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THE BOR AND MAJDANPEK COPPER-GOLD DEPOSITS IN THE CONTEXT OF THE BOR METALLOGENIC ZONE SERBIA YUGOSLAVIA

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Abstract- The Bor metallogenic district contains the three major copper producers Majdanpek Bor and Veliki Krivelj, which have a combined production of more than 90,000 tonnes of copper and 4 tonnes of gold per annum. Total metal content for deposits discovered in the district exceeds 20 million tonnes of copper. In the Bor district, the deposits are all of Upper Cretaceous age, related to calc-alkaline igneous activity, but they are highly variable in morphology and association. At Bor itself, andesitic subvolcanics and extrusive rocks host deeper porphyry copper mineralisation which passes into a stockwork through to high sulphidation massive sulphides developed close to palaeosurface. The whole mineralised system is exposed over 1500m depth in mine workings and exploration drilling. Alteration is both laterally and vertically zoned.

The deposits contain significant gold. Veliki Krivelj is only 5 km from Bor but is a gold-poor system. Here porphyry copper mineralisation relates to high-level dyke swarms and skarns. Majdanpek is a world class porphyry deposit (~1 billion tonnes @ 0.6% Cu) but is hosted in fractured basement gneisses intruded by narrow andesitic dykes which may relate to larger buried igneous bodies. Minor skarns and replacement massive sulphide bodies are hosted in marginal Jurassic limestones. The main deposit forms a long, narrow linear zone (4 km by 300 m) exploited by open pit. Other porphyry prospects in the belt include the Crni Vrh region where several large low-grade porphyries have been located by drilling.

Introduction

The Bor metallogenic zone is a sector of the Carpatho-Balkan Metallogenic Belt (CBMB) which is itself a segment of the Tethyan Eurasian Metallogenic Belt (Figure 1). The CBMB contains a number of major porphyry and high sulphidation deposits in Hungary (Recsk-Lahoca), Romania (Moldova Noua, Rosia Poieni), Bulgaria (Assarel, Medet, Elatsite, Chelopech) and Serbia (Bor, Majdanpek, Veliki Krivelj) (Table 1). The Bor metallogenic zone which contains the major active mines of Bor, Majdanpek and Veliki Krivelj deposits is over 80 km long and up to 20 km wide (Figure 2) (Milicic & Grujicic 1979, Jankovic et al. 1980).

The Bor metallogenic zone has a metal resource estimated at over 20 million tonnes of contained copper and 1,000 tonnes of gold. In the Bor district there are at present three main porphyry copper mines in operation and smaller production from the secondary enrichment zone above the Cerova porphyry system. The combined annual metal production from these deposits is about 90 - 100,000 tons of copper and 4 - 5 tonnes of gold. In addition to the working mines, substantial low-grade reserves have been drilled in the western part of the Bor metallogenic belt.

