

Mineralogy of Oxidized Ores at the Ik-Davlyat Gold–Base-Metal Deposit, the Southern Urals

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Received January 12, 2006

Abstract—Three types of oxidized ores are identified in the Ik-Davlyat gold–base-metal deposit in the southern Urals: (1) carbonate–sericite–chlorite mineralized rock, (2) vein-shaped quartz–goethite–illite clay, and (3) limonitized rock related to veins. Heavy concentrate of the first type of ore is composed of goethite, rutile, native gold $\text{Au}_{0.91}\text{Ag}_{0.08}\text{Cu}_{0.01}$, and chalcophanite $\text{Zn}_{1.02}\text{Mn}_{2.98}\text{O}_4 \cdot 3\text{H}_2\text{O}$. The second type of ore contains goethite, rutile, Pb-bearing jarosite, native gold $\text{Au}_{0.90-0.93}\text{Ag}_{0.06-0.08}\text{Cu}_{0-0.01}\text{Fe}_{0-0.01}$, silver amalgamide (schachnerite) $\text{Ag}_{0.75}\text{Hg}_{0.97}\text{Au}_{0.98}-\text{Ag}_{0.75}\text{Hg}_{0.97}\text{Au}_{0.28}$, coronadite $(\text{Pb}_{1.72}\text{Mn}_{7.51}\text{Fe}_{0.41}\text{Cu}_{0.36})_8\text{O}_{16}$, a chalcophanite–hydrohetaerolite mixture, and cerussite. Gold of the highest fineness ($\text{Au}_{0.98}\text{Ag}_{0.01}\text{Cu}_{0.01}$) is associated with silver amalgamide. The third type of ore is quite similar to the first variety but contains a jarosite impurity. The composition of oxidized ores indicates a difference in composition of primary ores, in particular, the presence of lead minerals in primary veins. The first finding of chalcophanite in Russia is confirmed by chemical, optical, and X-ray data.

DOI: 10.1134/S1075701507070148

INTRODUCTION

The Ik-Davlyat deposit is situated 30 km to the north of the town of Uchaly in Bashkortostan and the giant Uchaly massive sulfide deposit located nearby. The Ik-Davlyat deposit is a constituent of the Il'insky gold–base-metal field, which also includes the Murtykty deposit (Western, Eastern, and Intermediate zones) and a number of ore occurrences and showings. The mining of oxidized ore at the Ik-Davlyat deposit, small in reserves, started in the 1990s. However, in 1995, the work was stopped because of unconfirmed reserves in the open pit. The mineralogical study of the ores was initiated by the Bashkir Gold Mining Company for the purpose of forecasting gold–quartz mineralization at the western flank of the Ik-Davlyat deposit.

RESEARCH METHODS

Mineralogical samples (1–5 kg) were crushed and washed in a pan to gray heavy concentrate. The mineral composition of duplicate samples was determined with XRD on a DRON-2.0 diffractometer at the Institute of Mineralogy, Ural Division, Russian Academy of Sciences (analysts P.V. Khvorov and T.M. Ryabukhina; interpretation: E.V. Belogub and K.A. Novoselov). The gray heavy concentrate was cleaned in bromoform (2.9 g/cm^3). Concentrates were examined under a binocular microscope and analyzed with a URS-2.0 X-ray crystal analyzer (analyst E.D. Zenovich; interpretation: E.V. Belogub, and K.A. Novoselov). The composition

of gold and accessory minerals was studied in polished specimens prepared from concentrates on a REMMA-2M SEM/EDS (EDAX Inc.) at the Institute of Mineralogy, Ural Division, Russian Academy of Sciences (analyst V.A. Kotlyarov). The semiquantitative emission spectroscopy of ores was carried out at the laboratory of OAO Chelyabinskgeos'zemka.

THE IK-DAVLYAT DEPOSIT

The Ik-Davlyat deposit is located about 80 m above the Shartymka River valley near the top of a mountain that extends in the north-northeastward direction conformably with the regional structural grain. The slopes of the mountain are steep (20° – 30°) but flatten at the base. Such a geomorphic position caused insignificant watering of the deposit and incomplete oxidation of ore because the rate of denudation was higher than that of chemical weathering. The Ik-Davlyat deposit is situated in a zone of semiarid climate.

