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Typomorphic features of placer gold of Vagran cluster (the Northern Urals) and search indicators for primary bedrock gold deposits

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ABSTRACT

The Vagran placer cluster is located on the eastern slope of Northern Urals. During >100 years of gold mining history approximately 40 tons of gold have been extracted from the placer deposits.

Bedrocks of the region consist of high metamorphic Upper Proterozoic and Paleozoic terrigeneous, terrigeneous-volcanogenic and igneous rocks. Gold placer deposits are mostly alluvial genesis deposits and of Quaternary to Oligocene (?) age. The alluvial deposits consist of gravel with pebbles, boulders, and sandy clay covered by sandy silt and a soil layer. The thickness of the alluvial sequence is usually 5–10 m and reaches 18 m in the main watercourses of the third order. Nearly all of the alluvial sediments are gold bearing but concentrations of economic importance prevail in the bottom part of the sequence above the bedrock.

There are four different types of gold particles: (I) rounded and well-rounded particles of high fineness and homogeneous inner structure, (II) rounded to sub-rounded high fineness particles with a pure gold rim developed over a core, (III) crystallomorphic (idiomorphic) high fineness with a homogeneous inner structure, and (IV) irregular angular and subangular particles of medium fineness with a significant content of Ag (10–40 wt.%) and elevated Hg (up to 1.15 wt.%).

The first type is prevalent and comprises up to 65% of the total gold particles; it is uniformly distributed throughout the territory. There are features with initially complicated dendritic and laminar shaped particles which were rounded during transportation. The second and third types have a propensity for zones of the inherited erosion–tectonic depressions. Apparently, types I, II and III are related with orogenic mesothermal gold-sulfide-quartz mineralization; the differences of these types depend on the primary zonation of ore bodies and supergenic transformation of the alloys. They were connected with middle-depth ore bodies of an orogenic gold-sulfide-quartz formation. The fourth type is evident of nearby transportation from primary sources and a short duration of supergenic influence. It is controlled by a zone of NW-SE orientation, diagonal to the main structures of Ural Fold Belt.

The plot of Au content *vs* coefficient of heterogeneity (ratio of the Au content in the core and in the rim of the grains) is the distinguishing factor between the four types of gold grains both by primary hypogenetic characteristics and supergenetic features.

No corresponding lode occurrence of gold-sulfide-quartz mineralization has been identified to date in this region. Placer gold concentrations are related to the intermediate hosts of the Mesozoic-Cenozoic surfaces of the Ural peneplain uplift in the Oligocene and eroded in Miocene-Quaternary time. This factor determines the widespread distribution of placer gold in the territory of the Vagran cluster.

The large, Carlin-type Vorontsovsk gold deposit is located 60 km south-east from the Vagran area. It has a shallow erosional level, small size of native gold, and its distal location from the placer deposits makes it an unlikely primary source for the Vagran placers. However, mineralization of this type of deposit is noted within the cluster.

Gold of the fourth type nearly resembles the gold of the Vorontsovsk deposit and, apparently, the source is related to the same hydrothermal mineralization event. ICP MS analyses of the quartz-sulfide lodes in the floor of gold-bearing valleys revealed a gold content of 2.0–6.9 g/t in the zone of type IV distribution. Therefore, gold of the fourth type can be used as an indicator for the exploration of primary bedrock mineralization. The

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geological setting and typomorphic features of this placer gold shows that the primary gold mineralization is similar to the Vorontsovsk deposit and within the zone of distribution of the placer gold of the fourth type.

1. Introduction

Gold mining in Russia began in 1745 when the large Berezovsk gold–quartz deposit (Berezovsk Mines) was discovered in the Middle Urals region 13 km from Ekaterinburg. During 250 years of exploitation it produced approximately 300–350 t of gold. The first placer gold was found in the valley of the Chusovaya River (Middle Urals) in 1771. The discovery of the Beryozovsk gold deposit and numerous placers during the first half of the 19th century catapulted the Ural region into becoming the leading world supplier of gold, later eclipsed by discoveries of gold deposits in Australia, South Africa and North America (Bache, 1987; Boyle, 1987). Currently, the Ural region contains 570 t (both primary and placer deposits) of measured & indicated resources and approximately 400 t of inferred resources, which is 4.6% of the total gold resources of Russia (State Report, 2014).

The total volume of mined gold in Russia during last 250 years is an estimated 12,000 t, and approximately 80–85% was mined from placer deposits (Benevolsky, 1995). Placer deposits dominated the balance of Russian gold mining until the final quarter of the last century. Even now, as the majority of placer deposits are exhausted, the share of placer deposits in the total volume of Russian measured resources is 13.8% while the share in total mining in 2012 was 23.7% (Lalomov et al., 2015). Thus, placer gold deposits have not only been of economic importance in the present day, but specific features of the gold particles in placers can also be employed for the exploration and evaluation of primary bedrock gold deposits (Dill et al., 2009).

Several exploration attempts to locate bedrock ores in the Vagran cluster have yielded negative results and primary gold sources of placers remain undiscovered (Sazonov et al., 2011; Petrov, 2014). The generally accepted theory is that significant erosion of nearly 1500 m of material occurred since the Oligocene; all primary ore bodies were disintegrated in the weathered crust, eroded, and then re-deposited onto current surfaces (Lalomov et al., 2010). Research of geology and geomorphology of the study area, as well as typomorphic features of placer native gold has enabled a retrospective reconstruction of the history of the cluster, detection of the sources of placer gold (primary bedrock ore deposits and intermediate hosts), and the forecasting of new placer deposits and possible bedrock gold ores.

2. Geology and metallogeny of Middle and Northern Urals and Vagran cluster

2.1. Geological structure, tectonics and metallogeny

The Ural Fold System experienced two main complete cycles of geodynamic evolution in the Riphean–Mesozoic time. The first one took place in the Riphean and Vendian periods and was completed by the formation of the Timanides; the second, dated as Paleozoic–Early Mesozoic, belongs to the Uralides and can be divided into eight stages: (1) Continental riftogenesis (Cambrian – Early Ordovician), (2) Oceanic spreading (Middle-Late Ordovician), (3) Main subduction (Late Ordovician – Early Carboniferous), (4) Early collision (Late Devonian – Early Carboniferous) between the Magnitogorsk island arc and the passive margin of the Laurussia continent, (5) Late subduction of a relict oceanic crust of the Paleouralian ocean (Early-Carboniferous-Bashkirian), (6) Collision of the Laurussian and Kazakhstanian continents, (7) A limited post-collisional extension and superplume magmatism (Triassic), and (8) Thrust-and-fold deformation in the Early Jurassic time (Puchkov, 1997, 2016; Brown et al., 1997, 2002, 2011; Ivanov et al., 2013).

In the study area, the lower complex (Baikalian) is represented by Riphean metamorphosed sandstone, quartzite, and carbonaceous black shale with interlayers of metabasalt. The upper complexes (Hercynian) consist of Ordovician – Lower Silurian volcanogenic-sedimentary sequences with carbonaceous black shale, phyllite and metamorphosed gabbro of the Lower Ordovician, greenschist with carbonate interlayers of Middle Ordovician, metabasalt and tuff of an effusive origin metamorphosed to greenschist and amphibolite with concordant quartz dioritic porphyry of the Upper Ordovician. The Lower Silurian consists of basic tuff, diabase, andesite-basalt porphyry, and gabbro sequences with granitoide and plagiogranite dykes (Fershtater et al., 1997; Fershtater, 2013).

The Vagran cluster is located in the south part of the Isherim anticlinoriums, on the border of Central-Uralian and Tagil megazones, and to the west from the Main Uralian Fault (MUF) (Ivanov et al., 1975; Puchkov, 2013). The MUF is a tectonic structure of the first order that determines the principal geological features of the area. Faults of the second order have sub-latitude orientation; they divide the megazones into a few tectonic blocks. The current tectonic structure is represented by a complex folded-thrust system with inverted isocline folds of various orders (Herrington et al., 2005a, b).

The Vagran cluster is a part of the Sur'ya-Promyslovsky and Ashkinskaya metallogeny zones (Fig. 1). The structure contains complexes of paleoshelf (Middle-Upper Riphean; Middle Ordovician – Middle Devonian), riftogenesis (Upper Riphean), oceanic (Ordovician), and collisional (Upper Paleozoic – Lower Mesozoic) geodynamic settings.

The Ural Fold Belt contains numerous gold deposits of various types: intrusion-related, skarn, hydrothermal orogenic, “black shale”, Cu-Au-porphyry, VMS, epithermal low, and high sulphidation, *etc.* (Smirnov, 1977; Bortnikov et al., 1997; Lehmann et al., 1999; Kisters et al., 1999; Kisters et al., 2000; Plotinskaya et al., 2009; Soloviev et al., 2012). The two types of primary gold mineralization (“black shale” intrusive-related and Carlin-type) that are correlated to the placer deposits are represented in the Vagran cluster and surrounding area.

Gold mineralization in the black shales of the Upper Riphean Ashkinskaya and Ordovician Sur'ya-Promyslovsky zones is influenced by conjugate shear zones and fault disjunctive structures, formed in the upper intrusive zone of a granitoid body at the depth of 2 km, according to geophysical data (Petrov, 2014). Au mineralization is fixed in quartz veins, their selvages, and associated metasomatites and is represented by native gold in veins, metasomatites, and oxide sulfides. The gold contains Ag (15–20 wt.%) and Cu (0.03–0.1 wt.%) (Sazonov and Velikanov, 2010). Primary gold mineralization in the black shales is associated with pyrite and carbonaceous substances and is dated as Upper Riphean. Zones of black shales are prospective for gold mineralization of the Sukhoi Log type (Sazonov et al., 2011). Then, in the course of greenschist metamorphism (during the collision period), formation of “secondary” collectors of Au occurred. This stage is assigned to the Devonian (Necheukhin, 1998). Following this stage of Permian regional metamorphism, the gold mineralization of a “berezite” (quartz-sericite-carbonate-pyrite) type was formed in a depth of not >2 km at a T of not >340 °C. (Sazonov and Velikanov, 2010). Similar berezite-like alterations and vein structures occur and are typical for the Urals (Koroteev et al., 1997; Sazonov et al., 2001) and other regions of the world (Hutchinson, 1993). In spite of this presence of gold occurrences and points of mineralization, primary gold deposits of the black shale type have yet to be discovered on the Vagran cluster and surrounding area.

