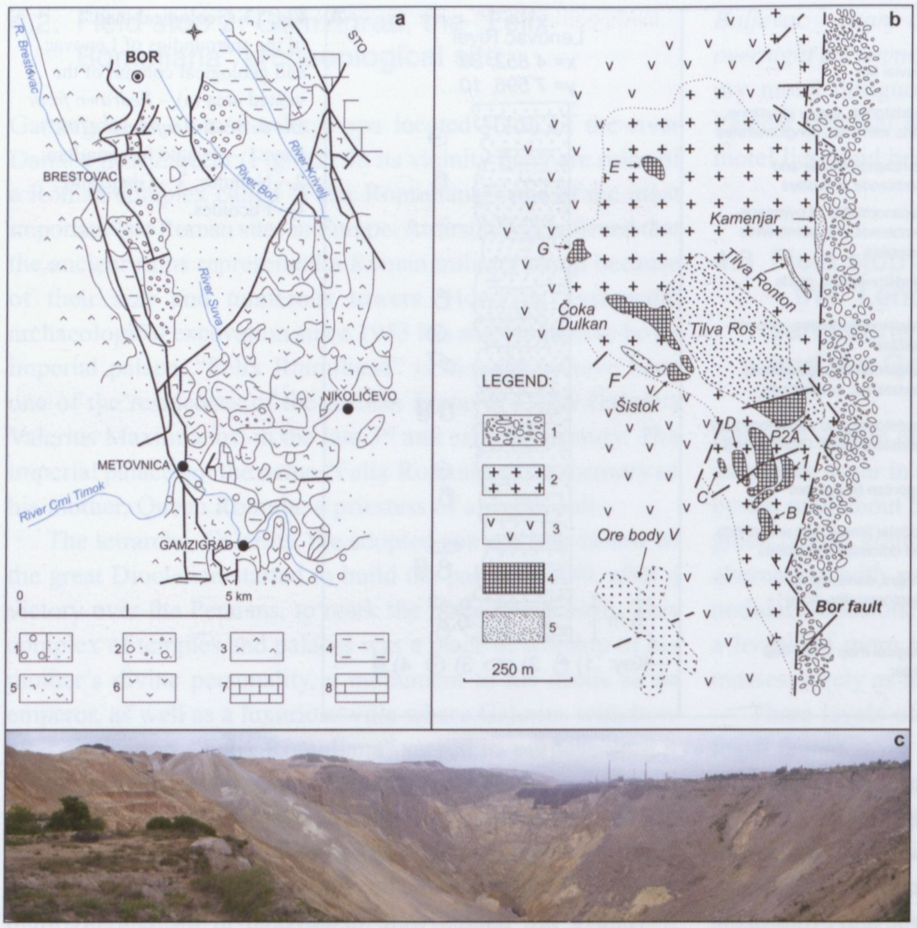

Fig. 15. (a) Outline geological map of Bor and its surroundings (Đorđević, 2005): 1 – Quaternary; 2 – Neogene; 3 – Bor conglomerates and sandstones (Maastrichtian); 4 – Senonian volcanoclastics and volcanic rocks; 5 – Upper Turonian and Senonian sediments; 6 – Epiclastics; 7 – Turonian volcanoclastics and volcanic rocks; 8 – Lower Cretaceous and Cenomanian; 9 – Jurassic; b) Position of ore bodies within the Bor open pit mine: 1 – Conglomerate, 2 – Hydrothermally altered andesites, 3 – Andesite, 4 – Massive replacement sulphide ore body; 5 – Pyrite stockwork–impregnated ore body; c) Bor open pit mine today – panorama view (photo courtesy by Dejan Koželj).

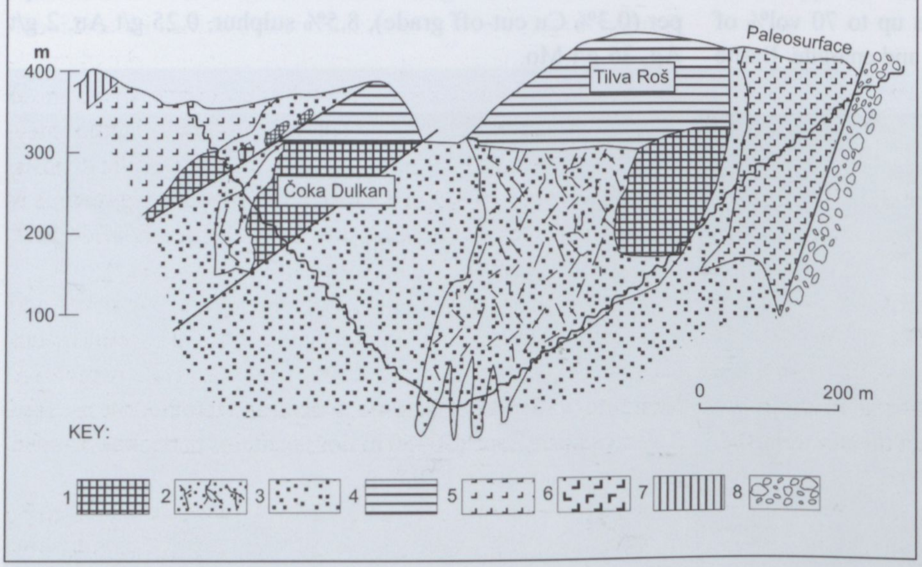

Fig. 16. A simplified geological section through the central part of the Bor deposit: 1 – Massive ore; 2 – Stockwork ore; 3 – Impregnation ore type; 4 – Hydroquartzites, 5 – Non-altered andesites; 6 – Hydrothermally altered andesites; 7 – Conglomerates; 8 – Siltstone and tuffs.

Tilva Roš, the largest massive sulphide ore body, is located in the central part of the Bor ore field (Fig. 15b, 16). Its size increases with depth to 130 km^2. The massive quartz abundant in precious metals appear in the upper level of the body. Beneath them massive to stockwork ores occur, containing 0.9% Cu, 11% S, 0.6 g/t Au and 2 g/t Ag. Occurrences of quartz diorite in the northern part of the pit and at its deeper level imply the presence of a shallow intrusive body. In the open pit, the zone with zunyite, pyrophyllite, kaolinite, alunite, quartz and diaspore appears at the + 100 m level while on the fifteenth horizon (–75 m altitude), a corundum–diaspore assemblage is characteristic. Moreover, gypsum, anhydrite and barite are also abundant at both the surficial and deeper levels. The ore mineral assemblage consists of pyrite (the most widespread), covelline, enargite, chalcocite, chalcopyrite, bornite, luzonite, tetraedrite and sulvanite. Concentration of metals within the ore body decreases laterally and with depth.

Borska Reka ore body (impregnation, vein, stockwork–impregnation) is located in the northwestern part of the Bor deposit. It is elongated, runs in a NW–SE direction and slopes SW at an angle of 45–55°. The maximum length of the body is 1410 m with 635 m width at 395 m altitude. The thickess of mineralization is ~300 m. The eastern and northwestern margins of the ore body are defined while the western margin is not defined yet due to its deep extension. The gradual transition into the ore body Tilva Roš is established at the higher levels of the southeastern margin of the Borska reka ore body. The ore body is hosted within hydrothermally altered andesite (Fig. 17). Mineralization is linked with potassium silicate alteration, and to a propylitic assemblage containing illite + chlorite. The uppermost levels of the Borska Reka deposit are characterized by advanced argillic alteration coupled with pervasive silicification marking an upward transition zone to the Tilva Roš massive sulphide deposit. The main ore minerals are pyrite, chalcopyrite, covellite, chalcocite and bornite. Rutile, magnetite,