In terms of regional geology, the Il'insky ore field is localized in the Tungatarovo Suture Zone of the Magnitogorsk Megasyntclorium. The Ik-Davlyat deposit is hosted in volcanic–sedimentary rocks of the Karamalytash Formation close to the Shartym Fault (Znamensky, 1992). The deposit is composed of cherty shale; volcanoclastic sandstone; and basaltic andesite strongly affected by sericitization, carbonatization, and chloritization. The ore-bearing NNE-trending and steeply dipping monocline is complicated by small folds in the sedimentary portion of the sequence and crosscut by thin mineralized zones, dipping at angles of 35° – 70°

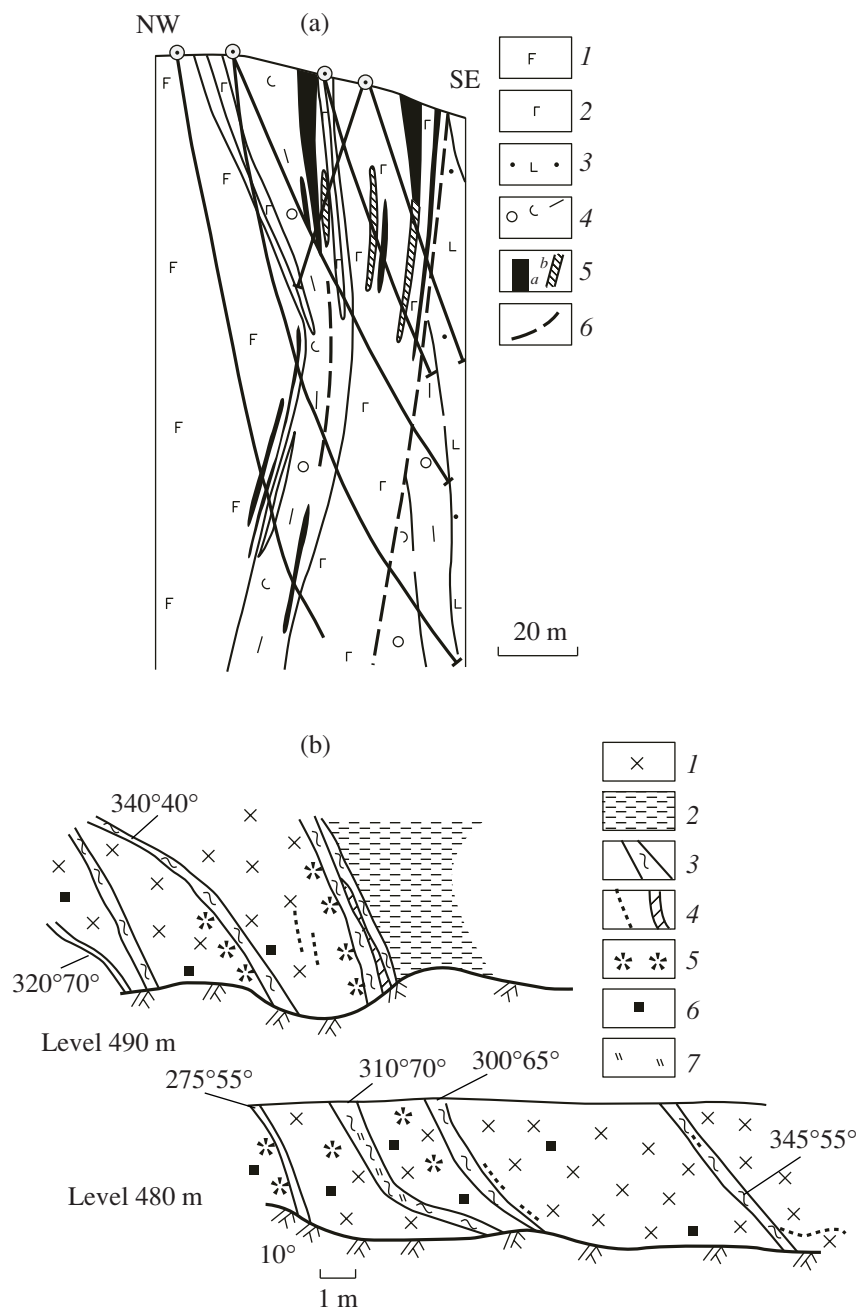


Fig. 1. (a) Geological section across the Ik-Davlyat deposit after Znamensky (1992) and (b) sketch of quartz-goethite-illite veins in the open pit. (a) (1) Subvolcanic dolerite and gabbrodolerite; (2) equigranular and porphyritic dolerites; (3) mafic tuff and tuffite; (4) tuffaceous gravelstone; (5) orebodies with (a) high and (b) low Au grades; (6) faults. (b) (1) Sericite-chlorite-carbonate metasomatic rock; (2) quartz-sericite schist; (3) quartz-goethite-illite vein; (4) quartz vein; (5) limonitization; (6) pyritization; (7) malachite mineralization.

northwestward or southeastward. A body of ore-bearing metasomatic rocks is sandwiched between members of clastic rocks and extends in the meridional direction (Fig. 1a). A thin hematite-quartz lens occurs at the contact of metavolcanic and metasedimentary rocks.

Two morphological types of orebodies are recognized at the Ik-Davlyat deposit. The first type comprises the main volume of the ore mass and is charac-

terized by low Au grades from 1 to 3 g/t; the Ag/Au ratio varies from 2 to 4. The oblong and lenticular orebodies, 1–15 m thick, are composed of metasomatized and limonitized basaltic andesites (massive and fragmented lavas). The orebodies of this type are enriched in Zn ((50–1000) × 10⁻³%), Pb (up to 150 × 10⁻³%), Cd, As, and Mo relative to global mean contents in intermediate igneous rocks.

