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GEOLOGY

Native Gold of the Porphyry Copper Mineralization in the Borov Dol Deposit (Republic of Macedonia)

A. V. Volkov, V. Stefanova, T. Serafimovski, and Corresponding Member of the RAS A. A. Sidorov

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Mineralogical study of gold in disseminated porphyry copper ores is complicated by its fine (often micrometer size) segregations and low contents (0.*n* g/t). This paper presents the results of investigation of gold in porphyry copper ores of the Borov Dol deposit (Republic of Macedonia) by an ingenious method.

Macedonia is located in the Serbian–Macedonian sector of the Eurasian metallogenic belt of the Tethys. The metallogeny of this region is related to the Cenozoic activation and formation of the volcanoplutonic rock complex in the course of scattered spreading [1].

The major porphyry copper deposits of Macedonia belong to the Leche–Chaldikidi metallogenic zone [2], which is sandwiched between the Serbian–Macedonian massif and the Vardar zone. Porphyry deposits of the Leche–Chaldikidi zone are genetically related to Tertiary minor subvolcanic stocks of the calc-alkaline composition, e.g., Bučim, Tular, Borov Dol, and Ilovica in Macedonia; Vakhi, Gerkaria, and Potokerasia in Greece; and others (Table 1) [3]. Reserves in these

Table 1. Characteristics of porphyry copper deposits and occurrences in Macedonia and Greece

Deposit	Kiseljak	Bučim	Borov Dol	Vakhi
Enclosing rocks	Andesites	Gneisses and andesites	Andesites	Rhyodacites
Age, Ma	12–23	25–28	24–28	30
Horizontal projection	0.24 km^2	0.25 km^2	0.15 km^2	150 × 700 m
Vertical dimension, m	300–500	250	300	500
Content	0.3% Cu, 0.3 g/t Au, 1.0 g/t Ag, 23 g/t Mo, 4–10% – pyrite	0.3% Cu, 0.5 g/t Au, 1.1 g/t Ag, 13 g/t Mo, 1–4% – pyrite, traces of: Pd, Se, Te	0.3% Cu, 0.25 g/t Au, 150 g/t Ag, 24 g/t Mo, 2% – pyrite	0.3% Cu, 0.15 g/t Au, 0.35 g/t Ag, 20 g/t Mo
Deposit	**Pondokerasia**	**Skories**	**Kadiitsa**	**Ilovica**
Enclosing rocks	Rhyodacites and granosyenites	Granodiorite porphyres	Quartz latites and schists	Quartz latites and biotite granites
Age, Ma	32	29.6	27.5	?
Horizontal projection	300 × 400 m	100 × 200 m	300 × 400 m	1.0 km^2
Vertical dimension, m	500	700	300	300
Content	0.3% Cu, 0.3 g/t Au, 0.35 g/t Ag, 20 g/t Mo	0.5% Cu, 0.7 g/t Au, 2.5 g/t Ag, traces of: Pd, Te, Pt	0.2% Cu, 0.2 g/t Au, 0.35 g/t Ag, 20 g/t Mo	0.5% Cu, 0.3–1.0 g/t Au, 5 g/t Ag, 50 g/t Mo

Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry, Russian Academy of Sciences, Staromonetnyi per. 35, Moscow, 119017 Russia
e-mail: tma2105@ya.ru
Faculty of Mining and Geology, Kiril and Metodie University of Skopje, Goce Delcev 89, 92000 Shtip, Republic of Macedonia