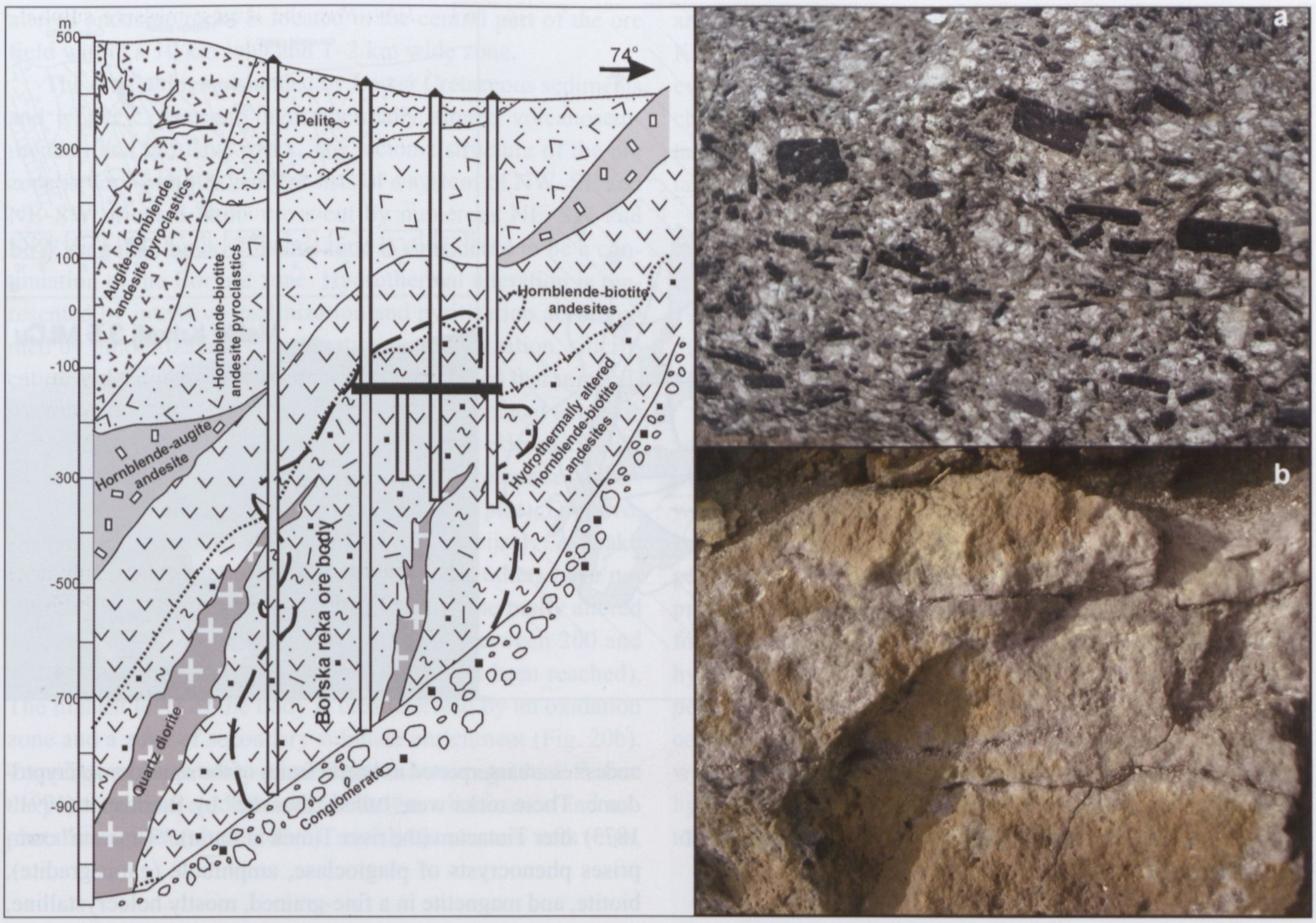

Fig. 17. Outline geological section through Borska Reka porphyry copper deposit; argillitized (a) and silicified and pyritized (b) hornblende biotite andesite.

hematite, sphalerite and galena are common, while tetrahedrite, tennantite, digenite, cubanite and native gold are rare. The total reserves are 636 Mt of ore with 0.606% Cu (0.03% cut-off-grade), 8.63% S, 1.81 g/t Ag, 0.21 g/t Au and 36 g/t of Mo, *i.e.* 3.9 Mt Cu, 55 Mt S, 1,2 Mt Ag, 140 t Au and 21 t Mo.

4.5 Field stop 5: Veliki Krivelj porphyry copper ore deposit

The approximately 5 km^2 Veliki Krivelj ore field is located about 3 km north of Bor. Shallow intrusions of diorite and quartz diorite caused intense tectonization of the surrounding volcanics and sedimentary rocks (pelites, limestones, marls), which resulted in intense fluid circulation. The intrusive rocks are fine-grained having interlocked plagioclase, biotite and amphibole crystals with xenomorphic quartz and potasium-feldspar in the interstices. The surrounding sediments are contact metamorphosed.

The porphyry copper ore is hosted in hydrothermally altered andesitic rocks and partly in diorites and quartz diorites (Todor stream). The deposit slopes SW. It is more than 1.5 km long and max. 700 m wide. The known vertical extent mineralization interval exceeds 800 m. The exploration has not still reached the deepest levels of the ore mineralization. The deposit has a NNW–SSE oriented oval shape in plan view, while it almost has an isometric shape in cross-section (Fig. 18). The ore body does not show decrease in copper content with depth.

The most common hydrothermal alterations are: a) K metasomatism (biotitization) accompanied by sercitization and silification; b) sericitization associated with silicification and locally intermediate argillitization; c) chloritization and carbonatization, seldom epidotization and weak silicification; d) advanced argillic alteration (pyrite, pyrophyllite, alunite, laumontite). Intensive pyritization is related to marginal part of the deposit. The appearance of sulphate minerals (anhydrite, gypsum) is characteristic for its deeper levels. In higher levels of deposit, over the sercitic zone, zeolite alteration is common.

The most frequent ore minerals are pyrite, pyrrhotite and chalcopyrite. Marcasite, bornite, chalcocite and covellite occur locally while enargite, digenite, molybdenite, magnetite, hematite, valleriite, sphalerite, galena and tetrahedrite are rare. The oxidation zone (30–50 m tick) contains malachite, azurite, tenorite, cuprite and native copper.

Ore reserves (cut-off grade 0.20% Cu) are estimated to be 702.21 Mt with 0.366% Cu, *i.e.* 2.57 Mt of Cu. The gold content is up to 0.20 g/t, and molybdenum content ranges 0.05 to 0.15 g/t. The exploitation of the Veliki Krivelj ore body started in 1982.

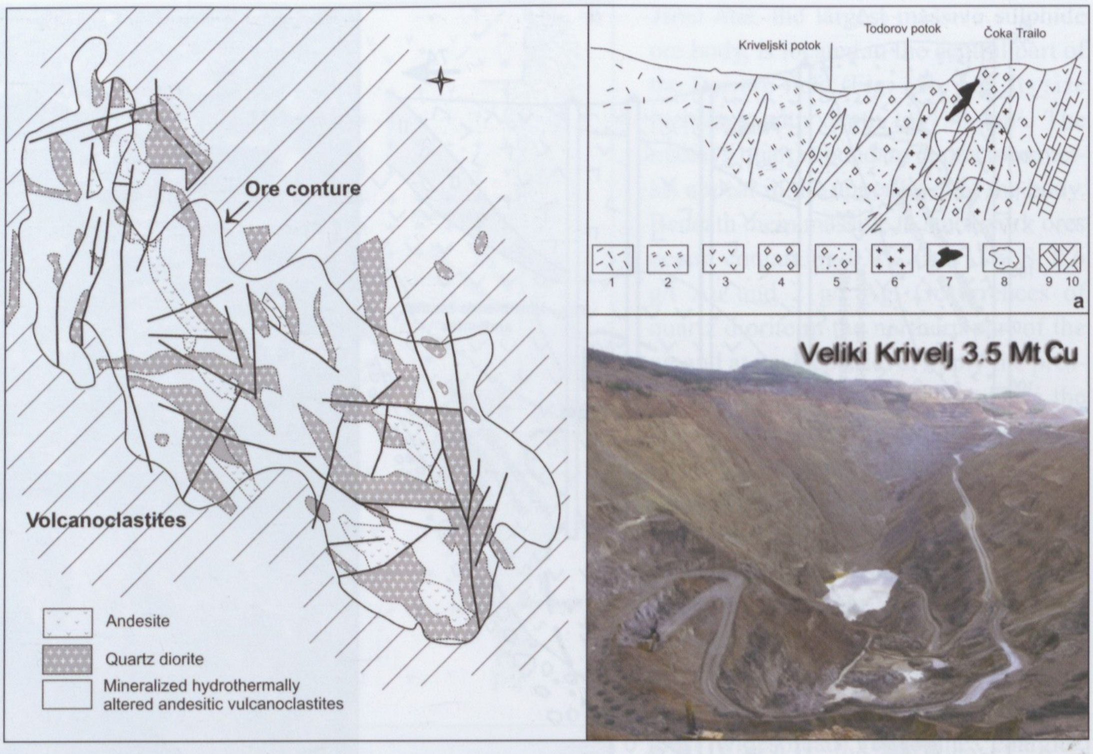

Fig. 18. Outline geological map of the Veliki Krivelj deposit (left) and section through the deposit (a; *redrawn from Cocić* et al. *2002)*. Panorama view of open pit mine Veliki Krivelj (b). Key: 1 – Andesitic volcanoclastites; 2 – Hornblende-pyroxene andesitic volcanoclastites with biotite; 3 – Hornblende-biotite andesites; 4 – Pyritized andesitic rocks; 5 – Silicified and pyritized andesitic rocks; 6 – Quartz diorite; 7 – Skarns; 8 – Ore body; 9 – Limestones; 10 – Shales.

4.6 Field stop 6: Turonian andesites of the first volcanic phase along the road cut between Veliki Krivelj and Mali Krivelj and the copper ore deposit at Mali Krivelj–Cerovo

The ages of these volcanics are 84.26 ± 0.67 Ma (by U/Pb zircon method) and 90–84 Ma (by K/Ar method) corresponding Turonian volcanic activity in the TMC, *i.e.* the first volcanic phase. The lava dome/cryptodome (Fig. 19) and lateral extrusive facies of hornblende-biotite andesites ca be seen in the road cut.

In the quarry, elements of columnar to platy jointing can be seen, and further, along the road, several outcrops of brecciated andesites are interpreted as lateral facies of the same dome/ cryptodome. These rocks were called "timazite" by Breithaupt (1791–1873) after Timacum (the river Timok in Latin). "Timazite" comprises phenocrysts of plagioclase, amphibole (gamsigradite), biotite, and magnetite in a fine-grained, mostly holocrystalline, feldspar-rich matrix. The rock is remarkable because of its large, sometimes cm-long prismatic amphibole phenocrysts.

