

GEOLOGICA MACEDONICA



Geologica Macedonica	Год.	15–16	стр.	1–70	Штип	2001–2002
Geologica Macedonica	Vol.		pp.		Štip	

SOME GENETIC ASPECTS OF THE BOR COPPER-GOLD DEPOSIT (SERBIA)

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Abstract: The Bor Cu-Au deposit consists of two principal types of mineralization hosted by the Upper Cretaceous andesites: epithermal high sulphidation Cu-Au (massive sulphide cupriferous pyrite mineralization of replacement type), and porphyry copper. First type of mineralization is characterized by high sulphur fugacity, which decreased during the evolution of hydrothermal ore-bearing solutions, accompanied by an increase of pH, reaching close to neutral. Porphyry copper type of mineralization is confined to subvolcanic level, in and above cupola zone of a calc-alkaline comagmatic stock. The principal constituents of ore were transported by chloride-bearing hydrothermal solutions, under low sulphur fugacity and low Eh. The subject of this paper are the some genetic aspects of the Bor Cu-Au deposit.

Key words: Bor; copper; gold; epithermal mineralization; porphyry copper; genetic model

1. INTRODUCTION

The Bor Cu-Au deposit was for a long period of time a main target of interest of numerous investigators. As a result we have nowadays detailed geological data about deposit (Janković, 1990a, 1990b; Janković et al., 1980; Karamata et al., 1983 etc.). On the contrary, the modeling of the genesis of the same type of mineralization are rare (Janković, 1990a; Janković, Jelenković, 1998; Jelenković, 1998; Koželj, 1999; Serafimovski et al., 2000).

The Bor deposit consists of several orebodies, grouped into NW (Brezanik), Central (Tilva Ros, Choka Dulkan a.a.), and SE group ("H", Novo Okno a.a.). The most significant orebodies are located in the Central group, related to structures of a volcano apparatus, the center of which is, most probably, restricted to Tilva Ros, surrounded by radially distributed orebodies.

2. GENETIC MODEL

A genetic model of the Bor Cu-Au deposit has to include processes and products of both epithermal high sulphidation and porphyry Cu systems formed along the same volcanic structure during the late Upper Cretaceous time.

Massive sulphide volcanogenic pyrite mineralization (high sulphidation epithermal mineralization) is developed in the upper part of mineralized system. The top of system is represented by the Au-bearing silicious cap, and at bottom the system grades into porphyry Cu mineralization. Mineralization occurs as massive sulphide, stockwork-disseminated, locally as veins, sporadically as small ore-clasts. The mineral association involves

pyrite as the most abundant sulphide, often of "gel" type, marcasite, covellite, enargite, chalcocite, less bornite, chalcopyrite, sporadically tetrahedrite, varieties of sulvanites (As-,W-Ge-,Ge-sulvanite), and gold. Traces of galena and sphalerite are found sporadically. Hematite dominates in the uppermost part of some orebodies. The principal hypogene gangue minerals are quartz, sporadically chalcidonic silica, minor barite, widespread anhydrite and locally native sulphur.

The spatial distribution of the mineral assemblage is characterized by vertical zoning. In the general case, in the upper parts of orebodies, abundant pyrite and covellite, chalcocite, and enargite

dominate, accompanied, at intervals, by hematite, while bornite and chalcopyrite, as well as, relatively minor pyrite prevail in the lower part of Central orebodies.

Pervasive silicification coupled with advanced argillitic alteration is the most common alteration type of enclosing andesite, particularly in the uppermost part of the Central orebodies. Advanced argillic assemblages involve pyrophyllite, diaspore, alunite, locally andalusite, zunyite, sericite, sporadically corundum. Alunite is particularly abundant in pyroclastic rocks in the uppermost parts of the Central orebodies. Kaolinization is also abundant and widespread (Karamata et al., 1981, 1983).

The general metallogenic features of this type of mineralization can be briefly summarized as follows:

Mineralization is a multistage process, which took place in a volcanogenic environment. Two main stages are recognized: (a) pre-ore stage, and (b) stage of ore mineralization.

