



Typomorphic features of placer gold from the Bystrinsky ore field with Fe-Cu-Au skarn and Mo-Cu-Au porphyry mineralization (Eastern Transbaikalia, Russia)

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ABSTRACT

Eastern Transbaikalia is one of the oldest gold-producing regions in Siberia, and for over 300 years it has been the largest source of the most important raw minerals in Russia. A large number of gold, gold-bearing complex, antimony, mercury and other mineral deposits are known within this region. The orogenic, intrusion-related, and epithermal deposits are important in the balance of gold reserves and gold production. Au-Cu-Fe-skarn deposits are located mainly in the northeastern and southeastern parts of the area, wherein the skarn Kultuma, Lugokan, and skarn-porphyry Bystrinsky deposits are the largest deposits.

Herein, we studied the the Bystraya River gold placers and tributaries, which are located to the east of the Bystrinsky massif near the Bystrinsky deposit. In this study, a microchemical characterization technique was applied to gold grains to facilitate the classification of alluvial gold localities in terms of the style or styles of source mineralization, thereby permitting a comprehensive interpretation of regional gold mineralization. In total, 55 samples were collected from four placers and processed for more than 1500 analyses of the native gold.

In the alluvial placers of the Bystrinsky deposit areas, weakly rounded native gold either prevails or is significantly present. A low portion of supergenically transformed of gold grains in the placers indicates that the placers formed directly from endogenous gold mineralization. The native gold from the Bystraya River catchment can be divided into 3 types and 1 subtype: (1) Cu-bearing gold grains with a fineness of 800 – 995‰, and a copper impurity of up to 0.73%; (2) Hg-bearing gold grains with a fineness of 800 – 995‰, and an impurity of Hg up to 4.68%; (2.1) Hg-poor gold grains with a fineness of 800 – 995‰, containing the same mineral microinclusions assemblages as the Type 2 gold grains; and (3) gold with a fineness of 400 – 770‰, containing up to 8.5% Hg.

The distinguished types of gold grains are manifested to varying degrees at the Bystraya, Left, and Right placers. At at the Yakovlevsky placer, there is no Hg-bearing low fineness and poorly occurring Cu-bearing native gold. Comparing of the obtained data with gold grain composition data from the hypogene deposits allows us to infer bedrock sources. The Cu-bearing high-fineness type of placer gold can be compared with the Cu-bearing native gold of the Bystrinsky, Lugokan, and Kultuma deposits. Hg-bearing low-fineness placer gold grains related to erosion of the Au-bearing base metal mineralization occurred at the Novoshirokinsky and Kultuma deposits. However, Hg-bearing high-fineness gold grains, which most widely occurring in the studied placers, are absent in the in-situ mineralization. Therefore, we suppose that the bedrock source of this gold grain type is linked to the completely eroded upper levels of the Bystrinsky deposit. Thus, our study shows that it is possible to speculate on the nature of eroded material from the gold particle signature. Hence, this generic approach informs regional metallogeny in a way that even detailed field-based classical geology/geochemistry cannot.

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1. Introduction

The uniqueness of placer gold is its ability to preserve the primary characteristics and features of its composition, even after a long period under the exogenous conditions. As a rule, only a marginal part of the grain is subjected to transformation. Generally, the central part of the gold reflects the composition of the primary endogenous gold. Thus, the fineness of the native gold remains, as well as a suite of major impurities, including mercury, silver, and copper. Microinclusions of ore minerals that are “protected” by native gold particles also carry important information regarding the mineral composition of the bedrock sources (Chapman et al., 2000, 2009; Potter and Styles, 2003).

The prevalence of Hg- and Cu-containing Au-Ag alloys, together with

their fineness and mineral composition of inclusions, allows placer to reflect the prevailing bedrock sources types, many of which are often not have identified. In contrast to morphological traits, the chemical composition of native gold is retained even with long distance alluvial transport. In the core of the gold grains, which do not undergo hypergene transformation, the chemistry remains unchanged (Nesterenko and Kolpakov, 2007; Chapman et al., 2000; Townley et al., 2003). Note that, to date, research in this field is based on this theoretical postulate.

Currently, alluvial placer gold deposits are not only of economic importance, but are the most important source of information that can predict and identify primary deposits (Nesterenko, 1991; Chapman et al., 2000, 2009, 2010; Townley et al., 2003). In the territories with poor outcrops, the value of alluvial gold as an indicator for gold

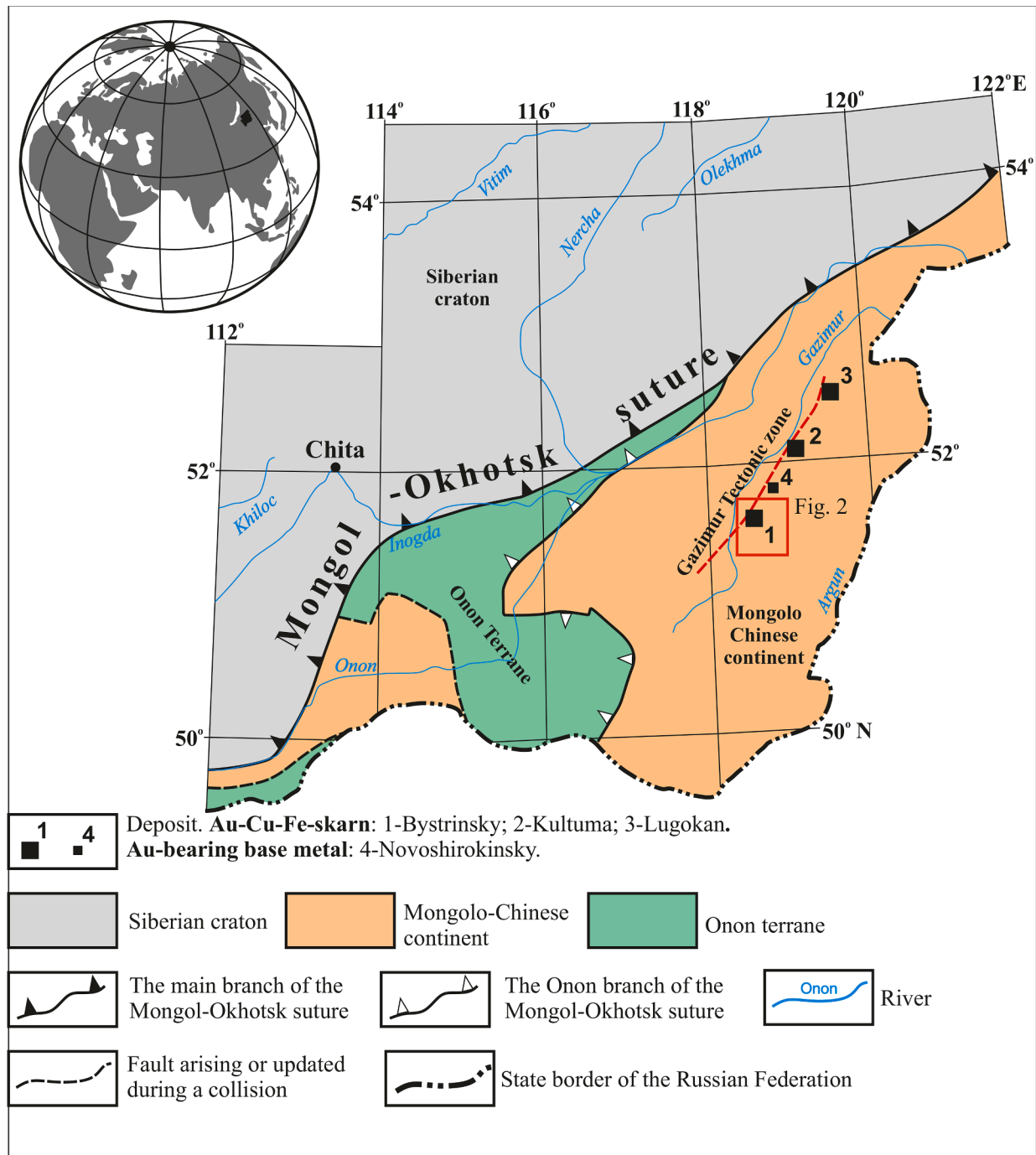


Fig. 1. Regional tectonic map of the Transbaikalia (simplified from Zorin et al., 1998, 2001).

mineralization increases. The most effective approach used to substantiate bedrock sources is to compare already obtained data with similar data from well-known primary deposits as well as amongst itself (Chapman et al., 2000, 2010; Chapman and Mortensen, 2016; McTaggart and Knight, 1993).

The roundness of gold grains, which is a function of the distance from its bedrock source and transfer conditions (Chapman and Mortensen, 2016; Townley et al., 2003), hides the primary morphological features of placer gold. However, a correct interpretation of the mechanical transformation of native gold in placers may provide useful information for predicting source conditions. The degree of chemogenic transformation in the individual grains of native gold can be estimated by the degree of development of high-fineness rims.

Therefore, we can formulate the basic postulates on which our research is based on as follows:

- Native gold from placers inherits the chemical characteristics of native gold from the primary endogenous bedrock source (at least in the central parts of the grains);
- Degree of roundness and mechanical transformation are functions of transfer distance and hydrodynamic flow (river or stream) characteristics;
- In general, chemogenic transformation is expressed through the formation of high-fineness rims;
- Mineral microinclusions in placer native gold are of primary origin and have a paragenetic relationship with native gold (true for unstable minerals in hypergene conditions such as sulfides, sulfosalts, intermetallic compounds, and tellurides, etc.).

As noted by Chapman et al. (2018), the development of exploration criteria for porphyry deposits based on mineral studies found in erosional products is one of the most important paths of modern research. Moreover, specific features of detrital gold grains are derived from porphyry-mineralization (e.g. low but detectable Cu in the alloy and Bi-Pb-Te-S signature in their mineral inclusion suites).

The objects of our study are the gold placers in the Bystraya River catchment, located in Transbaikalia to the east of the Bystrinsky massif near the large Bystrinsky porphyry-skarn deposit (2.2 Mt Cu, 250 t Au, 1100 t Ag, 75 Mt Fe according to Shevchuk et al. (2010) and Kovalenker et al. (2016), Kovalenker et al., 2018) (Figs. 1 and 2). The Bystraya gold placer tributaries were discovered in the mid-50 s of the 20th century and have been mined intermittently for the last 50 years. However, there is no accurate data regarding the amount of gold mined. According to regional exploration documents, several metric tons of gold have presumably been mined from the placers during this operation period. These placers are alluvial with the thickness of gold-bearing "sands" reaching the first meters. The thickness of the overlying sediments is relatively small and varies from the 1 m to 15 m. In addition, despite the long history of gold exploration in Eastern Transbaikalia, the issues regarding the typomorphic features of the placer gold remain mostly unresolved. Thus, there are still several important and unresolved issues, including (i) the characterization of gold from the placer localities reveals one or multiple sources; and (ii) the implications of in-situ mineralization in the Bystraya catchment. Therefore, identifying the typomorphic characteristics of the placer gold and comparing them with their potential primary bedrock source are the aims of our study.

