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MINERAL DRESSING

Mineralogical Examination of Gold Processing Plant Tailings

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Abstract—The results of the mineralogical examination of old sulphide and oxidized gold ore tailings of a mining and processing plant in the Krasnoyarsk Territory are presented. Secondary mineral forms of antimony, namely, antimony bloom Sb_2O_3 and tripuhyite $FeSBO_4$, as well as iron are found. Gypsum in the waste is a newly formed phase, undetected in the initial ore, revealed in sulphide and mixed ore tailings and is absent in oxidized ore tailings. The key valuable component is gold represented by fine accretions in arsenopyrite, free gold size is not more than a few first microns.

Keywords: Sulphide and oxidized gold ore, tailings, secondary mineral forms, supergene transformations.

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INTRODUCTION

An integral part of the mining and metal industry are tailing ponds, which impose a huge man-caused load on the ecology and landscape of production regions [1–3], in some cases leading to technologic disasters [4]. At the same time, tailings of sulphide and oxidized ores represent potential mineral resource base for the extraction of noble and nonferrous metals [5–9]. According to various estimates, the annual waste of mining and metal production in Russia amounts to > 5 billion tons [10]. In domestic practice, starting from the 2000s, both subsoil users and research organizations have been engaged in the re-processing of man-made raw materials of various material composition [11–13]. In gold mining, man-made placer objects are mostly involved in reprocessing, since the mineral composition and grain size of gold enable to obtain the maximum result without large capital expenditures [14–16].

Man-made raw materials of most gold-containing tailing ponds, formed as a result of sulphide and mixed ore processing using the flotation leaching technology, represent complex, difficult-to-process object, where the valuable component can be found in a free form to a lesser degree, to a greater degree it is presented by fine impregnation, frequently it has a micron or nanomicron size. In addition, the material during storage undergoes supergene transformations, as a result of which new mineral forms originate, whose technological properties are important for further investigations, in order to develop new solutions for the extraction of valuable components. In recent years, the study of supergenically modified forms of the mineral component in man-made raw materials has received much attention both in our country and abroad [17–22].

This paper aims at studying the substantial composition of tailing pond material and distribution of gold throughout the pond.

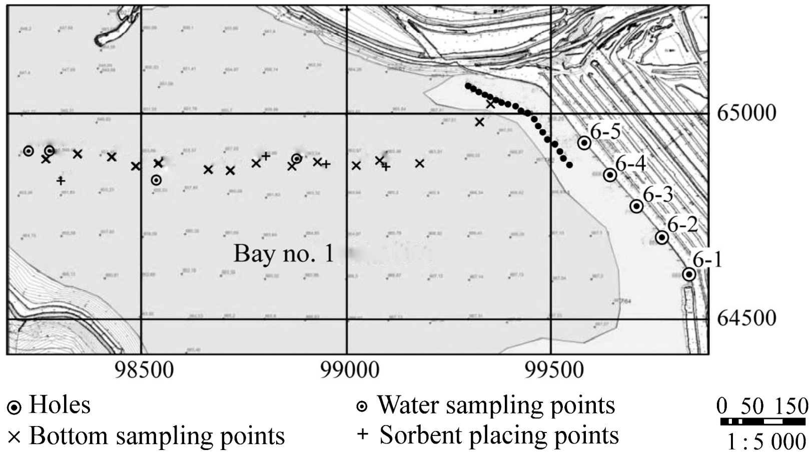

Fig. 1. Map of actual sampling from bund wall of tailing pond.

1. OBJECT OF RESEARCH

The initial raw product for investigations was the material from the tailing pond of gold processing plant of one enterprise in the Krasnoyarsk Territory, where the tailings of oxidized, mixed, primary sulfide gold ores have been accumulated over the years of operation. Storage of tailings at the tailings pond has been carried out since 1996. During the first five years, the plant processed the oxidized ore according to the cyanide leaching scheme. Later on, in addition to oxidized ores, the development of sulphide ores began using a combined technology of gravity separation–flotation–biohydrometallurgy. There were periods when the tailings of mixed ores (oxidized and sulphide) were dumped to the pond. In recent years, the tailings of primary sulphide ore are dumped to the tailing pond. The research material was taken from the holes drilled from the bund wall protecting the tailing pond of gold processing plant (Fig. 1). The depth of the holes drilled was more than 70 m.

