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Alluvial-Placer Gold of Northwestern Salair: Composition, Types, and Mineral Microinclusions

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Abstract—On the territory of the Egor'evsk district, 3500 results of probe microanalyses of surface gold particles taken from 17 placers, weathering crusts, and orebodies were processed and summarized. High-fineness and mercury-containing gold is predominantly found within mother lodes and placers, and medium- and low-fineness gold is distributed in subordinate and dramatically subordinate quantities, especially in the placers. A unique feature of the gold composition, rarely occurring in other districts, is the constant and commonly simultaneous presence of mercury and copper impurities. Analysis of Ag, Hg, and Cu content variations has enabled us to identify five main grades of gold. The mother lodes of the predominant gold grades are metasomatites with beresite and listwaenite compositions, which are developed primarily after lower Cambrian volcanoterrigenous-carbonate rocks and ore-bearing mafic dikes. Mercury-containing gold is characteristic of beresites, but copper-bearing gold is typical of listwaenites. The relationship between corresponding grades of surface and ore gold is confirmed by the presence of microinclusions in the gold grains. Nonconformity between the content of gold from mother loads, weathering crusts, and placers is explained by the losses of Hg and Ag impurities by endogenous gold under subsurface hypergene conditions. Identification of mineral-geochemical properties of surface gold is of exceptional practical importance in ore-grade gold mineralization prediction.

Keywords: alluvial placers, gold, mother lodes, gold fineness, impurity elements, grades/types of gold

INTRODUCTION

In accordance with statistic data more than 12,000 tons of gold have been mined in Russia over the last 250 years; notably, 80–85% of gold output accounts for gold placer mines (Benevolskii, 2002). Up to the present time, the gold placer mines have absolutely dominated by the total volume of gold production, and only in the second quarter of the last century the balance changed towards the hard-rock gold deposits. This could be explained by the fact that the development of large and unique deposits has been launched. Although most placer mines have exhausted their potential, their share accounts for 13.8% by gross volume of the prospected resources in Russia, and in 2012 the share of total output amounted to 23.7% (Lalomov et al., 2015).

In the Novosibirsk Region, 7 gold deposits in weathering crusts (suitable for open-cut mining) and 25 alluvial placer mines are included into the National Register. As of 01.01.2016, total gold reserves represented in the National Register were classified as category C_1—4481 kg, cat. C_2—746 kg; where alluvial placers account for: cat. C_1—1265 kg, cat. C_2—185 kg and gold-bearing weathering crusts account for: cat. C_1—3216 kg, cat. C_2—561 kg. The gold reserves of 716 kg are accounted for in the out-of-balance group. Mining companies supplies of alluvial placer resources will last for the following 6–7 years (in accordance with the production level for the last 5 years) (Germakhanov et al., 2017). The perspectives of the mineral reserve base development are connected with its primary deposits and gold-bearing weathering crusts. As all known placers have exhausted their potential or are under development, further growth of gold production requires the search and assessment of new placers and development of new ore-containing deposits and gold prospects.

Despite the 200-year history of placers development in the Egor'evsk district, the literature contains scarce information about surface gold composition (Nesterenko, 1991; Roslyakov and Sviridov, 1998; Roslyakov et al., 2001). This information is rather generalized and mainly refers to the fineness of gold from only some of the placers and only from few deposits and gold prospects. Meanwhile, the uniqueness of the district surface gold lies in the constant presence of Hg and Cu in its composition; besides, their content is rather significant and sometimes very high. Mechanical microinclusions of ore minerals preserved in the particles of native gold also contain important information about the material composition of the mother lodes (Chapman et al., 2000, 2009; Potter and Styles, 2003).

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The abundance of gold grades containing Hg and Cu in placers, its fineness and mineral composition of inclusions are the indicators of mother lodes, most of which, in spite of exhausted placers, haven't been found yet. Chemical composition characteristics of native gold, in contrast to morphological attributes, tend to remain preserved even for long-range alluvial transport. Chemical properties are left unchanged inside gold grains which haven't undergone complete compositional transition under hypergene conditions (Chapman et al., 2000; Townley et al., 2003; Nesterenko and Kolpakov, 2007). All the research done in this area is based on the above-given theoretical postulate, and consequently, it will be fairly applied for the Salair Mountain Range features.

Thus, at present gold placer mines have not only an economic value, but they are certain to be the most important information source, which could be used for prediction and search of primary deposits (Nesterenko, Chapman et al., 2000, 2009, 2010; Townley et al., 2003). The importance of surface gold as a predictive-search sign of ore-grade gold mineralization will increase when considering the lack of territorial exposure.

GEOLOGICAL DESCRIPTION AND DISTRICT GOLD MINERALIZATION

The Salair Range (Fig. 1) is an independent structural-tectonic unit within the western boundaries of the Altai–Sayan folded area (Kanygin and Sviridov, 1999). It is a folded tectonic structure of northwestern strike, which suddenly changes to a southwestern one at nearly a right angle in the vicinity of the Gorlovka and northwestern Kusnetsk troughs that form its boundaries. The axial zone of the Salair Range is dominated by Cambrian carbonate-volcanogenic deposits (Fig. 2), which are intensively dislocated with northwest striking linear and isoclinal folding. The periphery of the fold structure is dominated by less dislocated Ordovician and Silurian carbonate-terrigenous rocks (Roslyakov et al., 2001).

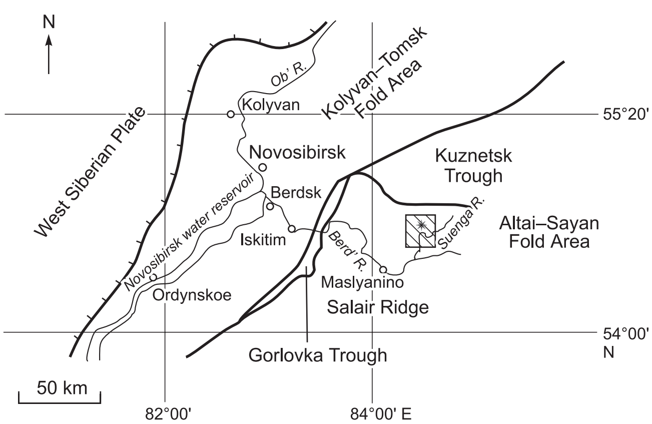


Fig. 1. The overview diagram of tectonic zoning of the juncture of the Kolyvan-Tomsk folded area and the Salair Range. The shaded area—the Egor'evsk ore-placer district.

Gold appears to be a primary metal for the explored northwestern part of the Salair Mountain Range. Here all the endogeneous zones, alluvial (weathering crusts) and other placer mines, including the great number of gold prospects, mineralization sites, geochemical and concentrate aureoles and flows are well known and all included into the Egor'evsk ore-placer district. Within its boundaries, the ore-grade gold mineralization process is mainly represented by gold–quartz/gold–sulfide–quartz and gold–sulfide, gold–antimony, gold–mercury and gold-containing polymetallic formations (Roslyakov et al., 2001).

The overwhelming majority of ore-grade gold mineralization tends to localize in the lower Cambrian terrigenous-volcanogenic-carbonate deposits of the Kinterep and Suenga Formations, and also in sheared volcanogenic-sedimentary rocks of the lower Cambrian Pecherkino Formation (Fig. 2). These rocks are saturated with ore-bearing small intrusions mainly of diorite composition, which are referred to the Taily complex of small intrusions (Kanygin and Sviridov, 1999).

Gold–quartz and gold–sulfide–quartz occurrences are located in the deposits of the Kinterep and Suenga Formations. Ore-grade gold mineralization is represented, as a rule, by gold-bearing quartz-micaceous-carbonate metasomatites with an alternating quantity of quartz veins and veinlets. Gold-bearing metasomatites are considered to be the main source of gold in weathering crusts (Kalinin et al., 2006). According to publications (Roslyakov et al., 1995), gold-bearing metasomatites are widespread in the Egor'evsk ore-placer district. Based on the results of thorough mineral-geochemical investigation of micaceous metasomatites, N.A. Roslyakov et al. (1995) came to conclusion that the protolith for these rocks appeared to be both diorites and terrigenous deposits of the Suenga Formation. The protolith compositions affect the characteristics of metasomatites derived from them. For instance, listwaenite tend to develop over small mafic intrusions of the Taily complex, at the same time beresites are found along terrigenous deposits of the Suenga Formation.

The largest ore production sites are known to be the Novolushnikovskoe deposit of the gold–sulfide–quartz formation with a veined stock-work type of ore mineralization and the Egor'evskoe gold deposit in the weathering crusts (Roslyakov et al., 1995). Endogenous primary ores usually contain a small amount of sulfides and sulphosalts; moreover, telluride mineralization is sometimes detected. The average ore minerals content equals 5%, and in rare cases it reaches 10%.

Gold-grade polymetallic mineralization spatially coincides with the Pecherkino Formation deposits (Fig. 2) and judging by the set of objective attributes it could be parallelized with the northeast Salair deposits (the Ur, Salair ore fields). Gold–(sulfide)–quartz ore mineralization (Roslyakova et al., 1983) is often in evidence within polymetallic de-

