
MINERALS AND MINERAL PARAGENESES

Veresovka River Deluvial Placer, Veresovoborsky Dunite–Clinopyroxenite Massif (Middle Urals)

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Received January 30, 2018; revised June 14, 2018; accepted June 14, 2018

Abstract—For the first time data on platinum group minerals (PGM) from the deluvial placer of the Veresovka River are given; their root source are dunites of the northern part of the Veresovoborsky massif. Among minerals typical of this type of placers, Pt–Fe minerals, Os–Ir–(Ru) intermetallic compounds, kashinite, bowieite, laurite, erlichmanite, and Ir–Rh thiospinels have been identified. Irarsite, hollingworthite, zvyagintsevite, potarite, cooperite, ferhodsite, and some unnamed Pb–Te minerals were also revealed, which are rare for platinum placers associated with zonal clinopyroxenite–dunite massifs, but are widely distributed in the studied placer. Xingzhongite was detected there for the first time in placers of the Ural Platinum Belt. The morphological features of all these minerals are characterized in detail, together with their chemical composition, determined by X-ray spectral analysis. Their genetic relationships are characterized taking into account the aggregate data obtained. This comprehensive study of PGM individuals and aggregates is used as a basis to distinguish the parageneses in their association.

Keywords: Ural Platinum Belt, Veresovoborsky massif, platinum placers, isoferroplatinum, Pt–Fe minerals, osmium, iridium, kashinite, erlichmanite, tetraferroplatinum, potarite, zvyagintsevite, xingzhongite, mineral parageneses

DOI: 10.1134/S1075701519080117

The clinopyroxenite–dunite massifs of the Urals and other regions of the world are sources for the formation of large placers; however, particularly large placers have formed precisely within the Ural Platinum Belt, with total reserves exceeding 500 t (Mosin, 2002). It should be noted that only a limited number of published studies are devoted to the formation of Ural platinum placers, the platinum distribution therein, and description of their PGM **mineral** assemblages (Vysotskii, 1913; Lazarenkov, 1992; Razin, 2008). A large number of studies were based on factual material acquired within placers associated with the Nizhni Tagil massif. Single studies address PGM from placers of the **Isovo–Turinsky** system. There are hardly any descriptions of eluvial, eluvial–deluvial, and deluvial placers occurring within the contours of the dunite “cores” of the Svetloborsky and Veresovoborsky massifs, due to the erosion of which most placers of the **Isovo–Turinsky** placer system formed.

Studying eluvial and deluvial placers mainly makes it possible to understand the processes occurring at the

initial stages in the formation of massif placer objects, as well as to tie placer mineralization to a certain time of root mineralization. This study describes for the first time PGM from a deluvial placer in the upper reaches of the Veresovka River, the source region for which is the northern part of the dunite core of the Veresovoborsky clinopyroxenite–dunite massif.

MATERIALS AND METHODS

The Veresovka River originates in a small valley between two unnamed elevations. Its left tributaries at their sources drain dunites of the Veresovoborsky massif (Fig. 1a). The Veresovka River placer is a valley whose ravine deposits from its riverbed have been prospected (Fig. 1b). Today, in the upper reaches of the river, there are still unmined placers. Their location placers at the foot of an unnamed elevation 607.2 m in height, the widespread poorly sorted sediments with predominant sandy and clayey loam, and the absence of layering in sediments make it possible to attribute them to deluvium (Obshchaya geomorfologiya, 2006).

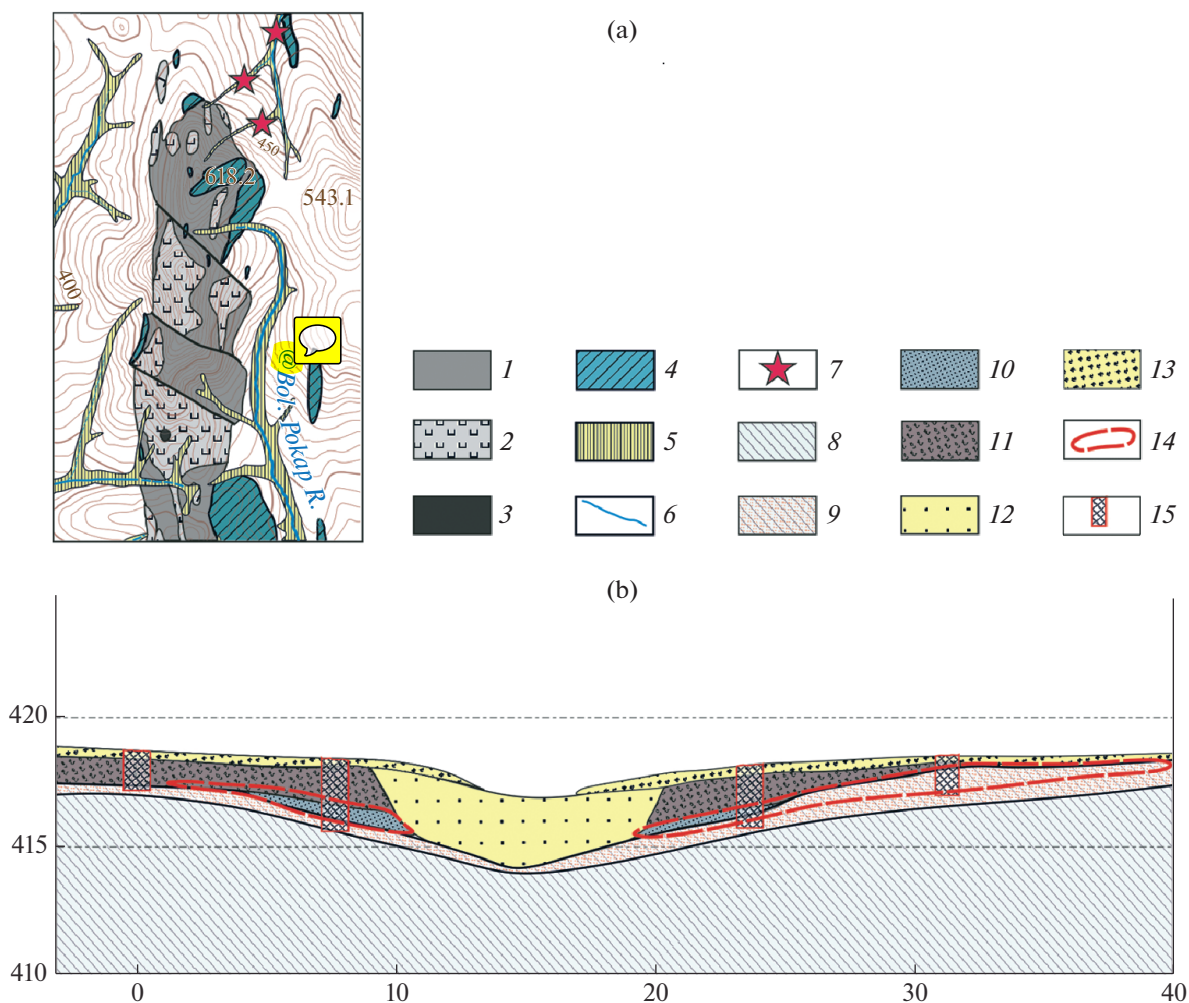


Fig. 1. Geological structure of northern part of Versovoborsky massif (a) using data of (Ivanov, 1997) and section of placer in upper reaches of Veresovka River (b). Dunites: 1, fine-grained; 2, medium-grained; 3, coarse-grained; 4, clinopyroxenites; 5, river valley sediments; 6, streams; 7, sampling points; 8, epidote-chlorite schists; 9, same, weathered; 10, sands; 11, deluvial, primarily clay sediments; 12, technogenic sediments; 13, soil-turf layer; 14, intervals with Pt content $>0.4 \text{ g/m}^3$; 15, survey pits.

The interrelations between platinum-bearing sediments on the slope of the valley and alluvial sediments of the Veresovka River correspond to the classical structural patterns of deluvial placers described in (Bilibin, 1956). In a deluvial placer, platinum accumulates directly on the bedrock, which is a “brush” of metamorphic and foliated volcanic rocks with an epidote-chlorite facies (Fig. 1b). In the marginal parts of the valley, schist that disintegrated in the near-surface area is enriched in placer platinum and is located directly under the soil-plant horizon. Closer to the central part of the valley, this schist is overlain by clayey deluvial sediments. In the near riverbed area, small intercalations of sandy loam are observed, which are also characterized by elevated placer platinum contents.

In order to sample the deposits within the valley of one of the Veresovka's tributaries, a prospecting profile was carried out across the trend of this valley. In

prospecting pits from different types of deposits, 0.25 m^3 of samples were collected and then washed in a pan or a centrifugal concentrator. When recovering signs of platinum group minerals (PGM) and calculating the platinum content from the results of their in situ weighing, we revealed intervals with an average content of 0.4 g/m^3 . We also recovered additional samples with a total volume of 0.57 m^3 to obtain a representative portion of the placer platinoid assemblage.

Later, PGM individuals and aggregates were meticulously studied under a binocular microscope, and some of them were studied by raster electron microscopy. Then, after preparation of an artificial thin section, the grain anatomy of platinoids was studied, with preliminary determination of the PGM compositions by X-ray microanalysis with an EDS spectrometer (CamScan MV2300 microscope with an INCA Energy 350 detector; Institute of Experimental

Mineralogy, analyst D.A. Varlamov). To refine the mineral composition, a Camebax SX 50 microanalyzer with wave spectrometers was used (Moscow State University, analyst D.A. Khanin).