The Vorontsovsk gold deposit ascribed to the Carlin-type is the most proximate to the studied district. It is situated 45 km south-east from

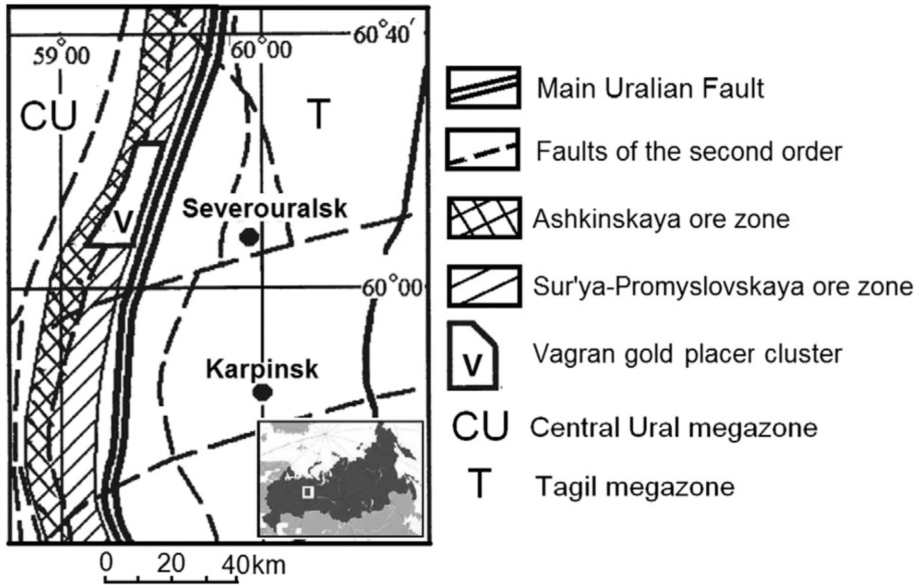


Fig. 1. Location of the Vagran gold placer cluster in the tectonic structures of Middle and Northern Urals from Sazonov and Velikanov (2010).

the Vagran placer cluster. The ore field is localized in an andesite volcanic belt of Early-Middle Devonian time and in a slightly sloping monocline of a north-west dip. The ore bodies are confined to a contact of underlying limestones and overlying volcanogenic sedimentary rocks. The rocks are intensively brecciated, silicified, and argillized along the contact. The ore deposit consists of slightly sloping metasomatic gold-bearing zones with disseminated and veinlet quartz-sulfide gold mineralization (Sazonov et al., 1998; Murzin et al., 2010). Three of the explored ore bodies contain 90% of the resources. One body consists of oxidized ore and two other of primary, unaltered ore. Bodies of the second order accompany the main ore bodies on the hanging and foot walls. Gold mineralization has been traced laterally within 3 km and 500 m along dip. The upper zone to the dip of 10–80 m is represented by friable oxidized ore which contains approximately 30% of the total deposit resources. Ores of the lower zone (70% of total resources) have a carbonate and silicate character. The ore contains 3–8% of disseminated and veinlet sulfides (pyrite and arsenopyrite with cinnabar, realgar and orpiment) (Ridziunskaya et al., 1995; Cheremisin and Zlotnic-Khotkevich, 1997).

Native gold is in the fine size class and ranges from 0.001 mm to 0.07 mm in size. Fineness varies from 910–998 for the early gold to 680–690 for the gold of later generation; content of Ag in the alloys is up to 30%. The content of Hg reaches 1–4%. The gold has a positive correlation with Ag, As, Hg, Co, Ni, Pb, Ba in ores. In the oxidized ores the content of sulfides is $<1\%$ (Savelieva and Nesbitt, 1996; Sazonov et al., 1998, 2001; Bortnikov and Vikentyev, 2013; Vikentyev and Vikentyeva, 2015). The total volume of the measured resources is 18.4 t at gold content 12.4 g/t (State Report, 2014), or approximately 60 t at gold content 2.8 g/t (Vikentyev and Vikentyeva, 2015).

2.2. Late Mesozoic to Quaternary geological history of the region

The major factors which defined the development of relief and weathered crusts of the Urals and the formation of the placer deposits were tectonics and climate. In the beginning of the Triassic, the Urals Hercynian mountain system was nearly completely eroded and the territory began to develop the platform regime.

According to A.P. Sigov (1971), five tectonic-climate stages are allocated to the Mesozoic and the Cenozoic. The first stage from the beginning of the Triassic to the Upper Jurassic was characterized by moderate tectonics and a tropic to sub-tropic climate with developing tectonic depressions that filled with thicknesses of coal-bearing deposits. The second stage, proceeding from Early Jurassic to Oligocene, was characterized by a stable tectonic situation in the area of the Ural fold system and slow epeirogenic-negative tectonic movements in the adjacent areas. The climate of the second stage was warm and damp which resulted to a smoothing of the relief, intensive weathering, and the formation of kaolin weathered crusts from 10–20 to 100 m thick. Existence of the relicts of two stages of peneplanation (Mesozoic and Paleogene) is evidence of the periodic tectonic movements of the Ural Mountain Belt (Shub et al., 1998; Puchkov, 2010).

Insignificant activation of tectonic movements at the end of this stage led to the formation of meridianal oriented erosion-structural depressions and *in situ* accumulation of weathered, but dynamically unsorted, detrital material. Mesozoic and Early-Middle Paleogene placers of gold, platinum and titanic minerals are connected with these depressions. The surfaces of a Mesozoic and Paleogene peneplain are allocated on the watersheds and highlands (Sigov, 1971; Puchkov, 2010, 2013).

During the third (Oligocene) stage there was a neotectonic activation and block uplift of the Ural Fold System that led to the formation of the mountains, erosion of the weathered crusts and re-deposition of detrital material into a system of valleys which produced erosion-structural depressions (Sigov, 1971). Initial uplifting of the mountain system resulted in erosion of the weathered crusts, separation of the eroded material in the series of regressive coastal zones of West-Siberian Oligocene basin, and the formation of rare-metal – titanium placer deposits (heavy mineral sands) (Patyk-Kara et al., 2009).

At the fourth stage assigned to the Miocene there was an advancing denudation of mountain areas against moderate, positive tectonic movements (Rozhdestvensky and Zinyakhina, 1997).

During the fifth (Quaternary) stage there was a stabilization of the topography and formation of alluvial deposits of modern valleys. It was followed by an active hydrodynamic processing of a substantial volume of detrital material and formation of Quaternary gold and platinum placers. In the raised blocks the weathered crusts were nearly completely eroded. Relics of weathered crust remained on the watersheds, highlands, and in the lowered blocks connected with the negative tectonic movements within erosion-structural depressions (Sigov, 1971; Ivanov et al., 1975; Puchkov, 2013).

3. Sample collection and analysis

The research consisted of four different parts: geomorphology of the cluster, lithology of alluvium, collection of heavy mineral samples of alluvial, slope and eluvial sediments over an area of approximately 400 km^2, and selective collection of samples of quartz-sulfide veins and zones of silicification for study of the hydrothermal alteration.

Bulk samples of the river valley sediments each with an approximate weight of 20 kg were taken from native outcrops, stream beds, river spits and gold mine pits. Hand-panning was carried out in the field to reduce the weight of the sample and to obtain 20–30 g of heavy mineral concentrates. For the final concentration the gold grains were separated by heavy liquid in the laboratory of IGEM RAS. Technicians logged and washed 22 samples originating from 13 localities and received 372 grains of placer native gold (Fig. 2). The analyses of the samples from one locality were averaged.

Informed speculation on the nature of the source bedrock mineralization is possible through comparison of the microchemical signature of placer grains with the generic characteristics of gold from different styles of mineralization. This is especially important in the areas of poor exposure (Chapman and Mortensen, 2006); therefore, the study of placer gold grains morphology, inner structure, and inclusions was compared with documentation of the available and possible bedrock gold mineralization.

Obtained gold grains were studied for morphology and divided into 4 morphological types (Table 1). Back-scattered-electron (BSE) images of the gold were taken for 94 original grains using a Scanning Electron Microscope (SEM) GSM 5610LV.

After SEM the grains were studied for composition, inclusions, and inner structure. The grains were mounted into resin blocks, and the blocks were ground and polished to provide a cross-section through every grain.

The grains were later analyzed by electron microprobe at the Analytical Laboratory of IGEM RAS (Moscow, Russia) using JEOL JXA-8200 electron microbrobe (Japan) with five wavelength dispersive spectrometers and an energy dispersive spectrometer under the following operating conditions (Table 2) by analyst E. Kovalchuk.

The composition of 112 Au grains was analyzed twice for every grain (in the rim and in the core).

Silver is present above the detection limit (3 σ) of 0.037% in all grains. Cu and Hg was above the detection limits (0.06% and 0.1% respectively) in the cores of 53 particles (47%) and 9 particles (8%), respectively. Additionally, inclusions and grains with pronounced rim-core zoning were studied in detail with SEM and energy dispersive spectrometer INCA-Energy 450.