2. Background geology

Eastern Transbaikalia is one of the oldest gold-producing regions of Siberia. Moreover, for over 300 years, it has been the largest source of the most important types of raw minerals in Russia. A large number of gold, gold-bearing complex, antimony, mercury, and other mineral deposits have been found within the region. Until recently, intrusion-related (Darasun, Klyuchevskoye, Itakinskoe, Sredne-Golgotayskoye and others), orogenic (Pogromnoe), and epithermal (Baley,

Taseyevskoye) deposits were important for the balance of gold reserves and gold production (Zorin et al., 2001; Volkov et al., 2011; Redin et al., 2015). Other genetic types of gold deposits (sedimentary hosted and Carlin-like), while distinguished by a number of authors, have not yet received a proper assessment nor been sufficiently studied in geological and geochemical terms (Spiridonov et al., 2006 and references therein). As of late, a significant increase in gold reserves has been achieved owing to the exploration and reevaluation of gold-copper-iron-skarn deposits, which now form the basis of the gold resources in the Transbaikalia region.

The studied area is located in the southeast of the eastern Transbaikalia region within the Aga – Borzja tectonostratigraphic terrane of the Mongolia – Okhotsk collisional belt (Zorin et al., 2001) within to the Gazimur regional tectonic zone. The Gazimur tectonic zone is represented by a complex system of smaller order conjugate faults. Most of these faults are thrusts or faults in kinematics. According to the previous data (Spiridonov et al., 2006), the faulting time is the Late Jurassic-Early Cretaceous, which corresponds to the collision and post-collisional stages of the Mongol-Okhotsk orogenic belt development.

Within the study area, there are several gold and gold-bearing deposits that are relevant to porphyry-skarn and epithermal types according to Spiridonov et al. (2006), Redin et al. (2015), Kovalenker et al. (2016), and Prokofiev et al. (2017). The largest deposits include the Bystrinsky, Kultuma, Lugokan porphyry-skarn (Spiridonov et al., 2006; Redin et al., 2015; Kovalenker et al., 2016), and the Novoshirokinsky gold-bearing deposits (Prokofiev et al., 2017) (Fig. 1). According to the available open access data, the total gold reserves of these deposits is estimated at approximately 460 metric tons (www.nornickel.com).

Because the studied placers are near the Bystrinsky deposit, we considered its geological structure in more detail. The Bystrinsky deposit is situated in the southern part of the Uryumkan–Budyumkan tectono-metallogenic terrain at the intersection of the Uryumkan–Budyumkan and Nerzavod–Sretensky faults (Tauson et al., 1985; Shevchuk et al., 2010). A complex, multi-stage, and multi-order system of folding and faults is the main ore-controlling factor. This system is expressed by a series of extended (from north to south), long-lived faults, and a system of lesser order feathering faults (Spiridonov et al., 2006).

The deposit area comprises Early Cambrian, Middle Devonian, and Middle Mesozoic terrigenous-carbonate sediments (limestone, sandstone, siltstone, mudstone, and conglomerate). The sedimentary rocks are intruded by diorite, diorite–granodiorite, granite, and their porphyries, andesite, and dacite forming the Bystrinsky massif in the center of the structure (Bystrinsky, 2002; Kovalenker et al., 2018) (Fig. 2).

The Lower Cambrian Bystrinsky Formation is distributed throughout the southern and southeastern edges of the Bystrinsky massif. Here, sedimentary rocks are represented by thick layers of carbonate rocks (limestone, gray, or brownish-gray marbled dolomites that are penetrated by numerous thin veins of calcite and quartz), with interlayers and lenses of sandstones, siltstones, carbonaceous, mica, and biotite-amphibole shales (Kormilitsin, Ivanova, 1968). Limestones and dolomites are metasomatically altered to garnet, pyroxene, amphibole, and phlogopite skarn along with contacts with the intrusive bodies of the Shakhtama complex.

The Middle Devonian Ildikan Formation is distributed in the form of small outcrops of terrigenous sedimentary rocks throughout the field, with relatively large areas located in the central and northeast (Bystrinsky II site). This sequence is composed of sandstones, siltstones, argillites, limestones, and conglomerates in the basal part of the section. The rocks of the Ildikan Formation also undergo metasomatic alteration (locally skarn formation). The Lower Jurassic Gosudarevsky Formation comprises an interlayer of conglomerates at the base of the section, containing a thick package of alternating coarse and medium grained, gray or dark gray, polymictic sandstones, carbonaceous and clay, and clayey siltstone and argillite (Bystrinsky, 2002).

The Bystrinsky massif is composed of a large stock of diorites deposited during the first phase of the Middle-Late Jurassic Shakhtama

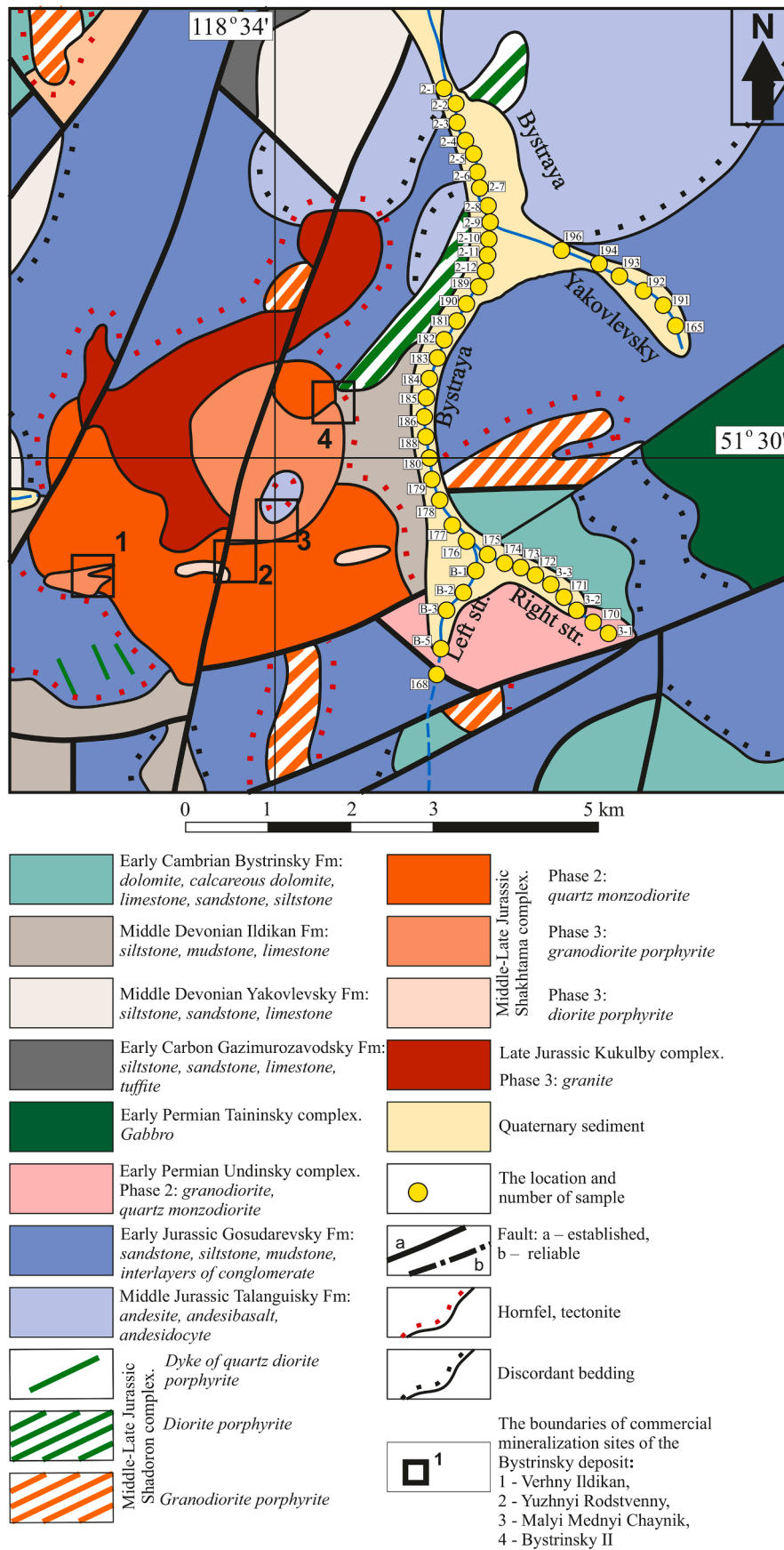


Fig. 2. Geological map of deposit with sample location (simplified from Starchenko (ed.), 1999; the positions of sites of the Bystrinsky deposit are from Kovalenko et al., 2016).

intrusive complex, and relatively small rod-shaped bodies of granodiorite porphyries and diorite porphyries from the second phase of the Shakhtama complex. In addition, dikes and stocks of andesites, andesitic dacites, and dacites of the Middle- Late Jurassic Shadoron complex and dykes, dyke-like bodies of lamprophyres, basalts, and andesites of the Late Jurassic Nerchinskoyavodskoy complex are common within the deposit area (Fedorova and Chernysheva, 2009; Kovalenker et al., 2015, 2016).

According to the exploration reports and available data (Shevchuk et al., 2010; Kovalenker et al., 2016, 2018), four commercial mineralization sites were identified within the ore field: (I) Verhny Ildikan, (II) Yuzhnyi Rodstvenny, (III) Malyi Mednyi Chaynik, and (IV) Bystrinsky II (Fig. 2). Magnetite ores (with superimposed gold-sulfide mineralization) are confined to the skarns located along the contacts the Shakhtama complex intrusive rocks of and the terrigenous sedimentary rocks of the Bystrinsky and Ildikan Formations. Less commonly, gold-sulfide mineralization is related to quartz-carbonate veins (up to 10 m in thickness) that are hosted in the Gosudarevsky Formation. Ore bodies are represented by veins, layers, and lenticular forms, and their thickness is not sustained and can vary from the one to the tens of meters. Most of the ore bodies herein lie subconsistent with the intrusion margin, but, in some cases, there are cutting orebodies formed due to the presence of intense tectonic zone near the endocontact of the skarn (Fig. 2).

Within the **Bystrinsky** deposit, two mineral assemblages are widely occurring: gold-magnetite-pyrite-chalcocopyrite, and gold-pyrite-arsenopyrite-chalcocopyrite (Kovalenker et al., 2018; Redin et al., 2018). The shape of the individual gold grains is isometric, and often interstitial. The size of the native gold particles ranges from <1 μm to 95 μm , and the length of the native gold microveiners does not exceed 100 μm , although grains up to 3 mm have been noted (Kiseleva et al., 2020). Native gold from the gold-magnetite-pyrite-chalcocopyrite mineral assemblage appeared as inclusions in the magnetite, pyrite, and chalcocopyrite, and was characterized by a fineness of 870 – 950‰ (with an impurity of Cu up to 1.32%). Meanwhile, native gold from the gold-pyrite-arsenopyrite-chalcocopyrite mineral assemblage (quartz veins with pyrite, arsenopyrite, and chalcocopyrite) occurred as inclusions in only the pyrite and chalcocopyrite, wherein the fineness of the native gold is 850 – 1000‰, with an admixture of Cu up to 0.1%.

