

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

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

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

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

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

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Introduction

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

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

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

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

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

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

a. Superposition in the Timok volcanogenic complex;

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

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

d. Discordances, transgressions and the like.

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

Geology

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

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

The Underlying Krivelj Formation

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

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

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

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

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

Table 1. Formational model of the Bor copper deposits

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

← 270°

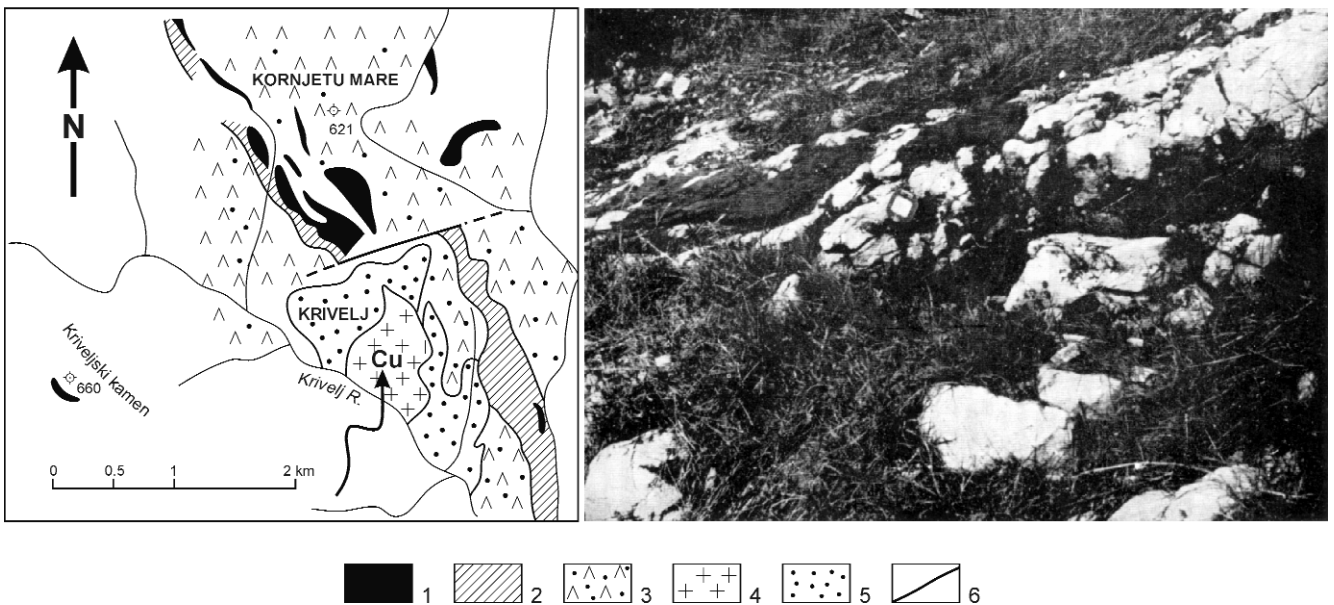


Fig. 1. Krivelj Formation and Veliki Krivelj copper deposit. Map left: **1**, Albian–Cenomanian (Vraconian); **2**, Cenomanian–Turonian; **3**, Volcanogenic Turonian; **4**, Veliki Krivelj deposit; **5**, Hydrothermally altered rocks (3, 4, 5 the Timok Formation); and **6**, Fault. Photo right: Dark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

