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Polygenic gold mineralization in quartz-pebble formations on the Takyr-Kaljir site of the Southern Altai, East Kazakhstan Region

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Abstract

Purpose. The research purpose is to study the forms of gold occurrence in the Takyr graben alluvial-proluvial deposits in order to develop a low-waste resource-saving processing technology.

Methods. At the first stage, in the course of field studies, the geological structure of the site is specified, samples are taken for mineralogical-technological analysis, which includes the following procedures: studying granulometric and mineral composition of detrital material; fractional gravitational beneficiation of the source material; fractional beneficiation of material pre-processed in the autogenous mill (AG mill); studying free (native) and bound gold in beneficiation products, their quantitative assessment. The samples are processed under the three-stage scheme using an autogenous mill for sample preparation.

Findings. For the first time, the geological structure of the site has been specified with the identification of the deposits in the Turangi and Tuzkabak suites within its boundaries, as well as granulometric and petrographic composition of gold-bearing deposits, and the specifics of gold bearing. The detrital material, represented by quartz with a sharply subordinate amount of quartzite, quartz diorites and jasperoids, is practically identical in all fractions.

Originality. For the first time, various types of gold mineralization have been identified in placer sands: clastogenic, newly-formed hypergene, newly-formed hydrothermal and residual. Fractional beneficiation makes it possible to estimate the gold content in each fraction and gravitational beneficiation products, as well as the ratio of free and bound native gold in different fractions. The largest amount of free native gold has been revealed in fractions of -0.25 + 0.1 mm (60%) and -0.074 + 0.044 mm (~40%). Gold is high-grade (96.5%) with an admixture of silver and iron. Together with gold, ilmenite, zircon, scheelite, native bismuth, as well as barite, galena, sphalerite, and dolomite have been identified.

Practical implications. The research results make it possible to reassess the prospects of similar objects, to adjust the scheme and methodology for processing stream-sediment samples, to solve the issues of productive sand processing technology, as well as to improve the efficiency of geological exploration and eliminate the "underestimation" of gold deposits. The results obtained can be recommended for implementation by both domestic and foreign organizations specializing in the exploration and mining of gold deposits.

Keywords: *gold, placer, mineralogical-technological analysis, gravitational beneficiation, mineralogical composition*

1. Introduction

The urgency of expanding the raw material base of Kazakhstan's gold mining industry is undeniable. At the same time, the prospects for reserves growth are linked to new unconventional types of ore and placer deposits. This requires a special approach to exploration work, including sample processing [1], [2]. Issues of increasing the geological exploration work efficiency are solved through special research in this area [3]. In a number of gold-bearing provinces of the world, there are known ore and placer deposits, where the predominant part of the native gold grains belongs to fine or submicroscopic grain-size classes [4]. Deposits of this type are found in the United States, Canada and other countries. A significant part of fine and submicroscopic gold in ore bodies is not even accounted for in the balance sheet, but it is not mined due to the lack of technological solutions for its processing [5]-[7].

In addition, a peculiarity of the ores of many large-scale deposits is the presence of "invisible" gold [8]. Such types of deposits with a high content of invisible gold include Fairview (Republic of South Africa) – 1400 g/t Au, Carlin (USA) – 4000 g/t Au; Gegchell (USA) – 2400 g/t, etc. [9]. The in-fluence of fine and dust gold, which is also contained, among other things, in sulfide and arsenide minerals, can be significant, reaching a content of 2-5 g/t for the entire ore mass [10]-[13].

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The intensification of gold mining in Kazakhstan determines the need to involve placer deposits in mining. At the same time, the potential of placers, linked to river valleys on the territory of the Republic, is limited and by now has been practically exhausted [14]-[16]. The prospects for placers of graben-like depressions, similar to those known in the territories of East Asia, South America and other regions, are much more significant [13], [17], [18]. This type of gold-bearing placers is characterized by the following peculiarities and conditions of localization: the consedimentary nature of the formation of numerous seams, the presence of level-arranged gold-bearing seams that are not consistent in width, strike and thickness, and huge volumes of sand, the predominance of fine and thin platy gold in them. The predominance of gold of fine and dust grain-size classes of platy and scaly morphology requires a special technological approach in their processing [19].

One of such objects is the Takyr-Kaljir site in the Southern Altai gold-bearing region of East Kazakhstan [20], [21]. The predicted placer gold resources within its limits are over 300 tons. The site is located within the Takyr graben, bounded in the northeast by a neotectonic bench formed along the Prirechensk fault zone with displacement amplitude of 70-100 m; its southwestern flank is less pronounced. The graben bottom is complicated by low-order tectonic faults. Graben consists of alluvial-proluvial Middle Eocene deposits, composed of quartz pebbles with lenses, as well as sand and clay intercalations.

Wastes from the mining and processing of ores from natural deposits are also a significant reserve of economic efficiency in gold production. In particular, in the general structure of world resources and reserves of gold, the share of technogenic objects accounts for about 7-12% [22], [23].

The research purpose is to develop methodological techniques for increasing the mining efficiency of gold-ore and gold-placer deposits both at the stage of geological exploration by in-depth study of the sample composition and operational study of gold occurrence forms, as well as at the operation stage by introducing new technological methods.

2. Study area

2.1. Studying the placer gold-bearing degree of the site

The described quartz pebbles were mentioned for the first time by D. Murashov in the "Conditions of gold-bearing quartz pebbles in the village of Hornoe", published in the studies of the Semipalatinsk Geographical Society in 1909. He interpreted them as the remains of gold-bearing quartz veins containing ore gold.

In 1914, G.G. Kel explored quartz pebbles by driving five lines of mine workings (11 wells to a depth of 23 m and about 100 boreholes). Among 700 samples, 250 samples had the gold content up to 110 mg/m^3, 12 samples – 194 mg/m^3, two samples – 305 mg/m^3 each, one – 1416 mg/m^3. The layout plan of the mine workings has not been preserved.

In 1948, the site was studied by the "Altaizoloto" Trust enterprises by driving 70 boreholes with a depth of 5-25 m along a network of 250×1000 m. The gold-bearing intercalations are identified throughout the entire thickness. Gold is fine (0.5-0.25 mm) and very fine (0.25-0.1 mm), ground, platy.