As previously mentioned, besides the Bystrinsky deposit, the Lugokan and Kultuma gold skarn and Novosibirsk gold-bearing base metal epithermal deposits are located near the Gazimur zone. Therefore, it is very important to briefly consider the composition features of their mineralogy.

Mineral assemblages represented at the **Lugokan** deposit include gold-magnetite-pyrite-chalcocopyrite, gold-pyrite-pyrrhotite-arsenopyrite-chalcocopyrite, quartz-molybdenite, gold-polymetallic, and gold-bismuth. The main Au-bearing groups are the gold-pyrite-chalcocopyrite-arsenopyrite and gold-bismuth, wherein, the grains of native gold are round, often irregular, and interstitial. The size of these individual grains varies from 50 μm to 250 μm . Three generations of native gold are distinguished at the deposit (Redin et al., 2015). Native gold I is found in intergrowths with arsenopyrite, pyrite, and chalcocopyrite as well as in the host rocks. The fineness of this native gold varies from 890‰ to 950‰ (with a Cu impurity of up to 0.1% and Hg up to 0.4%). Native gold II is found in intergrowths with galena and tetrahedrite and has a fineness of 750 – 820‰. Finally, native gold III is observed in the intergrowths and as inclusions of bismuth-bearing minerals (bismuthinite, tsumoite, and kozalite). The fineness of native gold III varies from 800‰ to 940‰ (with a Cu impurity of up to 0.1%) (Redin et al., 2015).

The following mineral associations were established at the **Kultuma** deposit and other Au-Cu-Fe-skarn deposits: gold-magnetite-pyrite-chalcocopyrite, gold-pyrite-pyrrhotite-arsenopyrite-chalcocopyrite, quartz-molybdenite, gold-polymetallic and gold-bismuth (Redin et al., 2018). The most widespread mineral associations in this deposit are the gold-

magnetite-pyrite-chalcocopyrite and Au-bearing base metal. The shape of the grains is mainly determined by the structure of the host rocks. Thus, they are elongated, isometric, and rarely in the form of crystals. The bulk of the gold grains belongs to the fine class with a grain size not exceeding tens of microns (Kovalev et al., 2019). According to the first obtained data, two generations of native gold can be distinguished. Native gold I is established in inclusions in magnetite, pyrite, and chalcocopyrite, with a fineness of 900 – 980‰ and a Cu impurity of up to 0.3%. Meanwhile, native gold II was found in the form of inclusions and intergrowths, mainly with galena and tetrahedrite. The fineness of native gold II ranges from 780‰ to 810‰, with an admixture of mercury up to 0.3%.

The **Novosibirsk** Au-bearing base metal deposit is located in the Gazimur deep-seated fault zone and is governed by an eponymous dome-ring structure. Here, the ores are hosted by volcanic rocks in the central part of the structure and extend down to a depth of 2 km. According to Prokofiev et al. (2017), there are six mineral assemblages in the deposit: (1) pre-ore quartz-tourmaline, (2) quartz-sericite-carbonate with pyrite (altered wall rocks), (3) quartz-chalcocopyrite-pyrite, (4) quartz-base metal, (5) quartz-hematite-base metal, (6) carbonate-base metal, and (7) post-ore carbonate. Mineral assemblages 3, 4, and 5 are the economic gold-bearing, wherein the size of the gold particles ranges from below 1 μm to 129 μm , while in some cases, it can reach up to 0.5 mm. The shape of the fine grains that are 25 – 30 μm in size is spherical and drop-like. The less frequently occurring larger grains of gold are elongated (Prokofiev et al., 2017 and references therein). Gold fineness widely ranges from 410‰ to 884‰ with a continuously increasing Ag content of 11% to 58%. Prokofiev et al. (2017) reported that the Au concentrations in most gold particles ranges from 76.1% to 88.47%, wherein a smaller number of particles has an Au concentration of 66.8% to 71.2%. However, a few particles have Au concentrations ranging from 49.8% to 55.8%. Highly fine gold (800‰ and higher) was found only in hematitized quartz. Native gold contains impurities of Cu (from 0.01% to 1.34%) and, more rarely Hg (from 0.22% to 0.55%).

3. Sampling and analytical methods

Samples were taken from the waste dumps of alluvial deposits as well as, when available, from the clay-pebble horizons on the sides of the valleys that were not affected by mining. Each sample with an approximate weight of 20 kg was taken at separated distances of approximately 250 m. Hand-panning was conducted in the field to reduce the weight of the sample and to obtain 20 – 30 g of heavy mineral concentrates. These concentrates, containing particles of native gold, were packed in envelopes and dried. Grains of native gold were handpicked from the concentrates under binoculars. In total, 55 samples were collected from four placers (Bystraya, Left Stream, Right Stream and Yakovlevsky), and gold grains were selected for research from 46 samples (Fig. 2).

These grains were later analyzed using an electron microprobe at the Analytical Center for multi-elemental and isotope research Siberian Branch of the Russian Academy of Sciences in Novosibirsk, Russia, using a JEOL JXA-8100 electron microprobe (Japan) with five wavelength dispersive spectrometers and an energy dispersive spectrometer. The analytical conditions were an accelerating voltage of 20 kV, a beam current of 20 nA, and a counting time of 10 s. The estimated detection limit was 0.05% for Au, Ag, Hg, and Cu. The composition of more than 750 Au grains was analyzed twice for every grain (in the rim and in the core), to determine the degree of their compositional heterogeneity. We processed more than 1500 analysis results of native gold particles taken from 4 placers and a few gold deposits in the Eastern Transbaikalia. For calculations and graphing, only the analyses of the central parts of the gold grains were used. The results of the analyses as well as the number and size of grains in the sample, are provided in the [Supplementary Table](#).

The study of mineral microinclusions in the native gold was

conducted using an Olympus BX51 optical microscope, fitted with a Color View III digital camera. Further instrumental diagnostics were performed with a LEO 1430VP scanning electron microscope (SEM).

In the sampled placers, the silver content was illustrated relative to Ag weight composition using cumulative percent diagrams. With the aid of these diagrams, it is easy to compare the silver distribution in different gold samples despite the large quantity of grains studied (Chapman et al., 2000). The similarity of the graphs plotted for different sampled data indicates the similarity of the bedrock source. A broken curve or a gradient or change in the slope within one sample can be interpreted to indicate the presence of native gold from different types of bedrock sources, especially when the silver content is correlated with other gold content particularities, such as Hg and Cu impurities, or the occurrence of microinclusions.

4. Results

4.1. Morphology and internal structure of gold grain

Native gold grains were found in 46 of the 55 samples with 2–149 grains in each (Supplementary Table). The estimated gold contents ranged from less than 0.05 g/m^3 to 3.1 g/m^3 . The distribution of gold grains over the area is uneven, and the samples collected from the Right stream, Yakovlevsky, and Bystraya placers are more enriched by placer gold. In all the placers, the predominant gold grain size is less than 0.25 mm. At the Yakovlevsky placer, most of the gold grains are thin (<0.1

mm), whereas at the Bystraya and Right stream placers, there exist single gold grains larger than 1 mm. In general, a gold grain fraction of 0.1–0.25 mm is most common in placers.

The morphology of gold grains is diverse. However, the most common types are:

1. Interstitial - angular to subangular, slight or no flattening, includes intergrowths with quartz.
2. Lamellar-flattened - angular to subangular, includes intergrowths with quartz as well as flakes of irregular shape, and plates.
3. Lumpy-massive and massive - sub-rounded, with smooth edges.
4. Crystals and their intergrowths - rounded and oval individuals.

In samples collected from the Yakovlevsky placer (Fig. 3a), sub-rounded to subangular and lumpy-massive gold grains predominate, while crystals are less common. The placer gold from the Right stream (Fig. 3b) is equally represented by all the morphological varieties, including both angular and rounded grains. However, at the Left stream (Fig. 3c), the placer gold grains are mostly angular to subangular and flattened (morphological types 1 and 2), but lumpy-massive grains are also noticeably present. The most representative variation of gold grains in the Bystraya placer (Fig. 3d) exist where rounded gold grains are prevalent, but angular and crystal forms have also been found.

Most of the native gold grains from the Bystraya placer are characterized by a homogeneous structure, even though some grains are heterogeneous (Fig. 4). Among the large number of studied native gold

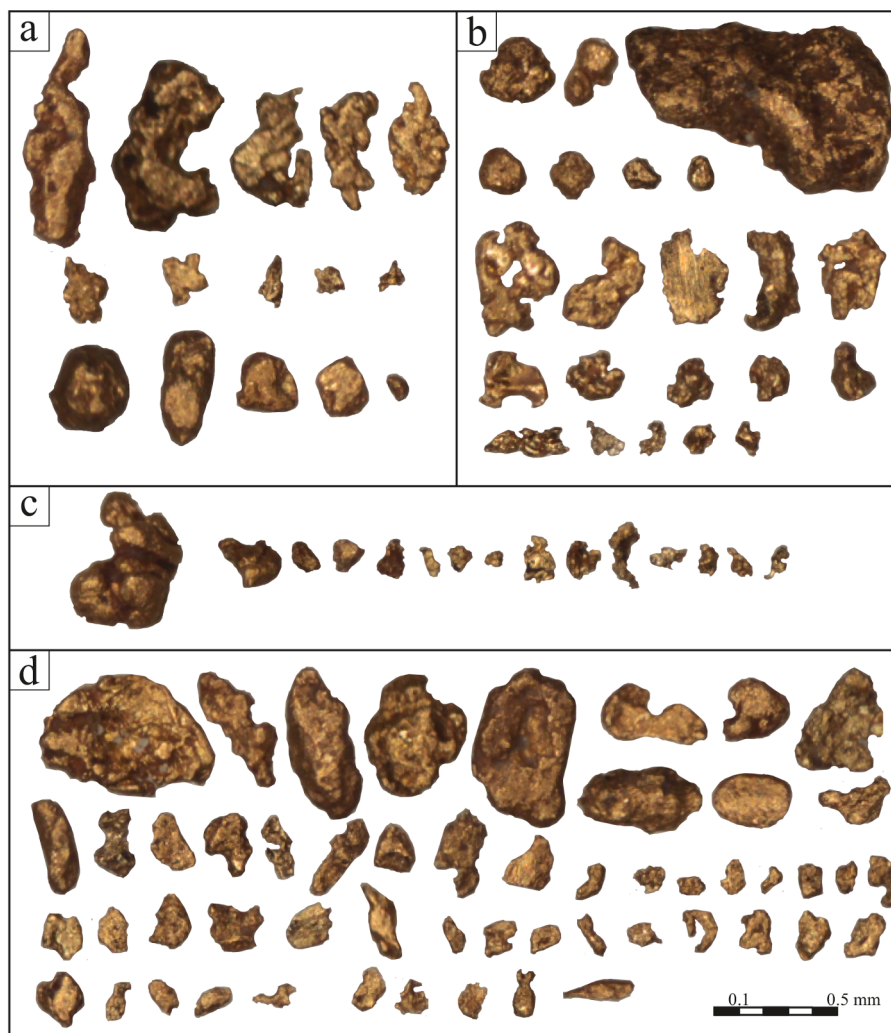


Fig. 3. Photographs of gold grains from placers showing grain morphology: (a) Yakovlevsky; (b) Right stream; (c) Left stream; (d) Bystraya.

