The Distribution and Speciation of PGEs in Chromitite from the Svetloborsky, Veresovoborsky, and Kamenushensky Clinopyroxenite–Dunite Massifs (Middle Urals)

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Abstract—The mineralogical and geochemical patterns of platinum-bearing vein–impregnated and massive chromitite from dunite of the Svetloborsky, Veresovoborsky, and Kamenushensky clinopyroxenite–dunite massifs (Middle Urals) are reported. Platinum is characterized by an extremely uneven distribution in chromitite and is concentrated in the form of Pt–Fe intermetallic compounds. The structural and textural patterns of chromitite from these massifs, the PGE distribution in it, and the composition of chrome spinels are similar to those in well-studied chromitite from the zoned clinopyroxenite–dunite massifs of the Urals (Nizhny Tagil) and Koryakia (Gal'moenansky).

Keywords: native Pt mineralization, zoned clinopyroxenite–dunite massifs, PGEs, PGMs, chromitite, chrome spinels, Middle Urals

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INTRODUCTION

The clinopyroxenite–dunite massifs of the Urals, the sources for large platinum placers and promising native PGE deposits, have been studied for more than 100 years. The most detailed studies of dunite and chromitite were carried out for the Nizhnetagil'skii massif (Betekhtin, 1928; Ivanov, 1997; Lazarenkov et al., 1992; Pushkarev et al., 2007; Stepanov et al., 2015; Zavaritskii, 1935), which is a part of the kachkanar plutonic complex. In addition, this complex includes the Uktusskii, Svetloborsky, Veresovoborsky, and Kamenushensky, and other massifs. The patterns of the geological structure, regularities in the distribution of PGEs, and their speciation for the Uktus massif were considered in detail by Pushkarev (2000). Chromitite and PGMs contained in them from the Kamenushensky massif were studied by Tolstykh et al. (2011). Zones with high concentrations of chrome spinel were discovered in dunite and chromitite bodies from the Svetloborskii and Veresovoborskii massifs by

one of the authors of this paper during geological studies (Stepanov, 2014). The regularities in the geological structure and PGMs were characterized for these zones (Malitch et al., 2017; Stepanov et al., 2017); however, there is still no complete analysis of the content and distribution of PGEs in chromitite.

Here, we report the original results of sampling of chromitite and host dunite for PGEs using the methods of ICP-MS, assay, and mass study of PGM fractions in rocks and ores. Comparison of the results allows us to suggest the most correct methodology for sampling during geological prospecting works and to estimate the concentration of platinum in dunite and chromitite. It is shown that chromitite of the Svetloborsky, Veresovoborsky, and Kamenushensky clinopyroxenite–dunite massifs are characterized by some geochemical patterns related to the distribution character and composition of PGMs.

MATERIALS AND METHODS OF STUDY

The sampling for this study was carried out during the field studies in 2013−2014. The detailed study of trenches and natural outcrops within the Svetloborsky and Veresovoborsky massifs allowed us to collect lump samples of chromitite and host dunite. The petrographic and mineragraphic polished sections were prepared from lumps and studied on a Leica DM2500P optic microscope in transmitting and reflected light. Based on the petrographic and mineragraphic studies, we selected the most typical samples of dunite and chromite dunite, as well as vein-disseminated and massive chromitite. The composition of these samples and particularly the concentration of PGEs in them were studied by ICP-MS on an ELAN-6100 DRC mass spectrometer at the Central Analytical Laboratory, Russian Geological Research Institute (analysts V.A. Shishlov and V.L. Kudryashov). To analyze the concentration of platinum, the samples were studied by the fire assay atomic emission method at the Mekhanobr Inzhiniring Analit Regional Analytical Center: the assay concentration was determined according to STP1401.151.1-2014 (silver kinglet); the atomic emission study was performed using the NSAM 366-S instruction on an ICAP 6300 atomic emission spectrometer (certificate of verification no. 015876 from October 24, 2017). The weight proportion of Os was measured by the ICP-MS method (STP 35-12-241 and STP 35-12-282) on an ICAPQc spectrometer at the Institute Gipronikel (analysts A.A. Belyakov, P.N. Solov'ev, L.B. Krasotina, and S.I. Belyaninova). Considering that most PGEs in the zoned dunite−clinopyroxenite massifs form proper minerals with predomination of Pt−Fe intermetallic compounds (Lazarenkov et al., 1992), large-volume samples with a weight of 50−70 kg were collected from chromitite for further crushing and enrichment on a KR-400 centrifugal concentrator with extraction of PGM aggregates and individual grains (a total of 17 large-volume samples). The concentration of platinum in these samples was calculated by weighing the PGM concentrate with account for the average platinum concentration in the composition of Pt−Fe intermetallic compounds, as well as for the abundance of secondary minerals of the tetraferroplatinum group (0.85 in the Svetloborsky massif, 0.78 in the Veresovoborsky massif, and 0.83 in the Kamenushensky massif).

The morphology of PGM grains and aggregates was studied on a CamScan MX2500 electron microscope at the Russian Geological Research Institute (analyst A.V. Antonov) and on a CamScan MV2300 electron microscope at the Institute of Experimental Mineralogy, Russian Academy of Sciences (analyst D.A. Varlamov). The composition of minerals and the morphology of their grains were studied by the method of X-ray spectral microanalysis with energy-dispersive spectrometers on a CamScan MV2300 electron microscope equipped with an INCA Energy 350 detector at the Institute of Experimental Mineralogy, Russian Academy of Sciences (analyst D.A. Varlamov), and on a Camebax SX50 microanalyzer equipped with wavelength detectors at the Moscow State University (analyst D.A. Khanin).

To classify chrome spinels, we used diagrams based on the concentration of trivalent cations, TiO_2, and the coefficients $Cr\# = Cr/(Cr + Al)$ and $Mg = Mg/(Mg + Fe^{2+})$.

CHARACTERIZATION OF CHROMITITE

Based on the results of mapping of dunite from the Svetloborsky, Veresovoborsky, and Kamenushensky massifs and study of the lump ore material performed by the authors, chromitites were divided into the vein−disseminated and massive types. Some authors (Pushkarev et al., 2007; Zavaritsky, 1935) classify the vein−impregnated chromitite as syngenetic and the massive type as epigenetic in relation to the host dunite.