When recording the reference profiles of the series of characteristic X-ray lines on the EDS spectrometers, the following standards were used: for PGE—pure metals (along the L line); Cu—Cu_{met}; Fe—Fe_{met}; Co—CoAsS; S—FeS_{2sint}; As—InAs; Sb—CuSb₂; Fe, S—FeS; Ni—NiS; Co, As—CoAsS; Hg—HgTe; Pb—PbS; Bi—Bi₂S₃. For X-ray microanalysis (XRM), the following references were used: PGE—pure metals; Cu, SbCuSbS₂; Fe, S—FeS; Ni—NiS; Co, As—CoAsS; Hg—HgTe; Pb—PbS; Bi—Bi₂S₃.

The microanalysis conditions for the Link Petafet detector (Oxford Instruments) were as follows, Si(Li): accelerating voltage 20 kV, operating distance 35 mm, spectral accumulation time 70 s (ignoring dead time). The analytical conditions for the INCA Energy 450 were as follows: accelerating voltage 20 kV, operating distance 25 mm, spectral accumulation time 70 s (ignoring dead time). On the Camebax SX 50 X-ray microanalyzer, measurements were conducted at an accelerating voltage of 20 kV and a probe charge of 30 nA, measurement of the peaks of principal elements of 20 s, and a background of 10 s on each side. For impurity elements: peak, 40 s; background, 20 s. The detection limits are (wt %): Os, 0.08; Ir, 0.1; Ru, 0.05; Rh, 0.05; Pd, 0.05; Pt, 0.05; Fe, 0.03; Ni, 0.03; Cu, 0.03; S, 0.05; As, 0.05; Co, 0.03; Pb, 0.08; Bi, 0.1. When calculating contents, a ZAF correction was introduced. XRD was used for precise identification of Pt—Fe minerals. XRD studies employed equipment of the Science Park resource center of St. Petersburg State University. Qualitative XRD analysis was done by the Gandolfi method with a Rigaku R-AXIS RAPID II single-crystal diffractometer (CoK α radiation; analyst A.A. Zolotarev) with subsequent data processing with PDXL-2 software.

PGM MINERAL ASSEMBLAGE

Pt—Fe minerals predominate among the PGM in the Veresovka deluvial placer. They are encountered as aggregates of several grains with an average size of 100–500 μ m, the surfaces of which have poorly developed mechanical wear traces. Frequently, intergrowths of Pt—Fe minerals 3–4 mm in size are encountered in the placer. An overall assessment of the sizes of platinum aggregates established that the placer is dominated by grains from 0.2 to 0.4 mm in size with a subordinate amount (less than 5%) of fine platinum (less than 0.1 mm). Cubic individuals of Pt—Fe minerals and their intergrowths are encountered relatively frequently (Fig. 2a). In most cases, the boundaries of Pt—Fe minerals, in addition to their natural crystallographic shapes, are represented by joint-growth surfaces (Fig. 2b) and, to a lesser extent, by xenomorphic

surfaces that reflect the morphological features of individuals and aggregates of earlier formed minerals (Fig. 2c). Study of Pt—Fe mineral aggregates under a raster electron microscope established their intergrowth with chrome spinel, laurite, and iridosmine. Most Pt—Fe grains of intermetallic compounds are characterized by a smooth, unaltered surface; however, there are widespread grains that have been replaced from the surface by an aggregate of tetraferroplatinum and other PGM.

Unaltered Pt—Fe mineral individuals are characterized by a regular internal structure (Figs. 3a, 3b). The Pt—Fe matrix hosts inclusions of Os—Ir—(Ru) intermetallic compounds, Ir—Rh thiospinels, and minerals of the kashinite—bowieite and laurite—erlichmanite isomorphous series. In determining the chemical composition of Pt—Fe minerals, it was established that it varies insignificantly within a single grain. Compositionally different grains from the placer may correspond to both Pt₃Fe and Pt₂Fe with a broad set of intermediate varieties (Fig. 3c; Table 1). XRD analysis of these minerals established that the Pt—Fe solid solution, even that corresponding to the composition of Pt₂Fe, has a primitive crystal cell structure (space group *Pm3m*). This makes it possible to state that all Pt—Fe minerals of the Veresovka River placer are isoferroplatinum.

Isoferroplatinum contains a significant amount of inclusions, dominated by platy euhedral osmium crystals (Fig. 4a). The size of individuals may reach 300 μ m along the pinacoid face with a thickness of no more than 50 μ m. Less widespread are inclusions of osmiridium in the form of isometric individuals with an average size of 25 μ m, which result from breakdown of the primary Pt—Ir—Fe solid solution (Fig. 4b) into iridosmine and platinum-enriched iridium. Its composition within an individual is not subjected to substantial alterations. The contents of the main components in Os—Ir intermetallic compounds vary significantly. For example, different osmium crystals may have a different iridium content with a mean value of 22 at % (Fig. 4c, Table 2).

Among sulfides minerals, the kashinite—bowieite and laurite—erlichmanite isomorphous series are widely encountered in isoferroplatinum as inclusions (Table 3). Kashinite predominates among sulfide in isoferroplatinum inclusions. Three morphological varieties of kashinite have been revealed: the first is fine euhedral grains up to 20 μ m in size (Fig. 5a), the second is complexly faceted coarse grains 70–150 μ m in size (Fig. 5b), and the third is partial or complete pseudomorphs after iridosmine (Fig. 5c). The majority of kashinite individuals, despite their belonging to a specific morphological variety, possess distinctly expressed zoning with an increased content of bowieite endmember toward the boundary of an individual. In comparison to kashinite, laurite is less widespread and is encountered either in the form of fine

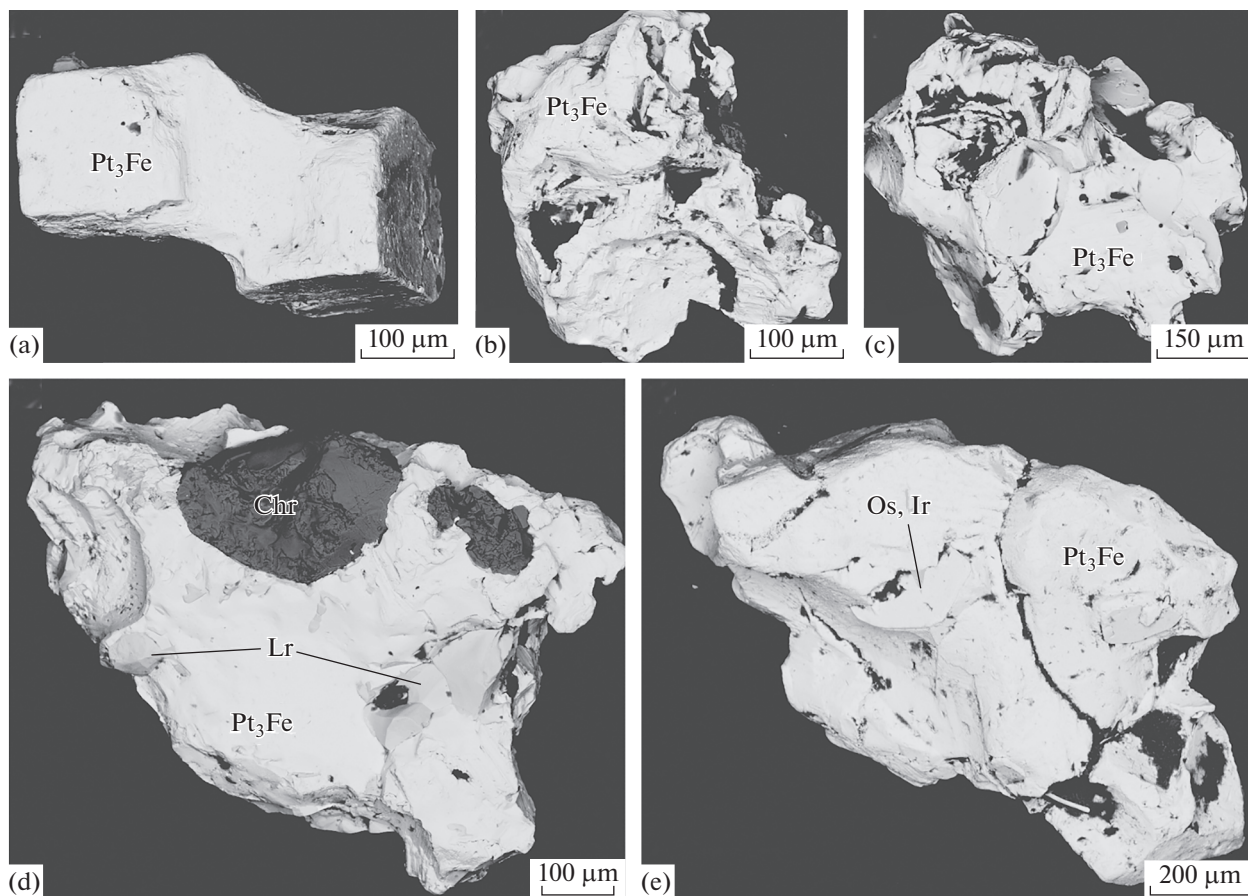


Fig. 2. Morphological features of Pt–Fe mineral individuals and aggregates (SEM images). Pt₃Fe, isoferroplatinum; Chr, chrome spinel; Lr, laurite; Os, Ir, iridosmium.