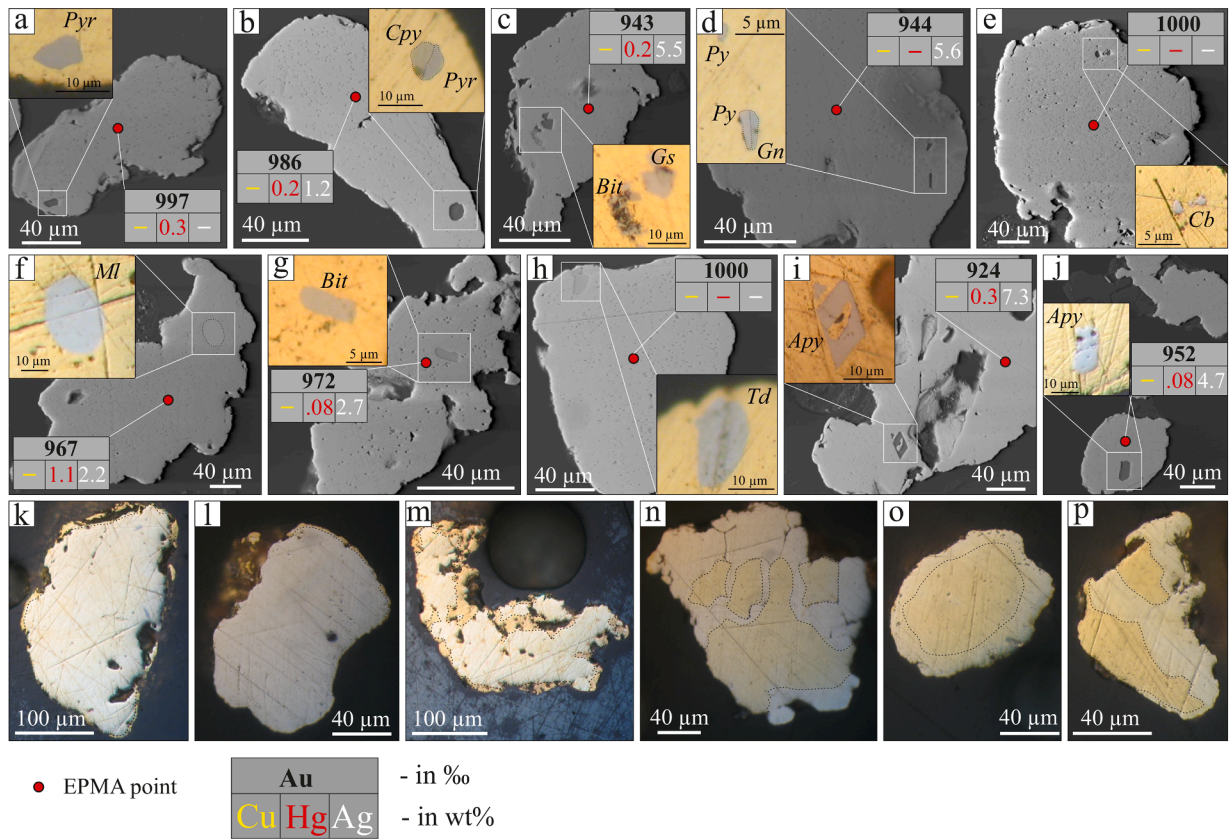


Fig. 4. Microphotographs of gold grains from the Bystraya placer showing homogeneous internal structure and mineral microinclusions (a-j), high-gold supergenic rims (k-m), and heterogeneous and zonal structure (n-p). Mineral abbreviation: Pyr – pyrrhotite, Cpy – chalcopyrite, Py – pyrite, Gs – gersdorffite, Bit – bismuthinite, Gn – galena, Cb – cobaltite, Ml – maldonite, Td – tetradymite, Apy – arsenopyrite.

grains, there are some grains in the central parts of which were identified areas with varying of fineness. In some cases, thin intragranular veinlets, composed of low-fineness alloys in relation to the grain itself, have been noted. The thickness of these veinlets does not exceed 5 μm. Some grains are characterized by a zonal structure, as shown in Fig. 4. In

the core of such grains, the gold content is higher than that within the rim. The fact that a hypergene high-gold rim has developed over it indirectly indicates the hypogenic nature of a low-gold zone of grain. A relatively common feature of the native gold grains from the Bystraya placer is the development of high-gold supergenic rims; wherein, in most

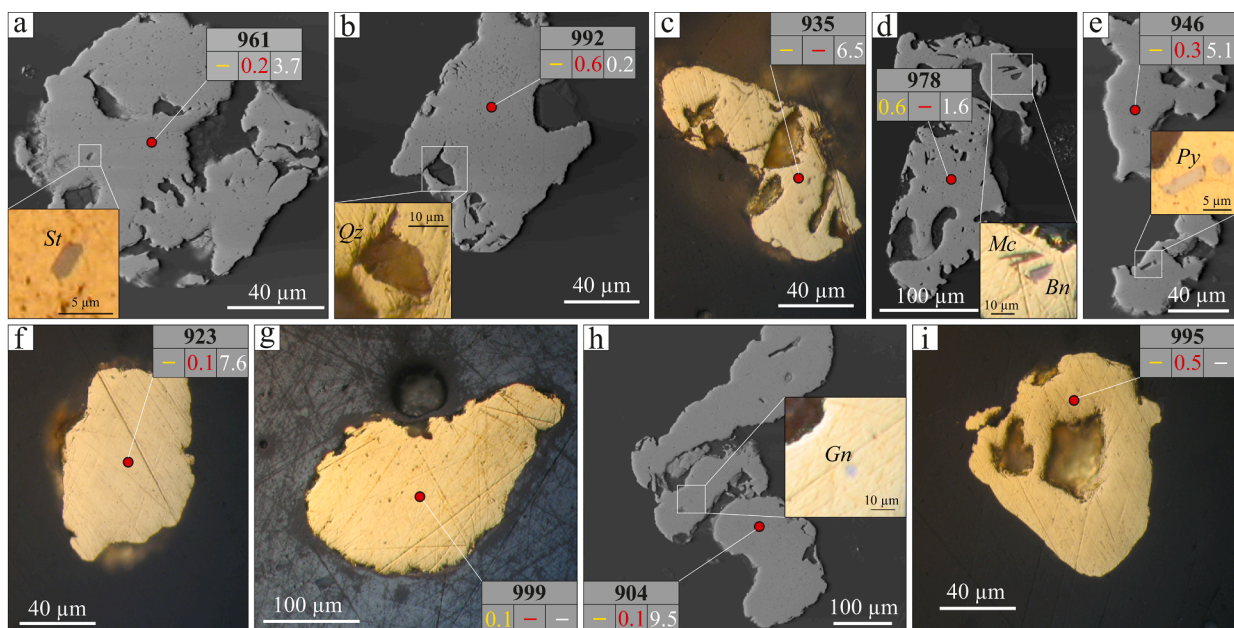


Fig. 5. Microphotographs of gold grains from the Left stream showing homogeneous internal structure and mineral microinclusions. Mineral abbreviation: St – stannite, Qz – quartz, Mc – mica, Bn – bornite, Py – pyrite, Gn – galena. For legend see Fig. 4.

cases, the rims have a thickness of a few microns.

Native gold grains from samples collected from dumps of the Left, Right, and Yakovlevsky stream placers are mainly characterized by a homogeneous structure with no heterogeneity of the composition within the individual grains (Figs. 5–7). In some grains, high-Au rims are distinguished, but their thickness is a matter of microns. Note that the mosaic and block structure gold grains are not identified.

4.2. Chemical composition of placer gold

The generalized results of the analysis are listed in Table 1 and shown at Figs. 8–11, for more detail you can see Supplementary Table. The dispute of the types of gold grains and assumption groups in composition we offer below in the Discussion section.

4.2.1. Bystraya placer

The chemical composition of native gold from the Bystraya placer varies significantly (Fig. 8, Table 1, and Supplementary Table). The fineness of native gold varies from approximately 400‰ to 1000‰, with a clear peak at 950–1000‰. Based on more than 500 spot analyses, the average fineness of the Bystraya placer gold is 935‰. The copper content is not high, but there is a pattern of increasing copper content with an increasing native gold fineness. Significant copper contents (above the detection limit) were noted in a quarter of all the analyses, wherein the maximum value was found to be 0.73%. Note that almost all grains with a significant copper content have a fineness of more than 900‰. Conversely, the mercury content in native gold is variable, and the maximum concentration in some grains can reach 8.53%. Mercury (with a concentration above the detection limit) was detected in 67% of the analyses, with an average content of 0.25%.

Studying the mineral composition of the microinclusions in the native gold, we have been identified numerous mineral forms (Figs. 4, 13, and Table 1). Among them, several ore minerals groups can be distinguished, including as Fe-(As)-bearing sulfides (pyrite, As-bearing pyrite (2% As), pyrrhotite, arsenopyrite), Cu sulfides (bornite and chalcopyrite), Bi minerals (bismuthinite, gustavite, maldonite, tetrady-mite, and tsumoite), and Ni-Co-bearing sulfides (Ni-bearing pyrrhotite

(Ni up to 2%), gersdorffite, cobaltite, and rammelsbergite). Note that the base metal minerals are represented only by galena. Some host rock and gangue minerals were also identified, including goethite, dolomite, quartz, potassium feldspar, tourmaline, and rutile. Notably, one microinclusion contained a grain of aurostibite. However, almost all of the native gold grains containing identifiable mineral inclusions are characterized by high-fineness and are either Hg-containing or impurity-free. In total, only 4 of 75 mineral inclusions were found in Cu-bearing native gold (Fig. 8).

4.2.2. Left stream placer

The chemical composition of the native gold in the Left stream is shown in the Fig. 9 and summarized in Table 1. Here, the native gold is characterized by a high fineness in the range of 739–999‰, with an average of approximately 948‰. Further, the silver content reaches 23.24% in the single grains, with the average content of 38 grains at 4.66%. The copper content is low, wherein only 21% of the analytical data contained detectable Cu. Native gold had a copper content of up to 0.55%, and a mercury content up to 4.68%, wherein the average mercury content was approximately about 0.5%. In 71% of the analyses, mercury content was observed to be above the detection limit.

Only four ore minerals were found as microinclusions in gold grains: stannite, galena, bornite, and pyrite (Figs. 5 and 13 and Table 1). In addition, a few grains of host rock and gangue minerals (hornblende, quartz, and mica) were identified. The relationships between the compositions of native gold and mineral microinclusions (Fig. 9) allowed us to identify certain patterns. Thus, bornite inclusions were found to exist in high-fineness native gold with a relatively high copper content (0.55%). Conversely, galena occurred as microinclusions in gold grains with a fineness of 900‰.