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

The Timok Ore-Bearing Formation

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

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

1. Hornblende-biotite andesite association;
2. Diorite and quartz diorite; and

3. Hydrothermally altered rock zones, deposits or ore occurrences.

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

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

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

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

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

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

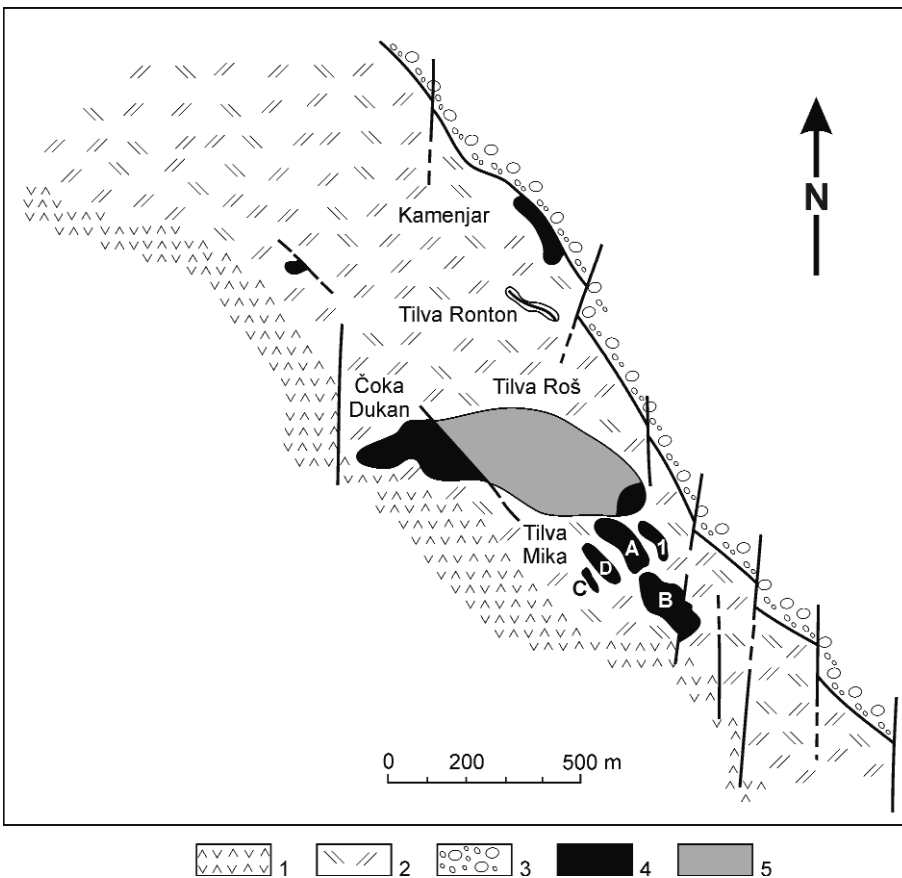


Fig. 2. Sketch geological map of Central Bor ore bodies. 1, Timok volcanogenic Formation (Timozite); 2, Hydrothermally altered Timozite; 3, Bor conglomerates; 4, Massive copper sulfide minerals (pyrite ore bodies); 5, Impregnated ore bodies (DROVENIK F. & DROVENIK M. 1956, modified).

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

sedimentary Novo Okno copper deposit of olistostrome derivation (ANTONIJEVIĆ 2011) formed at the depth of 270 metres.

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

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

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

Additional mapping and map revision must separate epiclastics and pyroclastics as

it has been done for the Novo Okno olistostrome copper deposit (ANTONIJEVIĆ 2010).

The Superlain Formation

Pelite, Tuff and Bor Conglomerates

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

Pelite associated with tuff at Bor is generally referred to as the alternating volcanogenic-sedimentary rock association of Campanian age. This group of rocks overlay discordantly the ore-bearing Timok Formation and Senonian epiclastics. The upper units

