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PGM in chromitites of Kraka massifs (the Southern Urals): diversity and origin

D.E. Saveliev

Institute of Geology of the Ufa Federal Research Centre of the Russian Academy of Sciences, Ufa, Russian Federation
e-mail: savl71@mail.ru

Abstract. The paper provides results of study of platinum group minerals (PGMs) from 18 ore occurrences and deposits of the Kraka massifs, most of these located in ultramafic rocks of the upper mantle section (15), and several occurrences in a crust-mantle transition complex (3). It is shown that chromitites in the upper mantle section have refractory geochemical specialization (Os-Ir-Ru), while chromitites of the transition complex typically contain Pt and Pd minerals. The highest concentrations of the platinum group elements (PGE) are observed in chromitites of the transition complex (up to 2500 ppb of the total PGE). However, minor amounts of chromitites at these sites do not allow us to consider this mineralization type as promising in practical terms. Chromitites in the upper mantle section are about an order lower in PGE (50–200 ppb of the total PGE). Analysis of the obtained data suggests the following explanation for various PGM types identified. PGMs occurred in chromitites of the upper mantle section at two stages: 1) disulfides of the laurite-erlichmanite series and, to a lesser extent, Os-Ir-Ru alloys were formed within chromite grains in result of subsolidus processes in the upper mantle restite during solid-phase segregation of PGEs initially incorporated in the crystal lattice of chromite; 2) sulfoarsenides and other PGE compounds with basic metals and antimony were formed by hydrothermal processing of chromitites in crustal conditions. Pt and Pd minerals were produced by differentiation of magmatic melts separated from restite; they were completely or partly transformed under the impact of hydrothermal processes.

Keywords: ultramafic rocks, ophiolite, chromitite, PGM, Kraka

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Introduction

Platinum group elements (PGE) are valuable metals used in high-tech industries. The group includes six elements, i.e. platinum (Pt), palladium (Pd), rhodium (Rh), ruthenium (Ru), iridium (Ir) and osmium (Os). All these elements relate to igneous complexes of the mantle origin and basic or ultrabasic composition. Yet behavior of some elements in endogenous processes can be markedly different. In result, various PGE concentrate in different rock complexes. Thus, two PGE subgroups are divided, i.e. relatively low-melting elements (Pt, Pd and Rh) that form the Pt subgroup (PPGE) and refractory ones (Ru, Ir and Os) that constitute the Ir subgroup (IPGE).

Copper-nickel (Cu-Ni) ores of layered platform-type intrusions are the main source for Pd. Here, this element occurs as sulfide, showing strong chalcophile properties. Cu-Ni ores in the Norilsk region are specifically high in Pd. The largest Pt reserves are associated with bedrock deposits of the Bushveld layered intrusion in South Africa. However, placers of the Middle and Northern Urals are another important source for this element. In these placers, Pt enters during destruction of minor chromitite bodies located in dunites of the Urals Platinum Belt. Other PGEs are far less abundant and mainly concentrated in podiform chromitites of ophiolite complexes.

Podiform chromitites associated with ophiolite massifs are widespread in the Ural folded belt (Perevozchikov et al., 2000). Their PGE content and mineralogy have been actively studied since the 1990s. Nowadays, deposits of many, though not all, massifs have been described with a varied degree of accuracy. Several papers are dedicated to the study of PGMs in the Kraka massifs (Saveliev et al., 2014; 2015; Garuti et al., 2021; Rakhimov et al., 2021; Saveliev, Gataullin, 2023), describing specific deposits and ore occurrences.

The aim of this paper is to summarize currently available data on distribution of various PGMs in mantle and crustal chromitites of the Kraka massifs, to expand the range of the studied deposits and ore occurrences and to analyze formation settings of the PGE mineralization.

Object and methods of the study

Chromitite samples collected from 18 small deposits, ore occurrences and localities within four Kraka massifs (Fig. 1) were the study objects. The bulk composition of PGE in chromitites was determined by the atomic absorption method at TsNIGRI (in 1998–1999) and the ICP-MS method at the Institute of Geochemistry SB RAS with preliminary sample preparation according to (Menshikov et al., 2016). Some of these data had been published earlier (Snachev et al., 2001; Saveliev et al., 2014; 2015; Rakhimov et al., 2021). The current paper provides summarized and supplemented data.

To study the mineralogy of chromitites, polished sections 20x30 mm in size were made from the samples. The sections were previously studied on a polarizing microscope POLAM R-312 in reflected light. Electron microscopic studies were carried out on a Tescan Vega 4 Compact scanning electron microscope (Tescan, Czech Republic) with an Xplorer 15 energy-dispersive analyzer (Oxford Instruments, UK) (IG UFRC RAS, Ufa). The chemical composition spectra were processed using the AzTec One software package. The following settings were used in imaging: accelerating voltage 20 kV, probe current in the range of 3-4 nA, spectrum accumulation time at a point of 60 s in the Point&ID mode.

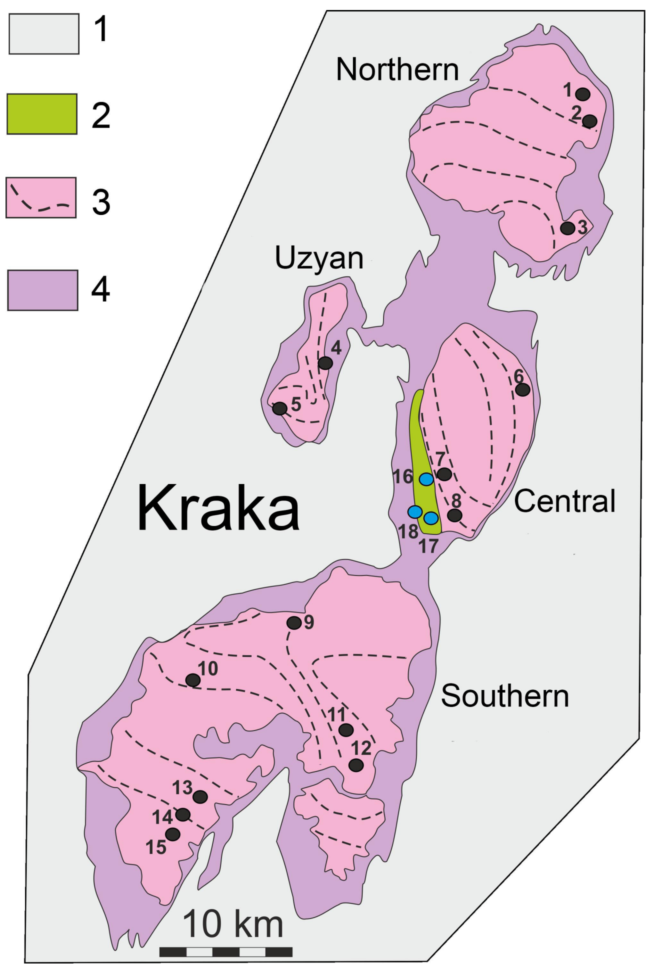

Fig. 1. Overview map of the Kraka massifs and the position of the studied chromitites. 1 – sedimentary host rocks, 2 – ultramafic rocks, 3 – basic rocks, 4 – serpentinites; #occurrences: 1 – Shigaevo-1, 2 – Shigaevo-2, 3 – Rudnaya Gora, 4 – Orlov, 5 – Chernaya Rechka, 6 – Deposit No. 33, 7 – Klyuchevskoe, 8 – Akbura, 9 – Bolshoy Log, 10 – Pridorozhnoe, 11 – Deposit No. 18, 12 – Bezymyannoe, 13 – Bolshoy Bashart, 14 – Menzhinsky, 15 – Maly Bashart, 16 – Loginov, 17 – West-Saksey, 18 – Babai

Previous study and geological background

The Kraka ophiolite massifs expose over a significant area in the northern part of the Zilair synclinorium in the Southern Urals. Administratively, they are located in three districts of the Republic of Bashkortostan, i.e. the Beloretsky, Burzyansky and Abzelilovsky. The southeastern part of the area is composed of ultramafic rocks and belongs to the Bashkir State Reserve. The geological study of ophiolite massifs started in the 1920-1930s, when several groups of Bashkhromite and Soyuzkhromite searched for chromitites on their territory (Kvyatkovsky, 1929; Tikhovidov, 1932; Loginov, 1933; Farafontiev, 1937; Sokolov, 1948). Systematic geological mapping of the massifs was carried out in the 1960s (Klochikhin et al., 1969), and the internal structure was studied by a group of the Geological Institute of the Russian Academy of Sciences (Savelieva, 1987; Denisova, 1990). The interest in chromitites increased due to the loss of deposits of the Kempirsai group. The massifs were studied by employees of the Institute of Geological Research of the UFRC RAS (Kovalev, Snachev, 1998; Snachev et al., 2001; Saveliev et al., 2008; Saveliev, 2018) and some industrial organizations (LLC GDK Chrome, Bashkirgeology).

