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Gold and platinum group minerals in placers of the South Urals: Composition, microinclusions of ore minerals and primary sources

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ABSTRACT

Gold and platinum group minerals from the gold placers of the South Urals are studied in order to identify the metal sources. In placers from the Main Uralian fault zone (MUF), the primary gold contains Ag (up to 29 wt.%), Cu (up to 2 wt.%) and Hg (up to 4 wt.%) and its fineness ranges from 538 to 997‰. Tetra-auricupride and cupriferous gold (up to 20 wt.% Cu) are common for the Nizhny Karabash placer of the MUF zone. In the eastern part of the South Urals, the placer gold is mainly characterized by high fineness of 900–1000‰ and low Cu contents (max 1.38 wt.%). Most of the placer gold grains consist of the primary domains, which are rimmed by secondary high-fineness gold with diffuse and clear boundaries. The secondary gold also develops along the shear dislocations of primary gold. Gold contains microinclusions of geerite, balkanite, chalcopyrite, Se-bearing galena, sphalerite, pyrite, pyrrhotite, arsenopyrite and hematite.

Twenty four (including five unnamed) platinum group minerals (PGMs) were found in 28 placers; those from the Kialim and Maly Iremel placers of the Miass placer zone were studied in details. In the Kialim placer, ruthenium is most abundant PGM, which hosts microinclusions of isoferroplatinum, ferroan platinum, laurite, cupriferous gold, a mineral similar in composition to tolovkite, heazlewoodite and unnamed RhSbS phase. The osmium contains microinclusions of erlichmanite and laurite. The iridium grains hosts various sulfides and arsenides of platinum group elements (PGEs). The inclusion-free PGMs form Ru compositional trend in contrast to Os–Ru trend of the Ir-depleted inclusion-hosted PGMs. The isoferroplatinum from the Maly Iremel placer hosts laurite, rhodarsenite, bowieite, a mineral similar in composition to miassite and unnamed sulfide of Pt ($Pt_{1.11}S_{2.00}$) and antimonide of Pd ($(Pd_{2.41}Rh_{0.43}Fe_{0.17})_{3.01}(Sb_{0.91}Te_{0.09})_{1.00}$). Ruthenium is a host to isoferroplatinum, PGE sulfides and arsenides, and heazlewoodite. Osmium contains microinclusions of ferroan platinum; iridium is a host to a mineral similar in composition to hongshiite. Three types of PGM intergrowths were identified in the Maly Iremel samples: (1) the intergrowths of platy grains of ruthenium with isoferroplatinum and a mineral similar in composition to tulameenite; (2) the open-latticework intergrowths of platy crystals of ruthenium with interstitial aggregates made up of gold, isoferroplatinum and a mineral similar in composition to xingzhongite and (3) the intergrowths of osmium and irarsite and iridarsenite, which are developed along cleavage of the osmium grains. Nickel sulfides associated with some PGMs contain Ru (11.32 wt.%) and Rh (2.21 wt.%) in millerite and Ir (31.00 wt.%), Ru (5.81 wt.%) and Rh (2.87 wt.%) in vaesite.

The primary metal sources were determined on the basis of the mineral assemblages and composition of minerals, taking into account the nearby mineral deposits and directions of rivers. The rodingite-associated gold, gold-bearing massive sulfide and chromite deposits are major sources of gold and PGMs in placers of the Miass placer zone confined to the MUF structure of the South Urals. In the southern part of this structure, gold was mainly originated from orogenic gold–sulfide deposits associated with volcanic/volcaniclastic rocks and listvenite-associated gold deposits. The placer PGMs were derived from the adjacent ultramafic massifs of ophiolitic origin. The distance between the placers and primary deposits varies from 2 to 5 km (up to 20 km in the extended valley of the Miass River). Usage of ore microinclusions and associated PGMs in study of placer gold is far more advanced than an ordinary consideration of gold composition alone. This approach allowed us to identify the concrete sources for individual placers and to predict some mineralogical findings in already known primary occurrences.

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1. Introduction

The South Urals gold placers have been the sources of precious metals since the beginning of the 19th century. Over this period, about 250 t of gold and platinum group minerals (PGMs) have been extracted from about 600 placers (unpublished reports of Petrov, 1999; Ivanishchev et al., 2005). At present, gold is being extracted only from three placer deposits in Chelyabinsk district (Bayramgulovo, Ingul, Kazanskaya). It is generally considered that the orogenic gold–quartz and gold–sulfide deposits including rodingite-, listvenite- and skarn-related deposits and PGM-bearing chromite occurrences, were the sources of metals (Koroteev et al., 1997; Ovchinnikov, 1998; Zaykov et al., 2012, 2016).

The majority of the relevant literature on the placer geology of the South Urals has been published in Russian (Rozhkov, 1948; Shub et al., 1993; Sazonov et al., 2001; Kazakov and Salikhov, 2006; Barannikov, 2006; Zaykov et al., 2012). Papers devoted to the gold placers of the South Urals are unknown in international journals. The microinclusions of ore minerals in gold from the South Urals placers are poorly characterized even in Russian mineralogical literature, whereas those from other world regions, e.g., placers of Great Britain, the United States, Slovakia or Russia, are well described (Chapman et al., 2000, 2009, 2011; Nikiforova and Glushkova, 2009; Žitnan et al., 2010; Nikiforova, 2014; Nikiforova et al., 2011). The aim of our work is to identify the primary metal sources of the Southern Urals gold placers based on the composition of placer gold, PGMs and microinclusions of ore minerals.

2. Geological background

2.1. Brief geological outline of the South Urals

Geological structure and metallogeny of the South Urals with respect to placers have been studied by many researchers. The most complete data can be found in works of Shub et al. (1993), Koroteev et al. (1997), Herrington et al. (2005) and Puchkov (2017), who analyzed the geological evolution of the Urals fold belt and peculiarities of its ore genesis.

According to the current geological conceptions, the mountainous and adjacent plain parts of the South Urals are divided on several structural zones (Central Uralian, Main Uralian fault (MUF), Magnitogorsk and East Uralian). Each of them is a host to the numerous gold placers. In the Proterozoic, the western part of the region was a sedimentation area, which is now marked by metamorphic schists of the Central Uralian zone. The oceanic crust and island arcs of the Magnitogorsk and East Uralian zones with numerous volcanogenic-hosted massive sulfide (VHMS), porphyry copper and various gold deposits were formed starting from the Ordovician to the Devonian time. The Cyprus-type VHMS deposits are hosted by oceanic basalts. The Uralian-type copper–zinc and Baimak(Kuroko)-type gold-bearing polymetallic VHMS deposits with smoker chimneys occur within the island-arc complexes. The Au–Cu porphyry deposits are related to the island arc granitic complexes. The MUF zone is approximately 10 to 20 km wide and exposes the serpentinite mélange with ophiolitic ultramafic rocks, which host several deposits types including chromite, Co-bearing

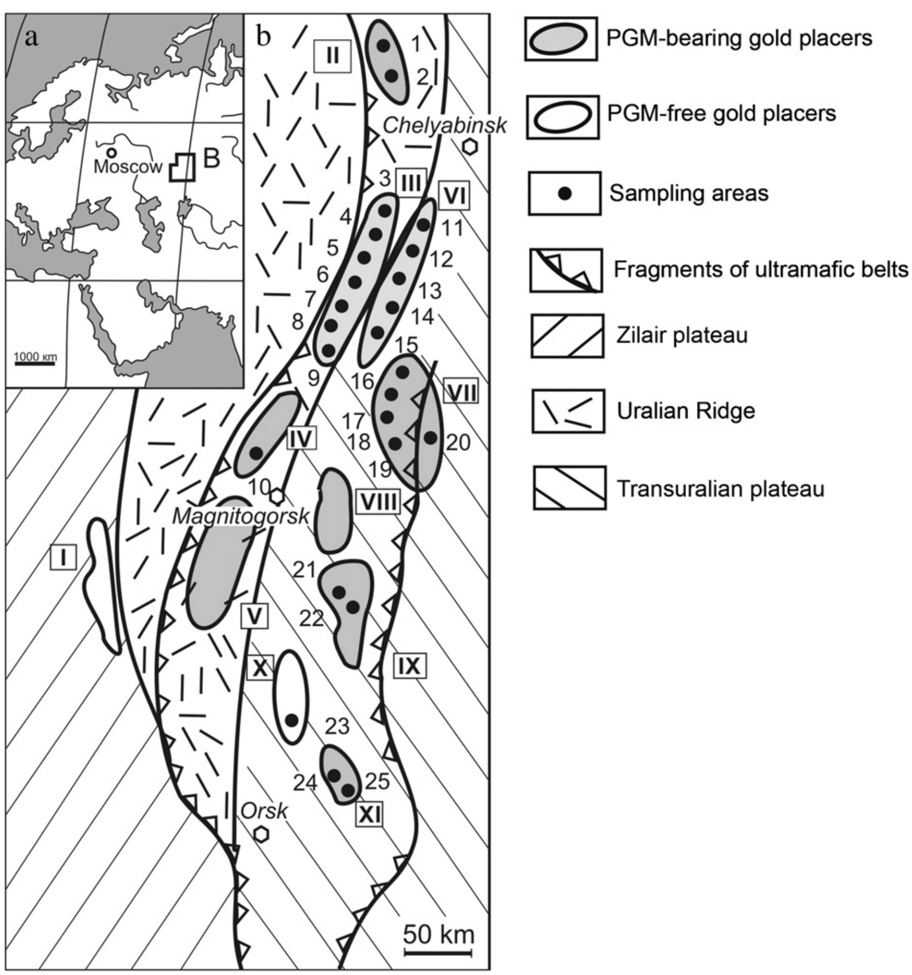

Fig. 1. Geographic setting of the South Urals (a) and location of the main placer zones, placers with available data on gold composition and places of sampling (b). For identification of Roman numerals, see text (part 2.3). Arabic numerals correspond to the numbers of placers in Table 2.

ultramafic–mafic-hosted massive sulfide and orogenic gold–sulfide, and rodingite-, scarn- and listvenite-associated gold deposits.

Collision zones (e.g., MUF zone), hosting several orogenic gold deposits, have been formed in the Late Devonian to Early Carboniferous time. In the Mesozoic and Cenosoic, the territory of the Urals underwent denudations with subsequent formation of erosion–tectonic depressions and weathered rocks. No glaciation traces are known in the South Urals. The southernmost glacial rocks occur ca. 500 km north from Chelyabinsk, at 61° N (Boch and Krasnov, 1946).

2.2. Geomorphological evolution and setting of placers of the South Urals

The gold placer zones are located within the Uralian Ridge, which corresponds to the Central Uralian, MUF and, partly, Magnitogorsk zones, and adjacent plateaus: Zilair from the west, which includes a fragment of the Central Uralian zone, and Transuralian from the east, which spans most part of the Magnitogorsk and East Uralian zones (Fig. 1) (Bachmanov et al., 2001). The Uralian Ridge consists of the ranges 600–1600 m high, which are cross cut by mostly longitudinally oriented rivers (Ural, Miass, Sakmara, Tanalyk). The Zilair plateau is a flattened area of 100–120 km wide, 400 km long and 200–600 m high. The majority of its rivers is transverse or diagonal and flows from the east to the west. The Transuralian plateau is 150–200 km wide and 500 km long and gently transits to the West Siberian depression. The rivers of the plateau flow from the west to the east. By morphology of the surface, which is extended from the bench of the MUF zone, this relief corresponds to the pediment (cf., Jackson, 1997).

The gold placers were formed at the continental stage of the Urals evolution, which began in Triassic and continued over 250 million years (Shub et al., 1993). In Mesozoic and Paleogene, the pre-

Table 1
Brief description of placers of the South Urals.

Placer zone	Characteristics of placers	Placers	Amount of extracted gold (kg)	Fineness (group)
Avzyan	Quaternary alluvial valley (including bench) placers 0.4–1.5 km long. Coarse gold 0.5–5 mm in size.	Kamenny Klyuch	177	926–979 (B–A)
		Kuchanov		950–980 (B–A)
Kyshtym	Quaternary alluvial valley (including bench) placers 1.5–15.0 km long and 20–300 m wide. Small to coarse medium-rounded gold 0.1 to 1.5 mm in size.	Mauk, Zyuzelka[a], Korkodin[a], Vishnevogorsk,	726	926–979 (B–A)
		Kyshtym	n.d.	950–980 (B–A)
Miass	Quaternary and Neogene alluvial valley (including bench) and eluvial placers of a total length of 130 km. Twelve placers contain PGMs. In the northern part, the placers 3–4 km long and 30–250 m wide occur in the left tributaries of the Miass River. In the central part, discontinuous placers of a total length of ~30 km and a width of 50–100 m mostly contain gold grains 0.4–1.5 mm in size. In southern part, the placers up to 400 m wide belong to the sources of the Miass and Uy rivers. The PGM contents in the Maly Iremel placer reached 11.7 g/m^3; the nuggets 200 and 500 g were found.	Nizhny Karabash[a], Kialim[a], Andreevskaya distantsiya (polygon no. 7), Atlyan[a]	9063	900–920 (B)
		Central Miass (polygon no. 6), Tashkutarganka[a], Maly Iremel[a]	12,956	870–930 (C–B)
		Mayak I, Vorontsovsky Log[a], Sharambay Naduv	1240	900–907 (B)
		Bogaty Sarat, Uy[a], Petrovskaya[a]	15,122	850–887 (C)
		Suleymenovo[a], Zhuravlevskaya, Ustinovo[a]	1435	900–922 (B)
		Karasul[a], Dzhimbet–Rysaevo	2493	802–920 (C–B)
Mindyak	A 70-km long zone hosts alluvial valley (including bench) and, locally, Neogene and Quaternary eluvial placers 2–3 km long and 50–90 m wide. The coarse, well rounded gold is characterized by clumpy, tabular and lamellar morphology; the gold nuggets up to 10 g in weight are locally found. Five placers contain PGMs, the amount of which is 1–2% of total amount of gold.	Terassovaya I[a], Kuru-Elga[a], Afoninskaya[a], Mindyak	2547	800–892 (C)
		Tarlaus[a]	62	934 (B)
Irendyk	Quaternary, Neogene and Mesozoic alluvial valley and eluvial placers of the total length of 70 km. The individual placers are 2–3 km long and 50–90 m wide. Coarse, well-rounded gold is characterized by lumpy, tabular, and platy morphology. Gold nuggets may reach 10 g in weight. Three placers contain PGMs (1–2%).	Yaprakty[a], Baskunzyak, Sultan–Khalilovo	232	898–926 (C–B)
		Sultanovo[a]	4687	900–915 (B)
		Gadelshin	2373	886 (C)
Nepryakhino	Quaternary alluvial valley and Miocene–Pliocene eluvial placers 1.4–3.5 km long and 40–350 m wide. The largest Argazi placer is 27.5 km long and 350–1000 m wide. Gold is coarse, poorly rounded; the weigh of gold nuggets is 15–20 g, rarely up to 95 g. The PGMs were found in several placers.	Argayash[a], Bayramgulovo[a], Argazi (polygon no. 80)[a]	2500	966 (B)
		Mokhovoe Boloto, Fambulovo, Ingul[a]	1548	862–870 (C)
Kochkar	Miocene to Quaternary alluvial valley (including bench) placers 0.5–4.0 km long and 40–400 m wide. Some placers are confined to the erosion–tectonic depressions.	North Svetlinskaya[a], Zoinsko–Il'inskaya, Etovna, Sukhteli	1348	912–978 (B–A)
Gumbeyka	Miocene to Upper Pleistocene alluvial valley and eluvial placers 0.5–2.5 km long and 12–120 m wide.	Polenovskaya[a], Poverennaya[a], Kassel'sky[a], Fershampenuaz, Eleninskaya, Burlachka, Chernaya Rechka, Kordonnogo Loga	2443	850–900 (C–B)
Gogino	Mesozoic and Miocene karst and eluvial placers 1.0–3.0 km long and 80–200 m wide. Gold is mostly small and poorly rounded; the gold nuggets are up to 250 g in weight. Some placer contains PGMs, as well as single nuggets up to 4 g in weight.	Bessonovskaya, Kazan[a], Amur[a]	3792	925–978 (B–A)
Suunduk	Cretaceous karst placers as “oblique beds” and less productive Miocene and Pliocene eluvial placers 7 to 15 km long. Gold is characterized by clumpy, angular and scaly morphology.	Kolchinskaya[a], Nazarovskaya	6000	980–990 (A)
Amambayka	Miocene eluvial placers. The Alexandrovka III placer contains a gold-bearing clayey layer with goethite “beans” at depth of 0.5–2 m. The size of gold grains reaches 12 mm.	Alexandrovka III	n.d.	900–960 (A–B)
Total			70,567	

Table is compiled after (unpublished reports of Petrov, 1999 and Ivanishchev et al., 2005; Salikhov et al., 2001; Barannikov, 2006; Kazakov and Salikhov, 2006).
[a] PGM-bearing placers.

Mesozoic geological structures were eroded and the weathering mantles of kaolinite type were formed under stable tectonic conditions in warm and wet climate. The river systems inherited the weakened zones of the tectonic and lithological contacts and formed longitudinal erosion–tectonic depressions, which hosted the major river valleys. Long evolution of the river systems resulted in formation of alluvial valley (including bench), eluvial and karst gold placers. The karst placers were exposed at depth of 50–100 m and mostly remained on the Transuralian plateau. During repeated renewal of karsts, the gold-bearing sediments were subjected to deformations and collapses, which led to the formation of the so-called Au-rich "oblique beds" (Barannikov, 2006).