The orebodies of the second type occur as crosscutting zonal veins up to 10 cm–1.5 m in thickness (Fig. 1b) and hundreds of meters in length. They are steeply dipping (80°) and strike at an azimuth of 220°–240° SW. These veins are distinguished by high concentrations (wt %) of Pb (up to 4), Zn (up to 4.7), Cu (up to 1), and As (up to 0.1) (data of the Bashkir Gold Mining Company). The axial zones of veins are composed of limonitized illite clay with milky white quartz fragments. The Au content in illite clay is nonuniform but rarely is below 10 g/t; the Ag/Au ratio is less than 1. Quartz in veins contains 0.2 g/t Au; the Ag/Au ratio is equal to 3. The limonitized, pyritized, and sericitized host rocks at the contacts with veins are characterized by a rather high Au content in the hanging wall (5 g/t, on average) and elevated Ag contents (about 15–20 g/t). The thickness of the altered zone is comparable with that of the axial zone. Ore shoots with anomalously high Au contents are confined to the intersections of two or more fractures with lenticular orebodies of the first type (up to 1.5 kg/t Au at the intersection of four fractures with a lenticular orebody 6 m thick).

Hematite–quartz rock contains up to 2.3 g/t Au and up to 45 g/t Ag and is not regarded as a special ore type because of its insignificant abundance.

MINERAL COMPOSITION OF ORES

The ore-bearing rocks are subdivided into three groups: (1) nonuniformly limonitized massive carbonate–sericite–chlorite metasomatic rock, (2) quartz–goethite–illite clay, and (3) limonitized rock related to veins.

The ore of the first type is characterized by massive and taxitic (metamygdaloid and metaclastic) textures. Aggregates of quartz, sericite, chlorite, calcite, and metacrystals of dolomite and pyrite are products of metasomatism. Acicular rutile intergrowths are also characteristic of this ore. The primary structure of the rock is obliterated almost entirely. Relics of intersertal texture are rarely observed in massive ore. Amygdules are replaced by a zonal aggregate of chlorite, sericite, and pyrite in the outer zone and by carbonate and quartz in the inner zone. The textural pattern of some metasomatic rocks allows the suggestion that their protoliths were holocrystalline rocks. Pyrite is the most abundant sulfide in the metavolcanic rocks. This mineral occurs around large amygdules and pervades metasomatic rocks, whereas chalcopyrite is sporadic.