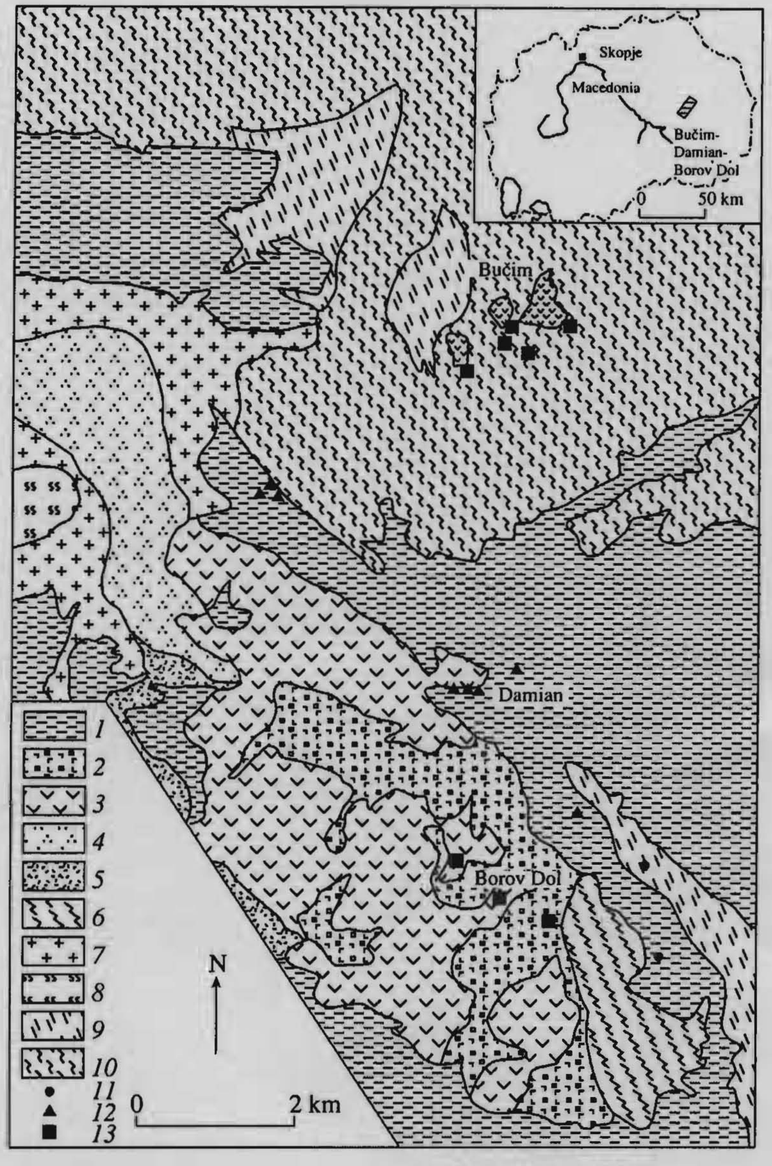

Fig. 1. Geological map of the Bučim–Damian–Borov Dol ore region [6]. (*1*) Paleogene, Neogene, and Quaternary sedimentary rocks; (*2*) Pyroclasts; (*3*) andesites and latites; (*4*) Quaternary flysch; (*5*) carbonatites; (*6*) carbonate schists; (*7*) granites; (*8*) serpentinites; (*9*) muscovite schists; (*10*) gneisses; (*11*) Pb–Zn vein mineralization; (*12*) Fe skarn mineralization; (*13*) porphyry copper mineralization.

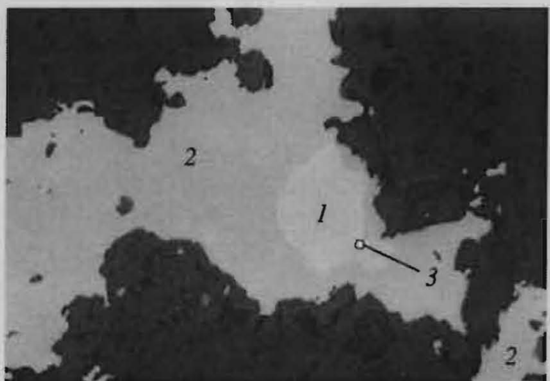

Fig. 2. (*2*) A large allotriomorphic chalcopyrite grain with (*1*) polydymite inclusion and (*3*) fine-dispersed gold. Polished section. Magn. 126×.