In Pliocene, due to uplift of the Ural Mountains (Puchkov, 2017–in this issue), the Transuralian plateau became inclined to the east that yielded re-orientation of some river valleys from longitudinal to transverse and diagonal direction. Similar processes of reorientation of the drainage systems are also documented in New Zealand (Craw, 2013). The alluvial valley placers in the Uralian rivers were mostly formed at the expense of re-washing of the Mesozoic and Paleogene gold-bearing sediments. This period was characterized by semiarid climate, intense erosion of the areal weathering mantle and formation of branchy eluvial system, which often contains high-productive eluvial gold placers.

Quaternary was a period of active denudation processes and formation of the modern drainage systems. The climate became moderately cold and humid. The drainage systems were strongly distinct from those of the previous epochs. In the headwaters, the rivers inherited the morphology of the ancient valleys (e.g., longitudinal segment of the Miass River), whereas, downstream, they were characterized by transverse and diagonal direction. Major amount of gold in Quaternary placers derives from the ancient gold-bearing sediments. The Pliocene–Quaternary gold placers (the richest in Au grades and reserves) are localized within the contours of the present drainage system, which is confined to the erosion–structural depressions.

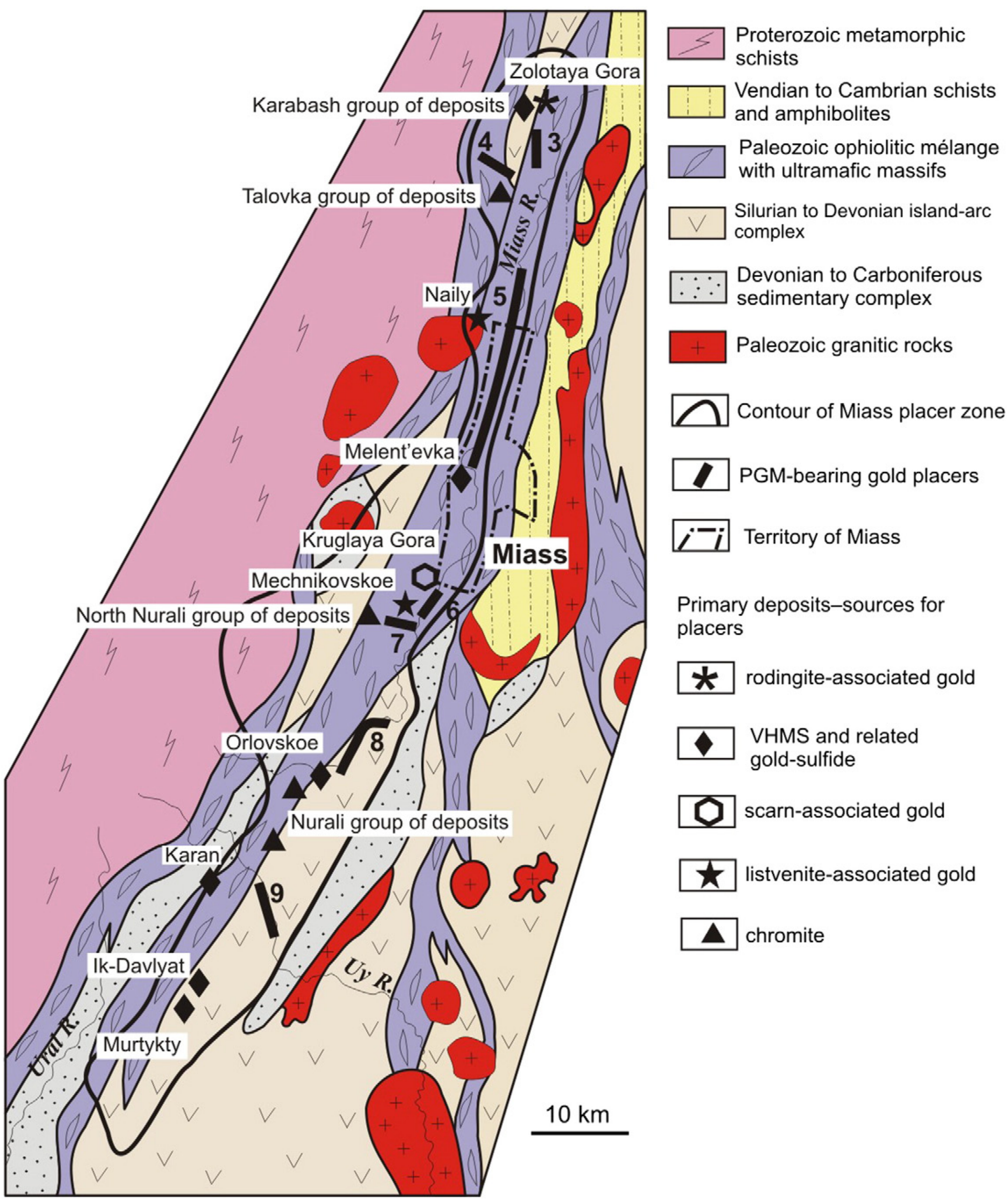

Fig. 2. Schematic structure of the Miass placer zone. Arabic numerals correspond to the numbers of the placers in Table 2.

In the South Urals, the alluvial valley and eluvial placers are the most abundant genetic types of placers. The productive alluvial valley sediments are mostly composed of gravel–pebble sediments of various rocks and sandy–clayey matrix (typical sediments of the river valleys). These sediments are clearly layered and contain lenses of coarse-grained sands and clays and, locally, the assemblages of the goethite beans. The pebbles and gold are well rounded. The eluvial sediments host rubble in combination with variegeted clays; the thickness of the productive layers varies from several centimeters to 1–2 m. The placer bedrocks of the MUF zone are often composed of ultramafic rocks, as well as marbles and limestones in the karst placers. The rare lake placers are confined to the terraces, which are situated 1.0–1.5 m higher relatively to the water surface (Rozhkov, 1948). The burial gold-bearing sediments in these placers occur at depth of the first tens of meters.

2.3. Brief characteristics of major placer zones

The data on the type of placers, their age, gold fineness and the amount of gold extracted from individual placers are summarized in Table 1. The total known amount of gold extracted from all Placer zones is estimated at ~227 t.

The Avzyan placer zone (I; Fig. 1) is located in the eastern part of the Zilair plateau and includes 49 placers from the Avzyan, Pribel'sky and Zilair regions, totaling 2646 kg of gold.

The Uralian Ridge hosts four placer zones: Kyshtym, Miass, Mindyak and Irendyk. The Kyshtym zone (II; Fig. 1) is located at the junction of the South and Central Urals and includes 37 placers, which produced 2981 kg of gold. The Miass zone (III; Fig. 1), which is known as Miass Gold Valley, includes a record number of placers (136) – it is the richest and the most extended placer zone in the South Urals (Fig. 2). The amount of extracted gold from this zone is totaling 140 t. Gold dredging in the Miass River occurred until the end of the 20th century. Numerous gold nuggets were extracted from various placers including the largest Russian gold nugget *Big triangle* which has a record weight of 36.2 kg. It was found in 1842 and now stored in the Diamond Fund of Russia in Moscow. The bedrock of this placer is a host to the Melent'evka gold-bearing VHMS-related deposit. The Mindyak zone (IV; Fig. 1) spans the upper reaches of the Ural River and its right tributaries. It includes 76 placers, which yielded a total of 8003 kg of gold. The Irendyk placer zone (V; Fig. 1) is located in the basins of the right tributaries of the Ural River and includes 197 placers in the Irendyk and Tanalyk regions, where the rhyolite–basaltic and andesite–basaltic paleoisland arc complexes are exposed. The amount of gold extracted is totaling 10,346 kg.

The Transuralian plateau is a host to the Nepryakhino, Kochkar, Gumbeyka, Gogino, Amambayka and Suunduk placer zones. The Nepryakhino placer zone (VI; Fig. 1) is situated at the right bank of the Miass River and confined to the eastern branch of the MUF zone. It hosts 47 placers, which produced a total of 5071 kg of gold.

The Kochkar zone (VII; Fig. 1) includes 81 placers, which were the source for 37,995 kg of gold. These placers were derived from the erosion of the gold–sulfide–quartz veins of the Kochkar orogenic gold deposit, which is confined to the Plast granitic pluton. Primary gold deposits of this region were discovered by the findings of gold–quartz veins in the placer bedrocks. Gold was extracted by dredges.

The Gumbeyka zone (VIII; Fig. 1) is located in the basins of the Gumbeyka and Zingeyka rivers and consists of 50 placers, which yielded a total of 14,570 kg of gold. The Gogino zone (IX) includes 20 placers with most productive karst placers which produced a total of 5429 kg of gold.

The Suunduk zone (XI; Fig. 1) is similar to that of the Gogino zone in respect of structure of gold-bearing sediments and a scale of gold production. The least significant Amambayka zone (X; Fig. 1) consists of 19 placers in the right tributaries of the Bol'shaya Karaganka River and adjacent dry creeks. Only 393 kg of gold was recovered from this zone.

3. Material and methods

Samples for our study were donated by the staff of the Urals State Mining University (Yekaterinburg, Russia), Il'meny State Reserve (Miass, Russia) and Miass Mining Company (Miass). These samples were collected from the placers adjacent to the MUF zone and the East Uralian zone. Our paper presents the data on 11 placer zones, the location of which is shown on the Fig. 1. The PGMs were identified in 28 placers.

The morphology and structure of gold and PGMs were studied using the Axiolab (Carl Zeiss) and Olympus BX-51 optical microscopes at the Institute of Mineralogy, Urals Branch, Russian Academy of Sciences (IMin UB RAS, Miass). Major element composition of minerals was analyzed at the IMin UB RAS on a REMMA-202M and Tescan Vega3 electron

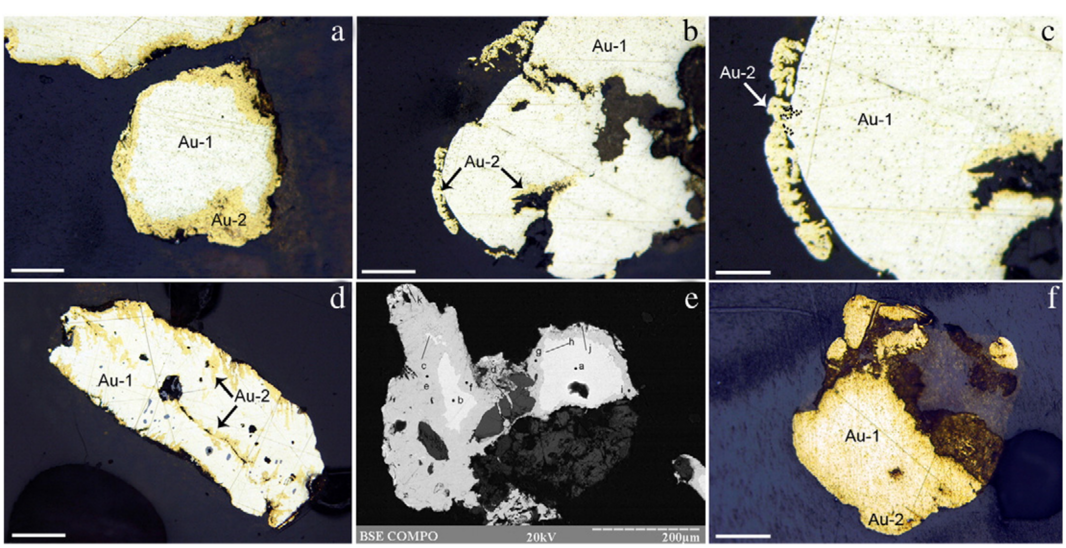

Fig. 3. Structure of gold minerals from placers of the South Urals: a) primary gold (Au-1) rimmed by secondary gold (Au-1) with diffuse boundaries, grain 3441, Vishnevogorsk placer; b) primary gold (Au-1) overgrown by secondary gold (Au-1), grain 3441, Vishnevogorsk placer; c) detail of fig. b, which shows how the secondary gold penetrates to the primary one (underlined by black dots); d) primary gold (Au-1) with secondary gold (Au-2) developed along the shear dislocations and inclusions of copper sulfides (gray), grain 3446, Nizhny Karabash placer; e) aggregates of tetra-auricupride (points a, b, c, h) and cupriferous gold (points e, f, g, i), grain 3446-2, Nizhny Karabash placer; f) grains of secondary gold with fine relics of primary gold. Vishnevogorsk placer. Photos a–d, f, reflected light; photo e, SEM-image. Scale bar is 200 (photos a, b, d, f) and 50 (photo c) µm.

Table 2
Chemical composition of the central domains of gold grains from South Urals placers.

Grain number	Number of analyses	Au	Ag	Cu	Hg	Total	Fineness (group)
II. Kyshtym placer zone							
1. Mauk placer (Vishnevye Gory area) (gold with high-fineness rim)							
3441	1	85.4	14.5	n.d.	n.d.	99.9	855 (C)
3441-1	5	84.7	15.0	bdl	bdl	99.7	850 (C)
2. Kyshtym placer (Borzovka River area) (gold with high-fineness rim)							
3445-a	1	86.0	13.7	n.d.	n.d.	99.7	863 (C)
3445-b	3	94.6	5.1	bdl	bdl	99.7	948 (B)
3445-1a	1	85.6	13.2	n.d.	bdl	98.8	865 (C)
3445-1b	4	92.2	7.6	n.d.	n.d.	99.8	924 (B)
3445-1c	1	90.3	bdl	n.d.	9.3	99.6	906 (B)
3445-1d	1	78.8	21.1	n.d.	n.d.	99.9	788 (D)
III. Miass placer zone							
3. Nizhny Karabash placer (Soymon area) (gold with high-fineness rim)*							
3446-a1	3	66.7	27.4	1.3	4.2	99.6	669 (D)
3446-a2	3	64.4	28.8	2.3	4.2	99.7	646 (E)
3446-b	3	68.1	27.2	n.d.	4.1	99.4	684 (D)
3446-c	4	88.1	11.9	n.d.	bdl	100.0	881 (C)
3446-2a	7	98.3	0.7	0.9	n.d.	99.9	985 (A)
3446-2b	1	96.9	0.4	2.4	n.d.	99.7	972 (A)
3446-2c	3	99.1	bdl	0.7	n.d.	99.8	992 (A)
4. Kialim placer*							
K2-6	3	93.5	4.2	2.0	bdl	99.7	937 (B)
K2-C-1a	5	92.3	6.00	1.4	n.d.	99.7	925 (B)
K2-C-1b	1	91.7	6.9	1.2	n.d.	99.8	919 (B)
5. Central Miass placer (polygon no. 6 area)*							
3444-a	2	91.5	8.2	bdl	0.3	99.9	915 (B)
3444-a-1	1	94.3	5.2	n.d.	n.d.	99.5	948 (B)
3444-b	1	87.7	12.1	n.d.	bdl	99.8	878 (C)
3444-c	1	53.7	44.9	n.d.	1.2	99.8	538 (E)
3444-1a	1	86.9	12.8	n.d.	n.d.	99.7	872 (C)
3444-1b	1	94.3	5.2	n.d.	n.d.	99.5	948 (B)
3444-2a	1	80.5	19.0	n.d.	n.d.	99.5	809 (C)
3444-2b	1	84.2	15.0	n.d.	n.d.	99.2	849 (C)
3444-2c	1	92.6	7.3	n.d.	n.d.	99.9	927 (B)
3444-2d	1	92.2	7.8	n.d.	n.d.	100.0	922 (B)
3444-2e	1	90.7	8.9	n.d.	n.d.	99.6	911 (B)
3444-2f	1	86.5	12.8	0.4	n.d.	99.7	867 (C)
3444-2g	1	90.3	9.7	n.d.	n.d.	100.0	903 (B)
3444-2f	1	90.8	9.1	n.d.	n.d.	99.9	909 (B)
3444-2k	1	90.1	9.7	n.d.	n.d.	99.8	903 (B)
6. Tashkutarganka placer							
Tash	2	88.0	11.3	n.d.	n.d.	99.3	885 B
7. Maly Iremel placer							
Ir3-5-1a	3	82.3	16.5	n.d.	n.d.	98.8	833(C)
Ir3-5-1b	1	92.2	7.0	n.d.	n.d.	99.2	929 (B)
Ir3-5-2a	3	81.3	10.2	8.7	n.d.	100.2	811 (C)
Ir3-5-2b	2	79.0	1.9	18.7	n.d.	99.6	799 (D)
Ir3-5-3a	1	81.7	11.3	6.7	n.d.	99.7	819 (C)
Ir3-5-3b	1	80.3	2.1	17.6	n.d.	100.0	803 (C)
8. Suleymenovo placer*							
B3-1	3	91.7	7.7	0.3	n.d.	99.7	920 (B)
9. Polyakovka placer (gold with high-fineness rim)*							
3439a	2	87.3	12.5	bdl	bdl	99.8	874 (C)
3439b	3	91.7	8.2	n.d.	n.d.	99.9	918 (B)
3439-1	3	91.4	8.3	n.d.	n.d.	99.7	917 (B)
3439-2	1	93.4	6.2	n.d.	n.d.	99.6	938 (B)
3439-2a	2	86.3	13.3	n.d.	0.3	99.9	864 (C)
3439-2b	4	91.7	8.3	n.d.	n.d.	100.0	917 (B)
3439-2c	1	99.5	0.3	n.d.	n.d.	99.8	997 (A)
IV. Mindyak placer zone							
10. Kuru-Elga placer							
BR-1	2	82.2	17.5	bdl	n.d.	99.7	823 (C)
VI. Nepryakhino placer zone							
11. Berezovsky placer (newly formed gold or gold from oxidation zones)							
3063	2	98.8	1.0	0.3	n.d.	100.1	988 (A)
7468	2	99.5	0.3	bdl	n.d.	99.8	996 (A)
12. Bayramgulovo placer (gold with high-fineness rim)*							
8411a	1	82.6	16.9	bdl	n.d.	99.5	829 (C)
8411b	1	93.0	6.5	bdl	n.d.	99.5	933 (B)
8411-1	1	86.7	12.8	0.3	n.d.	99.8	869 (C)
Br-1-5-1	1	94.0	0.2	n.d.	5.8	100.0	940 (B)
13. Shakhmatovo placer							
1496a	2	85.4	14.3	0.2	n.d.	99.9	855 (C)
4496b	2	92.5	7.2	0.2	n.d.	99.9	926 (B)
14. Kurtmak placer (gold with high-fineness rim)							