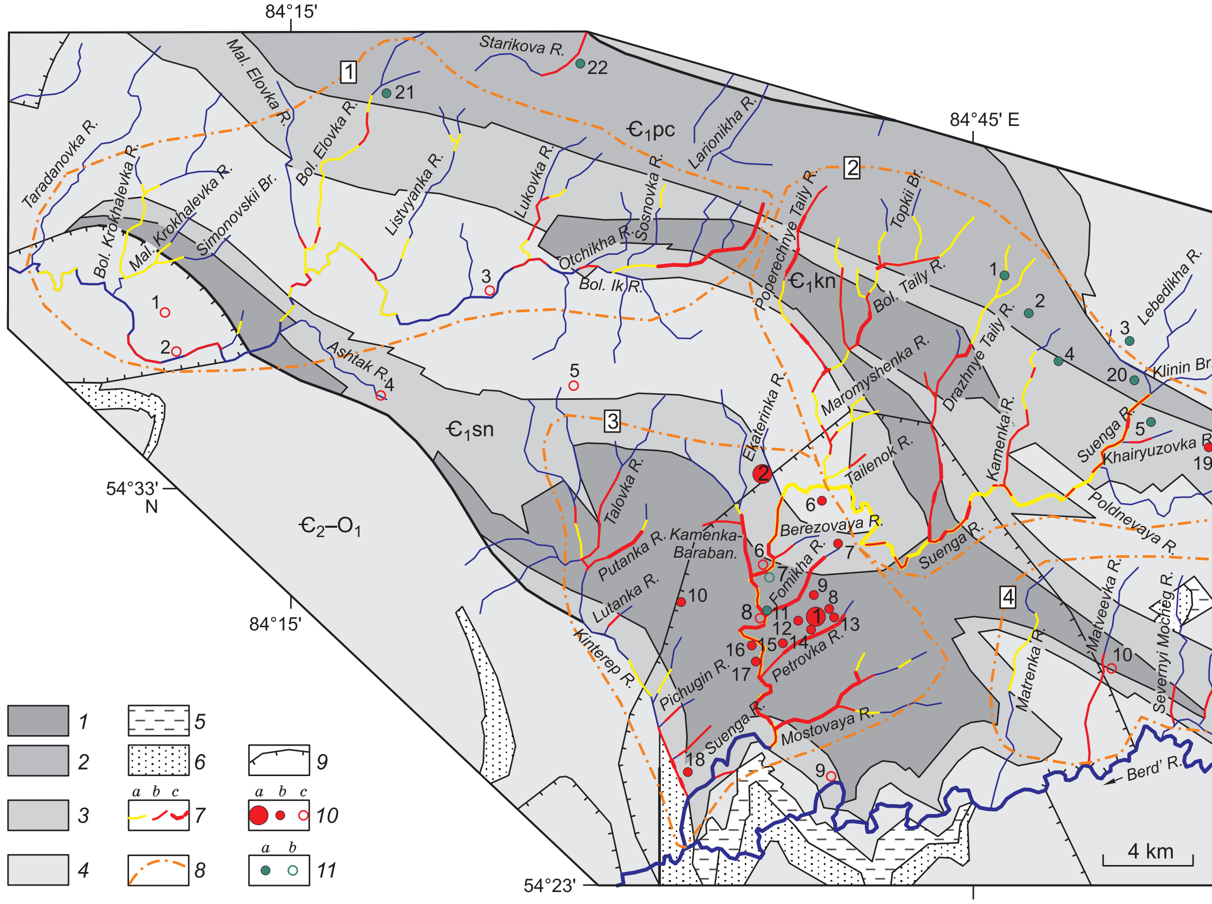


Fig. 2. Scheme of the geology and gold mineralization of the Egor'evsk ore placer district (based on the State Geological Map) (Belyaev et al., 2001). *1*, Kinterep Formation (Є$_1$kn), marmorized limestone with interlayers of coaly matter, sandstones and siltstones; *2*, Pecherkino Formation (Є$_1$pc), sheared plagiorodacites and their tuffs, quartz-epidote-chlorite-sericite-albite-carbonate and carbonaceous shales; *3*, Suenga Formation (Є$_1$sn), volcanoterrigenous-carbonate deposits; *4*, green-purple series (Є$_2$–O$_1$), volcanoterrigenous depositions; *5*, limestones, siltstones, clay shale, sandstone (O$_2$–S$_1$); *6*, limestones, clay shale, bauxites, allites, siallites (D$_{1-2}$); *7*, placer gold (Belyaev et al., 2001; Roslyakov et al., 2001) with linear productivity less than 20 kg/km (*a*), 20–100 kg/km (*b*), 100–150 kg/km and more (*c*); *8*, placer fields: 1, Ik, 2, Taily, 3, Suenga, 4, Berd'; *9*, contours of ultimately eroded relief blocks; *10*, gold ore deposits (*a*), ore occurrences (*b*) and mineralization sites (*c*); *11*, pyrite-(barite)-polymetallic gold-bearing ore occurrences (*a*) and mineralization sites (*b*) (Belyaev et al., 2001; Roslyakov et al., 2001). Deposits: 1, Egor'evskoe, 2, Novolushnikovskoe (Vein 13). Ore occurrences: 1, Ekaterininsk, 2, Kotorovo, 3, Ust-Kalistratikha, 4, Verkhnyaya Kamenka, 5, Volkova Zaimka, 6, No. 9, 7, Kratovo-Fomikha, 8, Lenivyi ravine, 9, Kolokol'tsevo, 10, Lutanskoe, 11, No. 20, 12, Fomikha, 13, Lapinskii ravine, 14, Guselnyatskii, 15, Petrovka ravine, 16, Bobrovskii ravine, 17, Fon–Shtremlevo, 18, Sukhoi Log, 19, Bolshoe Chesnokovo, 20, Lebedikha, 21, Elovka, 22, Smirnovskii. Mineralization sites: 1, Vershina Ika Village, 2, Vyazky, 3, Ik River Head, 4, Ashtak River, 5, Kinterep, 6, Suenga-2, 7, Suenga-1, 8, Udivitel'nyi ravine, 9, Kratovsk–Berd', 10, Matveevka area.

posits, and it can go far beyond these bounds (Roslyakov et al., 1995). Many ore occurrences and gold–grade pyrite–(barite)–polymetallic mineralization sites are known in the district. The Lysaya Gora, Volotomikha, Tars'ma, Elovka, Volkova Zaimka, Ogneva Zaimka, Romanovo occurrences are exemplary of this mineralization type. Pyrite is the main ore mineral associated with galena, false galena, and small grains of chalcopyrite. The Elovka occurrence is supposed to be a massive body with ore zones of sulfide (barite polymetallic) mineralization and broad-scale gold–quartz ore mineralization (Roslyakov et al., 2001).

Many gold placers are on record in the district, mainly of medium and low productivity. The medium productivity of high-grade placers is measured in kg/km: Kamenka-Barabanovskaya—189; Fomikha—184; Mostovaya (Kuznechnyi ravine)—160; Petrovka (with feeders)—153; Drazhnye Taily—150. However, the predominant part is characterized by average productivity estimates—about 50–100 kg/km (Roslyakov et al., 2001). Most placers, including the richest ones, are enclosed in carbonate and terrigenous-carbonate rocks (Nesterenko et al., 1984). Placers are not typical of the river valleys dominated by, for example, harder intrusive rocks. Consequently, the placers have a complex discontinuous structure, which is also due to the mother lodes diversity. Besides known ore occurrences and mineralization sites, over 200 quartz and quartz-carbonate vein outcrops have been found in the district et the beginning of last century, and some of them appeared to be gold-bearing. Many veins have been revealed by miners working on placers. Judging by the practical significance and abundance, emerging valley alluvial placers and smaller autochthonous-type ravine placers take predominant position (Nesterenko et al., 2003).

The Suenga, Ik, Taily, and the predicted Berd' placer fields are associating with ore–bearing areas (Fig. 2) (Roslyakov and Sviridov, 1998; Belyaev et al., 2001). Nearly all the ore bodies of the gold–(sulfide)–quartz type and highly productive placers are concentrated in the Suenga district, but polymetallic ore mineralization occurs both in the Ik and in the east of the Taily district, and ore-grade gold–(sulfide)–quartz mineralization is predicted in the least explored Berd' placer field (Roslyakov et al., 2001).

The alluvial placer gold grains vary in size from finely dispersed (< 10 μm) to large (2–3 mm and more), which mostly corresponds to the grain sizes in the mother lodes. Larger size gold grains and even small nuggets weighing up to several hundreds of grams (possibly from gold–(sulfide)–quartz mother lodes) are present in most of the district placers. Gold morphology is different, and the degree of grain rounding is average or high. Ore-grade gold of poor rounding is found in relatively small quantities within all the placers. The study particularly concentrates on gold composition and characteristics of its mineral microinclusions, since the roundness is considered to be a 'function' of transport distance to a mother-lode and transport conditions (Townley et al., 2003; Chapman and Mortensen, 2016), that in its turn conceals the primary morphological features of surface gold. The most informative approach to the validation of mother-lode placers will be the detailed and statistically meaningful study of these characteristics, and comparison of the obtained information with the analogous data on known primary deposits (McTaggart and Knight, 1993; Chapman et al., 2000, 2010; Chapman and Mortensen, 2016).

METHODOLOGY

The grains content of native gold in polished samples (checkers/artificial polished section—thinned polished section) was determined with the use of a Camebax-Micro dispersion spectrometer in the CUC of Multielement Isotope Study, SB RAS. Detection limits for gold assays were as follows: for Au—0.065 wt.%, for Ag—0.065 wt.%, for Hg—0.096 wt.% and for Cu—0.061 wt.%. Measurements were done both in the centers and at the edges of separate gold grains to determine the degree of their compositional transition which leads to formation of rims and sites with the fineness of 990–1000‰ or to complete compositional transition of grains. The analysis data for transformed Au grains (usually at the edges) was not considered for calculations. We have processed more than 3500 analyses results of native gold particles taken from 17 placers, the data on 3 weathering crusts profiles and of 3 ore-bodies. The study of mineral microinclusions in native gold was carried out with the use of an Olympus BX51 optical microscope, fitted with a Color View III digital camera. Further instrumental diagnostics was done with a LEO 1430VP scanning electron microscope (SEM).

In some sampled placers, silver content is illustrated relative to Ag weight composition with cumulative percent diagrams. With the aid of these diagrams, it's easy to compare silver distribution in different gold samples in spite of the quantity of the grains studied (Chapman et al., 2000). The similarity of graphs plotted for different sampled data could indicate the similarity of mother lodes. A broken curve or a gradient/change in the slope within one sample could be interpreted as an indicative of native gold presence from different types of mother lodes, especially when silver content could be correlated with other gold content particularities, such as the presence of Hg and Cu impurities, and also the occurrence of microinclusions in the gold grains and their composition.

PLACER GOLD COMPOSITION

The Ik placer field (Fig. 2) consists of the Bolshoi Ik River basin and its right streams, starting from the waterparting of the Pikhtovyi Ridge, which is mainly dominated by the lower Cambrian Suenga and Pecherkino Formations. The left feeders of the Bolshoi Ik are not gold-bearing. We have studied pieces of native gold sampled from the range of the right streams of the first and second order (from west to east), these are the rivers: Listvyanka, Bolshaya Elovka, Malaya Elovka, Simonovskii Brook, Malaya Krokhalevka and Bolshaya Krokhalevka. Figures 3*A*, *B* represent the native gold composition from the Elovka/Krochalevka parts covered by the Ik placer field.

Bolshaya Krokhalevka. The native placer gold is characterized by fineness within the range from 740 to 999‰ with a strong predominance of high-fineness gold (more than 900‰) (Fig. 3*A*, *b*, *d*). Silver content can reach 25 wt.% (Fig. 3*A*, *c*, *e*). Mercury and copper concentrations in native gold could amount to ~4 and ~3.3 wt.%, respectively (Fig. 3*A*, *b–e*). As seen in Fig. 3*A*, three grades of native gold are identified in accordance with the distribution pattern of silver. The first group is the commonest with silver content up to 7 wt.% (about 80–85% of the whole sampling). The second group with Ag content up to 12 wt.% accounts for 10% of the whole sampling. The third group appears to be the worst represented (about 5% of sampling) and exhibits a silver content of 12–25 wt.%.

Malaya Krokhalevka. Native gold fineness equals 850–990‰, with obvious predominance of high-fineness gold (Fig. 3*A*, *b*, *d*). Concentrations of Ag, Hg and Cu reach 15, 8.5, and 2.8 wt.%, respectively (Fig. 3*A*, *b–e*). The cumulative diagram analysis (Fig. 3*A*, *a*) lets us suppose the resemblance of two types based on silver content. The most multiple group (about 98% of the whole sampling) is marked by silver impurity content which reaches 7 wt.%. The second group includes very few grains with silver impurity content up to 15 wt.%.