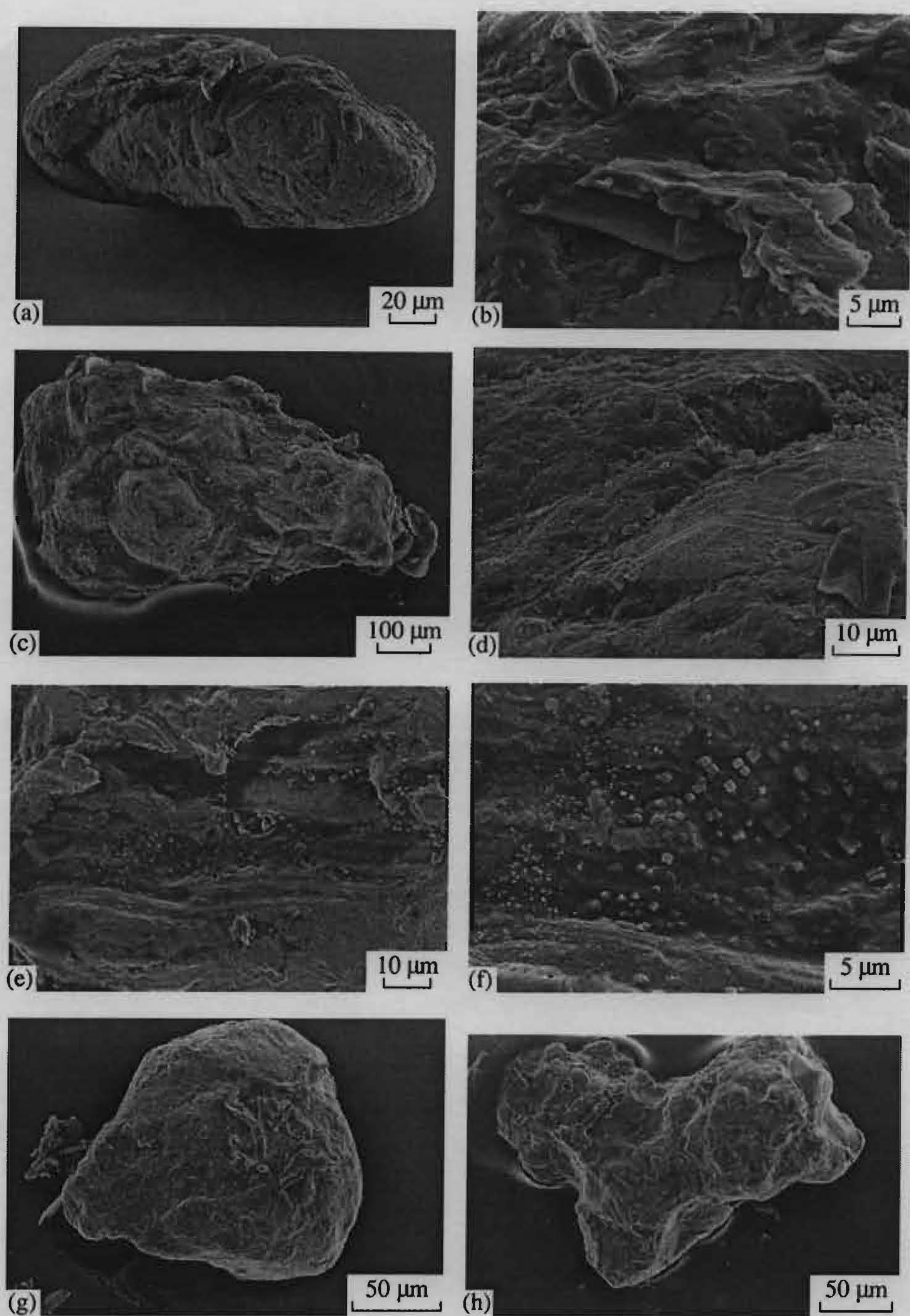

Fig. 3. Morphology of gold segregations and aggregates from the Borov Dol deposit: (a) elongate-columnar gold aggregate, (b) gold flakes (closeup of Fig. 3a), (c) isometric gold aggregate, (d) closeup of Fig. 3c, (e, f) crystalline gold (closeup of Fig. 3d), (g) globular gold aggregate, (h) irregular isometric aggregate.

deposits do not exceed 1 Mt Cu (Table 1), but they are characterized by favorable mining-geological and economic conditions for exploitation. However, only the Bučim deposit (Macedonia) is mined at present. The Borov Dol deposit, a reserve body for the Bučim Mine, is located in the southern area of the Bučim–Damian–Borov Dol ore region (approximately 150 km^2 in area) located 5 km south of the Bučim deposit (Fig. 1). The Borov Dol deposit is characterized by the development of NW-striking faults that govern the Neogene quartz–latite dikes, necks, and lavas. Porphyry copper mineralization is paragenetically associated with the volcano-

