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Platinum-Group Minerals of Pt-Placer Deposits Associated with the Svetloborsky Ural-Alaskan Type Massif, Middle Urals, Russia

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Abstract: The alteration of platinum group minerals (PGM) of eluval, proximal, and distal placers associated with the Ural-Alaskan type clinopyroxenite-dunite massifs were studied. The Isovsko-Turinskaya placer system is unique regarding its size, and was chosen as research object as it is PGM-bearing for more than 70 km from its lode source, the Ural-Alaskan type Svetloborsky massif, Middle Urals. Lode chromite-platinum ore zones located in the Southern part of the dunite "core" of the Svetloborsky massif are considered as the PGM lode source. For the studies, PGM concentrates were prepared from the heavy concentrates which were sampled at different distances from the lode source. Eluvial placers are situated directly above the ore zones, and the PGM transport distance does not exceed 10 m. Travyanistyi proximal placer is considered as an example of alluvial ravine placer with the PGM transport distance from 0.5 to 2.5 km. The Glubokinskoe distal placer located in the vicinity of the Is settlement are chosen as the object with the longest PGM transport distance (30–35 km from the lode source). Pt-Fe alloys, and in particular, isoferroplatinum prevail in the lode ores and placers with different PGM transport distance. In some cases, isoferroplatinum is substituted by tetraferroplatinum and tulameenite in the grain marginal parts. Os-Ir-(Ru) alloys, erlichmanite, laurite, kashinite, bowieite, and Ir-Rh thiospinels are found as inclusions in Pt-Fe minerals. As a result of the study, it was found that the greatest contribution to the formation of the placer objects is made by the erosion of chromite-platinum mineralized zones in dunites. At a distance of more than 10 km, the degree of PGM mechanical attrition becomes significant, and the morphological features, characteristic of lode platinum, are practically not preserved. One of the signs of the significant PGM transport distance in the placers is the absence of rims composed of the tetraferroplatinum group minerals around primary Pt-Fez alloys. The sie of the nuggets decreases with the increasing transport distance. The composition of isoferroplatinum from the placers and lode chromite-platinum ore zones are geochemically similar.

Keywords: Ural Platinum belt; Ural-Alaskan massif; Svetloborsky massif; placer system; platinum group elements; platinum group minerals

1. Introduction

At the beginning of the 20th century, clinopyroxenite-dunite massifs, also called Ural-Alaskan type massifs, were found to be the lode sources of the globally unique Ural placer deposits [1–3]. However, for almost 200 years of industrial history of the Ural placer deposit development, only the Solovyeva Mountain lode deposit of the Nizhnetagilsky massif was discovered [3]. At the same time, despite the obvious industrial significance of placers, clinopyroxenite-dunite massifs were studied to a greater extent [4–14]. The last comprehensive work on the geology of placers and the conditions of their formation, as well as platinum-group mineral (PGM) assemblages is the work of N. K. Vysotsky [2], published at the beginning of the last century. Regardless of a number of separate contemporary studies, including those characterizing the PGM assemblages from the placers associated with the Nizhnetagilsky massif [15–17], the platinum-group minerals from other placer systems (e.g., Isovsko-Turinskaya, Nyasminskaya, etc.) have not been studied using modern analytical techniques.

Furthermore, the changes in the platinum-group minerals occurring during their transport from a lode source to a placer were not studied in detail. Despite the significant amount of work devoted to the Koryak-Kamchatka region, as well as the Bushveld complex and the Great Dyke (South Africa), where the formation of the platinum placers [18–24] was investigated in detail, similar studies of the Ural Platinum Belt placers have not been conducted yet.

The aim of this work is to establish the changes in the platinum-group minerals during their transport from the lode source to the alluvial placer by the example of the placer system associated with the Svetloborsky clinopyroxenite-dunite massif.

The present work determined the morphological feature obtained during alteration accompanying the transport of detrital material from the lode source to the placers, and the relationships of mineral assemblages from the alluvial placers of the Isovsko-Turinskaya placer system and the chromite-platinum ore zones of the Svetloborsky massif.

2. Materials and Methods

2.1. Geological Setting

Like other clinopyroxenite-dunite massifs of the Urals, the Svetloborsky massif is located in the western part of the Tagilo-Magnitogorsk megazone (Figure 1a), 15 km east of the Main Uralian Fault [5]. The massif is composed of rocks of the Late Ordovician Kachkanar dunite-clinopyroxenite-gabbro complex and is a tectonic detachment occurring in Silurian metabasalts. The geological structure of the massif is typical of zonal clinopyroxenite-dunite massifs (Figure 1b). Its major part comprises a dunite core composed of fine and medium-grained dunites surrounded by a clinopyroxenite rim of variable thickness. The valleys of transient or weak watercourses forming numerous ravines are well-represented across the massif's area. The Svetloborsky massif is drained by the river Kosya valley in the Southern part, and by the river Is valley in its Northern part. All ravines and river valleys are platiniferous to different degrees.

Two types of lode platinum mineralization are distinguished within the Svetloborsky massif, (1) Platinum-bearing dunites and (2) chromite-platinum mineralization. The first type of mineralization was described in detail by N. D. Tolstykh et al. [9]. The parameters of chromite-platinum mineralization are given in Reference [14].

The manifestation of chromite-platinum mineralization is found for the area of the Vershinniy exploration site, which is located in the South-Western part of the massif. In main trenches dug during geological exploration, vein-disseminated and massive chromitite zones were identified. These zones are located in the fine to medium-grained dunite transition zone with platinum in the concentration range from two to 50 g/t. The majority of individual grains and aggregates of platinum-group minerals in such zones are spatially associated with chromitite segregations [14]. To the West of the Vershinniy exploration site, in the vicinity of the contact between the dunite core and pyroxenites, the Vysotsky site is located, where platinum-bearing dunites were observed. The zone is a linear stockwork with an intensely serpentinized dunite substrate with numerous dykes, lenticular bodies, and veins of pyroxenite, hornblendite and isite (local name, fine-grained melanocratic vein variety of hornblendite named after the river Is in the Urals, Russia). Here, the chromites do not form significant concentrations, and the platinum-group minerals are found directly in the olivine-serpentine matrix without any spatial connection to the chromites [9].

The mineralized zones were subjected to erosion followed by the formation of eluvial placers. The transport of material from eluvium and its subsequent redeposition led to the formation of alluvial placers.

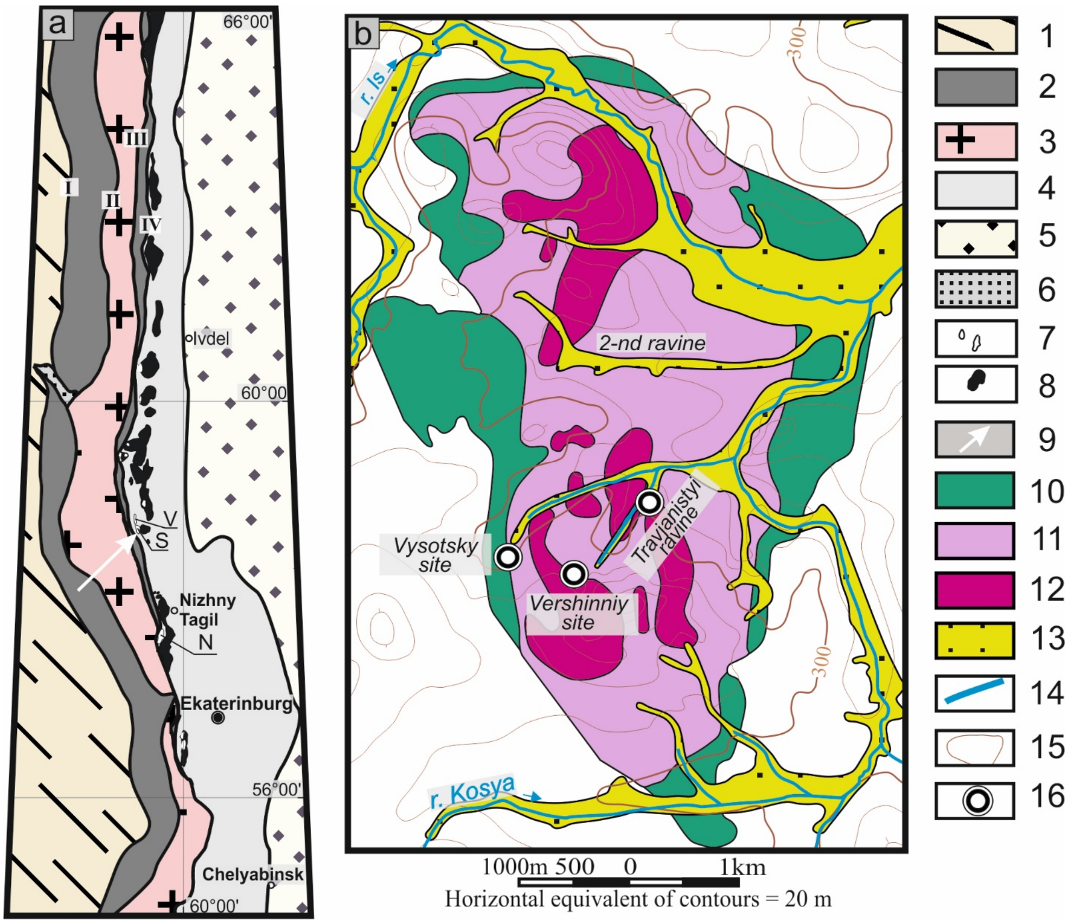

Figure 1. (**a**) The Ural-Alaskan type massifs in the structure of the Urals (compiled from state geological maps of 1:1,000,000 scale): 1—Paleozoic of the East European Platform; 2—Western Ural fold-thrust zone; 3—Central Ural uplift; 4—Tagilo-Magnitogorskaya megazone; 5—sedimentary cover of the West Siberian platform; 6—Polyudovsk uplift; 7, 8—the massifs of the Ural Platinum Belt: 7—dunite bodies, 8—pyroxenites, gabbros, volcanites; 9—the location of Svetloborsky clinopyroxenite-dunite massif. Roman numerals indicate the main faults (thrusts): I—Main Western Ural; II—Osevoy; III—Prisalatimsky; IV—Main Uralian Fault. Letters denote the Ural-Alaskan type massifs: N—Nizhnetagilsky, S—Svetloborsky; and V—Veresovoborsky. (**b**) The Svetloborsky massif's geological structure, compiled from [5] with additions: 10—pyroxenites; 11–12—dunites: 11—fine-, small-grained, 12—medium-grained; 13—alluvial sediment; 14—rivers, streams; 15—contour lines; and 16—sites of detailed sampling.

All studied placers belong to a single connected drainage system. The section of modern sediments of the Vershinniy exploration site (Figure 1b) overlapping the allocated chromite-platinum zone is given as an example of eluvial placer [14]. The structure, characteristics and composition of the PGM assemblages from this placer were described in detail earlier [25]. Travyanistyi ravine is taken as an example of a ravine, proximal or alluvial placer with a small transport distance of the detrital material, whose sources are located on the Vershinniy site. The transport distance of the detrital material from the lode source to the sampling site is slightly more than 1 km. The sampling site of the alluvial placer with a transport distance of more than 30 km (distal placer) is represented by the Glubokinskoe site belonging to the Isovsko-Turinskaya placer system (Figure 2).