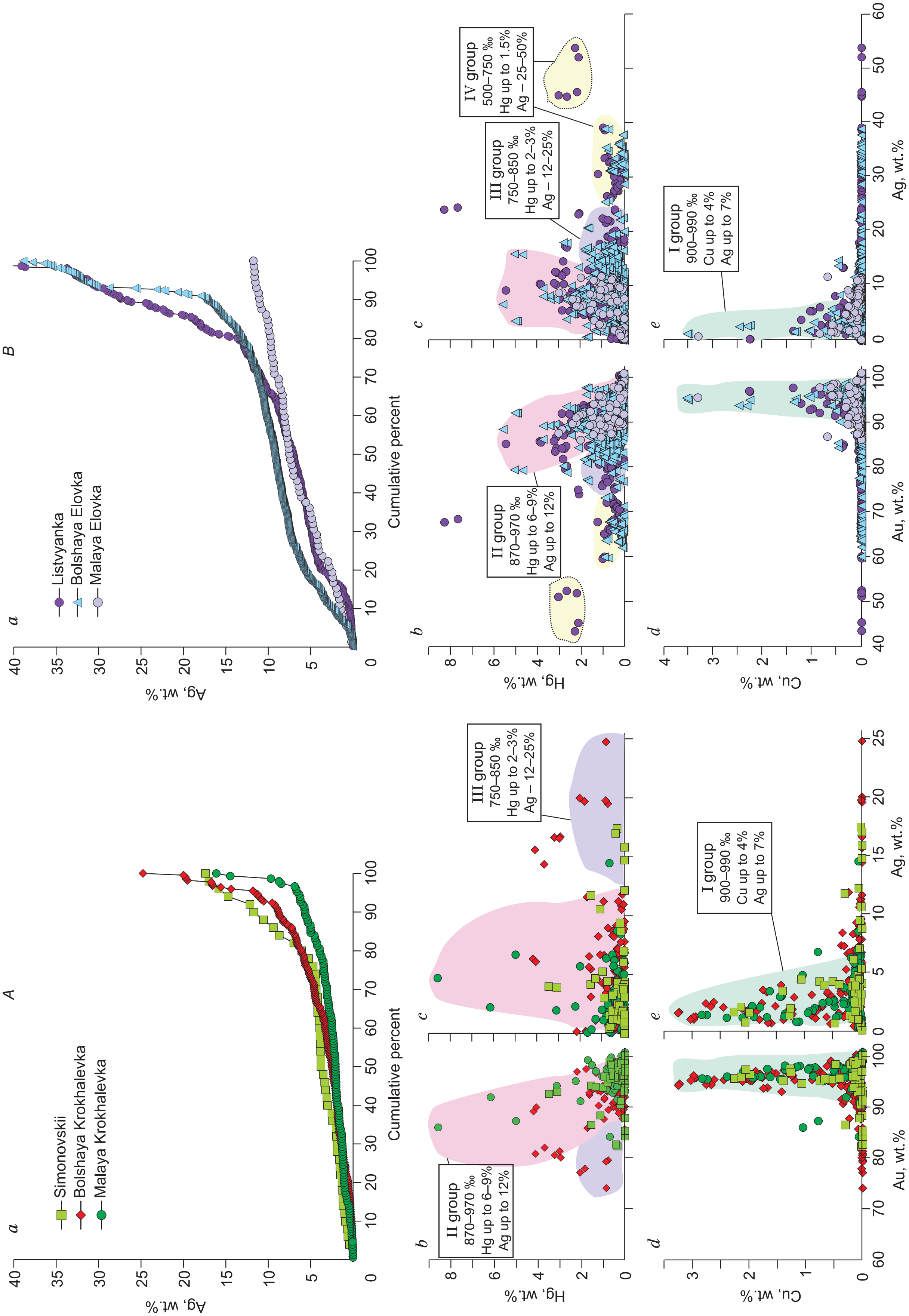
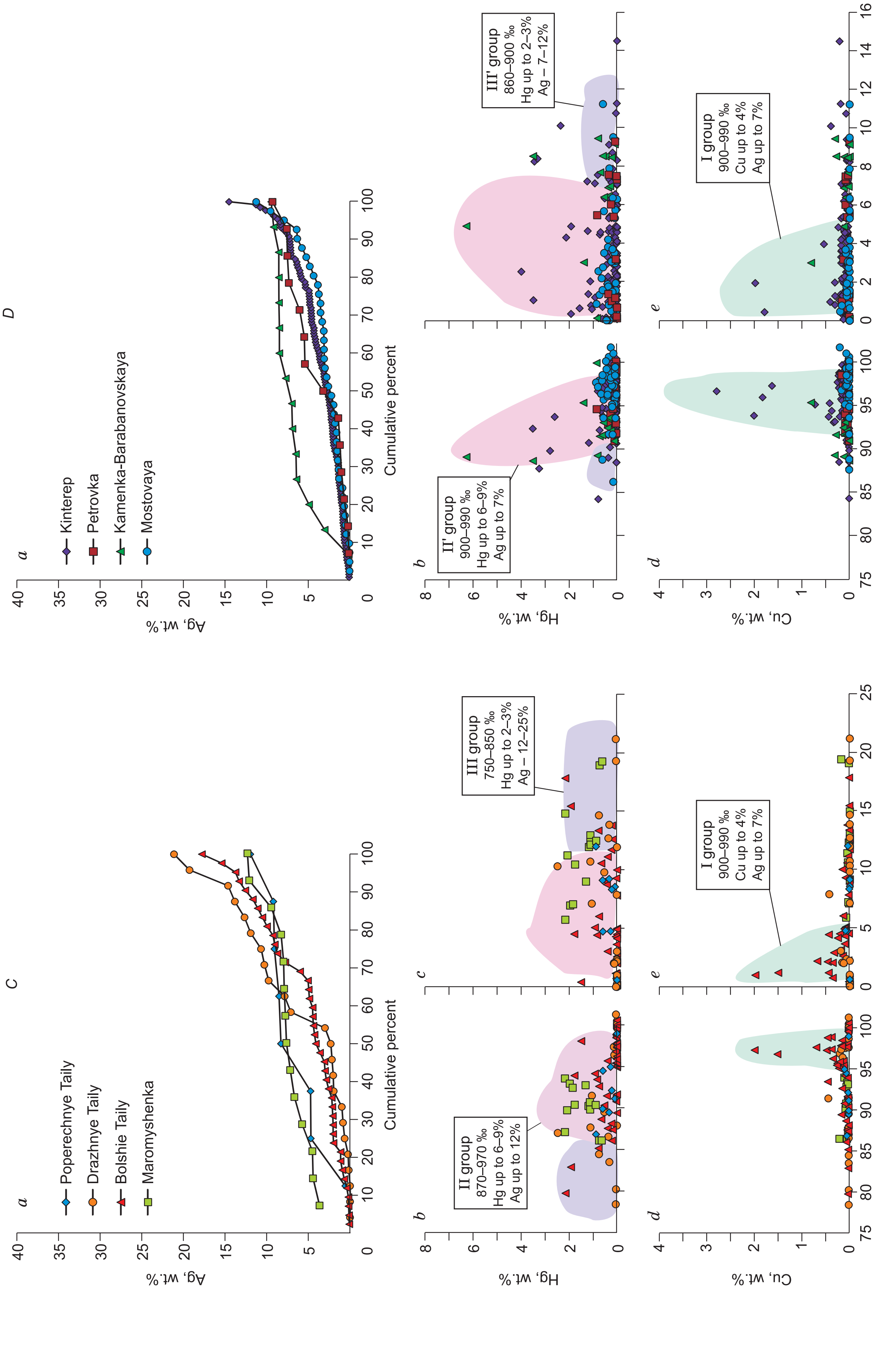


Fig. 3 (*to be continued*).



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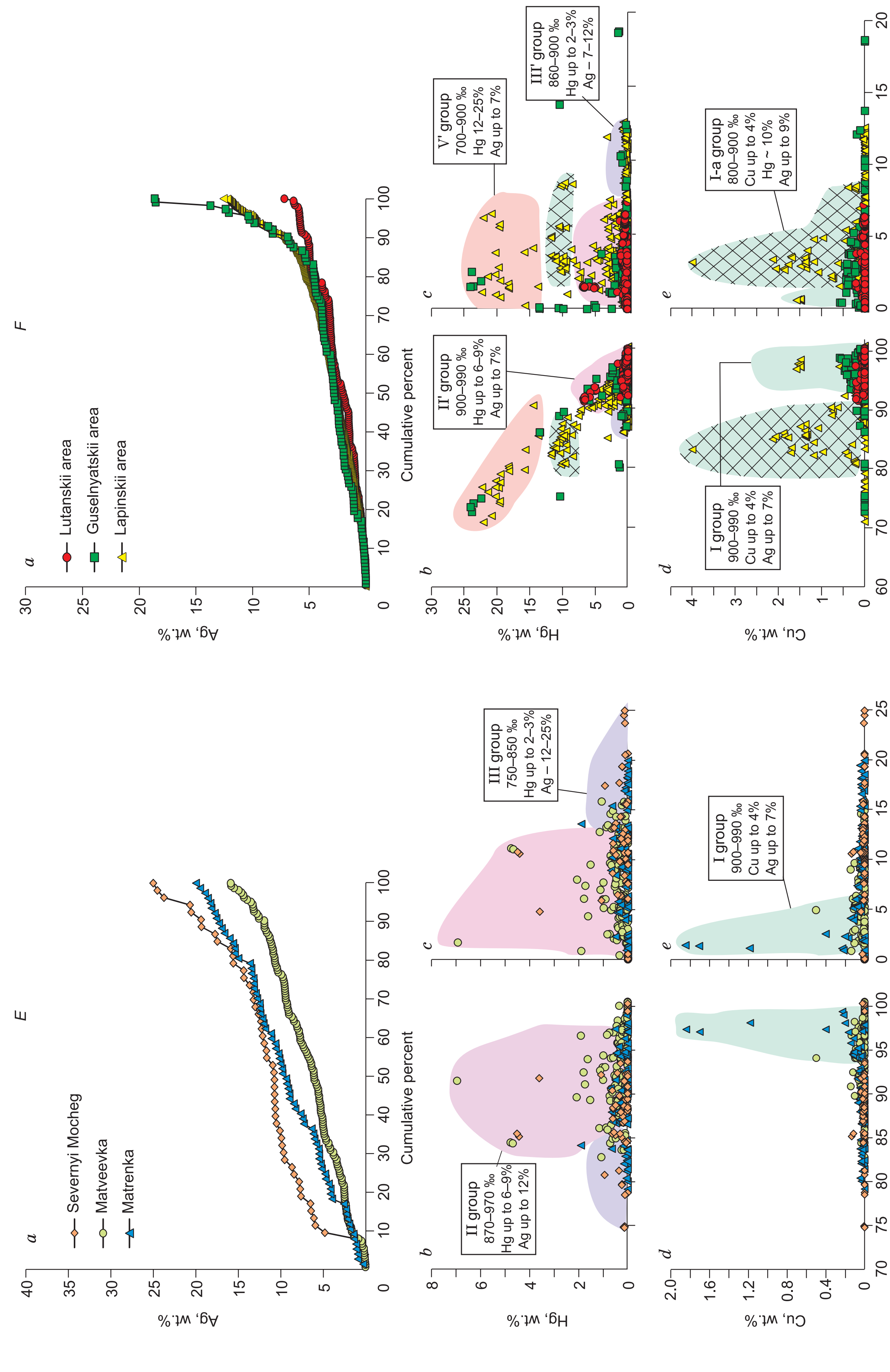

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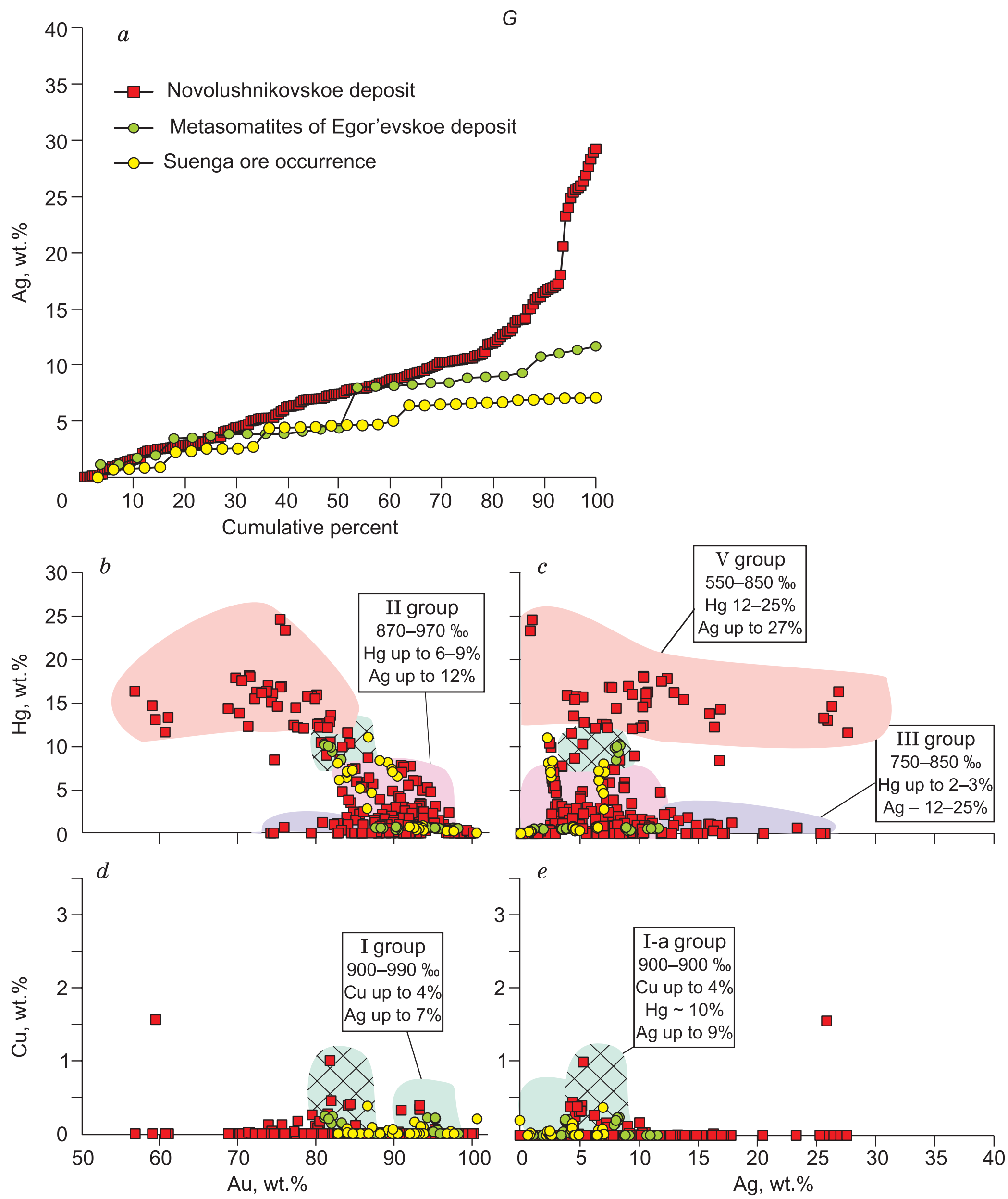

Fig. 3. The content of native gold from the placers of the Krochalevskii area within the Ik placer field (*A*), of the Elovskii area within the Ik placer field (*B*), of the Taily placer field (*C*), of the Suenga placer field (*D*), of the Berd' placer field (*E*), from weathering crusts (*F*), primary ore occurrences (*G*). *a*, The content of placer gold from the Krochalevskii area of the Ik placer field; *b*, the relation of Hg concentration to Au content; *c*, the relation of Hg content to Ag concentration; *d*, the relation of Cu concentration to Au concentration; *e*, the relation of Cu concentration to Ag concentration.