Lherzolites and harzburgites play the main role in the geological structure of the massifs. They are subject to low-temperature serpentinization of a varying degree. Dunites form bodies with different size and morphology and occupy a subordinate position. Notably, the largest dunite bodies are observed in the western part of the Central Kraka massif, at the boundary between the mantle and crustal sections. In literary sources, this boundary is often compared with the position of the ancient Mohorovicic boundary (the so-called "petrological Moho"). Gabbro and rocks of the crust-mantle transition complex (CMTC) represented by clinopyroxenites, wehrlites and websterites are only widespread in the west of the Central Kraka massif. In inner parts of the massifs, dikes of basic rocks, i.e. hornblende gabbro and dolerites, are minor; garnet gabbro (granulites) are rare. Marginal parts of all four massifs are composed of completely serpentinized and tectonized ultramafic rocks, forming the so-called "serpentinite melange" zone. It was formed due to cold tectonic emplacement of ultramafic rocks into the upper crust (Kazantseva, Kamaletdinov, 1969).

Results

Bulk PGE content in chromitites

In total, 18 occurrences have been studied, with 15 of them located in the upper mantle section and three of them among pyroxenites in CMTC. Only four of the studied sites can be classified as minor deposits (Menzhinsky, Bolshoy Bashart, Maly Bashart, Akbura). The rest sites are ore occurrences with reserves of less than 10 thousand tons of the ore.

In chromitites, the bulk PGE content varies in a fairly wide range, with the highest total contents (900–2500 ppb) recorded in chromitites of CMTC (West Saksey and Loginov). In studied chromitite occurrences of the upper mantle section (UMS), the bulk PGE content is usually 50–200 ppb. In chromitites of the UMS, IPGEs dominate, while in CMTC, chromitites are rich either in Pt only, or in Pt and Pd in approximately equal amounts (Table 1).

On plots of C1 chondrite-normalized values, UMS chromitites show nearly horizontal ("subchondritic") distributions with the minimum of Pt, while CMTC chromitites are rich in almost all PGE (Fig. 2). However, the Loginov shows a gradual increase in contents from Os to Pd, the West-Saksey displays a sharp increase in Pt > Rh = Pd, and the Babai demonstrates a sharp increase in Pt concentration with a moderate increase in IPGE.

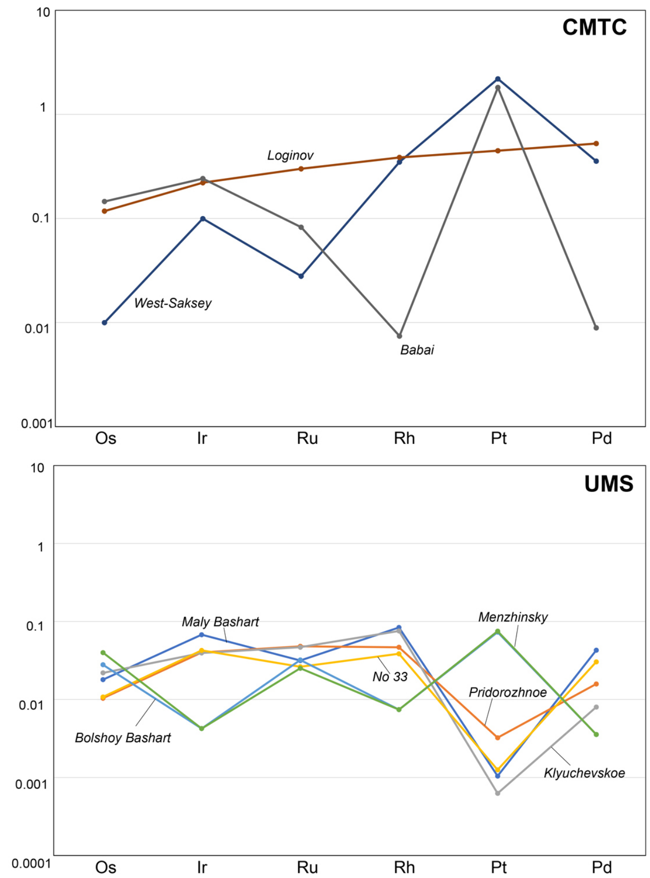

Fig. 2. Chondrite-normalized PGE abundances in Kraka chromitites. Composition of chondrite C1 after (Tagle, Berlin, 2008)

PGE mineralogy of UMS chromitites

In 15 of the studied deposits and ore occurrences, PGE mineralogy is characterized by a significant prevalence of IPGE minerals, i.e. Ru, Ir, Os: sulfides of the laurite-erlichmanite series, sulfoarsenides, Ru-Ir-Os alloys and oxide phases of the same composition.

At the Menzhinsky deposit, several grains of Ru-Os-Ir alloys were discovered. They occur as Ru intergrowths low in other PGE and smaller inclusions of Ir-Ru and Os. PGE sulfide phases are exclusively represented by laurite, which forms euhedral inclusions in internal parts of chromite grains. In addition to the mentioned PGMs, interstices of chromite grains commonly contain nickeline grains with an admixture of PGEs, i.e. Ru and Rh (up to 1 wt.%).

Chromitites of the Bolshoy Bashart deposit are high in PGM grains oxidized in a varying degree. They are initially represented by both sulfides of the laurite-erlichmanite series and alloys. Among unaltered grains, laurite dominates (90% of finds), while native Ru was identified only once. A large number of laurite inclusions was recorded at the Maly Bashart; single

#	Deposit / occurrence	Os	Ir	Ru	Rh	Pt	Pd	Total PGE
1	Maly Bashart	9.0	31.9	22.6	11.3	1.0	24.1	99.9
2	Pridorozhnoe	5.2	18.9	34.4	6.3	3.1	8.9	76.8
3	Klyuchevskoe	11.0	18.6	33.5	10.2	0.6	4.5	78.4
4	Deposit No. 33	5.4	20.1	18.8	5.2	1.2	17.1	67.8
5	Bolshoy Bashart	14	2	23	n.d.	70	2	112
6	Menzhinsky	20	2	18	n.d.	72	2	115
7	West-Saksey	5.0	47.0	20.0	47.0	2103.0	200.0	2417.0
8	Loginov	59.0	104.0	215.0	52.0	429.0	295.0	1154.0
9	Babai	73.0	114.0	59.0	n.d.	1737.0	5.0	1987.0

Table 1. Bulk-rock PGE composition of chromitites from some occurrences of Kraka massif (ppb). Note: after works (Snachev et al., 2001; Saveliev et al., 2014; Rakhimov et al., 2021), n.d. – not detected

grains are compositionally close to erlichmanite. In addition, several grains of native Ru, Ir and ruarsite were discovered.