The areas of the greatest accumulation of chromite are controlled by the zones of gradual transition, namely the facies contacts of dunite "fields" with different grain sizes. As an example, the zone of transition between fine-granular and small-granular dunite at the southwestern endocontact (Utyanka and Seventh Log occurrences) contains numerous veins of massive chromitite. Zones with high contents of the vein−disseminated and massive chromitites in the Vershinnoe ore occurrence are located in the zone of the facies contact between fine-granular and medium-granular porphyraceous dunites (Stepanov et al., 2017). The highest concentration of chromitite in the contour of the dunite core of the Veresovoborsky massif was registered in the area of the facies contact of coarse-granular dunite and dunitic pegmatite with medium-granular porphyraceous dunite (Stepanov et al., 2017). The zone of the high chromitite content in the upper reaches of the Bolshaya Kamenushka River, which flows through the dunite core of the Kamenushensky massif occurs at the contact between the small body of coarse-granular dunite and medium-granular porphyraceous dunite. As a whole, the location of chromitite in the Svetloborsky, Veresovoborsky, and Kamenushensky massifs are in agreement with the regularities that were previously revealed for the Nizhny Tagil (Ivanov, 1997; Pushkarev, 2007) and Konder (Stolyarov, 2002) clinopyroxenite−dunite massifs.

The vein−impregnated chromitite is represented by thickening of thin veinlets in the dunite mass. The lowest content of chrome spinel (60−65%) is typical of thin segregations of vein−impregnated chromitite (Fig. 1a). Numerous bodies of vein−impregnated chromitite are often agglomerated into the thicker vein segregations surrounded by numerous chrome spinel aggregates, in which chrome spinel grains form chains. These chains reveal the gradual contacts between chromitite and host dunite (Fig. 1b). At a distance
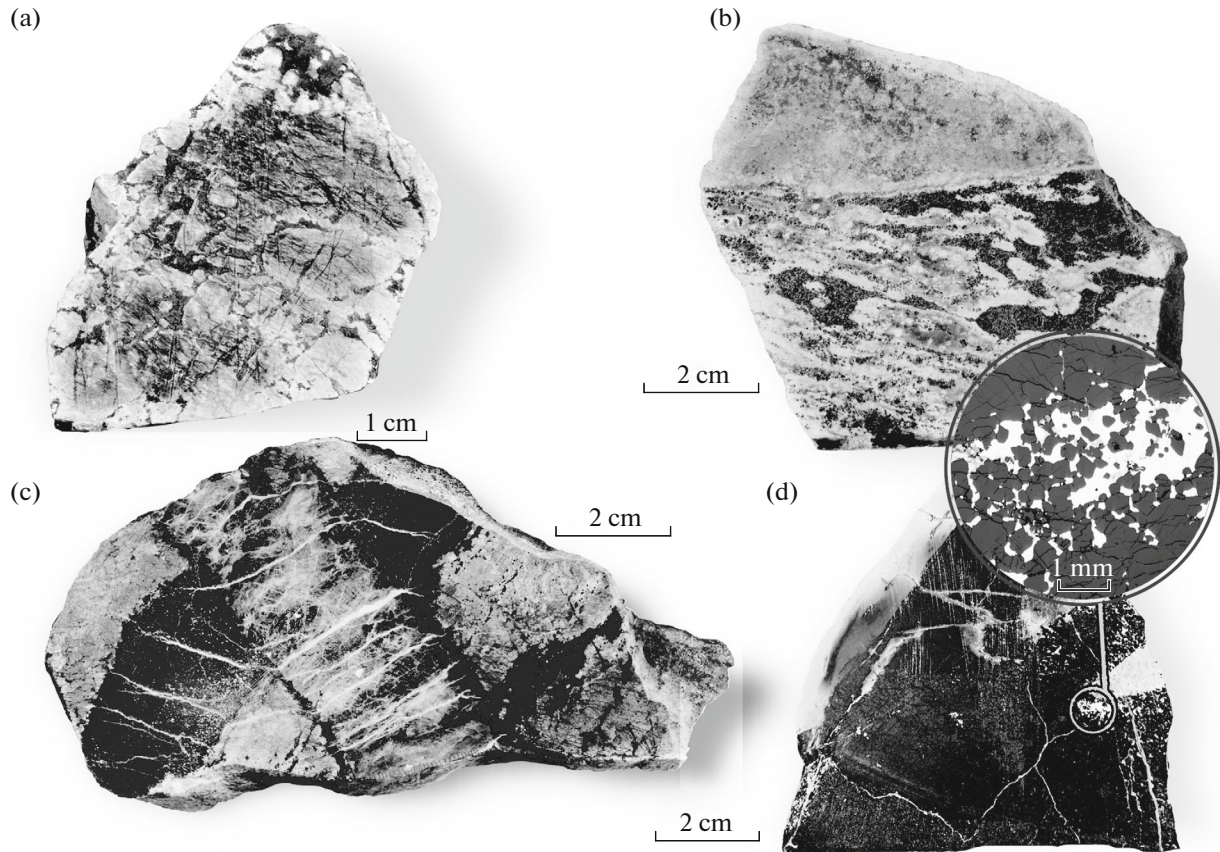
Fig. 1. The textural and structural patterns of chromitite from the clinopyroxenite−dunite massifs of the Middle Urals. (a) rare vein−impregnated chromitite in serpentinized dunite (Veresovoborsky massif); (b) densely vein-disseminated chromitite in serpentinized dunite (Svetloborsky massif); (c) massive vein chromitite crossed by the pyroxenite vein (Kamenushensky massif); (d) a large aggregate of the Pt−Fe minerals in massive vein chromitite (Veresovoborskii massif).

from the bodies of vein−impregnated chromitite, the content of chrome spinel in dunite decreases with transition to chromite dunite, which is accompanied by dunite aureoles with a high content of accessory chromitite impregnation. The thickness of vein−impregnated chromitite bodies does not exceed 20−25 cm; their maximum length does not exceed 1.5 m. This type of chromitite is most abundant within the Vershinnoe ore occurrence in the southern part of the dunite core of the Svetloborsky massif (Malitch et al., 2017; Stepanov et al., 2017).

The massive vein chromitite (Figs. 1c and 1d) forms bodies with a thickness up to 30 cm, mostly with sharp contacts with dunite. Individual veins have a length up to 1 m. However, the veins of massive chromitite often form dense segregations of an isometric shape resembling schliren similar to those described in the Gospodskaya Mine and Syrkovyi Log of the Nizhnetagil'skii massif (Zavaritsky, 1935). Because of the density of numerous veins of massive chromitite, the ore bodies often have a brecciated texture. Some bodies of massive vein platinum-bearing chromitite from the Veresovoborskii massif show zoning resulting from

the presence of coarse-granular chromitite in the central part of the vein with a gradual decrease in the chrome spinel grain size towards the boundary of the vein body. This chromitite contains large segregations of Pt−Fe minerals with the diameter rarely reaching 5 cm (Fig. 1d).