Table 1. Chemical composition of Pt–Fe minerals (wt %)

Analysis	Element content, wt %									Total
	Fe	Ni	Cu	Ru	Rh	Pd	Os	Ir	Pt	
1	10.6	0.21	0.41	0.29	1.50	0.28	—	4.85	82.0	100.2
2	8.95	0.09	0.11	0.05	0.30	0.44	—	4.08	86.9	99.8
3	9.52	0.25	0.49	0.20	—	0.51	0.23	0.83	87.7	99.2
4	11.3	0.59	0.67	0.32	0.62	0.11	—	1.44	84.2	99.7
5	11.2	0.31	0.54	—	0.56	0.62	0.19	—	86.2	99.3
6	13.3	0.18	0.42	0.46	0.92	0.71	0.10	2.05	81.2	100.5
7	12.5	0.34	0.59	0.40	0.34	0.48	—	2.00	83.9	100.5
8	12.5	0.53	0.35	0.42	0.29	0.22	0.50	6.71	78.9	100.9
9	12.8	0.27	0.79	0.25	0.72	0.54	—	0.54	83.8	98.3
10	12.4	—	0.91	0.37	0.25	—	—	—	84.4	99.7
11	11.5	—	0.61	0.20	0.91	—	0.18	1.55	84.3	99.5
12	13.1	—	1.19	0.29	0.40	—	—	—	84.5	100.9
13	12.8	0.09	0.51	0.29	1.10	0.27	—	5.15	79.9	99.1
14	12.3	0.26	0.28	0.43	1.48	1.18	—	6.15	77.2	101.1
15	12.5	0.10	0.35	—	1.03	0.30	1.61	6.78	78.5	100.2
16	15.4	0.49	2.10	—	0.31	0.48	—	—	81.4	100.9
17	16.8	0.34	1.41	0.41	0.76	0.94	—	3.60	76.6	100.7
18	16.8	0.77	0.94	0.08	0.54	0.22	—	4.10	77.4	99.3
19	15.8	0.79	2.72	0.27	0.09	—	0.67	0.40	80.2	100.1
20	16.3	0.78	1.38	0.16	—	—	—	5.63	74.8	99.3

Dash, element content is below detection limit.

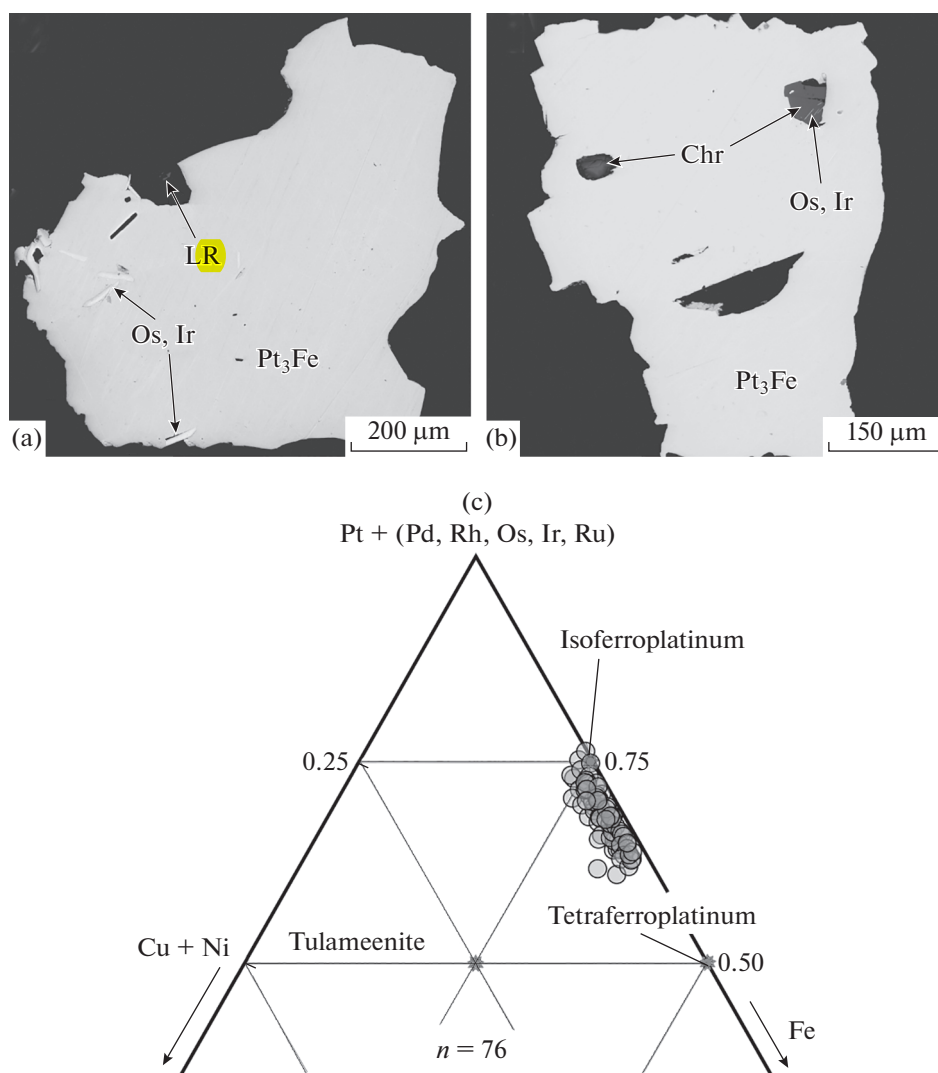


Fig. 3. Anatomy of Fe-platinum and isoferroplatinum individuals (a, b) and ternary diagram of Pt–Fe mineral compositions in Cu + Ni–PGE–Fe coordinates in at. %. Pt₃Fe, isoferroplatinum; Pt₂Fe, Fe-platinum; Os, Ir, osmium; Chr, chrome spinel.

inclusions in isoferroplatinum (Fig. 5d) or as partial pseudomorphs after iridosmium (Fig. 5e). Laurite replacing iridosmium is associated with an increased content of erlichmanite endmember up to transition to erlichmanite. A stark feature of erlichmanite that replaced iridosmium is a high (13–14 wt %) Ir content with respect to the majority of erlichmanite and laurite grains in the Pt–Fe matrix from other zonal massifs of the Middle Urals. Among inclusions, Ir–Rh with predominant ferrorhodsites and a subordinate amount of cuproiridsite are widespread. The majority of their individuals consist of isometric inclusions no more than 100 μm in size (Fig. 5f), for which distinctly expressed zoning is atypical.

Some of the isoferroplatinum grains have been replaced by tetraferroplatinum group minerals. These minerals form either rims around isoferroplatinum grains (Fig. 6a) or they develop within individuals

along cleavage fractures in the (111) and (100) directions (Fig. 6b). Compositionally, the majority of tetraferroplatinum group minerals correspond to tetraferroplatinum proper or cuprous tetraferroplatinum (Table 4). Tulameenite has been found in singular cases, characterized by filling of small fissures in Pt–Fe mineral individuals.

In Pt–Fe minerals, aggregates and single metacrystals of late sulfide, sulfoarsenides, plumbides, and mercurides of PGM elements are widespread along fissures or grain boundaries (Table 5). Cooperite (PtS) is found as a euhedral metacrystal intergrown with pyrrhotite in isoferroplatinum (Fig. 7a). Ferhodite—a structural analog of pentlandite—is relatively widespread and has been found in placers of the Nizhny Tagil massif (Begizov et al., 2016). It is characteristically found in small voids and fissures in isoferroplatinum in the form of aggregates frequently inter-