In chromitites of Deposit No. 33, laurite co-exists with different unnamed PGE phases of varying composition: Ni-Fe-Ru-S, Ni-Fe-Ir, Rh-Ni-As, Ru-Rh-Ir-Ni and Ru-Ni-Fe-Os. A large number of PGMs were found in the Akbura deposit, which is located near the boundary of major dunite bodies of UMS and the transition wehrlite-clinopyroxenite complex. Disulfides of the laurite-erlichmanite series prevail here with a widely varied Ru/Os ratio. At the Shigaevo-1, Shigaevo-2 and Klyuchevskoe ore occurrences, only laurite inclusions were identified. At the Pridorozhnoe occurrence, single ruarsite inclusions were found along with laurite.

In the eastern part of the South Kraka massif (Bezymyannoye, Deposit No. 18), chromitites comprise minor inclusions of Ir sulfide, which also contains Cu (4.88–7.77 wt.%), Ni (3.2–4.5 wt.%), Rh (5.34–8.01 wt.%) and Fe (up to 1 wt.%). At the Bolshoy Log occurrence, a Rh-Cu-Sb mineral phase was observed. A specific geochemical specialization of PGMs is typical of ore occurrences in the Uzyan Kraka massif. In chromitites of the Orlov occurrence, grains of hollingworthite (?) were found, as well as Rh-Ni-Sb, Ni-Co-PGE-S and Ir-Ni-As-S phases. At the Chernaya Rechka occurrence, chromite grains contain inclusions of the Ru-Os-Ni-Co-S phase.

Thus, laurite is the most widespread PGM. Isometric grains, usually with a high degree of idiomorphism, prevail in laurite (Fig. 3a–3d). It commonly forms inclusions in internal parts of chromite grains and co-exists with amphiboles (Fig. 3a, 3b, 3d). Laurite can produce both monomineral PGE segregations and intergrowths, where it occurs as a matrix, while smaller inclusions are formed by PGE alloys (Fig. 3c), oxide phases and rare erlichmanite (Fig. 3d).

Unlike PGE disulfides, sulfoarsenides are mainly confined to interstices in chromite grains (Fig. 3f) or fine cracks (Fig. 3e). In addition to minerals of this group, all rarer PGE minerals were found in interstices and serpentine areas in chromitites, i.e. sulfides of complex composition, alloys and oxide phases of the Os-Ir-Ru composition, unnamed mineral phases of a varied composition (Fig. 3g, 3h). All the above PGM grains commonly show xenomorphic outlines, often spongy morphology and heterogeneous nature.

PGE mineralogy of CMTC chromitites

Though only three ore occurrences have been studied in CMTC, all of them contain various PGMs and thus differ in their geochemical specialization. In the West Saksey ore occurrence, Pt minerals strongly prevail. They commonly occur as Pt-Fe-Ni-(Cu) alloys (predominantly tetraferroplatinum) and often oxidized to form oxide phases (Figs. 4a–4c). Other minerals are sperrylite ($PtAs_2$), stibiopalladinite (Pd_5Sb_2), Pt-Fe-Ni-S sulfides and erlichmanite (OsS_2). Most analyses suggest that Pt-Fe alloys compositionally refer to tetraferroplatinum PtFe with impurities of Ni and Cu. Notably, the Ni content is higher, varying from 11 to 22 wt.% in about half of the analyses, while Cu is up to 4.5 wt.%. Some analyses show high Pd contents (up to 11–13 wt.%) always associated with impurities of Sn (1.2–1.5 wt.%) and Sb (4.1–4.5 wt.%). Analyses of stibiopalladinite regularly display the presence of Sn (8.5–8.9 wt.%) and Cu (4.2–4.5 wt.%).

The Loginov ore occurrence shows the richest PGE mineralogy with the leading role of Pd and Pt. However, most of them cannot be attributed to the known mineral species. Tiny alloy grains of the following composition were observed: Pd-Hg (potarite?), Cu-Pd-Pt-Hg, Cu-Pd-

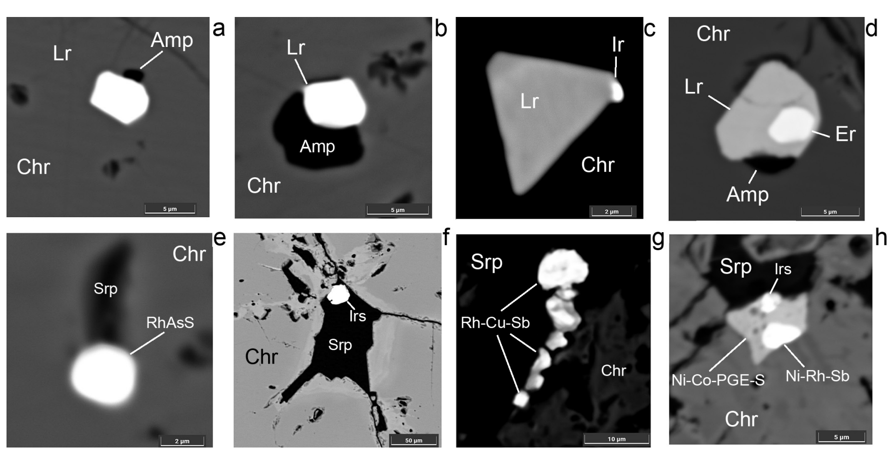

Fig. 3. Morphology of PGM inclusions in chromitites of the upper mantle section of the Kraka massif. a, b – laurite associated with amphibole (a – Pridorozhnoe, b – Deposit No. 33), c – euhedral laurite grain with tiny precipitate of iridium (Maly Bashart), d – laurite-erlichmanite intergrowth associated with amphibole (Babai), e – hollingworthite (?) close to crack filled with serpentine (deposit No. 33), f – irarsite in chromite grains interstitium filled with serpentine (Deposit No. 18), g – chain of Rh-Cu-Sb phase tiny grains in serpentine close to chromite grain (Bolshoy Log), h – PGE-sulphide with irarsite and Ni-Rh-Sb phase inclusions (Orlov). Chr – chromite, Srp – serpentine, Amp – amphibole, Lr – laurite, Er – erlichmanite, Irs – irarsite

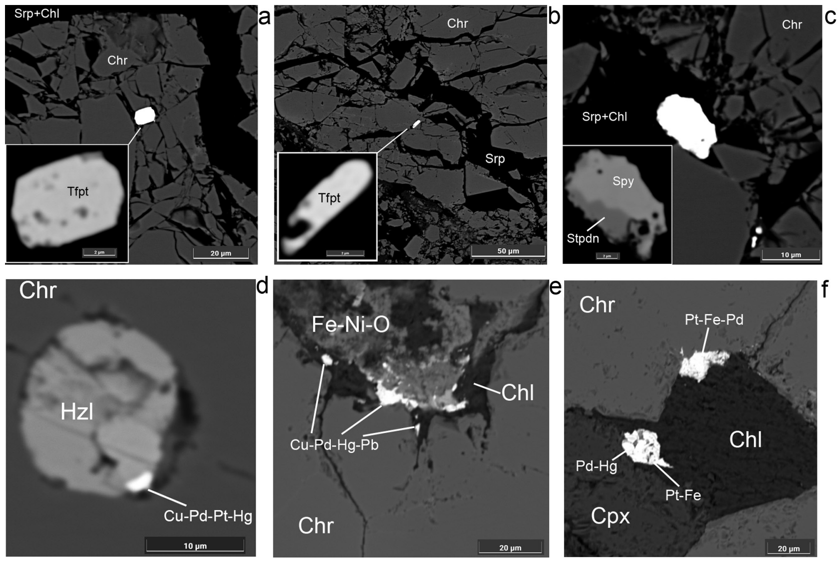

Fig. 4. Morphology of PGM inclusions in chromitites of the transitional crust -mantle unit of the Central Kraka massif. a – c – West-Saksey occurrence; d – f – Loginov occurrence. Chr – chromite, Chl – chlorite, Cpx – clinopyroxene, Hzl – heazlewoodite, Srp – serpentine, Spy – sperrylite, Stpdn – stibiopalladinite, Tfpl – tetraferroplatinum

Hg-Pb, Cu-Pd, Cu-Pt-Pd, Cu-Pt, Fe-Ru-Os, Pt-Ni-Fe, Pt-Fe, Ir-Pt-Fe, Pt-Fe-Pd-Ni and Rh-Pt-Te-Pb (Fig. 4d–4f). Besides, oxide phases, mainly IPGE, were found in chromitites. Findings of laurite (RuS_2) dominate among sulfides. In addition, complex arsenide (Rh-Ir-Ni-Fe_As) was discovered. The obtained results require further precision studies for more accurate diagnostics of the identified mineral phases.