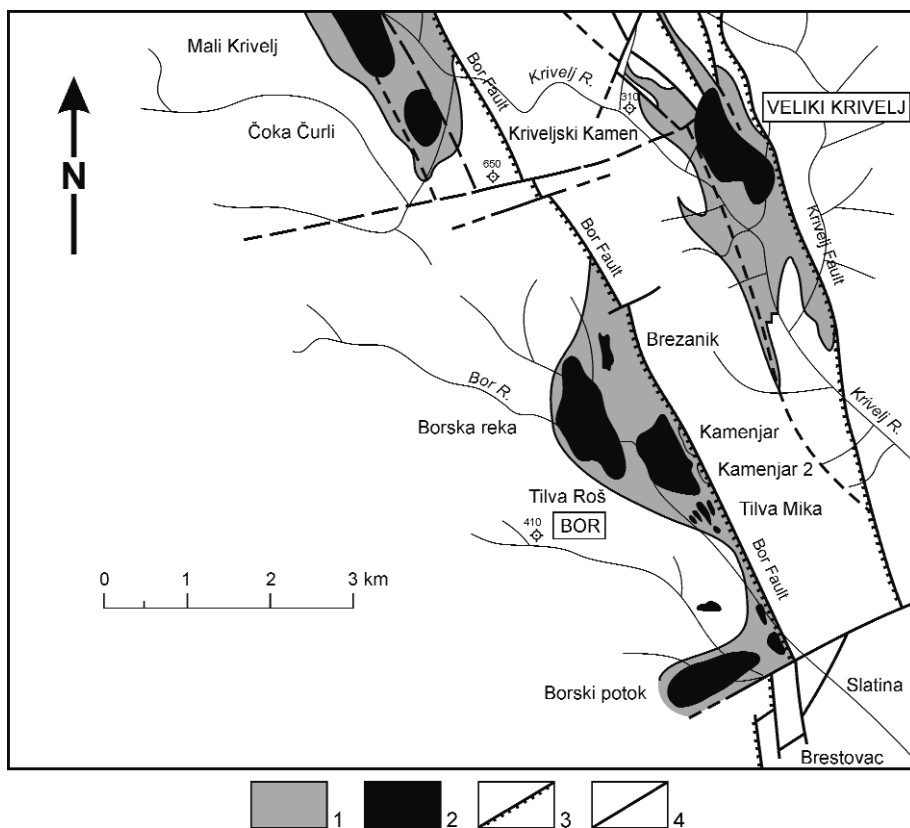


Fig. 3. Sketch tectonic map of Bor province: fault system and three hydrothermally altered zones with copper deposits Bor, Mali Krivelj and Veliki Krivelj. **1**, Hydrothermally altered zone; **2**, Ore bodies with different pyrite and copper sulphide proportions; **3**, Thrust; **4**, Fault (DROVENIK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

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

The Overlying (Metovnica) Formation

Senonian epiclastic unit (ĐORĐEVIĆ 1994) overlies the Timok Formation and copper deposit transgressively laid with conglomerate and breccia of hornblende-biotite andesite, reworked tuff and fragments of the underlying rocks locally including Cenomanian glauconite sandstone and ore-clasts of massive sulphide coppers. In the Jugoistok orebody, south of Bor, the

of the group form a succession of pelite and tuff alternating with fine pyroclastics dominantly of andesite-basalt phreatic tuff. ĐORĐEVIĆ *et al.* (1997, p. 87) treat Bor pelite and tuff as members of the andesite-basalt Dumbrava Formation, west of Bor.

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

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

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

Types of Ore Mineralisation

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

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

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

Massive sulphide copper Mineralisation

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

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

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

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

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

Hydrothermal-Vein Type Copper Mineralisation

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

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

Porphyry Copper Mineralisation

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

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

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

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

Ore-Clasts of Massive Sulphide Mineralisation

Ore mineralization of the olistostrome derivation in Bor is a type apart; it forms chaotic mechanical as-

semblages of ore and non-ore fragments, ore-clasts, in continental or olistoliths in marine environment. Ore-clasts are formed by explosive destruction of the primary massive sulphide copper deposits of Bor, their ejection onto the surface and gravity slide down the volcanic land-slopes (“slumping phenomenon”) into a sea basin (ANTONIJEVIĆ 2011).

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

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

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

Copper Deposit Severozapad

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

The deposit Brezanik is geologically well explored. Its formational environment, hydrothermal alterations and paragenetic ore sequences are described by MILIČIĆ & GRUJIĆIĆ (1979), JANKOVIĆ *et al.* (2002), DROVENIK (2005).