In most cases, the grains of accessory chrome spinels and those composing vein−impregnated and massive chromitite do not have clear zoning or a sectoral character. Only the crystals of chrome spinel included in the aggregate of Pt−Fe minerals from the Kamenushensky massif show zoning and sectoral character with significant variation in the Fe_2O_3 concentration. As a whole, according to the classification of Pavlov (1979), the composition of chrome spinel corresponds to subferrichromite and subaluminoferrichromite (Fig. 2a, Table 1) and plots on the trend typical of chrome spinels from zoned clinopyroxenite−dunite massifs (Lazarenkov et al., 1992). Chrome spinels from all studied massifs are characterized by high Cr# (0.87) and low Mg# (0.27). Accessory chrome spinels are characterized by the lowest Cr# and Mg# values, whereas chrome spinels from
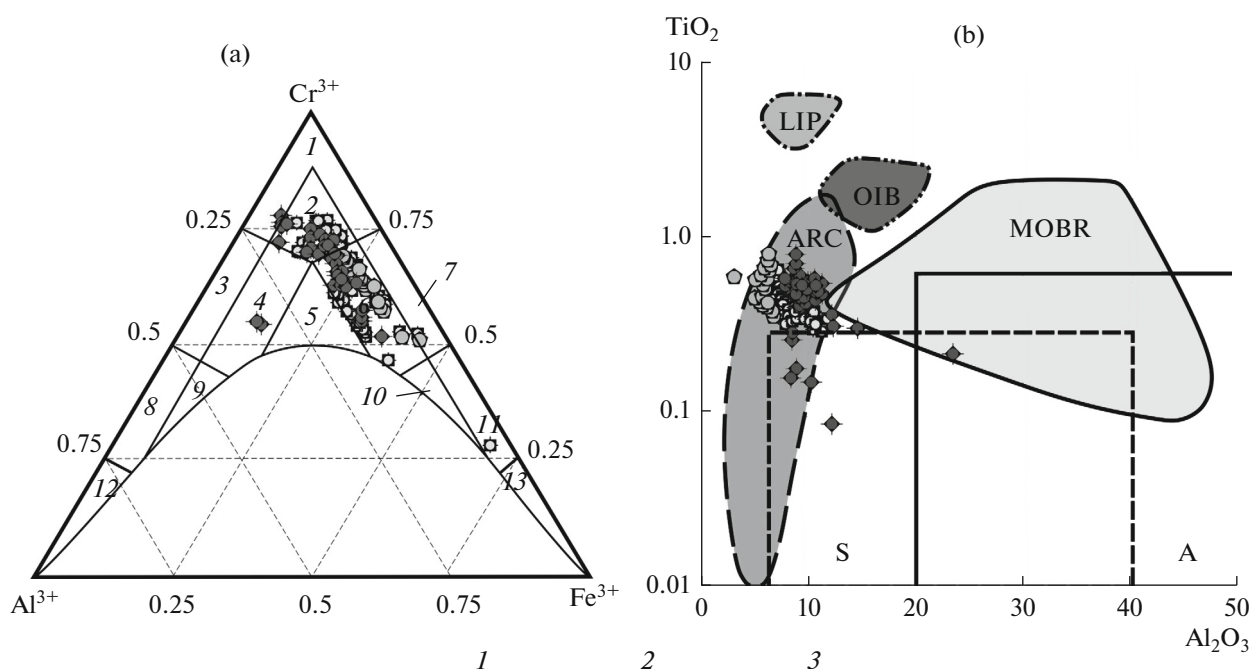
Fig. 2. The composition of chrome spinels according to the results of X-ray spectral microanalysis. (a) Classification diagram of N.V. Pavlov et al. (1979): (*1*) chromite; (*2*) subferrichromite; (*3*) aluminochromite; (*4*) subferrialuminochromite; (*5*) ferrialuminochromite; (*6*) subaluminoferrichromite; (*7*) ferrichromite; (*8*) chrompicotite; (*9*) subferrichromepicotite; (*10*) subaluminochromemagnetite; (*11*) chromemagnetite; (*12*) picotite; (*13*) magnetite. (b) Discrimination Al_2O_3–TiO_2 diagram (Kamenetsky et al., 2001): LIP, large igneous provinces; OIB, basalt of oceanic islands; ARC, volcanic rocks of island arcs; MORB, volcanic rocks of mid-ocean ridges; A, mid-ocean ridge peridotite; S, peridotite from the supersubduction zones; (*1*–*3*) chrome spinels from chromitite of the Svetloborsky (*1*), Veresovoborsky (*2*), and Kamenushensky (*3*) massifs.

massive vein chromitite show the maximum values. The analyzed chrome spinels on the TiO^2–Al_2O_3 diagram (Fig. 2b) plot in the compositional field typical of volcanic rocks of island arcs (Kamenetsky et al., 2001).

PLATINUM-GROUP MINERALS

The PGM minerals in chromitite from the Svetloborskii, Veresovoborskii, and Kamenushenskii massifs include predominant Pt−Fe intermetallic compounds with compositions corresponding to isoferroplatinum Pt_3Fe and native platinum with the formula Pt_2Fe (iron-bearing platinum). The Pt−Fe minerals are mostly observed as aggregates with a size of 0.2−1.0 mm and rarely as individual grains with a size of less than 0.1 mm. Chromitite of the Veresovoborsky massif include quite large aggregates of Pt−Fe minerals with a size of a few centimeters. A platinum nugget with a size of 2.5 cm was described in prospecting hole no. 109 (Trushin et al., 2017). A segregation of PGMs with a size of 0.3 × 1.2 cm was found in tailings of prospecting trench no. 110 in massive vein chromitite.

Grains of Pt−Fe minerals with a size of less than 0.1 mm included in chrome spinel are mostly euhedral (Figs. 3a−3c). In most cases, the large grains of the Pt−Fe minerals contain induction faces (Figs. 3c and 3d)

formed upon their synchronous growth with chrome spinel, with a small number of anhedral (imprint) surfaces. There are occasional grains of Pt−Fe minerals with the proper crystallographic forms and predomination of {100} faces. The average concentration of platinum in intermetallic compounds from chromitite (without account for the tetraferroplatinum-group minerals) is 89.8% for the Svetloborsky massif (450 analyses), 85.6% for the Veresovoborsky massif (215 analyses), and 87.5% for the Kamenushensky massif (137 analyses). The low average content of platinum in the Pt−Fe association from chromitite of the Veresovoborsky massif is explained by the relatively wide abundance of iron-bearing platinum Pt_2Fe.

The primary Pt−Fe intermetallic compounds in chromitite of the Veresovoborsky and Kamenushensky massifs are substantially replaced with tetraferroplatinum-group minerals. The most abundant among them is tulameenite, which forms rims around Fe-rich platinum or (rarely) isoferroplatinum. Tulaminite, in turn, is replaced with tetraferroplatinum and mineral with the composition Cu_3Pt.