The Babai ore occurrence is located in CMTC, but is actually emplaced in serpentinites. Chromitites show refractory mineralization with prevalent disulfides of the laurite-erlichmanite series, a few grains of native Ru and IPGE oxide phases.

Discussion

In terms of the geochemical specialization, the PGE mineralization in the studied chromitites is represented by two contrasting types. The first geochemical type of PGMs is the most widespread in the studied objects. It is characterized by prevalence of IPGEs, i.e. Ru, Ir and Os, a subordinate role of Rh and Pt and a complete absence of Pd. This complies with results formerly obtained for other deposits in the ophiolite upper mantle section of the Southern Urals, i.e. the southeastern part of the Kempirsai massif (Distler et al., 2008; Melcher, 2000; Saveliev et al., 2023), Kraka and Nurali (Rakhimov et al., 2022; Zaccarini et al., 2018; Garuti et al., 2021), Ufaley (Saveliev, 2022) and Karabash (Popova et al., 2023). In the second type, Pt and Pd minerals prevail. This type is only observed in small isolated ore occurrences among the wehrlites and pyroxenites of CMTC in the Central Kraka massif.

Consider morphological and structural features of the first-type PGM. Some of them are mainly confined to internal parts of chromite grains with no visible connection with cracks or interstices. However, they are often associated with hydroxyl-containing minerals; in the samples we studied, this is always amphibole. Inclusions of this subtype are usually composed of disulfides of the laurite-erlichmanite series, less often Os-Ir-Ru alloys. In the studied samples, laurites (Table 2) with prevalent Ru or native Ru are the most common (Fig. 5a, 5b), while compositions corresponding to erlichmanite are observed in fairly large quantities in chromitites of the Akbura deposit only (Fig. 5b). Sulfides of complex composition with prevalent Ir, compositionally close to cuproiridsite, were found only in occurrences in the southeastern part of the Southern Kraka massif.

In addition to the subtype discussed above, there are many PGM segregations confined to interstices in chromite grains or tending to fracture zones and replacement rims (Figs. 3e–3h). The composition of PGMs of this subtype is very diverse. Generally, IPGE sulfoarsenides dominate (Table 3, Fig. 5c, 5d). However, in the studied samples, we also found quite many phases that cannot be attributed to the known mineral species as well as recently approved IMA mineral zaccariniite (Table 3). Notably, minerals with three prevailing PGEs, i.e. Ru, Ir and Rh, were found in approximately equal quantities (Fig. 5d), while Os is not typical of minerals of this subtype.

Based on the location, morphology and composition of inclusions, literary sources suggest several different mechanisms to explain the genesis of PGM inclusions in chromitites of podiform deposits (Gijbels et al., 1974; Naldrett, Cabri, 1976; Cabri, 1981; Augé, Johan 1988; Stockman, Hlava 1984; Garuti et al., 1999; O'Driscoll, González-Jiménez, 2016, etc).

#	#Deposit*	S	Fe	Co	Ni	Cu	As	Ru	Rh	Pd	Ag	Os	Ir	Total	Mineral	Formula
1	1	35.39	0.60	–	–	–	0.43	41.64	–	–	–	16.71	5.01	99.78	Laurite RuS_2	$(Ru_{0.75}Os_{0.16}Ir_{0.047}Fe_{0.02})_{0.977}(S_{2.012}As_{0.01})_{2.022}$
2	1	36.24	0.76	–	0.49	–	–	39.16	1.07	–	–	13.69	10.44	101.85	Laurite RuS_2	$(Ru_{0.693}Os_{0.129}Ir_{0.097}Fe_{0.024}Rh_{0.019}Ni_{0.015})_{0.976}S_{2.024}$
3	2	35.09	0.60		0.00	1.33	–	40.16	–	–	–	13.91	8.00	99.09	Laurite RuS_2	$(Ru_{0.727}Os_{0.134}Ir_{0.076}Cu_{0.038}Fe_{0.02})_{0.995}S_{2.005}$
4	4	36.15	0.21	0.25	0.58	–	2.22	53.91	2.31	0.61	0.44	–	1.94	98.62	Laurite RuS_2	$(Ru_{0.913}Rh_{0.038}Ir_{0.017}Ni_{0.017}Pd_{0.01}Co_{0.007}Ag_{0.007}Fe_{0.006})_{1.016}(S_{1.933}As_{0.051})_{1.984}$
5	4	35.33	0.62	–	0.27	–	0.43	35.16	0.86	0.65	–	18.28	10.70	102.30	Laurite RuS_2	$(Ru_{0.637}Os_{0.176}Ir_{0.102}Fe_{0.02}Rh_{0.015}Pd_{0.011}Ni_{0.008})_{0.97}(S_{2.02}As_{0.01})_{2.03}$
6	5	36.76	0.44	–	–	–	–	41.99	3.44	–	–	13.50	5.79	101.92	Laurite RuS_2	$(Ru_{0.731}Os_{0.125}Rh_{0.059}Ir_{0.053}Fe_{0.014})_{0.981}S_{2.019}$
7	6	36.39	0.55	–	0.36	–	–	38.84	–	–	–	15.92	11.13	103.19	Laurite RuS_2	$(Ru_{0.687}Os_{0.150}Ir_{0.104}Fe_{0.018}Ni_{0.011})_{0.969}S_{2.031}$
8	7	35.22	0.48	–	–	–	–	40.84	1.01	–	–	14.33	6.90	98.78	Laurite RuS_2	$(Ru_{0.742}Os_{0.138}Ir_{0.066}Rh_{0.018}Fe_{0.016})_{0.98}S_{2.02}$
9	7	34.21	–	–	–	–	–	48.92	1.16	1.01	–	6.76	7.94	100.00	Laurite RuS_2	$(Ru_{0.88}Os_{0.065}Ir_{0.075}Rh_{0.02}Pd_{0.017})_{1.058}S_{1.942}$
10	8	28.69	6.76	–	–	–	–	8.58	–	–	–	43.19	12.78	100.00	Erlichmanite OsS_2	$(Os_{0.488}Ru_{0.183}Ir_{0.143}Fe_{0.259})_{1.073}S_{1.927}$
11	8	31.43	1.98	–	–	–	–	18.46	–	–	–	35.55	12.59	100.01	Erlichmanite OsS_2	$(Os_{0.386}Ru_{0.377}Ir_{0.135}Fe_{0.073})_{0.972}S_{2.028}$
12	8	34.91	0.94	–	–	–	–	36.76	1.22	–	–	17.12	8.01	98.96	Laurite RuS_2	$(Ru_{0.676}Os_{0.167}Ir_{0.077}Fe_{0.031}Rh_{0.022})_{0.974}S_{2.026}$
13	8	30.63	7.01	–	–	–	–	25.00	1.07	–	–	24.32	11.97	100.00	Laurite RuS_2	$(Ru_{0.485}Os_{0.251}Ir_{0.122}Fe_{0.245}Rh_{0.02})_{1.124}S_{1.876}$
14	9	38.78	2.15	–	–	–	–	39.27	–	0.67	–	12.28	6.16	99.31	Laurite RuS_2	$(Ru_{0.67}Os_{0.111}Fe_{0.066}Ir_{0.055}Pd_{0.011})_{0.913}S_{2.087}$
15	10	35.31	0.51	–	–	–	–	37.17	1.72	–	–	18.47	8.57	101.75	Laurite RuS_2	$(Ru_{0.674}Os_{0.178}Ir_{0.082}Rh_{0.031}Fe_{0.017})_{0.98}S_{2.02}$
16	11	35.66	0.32	–	–	–	–	43.30	–	–	–	15.06	4.73	99.07	Laurite RuS_2	$(Ru_{0.778}Os_{0.144}Ir_{0.045}Fe_{0.01})_{0.977}S_{2.023}$
17	13	35.60	0.46	–	0.51	–	–	41.60	1.48	–	–	8.72	10.59	98.96	Laurite RuS_2	$(Ru_{0.746}Os_{0.083}Ir_{0.1}Rh_{0.026}Ni_{0.016}Fe_{0.015})_{0.986}S_{2.014}$
18	14	36.43	0.30	–	–	–	–	42.77	2.80	–	–	11.72	6.97	100.99	Laurite RuS_2	$(Ru_{0.751}Os_{0.109}Ir_{0.064}Rh_{0.048}Fe_{0.01})_{0.982}S_{2.018}$
19	14	35.05	0.55	–	0.29	–	0.37	33.92	2.87	–	–	19.34	9.46	101.85	Laurite RuS_2	$(Ru_{0.618}Os_{0.187}Ir_{0.091}Rh_{0.051}Fe_{0.018}Ni_{0.009})_{0.975}(S_{2.016}As_{0.009})_{2.025}$
20	15	35.25	0.45	–	–	–	1.85	46.59	1.83	0.57	–	5.95	6.40	98.89	Laurite RuS_2	$(Ru_{0.822}Ir_{0.059}Os_{0.056}Rh_{0.032}Fe_{0.014}Pd_{0.01})_{0.993}(S_{1.963}As_{0.044})_{2.007}$
21	15	35.72	0.51	–	–	–	1.07	44.29	2.68	–	–	7.43	8.80	100.50	Laurite RuS_2	$(Ru_{0.779}Ir_{0.081}Os_{0.069}Rh_{0.046}Fe_{0.016})_{0.992}(S_{1.983}As_{0.025})_{2.008}$
22	15	34.30	0.52	–	–	–	–	35.14	2.58	–	–	19.56	7.64	99.74	Laurite RuS_2	$(Ru_{0.654}Os_{0.193}Ir_{0.075}Rh_{0.047}Fe_{0.017})_{0.986}S_{2.014}$
23	18	29.67	–	–	0.31	–	–	2.44	–	–	–	68.45	–	100.87	Erlichmanite OsS_2	$(Os_{0.821}Ru_{0.055}Ni_{0.012})_{0.89}S_{2.11}$
24	18	37.37	0.09	–	0.36	–	–	48.16	–	–	–	10.88	3.21	100.07	Laurite RuS_2	$(Ru_{0.829}Os_{0.1}Ir_{0.029}Ni_{0.011}Fe_{0.003})_{0.971}S_{2.029}$