The Mali Krivelj–Cerovo porphyry copper ore deposit is located 10 km northwest of Bor. It extends from Čoka Čuruli and Kriveljski Kamen to the villages of Mali Krivelj and Cerovo and further northwards (Fig. 20a). The area of hydrothermally

Fig. 19. Columnar to platy jointing in hornblende-biotite andesite (timazite) lava dome/cryptodome facies (a) and autobrecciated lateral lava dome/cryptodome facies (b) – photo courtesy by Miodrag Banješević (a) and Kristina Šarić and Vladica Cvetković (b).

altered andesitic rocks is located in the central part of the ore field within a 10 km long and 1–2 km wide zone.

The ore field is surrounded by Lower Cretaceous sediments and Upper Cretaceous, hydrothermally altered volcanosedimentary and intrusive rocks. The tectonic structure of the ore zone is very complex and consists of a system of NW–SE and NE–SW oriented faults cross-cut by numerous NE–SW and E–W diagonal faults. This ore zone is considered to be a continuation of the Bor ore zone. Hydrothermal alteration is represented by intensive kaolinization and pyritization accompanied by limonitization, chloritization, carbonatization, silicification and sulphate mineralization. It is assumed that mineralization in the Mali Krivelj–Cerovo ore field is related to quartz diorite dykes similar to the copper porphyry ore deposit Veliki Krivelj. The ore field at Mali Krivelj–Cerovo comprises several ore bodies: Cerovo-Primary (in its northern part), Drenovo, Cementacija-1, 2 and 3. The ore body Cementacija-1, *i.e.* Kraku Bugaresku (Fig. 20b) is still mined while the others have not opened yet. The ore body is located in hydrothermally altered andesites and its volcanoclastites at a depth between 200 and 400 m (its downward continuation has not yet been reached). The highest level of the body is characterized by an oxidation zone and a zone of secondary sulphide enrichment (Fig. 20b). Transition to the primary mineralization zone is gradual. Within the primary zone, chloritization as well as silicification and sulphatation (gypsum, anhydrite), mostly as clusters and veins, are the most extensive hydrothermal processes. Albitization, K-feldspar alteration, epidotization and biotitization are less evident. Among ore minerals, the most frequent are pyrite and chalcopyrite. The zone of secondary sulphide enrichment contains pyrite, chalcocite and covelline. The oxidatione zone contains cuprite, tenorite, hematite, magnetite, malachite, limonite.

Copper ore reserves in the ore body Cementacija-1 are estimated to be 20.1 Mt. The average content of Cu is 0.68% with 0.07 g/t Au and 1.5 g/t Ag. The Cementacija-2 ore body contains 19 Mt of copper ore with 0.36% Cu, 0.08 g/t Au, 1.1 g/t Ag. Within the other ore bodies, copper ore reserves range from 0.96–4.5 Mt with 0.34% Cu, 1.1 g/t Au and 1.8 g/t Ag on average.

Facies of hydrothermal alteration show vertical and horizontal zonality and differ in intensity. The distinct feature of the Mali Krivelj–Cerovo ore deposit in relation to other deposits within the Bor metallogenetic zone is alteration of the ore minerals due to surficial secondary processes. The origin of the copper deposit at "Cerovo" has not yet been studied in detail. The primary pyrite–chalcopyrite ore mineralization was probably formed under complex physico-chemical conditions during hydrothermal activity. The presence of high to medium temperature minerals (magnetite, rutile, pyrite, pyrrhotine, chalcopyrite, bornite), low-temperature sphalerite and galenite, as well as different forms of these minerals indicate multi-phase hydrothermal activity accompanied by changes in pressure, temperature, and pH and Eh of the ore solutions.

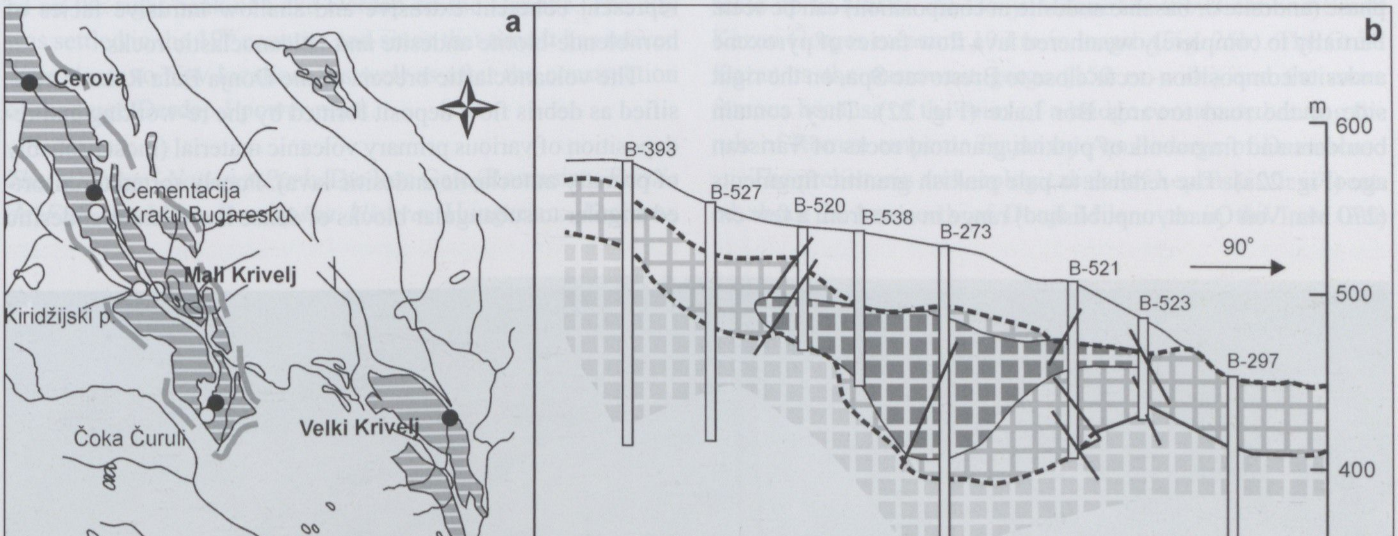

Fig. 20. Location of the ore field Mali Krivelj–Cerovo in the Bor metallogenitic district (a) and outline cross section of the copper deposit Cementacija-1: Kraku Bugaresku (b). Key: (a) 1 – Hydrotermally altered andesitic rocks; 2 – porphyry ore; 3 – massive sulphide ore; 4 – conture of ore field Mali Krivelj–Cerovo; (b) 1 – Zone of sulphide enrichment; 2 – Ore body; 3 – Hydrothermally altered andesitic rocks; white area over zone of sulphide enrichment represents oxidation zone.

4.7 Field stop 7: The road cut between Bor and Brestovac Spa: andesite volcanoclastics cut by an albite- trachyte dyke

In appearance, this section is typical of the second (Senonian) volcanic phase in the TMC. Here, autoclastic and hyaloclastic piles of pyroxene- and amphibole-bearing basaltic andesite are cut by a westward dipping albite-trachyte dyke (81.79 ± 0.54 and 82.27 ± 0.35 Ma by K-Ar method, Banješević, 2006). The whole sequence is overlaid by resedimented hyaloclastites and autoclastites whose outcrops can be also seen along the road towards Bor.

The albite-trachyte dyke is pale grey to pinkish grey in color (Fig. 21). It is characterized by thin chilled margins and crystalline groundmass with albite phenocrysts which are almost oriented in parallel.

Within the *in situ* or slightly reworked hyaloclastites remains of pseudopillows (see Yamagishi, 1991) or lava lob, features with a preserved chilled margin are also noticed. The matrix is fine-grained within a jigsaw-fit puzzle structure.

4.8 Field stop 8: Road cut between Brestovac Spa and Bor Lake: coherent andesitic volcanoclastic facies from the Senonian period

Along the road from the cross-section Bor–Brestovac Spa and further to Bor Lake, numerous outcrops of the second volcanic phase (andesite or basaltic andesite in composition) can be seen. Partially to completely weathered lava flow facies of pyroxene andesite composition occur close to Brestovac Spa, on the right side of the road towards Bor Lake (Fig. 22). They contain boulders and fragments of pinkish granitoid rocks of Variscan age (Fig. 22a). The reddish to pale pinkish granitic fragments (270 Ma, Von Quadt, unpublished) range in size from a few cm to > 2 m in diameter. In mineral composition (quartz, K-feldspar, plagioclase, biotite), they are analogous to the syenitic granite of the Variscan Gornjane Granitoid Massif (north of Bor).

Outcrops of Senonian pyroxene andesites can be traced further along the road cuts going towards Bor Lake. Various volcanoclastic facies, *in situ* autoclastic deposits, primary and reworked hyaloclastic deposits as well as debris flow deposits prevail. Some outcrops with characteristics of debris avalanche deposits also occur.

4.9 Field stop 9: Bor Lake: massive columnar to platy pyroxene andesite

On the left side of the road leading further to the northwest as well as along the lake shores, outcrops of massive pyroxene andesite with columnar and platy jointing (Fig. 23) occur and probably represent typical deeper effusive facies of Senonian basaltic andesite. Its roof segments are usually brecciated or disrupted by hydraulic fracturing suggesting that this zone was in contact with water (*e.g.* subaqueous emplacement,.

4.10 Field stop 10: Upper Cretaceous volcanoclastic rocks of Donja Bela Reka

These terrestrial volcanoclastic deposits close to the village of Donja Bela Reka are related to the first volcanic phase and were deposited above Albian–Cenomanian sediments. They represent coherent extrusive and shallow intrusive facies of hornblende-biotite andesite and volcanoclastic rocks.