The material of core samples is combined in sections of 5 m for further comprehensive study. According to the results of core sample study, the samples were formed with respect to the type of raw material (sulfide, mixed, oxidized) for further technological researches.

Figure 2 shows the levels of the tailing pond filling with tailings of various material constitution.

2. MATERIAL AND EQUIPMENT

Chemical analysis of man-made feedstock was carried out by X-ray fluorescence and spectral methods. The product solutions were analyzed by atomic emission spectral method with inductively-coupled plasma. Gold assay test with atomic absorption end was performed to determine gold content. X-ray microanalysis and optical method were used in mineralogical studies.

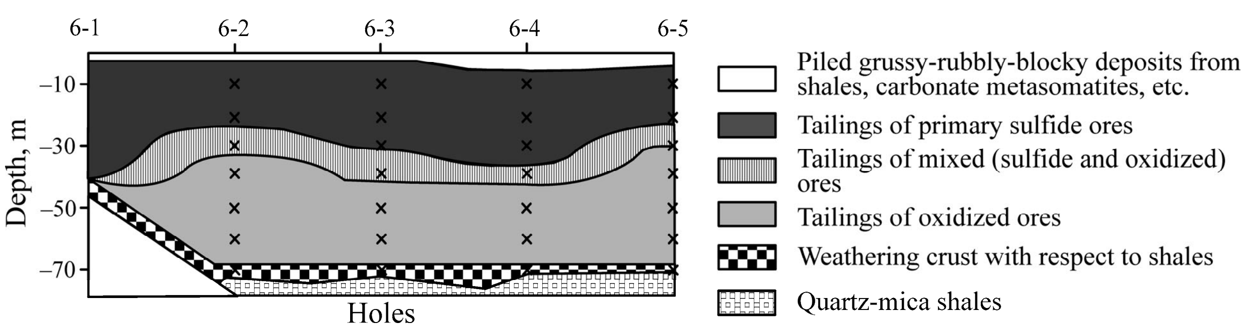

Fig. 2. Geological section with respect to the lines of holes drilled from the bund wall of tailing pond (the position of holes on the wall is shown in Fig. 1).

Table 1. Mineral composition of rock-forming minerals of tailings according to the results of X-ray phase analysis

Abundance of minerals	Tailings of ore processing	
	primary	oxidized
Basic	Quartz (75.9–36.0/54.3) muscovite+biotite (29.1–8.57/18.3) calcite (14.8–6.6/9.93) chlorite (16.3–2.38/10.1)	Quartz (90.4–60.0/81.2) muscovite+biotite (17.7–5.25/11.83)
Secondary	Dolomite (3.76–0/2.05) albite (6.7–0/2.89) gypsum (4.4–0.16/1.52)	Calcite (4.8–0/1.15) dolomite (0.96–0/0.36) chlorite (19.3–0/4.1) albite (3.76–0/0.65)
Rare	Rutil (0.9–0.11/0.2)	Scheelite (0.16–0/0.01) rutil (0.79–0/0.23), gypsum (1.6–0/0.16)

In brackets, the max. to min. content and average contents are given in %.

Microscopical research[1] was conducted by binocular microscope LOMO MS-1 and microscope Axioscope 40 A Pol. The diffracton patterns were recorded using an automated XRD-6000 X-ray diffractometer (Shimadzu, Japan), and the data were calculated and interpreted according to a standard procedure using the JCPDS standard powder spectra data files. X-ray fluorescence analysis was performed by X-ray fluorescence XRF-1800 spectrometer (Shimadzu, Japan) according to the standard technique— semi-quantitative analysis by the method of fundamental parameters using the equipment supplier's software. Electron microscopic researches and X-ray spectral microanalysis were performed on a TM-3000 scanning electron microscope (Hitachi, Japan) with a Quantax 70 microanalysis system (Bruker, Germany). The samples before microscopic study were prepared by impregnating with EpoFix epoxy resin, sequential surface treatment with emery paper SiC P200-P2000 and corundum suspensions of various sizes, followed by final polishing with suspensions of colloidal silica on a TegraPol-15 grinding and polishing machine (Struers, Switzerland).