Let us focus on the composition of inclusions in Pt−Fe minerals. A wide abundance of inclusions of native Ir and PGE sulfides of the kashinite−bowieite and erlichmanite−laurite isomorphic series, as well as

Table 1. The composition of chrome spinels from the clinopyroxenite–dunite massifs of the Middle Urals

No.	Sample	MgO	MnO	FeO	NiO	Al_2O_3	TiO_2	Cr_2O_3	Fe_2O_3	Type	Σ	Cr#	Mg#	Formula
								Kamenushenskii massif						
1	K-7.2	6.32	0.12	20.60	0.12	11.20	0.45	45.90	14.50	1	99.22	0.80	0.23	$(Fe_{0.65}Mg_{0.33})_{0.98}(Cr_{1.24}Al_{0.45}Fe_{0.31}Ti_{0.01})_{2.02}O_4$
2	K-0.3	5.79	0.29	23.80	0.12	9.95	0.38	44.80	15.50	2	100.61	0.82	0.20	$(Fe_{0.70}Mg_{0.30}Mn_{0.01})_{1.01}(Cr_{1.21}Al_{0.40}Fe_{0.37}Ti_{0.01})_{1.99}O_4$
3	5_13	5.89	0.58	21.70	–	8.46	0.41	35.90	26.30	3	99.29	0.81	0.21	$(Fe_{0.68}Mg_{0.31}Mn_{0.02})_{1.01}(Cr_{0.99}Fe_{0.64}Al_{0.35}Ti_{0.01})_{1.99}O_4$
4	5_16	6.56	0.78	24.00	0.23	7.72	0.36	49.10	12.00	3	100.82	0.86	0.21	$(Fe_{0.64}Mg_{0.34}Mn_{0.02})_{1.01}(Cr_{1.32}Al_{0.31}Fe_{0.35}Ti_{0.01})_{1.99}O_4$
5	K-0.1	9.30	0.10	18.00	0.15	10.20	0.53	51.50	10.70	2	100.52	0.83	0.34	$(Fe_{0.52}Mg_{0.46})_{0.98}(Cr_{1.35}Al_{0.40}Fe_{0.25}Ti_{0.01})_{2.02}O_4$
								Veresovoborskii, massif						
6	B-6/1	8.54	0.14	18.10	0.08	7.23	0.81	42.90	21.40	1	99.14	0.86	0.32	$(Fe_{0.55}Mg_{0.44})_{0.99}(Cr_{1.17}Fe_{0.52}Al_{0.29}Ti_{0.02})_{2.01}O_4$
7	B-6/2	8.23	0.16	17.40	0.12	6.78	0.69	45.30	22.10	1	100.83	0.87	0.32	$(Fe_{0.57}Mg_{0.42})_{0.99}(Cr_{1.22}Fe_{0.49}Al_{0.27}Ti_{0.02})_{2.01}O_4$
8	B-6/3	7.89	0.26	15.90	–	6.52	0.71	47.70	20.90	1	100.04	0.88	0.33	$(Fe_{0.60}Mg_{0.41}Mn_{0.01})_{1.02}(Cr_{1.30}Fe_{0.40}Al_{0.26}Ti_{0.02})_{1.98}O_4$
9	B-1/1	9.36	0.12	16.90	0.11	6.57	0.74	44.70	20.00	2	98.55	0.87	0.36	$(Fe_{0.51}Mg_{0.48})_{0.99}(Cr_{1.22}Fe_{0.49}Al_{0.27}Ti_{0.02})_{2.01}O_4$
10	B-1/2	9.32	0.23	17.30	0.17	6.59	0.75	45.10	19.50	2	98.91	0.87	0.35	$(Fe_{0.53}Mg_{0.48}Mn_{0.01})_{1.02}(Cr_{1.22}Fe_{0.47}Al_{0.27}Ti_{0.02})_{1.98}O_4$
11	B-1/3	9.43	0.12	16.90	0.07	6.75	0.77	46.30	19.10	2	99.47	0.87	0.36	$(Fe_{0.51}Mg_{0.48})_{0.99}(Cr_{1.25}Fe_{0.46}Al_{0.27}Ti_{0.02})_{2.01}O_4$
								Svetloborskii massif						
12	C-8/4	4.58	0.74	31.40	–	9.35	0.45	35.15	20.3	1	101.97	0.79	0.13	$(Fe_{0.76}Mg_{0.23}Mn_{0.02})_{1.01}(Cr_{0.95}Fe_{0.65}Al_{0.38}Mn_{0.02}Ti_{0.01})_{1.99}O_4$
13	C-3/1	8.63	0.43	23.50	–	7.05	0.55	50.37	11.45	2	101.98	0.88	0.27	$(Fe_{0.57}Mg_{0.43}Mn_{0.01})_{1.01}(Cr_{1.33}Fe_{0.37}Al_{0.28}Ti_{0.01})_{1.99}O_4$
14	C-3/4	10.20	0.82	20.80	–	6.78	0.70	49.75	13.10	2	101.95	0.88	0.33	$(Fe_{0.50}Mg_{0.50}Mn_{0.02})_{1.02}(Cr_{1.30}Fe_{0.40}Al_{0.26}Ti_{0.02})_{1.98}O_4$
15	C-0/1	4.14	0.44	24.00	0.12	5.45	0.60	40.60	22.70	3	98.05	0.88	0.15	$(Fe_{0.75}Mg_{0.23}Mn_{0.01})_{0.99}(Cr_{1.16}Fe_{0.59}Al_{0.23}Ti_{0.02})_{2.01}O_4$
16	C-0/3	9.41	0.12	18.00	0.11	6.60	0.74	44.90	19.30	3	99.18	0.87	0.34	$(Fe_{0.51}Mg_{0.48})_{0.99}(Cr_{1.21}Fe_{0.50}Al_{0.27}Ti_{0.02})_{2.01}O_4$