The volcanoclastic breccia of the Donja Bela Reka is classified as debris flow deposit formed by the re-working and re-deposition of various primary volcanic material (most probably of primary autoclastic andesitic lava). Poorly sorted to unsorted angular to subangular blocks of dense hornblende-andesitic

Fig. 21. Outcrops on the crossroad Bor–Brestovac Spa: (a) a grey-pinkish intrusion of albite trachyte dyke into basaltic andesite volcanoclastites; (b) resedimented volcanoclastites (photo courtesy by Miodrag Banješević).

Fig. 22. Outcrop of altered Senonian pyroxene andesite lava flow with fragments of Variscan granite on the road cut close to Brestovac spa; granite xenolith form the outcrop (a).

lava (> 0.2–1 m in diameter) are set in a finegrained matrix composed of mm-sized particles of dense andesitic lava, phenocrysts and rare glass (Fig. 24). Due to the variable amount of matrix within the breccia, a closed (low amount of matrix) and open framework fabric (high amount of matrix) can be seen. These features, in combination with the weak grading of the larger fragments, suggest an *en masse* transport of dense, probably hyperconcentrated volcanoclastic material.

Donji Milanovac – Hotel Lepenski Vir – overnight accommodation. Donji Milanovac, the lovely "Town of Roses" is located on the right bank of Lake Đerdap on the Danube. The city was settled in the 19th century, and since that time it has moved three times to new locations, as well as after the construction of the huge Đerdap I power plant.

The "Đerdap" National Park. The Iron Gate (Romanian: *Porțile de Fier*, Serbian: *Đerdapska klisura*, Hungarian: *Vaskapu*, Turkish: *Demirkapý*, German: *Eisernes Tor*) is a gorge (134 km long) on the Danube River – the border between Serbia and Romania (Fig. 25). Here the Danube river separates the southern Carpathian Mountains from the northwestern foothills of the Balkan Mountains. The Danube reaches its greatest depth at a point 40 km southeast from Majdanpek, a place called Kazan, where the depth is 84 m (Fig. 25b).

The first narrowing of the Danube takes place beyond the Romanian isle of Moldova Veche and is known as the Golubac Gorge (Fig. 25a). It is 14.5 km long and 230 m wide at its narrowest point. There is a medieval fort at Golubac. The cliffs scale up to 500 m. At Donji Milanovac the Great and Small Kazan Gorges measure 19 km in length (Fig. 25b). The Great Kazan is the narrowest gorge (150 m wide) and the more famous because of the ruins of a bridge constructed during the rule of Roman emperor Trajan by Apollodorus of Damascus.

The prehistoric archaeological site of Lepenski Vir is located about 20 km north of Donji Milanovac in the Iron Gate

Fig. 23. Columnar (a) and more platy jointed (b) Senonian basaltic andesite close to the end of Bor Lake.

Fig. 24. Outcrop of andesite volcanic breccia and a detail (a) near the village Donja Bela Reka (Photo courtesy by Kristina Šarić and Vladica Cvetković).

(Field stop 11). The major part of the "Đerdap" National Park forms part of Majdanpek municipality. Diverse flora, trees centuries old and an abundance of game (deer, bear, wildcat) attract numerous lovers of untouched nature. Moreover, the stretch of the Danube that is richest in fish (catfish, perch, carp) is located near Donji Milanovac.

4.11 Field stop 11: Lepenski Vir, archaeological site

The archaeological site at Lepenski Vir is one of the most marvelous and fabulous prehistoric locations (archeologists call it "the cradle of European civilization"). A great number of monumental fish-like stone sculptures carved from coarse sandstones (the oldest in the world – 6000 BC) are a feature of the site. The first excavations started in 1965, but its importance was only fully grasped in 1967, *i.e.* after the discovery of the first Mesolithic sculptures. Excavation ended in 1971. Then, the whole site was relocated 29.7m up onto higher ground to avoid flooding from a new artificial lake created at the Iron Gate along the Danube river. Exploration of the site was spearheaded by Srejović (1972).

Lepenski Vir consists of one large settlement and several satellite villages. Evidence dates the first human presence in the locality at around 7000 BC and the peak of this civilization as occurring between 5300 BC and 4800 BC.

The main site consists of several archaeological phases, with occupation spanning over a millennium, from the Mesolithic to the Neolithic period. The discovered artefacs include: tools made from stone and bone, remains of houses and numerous sacral objects among which the most important are the unique stone sculptures (Fig. 26). It is assumed that the people of Lepenski Vir were descendants of the early European population of the Brno-Předmost hunter-gatherer culture from the end of the last Ice Age. The major food source was probably fish. Fishing communities of this type are typical of the wider Danube region during this period. The complex social structure is influenced by a religious cult as can be seen from the numerous sacral objects.

Fig. 25. Iron Gate, (a) Golubac Gorge and (b) Kazan Gorge at Donji Milanovac.

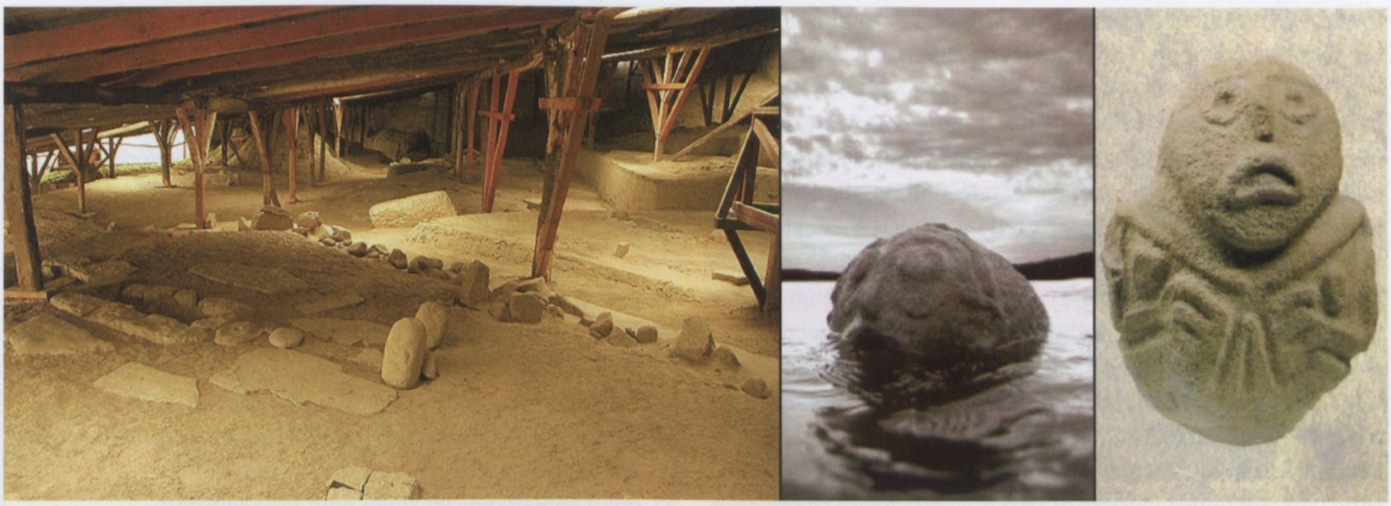

Fig. 26. Remains of Mesolithic house and fish-like sculptures in prehistoric site Lepenski Vir.

4.12 Field stop 12: The Majdanpek mine – porphyry copper deposit and Rajko's Cave

The small town of Majdanpek is located in the crater of a long-extinct volcano. It is known for its rich deposits of copper and gold, and its mining tradition which dates from long before the Romans forced their way into this region (1st century AD). At that time, copper was obtained by the settling method and gold by washing sand from the River Pek or by mining native gold from quartz veins. The oldest cast copper object (pickaxe in shape) was discovered in the immediate surroundings of the present-day Copper Tube Plant Majdanpek. This object (copper content 98.50%) is on display in Majdanpek's Museum of Mining and Metallurgy. Mining continued during the Middle Ages. In the first half of the 19th century, organized copper mining started, using modern technologies. The mining and processing industry fully developed in the second half of the 20th century. Up to 1962, the Majdanpek porphyry deposit was a mine of massive pyrite and limonite (Janković, 1990). After that time, it was transformed into an open pit with an annual output of 12–14 million tons. Reserves exceeded 800 million tons of ore with 0.4–0.8% of Cu and 0.25–1 g/t Au and mining had started with 0.82% of Cu and ~0.8 g/t Au. The deposit contains a significant quantity of massive pyrite (~15 Mt) with 3–15 g/t of Au and a few million tons of Pb–Zn (~7%). Within the highest level of porphyry copper mineralization, a high concentration of Au is found (1 g/t in average). Today the town is known for its production of high quality and durable utility and industrial copper tubes.

The open mine at the very entrance to Majdanpek, from the Belgrade direction, is an example of a manmade landscape (Fig. 27). It is an incredible and very rare sight of wide terraces and roads that make up a huge funnel with a basin at the bottom.