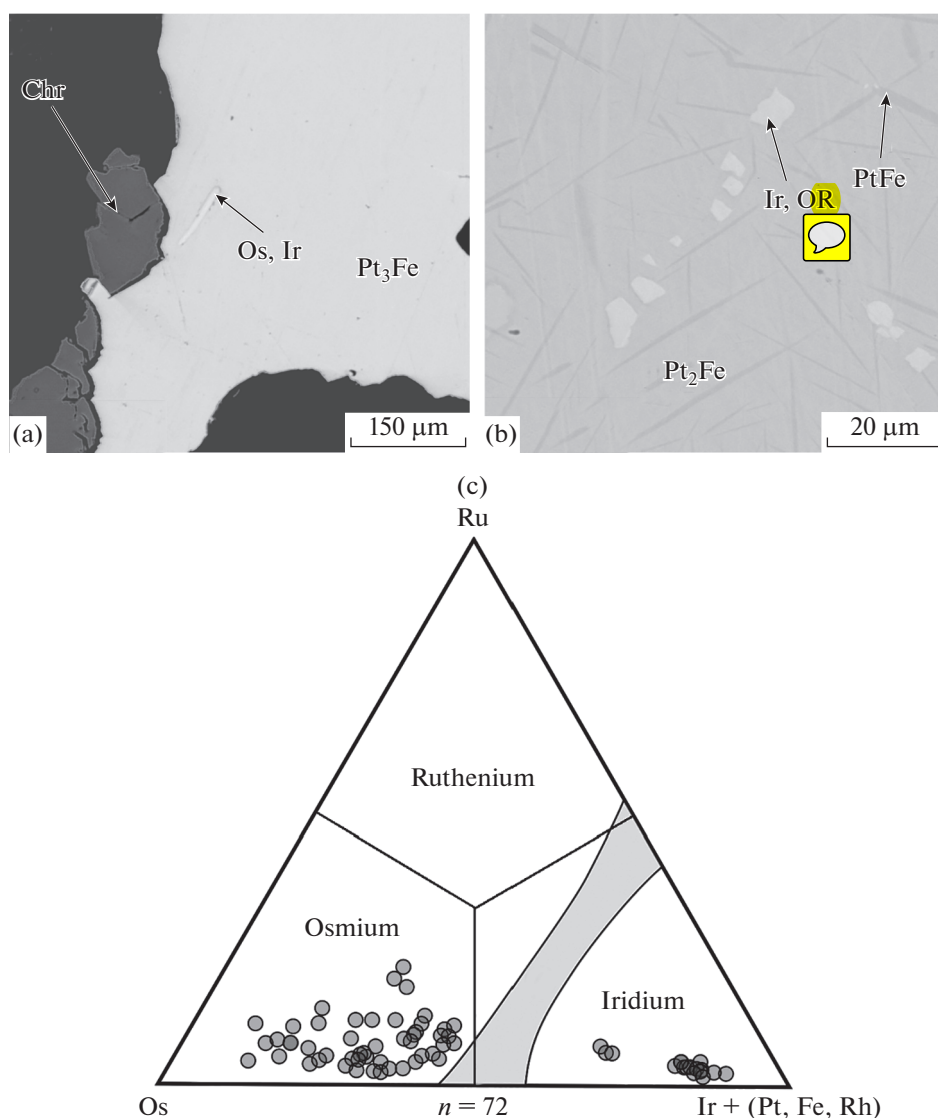


Fig. 4. Anatomy of iridosmium (a) and osmiridium (b) and ternary diagram of compositions of Os–Ru–Ir solid solutions in Os–Ru–Ir + (Pt, Fe, Rh) coordinates in at.%. Pt₃Fe, isoferroplatinum; Pt₂Fe, Fe-platinum; PtFe, tetraferroplatinum; Os, Ir, iridosmium; Ir, Os, osmiridium; Chr, chrome spinel.

grown with tetraferroplatinum no more than 100 µm in size (Fig. 7b). Osarsite, irarsite, hollingworthite, and ruarsite are found among sulfoarsenides. In the majority of cases, osarsite replaces iridosmium (Fig. 7c). Irarsite develops over osmiridium inclusions in isoferroplatinum. Ruarsite and hollingworthite are found as fine single grains in fissures in isoferroplatinum individuals (Fig. 7e). Pb-bearing minerals also include xingzhongite, found as very fine-grained metacrystals in isoferroplatinum (Fig. 7f). Zvyagintsevite Pd₃Pb has been revealed among plumbides. It makes up thin veinlets less than 20 µm in size in isoferroplatinum (Fig. 7g). Potarite is found as fine metacrystals in metasomatic tetraferroplatinum aggregates (Fig. 7h) replacing isoferroplatinum. Bi- and Te-bearing phases are extremely rare. For example, the unnamed mineral

with the composition (Rh,Pt)Pb(Bi,Te)₂ metasomatically replaced isoferroplatinum along very fine fissures, forming aggregates less than 20 µm in size (Fig. 7i).

DISCUSSION

The multiyear history of working the platinum placers of the Urals was accompanied by research to reveal the formation and localization patterns of platinum placer mineralization, as well as to study placer PGM assemblages. However, a multidisciplinary study of the geological structural features of platinum placers was carried out more than 100 years ago (Vysotskii, 1913). As a result, researchers have mainly focused on the richest and largest Quaternary alluvial and ravine placers (Lazarenkov et al., 1992; Stepanov

Table 2. Chemical composition of Os–Ir–(Ru) intermetallic compounds (wt %)

Analysis	Element content, wt %							Total	Formula
	Fe	Си	Ru	Rh	Pd	Os	Ir	Pt	
1	—	—	4.65	0.47	—	80.9	14.4	—	(Os _{0.77} Ir _{0.14} Ru _{0.08} Rh _{0.01})
2	—	—	2.31	0.20	—	68.2	29.4	0.48	(Os _{0.67} Ir _{0.28} Ru _{0.04})
3	0.90	0.28	13.3	—	0.30	56.1	28.9	0.13	(Os _{0.49} Ir _{0.25} Ru _{0.22} Fe _{0.03} Cu _{0.01})
4	0.27	—	6.70	0.81	—	59.8	30.6	0.36	(Os _{0.57} Ir _{0.29} Ru _{0.12} Fe _{0.03} Rh _{0.01})
5	0.39	—	11.4	0.54	—	55.1	29.0	4.63	(Os _{0.49} Ir _{0.26} Ru _{0.19} Pt _{0.04} Fe _{0.01} Rh _{0.01})
6	0.43	—	4.29	0.84	0.31	51.2	41.7	—	(Os _{0.49} Ir _{0.40} Ru _{0.08} Fe _{0.01} Rh _{0.01} Pd _{0.01})
7	0.15	—	6.00	1.25	—	52.8	39.1	—	(Os _{0.50} Ir _{0.37} Ru _{0.11} Rh _{0.02})
8	0.32	—	5.08	1.64	—	53.1	39.5	—	(Os _{0.50} Ir _{0.37} Ru _{0.09} Rh _{0.03} Fe _{0.01})
9	0.15	—	5.05	0.83	—	53.2	40.4	—	(Os _{0.51} Ir _{0.38} Ru _{0.09} Rh _{0.01})
10	0.34	—	4.28	0.83	—	53.7	40.1	—	(Os _{0.52} Ir _{0.38} Ru _{0.08} Fe _{0.01} Rh _{0.01})
11	0.30	—	11.4	0.50	0.21	58.3	28.4	—	(Os _{0.53} Ir _{0.26} Ru _{0.19} Fe _{0.01} Rh _{0.01})
12	0.12	0.23	1.37	—	—	63.6	33.7	—	(Os _{0.63} Ir _{0.33} Ru _{0.03} Cu _{0.01})
13	—	—	3.35	0.21	0.29	66.7	29.1	—	(Os _{0.65} Ir _{0.28} Ru _{0.06} Pd _{0.01})
14	0.76	0.28	2.99	—	—	66.8	22.7	5.77	(Os _{0.64} Ir _{0.22} Pt _{0.05} Ru _{0.05} Fe _{0.02} Cu _{0.01})
15	—	—	4.13	0.51	—	78.3	16.3	—	(Os _{0.76} Ir _{0.16} Ru _{0.08} Rh _{0.01})
16	—	—	4.56	0.23	—	78.9	17.1	—	(Os _{0.75} Ir _{0.16} Ru _{0.08})
17	0.42	—	3.47	1.60	—	27.5	57.9	8.62	(Ir _{0.55} Os _{0.26} Pt _{0.08} Ru _{0.06} Rh _{0.03} Fe _{0.01})
18	1.24	0.16	2.38	2.37	—	16.1	71.1	6.54	(Ir _{0.66} Os _{0.15} Pt _{0.06} Ru _{0.04} Fe _{0.04} Rh _{0.04})
19	1.29	—	1.60	2.08	0.80	16.1	72.2	6.79	(Ir _{0.67} Os _{0.15} Pt _{0.06} Fe _{0.04} Rh _{0.04} Ru _{0.03} Pd _{0.01})
20	1.44	—	1.58	2.27	—	14.2	75.2	5.36	(Ir _{0.70} Os _{0.13} Pt _{0.05} Fe _{0.05} Ru _{0.03} Rh _{0.04})
21	1.20	—	1.64	1.75	—	14.5	74.8	6.19	(Ir _{0.71} Os _{0.14} Pt _{0.06} Fe _{0.04} Ru _{0.03} Rh _{0.03})

Analyses 1–16, osmium; analyses 17–21, iridium; formulas calculated per one atom (100 at %). Dash, element content is below detection limit.