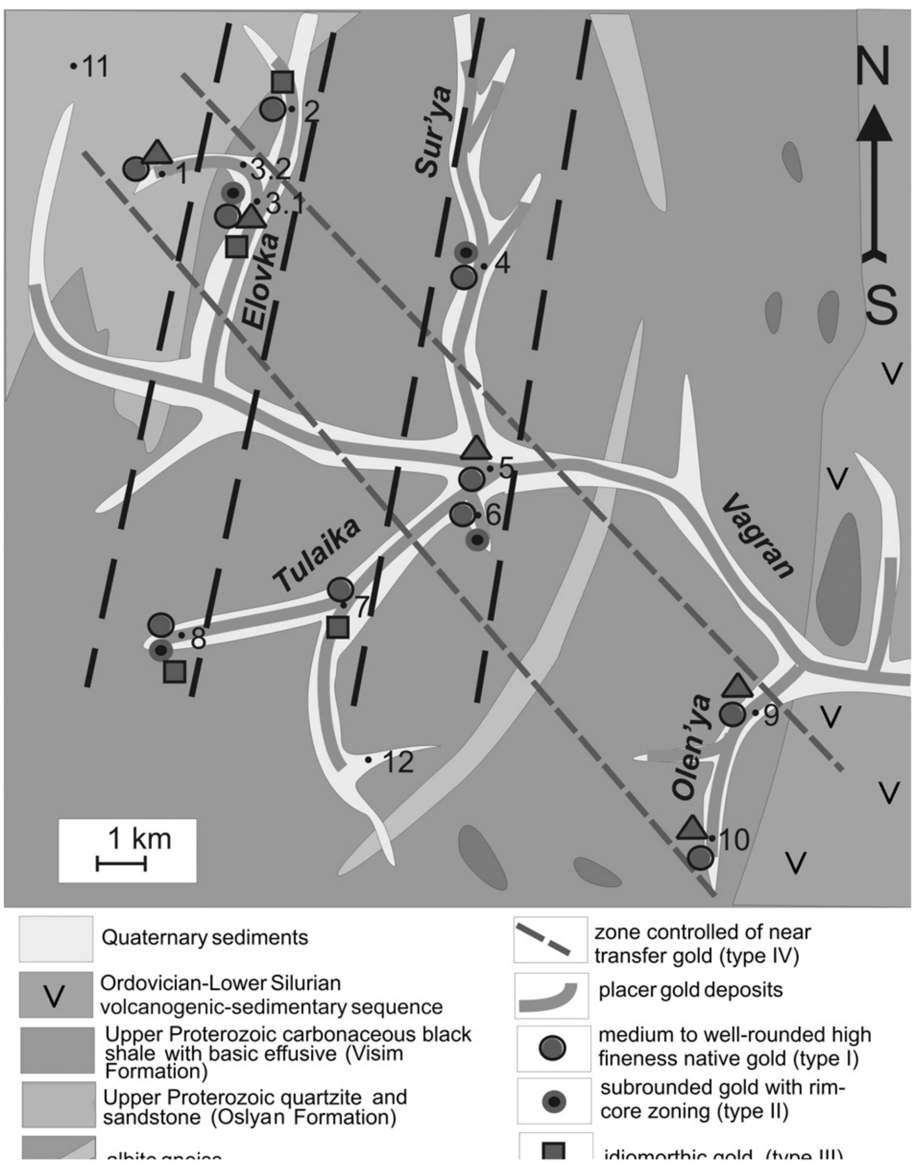


Fig. 2. Geological map of Vagran gold cluster with placer gold metallogeny (based on the Geological report, 1967) with data from current research that demonstrates the distribution of various types of the placer native gold over the territory of the cluster. The zone of NW-SE trend indicates the location of the gold with short transport indicators.

Table 1
Number of sampled gold grains of various morphological types.

Localities (see Fig. 2)	Number of gold particles of various size			Morphological types			
	>0.5 mm	<0.5 mm	Sum	Rounded to well-rounded (I)	Sub-rounded (II)	Idiomorphic with smoothed edges (III)	Angular to subangular (IV)
1	12	14	26	22	0	0	4
2	6	13	19	14	0	5	0
3.1	28	68	96	57	22	14	3
3.2	19	32	51	28	9	5	9
4	12	26	38	32	6	0	0
5	3	10	13	7	2	0	4
6	8	12	20	14	5	0	1
7	14	20	34	33	0	1	0
8	13	25	38	22	7	9	0
9	7	13	20	11	0	0	9
10	4	13	17	4	0	0	13
11	0	0	0	0	0	0	0
12	0	0	0	0	0	0	0
Total	126	246	372	244	51	34	43

The composition of bedrock samples were analyzed using inductively coupled plasma mass spectrometry (ICP-MS). Au, Ag, Cu, Te, Bi were assayed in Laboratory of IGEM RAS by ICP-MS, X-series II, Thermo-Scientific, by analyst Y·Bychkova. As was analyzed in the laboratory of Moscow State University, ICP-MS Element 2, Thermo-Scientific, by analyst Y·Bychkova. Hg was assayed by direct mercury determination by thermal decomposition, amalgamation and atomic absorption detection by UMC-1MC (EcON Lab., Moscow State University, analyst R. Mukhamadiyarova).

4. Gold mineral deposits of Vagran cluster and surrounding area

4.1. Geomorphology of territory, lithology of host Cenozoic-Quaternary deposits and gold placers mineralization

The Vagran cluster is situated in a transition zone from the mid-mountain area of the Main Ural Ridge to the hilly piedmont of the eastern slope of the Urals. Gold placers are located in valleys of 1–3 orders. The length of gold-bearing valleys reaches 20 km. The width changes from 0.2 km for valleys of the first order to 1–1.5 km for valleys of the third order. The watersheds are flat, smoothed, and their extent over the bottoms of valleys does not exceed 50–100 m. Practically all valleys, except for upper parts on the valleys of the first order, are in an equilibrium state between the erosion and deposition of detrital material. The current valleys of the creeks Sur'ya – Tulaika and Elovka inherit the zones of erosion-structural depressions.

The sedimentary deposits of the valleys generally present medium and coarse-grained alluvium. In the bottoms of valleys, upon transition to bedrock, the eluvial horizon is commonly observed to contain angular particles of quartz grus and clay. The lateral perimeters of the valley slope deposits consist of sandy clay with subangular pebbles and angular stones of the local rocks. In the central part of the valleys and on terraces the detrital deposits are overlain by a soil layer.

Table 2
Measurement conditions of electron microbrobe analysis.

	Ag	Au	Hg	Cu	Fe
Accelerating voltage (kV)	20	20	20	20	20
Sample current (nA)	20	20	20	20	20
Beam diameter (μm)	1	1	1	1	1
X-ray	Lα	Lα	Mβ	Kα	Kα
Crystal-analyzer	PETH	LIF	PETH	LIF	LIF
Time on peak (s)	20	20	20	20	20
Time on back (s)	10	10	10	10	10
Standard name	$AgSbS_2$	Au_s	HgS_s	Cu_s	$CuFeS_2$

Alluvial deposits are presented by Quaternary gravel with pebbles, boulders, and sandy clay. The pebbles consist mostly of local Upper Paleozoic metamorphic terrigeneous rocks (sandstones and shales), rarely from the rocks of Ordovician-Silurian volcanic complex. The presence of volcanic pebbles in the Elovka and Sur'ya valleys indicate that rocks of the volcanic complex covered the territory before last erosion cycle.

Two cycles in a Quaternary sequence structure are observed (Lower Quaternary Q_1 and Middle-Upper Quaternary to Holocene Q_{2-3}–Q_4). Gold placers of economic importance are concentrated in the deposits of the Q_1 cycle. Upper cycle deposits rarely contain significant gold concentrations. In the Vagran River valley, paleo-thalweg with gold-bearing Oligocene (E_3) (?) sediments are confirmed by drilling. The depth of the paleo-thalweg below the bottom of Quaternary valley is 5–8 m. The standard thickness of the alluvial sequence is approximately 5–7 m and extends 10–15 m in the main valleys of the third order (Geological report, 1967).

Placer deposits are confined to the valley equilibrium and erosional states. In the valleys that are in the accumulative stage, the placer deposits are buried under thick, barren sequences. In the cross section of the valley, the placer bodies are located in the deepest central part and on the lateral terraces (Fig. 3).

According to the data from Geological report (1967), gold belongs to large and medium size classes, from 25.3 to 79.7% (average 57.3%) of gold is in a class >0.5 mm (Table 3). According to our data, the content of the size class >0.5 mm varies from 23.1% to 46.2% (average 33.9%) (Table 1). Apparently, the smaller size of our analyzed placer gold is related to the optimal extraction of the small classes of the gold using heavy liquid.

The fineness of the gold is 880 to 980. The alloys contain Ag and some trace admixtures (Cu, Hg). Placer gold of Olen'ya Creek is an exception with a fineness of 840–890 due to a higher content of Ag and partly Hg. Gold grains of a size class >0.5 mm are mainly well-rounded, however subangular grains sometimes occur. Small grains (<0.5 mm) are rounded to subrounded. The shape of the grains is mostly irregular, spherical to semi-sherical, and flattened. The surfaces of the grains are generally rough, smooth-pitted with branching-coral type features, hackly to grainy and irregular lobate in the classification of Groen et al. (1990). The gold of Olen'ya Creek is mostly irregular and subangular (up to 80% of the particles) with smooth surfaces.

4.2. Bedrock gold mineralization of Vagran cluster

Sampling of bedrock was not the goal of the current research, but we took two samples of quartz-sulfide lode mineralization from the bottom of the placer pits in locality 3.1 (Elovka Creek and Olen'ya Creek) and between localities 9 and 10. The mineralization of locality 3.1 in the

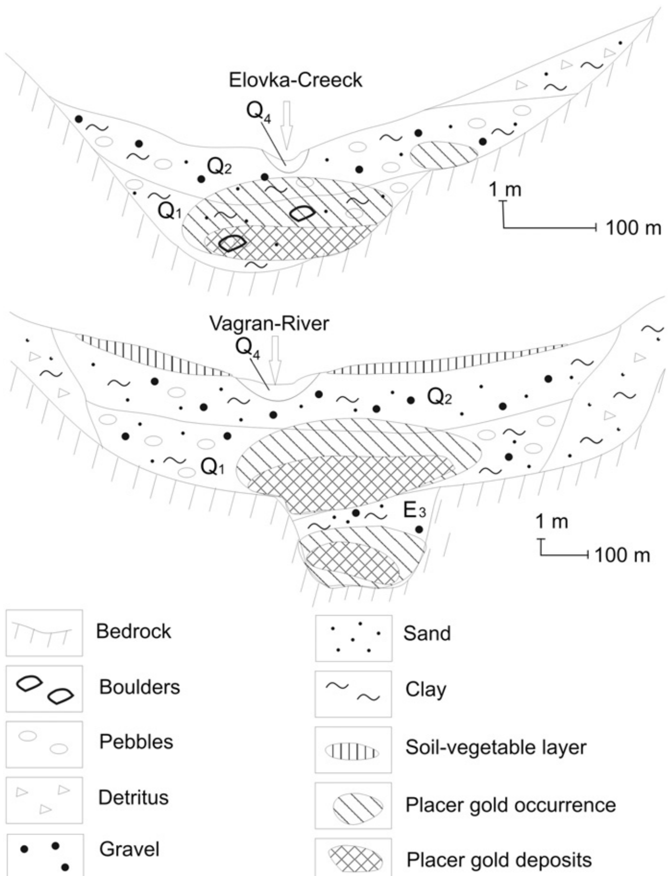


Fig. 3. The generalized cross-sections of alluvial deposits of Elovka Creek (second order) and Vagran River (third order) (based on Geological report, 1967). Valleys of the second order had a two-cycle development assigned to the Lower Quaternary (Q_1) and Middle Quaternary (Q_2) – Holocene (Q_4) stages. In the valleys of the third order, the third Oligocene (E_3) cycle deposits are located in the paleo-thalweg. Placer gold is associated mainly with Oligocene and Lower Quaternary deposits of the central part of the valleys, and is rarely located on terraces.

bedrock of the currently exploited pit is represented by thin (up to 1–1.5 cm) veinlets of milky-white quartz and zones of silicification of green schists with rare inclusions of pyrite of 1–2 mm. A secondary sample was obtained from the dump of a placer pit in the middle part of Olen'ya Creek. The dump consists of angular schist and quartz detritus with brown-red ocherous clay of eluvial genesis. The quartz has a cavernous texture with iron oxides located in the cavities and is the result of sulfide oxidation. Results of ICP MS analyses are represented in Table 4.