In 1980-1982, Kurchum GRP PGO "Vostkazgeologia" (A.I. Demchenko, E.G. Maximov and others, 1982) discovered gold in tin-bearing placers of the Takyr River valley on the site of its intersection with the quartz pebble stratum. The flood-plain placer has gold content from 958 to 2016 mg/m^3; the terrace placer has gold content up to 420 mg/m^3. The Sukhoi Log stream placer, completely located among quartz pebbles, has a gold content of up to 4008 mg/m^3. Gold is of very fine and fine fractions, thin-platy. Based on the conclusion of these researchers, the source of gold is an intermediate reservoir – quartz pebbles of the Turangi suite. The average grade of gold in the placers of the Takyr River valley is 973.

In 1983-1986, the prospects for the placer gold content of quartz pebbles were studied by the Altai expedition of the Mining and Processing Plant "AltaiZoloto" (V.V. Maslennikov and others, 1987). As a result of surveying work, the gold content was determined to be 720 mg/m^3. Gold of small fractions prevails, platy shapes with a low hydraulic grain-size class.

In 2006-2008, prospecting-assessing work for large-scale gold placers was conducted by TOO "GRK "Topaz" (T.M. Panagushin and others, 2009). The gold content of quartz pebbles of the Turangi suite has been confirmed for up to 400 mg/m^3. Gold of fine and dust grain-size classes of platy and scaly morphology prevails.

In 2014, selective testing of pebble samples was conducted by Takyr-Kaljir Altyn LLP. In the Tuzkabak suite deposits, the gold content was found to be 0.77 g/t (1.54 g/m^3), in the Turangi suite deposits – 0.15 g/t (0.3 g/m^3).

Since 2021, exploration work in the northern part of the site has been conducted by TOO "GeomonitoringSystems" on the basis of a license for the right to explore.

2.2. Refined data on the geological structure of the site

In the western and eastern parts of the site, a significant area is occupied by rocks of the Pugachev suite of the Eifelian Middle Devonian Stage (sandstones, interstratified siltstones). Mesozoic and Cenozoic deposits predominate. In their composition, taking into account the ideas of previous researchers [24], [25] and the results of their own observations, Late Cretaceous-Middle Eocene deposits of the Severozaysan suite have been identified (K_2-Pg_2^2); Eocene deposits of the Turangi suite ($Pg_2\,tg$), Eocene-Oligocene deposits of the Tuzkabak suite ($Pg_{2-3}\,tz$) and Quaternary age deposits. The Tuzkabak suite deposits on the site area have been identified for the first time.

The Severozaysan suite deposits (K_2-Pg_2^2) are locally outcropping. They are represented by variegated gypsum clays, sands with an admixture of gravel, pebbles and rubble. The deposit thickness is up to 200 m.

The Turangi suite deposits ($Pg^3\,tg$), overlying Paleozoic rocks and Severozaysan suite deposits, extend to the northern part of the site. The suite section is represented by pebbles and gravelstones with sand and clay intercalations. The rocks are light gray, white and yellowish-brown. The coarsely-detrital rock varieties account for 70-80% of the deposit mass. The bulk of the detrital material is represented by quartz and siliceous rocks, and only an insignificant part, about 1%, is pebbles of other rocks. The pebbles are often covered with quartz-flooded ferruginous sandstone crusts. The suite deposit thickness varies from a few meters to 45 m. The granulometric composition of the described suite pebbles is illustrated in Table 1.

The coarsely-detrital material composition (fractions larger than 2 mm) is dominated by milky-white quartz, while gray quartzite, jasperoids and quartz porphyry are much less common. The fine-detrital mineral composition is determined by X-ray phase analysis (Table 2).

Table 1. Granulometric composition of the Turangi suite pebbles

Grain-size class, mm	+60	-60 +40	-40 +20	-20 +10	-10 +5	-5 +2	-2 +1	-1 +0.5	-0.5 +0.25	-0.25 +0.1	-0.1 +0.044	-0.044	Total
Yield, %	4.1	9.26	15.29	18.18	8.68	10.25	12.23	8.02	5.45	2.64	2.81	3.06	100

Table 2. Mineral composition of fine grain-size classes of the Turangi suite deposits according to diffractometry data

Grain-size class, mm	Minerals, %					
	Quartz	K-spar	Albite	Kaolinite	Mica	Calcite
-2 + 1	100.0	–	–	–	–	–
-0.25 + 0.1	98.0	2.0	–	–	–	–
-0.1 + 0.044	95.5	3.0	1.4	–	–	–
-0.044	52.4	3.7	8.4	25.3	8.2	1.9

Noteworthy is the uniform quartz composition (95.5-100%) of sand fractions with a small admixture of feldspars, as well as the presence of kaolinite and calcite in the fine class. The chemical composition (Table 3) corresponds entirely to the mineral one. Silica predominates from 93 to 98% in sand fractions, while alumina, alkalis, calcium appear in fine classes.

Pebbles are often covered with quartz-flooded ferruginous coarse-grained sandstone crusts (Fig. 1) and filmy ferruginous coat.

The Tuzkabak suite deposits (Pg_{2-3} *tz)*, identified on the site for the first time, overlie those described above. They form a field of considerable size in the central part of the site.

Figure 1. Crusts of ferruginous quartz-flooded material on the surface of pebbles from the Turangi suite deposits

Table 3. Chemical composition of fine fractions of the Turangi suite deposits

Grain-size class, mm	Components, %								Total
	SiO_2	$A1_2O_3$	Na_2O	K_2O	CaO	MgO	TiO_2	FeO	
-2 + 1 mm	98.09	0.34	–	–	–	–	–	1.57	100
-0.25 + 0.1 mm	93.24	2.96	–	1.82	–	–	0.42	1.56	100
-0.1 + 0.044 mm	93.96	2.63	–	1.76	0.56	–	–	1.10	100
0.044 + 0 mm	71.04	18.52	0.42	3.15	1.34	1.08	0.94	3.51	100

The stratum is composed of grayish-brown, dark-brown sandy clays with an insignificant amount of detrital material of predominantly quartz composition of various roundness, as well as pebbles, gravel-pebbles and red, orange and pale sands. The results of field observations indicate that the clay and pebble parts of the section replace each other in facies. Since the placer gold content is associated with the pebble parts of the suite, they will be described in more detail. The granulometric characteristics of the Tuzkabak suite pebbles are given in Table 4.