The oxidation of metasomatic rocks resulted in the decomposition of carbonates, pseudomorphic replacement of pyrite by hematite and goethite, formation of jarosite, hydration of chlorite and sericite, and development of iron and manganese oxyhydroxides. According to XRD data, quartz, illite, and hydrated chlorite are predominant in the oxidized altered rocks. Albite, calcite, and dolomite occur only in the least oxidized varieties. The heavy concentrate is composed of predominant pseudomorphs of goethite and hematite after

pyrite; angular hematite fragments; colloform aggregates of manganese hydroxides; chlorite intergrowths; leucoxene; and sporadic grains of unoxidized pyrite, acicular rutile, chalcophanite, and native gold.

The second type of ore occupies the axial portions of veins and is composed of white and cream-pink plastic clays with inclusions of angular fragments of massive and cavernous milky white veined quartz. According to XRD data, the bulk mineral composition of the ore is the following: illite (major mineral), quartz, Pb-bearing jarosite, and occasional goethite. Malachite pockets and ocherous manganese oxides are noted in a single vein. Four varieties of quartz—chalcedonic, milky white, limonitized, and clear transparent crystalline—were observed in an elutriated sample. The heavy concentrate is composed of biotite, rutile, leucoxene, goethite, colloform aggregates of manganese hydroxides, jarosite, coronadite, cerussite, malachite, and native gold. The heavy concentrate from veined quartz fragments contains biotite and rutile but is devoid of visible gold.

The third type of ore is limonitized metavolcanic rock that adjoins the contacts with veins. According to XRD results, the ore contains quartz and illite in almost equal amounts and scarce feldspar and calcite. The heavy concentrate mainly consists of compact limonite concretions, pseudomorphs of goethite after pyrite, hematite, rare rutile segregations, and occasional cerussite and Pb-bearing jarosite.

To determine more precisely the composition of productive mineral assemblages, the ore minerals were studied in more detail.

Native gold is present in heavy concentrates of quartz–illite clay and gold-bearing metasomatic rocks as light yellow flattened, lumpy, and dendritic particles up to 0.4 mm in size and intergrowths with goethite. A latticed core and a narrow massive rim with altaite inclusions are observed in large lumpy grains (Fig. 2). The core and the rim have the same composition (Table 1). The latticed gold is likely to have been formed as a result of telluride exsolution, while the rim is residual.

In intergrowths with goethite, gold occurs as thin zonally arranged isometric impregnations. In some cases, goethite nodules contain both gold and silver amalgamides (Fig. 3). This gold is of the highest fineness (Table 1). Obviously, finely dispersed gold associated with goethite is a product of a supergene process.

Silver amalgamide (*schachnerite*?) has been detected in heavy concentrate from quartz–illite ore in zonal goethite nodules along with high-grade gold. Silver amalgamide forms oblong segregations in goethite up to 10 μ m in size (Fig. 3). Silver amalgamide is creamy yellow, highly reflective, soft, and isotropic or slightly anisotropic. In reflected light, this mineral is virtually indistinguishable from gold. In SEM image, silver amalgamide is less contrasting in comparison with gold. Insignificant impurities of Cu, Au, and occasionally Zn are characteristic of amalgamide (Table 1).