Table 2 (*continued*)

Grain number	Number of analyses	Au	Ag	Cu	Hg	Total	Fineness (group)
4462	1	79.9	19.8	0.2	n.d.	99.9	800 (C)
4496	1	79.6	20.0	0.3	n.d.	99.9	797 (D)
4339	1	90.2	9.5	bdl	n.d.	99.7	903 (B)
15. Shershni placer							
3443-1	1	90.7	9.2	n.d.	n.d.	99.9	908 (B)
3443-2	2	83.4	16.4	n.d.	n.d.	99.8	835 (C)
3443-3	2	94.9	5.0	n.d.	n.d.	99.9	950 (B)
3443-4	1	84.6	14.8	n.d.	0.4	99.8	848 (C)
3443-4a	1	95.2	4.7	n.d.	n.d.	99.9	953 (B)
VII. Kochkar placer zone							
16. Eleninskaya placer							
12-s-1	2	89.3	10.3	0.3	n.d.	99.9	894 (C)
12-s-2	2	94.3	5.4	0.2	n.d.	99.9	944 (B)
17. Svetlinskaya placer							
1	1	99.2	0.8	0.1	n.d.	100.1	991 (A)
2	1	97.0	0.8	0.2	n.d.	98.0	991 (A)
3	1	98.1	1.0	0.2	n.d.	99.3	988 (A)
4	1	96.5	2.3	0.1	n.d.	98.9	976 (A)
5	1	96.0	2.4	0.1	n.d.	98.5	975 (A)
6	1	94.1	2.8	0.1	n.d.	97.0	970 (A)
7	1	94.9	3.2	0.1	n.d.	98.2	967 (B)
8	1	95.1	3.5	0.0	n.d.	98.6	966 (B)
9	1	94.9	3.5	0.1	n.d.	98.5	963 (B)
10	1	92.9	5.6	0.0	n.d.	98.5	943 (B)
11	1	91.7	6.7	0.1	n.d.	98.5	932 (B)
12	1	91.8	7.3	0.2	n.d.	99.4	924 (B)
13	1	88.5	10.1	0.1	n.d.	98.7	896 (C)
14	1	96.9	0.1	2.1	n.d.	99.1	978 (A)
15	1	98.4	0.1	2.6	n.d.	101.1	973 (A)
18. Kuchinskaya placer (gold with high-fineness rim)							
3442-1	4	89.5	10.4	n.d.	n.d.	99.9	896 (C)
16	1	97.8	0.4	0.1	n.d.	98.3	994 (A)
19. Andreevo-Yul'evskaya placer							
17	1	96.3	bdl	1.4	n.d.	97.7	986 (A)
18	1	97.0	2.0	0.2	n.d.	99.2	978 (A)
20. Uy placer (gold with high-fineness rim)							
7653	1	91.4	8.1	0.2	n.d.	99.7	916 (B)
IX. Gogino placer zone							
21. Kazanskaya placer (gold with high-fineness rim)							
16-1	2	90.0	9.6	0.3	n.d.	99.9	901 (B)
22. Kamyshly-Ayat placer (gold with high-fineness rim)							
141-1	1	90.6	8.6	0.2	n.d.	99.4	911 (B)
X. Amambayka placer zone							
23. Alexandrovskaya III placer (gold with high-fineness rim)							
PME-1	2	95.7	4.3	n.d.	n.d.	100.0	957 (B)
PME-2	3	95.6	4.3	n.d.	n.d.	99.9	957 (B)
PME-3	2	96.0	4.5	n.d.	n.d.	100.5	955 (B)
Tr1-4	3	94.4	5.3	bdl	n.d.	99.7	946 (B)
Tr1-15	3	91.0	8.8	n.d.	n.d.	99.8	912 (B)
XI. Suunduk placer zone							
24. Kolchinskaya placer (newly formed gold or gold from oxidation zones)							
2	2	99.6	bdl	bdl	n.d.	99.6	998 (A)
11	2	98.4	1.1	bdl	n.d.	99.5	987 (A)
25. Nazarovskaya placer (newly formed gold or gold from oxidation zones)							
6	2	99.2	0.3	bdl	n.d.	99.5	995 (A)
10	2	99.7	0.1	bdl	n.d.	99.8	997 (A)

Numbers of placer zones correspond to those from Fig. 1.
*, Gold with microinclusions of ore minerals; n.d., not detected.
The material for study was provided by A.G. Barannikov (placers nos. 8, 9, 10–19, 21, 22), V.V. Murzin (4), A.M. Yuminov and M.E. Romanenko (20), Miass Placer Mining Company (6) and Natural Museum of Ilmeny State Reserve (1–3, 5, 7, 14).
Data on Svetlinskaya, Kuchinskaya (except for 3442-1) and Andreevo-Yul'evskaya placers are taken from (Sazonov et al., 2001) and those of Tashkutarganka River, from (Borodaevsky, 1948).

microscopes by analysts V.A. Kotlyarov and I.A. Blinov. The first one is equipped with a Link ED-System with 1 μm electron beam, 15 nA beam current, 20 kV accelerating voltage, counting time of 120 s and MINM-25-53 standard from ASTIMEX Scientific Limited (mineral mount no. 01–044). The latter one is equipped with an Oxford Instruments X-act ED-system with 3 μm electron beam, 20 nA beam current, 20 kV accelerating voltage for sulfides and 30 kV accelerating voltage for gold and PGMs, counting live time of 120 s, dead time of 10–15% for peaks and the registered standard no. 1362 (Microanalysis Consultants Ltd.). The sensitivity of detectors is ~0.2 wt.% due to the analytical regime and large live time (cf., Lavrent'ev et al., 2015).

About 100 grains of gold from 25 placers were analyzed. Five groups of gold fineness were distinguished on the basis of the composition of gold (‰): 1000–970 (A), 969–900 (B), 899–800 (C), 799–650 (D) and 649–400 (E). The first group mostly corresponds to the high-fineness rims and veinlets of secondary gold. Groups B and C include the high- and medium-fineness gold, respectively. Gold of groups D and E corresponds to the low-fineness gold and electrum, respectively. The microinclusions of PGMs were studied in detail from the Kialim and Maly Iremel placers, which are part of the Miass placer zone. The microinclusions of ore minerals were found in five gold grains from the Nizhny Karabash, Suleymenovo, Bayramgulovo and Polyakovka placers.

4. Results

4.1. Structure and composition of placer gold

The gold grains are typically poorly rounded and angular, sized 1–2 mm and contain the remnants of quartz, calcite and sulfides crystals on the surface. Some grains, as well as their small ledges and appendices, are rumpled or cut off. Most of the gold grains consist of the central domain (primary gold) and continuous or discontinuous rim of secondary high-fineness gold with vague boundaries between primary and secondary gold (Fig. 3a). Very rare, one can find secondary gold, which evidently overgrows the primary low-fineness gold (Fig. 3b, c). Locally, the secondary high-fineness gold forms veinlets in primary gold or is developed along the cleavage fractures of primary gold (Fig. 3d). Most studied placer grains are free of microinclusions of ore minerals (further, "inclusion-free"). Microinclusions of sulfides and hematite were found only in five gold grains (see below). In the Kyshtym, Miass and Mindyak placer zones within the MUF zone, the fineness of primary gold varies from 538 to 997‰ with mean and median values of 874 and 903‰, respectively (Table 2, Fig. 4). The Ag content of gold from these placer zones significantly varies from 0.34 to 28.79 wt.%, with mean and median values of 10.89 and 9.07 wt.%, respectively (Table 2).

Locally, gold contain Cu (up to 2.41 and 2.04 wt.% in the Nizhny Karabash and the Kialim placers, respectively) (Table 2). Cupriferous gold (Cu contents vary in a range from 6.67 to 18.73 wt.%) was found in the Maly Iremel and Nizhny Karabash placers. In the Maly Iremel placer, grains of cupriferous gold are cemented by secondary gold. Some gold grains from this placer are intergrown with ruthenium and contain the lower Cu contents (3–4 wt.%). In the Nizhny Karabash placer, cupriferous gold (3–20 wt.% Cu, 1–10 wt.% Ag) forms the rims 20–60 μm thick around the tetra-auricupride and is covered by a discontinuous rim of high-fineness gold (Fig. 3e). Tetra-auricupride (80 wt.% Au, 20 wt.% Cu, 0.3 wt.% Ag) is characterized by exsolution structure; the exsolved phase contains 10 wt.% Ag and 3 wt.% Cu.

Gold from some MUF placers (mostly from the Kyshtym placer and, to a lesser extent, the Nizhny Karabash, Central Miass and Polyakovka placers) contains up to 9.28 wt.% Hg (Table 2). In the MUF placers, the secondary gold forms the rims 10 to 200 μm thick or veinlets in primary gold. The rims are characterized by diffuse and clear boundaries with primary gold (Fig. 3b, c). Secondary gold can also develop along the shear dislocations of primary gold (Fig. 3d). Insignificant amount of grains is composed of gold with fineness of >980‰.

The fineness of gold from the Nepryakhino placer zone, which is located close to the MUF zone from the east (Fig. 1), varies from 797 to 996‰, with mean and median values of 892 and 903‰, respectively, which is similar to that of the MUF placer zones (Table 2, Fig. 4). Gold from the Nepryakhino zone is comparable with the MUF placer zones in terms of Ag contents (0.25–19.97 wt.%; mean 10.55 wt.%; median 9.52 wt.%, Table 2). The Cu contents in gold are scarce and low (0.21–0.29 wt.%); Hg was detected in one analysis only (0.42 wt.%; Table 2).

In the eastern part of the South Urals (Kochkar, Amambayka, Suunduk placer zones), the fineness of gold is generally higher relatively to the above mentioned zones and range from 894 to 998‰, with mean and median values of 956 and 966‰, respectively (Table 2, Fig. 4). The contents of Ag are lower and vary from 0.08 to 10.31 wt.%, with mean and median values of 4.05 and 3.46 wt.%, respectively (Table 2, Fig. 4). The Cu contents are generally low, locally reaching 2.59 wt.% (Table 2). No mercury was detected in gold from these placer zones (Table 2).

4.2. Microinclusions of ore minerals in placer gold

Data on microinclusions of ore minerals, which were identified in gold from the Nizhny Karabash, Suleymenovo, Bayramgulovo and Polyakovka placers, are summarized in Table 3.

Numerous inclusions of *copper sulfides* form "swarms" of 10–20 particles in the gold grain from the Nizhny Karabash placer. In most cases, they occurs as grains 10–30 μm in size and aggregates of elongated crystals 5 μm thick and 50 μm long (Fig. 5a) and contains 0.5–0.7 wt.% Ag and 4.56 wt.% Fe (Table 3). By Cu/S ratio (Table 3), most compositions of copper sulfides correspond to geerite ($Cu_{1.60}S_{1.00}$) (cf., Goble, 1985). A mineral similar in composition to balkanite ($Cu_9Ag_5HgS_8$) (Atanassov and Kirov, 1973) was found as round grains 25–30 μm in diameter in geerite making an open-latticework structure in it (Fig. 5b). In comparison with balkanite from Sedmochislentsi Mine (Bulgaria), that from the Nizhny Karabash placer has similar Ag (32.55 wt.%), Cu (38.64 wt.%) and S (18.50 wt.%) contents, is depleted in Hg (9.37 wt.%) and contains Fe (0.64 wt.%; Table 3). The host gold contains high amount of Ag (avg 23.8 wt.%).

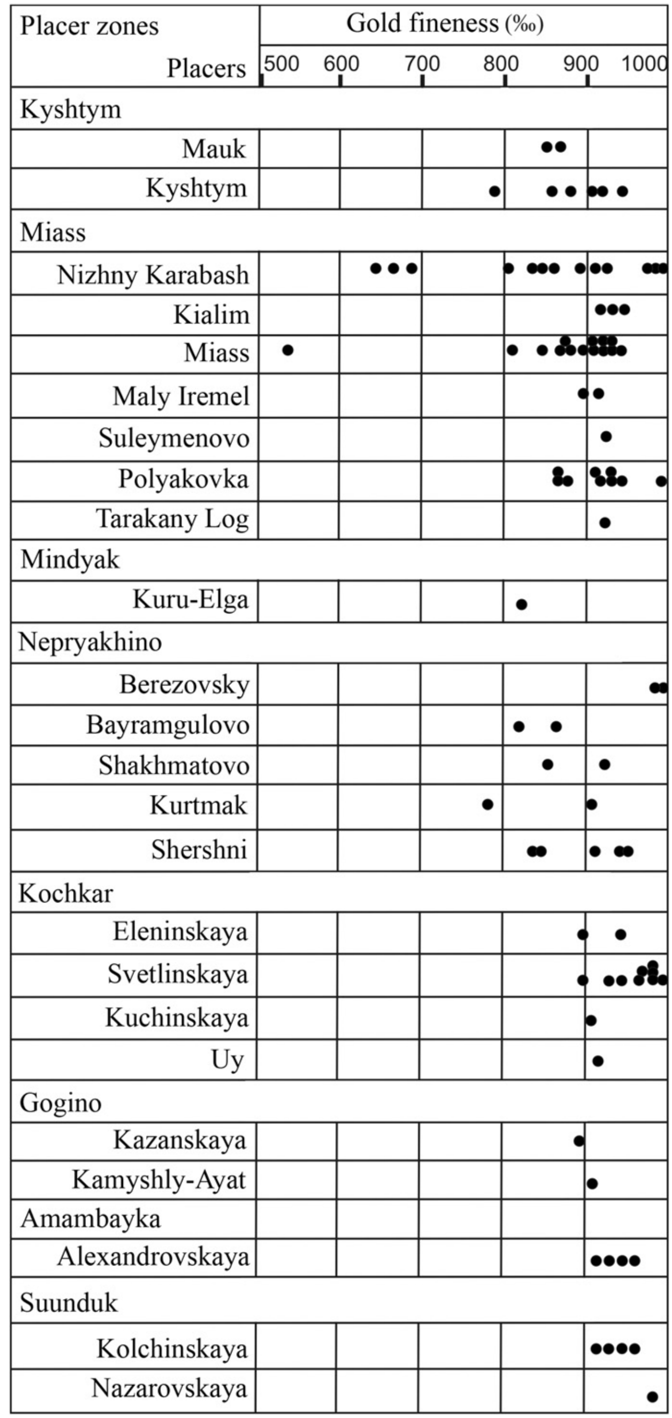

Fig. 4. Fineness of gold from placers of the South Urals.

Table 3
Microinclusions of ore minerals in gold grains from the Miass placer zone.

Placer	Grain number	Host gold	Mineral	Ag	Cu	Fe	Hg	Pb	Se	As	Zn	S	Total	Formula
Nizhny Karabash	3446	$Au_{0.57}Ag_{0.42}Cu_{0.01}$	Geerite (n 18)	0.9	71.1	4.6	n.d.	n.d.	n.d.	n.d.	n.d.	23.2	99.8	$(Cu_{1.55}Fe_{0.11}Ag_{0.01})_{1.67}S_{1.00}$
			Balkanite? (n 3)	32.6	38.6	0.6	9.4	n.d.	n.d.	n.d.	n.d.	18.5	99.7	$Cu_{8.41}Ag_{4.14}Hg_{0.69}Fe_{0.14}S_{8.00}$
Suleymenovo	B3-1	$Au_{0.85}Ag_{0.14}Cu_{0.01}$	Galena	n.d.	n.d.	n.d.	n.d.	84.4	1.3	n.d.	n.d.	13.9	99.6	$Pb_{0.91}(S_{0.96}Se_{0.04})_{1.00}$
Bayramgulovo	Br1-5-1	$Au_{0.94}Hg_{0.06}$	Galena (n 1)	n.d.	n.d.	n.d.	n.d.	85.5	1.1	n.d.	n.d.	13.3	99.9	$Pb_{0.96}(S_{0.97}Se_{0.03})_{1.00}$
Polyakovka	3439-1	$Au_{0.83}Ag_{0.17}$	Arsenopyrite* (n 4)	n.d.	n.d.	32.6	n.d.	n.d.	n.d.	n.d.	47.1	19.0	98.7	$Fe_{0.99}(As_{1.06}Sb_{0.01})_{1.07}S_{1.00}$
	3439	$Au_{0.91}Ag_{0.09}Hg_{0.01}$	Galena (n 3)	n.d.	n.d.	n.d.	n.d.	85.5	1.3	n.d.	n.d.	12.9	99.7	$Pb_{0.99}(S_{0.96}Se_{0.04})_{1.00}$
			Arsenopyrite (n 4)	n.d.	n.d.	33.1	n.d.	n.d.	n.d.	48.8	n.d.	18.1	100.0	$Fe_{1.05}As_{1.15}S_{1.00}$
			Chalcopyrite (n 3)	n.d.	34.1	30.1	n.d.	n.d.	n.d.	n.d.	n.d.	35.8	100.0	$Cu_{0.96}Fe_{0.97}S_{2.00}$
			Sphalerite (n 1)	n.d.	n.d.	5.9	n.d.	n.d.	n.d.	n.d.	60.5	33.6	100.0	$(Zn_{0.88}Fe_{0.10})_{0.98}S_{1.00}$
			Pyrite (n 1)	n.d.	n.d.	46.0	n.d.	n.d.	n.d.	n.d.	n.d.	54.0	100.0	$Fe_{0.98}S_{2.00}$
			Pyrrhotite (n 1)	n.d.	n.d.	60.4	n.d.	n.d.	n.d.	n.d.	n.d.	39.6	100.0	$Fe_{0.88}S_{1.00}$

n, number of analyses; n.d., not detected; *, mineral contains 0.78 wt.% Sb.
The formulas of minerals are recalculated to: one (chalcocite, galena, arsenopyrite, sphalerite, pyrrhotite), two (chalcopyrite, pyrite) and eight (balkanite) sulfur atoms.