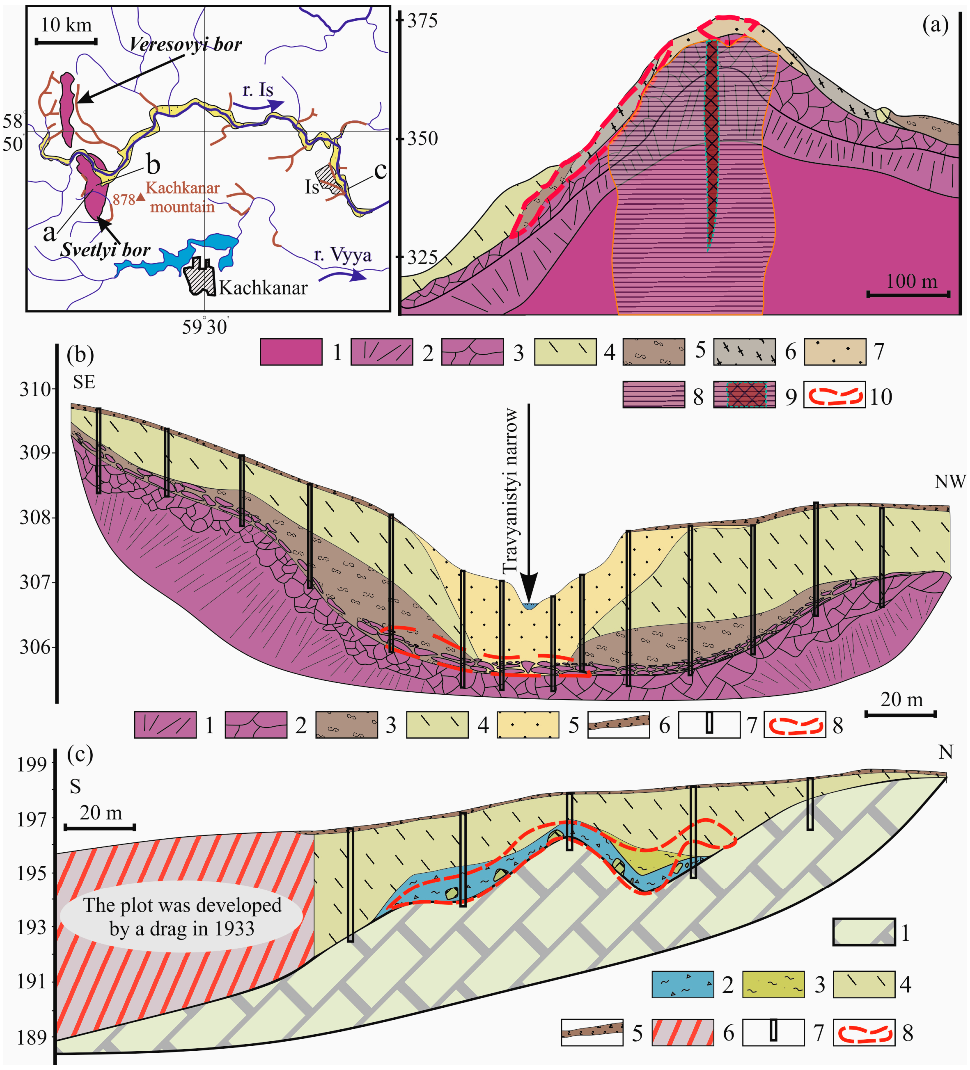

Figure 2. On the map are the rivers Is and Viya, Is and Kachkanar villages, as well as the sampling sites: Vershinniy eluvial (**a**), Travyanistyi proximal (**b**) and Glubokinskoe distal (**c**) placers. Platinum placers are designated by brown (**a**): 1—dunites, 2—serpentinized fractured dunites, 3—weathered serpentinized dunites, 4—sediments of temporary watercourses, 5—clay-eluvial sediments, 6—eluvial with low clay amount, 7—eluvial, 8—vein-disseminated chromitites, 9—massive chromitites, 10—the contour with the platinum content of more than 200 mg/m^3. (**b**): 1—serpentinized fractured dunites, 2—weathered serpentinized dunites, 3—clay-eluvial sediments, 4—sediments of temporary watercourses, 5—alluvial sediments, 6—soil-turf layer, 7—dug holes, 8—the contour with the platinum content of more than 200 mg/m^3. (**c**): 1—Silurian limestone, 2—Jurassic alluvial, 3—Neogenic sediments of temporary watercourses, 4—sediments of temporary watercourses, 5—soil-turf layer, 6—anthropogenic sediments, 7—dug holes, and 8—the contour with the platinum content of more than 200 mg/m^3.

During geological exploration, a heavy concentrate survey was carried on a 40 × 20 m grid at the Vershinniy site. As a result, a platinum anomaly was found in eluvial sediments, and its contours were drawn up according to the platinum contents of 0.2 g/m^3. The eluvial deposits enriched with platinum minerals are located at the top of the hill (Figure 2a), directly above the development zone of massive chromitites. These deposits are represented by unsorted gravel-sand mixtures having a small fraction of clay component and an uneven PGM distribution. The contour of the platinum anomaly generally follows the contour of the lode chromite-platinum ore zone.

The eluvial deposits occurring on the slope of the hill are characterized by a larger amount of clay and a smaller fraction of the dunite fragments compared to eluvial deposits from the top of the hill. PGM in such sediments are slightly concentrated in the lower parts of the section, but generally, the sorting of the material remains poor.

The modern sediments, largely sorted during the further transport of detrital material by temporary watercourses, cover the previously formed eluvial-clay sediments in many parts of the placer (Figure 2b). In the valley's central part, directly in the river bed, the alluvial deposits are formed with a section typical for such placers (from top to bottom): soils (up to 1 m thick), clay deposits (up to 1 m), sometimes a small layer of gravel, and a layer of sand (about 0.2 m). The rock names in such sections are given after the predominant fraction in the composition of clay-sand-gravel mixtures. Most PGM are concentrated in the sand layer.

The tested alluvial placer deposits having a long transport distance belong to the site of the first terrace of the Is river valley. The Mesozoic alluvial (according to state geological maps of 1:200,000 scale) deposits occurring on Silurian limestone (Figure 2c) are platinum-bearing. In the Paleogene, these deposits were largely washed up, resulting in a platinum-bearing Paleogene sediment formation. The Jurassic and Paleogene sediments are covered by modern sediments of up to 4 m thick, with platinum-bearing areas being present in some of its parts, represented by washed-up ancient sediments. The large thicknesses of clay and gravel deposits are noted for the alluvial placer with a long transport distance as compared to the section of the proximal placer sediments. The major amount of PGM is also concentrated in the sands.

2.2. Sample Collection and Preparation

In order to extract the platinum-group minerals from the chromitites of the Svetloborsky massif (Figure 3), bulk samples of chromitite rocks weighing 60–80 kg were collected from the lode outcrops and main trenches, which were studied during the geological exploration survey for the lode platinum mineralization by ZAO Ural-MPG (closed joint stock company Ural-MPG). The samples were crushed to a fraction of −1 mm and enriched with a centrifugal concentrator.

The eluvial placer of the Vershinniy site was tested by a heavy concentrate survey with the sampling of modern sediments with a volume of 20 L. These heavy concentrate samples were kindly given to us for further research by A. V. Korneev, ZAO Ural-MPG chief geologist.

The proximal placer of the Travyanistyi ravine and the distal placer of the Isovsko-Turinskaya placer system were tested during independent expeditionary work. Samples with a volume of 50 L each were taken from the already processed sites. The samples were enriched using a centrifugal concentrator.

The concentrates and heavy mineral concentrates consist mainly of chromit and PGM grains. The PGM were extracted from the concentrates using the "blow-off", one of the varieties of the air separation method that can be used on-site during the fieldwork. It is based on the difference in the density of chromit and PGM. Under the action of air flow from human lungs, less dense chromites are removed from the concentrate, while denser PGM remain. PGM grains were studied under a binocular microscope, followed by their mounting on carbon conductive adhesive tape, and studied by scanning electron microscopy. PGM compositions of the grains were analyzed by EPMA (electron probe microanalyzer) after the grains were placed in polished sections made of epoxy resin.

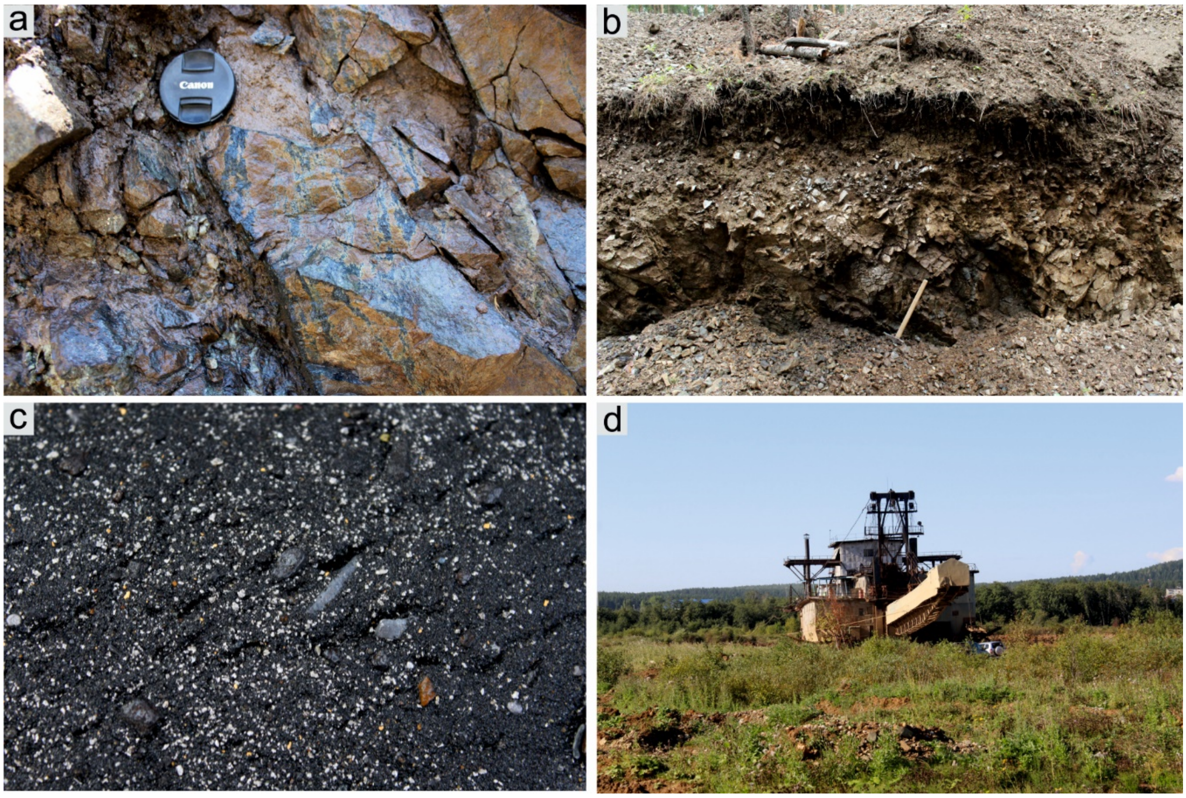

Figure 3. (**a**) Photo of chromitite in bedrock of Svetloborsky massif, (**b**) dunite gutter with modern sediments at proximal placer, (**c**) heavy mineral concentrate with PGM, and (**d**) the last dredge at the Isovsko-Turinskaya placer system.

2.3. Analytical Methods

The morphological features of PGM were studied using a CamScan MX2500 scanning electron microscope (VSEGEI, Saint-Petersburg, Russia). The morphological features of PGM, as well as their internal structure and composition, were examined using a CamScan MV2300 SEM with the INCA Energy 350 detector at an accelerating voltage of 20 kV, working distance 25 mm, and spectral accumulation time of 70 s (IEM RAS, Chernogolovka, Russia). The following standards were used: Pure metals for platinum-group elements (using the Lα-line), Cu, Fe, Ni, Co, FeS_2 synt for S, InAs for As, pure element for Sb. The size of the electron beam spot on the surface of the sample varied from 115 to 140 nm, in a scanning mode to 60 nm, while the excitation zone can reach 4–5 µm (depending on the microrelief, structure and composition of samples). The SEM images were obtained in the backscattered electron mode with material contrast and 10× to 2500× magnification.

The chemical composition of the PGM was determined using a Camebax SX50 X-ray microanalyzer in WDS-mode at an accelerating voltage of 20 kV and a probe current of 30 nA (MSU, Moscow, Russia). The following reference materials were used for calibration: pure metals for Ru, Rh, Pd, Os, Ir and Pt; $CuSbS_2$ for Sb and Cu; CoAsS for Co; NiS for Ni; FeS for Fe and S. Detection limits were (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, and Bi—0.1.

3. Results

3.1. Morphological Features

The platinum-group minerals from the bedrock are characterized by a variety of surfaces. Idiomorphic cubic crystals with sizes less than 50 µm, described for different types of lode mineralization, are distinguished [9,14], as well as relatively large aggregates cementing the chromit grains, rarely exceeding 1 mm in size. Xenomorphic grains of similar size with dissolved surfaces are found in the dunite type of mineralization. Quite often, individual grains with idiomorphic and xenomorphic surfaces are intergrown and form relatively large (about 300 um on average) aggregates with well-developed own growth and inherited impression surfaces. For most grains, numerous plane-faced surfaces are observed as well as well-pronounced edges and vertices of the crystals. Many surfaces are characterized by the presence of growth striations that formed both in the process of joint growth of Pt-Fe alloys with chromits (Figure 3b–d) and as a result of the simple form alternation of individual platinum grains during the crystal growth.

The individuals and aggregates of Pt-Fe alloys from the eluvial placer of the Vershinniy site are characterized by morphological features similar to the PGM from the lode sources. There are single individuals with a cubic faceting (Figure 4e). The grains with the plane-faced surfaces and growth striations are quite widespread. Their edges and vertices are not as clearly expressed as those of the Pt-Fe alloy grains from the chromitites. Some grains show signs of mechanical deformations such as poor rounding and irregular grooves (Figure 4f). Hexagonal osmium plates retaining their idiomorphic form were found in a single case.

PGM nuggets from the Travyanistyi proximal placer are characterized both by the abundance of plane-faced growth surfaces (Figure 5a,b) and by the prevalence of deformed fragments (Figure 5c). Growth striations are rare. About 60% of PGM nuggets have size of 0.5–1.5 mm. Hexagonal pinacoidal osmium inclusions are found in some of the individuals (Figure 5d).