The Majdanpek ore deposit contains several types of mineralization (Janković *et al.*, 1980; Janković, 1989). In addition to the dominant porphyry copper mineralization, massive sulphide pyrite ore bodies, skarn magnetite mineralization, Pb–Zn sulphide ore bodies and hydrothermal vein types are

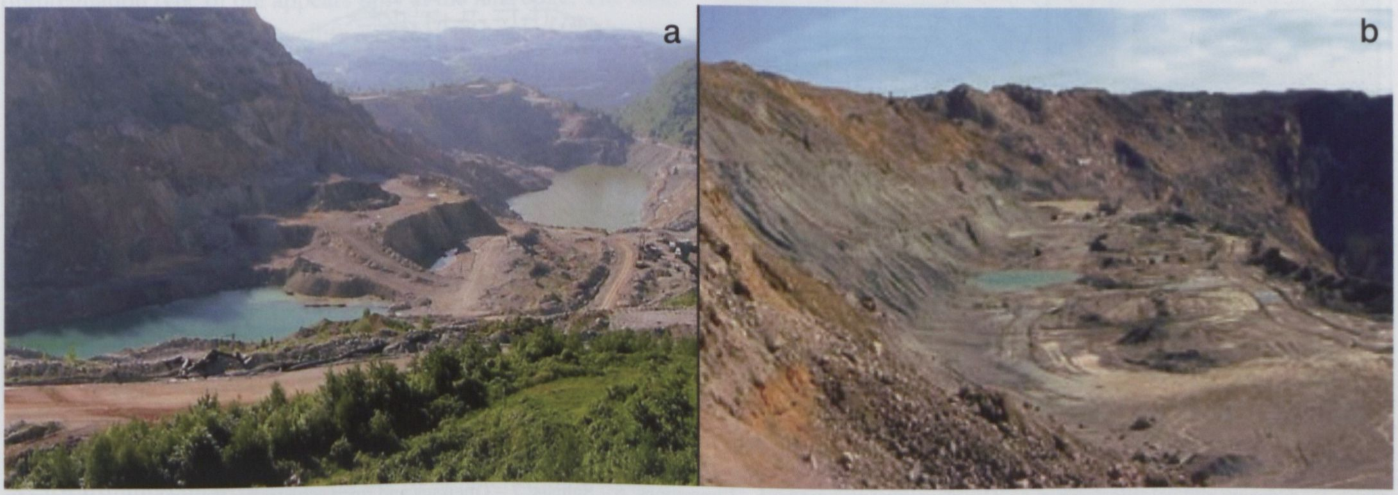

Fig. 27. Majdanpek open pit mine: (a) northern and (b) southern mining area.

found. All are related to the same structure during multi-stage ore-forming processes (Spasov, 1967; Janković, 1990).

The Majdanpek deposit formed along a very narrow zone (0.3×5 km) between Jurassic limestone and Rifeo-Cambrian metamorphics (gneiss, mica schist, amphibolites) intruded by andesite dykes and bodies (Fig. 27). Initial magmatic activity is linked to the Alpine orogene phase. It consists of calc-alkaline volcanic rocks (andesite, dacite, pyroclastite). During the Laramian period, they were dissected by small intrusions (mostly dikes) of diorite and quartz diorite, which were especially important in forming the copper deposit.

The Majdanpek Cu–Au porphyry system is emplaced close to the Santonian–Campanian boundary, at ~83–84 Ma, *i.e.* during the later stages of eruption of timocitic, high-potassium calc-alkaline andesites of first volcanic phase of the period 83 ± 1 to 89.0 ± 0.6 Ma, Clark & Ullrich (2004).

The Majdanpek copper ore deposit consists of a southern and a northern mining area (Fig. 28). The first is located S–SW about 500 m from the town. It is named "Knez Lazar" and comprises Cu–Au porphyry and massive Cu–Au–Ag pyrite bodies. The northern Area is situated ~1km N–NW from the town and contains the "Tenka" polymetallic/gold deposit, the "Dolovi" porphyry ore body, the "Central ore body" (stockwork–impregnation), the "Dolovi-2"massive sulphide ore body, the "Stari Dušan" pyrite body, and the "Blansard" limonite ore body. The order of mineralization in the porphyry copper deposit of Majdanpek is as follows:

1) garnet–magnetite
2) quartz–molybdenum stage with pyrrhotite, pyrite, molybdenite, chalcopyrite, sphalerite, cubanite, bismuthinite, tetrahedrite, bornite, As-bearing pyrite
3) quartz–pyrite stage with a small amount of gold, marcasite and melnikovite
4) quartz–chalcopyrite stage with tetrahedrite
5) quartz–sphalerite stage with chalcopyrite, molybdenum, galena, gold, calcite and barite

Within the *Southern Mining Area* (Figs. 27b, 28b), the *Cu-Au porphyry ore body* is located within hydrothermally altered

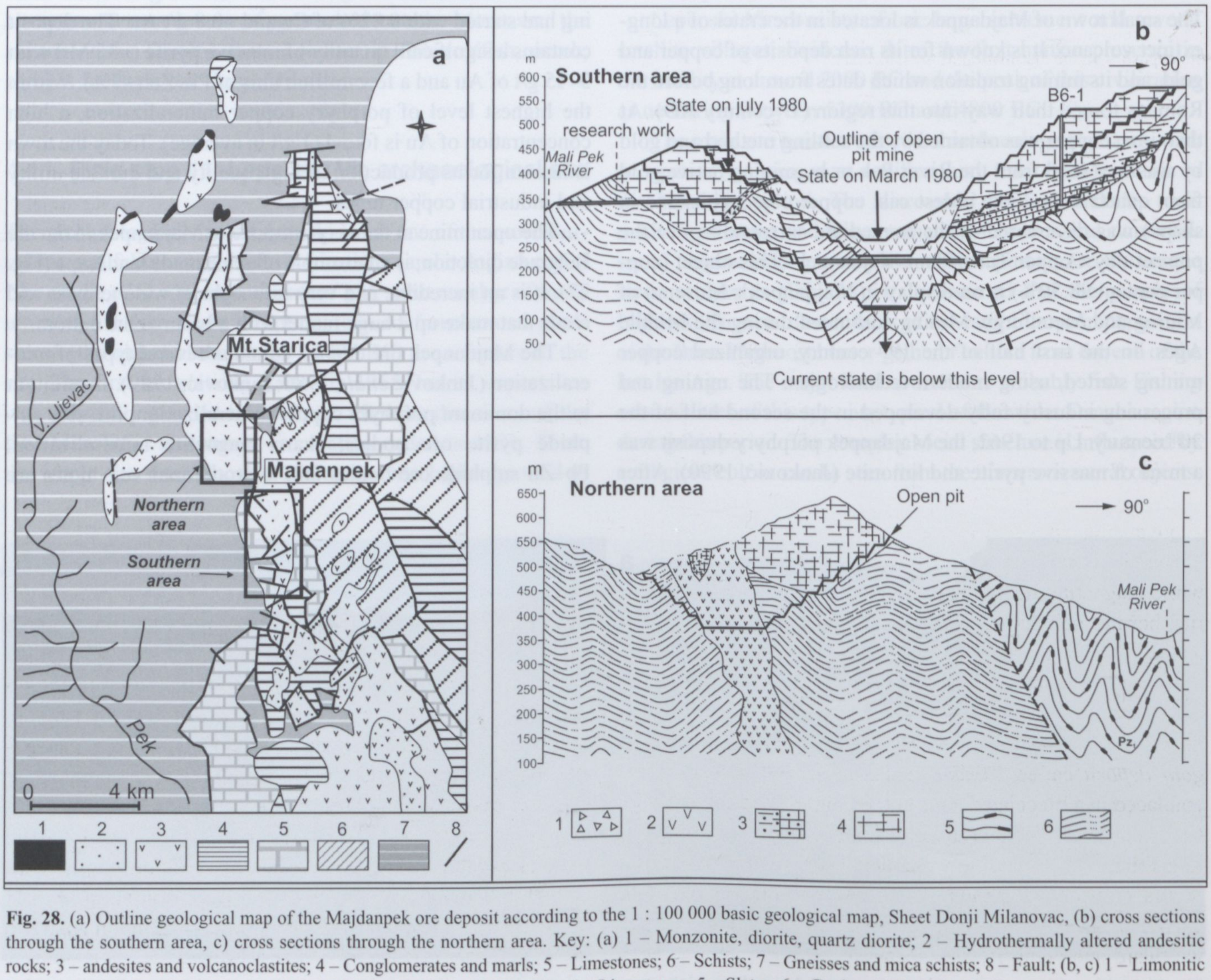

Fig. 28. (a) Outline geological map of the Majdanpek ore deposit according to the 1 : 100 000 basic geological map, Sheet Donji Milanovac, (b) cross sections through the southern area, c) cross sections through the northern area. Key: (a) 1 – Monzonite, diorite, quartz diorite; 2 – Hydrothermally altered andesitic rocks; 3 – andesites and volcanoclastites; 4 – Conglomerates and marls; 5 – Limestones; 6 – Schists; 7 – Gneisses and mica schists; 8 – Fault; (b, c) 1 – Limonitic breccia; 2 – Andesitic rocks; 3 – Marly sandstones and sandy limestones; 4 – Limestones; 5 – Slates; 6 – Gneisses and mica schists.