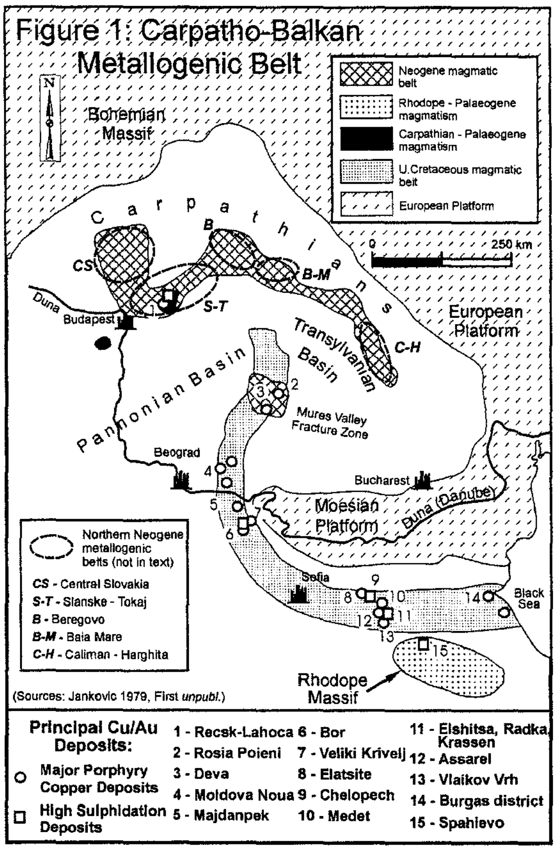


Figure 1: Carpatho-Balkan Metallogenic Belt

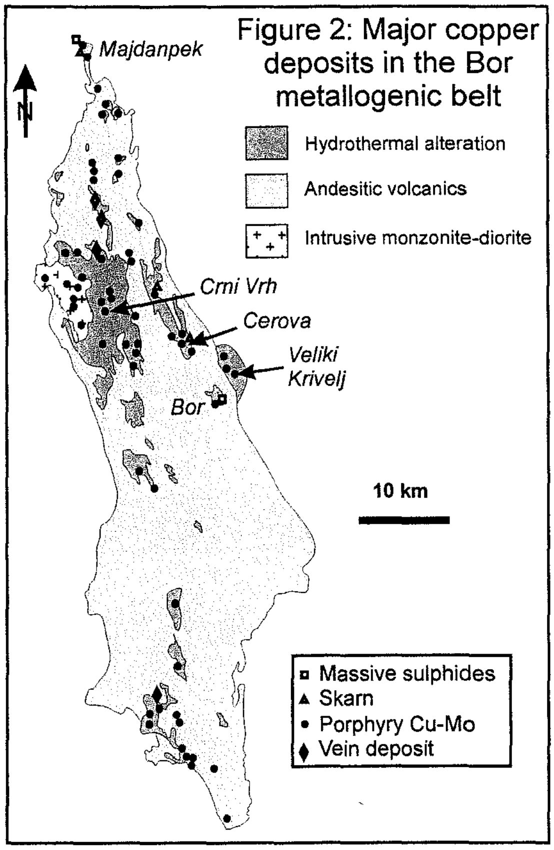


Figure 2: Major copper deposits in the Bor metallogenic belt

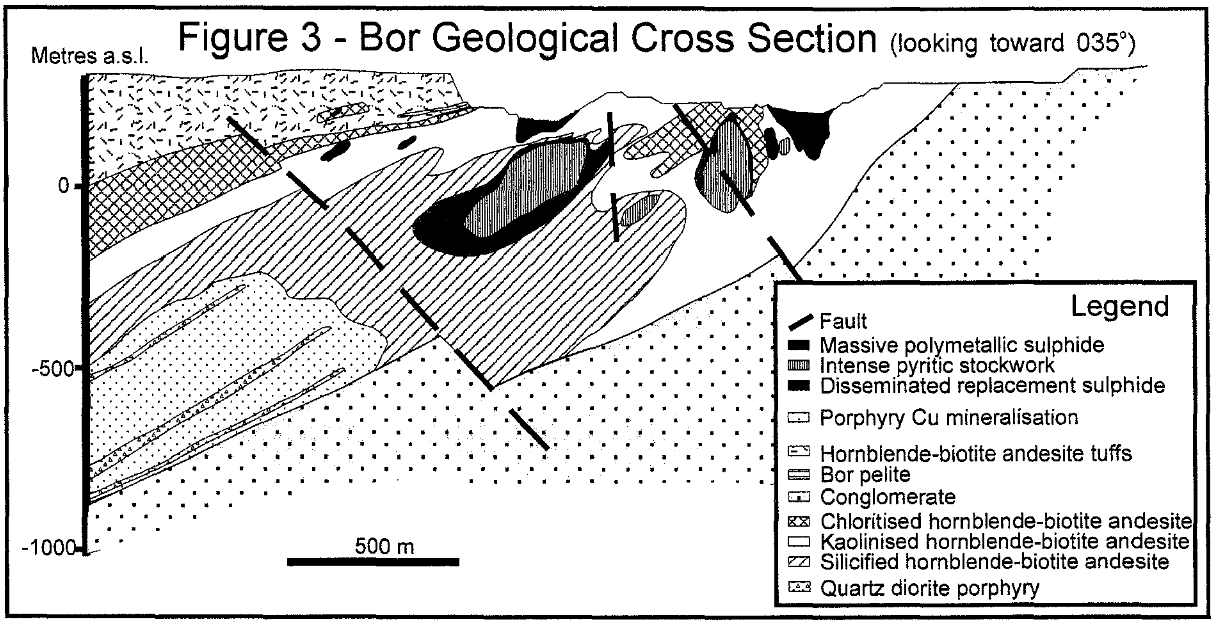
Table 1 - Porphyry Copper Deposits - Carpatho-Balkan Metallogenic Belt

(Tonnages from pers. comm. mine personnel)

Deposit / Country	Tonnage @ Grade	Supergene Zone	Age
Rosia Poieni / Romania	+1000 MT @ 0.4% Cu	None	Neogene
Deva / Romania	Not Known	None	Neogene
Recsk / Hungary (High Sulphidation)	700 MT @ 0.66% Cu (3 MT @ 0.8% Cu)	None	Upper Eocene
Moldova Noua / Romania	500 MT @ 0.35% Cu	None	Late Cretaceous
Majdanpek / Serbia	1000 MT @ 0.6% Cu	20 Metres	Late Cretaceous
Bor / Serbia (High Sulphidation)	450 MT @ 0.6% Cu (90 MT @ +1% Cu)	Minor	Late Cretaceous
Veliki Krivelj / Serbia	750 MT @ 0.44% Cu	30 Metres	Late Cretaceous
Elatsite / Bulgaria	260 MT @ 0.37% Cu	Minor	Late Cretaceous
Medet / Bulgaria	200 MT @ 0.34% Cu	Several Metres	Late Cretaceous
Assarel / Bulgaria	360 MT @ 0.44% Cu	70-100 Metres	Late Cretaceous
Vlaikov Vrh / Bulgaria	Not Known	Several Metres	Late Cretaceous