The grains from the distal placer show both elongated (Figure 5e,f) and isometric forms (Figure 5g,h). Almost all edges and vertices of the individuals are smoothed. Single grooves formed by mechanical abrasion during the transport of the detrital material are rarely found on the surfaces of Pt-Fe alloy grains. In this placer, PGM nuggets have a prevailing size of 0.1–0.5 mm comprising about 75% of PGM in heavy concentrate.

Pt-Fe alloys retain the primary morphological features characteristic of lode PGM in the placers with a small distance of clastic material transport. At a long distance (more than 10 km), the degree of mechanical attrition of PGM becomes significant, and the morphological features characteristic of lode PGM assemblages (plane-faced surfaces and growth striations) are practically not preserved. During of transport the rim integrity around isoferroplatinum, commonly composed of tetraferroplatinum group minerals were destroyed. In the placer with longest transport distance they are completely destroyed. The size of the nuggets decreases with an increasing transport distance from lode chromite-platinum zone oin prximal and distal placers.

3.2. Chemical Composition of Platinum-Group Minerals

PGM assemblages of the Ural-Alaskan type massifs has been studied to a great extent. All PGM nuggets are Pt-Fe alloys with rare inclusions of accessory minerals (Os-Ir-Ru alloys and PGE sulfides). The content of accessory do not exceed 3% of grain volume. Iridium nuggets occure extremely seldom. Pt-Fe alloys (native platinum, isoferroplatinum and ferroan platinum according to classification [26]) and minerals of the tetraferroplatinum group (tetraferroplatinum-tulameenite-ferronickelplatinum solid solution), are predominating. The mineral inclusions of Os-Ir-(Ru) alloys are abundant in Pt-Fe alloys. Sulfides of the laurite-erlichmanite isomorphous series are also common as inclusions in Pt-Fe minerals. Sulfides of the kashinite-bowieite isomorphous series, as well as the minerals of the Pt-Ir-Rh thiospinel group are relatively rare, and by analogy with other sulfides and Os-Ir-(Ru) alloys, form inclusions in Pt-Fe alloys.

Some Pt-Fe alloys that can be defined only by their crystal structure, and therefore, the mineral with Pt_3Fe composition or close to it is referred to as isoferroplatinum, and Pt_2Fe composition or close to it as ferroan platinum.

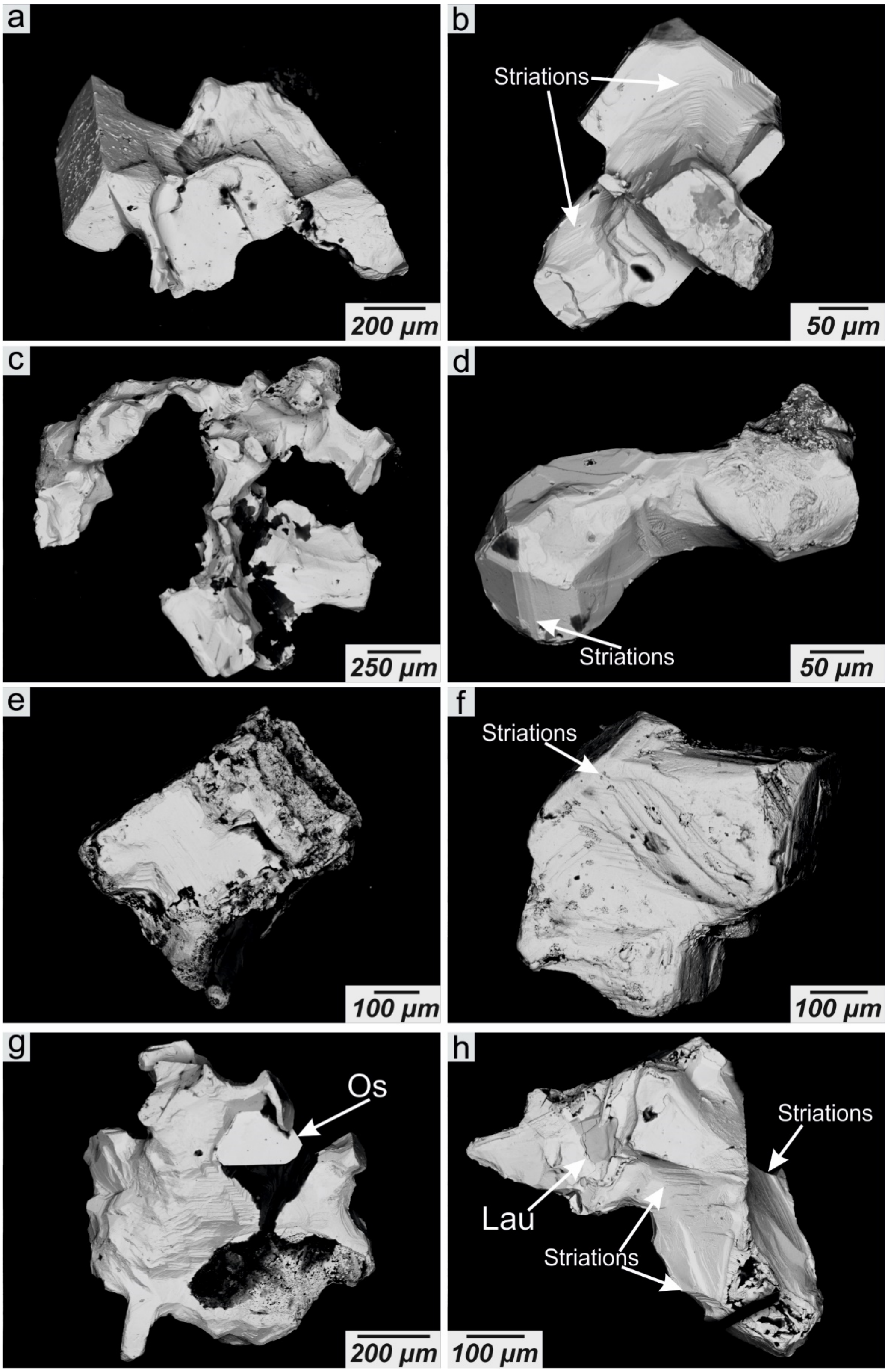

Figure 4. The morphological features of Pt-Fe alloy grains from lode chromite-platinum mineralization (**a**–**d**) and Vershinniy eluvial placer (**e**–**h**). Os—osmium, Lau—laurite. The **g** photo was published in Reference [25]. BSE images (SEM).

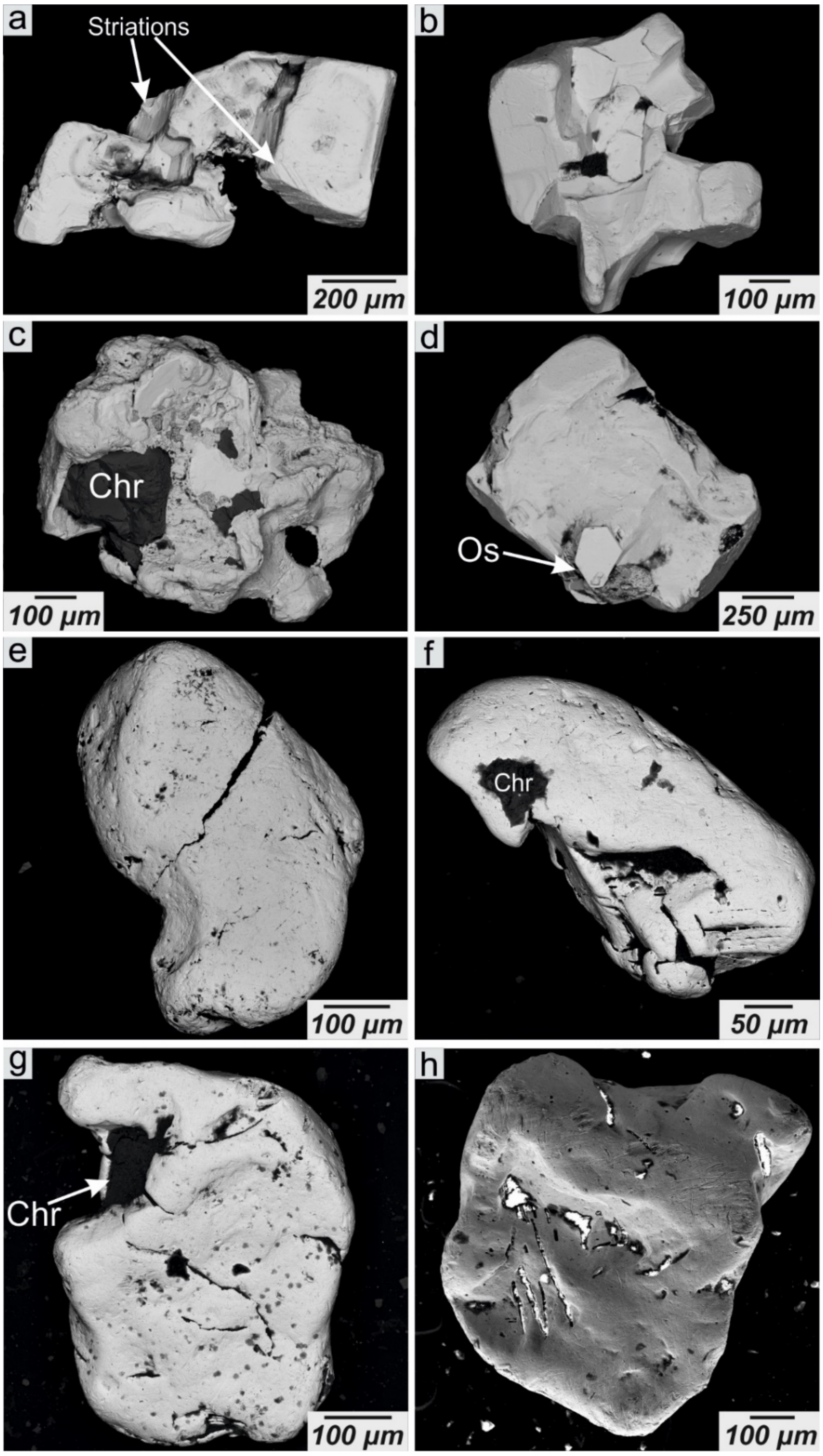

Figure 5. Morphological features of Pt-Fe alloy grains from the Travyanistyi proximal placer (**a**–**d**) and Glubokinskoe distal placer (**e**–**h**). Os—osmium, Chr—chromite. BSE images (SEM).

3.2.1. Pt-Fe Alloys

The assemblages of Pt-Fe alloys from the bedrock of the Svetloborsky massif and the placers is characterized by the predominance of isoferroplatinum (>95%). Native platinum is not present, and ferroan platinum is observed as single small inclusions in isoferroplatinum.

Isoferroplatinum mainly forms homogeneous grains both in primary ores and in the placer assemblages (Figure 6). However, the Pt content of isoferroplatinum varies considerably from 55.6 to 76.9 at. %, while the amount of total PGE lies within a smaller range and comprises 74 at. % on average, close to the isoferroplatinum theoretical formula (Table 1). Such a consistent average content of the PGE totals, with a significant fluctuation of Pt is due to the significant concentrations of impurity components, which can reach 12.8 at. %. Iridium is characterized by the highest concentrations (up to 7 at. %). Rh and Pd contents are relatively consistent, and on average do not exceed 1 at. %. Ru is characterized by very low concentrations, on average below 0.2 at. %. Os content can reach 1 at. %, however, this may be due to small inclusions of the Os-Ir-Ru alloys. Cu shows consistent concentrations ranging from 1.3 to 1.8 at. %. Ni does not exceed 0.2 at. %, however, its content is characterized by an inverse relationship with the amount of the PGE, reaching 1.6 at. %.

Table 1. Compositions of isoferroplatinum (1–20) and ferroan platinum (18–22) from the chromite-platinum ore zones of the Svetloborsky massif and associated placers.