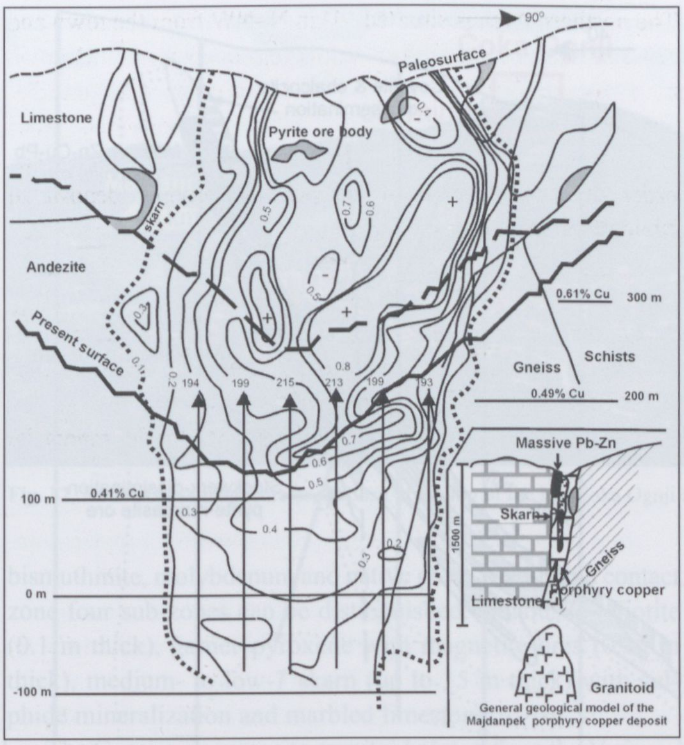

Fig. 29. Outline section through the Southern Mining Area of the Majdanpek ore deposit with the distribution of the Cu content.

andesite and Rifeo-Cambrian gneisses and schists (Fig. 29) It contains magnetite, chalcopyrite, pyrite, sphalerite and galena. The eastern part of the body is bordered by unmineralized greenschist with small bodies of serpentinite, metadiabase dykes and quartz veins with Cu, Pb, and Zn suphides and gold. The southern part of the body, called Čoka Muskal, is built of Jurassic limestone intruded by narrow dykes and small irregular ore bodies (nest-like-veinlets) of andesite and comprises pyrite and chalcopyrite. Another *Cu–Au–Ag pyrite ore body* (called *"Knez Lazar"*) is placed south from the previous one at a depth of ~400 m in the form of an irregular lens within tectonized marble at the point of contact with hydrothermally altered amphibole-biotite andesite. The massive sulphide mineralization (with 20–28% pyrite) is mostly controlled by N–S fractures. The vein-impregnation type of ore appears only at the lens edge. The chief mineral is chalcopyrite; covellite and chalcocite are less abudant, while magnetite, hematite, pyrrhotite, melnikovite, arsenopyrite, bornite, sphalerite, galena and native gold appear sporadically. *Gold-quartz veins* (0.5–3 m thick) are hosted along the schistosity of the Rifeo-Cambrian gneisses and greenschists.

In the *Northern Mining Area* (Figs. 27a, 28c) the *polymetallic gold deposit* called *"Tenka"* consists of several ore bodies emplaced in a brecciated zone at the point of contact of Upper Cretaceous volcanics and Jurassic limestone. The main type of mineralization is massive while stockwork–impregnation ore occurs only on its margin. There are three ore bodies with columnar, lensoid or irregular shape. The first one plunges westward and comprises fragments of sphalerite in a tectonic breccia and narrow strips of massive pyrite; the second contains massive pyrite with jets and strips of sphalerite – it was generated through the deposition of Pb–Zn mineralization in the previously formed massive Cu–pyrite ore body and has a lower concentration of Zn and Pb and a higher content of S, Au and Cu; the third is formed in tectonized zones at the point of contact of limestone (Mt. Starica) and Upper Cretaceous volcanics and comprises Cu–pyrite-type mineralization with subordinate Pb–Zn. The most widespread ore minerals within "*Tenka*" are pyrite, sphalerite, galena chalcopyrite, enargite, luzonite and bornite. Rutile, marcasite, pyrrhotite, digenite, tetrahedrite, tennantite, native gold, petzite and lindströmite appear sporadically. The "*Tenka*" deposit contains a high concentration of gold in native form (grains) and in aggregates with lindströmite and hessite–petzite. The narrow oxidation zone close to the limestone contains limonite, azurite, malachite, native copper, cerussite, smithsonite, cuprite *etc.* Oxidation "pockets" along the fault zones contain chalcocite, covellite, bornite and idaite.

The central chalcopyrite ore body has an oval shape in plan view and is a stockwork–impregnation type controlled by NNW–SSE fault structures. Here, andesite and quartz diorite dykes are intruded into the gneisses. The average copper content is 0.45% with 0.4 g/t of Au. A smaller Cu–pyrite massive and metasomatic ore bodies are located west and east of the Norther Mining Area.

The Čoka Marin polymetallic massive sulphide ore deposit is located south of Majdanpek in the Vlaole-Jasikovo ore field. The volcanic area of Čoka Marin comprises volcanics and volcanoclastics (hornblende-biotite or pyroxene andesite, dacite, volcanic breccia, tuff) and associated quartz diorite of 74–69 Ma and diorite of ~70 Ma (K-Ar data: Živković & Knežević, 2002). Andesite–dacite volcanic breccia and tuffs (72 Ma, K-Ar data: Živković & Knežević, 2002) host ore mineralization (Fig. 30). According to Clark & Ullrich (2004), ages of 83 ± 1 to 89.0 ± 0.6 Ma are obtained for the high-potassium calc-alkaline andesites of the first volcanic stage (^{40}Ar-^{39}Ar data). It is a volcanogenic-hydrothermal high sulphidation type epithermal ore deposit hosted within the Late Maastrichtian andesite–dacite. The main hydrothermal alteration zones contain quartz, alunite. sericite, kaolinite, diaspore ± corundum (Živković *et al.*, 1996; Živković & Knežević, 2002, and reference therein).

Ore bodies appear in irregular lenses in similar order to the stratiform type of mineralization (Janković, 1990) and contain massive, stockwork and disseminated ore. Massive sulphide ore content reaches up to 3% Cu, 5–8% Zn and up to 1% Pb with ł 60% pyrite content. The main ore minerals are pyrite, "gelpyrite", pyrrhotite, marcasite, enargite, luzonite, chalcopyrite. Bornite, native gold, sphalerite, galena, Pb-Sb sulphosalts, stannite, cassiterite and bravoite appear sporadically. Distribution of pyrite-Cu and pyrite–sphalerite–galena–chalcopyrite mineralization is zonal. Gold occurs in native form or in association with sulphides. The highest Au concentration (4.6–23 g/t) occurs between the advanced argillitic alteration zone and the silicificated and kaolinized andesite breccia. This ore contains 159 g/t of Ag, 0.6% of Cu 7.4% of Zn and 2.25% of Pb.

Rajko's Cave is located 2.5 km from the center of Majdanpek. The overall length of the cave is 2304 meters. Air temperature is constant, 8 °C and the relative humidity is 100%. The cave consists of two physically separated caverns: an underground river channel and a spring cave, both of which have two floors. It is very rich in cave jewelry: marvelously-shaped stalactites and stalagmites, halls and galleries, cave columns, curtains, draperies, *etc.* (Fig. 31). The cave was first explored by Serbia's greatest geographer Jovan Cvijić in 1894.

15th km from Majdanpek toward Donji Milanovac there is a natural stone arch – overpass (about 20 m high).

4.13 Field stop 13: Rudna Glava – magnetite ore deposit

Rudna Glava is located in the area of the Porečka River headwaters (Fig. 32). It belongs to Majdanpek municipality. The administrative center of the village is located 24 km from Majdanpek along the Pozarevac–Majdanpek–Negotin highway. The total area of the community is 115,6 km^2. The landscape is Alpine with heights ranging between 190 and 830 m *a.s.l.* Rudna Glava is a dispersed type of settlement with dwellings located on the hill slopes and summits (called "kulma"). The magnetite ore deposit is situated on the southern and southeastern slope of Okno Hill.

The oldest traces of human presence in the Rudna Glava community date from the Eneolithic period (5000 BC), the closing epoch of the Stone Age. In 1968, a prehistoric mine site was discovered on the hill Čoka Oknji (473 m a.s.l.), 2.4 km from the center of the town. The scientific public is almost unanimous in considering this site to be Europe's the oldest copper mine. It is further regarded as the best preserved prehistoric mining site in the world. Since prehistoric times there have been numerous periods of mining activity (Fig. 34a). In fact the name Rudna Glava is a Slavic term related to the ore and it probably originates from the Middle Ages. Mining continued in the period of Ottoman domination and also during

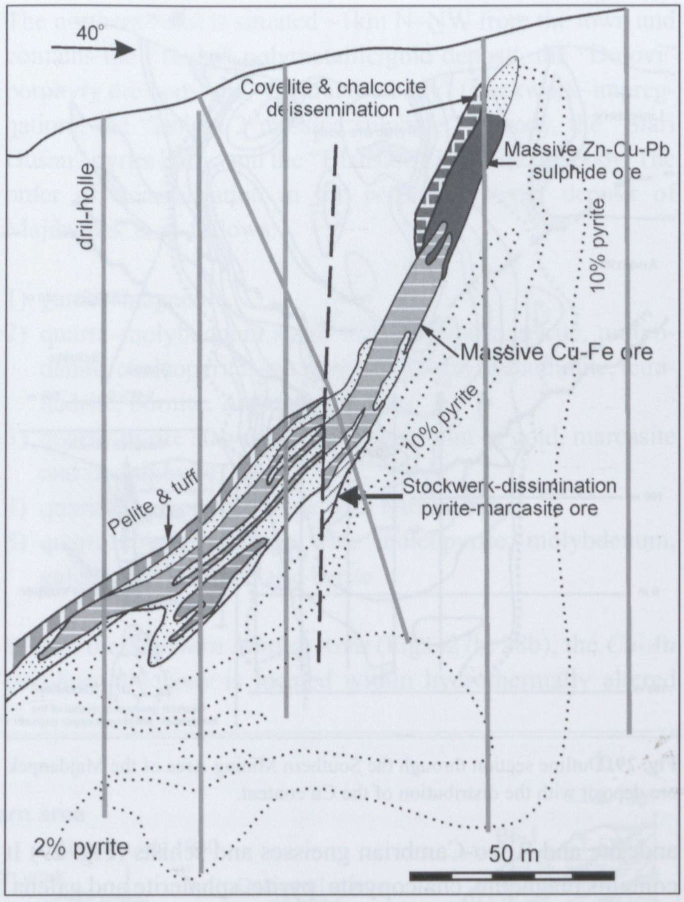

Fig. 30. Outline section through the ore body Čoka Marin.