Bor

The Bor deposits are hosted within the first of the three-stage Upper Cretaceous volcano-sedimentary packages responsible for the large volcanic complex of the Timok (Bor) region (Figure 2). The complex is dominated by andesitic and more minor dacitic volcanics together with their pyroclastic equivalents (Jankovic 1990a). Most typical in the Bor area itself are porphyritic hornblende-biotite andesites. These volcanic rocks have initial Sr values of around 0.71, which suggests that these calc-alkaline volcanics are not explained by a simple island arc



model and that continental crustal sources contributed to the melts. Associated with the volcanics, but nowhere mineralised, are a series of Upper Cretaceous conglomerates and sandstones which underlie the volcanics and a sequence of pelitic sediments post-dating the igneous rocks. At Bor, subcropping massive high sulphidation ore was discovered at the turn of the 20th century. Several decades of mining and exploration has shown that massive sulphide bodies relate spatially to deeper porphyry mineralisation. Uniquely in a porphyry setting, mineralisation is continuous from the subcropping massive sulphide system down through a transitional stockwork to underlying porphyry copper mineralisation (Figure 3). The length of the altered and mineralised structural zone exceeds 2000 m with a width of around 1000m and mineralisation is drill tested to at least 1500m of vertical section.

High sulphidation mineralisation is characterised by a series of massive cigar-shaped and pipe-like bodies together with mineralised fracture zones and mineralised volcanic breccias (see Figure 4). The largest of the sulphide bodies is Tilva Rosh with other major bodies named Choka Dulkan and Tilva Mika. Tilva Rosh measured some 650 by 300 metres in its largest dimensions and extended vertically for some 800m. The body comprised both massive and disseminated sulphide mineralisation. The massive sulphide orebody of Choka Dulkan has a strike of some 150m, thickness of some 60-70m and a vertical extent of some 300m. The massive ore contains 3 to 6% Cu and comprises fine-grained pyrite up to 70% by volume) with main copper minerals being chalcocite, covellite and enargite. Spectacularly bladed hypogene covellite is common in the massive sulphide ore. Marcasite, chalcopyrite, tetrahedrite and sulvanite are often found. Traces of galena and sphalerite are present in the Bor massive sulphides (N.B. these minerals form a major component of the Choka Marin high-sulphidation body which lies north of Bor). Associated gangue minerals are significant silica, barite, ubiquitous anhydrite and native sulphur. Barite is more common in the upper parts of the system with sulphate minerals in the lower parts represented by anhydrite. Native sulphur accompanies high-grade enargite and covellite veining in one of the orebodies ("L"). Very late gypsum veins are common. There is a suggestion of sulphide mineralogy zonation in the massive ore to a pyrite-chalcopyrite-bornite (even pyrrhotite occasionally) association in the lower part which may indicate a change in sulphur activity. The massive ores grade laterally and at depth to disseminated mineralisation. A system of thin sub-parallel veins is developed beneath the large Tilva Rosh body although post-ore faulting has removed the lower parts of bodies such as Choka Dulkan. The disseminated zones also carry significant sulphide mineralisation (> 0.6% Cu) and form part of the ore reserves.

Alteration is distinctive around the high-sulphidation deposits with a distinct change at depth towards the porphyry mineralisation (Figure 4). In the upper parts of the high-sulphidation system, silicification is the common alteration with vuggy silica developed close to the interpreted palaeosurface. Advance argillic alteration around the bodies comprises pyrophyllite, diaspore, and alunite with locally andalusite, zunyite, sericite and some corundum. Alunite is most common in the upper parts of the alteration. Kaolinite is commonly associated with the alunite (Karamata et al. 1983).

At Bor there is development of an unusual clastic orebody, Novo Okno. The clasts are clearly polymictic with both pyrite-sulphosalt and bornite-chalcopyrite fragments present with both hydrothermally altered and fresh andesite. The matrix is tuffaceous and the unit is covered by a pelitic horizon. There is some evidence of grading in the fragments to support the clastic origin.