Table 4. Granulometric composition of the Tuzkabak suite pebbles

Grain-size class, mm	Average, (%)	Grain-size class, mm	Average, (%)
-150 + 80	0.67	-1 + 0.5	7.26
-80 + 40	3.92	-0.5 + 0.2	4.70
-40 + 20	10.43	-0.2 + 0.1	2.13
-20 + 10	16.78	-0.1 + 0.074	1.20
-10 + 5	14.45	-0.074 + 0.044	3.87
-5 + 2	12.45	-0.044	16.80
-2 + 1	7.85	–	–

The detrital material petrographic composition is almost identical in all fractions. Coarse-grained material (larger than 2 mm) is represented by fragments of milky-white quartz and grayish-blue quartzite. The fine-grained material has the similar composition. The pebbles of the described deposits are often covered with carbonate crusts, while carbonate “nodules” are observed in the section, and less often – quartz-flooded ferruginous sandstone (Fig. 2).

Figure 2. Newly-formed carbonate crusts on the pebbles of the Tuzkabak suite deposits

The mineral fine-grained material composition is determined by the X-ray diffraction method (Table 5). The main minerals are quartz (42.6%), calcite (26.3%), feldspars and kaolinite-mica minerals.

The chemical composition of the sands is determined from the silty fraction (-0.1 + 0 mm), the material of which is mainly formed due to the abrasion of larger fractions.

Table 5. Results of semi-quantitative X-ray phase analysis of -0.1 mm class material

Phase name	Formula	Concentration, %
Quartz	SiO_2	42.6
Calcite	$Ca(CO_3)$	26.3
Albite	$Na(AlSi_3O_8)$	9.0
Muscovite	$Kal_2(AlSi_3O_{10})(OH)_2$	7.9
Orthoclase	$K(AlSi_3O_8)$	5.3
Kaolinite	$Al_2[Si_20_5](OH)_4$	8.9

The chemical composition of the silty material is aluminum-calcium-silicate (Table 6), which correlates well with the mineral composition.

During the exploration work, “exotic” formations in both suites have been identified – boulders and pebbles of conglomerates and gravels (Fig. 3), in which rounded quartz fragments are cemented by dense polymictic sandstones with a ferruginous-siliceous matrix [8], [26], [27]. The size of conglomerate boulders reaches 0.5-0.6 m in the transverse, and the detrital material size in them is up to 4-5 cm in the transverse, which fundamentally corresponds to the dimension of pebbles in the deposits of the Turangi and Tuzkabak suites. The roundness of pebbles in conglomerates is mostly good and similar to that in the rocks of the above-mentioned suites (Fig. 3a, b). Separate fragments have the “dissected” pebble material (Fig. 3c, d).

Table 6. Chemical composition of the silty fraction (-0.1 mm)

Spectrum	Components, weight, %									
	O	Na	Mg	Al	Si	K	Ca	Ti	Fe	Total
Spectrum 1	54.50	0.55	1.39	6.80	19.15	1.98	11.97	0.26	3.42	100.0
Spectrum 2	54.30	0.45	1.42	6.94	20.09	2.39	10.52	0.33	3.56	100.0
Spectrum 3	53.77	0.60	1.64	7.31	19.91	2.35	10.12	0.37	3.93	100.0
Average	54.19	0.53	1.48	7.02	19.72	2.24	10.87	0.32	3.64	100.0
Standard deviation	0.38	0.08	0.14	0.27	0.50	0.23	0.97	0.06	0.27	–
Maximum	54.50	0.60	1.64	7.31	20.09	2.39	11.97	0.37	3.93	–
Minimum	53.77	0.45	1.39	6.80	19.15	1.98	10.12	0.26	3.42	–

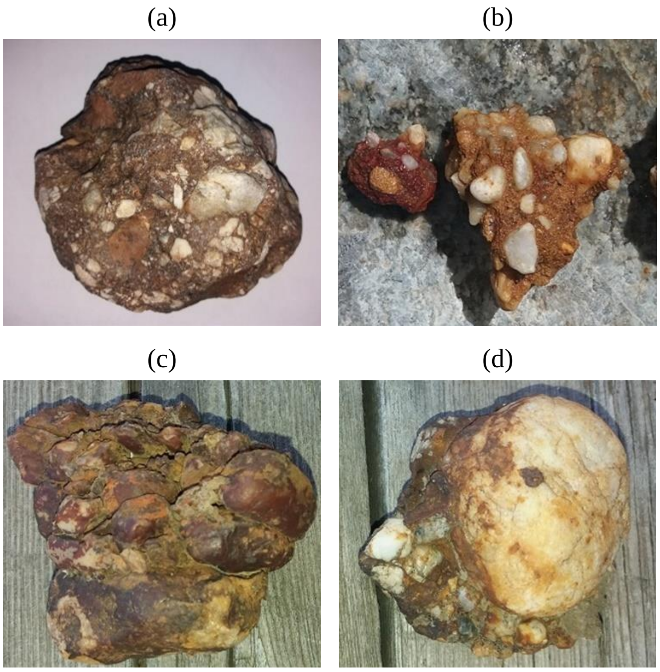

Figure 3. Fragments of a quartz conglomerate from the deposits of the Turangi and Tuzkabak suites: (a), (b) rounded pebbles in conglomerates; (c), (d) fragments of “dissected” pebble materials

The first idea about these conglomerates was that they form a certain layer in the section of the Turangi suite deposits, which may be the marking horizon. However, on-site observations show that these formations occur throughout the entire Eocene section from the Turangi suite base to the Tuzkabak suite roof. This suggests that they are synchronously deposited in the form of fragments with the accumulation of suite deposits during the Eocene period.

The study of available geological materials did not allow the authors to correlate the described conglomerates with the rock complexes of the Southern Altai region. They are probably related to ancient pre-Paleozoic deposits developed in the area of detrital material outcropping.

The Quaternary deposit composition includes Middle-Upper Quaternary undifferentiated, Upper Quaternary, Upper Quaternary-Holocene undifferentiated and modern deposits. They form fragmentarily preserved above-floodplain terraces in the valley of the Bala-Kaljir River. They are composed of pebbles, boulder-pebbles with sandy-loamy filler.

Igneous rocks are developed within the graben frame. They are represented by Devonian ultrabasites, Early Carboniferous intrusive and subvolcanic formations of the Irtysh complex, and granitoids of the Kunush and Kalba complexes.

3. Research methods

This research uses complex research methodologies. New and well-known theoretical research methods in the field of geology of solid and placer minerals, mineralogy, morphology, sampling and processing of samples, ore preparation and beneficiation of minerals are involved to solve the task set.