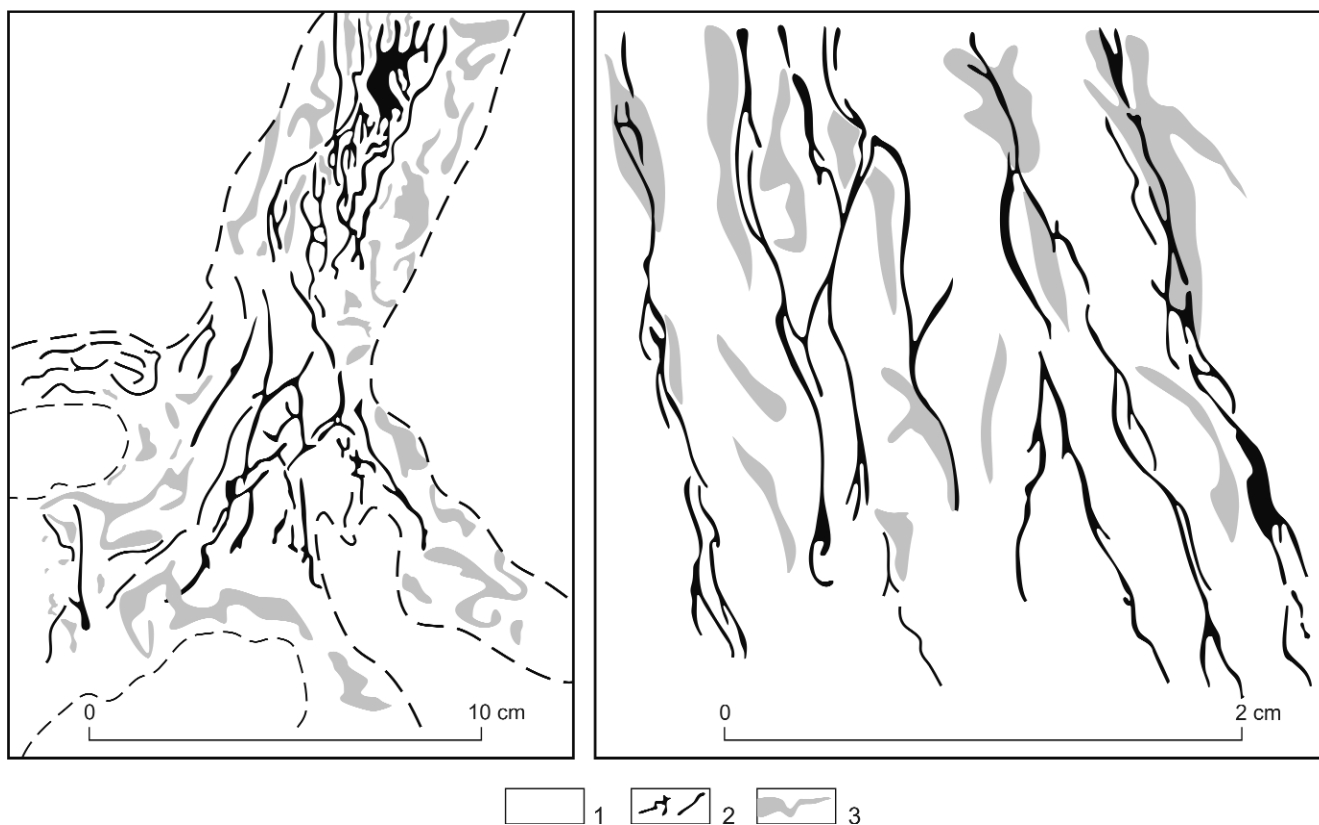


Fig. 4. Types of vein mineralization in the Brezanik deposit. 1, Hydrothermally altered andesite; 2, Sulphide mineralization (pyrite-chalcopyrite); 3, Adjacent impregnations (MILIČIĆ & GRUJIĆIĆ 1979).

Geological Overview of Deposits

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

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

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

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

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

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

Central Bor Deposits

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

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

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

Massive Sulphide Copper Deposits

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

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

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

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

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

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

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

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

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

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

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

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

Porphyry Copper Deposits

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

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

Borska reka is the largest deposit of the Bor copper district, a volume of about 557 million tons and average Cu 0.6%. At a copper metal recovery of 3.6 million tons, this deposit is expected to produce more

than the total amount of the copper ore extracted so far from all the mined ore bodies in Bor (DROVENIK 2005, p. 29)!

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

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

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

The deposit is currently being prepared for exploitation. More details on the paragenetic sequence, metallogenetic and geological evaluation of the Borska Reka porphyry deposit can be obtained by referring to the Bor Mine Works records and publications by MILI-

ČIĆ & GRUJIĆIĆ (1979), BRAJKOVIĆ & PAVLOVIĆ (1989), JANKOVIĆ (1990, 2002), DROVENIK (2005), etc.