Simonovskii Brook is the left stream of the Malaya Krokhalevka River. The content of Hg and Cu in native gold amounts to 3.5 wt.% and 2.3 wt.%, respectively (Fig. 3*A*, *b–e*). Ag content reaches up to 17.5 wt.%, and the fineness varies within the range of 820 to 990‰ (with the predominance of high-fineness gold) (Fig. 3*A*, *b–d*). Three groups of gold are clearly distinguished from the slope/gradient of the cumulative curve and its discontinuities (Fig. 3*A*, *b–e*). The first group is the most numerous (78% of all the analyses), where Ag content will be up to 6 wt.%. The second and third groups are less prominent and account for 14 and 8% of all the analyses, respectively. Ag content of the first group is up to Ag 12 wt.%, and for the second grade—14–17 wt.%.

Malaya Elovka. The behavior pattern of the cumulative diagram curve doesn't allow us to determine confidently several groups of native gold based on silver content (Fig. 3*B*, *a*). Taken together, the fineness of native gold from the placer ranges from 860 to 990‰; however, for most grains the fineness is in the interval of 900–990‰. The amount of copper and mercury is 3.3 and 3 wt.%, respectively (Fig. 2*B*, *b–e*).

Bolshaya Elovka. The value of native gold fineness varies over a wide range from 420 to 999‰. Nevertheless, the most common fineness is approximately equal to 850–950‰ (Fig. 3*B*, *b–e*). The almost constant presence of Hg impurity within native gold content is quite distinctive; its concentration in separate grains reaches 8.5 wt.% (Fig. 3*B*, *b*, *c*). The occurrence of copper is much less common. Copper content in separate native gold grains amounts to 2.3 wt.% (Fig. 3*B*, *d*, *e*). We were able to determine several grades of native gold from Ag distribution curve pattern on the cumulative diagram (Fig. 3*B*, *a*). The first group accounts for ~20% of the whole sample, where the content of silver impurity in native gold is up to 5 wt.%. Although it is admitted that some part of native gold belonging to the group represents the result of complete compositional transition under endogenous conditions (or an unrepresentative grain section in the checker with the inclusion of an edge high-fineness rim). The most conventional second group (with ~60% analyses coverage) is marked by a steady increase of Ag content up to 12–13 wt.%. Then at the value of 80% Au, the silver distribution curve steeply slopes up (change in gradient), that provides reasons to identify the native gold grade with Ag content from 12 to 25 wt.%. This group accounts for 8% of all the analyses. The lowest-fineness native gold (up to electrum) with Ag content of 25–55 wt.% is referred to the last fourth grade where 12% of all the analyses are included.

Listvyanka. The chemical composition characteristics of gold from the Listvyanka River placer are practically in full compliance with those ones of the Bolshaya Elovka placer. The predominant fineness accounts for 850–950‰ when the values can vary within a wider range from 600 to 999‰ (Fig. 3*B*, *b*, *d*). Hg and Cu content in placer gold composition reaches 6 wt.% and 3.5 wt.%, respectively (Fig. 3*B*, *b–e*). Four grades of placer gold in relation to Ag content are distinguished from the slope of the cumulative curve and its discontinuities (Fig. 3*B*, *a*): (1) Ag up to 7 wt.%—about 20% of all the analyses; (2) Ag up to 12 wt.%—60% of all the analyses; (3) sharp increase in Ag from 12 to 25 wt.%—12% of all the analyses; and (4) Ag—25–40 wt.% ~ 8% of the whole sampling.

The Taily placer field includes both streams of the Suenga River on its upper reaches (Fig. 2). The main placers are usually assigned to the first order streams, and rarely to the streams of the second order. Most rivers with mineable placer gold mineralization flow out from the deposition area of the Pecherkino and Suenga Formations. The composition of native gold of the Taily placer field is given in Fig. 3*C*.

Maromyshenka. Despite the smaller amount of analytical data, the obtained results illustrate the range of fineness variation within the range of 860 to 930‰ (Fig. 3*C*, *b*, *d*). Most grains are characterized by the constant presence of Hg impurity at the level of 1–2 wt.% (Fig. 3*C*, *b*, *c*). Cu content in the placer gold composition is below the detection limit (Fig. 3*C*, *d*, *e*). Ag distribution pattern indicates the existence of one grade of the placer gold (4–12 wt.% Ag).

Poperechnye Taily. Few analysis samples of native gold reveal fineness of 860 to 990‰ predominantly at 900‰ (Fig. 3*C*, *b*, *d*). Mercury presence in the placer gold composition is determined for all the grains, but its content is low: up to 1 wt.% (Fig. 3*C*, *b*, *c*). Copper in the placer gold composition hasn't been detected (Fig. 3*C*, *d*, *e*). The pattern of the cumulative diagram curve (Fig. 3*C*, *a*) points to the only placer gold group. The value of silver content ranges from 5 to 12 wt.%.

Drazhnye Taily. The value of native gold fineness varies over a wide range from 770 to 1000‰ (Fig. 3*C*, *b*, *d*). The pattern of the cumulative diagram curve allows us to determine four groups of placer gold in relation to silver content as a minimum (Fig. 3*C*, *a*). The first group includes the highest-grade native gold with silver impurity content up to 1.5 wt.%. This group may include the grains with a high degree of hypergene transition. The second group of the placer gold is characterized by Ag impurity content up to 3 wt.%, and accounts for ~18% of all the analyses. The commonest is the group which accounts for 32% of the sampling and is marked by silver content of 7 to 15 wt.%. Another two analysis samples have yielded silver content of 19–21 wt.%; that allows us to admit the existence of one more group with the lowest grade. Hg presence in native gold is not always defined although its content sometimes reaches 2.6 wt.% (Fig. 3*C*, *b*, *c*). In most cases, copper concentration in placer gold does not exceed the detection limit, and its value reaches 0.5 wt.% only in individual cases (Fig. 3*C*, *d*, *e*).

Bolshie Taily. The fineness value of the placer gold tends to vary within the range of 800 to 1000‰ (Fig. 3*C*, *b*, *d*). Mercury content in native gold is detected in a great number of gold grains. Maximum mercury content reaches ~2 wt.% even though Hg content usually amounts to ~0.5 wt.% (Fig. 3*C*, *b*, *c*). In single cases, copper impurity content in native gold was estimated below 2 wt.% (Fig. 3*C*, *d*, *e*). Three grades of placer gold could be identified by the curve pattern on the cumulative diagram (Fig. 3*C*, *a*). The most typical group (70% of all analyses) includes the placer gold with Ag impurity content up to 7 wt.%. The second group accounts for 20% of sampling and represents placer gold with Ag impurity content from 7 to 15 wt.%. Furthermore, only 10% of sampled gold contains a silver impurity in the amount of over 15 wt.%.

The Suenga field includes the placers situated along the left feeders of the Suenga River, and the Kinterep River basin (Fig. 2). The placers enclosed by the field are known for the maximum linear growth of productivity. Most rivers and brooks start from the area of gold-bearing weathering crusts distribution. Figure 3*D* presents the content of native gold from the placers of the Suenga field.

Kinterep. The fineness value of native gold across the placer varies from 840 to 1000‰, meanwhile, the predominant fineness is 950–1000‰ (Fig. 3*D*, *b*, *d*). Mercury content in separate grains can reach 4 wt.%, although the estimated value is up to 1 wt.% for most analyses (Fig. 3*D*, *b*, *c*). Most of the analyzed grains are characterized by copper content up to 0.5 wt.% (predominantly analyses below the determination limit) (Fig. 3*D*, *d*, *e*). Only few grains of placer gold contain copper in the amount of 2 wt.%. Considering silver distribution pattern on the cumulative diagram (Fig. 3*D*, *a*) two grades of native gold can be determined. The first group is the most typical (about 90% of the whole sampling) and distinguished by the grains with silver impurity content up to 7 wt.%. The second group comprises native gold with Ag impurity content of 7–12 wt.%. This grade of placer gold accounts for ~10%.

Petrovka. The fineness value of the placer gold ranges from 910 to 1000‰ (Fig. 3*D*, *b*, *d*). Mercury content does not exceed 1 wt.% (Fig. 3*D*, *b*, *c*), and only in few cases maximum copper concentrations reach 0.2 wt.% (Fig. 3*D*, *d*, *e*). As for silver distribution pattern (Fig. 3*D*, *a*) we suppose the existence of two groups of native gold. The first group exhibits Ag content up to 2 wt.%. The second group is comprised of native gold with Ag impurity content of 5–7 wt.%. Both groups make equal contribution in the total gold balance across the placer.

Kamenka-Barabanovskaya. The fineness value of placer gold ranges from 880 to 1000‰ (Fig. 3*D*, *b*, *d*). Fineness distribution is uniform enough across the sample, without apparent maximum. Hg concentration in native gold across the placer, as a whole, amounts to 1 wt.% though its concentration reaches 6.5 wt.% in separate grains (Fig. 3*D*, *b*, *c*). Copper impurity content is below a determination level for most grains, and only in singular cases, it ranges from 0.4–0.7 wt.% (Fig. 3*D*, *d*, *e*). Excluding the results of separate analyses, the curve pattern on the cumulative diagram (Fig. 3*D*, *a*) lets us consider the existence of one group of the placer gold.

Mostovaya. The fineness value is rather high with the apparent dominance of a 950–1000‰ group. Nevertheless, a few analyses are characterized by the fineness up to 860‰ (Fig. 3*D*, *b*, *d*). Mercury is detected practically in all the studied grains with the content up to 1 wt.% (Fig. 3*D*, *b*, *c*). Two groups of native gold are defined from the slope of the silver distribution curve (Fig. 3*D*, *a*). The most typical group is comprised of grains with silver impurity content up to 4 wt.%. The second group is represented by few grains with Au content from to 10 wt.%.

The Berd' placer field. The field encloses the right feeders of the Berd' River above the mouth of the Suenga River (Fig. 2). The analyzed native gold was sampled from placers along the Matrenka, Severnyi Mocheg, and Matveevka Rivers. The rivers flow across deposits of the lower Cambrian Suenga and Kinterep Formations, and across nondifferentiated Cambrian–Ordovician formations. The placer gold content is given in Fig. 3*E*.

Severnyi Mocheg. Placer gold is characterized by fineness, which ranges from 750 to 999‰. Herewith, the analyses maximum lies in the range of 870—950‰ (Fig. 3*E*, *b*, *d*). Mercury content sometimes reaches 4.5 wt.% though it does not exceed 1 wt.% in most cases (Fig. 3*E*, *b*, *c*). Copper nearly absent in the placer gold composition. Nevertheless, in a few instances, its concentrations reach 0.2 wt.% (Fig. 3*E*, *d*, *e*). With reference to the change in the curve pattern on the cumulative diagram (Fig. 3*E*, *a*) and Ag content, three groups of native gold can be determined. The first group accounts for about 8% from the set of analyses and includes the grains with gold content less than 1–2 wt.%. The second group is represented by native gold with steady increase of Ag from 5 to 12 wt.%. This group is the most numerous and accounts for ~70% of all the analyses. The third group accounts for 22% of the whole sampling and is distinguished by silver content value of 12 to 25 wt.%.

Matveevka. The fineness value of the placer gold varies within the range of 830 to 990‰ (Fig. 3*E*, *b*, *d*). Fineness estimates distribution tends to be uniform without apparent peaks and discontinuities. Mercury content reaches 2 wt.% (Fig. 3*E*, *b*, *c*). Copper has not been detected in the composition of native gold apart from certain analyses with the impurity content up to 0.5 wt.% (Fig. 3*E*, *d*, *e*). As for the curve pattern on the cumulative diagram (Fig. 3*E*, *a*), three groups of native gold (which differ by silver content) can be determined. The first group is the least typical (~8% of the sampling). It is comprised of high-fineness native gold and practically doesn't contain any Ag impurity. The second group is the commonest (82% of all the grains); it is characterized by uniform distribution of Ag content estimates from the first ones up to 12 wt.%. The third group is marked by the contribution into the total sample up to 10% and includes native gold with Ag impurity content of 12–16 wt.%.