Table 2. Microprobe analyses of gold from the Borov Dol deposit

Sample no.	Sampling point	Element					Chemical formula
		Au	Ag	Cu	Fe	Total	
BD-5	Center	95.50	4.26	0.53	0.08	100.4	$Au_{0.90}Ag_{0.08}Cu_{0.02}$
	Periphery	94.31	4.4	0.42	0.08	99.21	$Au_{0.91}Ag_{0.08}Cu_{0.02}$
	The same	95.40	3.56	0.46	–	99.42	$Au_{0.92}Ag_{0.06}Cu_{0.02}$
	Average	**95.07**	**4.07**	**0.47**	**0.05**		
BD-5	Periphery	90.96	8.92	0.55	–	100.4	$Au_{0.84}Ag_{0.14}Cu_{0.02}$
	The same	87.31	12.66	0.39	–	100.3	$Au_{0.7}Ag_{0.21}Cu_{0.02}$
	The same	83.45	15.77	0.34	0.26	99.82	$Au_{0.72}Ag_{0.26}Cu_{0.02}$
	Average	**87.24**	**12.45**	**0.42**	**0.08**		
BD-9	Center	90.87	8.51	0.61	–	99.98	$Au_{0.84}Ag_{0.14}Cu_{0.02}$
	Periphery	86.02	12.60	0.60	–	99.22	$Au_{0.77}Ag_{0.21}Cu_{0.02}$
	Average	**88.44**	**10.55**	**0.65**	**0**		
BD-10, grain 1	Center	94.85	4.57	0.36	0.13	99.91	$Au_{0.91}Ag_{0.08}Cu_{0.01}$
	Periphery	93.09	5.95	0.38	–	99.40	$Au_{0.90}Ag_{0.09}Cu_{0.01}$
	The same	91.27	7.98	0.61	0.15	99.35	$Au_{0.85}Ag_{0.13}Cu_{0.02}$
	The same	95.10	3.77	0.24	–	99.10	$Au_{0.92}Ag_{0.07}Cu_{0.01}$
	The same	95.69	3.57	0.39	–	99.65	$Au_{0.93}Ag_{0.06}Cu_{0.01}$
	The same	93.70	5.71	0.35	–	99.75	$Au_{0.90}Ag_{0.09}Cu_{0.01}$
	The same	96.04	2.94	0.59	–	99.57	$Au_{0.93}Ag_{0.05}Cu_{0.02}$
	The same	93.24	5.67	0.47	0.15	99.52	$Au_{0.90}Ag_{0.09}Cu_{0.01}$
	The same	92.30	6.81	0.54	–	99.65	$Au_{0.87}Ag_{0.11}Cu_{0.02}$
	Average	**93.92**	**5.21**	**0.43**	**0.04**		
BD-10, grain 2	Center	93.54	5.62	0.39	0.09	99.63	$Au_{0.89}Ag_{0.09}Cu_{0.02}$
	Periphery	89.31	9.82	0.59	–	99.72	$Au_{0.82}Ag_{0.16}Cu_{0.02}$
	The same	88.39	10.05	1.56	–	99.58	$Au_{0.79}Ag_{0.16}Cu_{0.05}$
	The same	87.71	11.65	0.31	0.09	99.75	$Au_{0.79}Ag_{0.2}Cu_{0.01}$
	The same	90.71	8.81	0.47	–	99.98	$Au_{0.85}Ag_{0.14}Cu_{0.01}$
	The same	93.13	6.05	0.50	–	99.67	$Au_{0.87}Ag_{0.12}Cu_{0.01}$
	The same	90.65	8.97	0.29	0.08	99.98	$Au_{0.85}Ag_{0.14}Cu_{0.01}$
	The same	92.26	6.54	0.53	–	99.32	$Au_{0.87}Ag_{0.11}Cu_{0.02}$
	Average	**90.71**	**8.43**	**0.58**	**0.03**		
BD-10, grain 3	Center	93.37	5.94	0.34	0.18	99.82	$Au_{0.88}Ag_{0.11}Cu_{0.01}$
	Periphery	89.39	9.61	0.61	0.21	99.81	$Au_{0.81}Ag_{0.16}Cu_{0.02}Fe_{0.01}$
	The same	92.27	7.04	0.65	0.14	100.1	$Au_{0.85}Ag_{0.13}Cu_{0.02}$
	The same	92.40	6.98	0.42	0.15	99.95	$Au_{0.86}Ag_{0.12}Cu_{0.02}$
	Average	**91.85**	**7.39**	**0.50**	**0.17**		

plutonic complex (Fig. 1). The deposit has been known since 1930 when the first boreholes drilled in this region recovered copper mineralization (Cu 0.2–0.7%). Systematic exploration was performed in the years 1973–1977 after detailed regional geochemical, geophysical, and geological works. Boreholes were drilled in a 200 × 200 m grid (up to 100 × 100 m in the central part). The reserves were estimated at more than 40 Mt with a grade of 0.3% Cu and 0.28 g/t Au [4].

The ring-shaped porphyry copper mineralization surrounds an andesite pluton among older volcanic rocks that underwent intense hydrothermal alteration. Thus, precisely the older volcanic rocks serve as an ore-enclosing medium for copper mineralization. Potassic metasomatism, biotitization, sericitization, and silicification are the typical hydrothermal alterations.