4.2.3. Right stream placer

The fineness of native gold from the Right stream placer ranges from 743‰ to 1000‰, with an average of 959‰ (Fig. 10, Table 1). Native gold content impurities of copper (up to 0.15%), mercury (up to 4.52%), and silver (up to 23.6%) were found. Copper and mercury were detected in 20% and 82% of the analyses, respectively. In a pair of Cu-Au, a

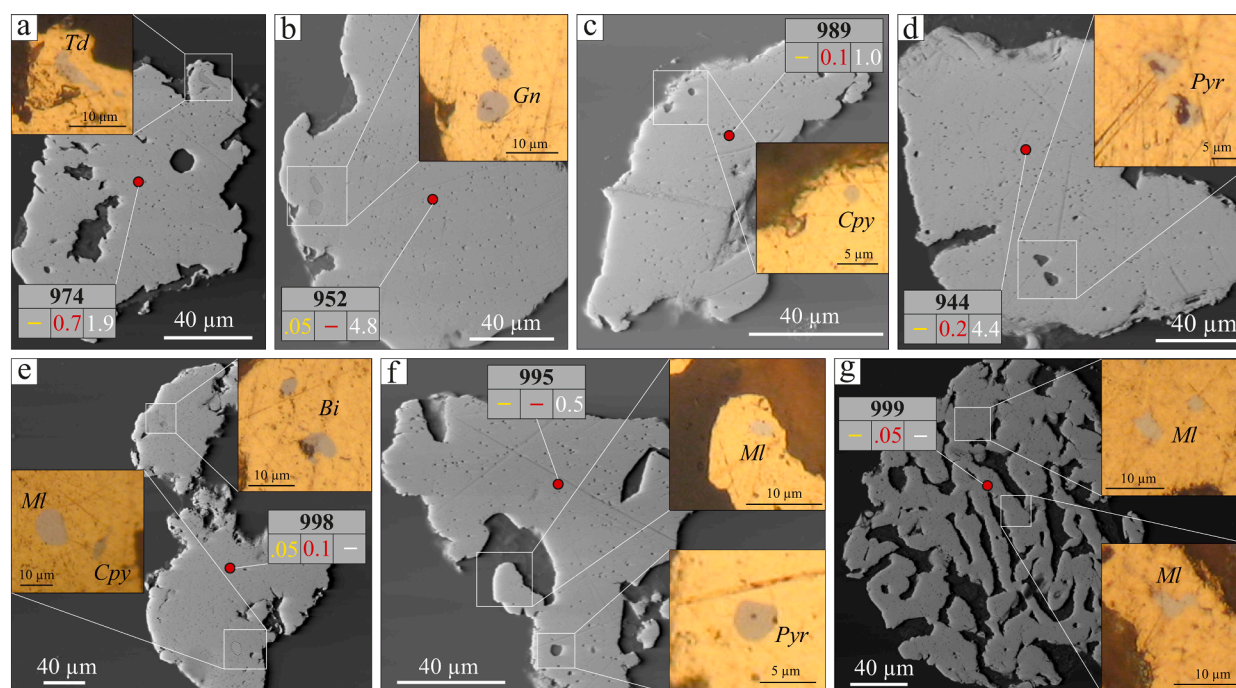


Fig. 6. Microphotographs of gold grains from the Right stream showing homogeneous internal structure and mineral microinclusions. Mineral abbreviation: Td – tetradymite, Gn – galena, Cpy – chalcopyrite, Pyr – pyrrhotite, Bi – native bismuth, Ml – maldonite. For legend see Fig. 4.

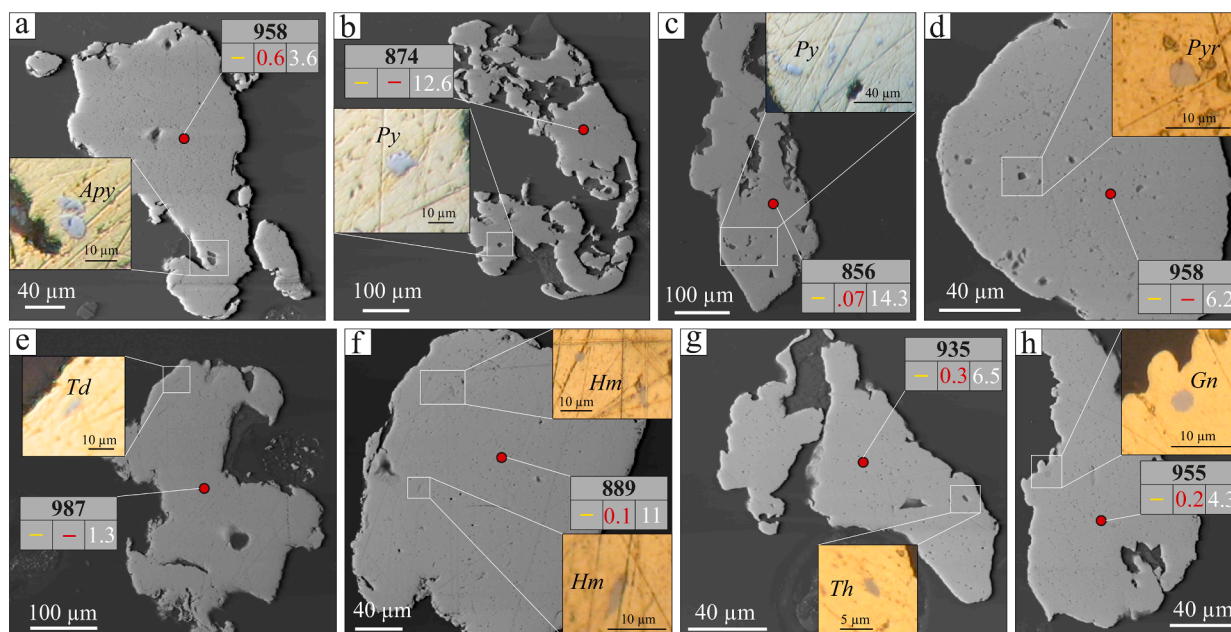


Fig. 7. Microphotographs of gold grains from the Yakovlevsky placer showing internal structure and mineral microinclusions. Mineral abbreviation: *Apy* – arsenopyrite, *Py* – pyrite, *Pyr* – pyrrhotite, *Td* – tetradymite, *Hm* – hammarite?, *Th* – tetrahedrite, *Gn* – galena. For legend see Fig. 4.

Table 1

Characteristics of gold grains from studied placers.

Placer	Number of grain	Fineness, % min–max aver	Impurities, wt%						Mineral Inclusions (MIs)				
			Cu		Hg		Ag		n	Ore minerals			
			min-maxaver	% above DL	min-maxaver	% above DL	min-maxaver	% above DL					
Bystraya	502	416–1000935	0–0.73	0.05	24	0–8.53	0.25	65	0–56.14	6.18	87	75	<i>Apy</i> , <i>Asb</i> , <i>Bit</i> , <i>Bi-sulf</i> , <i>Bn</i> , <i>Cb</i> , <i>Cpy</i> , <i>Gn</i> , <i>Gs</i> , <i>MI</i> , <i>Py</i> , <i>Pyr</i> , <i>Ram</i> , <i>Td</i>
Left stream	38	739–999948	0–0.55	0.05	21	0–4.68	0.52	71	0–23.24	4.66	84	4	<i>Bn</i> , <i>Gn</i> , <i>St</i> , <i>Py</i>
Right stream	143	743–1000959	0–0.15	0.02	20	0–4.52	0.3	82	0–23.63	7.74	80	23	<i>Bi</i> , <i>Bi-sulf</i> , <i>Bit</i> , <i>Cpy</i> , <i>Gn</i> , <i>MI</i> , <i>Py</i> , <i>Pyr</i> , <i>Td</i> , <i>Tel</i>
Yakovlevsky	67	800–998922	0–0.66	0.02	6	0–1.05	0.21	73	0–19.97	5.58	99	11	<i>Apy</i> , <i>Bi-sulf</i> , <i>Gn</i> , <i>Py</i> , <i>Td</i> , <i>Th</i>

Notes: Mineral abbreviation: *Apy* – arsenopyrite, *Asb* – aurostibite, *Bit* – bismuthinite, *Bi* – native bismuth, *Bi-sulf* – Bi-bearing sulfosalts (such as hammarite, tsumoite, gustavite), *Bn* – bornite, *Cb* – cobaltite, *Cpy* – chalcopyrite, *Gn* – galena, *Gs* – gersdorffite, *MI* – maldonite, *Py* – pyrite, *Pyr* – pyrrhotite, *St* – stannite, *Ram* – rammsbergite, *Td* – tetradymite, *Th* – tetrahedrite, *Tel* – Te-bearing minerals (such as coloradoite, altaite, telluroantimonite)

pattern of an increasing copper content was detected with an increasing native gold fineness. Conversely, relatively high mercury contents are more typical for low-fineness native gold (Fig. 10).

In total, 23 mineral microinclusions were identified in 143 gold grains (Fig. 13). Almost all the detected inclusions can be divided into four groups: Bi-bearing (Bi-bearing galena, bismuthinite, maldonite, tetradymite, and tsumoite), Te-bearing (altaite, coloradoite, and telluroantimonite), Fe-bearing (pyrite and pyrrhotite), and Cu-bearing. The last group was represented only by chalcopyrite, wherein the base metal minerals include galena. Moreover, a few gangue minerals were found, including quartz, potassium feldspar, and rutile. Note that a significant amount of the mineral inclusions belong to high-fineness native gold with low but detectable Hg content.

4.2.4. Yakovlevsky stream placer

In the Yakovlevsky stream placer, the native gold was characterized by high-fineness, ranging from 800‰ to 998‰, with an average of 922‰ (Fig. 11, and Table 1). Copper impurities exceeding the detection limit were established in only four grains (6% of analyses), wherein content reached up to 0.66%. Meanwhile, mercury was found to be widespread (73% of analyses) with content of up to 1.05%. Overall, silver was the main impurity found in the native gold, wherein its

concentration, according to the above fineness, reached up to 19.9% (Fig. 11).

The study of native gold grains allowed us to establish a number of mineral inclusions of various compositions. Thus, the following mineral microinclusions were identified (Figs. 7 and 13): Fe-(As)-bearing sulfides (pyrite, arsenopyrite), Cu-bearing (tetrahedrite), and Bi-bearing (tetradymite, emplectite, and hammarite). In addition, galena microinclusions were found in one gold grain. Fig. 11 shows the composition of the native gold grains in which mineral inclusions were identified. Note that all the identified inclusions correspond to gold grains with high-fineness and low but detectable Hg content.

5. Discussion

5.1. Types of native gold

The comprehensive research herein has enabled us to characterize native gold based on its chemical features and mineral microinclusion assemblages. The identification of native gold types according to their chemistry is an integral part of forecasting and prospecting development as it allows us to infer the formation type of the potential bedrock source of the placers.