Matrenka. The fineness of the placer gold is 800–1000‰ and is usually determined by the impurity content (Fig. 3*E*, *b*, *d*). The distribution of fineness estimates tends to be uniform without apparent peaks. For most analyses, mercury content does not exceed 1 wt.%, apart from a single analysis where its concentration was ~2 wt.% (Fig. 3*E*, *b*, *c*). For most cases, copper is detected in the composition of the placer gold (up to 1.8 wt.%). Nevertheless, for most grains, copper concentrations are either below the detection limit or not more than 0.2 wt.% (Fig. 3*E*, *d*, *e*). Despite the gradual change in silver content across the total sample, we are able to define four groups of native gold from the 'steps' on the cumulative diagram (Fig. 3*E*, *a*). The first grade (18% of the sampling) is represented by grains with silver impurity content up to 3–4 wt.%. The second step is comprised of 18% analyzed grains and characterized by a silver content of 4–7 wt.%. Forty-four per cent of the sampled native gold contains up to 12 wt.% of silver impurity and comprises the third group. The last group is identified by silver impurity content of 12–25 wt.% and accounts for 20% of all the analyses.

COMPOSITION OF NATIVE GOLD FROM MOTHER LODES AND WEATHERING CRUSTS

Gold-bearing weathering crusts of Cretaceous–Paleogene age are widespread within the Salair Mountain Range and particularly on the territory of the Egor'evsk ore-placer district (Roslyakov et al., 1995, 2001). Mineable gold concentrations are associated with loamy eluvium. According to the results of sampling, seven areas belonging to the Egor'evsk gold-placer mine have been delineated: Lutanskii, Lapinskii, Guselnyatskii, Krutoi, Shcherbakovskii, Topkinskii, and Sukhoi Log. The analyses results of native gold grains from the first three areas are used in the proposed study. The shape of bodies in the weathering crust is defined by the structural integrity of the loamy eluvium and by the degree of redeposition. In general, a number of studies are devoted to the detailed description of the weathering crusts position and their main attributes (Roslyakov et al., 1995, 2001; Kalinin et al., 2006). Micaceous metasomatites of beresite and listwaenite types (depending on the protolith) appear to be original substrates for weathering crusts formation (Roslyakov et al., 1995). The composition of native gold of weathering crusts is presented in Fig. 3*F*.

Lutanskii area. The native gold is high-grade; the whole sample is generally characterized by a fineness of 920–100‰ (Fig. 3*F*, *b*, *d*). At the same time, distribution of gold fineness grades and silver content appear to be uniform without apparent maximum across the sample. Maximum values of copper content are determined as 0.2 wt.% (Fig. 3*F*, *d*, *e*) although most analyses have not revealed copper presence in native gold composition. Mercury was detected in most analyses, and the detected content was equal up to 1 wt.%, though a separate group of grains represents Hg enrichment up to 5–6 wt.% (Fig. 3*F*, *b*, *d*). The curve pattern on the cumulative diagram (Fig. 3*F*, *a*) illustrates the existence of a single group with regard to silver content.

Guselnyatskii and Lapinskii areas. Native gold from these areas is characterized by practically similar composition (with some variations). Fineness values vary over a wide range from 700 to 1000‰. Nevertheless, the fineness of most grains is 900–1000‰ (Fig. 3*F*, *b*, *d*). The presence of mercury is almost constantly detected, and it reaches its maximum of 25 wt.% (Fig. 3*F*, *b*, *c*). The amount of copper in native gold reaches 4 wt.%, although most analyses determine its concentration of 0.5 wt.% and below (Fig. 3*F*, *d*, *e*). The curve pattern of the cumulative diagram exhibits the existence of at least two native gold groups (Fig. 3*F*, *a*). The first one is the most numerous (85–88% of sampling) and comprised of native gold with silver impurity content up to 7 wt.%. The gold characteristics of this group are entirely congruent with those of the native gold from the Lutanskii area. The second group is distinguished by a steeper slope of the curve and includes native gold with silver impurity content from 7 to 12 wt.%. Higher values of silver content are registered for separate native gold grains from the Guselnyatskii area. Moreover, their sporadic appearance allows us to suppose the existence of one more group.

Primary ore-grade gold mineralization. Metasomatites of the Novolushnikovskoe and Egor'evskoe deposits are the most well studied in comparison with other multiple ore occurrences and gold mineralization sites within the Egor'evsk district (Roslyakov et al., 1995, 2001). In both cases, ore-grade gold mineralization is represented by micaceous metasomatites with sulphide content up to 10%. Alternatively, we observe significant gold mineralization of quartz veins and veinlets cross-cutting metasomatites. According to archive data, gold content in the quartz vein from the Novolushnikovskoe deposit reached 540 ppm (Roslyakov et al., 2001). G.V. Nesterenko has discovered the Suenga gold mineralization site from which gold was taken for the analyses described below. These are piles of debris screes from pyritized rocks which were found in the dredging dump of the Suenga river valley near Novolushnikovo Village. According to assay test data, the gold content amounts up to 1.6 ppm. Gold content estimates for primary ore occurrences are presented in Fig. 3*G*.

The Novolushnikovskoe deposit. The content of native gold from sulphidized metasomatites (predominantly of beresite type) and quartz veins was studied by representative sampling. The studies show that native gold is characterized by a wide range of fineness (560–1000‰) (Fig. 3*G*, *b*, *d*). Its distinctive characteristic appears to be high mercury content up to 25 wt.%, although most analyses show rather low values of Hg impurity up to 2.5 wt.% (Fig. 3*G*, *b*, *c*). Copper impurities have not been detected in the overwhelming majority of the grains, and only a few analyses reveal the impurity presence (up to 0.5–1 wt.%), (Fig. 3*G*, *d*, *e*). In the curve pattern of silver distribution across the sample, we are able to identify three groups of native gold (Fig. 3*G*, *a*). The first group accounts for ~80% of all the analyses and includes native gold with silver impurity concentration up to 12 wt.%. The second group (13% of the whole sampling) is clearly distinguished from the steep slope of the curve. The group is comprised of native gold with silver content from 12 to 18 wt.%. The third grade is distinguished by native gold with silver content from 22 to 28 wt.%.

Metasomatites from the Egor'evskoe deposit. Following N.A. Roslyakov et al. (1995), metasomatites from the Egor'evskoe deposit are understood to be sulphidized hard rocks, along which gold-bearing weathering crusts tend to develop. These rocks are represented by terrigenous carbonate rocks exposed to metasomatic transition, and greenstones with sulphide content of 5–10%. The fineness of native gold varies across the whole sampling within the range from 810 to 980‰ (Fig. 3*G*, *b*, *d*). Three groups are defined due to the silver content value (Fig. 3*G*, *a*). The first one accounts for 15% of sampling and is characterized by Ag impurity content up to 2 wt.%. Ag content reaches 4 wt.% in the second group. The third group accounts for half the analyses, and it is comprised of native gold with Ag content of 8–10 wt.%. Ag content amounts to 10 wt.% in separate grains. Nevertheless, it is found to be less than 1 wt.% in most grains. The presence of copper impurities is not detected in most grains (Fig. 3*G*, *d*, *e*).

The Suenga gold mineralization site. Gold content is nearly congruent with that of for metasomatites from the Egor'evskoe deposit. The fineness value of native gold lies over the interval from 830 to 1000‰ (Fig. 3*G*, *b*, *d*). Fineness distribution is uniform within the sampling. Copper is not found in the composition of native gold for the most grains; only a few analyses revealed its content up to 0.5 wt.% (Fig. 3*G*, *d*, *e*). Mercury varies within a wider range. Maximum concentrations are equal to 11 wt.%, although a portion of grains does not contain mercury in their composition (Fig. 3*G*, *b*, *c*). According to the silver distribution pattern on the cumulative diagram, four groups of native gold can be determined (Fig. 3*G*, *a*). The first group is comprised of the highest-fineness gold, where silver content doesn't exceed 1 wt.%. Silver content in native gold of the second group amounts to 3 wt.%. Ag impurity content reaches 5 wt.%, which is typical of the third most numerous group of grains. About 40% of all the analyses are represented by native gold with silver impurity content of 7 wt.%.

MINERAL MICROINCLUSIONS IN NATIVE GOLD

Mineral microinclusions in native gold contain very important information about the main characteristics of endogeneous ore-grade gold mineralization. An optical microscope was used to study more than 1400 grains of native gold in checkers with an artificial polished section, where 113 inclusions of ore minerals have been detected. High-quality diagnostics was conducted with the use of a scanning electron microscope (SEM). The size of mineral inclusions varies from 5 to 80 μm (Fig. 4). The following minerals have been detected (the number of pieces/pcs is given in brackets): pyrite (34), arsenical pyrite (20), chalcopyrite (17), fahlite (10), tellurides and bismuth minerals (10), galena (7), rutile (6), covelline (6), magnetic iron oxide (2) and titanic iron ore/ilmenite (1). Tellurides and bismuth minerals include coloradoite (HgTe), tellurobismuthite (Bi_2Te_3), altaite (PbTe), emplectite ($CuBiS_2$). In some cases, we managed to detect several microinclusions of different minerals within separate Au grains. For instance, pyrite usually associates with chalcopyrite, tetrahedrite, arsenopyrite; magnetic iron oxide associates with chalcopyrite; galena sometimes tends to originate mineral intergrowth and create strong bonds with tellurides.

RESULTS AND DISCUSSION

Definition of native gold types by composition. To describe the properties of native gold chemical composition across each placer, the groups should be preliminarily identified with regard to silver content, occurrence and concentration grade of mercury and copper impurities in gold. However, correlations of Hg and Cu have not been considered. According to Fig. 3, in most cases copper content reaches 4 wt.%; and mercury can be a major impurity. Correlation analysis of high Hg and Cu content in native gold composition allows admitting the absence of correlation between these elements (Fig. 5). Native gold is characterized by copper content which will be more than 0.2–0.3 wt.%, but mercury content usually reaches up to 1 wt.% (Fig. 5*a*–*c*). In contrast, significant copper concentrations are not detected in mercurous placer gold (Hg more than 0.5–1 wt.%), (Fig. 5 *a*, *c*, *e*). With regard to Ag, Hg, and Cu in Au composition, we define several types of native gold from placers, mother lodes and weathering crusts (Table 1).

Alluvial placer gold. *Type I* is defined by a set of parameters, such as high fineness (900–990‰), low concentration of mercury (up to 1 wt.%) and constant occurrence of copper impurity up to 4 wt.%. Silver content varies in relation to copper concentration within the range from 0 to 7 wt.%. The gold of this type is distinguished by maximum occurrence in the placers of the Ik and Krokhalevka fields (Fig. 3*A*).

Type II is considered the most widespread grade of native gold found in the Egor'evsk gold-bearing district. This type is thought to be dominating in terms of quantity both in placers and gold-bearing metasomatites (Fig. 3*A*–*C*, *E*, *G*). The type definition is based on high fineness (870–970‰), negligible copper impurity concentrations (up to 0.3 wt.% and frequently below the detection limit), and constantly

Table 1. Types of native gold identified in accord with its chemical content

Gold type	Fineness, ‰	Impurity content, wt.%			Mineral microinclusions
		Ag	Hg	Cu	
I	900–990	up to 7	up to 1	up to 4	Chalcopyrite, pyrite, magnetic iron oxide, ilmenite, rutile, covelline
I-a*	800–900	up to 9	~10	up to 4	
II	870–970	up to 12	up to 6–9	up to 0.3	Pyrite, arsenopyrite, galena, chalcopyrite, fahlore, bismuth telluride (Bi_2Te_3), altaite (PbTe)
II′	900–990	up to 7	up to 6–9	up to 0.3	Pyrite, arsenopyrite, fahlore, coloradoite (HgTe), emplectite ($CuBiS_2$)
III	750–850	12–25	up to 2–3	–	Pyrite, arsenopyrite, galena, fahlore, chalcopyrite
III′	860–900	7–12	up to 2–3	–	
IV	500–750	25–50	up to 1.5	–	Galena
V*	550–850	up to 27	10–25	up to 0.2	Altaite (PbTe), coloradoite (HgTe), galena, bismuth telluride (Bi_2Te_3)
V′*	700–900	up to 7	10–25	up to 0.2	

*Types of native gold found exclusively in primary mother lodes and crusts of weathering.