Types 1–3: (1) accessory chrome spinel in dunite; (2) chrome spinel from the vein–disseminated or massive chromitite; (3) chrome spinel intergrown or included in the Pt–Fe minerals. Cr# = Cr/(Cr + Al); Mg# = Mg/(Mg + Fe^{2+}); (–) below the detection limits. Formulas are calculated for four oxygen atoms. Analyses were obtained on a Camebax SX 50 electron microprobe (analyst D.A. Khanin).
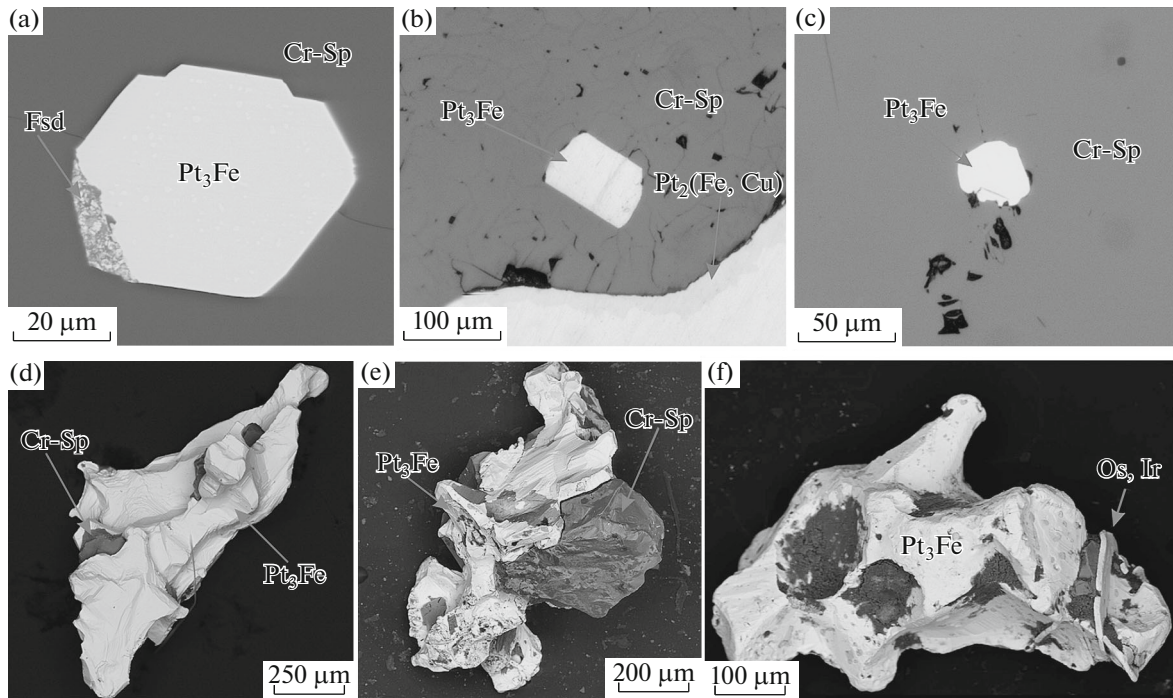
Fig. 3. The morphological features of individual and aggregates of grains and aggregates of the Pt−Fe minerals from chromitite of the Svetloborsky (a, d), Veresovoborsky (b, e), and Kamenushensky (c, f) clinopyroxenite−dunite massifs of the Middle Urals. Cr-Sp, chrome spinel; Pt_3Fe, intermetallic compounds with the composition of isoferroplatinum; $Pt_2(Fe,Cu)$, tulameenite; (Os,Ir), Ir-bearing Os; Fsd, ferhodsite.

the minerals of the Ir−Rh tiospinel group (cuproir-idsite−cuprorhodsite), is the distinguishing feature of chromitite of the Svetloborskii massif in comparison with chromitite from other clinopyroxenite−dunite massifs of the Uralian Platinum Belt (Stepanov et al., 2017). Native Ir forms exsolutions in Pt−Fe minerals (Fig. 4a) and rarely individual aggregates (Pala-marchuk, 2016). The composition of this mineral varies significantly in relation to the concentrations of Os and Pt. The minerals of the erlichmanite−laurite group were found as zoned euhedral inclusions in the Pt−Fe matrix (Stepanov et al., 2017), rarely inter-grown with chrome spinel. The zoning is reflected in an increase of the Os concentration in laurite from the central part of the grain to the margin with transition to erlichmanite (Fig. 4b). The morphological and ana-tomical patterns of grains of the kashinite−bowieite mineral series in most cases are similar to those of laurite. Their zoning demonstrates an increase in the Rh concentration from the center of a crystal to the margin with the transition from bowieite to kashinite. However, we found grains without zoning as well (Fig. 4c).

Among the major inclusions in the Pt−Fe minerals from chromitite of the Veresovoborsky massif are hexagonal euhedral lamellae of native Os in the Pt−Fe matrix or rarely in chrome spinel. PGE sulfides are less abundant.

PGE sulfide inclusions are widely abundant in the Pt−Fe minerals from chromitite of the Kamenushen-sky massif (Kozlov et al., 2011; Tolstykh et al., 2011). They form small (25 μm), often zoned grains, usually of an isometric shape. Laurite is the most abundant among the laurite−erlichmanite and bowieite−kashi-nite mineral series. Among the minerals of the bowie-ite−kashinite series, only bowieite was detected. In addition to PGE sulfides, inclusions are widely represented by Os−Ir−(Ru) solid solutions. These are lamellae of native Os and isometric grains of native Ir. The unique feature of these minerals is the high concentration of Ru, which reaches high values (up to 21 at %), which is not typical of the Os−Ir−(Ru) minerals in chromitite from other zoned clinopyroxenite−dunite massifs.

Predomination of the Pt−Fe minerals over other PGMs is the general feature of chromitite from the studied massifs. The specifics of PGE mineralization in various massifs are controlled by the abundance of inclusions in the Pt−Fe matrix and their chemical composition.

PGEs IN CHROMITITE AND DUNITE

As was established during the analytical studies, the different methods of analysis of the weight fraction of platinum in chromite provide significantly different results (Table 3). As an example, the PGE concentration obtained using ICP-MS without preliminary assay melting is significantly underestimated. The data

Table 2. The composition of the Pt–Fe minerals from chromitite of the clinopyroxenite–dunite massifs of the Middle Urals