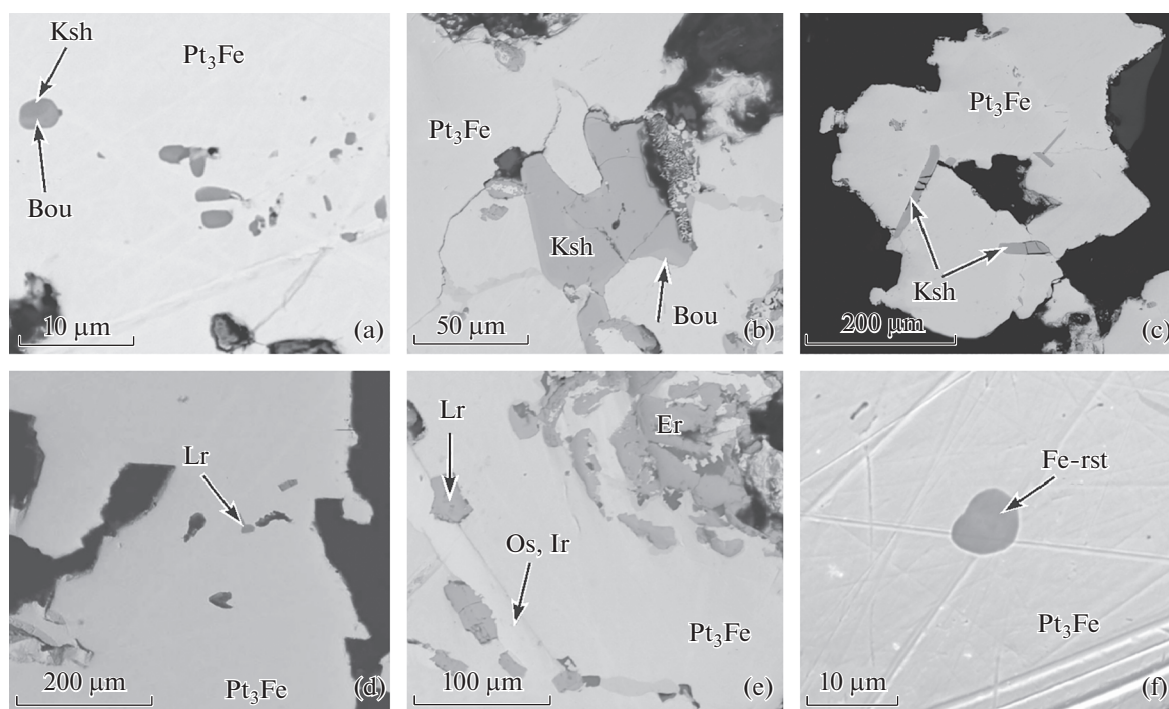


Fig. 5. Anatomy of inclusions in Pt–Fe minerals (a–f). Ksh, kashinite; Bou, bowieite; Pt₃Fe, isoferroplatinum; Lr, laurite; Er, erlichmanite; Os, Ir, **iridosmium**; Fe-rst, ferrosiderite.

et al., 2015). A limited number of studies are aimed at eluvial and deluvial placers of the Ural Platinum Belt (Razin, 2008; Duryagina et al., 2015; Palamarchuk et al., 2017). Meanwhile, study of the distribution features and character of platinum mineral concentration in eluvial and deluvial placers facilitates understanding of the general patterns of placer system formation and makes it possible, owing to the insignificant transport distance of detrital material, to characterize platinoid mineralization in eroded parts of clinopyroxenite–dunite massifs.

The geological structure of the Veresovka River placer has only been characterized in (Vysotskii, 1913), and only the riverbed portion of the ravine placer was considered, which is 1.5–2 km from the orebody. The present paper characterizes the deluvial placer in the upper reaches of the river and describes the “subturf” metal–platinum–concentrated directly in ore rocks under the soil–turf layer. It should be noted that, on the whole, platinoid mineralization in the Veresovka massif has not been completely studied and study of the placer platinum assemblage associated with the erosion of dunites in the northern part of the massif has contributed substantially to the topomineralogy of the Ural Platinum Belt.

PGM in the Veresovka River placer are dominated by the Pt–Fe solid solutions, which on the whole are characteristic of placer objects associated with zonal clinopyroxenite–dunite massifs (Lazarenkov et al., 1997; Vil’danov et al., 2002; Sidorov et al., 2012). It is

noteworthy that the placer hosts isoferroplatinum, identified by XRD, which corresponds in composition both to Pt₃Fe and Pt₂Fe with the complete series of intermediate varieties. As a whole, the scatter of compositions is not characteristic of placer systems related to an orebody. Thus, e.g., in placers of the Nizhny Tagil massif, a mineral corresponding in composition to Pt₂**FE** predominates over other Pt–Fe intermetallic compounds (Malitch et al., 2002; Stepanov et al., 2015). In placers associated with the Svetloborsky massif, isoferroplatinum completely predominates (Palamarchuk and Stepanov, 2017; Palamarchuk et al., 2017).

The set of inclusions in Pt–Fe of the Veresovka River placer with the predominant Os–Ir–(Ru) intermetallic compounds and widespread minerals of the kashinite–bowieite and erlichmanite–laurite isomorphous systems, as well as Ir–Rh thiospinels, is on the whole analogous to the earlier established paragenesis in source chromatites of the Veresovoborsky (Stepanov et al., 2017), Svetloborsky (Tolstykh et al., 2015), Kamenushensky (Tolstykh et al., 2011), Nizhny Tagil (Tolstykh et al., 2017), and other zonal massifs of the Urals. A similar distribution of inclusions in Pt–Fe minerals is characteristic of the majority of placers adjacent to clinopyroxenite–dunite massifs (Lazarenkov et al., 1992; Auge et al., 2005; Sidorov et al., 2012).

The uniqueness of the placer PGM assemblage from the Veresovka River placer is governed by widespread aggregates and metacrystal individuals of PGE

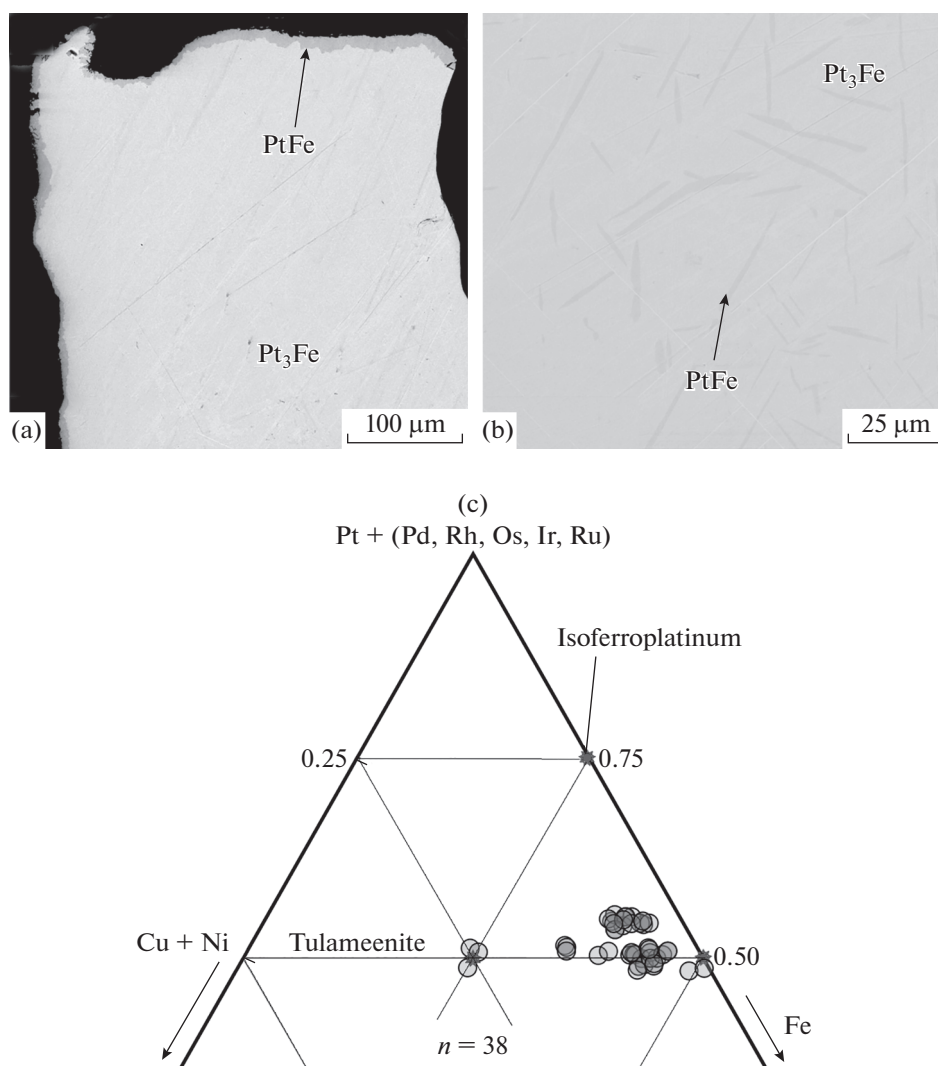


Fig. 6. Anatomy of tetraferroplatinum group mineral individuals and aggregates (a, b) pseudomorphously replacing isoferroplatinum and ternary diagram of their compositions in at % (c). Pt₃Fe, isoferroplatinum; PtFe, tetraferroplatinum.

sulfoarsenides, plumbides, tellurides, and mercurides. Thus, on the whole for PGM among the chromitites and placers of zonal clinopyroxenite–dunite massifs, finds of Os, Ir, and Rh sulfoarsenides, zvyagintsevite, and potarite, as well as Te- and Pb-bearing minerals, are extremely rare.

Sulfoarsenides of the irarsite–hollingworthite and osarsite–ruarsite isomorphous series have a limited distribution in source ores and placers of zonal clinopyroxenite–dunite massifs of the Urals. Among these minerals, irarsite and hollingworthite are characterized by a larger occurrence frequency. Irarsite was earlier established in chromitites and placers of the Nizhny Tagil massif (Bergizov et al., 1976; Stepanov et al., 2015), in chromitites of the Svetloborsky and Kamenushensky massifs (Tolstykh et al., 2011, and in chromitites of the Iovsky dunite body of the Konzha-kov complex in the Northern Urals (Palamarchuk

et al., 2017). Irarsite has also been described in ores of zonal clinopyroxenite–dunite massifs of the Koryak highlands (Sidorov et al., 2012; Mochalov, 2013; Kuttyrev, 2017). Ruarsite and osarsite have not been found in ore rocks and placers of Ural clinopyroxenite–dunite massifs, but they have been found in placers of the Koryak–Kamchatka Platinum Belt (Tolstykh et al., 2004; Sidorov et al. 2012). On the whole, widespread Ir, Rh, Os, and Ru sulfoarsenides are to a greater extent characteristic of the **PMG** assemblage of ultramafic ophiolite association complexes (Distler et al., 2008; Kiselev et al., 2014; Zaikov et al., 2016; Savel'ev and Sergeev, 2017; etc.).