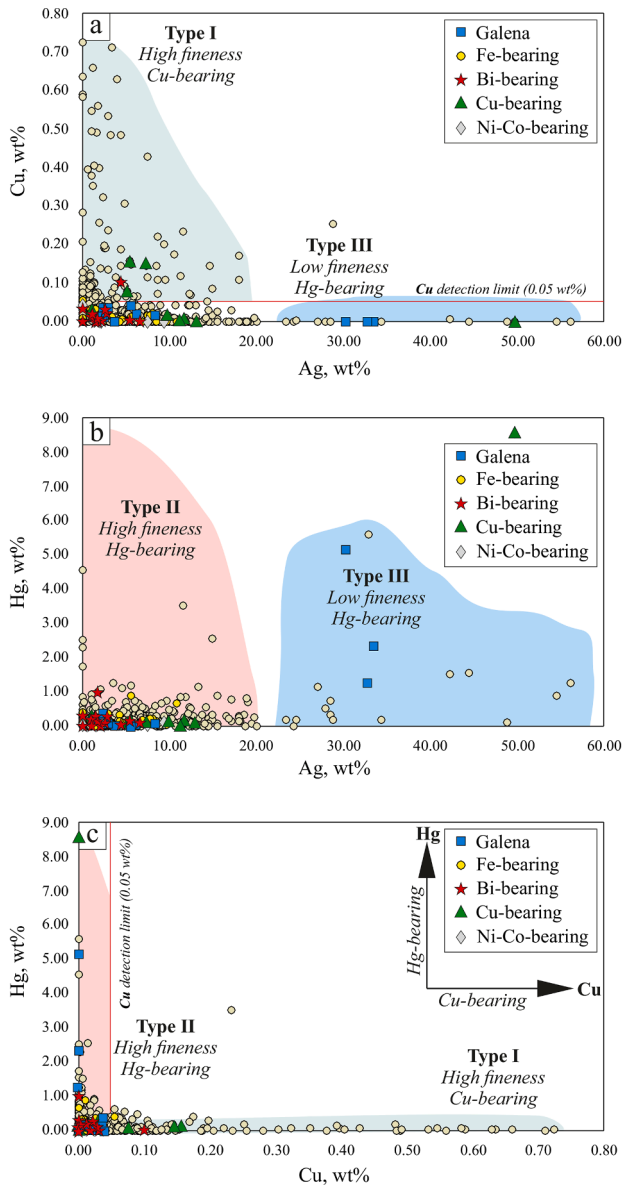


Fig. 8. Chemical composition of gold grains from Bystraya placer.

Herein, the analyses performed did not always provide reliable typing within the sample. This may be due to both the small number of analyses themselves (statistically insignificant sample) and the non-normative nature of the results. In reality, we had to choose between a large and statistically significant sample, wherein there would be no specific features that allow grouping (the content of impurity elements, and mineral inclusions), and the sample size used herein. By using a small number of samples, we were able to distinguished the gold grain groups based on various bivariate graphs (Figs. 8–11) and a cumulative curves (Fig. 14). We can provide our proofs of the distinguished groups in the three following steps:

1. As previously mentioned, the fineness of the native gold from the Bystraya placer varies in a wide range from approximately 400‰ to 1000‰, with a peak at 950 – 1000‰. Thus, a group of low-grade native gold with a fineness up approximately 400 – 770‰ was distinguished (Fig. 8a-b) according to silver content. The typomorphic features of this gold grain type are the relatively high Hg (up to 8.53%) and the microinclusions of galena and, more rarely, chalcopryrite (Fig. 8). In addition, low-fineness gold grains are shown in the

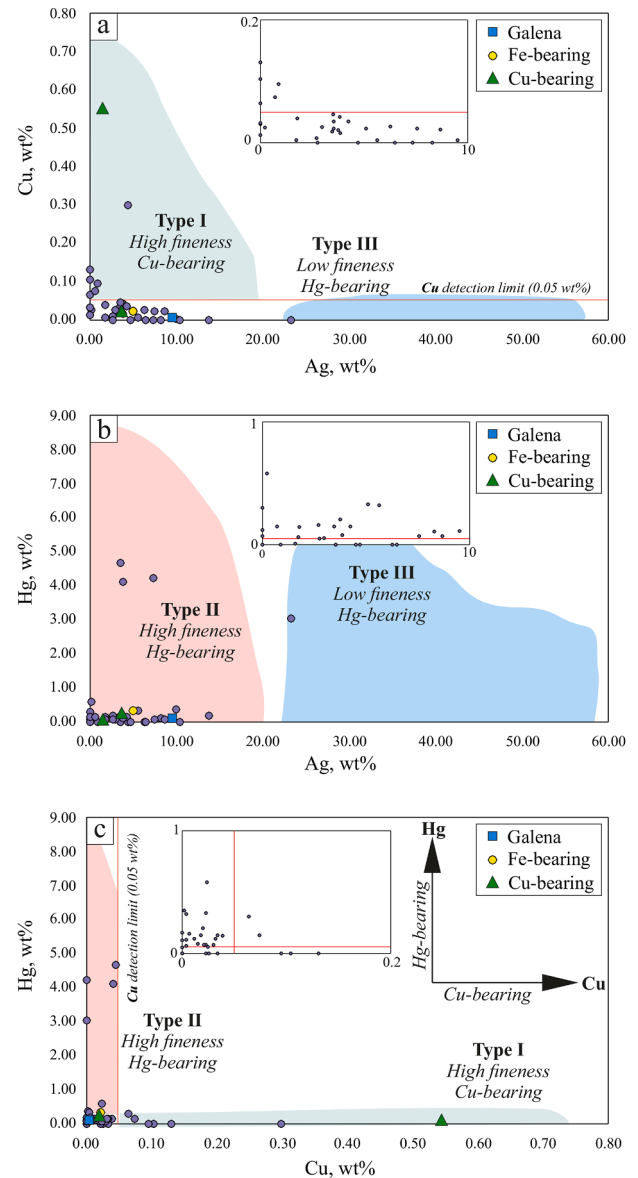


Fig. 9. Chemical composition of gold grains from Left stream placer.

cumulative curve (Fig. 14a). In quantitative terms, these gold grains are insignificant. Thus, in the Bystraya placer, approximately 4% of all the analyses correspond to the low-grade Hg-bearing type (Figs. 8 and 14a). Conversely, in the Left (Fig. 9) and Right (Fig. 10) stream placers, only a single grain is identifiable as this type. Further, in the Yakovlevsky placer, low-fineness gold grains are completely absent (Fig. 11).

2. Most of the analyses are characterized by high-fineness (greater than 800‰) and the sporadic presence of mercury and copper impurities. Furthermore, there are many analyses that correspond to grains of high-fineness native gold that do not contain any trace elements. Thus, the discrete distribution of copper and mercury impurities in the gold grains are notable. Moreover, such a pattern appears in all the studied placers (Fig. 8c, 9c, 10c, and 11c). Native gold that contains a copper impurity greater than the microprobe detection limit (more than 0.05%) is usually mercury free. Likewise, Hg-bearing native gold does not contain copper. Based on this phenomenon, we propose the allocation of Cu-bearing and Hg-bearing high-fineness native gold.

The Cu-bearing type of native gold is characterized by high-fineness

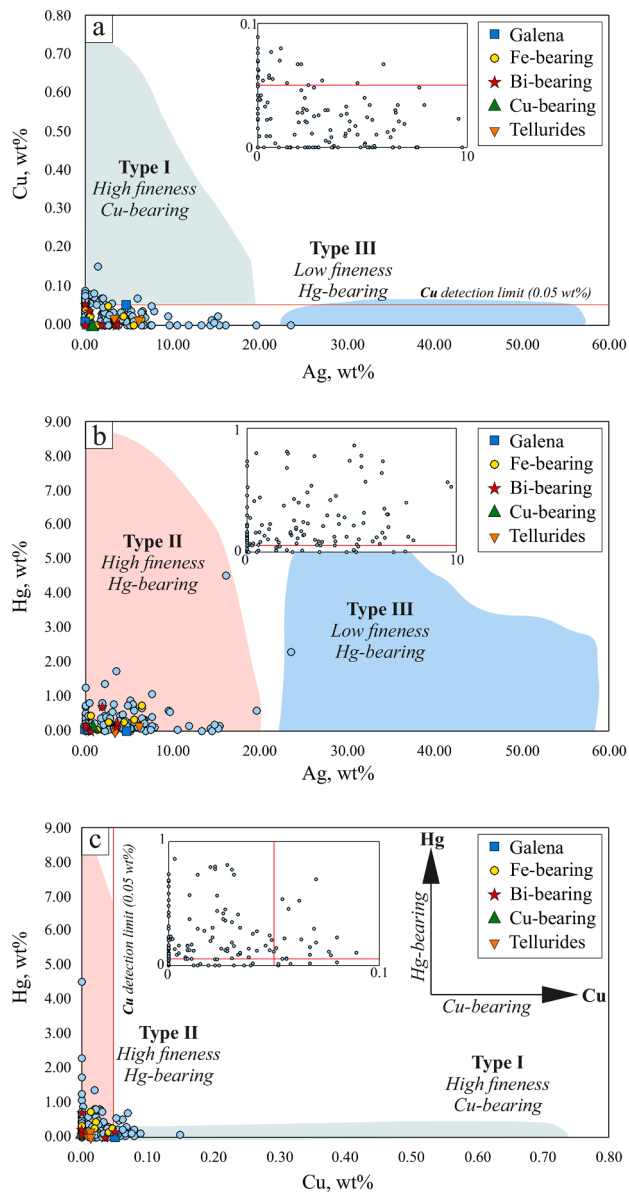


Fig. 10. Chemical composition of gold grains from Right stream placer.

(800 – 999‰) with a clear prevalence of fineness over 950‰ (Fig. 8a, 9a, 10a, and 11a). Here, the copper content is not high, reaching only up to 0.73% (Fig. 8a). As previously mentioned, few mineral inclusions corresponds to Cu-bearing gold. Among these are 1 grain of pyrite and tetradymite, and 2 grains of chalcopyrite and bornite (Fig. 8a and 9a). This type of the gold grain has been identified in all the studied placers, but its quantity is not constant. In the Bystraya placer with Left and Right streams, Cu-bearing gold occurs in approximately 20% of the studied grains (Fig. 14a). Meanwhile, only 6% of analyses (four grains) correspond to this group at the Yakovlevsky placer (Fig. 11a). Based on the composition data of the native gold according to Chapman et al. (2018), Cu-bearing high-fineness native gold corresponds to gold from porphyry deposits.

The Hg-bearing native gold has a fineness of 800 – 999‰ and contains, in addition to silver, an admixture of mercury content up to 4.68% (Fig. 8b, 9b, 10b, and 11b). Approximately 80% of this gold grain type has a fineness greater than 900‰. In general, the mercury content ranges from 0.05% to 1% (Fig. 14a). This type of gold is the most distributed among the studied placers. Thus, approximately 70% of the studied gold grains corresponded to the Hg-bearing high-fineness type.