The pre-ore stage involves interaction between volcanic gasses and vapours and enclosed andesitic volcanics, resulting in the development of widespread pyritization and silicification. These processes took place under high acid solutions, high sulphur fugacity and in presence of H_2S and SO_4^{2-} . This stage is barren with respect to copper mineralization, although insignificant contents of copper have usually been recorded (less than 0.2 % Cu).

The pre-ore stage was followed by fracturing of silicified and pyritized andesites, giving ways to inflow of hydrothermal ore-bearing solutions. Several phases are recognized within this ore-bearing stage, subsequently superimposing each other.

The ultimate source(s) of ore constituents – Cu, As, Se, Au, Ag, minor Pb, Zn, Ge, Sb, V, W, rarely Te, Mo, PGE, is (are), most probably, Upper Cretaceous calc-alkaline magma(s). The values $\delta^{34}S$ (from +4.83 through –20.45 ‰; max +0.52 through –5.15, mean –1.6 ‰) indicate a magmatogenic source for sulphur in sulphides (Drovenik et al., 1975).

The ore constituents were transported by high acid hydrothermal solutions under conditions of high sulphur fugacity, particularly in the first phases of mineralization.

Research of physico-chemical features, temperature and salinity of the hydrothermal fluids was based on detailed laboratory analysis (fluid-

gas inclusions – Koželj, 1999). According to the research in the areas of high sulphidation mineralizations in Bor metallogenic zone, there have been distinguished few types of hydrothermal fluids:

- Higher salinity magmatogene solutions (10–14 % eq.wt.) in the root parts of high sulphidation gold mineralization (veinlets-impregnation variety of mineralization).
- Low salinity magmatogene solutions (2–6 % eq.wt.) where transport of metals steeply descends with lowering of the temperature and pressure.
- Heated sulphate acid waters, formed as a result of mixing of condensated magmatogene vapour and gas with cold groundwater.

But the temperature of hydrothermal fluids there have been distinguished:

- Hydrothermal solutions of medium deepness (150–250 °C) with salinity from 2 up to 14 % eq.wt. NaCl / quartz – Tilva Ros: 190–230 °C, mean 215 °C; Kamenjar: 160–290 °C, mean 220 °C, and barite 170 °C.
- Low temperature hydrothermal solutions (130–220 °C) with salinity lower than 5 % eq. wt. NaCl connected to later stages of hydrothermal activities and formation of Au-barite mineralizations.

Precipitation of sulphides took place in shallow-depth of volcanic piles. Locally, deposition from colloidal solutions is widespread, particularly in the orebody "H". Due to a sharp drop in pressure in such a depositional environment, secondary boiling took place causing precipitation of massive sulphides (pyrite, including its colloidal types, covellite, chalcocite and enargite). Deposition of this mineral association is related to an environment characterized by significant oxygen fugacity and acid hydrothermal solutions, as well as by high copper activity. High arsenic fugacity is responsible for deposition of enargite.

The deposition of native sulphur is related to low acid environment, the pH of which can be near neutral and to low oxygen fugacity, but very high sulphur fugacity.

Deposition of a chalcopyrite-bornite-pyrite (or pyrrotite) association in the lower parts of orebodies took place from slightly acidic solutions and low Eh. Precipitation of chalcopyrite or bornite depends on the abundance of sulphur (HS^- and S^{2-}) and the complex copper ion in hydrothermal solutions. Apart from the sulphur fugacity, precipita-

tion of bornite depends on the ratio between Fe^{2+} and Cu-complex.

The sulphur fugacity was decreasing during the evolution of hydrothermal ore-bearing solutions, accompanied by an increase of pH, reaching close to neutral. The precipitation of sulphates (barite and anhydrite) is associated with such depositional environment. Deposition of barite took place usually under higher values of Eh, related to shallower depths than anhydrite.