Chalcopyrite grains (2×3 μm in size) of stoichiometric composition were detected in the gold grains from the Polyakovka placer (Table 3). The Se-bearing *galena* was found in gold from three placers. In the Bayramgulovo placer, a fractured tabular galena grain (1.14 wt.% Se) was included in the porous gold grain (Fig. 6a; Table 3). The gold grain (200×300 μm in size) from the Polyakovka placer contains an oval microinclusion of galena (1.3 wt.% Se, Table 3) with zigzag boundaries, which possibly indicate the compromise growth surfaces of galena and gold. In the Suleymenovo placer, similar microinclusion of galena with 1.30 wt.% Se (Table 3) is located at the boundary between primary and secondary gold.

The gold from the Polyakovka placer hosts numerous micrometer-size round grains of Sb-bearing *arsenopyrite* and microinclusions of *Fe-bearing sphalerite*, *pyrite* and *pyrrhotite*, which are associated with triangle rutile grains (Table 3).

A *hematite* aggregate was found in gold from the Nizhny Karabash placer (Fig. 6b). Hematite contains 0.30 wt.% VO and 0.80 wt.% MgO.

The primary gold with inclusions of various sulfides from the Suleymenovo, Bayramgulovo and Polyakovka placers contains the lower amount of Ag: from 0.23 (Bayramgulovo) to 7.70 (Suleymenovo) and 13.33 (Polyakovka) wt.% (Table 2).

4.3. PGMs in the Miass placer zone

Various PGMs comprise the first percents of total volume of gold and include Pt- and Os–Ir–Ru-rich phases. They were found in several placers of the Miass placer zone and include ruthenium, osmium, iridium, isoferroplatinum, ferroan platinum and sulfides, arsenides, sulfarsenides and antimonides of platinum group elements (PGEs; Table 4). The minerals from the Kialim and Maly Iremel placers were collected from the heavy concentrates and were studied in more details. In most cases, PGMs represent the 1–2-mm platy grains with cleavage and various degrees of roundness or isometric crystals and their intergrowths. On the basis of contents of major elements, the minerals of the Os–Ir–Ru system are subdivided into three groups: ruthenium, osmium and iridium (cf., Harris and Cabri, 1991).

4.3.1. Kialim placer

The mineral composition of 24 grains from a heavy concentrate sample is dominated by ruthenium grains (59%) at subordinate amount of osmium (25%), iridium (8%) and PGM intergrowths (8%) (Fig. 7a). Composition of PGMs without visible microinclusions of sulfides and arsenides forms a Ru trend on the triangle plot (Fig. 8a, b), whereas the PGM grains with inclusions are depleted in Ir and form an Os–Ru trend (Fig. 8c, d).

The first (most abundant) group, which spans an elongated area on the Ru part of the plot, represents the Ir–Os-bearing ruthenium grains up to 2 mm in size. They contain crystalline microinclusions of ferroan platinum and isoferroplatinum together with laurite. The Rh–Pt–It–Os-bearing ruthenium grains contain microinclusions of isoferroplatinum, which shows significant contents of Rh, Ni and Cu (Table 4). Some grains host Os–Ir- and As-bearing laurite (Table 4), which mostly occurs as platy aggregates up to 30 μm in size along the cleavage and, rarely, as crystals partly replaced by cupriferous gold (wt.%: Au 93–95; Ag 2–6; Cu 2–4) and a mineral similar in composition to tolovkite (Fig. 9a). The latter contains notable amount of Rh (2.31–3.17 wt.%) and Pt (2.49–3.00 wt.%) and minor amount of Ru (0.86 wt.%) and Cu (0.12 wt.%) (Table 4). Despite good analytical total, the mineral exhibits poor stoichiometry with deficit in metals and antimony and significant excess of sulfur. The grain K2-S-1 contains microinclusions of ferroan platinum, Os- and As-free Ir–Rh-bearing laurite (Table 4), which is partly replaced by gold and heazlewoodite. One microinclusion of gold contains an inclusion of Rh- and Ir-bearing sulfoantimonide (Fig. 9b; Table 4). Similarly to tolovkite, this mineral has poor stoichiometry with deficit of metals and antimony and excess of sulfur. By predominance of Rh over Ir, its composition resembles an unnamed RhSbS phase, which was described

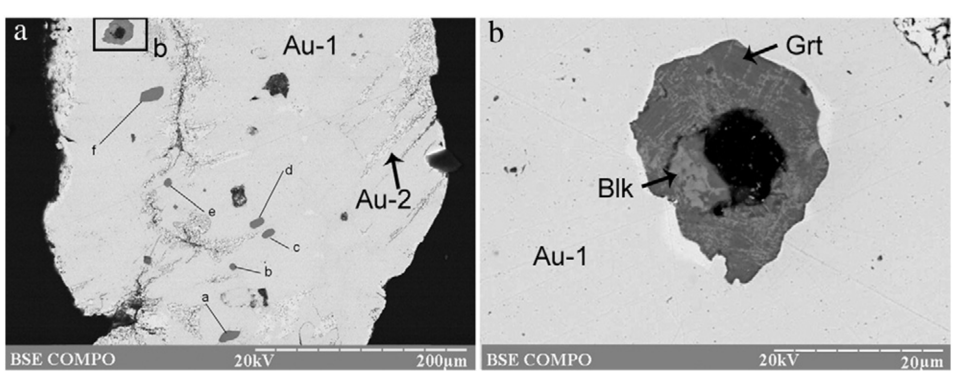

Fig. 5. Microinclusions of copper sulfides in placer gold: a) subhedral grains of geerite (points a–f), b) detail of fig. a: anhedral aggregates and open-latticework structure of balkanite (Blk) in geerite (Grt), grain 3446, Nizhny Karabash placer. SEM images.

Table 4
Average composition of PGMs from the Kialim and Maly Iremel placers.

Grain	Mineral	Composition, wt.%													Mineral or idealized formula	Formula
		Os	Ir	Ru	Rh	Pt	Pd	Cu	Fe	Ni	Sb	As	S	Total		
Kialim placer																
K2-A	H (n 3)	34.9	28.7	31.0	2.4	2.4	n.d.	bdl	0.4	bdl	n.d.	n.d.	n.d.	99.8	Ruthenium	$(Ru_{0.46}Os_{0.27}Ir_{0.22}Rh_{0.03}Pt_{0.02})_{1.00}$
	I (n 5)	n.d.	n.d.	n.d.	3.7	85.7	n.d.	1.4	7.7	1.1	n.d.	n.d.	n.d.	99.9	Isoferroplatinum	$(Pt_{2.66}Rh_{0.24})_{2.90}(Fe_{0.85}Ni_{0.12}Cu_{0.12})_{1.09}$
K2-1	H (n 4)	24.0	20.9	43.8	4.5	6.6	n.d.	bdl	bdl	bdl	n.d.	n.d.	n.d.	99.7	Ruthenium	$(Ru_{0.58}Os_{0.17}Ir_{0.15}Rh_{0.06}Pt_{0.04})_{1.00}$
	I (n 4)	n.d.	n.d.	n.d.	6.2	83.5	n.d.	0.5	8.0	1.7	n.d.	n.d.	n.d.	99.9	Isoferroplatinum	$(Pt_{2.57}Rh_{0.36})_{2.93}(Fe_{0.84}Ni_{0.20}Cu_{0.06})_{1.10}$
K2-6 ^{Au}	H (n 6)	32.1	30.3	32.0	1.5	4.0	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	99.9	Ruthenium	$(Ru_{0.47}Os_{0.25}Ir_{0.23}Rh_{0.02}Pt_{0.03})_{1.00}$
	I (n 1)	16.8	15.4	36.4	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.9	30.3	99.8	Laurite	$(Ru_{0.75}Os_{0.18}Ir_{0.17})_{1.10}(S_{1.97}As_{0.03})_{2.00}$
	I (n 3)	n.d.	46.8	0.4	2.3	3.0	n.d.	n.d.	n.d.	n.d.	33.9	n.d.	13.3	99.7	Tolovkite?	$(Ir_{0.59}Rh_{0.05}Pt_{0.04}Ru_{0.01})_{0.69}Sb_{0.67}S_{1.00}$
K2-S-1 $^{Au, Ni_3S_2}$	H (n 4)	30.9	24.3	41.0	2.3	1.3	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	99.8	Ruthenium	$(Ru_{0.56}Os_{0.23}Ir_{0.17}Rh_{0.03}Pt_{0.01})_{1.00}$
	I (n 2)	n.d.	n.d.	n.d.	7.6	72.8	n.d.	3.4	10.1	6.2	n.d.	n.d.	n.d.	100.1	Ferroan platinum	$(Pt_{0.47}Fe_{0.24}Ni_{0.13}Rh_{0.09}Cu_{0.07})_{1.00}$
	I (n 6)	n.d.	13.0	48.2	1.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	36.5	99.6	Laurite	$(Ru_{0.84}Ir_{0.12}Rh_{0.03})_{0.99}S_{2.00}$
	I (n 1)	n.d.	21.0	n.d.	20.8	n.d.	n.d.	n.d.	n.d.	n.d.	40.7	n.d.	13.2	99.9[1]	RhSbS	$(Rh_{0.49}Ir_{0.27}Au_{0.05})_{0.81}Sb_{0.80}S_{1.00}$
K2-S-2	H (n 5)	48.7	41.8	8.5	0.5	n.d.	n.d.	n.d.	0.4	bdl	n.d.	n.d.	n.d.	99.5	Osmium	$(Os_{0.45}Ir_{0.38}Ru_{0.15}Rh_{0.01}Fe_{0.01})_{1.00}$
	I (n 3)	29.1	29.7	4.8	n.d.	n.d.	n.d.	n.d.	0.2	0.5	n.d.	10.0	25.8	100.1	Erlichmanite	$(Os_{0.32}Ir_{0.32}Ru_{0.11}Ni_{0.02})_{0.77}(S_{1.72}As_{0.28})_{2.00}$
K2-4-2-1	H (n 3)	55.0	39.5	5.0	n.d.	n.d.	n.d.	n.d.	0.3	bdl	n.d.	n.d.	n.d.	99.7	Osmium	$(Os_{0.53}Ir_{0.37}Ru_{0.09}Fe_{0.01})_{1.00}$
	I (n 3)	n.d.	12.4	48.8	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	38.6	99.8	Laurite	$(Ru_{0.80}Ir_{0.11})_{0.91}S_{2.00}$
K2-3-2	H (n 4)	26.3	60.5	5.2	1.3	5.6	n.d.	n.d.	0.8	0.3	n.d.	n.d.	n.d.	100.0	Iridium	$(Ir_{0.55}Os_{0.25}Ru_{0.09}Pt_{0.05}Fe_{0.03}Rh_{0.02}Ni_{0.01})_{1.00}$
	I (n 1)	26.1	41.7	16.5	n.d.	n.d.	n.d.	n.d.	1.2	0.5	n.d.	bdl	14.0	100.0	UM1974-12-S:IrNiRh	$(Ir_{0.50}Ru_{0.36}Os_{0.32}Fe_{0.05}Ni_{0.02})_{1.25}S_{1.00}$
	I (n 1)	29.3	41.3	13.1	n.d.	n.d.	n.d.	n.d.	1.4	0.6	n.d.	2.4	11.8	99.9		$(Ir_{0.55}Os_{0.38}Ru_{0.33}Fe_{0.08}Ni_{0.02})_{1.36}(S_{0.92}As_{0.08})_{1.00}$
	I (n 2)	30.5	49.0	5.9	n.d.	n.d.	n.d.	n.d.	1.4	0.6	n.d.	5.3	7.2	99.9	Ir-Os Sulfide	$(Ir_{1.74}Os_{1.09}Ru_{0.65}Fe_{0.18}Ni_{0.07})_{3.47}(S_{1.52}As_{0.48})_{2.00}$
Maly Iremel placer, inclusions																
Ir1-5-4	H (n 1)	n.d.	n.d.	n.d	4.6	85.1	n.d.	n.d.	8.9	0.8	n.d.	n.d.	n.d.	99.3	Isoferroplatinum	$(Pt_{2.71}Rh_{0.25})_{2.96}(Fe_{0.98}Ni_{0.06})_{1.04}$
	I (n 1)	n.d.	n.d.	48.8	6.9	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	4.5	39.9	100.1	Laurite	$(Ru_{0.74}Rh_{0.10})_{0.84}(S_{1.91}As_{0.09})_{2.00}$
	I (n13)	n.d.	n.d.	n.d.	54.4	6.2	12.3	n.d.	0.7	0.4	1.5	24.3	n.d.	99.8	Rhodarsenite	$(Rh_{1.57}Pd_{0.34}Pt_{0.09}Fe_{0.04}Ni_{0.02})_{2.06}(As_{0.96}Sb_{0.04})_{1.00}$
Ir49-srB-1	H (n 5)	n.d.	n.d.	n.d.	1.7	91.3	n.d.	n.d.	6.8	0.2	n.d.	n.d.	n.d.	100.0	Ferroan platinum	$(Pt_{0.77}Fe_{0.20}Rh_{0.03})_{1.00}$
	I (n 2)	n.d.	n.d.	1.0	64.8	n.d.	8.7	0.7	1.0	2.1	n.d.	n.d.	23.2	101.5	Miassite?	$(Rh_{13.06}Pd_{1.41}Cu_{0.23}Fe_{0.36}Ni_{0.75})_{16.01}S_{15.00}$