No.	Fe	Ni	Cu	Ru	Rh	Pd	Ir	Pt	Total	No.	Fe	Ni	Cu	Ru	Rh	Pd	Ir	Pt
					wt. %									*at. %*				
1	7.85	0.13	0.86	0.12	1.03	0.26	0.51	88.67	99.43	1	22.43	0.35	2.16	0.19	1.60	0.39	0.42	72.46
2	8.72	0.13	0.84	bdl	0.73	0.54	bdl	88.76	99.72	2	24.46	0.35	2.07	bdl	1.11	0.79	bdl	71.22
3	8.73	0.02	0.51	bdl	0.67	0.77	1.03	87.22	98.95	3	24.79	0.05	1.27	bdl	1.03	1.15	0.85	70.86
4	7.89	0.07	0.87	bdl	1.24	0.18	3.44	85.90	99.59	4	22.51	0.19	2.18	bdl	1.92	0.27	2.85	70.08
5	7.83	0.09	0.73	0.02	0.83	1.03	1.18	89.07	100.78	5	22.13	0.24	1.81	0.03	1.27	1.53	0.97	72.02
6	7.41	bdl	1.03	bdl	0.17	0.47	1.95	89.58	100.61	6	21.27	bdl	2.60	bdl	0.26	0.71	1.62	73.54
7	7.70	0.06	0.70	bdl	0.54	0.58	4.60	86.42	100.60	7	21.99	0.17	1.76	bdl	0.83	0.87	3.81	70.57
8	7.47	0.02	0.75	bdl	0.59	0.57	7.52	83.45	100.37	8	21.46	0.05	1.89	bdl	0.92	0.86	6.27	68.55
9	7.84	0.09	0.59	0.24	0.85	bdl	1.60	89.51	100.72	9	22.33	0.24	1.48	0.38	1.31	bdl	1.32	72.94
10	7.84	0.04	0.63	0.56	0.88	0.41	1.85	88.50	100.71	10	22.22	0.11	1.57	0.88	1.35	0.61	1.52	71.74
11	8.56	0.37	0.84	bdl	0.73	0.11	bdl	90.08	100.69	11	23.87	0.98	2.06	bdl	1.10	0.16	bdl	71.83
12	8.19	0.05	0.10	0.20	1.02	0.56	0.15	90.64	100.91	12	23.23	0.13	0.25	0.31	1.57	0.83	0.12	73.56
13	8.80	bdl	0.44	0.21	0.49	0.47	5.07	84.01	99.49	13	24.94	bdl	bdl	1.14	bdl	0.06	4.67	69.19
14	8.55	0.25	0.62	0.31	1.13	0.84	3.93	83.48	99.11	14	24.03	0.67	1.53	0.48	1.72	1.24	3.21	67.12
15	8.64	0.66	1.16	0.24	0.87	0.38	4.06	83.88	99.89	15	23.83	1.73	2.81	0.37	1.30	0.55	3.25	66.16
16	8.62	0.19	0.69	0.11	0.39	0.29	5.15	83.56	99.00	16	24.47	0.51	1.72	0.17	0.60	0.43	4.24	67.86
17	8.27	bdl	0.41	bdl	0.50	0.80	bdl	90.58	100.56	17	23.48	bdl	1.02	bdl	0.77	1.19	bdl	73.54
18	13.59	bdl	1.03	bdl	bdl	bdl	bdl	84.16	98.78	18	35.24	bdl	2.35	bdl	bdl	bdl	bdl	62.41
19	11.54	bdl	1.26	bdl	bdl	bdl	bdl	88.13	100.93	19	30.49	bdl	2.91	bdl	bdl	bdl	bdl	66.60
20	11.63	bdl	1.09	0.05	0.92	bdl	1.26	85.82	100.77	20	30.58	bdl	2.52	0.07	1.32	bdl	0.96	64.55
21	14.60	0.51	0.82	bdl	0.80	0.44	6.00	76.25	99.42	21	36.48	1.21	1.80	bdl	1.08	0.58	4.35	54.50
22	13.36	0.56	0.27	bdl	0.37	0.47	6.10	78.25	99.38	22	34.50	1.37	0.61	bdl	0.52	0.64	4.57	57.79

Locations: the chromite-platinum ore zones of Svetloborsky massif (No. 1–4; 18–19), Vershinniy eluvial placer (No. 5–8; 20), Travyanistyi proximal placer (No. 9–12) and Glubokinskoe distal placer (No. 13–17; 21–22). bdl—below detection limits.

A single grain of ferroan platinum was found in the Glubokinskoe distal placer. Basically, ferroan platinum usually forms single small inclusions in isoferroplatinum. The composition of the ferroan platinum is variable and rarely corresponds to theoretical Pt_2Fe. The minerals of the tetraferroplatinum group occur in subordinate quantities. They form rims around isoferroplatinum with a thickness of up to 50 μm (Figure 6c). Tetraferroplatinum and tulameenite are identified, and the compositions of all studied grains are close to theoretical values (Table 2). The amount of the tetraferroplatinum group minerals regularly decreases from the lode source to the most distant placers, where the rims composed of these minerals are absent.

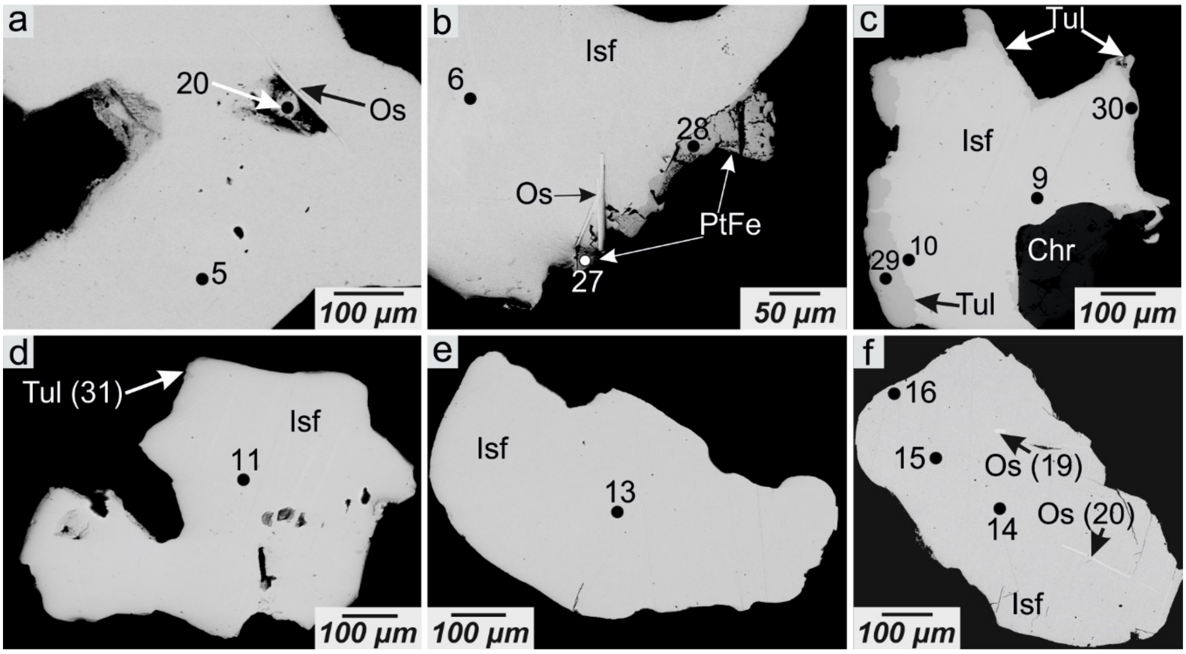

Figure 6. BSE images (SEM) of Pt-Fe aggregates from Vershinniy eluvial (**a**,**b**), Travyanistyi proximal (**c**,**d**) and Glubokinskoe distal (**e**,**f**) placers. The number of points corresponds to the data in Table 1 for isoferroplatinum (No. 5–6, 9–11, 13–16) and ferroan platinum (No. 20), in Table 2 for tetraferroplatinum–tulameenite (No. 27–31) and in Table 3 for osmium (No. 19, 20). Isf—isoferroplatinum, PtFe—tetraferroplatinum Tul—tulameenite, Os—osmium, Ir—iridium, and Chr—chromite. The **a** and **b** photo were published in [25].

Table 2. Compositions of tetraferroplatinum group minerals from the chromite-platinum ore zones of the Svetloborsky massif and associated placers.

No.	Fe	Ni	Cu	Ru	Rh	Pd	Ir	Pt	Total	No.	Fe	Ni	Cu	Ru	Rh	Pd	Ir	Pt
				wt. %										*at. %*				
23	10.66	bdl	13.23	bdl	bdl	bdl	bdl	76.11	100.00	23	24.20	bdl	26.38	bdl	bdl	bdl	bdl	49.42
24	18.90	bdl	3.26	bdl	bdl	bdl	bdl	77.41	99.57	24	43.04	bdl	6.52	bdl	bdl	bdl	bdl	50.44
25	16.28	bdl	2.72	bdl	bdl	bdl	bdl	80.35	99.35	25	39.09	bdl	5.73	bdl	bdl	bdl	bdl	55.18
26	14.93	bdl	1.67	bdl	bdl	bdl	bdl	82.26	98.86	26	37.40	bdl	3.67	bdl	bdl	bdl	bdl	58.93
27	17.44	0.09	1.18	bdl	0.02	0.31	0.39	79.53	98.96	27	41.92	0.21	2.49	bdl	0.03	0.39	0.27	54.69
28	16.78	0.10	2.30	bdl	0.34	1.71	0.06	77.78	99.07	28	39.72	0.23	4.78	bdl	0.44	2.12	0.04	52.67
29	8.75	0.23	13.28	bdl	0.38	0.09	2.86	75.08	100.67	29	20.26	0.51	27.00	bdl	0.48	0.11	1.92	49.72
30	9.31	0.22	12.44	0.49	1.05	0.14	2.52	73.71	99.88	30	21.57	0.48	25.31	0.63	1.32	0.17	1.69	48.83
31	10.61	0.27	11.80	0.15	0.41	0.36	bdl	76.84	100.44	31	24.28	0.59	23.71	0.19	0.51	0.43	bdl	50.29
32	18.17	0.30	1.19	0.41	bdl	0.06	bdl	78.96	99.09	32	42.91	0.67	2.47	0.53	bdl	0.07	bdl	53.35

Locations: the chromite-platinum ore zones of Svetloborsky massif (No. 1–4), Vershinniy eluvial placer (No. 5–6), Travyanistyi proximal placer (No. 7–10). bdl—below detection limits.

A comparative analysis of the Pt-Fe alloy assemblages from the various placers established a general coincidence of the mineral assemblages (Figure 7). The predominance of isoferroplatinum with a relatively consistent composition is characteristic of all the placers studied. Ferroan platinum occurs in the form of small inclusions in the Pt-Fe alloys from the eluvial placer and in the form of a relatively large individual from the Glubokinskoe distal placer. On the contrary, the secondary minerals of the tetraferroplatinum group are found in relatively large amounts in the Pt-Fe alloys from the Travyanistyi ravine; they are present as a single grain in the eluvial placer and are not detected in the Glubokinskoe distal placer. The latter can be explained by a significant transport distance, resulting in the mechanical destruction of the low-hardness tetraferroplatinum group minerals that compose thin peripheral rims.

Table 3. Composition of osmium from the chromite-platinum ore zones of Svetloborsky massif and associated placers.

No.	Ru	Rh	Pd	Os	Ir	Pt	Total	No.	Ru	Rh	Pd	Os	Ir	Pt
			wt. %								*at. %*			
1	6.20	bdl	bdl	50.59	43.21	bdl	100.0	1	11.11	bdl	bdl	48.18	40.71	bdl
2	0.95	bdl	bdl	68.10	30.93	bdl	99.98	2	1.78	bdl	bdl	67.77	30.45	bdl
3	1.65	bdl	bdl	72.02	26.28	bdl	99.95	3	3.07	bdl	bdl	71.22	25.71	bdl
4	1.05	bdl	bdl	73.68	25.27	bdl	100.0	4	1.96	bdl	bdl	73.20	24.84	bdl
5	1.34	bdl	bdl	74.87	23.78	bdl	99.99	5	2.50	bdl	bdl	74.18	23.32	bdl
6	0.14	0.34	bdl	62.54	34.73	1.10	98.85	6	0.26	0.63	bdl	63.27	34.76	1.08
7	0.17	0.68	bdl	67.41	30.86	0.55	99.67	7	0.33	1.26	bdl	67.36	30.51	0.54
8	0.55	0.21	0.16	67.84	29.79	0.19	98.74	8	1.04	0.38	0.29	68.39	29.72	0.18
9	2.43	0.16	0.20	68.36	28.90	1.14	101.19	9	4.44	0.28	0.34	66.17	27.69	1.08
10	0.83	0.46	bdl	89.91	6.57	2.79	100.56	10	1.54	0.83	bdl	88.55	6.40	2.68
11	0.71	0.32	bdl	93.29	5.23	bdl	99.55	11	1.33	0.59	bdl	92.93	5.15	bdl
12	0.68	0.48	bdl	93.1	4.66	bdl	98.92	12	1.28	0.89	bdl	93.21	4.62	bdl
13	0.71	0.34	bdl	92.73	4.87	bdl	98.65	13	1.34	0.63	bdl	93.19	4.84	bdl
14	0.87	0.34	bdl	92.74	5.23	bdl	99.18	14	1.63	0.63	bdl	92.57	5.17	bdl
15	1.01	0.41	bdl	92.72	4.88	bdl	99.02	15	1.90	0.76	bdl	92.52	4.82	bdl
16	2.04	0.89	bdl	76.05	21.34	bdl	100.32	16	3.74	1.61	bdl	74.08	20.57	bdl
17	2.18	0.65	bdl	75.47	22.07	bdl	100.37	17	4.00	1.17	bdl	73.55	21.28	bdl
18	1.05	0.69	bdl	93.26	4.29	bdl	99.29	18	1.95	1.26	bdl	92.58	4.21	bdl
19	6.97	0.30	0.60	60.54	30.40	0.39	99.19	19	12.40	0.52	1.01	57.26	28.45	0.36
20	8.58	0.55	bdl	59.10	28.96	2.82	100.02	20	15.00	0.95	bdl	54.88	26.62	2.55

Locations: the chromite-platinum ore zones of Svetloborsky massif (No. 1–5), the Vershinniy eluvial placer (No. 6–10), the Travyanistyi proximal placer (No. 11–17), and the Glubokinskoe distal placer (18–20). bdl—below detection limits.