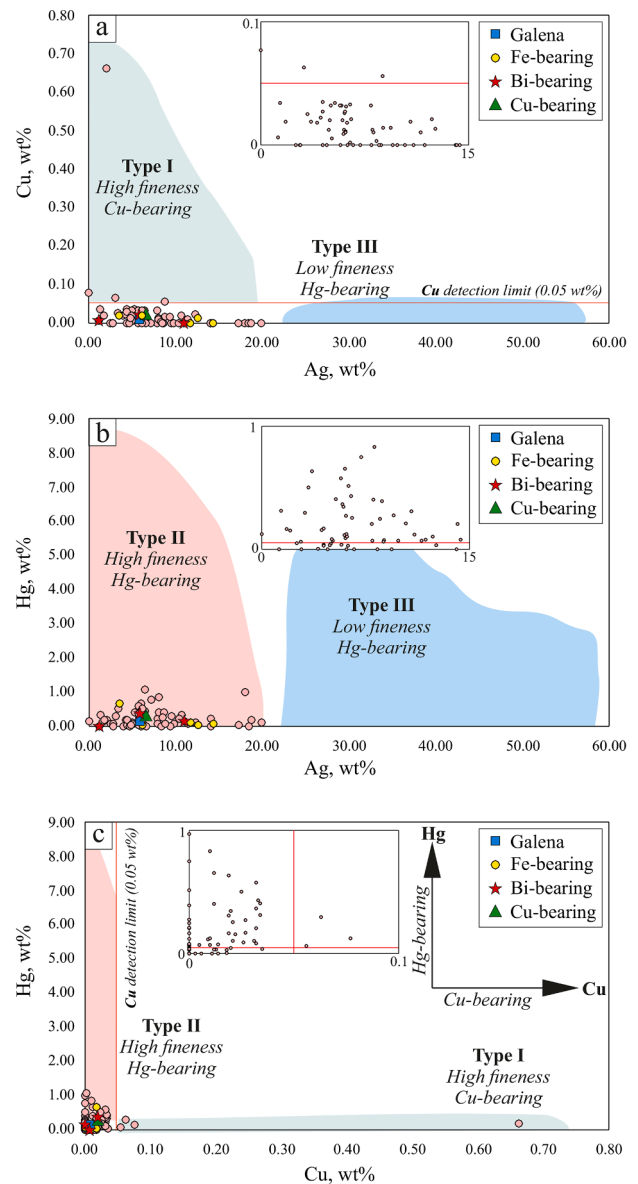


Fig. 11. Chemical composition of gold grains from Yakovlevsky placer.

Microinclusions, which are identified in this type, are represented by a wide variety of minerals, which can be categorized into a few mineral groups, including Fe-, Cu-, Bi-, and Co-Ni-bearing. Base metal mineral microinclusions of this type are represented by galena (Fig. 13).

- As previously mentioned, there are high-fineness Hg-Cu-impurity free gold grains. Such gold grains are very difficult to classify into certain types because the specific features that are often used as discriminators are absent. The fineness of these gold grains is high, varying from 800‰ to 1000‰. In addition, a group of gold grains with extremely high-fineness (approximately 1000‰) can be distinguished. The quantity of such gold grains is small. In the placers studied herein, they can be attributed to, on average, approximately 17% of the gold grains. However, they are practically absent in the Yakovlevsky placer (Fig. 14). Mineral microinclusion assemblages in Cu- and Hg-poor high-fineness gold grains are similar to the Hg-bearing type. In gold grains Fe-, Cu-, and Bi-bearing minerals, as well as a few inclusions of galena were identified. Further, the absence of sharp changes in the cumulative curve shown in Fig. 14a

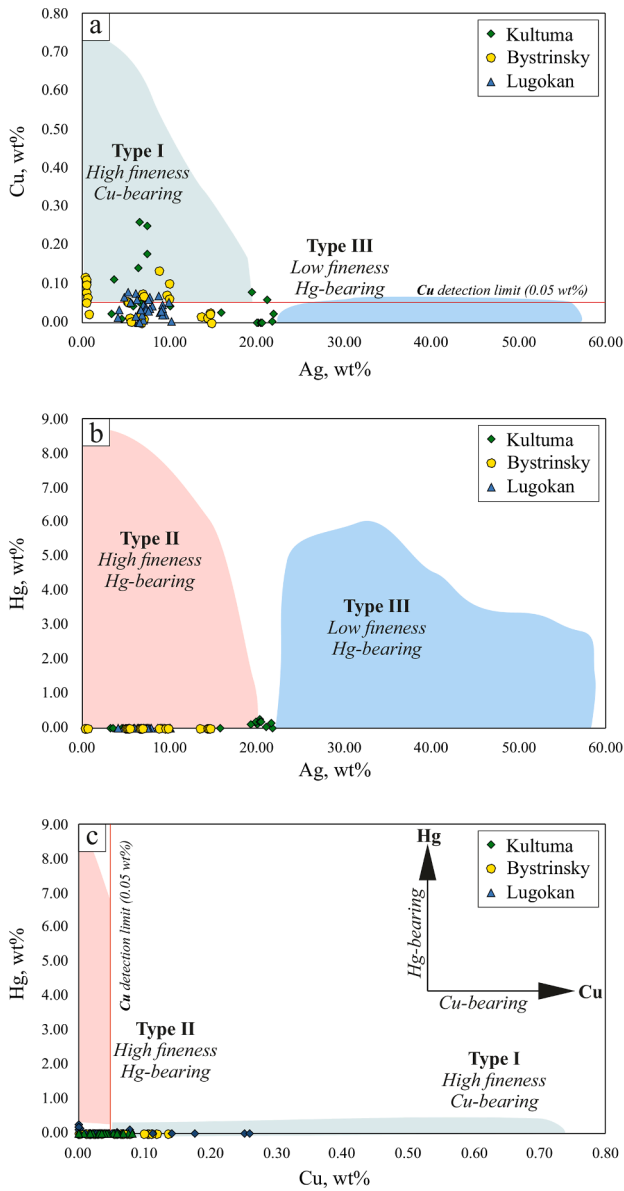


Fig. 12. Chemical composition of native gold from the Lugokan, Kultuma, and Bystrinsky deposits.

suggests that this type of native gold is more likely to refer to the aforementioned Hg-bearing high-fineness type.

Thus, according to the chemical composition, the native gold from the placers in the Bystraya River catchment can be divided into 3 types

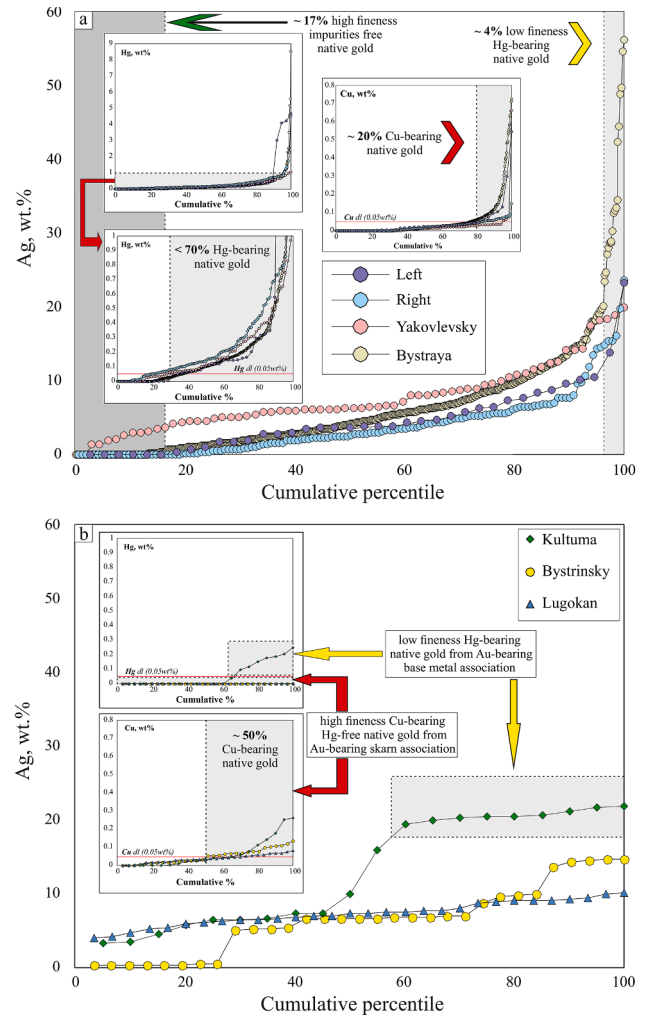


Fig. 14. Characterization of gold grains from placers (a) and hypogene ore deposit (b) illustrating quantitative ratio between different types of Au alloys.

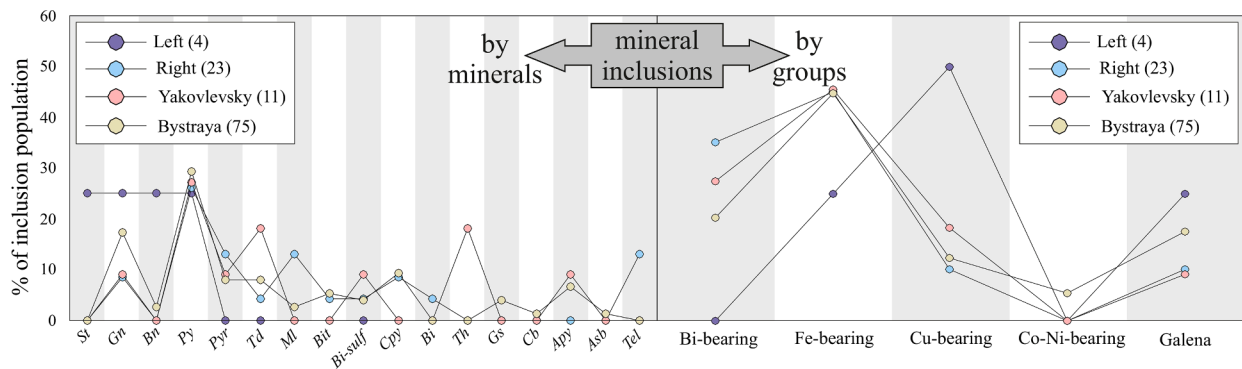


Fig. 13. Depiction of inclusion assemblages. Comparison illustrated by minerals (left) and by groups of minerals (right). Mineral abbreviation: Apy – arsenopyrite, Asb – aurostibite, Bit – bismuthinite, Bi – native bismuth, Bi-sulf – Bi-bearing sulfosalts (such as hammarite, tsumoite, gustavite), Bn – bornite, Cb – cobaltite, Cpy – chalcocyprite, Gn – galena, Gs – gersdorffite, Ml – maldonite, Py – pyrite, Pyr – pyrrothite, St – stannite, Td – tetrahedrite, Th – Te-bearing minerals (such as coloradoite, altaite, telluroantimonite). Key to mineral group abbreviation: “Bi-bearing” = Bi + Bit + Bi-sulf + Ml + Td; “Fe-bearing” = Py + Pyr + Apy; “Cu-bearing” = Cpy + Bn + Th; “Co-Ni-bearing” = Cb + Gs + rammelsbergite.

and 1 subtype:

Type 1 – Cu-bearing gold grains with a fineness of 800 – 995‰ and with an impurity of copper up to 0.73%.