	I (n 1)	n.d.	n.d.	3.0	61.4	n.d.	2.1	n.d	bdl	0.3	n.d.	n.d.	32.5	100.3[2]	Bowieite	$(Rh_{1.70}Ru_{0.27}Fe_{0.02})_{1.99}S_{3.00}$
	I (n 4)	n.d.	n.d.	n.d	45.5	n.d.	n.d.	17.7	0.4	0.4	n.d.	n.d.	36.0	100.0	Cuprorhodsite	$(Cu_{0.99}Fe_{0.03}Ni_{0.02})_{1.04}Rh_{1.57}S_{4.00}$
	I (n 4)	n.d.	n.d.	n.d	n.d	76.8	n.d.	n.d.	n.d.	n.d	n.d.	n.d	22.6	99.4	PtS_2	$Pt_{1.11}S_{2.00}$
	I (n 1)	n.d.	n.d.	n.d	10.2	n.d	59.0	n.d	2.0	n.d	25.8	n.d	n.d	97.0	Pd_3Sb	$(Pd_{2.41}Rh_{0.43}Fe_{0.17})_{3.01}(Sb_{0.91}Te_{0.09})_{1.00}$
Ir3-srA-3	H (n 1)	29.0	25.6	32.3	4.3	8.1	n.d.	n.d.	0.7	n.d.	n.d.	n.d.	n.d.	100.0	Ruthenium	$(Ru_{0.45}Os_{0.22}Ir_{0.19}Rh_{0.06}Pt_{0.06}Fe_{0.02})_{1.00}$
	I (n 3)	n.d.	n.d.	n.d.	2.4	88.4	n.d.	n.d.	8.4	0.5	n.d.	n.d.	n.d.	99.7	Isoferroplatinum	$(Pt_{2.86}Rh_{0.13})_{2.99}(Fe_{0.95}Ni_{0.06})_{1.01}$
Ir3-srA-7	H (n 1)	37.0	32.7	25.8	1.5	1.9	n.d.	n.d.	0.4	n.d.	n.d.	n.d.	n.d.	99.4	Ruthenium	$(Ru_{0.39}Os_{0.30}Ir_{0.26}Rh_{0.02}Pt_{0.02}Fe_{0.01})_{1.00}$
	I (n 6)	n.d.	n.d.	n.d.	1.6	88.5	n.d.	n.d.	8.7	0.7	n.d.	n.d.	n.d.	99.5	Isoferroplatinum	$(Pt_{2.86}Rh_{0.06})_{2.92}(Fe_{1.01}Ni_{0.06})_{1.07}$
Ir2-3-5	H (n 3)	27.3	33.1	34.0	3.5	1.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	99.6	Ruthenium	$(Ru_{0.48}Ir_{0.25}Os_{0.21}Rh_{0.05}Pt_{0.01})_{1.00}$
	I (n 4)	n.d.	n.d.	59.0	2.7	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	37.7	99.4	Laurite	$(Ru_{0.99}Rh_{0.04})_{1.03}S_{2.00}$
Ir2-3-7	H (n 3)	32.6	24.8	39.5	2.2	0.5	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	99.7	Ruthenium	$(Ru_{0.55}Os_{0.24}Ir_{0.18}Rh_{0.03})_{1.00}$
	I (n 3)	n.d.	n.d.	47.7	4.7	n.d.	n.d.	n.d.	n.d.	2.9	n.d.	43.8	n.d.	99.1	Ruthenarsenite	$(Ru_{0.81}Ni_{0.08}Rh_{0.08})_{0.97}As_{1.00}$
		n.d.	48.7	5.2	0.7	5.4	n.d.	n.d.	n.d.	n.d.	n.d.	22.5	17.2	99.7	Irarsite	$(Ir_{0.61}Ru_{0.12}Pt_{0.07}Rh_{0.02})_{0.81}As_{0.72}S_{1.28}$
Ir49-srБ-5	H (n 3)	44.6	39.5	13.6	1.2	0.3	n.d.	n.d.	0.6	bdl	n.d.	n.d.	n.d.	99.8	Osmium	$(Os_{0.39}Ir_{0.34}Ru_{0.23}Rh_{0.02}Fe_{0.02})_{1.00}$
	I (n 1)	n.d.	9.6	n.d.	1.1	77.1	n.d.	n.d.	9.1	2.4	n.d.	n.d.	0.3	99.3	Ferroan platinum	$(Pt_{0.60}Fe_{0.25}Ni_{0.06}Ir_{0.06}Rh_{0.03})_{1.00}$
Ir49-sr3-26	H (1)	38.4	52.3	2.2	0.2	6.8	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	99.9	Iridium	$(Ir_{0.52}Os_{0.38}Pt_{0.07}Ru_{0.04})_{1.00}$
	I (n 3)	n.d.	0.5	bdl	0.8	77.4	n.d.	20.3	bdl	n.d.	n.d.	n.d.	n.d.	99.3	Hongshiite?	$(Pt_{1.10}Rh_{0.03})_{1.13}Cu_{0.88}$
Maly Iremel placer, intergrowths																
Ir49-sr-2	(n 3)	33.8	27.1	30.8	3.2	4.7	n.d.	n.d.	bdl	n.d.	n.d.	n.d.	n.d.	99.5	Ruthenium	$(Ru_{0.45}Os_{0.25}Ir_{0.21}Rh_{0.05}Pt_{0.03})_{1.00}$
	(n 4)	n.d.	n.d.	bdl	4.5	85.8	n.d.	n.d.	8.6	0.9	n.d.	n.d.	n.d.	99.7	Isoferroplatinum	$(Pt_{2.71}Rh_{0.25})_{2.96}(Fe_{0.92}Ni_{0.12})_{1.04}$
	(n 2)	n.d.	n.d.	0.4	0.2	77.5	n.d.	8.5	6.5	2.2	1.1	n.d.	n.d.	99.8[4]	Tulameenite?	$Pt_{2.00}(Fe_{0.60}Ni_{0.20})_{0.80}(Cu_{0.72}Sn_{0.15}Sb_{0.05})_{0.92}$
Ir2-4-5 [Au]	(n 5)	36.1	25.7	30.4	3.8	3.1	n.d.	n.d.	0.5	n.d.	n.d.	n.d.	n.d.	99.7	Ruthenium	$(Ru_{0.45}Os_{0.28}Ir_{0.19}Rh_{0.05}Pt_{0.02}Fe_{0.01})_{1.00}$
	(n 6)	n.d.	20.5	0.4	12.4	19.4	n.d.	4.0	0.3	bdl	n.d.	n.d.	30.7	100.3[3]	Xingzhongite?	$(Pb_{0.25}Cu_{0.25})_{0.50}(Rh_{0.50}Ir_{0.45}Pt_{0.42})_{1.37}S_{4.00}$
	(n 1)	n.d.	n.d.	n.d.	n.d.	84.34	n.d.	n.d.	n.d.	0.89	n.d.	n.d.	15.41	100.64	Cooperite	$(Pt_{0.90}Ni_{0.03})_{0.93}S_{1.00}$
Ir2-4-2	(n 3)	50.9	39.5	8.2	0.3	n.d	n.d.	n.d	0.2	n.d.	n.d.	n.d.	n.d.	99.0	Osmium	$(Os_{0.48}Ir_{0.36}Ru_{0.14}Fe_{0.01})_{1.00}$
	(n 12)	n.d.	56.4	3.1	bdl	0.7	n.d.	n.d.	n.d.	n.d.	n.d.	22.0	15.9	98.2	Irarsite	$(Ir_{0.73}Ru_{0.08})_{0.81}As_{0.73}S_{1.27}$
	(n 3)	1.0	54.5	1.2	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	41.6	0.8	99.2	Iridarsenite	$(Ir_{0.97}Ru_{0.03}Os_{0.03})_{1.03}(As_{1.93}S_{0.07})_{2.00}$

H, host mineral; I, inclusion; n, number of analyses; n.d., not detected; bdl, below detection limit.

Minerals contain: [Au], inclusions of gold; [Ni_3S_2], inclusions of heazlewoodite; [1], 4.2 wt. % Au; [2], 3.1 wt.% Te; [3], 11.6 wt.% Pb and 1.0 wt.% Cd; [4], 3.4 wt.% Sn.

The formulas of minerals are recalculated to: metal sum of 1 (ruthenium, osmium, iridium, ferroan platinum), metal sum of 4 (isoferroplatinum, tulameenite), and 2 (hongshiite), anion sum of 2 (laurite, erlichmanite, irarsite, iridarsenite, unnamed Ir–Os sulfide), one (tolovkite, RhSbS, unnamed Ir sulfides, cooperite), two (PtS_2), three (bowieite), four (cuprorhodsite, xingzhongite) and 15 (miassite) sulfur atoms, one arsenic (rhoarsenite, ruthenarsenite), and one antimony (Pd_3Sb) atoms.

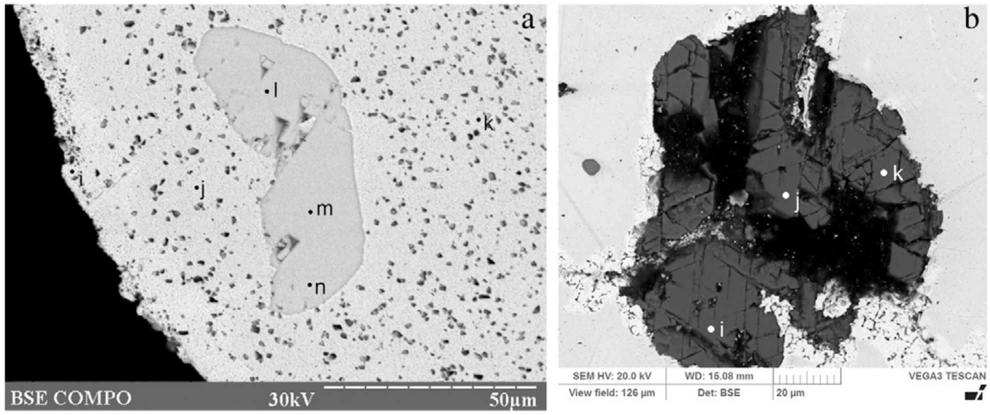

Fig. 6. Microinclusions of some ore minerals in placer gold: a) aggregate of Se-bearing galena (points l, m, n) in porous gold grain Br1-5-1 (point j), Bayramgulovo placer; b) aggregate of hematite crystals (points i, j, k) in fracture of a gold grain, Nizhny Karabash placer. SEM images.

in the Tulameen district of British Columbia (Nixon et al., 1990) and, probably, represents a member of a hypothetical isomorphic series with tolovkite.

The second group includes clasts of homogeneous crystals and rounded Ir–Rh osmium grains 100–300 μm in size, which contains microinclusions of sulfides of Os (erlichmanite, grain K2-S-2) and Ru (laurite, grain K2-4-2-1). The erlichmanite contains high amount of Ir, Ru and As (Table 4). The third group consists of iridium grains, which host a number of microinclusions of heazlewoodite and nonstoichoimetric PGE sulfides, e.g., metal-rich As-free and As-bearing sulfides close by metal/sulfur ratio to unnamed minerals (Ir,Rh,Ni)S and $(Ir,Os)_3S_2$ (UM1974-12-S:IrNiRh and Ir-Os Sulphide II, respectively, www.mindat.org) (Table 4).

Some PGMs occur as intergrowths, e.g., of iridium and osmium. Osmium contains microinclusions of laurite grains. An aggregate of heazlewoodite and Ir-bearing Ni sulfide was observed at the contact between osmium and iridium. In addition to major Ni (19.98 wt.%) and Ir (31.00 wt.%), the mineral also contains (wt.%): 5.81 Ru, 2.87 Rh, 2.20 Cu, 2.93 Fe. By the S content (avg. 35 wt.%) and metal/sulfur ratio, it is close to vaesite $(Ni_{0.62}Ir_{0.29}Ru_{0.11}Fe_{0.09}Cu_{0.06}Rh_{0.06})_{1.23}S_{2.00}$.

4.3.2. Maly Iremel placer

We studied a total of 119 PGM grains from heavy concentrates collected by the Miass Mining Company during the exploitation of the placer in 1998–2004. The mineral composition of the samples is also dominated by ruthenium grains (30%), which are followed by approximately similar amount of Pt-rich minerals (24%) and osmium (22%) at minor content of iridium (6%). The amount of PGM intergrowths is 18% (Fig. 7b). The chemical composition of PGMs is shown in Fig. 8.

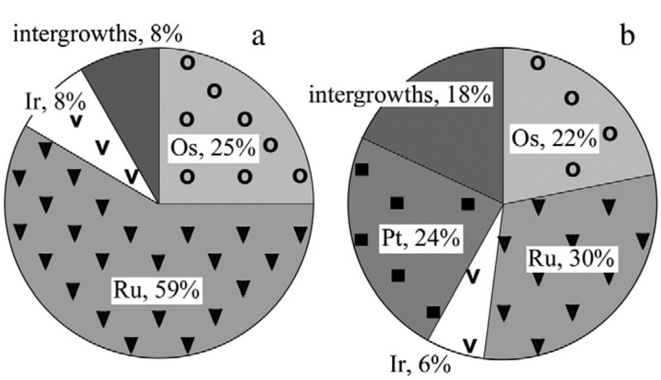

Fig. 7. PGM ratio of the studied samples from Kialim (a) and Maly Iremel (b) placers.

The PGE-depleted isoferroplatinum grains host a chain of elongated Rh- and As-bearing laurite crystals and chaotic isometric and lens-shape microinclusions of Pd- and Sb-bearing rhodarsenite (Table 4). The ferroan platinum grains contain microinclusions of Rh-bearing bowieite, which makes up the disintegrated aggregates of elongated and, crystal-shape grains, filling the fracture in ferroan platinum or intergrowths with laurite (Fig. 10a). The mineral is characterized by the high Cu contents (17.52–23.54 wt.%) and low contents of Fe (0.42–0.58 wt.%), Ni (0.10–0.35 wt.%) and Pd (0.04–0.27 wt.%; Table 4). Laurite contains Os, Rh and Fe (Table 4).

In addition to bowieite, the ferroan platinum grain Ir49-srB-1-1 is a host to a number of various PGM inclusions including a mineral similar in composition to miassite, cuprorhodsite and unnamed Pt sulfide and Pd antimonide. Metal-deficient miassite? forms small (max 5 μm in size) oval to angular inclusions (Fig. 10a) and contains high amount of Pd (7.21–8.73 wt.%) and minor amounts of Fe (0.98 wt.%), Ni (1.90–2.12 wt.%) and Cu (0.58–0.72 wt.%) (Table 4). Cuprorhodsite forms aggregates of elongated and angular grains in a fracture of ferroan platinum (Fig. 10b; Table 4).

Small (5 to 20 μm in size) isometric or elongated angular grains and aggregates of Pt sulfide occur in fractures of the ferroan platinum aggregate (Fig. 10a). The mineral contains only Pt and S in composition, which vary from 74.35 to 78.15 wt.% and from 21.28 to 25.02 wt.%, respectively. The composition of the Pt sulfide can be best recalculated to formula PtS_2, where Pt ranges from 0.97 to 1.21 a.p.f.u. (avg 1.11) (Table 4).

A small (few micrometers in size) subhedral grain of unknown Pd antimonide is intergrown with miassite? (Fig. 10a). Its composition with major Pd and Sb and subordinate Rh, Fe and Te can be recalculated to the formula $(Pd_{2.41}Rh_{0.43}Fe_{0.17})_{3.01}(Sb_{0.91}Te_{0.09})_{1.00}$. By assemblage with Fe-bearing platinum, cation/anion ratio of 3:1 and the presence of Sb and Te, this mineral is similar to vincentite $(PdPt)_3(AsSbTe)$ (Stumpfl and Tarkian, 1974; Tarkian et al., 2002). It is distinct from the classical vincentite by the presence of Rh and the absence of Pt and As and can probably represent an end-member of a hypothetical isomorphic series between As- and Sb-rich Pd sulfosalt.

Two grains of ruthenium from sample Ir-49 host only microinclusions of isoferroplatinum crystals, whereas ruthenium from sample Ir-2-3 contains a number of inclusions of PGE-bearing sulfides and arsenides (Fig. 11; Table 4): the radial aggregates of the oval and platy laurite grains; chaotically distributed microinclusions of oval ruthenarsenite grains and irarsite grains, partly, with crystal shape; microinclusions of Ni-poor heazlewoodite intergrown with a Ni sulfide (48.08 wt.% Ni, 31.93 wt.% S). The latter contains (wt.%) 11.32 Ru, 2.21 Rh and 6.14 Fe and its stoichiometry corresponds well to millerite $(Ni_{0.82}Fe_{0.11}Ru_{0.11}Rh_{0.02})_{1.06}S_{1.00}$.

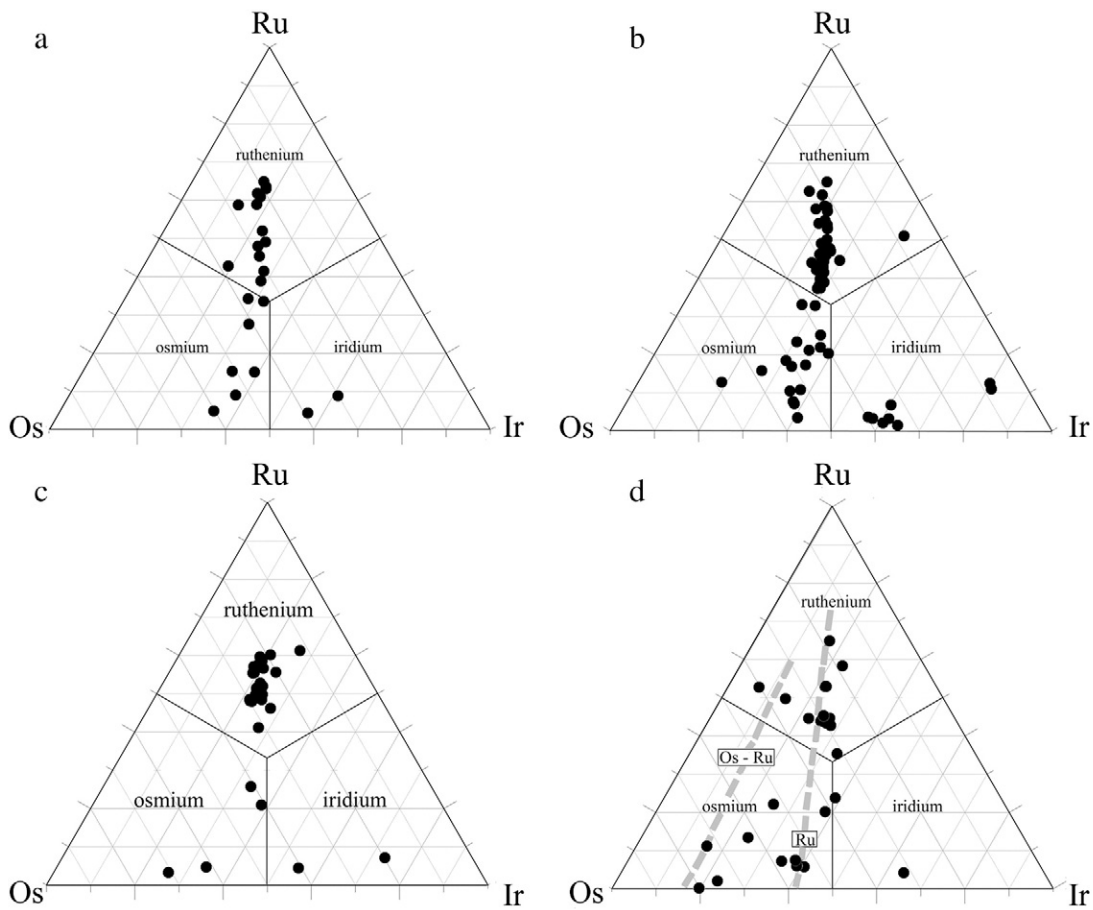

Fig. 8. Atomic ratio of Os, Ir and Ru in PGMs of the Kialim (a) and Maly Iremel placers (b–d): a, b) inclusion-free PGMs; c) PGMs intergrown with isoferroplatinum; d) PGMs intergrown with PGE sulfides and sulfarsenides.