Quartz of Olen'ya Creek contains an increased content of gold, up to economic importance, though gold content in Elovka sample also has a prospecting interest. The content of Ag and Cu is higher in the Elovka sample, while Te and Bi are observed in approximately equal concentrations. Hg prevails in the Elovka sample, whereas as As prevails in the Olen'ya sample. The high content of As indicates the presence of arsenopyrite.

Table 3
Grain size of the gold grains in placers of Vagran cluster (Geological report, 1967).

Placer	Content (%) of the size class (mm)							
	>5	3–5	2–3	1–2	0.5–1	0.25–0.5	0.1–0.25	<0.1
Elovka	1.8	5.3	12.8	24.5	27.1	20.6	7.5	0.4
Sur'ya	9.2	15.1	13.5	21.3	20.6	19.4	0.9	0.0
Tulaika	0.0	2.9	9.6	28.3	22.2	30.1	6.8	0.1
Olen'ya	0.0	0.0	1.8	10.6	12.9	44.1	30.1	0.5
Vagran (proximal part)	0.0	4.0	14.2	18.1	21.5	33.2	9.0	0.0
Vagran (distal part)	0.0	0.0	4.0	25.5	17.2	37.0	16.0	0.3

Table 4
ICP MS analyses of bedrock quarts-sulfide mineralization.

Locations (Fig. 2)	Content, ppm						
	Au	Ag	Cu	Hg	Te	Bi	As
Elovka Creek, locality 3.1	2.0	3.6	41	0.105	0.64	1.2	107
Olen'ya Creek, between localities 9 and 10	6.9	1.7	11	0.051	0.71	1.6	223
Relative standard deviation (%).	4	4	3	1.5	5	3	2

An occurrence of vein-disseminated sulfide mineralization with a gold content of 8 g/t and platinum of 3.7 g/t was discovered in the headwater of Sur'ya Creek. This occurrence was ascribed to the "black shales" mineral deposit type (Petrov, 2014).

5. Typomorphic features of the placer gold of Vagran cluster

The four types of native gold observed in the Vagran cluster are classified by morphology, composition, microchemical signature, and internal structure (Figs. 4, 5, Table 4).

The first type (I) is classified as medium to well-rounded particles of high gold fineness (more 880). The coefficient of roundness is calculated as the average roundness of all particles of this type, estimated visually by a 5 tiered grade scale (from angular equal to 0 to well-rounded equal to 4) for every particle, is 2.7. The grains are of a spherical to wafer and flake shape. The surface of the grains is rough, rarely slightly smooth, and pitted (Fig. 5A). The inner structure is vuggy, spongey, and a laminar to homogeneous character. The fineness of the gold varies from 889 to 973. Silver is a permanent component of the alloy and it varies from 2 to 12 wt.%. Copper is the most frequent trace element - in 25 of 52 studied grains the Cu content is above the detection limit, up to 1.08 wt.%. The mercury content exceeds the detection limit in 1 grain (0.27 wt.%). The alloys of this type have a monotonous geochemical structure; neither a gold-rich rim nor inclusions were observed in the grains (Fig. 5A). Gold particles of the type I amount approximately 2/3 of total Vagran cluster placer gold; the grain content of this type in different localities vary from 24% to 97% (Table 1).

The research conclusions of the alloy inner structure are represented in Fig. 5. For populations of homogenous gold grains, duplicate sampling generates reproducible data (Chapman et al., 2010b). In order to establish the degree of heterogeneity within both heterogeneous and apparently homogeneous grains, it is necessary to analyze it at five-point locations in their sections (Chapman et al., 2011), therefore the inner structure of the complex alloys was studied at several points.

The second type (II) is represented by rounded to subrounded gold grains, with a rough to slightly smooth surface. Occasionally they are of a wired bent and semi-bent shape. The analysis of the inner structure of polished grains reveals rim-core zoning that has a sharp border to the core (Fig. 5B, C). The contents of Au, Ag and Cu in the grain core is approximately the same as in the type I: the gold content in the core varies from 90 to 96 wt.% (average 93.11 wt.%), silver – 2.95–10.31 wt.% (average in the core 6.38 wt.%). The content of copper in the core exceeds the detection limit in 13 out of 20 samples and up to 1.02 wt.% (average 0.16 wt.%). Mercury above detection limits was not observed.

The concentration of gold in the rim and gold-rich inner fracturing zones reaches 99.7 wt.% with silver contents of 3.81 to 0.37 wt.% (average 1.31 wt.%) with a complete absence of Cu and Hg. The coefficient of heterogenity (ratio of rim/core concentrations of gold) varies from 1.02 to 1.11, with an average 1.06.

Gold of the second type settles within the erosion-structural depressions that partially correspond to the Elovka valley (localities 3.1, 3.2 and upper part of Tulaika, locality 8, Fig. 2), and Tylaika – Sur'ya valley (localities 4 and 6, Fig. 2). The content of this type of grain varies from 0 to 25% (average 13.8%) in total gold of the locations.

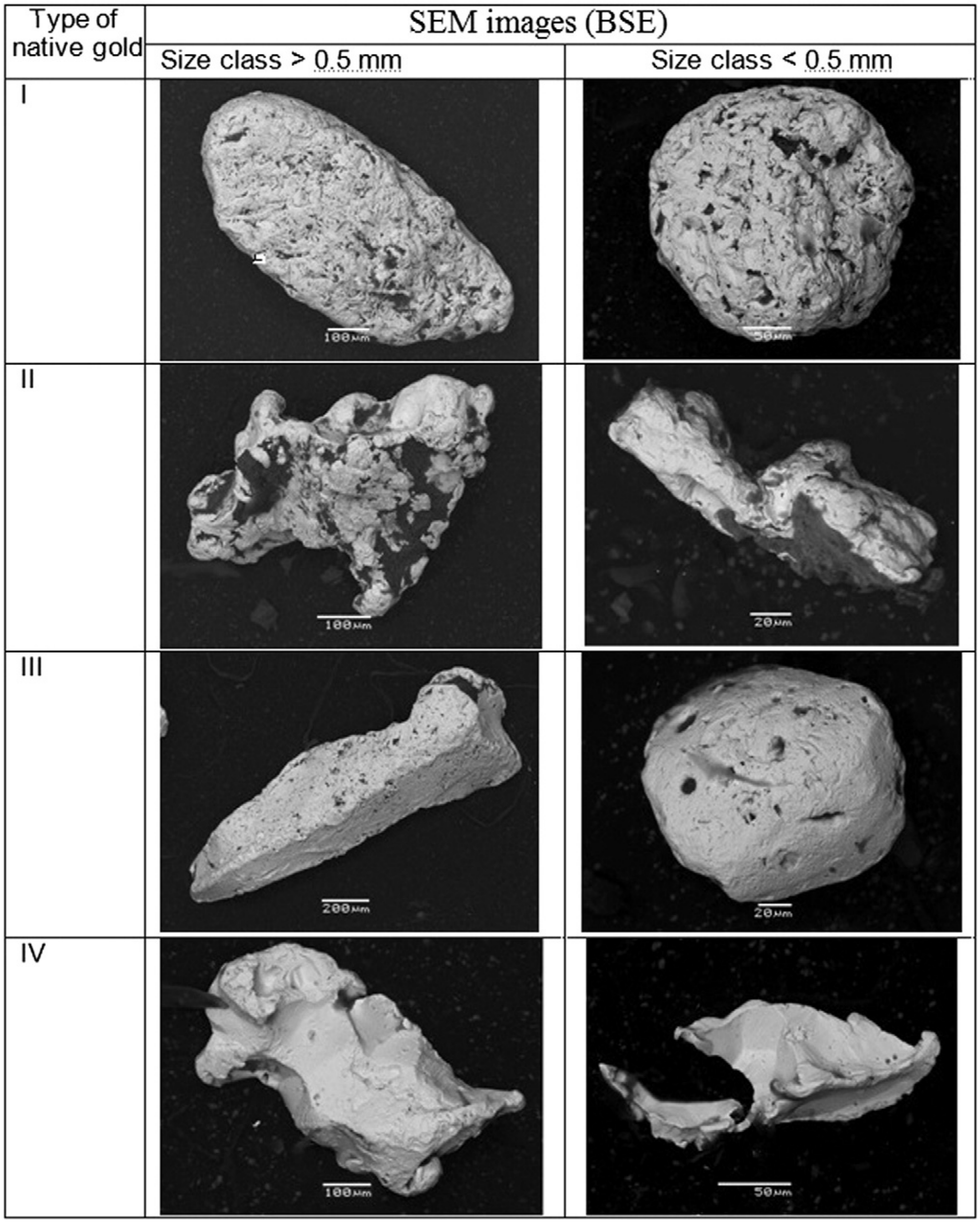


Fig. 4. SEM images of examples of different types of placer gold of the size classes (>0.5 mm and <0.5 mm): type I – medium to well-rounded with high fineness, type II – subrounded, III – idiomorphic with smoothed edges, IV – irregular angular to sub-angular.

Gold grains of types I and II have transitional forms: some grains have moderate to poor roundness (character to type II), but lack gold-rich rims. In this case we chose the inner structure as a distinction: subrounded grains without rims were assigned to type I and rounded grains with a pronounced gold-rich rim (>1.01 value) were assigned to type II.

The third type (III) is represented by idiomorphic grains with smooth surfaces and semi-rounded edges. Faces of the crystals occasionally exhibit scratches and drag traces. The fineness varies from 923 to 966, with an average of 948. The rim zone is absent (Fig. 5D). The content of Ag varies from 2.29 to 7.15 wt.% (average in the core is 4.76 wt.% and in the rim is 4.60 wt.%). The Cu content exceeds detection limits in 12 of 20 grains that were analyzed, and the content reaches to 0.48 wt.% (average in the core and in the rim are 0.17 wt.% and 0.16 wt.%). The content of Hg above the detection limit was observed in 1 grain (0.12 wt.% in the core) and 0.08 wt.%, which is below the detection limit of 0.1 wt.%, in the rim. This type contains 9.2% of the cluster placer gold. Almost all of the samples where idiomorphic particles of placer gold were found (Elovka Creek valley, localities 2, 3.1, 3.2 and upper part of Tulaika Creek valley, locality 8) are associated with a sub-meridianal zone that coincides with erosion-structural depressions. Single idiomorphic grains of gold were found in the middle part of Tulaika Creek valley outside of the zone of depression (locality 7).