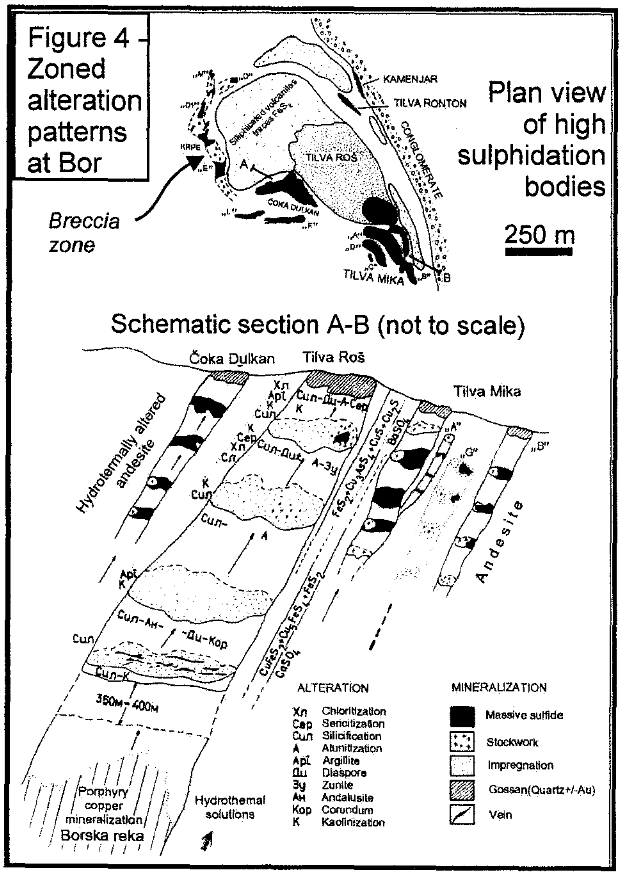


Figure 4 - Zoned alteration patterns at Bor

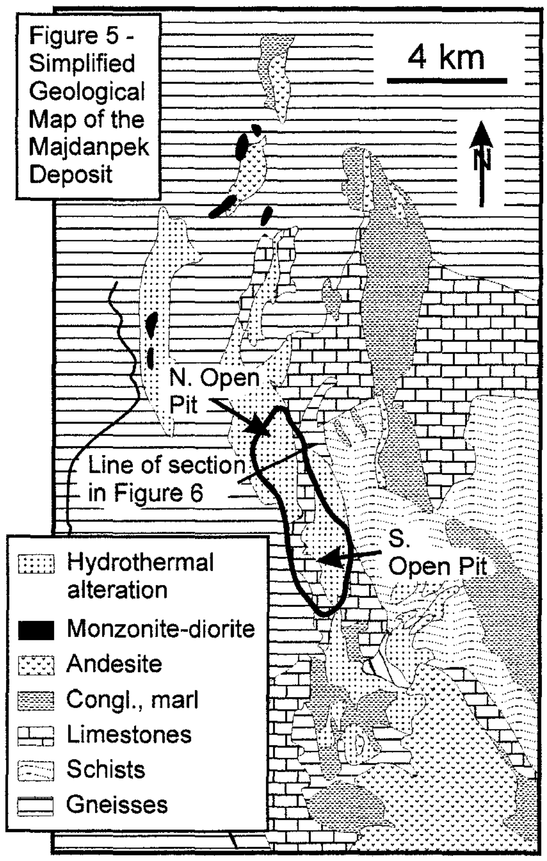


Figure 5 - Simplified Geological Map of the Majdanpek Deposit

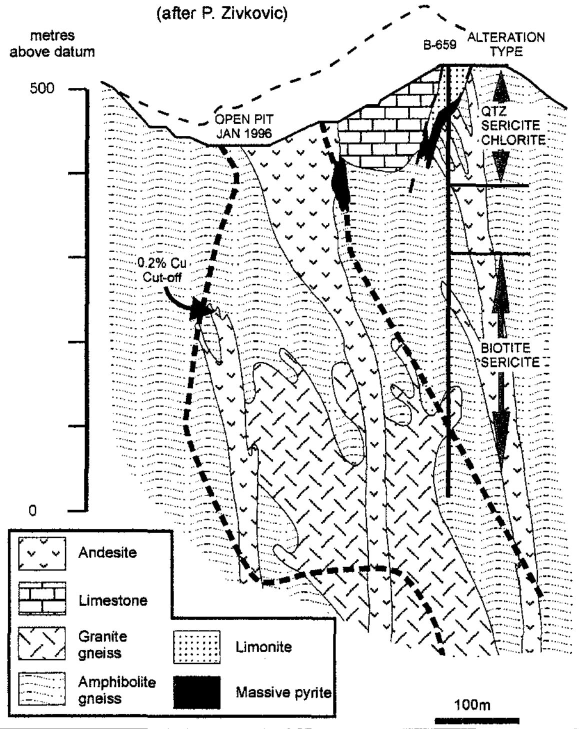
Majdanpek

Until 1962, mining at Majdanpek was confined to massive pyrite and limonite bodies developed in Jurassic limestones marginal to the Majdanpek system. Exploration that started in the late 1940s discovered the large mineralised porphyry system, which came into production in 1962. The deposit had annual output of 12 – 14 millions tonnes of ore from two open pits at its peak. Current reserves exceed 800 million tonnes of ore, containing something over 0.4 % Cu and 0.3 g/t gold (the initial mine operation in the 1960s started with ore grades of 0.82 % Cu and close to 0.8 g/t gold). Apart from copper, the deposit had significant reserves of massive pyrite ore in the limestones (about 15 million tonnes) that contains 3–15 g/t gold. In addition there are also a few million tons of undeveloped replacement lead – zinc ore also in the limestones (grade: 7 % Pb + Zn). The estimated total resource of the Majdanpek porphyry before mining was some 1 billion tonnes of ore @ 0.5% Cu, 0.3 g/t Au.

The host rocks are dominated by schists of the basement complex comprising Cambrian granitic gneiss, amphibolite and phyllite which is covered partly by Jurassic limestone (Figures 5 and 6). Upper Cretaceous igneous bodies intrude the basement as minor dikes and subvolcanic intrusive bodies, clearly located along a regional fracture system running roughly North-South. This host fracture is located between Cambrian crystalline schist to the east and Jurassic limestone to the west. Minor quartz diorite porphyry dykes are found in the lower part of the open pit, which may relate to more significant plutons at depth.