Austrian Occupation (1718–1739). In the liberated Principality of Serbia, mining operations were reactivated in 1848. However, mining faced continuous decline in the late 19th and early 20th century and finally ceased in 1963 (~350 Mt of magnetite was extracted).

The magnetite deposit is located at the point of contact of the Variscan granitoid body named Gornjane and calcareous rocks metamorphosed into garnet and pyroxene skarn and hornfels. On the margins of the magnetite ore body, younger sulphide mineralization occurs (mostly chalcopyrite, sphalerite,

Fig. 31. Rajko's cave.

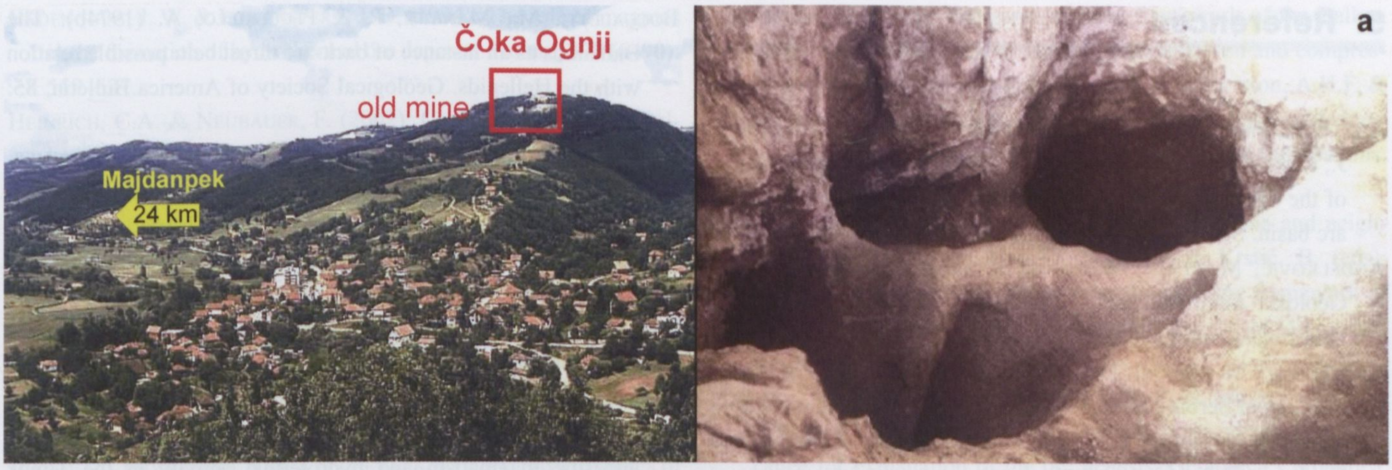

Fig. 32. Rudna Glava magnetite ore deposit at the top of the hill Čoka Ognji and remains of old mining holes (a).

bismuthinite, molybdenum and native gold). Within the contact zone four sub-zones can be distinguished: andalusite– biotite (0.1 m thick), garnet–pyroxene with magnetite ores (0.15 m thick), medium- to low-*T* skarn (up to 15 m thick) with sulphide mineralization and marbled limestone.

The Gornjane composite granitoid pluton from the Variscan age is granodioritic in composition and is one of the largest in East Serbia (160 km^2). Quartz monzonites and granites make up its central part. Quartz monzodiorite, quartz diorite, diorite and syenite occur along the margins of the granodiorite body. Transition to tonalities is also noted.

The granitoid pluton is intruded into metamorphic and sedimentary Paleozoic rocks. The age of the pluton has not been precisely determined – there are two data available only: 222 Ma (made on radiogenic lead from zircon) and 304 Ma (Rb/Sr method on biotite), Deleon *et al.* (1962).

4.14 Field stop 14: Đerdap Gorge and the Golubac medieval fortress

It is amazing to drive along the bank of the Danube. Locations such as this where nature and cultural heritage are so interwoven are very rare in the world. From ancient times, the Danube has provided a livehood to all those who lived along its banks. Here, civilizations have followed each other in succession for more than ten thousand years, from prehistory to Roman times, from the Middle Ages to the present day. The high, mostly carbonate, mountains protected their inhabitants from Barbarian attacks. The remains of the Lepenski Vir prehistoric settlement, Trajan's Road, Table and Bridge, whose pillar stands today in the Forum in Rome, the Diana fortress close to Kladovo, as well as the medieval Golubac Fortress all bear witness to the past (Fig. 33).

Fig. 33. The medieval Golubac fortress.

Acknowledgment

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Appendix 1 – Itinerary for IMA2010 RS2 Field trip

Saturday, August 28, 2010 (Day 0)

Travel from Budapest to Beograd

Sunday, August 29, 2010 (Day 1)

8.00–8.30	Travel from Beograd through Čukarica – Makiš – Rakovica from north to south-west
8.30–10.30	Field stop 1: Lower Cretaceous glauconitic sandstone at the section Čukarica – Makiš and Rakovica stream
10.30–12.30	Travel to Gamzigrad via Paraćin along highway E75. Refreshment will be available during travel
12.30–13.00	A short coffee break on the highway between Batočina and Jagodina
13.00–15.00	Travel to Gamzigrad via Paraćin
15.00–17.00	Field stop 2: Sightseeing of Roman emperor palace "Felix Romuliana" and coffee break
17.00–17.30	Travel to Boljevac: Hotel Balašević, accommodation

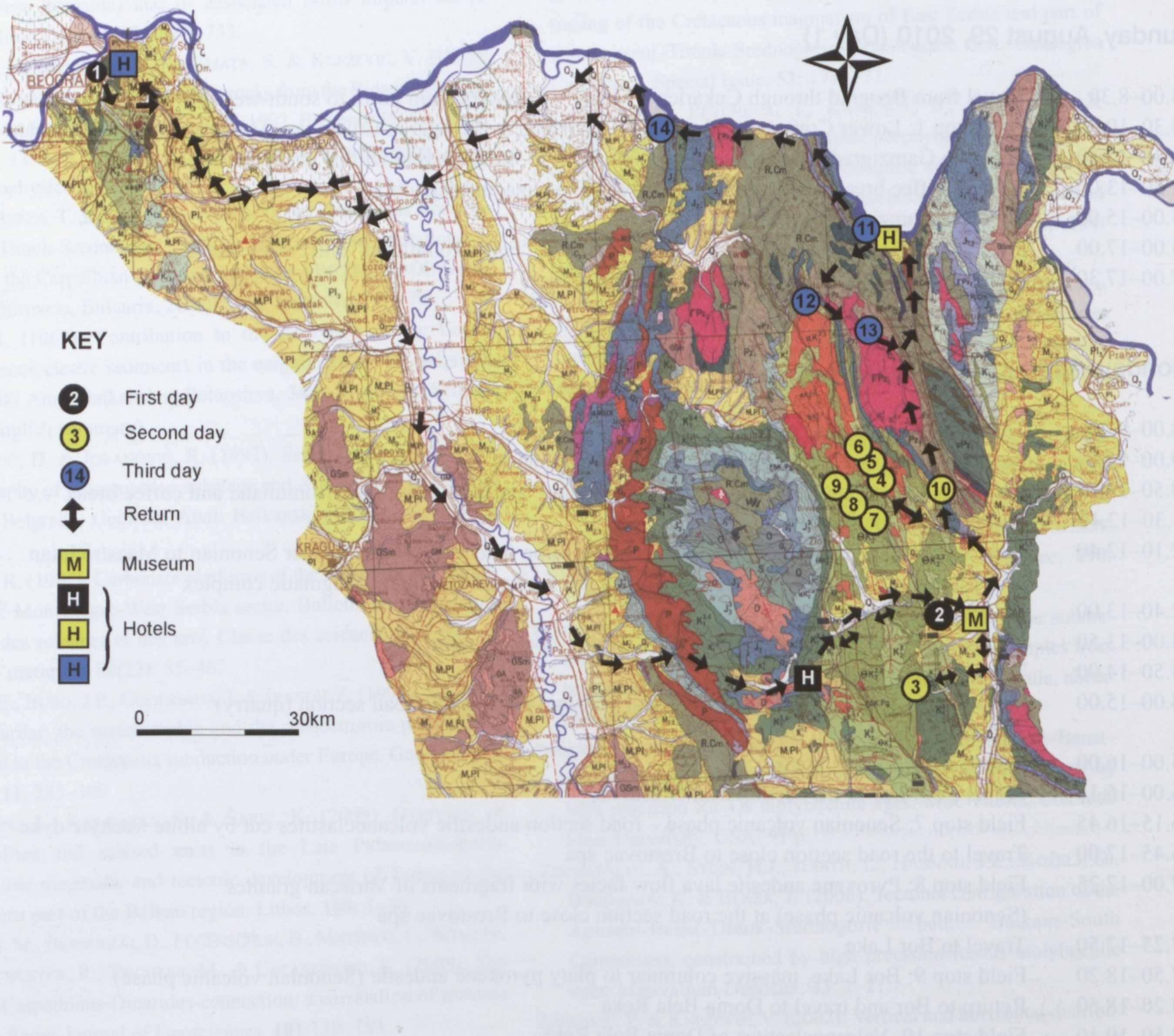
Monday, August 30, 2010 (Day 2)