The fourth type (IV) is significantly different from the other types previously described (Figs. 5D, 6). It is distinguished by angular to subangular irregular particles with smooth surfaces, sometimes by joints of crystals with irregular incrustations. The content of Ag varies from 10 to 44 wt.% (average 16.86 wt.% in the core and 18.12 wt.% in the rim). The particles are quite homogeneous, C_h is close to 1.0. Cu was not detected. Mercury content exceeds detection limit in 6 grains of 20 up to 1.15 wt.%), average Hg content in the core is 0.09 wt.%.

This type has a very irregular spatial distribution with an average content of 11.6% of total gold. It prevails in the upper and middle parts of the Olen'ya Creek valley (localities 10 and 9) containing 76% and 45% of the total gold, respectively. Near the confluence of the Tylaika and Sur'ua with the Vagran River (localities 5 and 6)

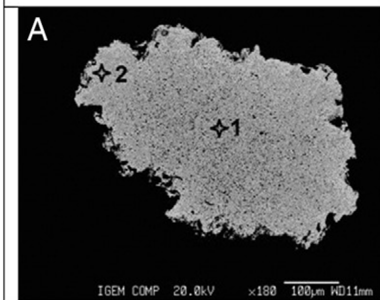
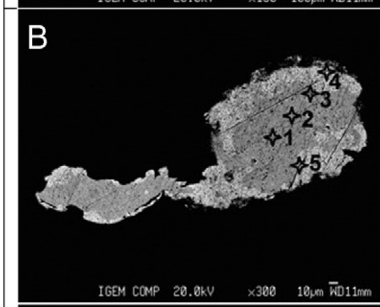
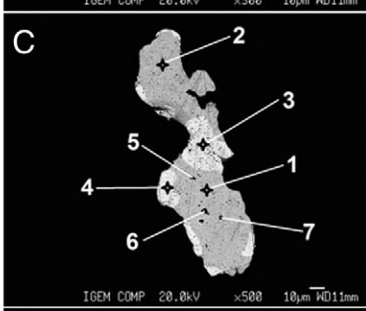
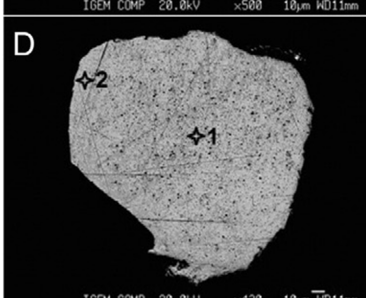
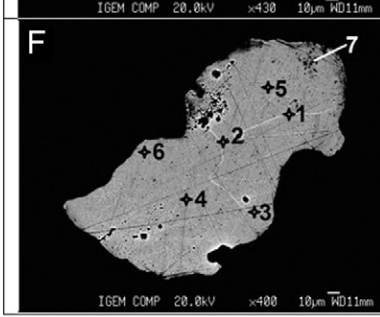
	Type of gold	Point	Content, wt.%			
			Au	Ag	Cu	Hg
	I	1	91.41	7.14	0.00	0.00
		2	92.73	6.83	0.00	0.00
	II	1	93.99	5.14	0.42	0.00
		2	95.10	3.94	0.31	0.00
		3	95.04	4.16	0.32	0.00
		4	99.49	0.53	0.00	0.00
		5	potassium feldspar			
	II	1	91.17	8.83	0.00	0.00
		2	92.29	7.71	0.00	0.00
		3	98.37	1.63	0.00	0.00
		4	98.89	1.11	0.00	0.00
		5	Cobaltite			
		6	Cobaltite			
		7	Cobaltite			
	III	1	96.10	2.92	0.34	0.00
		2	96.89	2.81	0.31	0.00
	IV	1	84.57	14.33	0.00	0.25
		2	83.75	14.63	0.00	0.65
		3	82.96	15.97	0.00	0.48
		4	84.58	15.13	0.00	0.12
		5	83.51	15.35	0.00	0.18
		6	83.35	15.25	0.00	0.18
		7	SiC polishing powder (?)			

Fig. 5. The composition of the placer gold grains, with BSE images of the polished sections, are classified within types I–IV and the content of detected elements is determined by electron microprobe analysis on different points of the polished surface. Types I (A) and III (D) have a monotonous structure without inclusions; type II (B, C) has a gold-rich rim and inclusions of potassium feldspar and cobaltite; type IV (F) has a monotonous structure with Hg-rich stringers (points 1, 2, 3). Remnants of polishing powder and defects of polishing occasionally resemble inclusions in the SEM images. More detailed research of inclusions is represented in Fig. 7.

the content of type IV is 15.2%. In the middle part of Elovka Creek (localities 1, 3.1 and 3.2) the average concentration of subangular gold particles with high content of Ag is 9.2% of total. In other locations type IV is absent (Fig. 2, Table 1).

Inclusions are rarely found in the placer gold of the cluster. In the Au-Ag alloys of the types I and III inclusions were not detected. Inclusions of undetermined aluminosilicate and cobaltite were observed in the alloys of the type II. The aluminosilicate (Fig. 7C) consists of K (4.93 wt.%), Al

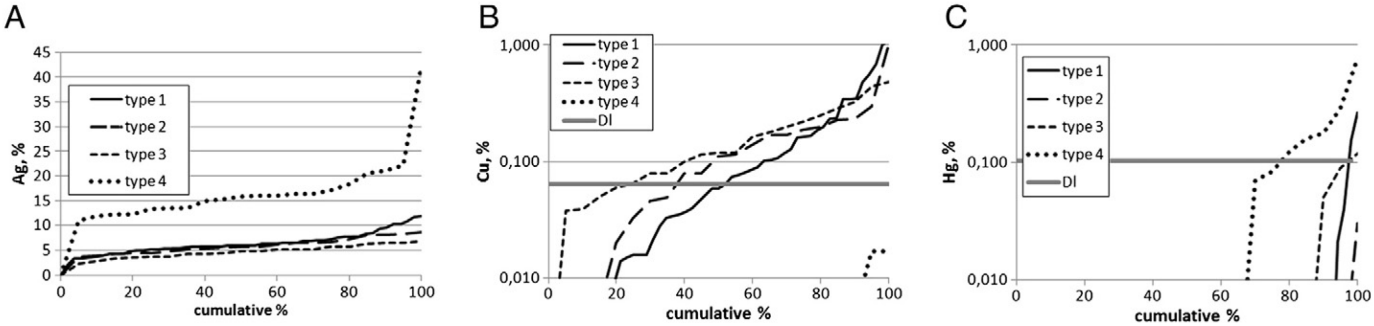


Fig. 6. The cumulative frequency plots of the alloy compositions in the Au grain core from the Vagran placer gold cluster (A) Ag content, (B) Cu content, (C) Hg content (note the logarithmic scale on vertical axis for Cu and Hg). DL indicates detection limit of 0.064 wt.% for Cu and 0.103 wt.% for Hg. If Cu and Hg were not detected, they are plotted at a 0.01 wt.% content; values in the range from 0.01 wt.% to DL are instrumentally recorded but may not be reliable.

(21.81 wt.%), Si (24.71 wt.%) and O (48.56 wt.%) that roughly corresponds to potassium feldspar, but whereas original potassium feldspar contains approximately 14 wt.% of K, 10 wt.% of Al and 30 wt.% of Si, the analyzed inclusion corresponds to the composition of highly kaolinized potassium feldspar. It is remarkable that the inclusion occurs on the border of the core and gold-rich rim.

The second type of inclusion in the alloys of the type II was identified as cobaltite (Fig. 7B). Cobalt can be isomorphously substituted by iron and nickel. Chemical composition of cobaltite varies from Co – 28.64%, Fe – 4.11%, Ni – 3.06%, As – 44.77%, S – 19.34% to Co – 33.2%, Fe – 2.8%, Ni – 0.6%, As – 43.4%, S – 20.6% (Giese and Kerr, 1965; Bayliss, 1969). The composition of cobaltite from the type II alloys of the Vagran cluster is Co – 28.46%, Fe – 5.19%, Ni – 3.06%, As – 43.83%, S – 19.44%.

Inclusions of albite (Fig. 7A) have been found in the alloys of type IV. The alloys also contain thin (<1 μm) Hg-rich stringers (Figs. 5F, points 1, 2, 3 and 7D, point b). It should be noted that some of the optically distinct stringers may actually have a higher content of Hg, because the analytical volume of excitation may overlap or penetrate the surrounding electrum (Groen et al., 1990).

6. Styles of source mineralization, supergenic transformation of the gold grains and origin of the placer gold

Analysis of the inner structure of the gold particles, roundness, shape, character of the surface, fineness, concentration of trace elements, and the character of inclusions are used in the interpretation of the bedrock primary source and supergenic history of the placer gold.

6.1. Initial morphology of native gold and mechanic changes of the grains

Hypogenic features are clearly inherited by the detrital expression, while metamorphoses of both chemical and mechanical characteristics indicates the influence of a supergenic environment. The transformation of the shape in surficial conditions allows the determination of the distance of transportation from the primary sources (Groen et al., 1990; Rasmussen et al., 2006; Nesterenko and Zhmodik, 2014).

Newly liberated gold grains are usually irregularly shaped. As a result of the progressive transformation and separation in streamflow they become semispherical, wafer-shaped, and finally flake-shaped. Their surfaces evolve from smooth and clean to pitted, hackly, and, finally, to lobate-textured, although variations in the stream's composition, energy and sediment type somewhat modify this general trend. Flaky and small size particles are easier to transport; distal placers consist of predominantly flake-shape gold of small size classes (Groen et al., 1990).

Types III and IV have a clearly discernible initial shape, but it is necessary to take into account that crystallomorphic grains have a shape that is more resistant against mechanical forces. Therefore, the similarity of the initial shape preservation is not definitive of a similar surficial history. The crystallomorphic shape of the type III grain is compatible with middle-depth native gold ore bodies of the orogenic gold-sulfide-quartz form of mineralization (Petrovskaya, 1973).

The grains of type IV have an irregular angular shape that is easily modified during transportation, therefore it indicates a short distance of transportation and a short history within a surficial environment.

The initial shape of the gold grains of types I and II is not observed. The rounded shape of the type I is evident of a distant primary gold source. According to this criterion, type II had a shorter distance of transportation than type I. A rough surface with embayments and pits can be both of relict and mechanic origin. There are indications that the main placer gold of type I initially had complicated irregular to dendritic shapes that correspond to the upper parts of gold-bearing ore bodies of mesothermal gold-sulfide-quartz mineralization (Petrovskaya, 1973; Shelton et al., 1988).