No.	Locality	Fe	Ni	Cu	Ru	Rh	Pd	Os	Ir	Pt	Σ PGE	Σ	Formula
								Svetloborsky massif					
1	El–Del-1	7.52	–	0.68	–	0.10	0.47	–	1.80	89.70	92.11	100.27	$(Pt_{2.97}Ir_{0.06}Pd_{0.03}Rh_{0.01})_{3.06}(Fe_{0.87}Cu_{0.07})_{0.94}$
2	El–Del-1	7.50	–	0.60	–	0.85	0.55	0.13	2.74	87.84	92.13	100.21	$(Pt_{2.89}Ir_{0.09}Rh_{0.05}Pd_{0.03})_{3.07}(Fe_{0.86}Cu_{0.06})_{0.92}$
3	El–Del-1	7.00	0.08	0.71	0.16	1.44	0.38	0.40	3.56	86.90	92.84	100.63	$(Pt_{2.86}Ir_{0.12}Rh_{0.09}Pd_{0.02}Os_{0.02}Ru_{0.01})_{3.11}(Fe_{0.81}Cu_{0.07}Ni_{0.01})_{0.89}$
4	Trench-36	8.76	–	0.63	–	0.82	0.71	0.27	1.15	87.67	90.62	100.01	$(Pt_{2.82}Rh_{0.05}Ir_{0.04}Pd_{0.04}Os_{0.01})_{2.95}(Fe_{0.98}Cu_{0.06})_{1.05}$
5	Trench-36	8.24	–	0.73	–	0.68	0.24	0.26	1.39	88.33	90.90	99.87	$(Pt_{2.88}Ir_{0.05}Rh_{0.04}Pd_{0.01}Os_{0.01})_{2.99}(Fe_{0.94}Cu_{0.07})_{1.01}$
6	Trench-32	8.71	–	0.53	–	0.57	0.19	0.21	0.56	88.45	89.98	99.22	$(Pt_{2.88}Ir_{0.04}Ir_{0.02}Pd_{0.01}Os_{0.01})_{2.95}(Fe_{0.99}Cu_{0.05})_{1.05}$
7	Trench-32	8.41	–	0.71	–	0.68	0.49	0.28	2.18	86.44	90.07	99.19	$(Pt_{2.82}Ir_{0.07}Rh_{0.04}Pd_{0.03}Os_{0.01})_{2.97}(Fe_{0.96}Cu_{0.07})_{1.03}$
Average		8.02	0.02	0.66	0.03	0.73	0.43	0.23	1.91	87.90	91.24		
								Veresovoborsky massif					
8	Trench-106	8.22	0.05	0.93	–	0.59	–	0.14	0.70	89.35	90.78	99.98	$(Pt_{2.90}Ir_{0.02}Rh_{0.04})_{2.96}(Fe_{0.93}Cu_{0.09}Ni_{0.01})_{1.03}$
9	Trench-106	8.35	0.09	1.02	–	0.57	0.12	0.21	0.32	90.05	91.27	100.73	$(Pt_{2.89}Rh_{0.03}Ir_{0.01}Pd_{0.01}Os_{0.01})_{2.95}(Fe_{0.94}Cu_{0.10}Ni_{0.01})_{1.05}$
10	Trench-106	8.17	0.20	0.38	–	0.54	0.41	–	–	90.74	91.69	100.44	$(Pt_{2.95}Rh_{0.03}Pd_{0.02})_{3.01}(Fe_{0.93}Cu_{0.04}Ni_{0.02})_{0.99}$
11	Trench-110	8.39	–	0.50	–	0.47	0.21	–	–	89.77	90.45	99.34	$(Pt_{2.95}Rh_{0.03}Pd_{0.01})_{2.99}(Fe_{0.96}Cu_{0.05})_{1.01}$
12	Trench-110	6.79	–	1.61	0.53	1.04	0.46	–	–	89.43	91.46	99.86	$(Pt_{2.93}Rh_{0.06}Pd_{0.03}Ru_{0.03})_{3.06}(Fe_{0.78}Cu_{0.16})_{0.94}$
13	Trench-110	10.58	0.86	1.33	–	0.25	0.51	–	5.64	80.60	90.90	99.87	$Pt_{0.61}Fe_{0.28}Ir_{0.04}Cu_{0.03}Ni_{0.02}Pd_{0.01}$
14	El–Del-2	11.89	–	–	–	0.07	0.11	–	0.21	88.11	88.50	100.39	$Pt_{0.68}Fe_{0.32}$
15	El–Del-2	8.81	–	0.55	–	0.42	0.14	–	–	90.60	91.16	100.52	$(Pt_{2.92}Rh_{0.03}Pd_{0.01})_{2.95}(Fe_{0.99}Cu_{0.05})_{1.05}$
Average		8.90	0.15	0.79	0.07	0.49	0.25	0.04	0.86	88.58	90.78		
								Kamenushensky massif					
16	El–Del-3	8.76	–	–	0.64	1.09	–	0.65	4.60	84.72	91.70	100.46	$(Pt_{2.73}Ir_{0.15}Rh_{0.07}Os_{0.02}Ru_{0.04})_{3.01}(Fe_{0.99}Cu_{0.00})_{0.99}$
17	El–Del-3	8.13	–	0.59	–	0.74	–	0.19	0.79	89.63	91.35	100.07	$(Pt_{2.93}Rh_{0.05}Ir_{0.03}Os_{0.01})_{3.01}(Fe_{0.93}Cu_{0.06})_{0.99}$
18	El–Del-3	7.61	–	1.29	0.53	1.07	–	0.86	0.08	88.65	91.19	100.09	$(Pt_{2.88}Rh_{0.07}Os_{0.03}Ru_{0.03})_{3.01}(Fe_{0.86}Cu_{0.13})_{0.99}$
19	El–Del-3	8.68	–	–	–	0.97	–	0.38	–	89.26	90.61	99.29	$(Pt_{2.93}Rh_{0.06}Os_{0.01})_{3.00}(Fe_{1.00}Cu_{0.00})_{1.00}$
20	Khr–Uv-1	7.79	–	0.92	–	0.22	–	–	0.81	89.69	90.72	99.43	$(Pt_{2.97}Ir_{0.03}Rh_{0.01})_{3.01}(Fe_{0.90}Cu_{0.09})_{0.99}$
21	Khr–Uv-2	8.15	–	0.54	0.41	1.03	–	1.02	1.16	88.09	91.71	100.40	$(Pt_{2.86}Rh_{0.06}Ir_{0.04}Os_{0.03}Ru_{0.03})_{3.02}(Fe_{0.93}Cu_{0.05})_{0.98}$
22	Khr–Uv-3	8.19	–	0.66	–	0.79	–	0.86	–	89.89	91.54	100.39	$(Pt_{2.92}Rh_{0.05}Os_{0.03})_{3.00}(Fe_{0.93}Cu_{0.07})_{1.00}$
23	Khr–Uv-4	7.71	0.17	0.91	0.60	1.43	0.22	–	2.29	85.86	90.40	99.19	$(Pt_{2.80}Rh_{0.09}Ir_{0.08}Ru_{0.04})_{3.01}(Fe_{0.88}Cu_{0.09}Ni_{0.02})_{0.99}$
24	Khr–Uv-5	7.90	–	–	–	1.40	–	–	0.40	88.91	90.71	98.61	$(Pt_{2.97}Rh_{0.09}Ir_{0.01})_{3.08}Fe_{0.92}$
25	Khr–Uv-6	12.10	0.33	0.19	0.94	1.35	–	–	0.85	84.85	87.99	100.61	$Pt_{0.63}Fe_{0.32}Rh_{0.02}Ir_{0.01}Ru_{0.01}Ni_{0.01}$
26	Khr–Uv-7	11.85	0.25	0.59	0.23	1.14	0.85	–	1.14	83.38	86.74	99.43	$Pt_{0.63}Fe_{0.31}Rh_{0.02}Ir_{0.01}Ru_{0.01}Cu_{0.01}Ni_{0.01}$
Average		8.81	0.07	0.52	0.30	1.02	0.10	0.36	1.10	87.54	90.42		