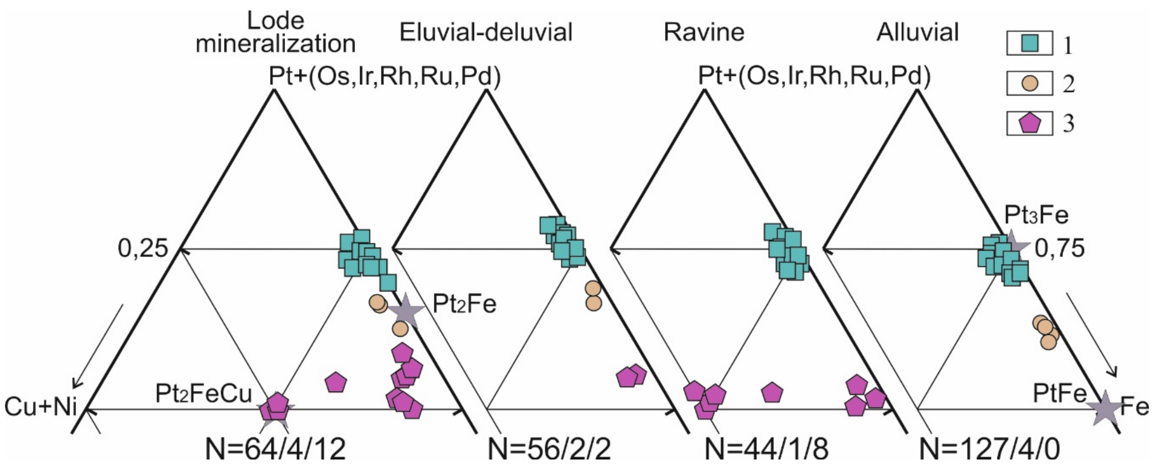

Figure 7. Composition (at. %) of isoferroplatinum (1), ferroan platinum (2) and tetraferroplatinum-tulameenite (3) from placers associated with the Svetloborsky massif and lode chromite-platinum ore zones. N—number of isoferroplatinum/ferroan platinum/tetraferroplatinum-tulameenite. The grey Pentagrams are stoichiometric formulae.

3.2.2. Os-Ir-Ru Alloys

Os-Ir-Ru alloys form four minerals: Osmium, iridium, ruthenium, and rutheniridosmine. However, like in other placers, associated with the Ural-Alaskan type massifs, only osmium and iridium are observed in the placers studied.

Osmium forms predominantly pinacoidal hexagonal inclusions in Pt-Fe alloy grains or regular accretions of lamellar subindividuals (Figure 8a,b). In some Pt-Fe aggregates, osmium is clearly tending towards the phase boundaries of the isoferroplatinum and chromit (Figure 8a,b); in others, it occurs in the form of inclusions in the central parts of the PGM grains (Figure 8c).

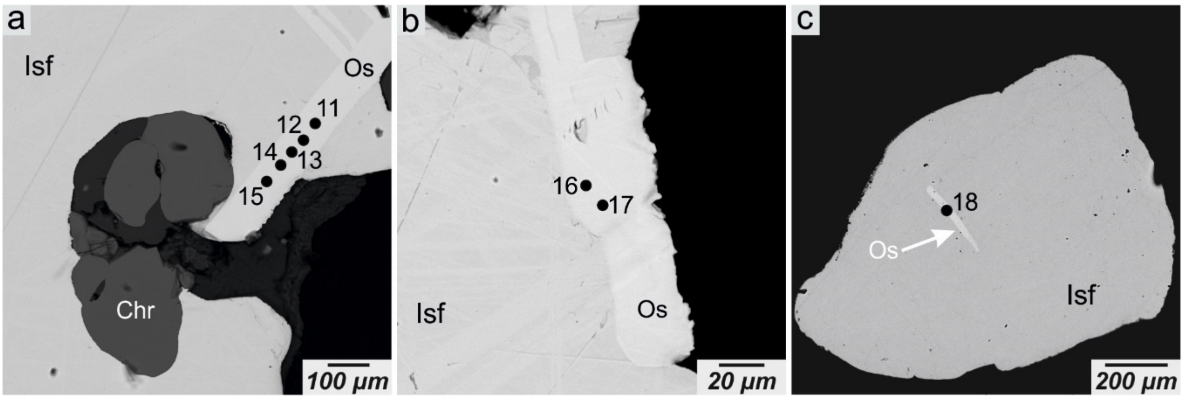

Figure 8. BSE images (SEM) of osmium inclusions in isoferroplatinum from the Travyanistyi proximal placer (**a**,**b**) and the Glubokinskoe distal placer (**c**). The number of points corresponds to the data in Table 3 (No. 11–18). Isf—isoferroplatinum, Os—osmium, and Chr—chromite.

Osmium composition varies considerably (Table 3). Like most Os-Ir-Ru inclusions in Pt-Fe alloy grains from placers associated with the Ural-Alaskan type massifs and their lode sources [6–14,18–24,26–33], Ru is low in the Os-Ir-Ru solid solutions (Figure 9), and its concentration does not exceed 15 at. %. Low Rh concentrations do not exceed 1.6 at. %. In some analyzes, Pd is present and not exceeding 1.0 at. %.

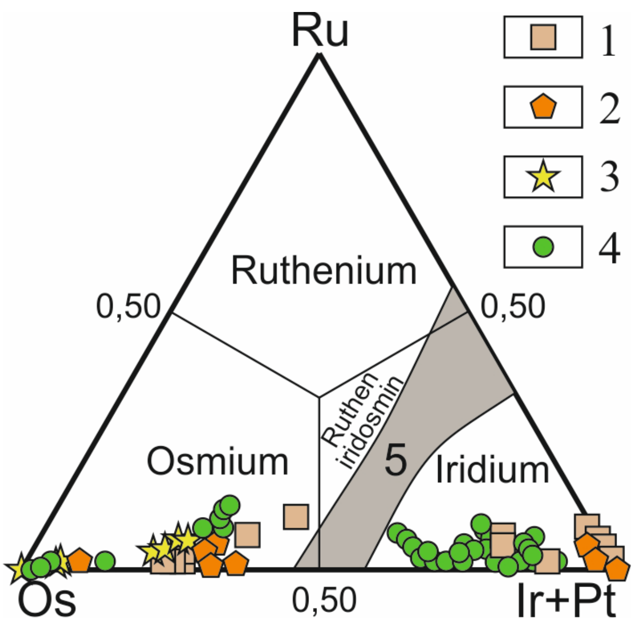

Figure 9. Composition (at. %) of Os-Ir-Ru inclusions in Pt-Fe alloys from the lode chromite-platinum mineralization (1), the Vershinniy eluvial placer (2), the Travyanistyi proximal placer (3), and Glubokinskoe distal placer (4). (5)—miscibility gap.

Iridium is most often encountered as small isometric inclusions (Figure 10a–e). Occasionally it forms larger roundish inclusions in isoferroplatinum (Figure 10c). In the eluvial placer, a nugget of iridium about 0.6 mm in size was found, overgrown by isoferroplatinum (Figure 10f).

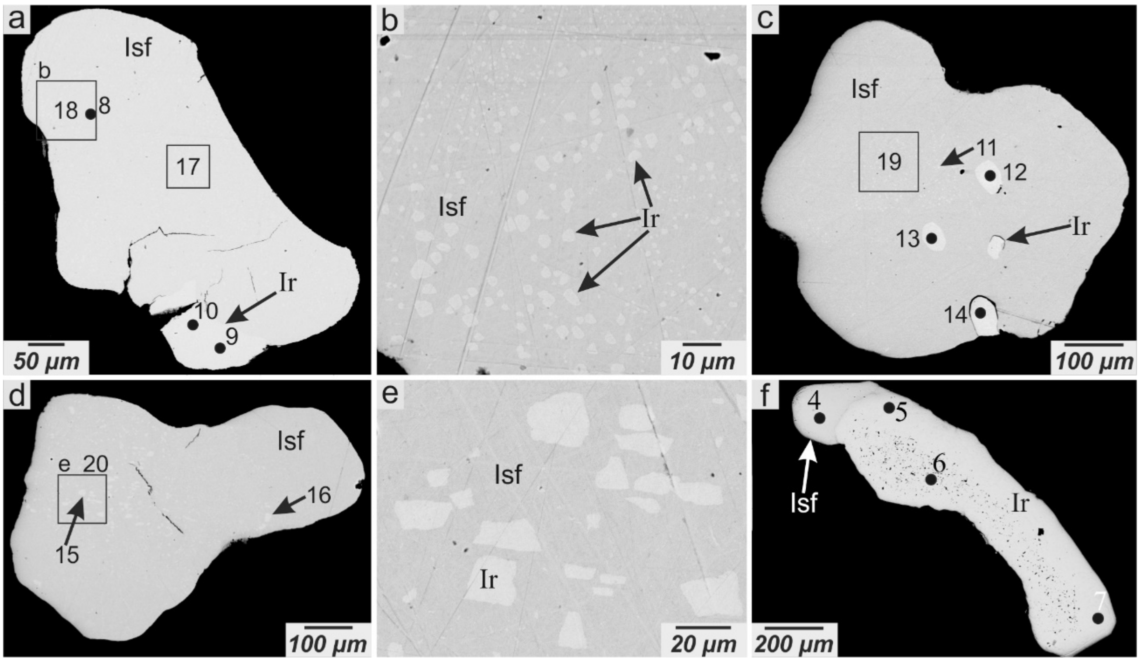

Figure 10. BSE images (SEM) of Ir exsolutions (**a**–**e**) in isoferroplatinum from the Glubokinskoe distal placer and (**f**) nugget of iridium from the Vershinniy eluvial placer. The number of points and fields corresponds to the analyses in Table 4 (No. 4–6, 8–20). The figures **b** and **e** are magnifications of figures **a** and **d**, respectively. Isf—isoferroplatinum, Os—osmium, Ir—iridium. The **f** photo was published in Reference [25].

The composition of iridium varies widely (see Figure 9). Ru impurities are low. However, unlike osmium, significant impurities of other PGE (Table 4) in iridium comprise Pt, with contents that may reach 16 at. %. Rh is noted in amounts up to 6.3 at. %. Pd concentrations do not exceed 1.4 at. %. In some analyzes, along with PGE, Fe concentrations (up to 30 at. %) are noted.

In summary, the inclusions of Os-Ir-Ru alloys show a wide variation of compositions. Osmium is found in relatively small quantities in all samples, however iridium exsolutions are characteristic and primarily of the Glubokinskoe distal placer, and iridium nuggets are found only in the eluvial placer.

3.2.3. PGE sulfides

PGE sulfides are represented by minerals of two solid solution series: laurite-erlichmanite (RuS_2–OsS_2) and kashinite-bowieite (Ir_2S_3-Rh_2S_3). In general, the minerals corresponding to erlichmanite composition are clearly predominant in Pt-Fe alloys in all types of placers (Figure 11a–d). Erlichmanite forms either large individuals with complex faceting and inhomogeneous zoned structure (Figure 11d) or small rounded inclusions (Figure 11d). Laurite is less common and is found in the form of small idiomorphic zonal inclusions in isoferroplatinum (Figure 11e,f). Zonality is caused by an increase in Os/Ru ratios towards the edge of the crystals.

Table 4. Composition of Os-rich iridium from the chromite-platinum ore zones of Svetloborsky massif and associated placers.