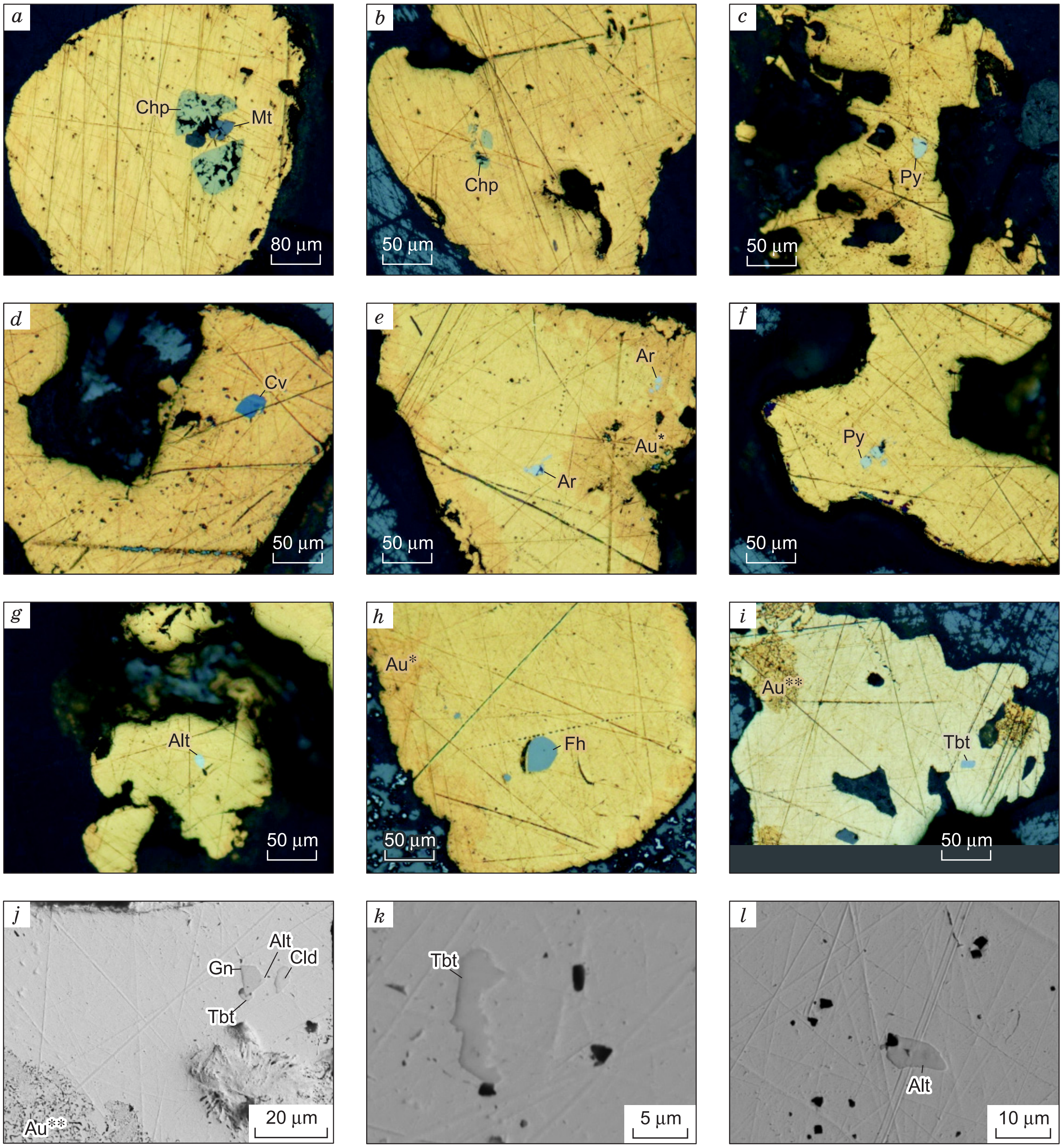

Fig. 4. Mineral microinclusions in native gold assigned to the types in accord with their content: I (*a–d*), II (*e–h*), V (*i–l*). Minerals abbreviations stand for: chp, chalcopyrite, mt, magnetic iron oxide, py, pyrite, cv, covelline, ar, arsenopyrite, alt, altaite, fh, fahlore, tbt, bismuth telluride, gn, galena, cld, coloradoite, au*, high-fineness hypergene rim, au**, "sponge" native gold with Hg content of 6–9 wt.%, which formed in the result of demercurization of mercurous gold (up to 24 wt.% Hg).

high grade of mercury concentration in native gold, which reaches 6–9 wt.% in separate grains. Silver content does not usually exceed 12 wt.%.

Type III is conventionally determined. Native gold comprising this group is characterized by average fineness of (750–850‰), low copper content (up to 0.3 wt.%, or its lack) and low mercury concentration (up to 2–3 wt.%). Consequently, the fineness grade of native gold is determined by Ag impurity content of 12–25 wt.%. Type III is as common as type II in gold placers and primary gold deposits (Fig. 3*A*–*C*, *E*, *G*). Though in terms of dramatically subordinate quantity, type III is strongly dependent on type II, and they are marked by simultaneous occurrence.

Subtypes II′ and III′ are included into separate groups due to a higher grade of fineness (corresponding to lower silver content) when Cu and Hg concentration grades are constant in comparison with types II and III, respectively. Native gold of this type is distributed in gold-bearing weathering crusts and placers of the Suenga field "being fed" at the expense of weathering crusts (Fig. 3*D*, *F*).

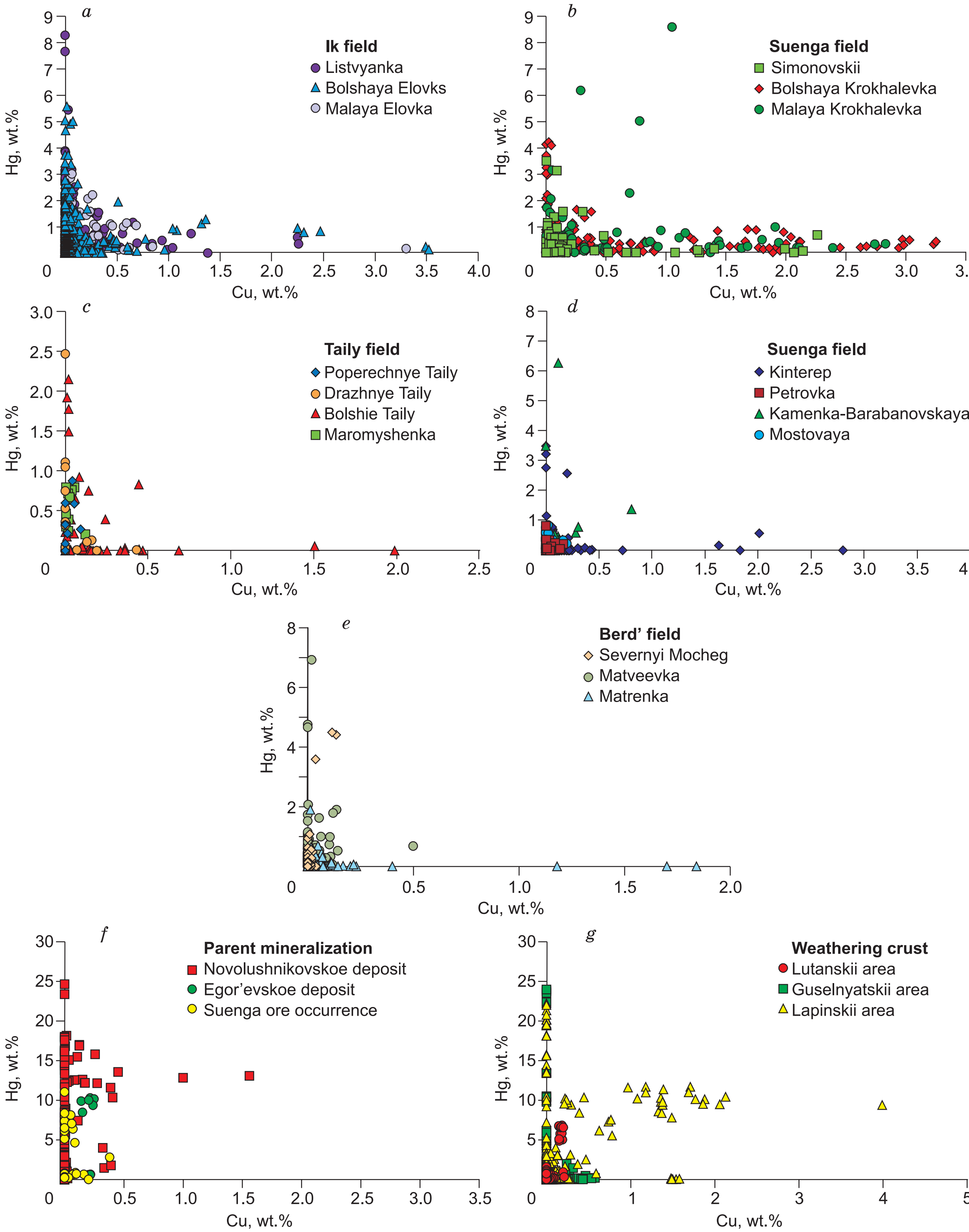

Fig. 5. Cu and Hg concentration ratio in the composition of native gold from placers, mother lodes and weathering crusts. *a*, The Elovskii area within the Ik placer field; *b*, the Krochalevskii area within the Ik placer field; *c*, the Taily placer field; *d*, the Suenga placer field; *e*, the Berd' placer field; *f*, primary gold-ore mineralization; *g*, weathering crusts.

Type IV is represented by native gold with the lowest fineness grade. It is developed in dramatically subordinate quantities. The fineness value of type IV lies within the range from 500 to 750‰. Copper is totally absent in its composition, and mercury concentrations are low up to 1.5 wt.%. Native gold with this composition is found in large quantities only in the placers along the Listvyanka and the Bolshaya Elovka Rivers (Fig. 3*B*), which rise in the distribution area of the lower Cambrian Pecherkino Formation rocks.

Native gold from mother lodes and weathering crusts. *Type I-a* is subordinated in its development and is not found among the grades of native gold from the alluvial placers. This type of native gold is identified by the total of high copper (up to 4 wt.%) and mercury concentrations of 10 wt.% (Fig. 5*f*, *g*). Silver content reaches 9 wt.%; and fineness varies from 800 to 900‰, depending on the amount of impurities. Native gold of this type is found among metasomatites of the Novolushnikovskoe and Egor'evskoe deposits at the Suenga gold mineralization site, and in the weathering crusts distributed within the *Lapinskii area* (Fig. 3*F*, *G*).

Type V may be the most specific type of native gold. Its identification is owing to "abnormally" high concentration of mercury from 10 to 25 wt.%. The presence of copper in significant quantities is not detected in the native gold composition. Silver content varies within a wide range from zero values up to 27 wt.%. The fineness grade of native gold is determined not only by silver impurity content but by mercury impurity as well; it fits for a wide range of values from 550 to 850 wt.%. It is notable that type V native gold is contained only in ores from the Novolushnikovskoe deposit (Fig. 3*G*), so we cannot cast any doubt on its natural occurrence. The fact of its complete absence in gold placers is of special interest. The reasons of this phenomenon will be considered below.

Similar to subtypes II′ и III′, *Subtype V′* has been selected to form a group being independent from type V on the grounds of much lower silver concentration (up to 7 wt.%), but concentration grades of copper (up to 0.2 wt.%) and mercury (10–25 wt.%) stay the same. Native gold of such a type tends to be distributed in deposits of gold-bearing weathering crusts belonging to the Guselnyatskii and Lapinskii areas (Fig. 3*F*). Like type V, this type of native gold is of a unique occurrence and hasn't been detected in the placers "being fed" within the weathering crusts area.

Obviously, the highlighted types are rather conventional. The types frequently overlap each other by their specific data. Occasionally, an obvious agreement is not found between composition borderline of the definite type with the results of grain analyses from particular placers. Moreover, difficulties arise with assigning a portion of native gold to any definite type owing to the absence of copper and mercury impurities. For example, native gold of fineness ~950‰ and marked only by silver content of 5 wt.% could correspond to both types I and II.

Types I and II appear to be the most widespread types of native gold from the Egor'evskoe district placers. The definition of the first type is based on a high fineness grade of native gold coupled with significant value of copper content; on the contrary, the second type is identified by average—high fineness degrees coupled with mercury impurity content. When taking into consideration the fact of mercury and copper discrete behavior, triangle diagrams were constructed on the coordinates: Au–Ag·10–Cu·100 and Au–Ag·10–Hg·100 (Fig. 6).

The diagrams show that maximum distribution of copper-bearing native gold of the first type is typical of the Krokhalevskii area of the Ik placer field (Fig. 6*A*, *b*). Gold of this type is less distributed within the Elovskii area placers (Fig. 6*A*, *a*); and its distribution pattern is predetermined in dramatically subordinate quantities within the boundaries of the Taily, Berd', and Suenga placer fields (Fig. 6*A*, *b*–*g*). The distribution pattern for mercury-containing native gold of the second type contrasts with the above-given pattern of type I. The maximum distribution of this type of gold is detected in the placers of the Elovskii area belonging to the Ik placer field (Fig. 6*B*, *a*). Furthermore, the most amount of native gold from the placers of the Taily and Berd' fields also refers to this type of gold (Fig. 6*B*, *b*, *d*). It should be noted that most analyses of native gold from mother lodes also correspond to this type (Fig. 6*B*, *e*). At the same time, the number of native gold (distributed in weathering crusts and placers of the Suenga field) composition points lies below the composition borderline of the second type and is displaced in the direction of higher fineness and lower silver content (Fig. 6*B*, *f*, *g*).