Type 2 – Hg-bearing gold grains with a fineness of 800 – 995‰ and an Hg impurity up to 4.68%.

Subtype 2.1 – Hg-poor gold grains with a fineness of 800 – 995‰, with the same mineral microinclusion assemblages as Type 2 gold grains.

Type 3 – Gold with a fineness of 400 – 770‰ that contains up to 8.5% Hg.

5.2. Specific features of the native gold

In the studied placers, a large amount of weakly rounded and unrounded gold was observed (Fig. 3). High contents of such ore-type gold are often observed, indicating that the formation of the placers are due to nearby primary sources, for example, in the Yakovlevsky and Right streams and some places of the Bystraya River.

The morphological and chemical characteristics of the placer's native gold allow us to conclude that the native gold underwent insignificant supergenic transformation. Grains of native gold from the Bystraya placer are mainly weakly rounded, which is evidence of a nearby source of the placer source rock. The degree of chemical transformation, which is expressed in the development of high-fineness rims, is not significantly represented. These results suggest that the bedrock source is in close proximity.

Another informative feature is the sporadically manifested low-fineness rim of native gold in the zonal grains. Gold grains that are characterized with a zonal compositional gradually increasing in the Ag content from the center to the edge are rarely described in the literature, even though their presence is not unique. Gold with silver-rich rims from placers, weathering zones, and ore deposits have been previously described in a number of studies (for examples, see Nefedov et al., 1982; Healy and Petruk, 1990; Huston et al., 1992; Sheets et al., 1995; Jianjun et al., 2000; Svetlitskaya et al., 2018). However, zonal gold grains are rarely observed and, apparently, are associated exclusively with increasing in the Ag/Au ratios in ore solutions during gold formation (Desborough et al., 1971; Carrillo Rosúa et al., 2002; Naden et al., 1994), which is a feature of the ore process. Morrison et al. (1991) noted that the zoning of individual gold grains from Ag-rich rims to high-fineness central parts is a characteristic feature of volcanic-hosted massive sulfide (VHMS) deposits. For example, these grains are widely manifested in gold from Zn-Cu-Pb (-Ag-Au) volcanogenic stratabound massive sulfide ores of the Kuroko deposits in Japan. Native gold from epithermal deposits is also characterized by a similar reverse zoning. However, as a rule, these experience more complex zoning (Morrison et al., 1991). In addition, gold, with gradually increasing Ag content from the center to the edge has been described in the Baochun skarn-type gold mine in China (Jianjun et al., 2000). The mineralization associated with Au-Ag skarn is also suggested as a potential source of Ag-zonal native gold from the Pt-Au placer of the Inagli River (Yakutia, Russia) (Svetlitskaya et al., 2018).

Because some grains of native gold from the Bystraya placer experience a gradual decrease in fineness from the center of the grain to the edge (Fig. 4n-p), we assume that the evolution of the physicochemical parameters occurred during ore formation. Thus, these changes led to an increase in the Au/Ag ratio in the ore-forming fluid, which caused the formation of zonal native gold. A distinctive feature of the internal structure of zonal native gold grains from the Bystraya placer is the gradual increase of silver content from the center to the periphery of the grain and the presence of Au-rich rims. These features indicate that zoning in silver content is a hypogenous characteristic of gold and is not associated with the supergenic transformation processes that occur in placers.

Identification on the morphological features, mineral associations, and chemical composition of the studied gold lead to the following

conclusions:

- In the Bystraya placer, there is a large amount of weakly rounded gold grains (ore-like morphology) that are not far removed. Their distribution over the area is uneven, which indicates an abundance of bedrock sources.
- A weak degree of supergenic transformation of the placer gold grains indicates that the formation of these placers occurs directly owing to endogenous gold mineralization, without intermediate collectors.

5.3. Potential bedrock source and compression with in-situ mineralization

The composition analysis of the native gold grains from the Bystrinsky, Lugokan, and Kultuma deposits made it possible to understand some general features, as shown in Fig. 12 and listed in the Supplementary Table.

The native gold in the studied deposits has, in general, high-fineness in the range of 900 – 950‰. A slightly lower fineness (approximately 750 – 850‰) is characteristic of the native gold of the late Au-bearing base metal association of the Kultuma deposit (Figs. 12 and 14b). Moreover, according to Prokofiev et al. (2017), gold grains from the Au-bearing base metal Novoshirokinsky deposit are characterized by a fineness of 410 – 884‰.

Mercury in the studied native gold is not a characteristic impurity. According to our research and the available published data (Prokofiev et al., 2017), an admixture of mercury in gold grains is noted only in the low-fineness native gold from Au-bearing mineralization (Novoshirokinsky deposit and late mineral association of the Kultuma deposit). In this type of native gold, the mercury content ranges up to 0.3% and 0.55% for the Kultuma (Fig. 12b-c and 14b) and Novoshirokinsky deposits, respectively.

Copper impurities, meanwhile, are noted in almost all the studied native gold grains, but their concentration did not reach high values. The maximum copper content and relative amounts of copper-bearing gold are characteristic of native gold from the Kultuma and Bystrinsky Au-Cu-Fe deposits. Thus, gold grains from the skarn of the Kultuma deposit contain an impurity of copper up to 0.25%. Almost all the studied gold grains from skarn mineralization at the Kultuma, Lugokan, and Bystrinsky deposits had low but detectable Cu contents.

Therefore, two types of native gold at in-situ mineralization can be distinguished:

Type 1 - Cu-bearing gold grains with a fineness of 850 – 999‰ with low but detectable copper impurity content. This type of gold grain corresponds to porphyry-skarn mineralization.

Type 2 – Hg-bearing gold grains with a fineness of 400 – 800‰. This type corresponds to Au-bearing base metal mineralization, which is genetically related to the porphyry system.

A comparison of the types of alluvial gold identified previously with the chemical composition of the gold from the in-situ deposits reveals the following patterns:

- 1) The chemical composition of Cu-bearing high-fineness native placer gold by can be compared with the Cu-bearing native gold of the porphyry-skarn Bystrinsky, Lugokan, and Kultuma deposits.
- 2) Hg-bearing low-fineness placer gold grains related to erosion of the Au-bearing base metal mineralization occurred at both the Novoshirokinsky and Kultuma deposits.
- 3) In the studied deposits, the Hg-bearing high-fineness type of gold grains, which occur most widely in the studied placers, are absent.

The presence of Cu-bearing, high-fineness native gold in the placers of the Bystraya River basin is logical and expected. However, the presence of mercury-rich native gold requires additional clarification. Their occurrence could be attributed to several reasons, the most plausible of which are as follows: (i) this type of native gold can be linked to other unknown bedrock sources; (ii) the bedrock source is represented by

scattered quartz veins that do not form economically significant mineralization; and (iii) heterogeneity of the gold grain composition at the bedrock source (e.g. the vertical zonation of mineralization). As the first two reasons are obvious, then the third requires further clarification.

We assumed that during in-situ mineralization (e.g. Bystrinsky deposit) there was vertical zoning, which was expressed in the gold grain composition. At the upper levels of the porphyry-epithermal system, the temperature of the mineral formation could be lower because of the water–rock interaction and mixing with meteoric waters (Sillitoe, 2010). Meanwhile, at lower levels, near to the magma chamber, the temperature could be higher. To date, the lower level of the porphyry-epithermal system that displays in-situ mineralization as igneous rocks, which have associated mineralization, are outcropped. Thus, it is logical to assume that the mineralization of the upper levels was completely eroded. Therefore, we assume that the bedrock source of the Hg-bearing high-fineness gold widely occurred at the studied placers is the completely eroded upper levels of the Bystrinsky deposit (Gas'kov, 2017).

The evidence for this viewpoint is based on the following. First, all the studied gold grains are weakly rounded or have ore-like morphology, which indicates a slight displacement of grains without a remoteness of the bedrock source. In addition, there is no correlation between the degree of roundness and the composition of the gold grains. Second, the mineral microinclusion assemblages in the Hg-bearing high-fineness gold grains (Fe-, Cu-, Bi-bearing) correspond to the Bi-Pb-Te-S signatures of the mineral inclusion suites for the porphyry-skarn system (Chapman et al., 2018). Conversely, the assemblage reflects the mineral composition of the primary sulfide ores of the Bystrinsky deposit (Kovalenker et al., 2018; Redin et al., 2018). Third, there are no gaps and/or changes in the angle of inclination at the cumulative curves (Fig. 14a) that would allow substantiating another population of gold grains.

Based on this, we suppose that the Hg-bearing high-fineness gold grains widely that occurred at the placers are a “mirror” of the eroded upper levels of mineralization of the Bystrinsky deposit. This type of gold grain is more pronounced in the studied area than the Cu-bearing type, which, for example, is practically absent in the Yakovlevsky placer. Consequently, the primary mineralization at the upper levels of the Bystrinsky deposit was more widely occurring than that presented today.

6. Conclusion

- 1) In alluvial placer deposits of the Bystrinsky deposit areas, weakly rounded native gold is significantly present and is not far removed from its bedrock sources. A weak degree of supergenic transformation of gold grains in the placers indicates that placers are formed directly from endogenous gold mineralization, without the intermediate collectors.
- 2) According to the chemical composition, the native gold from the placer in the Bystraya River catchment can be divided into 3 types and 1 subtype: (1) Cu-bearing gold grains with a fineness of 800 – 995‰ and a copper impurity up to 0.73%; (2) Hg-bearing gold grains with a fineness of 800 – 995‰, and an Hg impurity of up to 4.68%; (2.1) Hg-poor gold grains with a fineness of 800 – 995‰, and the same mineral microinclusion assemblages as those in the Type 2 gold grains; and (3) gold with a fineness of 400 – 770‰, containing up to 8.5% Hg.
- 3) All the distinguished types of gold grains are manifested to varying degrees at the Bystraya, Left, and Right placers. However, at the Yakovlevsky placer, there is no Hg-bearing low-fineness and only poorly occurring Cu-bearing native gold.
- 4) The Cu-bearing high-fineness type of native placer gold by chemical composition can be compared with the Cu-bearing native gold of the porphyry-skarn Bystrinsky, Lugokan, and Kultuma deposits.

- 5) Hg-bearing low-fineness placer gold grains related to erosion of the Au-bearing base metal mineralization occur at the Novoshirokinsky and Kultuma deposits.
- 6) Hg-bearing high-fineness type of gold grains, which widely occur in the studied placers, are absent in the in-situ mineralization.
- 7) The bedrock source of Hg-bearing high-fineness gold, which occurs widely at the studied placers, is linked to the completely eroded upper levels of the Bystrinsky deposit.
- 8) Based on the placer gold particle signatures, it is possible to speculate on the nature of eroded material and therefore make assumptions about regional metallogeny.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.oregeorev.2020.103948>.

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