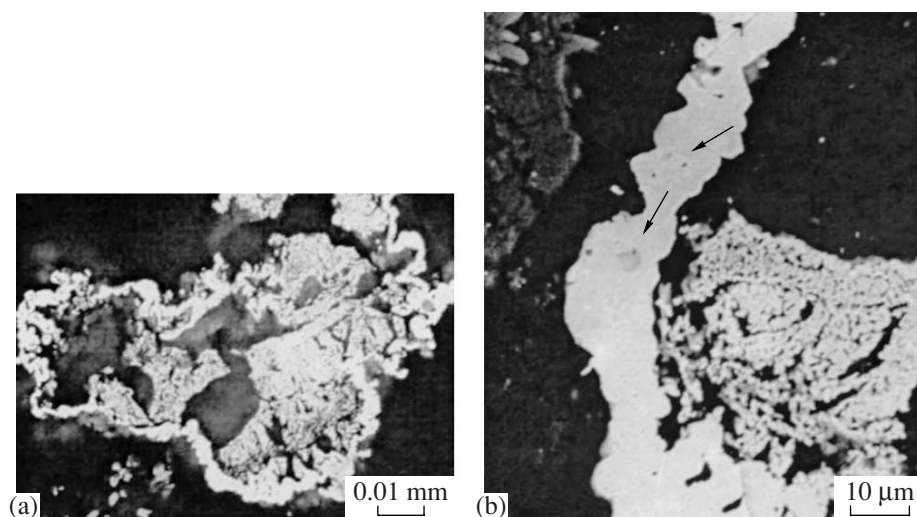


Fig. 2. Morphology of gold grains: (a) a grain with latticed core in reflected light and (b) altaite inclusions in gold (indicated with arrows), SEM image.

The calculated formula of amalgamide is similar to that of schachnerite $\text{Ag}_{1.1}\text{Hg}_{0.9}$ (Vasil'ev, 2004). It should be noted that three phases (α , β , and γ) have been established in the synthetic Ag–Hg systems. The first phase is mercury silver, containing up to 52.5% Hg. The β phase is hexagonal schachnerite and orthorhombic pseudohexagonal paraschachnerite, containing 58.88–65.03% Hg. The γ phase is cubic moschellandsbergite, containing 70–73% Hg (Vasil'ev, 2004). Silver amalgamide from the Ik-Davlyat deposit is closest to

schachnerite in composition, which is consistent with experimental data on the synthesis of the β phase with an Ag/Hg ratio close to 1 : 1 (Nirmal and Gowd, 1975). However, the optical characteristics of this mineral differ from those of schachnerite and paraschachnerite, so that the identification of mineral species requires additional study.

Silver amalgamide is rare in nature. According to Vasil'ev (2004), paraschachnerite and moschellandsbergite have been described in Russia only from the

Table 1. Composition (wt %) and crystallochemical formulas of native gold, silver amalgamide, and altaite

No.	N^*	Fe	Cu	Ag	Au	Zn	Hg	Formula
Gold								
1	2	0.23	0.14	3.96	95.60	0.00	0.00	$\text{Au}_{0.92}\text{Ag}_{0.07}\text{Fe}_{0.01}$
2	6	0.08	0.21	4.42	95.22	0.00	0.00	$\text{Au}_{0.91}\text{Ag}_{0.08}\text{Cu}_{0.01}$
3	3	0.35	0.19	4.36	95.06	0.00	0.00	$\text{Au}_{0.91}\text{Ag}_{0.08}\text{Cu}_{0.01}\text{Fe}_{0.01}$
4	3	0.12	0.20	3.29	96.31	0.00	0.00	$\text{Au}_{0.93}\text{Ag}_{0.06}\text{Cu}_{0.01}$
5	2	0.33	0.11	5.29	94.24	0.00	0.00	$\text{Au}_{0.90}\text{Ag}_{0.10}\text{Fe}_{0.01}$
6	9	0.13	0.19	4.67	94.94	0.00	0.00	$\text{Au}_{0.91}\text{Ag}_{0.08}\text{Cu}_{0.01}$
7	2	0.00	0.20	0.82	98.75	0.14	0.00	$\text{Au}_{0.98}\text{Ag}_{0.01}\text{Cu}_{0.01}$
Silver amalgamide								
8	1	0.00	0.56	30.67	4.68	0.00	63.88	$\text{Au}_{0.91}\text{Hg}_{1.02}\text{Au}_{0.07}$
9	1	0.00	0.20	29.81	7.41	0.00	62.46	$\text{Au}_{0.88}\text{Hg}_{1.00}\text{Au}_{0.12}$
10	1	0.00	0.45	24.32	17.14	0.24	57.65	$\text{Au}_{0.75}\text{Hg}_{0.97}\text{Au}_{0.28}$
Altaite								
11		Cu	Ag	Au	Sb	Te	Pb	
12	1	0.00	0.27	0.00	0.82	39.37	59.41	$(\text{Pb}_{0.93}\text{Sb}_{0.02}\text{Ag}_{0.01})_{0.96}\text{Te}_{1.00}$

Note: (1, 2) Latticed grain: (1) rim and (2) core; (3–5) native gold grains from veins; (6) native gold from metasomatic rock; (7) gold associated with silver amalgamide.