Zvyagintsevite was first discovered in placers associated with clinopyroxene–dunite massifs of the Northern Urals. Earlier, this mineral was described in zonal massifs of the Koryak highlands (Sidorov et al.,

Table 4. Chemical composition of tetraferroplatinum group minerals (wt %)

Ana- lysis	Element content, wt %;									Total	Formula
	Fe	Co	Ni	Cu	Ru	Rh	Pd	Os	Ir	Pt	
1	14.0	—	1.04	5.93	0.22	0.41	—	1.94	0.79	75.3	(Pt _{1.00} Os _{0.03} Rh _{0.01} Ir _{0.01} Ru _{0.01}) _{1.06} (Fe _{0.65} Cu _{0.24} Ni _{0.05}) _{0.94}
2	14.2	0.23	0.90	5.80	—	—	—	—	2.44	76.2	(Pt _{1.02} Ir _{0.03}) _{1.05} (Fe _{0.66} Cu _{0.24} Ni _{0.04} Co _{0.01}) _{0.95}
3	14.7	—	0.97	3.47	0.07	0.34	0.10	—	1.75	77.0	(Pt _{1.06} Ir _{0.02} Rh _{0.01}) _{1.09} (Fe _{0.71} Cu _{0.15} Ni _{0.04}) _{0.90}
4	15.4	—	0.61	2.51	—	0.46	0.22	1.40	1.62	75.3	(Pt _{1.05} Os _{0.02} Ir _{0.02} Pd _{0.01} Rh _{0.01}) _{1.11} (Fe _{0.75} Cu _{0.11} Ni _{0.03}) _{0.89}
5	16.3	0.24	0.78	1.38	0.16	—	—	—	5.63	74.8	(Pt _{1.03} Ir _{0.08} (Fe _{0.78} Cu _{0.06} Ni _{0.04} Co _{0.01}) _{0.89}
6	17.9	—	0.33	3.42	0.11	—	0.25	—	0.57	77.7	(Pt _{1.01} Pd _{0.01} Ir _{0.01}) _{1.03} (Fe _{0.82} Cu _{0.14} Ni _{0.01}) _{0.97}
7	18.6	—	0.32	2.28	0.14	0.16	0.40	0.08	6.06	70.3	(Pt _{0.93} Ir _{0.08} Pd _{0.01}) _{1.02} (Fe _{0.86} Cu _{0.09} Ni _{0.01}) _{0.96}
8	18.5	0.25	0.29	1.23	0.52	0.36	—	—	1.12	78.6	(Pt _{1.04} Rh _{0.01} Ir _{0.01} Ru _{0.01}) _{1.07} (Fe _{0.85} Cu _{0.05} Ni _{0.01} Co _{0.01}) _{0.92}
9	18.1	0.12	0.28	2.12	—	—	—	—	1.16	78.3	(Pt _{1.04} Ir _{0.02}) _{1.06} (Fe _{0.84} Cu _{0.09} Ni _{0.01} Co _{0.01}) _{0.95}
10	19.3	—	0.64	1.23	—	—	—	—	2.29	75.0	(Pt _{1.00} Ir _{0.03}) _{1.03} (Fe _{0.90} Cu _{0.05} Ni _{0.03}) _{0.98}
11	18.9	0.18	0.73	1.95	0.26	0.35	—	—	—	76.0	(Pt _{1.00} Rh _{0.01} Ru _{0.01}) _{1.02} (Fe _{0.87} Cu _{0.08} Ni _{0.03} Co _{0.01}) _{0.99}
12	16.3	0.21	1.10	4.41	—	0.38	—	—	—	77.6	(Pt _{1.01} Rh _{0.01}) _{1.02} (Fe _{0.74} Cu _{0.18} Ni _{0.05} Co _{0.01}) _{0.98}
13	16.4	0.29	0.42	3.20	—	0.99	0.95	—	1.28	76.2	(Pt _{1.01} Pd _{0.02} Ir _{0.02} Rh _{0.02}) _{1.07} (Fe _{0.76} Cu _{0.13} Ni _{0.02} Co _{0.01}) _{0.92}
14	19.6	0.10	0.76	1.05	0.34	1.40	0.20	—	1.69	75.4	(Pt _{0.97} Ir _{0.02} Rh _{0.03} Ru _{0.01}) _{1.03} (Fe _{0.88} Cu _{0.04} Ni _{0.03}) _{0.95}
15	19.5	0.19	0.88	1.35	0.27	0.94	0.56	—	—	75.5	(Pt _{0.98} Rh _{0.02} Pd _{0.01} Ru _{0.01}) _{1.02} (Fe _{0.88} Cu _{0.05} Ni _{0.04} Co _{0.01}) _{0.98}
16	21.7	0.21	0.25	0.12	0.37	0.58	0.28	—	0.56	74.8	(Pt _{0.96} Rh _{0.01} Pd _{0.01} Ru _{0.01}) _{1.00} (Fe _{0.98} Cu _{0.00} Ni _{0.01} Co _{0.01}) _{1.00}
17	21.3	0.25	0.47	0.60	—	0.48	—	—	0.97	75.2	(Pt _{0.97} Rh _{0.01} Ir _{0.01}) _{0.99} (Fe _{0.96} Cu _{0.02} Ni _{0.02} Co _{0.01}) _{1.01}
18	10.8	0.10	1.05	11.9	—	0.87	0.32	—	—	75.1	(Pt _{0.97} Rh _{0.02} Pd _{0.01}) _{1.00} (Fe _{0.49} Cu _{0.47} Ni _{0.04}) _{1.00}
19	10.4	0.16	0.74	11.5	1.19	0.37	—	1.27	1.12	74.2	(Pt _{0.96} Ru _{0.30} Os _{0.02} Ir _{0.01} Rh _{0.01}) _{1.03} (Fe _{0.47} Cu _{0.46} Ni _{0.03} Co _{0.01}) _{0.97}
20	11.0	—	0.92	11.2	0.29	—	0.76	—	0.58	75.5	(Pt _{0.98} Pd _{0.02} Ir _{0.01} Ru _{0.01}) _{1.02} (Fe _{0.50} Cu _{0.45} Ni _{0.04}) _{0.99}

Analyses 1–17, tetraferroplatinum and cuprous tetraferroplatinum; analyses 18–20, tulameenite; formulas calculated per two atoms. Dash, element content is below detection limit.

Table 5. Chemical composition of PGE sulfides, sulfoarsenides, plumbides, mercurides, and tellurides (wt %)

Ana-lysis	S	Fe	Ni	Cu	As	Ru	Rh	Pd	Te	Os	Ir	Pt	Pb	Bi	Total	Mineral
1	13.7	0.32	0.26	0.15				2.74				82.9			99.9	@Сперрилит
2	29.5	16.6	9.59	5.46	—	—	11.1	—	—	—	26.8	0.45	—	—	99.5	Ferrorhodsite
3	13.8	1.61	0.23	0.17	10.3	1.85	5.03	—	—	30.7	17.9	18.3	—	1.33	101.2	Osarsite
4	19.8	—	—	—	10.1	2.14	3.24	—	—	45.8	11.9	5.59	—	1.01	99.7	"
5	11.6	1.85	—	0.24	19.9	1.13	2.71	—	—	—	52.3	9.38	—	0.44	99.6	Irarsite
6	13.5	0.53	—	—	21.0	1.26	3.04	0.35	—	—	56.8	3.85	—	0.91	101.2	"
7	12.6	0.28	—	—	27.4	1.16	12.1	—	—	—	42.4	3.90	—	1.10	100.7	Irarsite—holling-worthite
8	20.1	1.14	1.14	5.13	—	—	13.0	—	—	—	30.9	14.3	15.0	—	100.8	Xingzhongite
9	21.7	0.76	2.95	6.13	—	—	16.1	0.52	—	—	24.6	8.73	17.3	—	98.8	"
10	—	0.62	—	—	—	—	—	50.6	—	—	—	5.25	34.5	—	91.1	Zvyagintsevite
11	—	0.68	—	—	—	—	—	51.6	—	—	—	5.17	32.9	—	90.3	"
12	26.5	15.4	7.51	4.73	—	—	12.4	—	—	—	21.5	12.4	—	—	100.3	Ferrorhodsite
13	26.9	18.3	6.54	4.45	—	—	14.4	—	—	—	21.9	6.67	—	—	99.0	"
14	27.7	16.1	9.12	5.97	0.93	—	15.5	—	—	—	23.2	1.32	—	—	99.8	"
15	—	0.16	0.11	—	—	—	21.3	—	48.7	—	—	1.74	9.93	13.9	98.0	Unnamed
16	0.10	0.28	—	0.28	—	—	25.9	—	49.8	—	1.72	1.71	11.3	11.2	102.4	"
17	—	0.34	—	—	—	0.39	24.0	—	50.2	—	2.68	1.57	11.4	10.7	101.3	"
18	—	0.27	—	0.27	0.48	—	24.7	—	50.2	—	1.96	2.68	11.4	10.0	101.9	"

Dash, element content is below detection limit.