Table 2. Chemical composition of the samples studied, %

Component	Sample		
	sulfide	mixed	oxidized
Na_2O	0.76	0.54	0.15
MgO	2.04	1.86	0.69
Al_2O_3	9.99	8.38	6.58
K_2O	2.49	2.14	1.51
CaO	10.46	10.14	2.11
MnO	0.24	0.24	0.31
SiO_2	58.28	61.79	80.45
P_2O_5	0.14	0.13	0.09
Fe_2O_3 (total)	5.35	4.58	4.52
Fe_2O_3 (ferric iron)	2.17	2.06	4.39
FeO (ferrous iron)	2.86	2.27	0.11
S (total)	0.64	0.56	0.10
S (sulfide)	0.46	0.39	0.068
SO_3 (sulfate)	0.46	0.42	<0.25
Sb (oxidized)	0.083	0.088	0.045
Sb (sulfide)	0.037	0.062	0.23
TiO_2	0.46	0.38	0.31
LOI	9.24	9.29	3.21

[1] Electron microscopical studies were carried out on the equipment of the Krasnoyarsk Regional Core Facility Center, Siberian Branch, Russian Academy of Sciences.

3. RESULTS AND DISCUSSION

The tailing pond material under study is mainly represented by a finely dispersed fraction, there are individual metal particles of man-made origin, fragments of rocks (shale), single grains of quartz and granite, single secondary accretions of dust and sand particles cemented by gypsum (tailings of primary ore processing) and iron hydroxides (oxidized tailings). The color varies from light gray (products of primary ore processing) to light brown (tailings of oxidized ores). According to the results of X-ray phase analysis, the rock-forming part of the tailing material is represented mainly by quartz and micas. Calcite, chlorite, dolomite and gypsum in greater quantities are in the tailings of primary ores, in a smaller quantity—in the tailings of oxidized ores (Table 1). The chemical composition of the samples studied is given in Table 2.

Gypsum is a newly formed phase, which is not found in base ores. It is noted in the tailings of unoxidized and mixed ores and is almost absent in the tailings of oxidized ores (Table 1). This distribution is associated both with the formation of sulfate sulfur in oxidation of sulfides, and with man-made sulfates of recycle water. In electron microscopic study it was found that gypsum forms incoherent and continuous rims and deposits on the surface of various mineral phases, especially enriched in calcium. The rim is most often represented by dust particles of tailing minerals cemented by gypsum.

All tailing samples are characterized by a decrease in the quartz content in small grain-size classes and an increase in the share of micas and chlorite. This is obviously associated with the higher resistance of quartz to crushing and attrition. In contrast, the content of muscovite, biotite, and to a lesser extent chlorite increases to a smaller grain-size class.

The basic ore minerals of tailing samples are magnetite, pyrite, pyrrhotine, arsenopyrite and antimonite. Galenite and some primary antimony minerals (jamsonite, gudmundite, berthierite, and ulmannite) are found in the form of single segregations mainly in samples of nonoxidized tailings. Secondary mineral forms of iron and antimony, resulting from man-made transformations, were also found (Fig. 3). Among the secondary minerals of antimony, valentineite Sb_2O_3 and tripuhyite $FeSbO_4$ are present in the form of thin deposits and crusts, porous aggregates, found mainly in the material of oxidized tailings.

When arsenopyrite is oxidized, films and clusters of scorodite, goethite, valentine and other secondary minerals are formed on the surface of grains, less often inside them (Fig. 3b). Almost complete absence of sulfur in the products of supergenic mineral formation with respect to arsenopyrite is characteristic.