El–Del are the eluvial–delluvial deposits overlying the ore zones on the prospecting areas Vershinny (El–Del-1), Veresovoborsky (El–Del-2), and Khromitovy Uval (El–Del-3); Khr–Uv are the original outcrops within the Khromitovy Uval. (1–12, 15–24) Isoferroplatinum, the formula is calculated for four atoms; (13, 14, 25, 26) Fe-rich Pt, the formula is recalculated for 100%. Analyses were obtained on a Camebax SX 50 electron microprobe (analyst D.A. Khanin).
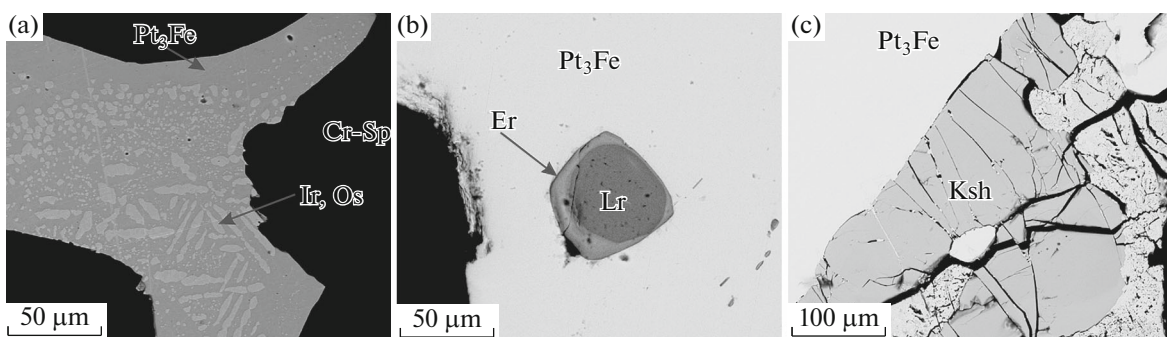
Fig. 4. Inclusions of the Pt−Fe minerals from the Svetloborsky (a), Veresovoborsky (b), and Kamenushensky (c) massifs. Cr-Sp, chrome spinel; Pt_3Fe, intermetallic compounds with the composition of isoferroplatinum; (Ir,Os), Os-bearing Ir; Er, erlichmanite; Lr, laurite; Ksh, kashinite.

of mass spectrometry with preliminary fire assay melting show a higher platinum concentration with a good reproducibility of analyses. Generally, such a significant difference in the results may be explained by accumulation of PGEs in individual minerals and the relative sizes of their grains and aggregates. Because of this, the accuracy of analysis depends directly on the size of the sample, which is significantly higher for assay melting prior to the study of an element weight fraction on a mass spectrometer. We should especially consider the difference between the results of chemical analyses and measurement of the platinum concentration by weighing gravitationally enriched PGM segregations. Thus, chromitites from the Svetloborsky and Kamenushensky massifs without large PGM aggregates are characterized by a high convergence of the results obtained using different analytical methods. At the same time, chromitite from the Veresovoborsky massif shows a significant difference between the results of assay analysis and those obtained from measurement of a weight fraction of platinum by weighing platinum concentrate. This peculiarity may be explained by the presence of very large PGM aggregates in chromitite of the Veresovoborsky massif, which are depend entirely upon the gravitational enrichment of large samples and result in wide variations in the data of the chemical analysis.

To analyze the contents of other PGEs (Os, Ir, Ru, Rh, and Pd) with very low values even in chromitite, we may apply the method of ICP-MS without preliminary assay melting. The methods of assay melting are less productive for analysis of the PGE concentrations in dunite due to the high detection limit in comparison with the ICP-MS method. As an example, the lower detection limit for platinum during the assay atomic emission analysis is 0.1 ppm at an average concentration of this element in dunite of 0.035−0.040 ppm.

According to the data of the assay analysis and ICP-MS, the distribution of platinum in chromitite is very heterogeneous. The lowest, highest, and average platinum concentrations for the Svetloborsky massif are 1.76, 80.60, and 22.00 ppm, respectively. The aver-

age weight fraction of platinum in chromitite from the Veresovoborsky massif is 25 ppm with a highest content of 37.6 ppm and a lowest content of 2.27 ppm. The variations in the concentrations of other PGEs are narrower.

The distribution of PGEs from chromitite of the Svetloborsky, Veresovoborsky, and Kamenushensky massifs is characterized by an M-like spectrum (Fig. 5) typical of chromitite of the zoned massifs of dunite−clinopyroxenite−gabbro formations (Malitch et al., 2013). Chromitite demonstrate an absolute predomination of platinum over other PGEs resulting from the wide abundance of the Pt−Fe solid solutions among PGMs, which is typical of the clinopyroxenite−dunite massifs (Lazarenkov et al., 1992; Sidorov et al., 2012). In contrast to the Veresovoborsky and other clinopyroxenite−dunite massifs of the Urals, chromitite of the Svetloborskii massif is distinguished by clear Ir specialization resulting from the occurrence of native Ir as quite large aggregates with a weight of up to a few grams in chromitite. Chromitite of the Kamenushensky massif has the high concentration of Ru, which is explained by abundance of Ru-bearing Os−Ir solid solutions and laurite as inclusions in the Pt−Fe minerals. The concentration of Au in chromitite is of special interest, since native Au was detected in placers inside the dunite core. The maximum Au concentration in chromitite of the Veresovoborsky massif is close to 100 ppb. Au in such chromitite most likely forms proper minerals, which transit into placers upon destruction of the chromite−Pt ore zones.

The average concentrations of platinum in dunite from the Svetloborsky, Veresovoborsky, and Kamenushensky massifs are 0.02, 0.04, and 0.05 ppm, respectively. The concentration of platinum decreases from fine- and medium-granular dunite (an average of 0.05 ppm) to coarse-granular and pegmatoid varieties (an average of 0.023 ppm). The spectrum of PGE distribution in dunite is similar to that for chromitite. Dunite has an Ir−Pt geochemical specialization. The concentration of PGEs in chromitite (except for extremely rich sam-

Table 3. The concentration of noble metals in chromitite and dunite from the Svetloborsky (1−3, 11, 12), Veresovoborsky (4−7, 13−16), and Kamenushensky (8−10, 17−19) clinopyroxenite−dunite massifs (ppm)