2012; Mochalov, 2013) and in the Konder massif (Cabri and Laflamme, 1997).

Among PGM associated with zonal massifs of the Urals, potarite was first described in chromatites of the Uktusky massif (Pushkarev et al., 2007); it was then found in clinopyroxenite of the Butyrinsky vein in the Kytlymsky massif (Moloshag et al., 2008). On the whole, this mineral is quite rare among PGM from the zonal clinopyroxenite—dunite massifs and is widespread in ore rocks of ophiolite massifs (Yang and Secombe, 1993; Arai et al., 1999; Malitch et al., 2001) and their related placers (Hagen et al., 1990), as well as layered intrusions typical of platinoid mineralization (Tolstykh and Podlipskii, 2010; Kislov, 2015).

When performing comparative analysis of the studied placer mineralization from deluvial sediments of the upper reaches of the Veresovka river and the results of studying source chromite—platinum ores of the zonal clinopyroxenite—dunite massifs of the Urals, taking into account the morphological features of the characterized PGM, it seems possible to distinguish three mineral parageneses in accordance with the classification proposed in (Stepanov et al., 2017). The following should be attributed to the first, igneous, paragenesis: Pt—Fe solid solutions of variable composition from Pt₃Fe to Pt₂Fe, Os—Ir—(Ru) intermetallic compounds, kashinite—bowieite, laurite—erlichmanite, and Ir—Rh thiospinels. The second, postigneous par-

agenesis, caused by the active serpentinization of dunites, includes tetraferroplatinum group minerals. The third, latest paragenesis, apparently associated with metamorphic processes of predominant dunites, includes ferrorhodsite, Os, Ir, Ru, and Rh sulfoarsenides, zvyagintsevite, potarite, and Te- and Pb-bearing minerals.

The features of PGM in the deluvial placer in the upper reaches of the Veresovka river and, primarily, the wide distribution of minerals from the overprinted low-temperature assemblage indicate the maximum manifestation of secondary transformation processes of source ores within the Veresovoborsky massif compared to other massifs of the Ural Platinum Belt. To reveal the reasons for the widespread sulfides, sulfoarsenides, plumbides, mercurides, and other minerals requires in-depth analysis of the crystallization processes of clinopyroxenite—dunite massifs and subsequent transformation of the rocks they consist of during the formation and tectonic transformation of the western part of the Tagil—Magnitogorsk megazone.

CONCLUSIONS

The placer in the upper reaches of the Veresovka River, based on the genetic classification of (Bilibin, 1955), is attributed to deluvial placers with an insignif-

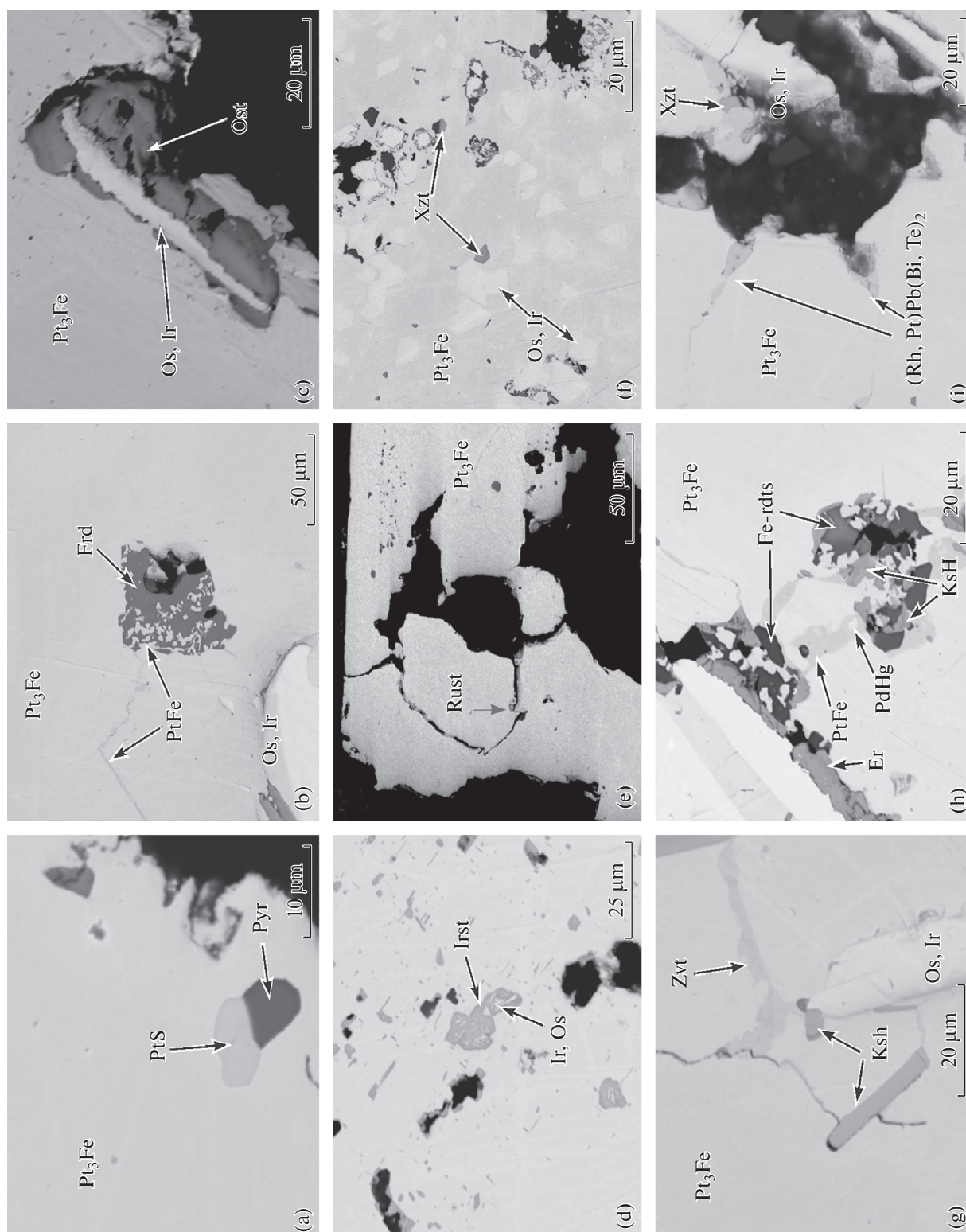


Fig. 7. Assemblage of PGE sulfides, sulfarsenides, plumbides, and mercurides in Pt-Fe minerals. Pt_3Fe , isoferroplatinum; $PtFe$, tetraferroplatinum; Os , Ir, **iridosmium**; Ir , **osmium**; Os , **osmiridium**; PtS , cooperite; Pyr , pyrrhotite; Frd , ferrosulfide; Ost , osarsite; $Irst$, irarsite; $Rust$, ruarsite; Xzt , xingzhongite; Zvt , zvyagintsevite; Ksh , kashinite; Er , erlichmanite; $PdHg$, potarite; $Fe-rdts$, ferrosulfide; $(Rh, Pt)Pb(Bi, Te)_2$, unnamed mineral.

icant transport distance of detrital material from the orebody—dunites of the northern part of the Veresovoborsky massif.

The morphological features of the studied PGM owing to their weakly manifested transformation processes during the transport of detrital material allow extrapolation of the genetic observations of individuals from the placer assemblage to the ore mineralization. This makes it possible to use the proposed mineral-formation model to identify the parageneses of PGM from the placer assemblage.

Owing to the predominance among PGM of Pt—Fe minerals with inclusions of Os—Ir—(Ru) intermetallic compounds, kashinite, bowieite, erlichmanite, laurite, and Ir—Rh spinels, it is possible to consider that the Veresovka River placer **PMG** assemblage is similar to the platinoid mineralization of zonal clinopyroxenite—dunite massifs and their related placers. A stark distinguishing feature of the PGM assemblage of the Veresovka River placer, in comparison to other zonal massifs of the Urals and their adjacent platinum placers, is widespread later overprinted minerals from the group of PGE sulfides, sulfoarsenides, plumbides, mercurides, and tellurides.

ACKNOWLEDGMENTS

The study was supported by the Russian Foundation for Basic Research (project no. 18-35-00151-**18**).