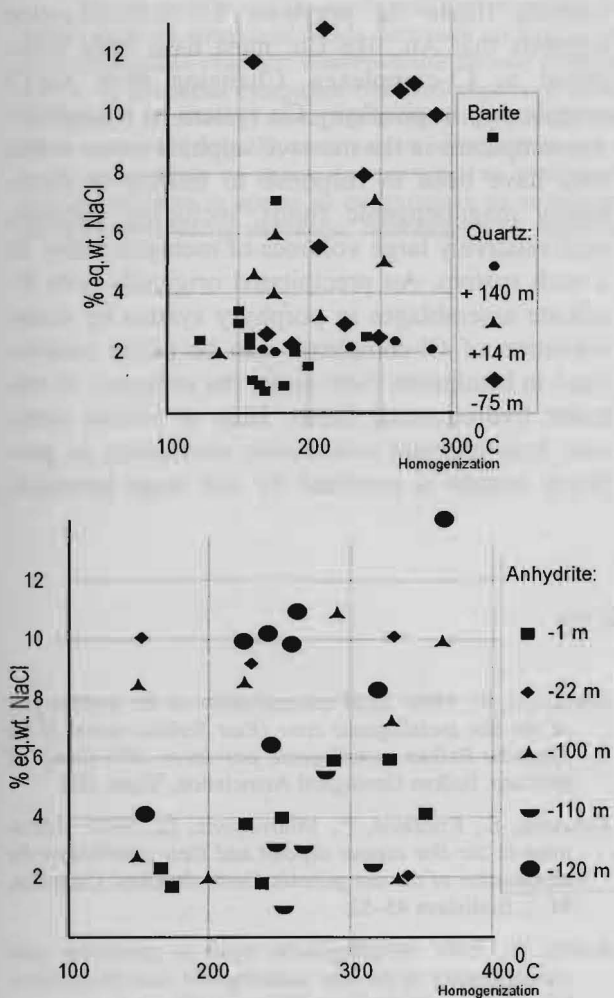


Fig. 1. Fluid-gas inclusion chart of quartz, barite and anhydrite of the Bor deposit (Koželj, 1999)

The spatial distribution of trace elements exhibits a certain zoning, controlled by the rate of their solubility in hydrothermal solutions under conditions existing during their evolution. In the uppermost part of orebodies and near the hanging-wall, some enrichment of Ag, Sb, As, Tl, Ge, Se and, to some extent, of Pb, Zn and Sn has been established. Due to intense hydrolytic leaching of andesite by strong acid solutions, the ore-bearing environment exhibits impoverishment in alkalis (0.2–0.5 % K_2O) and manganese with respect to hanging- and footwall.

The vertical extension of massive sulphide bodies is short—maximum 300 m, but the most common length does not exceed 100–150 m.

Such a short distance of precipitation of massive sulphide ore is usually found in shallow emplacements of ore-bearing solutions in volcanogenic environments.

The porphyry copper mineralization is confined to subvolcanic level, in and above cupola zone of a calc-alkaline comagmatic stock. Chalcopyrite and pyrite are the most abundant mineral constituents, accompanied by minor molybdenite, sporadically bornite, magnetite (up to 1 %), exceptionally enargite, as well as pyrrhotite (mainly transformed into pyrite).

Copper and gold are the main ore constituents. They were most probably transported by Cl-bearing hydrothermal solutions, under low $f\text{S}_2$ and low Eh. Alteration assemblage is represented by K-silicate alteration, characterized by prevailing K over Na, silicification, illitization, to some extent by chloritization, while in the uppermost part of mineralized system local occurrences of alunite are identified. The thin veinlets of anhydrite are widespread.

The process of generation of the Bor deposit lasted approximately 10–12 mill. years. Several intermineralization movements, including hydrothermal brecciation, followed up by inputs of hydrothermal ore bearing-solutions, have been identified in the stage of generation of massive sulphide mineralization.