Porphyry copper mineralisation is dominant in the Majdanpek deposit. The porphyry copper deposit measures some 4 km long and only 300 m wide at its widest. The morphology of the orebody undoubtedly relates directly to the trend of the deep structural zone within which are intruded the igneous bodies. Stockwork type mineralisation prevails in the central part of the deposit, while disseminated type is developed mainly along the margin of deposit. Stockwork mineralisation occurs as elongated ore bodies, where the length to width ratio is between 8 and 10. The stockwork contains high grades of copper locally (1-2% Cu) but total tonnage of copper is less than in the disseminated mineralisation. The upper parts of the porphyry mineralisation contained high gold grades (~1.0 g/t gold). With progressive mining this has decreased downwards to an average of 0.25 g/t Au deeper than 300 m which remains constant for a vertical interval of over 1000 m. Figure 7 shows the distribution pattern of copper, clearly showing a certain impoverishment of copper in the central part of deposit. In general, there is increased copper content in zones of potassium silicate alteration development and lower copper in chlorite – epidote – sericite (propylitic) alteration (0.2 – 0.3% Cu). Mo content is overall rather low, mostly 30 – 80 ppm although the molybdenite is characterized by high Re contents (up to 2700 ppm). In addition to Cu, Mo, Ag, Au and Te, elevated levels of Pd, Pt, Sn and W are present in the porphyry which is a specific geochemical signature of the Majdanpek deposit.

Figure 6 - MAJDANPEK - NORTH OPEN PIT
GEOLOGICAL CROSS SECTION
PARALLEL TO 063°
(after P. Zivkovic)



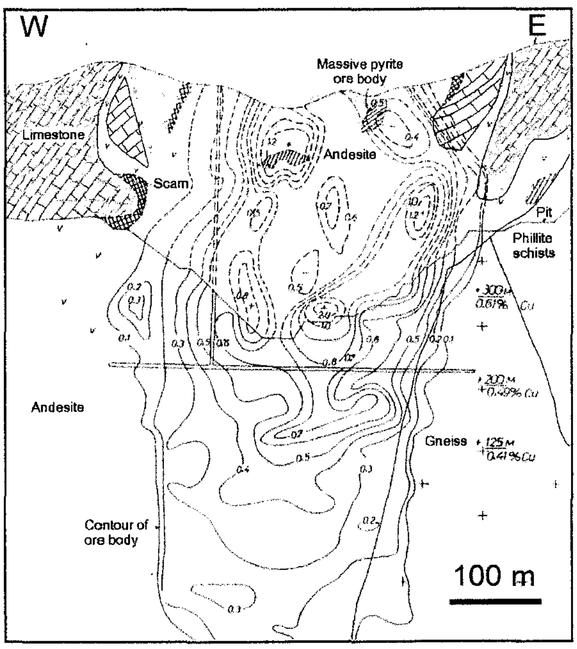


Figure 7 - Majdanpek section (south pit) showing contour plot of copper grades

Mineral association includes chalcopyrite, accompanied by pyrite, molybdenite and magnetite. Rarer phases include pyrrhotite, bornite and traces of galena and sphalerite, marcasite, tetrahedrite, arsenopyrite, enargite, stannite, colusite, as well as tellurides of Ag, selenides of Ag, native bismuth, and gold. Gold occurs as both native grains and / or with sulphides. Significantly, traces of Pd – telluride have been identified with variable contents of Ag (the composition: $Pd(Ag)Te_2$ up to $PdAgTe_2$ (Jankovic, 1990b). These tellurides from Majdanpek display lower contents of Pt and Bi compared to other occurrences and are characterized by low Sn contents (Pavicevic et al, 1981). Minor PGE are recovered from the Majdanpek copper concentrates.

Skarns are developed along the contact between andesite and quartz diorite with the Jurassic limestone. The skarn mineral association includes garnet, epidote, chlorite, calcite, magnetite, and hematite. The skarn rocks are mostly of small size – the width of each is up to a few metres. Skarns laterally often grade in to marble and limestone. Mineralisation in the skarns is dominated by magnetite, accompanied by minor hematite, pyrite, pyrrhotite, sporadically lead – zinc sulphides, and Pb/ Sb sulphosalts. The ore of some skarn ore bodies contains 42% Fe, 2,35% Cu, 6,76% S, 1,75 g/t Au and 4,2 g/t Ag; the lead and zinc contents are mostly less than 1% (Jankovic, 1990 b).

Massive pyrite occurs as elongated bodies, within Jurassic limestone and marble, close to the contact with andesite and quartz diorite porphyry dikes. The size of these bodies is particularly significant where N-S and NE-SW fractures intersect. The bodies form lenses and sheets (Figure 6) with the vertical extent of mineralisation exceeding 300 m in places. Such lenses contain some 10,000 to 700,000 tons on average but larger bodies have been recorded (Donath, 1952). These massive pyrite bodies contain 30 – 80% of pyrite and are situated above or in the same level at the margin of porphyry copper mineralisation, more exceptionally within the boundaries of the porphyry copper mineralisation itself. The massive pyrite ore contains up to 1.7% Cu, 35% S, 0.29% Pb, 0.7% Zn, 0.05% As, 3 ppm Mo, 2.8 g/t and 24 g/t Ag. The gold contents are variable, reaching locally even 20 g/t. In addition to pyrite, the mineralogy of the massive sulphide bodies includes chalcopyrite, minor pyrrhotite, 'melnikovite' – pyrite, bornite, tetrahedrite, magnetite, hematite, sphalerite, rare arsenopyrite and gold associated with quartz. The gangue minerals are quartz and minor ankerite.