The morphology of the orebody along the dip is similar to that of the andesite stock. The mineralization is represented by dissemination (70%) and stockwork (30%) types. Primary ores are mainly composed of chalcopyrite. The subordinate minerals are represented by pyrite, molybdenite, magnetite, zolotite, and bornite. Enargite, fanitite, galena, and tennantite are rare.

Gold occurs in the Borov Dol deposit as two varieties (native mineral and telluride constituent) [2]. The native gold is associated with pyrites of all generations. This variety is observed as microinclusions in chalcopyrite 1 and polydymite (Fig. 2). In addition, the native gold occurs in sphalerite and the rock matrix. Based on microprobe data, the fineness of gold inclusions (up to 10 μm across) is as high as 837‰.

We investigated gold under field and laboratory conditions. Samples of exogenic mineralization were panned according to the standard technology along rivers draining the Borov Dol deposit. Pyrite, magnetite, chalcopyrite, ilmenite, amphiboles, pyroxenes, zircon, and garnet were the most common minerals in the panned samples. Gold was found only in five samples (35 nuggets). The gold grain size varied from 150 μm to 1 mm. The morphology and composition of gold grains were investigated with a JMS-5510-JEOL scanning microscope (Department of Chemistry, Sofia University, Bulgaria). The chemical composition of gold was determined by X-ray structural analysis with a TRACTOR NORTHERN TN-2000 microprobe and JEOL LMS 35 CF electron microscope. Measurements were carried out based on the JEOL standards at a voltage of 25 kV for samples 2×10^{-9} Å in size. Microprobe analyses were also carried out with a Philips SEM 505 electronic microscope (EDAX model 91000/60, voltage 20 kV) in the Central Laboratory of Photoprocesses, Bulgaria. Gold grains have elongate, isometric, and oval shapes (Fig. 3), suggesting their input from a primary bedrock source [5]. The gold grains display a zonal porous internal structure (Fig. 3).

Microprobe analyses of the chemical composition of gold (Table 2) revealed that they represent native gold with a high fineness (834–981).

Silver occurs as an admixture (0.82–15.85 wt %). Some grains demonstrate internal zonality: the central part is depleted in Ag relative to the periphery. In general, gold aggregates have a homogeneous composition. However, grain BD-9 is characterized by a very high fineness (977–984) and low Ag content (0.82–1.09%).

The Ag content varies from 7.62 to 48.91% in some samples. The gold also contains Fe (0.02–0.05%). The Cu admixture is relatively uniform (0.4–0.6%). The average Au content in gold grains from the Borov Dol deposit varies from 88.44 to 98.15% (average 91.20%). The average content of admixtures in gold is as follows (%): Ag 7.87, Fe 0.036, and Cu 0.49 (Fig. 4). The mineralogical–geochemical analyses revealed that gold from the porphyry copper deposits in the Bučim–Damian–Borov Dol ore region (Macedonia) are characterized by typomorphic features. The gold contains Fe and Cu. Its chemical composition does not depend on the morphology of grains. Their morphology suggests the proximity to a bedrock source (Table 2).

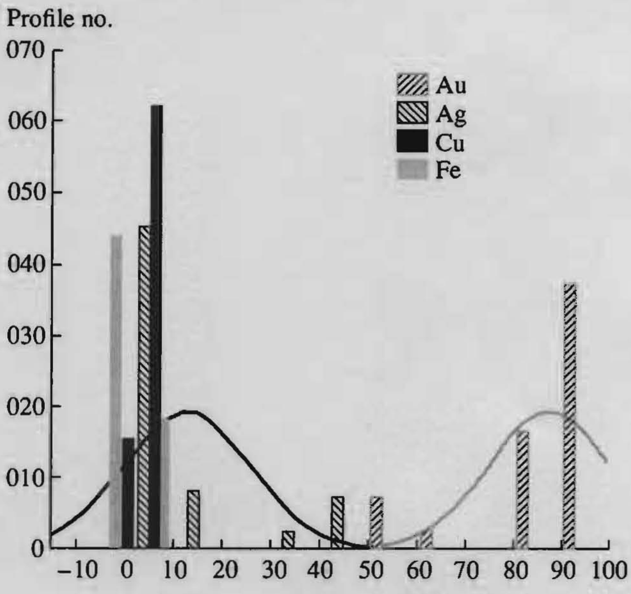

Fig. 4. Bar chart of the distribution of Au, Ag, Cu, and Fe in the panned gold from the Borov Dol deposit.

Hence, the composition and morphology of grains serve as a prospecting guide for the porphyry copper mineralization. Panning and investigation of the typomorphism of gold can serve as an efficient tool in the prospecting for porphyry copper deposits.

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