One grain of osmium contains microinclusion of ferroan platinum (Fig. 12a; Table 4), while iridium contains numerous small crystals of mineral similar to composition to hongshiite (Fig. 12b; Table 4).

Three types of PGM intergrowths were revealed in the Maly Iremel samples. Type 1 includes intergrowths of platy grains of ruthenium 5–10 μm thick with isoferroplatinum and a mineral similar in composition to tulameenite (Fig. 13a, b; Table 4). Type 2 represents open-latticework intergrowths of platy crystals of ruthenium 7–15 μm thick with interstitial aggregates made up of gold, isoferroplatinum and mirmekite-like aggregates of PGE sulfides 5–30 μm in size (Fig. 13c, d). By composition, the most PGE sulfides are similar to that of xingzhongite (Fleischer et al., 1976), which is characterized by excess of S, Rh, Pt and Ir and lack of Pb and Cu (Table 4). The elongated grains of cooperite 5 × 20 μm in size are rare. Type 3 represents the intergrowths of osmium with chromite, irarsite and iridarsenite, which are developed along the cleavage of osmium grains (Fig. 14, grain Ir2-4-2).

5. Discussion

5.1. Comparison of composition of gold from placers and lode gold deposits

Figs. 15 and 16 compare the fineness of gold from the placer and lode gold deposits. The most striking modes are typical of gold from orogenic gold–sulfide and porphyry copper (940–980‰) and listvenite-related gold (900–980‰) deposits. In contrast, the gold-bearing VHMS deposits are characterized by highly variable fineness of gold (520–1000‰) and

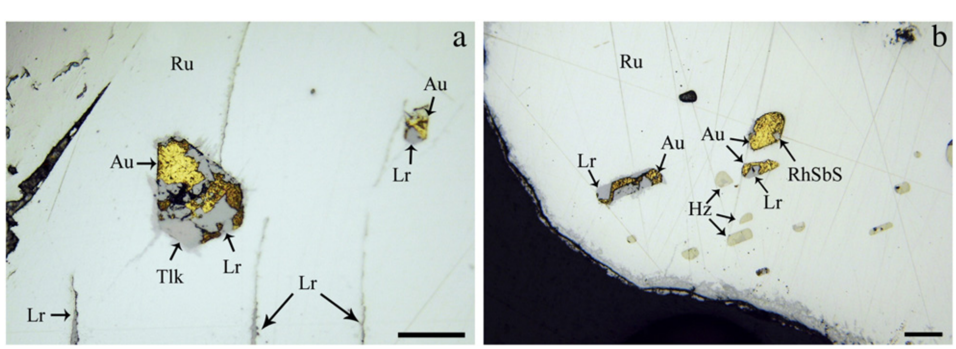

Fig. 9. Ruthenium grains K-5-2 (a) and K2-S-1 (b) with inclusions of heazlewoodite (Hz) and laurite (Lr) crystals replaced by gold (Au), tolovkite? (Tlk) and unnamed sulfoantimonide of Rh (RhSbS) from the Kialim placer. Scale bar is 50 μm. Reflected light.

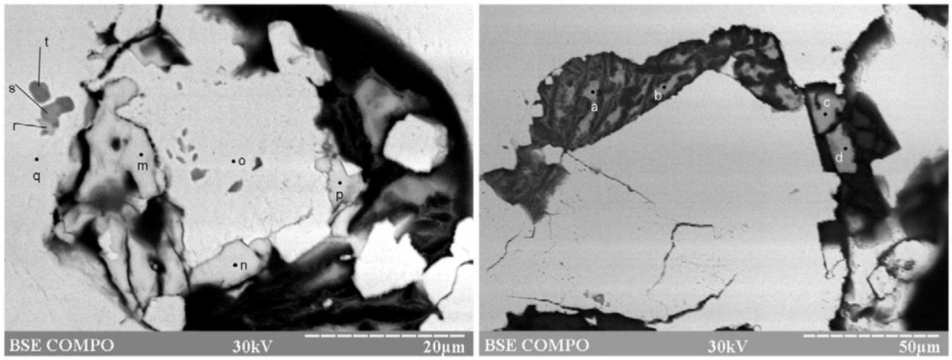

Fig. 10. Microinclusions of bowieite (point t), miassite? (point s), unnamed sulfide of Pt (points m, n, p) and antimonide of Pd (point r) in ferroan platinum (a) and cuprorhodsite (points a–d) in fracture of ferroplatinum (b). SEM images.

vague modes, which correspond to the low-fineness gold (760–840 and 700–760‰). The fineness of gold in the Central Miass and Maly Iremel placers is similar to that of gold from the listvenite-related gold deposits in the area of the Miass placer zone with a mode of 900–960‰ and a total range of 740–1000‰. Gold from the Kazanskaya placer in the Gogino placer zone is similar by composition to that of the Miass zone, although no listvenite-related gold deposits are known in this area. The Svetlinskaya placer in the Kochkar zone contains gold with the highest fineness (920–1000‰), which corresponds to that of gold from porphyry copper deposits.

The Cu content in placer gold is typically in a range of 0.1–2.4 wt.%, except for the Cu-bearing (6–19 wt.% Cu) gold from the Maly Iremel placer, which is similar to cupriferous gold from the rodingite-related Zolotaya Gora gold deposit. Mercury (4–9 wt.%) is present in gold from the Nizhny Karabash and Kyshtym placers. The high Hg content is typical of the oxidation zones of massive sulfide deposits.

Comparison of gold composition from the major South Urals placer zones (Kyshtym, Miass, Nepryakhino, Kochkar) by means of cumulative curves (cf., Chapman et al., 2000) shows the similar Ag contents of gold from the areas confined to the ultramafic-hosted fault zones (Kyshtym, Miass, Nepryakhino). This contrasts with the gold derived from the quartz veins hosted by granitic rocks, such as the Kochkar placer zone (Fig. 17). The steep slope typical of the cumulative curve of the Miass placer zone is related to the presence of the Ag-rich gold from the Nizhny Karabash placer.

The presence of rims of the high-fineness gold (970–1000‰) at the boundaries of gold grains is an important feature of the studied placer gold. Several processes can account for the formation of gold-rich rims on placer gold: dissolution of Ag (as well as Hg and Cu; Knight et al., 1999) during weathering and transport, precipitation of gold from oxidizing Au-bearing streams, self-electrorefining of placer gold probably coupled with dissolution–precipitation (Groen et al., 1990) or bacterial precipitation (Barannikov and Osovetsky, 2013). Most studied secondary rims are characterized by vague boundaries with primary gold and only several grains show overgrowing of primary gold by secondary gold (Fig. 3b, c). Judging from example shown in Fig. 3c, the formation of secondary gold includes, at least, two stages: (i) formation of new grains, which overgrow the primary ones from Au-bearing solutions, and (ii) penetration of secondary gold into the primary one and further replacement of primary low-fineness gold by newly formed high-

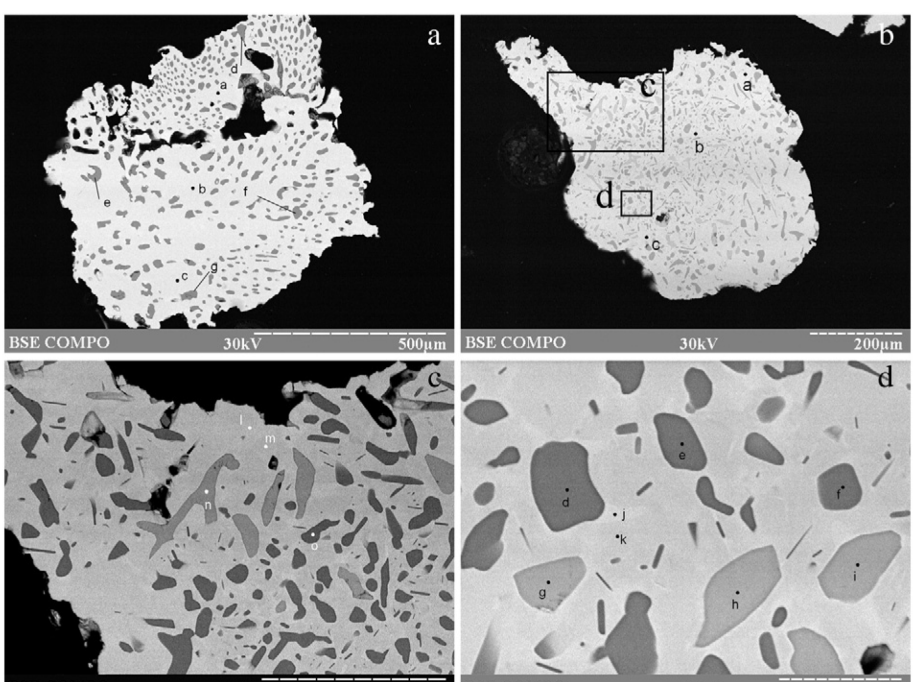

Fig. 11. Ruthenium grains with synchronous microinclusions of sulfarsenides and arsenides: a) grain Ir-2-3-5, ruthenium (points a–c) with laurite (points d, e, f, g); b) grain Ir-2-3-7, ruthenium (points a–c); c, d) details of fig. b: c) ruthenium (points l, m) with osmium (point j), ruthenarsenite (points o, d, e, f) and irarsite (points n, g, h, i). SEM images.

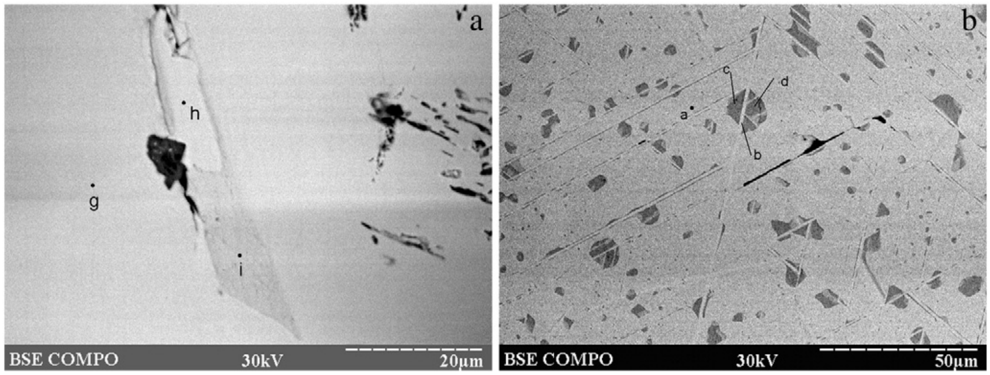

Fig. 12. Inclusions of minerals in osmium and iridium: a) angular inclusion of ferroan platinum (point i) in osmium (points g, h), grain Ir49-srB-5; b) hongshiite? crystals (points c, d, e) in iridium (point a), grain Ir49-sr3-26.

fineness gold. This mechanism is also supported by the minor amount of grains, which are totally composed of gold with fineness of >980‰. The hypogene origin of such high-fineness gold can be advocated by the composition of gold from some primary deposits (Fig. 15). Meanwhile, the high-fineness gold from orogenic gold–sulfide, gold-bearing VHMS, porphyry Au–Cu and listvenite-related gold deposits is limited to only 2–6% of the total amount of gold. Thus, the presence of high-fineness placer gold with very fine relics of primary lower fineness gold most likely indicates their secondary origin (Fig. 3f).

The occurrence of abundant high-fineness gold in placers of the Transuralian plateau (which also hosts the preserved Mesozoic karst placers) indicates the recycling of placers, i.e., redeposition of modern placers from paleoplacers. Meanwhile, poorly rounded high-, intermediate- to low-fineness gold grains from the Miass placer zone within the Uralian Ridge are characterized by remnants of crystals of other minerals and were mostly formed in Neogene–Quaternary period directly from the primary sources.

5.2. Assemblage of placer gold and PGMs

An assemblage of gold and PGMs in placers is traditionally explained by co-existence of erosion products of various primary precious metal deposits: orogenic gold (including listvenite-, skarn- and rodingite-related) deposits and PGM-bearing chromite deposits. In some cases, this results in formation of gold–PGM aggregates morphologically similar to sandstones, which are cemented by secondary gold (Fig. 18a, b). At the same time, our data indicate the possible presence of combined gold–PGM source (e.g., chromite deposits) that is supported by the finding of discontinuous rim of Cu-bearing (3–4 wt.% Cu) gold with fineness of 829–853‰ in Os-bearing ruthenium grain from the Maly Iremel placer (Fig. 18c, d). At the contact with gold, the Os-bearing ruthenium is transformed to Ir-bearing ruthenium, the Os contents of which decrease to 1–7 wt.%. The removal of Os was previously detected in archaeological gold with PGM inclusions (Zaykov et al., 2016). In the Kialim placer, the later gold (in assemblage with tolovkite?

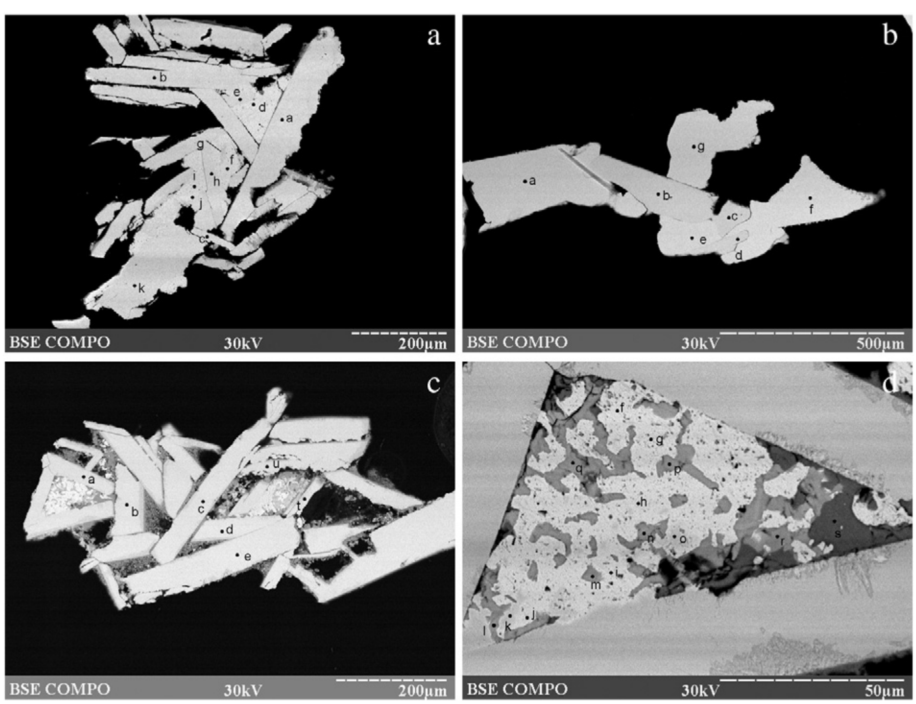

Fig. 13. Intergrowths of PGMs from the Maly Iremel placer: a) platy ruthenium crystals (points a, b, c, e, g, h, k) with interstitial isoferroplatinum (points d, f, i), grain Ir49-sr2-1; b) aggregate of ruthenium (points b, c, d) and isoferroplatinum (points a, e, f, g) crystals, grain Ir49-sr2-16; c) aggregate of platy ruthenium crystals (points a, b, c, d, e, u) with interstitial intergrowths of xingzhongite? (points l, m, n, p, q, r) and gold (points f, h, i, j). SEM images.

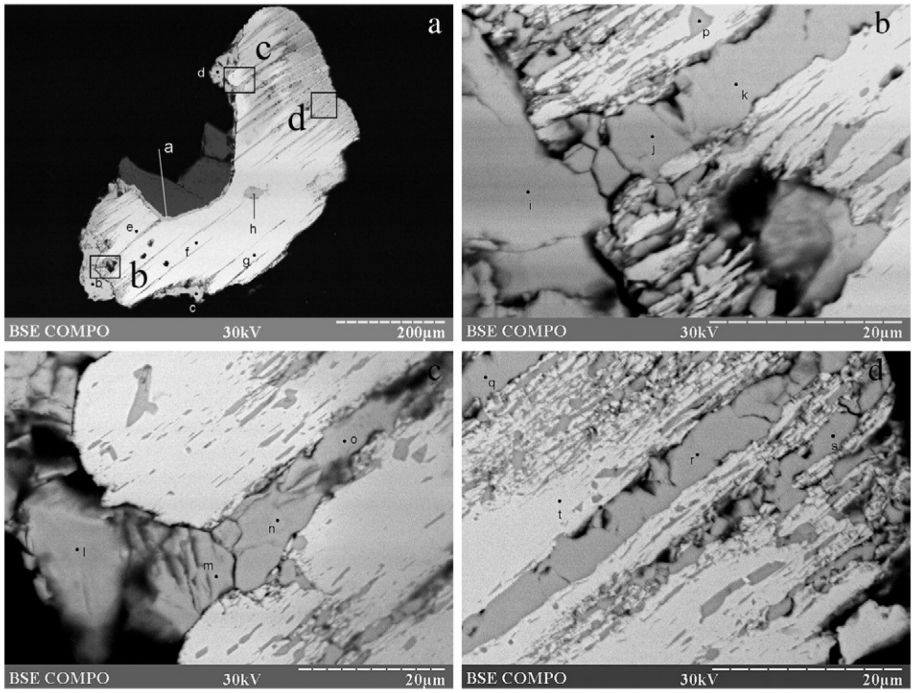

Fig. 14. Osmium grain Ir2-4-2 (points e, f, g), which is developed around the chromite grains (point a) and intergrown with Ir sulfarsenides: irarsite (points a–d, h–k, l–o) and iridarsenide (points q, r, s). SEM images.

and unnamed RhSbS) replaces the laurite grains included in ruthenium (Fig. 9).