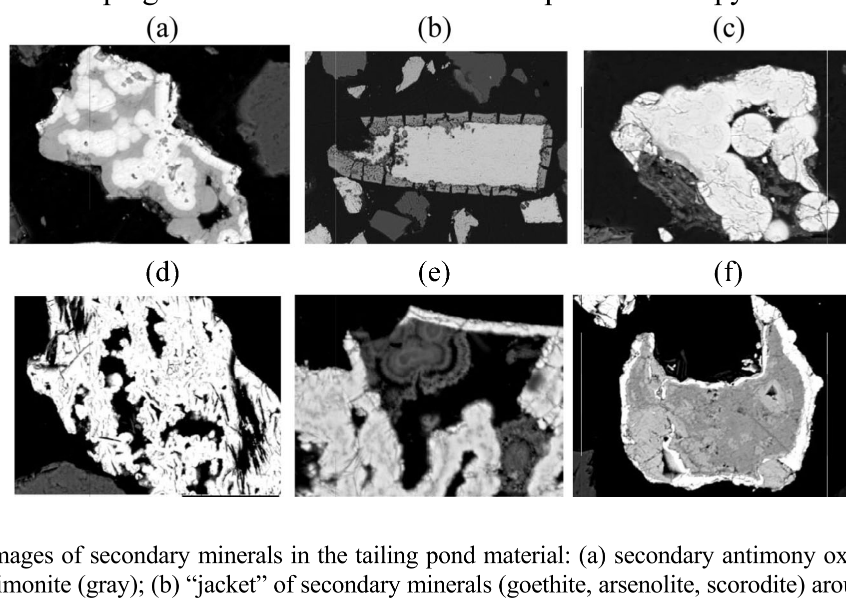

Fig. 3. SEM images of secondary minerals in the tailing pond material: (a) secondary antimony oxides (light gray) accreted with limonite (gray); (b) "jacket" of secondary minerals (goethite, arsenolite, scorodite) around arsenopyrite crystal; (c) spherolite segregations of valentine; (d) colloform segregations of tripuhyite with imprints of lamellar silicates; (e) supergenic apatite (dark gray) accreting on secondary tripuhyite; (f) aggregate of goethite overgrown with a rim of secondary oxides of antimony and iron (valentinite and tripuhyite).

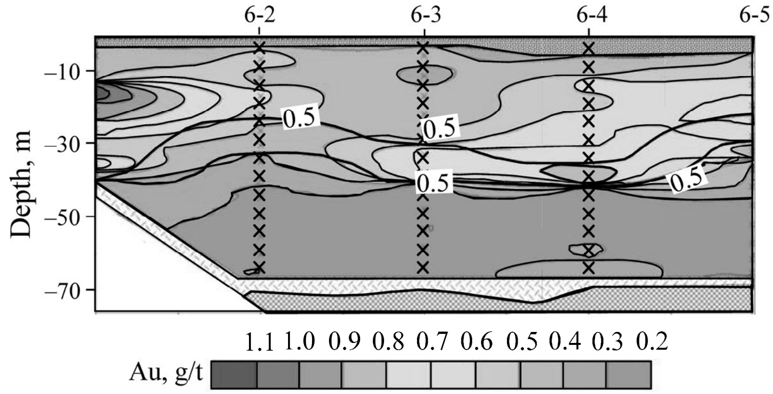

Fig. 4. Pattern of gold content distribution along tailing section in the profile of holes drilled from bund wall.

The analysis of gold content distribution in the section (Fig. 4) shows its relatively low 0.2–0.4 g/t (average 0.292 g/t) concentration in the lower part (tailings of oxidized ores) and the higher concentration—in the upper part of the section—in the tailings of mixed and sulphide ores 0.70–1.13 g/t (average 0.602 g/t). Close correlation of gold with sulfur, arsenic and carbon is noticeable in sulfide tailings. Correlation of gold with antimony and tungsten is characteristic of oxidized raw materials. The concentration of these elements in oxidized raw materials exceeds the same in the tailings of primary ores twice and more.

According to the hole sampling data, gold grade variation was 50%. The level of increased gold concentration (> 0.7 g/t) coinciding with the level of mixed tailings – transition from oxidized ore tailings to primary ore tailings (between –40 m and –20 m points) is distinguished clearly in the holes 6-3, 6-4 and 6-5. This indirectly confirms the workflow instability and relatively increased losses of metal with tailings during the processing of mixed raw materials in the plant.