*Table 2. Compositions of laurite-erlichmanite disulphides (wt.%). * #Deposit is a number of occurrences on the geological map (see Fig.1)*

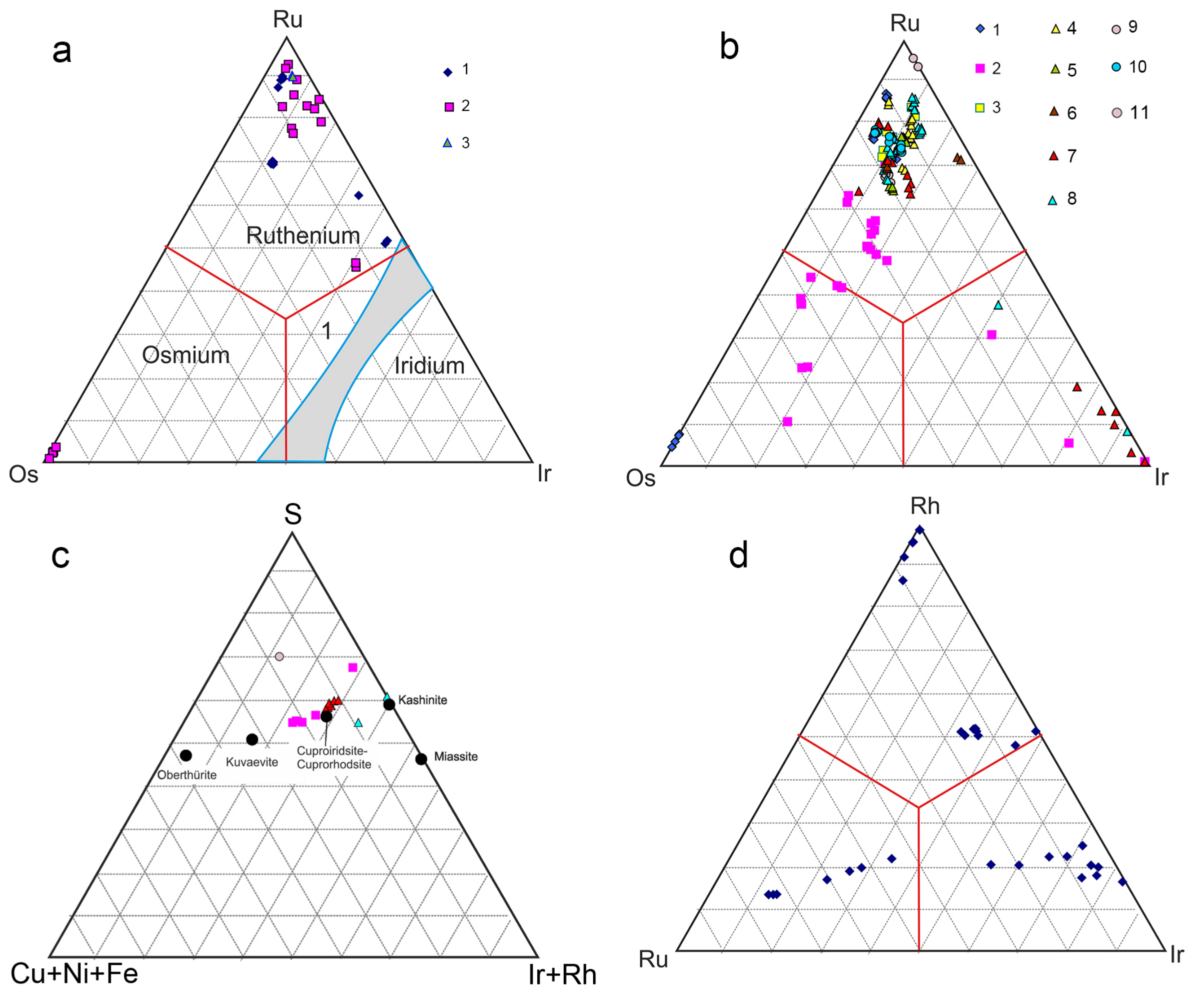

Fig. 5. PGM compositions from chromitites of deposits and occurrences of upper mantle section. a – composition of Os-Ru-Ir alloys: 1 – Central Kraka, 2 – Southern Kraka, 3 – Uzyan Kraka, gray is immiscibility field after (Harris, Cabri, 1991), field 1 — ruteniridosmine; b – sulphide compositions, occurrences (b, c): 1 – Deposit No. 33, Babai, 2 – Akbura, 3 – Klyuchevskoe, 4 – Bolshoy Bashart, 5 – Menzhinsky, 6 – Pridorozhnoe, 7 – Bezymyannoe and Deposit No. 18, 8 – Maly Bashart, 9 – Orlov and Chernaya Rechka, 10 – Shigaevo-1 and Shigaevo-2, 11 – Bolshoy Log; c, d – compositions of PGE-BM-As-S-Sb rare phases

Provided below are the main hypotheses explaining the genesis of the first-subtype inclusions: 1) the entry of IPGEs into chromite at high mantle temperatures and their release as their own phases upon cooling (Gijbels et al., 1974; Naldrett, Cabri, 1976); 2) crystallization simultaneously with chromite from melts or during the melt+peridotite reaction (Auge, 1985; Gervilla et al., 2005); 3) crystallization from fluids and/or melts seeping through ultramafic rocks (Thalhammer, 1996), including "supercritical fluids" (Distler et al., 2008).