Geological and geomorphological types of gold-ore deposits have been studied, including those containing fine dust (10 mcm) free native gold in primary ores and weathering crusts developed on them, overlying sedimentary deposits, as well as its minerals and pathfinder elements. When processing sample materials, gold grains of 10-15 mcm in size were collected, even from clay material. The resulting research products were studied under a binocular microscope to determine the possibility of optimizing the technological scheme at the beneficiation stage by the distribution of grains by size and density. The mineralogical-technological research includes the following procedures:

– studying granulometric and mineral composition of detrital material;

– fractional gravitational beneficiation of the source material;

– fractional beneficiation of material pre-processed in the autogenous mill (AG mill);

– studying free (native) and bound gold in beneficiation products, their quantitative assessment.

For rational conduct of the above procedures and obtaining optimal results, a “modular set” of equipment has been developed that consistently performs research work. Modular assembly of laboratory equipment makes it possible to vary the composition of “filling” the equipment satisfying any raw material, up to a three-section configuration, consisting of sample preparation section (washing, crushing, grinding), beneficiation section (screw, magnetic separators, four hydraulic concentrators), microscopic diagnostic section, and computer processing (three microscopes, personal computers, plotter, scanners, etc.).

The research uses certified program "Outokumpu Oy", a complex of physical-chemical methods of analysis: method of scanning electron microscopy using a raster electron microscope, qualitative and semiquantitative X-ray phase analysis on an XIPertPANalytical X-ray diffractometer, titrimetric and atomic absorption methods for determining elements.

Beneficiation is performed using Carla plant ("KRITS-NTK" LLP), in a cascade version – a vibratory screw separator – vibration centrifugal device, which makes it possible to extract all (≥ 10 microns in size) free native gold into the centrifugal device gravity concentrate, and bound gold (inclusions in the rock minerals) into the vibratory screw separator concentrate. The resulting material has been studied by instrumental analysis methods (electron microscopy, X-ray diffractometry).

By the X-ray spectral microanalysis method, the samples are studied using a Superprobe 733 electron probe microanalyzer (JEOL, Japan). The elemental composition analysis of the samples and photography in various types of radiation are performed using an INCAENERGY energy dispersive spectrometer (Inca Energy) from OXFORDINSTRUMENTS Company (Oxford Instruments, England), mounted on a Superprobe 733 electron probe microanalyzer, at an accelerating voltage of 25 kV and a probe current of 25 nA.

4. Results of research on mineral assemblages

As a result of the research performed, following mineral assemblages have been distinguished, differing both in composition and in gold occurrence form: clastogenic, newly-formed hydrothermal, newly-formed hypergene and residual (Table 7).

Table 7. Mineral assemblages of the Takyr-Kaljir site pebbles

Clastogenic	Newly formed		Residual
	Hydrothermal	Hypergene	
Gold, native silver, native bismuth, ilmenite, zircon, rutile, garnet, scheelite, wolframite, rare-earth mineralization (monazite, xenotime, gadolinium silicate)	Gold, dolomite, barite, quartz, galena, sphalerite, rare-earth calcium phosphates, Fe-bearing microspheres, hematite	Gold, calcite, mixed-layer montmorillonite, mica, Fe and Mn hydroxides, X-ray amorphous compounds, decay products of microorganisms (cyanobacterium)	Gold, silver, galena, arsenic pyrite, rare-earth mineralization, amorphous ferruginous-silicate compound

4.1. Clastogenic mineral assemblage

In the clastogenic mineral assemblage, along with free native gold, native bismuth, ilmenite, zircon, wolframite, scheelite, native silver, and rare-earth mineralization have been identified. Gold is characterized by flattened, platy shape with rounded end-type faces. The flatness ratio is > 7.5-10. Figures 4 and 5 show the surface of gold grains with different grain-size classes under an optical microscope and in back-scattered electrons.

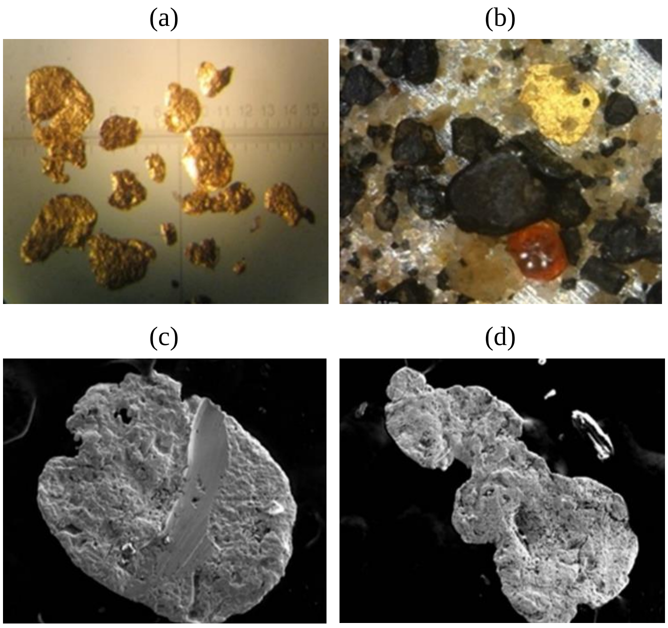

Figure 4. Clastogenic native gold (grain-size class -0.5 + 0.25 mm): (a), (b) under an optical microscope; (c), (d) in back-scattered electrons

The composition of gold grains and other minerals is determined by X-ray spectral microanalysis using a Superprobe 733 electron probe microanalyzer (JEOL, Japan). Almost all gold grains are high-grade (100%) and only one grain has an insignificant (~0.5%) copper admixture.

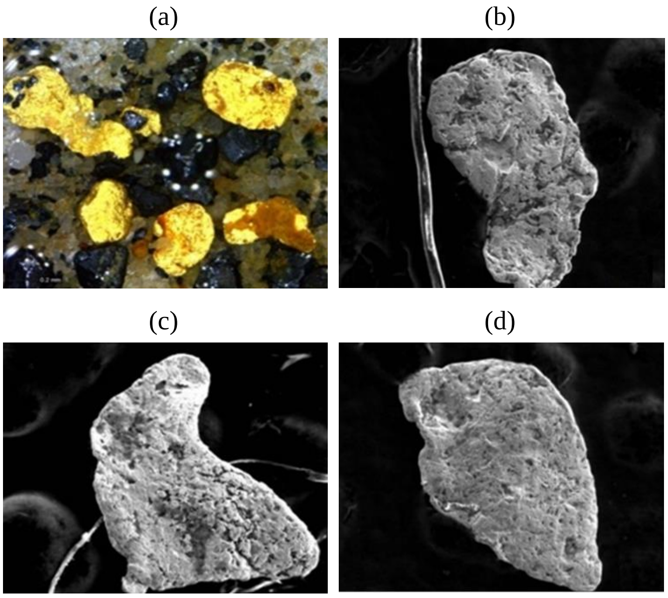

Figure 5. Clastogenic native gold (grain-size class -0.25 + 0.1 mm): (a) the surface of gold grains under an optical microscope; (b), (c), (d) in back-scattered electrons

Thus, typomorphic signs of the gold clastogenic assemblage are platy morphology with riveted grains with rounded end-type faces and high grade (100%).