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

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

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

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

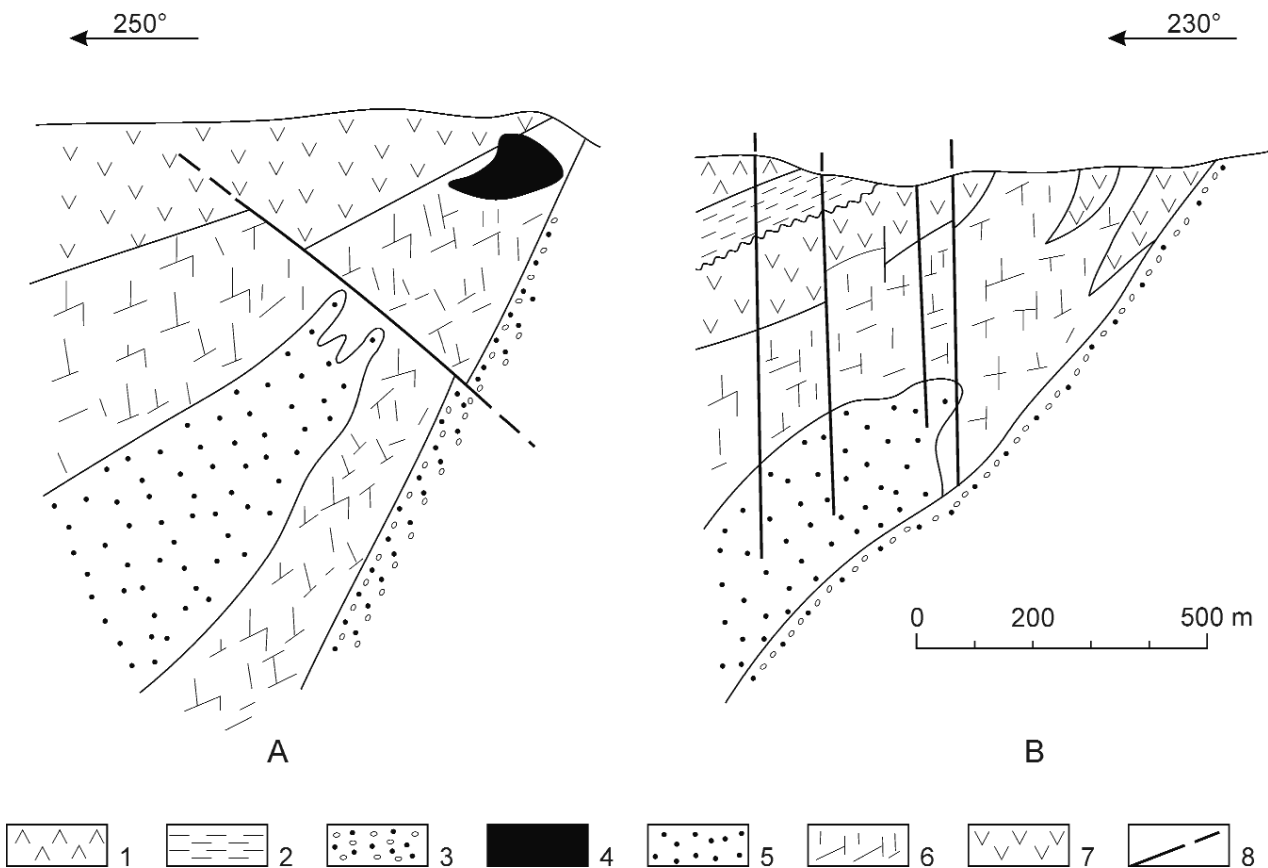


Fig. 5. Porphyry copper deposits Borski Potok (A) and Borska Reka (B). **1**, Pyroxene andesite; **2**, Bor pelite and tuff, (1–2) Dumbrava Formation; **3**, Bor Conglomerate; **4**, Massive sulphide copper (orebody X); **5**, Porphyry copper mineral; **6**, Hydrothermally altered minerals; **7**, Hornblende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

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

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

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

Jugoistok Copper Deposit

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

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

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

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

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

Orebody J is composed of a few minor lens-like massive sulphide concentrations, marginally stock-

work-impregnated, and a lower proportion of copper. The question: Was the 'deeper' part of this orebody affected by disseminated mineralization of the stockwork-impregnated type X? (JANKOVIĆ 1990, p. 316) is left open.