Inclusions of the second subtype are usually interpreted as products of in situ destabilization of pre-existing Os-Ir-Ru sulfides or sulfoarsenides (Gonzalez-Jiménez et al., 2014). It is assumed that at the initial stage of the process a "spongy" structure was formed, some sulfur was removed and IPGE were partially replaced by Cu and Fe. Advanced stages of the process lead to complete replacement of primary minerals to produce a secondary alloy or a Pt group oxide (Augé, Legendre, 1994; Gonzalez-Jiménez et al., 2014). Most of the samples we studied show a preserved composition of primary sulfoarsenides, morphological changes, a "spongy" internal structure of grains, and a slight increase in the Fe content. Yet there is also a large number of analyses with a high oxygen content, which indicates significant oxidation of primary minerals.

PGM inclusions in CMTC chromitites are mainly located in interstices of chromite grains (West Saksey occurrence) or associate with base metal sulfides (Loginov occurrence) (Fig. 4). In the former case, they mostly occur as Pt-Fe-Ni-Cu alloys (Table 4). The triangular diagram (Fig. 6) shows that analysis points form two clusters, one of which is close to the tetraferroplatinum composition, while the other with an approximate formulae $Fe_4Pt_3(NiCu)_3$ cannot be referred to approved mineral species. The PGE mineralization of chromitites in the Loginov occurrence is more diverse (Table 5). It shows a fairly wide range of mineral phases with a predominance of Pd and Pt; many phases cannot be referred to the approved mineral species either.

#	# Deposit*	S	Fe	Co	Ni	Cu	As	Ru	Rh	Pd	Ag	Sb	Os	Ir	Pt	Total	Mineral	Formula
1	2	1.85	11.61	0.69	37.18	–	–	32.22	–	–	–	–	11.88	3.61	–	99.0	Unnamed (Ni,Ru,Fe…)	$(Ni_{0.483}Ru_{0.243}Fe_{0.158}Os_{0.048}Ir_{0.014}Co_{0.009})_{0.956}S_{0.044}$
2	3	13.31	1.04	–	–	–	28.13	3.00	8.13	–	–	–	–	46.84	–	100.5	Irarsite (Ir,Rh)AsS	$(Ir_{0.63}Rh_{0.204}Ru_{0.077}Fe_{0.048})_{0.96}(As_{0.968}S_{1.074})_{2.04}$
3	4	28.70	3.49	6.76	55.53	–	0.26	5.37	–	–	–	0.25	–	–	–	100.4	Unnamed Ni_4S_3 (+Ru)	$(Ni_{3.186}Co_{0.386}Fe_{0.21}Ru_{0.179})_{3.96}(S_{3.021}As_{0.012}Sb_{0.007})_{3.04}$
4	4	17.79	0.19	–	0.76	–	29.00	–	19.72	–	–	–	–	33.77	–	101.2	Unnamed (Rh,Ir)AsS	$(Rh_{0.433}Ir_{0.398}Ni_{0.029}Fe_{0.008})_{0.87}(S_{1.258}As_{0.875})_{2.13}$
5	4	0.29	0.61	–	21.64	–	–	–	16.51	–	–	61.87	–	–	0.75	101.7	Unnamed (Ni,Rh)Sb	$(Ni_{0.696}Rh_{0.302}Fe_{0.021})_{1.025}(Sb_{0.957}S_{0.017})_{0.975}$
6	5	9.98	4.43	7.47	17.88	–	–	34.65	1.16	0.50	–	–	15.01	10.45	–	101.5	Unnamed $(Ru,Co,FeOs,Ir)_3S$	$(Ru_{1.044}Ni_{0.927}Co_{0.385}Fe_{0.241}Os_{0.24}Ir_{0.166}Rh_{0.034}Pd_{0.014})_{3.05}S_{0.949}$
7	6	17.41	0.54	–	–	–	26.91	5.29	23.02	–	–	–	–	29.35	–	102.5	Unnamed (Rh,Ir)AsS	$(Rh_{0.50}Ir_{0.342}Ru_{0.117}Fe_{0.022})_{0.98}(S_{1.217}As_{0.803})_{2.02}$
8	6	0.91	16.68	0.38	55.42	3.00	–	2.35	8.69	–	–	–	–	11.72	–	99.2	Unnamed (Ni,Fe,Rh,Ir)	$(Ni_{0.632}Fe_{0.20}Rh_{0.057}Ir_{0.041}Cu_{0.032}Ru_{0.016}Co_{0.004})_{0.98}S_{0.02}$
9	6	–	1.74	–	26.73	–	–	1.26	41.54	–	0.77	–	–	–	–	102.7	Zaccariniite RhNiAs	$Ni_{1.037}(Rh_{0.918}Fe_{0.071}Ru_{0.028}Ag_{0.016})_{1.032}As_{0.93}$
10	6	–	4.43	–	14.00	–	0.37	37.80	–	–	–	–	–	42.62	–	99.2	Unnamed (Ru,Ni,Ir,Fe)	$(Ru_{0.407}Ni_{0.260}Ir_{0.242}Fe_{0.086})_{0.995}As_{0.005}$
11	6	–	1.78	–	6.43	–	–	33.54	–	–	–	–	3.30	54.00	–	99.1	Unnamed (Ru,Ir,Ni,Fe)	$(Ru_{0.43}Ir_{0.364}Ni_{0.142}Fe_{0.041}Os_{0.022})$
12	6	–	10.22	–	17.96	–	0.95	51.63	–	–	–	–	10.05	8.95	–	99.8	Unnamed (Ru,Ni,Fe,Os,Ir)	$(Ru_{0.46}Ni_{0.275}Fe_{0.164}Os_{0.048}Ir_{0.042})_{0.989}As_{0.011}$
13	6	–	4.04	–	21.26	0.48	9.56	25.41	13.21	–	–	–	1.79	25.34	–	101.1	Unnamed (Ni,Ru,Ir,Rh,Fe,Os)	$(Ni_{0.332}Ru_{0.231}Ir_{0.121}Rh_{0.118}Fe_{0.066}Os_{0.009})_{0.88}As_{0.12}$
14	8	25.35	4.42	–	1.04	9.07	–	–	8.26	–	–	–	–	47.33	4.53	100.0	Cuproiridsite $(Cu,Fe)Ir_2S_4$	$(Cu_{0.723}Fe_{0.40})_{1.123}(Ir_{1.249}Rh_{0.406}Pt_{0.118}Ni_{0.009})_{1.782}S_{4.014}$
15	8	–	4.60	–	0.68	–	–	54.41	–	–	–	–	24.57	15.74	–	100.0	Ruthenium (Ru,Os,Ir)	$(Ru_{0.638}Os_{0.153}Ir_{0.097}Fe_{0.097}Ni_{0.014})$
16	8	–	42.64	1.66	3.97	0.67	–	–	14.53	–	–	–	–	30.07	6.46	100.0	Unnamed (Fe,Ir,Rh,Ni,Pt)	$(Fe_{0.635}Ir_{0.131}Rh_{0.118}Ni_{0.056}Pt_{0.028}Co_{0.023}Ni_{0.009})$
17	9	–	1.09	–	0.57	14.44	–	–	52.00	–	–	30.93	–	–	–	99.0	Unnamed $CuRh_2Sb$	$(Cu_{0.895}Fe_{0.077}Ni_{0.038})_{1.01}Rh_{1.99}Sb_{1.00}$
18	10	17.44	2.31	–	1.09	–	17.57	24.72	8.64	–	–	0.87	2.47	22.25	3.96	101.3	Unnamed $(Ru,Ir,Rh)_2(S,As)_3$	$(Ru_{0.924}Ir_{0.438}Rh_{0.317}Fe_{0.155}Pt_{0.077}Os_{0.049})_{2.03}(S_{2.058}As_{0.885}Sb_{0.027})_{2.97}$
19	11	12.64	–	–	–	–	27.55	1.40	9.13	–	–	–	–	48.56	–	99.3	Irarsite (Ir,Rh)AsS	$(Ir_{0.679}Rh_{0.238}Ru_{0.037})_{0.95}(S_{1.06}As_{0.99})_{2.05}$
20	12	25.15	0.96	–	3.32	7.11	–	–	5.38	–	–	–	–	58.61	–	100.5	Cuproiridsite? $(Cu,Ni,Fe)Ir_2S_4$	$(Cu_{0.589}Ni_{0.298}Fe_{0.090})_{0.977}(Ir_{1.608}Rh_{0.275})_{1.883}S_{4.14}$
21	13	–	4.17	–	2.34	–	–	60.96	1.33	–	–	–	13.32	15.84	–	98.0	Ruthenium (Ru,Ir,Os)	$(Ru_{0.683}Ir_{0.093}Os_{0.079}Fe_{0.084}Ni_{0.045}Rh_{0.015})$
22	14	–	0.60	–	14.56	0.57	4.61	52.58	1.68	–	–	3.60	0.94	18.89	–	98.0	Unnamed (Ru,Ni,Ir,Fe)	$(Ru_{0.521}Ni_{0.248}Ir_{0.098}Fe_{0.011}Cu_{0.009}Os_{0.005})(As_{0.062}Sb_{0.030})$
23	14	–	2.00	–	4.09	–	–	30.36	–	–	–	0.42	14.56	49.66	–	101.1	Ruthenium (Ru,Ir,Os)	$(Ru_{0.404}Ir_{0.347}Os_{0.103}Ni_{0.094}Fe_{0.048})$
24	15	16.56	0.74	–	–	–	22.72	6.95	7.42	–	–	–	2.61	41.12	–	98.1	Irarsite (Ir,Rh,Ru)AsS	$(Ir_{0.534}Rh_{0.18}Ru_{0.172}Os_{0.034}Fe_{0.033})_{0.95}(S_{1.291}As_{0.756})_{2.05}$
25	15	16.23	1.66	–	–	–	25.34	6.46	22.20	–	–	–	1.47	25.85	–	99.2	Hollingworthite ? (Rh,Ir,Ru)AsS	$(Rh_{0.499}Ir_{0.312}Ru_{0.148}Fe_{0.069}Os_{0.018})_{1.04}(S_{1.174}As_{0.782})_{1.96}$
26	15	–	1.71	–	0.68	–	–	69.29	–	–	–	–	3.66	26.43	–	101.8	Ruthenium (Ru,Ir)	$(Ru_{0.775}Ir_{0.156}Fe_{0.034}Os_{0.022}Ni_{0.013})$
27	18	–	3.45	–	3.00	–	–	78.86	–	0.88	–	–	8.09	5.19	–	99.5	Ruthenium Ru	$(Ru_{0.804}Fe_{0.063}Ni_{0.053}Os_{0.044}Ir_{0.028}Pd_{0.009})$