Native bismuth has been identified among other native metals (Fig. 6). The grains are angular, fine (~0.1 mm). Bi content is 79.12%. There are admixtures of thorium, calcium, iron.

Ilmenite and zircon are the most widespread among other clastogenic minerals (Fig. 7).

Ilmenite – tabular-shaped grains, almost unrounded, fine-grained (80×35×20 mcm). Mineral is of dark gray color. It composition, in addition to Fe (23.80%), Ti (24.35%) has admixtures of Mn (0.78%), V (0.47%), Si (0.68%), and Al (0.34%).

Zircon – perfectly formed prismatic crystals, fine (80×25×10 mcm). Composition is Zr – 50.34%, Si – 17.15%, Al – 0.75%.

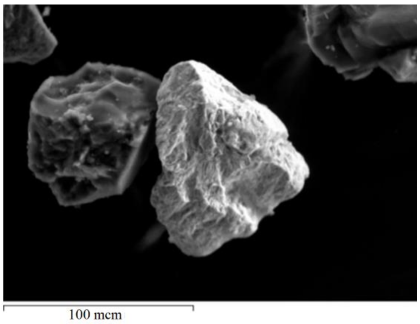

Figure 6. Native bismuth in back-scattered electrons

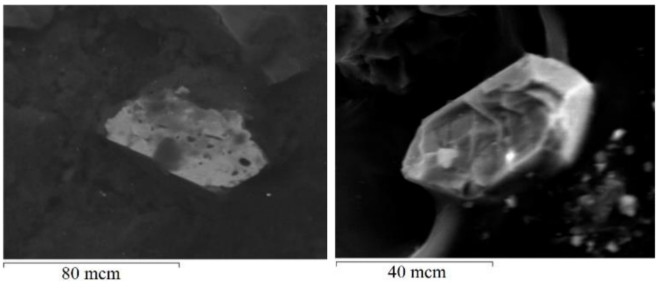

Figure 7. The most widespread clastogenic minerals: (a) ilmenite in back-scattered electrons; (b) zircon in back-scattered electrons

Among other clastogenic minerals that deserve attention as a potential source of rare-metal and rare-earth raw materials are scheelite, wolframite and rare-earth minerals (Fig. 8).

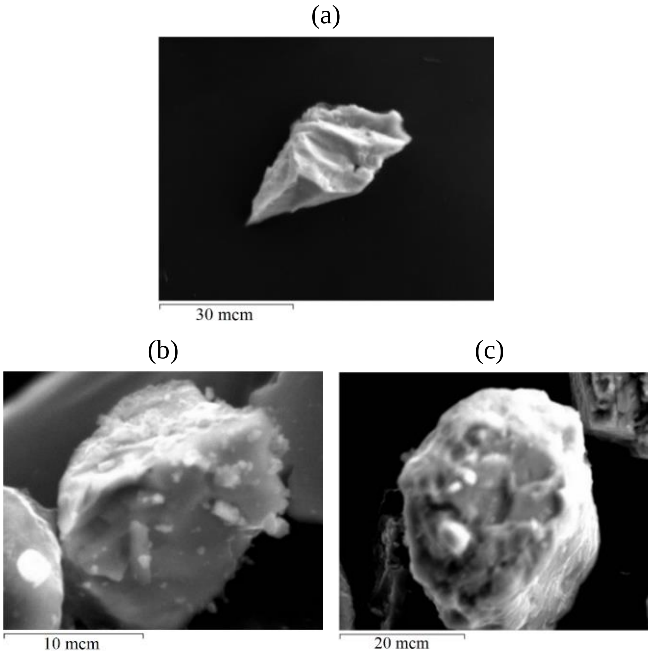

Figure 8. Other clastogenic minerals containing rare-metal and rare-earth raw materials: (a) scheelite under an electron microscope; (b) gadolinium silicate; (c) rounded monazite grain in back-scattered electrons

The results of observation under an electron microscope of each clastogenic mineral with content of scheelite: W – 51.82%, Ca – 11.30%, P – 0.37%; gadolinium silicate: Gd – 46.83%, Ce – 4.20%, La – 3.18%, Si – 14.93%, Ca – 2.89%, Al – 0.75%; rounded monazite grain in back-scattered electrons: Ce – 14.30%, La – 12.20%, Si – 8.13%, ThO_2 – up to 10%, Y_2O_3 – up to 5%, UO_2 – up to 4%, ZrO_2, CaO, SiO_2, SO_3 – up to 5%.

4.2. Hydrothermal mineral assemblage

Hydrothermal newly-formed elements have a fine-grained structure and are distinguished only under an electron microscope in the totality of the shape and composition of the grains. For the first time in coarse-grained (-2 + 0 mm) material, it became possible to identify an assemblage of minerals, which is not typical for placer gold deposits. In addition to free native gold, there are galena, sphalerite, barite, dolomite, iron-bearing microspheres, and calcium phosphates of rare earths – combined into gold – polymetallic with barite and dolomite – rare-earth types of mineralization.

Figure 9 shows the characteristic shapes of the minerals of this assemblage and their composition.