5.3. Microtextural and compositional features of placer PGMs

The assemblages and interrelations between placer PGMs of the South Urals reflect the specific trends of mineral formations, which are similar to those established for the primary PGM deposits: iridium and osmium → ruthenium → platinum → laurite + erlichmanite → sulfarsenides + sulfides of base metals (e.g., Bird and Basset, 1980; Garuti et al., 1997; Tolstykh et al., 2000). For instance, the open-latticework aggregates of euhedral to subhedral ruthenium crystals with interstitial isoferroplatinum from the Maly Iremel placer suggest that crystallization of ruthenium was followed by formation of isoferroplatinum (Fig. 13a). These aggregates are similar to those found in placers of Oregon, the United States (Bird and Basset, 1980), Tibet, China (Bai et al., 2000) and Kamchatka, Russia (unpublished data of Sidorov, 2009).

Our studies also provide evidences of possible co-crystallization of minerals of the Os–Ir–Ru system and PGE sulfides and sulfarsenides, such as intimate intergrowths of ruthenium with laurite, irarsite and ruthenarsite from the Maly Iremel placer, which resemble exsolution textures (Fig. 11). Some observations show that the formation of the PGE sulfides postdates crystallization of the Os–Ru–Ir minerals. Locally, laurite is developed along the cleavage of ruthenium grains (Maly Iremel and Kialim placers) (Fig. 9). These aggregates were formed after opening of the cleavage fractures under later stress conditions and are similar to those described in placers of Salair and East Sayany regions, Russia (Tolstykh et al., 1999; Kiseleva et al., 2014). Replacement of the Os–Ru–Ir minerals by the PGE sulfides and sulfarsenides from mineral boundaries is also abundant. In the Maly Iremel placer, ruthenium is metasomatically replaced by laurite and irarsite (Figs. 19, 20a–c), whereas osmium is replaced by erlichmanite and laurite (Fig. 20d–f). In PGMs from placers of the Verkhyaya Neyva massif in the Central Urals, the replacement rims are characterized by well-visible zoning: Os–Ir–Ru sulfarsenides and arsenides combined with osmium – mixture of sulfarsenides and sulfides – sulfides, sulfantimonides and newly formed intermetallides ($OsIr_2$) – laurite + erlichmanite (Murzin et al., 2015). Some ruthenium grains are enveloped by a discontinuous supergene rim of unusual composition, where Os content decreases to 2–10 wt.% and Ir and Ru contents increase to 18–24 and 13–16 wt.%, respectively.

Different compositional trends of the PGMs with and without visible microinclusions of sulfides and arsenides (Fig. 7) are similar to those identified for PGMs in chromitites, which underwent the influence of granitic intrusions. In the South Tibet (Bai et al., 2000), PGMs in chromitites situated near the Gandese batholite occupy the left field of the plot. The Os–Ru trend is characteristic of the PGMs from a placer of the Alabashka River in the Central Urals within the area of the Murzinsky–Aduy granite gneiss complex (Murzin et al., 2015). These data allow us to suggest that the PGM compositional variations are caused by the influence of heat from the intrusion or, in our case, late hydrothermal fluids.

5.4. Sources for placers in structure of the Main Uralian fault

The MUF is a suture zone, which hosts the Alpine-type ultramafic rocks, fragments of oceanic crust and island-arc structure and granitic plutons (Fig. 2; Puchkov, 1997; Ivanov, 1998). Combination of various geological complexes resulted in the presence of gold (lode and placer), chromite, PGM, iron, sulfide and other types of deposits (Koroteev et al., 1997; Ovchinnikov, 1998). Here, we focus on the metal sources for the Miass placer zone, which spans the central segment of the MUF zone (Fig. 2). The Miass zone is rich in precious metals, as well as in microinclusions of ore minerals in gold. These features are related to the presence of various types of placer-forming orogenic gold deposits associated with volcanic and metasedimentary rocks, rodingites, listvenites and skarns (Ovchinnikov, 1998; Sazonov et al., 2001). Each deposit is characterized by specific assemblage of ore minerals, which are present as microinclusions in gold from placers. For most placers, we identified the genuine sources on the basis of gold fineness and relevant microinclusions in gold, assuming the presence of the nearby mineral deposits and the direction of the water streams. The approximate distance between the placers and possible primary sources is shown in Table 5. In most cases, the distance ranges from 2 to 5 km,

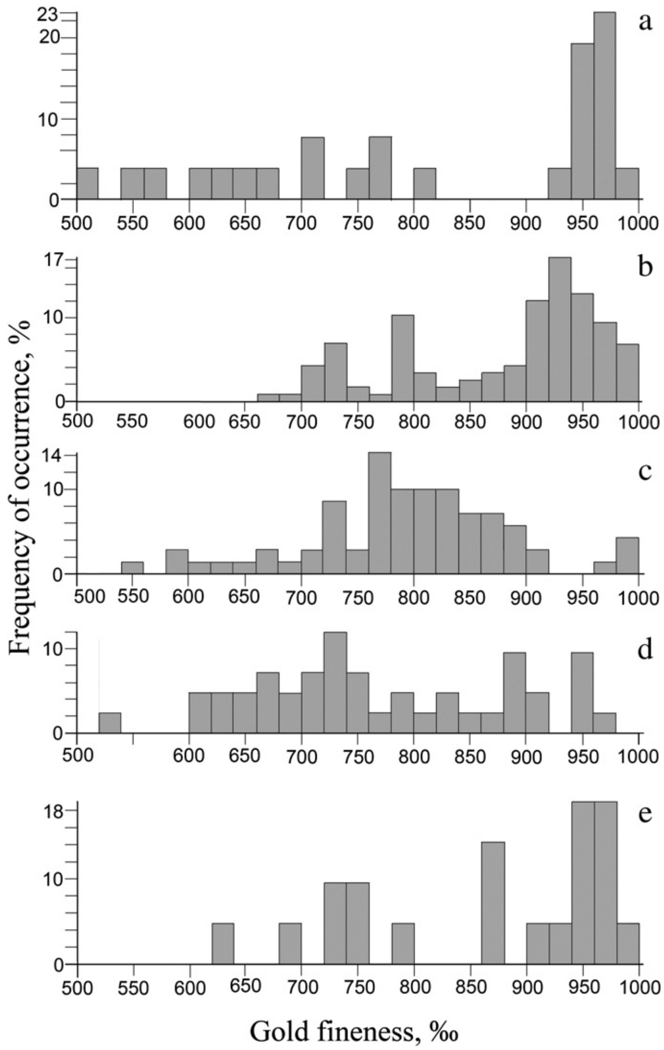

Fig. 15. Histograms of fineness of gold from various deposits: a) orogenic gold–sulfide (n = 26); b) orogenic listvenite-associated (n = 115); c) Au-bearing VHMS (n = 70); d) Au-bearing VHMS of Baymak type (n = 42); e) Au-bearing porphyry copper from East Uralian zone (n = 38).

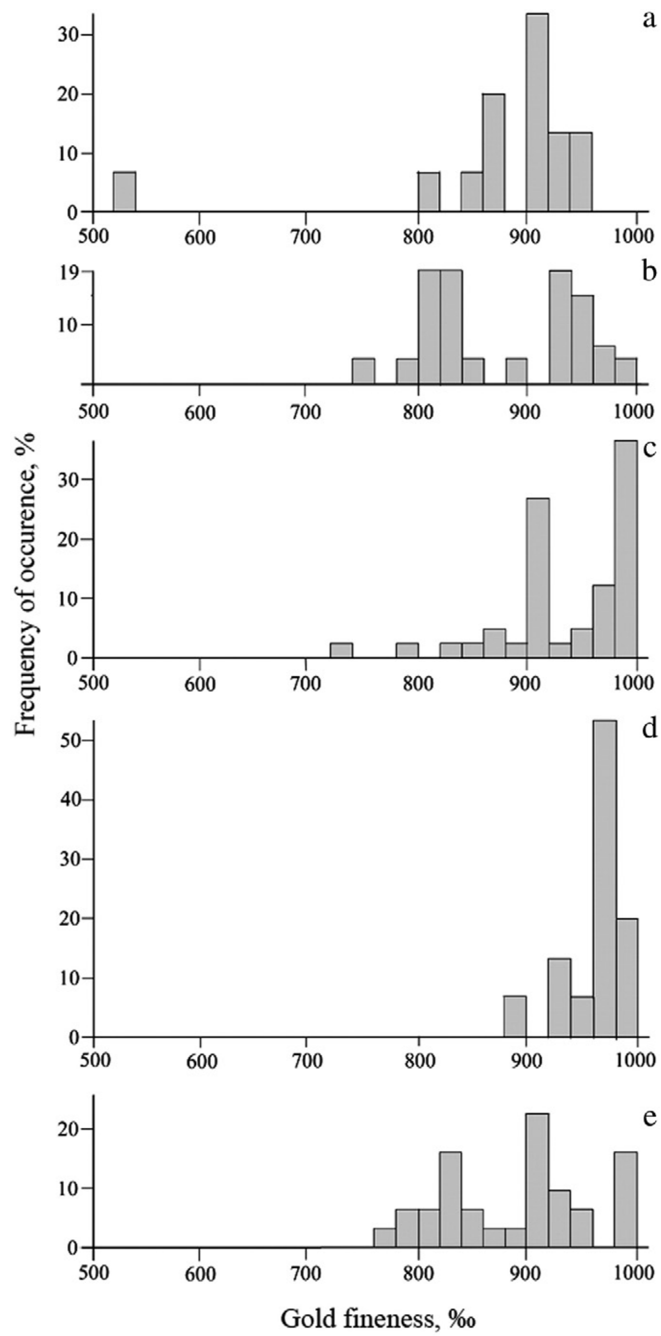

Fig. 16. Variations in fineness of placer gold: a) Central Miass (polygon no. 6 area, n = 15), b) Maly Iremel (n = 47), c) Bayramgulovo (n = 41); d) Svetlinskaya (n = 15); e) Kazanskaya (n = 31).

excluding the Central Miass placer because of its great extension and occurrence of the Melent'evka deposit in the placer bedrock.

5.4.1. Source of Cu-bearing gold and tetra-auricupride

Cupriferous gold in placers was found in a number of localities, e.g., placers of Scotland (Philip Burn) and Czech Republic (Kraskov), which are related to Silurian turbiditic graywackes (Philip Burn) and Permian red beds (Kraskov) (Chapman et al., 2009). Although it was suggested that the composition of Cu-bearing gold appears to be most similar to orogenic gold, it was finally concluded that gold was derived from mineralization hosted by Lower Paleozoic sedimentary rocks (Chapman et al., 2009). In the Northern Ireland, the findings of gold with, at least, 0.8% Cu are permissible within orogenic gold deposits (Moles et al., 2013). In our case, cupriferous gold and tetra-auricupride of the Nizhny Karabash placer were most obviously derived from the near-by Zolotaya Gora orogenic rodingite-hosted gold deposit (Fig. 2). This deposit is hosted by a rare type of rocks: gold-bearing listvenitized rodingites (Spiridonov and Pletnev, 2002). The ore bodies are located in a foliation zone 2 km long and 100–300 m wide in the provenance of the Nizhny Karabash placer. Stringer–disseminated mineralization is confined to the rodingite dikes rimmed by listvenitized serpentinites and chloritolites. The composition of placer gold intergrown with tetra-auricupride and that of primary gold from the deposit is identical (wt.%): Au 86, Ag 13, Cu 1.

5.4.2. Source of sulfide microinclusions

The microinclusions of copper sulfides in gold of the Nizhny Karabash placer could derive from the oxidation zone of the VHMS deposits of the Karabash ore region, which are confined to a zone of foliated volcanosedimentary rocks located 8 km north from the placer (Fig. 2) (cf., Prokin and Buslaev, 1999). The most important Yuzhnoe deposit occurs in the carbonate–albite–chlorite–quartz–sericite metasomatites. The ore bodies of the deposit are fully oxidized to depth of 10–12 m; quartz–barite sands and oxidized ores occur below this depth. They crown the massive sulfide body at depth of 40–50 m, which contains

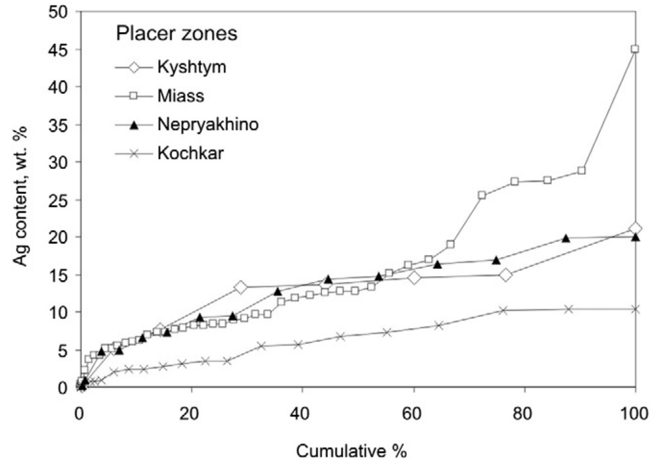

Fig. 17. Relationship between Ag contents in gold from the major gold placer zones of the South Urals.

1–4% Cu, 1–2% Zn, 3–4 g/t Au and 34–47 g/t Ag. The Nizhny Karabash placer with copper sulfide-bearing gold is located at the southern continuation of this massive sulfide zone. Typically, the oxidation zones of many VHMS deposits of the Urals (Sergeev et al., 1994; Belogub, 2004) and other regions (e.g., Rudny Altai; Gas'kov et al., 2001) contain two types of gold (hypogene and supergene). The primary character of gold with microinclusions of copper sulfides in the Nizhny Karabash placer is supported by its composition, in particular, high Ag contents (Table 2). The higher Hg contents (up to 4 wt.%; Table 2) in gold also link this placer with massive sulfide mineralization. Similar higher Hg contents (4–6 wt.%) were detected by the authors in gold from the Talgan VHMS deposit located 150 km south of the Miass placer zone.

The Orlovskoe gold–sulfide deposit in the head of the Suleymenovo placer, which is extended along the Miass River, was the source of galena microinclusions for this placer (Fig. 2). Two zones of foliated volcanic rocks 1–3 km long were exposed at the deposit (Salikhov et al., 2003). The mineralization is confined to the sulfidized basalts with quartz–carbonate veins. The gold-bearing ore body is 5–10 m thick and 200 m long. Gold is associated with pyrite, arsenopyrite, chalcopyrite and galena.

The Bol'shoi and Maly Karan deposits, which are located in the basin of the Uy River (Fig. 1), were most likely sources of sulfides for the Polyakovka placer too (Fig. 2). The Bol'shoi Karan gold–arsenopyrite–

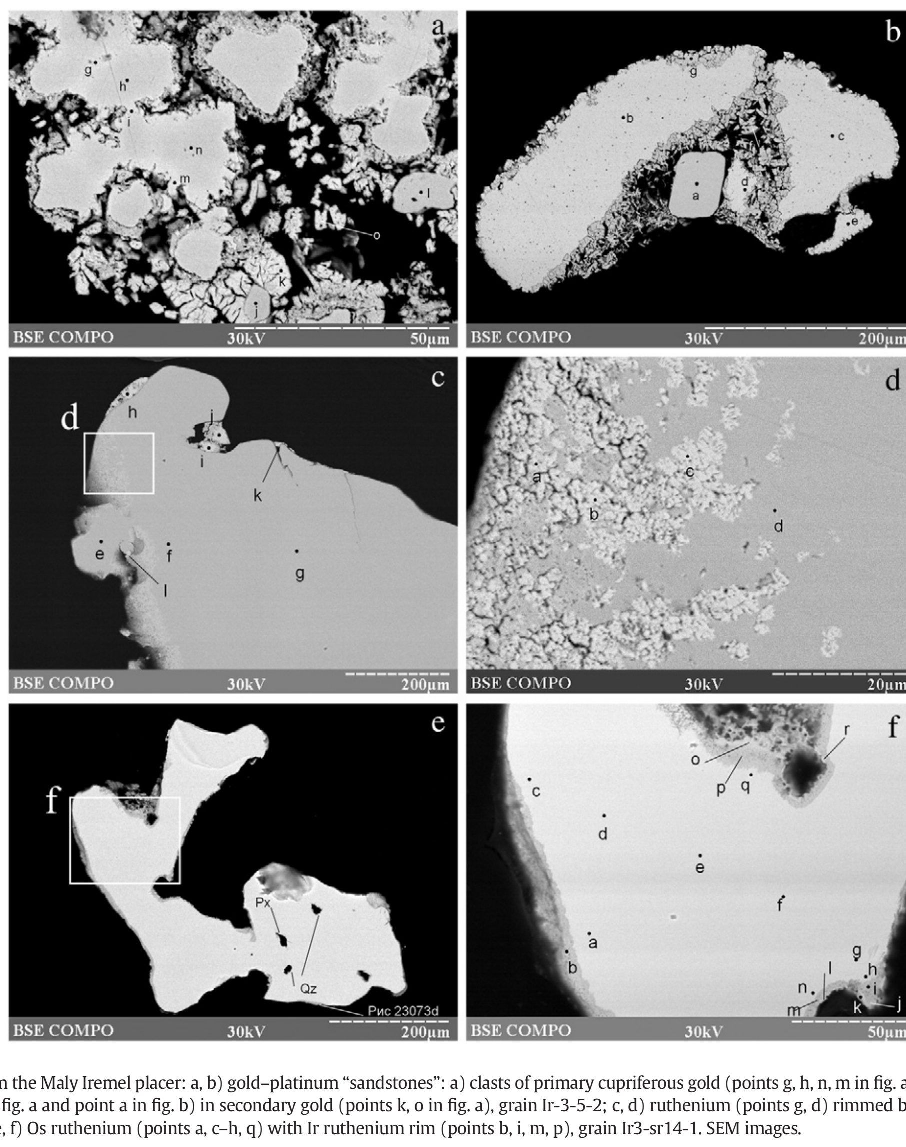

Fig. 18. PGM intergrowths from the Maly Iremel placer: a, b) gold–platinum "sandstones": a) clasts of primary cupriferous gold (points g, h, n, m in fig. a and points b, c, d, e in fig. b) and isoferroplatinum (points i, j in fig. a and point a in fig. b) in secondary gold (points k, o in fig. a), grain Ir-3-5-2; c, d) ruthenium (points g, d) rimmed by gold (points h, i, j) and iridium (points a, d, c), grain Ir1-5-1; e, f) Os ruthenium (points a, c–h, q) with Ir ruthenium rim (points b, i, m, p), grain Ir3-sr14-1. SEM images.