* Number of analyses used for averaging.

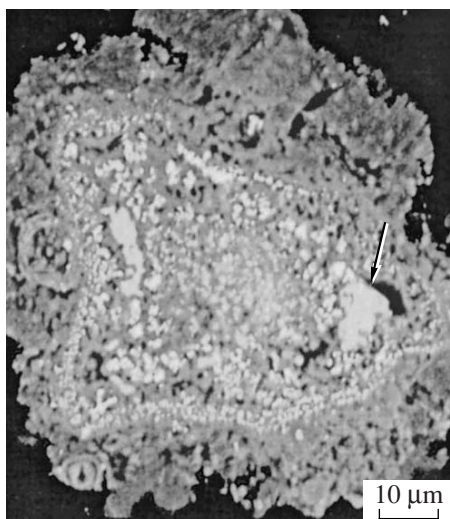


Fig. 3. A zonal goethite nodule with gold inclusions of high fineness (white) and silver amalgamite (indicated with arrow), SEM image.

Terlig-Khaya mercury deposit (Vasil'ev, 1972). The Landsberg deposit (Moschellandsberg, Germany), the Sala Mine (Sweden), and deposits of Mongolia were mentioned as localities of other findings. Thus, the suggested schachnerite from the Ik-Davlyat deposit might be the first finding of this mineral in Russia.

Coronadite $\text{Pb}(\text{Mn}^{4+}\text{Mn}^{2+})_8\text{O}_{16}$ has been identified by SEM study of heavy concentrate of Au-bearing quartz–illite clay. Coronadite forms narrow rims up to 15 [μm] wide and layer-plane ingrowths in hydromica packets (Fig. 4a). Coronadite is characterized by insignificant Cu and Fe impurities (Table 2).

Coronadite is considered to be a rare mineral (Strübel and Zimmer, 1987). In the former Soviet Union, it was described for the first time in the oxidation zone of the Kurgashinkan deposit, Uzbekistan, as a fine mixture with manganite (Golovanov, 1965). According to Semenov and Zarubeeva (1998), coronadite is known in Russia but has not been mentioned in the Urals.

Chalcophanite $(\text{Zn}, \text{Fe}^{2+}, \text{Mn}^{2+})\text{Mn}_3^{4+}\text{O}_7 \cdot 3\text{H}_2\text{O}$ has been identified in heavy concentrate of limonitized metasomatic rocks after amygdaloid basaltic andesite and in black ocher from a “copper” vein. The mineral occurs as steel-gray grains with a submetallic luster. The tabular segregations, strong anisotropy, birefractance, and slight pleochroism in bluish hues characteristic of chalcophanite are revealed in reflected light (Fig. 4b). The X-ray pattern corresponds to the chalcophanite–aurorite series (Frenzel et al., 1980). Zn, Mn, and occasionally Fe are detected in chalcophanite (Table 2). The X-ray pattern of black manganese ocher from a “copper” vein is interpreted as a mixture of chalcophanite and *hydrohetaerolite* $\text{Zn}_2\text{Mn}_4^{3+}\text{O}_8 \cdot \text{H}_2\text{O}$. An endothermic effect with a maximum at 200°C, corresponding to the transition of hydrohetaerolite to ZnMn_3O_7 , is the most distinct in the DTA curve (Frenzel et al., 1980). According to Semenov and Zarubeeva (1998), chalcophanite was not detected in Russia previously, but was described from Uzbekistan.