Lead and zinc sulphides occur as both disseminations in porphyry copper mineralisation, in more discrete copper-rich bodies (0.2 – 0.6 m wide) in the southern part of deposit, and lastly as masssive sulphide bodies marginal to part of the porphyry copper mineralisation in the NE part of deposit. The latter bodies have recently been drilled off and have a reserve of about 4 million tons with 8% combined Pb-Zn with a Zn-Pb ratio of around 5: 1. Gold grades are in the order of 3-4 g/t. Mineralogy is dominated by sphalerite, galena, together with pyrite, chalcopyrite, arsenopyrite and marcasite. Collomorphic sulphide textures are very common. Pb and Sb sulphosalts are present with Ag – rich tetrahedrite, freibergite and native gold. Quartz, calcite and rare barite are the main gangue minerals.

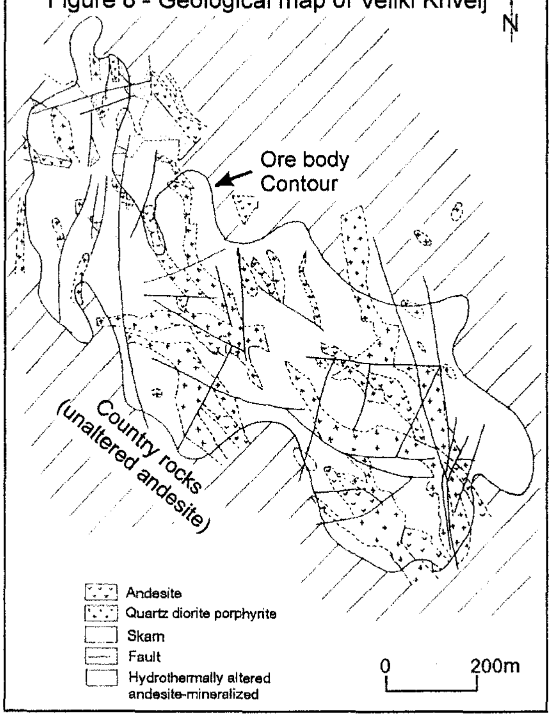
Alteration is dominated by potassium silicate in the central part of deposit, particularly around the dioritic porphyry bodies. This is largely represented by the development of secondary biotite with some potassium feldspar development. The K-silicate zone is surrounded by a zone of sericitisation, sporadically pyritisation and calcitisation, accompanied by intense silicification. Marginal to the mineralised zone a halo of chloritisation occurs. Argillic alteration is a minor feature associated with the andesite dikes, particularly in the vicinity of massive pyrite bodies. Hydrothermal alteration of wallrocks appears to have taken place in several stages. The patterns are thus rather complex, with superimposed alteration present in many cases.

There are no recent studies of the mineralisation at Majdanpek. In the past, the studies of the Majdanpek deposit were either in general terms (Spasov, 1965) or related to specific metallogenic aspects only. Preliminary fluid inclusion analysis of quartz indicates a range of formation temperatures for the deposit between 340^0 and 150^0 (Jankovic, 1972). This work also suggests only a minor temperature drop in the formation conditions over a vertical interval of 500 m indicating that cooling of the system was not a critical factor for the deposition of mineral associations containing quartz. Preliminary sulphur isotope analysis shows that the sulphur in sulphides is of magmatic origin. The $\delta^{34}S$ values range for chalcopyrite lie between + 2,96 $^{0}/_{00}$ and + 0,59 $^{0}/_{00}$, with a mean + 1.67 $^{0}/_{00}$, and pyrite from + 4.80 $^{0}/_{00}$ to + 1.98 $^{0}/_{00}$, with a mean + 1,5 $^{0}/_{00}$ (Drovenik et al., 1974/75).

Veliki Krivelj

The Veliki Krivelj deposit lies only 3 km to the NE of Bor. The deposit is 1.5 km long and up to 700 m wide with a vertical extent of more than 800 m (proved by diamond drilling to extend beyond this). The mineable resources of Veliki Krivelj deposit are about 2.5 million tonnes of copper at 0.44% Cu at a 0.15 % Cu cut-off grade (Figure 8). Molybdenum is low in the deposit (30-50 ppm, locally 200-300 ppm) but unlike Majdanpek, molybdenite at Veliki Krivelj runs less than 200 ppm Re. The deposit has been previously described by Aleksic (1969, 1979), Jankovic et al., 1980, Jankovic (1990a, 1990b). The porphyry copper mineralisation occurs in hydrothermally altered Upper Cretaceous hornblende andesite and its pyroclastic equivalents (breccia, tuffs and agglomerate) as well as the Upper Cretaceous volcano-sedimentary series (pelite, limestone, shale). This is superimposed on earlier skarns in addition to overprinting quartz diorite porphyry and andesite dykes swarms.