No.	Fe	Ni	Cu	Ru	Rh	Pd	Os	Ir	Pt	Total	No.	Fe	Ni	Cu	Ru	Rh	Pd	Os	Ir	Pt
					wt. %											*at. %*				
1	11.09	bdl	bdl	bdl	1.41	bdl	bdl	72.58	14.72	99.80	1	29.87	bdl	bdl	bdl	2.06	bdl	bdl	56.73	11.34
2	1.96	bdl	bdl	4.60	3.83	bdl	bdl	79.03	10.59	100.01	2	6.02	bdl	bdl	7.80	6.38	bdl	bdl	70.49	9.31
3	0.43	bdl	bdl	2.64	1.53	bdl	23.49	66.27	5.64	100.00	3	1.41	bdl	bdl	4.79	2.72	bdl	22.62	63.16	5.30
4	10.31	0.56	0.23	bdl	1.08	0.64	bdl	15.95	71.66	100.43	4	27.79	1.45	0.54	bdl	1.58	0.91	bdl	12.48	55.25
5	2.86	0.18	bdl	2.71	2.42	0.82	2.83	79.63	8.75	100.20	5	8.74	0.52	bdl	4.58	4.00	1.32	2.54	70.65	7.65
6	2.52	0.15	bdl	2.38	2.02	0.69	1.82	73.68	16.82	100.08	6	7.85	0.44	bdl	4.08	3.41	1.13	1.66	66.47	14.96
7	2.72	0.14	bdl	1.22	1.73	0.68	2.93	73.08	17.35	99.85	7	8.55	0.41	bdl	2.11	2.94	1.12	2.70	66.59	15.58
8	0.74	bdl	0.14	3.43	3.50	bdl	15.53	68.37	8.18	99.89	8	2.36	bdl	0.40	6.03	6.05	bdl	14.51	63.20	7.45
9	1.42	0.16	0.72	2.55	2.52	bdl	18.71	57.56	15.64	99.28	9	4.49	0.48	2.00	4.46	4.32	bdl	17.34	52.75	14.13
10	1.04	bdl	bdl	2.76	2.14	0.87	22.01	62.78	7.99	99.59	10	3.34	bdl	bdl	4.88	3.73	1.47	20.73	58.52	7.33
11	0.55	bdl	bdl	2.62	2.79	0.10	16.70	70.19	7.03	99.98	11	1.77	bdl	bdl	4.68	4.91	0.18	15.88	66.06	6.52
12	0.35	0.06	bdl	3.37	2.20	bdl	21.91	59.09	12.26	99.24	12	1.15	0.19	bdl	6.09	3.91	bdl	21.04	56.14	11.48
13	0.39	0.36	0.28	3.90	1.35	bdl	18.83	62.07	12.02	99.20	13	1.27	1.11	0.79	6.99	2.37	bdl	17.91	58.41	11.15
14	0.14	0.17	0.20	3.79	2.08	0.08	13.75	68.90	11.11	100.22	14	0.45	0.52	0.57	6.76	3.64	0.14	13.03	64.62	10.27
15	0.39	0.07	0.25	2.82	2.23	0.17	20.23	65.74	7.58	99.48	15	1.26	0.22	0.73	5.07	3.94	0.30	19.32	62.10	7.06
16	0.53	bdl	0.15	1.30	3.53	bdl	12.93	71.32	9.74	99.50	16	1.73	bdl	0.44	2.35	6.26	bdl	12.40	67.71	9.11
										Field										
17	7.67	0.30	0.70	bdl	0.94	0.71	bdl	14.42	80.76	105.50	17	20.88	0.78	1.67	bdl	1.39	1.01	bdl	11.39	62.88
18	8.21	0.03	0.72	0.25	1.14	0.32	bdl	13.27	77.33	101.27	18	22.96	0.08	1.77	0.39	1.73	0.47	bdl	10.77	61.83
19	7.88	bdl	1.12	0.24	0.39	0.44	bdl	10.14	82.77	102.98	19	21.85	bdl	2.73	0.37	0.59	0.64	bdl	8.16	65.66
20	7.16	0.15	0.23	0.30	0.54	0.05	bdl	15.99	74.29	98.71	20	21.13	0.42	0.60	0.49	0.86	0.08	bdl	13.70	62.72

Note: Iridium exsolutions in isoferroplatinum from the chromite-platinum ore zones of Svetloborsky massif (No. 1–3), Glubokinskoe distal placer (No. 8–20), and the composition of iridium nugget from Vershinniy eluvial placer (No. 4–7). The analyses No 4, 17–20 are Ir-containing platinum. bdl—below detection limits.

Table 5. The composition of laurite–erlichmanite (1–20) and kashinite–bowieite (20–25).

No.	S	Ru	Rh	Pd	Os	Ir	Total	Calculated Mineral Formulae
				Laurite-Erlichmanite				
1	25.61	8.86	bdl	bdl	59.60	6.30	100.37	$(Os_{0.77}Ru_{0.21}Ir_{0.08})_{1.06}S_{1.94}$
2	28.00	14.06	bdl	bdl	50.56	6.09	98.71	$(Os_{0.61}Ru_{0.32}Ir_{0.07})_{1.00}S_{2.00}$
3	31.38	22.79	2.09	bdl	36.64	6.26	99.16	$(Ru_{0.46}Os_{0.40}\ Ir_{0.07}Rh_{0.04})_{0.97}S_{2.03}$
4	33.15	28.65	1.71	bdl	30.05	5.54	99.10	$(Ru_{0.56}Os_{0.31}Ir_{0.06}Rh_{0.03})_{0.96}S_{2.04}$
5	25.94	0.79	2.85	bdl	64.95	4.60	99.13	$(Os_{0.84}Ru_{0.02}Rh_{0.07}Ir_{0.06})_{0.99}S_{2.01}$
6	27.03	0.85	2.66	bdl	66.11	2.36	99.01	$(Os_{0.85}Ru_{0.02}Rh_{0.06}Ir_{0.03})_{0.96}S_{2.04}$
7	31.37	18.88	1.32	bdl	42.15	6.15	99.87	$(Os_{0.46}Ru_{0.39}Ir_{0.07}Rh_{0.03})_{0.95}S_{2.05}$
8	29.05	13.63	1.90	bdl	49.38	5.93	99.89	$(Os_{0.58}Ru_{0.30}Ir_{0.07}Rh_{0.04})_{0.99}S_{2.01}$
9	29.26	15.25	2.31	bdl	50.16	2.14	99.12	$(Os_{0.59}Ru_{0.33}Rh_{0.05}Ir_{0.02})_{0.99}S_{2.01}$
10	29.40	12.95	1.91	0.47	52.48	1.97	99.18	$(Os_{0.62}Ru_{0.28}Rh_{0.04}Ir_{0.02}Pd_{0.01})_{0.97}S_{2.03}$
11	27.77	12.23	1.91	bdl	54.79	4.65	101.35	$(Os_{0.65}Ru_{0.28}Ir_{0.06}Rh_{0.04})_{1.03}S_{1.97}$
12	29.26	20.33	2.51	bdl	43.25	4.98	100.33	$(Os_{0.49}Ru_{0.43}Ir_{0.06}Rh_{0.05})_{1.03}S_{1.97}$
13	37.43	51.82	1.38	bdl	5.91	4.36	100.90	$(Ru_{0.88}Os_{0.06}Ir_{0.04}Rh_{0.02})_{1.00}S_{2.00}$
14	38.15	50.88	1.06	bdl	6.96	3.87	100.92	$(Ru_{0.86}Os_{0.06}Ir_{0.03}Rh_{0.02})_{0.97}S_{2.03}$
15	32.27	28.97	1.64	bdl	33.51	4.19	100.58	$(Ru_{0.58}Os_{0.35}Ir_{0.04}Rh_{0.03})_{1.00}S_{2.00}$
16	36.02	47.71	2.53	0.72	8.88	4.89	100.75	$(Ru_{0.84}Os_{0.09}Ir_{0.04}Rh_{0.04}Pd_{0.01})_{1.02}S_{1.98}$
17	31.57	33.72	2.46	0.54	24.13	6.60	99.02	$(Ru_{0.66}Os_{0.25}Ir_{0.07}Rh_{0.05}Pd_{0.01})_{1.04}S_{1.96}$
18	32.60	33.51	2.90	0.38	23.72	6.46	99.57	$(Ru_{0.65}Os_{0.24}Ir_{0.07}Rh_{0.05}Pd_{0.01})_{1.02}S_{1.98}$
19	29.36	17.63	1.95	bdl	45.78	5.80	100.52	$(Os_{0.52}Ru_{0.38}Ir_{0.07}Rh_{0.04})_{1.01}S_{1.99}$
				Kashinite-Bowieite				
20	22.13	bdl	8.21	bdl	bdl	70.12	100.46	$(Ir_{1.61}Rh_{0.35})_{1.96}\ S_{3.04}$
21	23.53	bdl	15.34	bdl	bdl	61.34	100.21	$(Ir_{1.33}Rh_{0.62})_{1.95}\ S_{3.05}$
22	25.35	bdl	22.42	bdl	bdl	51.88	99.65	$(Ir_{1.06}Rh_{0.85})_{1.91}\ S_{3.09}$
23	26.49	0.14	30.95	bdl	bdl	41.46	99.04	$(Rh_{1.12}Ir_{0.80}Ru_{0.01})_{1.93}\ S_{3.07}$
24	23.70	bdl	21.04	bdl	bdl	55.10	99.84	$(Ir_{1.17}Rh_{0.83})_{2.00}\ S_{3.00}$
25	24.09	bdl	22.60	bdl	bdl	53.58	100.27	$(Ir_{1.12}Rh_{0.87})_{1.99}\ S_{3.01}$

Location: PGM from the chromite-platinum ore zones of the Svetloborsky massif (No. 1–4; 20–23), the Vershinniy eluvial placer (No. 5–8; 24–25), the Travyanistyi proximal placer (No. 9–12) and the Glubokinskoe distal placer (No. 13–19). Formulae of analyses No 1–19 are calculated on the basis of 3 atom per formulae, those of analyses No. 20–25 are calculated on the basis of 5 apfu. bdl—below detection limits.

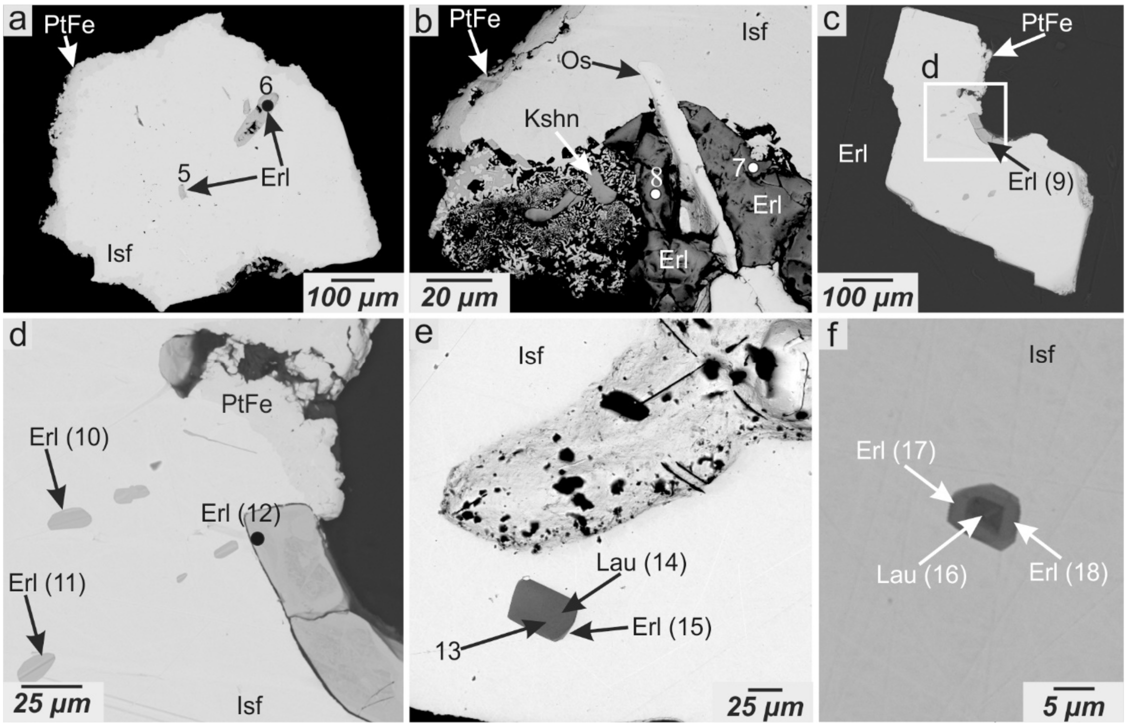

Figure 11. BSE images (SEM) of laurite–erlichmanite (Lau-Erl) in isoferroplatinum from (**a**,**b**) the Vershinniy eluvial placer, (**c**,**d**) the Travyanistyi proximal placer and (**e**,**f**) the Glubokinskoe distal placer. The number of points corresponds to the analyses in Table 5 (No. 5–18). Isf—isoferroplatinum, Pt-Fe—tetraferroplatinum, Erl—erlichmanite, Kshn—kashinite, and Lau—laurite. The **a** and **b** photo were published in Reference [25].

The compositional range of laurite-erlichmanite varies within wide limits (Figure 12). The concentration of Ir varies from 0.6 to 2.7 at. %, whereas Rh does not exceed 2.3 at. %. Pt and Pd contents are below detection limit.