No.	Texture	Sample	Ru	Rh	Pd	Os	Ir	Pt *	Pt**	Pt (mass)	Au
						Chromite					
1	Massive	SB-125	86.0	150.0	45.0	350.0	1060.0	3930.0	6200	5700.00	7.4
2	The same	SB-126	32.0	60.0	5.1	230.0	65.0	930.0	1760	1540.00	5.1
3	V-impr	KP-032	150.0	58.0	99.0	630.0	2710.0	15900.0	80 600	97 200.00	15.0
4	The same	KP-106	22.0	29.0	12.0	17.0	39.0	1280.0	225	19 200.00	82.0
5	Massive	VB-109	67.0	95.0	41.0	210.0	19.0	6220.0	1730	36 730.00	99.0
6	The same	SB-130	51.0	120.0	27.0	53.0	190.0	1280.0	8770	29 800.00	9.3
7	The same	SB-135	7.0	31.0	13.0	61.0	23.0	6220.0	2270	24 500.00	3.6
8	V-impr	KR-36	74.0	77.0	6.8	54.0	110.0	1150.0	3200	4530.00	14.0
9	Massive	KR-60	180.4	182.4	92.8	250.0	384.4	923.2	5750	7900.00	37.6
10	The same	Khr-Uv	111.0	29.5	85.5	120.0	3471.7	18 619.5	n.d.	27 300.00	3.9
Average			78.0	83.2	42.7	197.5	807.2	5 645.3	12 278.3	25 440	27.7
						Dunite					
11	F-g	SB-114	b.d.l.	b.d.l.	2.1	12.0	21.0	33.0	—	—	2.8
12	M-g	SB-116	2.9	b.d.l.	38.0	b.d.l.	4.5	13.0	—	—	6.3
13	F-g	VB-2	0.9	b.d.l.	b.d.l.	b.d.l.	4.7	28.0	—	—	4.6
14	M-g	VB-24	1.7	b.d.l.	b.d.l.	11.0	4.3	88.5	—	—	b.d.l.
15	C-g	SB-113	b.d.l.	b.d.l.	2.1	b.d.l.	b.d.l.	5.0	—	—	b.d.l.
16	Pegm	SB-111	b.d.l.	b.d.l.	b.d.l.	b.d.l.	b.d.l.	42.0	—	—	4.1
17	M-g	KR-48	b.d.l.	b.d.l.	b.d.l.	14.0	22.9	61.0	—	—	8.6
18	″	KR-68	2.4	b.d.l.	b.d.l.	b.d.l.	23.3	44.1	—	—	3.7
19	C-g	KR-69	0.8	b.d.l.	b.d.l.	b.d.l.	17.7	17.2	—	—	16.6
Average			1.4	—	14.1	7.3	10.0	36.9	—	—	6.7
The lower detection limit			2	2	2	10	2	2	100	—	2

Pt* is the data of ICP-MS (Central Laboratory, Russian Geological Research Institute); Pt** is the data of the assay atomic emission analysis (Regional Analytical Center "Mekhanobr Inzhiniring Analit"); Pt (mass) is the concentration of platinum obtained by weighing gravitationally enriched PGM samples; b.d.l., below the detection limits; (−), not determined. Chromite: (mass) massive; (v-impr) vein−impregnated. Dunite: (f-g) fine-granular; (m-g) medium-granular; (c-g) coarse-granular; (pegm) pegmatoid.

ples) is higher than that in dunite by two orders of magnitude.

RESULTS AND DISCUSSION

The structural−material regularities, geological setting, and textural−structural patterns of rocks, as well as the composition of chrome spinels, the distribution, composition, and morphology of PGM grains and aggregates, and the PGE distribution in chromitite and dunite from the chromite−Pt mineralized zones of the Svetloborsky, Veresovoborsky, and Kamenushensky massifs are consistent with the analogous parameters previously obtained for the chromite−Pt ore zones of the Nizhny Tagil massif (Lazarenkov et al., 1992; Malitch et al., 2013; Pushkarev et al., 2007) in the Middle Urals and Gal'moenansky massif (Mochalov, 2013; Sidorov et al., 2012) in Koryakia. Analysis of the weight fraction of platinum

in chromitite allowed us to confirm the very heterogeneous character of its distribution, which is explained by accumulation of platinum only in the composition of the Pt−Fe minerals with the formation of large grains and their aggregates.

For chromitite from clinopyroxenite−dunite massifs containing bodies of coarse-granular dunite and dunitic pegmatite, the most promising for native chromite−Pt mineralization are characterized by the formation of very large aggregates of PGMs, which makes it difficult to collect accurate data during the sampling of native ores. In general, accounting for the structural−material regularities, obtaining the most reliable data on the concentration and distribution of platinum requires large-scale sampling, which was performed during the prospecting studies on the Krasny Ural Mine in the Nizhny Tagil massif in the 1930s and confirmed during the experimental−meth-
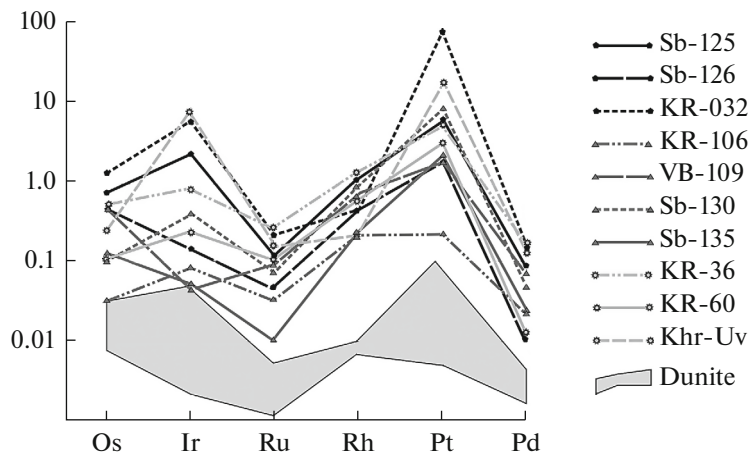
Fig. 5. Chondrite-normalized (McDonough and Sun, 1995) PGE concentrations in chromitite from the Svetloborsky (SB-125, SB-126, and KR-032), Veresovoborsky (KR-106, VB-109, SB-130, and SB-135), and Kamenushensky (KR-36, KR-60, and Khr-Uv) zoned clinopyroxenite−dunite massifs.

odological works of the Polimetall Company on the Veresovoborskii massif (Trushin et al., 2017).

CONCLUSIONS

Chromitite of the Svetloborsky, Veresovoborsky, and Kamenushensky massifs is characterized by the Ir−Pt specialization that is typical of chromitite from zoned clinopyroxenite−dunite massifs, which is supported by the results of the study of an association of PGMs. The character of the platinum distribution in chromitite bodies is extremely heterogeneous. It was shown that the assay atomic emission method of analysis is preferable for obtaining an accurate result for the weight fraction of platinum in chromitite. However, if PGEs are accumulated as large nuggets, as in chromitite from the Veresovoborsky massif, the results of measurements of the weight fraction of platinum using preliminary assay melting are significantly underestimated in comparison with the data obtained by weighing PGM samples enriched using gravitational methods.

Thus, significant attention during geological prospecting studies aimed at searching for native chromite−Pt mineralization should be paid to the methods of sample preparation and analytical studies for the most accurate estimation of the resources in order to decrease the influence of the extremely heterogeneous distribution of platinum in chromitite.

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