Gold distribution by core samples in large grain-size (–100 + 40 μm) classes and in slime fractions (–40 μm) was studied using the survey profile of bund wall (Fig. 5). The distribution of gold with respect to grain-size classes is nonuniform. The areas with a higher gold content (> 0.7 g/t) of –100 + 40 μm class in the tailings of primary sulfide ores indicate incomplete metal disclosure during processing, which is most likely due to its fine impregnation. The lower levels of the tailing pond, represented by the tailings of oxidized ores in both sand and slime fractions are gold-depleted, as compared to the upper levels.

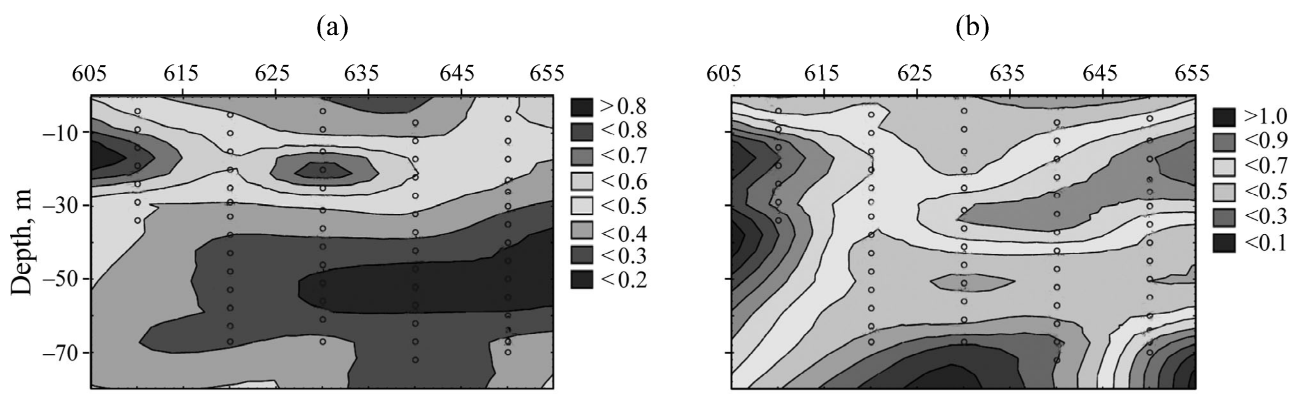

Fig. 5. Map of gold content in (a) –100 + 40 μm and (b) –40 μm classes.

Table 3. Gold assay testing of the samples under study

Gold deportment	Gold content, g/t			Gold distribution, %		
	Sample					
	sulfide	mixed	oxidized	sulfide	mixed	oxidized
Free gold and in accretions (recovered by cyanidation)	0.36	0.36	0.12	56.25	50.0	33.33
Recovered by cyanidation after treatment with hydrochloric acid solution of tin dichloride (associated with iron oxides and hydroxides, carbonates)	0.08	0.08	0.10	12.50	11.11	27.78
Associated with sulfides	0.11	0.20	0.05	17.19	27.78	13.89
Finely impregnated into rock-forming minerals	0.09	0.08	0.09	14.06	11.11	25.00
Total	0.64	0.72	0.36	100.00	100.00	100.00

In slime fractions, the areas with a higher gold content (> 0.7 g/t) are observed in oxidized, sulfide and mixed raw materials. The pattern of the isolines in Fig. 4 reflecting the distribution of gold contents along the profile of the tailing dump indicates washing off of the fine fractions containing increased contents of metal, deeper from the bund wall.

Gold assay test showed that the maximum amount of metal 56.25% in cyanidable form can be found in sulfide material of tailings. In the sample characterizing mixed raw materials, 50% of gold is present in cyanidable form. The oxidized material, where only 33% of gold is concentrated, turned out to be the most difficult to process. The mixed raw material, where gold content is 0.72 g/t, is considered as relatively concentrated. The sulfide and oxidized materials contain 0.64 g/t and 0.36 g/t of metal, respectively.

According to the results of electron microscopic study, gold in the tailing pond material is in fine accretions mainly with arsenopyrite or arsenopyrite replaced by pyrrhotine. When replacing, concentration of invisible gold in the remaining part of the arsenopyrite crystal and formation of its dispersed particles take place. Increased gold content in the level of primary ore tailings indirectly indicates arsenopyrite as the main carrier of gold in tailings. The increase in the gold content in samples and fractions enriched in finely dispersed (–20 μm) X-ray amorphous iron hydroxides is associated with gold sorption on the active surface of limonite.