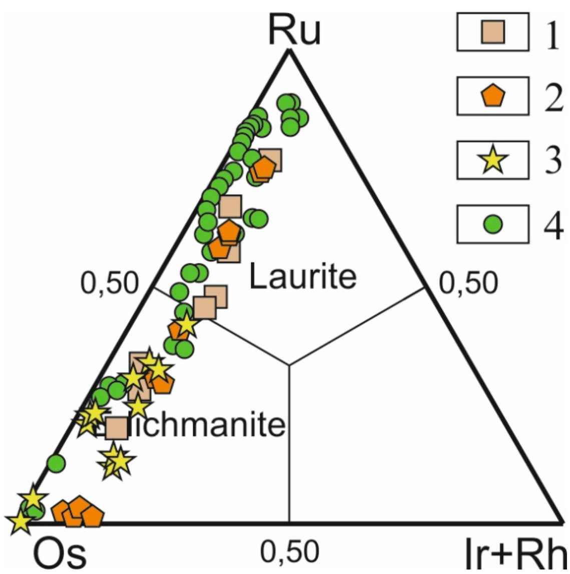

Figure 12. Compositional range (at. %) of laurite–erlichmanite from chromite-platinum ore zones of the Svetloborsky massif (1), the Vershinniy eluvial placer (2), the Travyanistyi proximal placer (3), and the Glubokinskoe distal placer (4).

Kashinite-bowieite grains were only detected in the Vershinniy eluvial placer, associated with other PGE sulfides and Pt-Ir-Rh thiospinels (Figures 11b and 13a). In the studied placers, only kashinite is found with a composition close to bowieite. In contrast to the minerals of the laurite-erlichmanite isomorphous series, the almost complete absence of impurity components is characteristic of all the studied kashinite samples (Table 5).

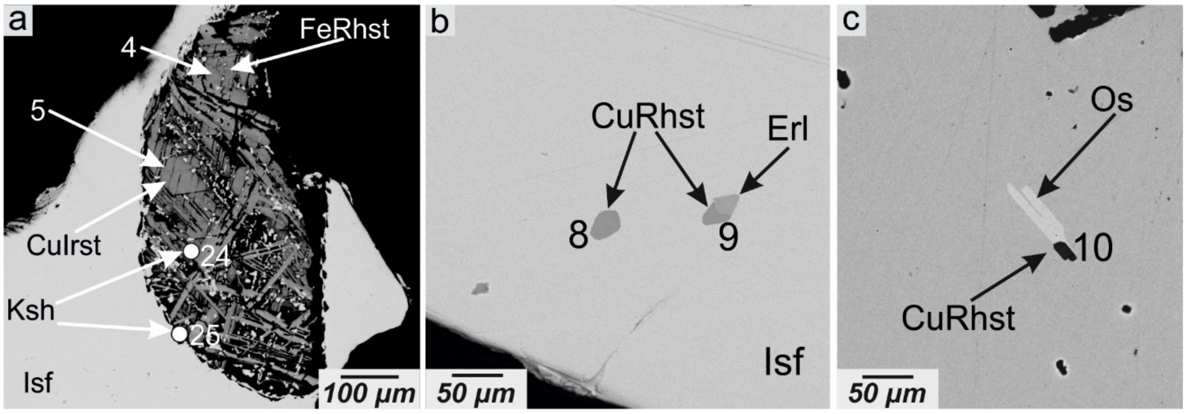

Figure 13. BSE images (SEM) of Pt-Ir-Rh thiospinels from the Vershinniy eluvial (**a**), the Travyanistyi proximal (**b**) and the Glubokinskoe distal placers (**c**). The number of points corresponds to the data in Table 6 for thiospinels (No. 4, 5, 8–10) and Table 5 for kashinite (No. 24, 25). Isf—isoferroplatinum, Erl—erlichmanite, Os—osmium, CuIrst—cuproiridsite, FeRhst—ferrorhodsite, and CuRhst—cuprorhodsite.

Table 6. Composition of Ir-Rh-Pt thiospinels from the chromite-platinum ore zones of the Svetloborsky massif (1–4), the Vershinniy eluvial placer (5–6), the Travyanistyi proximal placer (7–10), and the Glubokinskoe distal placer (11–13).

No.	S	Fe	Cu	Rh	Ir	Pt	Total	Calculated Mineral Formulae
1	24.86	bdl	11.77	6.53	41.73	14.68	99.57	$(Cu_{0.99}Fe_{0.00})_{0.99}(Ir_{1.15}Pt_{0.40}Rh_{0.34})_{1.89}S_{4.12}$
2	28.85	7.50	7.02	35.86	15.92	4.39	99.54	$(Fe_{0.59}Cu_{0.48})_{1.07}(Rh_{1.53}Ir_{0.36}Pt_{0.10})_{1.99}S_{3.94}$
3	30.32	6.63	6.99	36.64	15.30	3.15	99.03	$(Fe_{0.51}Cu_{0.47})_{0.98}(Rh_{1.53}Ir_{0.34}Pt_{0.07})_{1.94}S_{4.08}$
4	31.25	7.04	7.25	41.68	8.27	3.84	99.33	$(Fe_{0.53}Cu_{0.47})_{1.00}(Rh_{1.69}Ir_{0.18}Pt_{0.08})_{1.95}S_{4.05}$
5	25.34	5.18	6.00	13.50	50.22	bdl	100.24	$(Cu_{0.48}Fe_{0.47})_{0.95}(Ir_{1.33}Rh_{0.67})_{2.00}S_{4.05}$
6	25.48	5.50	5.13	30.16	34.51	bdl	100.78	$(Fe_{0.48}Cu_{0.39})_{0.87}(Rh_{1.42}Ir_{0.87})_{2.29}S_{3.86}$
7	26.08	bdl	11.91	19.23	21.20	21.32	99.74	$Cu_{0.93}$ $(Rh_{0.93}Ir_{0.55}Pt_{0.54})_{2.02}S_{4.05}$
8	26.18	bdl	11.99	19.88	20.52	21.15	99.72	$Cu_{0.93}$ $(Rh_{0.96}Ir_{0.53}Pt_{0.54})_{2.02}S_{4.05}$
9	26.48	bdl	12.31	20.07	20.71	20.05	99.62	$Cu_{0.94}$ $(Rh_{0.96}Ir_{0.53}Pt_{0.50})_{1.99}S_{4.05}$
10	26.29	bdl	12.11	19.66	20.85	20.33	99.24	$Cu_{0.94}$ $(Rh_{0.95}Ir_{0.54}Pt_{0.52})_{2.00}S_{4.06}$
11	25.87	bdl	11.81	18.77	32.47	10.22	99.14	$Cu_{0.94}$ $(Rh_{0.91}Ir_{0.85}Pt_{0.26})_{2.02}S_{4.04}$
12	26.03	bdl	11.85	19.26	32.35	10.42	99.91	$Cu_{0.93}$ $(Rh_{0.93}Ir_{0.84}Pt_{0.27})_{2.03}S_{4.04}$
13	26.02	bdl	12.18	19.53	32.57	9.80	100.10	$Cu_{0.95}$ $(Rh_{0.94}Ir_{0.84}Pt_{0.25})_{2.03}S_{4.02}$
14	31.23	14.30	5.08	24.58	10.82	11.39 * 1.87 **	99.27	$S_{53.19}Fe_{13.99}Rh_{13.04}Ni_{10.60}Cu_{4.37}Ir_{3.07}Co_{1.73}$

Note: Analyses No. 1, 5—cuproiridsite, No. 2–4—ferrorhodsite, No. 6—Ir-bearing ferrorhodsite, No. 7–13—cuprorhodsite, the formulae are calculated on the basis of 7 apfu, No. 14—unnamed phase, the formula is calculated for 100 at. %. *—Ni containing, **—Co containing. bdl—below detection limits.

The distribution of PGE sulfides in different placers is significantly different. Kashinite was found only in the Vershinniy eluvial placer. Among Os and Ru sulfides, only erlichmanite was found in the Travyanistyi proximal placer, while both erlichmanite and laurite were found in the eluvial and distal placers. At the same time, all sulfides are characterized by very wide variations of chemical composition.

3.2.4. Pt-Ir-Rh Thiospinels

Minerals of the thiospinel group ((Fe,Cu)(Rh,Ir,Pt)$_2$S$_4$) are rare in the placers studied. Cuprorhodsite ($CuRh_2S_4$) prevails forming small idiomorphic individuals (Figure 13b,c). It is characterized by consistent copper concentrations, which are the largest possible for thiospinels, and varying Rh, Ir, and Pt contents (Table 6; Figure 14). Generally, cuprorhodsite occupies an intermediate position in the malanite ($CuPt_2S_4$)-cuprorhodsite ($CuRh_2S_4$) isomorphous series.

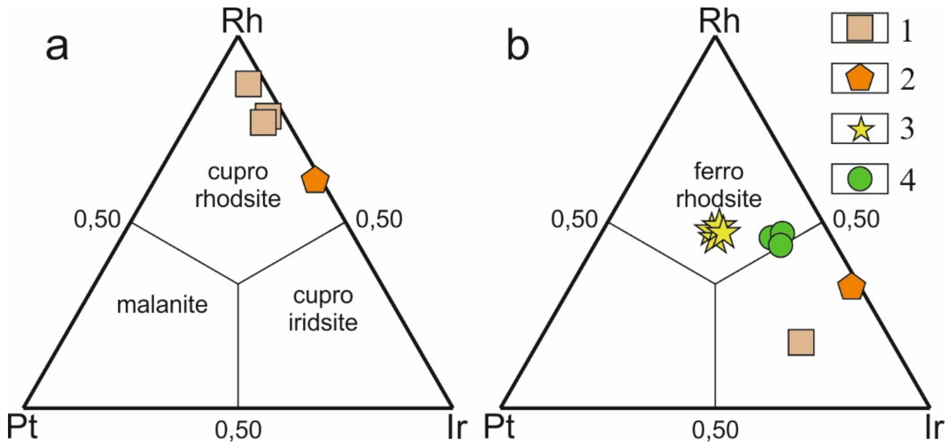

Figure 14. The composition (at. %) of Cu bearing (**a**) and Fe bearing (**b**) Pt-Ir-Rh thiospinels in isoferroplatinum from chromite-platinum ore zones of the Svetloborsky massif (1), the Vershinniy eluvial placer (2), the Travyanistyi proximal placer (3), and the Glubokinskoe distal placer (4).

In addition to cuprorhodsite, cuproiridsite ($CuIr_2S_4$) and ferrorhodsite ($FeRh_2S_4$) were found once only. They form complex intergrowths with various sulfides (mainly kashinite), located near the boundaries of Pt-Fe alloy grains (Figure 13a).

3.2.5. Other Platinum Group Minerals

One elongated grain of modified Ir (presumably iridium oxide, according to the measured oxygen content; Figure 15a) was found in isoferroplatinum from the Travyanistyi ravine, and a small aggregate consisting of Pt-Fe alloys and an unnamed Rh-Fe-Ni sulfide phase (Figure 15b; Table 6, No. 14) located at the isoferroplatinum grain boundary, also from the Travyanistyi ravine.

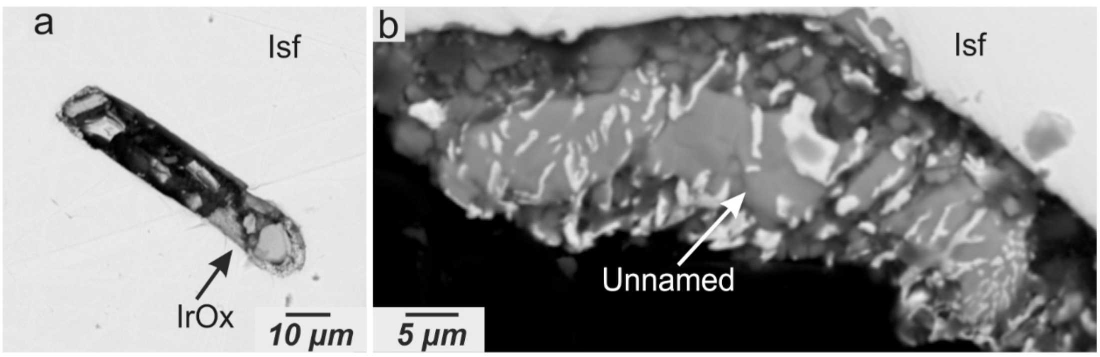

Figure 15. (**a**) the iridium oxide (IrOx) and (**b**) unnamed phase from the Travyanistyi proximal placer. Isf—isoferroplatinum. BSE images (SEM).

3.3. Mineral Assemblages—A Comparison

The present study established that the PGM assemblages of all studied placers are characterized by the absolute predominance of isoferroplatinum grains, with a small amount of ferroan platinum and minerals of the tetraferroplatinum group. For chromite-platinum mineralization, the similar characteristics of the assemblage composition are noted, along with slightly more common minerals of the tetraferroplatinum group (see Figure 6), whereas for the dunite-type mineralization, the pseudomorphs of tetraferroplatinum and tulameenite are noted in about half of the studied grains.