Cerussite was identified in heavy concentrates of Au-bearing quartz–illite clay and limonitized wall rocks. Cerussite forms euhedral grains up to 1 mm in size. The identification of this mineral has been confirmed by the X-ray pattern and the qualitative reaction with potassium iodide.

Malachite has been found in a single vein as pockets of radiate intergrowths in quartz–limonite aggregate.

A mineral from the jarosite group is usually present in the heavy concentrates of Au-bearing clays and limonitized rocks as intergrowths of rhombohedral microcrystals and cryptocrystalline zonal aggregates. At the contacts of clay and limonite, there are some areas enriched in this mineral. The zoning of segregations is expressed in variations of Pb, K, Fe, Al, and P contents (SEM/EDS data). The X-ray data indicate that the mineral belongs to the jarosite group; however, the doubling of the parameter C_0 characteristic of plumbogjarosite has not been detected.

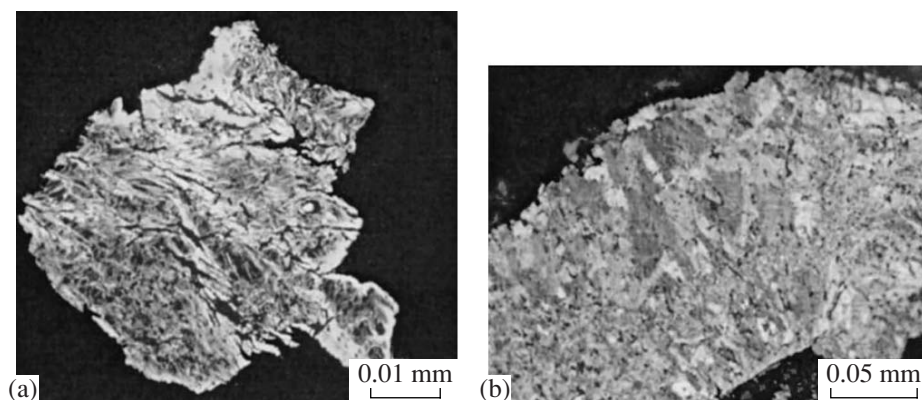


Fig. 4. Manganese minerals: (a) coronadite and (b) chalcophanite. In reflected light, crossed polars.

Table 2. Composition (wt %) and crystallochemical formulas of coronadite (1) and chalcophanite (2–4)

No.	MnO ₂	PbO ₂	Cu ₂ O	FeO	ZnO	Formula
1	53.13*	40.97	2.61	2.90	n.d.	(Pb _{1.72} Mn _{7.51} Fe _{0.41} Cu _{0.36}) ₈ O ₁₆
2	65.43	n.d.	n.d.	0.30	20.88	Zn _{1.02} Mn _{2.98} O ₄ · 3H ₂ O
3	65.49	"	"	n.d.	20.71	Zn _{1.01} Mn _{2.99} O ₄ · 3H ₂ O
4	65.47	"	"	"	20.97	Zn _{1.02} Mn _{2.98} O ₄ · 3H ₂ O

Note: *MnO contents; n.d., not detected.

Table 3. D spacing (*D/n*) in chalcophanite from the Ik-Davlyat deposit

Sample ID9		Chalcophanite (15-807, PDF)		Aurorite (19-88, PDF)		Sample ID9		Chalcophanite (15-807, PDF)		Aurorite (19-88, PDF)	
<i>d/n</i> , Å	<i>I</i>	<i>d/n</i> , Å	<i>I</i>	<i>d/n</i> , Å	<i>I</i>	<i>d/n</i> , Å	<i>I</i>	<i>d/n</i> , Å	<i>I</i>	<i>d/n</i> , Å	<i>I</i>
6.92	100	6.96	100	6.94	100	1.846	30	1.849	10	1.841	20
6.23	20	6.23	10	6.20	20	1.800	50	1.795	20	1.795	30
4.46	10							1.750	5	1.748	5
4.08	90	4.08	50	4.06	50	1.721	10	1.715	5	1.712	10
3.50	100	3.50	60	3.46	70	1.670	40	1.668	10	1.668	5
3.30	10	3.32	10	3.29	20	1.600	90	1.597	40	1.563	5
3.13	60	3.23	5	3.20	10	1.538	80	1.563	5	1.560	50
2.80	70	2.77	20	2.76	30			1.507	10	1.508	20
		2.71	5	2.70	5	1.432	90	1.431	30	1.429	50
2.57	100	2.57	40	2.54	50	1.401	20	1.402	5	1.398	5
2.46	80	2.46	20	2.45	40	1.323	10	1.324	5	1.321	10
2.39	70	2.41	20	2.40	40	1.302	10	1.308	5		
2.23	100	2.24	50	2.23	50	1.281	20	1.279	10	1.277	10
2.13	60	2.13	20	2.13	30					1.234	5
		1.986	5	1.98	5					1.204	10
1.900	70	1.900	30	1.899	40						