Figure 8 - Geological map of Veliki Krivelj



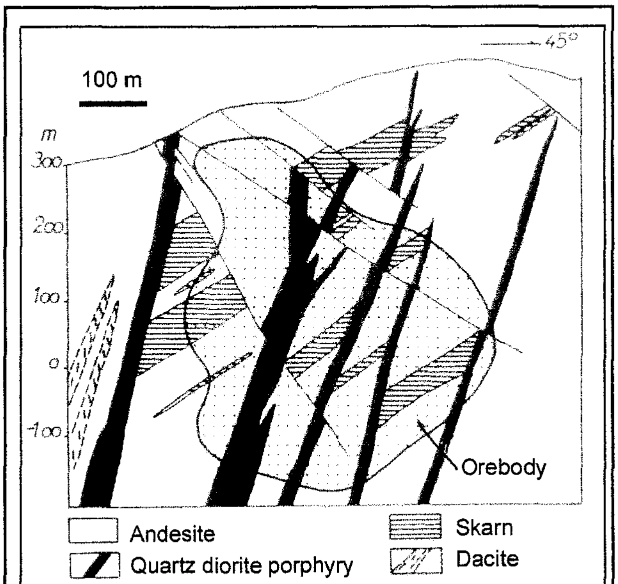


Figure 9 - Section through Veliki Krivelj deposit

Diorite and particularly quartz diorite porphyry are very significant features of Veliki Krivelj. These cut the subvolcanic and pyroclastic andesite bodies in the form of a number of dykes of Late Cretaceous to early Palaeogene age (Figure 9). Hydrothermal alteration is mainly developed in the pyroclastic facies of hornblende biotite andesite. Biotitisation, calcitisation, locally pyrophyllitisation are accompanied by silicification. Where silicification is weak, chloritisation, epidotisation and calcitisation is developed. Late intense zeolitisation and sulphatisation (gypsum and sporadically anhydrite) is apparent. Strong pyritisation associated with silicification occurred during hydrothermal alteration. This alteration forms zones peripheral to the porphyry copper mineralisation.

Porphyry copper mineralisation is dominated by chalcopyrite, pyrite, minor molybdenite, magnetite, pyrrhotite, hematite, traces of cubanite, enargite, bornite covellite, chalcocite and galena, sphalerite. The occurrence of pyrophyllite, alunite, kaolinisation and silicification zones in parts of the alteration system up to 50 metres thick indicates the presence of advanced argillite alteration, but this has not been studied systematically, neither has the potential for high sulphidation mineralisation been tested.

Skarn minerals formed in inter-stratified pelite and limestone. The mineral association includes garnet, calcite, epidote, quartz, quartz, biotite, pyrite, sporadically wollastonite; chalcopyrite occurs as disseminated mineralisation.

The $\delta^{34}S$ ratios ranges from – 0.09‰ to + 1.82 ‰ the mean value + 0.88 ‰ (Drovenik et al., 1974.), consistent with an igneous source.

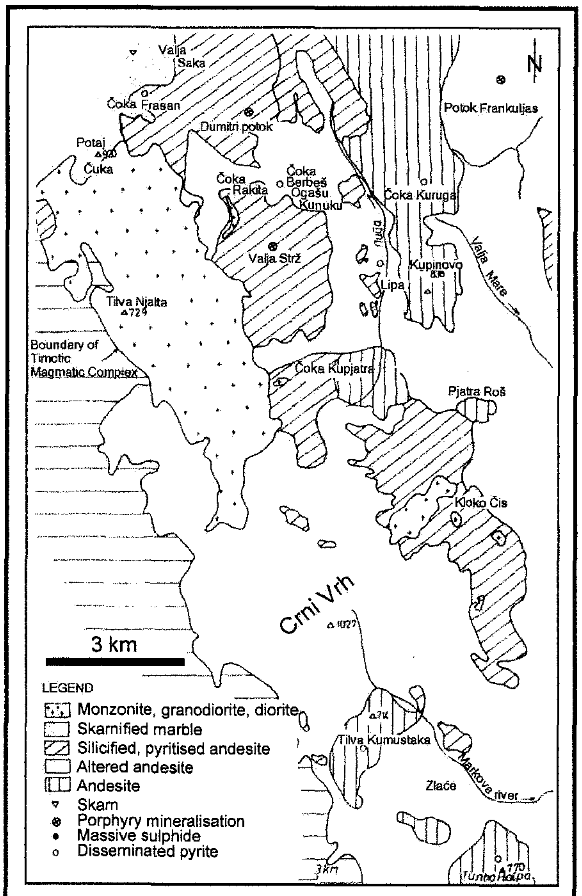


Figure 10 - Geological map of the Crni Vrh region

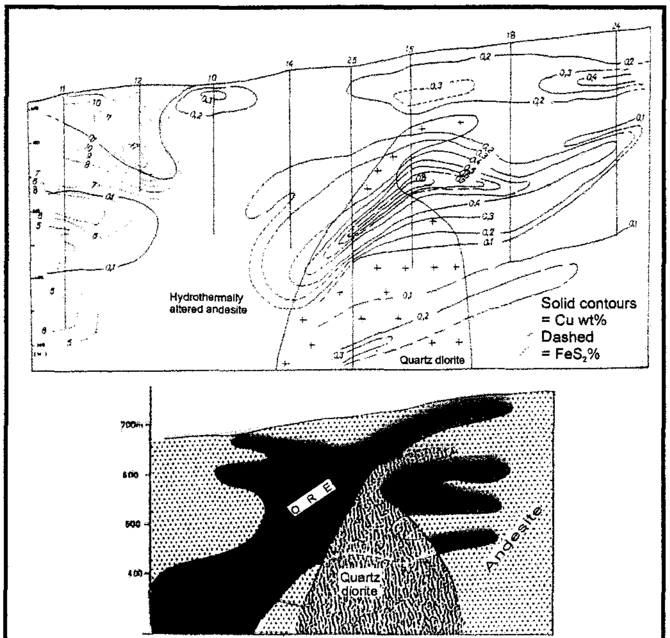


Figure 11 - Sketch geological section of the Valja Strz deposit showing copper grades contoured in weight %