Rounded to well-rounded, spherical to flattened morphology of the grains of the type I is accompanied with rough pitted to lobate surface textures. Sometimes relict laminar internal structures are observed in polished grains (Fig. 8). This indicates that the grains have been altered by the crumpling and wrapping of initially complicated dendritic and laminar shapes which then became rounded during transportation. As the distance of transportation influenced the gold grain morphology, various roundnesses of the grains indicates varying distances or hydrodynamic conditions of transportation.

Sub-rounded, irregular shape, and gold-rich rims of the type II are distinctive of a long and/or intensive chemical influence with moderate a distance of transportation.

6.2. Classification of microchemical signatures

The technique of microchemical classification of the placer gold grains (Chapman et al., 2000, 2010a, b, 2011; Chapman and Mortensen, 2006) has been applied to illuminate the types of placer gold and their relations to the source mineralization. One hundred and twelve Au grains were characterized in terms of the Au, Ag, Cu, and Hg content of their alloy. They were characterized twice for every grain (in the rim and in the core).

The chemical composition of the Vagran cluster placer gold is represented on triangular diagrams in terms of Ag–Cu–Hg (Fig. 9A) and Au–Ag–Cu (Fig. 9B). Fifty grains, of 112 grains analyzed from all morphological types, have neither Cu nor Hg above the detection limit. The grains related to types I, II and III have similar Au–Ag–Cu composition in the core. Isolated alloys have a Hg content exceeding the detection limit. Grains of type IV have a clear distinction from the other alloys, noted by the absence of Cu and elevated contents of Ag and Hg. According to Townley et al. (2003) diagram, the placer gold alloys correspond mainly to gold rich porphyry and partially to epithermal and gold-rich porphyry copper deposits that disagree with the general geological structure of the Vagran cluster and surrounding area. The reporting of Cu has been

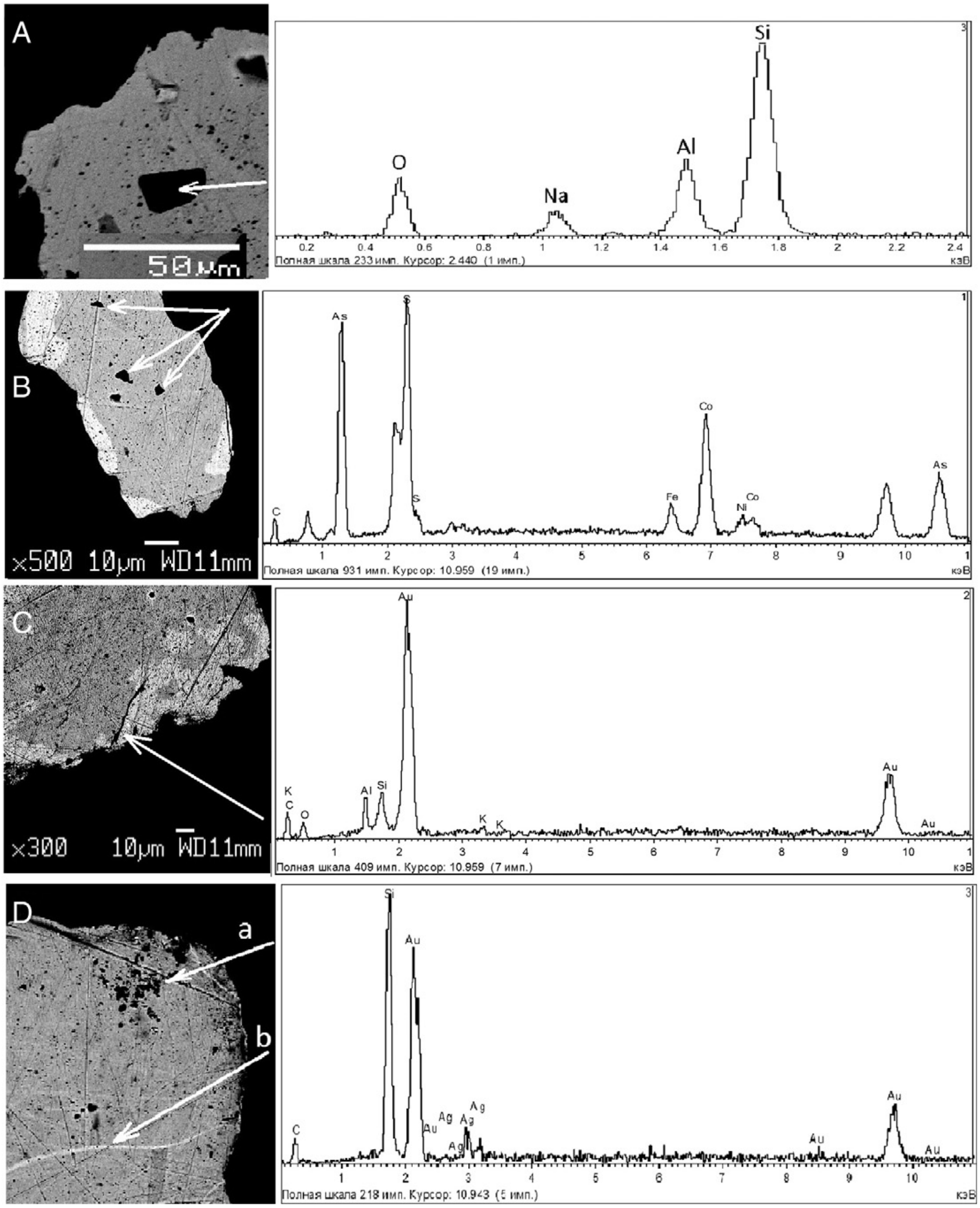


Fig. 7. Inclusions in the gold grains of the Vagran cluster (BSE images in polished sections and dot energy dispersive spectrums). A – inclusion of albite (Na – 7.29%, Al – 10.25%, Si – 33.1%, O – 49.36%) in the alloys of the type IV; B – inclusion of cobaltite (Co sulfarsenide) in alloy of type II, C – kaolinized potassium feldspar (K – 4.93%, Al – 21.81%, Si – 24.71%, O – 48.56%) in the alloy of the type II; D – remnants of polishing powder (?) (a) and Hg-rich stringers (b) in the alloy of type IV; energy dispersive spectrum in the point (a).

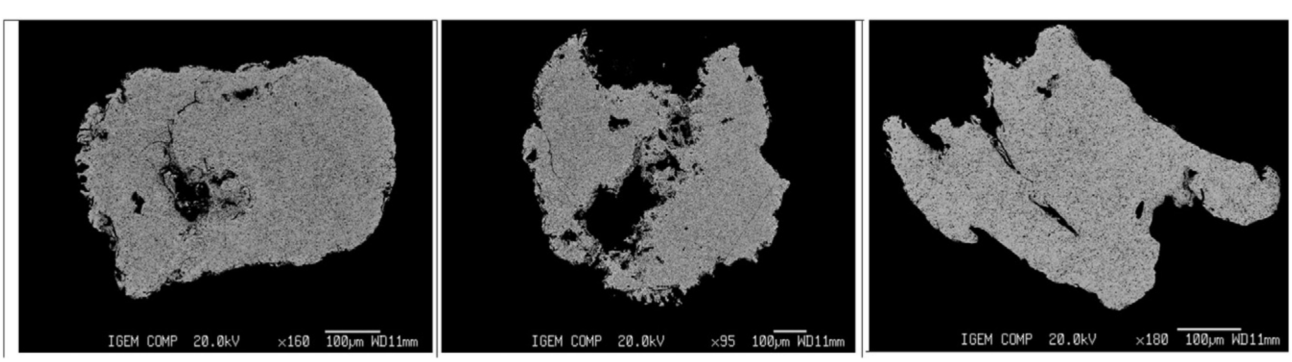


Fig. 8. Relict of laminar internal structures of the gold grains. BSE images in polished sections.

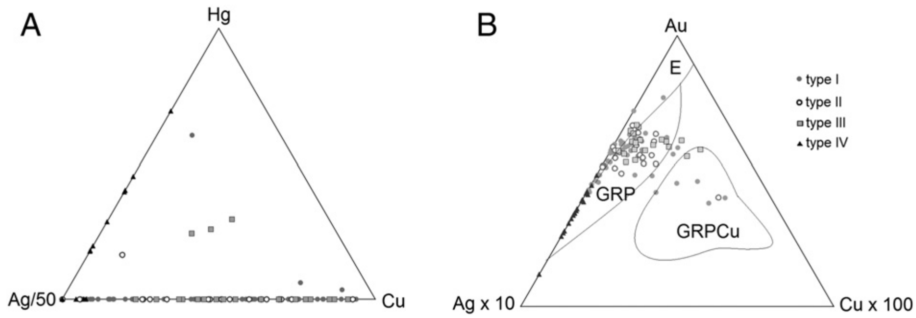


Fig. 9. The analysis of the chemical composition of Vagran cluster placer gold alloys from the cores of the grains, classified: A – in the terms of Ag/50–Cu–Hg; B – in the terms of Au–Ag × 10–Cu × 100. The compositional fields of gold grains according to Townley et al. (2003) and Chapman et al. (2011) and plotted on B: E – for epithermal deposits, GRP – for gold rich porphyry deposits, GRPCu – for gold-rich porphyry copper deposits.

largely confined to gold from porphyry-epithermal environments, and this has biased subsequent interpretations of observed Cu-bearing gold alloys (Moles et al., 2013). Slightly elevated (0.05–0.17%) Cu in the gold alloy, together with low (5–9%) Ag contents, suggest its derivation from an intrusion-related source (Chapman et al., 2011). On the other hand, Cu contents to at least 0.8% are permissible within orogenic gold (Moles et al., 2013).

Inclusions of cobaltite are of a diagnostic character. They indicate high temperature hydrothermal genesis of disseminated or vein mineralization (Bayliss, 1982; Fleet and Burns, 1990). Sulpharsenides can be used as an additional diagnostic feature for classification (Chapman et al., 2010a). Similar low-Ag gold grains in east-central British Columbia that contain Ni-Co-bearing sulpharsenide inclusions represent the centre of activity of a regional-scale hydrothermal system (Chapman and Mortensen, 2011).

This finding can be interpreted as participation of not only orogenic and granite-related gold lode deposits as bedrock sources for alluvial gold but also native gold of volcanogenic massive sulfide deposits. VMS deposits are usually characterized by invisible gold in sulfides and during metamorphism of the greenschist facies (up to amphibolites facies). The gold inclusions increase in size, forming small nuggets (Vikentyev, 2015) and, thus, can be source for placer gold during erosion. Some of such mafic-ultramafic-associated deposits occur inside the zone of the Main Ural Fault and contain Co–Ni sulfarsenides as common minerals (Melekestseva et al., 2013).