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

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

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

Morphogenetic characteristic of an olistostrome body is a chaotic mass of mechanically mixed ore-clasts, olistoliths, Classes A and B, in a sedimentary deposit of a basin. Ore-clasts of massive sulphide coppers, from 0.5 to 50 m³ in size, associated with amphibole andesite pyroclastics and fragments in matrix from the country rock are the main lithological member of the Novo Okno olistostrome or deposit (Fig. 7).

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

- (1) Turonian (pre-olistostrome) volcanic and
- (2) Senonian (olistostrome) submarine phases.

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

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

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

- Pyrite-covellite-chalcocite (Olistolith Class A from 0.5 to 50 m³);
- Chalcopyrite-bornite (Olistolith Class B from 0.5 to 10 m³); and
- Pyrite-chalcopyrite (ore-clasts and small rock fragments);

and rocks overlying the olistostrome sequences Classes A and B.

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

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

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

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

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

Discussion of the Deposit Formation and Origin

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

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

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

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

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

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

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

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

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

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

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

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

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

The Krivelj Formation, for example, is characterized by fossiliferous pelitomorphic rocks and the associated glauconitic sandstone and conglomerate at the base. It is transgressively underlain by the Veliki Krš carbonate monocline (Vlaole, Veliki Krivelj, Kvarnana) and the Krivelj Stone (Fig. 6). The upward

mentions stratigraphic position and age of the later uncovered Novo Okno deposit as evidence of the Upper Cretaceous Bor mineralization.

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

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

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

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

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

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

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

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

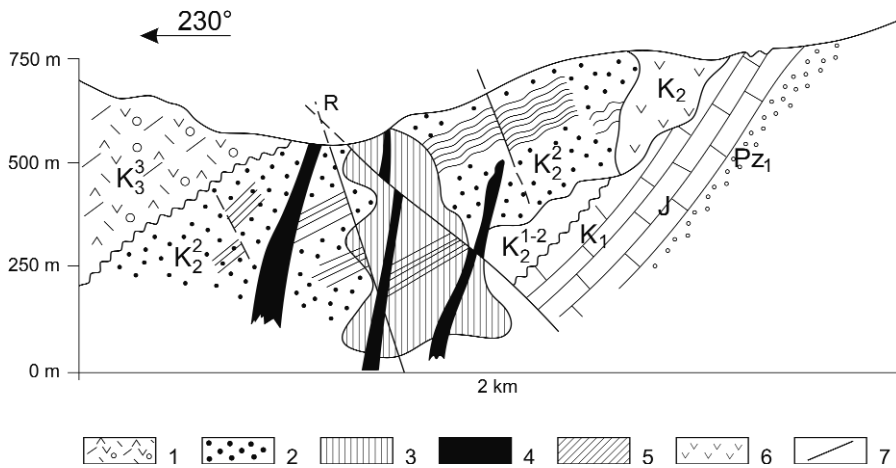


Fig. 6. Compiled section of the Veliki Krivelj porphyry copper ore bodies (ANTONIJEVIĆ 1953, 1973, OGNJANOVIĆ 1976, ALEKSIĆ 1979). 1, Epiclastics of the Metovnica Formation; 2, Hydrothermal alteration zone; 3, Copper deposit; 4, Diorite, Quartz diorite porphyry; 5, Skarn; 6, Hornblende andesite (K_2^{1-2} Cenomanian–Turonian, K_1 –J Jurassic–Cretaceous, P_z1 Paleosoic); 7, Fault.

extent and relationship of this deposit (Cenomanian–Lower Turonian) into and with the volcanogenic Turonian is a conjecture.

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

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

The described stratigraphic relationship has been located long before even in Bor, at the top of the Tilva Roš deposit (SPASOV *et al.* 1972), and explicitly confirmed in field (ĐORĐEVIĆ, 2005, p. 69). In a controversial argument with DROVENIK (1973) Đorđević