*Table 3. Compositions of IPGM (without Laurite-Erlichmanite group) (wt.%). * #Deposit is a number of occurrences on the geological map (see Fig.1)*

#	Fe	Co	Ni	Cu	As	Pd	Sn	Sb	Pt	Total	Mineral	Formula
1	20.1	–	4.43	2.84	–	–	–	–	72.89	100.2	Tetraferroplatinum PtFe	$Pt_{0.877}Fe_{0.842}Ni_{0.177}Cu_{0.105}$
2	16.7	–	0.35	0.85	6.52	–	–	0.64	73.44	98.5	Tetraferroplatinum PtFe	$(Pt_{0.958}Fe_{0.758}Cu_{0.034}Ni_{0.015})(As_{0.221}Sb_{0.013})$
3	19.9	–	2.93	2.4	–	–	–	–	74.14	99.4	Tetraferroplatinum PtFe	$Pt_{0.924}Fe_{0.863}Ni_{0.121}Cu_{0.092}$
4	20.2	–	–	–	–	–	–	–	79.38	99.5	Tetraferroplatinum PtFe	$Pt_{1.06}Fe_{0.94}$
5	17.6	–	0.55	4.27	–	0.89	–	–	78.27	101.6	Tetraferroplatinum PtFe	$Pt_{1.003}Fe_{0.785}Cu_{0.168}Ni_{0.023}Pd_{0.021}$
6	21.7	–	2.73	1.77	–	–	–	–	74.49	100.6	Tetraferroplatinum PtFe	$Fe_{0.918}Pt_{0.905}Ni_{0.11}Cu_{0.066}$
7	20.9	–	1.81	1.43	–	–	–	–	76.07	100.3	Tetraferroplatinum PtFe	$Pt_{0.955}Fe_{0.914}Ni_{0.076}Cu_{0.055}$
8	22.3	–	0.74	–	–	–	–	–	78.08	101.1	Tetraferroplatinum PtFe	Pt0.987Fe0.982Ni0.031
9	21.2	–	0.55	–	–	–	–	–	79.91	101.7	Tetraferroplatinum PtFe	$Pt_{1.027}Fe_{0.949}Ni_{0.023}$
10	18.9	–	1.1	4.22	–	–	–	–	75.8	100.0	Tetraferroplatinum PtFe	$Pt_{0.958}Fe_{0.832}Cu_{0.164}Ni_{0.046}$
11	24.7	0.93	15.6	1.74	–	–	–	–	55.54	98.5	Unnamed (Fe,Pt,Ni,Cu)	$Fe_{0.426}Pt_{0.275}Ni_{0.257}Cu_{0.026}Co_{0.015}$
12	27.6	0.86	13.75	0.63	–	–	–	–	57.29	100.1	Unnamed (Fe,Pt,Ni,Cu)	$Fe_{0.471}Pt_{0.281}Ni_{0.224}Co_{0.014}Cu_{0.009}$
13	23.4	0.52	21.22	0.93	–	–	–	–	53.16	99.2	Unnamed (Fe,Pt,Ni,Cu)	$Fe_{0.389}Ni_{0.336}Pt_{0.253}Cu_{0.014}Co_{0.008}$
14	23.2	0.44	18.76	0.5	0.28	–	–	–	55.87	99.1	Unnamed (Fe,Pt,Ni,Cu)	$Fe_{0.399}Ni_{0.307}Pt_{0.276}Cu_{0.008}Co_{0.007}As_{0.004}$
15	24.6	–	18.25	0.54	–	–	–	–	55.97	99.3	Unnamed (Fe,Pt,Ni,Cu)	$Fe_{0.420}Ni_{0.297}Pt_{0.274}Cu_{0.008}$
16	–	–	–	4.22	–	65.76	8.74	21.45	0.61	100.8	Stibiopalladinite Pd5Sb2	$(Pd_{4.617}Cu_{0.496})_{5.136}(Sb_{1.314}Sn_{0.55})_{1.864}$
17	3.1	–	–	–	33.38	–	–	1.8	61.53	99.8	Unnamed $(Pt,Fe)_4As_5$	$(Pt_{3.419}Fe_{0.60})_{4.02}(As_{4.82}Sb_{0.16})_{4.98}$
18	0.3	–	–	–	42.94	0.34	–	0.55	55.48	99.6	Sperrylite $PtAs_2$	$(Pt_{0.981}Fe_{0.018}Pd_{0.011})_{1.01}(As_{1.974}Sb_{0.016})_{1.99}$

Table 4. Compositions of PGM in chromitites from West-Saksey occurrence (wt.%)