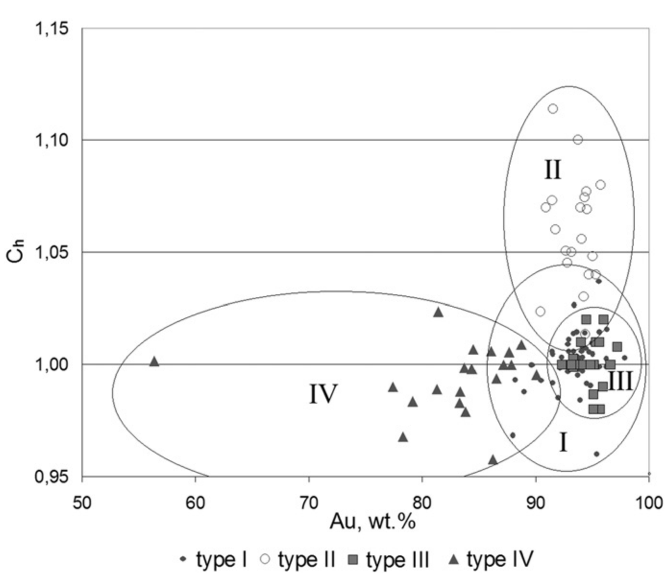


Fig. 10. Au content in the core of grains (wt.%) *vs* coefficient of heterogeneity (C_h) plot for Vagran cluster placer gold. The diagram distinguishes the types of gold grains both by primary hypogenic characteristics and supergenic features.

Additional information for classification of the placer alloys can be obtained from the plot of Au content (wt.%) *vs* coefficient of heterogeneity (C_h) which illustrates a visual division of general distribution into four individual fields. The fields of the types I, II and III have essential similarity in fineness with more variation of the alloys of type I (Fig. 10). The identity of the composition of the types I–III suggests a single form of original host mineralization. The variations of morphology could be a reflection of the zoning of primary ore bodies and supergenic history. In comparison with the core, the rim content of the type II is indicative of prevailing of Au (up to 99.5 wt.%), significantly decreasing the Ag content by 3 to 10 times and a complete absence of Cu (Table 5).

Despite the fact that the fields of types I and IV on the "Au content (wt.%) *vs* coefficient of heterogeneity (C_h)" diagram (Fig. 10) partially overlap, microchemical signatures of these types are essentially different, which is evidence of different bedrock sources of the placer gold types.

6.3. Gold-rich rims

Alloys of the type II placer gold have gold-rich rims. The individual rims on the various grains range from 5 to 30 μm in thickness. The boundary between the individual cores and rims is generally sharp, visually demonstrated in reflected light, and confirmed by microprobe analyses in polished sections (Fig. 5-IIa, IIb).

The relatively high Ag content of the gold cores and the presence of mineral inclusion species unstable in the surface environment indicate that they are relics of a hypogene gold particles source rather than authigenic gold or gold altered by weathering (Chapman et al., 2010b). While the composition of the alloy's homogeneous cores demonstrate the form of source mineralization, the rim/core difference of composition expressed by the coefficient of heterogenity, reflects both residual features of a primary grain's structure and supergenic transformation of the alloys.

Gold grains experience both physical and chemical changes during weathering, transportation and post-sedimentation processes. During the influence of supergene conditions, grains of placer gold develop an outer rim of nearly pure gold on the more silver-rich electrum core. The rim has a very sharp contact with the core, and appears to be the result of electrochemical processes active in weathered crusts, the stream, and stream sediment conditions. The rim is generally thickest on the grains with a long supergene history (Groen et al., 1990).

In the alloys of type II, the gold content in the rim reaches 99.5 wt.% with silver contents of 2.05 to 0.54 wt.% (average 1.02 wt.%) and a Cu and Hg content below the detection limit. Gold-rich rims are developed on the projections of grains and gold-rich inner fracturing zones (Fig. 5IIa, IIb). Film-shape inclusion of highly kaolinized potassium feldspar is observed on the core/rim interface (Fig. 7C).

In the terms of Au–Ag × 10–Cu × 100 diagram (Fig. 11), the fields of core and rim assays are completely different and contradict the gradual transformation of the core material into rim.

Table 5
Typomorphic characteristics of different types of placer gold of Vagran cluster.

Type	% in total	N[a]	R_{av} [b]		Content of the elements, wt.% Au Core	Au Rim	C_h [c]	Ag Core	Ag Rim	Cu Core	Cu Rim	Hg Core	Hg Rim
I	65.5	52	2.7	Min	88.20	88.92	0.98	2.03	1.92	0.00	0.00	0.00	0.00
				Max	96.99	97.28	1.02	11.62	11.17	1.08	1.07	0.27	0.31
				Av.	93.29	93.30	1.00	6.18	6.27	0.15	0.14	0.01	0.01
II	13.8	20	2.2	Min	90.06	96.69	1.02	2.95	0.37	0.00	0.00	0.00	0.00
				Max	95.74	99.74	1.11	10.31	3.81	1.02	0.07	0.03	0.00
				Av.	93.11	98.60	1.06	6.38	1.31	0.16	0.01	0.00	0.00
III	9.2	20	2.4	Min	92.30	92.30	0.98	2.29	1.89	0.04	0.04	0.00	0.00
				Max	96.60	97.92	1.02	6.90	7.15	0.48	0.47	0.12	0.08
				Av.	94.83	94.89	1.00	4.76	4.60	0.17	0.16	0.01	0.01
IV	11.5	20	1.6	Min	57.11	54.94	0.96	9.59	9.71	0.00	0.00	0.00	0.00
				Max	90.06	90.03	1.02	42.16	44.29	0.02	0.01	0.77	1.15
				Av.	82.82	81.46	0.99	16.86	18.12	0.00	0.00	0.09	0.10

[a] Number of analyzed grains.
[b] R_{av} - roundness of the type is calculated as average roundness of all particles of this type, estimated visually by 5 grade scale (from angular equal to 0 to well-rounded equal to 4).
[c] C_h (coefficient of heterogeneity) was calculated as the ratio of the Au content in the rim and in the core of the grains.

7. Discussion

Three problems are under discussion: (1) sources of the placer gold of various types; (2) reason of the appearance of the rims in the type II whereas types I and III do not have the gold-rich rims; (3) perspectives of discovering bedrock gold mineralization in the Vagran cluster.

7.1. Sources of the placer gold types

The origin of the types I–III of placer gold is quite comprehensible: morphology, composition of the alloys, and characteristics of inclusions indicates that the types of gold grains are of orogenic mesothermal gold-sulfide-quartz style of mineralization. The difference between the types could be the result of primary zonation of ore bodies and supergenic transformation of the grains.

The disintegrated gold from bedrock sources was concentrated in weathered crusts or re-deposited in erosion-structural depressions. The activation of tectonic movements led to uplift and active erosion of the peneplain surface. The gold of weathered crusts was re-deposited into the system of erosion-structural depressions. Placers of the depressions have economic importance and/or served as intermediate hosts for later alluvial placers.

Spatial distributions of distinguished types of placer native gold on the territory of the Vagran cluster correspond to stages of supergene mobilization of bedrock sources. Gold of the type I has approximately uniform distribution over the cluster that could be evidence of disintegration of the sources on the early stage of peneplanation and widespread forming of weathered crusts.

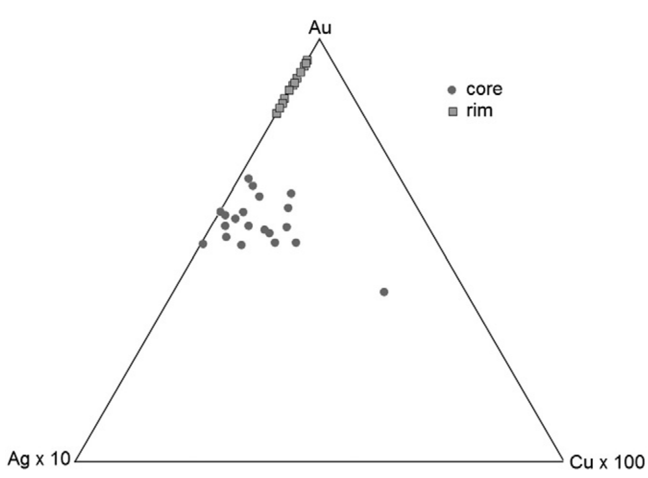


Fig. 11. Analysis of the chemical composition of zoning alloys of the type II in the terms of Au–Ag × 10–Cu × 100 for core and rim parts of the gold grains.

Gold of the second type (II) tends to the position of erosion-structural depressions which partly coincide with inherited Quaternary valleys. It is evidence of later (in comparison with the type I) transition of the gold to the supergene environment.

Crystallomorphic gold (type III) demonstrates moderate (both mechanical and chemical) supergene influence. The location of the type III (sub-meridian zone of erosion-structural paleodepression and inherited valleys of Elovka-Tulaika Creeks) indicates a more confined territory of primary source of idiomorphic gold or/and later erosion of the mineralization. It corresponds with the middle-depth level of an assumed source of the gold grains of type III.

In spite of widespread distribution of gold of these types in the placers, there is no bedrock mineralization of this style identified at present within the territory of Vagran cluster and surrounding area that could be the result of a deep erosion level (up to 1500 m according to last estimation of V.N. Puchkov (2010)) of the mountain system.

Genesis of the type IV is not obvious. High Ag and Hg content could indicate epithermal generation of this type (Shikazono and Shimizu, 1988; Safonov, 2003), but in spite of high Ag and Hg there are compatibilities with particulate Au from epithermal sources (Morrison et al., 1991) that are not diagnostic features. There are many examples of orogenic Au with high Hg (see *e.g.* Youngson and Craw (1999), McTaggart and Knight (1993), Chapman et al. (2000)); high (>20%) Ag native gold is recorded in orogenic systems, sometimes as an easily identifiable later stage. R.J. Chapman et al. (2010a, 2010b) interpreted the presence of Hg as indicative of lower-temperature hydrothermal activity emplaced at higher structural levels.

According to Youngson et al. (2002), Au-Ag-Hg alloys of hydrothermal origin occur in epithermal hot spring deposits, fault-hosted veins in metamorphic belts, massive sulfide deposits, and in metamorphosed quartz pebble conglomerates of Witwatersrand type.