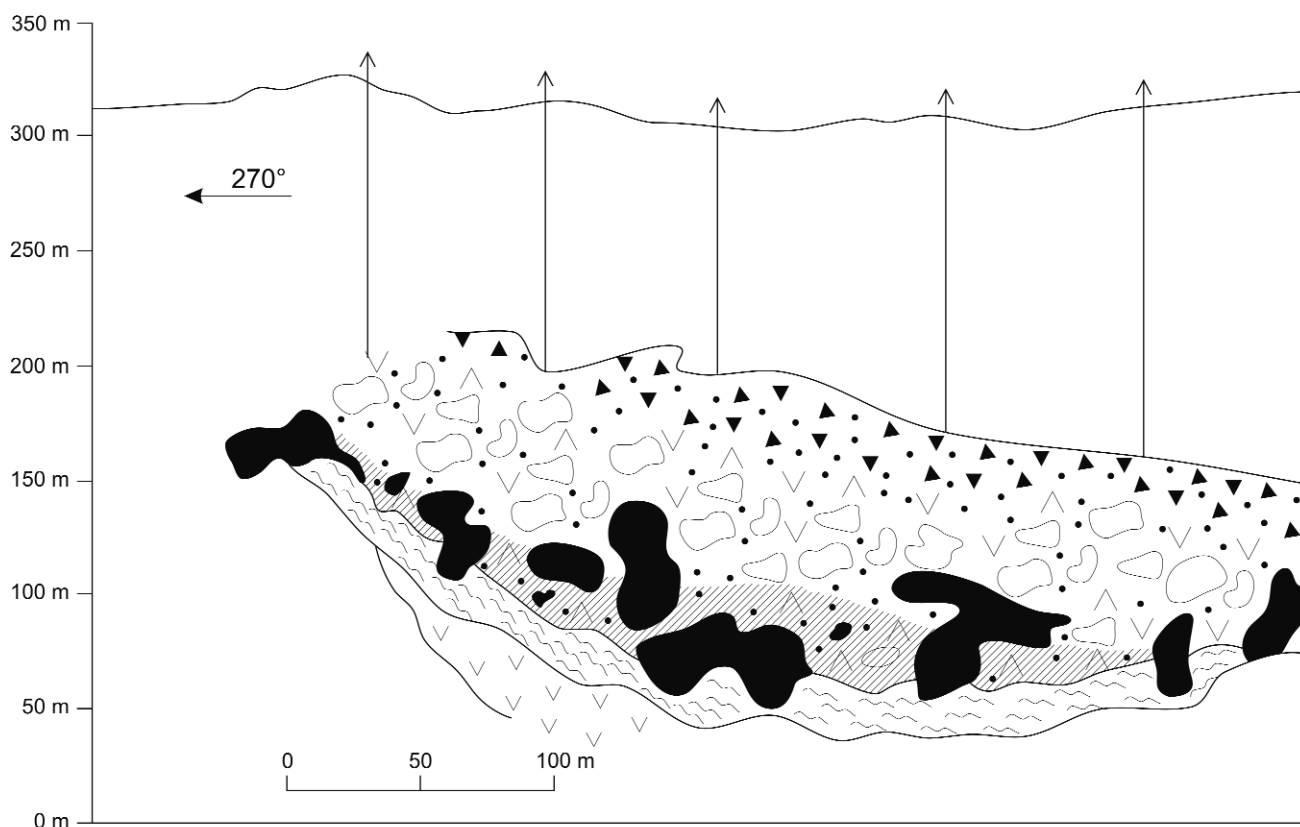


Fig. 7. Ore-clast deposit Novo Okno, K_2^{2-3} (schematic). 1, Olistoliths Class A; 2, Olistoliths Class B; 3, Matrix; 4, Subjacent pelite; 5, Hornblende-biotite andesite; 6, Superjacent epiclastics.

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

Summary

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The Jugoistok group includes the Novo Okno copper orebody of a different derivation, from an olistostrome.

Morphogenetic characteristics of the orebody and its position in Upper Cretaceous sedimentary deposits indicate a particular composition, a clastic, mechanical accumulation of ore-clasts, olistoliths, from 0.5 m³ to 50 m³ in size Classes A and B, slumped in sea basin (Upper Turonian–Lower Senonian).

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

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

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Резиме

Борска лежишта бакра: геологија, постанак и старост лежишта

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Групи лежишта Југоисток у Бору припада и “Ново Окно”, посебан тип лежишта бакра олистостромске генезе. Морфогенетске одлике лежишта и његов положај у седиментним горњокредним наслагама, указују на специфичну геолошку грађу и механичку хаотичну акумулацију рудокласта - олистолита (Slumping phenomenon), величине 0,5 до 50 m³, “A” и “B” класе, у морски басен (горњи турон–доњи сенон).

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

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