8.00–9.30	Travel to Lenovac via Zaječar
9.00–9.50	Field stop 3: Lower Cretaceous glauconitic sandstone of "Lenovac clastics"
9.50–11.30	Return to Zaječar and short visit of local Museum – artefacts from Felix Romuliana and coffee break
11.30–12.10	Travel to Bor via Rgotina
12.10–12.40	Field stop 4: Copper ore deposit Bor – open pit mine (panorama view), Upper Senonian to Maastrichtian "Bor" conglomerate and pelite, and the youngest facies of the Timok Magmatic complex
12.40–13.00	Travel to Veliki Krivelj
13.00–13.50	Field stop 5: Copper ore deposit Veliki Krivelj – open pit mine
13.50–14.00	Travel to Mali Krivelj
14.00–15.00	Field stop 6: Turonian andesite of the first volcanic phase along road section (quarry) and copper ore deposit Mali Krivelj
15.00–16.00	Return to Bor, lunch break
16.00–16.15	Travel from Bor to the section near Brestovac
16.15–16.45	Field stop 7: Senonian volcanic phase – road section andesitic volcanoclastites cut by albite trachyte dyke
16.45–17.00	Travel to the road section close to Brestovac spa
17.00–17.25	Field stop 8: Pyroxene andesite lava flow facies with fragments of Variscan granites (Senonian volcanic phase) at the road section close to Brestovac spa
17.25–17.50	Travel to Bor Lake
17.50–18.20	Field stop 9: Bor Lake, massive columnar to platy pyroxene andesite (Senonian volcanic phase)
18.20–18.50	Return to Bor and travel to Donja Bela Reka
18.50–19.10	Field stop 10. Volcanoclastites of Donja Bela Reka
19.10–20.00	Travel to Donji Milanovac and accommodation in the 3* Hotel "Lepenski vir"

Tuesday, August 31, 2010 (Day 3)

8.00–8.20	Travel to Lepenski vir
8.20–9.30	Field stop 11: Lepenski Vir, visit of Mesolithic archaeological site
9.30–10.30	Return to Donji Milanovac and travel to Majdanpek
10.30–12.30	Field stop 12: Majdanpek copper ore deposit and Rajko's cave
12.30–13.00	Return to Majdanpek, coffee break
13.00–13.30	Travel to Rudna Glava

13.30–14.00	Field stop 13: Magnetite ore deposit Rudna Glava
14.00–14.30	Travel to Donji Milanovac
14.30–15.30	Lunch break in Donji Milanovac
15.30–16.30	Travel along the Danube Gorge to Golubac
16.30–16.50	Field stop 14: Short visit of the medieval fortress Golubac
16.50–18.50	Travel to Beograd, accommodation (in 3* Hotel Union) or departure



Appendix 2 – Road log for IMA2010 RS2 Field trip

km 0	Budapest.
350	Budapest – Belgrade, travel to the south by train via Subotica and Novi Sad. The train passes through the great Pannonian Basin/Plain, composed of Quaternary sediments.
0–12	Field stop 1: Glauconitic sandstones. From Belgrade city center to the Čukarica – Makiš – Rakovica locality: through the city to the intersection with road E75, then west along the Sava River – road M22 for about 3 km (first outcrop), then southeast to Rakovica – along local road R204 (second outcrop) – 6 km further on. We pass hills of Lower Cretaceous (mostly sandstone and limestone) and Upper Miocene sediments.
12–20	Drive east along a local road ("ring-road") to highway E75. On the right we see the northern slope of Mt. Avala that signals the entry into the Main Vardar Zone made up of Upper Jurassic serpentinized peridotites and diabase – chert formations followed by Upper Cretaceous flysch sediments (sandstones, limestones) intruded by Tertiary calc-alkaline dykes (andesite–basalt, andesite, latite, quartz latite, dacite) and lamprophyre. It is here that Pb–Zn ore deposit occurs as a result of Tertiary magmatism.
20–27	Miocene (sandstone, claystone) and diluvial sediments, exit highway E75.
27–134	Turning on highway E75, we drive towards Paraćin. At the turn we enter the Serbo-Macedonian Massif, which is covered by Miocene–Pliocene sediments as far as until Batočina. Hills on both sides of the road are built from crystalline schists (mostly gneisses and micaschists) covered by Miocene–Pliocene sediments.
134	At Paraćin, turn off to regional road E761 (M5), travelling east via Boljevac to Gamzigrad. About 2 km after turning off we pass the gabbros of Paraćinska Glavica and Paleozoic low-grade metamorphics and then enter the Eastern Serbian Carpatho-Balkanides. The area from Davidovac to Boljevac is composed of Permian red sandstone, Devonian and Mesozoic sediments (limestones, sandstones, marls). Close to Boljevac we enter the Timok Magmatic complex (mostly andesite of the second volcanic phase and its volcanoclastites).
211	Field stop 2: Gamzigrad, archeological site "Felix Romuliana".
235	Return to Boljevac, Motel Rtanj – Balašević (accommodation).
280	Drive along E761 road to Zaječar, then turn southwest onto local road R248 to Lenovac – through Lower Cretaceous sediments (sandstone, limestone, marls).
320	Field stop 3: Village of Lenovac. (*"Lenovac clastics"*), Albian glauconitic sandstone along the section of road running from Lenovac to the Gornja river.
350	Return to Zaječar along the M25 and visit to local Museum.
378	Drive north along the E771 (M25) to Rgotina, then turn northwest to Bor on road R106b.
378	Field stop 4: Bor copper ore deposit.
385	Field stop 5: Veliki Krivelj ore deposit.
390	Field stop 6: Andesites and Mali Krivelj–Cerovo ore deposit.
406	Field stop 7: Road section Bor-Brestovac (R106b-R105). Ab-trachyte dyke and volcanoclastite.
410	Field stop 8: Brestovac Spa, pyroxene andesite lava flow facies with fragments of Variscan granites (Senonian volcanic phase) on the road section close to Brestovac Spa.
425	Field stop 9: Bor Lake, massive columnar to platy pyroxene andesite (Senonian volcanic phase).
444	Return to Bor–Brestovac road. Drive along road R106b.
472	At Zagrađe, turn north to the Donja Bela river.
482	Field stop 10. Volcanoclastites of the Donja Bela river.
507	Drive along road R106 to Miloševa Kula. After the Donja Bela river we pass through Paleozoic sediments and low grade metamorphics, intruded by Variscan Gornjane granitoid pluton.
535	From Miloševa Kula via Klokočevac to the intersection of R106–M25.1 we drive through the Poreč high-to-medium-grade crystalline complex (gneisses, mica schists, amphibolites, quartzites) and then along the Danube gorge (road M25.1) to Donji Milanovac.
544	Donji Milanovac, 3* Hotel Lepenski Vir (accommodation).
564	Field stop 11: Prehistoric settlement "Lepenski Vir", and return to Donji Milanovac.
587	Donji Milanovac–Majdanpek, road R104; the area is composed of the aforementioned crystalline rocks.
587	Field stop 12: Majdanpek porphyry copper deposit.
592	Visit to Rajko's Cave, and drive to Rudna Glava along the M24.
612	Field stop 13: Rudna Glava – magnetite ore deposit.
627	Miloševa Kula, then turn north on the R106 to the intersection with road M25.1.
648	To Donji Milanovac on road M25.1.
700	Field stop 14: Golubac, medieval fortress.
759	Along the M251 to Veliko Gradište and Požarevac to the intersection with highway E75.
819	Along highway E75 to Belgrade, overnight accommodation and departure.


ROMANIA
BULGARIA
KEY:
First day
Second day
Third day
Field stops
Hotels
Museum
0
30 km
BEOGRAD
Zemun
Pančevo
Smederevo
Kovin
Požarevac
Kostolac
V. Gradište
Golubac
Dobra
D. Milanovac
Majdanpek
Kučevo
Petrovac
Homoljske pl.
Žagubica
Beljanica
Bor
Zlot
Zaječar
Knjaževac
Negotin
Kladovo
Orşova
Severin
Mladenovac
S. Palanka
V. Plana
Svilajnac
Despotovac
Kragujevac
Jagodina
Ćuprija
Paraćin
Ćićevac
Ražanj
Soko Banja
Boljevac
Rgotina
Kučajske pl.
Malinik
Deli Jovan
Mlava
Resava
V. Morava
Dunav