Mineral inclusions in different types of native gold. Correlation of microinclusions with characteristics of native gold and its composition (in the context of sorting by types and subtypes) allows us to identify stable mineral assemblages. For example, the most characteristic inclusions of copper-bearing native gold of the first type are known to be: chalcopyrite, pyrite, magnetic iron oxide, ilmenite, rutile, and covelline (Table 1, Fig. 4*a*–*d*). Mineral inclusions of mercury-bearing native gold of type II are represented by pyrite, arsenopyrite, galena, fahlore, and, in a rare case, by chalcopyrite (Fig. 4*e*, *f*, *h*). Besides, singular inclusions of bismuth telluride and lead have also been found (Fig. 4*g*). Inclusions of pyrite, arsenopyrite, fahlore, and single inclusions of coloradoite and emplectite are detected in native gold of subtype II′. The assemblage of microinclusions in native gold of type III is distinguished by similar mineralogical composition, such as dominating pyrite, arsenopyrite and fahlore and rarely occurring galena and chalcopyrite. Native gold of type IV contains few inclusions of galena. The inclusions in native gold of type V (from the Novolushnikovskoe deposit metasomatites) turned out to be the most informative (Fig. 4*i*–*l*). We have managed to detect among other mineral inclusions the presence of lead telluride (altaite), mercury telluride (coloradoite) and bismuth telluride (tellurobismuthite), which are analogous to mineral microinclusions in native gold of the type II.

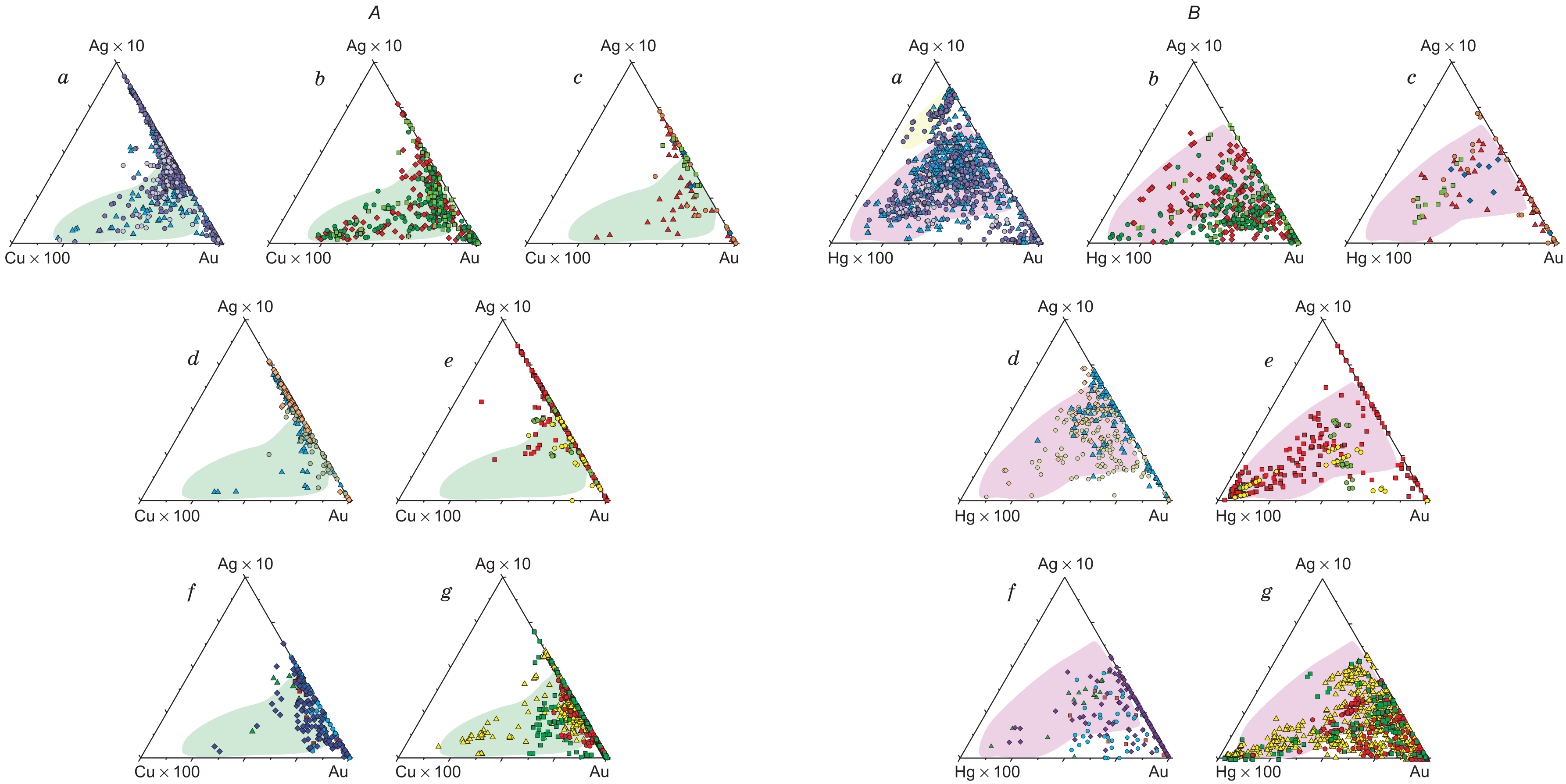

Fig. 6. Triangle diagrams constructed on the Au–Ag·10–Cu·100 (*A*) and Au–Ag·10–Hg·100 (*B*) coordinates of the compositions from native gold placers, mother lodes and weathering crusts. *a*, The Elovskii area within the Ik placer field; *b*, the Krochalevskii area within the Ik placer field; *c*, the Taily placer field; *d*, the Berd' placer field; *e*, primary gold-ore mineralization; *f*, the Suenga placer field; *g*, weathering crusts. The composition area of copper-bearing native gold of type I (*A*) and of mercury-containing native gold of types II and III (*B*) is color-coded; conventional symbols are given in Fig. 5.

Possible mother lodes for the identified native gold types. The analysis of geological setting in the areas of placer feeding, chemical gold composition and mineral composition of its microinclusions in comparison with data on analogous native gold characteristics from unknown deposits allowed us to suggest the existence of the further mother lodes for each identified type of native gold. For example, native gold of type IV is compared with the analogous one from the northwest Salair gold–barite–polymetallic deposits. According to (Alyamkin, 2010), two types of native gold with the fineness of 600–699‰ and 800–899‰ were determined at the Iyunsky. In accordance with later data (Alyamkin, 2012), the gold grade with the fineness of 580–630‰ dominated, and the occurrence of gold with the fineness of 860–870‰ and 960–970‰, and small amounts of mercury in gold were also registered. Low-fineness (<750‰) gold is mainly detected in ores of the Salair deposit. This comparative analysis is additionally supported by the following facts: (1) native gold of type IV is encountered only in placers firstly appearing within the distribution area of the lower Cambrian Pecherkino Formation, which is known for gold-containing ore occurrences (Roslyakov et al., 2001); (2) only galena inclusions were detected in native gold of type IV (Table 1), that is not typical of other grades of gold and in compliance with the mineral composition of primary rocks.

Native gold of types II and III is considered widespread in the placers of the Egor'evsk district. It also represents "original" gold from metasomatites of beresite composition from the Novolushnikovskoe and Egor'evskoe deposits. Based on these facts, gold-bearing metasomatites (similar to those encountered at famous ore mining sites) are considered to be main mother lodes or sources for feeding the placers. Permanent coexistence of native gold of types II and III, and their comparable quantitative relation to each other allows us to make a supposition that both types are the result of a single ore process, but fineness distribution and mercury concentration may reflect the stages of ore mineralization. The affinity of mineral composition of native gold inclusions gives evidence in favor of this interpretation.

The occurrence of copper-bearing gold of type I in the Egor'evsk district might be conditioned by high cross-section saturation with bodies of metamorphised gabbro and diorites with the width from a few up to 100 and more meters (Belyaev et al., 2001). These are intrusions which have a genetic and spatial relation to the Salair gold-grade ore mineralization that can localize directly inside them (Roslyakov et al., 1995). The mother-lode of native gold of type I can be represented by gold-bearing metasomatites with listwaenite composition, which tend to develop across widely spread diorites of the Taily complex; for example, the Lapinskii area of the Egor'evskoe deposit. Small bodies of altered diorites are actually positioned immediately in the placer bedrock of the Simonovskii Brook (the Krokhalevsky area of the Ik placer field). Specific mineral composition of microinclusions (significant chalcopyrite domination often through intergrowth with magnetic iron oxide; occurrence of singular ilmenite and rutile inclusions) in gold of type I could be an illustrative confirmation of such a conclusion. According to literature data, native gold with high Cu concentration (above 2–3 wt.%) is rarely found and peculiar to hydrothermal systems in basite-hyperbasite rock complexes (Murzin, 2010). High miscibility of Au, Ag, and Cu is caused by elevated-temperature gold crystallization. When temperature decreases, Au, Ag, Cu miscibility area sharply contracts, but tends to be observed even at 300 °C and below. In these conditions, Cu content in gold reaches less than 1 wt.% (Murzin, 2010). Magnetic iron oxide-chlorite-carbonate metasomatites from the Karabash Range (the Urals) developed at 380–430 °C. Copper concentration in the gold of these metasomatites is more than 3 wt.% (Murzin, 2010). The temperature of gold-bearing micaceous metasomatites from the Egor'evsk deposit is estimated within the range of 350–400 °C (Roslyakov et al., 1995), which is consistent with Cu concentration grade in Au. Copper-containing gold (as a rule up to 1% in Au) can be found in deposits of copper–skarn type, for example in postskarn hydrothermally altered ores of the Sinyukhinskoe deposit (Altai) with deposition temperatures not more than 350 °C (Gaskov et al., 2010). Besides, gold with lower copper content (up to 0.8 wt.%) occurs in aposkarn propylites from the Shilovskoe deposit (Ural) (Dvornik, 2011), copper concentration grade in gold from the Natal'evskoe deposit (Kuznetsk Alatau) is much lower up to 0.3 wt.%. Copper-bearing gold can develop in ore assemblages related to copper–sulphide ore mineralization because the chemical composition of gold depends on ore-mineralization host medium. Geochemical copper background is one of the determinants of copper-containing gold occurrence (Gaskov, 2017). Mineralization sites located within the Krokhalevskii area are known to be pure copper and gold–copper. For instance, Vyazkii mineralization site (No. 2 in Fig. 2) is represented by quartz-carbonate veins 10 cm thick and with chalcopyrite, hematite, and magnetic iron oxide. Copper content reaches up to 2 ppm, and copper up to 2.3 wt.% (Roslyakov et al., 2001).

It should be noted that despite substantial statistics representativity of native gold from the great number of placers and several thousands of analyses carried out, we have failed to detect placer gold of type V, which is characterized by anomalously high content of mercury impurity reaching up to 24 wt.%. Such a trend is probably related to demercurization processes in native gold under alluvial placer conditions. In this case, considerable losses of mercury are being observed, and residual placer gold acquires new type-chemical characteristics. For instance, the grains of native gold from the mine dump of the Novolushnikovskoe deposit are characterized by the rim from "sponge gold" (Fig. 4*i*, *j*). Herewith, the central part of a grain contains Hg impurity up to 20–24 wt.%, but altered 'sponge' gold is characterized by a grade of concentration up to 9 wt.%. It is known from archival records that the deposit was discovered in 1895, i.e., the grains of native gold were kept under surface conditions no more than 120 years, which is a rather short interval in the context of geological age. It is reasonable to suppose that mercurous native gold has been losing mercury since the moment of getting from the mother-lode into a placer, and the appeared rim tends to spread outward. Some loss of mercury will result in composition similarity of altered gold of type V with the gold of types II or III, depending on the initial amount of silver contained. This assumption will be implicitly confirmed by overlapping of microinclusions mineral composition in this type of gold, especially, by the occurrence of telluride inclusions, such as Hg, Bi, Pb.