3. CONCLUSION

Cu-Au mineralization as *cupriferous pyrite massive sulphides* is associated with an acid-sulphate alteration environment. Advanced argillic alteration and variable silicification are the primary wallrock alteration features of the acid-sulphate

environment. This geochemical environment is characterized by a high $f\text{S}_2$ resulting in the presence of native S, the local formation of large enargite orebodies; possibly indicating a significant increase of the total sulphur content of the system.

However, wallrock alteration and mineralogical studies suggest that the fS_2 was decreasing during the evolution of hydrothermal ore-bearing solutions.

Both Cu and Au are transported predominantly as Cl-complexes, it is also possible, at higher H_2S concentrations, that the cuprous bisulphide complexes may be the dominant Cu-bearing complex. The temperature range of sulphide deposition occurred between 150–320 °C. Late stage mineralization, such as barite (locally with native gold), was deposited between 130 and 220 °C (Koželj, 1999).

Based on the type of hydrothermal alteration minerals present, it can be concluded that pH of hydrothermal fluids is less than 3.0–3.5. During evolution of ore-bearing fluids, as a consequence of boiling, an increase of pH values occurred, bringing the overall pH to near neutral.

Precipitation of sulphides is related to shallow depths of volcanic complex, and is associated with significantly high fO_2 , as well as a high Cu activity, particularly in the central and upper parts of deposit. A high As fugacity is responsible for deposition of enargite, which dominates in the uppermost part of deposit. Deposition of chalcopyrite-bornite-pyrite association in the lower portion

of massive sulphide orebodies took place from slightly acidic hydrothermal fluids in a low Eh environment. Locally, deposition from colloidal solutions and Au concentration in colloform pyrite are widespread. Barite and gold association can be interpreted as near-surface assemblage produced under highly acid, oxidizing conditions.

Transport and deposition of both Cu and Au in *porphyry copper mineralization* occurred in a different geochemical environment as compared to massive sulphide mineralization. The oxidized, saline and higher temperature character of ore-forming fluids for porphyry Cu mineralization suggests that Au, like Cu, must have been introduced as Cl-complexes. Changing from Au-Cl complexing in porphyry Cu system to bisulphide-Au complexes in the massive sulphide zones at Bor may have been in response to mixing of dominantly magmatogenic fluids, including volatiles, with relatively large volumes of meteoric water. In a such system, Au precipitated originally with K-silicate assemblages in porphyry system by destabilization of Cl-complexes can be partly remobilized in bisulphide form under the influence of meteoric hydrothermal fluids. Heat to sustain meteoric hydrothermal convective circulation in porphyry system is provided by late stage intrusion.

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Резиме

НЕКОИ ГЕНЕТСКИ АСПЕКТИ НА НАОГАЛИШТЕТО НА БАКАР
И ЗЛАТО БОР (СРБИЈА)Раде Јеленковић¹, Дејан Кожељ², Тодор Серафимовски³¹Рударско-геолошки факултет, Бушина 7, 11000 Београд, С. Р. Југославија²Институт за бакар, Зелени булевар, 19000 Бор, С. Р. Југославија³Рударско-геолошки факултет, Гоце Делчев 89, 2000 Штип, Република Македонија**Клучни зборови:** Бор; бакар; злато; епитермална минерализација; порфирски бакар; генетски модел

Наоѓалиштето на Cu-Au Бор се состои од два основни вида на минерализација сместени во андезитит со горнокредна старост: епитермални високо сулфидни Cu-Au (масивни сулфидни бакарно-пиритски минерализации на замена) минерализации и порфирски минерализации на бакар. Првиот вид на минерализација е окарактеризиран со висок фугаситет на сулфурот, кој се намалува за време на еволуцијата на хидротермалните рудоносни раствори, проследени со зголему-

вање на рН, кој се приближува до неутрални вредности. Минерализацијата на бакар од порфирски тип е лоцирана во субвулкански нивоа и над куполната зона на калко-алкалниот комагматски штук. Главните состојки на рудата биле транспортирани со хлориден хидротермалне раствор, при низок фугаситет на сулфурот и низок Eh. Предмет на овој научен труд се некои од генетските аспекти на Cu-Au-наоѓалиштето Бор.