REFERENCES

- Arai, S., Prichard, H.M., Matsumoto, I., and Fisher, P.C., Potarite (Pd—Hg) in thermally metamorphosed dunite from the Inazumi—Yama ultramafic complex, southwestern Japan: an implication for the behaviour of mercury in PGE mineralization in peridotite, *Mineral. Mag.*, 1999, vol. 63, no. 3, pp. 369—377.
- Auge, T., Genna, A., Legendre O., Ivanov, K.S., and Volchenko, Yu.A., Primary platinum mineralization in the Nizhny Tagil and Kachkanar ultramafic complexes, Urals, Russia: a genetic model for PGE concentration in chromite-rich zones, *Econ. Geol. Bull. Soc. Econ. Geol.*, 2005, no. 4, pp. 707—732.
- Begizov, V.D., Zavyalov, E.N., and Khvostova, V.P., Minerals of the erlichmanite-laurite and hollingworthite-irarsite series from the Ural placers, *Zap. Vsesoyuz. Mineral. O-va*, 1976, vol. 2, pp. 213—218.
- Bilibin, Yu.A., *Osnovy geologii rossypei* (Principles of Placer Geology), Moscow: AN SSSR, 1955.
- Cabri, L.J. and Laflamme, J.H.G., Platinum-group minerals from the Konder massif, Russian Far East (Russia), *Miner. Rec.*, 1997, vol. 28, no. 2, pp. 97—106.
- Distler, V.V., Kryachko, V.V., and Yudovskaya, M.A., Ore petrology of chromite-PGE mineralization in the Kempir-sai ophiolite complex, *Mineral. Petrol.*, 2008, vol. 92, pp. 31—58.
- Duryagina, A.M., Talovina, I.V., and Nikiforova, V.S., Platinum bearing capacity of the weathering crust of the Svetloborsky and Nizhny Tagil massifs of the Ural, *Mater. XVth Mezhdunarodnogo Soveshchaniya po geologii rossypei i mestorozhdenii kor vyvetriviya*, (Materials of the XV International Meeting on the Geology of Placers and Weathering Crust Deposits), Perm: PGNIU, 2015, pp. 61—62.
- Ivanov, O.K., *Contsenrticheski zonal'nye piroksenite-dunitovy massivy Urala. Mineralogiya, Petrologiya, Genezis* (Concentric-Zonal Pyroxenite—Dunite Massifs of the Urals: (Mineralogy, Petrology, Genesis)), Yekaterinburg: Ural. Univ., 1997.
- Kiseleva, O.N., Zhdomik, S.M., Damdinov, B.B., Agafonov, L.V., and Belyanin, D.K., Composition and evolution of PGE mineralization in chromite ores from the Il'chir ophiolite complex (Ospa-Kitoy and Khara-Nur areas, East Sayan), *Russ. Geol. Geophys.*, 2014, vol. 55, no. 2, pp. 259—272.
- Kislov, E.V., Sulfide platinum-copper-nickel and low-sulfide platinum-mineralization of the Yoko-Dovyrensky intrusion, Northern Baikal region: differences in composition and genesis. *Metallogeniya drevnikh i sovremennykh okeanov* (Metallogeny of Ancient and Modern Oceans), 2015, no. 21, pp. 128—132.
- Kutyrev, A.V., PGM mineralization of dunites of the Snow concentric-zonal massif, Koryak highlands, *Metallogeniya drevnikh i sovremennykh okeanov* (Metallogeny of Ancient and Modern Oceans), 2017, no. 23, pp. 124—128.
- Lazarenkov, V.G., Malitch, K.N., and Sahyanov, L.O., *Platinometall'naya mineralizatsiya zonal'nykh ul'traosnovnykh i komatiitovykh massivov* (PGM Mineralization of Zonal Ultrabasic and Komatiite Massifs), Leningrad: Nedra, 1992.
- Malitch, K.N., Melcher, F., and Muhlhans, H., Palladium and gold mineralization in podiform chromitite at Krauth, Austria, *Mineral. Petrol.*, 2011, vol. 73, pp. 247—277.
- Malitch, K.N., Stepanov, S.Yu., Badanina, I.Yu., and Hiller, V.V., Bedrock platinum-group element mineralization of zonal clinopyroxenite-dunite massifs of the Middle Urals, *Dok. Earth Sci.*, 2017, vol. 476, no. 2, pp. 1147—1151.
- Mochalov, A.G., A genetic model of PGM hosted in cumulative gabbro—pyroxenite—dunite complexes of the Koryak Highland, Russia, *Geol. Ore Deposits*, 2013, vol. 55, no. 3, pp. 145—161.
- Moloshag, V.P., Garayev, A.A., and Voronina, L.K., Syngenetic PGE sulfide mineralization by the example of the Kosvinsky dunite body of the Kytlymsky massif, *Ezhegodnik*, 2008, vol. 156, no. 224—226.
- Mosin, K.I., *Istoriya dobychi platiny na Urale* (The History of Platinum Mining in the Urals) Nizhnaya Tura: Nizhneturinskaya Tipograf., 2002, p. 246.
- Palamarchuk, R.S. and Stepanov, S.Yu., Characteristics of platinum placers associated with Uralian-Alaskan complex in the Middle Urals, *XIth L. L. Perchuk International School of Earth Sciences*, Miass: 2017, vol. 11, pp. 35—37.
- Palamarchuk, R.S., Stepanov, S.Yu., Khanin, D.A., and Antonov, A.V., PGE mineralization of massive chromitites of the Iov dunite body (Northern Urals), *Moscow Univ. Geol. Bull.*, 2017, vol. 72, no. 6, pp. 445—454.
- Palamarchuk, R.S., Stepanov, S.Yu., Khanin, D.A., Antonov, A.V., and Zolotaryov, A.A., Comparative characteristics of platinum group minerals from eluvial-deluvial placers and chromites of the Svetloborsky clinopyroxenite—dunite massif (Middle Urals), *Mineralogiya*, 2017, vol. 3, no. 4, pp. 37—50.

- Pushkarev, E.V., Anikina, E.V., Garuti, J., and Zakkarini, F., Chromium–platinum mineralization of the Nizhny Tagil type in the Urals: Structural-material characteristic and genesis problem, *Litosfera*, 2007, no. 3, pp. 28–65.
- Razin, L.V., *Promyshlenno-perspektivnyi mineral'no-syr'evoi potentsial Ural'skogo Platinovogo poyasa* (Economically Promising Mineral–Raw Potential of the Urals Platinum Belt, Moscow: Univ. Kniga, 2008. Rychagov, G.I., *Obshchaya geomorfologiya* (General Geomorphology), Moscow: MGU, 2006.
- Savelyev, D.E. and Sergeev, S.N., Accessory mineralization in massive chromite rocks from the manifestation on the Chernyi Klyuch spring (Middle Kraka, Southern Urals), *Geol. Izv. Otd. Nauk Zemle Prir. Res. Akad. Nauk Bashkort.*, 2017, no. 23, pp. 51–58.
- Sidorov, E.G., Kozlov, A.P., and Tolstykh, N.D., *Gal'moenanskii bazit-giperbazitovyy massiv I ego platinonosnost* (Gal'moenan Basite-Hyperbasite Massif and its Platinum Content), Moscow: Nauchn. Mir, 2012.
- Stepanov, S.Yu., Malitch, K.N., Kozlov, A.V., Badanina, I.Yu., and Antonov, A.V., Platinum group element mineralization of the Svetly Bor and Veresovy Bor clinopyroxenite–dunite massifs, Middle Urals, Russia, *Geol. Ore Deposits*, 2017, vol. 59, no. 3, pp. 238–250.
- Stepanov, S.Yu., Palamarchuk, R.S., Kutyrev, A.V., Evolution of the chromite–platinum mineralization of zonal clinopyroxenite–dunite massifs of the Middle Urals, *Magma-tism of the Earth and Related Strategic Metal Deposits. Proceedings of XXXIV International Conference*, Miass: 2017, pp. 274–276.
- Stepanov, S.Yu., Pilyugin, A.G., and Zolotarev, A.A., Comparative characteristics of the compositions of minerals of the platinum group in chromites and placers of the Nizhny Tagil massif, Middle Urals, *J. Mining Inst.*, 2015, vol. 211, no. 1, pp. 22–28.
- Tolstykh, N.D. and Podlipsky, M.Yu., Heavy concentrate halos as prospecting guides for PGE mineralization, *Geol. Ore Deposits*, 2010, vol. 52, no. 3, pp. 196–214.
- Tolstykh, N.D., Sidorov, E.G., and Kozlov, A.P., Platinum-group minerals in lode and placer deposits associated with the Ural-Alaskan-type Gal'moenan complex, Koryak–Kamchatka platinum belt, Russia, *Can. Mineral.*, 2004, vol. 42, pp. 610–630.
- Tolstykh, N.D., Telegin, Yu.M., and Kozlov, A.P., Platinum mineralization of the Svetloborsky and Kamenushinsky massifs (Urals Platinum Belt), *Russ. Geol. Geophys.*, 2011, vol. 52, no. 6, pp. 775–793.
- Tolstykh, N., Kozlov, A., and Telegin, Yu., Platinum mineralization of the Svetly Bor and Nizhny Tagil intrusions, Ural Platinum Belt. *Ore Geol. Rev.*, 2015, vol. 67, pp. 234–243.
- Vildanova, E.Yu., Zaitsev, V.P., and Kravchenko, L.I., *Koryaksko-Kamchatskii region—novaya platinonosnaya provintsiya Rossii*, (Koryak–Kamchatka Region – a New Platinum-bearing Province of Russia, St. Petersburg: VSEGEI, 2002. Vysotsky, N.K., *MEstorozhdeniya platiny Isovskogo I Nezhne-Tagil'skogo raionov na Urale*, (Platinum Deposits of the Isovsky and Nizhne-Tagilsky Regions in the Urals), Tr. Geol. Kom., Novaya Ser., 1913, no. 62.
- Yang, K. and Seccombe, P.K., Platinum-group minerals in the chromitites from the Great Serpentine Belt, NSW, *Austral. Mineral. Petrol.*, 1993, vol. 47, pp. 263–286.
- Zaykov, V.V., Melekesseva, I.Yu., Kotlyarov, V.A., Zaykova, E.V., and Krainov, Yu.D., PGM intergrowths in the Miass placer zone (Southern Urals) and their bedrock sources, *Mineralogiya*, 2016, no. 4, pp. 31–47.

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