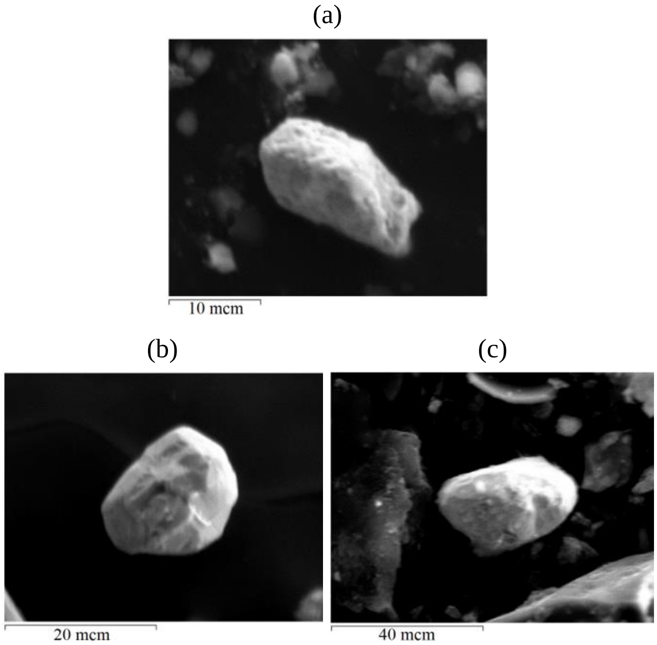

Figure 9. Newly-formed native gold in reflected electrons with sizes: (a) 10 mcm; (b) 20 mcm; (c) 40 mcm

Characteristic shapes of newly-formed native gold minerals in reflected electrons with sizes and admixture contents: 12×8×5 mcm – Au – 90.49%, Ag – 9.51%; 12×15×10 mcm – Au – 98.14%, Ag – 1.86%; 38×20×10 mcm – Fe – 1.03%, Ag – 2.08%, Au – 96.92%.

Gold grains are massive with angular-melted shapes, fine-grained. A distinguishing typomorphic sign of placer gold compared to clastogenic is the constant admixture of silver (from 1.8 to 9.5%). Among other minerals, there are barite, galena and rare-earth minerals (Fig. 10).

Placer gold with identified minerals and compositions: barite, composition: (BaO) 65.7%, (SO_3) 34.3%; galena under an electron microscope, composition: Pb – 87.11%, S – 12.99%; pseudomorphosis of Ag-bearing galena by wolframite, composition: W – 34.86%, Ag – 4.40%, Bi – 12.57%, Pb – 6.15%, S – 6.99%; pseudomorphosis of rare-earth mineral by zircon, composition: SiO_2 – 30.98%, ZrO_2 – 36.9%; rounded xenotime grain, composition: Y_2O_3 – 61.40%, P_2O_5 – 38.60%.

4.3. Hypergene mineral assemblage

Hypergene mineral assemblage has been identified in the quartz-kaolinite aggregate intercalations of the Turangi suite section and in kaolinite-quartz lenses developed in the Tuzkabak suite pebble deposits.

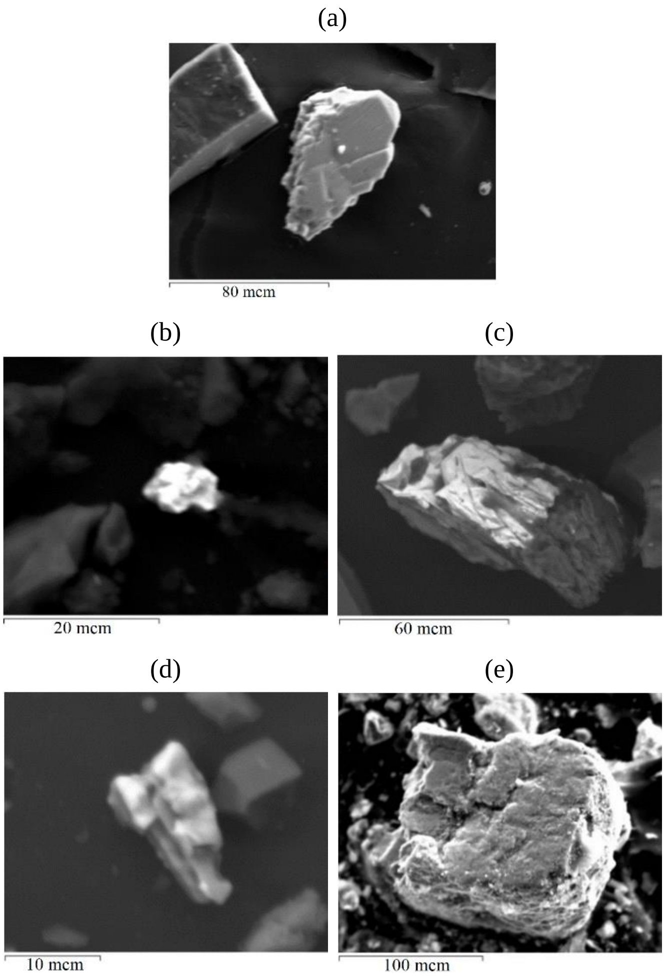

Figure 10. Other minerals identified: (a) barite (80 mcm); (b) galena under an electron microscope (20 mcm); (c) pseudomorphosis of Ag-bearing galena by wolframite (60 mcm); (d) pseudomorphosis of rare-earth mineral by zircon (20 mcm); (e) rounded xenotime grain (50 mcm)

Gold occurs in intercalations composed of fine-grained quartz sand and kaolinite in the form of sporadic leaf-shaped ("foil-shaped") signs of light yellow color with a greenish tint in clay-kaolinite intercalations.

In the clay fraction (-0.044 + 0 mm) of the Tuzkabak suite pebbles, calcite and mixed-layer mica – montmorillonite minerals have been identified, which can be classified as hypergene minerals. The content of these minerals in the clay fraction is over 50% (55.7%), (Table 8).

Table 8. Results of semi-quantitative X-ray phase analysis of the -0.044 mm fraction of the Tuzkabak suite pebbles

Phase name	Formula	Concentration, %
Mixed-layer montmorillonite	K-Na-Al-Si-O-(OH)	35.7
Kaolinite	$Al_2[Si_20_5](OH)_4$	24.5
Quartz	SiO_2	20.0
Calcite	$Ca(CO_3)$	7.6
Muscovite	$Kal_2(AlSi_3O_{10})(OH)_2$	3.9
Albite	$Na(Al\ Si_3O_8)$	2.9

In addition to the described newly-formed elements, the Tuzkabak suite pebbles are characterized by the presence of carbonate crusts containing "secondary bound" gold. Previously, V.L. Sukhoroslov indicated on the gold content of carbonate formations in the Ituri River Valley (Congo Basin, Central Africa) in his study "Peculiarities of the hydraulic network development and formation of gold placers in the Congo River Basin".

4.4. Residual mineral assemblage

The residual mineral assemblage is associated with the cement of quartz-pebble conglomerates, which have been studied on a small scale at the Institute of geological sciences of K.I. Satpayev.

In fact, quartz pebbles do not contain any useful components. More interesting results have been obtained in the study of the cementing material. The study of a polished section from conglomerate cement has revealed that it is composed of grains of quartz, plagioclase and mica, cemented with an amorphous ferruginous-silicate material (Fig. 11). A number of signs observed in the relationship between the detrital material and the cement (matrix), such as the angularity of the debris (Fig. 11), corrosive nature of the relationship between the debris and the matrix (Fig. 12a, b), indicates the aggressive nature of the matrix material penetration (introduction, intrusion) into the original substrate. In some cases, a "rupture" of quartz pebbles by an intruding matrix is observed.