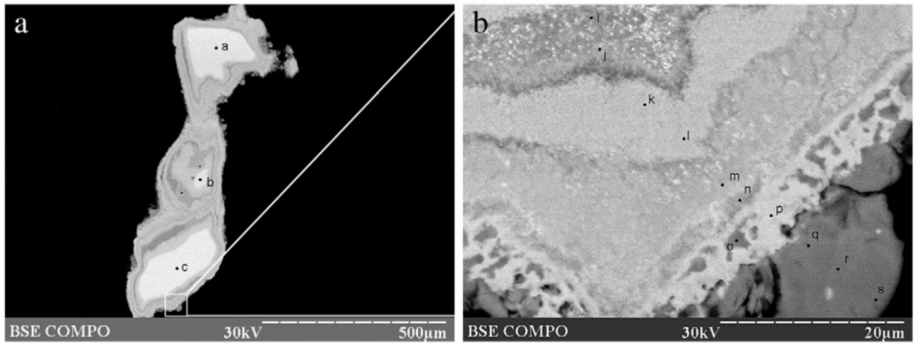

Fig. 19. General view (a) and detail (b) of replacement of ruthenium (points a, b, c) by laurite (points i, j, q, r, s) and irarsite (points h, k, l). SEM images.

quartz deposit is hosted by quartz diorites intruded by plagiogranite dikes (Salikhov et al., 2003). The ore-bearing sulfide–quartz and quartz–carbonate veins 0.2–0.5 m thick are confined to the dikes 600–700 m long. Gold occurs in assemblage with arsenopyrite, sphalerite, galena and chalcopyrite. The ore body of the Maly Karan gold–galena–quartz deposit represents discontinuous albitite lenses with sulfide–quartz veins. The largest ore bodies were up to 80 m long and 6–8 m thick. The fineness of gold from the heavy concentrates of this deposit is 930–960‰ (Belogub et al., 2014). Some amount of gold with sulfides for the Polaykova placer could also be supplied from the Murtykty and Ik-Davlyat gold–sulfide deposits with galena and arsenopyrite (Fig. 2) (Salikhov et al., 2003). The Au-rich Murtykty deposit is localized in a zone of sulfidized basalts 4 km long. The Ik-Davlyat deposit occurs at the northern continuation of this zone.

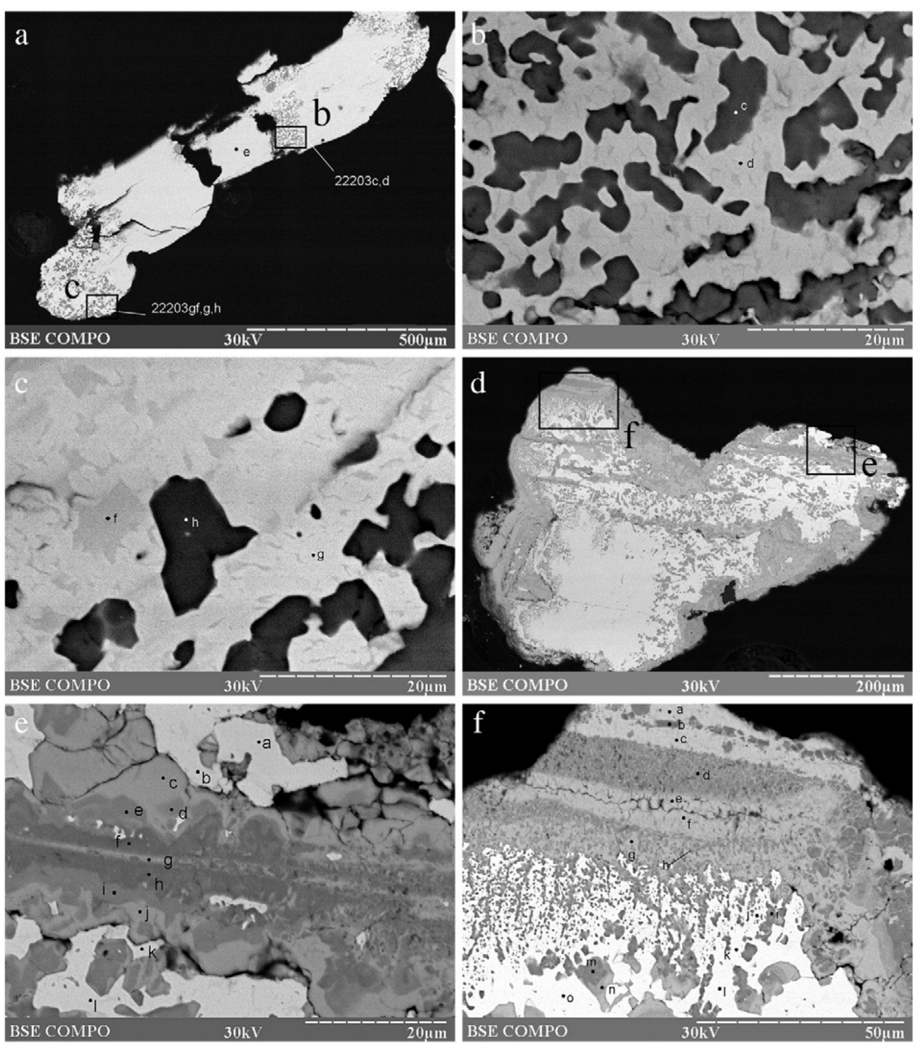

Fig. 20. Microtextures of aggregates of Os–Ir–Ru minerals and sulfides: a–c) ruthenium grains (point *e* in fig. a and *f* in fig. c) replaced by laurite (points *c, h* in fig. b and c) and osmium (point *g* in fig. c), grain Ir49-sr3-13; d–f) osmium (points *a, b, k, l*) crossed by zonal veinlets with erlichmanite (points *c, j*) in selvages and laurite (points *d, e, f, g, h, i*) in the central parts. SEM images.

Table 5
Comparison of precious metal placers and primary sources of the Miass placer zone.

Placer	Index minerals or microinclusions	Fineness of host gold	Fineness of gold in placer	Primary source	Fineness of gold	Approximate distance, km
Nizhny Karabash	Tetra-auricupride, cupriferous gold	860–990	880–980	Zolotaya Gora deposit, gold-bearing rodingites	800	2–3
	Sulfides	680	670–680	Oxidation zones of the Karabash group of VHMS deposits	500–700	3–5
Kialim	PGMs	930	920–940	Chromite occurrences	No data	3–4
Central Miass	Sulfides	900	540–970	Melent'evka gold–sulfide deposit	570–800	5–20
Maly Iremel	PGMs	920	800–930	Chromite occurrences	No data	2–3
Suleymenovo	Sulfides	910	920	Orlovskoe gold–sulfide deposit	920	1–5
Polyakovka	Sulfides, sulfarsenides	900–930	860–870	Karan gold–quartz–sulfide deposit	930–960	4–8
	Sulfides	930	920–940	Murtykty and Ik-Davlyat gold–sulfide deposits	950–990	?

5.4.3. Source of “inclusion-free” gold

Most studied gold grains (~95%) host no microinclusions of ore minerals, although some of them can easily be concealed inside the grains. However, even if we have missed some of the concealed ore microinclusions, the high amount of this gold reflects the general “inclusion-free” tendency. The possible sources of this gold of the Miass placer zone could be related to numerous listvenite-related gold deposits, e.g., Mechnikovskoe (Fig. 2) (Melekestseva et al., 2011; Belogub et al., 2017–in this issue) and Borisovskie Zhily (Artem'ev et al., 2014) deposits. The gold from these deposits is mostly included in quartz and contains no microinclusions of ore minerals (Belogub et al., 2017, this issue). The fineness of gold from these deposits is 860–980‰. The same fineness is typical of the placer gold from the Tashkutarganka River (the tributary of the Miass River) located close to the listvenite-related deposits. Similar deposits are known in the Central Urals (Sazonov et al., 2001), Armenia (Konstantinov et al., 2000), Canada (Hansen et al., 2004), Egypt (Zoheir and Lehman, 2011) and other regions. The Kruglaya Gora skarn-associated gold–magnetite deposit, which is located ~10 km southwest of Miass, could also contribute some amount of gold to the Miass placer zone (Fig. 2). The average fineness of gold from this deposit is 939‰; gold also contains 0.8 wt.% Hg (Zaykov et al., 2010). The gold grains with lower fineness (538‰) probably derive from the Melent'evka VHMS-related sulfide deposit with fineness of gold of 500–800‰. This deposit could also supply with Hg-bearing (up to 4 wt.%) gold.

The Mindyak placer zone is evidently related to the Mindyak gold deposit (Znamensky and Michurin, 2013). The mineralization at the deposit is hosted by a tectonic sheet, which is composed of the chaotically arranged bodies of serpentinites, pyroxenites, gabbros and diabases. The ores with economic Au grades are confined to the fault areas, which cross the diabase olistoliths (Seravkin et al., 2001). The highest Au grades are typical of the carbonate–quartz veinlets with pyrite, chalcopyrite and visible gold.

5.4.4. Source of PGMs

The predominance of ruthenium grains among the studied PGMs is in agreement with ophiolitic source regions (cf., Tolstykh et al., 2005, 2009; Craw et al., 2013). The PGMs of the Kialim placer have derived from the chromite ores from the Karabash and Talovka ultramafic massifs (Fig. 2). The osmium inclusion in gold was found in chromitites of the Karabash massif, composed of serpentinites after harzburgites and dunites (Zaykov et al., 2012). The massive and semimassive chromite ores were exposed there in a small quarry. The fineness of primary gold intergrown with PGM and that of placer gold is identical (920–930‰). In the northern part of the Talovka massif, the Sardatkul deposit and Indashta and Karymkin Log occurrences are known (Savel'ev et al., 2008). The mineral composition of these objects, which cover an area of 3 km^2, is still unknown, but their studies are promising for identification of primary PGM mineralization.

The source of the PGMs for the Maly Iremel placer is related to the ultramafic rocks of the northern part of the adjacent Nurali massif, which is composed of harzburgites and dunites and represents the lower horizon of the oceanic crust (Zoloev et al., 2001). Ten chromite occurrences were discovered in the area of the massif, which spans the headwaters of the Iremel River (Fig. 2). Disseminated accessory iridium, osmium and laurite were identified in the Mokraya Yama primary occurrence from this ultramafic massif. Similar minerals are present in the Maly Iremel placer.

The PGMs in the Suleymenovo placer are close in composition to those from the primary Priozernoe and West Sherambai PGM occurrences located in the central part of the Nurali ultramafic massif (Fig. 2). The major PGMs here are laurite–erlichmanite, osmium, iridium and ruthenium (Zoloev et al., 2001; Grieco et al., 2001).

5.5. Sources for placers east of the Main Uralian fault

The gold–quartz and gold–quartz–sulfide deposits with weathered rocks after schists and serpentinites are known within the Nepryakhino placer zone (Al'bov, 1960). According to the unpublished data of Ivanishchev et al. (2005), 1523 kg of gold have been extracted from the weathered rocks of these deposits. The Bayramgulovo and Ingul placers contain the PGMs, which derived from serpentinites. The galena microinlusions in gold of the Bayrambgulovo placer are similar to that from the sulfide vein exposed by Smolenskaya mine (Al'bov, 1960).

The gold–sulfide–quartz veins of large Kochkar deposit were the sources for the Kochkar placer zone. The veins with high Au grades (30–60 g/t), which were found in the bedrock of the Uspenskaya placer, have triggered the exploitation of the gold deposit (Borodaevskaya and Rozhkov, 1978). About 1200 veins are known in the area of the deposit, which yielded 120 t of gold. The Au grade in quartz is 11.8 g/t. The geological setting of veins of the deposit is similar to gold-bearing veins of the Royal granite pluton in the United States (Loen, 1994).

Hundreds of gold–sulfide–quartz veins up to 1.2 km long of the Aydyrlya ore field are considered to be the sources for the Suunduk placer zone. These veins were also the source for wolframite and scheelite (Barannikov, 2006).

6. Conclusions

Gold from the placer zones of the South Urals exhibits different composition depending on geographical and geological locations: the fineness of gold from the eastern slope of the Uralian Ridge (the area of the MUF zone) is lower and more variable (550–960‰) in contrast to that of gold from the Transuralian plateau (mostly, 900–1000‰). This may be explained by the higher fineness of gold from the primary sources located on the plateau, as well as by recycling of ancient placers. The rims and veinlets of high-fineness gold around primary placer gold is an important feature of placer gold. Most rims were formed in placers. The formation of secondary gold includes, at least, two stages: (i) formation of new grains, which overgrow the primary ones from Au-bearing solutions, and (ii) penetration of secondary gold into the primary one and further replacement of primary low-fineness gold by newly formed high-fineness gold.

Co-existence of gold and PGMs in placers is traditionally explained by accumulation of erosion products from various primary deposits. Our data indicate the possible presence of primary gold–PGM source (e.g., chromite deposits) in the source areas that is supported by the finding of discontinuous rim of Cu-bearing gold in Os ruthenium grain from the Maly Iremel placer.

The PGMs also exhibit evidences of possible co-crystallization of minerals of the Os–Ir–Ru system and PGE sulfides and sulfarsenides such as their intimate intergrowths, which resemble the exsolution textures. The formation of some PGE sulfides postdates crystallization of the Os–Ru–Ir minerals. Locally, laurite is developed along the cleavage of ruthenium and its formation follows the opening of cleavage fractures under influence of stress conditions. Replacement of Os–Ru–Ir minerals by PGE sulfides and sulfarsenides from mineral boundaries is also widespread: ruthenium is metasomatically replaced by laurite and irarsite, whereas osmium is replaced by erlichmanite and laurite. Different compositional trends of PGMs with and without microinclusions of sulfides and arsenides are probably induced by the influence of late hydrothermal fluids.

For most placers, we identified the genuine sources on the basis of gold fineness and relevant microinclusions in gold. The complicate geological structure of the South Urals, especially, the MUF zone leads to the erosion of different types of deposits not limited to the lode gold deposits, but also Au-bearing VHMS and iron deposits. The estimated distance between the placers and primary deposits varies from 2 to 5 km, increasing up to 20 km in the extended valley of the Miass River.

The Zolotaya Gora gold deposit was a source for tetra-auricupride and cupriferous gold of the Nizhny Karabash placer. The chalcocite micronclusions in the placer gold most likely derived from the oxidation zones of the Karabash VHMS deposits. The chromite ores from the Karabash and Talovka ultramafic massifs were the sources of PGMs of the Kialim placer. The inclusion-free gold from the Miass placers could be related to numerous listvenite-related gold deposits in the MUF zone. The PGMs of the Maly Iremel placer were originated from the ultramafic rocks of the adjacent Nurali massif. The Orlovskoe gold–sulfide deposit in the head of the Suleymenovo placer could be the source of galena microinclusions, whereas the PGMs of this placer are close in composition to those from the Priozernoe and West Sherambai PGM occurrences. The Bol'shoi and Maly Karan and, probably, Murtykty and Ik-Davlyat volcanic-hosted gold–sulfide deposits with galena and arsenopyrite were the sources of sulfides and gold for the Polyakovka placer. The Mindyak placer zone is directly related to the Mindyak gold deposit. The Bayramgulovo and Ingul placers contain the PGMs, which derived from serpentinites. The gold–sulfide–quartz veins of large Kochkar deposit were the sources for the Kochkar placer zone.

Usage of ore microinclusions and associated PGMs in study of placer gold is far more advanced than an ordinary consideration of gold composition alone. This allowed us to identify the concrete sources for individual placers and to predict some mineralogical findings in already known primary occurrences.

Conflict of interest

No conflicts of interest.

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