Native gold in the samples is noted in the form of single manifestations of less than 0.1 mm in size in stream-sediment material and in accretion with arsenopyrite, pyrrhotine and zircon (Fig. 6). An increased gold content is observed in the finely dispersed fractions, which is associated with X-ray amorphous iron hydroxides.

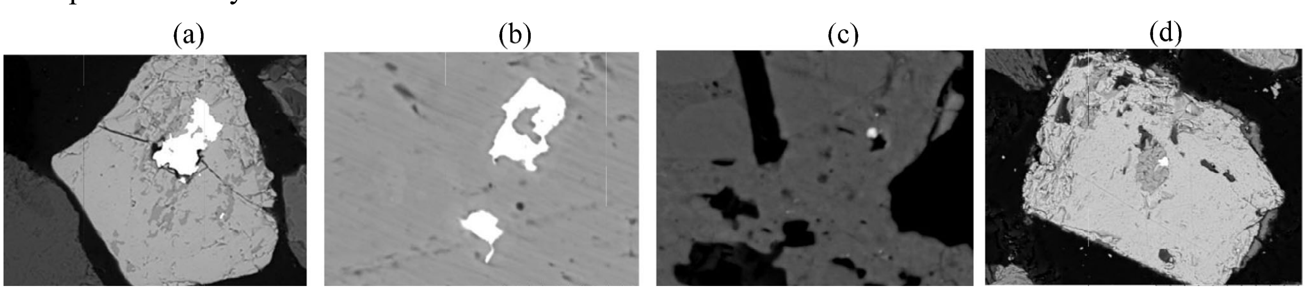

Fig. 6. SEM images of gold particles in the tailing pond material: (a) native gold in arsenopyrite replaced by pyrite: a particle length of about 25 μm, fineness in the range of 814–891‰, mercury content 5.21–10.32 mass.%; (b) native gold in arsenopyrite. The total length of particle aggregate is about 14 μm, fineness varies from 911 to 693‰; (c) native gold in zircon: transverse particle size of about 1 μm, (d) native gold in arsenopyrite, replaced by pyrrhotine: transverse particle size of about 3 μm, fineness is 934, the main impurity is mercury.

Free gold has light yellow color and a hooked shape. A characteristic feature of gold-bearing arsenopyrite is replacement by pyrrhotine. On the replacement front, invisible gold accumulates in arsenopyrite and relatively large particles appear. The gold fineness varies from high (934) to low (693), the main impurity is mercury, silver is almost absent.

In addition to gold, antimony in the form of both primary and secondary mineral formations and tungsten represented by scheelite should be noted as valuable components in the tailing pond material. The maximum concentrations of W and Sb are spatially conjugated with the tailings of oxidized ores.

CONCLUSIONS

A generalized model of the distribution of gold and related elements along a selected profile of geological boreholes has been compiled, giving a general idea of the distribution of metals from the surface of the tailing pond to its bed.

The distribution of gold and related elements corresponds to the sequence of mining and storage of various types of ores from oxidized to mixed and further, to sulfide ones. The minimum concentration of gold (average 0.29 g/t) and its close spatial correlation with antimony and tungsten are characteristic of the tailings layer of oxidized ores. The samples taken in the upper part of the section, with respect to the tailings of mixed and primary ores, have almost twice higher gold content than that one of oxidized ores. Sulfur, arsenic and carbon are found to be closely correlated with gold.

It has been established that free form is not typical of gold deportment. The metal is in fine accretions mainly with arsenopyrite, or arsenopyrite substituted with pyrrhotine.

The antimony mineralization is present both in the tailings of primary and oxidized ores, gravitating towards the latter, to a greater extent. Antimonite is most characteristic of the tailings of nonoxidized ores, rarely berthierite, gudmundite, jamsonite and ulmannite occur. Valentineite and tripuhyite are inherent in the tailings of oxidized ores; in addition to these phases, antimony is localized in limonite.

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