Similar features are observed when analyzing the nature of the impurity element distribution in isoferroplatinum (Table 7). According to the calculated average content of minor elements, the differences in isoferroplatinum contents, as a whole, do not go beyond the limits of calculation errors, and the compositions of isoferroplatinum from the placers and lode chromite-platinum ore zones are geochemically similar.

Table 7. Isoferroplatinum compositions from chromite-platinum ore zones of the Svetloborsky massif (1), the Vershinniy eluvial placer (2), the Travyanistyi proximal placer (3) and the Glubokinskoe distal placer (4).

No.	Fe	Cu	Ru	Rh	Pd	Ir	Pt	PGE
1	(19.6–27.8) 24.29	(0.4–2.6) 1.34	(0.0–0.3) 0.05	(0.0–2.2) 0.71	(0.2–1.6) 0.51	(0.0–12.5) 1.19	(55.2–75.4) 72.27	(70.3–78.7) 74.28
2	(22.6–28.8) 21.90	(0.0–1.9) 1.59	(0.0–2.1) 0.06	(0.0-3.3) 0.72	(0.0–1.5) 0.73	(0.0–1.4) 2.19	(65.3–77.4) 72.37	(71.1–77.4) 76.38
3	(21.9–27.4) 23.39	(0.6–3.2) 1.82	(0.0–1.0) 0.23	(0.0–1.9) 1.06	(0.0–1.5) 0.57	(0.0–6.7) 0.97	(64.9–74.0) 71.59	(70.6–75.2) 74.52
4	(21.9–27.4) 23.85	(0.6–3.2) 1.78	(0.0–1.0) 0.6	(0.0–1.9) 0.73	(0.0–1.5) 0.63	(0.0–6.7) 1.78	(64,9–74.0) 70.94	(70.6–75.2) 74.18

Note: The data are given in (minimum–maximum) and average. The number of analyses: No. 1—64; No. 2—56; No. 3—62; and No. 4—127.

The coincidence of the isoferroplatinum compositions from the proximal and distal placers and lode chromite-platinum mineralization is demonstrated in Figure 16, where the concentrations of impurity elements from the placers associated with other Ural-Alaskan type massif of the same region–Veresovoborsky–are given for greater clarity. In the Figure 16, the intermediate position of the isoferroplatinum from the Svetloborsky massif is noted regarding Ir, Pd, and Rh concentrations, whereas the isoferroplatinum of the Veresoborsky massif by Pd-Rh specifics.

Os-Ir-Ru alloy inclusions are found in all types of lode mineralization. They are characterized by the same wide compositional variation as the Os-Ir-Ru minerals from the placers. It should be noted that Ir nuggets weighing up to 12 g are found only in chromite-platinum ore zones, whereas osmium plates are more characteristic of dunite-type mineralization, and iridium is found in a subordinate amount [9].

The comparison of the peculiarities of the remaining PGM in this case is inexpedient due to their relative rarity in the studied objects, although the bowieite was established of dunite-type mineralization [27], whereas it was not found in the placers. The absence of a wide variety of rarer minerals in the studied assemblages emphasizes once again the difference of the PGM from the placers and dunite-type mineralization, where the Rh analogue of tolovkite, hollingworthite, irarsite, sperrylite, hexaferrum, etc. [9] were established, whereas such mineral and species diversity is not typical for the platinum ore zones of the Svetloborsky massif [14].

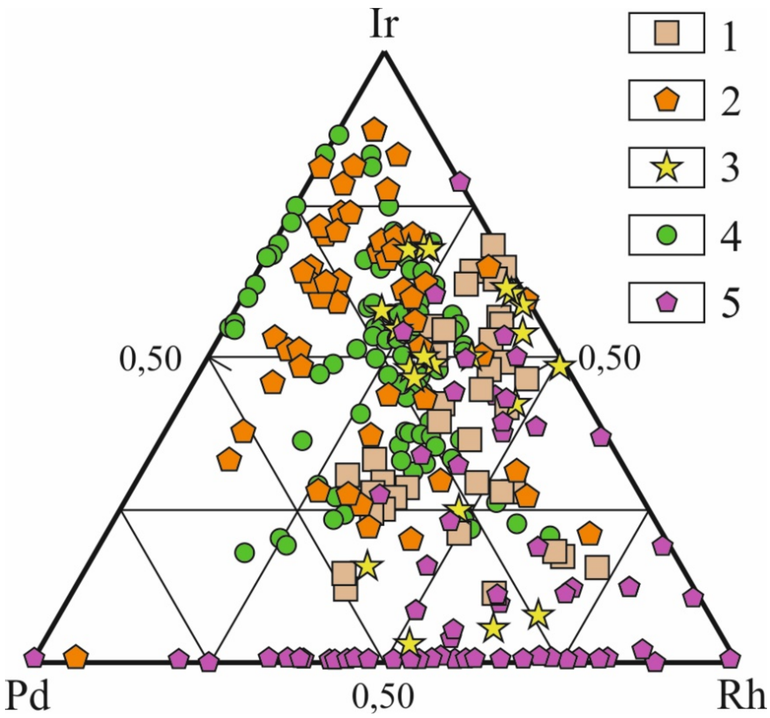

Figure 16. The concentrations of minor elements in isoferroplatinum from lode chromite-platinum mineralization (1), the Vershinniy eluvial placer (2), the Travyanistyi proximal placer (3), the Glubokinskoe distal placer (4), the lode and placer mineralization of the Veresovoborsky massif (5).

4. Discussion

The predominance of Pt-Fe alloys with inclusions of Os-Ir-Ru composition, as well as PGE sulfides (laurite-erlichmanite and kashinite-bowieite) in the studied objects is typical for the PGM assemblages from the placers and bedrocks of Ural-Alaskan type massifs in different regions of the world [18–24,28–35]. The presence of Pt-Ir-Rh thiospinels among the inclusions in Pt-Fe minerals from the placer assemblages is considered as a typomorphic feature of platinum placer objects associated with the Ural-Alaskan type massifs [36]. The placer assemblages studied, regardless of the distance from the lode source, completely correspond to the typical PGM assemblages of the lode sources, Ural-Alaskan type zonal massifs.

The analysis of the PGM assemblages of the proximal and distal placers allows the criteria for estimating the PGM transport distance to be singled out. The most important of these criteria is the nature of the morphology alteration of PGM individuals and aggregates. Pt-Fe alloys retain the primary morphological features characteristic of lode PGM in the placers with a small distance of clastic material transport. At a distance of more than 10 km, the degree of mechanical attrition of PGM becomes significant, and the morphological features characteristic of lode PGM assemblages are practically not preserved. Similar changes are established of gold and PGM grains from placers associated with different gold deposits of the world [37]. Another criterion for assessing the transport distance of PGM in placers is the degree of the rim integrity around isoferroplatinum, commonly composed of tetraferroplatinum group minerals. As a result of our research, it was found that with a long transport distance, these rims are completely destroyed due to mechanical wear during their transport to the placers, corroborating earlier studies of the placer systems associated with the Nizhnetagilsky massif [17].

A general analysis of the aggregate dimensions of the PGM made it possible to establish that in eluvial and distal placers with a short distance of material transport the average size of the PGM nuggets is larger than in distal placers located 10 km and more from the primary source. The nuggets of 0.5–1.5 mm in size prevailed in the Travyanistyi proximal placer comprising about 60% of the platinum in the entire volume of heavy concentrate. During early mining work nuggets were found weighing from the first grams to tens of grams [2]. In the Is river placer with transport distance of more than 10 km, the PGM grains with a size of 0.1–0.5 mm prevail. They comprise about 75% of the PGM in the entire volume of heavy concentrate. Throughout history of mining, nuggets were not found in these placers. A regular decrease in the dimensions of PGM grains with distance from the lode source was established for platinum placers of the Urals as a result of specialized investigations [16].

The comparative characteristics of the compositions of the Pt-Fe alloys and their inclusions from the placer assemblages and lode sources made it possible to establish their identity in many ways. Taking into account the presence of two types of mineralization—dunite and chromite-platinum—within the Svetloborsky massif, it is important to determine the contribution of each one to the platinum placer potential. The relationship of eluvial and proximal placers with chromite-platinum ore zones is out of question. This is confirmed by many facts, the main of which is the coincidence of the contours of the heavy concentrate anomaly (or the eluvial placer) and the designated zone of massive platinum-bearing chromitites, as well as the geomorphological features of the terrain. It is important to emphasize that the small size of platinum group minerals in the dunitic type of mineralization does not allow one to count on their significant contribution to the ore potential of the placer systems [38]. Proceeding from this, chromite-platinum mineralized zones appear to be the most likely lode source for the placers.

The volume of the PGM extracted from the Is river placers is more than 110 ton [39], which makes this placer unique and raises the question about the existence of other lode sources besides the Svetloborsky massif. A number of platinum-bearing rivers and ravines flows into the Is river, including the relatively large Prostakishenka and Pokap rivers. These rivers drain the dunites and the embedded chromite-platinum ore zones of the Veresovoborsky massif in the upper course. However, the contribution of the Veresovoborsky massif's bedrocks to the formation of the Isovsko-Turinskaya placer was not previously estimated. A different PGM assemblage is characteristic of the Veresovoborsky massif and the associated alluvial deposits as compared to the Svetloborsky massif. In the chromite-platinum ore zones of the Veresovoborsky massif, the ferroan platinum is largely observed, as well as the abundance of the tetraferroplatinum group minerals [14]. Along with this, the mineral inclusions in Pt-Fe alloys are not characteristic. The similar assemblages are also noted for the placers associated with the Veresovoborsky massif [40]. In addition, the difference in the trace element concentrations in the isoferroplatinum from the placers associated with the Svetloborsky and Veresovoborsky massifs is clearly demonstrated in Figure 16.

The Kachkanar gabbro-clinopyroxenite massif is considered as another lode source for the Isovskaya placer. The part of the ravines draining the clinopyroxenites of this massif flows into the Is river across the area from the Svetloborsky massif to the Glubokinskoe site. A number of works [26,41] provides the information that the clinopyroxenites of zonal Ural-Alaskan type massifs can serve as a source for the placer object formation. Similar placer objects, not related with the erosion of dunite bodies, were found within the Koryak Highlands [21,42]. However, the peculiarities of the chemical composition of the platinum group minerals from the placers associated with the clinopyroxenite fragments of zonal massifs or separate clinopyroxenite bodies differ in a number of features. The coincidence of most of the peculiarities of the PGM assemblages from the most remote part of the Isovskaya placer with the PGM assemblages from the chromite-platinum ore zones of the dunite core of the Svetloborsky massif indicates the insignificant influence of the bedrocks of the Kachkanar massif on the formation of the placer PGM assemblages.

Based on the coincidence of a number of the most significant features of the PGM mineralization of the Glubokinskoe site with the chromite-platinum ore zones of the Svetloborsky massif, combined with their significant difference from the PGM of the lode mineralization of the Veresovoborsky massif, it can be stated that the destruction of the chromite-platinum ore zones of the Svetloborsky clinopyroxenite-dunite massif provides the greatest contribution to the Isovsko-Turinskaya placer system.

The close chemical composition of Pt-Fe minerals from the placers located at different distances from the lode source can also be the evidence of the absence of pronounced zonality within the already destroyed part of the dunite core. However, for several PGM placer deposits, for example the deposits associated with the Galmoenan massif [21], a compositional variability of the Pt-Fe minerals is observed, which may be due to the existence of the vertical zonality of the lode platinum mineralization. The zonality of lode mineralization is also assumed proceeding from the existing models of Ural-Alaskan type massif formation and the experimental data [21,43–45].

5. Conclusions

The main transformation of PGM in placers is reduced to a regular change in the morphological features during their transport from a lode source to a placer. At a distance of more than 10 km, the degree of mechanical attrition of PGM becomes significant, and the morphological features characteristic of lode PGM are practically not preserved. In addition, in the placers with a significant transport distance, tetraferroplatinum group mineral rims on isoferroplatinum are completely destroyed. A general analysis of the aggregate dimensions made it possible to establish that in eluvial and alluvial placers with a short distance of material transport the average size of the platinum nuggets is larger than in distal placers located 10 km and more from the primary source. Composition of isoferroplatinum weakly change during of transport of detrital materials.

The results obtained indicate that the PGM bulk has entered the Isovsko-Turinskaya placer system as a result of the destruction of the chromite-platinum ore zones of the Svetloborsky massif. This proves that the chromite-platinum type of mineralization is the most important for the formation of the large placer systems associated with the Ural-Alaskan type massifs.

The coincidence of the compositional features of the PGM assemblages from the studied placers having different distances from the lode source may be the evidence of the absence of vertical zonality in the lode platinum mineralization within the destroyed part of the Svetloborsky massif.

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