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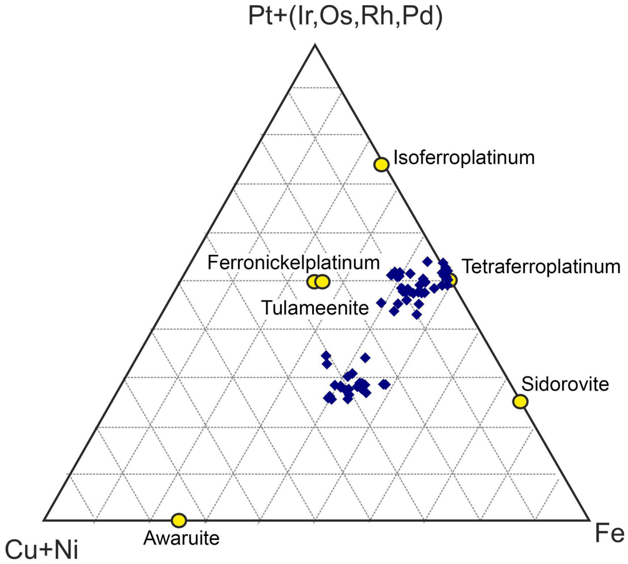

Fig. 6. PGM compositions from chromitites of CMTC occurrences

In view of morphological and compositional features of the inclusions, we can conclude that the genesis of Pt-Pd type minerals in CMTC chromitites is most likely associated with differentiation of magmatic melts separated from restite, as well as with later hydrothermal processes.

Conclusions

The conducted research allowed to summarize data on PGE mineralization in chromitites of two rock complexes of the Kraka ophiolite massifs, i.e. ultramafic rocks of UMS and CMTC. It was established that chromitites of these complexes had different geochemical PGE specialization. Chromitites of the upper mantle section contain minerals of Os-Ir-Ru(+Rh) composition, and ore occurrences of CMTC mainly show the Pt-Pd type of mineralization.

PGE minerals were formed in chromitites of UMS at two stages: 1) disulfides of the laurite-erlichmanite series and, to a lesser extent, Os-Ir-Ru alloys occurred in internal parts of chromite grains in result of subsolidus processes in the upper mantle restite during solid-phase segregation of PGEs initially dispersed in the crystal lattice of chromite; 2) sulfoarsenides and other PGE compounds with base metals and antimony were formed in result of hydrothermal processing of chromitites in crustal conditions. Pt and Pd minerals were formed by differentiation of magmatic melts separated from restite. They were completely or partially transformed under the impact of hydrothermal processes.

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#	S	Fe	Co	Ni	Cu	As	Ru	Rh	Pd	Ag	Te	Os	Ir	Pt	Hg	Pb	Bi	Total
1	–	7.62	–	8.0	63.74	–	–	–	20.18	0.53	–	–	–	0.99	–	–	–	101.1
2	–	1.67	–	0.3	12.53	–	–	–	45.24	–	–	–	–	–	22.71	20.17	–	102.6
3	2.61	4.78	–	3.43	16.43	–	–	–	20.39	–	–	–	2.07	16.71	36.76	–	–	103.2
4	–	5.68	–	5.76	65.16	–	–	–	2.88	–	–	–	3.0	16.6	–	–	–	99.1
5	–	26.63	1.76	14.28	1.06	–	–	1.84	–	–	–	–	–	54.67	–	–	–	100.2
6	–	28,59	–	21.27	5.71	–	–	–	–	–	–	–	–	43.84	–	–	–	99.4
7	–	21.08	–	25.92	0.85	–	–	–	–	–	–	–	–	51.38	–	–	–	99.2
8	7.11	30.8	–	1.68	2.76	–	–	2.6	–	–	–	–	31.23	26.88	–	–	–	103.1
9	–	38.38	0.9	53.27	0.45	–	–	–	–	–	–	–	–	5.44	–	–	–	98.4
10	–	0.6	–	–	1.37	–	–	–	35.52	–	–	–	–	–	63.37	–	–	100.9
11	–	16.79	–	4.29	0.98	–	–	–	7.45	–	–	–	–	66.98	4.73	–	–	101.2
12	–	16.66	–	10.54	5.62	–	–	–	8.01	–	–	–	–	50.81	8.28	–	–	99.9
13	34.77	1.56	–	0.35	–	–	39.05	–	–	–	–	15.54	7.11	–	–	–	–	98.4
14	1.9	15.37	–	17.93	–	15.05	–	22.03	–	–	0.58	1.94	21.18	–	–	–	–	96.0
15	–	11.88	–	14.69	–	14.2	–	24.53	–	–	9.24	–	20.18	–	–	–	10.25	105.0

#	Mineral	Formula
1	Unnamed (Cu,Pd,Fe,Ni)	$Cu_{0.68}Pd_{0.129}Fe_{0.092}Ni_{0.092}Pt_{0.003}Ag_{0.003}$
2	Unnamed $(Pd,Cu,Fe,Ni)_7HgPb$	$(Pd_{3.92}Cu_{1.816}Fe_{0.275}Ni_{0.047})_{6.956}Hg_{1.044}Pb_{0.898}$
3	Unnamed (Cu,Pd,Hg,Fe,Ni…)	$(Cu_{0.270}Pd_{0.201}Hg_{0.192}Fe_{0.089}Ni_{0.061}Ir_{0.011}Pt_{0.090})S_{0.085}$
4	Unnamed (Cu,Fe,Ni,Pt,Pd…)	$Cu_{0.758}Fe_{0.075}Ni_{0.073}Pt_{0.063}Pd_{0.020}Ir_{0.012}$
5	Unnamed (Fe,Pt,Ni…)	$Fe_{0.447}Pt_{0.264}Ni_{0.229}Co_{0.028}Rh_{0.017}Cu_{0.016}$
6	Unnamed (Fe,Ni,Pt,Cu)	$Fe_{0.430}Ni_{0.305}Pt_{0.189}Cu_{0.076}$
7	Unnamed (Ni,Fe,Pt,Cu)	$Ni_{0.403}Fe_{0.344}Pt_{0.241}Cu_{0.012}$
8	Unnamed (Fe,Ir,Pt…)	$Fe_{0.470}Ir_{0.139}Pt_{0.118}Cu_{0.037}Ni_{0.024}Rh_{0.022}$
9	Unnamed (Ni,Fe,Pt…)	$Ni_{0.552}Fe_{0.417}Pt_{0.017}Co_{0.009}Cu_{0.004}$
10	Potarite PdHg	$(Pd_{0.979}Cu_{0.063}Fe_{0.031})_{1.073}Hg_{0.927}$
11	Tetraferroplatinum PtFe	$Pt_{0.832}Fe_{0.726}Ni_{0.177}Pd_{0.170}Hg_{0.057}Cu_{0.037}$
12	Unnamed (Fe,Pt,Ni…)	$Fe_{0.316}Pt_{0.276}Ni_{0.190}Cu_{0.094}Pd_{0.080}Hg_{0.044}$
13	Laurite RuS_2	$(Ru_{0.713}Os_{0.151}Ir_{0.068}Fe_{0.051}Ni_{0.011})_{0.995}S_{2.005}$
14	Unnamed $(Fe,Ni,Rh,Ir)_3(As,Te,S)$	$(Ni_{1.036}Fe_{0.931}Rh_{0.726}Ir_{0.374}Os_{0.035})_{3.1}(As_{0.681}S_{0.201}Te_{0.015})_{0.9}$
15	Unnamed $(Fe,Ni,Rh,Ir)_3(As,Te,Bi)$	$(Ni_{0.897}Rh_{0.853}Fe_{0.760}Ir_{0.377})_{2.89}(As_{0.678}Bi_{0.176}Te_{0.259})_{1.11}$

Table 5. Compositions of PGM in chromitites from Loginov occurrence (wt.%)

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About the Author

D.E. Saveliev – Dr. Sci. (Geology and Mineralogy), Chief Researcher, Institute of Geology of the Ufa Federal Research Centre of the Russian Academy of Sciences

16/2 K.Marks st., Ufa, 450077, Russian Federation

e-mail: savl71@mail.ru

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