Subtypes II′, III′ and V′ differ from the corresponding basic types only by lower silver content. The native gold of these types is found only in weathering crusts and in the placers which are "fed" at their expense. The trend of change in fineness under transition in the system—primary mother-lode—weathering crust has been mentioned before (Nestrenko, 1991; Roslyakov et al., 1995). However, with reference to the bodies of the Egor'evsk ore placer district, the trend was explained not only by hypergene leaching of impurity but by the fact that concentrations of gold in weathering crusts are mainly produced owing to gold-bearing quartz veins destruction with always higher-grade gold in comparison with gold from metasomatites. Within the framework of the studies and generalization of the available materials, such problem interpretation could be put into question owing to the fact that metasomatites of the weathering crusts can easily and completely transport over the saprolite zone into structural eluvium (Roslyakov et al., 1995, 2001). On the contrary, quartz veins are exposed to chemical changes to a lesser extent. We admit that under weathering crust conditions, native gold selectively loses a portion of silver when the concentration grades of copper and mercury stay the same. The phenomena of selective silver transport in weathering crust settings without change of Cu and Hg concentration have been described in (Santosh, 1994; Nakagawa et al., 2005). The hypothesis obviously requires further investigation and at this stage appears to be a theory which needs an evidence base. We will not cast any doubt on the assumption that complete leaching of both Hg and Ag is taking place at the edges of gold grains from the weathering crusts (Roslyakov et al., 1995). Our assumptions are based on the common law of native gold fineness grade increase at the expense of silver losses in the mother-lode—weathering crust system.

The same complex, long process of hypergene compositional transition of endogenous native gold could be applied to explain the absence of type I-a in the gold placers. Native gold containing significant impurities both of copper and mercury can lose Hg impurity under dynamic conditions of alluvial transport that results in composition fields "alignment" of gold types I-a and I.

CONCLUSIONS

The chemical composition of native gold is defined by the mineragenic type of ore mineralization and its mineral-geochemical characteristics. The obtained data on the composition of the Egor'evsk district placer gold confirm the thesis that feeding endogeneous gold-grade ore mineralization is polygenic in the Salair (Roslyakov et al., 1995). It is represented not only by gold-quartz veins and gold-bearing polymetallic types but by gold–sulphide–quartz vein-stockworks comprising quartz, quartz–carbonate vein bodies and metasomatites with veinlet-impregnated mineralization. Gold-grade polymetallic ore mineralization distributed in volcanogenic sedimentary rocks of the Pecherkino Formation does not participate in feeding the placers because of dominating fine-grained gold, which commonly doesn't form placers.

Placer gold composition of the Egor'evsk district accounts for diversification of mother lodes among which gold-bearing metasomatites with beresite and listwaenite composition tend to dominate. High-fineness, mercury-containing native gold is typical of placers and mother lodes. Average and low-fineness gold is distributed in dramatically subordinate quantities, particularly in placers. The characteristic gold feature rarely occurring in other districts appears to be the constant and frequently simultaneous presence of significant Hg and Cu impurities in its composition. Regarding native gold chemical properties, mineral composition of microinclusions and common geological setting, we can suppose the existence of several types of gold marked by various degrees of distribution in placers, mother lodes and gold-bearing weathering crusts. The feasibility to predict gold-grade ore mineralization by predetermined mineral-geochemical gold placer attributes is of great practical importance.

The most common types of native gold found in all the placers prove to be grades II and III, where metasomatites of beresite composition are considered to be their mother lodes. The first type of copper-containing gold is of local occurrence, mainly the Krochalevskii area of the Ik placer field. Its mother lode is supposed to be metasomatites of the listwaenite type, which are mostly developed along the bodies of mafic small intrusions; it might be also vein-stockwork ore mineralization overlapping copper–pyrite gold-bearings. Average- and low-fineness gold dominates in the Ik placer field and mostly within the Elovskii area that indicates correlation with pyrite–polymetallic gold-grade ore mineralization assigned to the Pecherkino Formation. Despite pyrite–polymetallic ore occurrences in the Taily field (Fig. 2), the gold of fineness grade less than 750‰ (type IV) is almost absent in the placers of the Taily and Berd' fields. This phenomenon is not entirely understood and needs further investigation. Except for this type, the gold from the placers of the Taily field is distinguished by composition that has greater affinity with the gold from the Ik placer field; and the gold from the Berd' field has similarity with the gold content from the Suenga field, where the most gold–(sulphide)–quartz type ore occurrences tend to localize within the Egor'evsk district.

The lack of placer gold occurrence with high mercury concentration (typical of mother lodes and weathering crusts) is caused by significant mercury losses by gold, most of which is lost after the gold is released from weathering crusts under alluvial transport conditions. Mismatch between the composition of native gold in the weathering crust and the composition of gold-bearing metasomatites (acting as protoliths) is likely to be a result of selective silver leaching, with simultaneous conservation of copper and mercury concentration grades. However, most aspects of hypergene compositional transition of native gold require further investigation.

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REFERENCES

Alyamkin, A.V., 2010. Gold mineralization in weathering crusts of the Iyunsky deposit (Eastern Salair), in: Proc. 14th Int. Conf. "Geology of Placers and Weathering Crusts" [in Russian]. Apelsin, Novosibirsk, pp. 44–50.

Alyamkin, A.V., 2012. The Iyunsky deposit of gold in weathering crusts (Eastern Salair). Vestnik TGU 355, 144–147.

Belyaev, V.I., Nechaev, V.V., Dergachev, V.B., Zudin, A.N., Dagaev, Yu.G., 2001. The Explanatory Note to the State Geographical Map of the Russian Federation. Scale 1:200 000. Second edition. Series Kuzbasskaya, Sheet N-45-XIII [in Russian]. Department of Natural Resources of the Siberian Region, Novosibirsk Geologic Prospecting Party, Novosibirsk.

Benevolskii, B.I., 2002. Gold of Russia: Problems of Use and Reproduction of the Mineral Raw Material Base, second edition [in Russian]. Geoinfrmark, Moscow.

Chapman, R.J., Mortensen, J.K., 2016. Characterization of gold mineralization in the Northern Cariboo gold district, British Columbia, Canada, through integration of compositional studies of lode and detrital gold with historical placer production: A template for evaluation of orogenic gold districts. Econ. Geol. 111 (6), 1321–1345.

Chapman, R.J., Leake, R.C., Moles, N.R., Earls, G., Cooper, C., Harrington, K., Berzins, R., 2000. The application of microchemical analysis of alluvial gold grains to the understanding of complex local and regional gold mineralization: A case study in Irish and Scottish Caledonides. Econ. Geol. 95 (8), 1753–1773.

Chapman, R.J., Leake, R.C., Bond, D.P.G., Stedra, V., Fairgrieve, B., 2009. Chemical and mineralogical signatures of gold formed in oxidizing chloride hydrothermal systems and their significance within populations of placer gold grains collected during Reconnaissance. Econ. Geol. 104 (4), 563–585.

Chapman, R.J., Mortensen, J.K., Crawford, E.C., Lebarge, W., 2010. Microchemical studies of placer and lode gold in the Klondike District, Yukon, Canada: 1. Evidence for a small, gold-rich, orogenic hydrothermal system in the Bonanza and Eldorado Creek area. Econ. Geol. 105 (8), 1369–1392.

Dvornik, G.P., 2011. Morphological characteristics and composition of native gold from oxide-bearing ores of the gold-ore/gold-containing deposits of the main mineragenic types in the Urals, in: The Issues of Mineralogy, Petrography, and Metallogeny. Scientific Readings in Memory of P.N. Chervinsky [in Russian]. Perm, pp. 151–158.

Gaskov, I.V., 2017. Major impurity elements in native gold and their association with gold mineralization settings in deposits of Asian folded areas. Russian Geology and Geophysics (Geologiya i Geofizika) 58 (9), 1080–1092 (1359–1376).

Gaskov, I.V., Borisenko A.S., Babich, V.A., Naumov, E.A., 2010. The stages and duration of formation of gold mineralization at copper-skarn deposits (Altai–Sayan folded area). Russian Geology and Geophysics (Geologiya i Geofizika) 51 (10), 1091–1101 (1399–1412).

Germakhanov, A.A., Zaitsev, A.I., Isakov, A.V., Kudirmekov, A.A., Maksimov, A.P., 2017. The mineral raw material base of the Altai Republic, the Altai Territory, the Kemerovo Region, the Novosibirsk Region, and the Omsk Region. Razvedka i Okhrana Nedr, No. 3, 7–17.

Kalinin, Yu.A., Roslyakov, N.A., Prudnikov, S.G., 2006. Gold-Bearing Weathering Crusts in the South of Siberia [in Russian]. Geo, Novosibirsk.

Kanygin, A.V., Sviridov, A.G. (Eds.), 1999. Geological Structure and Mineral Resources of Western Siberia. Vol. I: Geological Structure [in Russian]. SO RAN, NITs OIGGM, Novosibirsk.

Lalomov, A.V., Bochneva, A.A., Chefranov, R.M., Chefranova, A.V., 2015. Placer deposits of the Russian arctic zone: an actual status and the ways of development of the mineral raw material base. Arktika: Ekologiya i Ekonomika, No. 2 (18), 66–77.

McTaggart, K.C., Knight, J., 1993. Geochemistry of Lode and Placer Gold of the Cariboo District, BC. British Columbia Ministry of Energy, Mines and Petroleum Resources, Open File 1993-30.

Murzin, V.V., 2010. Chemical composition of native gold as the index of deposition conditions (A case study: the Urals), in: Metallogeny of Ancient and Contemporary Oceans [in Russian]. IMin UrO RAN, Miass, pp. 155–159.

Nakagawa, M., Santosh, M., Nambiar, C.G., Matsubara, C., 2005. Morphology and chemistry of placer gold from Attappadi Valley, Southern India. Gondwana Res. 8 (2), 213–222.

Nesterenko, G.V., 1991. The Prediction of Gold-Grade Ore Mineralization in Placers [in Russian]. Nauka, Novosibirsk.

Nesterenko, G.V., Kolpakov, V.V., 2007. Fine gold particles and gold dust in alluvial autochthonous placers in southern West Siberia. Russian Geology and Geophysics (Geologiya i Geofizika) 48 (10), 783–798 (1009–1027).

Nesterenko, G.V., Gritsyuk, Ya.M., Osintsev, S.R., 1984. A new approach to investigation of buried gold placers on the Salair Ridge, in: The Issues of Continental Placer Formation [in Russian]. Vladivostok, pp. 225–234.

Nesterenko, G.V., Kalinin, Yu.A., Kolpakov, V.V., 2003. The placer formation evolution in poly-zonal landscapes, in: Geodynamics, Magmatism, and Minerageny of the Continental Margin of the North Pacific Ocean [in Russian]. Magadan, pp. 229–232.

Potter, M., Styles, M.T., 2003. Gold characterization as a guide to bedrock sources for the Estero Hondo alluvial gold mine, western Ecuador. Applied Earth Sciences IMM Transaction Section B 112 (3), 297–304.

Roslyakov, N.A., Sviridov, A.G. (Eds.), 1998. Geological Structure and Mineral Resources of Western Siberia. Vol. II: Mineral Resources [in Russian]. SO RAN, NITs OIGGM, Novosibirsk.

Roslyakov N.A., Nesterenko, G.V., Kalinin, Yu.A., Vasil'ev, I.P., Nevol'ko, A.I., Roslyakova, N.V., Osintsev, S.P., Sviridov, V.G., Kolpakov, V.V., Boboshko, L.P., 1995. Gold Mineralization of the Salairs Weathering Crusts [in Russian]. Publ. SB RAS, NITs OIGGM, Novosibirsk.

Roslyakov, N.A., Shcherbakov, Yu.G., Alabin, L.V., Nesterenko, G.V., Kalinin, Yu.A., Roslyakova, N.V., Vasil'ev, I.P., Nevol'ko, A.I., Osintsev, S.R., 2001. Minerageny of the Suture Zone of the Salair Ridge and the Kolyvan-Tomsk Fold Areas [in Russian]. Geo, Novosibirsk.

Roslyakova, N.V., Shcherbakova, Yu.G., Ageenko, N.F., Portyannikov, D.I., Bortnikova, S.B., Radostena, N.E., 1983. Gold mineralization conditions on pyrite-polymetallic deposits, in: Formation Conditions, Methodology of Prediction and Prospecting of Gold-Ore Deposits [in Russian]. Nauka, Novosibirsk, pp. 31–65.

Santosh, M., 1994. Gold-silver decoupling in weathering front: implications for gold exploration in lateritic terrains. J. Geol. Soc. India 43 (1), 51–65.

Townley, B.K., Herail, G., Maksaev, V., Palacios, C., de Parseval, P., Sepulveda, F., Orellana, R., Rivas, P., Ulloa, C., 2003. Gold grain morphology and composition as an exploration tool: application to gold exploration in covered areas. Geochemistry: Exploration, Environment, Analysis 3, 29–38.

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