DISCUSSION

The proximity to a deep fault gave grounds to state that the formation of this deposit was related to tectonic processes (Znamensky, 1992). The pyrite–quartz–bicarbonate metasomatic mineral assemblage of the Il'insky ore field fits the beresite type of alteration (Sazonov et al., 1998). Znamensky recognized (1) a massive sulfide stage of mineral formation with deposition of pyrite-rich clastic layers and (2) a gold–base-metal stage pertaining to the postvolcanic tectonic activity and related beresitization. The morphology and mineral composition of orebodies show that the Ik-Davlyat deposit was formed during at least three stages. The initial stage of ore deposition was related to the eruption of island-arc basaltic andesites. Stratiform bodies of volcanoclastic sediments were enriched in sulfides (first of all, pyrite) and gold and affected by chlorite and quartz–sericite metasomatism, characteristic of volcanic deposits. The presence of Au-rich hematite–quartz rocks thought to be formed as a result of a low-

temperature hydrothermal process caused by submarine volcanism (Zaikova, 1985) or considered to be a product of submarine oxidation of sulfide-bearing hyaloclastites (Maslennikov, 1999) indicates the submarine nature of the primary ore deposition. Metasomatic processes of so far unclear nature induced the redistribution and concentration of ore material; massive and fragmented lavas and subvolcanic bodies were subjected to metasomatism to the highest degree. Metasomatism was accompanied by redeposition of pyrite and sphalerite and formation of manganese-bearing carbonates, which were a source of Zn and Mn for chalcophanite in the process of oxidation. The youngest, high-grade gold–base-metal veins were formed as a result of tectonic processes leading to the brittle failure of rigid altered volcanic rocks and the ductile deformation of more competent sedimentary rocks. This ore is characterized by coarse gold of high fineness. The primary gold telluride, Pb and Zn sulfides, and Hg-rich Cu sulfosalts were a source of Pb, Hg, and Ag for the for-

mation of Pb-bearing jarosite, cerussite, coronadite, and schachnerite. High zinc concentrations in clay are likely related to the exchange complex in the hydro-mica structure.

The oxidation zone of the Ik-Davlyat deposit was formed under conditions of a semiarid climate. Insufficient humidity resulted in the formation of highly mineralized solutions, which led to the crystallization of not only goethite, hematite, cerussite, and malachite, characteristic of the upper portions of the oxidation zone at the sulfide deposits of the southern Urals, but also Pb-bearing jarosite, coronadite, and chalcophanite.

CONCLUSIONS

Thus, the supergene mineral assemblages of the ores formed at different stages of the Ik-Davlyat deposit formation are diverse but nevertheless remain base-metal as a whole. The oxidized ores are distinguished by the presence of rare Mn oxides: coronadite, chalcophanite, hydrohetaerolite, and native silver amalgam associated with native gold.

ACKNOWLEDGMENTS

We thank analysts P.V. Khvorov, E.D. Zenovich, and T.M. Ryabukhina for analytical results and E.V. Semibratova and E.V. Titova, students of the South Ural State University, for their assistance in analyzing heavy concentrates.

This work was supported by the Bashkir Gold Mining Company and the Russian Foundation for Basic Research (project no. 04-05-96014).

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