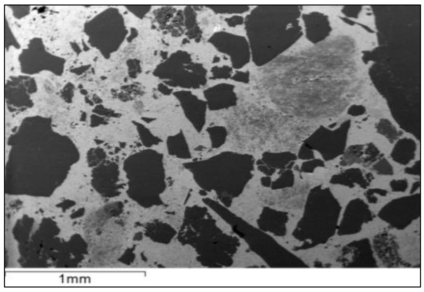

Figure 11. Polished section: shot in back-scattered electrons; the angular character of quartz debris (dark) and almost complete substitution of feldspar grains (shadow contours) are visible

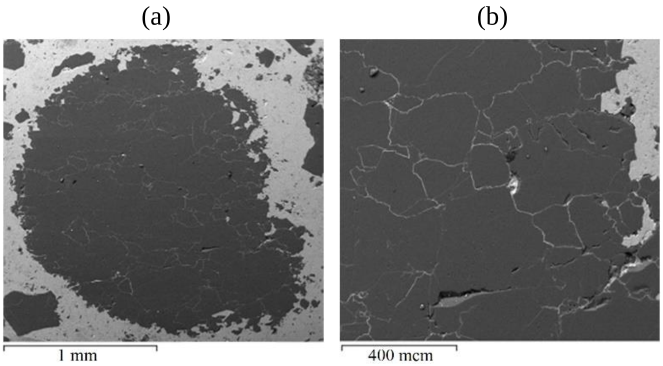

Figure 12. Quartz grain corroded with a ferruginous-silicate matrix: (a) along the periphery; (b) along internal fractures

The mineral composition of cement is determined by X-ray diffraction analysis (Table 9). According to X-ray spectral analysis data, the sandstone matrix has the following elemental composition (Table 10).

Table 9. Results of semi-quantitative X-ray phase analysis of the conglomerate cement material

Mineral	Formula	Concentration, %
Quartz	SiO_2	46.1-85.5
Goethite	$FeO(OH)$	28.1
Hematite	Fe_2O_3	8.2-21.2
Galena	PbS	0-4.6
K-spar	$KAlSi_3O_8$	0-2.5
Pyrite	FeS_2	0-3.8

Table 10. Elemental composition of the quartz conglomerate cement sandstone matrix

Spectrum	O	Mg	Al	Si	P	Ca	Fe	Total
Spectrum 1	40.83	0.06	4.16	4.53	0.50	0.10	49.81	100
Spectrum 2	39.50	–	1.35	2.61	0.46	–	56.08	100

When studying the samples-protocols from the cement of conglomerates obtained by "scrubbing" from quartz pebbles, free native gold in a quantity of up to several signs and arsenic pyrite have been identified (Fig. 13).

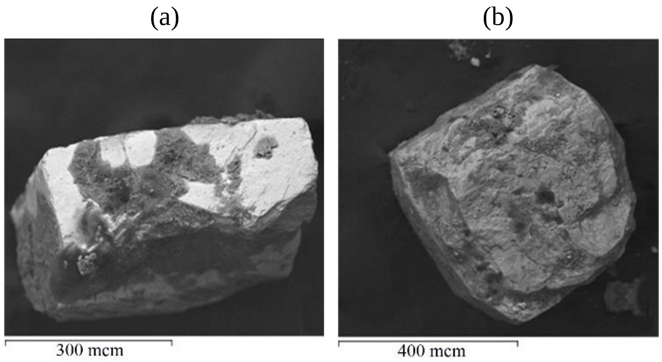

Figure 13. Grains of arsenic pyrite from cement conglomerates in back-scattered electrons: (a) 300 mcm; (b) 400 mcm

Pyrite is coated with a shirt of newly-formed minerals and, according to X-ray spectral analysis, has the following composition (Table 11).

Free native gold with a content of up to 0.33 g/t and silver (up to 172.7 g/t) have been identified in the conglomerate cement. Gold grains are platy, leaf-shaped, and no larger than 0.1 mm in size.

The described gold-silver-bearing conglomerates are undoubtedly similar to the quartz conglomerates of the world's largest Witwatersrand gold-uranium deposit [13]. This alone makes further research on these formations relevant.

5. Analysis of research results

On the territory of East Kazakhstan, for the first time, a placer localized in Eocene deposits constituting the Takyr graben has been studied in detail.

The structure of the gold-producing deposit section has been specified, and for the first time, deposits of the Tuzkabak suite with a complex lithological structure have been identified. The detrital material petrographic composition of both suites in all fractions is identical – it is represented by well-rounded pebbles of grayish, white quartz and sporadic pebbles of quartzites, jasperoids and quartz porphyries. In the strata, hypergene alterations are widely developed, represented by crusts of carbonate and ferruginous composition.

Table 11. Elemental composition of the arsenic pyrite and "shirt" of grains (Fig. 12a), (weight, %)

Spectrum	O	Al	Si	S	Ca	Mn	Fe	As	Total
Pyrite	–	–	–	24.43	–	–	34.53	41.03	100
Shirt	42.05	0.33	1.68	2.17	2.11	1.14	37.17	13.36	100

During the exploration work, "exotic" formations for both suites have been identified – boulders and pebbles of conglomerates and gravels, in which rounded quartz fragments are cemented by dense polymictic sandstones with a ferruginous-siliceous matrix. The size of conglomerate boulders reaches 0.5-0.6 m in the transverse, and the detrital material size in them is up to 4-5 cm in the transverse, which fundamentally corresponds to the dimension of pebbles in the deposits of the Turangi and Tuzkabak suites. The roundness of pebbles in conglomerates is mostly good and similar to that in the rocks of the above-mentioned suites.

Clastogenic, newly-formed hydrothermal, newly-formed hypergene and residual mineral assemblages have been identified, differing both in composition and form of gold occurrence, as well as formation conditions.

In the clastogenic mineral assemblage, along with free native gold, native bismuth, ilmenite, zircon, wolframite, scheelite, native silver, and rare-earth mineralization have been identified. Gold is characterized by flattened, platy shape with rounded end-type faces. The flatness ratio is > 7.5-10.