Placer gold of type IV is evident of a short distance of transportation and close location of bedrock sources. It was eroded later than sources of types I–III, therefore it was connected with a lower structural level of main stage of gold mineralization or superimposed mineralization of more recent stage; the second is more probable.

The location of the type IV is controlled by a zone of NW-SE orientation diagonal to the main structures of the Ural Fold Belt (Fig. 2). Structures of tectonic activation of similar orientation relative to stress were studied by Hafner (1951) and described in the east slope of the South and Middle Ural (Rozhdestvensky, 1971).

Presence of Au-Ag-Hg gold grains at several localities within the linear zone suggests the presence of a separate strong hydrothermal system. The exposed zone has neither evidence of fracturing or slipping of the rocks, nor connection with the elements of a geological structure shown on the geological map of scale 1:50,000. It coincides with the prevailing orientation of small valleys of the first order. It is possible that this zone is connected with the area of alternation of compression and extension zones with a certain structural step where generation is conditioned by standing autowaves of deformation of the rocks. Such zones are not marked by displacement of rock borders, therefore they are not registered by mapping. The alternation of compression and extension zones controls the permeability of the rocks for ore-bearing fluid, therefore it is pronounced in geochemical fields and allocation of ore mineralization (Coward and Potts, 1983; Mandl, 1988; Cox et al., 1995; Petrov, 1995; Wu et al., 1999; Shakin, 2002).

The Ag-Hg style of the placer gold of type IV appears similar to the mineralization of the hydrothermal Vorontsovsk gold deposit assigned to Carlin-type. The placers of Olen'ya Creek, which significantly consists of the gold of type IV, is located in carbonaceous black shales with basic effusives, but it is in close proximity to Ordovician (terrigeneous-carbonate) – Lower Silurian (volcanic) sequence (Fig. 2) which geological structure is similar to host formation of Vorontsovsk deposit. The discovery of the gold content of 2.0–6.9 ppm in bedrock quartz-sulfide veins and zones of silicification confirms the significance of the zone for primary gold ores.

The proposed description of the mineralization form of the type IV placer gold is a characteristic feature. A detection of the origin of the gold and estimation of economic perspectives of this zone for bedrock gold deposits will be the purpose of future investigations.

7.2. Origin of gold-rich rims in the gold alloys of type II

The published results of the research of polished sections of gold in vein quartz show no signs of development of a gold-rich rim, implying that the rim forms after liberation of the gold grains from the host rock. Furthermore, irregularly shaped grains of placer gold relatively new to the stream environment exhibit little or no development of a gold-rich rim (Groen et al., 1990), therefore presence of gold-rich rims is considered a result of supergenic transformations of the alloys. There are two opinions for the reason of formation of this feature of placer gold: selective leaching of Ag and other trace elements from the rim zone (Petrovsky et al., 2012), and self-electrorefining of placer electrum grains which probably operates in tandem with dissolution-precipitation (cementation) (Groen et al., 1990). Some researchers (Roslyakov et al., 2013; Nesterenko et al., 2014) suppose that the rims are a result of adhesion to small gold particles as well as the transition and deposition of chemical gold by organic-metallic complexes in supergenic environments.

Observed natural gradients of silver in the rim zone and calculated diffusion profiles of silver in gold alloys (Groen et al., 1990, Fig. 8) illustrate that the profile of silver content contradicts the gradual leaching model; this is attributed to the extremely slow rates of diffusion at low temperatures. The observed sharp rim-core contact in the gold alloys of Vagran placers corresponds to the precipitation model.

Groen et al. (1990) believe that the developing of the rim occurs mainly during gold grain transportation, meaning that the “transportation” is the period spent in the surficial environment: whether actively moving or residing within stream sediments. Taking into consideration that the phase of active movement of the grains in the stream is incomparably shorter than retention within the stream sediments, the growth of gold-rich rim in the sediments is obviously more efficient. Moreover, cementation of the gold in the rim is compensated by the erosion of grains during the transportation in the alluvial stream. Additionally, concentration of gold ions in groundwater is two orders more than in the stream (Groen et al., 1990, p. 218, Fig. 9A). While “a gold-rich rim apparently forms by precipitation of gold from the surrounding solution” (Groen et al., 1990, p. 207), these factors confirm the validity of our opinion that the condition of stream sediments is more favorable to rim forming than the stream environment itself.

According to Groen et al. (1990): “The rim generally is thickest on flake-shaped (most transported) grains and thinnest or absent on irregular (least transported) grains”. In our case, the least transported grains (type II) have the rim, while most transported grains (type I) do not have the rim. We made the proposal that this feature has a connection with the association of the type II (with erosion-structural depressions), whereas the type I is evident of long transportation. It is possible that the residence of the grains within the sediments of the depressions (from the Cretaceous to the Quaternary) is more favorable to rim formation than residence in dynamic stream conditions. The stream environment has a significant influence on the shape of the grains, but only a moderate influence on the inner structure of the alloys.

The grains of type II have not experienced significant transportation, but they have experienced long chemical reactions within infiltrating fluid conditions which has resulted in the growth of a gold-rich rim.

We acknowledge that this explanation is highly speculative in the absence of evidence observed from the examination of the original placers of the peneplain, erosion-structural depressions, and lode gold sources, therefore it needs further research. Nevertheless, we proposed our model for discussion as a more appropriate interpretation of available data.

7.3. Perspectives of the discovery of bedrock gold deposits in Vagran cluster

Thus, four typomorphic kinds of placer gold belong to two main primary ore types. The types I, II and III are linked to the mesothermal gold-sulfide-quartz type affected by deep chemical weathering and transportation. Type IV characterizes hydrothermal mineralization indicating the later stage of the orogenic systems similar in genesis to the Voromtsovsk gold deposit. There is evidence of the short distance of transportation indicative of potential distinguishing features for the exploration of bedrock primary gold ores in this region.

All researchers agree that main gold placers of the Vagran cluster were formed from gold-sulfide-quartz veins, stockworks, and zones of silicification. Also, they suppose a positive correlation between the grade of current primary ores and placer deposits – substantial primary ore deposits as being favorable to placer formation which are accompanied with considerable gold placer deposits. Consequently, the prevailing assumption is that any placer-bearing cluster should contain significant bedrock gold deposits (Wells, 1969). However, the majority opinion is often inaccurate and the evidence demonstrates a negative correlation – significant placer-bearing clusters in provinces such as Bodaibo (Trans-Baikal region) and some clusters of north-eastern Russia do not have comparable primary gold sources (Goldfarb et al., 2001; Goryachev and Pirajno, 2014). There are bedrock gold deposits of the disseminated high sulfide type which, due to the very fine grain size of the native gold, are not favorable for placer formation by the standard hydrodynamic and mechanical placer processes (Eremin et al., 1994; Distler et al., 2004; Safonov et al., 2007; Chapman and Mortensen, 2011).

A positive correlation of bedrock and placer gold deposits is possible in the special case of large primary placer-forming ore deposits and the medium level of erosion of ore bodies. In the case of deep erosion levels all bedrock ore bodies are transferred into friable sediments, therefore primary sources of the placers are absent in the current erosion level.

The second reason for the absence of bedrock ores in the placer clusters could be a dispersed character of bedrock mineralization. Scattered gold-sulfide-quartz veins, stockworks, and disseminated ores with a low gold content, in the case of preliminary disintegration and enrichment of weak gold-bearing deposits in the weathered crusts, in combination with intermediate hosts could form a significant source of placer cluster (Duk-Rodkin et al., 2001; Lowey, 2006). In the case of the Vagran cluster the Mesozoic weathered crusts and erosion-structural depressions could be factors of concentration of weakly-disseminated pre-Mesozoic primary gold mineralization to placer deposits of economic importance. In this case, prospecting to reach primary sources of placer gold is improbable.

On the other hand, the absence of gold-sulfide-quartz vein deposits does not exclude the presence of bedrock gold ores of other types. Exploration efforts in the territory that was oriented to the gold-sulfide-quartz type of bedrock ores gave negative results. The prospectors did not take into account the presence of high Ag and Hg gold (IV type) in placer deposits. Some researchers believe that high Hg placer gold has a technogenic origin as Ural gold was extracted using the mercury method during the last century (Sazonov and Velikanov, 2010). Our sampling of original alluvial deposits in outcrops of exploitation pits, typomorphic features, and a high content (up to 80%) of the IV type in total placer gold indicates that the gold has a natural origin.

8. Conclusions

Study of geology, geomorphology, and mineralogy of the Vagran gold placer cluster of the Northern Urals allows for modeling of gold placer forming processes and prediction of bedrock gold mineralization of the subject area.

Four different types of placer gold correspond to endogenous metallogeny of the Urals region, reflecting the structure of primary ore bodies and tectonic-geomorphological cycles. Type I is rounded to well-rounded grains of high fineness alloys; type II is rounded to sub-rounded grains with gold-rich rim; type III is represented by slightly rounded idiomorphic grains. These three types are related with orogenic mesothermal gold-sulfide-quartz mineralization; the differences of these types depend on primary zonation of ore bodies and supergenic transformation of the alloys.

The type IV (angular to sub-angular placer gold with higher Ag and Hg contents) does not exhibit evidence of weathering and prolonged transportation, thus it has a separate gold source of presumably hydrothermal gold mineralization of Carlin-type.

Three main stages of evolution of Urals Mountain System in Mesozoic-Cenozoic time had an influence on the placer forming process: (1) peneplanation of the region, development of the weathering crusts in Proterozoic-Paleozoic folded complex, and the establishment of the systems of the erosion-structural depressions; (2) tectonic activation of a block character, uplift, disintegration, and erosion of the peneplain surface; (3) formation of a modern relief and re-deposition of the native gold in Quaternary alluvial valleys.

The analysis of the collected data demonstrates the valid and reasonable perspectives of the subject territory for primary ores and gold placer deposits. Main valleys of the cluster have been prospected for gold placers and are currently quite exhausted. The placer deposits had intermediate hosts in the deposits of the peneplain and erosion-structural depressions, the relics of which are observed on the watersheds and lowered tectonic blocks. A widespread distribution of placer gold indicates that the placer deposits can be found not only within the perimeter of valleys but also on the high terraces and watershed zones.

The primary bedrock gold-sulfide-quartz deposits that generated placers of the Vagran cluster were evidently completely eroded, therefore perspectives of mineral exploration of this style in the cluster and on the surrounding area are, consequently, weak and improbable.

Angular and sub-angular placer gold with higher silver content (±Hg) can be used as an indicator for the prospecting of hydrothermal gold mineralization similar to the Vorontsovsk deposit.

Conflict of interest

There are no conflicts of interest associated with this manuscript.

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