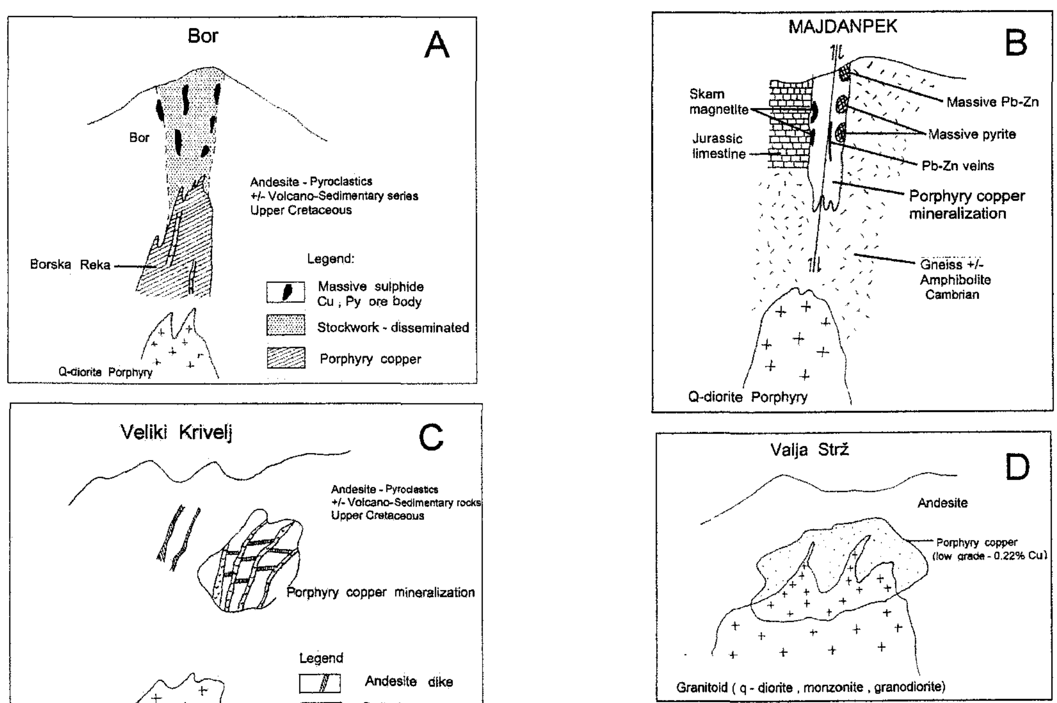
Crni Vrh region

The plutonic complexes of Crni Vrh were emplaced along a regional fracture zone at the western margin of the Bor metallogenic zone (Figure 10). The plutons were intruded into Turonian andesites and in part into Upper Cretaceous clay-rich sediments. The plutons are composite magmatic complexes represented by a potassic intrusive series. Initial strontium ratios ($^{87}Sr/^{86}Sr$) shows variation between 0.708 and 0.714, indicating a continental crust contaminated mantle source. In the deeper parts of the complex monzonite and granodiorite prevail, while syenite, quartz diorite and quartz diorite porphyry are developed along the margin (Terzic, 1966.)

Copper mineralisation is related to hydrothermally altered plutons and andesitic sub-volcanic and extrusive complexes. Extensive zones of alteration occur at the western margins and in the central parts of the plutonic complex in a zone which is over 8 km long. Alteration facies include propylitic alteration dominated by chlorite and epidote with silicification and pyritisation (Jovanovic, 1974). Several occurrences of copper mineralisation have been so far identified but only two large deposits of low, submarginal grades are known – Valja Strz (Figure 11) and Dumitru Potok (over 200 million tonnes of mineralisation each containing 0.22 % Cu). There are some indications of epithermal mineralisation developed at the margins of these mineralised bodies (Jovanovic 1974).

Summary

The Bor metallogenic zone contains substantial porphyry related copper-gold mineralisation including the world-class Majdanpek porphyry copper and Bor porphyry copper-high sulphidation deposits. The four deposits quite diverse deposits discussed in the text are all related to Upper Cretaceous calc-alkaline magmatism of similar petrochemistry. However, in each case the style of the deposits clearly reflect quite different local geological controls to the developed hydrothermal systems which influenced the type of mineralisation developed in each case. These diverse styles are summarised schematically in Figure 12.



A - Porphyry-high sulphidation continuum
B - Porphyry emplaced into structural zone
C - Porphyry development at level of dyke swarms
D - Porphyry development in apex of pluton

Figure 12 - Summary sketches of the four contrasting styles of orebodies seen in the Bor district

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