Hypergene mineral assemblage has been identified in the quartz-kaolinite aggregate intercalations of the Turangi suite section and in kaolinite-quartz lenses developed in the Tuzkabak suite pebble deposits. Gold occurs in intercalations composed of fine-grained quartz sand and kaolinite in the form of sporadic leaf-shaped ("foil-shaped") signs of light yellow color with a greenish tint in clay-kaolinite intercalations.

Hydrothermal newly-formed elements have a fine-grained structure and are distinguished only under an electron microscope in the totality of the shape and composition of the grains. For the first time in coarse-grained (-2 + 0 mm) material, it became possible to identify an assemblage of minerals, which is not typical for placer gold deposits. In addition to free native gold, there are galena, sphalerite, barite, dolomite, iron-bearing microspheres, calcium phosphates of rare earths – combined into gold – polymetallic with barite and dolomite – rare-earth types of mineralization.

The residual mineral assemblage is associated with the cement of quartz-pebble conglomerates, in which quartz, goethite, hematite, galena, arsenic pyrite, and native gold have been identified. The content of gold is 0.33 g/t, silver is up to 172.7 g/t and lead – up to 3%.

The main practical result of the conducted research is the identification of two phase gold varieties in the Takyr-Kaljir site placer sands: free in clastogenic assemblage, mined at the stage of gravitational beneficiation, as well as bound gold in residual and supergene assemblages in gravity tails.

The research results make it possible to reassess the gold-placer potential of ancient (Paleogene-Neogene) graben-like depressions of both the described Southern Altai and adjacent West Kalba gold-bearing regions of East Kazakhstan due to the involvement of gravitational beneficiation tailings in the research on sand fractions.

They also make it possible to adjust the methodology for further exploration and scientific research in order to study the bound gold typomorphism, as well as technological methods for its assessment at the stages of exploration and mining.

5. Conclusions

In the Eocene deposits of the Takyr-Kaljir site, not only clastogenic, but also overlying supergene and hydrothermal gold mineral assemblages, as well as residual gold, silver, rare-metal and rare-earth mineralization, have been identified.

As a technological research result, for each sample, not only the usual weight content of free native gold in sands, but also the amount of bound contents, that is, located in secondary – epigenetic minerals, has been obtained.

The obtained results of sample processing according to the above scheme indicate the following:

– a stable trend of increased gold concentrations associated with secondary minerals, independent of the age of the placers, has been revealed;

– the most interesting results for gravel-pebble material after scrubbing in an autogenous mill are that the yield of sand fraction (-2 + 0 mm) ranges from 11.7 to 20%, gold content from 1.11 to 1.37 g/t; gold is highly gravitational;

– extraction into the combined concentrate (vibratory screw separator – vibration centrifugal device) is 90-95%, and the gold content in the gravity concentrate is from 30 to 85 g/t.

When scrubbing beneficiation tailings, gravity concentrates with a gold content of 30 g/t and higher has also been obtained.

Thus, a technological breakthrough in the processing of placer gold samples is achieved due to the following:

– processing includes all sample material from sands to pebbles;

– additional procedures are involved for scrubbing detrital material from newly-formed minerals in the autogenous mill before beneficiation;

– for the first time, technological and geological-mineralogical parameters have been obtained at the stage of geological exploration: the content of free native gold in source gravel-sand fractions; content of bound newly-formed (epigenetic) gold in gravel-pebble formations and beneficiation sands.

For the first time in the process of sample processing, a chain of devices is used, consisting of a vibratory screw separator and centrifugal concentrators with mechanical activation of the test material in an autogenous mill. It became possible to obtain beneficiation products with free gold of gravity grain-size classes in the form of gravity concentrate and bound gold, as well as dust and nano-sized native gold in the form of gravity beneficiation tailings.

The research results make it possible to reassess the gold-placer potential of ancient (Paleogene-Neogene) graben-like depressions on the territory of Kazakhstan, as well as to adjust the methodology for further exploration and scientific research in order to estimate the reserves of objects at the stage of exploration and mining of the identified deposits.

Acknowledgements

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Полігенна золота мінералізація у кварцовогалькових утвореннях Такир-Кальджирської ділянки (Південний Алтай, Східно-Казахстанська область)

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Мета. Вивчення форм знаходження золота в алювіально-пролювіальних відкладах Такирського грабену для розробки маловідходної ресурсозберігаючої технології їх переробки.

Методика. На першому етапі проведені польові дослідження, в процесі яких уточнено геологічну будову ділянки, проведено відбір проб для мінералого-технологічних досліджень, до складу яких входили наступні процедури: вивчення гранулометричного та мінерального складу уламкового матеріалу; пофракційне гравітаційне збагачення вихідного матеріалу; пофракційне збагачення матеріалу, попередньо обробленого в млині самоподрібнення; вивчення вільного самородного та зв'язаного золота в продуктах збагачення, їх кількісна оцінка. Обробка проб проводилася за тристадіальною схемою із використанням млина самоподрібнення при пробопідготовці.

Результати. Уточнено геологічну будову ділянки, вперше в її межах виділено відкладення турангінської та тузкабакської свит, гранулометричний і петрографічний склади золотоносних відкладень, особливості золотоносності. Уламковий матеріал представлений кварцом з різко підпорядкованою кількістю кварцитів, кварцових діоритів та яшмоїдів і практично ідентичний у всіх фракціях.

Наукова новизна. Вперше в пісках розсипу виділено різноманітні типи золотої мінералізації: кластогенна, новостворена гіпергенна, новоутворена гідротермальна та залишкова. Пофракційне збагачення дозволило оцінити вміст золота у кожній фракції та продуктах гравітаційного збагачення; співвідношення вільного та зв'язаного самородного золота в різних фракціях. Встановлено найбільшу кількість вільного самородного золота у фракціях -0.25 + 0.1 мм (60%) та -0.074 + 0.044 мм (~40%). Золото високопробне (96.5%) з домішкою срібла та заліза. Спільно із золотом встановлені ільменіт, циркон, шеєліт, самородний вісмут, а також барит, галеніт, сфалерит, доломіт.

Практична значимість. Результати досліджень дозволили переоцінити перспективи аналогічних об'єктів, відкоригувати схему та методику обробки шлихових проб, вирішити питання технології переробки продуктивних пісків, а також дозволять підвищити ефективність геологорозвідувальних робіт і виключити "недооцінку" родовищ золота. Отримані результати можуть бути рекомендовані до впровадження як вітчизняним, так і закордонним організаціям, що спеціалізується на розвідці й видобутку родовищ золота.

Ключові слова: *золото, розсип, мінерало-технологічні дослідження, гравітаційне збагачення, мінералогічний склад*