Mineral Parageneses and the Origin of Isoferroplatinum Nuggets from the Ignali Placer Deposit (Siberian Platform)

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Mineral Parageneses and the Origin of Isoferroplatinum Nuggets from the Ignali Placer Deposit (Siberian Platform)

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Abstract—Results of a study of platinum group minerals (PGM) and associated mineral paragenesis from the Inagli placer deposit (the Aldan Shield, Siberian Platform) are given. The Ir trend is typical for isoferroplatinum, which is a principal PGM in the Inagli massif. It is continuous in Ir content, reaching 8 wt % and more. Some decrease in the Ir content along the placer is caused by a vertical zoning of the primary sources of Pt.

The isoferroplatinum nuggets from the placer were examined for the first time. They are classified as small nuggets. Their sizes and weights are from 5 to 15 mm and 0.5 to 4.5 g. The largest nugget, 45 x 30 x 22 mm in size, weighs 100.22 g and consists of the isoferroplatinum aggregate with abundant chrome-spinelide impregnation. Chrome-spinelides containing 44 to 62 wt % Cr_2O_3, Cr-bearing (up to 6 wt % Cr_2O_3) diopside, olivine (Fa_{2-5}), serpentine, phlogopite, Ni-bearing (up to 5 wt % NiO) vermiculite, K-feldspar, pectolite, apatite, and unidentified Ti-bearing K- and Ca-silicates in PGM were distinguished as intergrowths and inclusions in PGM. Chrome-spinelides intergrown with isoferroplatinum were identified as magnesium ferrichromites or more rarely as magnochromites. They are identical to chrome-spinelides from schlierens and differ from accessory chrome-spinelides due to their higher Mg content. This is evidence that principal primary sources of PGE in the Inagli placer are chromite segregations in dunites. The formation of polyphase multicomponent solid solutions displaying wide compositional variations and containing numerous various inclusions of parent crystals and exsolved isolated lamella is considered on the base of the ternary Ir-Os-Pt diagram.

INTRODUCTION

Platinum placers related to concentrically-zoned ring massifs of alkaline-ultramafic rocks at the Aldan Shield were initially studied and defined as the specific (Aldanian) type by Rozhkov *et al.* (1962). More recently, Cabri and Naldrett (1984) classified them as the Inaglian subtype alongside the Alaskian subtype within platinum-bearing deposits of zonal ultramafic massifs. Several publications dealt with placers of the Inagli massif (Rozhkov *et al.,* 1962; Razin, 1968; Rudashevskii *et al.,* 1983; Mochalov *et al.,* 1988; Malich, 1990; Okrugin *et al,* 1992, 1999; Kim *et al.,* 1991; Tolstykh and Krivenko, 1997; and others). Results of the recent study of the first isoferroplatinum nuggets from the Inagli placer and their mineral paragenesis are of interest from a mineralogical point of view and provide information on the origin of primary PGE ores.

CHARACTERISTICS OF THE INAGLI PLACER

The Inagli massif is situated 30 km west of the city of Aldan at the upper reaches of the Inagli River, which is a right tributary of the Aldan River. The massif intrudes rocks of the Archaean crystalline basement as a diapir. It has a rounded shape in aerial view, with a diameter about 5 km and a concentrically zoned structure with a dunite core. The latter is fringed with an interrupted ring of peridotites, pyroxenites, and alkaline gabbroids (mainly shonkinites) up to 0.5 km wide. Syenite-porphyries occurring as sills in the Vendian to Cambrian sediments are found around the massif. The Vendian to Cambrian sediments unconformably overlie Archaean metamorphic complexes.

According to K-Ar dating of gabbroids, pyroxenites, alkaline rocks and their minerals, the massif is of Jurassic-Cretaceous age (El'yanov and Moralev, 1961; Kravchenko and Vlasova, 1962; Glagolev *et al.,* 1974; Eremeev, 1984; Kostyuk *et al.,* 1990; Kononova *et al.,* 1995). Ugryumov and Kiselev (1969) suggested that dunites were formed during the Late Jurassic. This suggestion is based on paleomagnetic techniques and deformation of the Vendian-Early Cambrian sedimentary cover and the Middle-Late Jurassic syenite-porphyry sills. Kostyuk *et al.* (1990) referred ultramafic and alkaline rocks of the Inagli massif to a single alkaline-ultramafic association of the potassic series. Some researchers (Rozhkov *et al.,* 1962; El'yanov and Moralev, 1973; Shnai, 1980; etc.) adhere to the opinion of the polygenous origin of such massifs, in which the dunite core was formed during the Precambrian, while alkaline gabbroids and syenites were intruded during the Mesozoic.
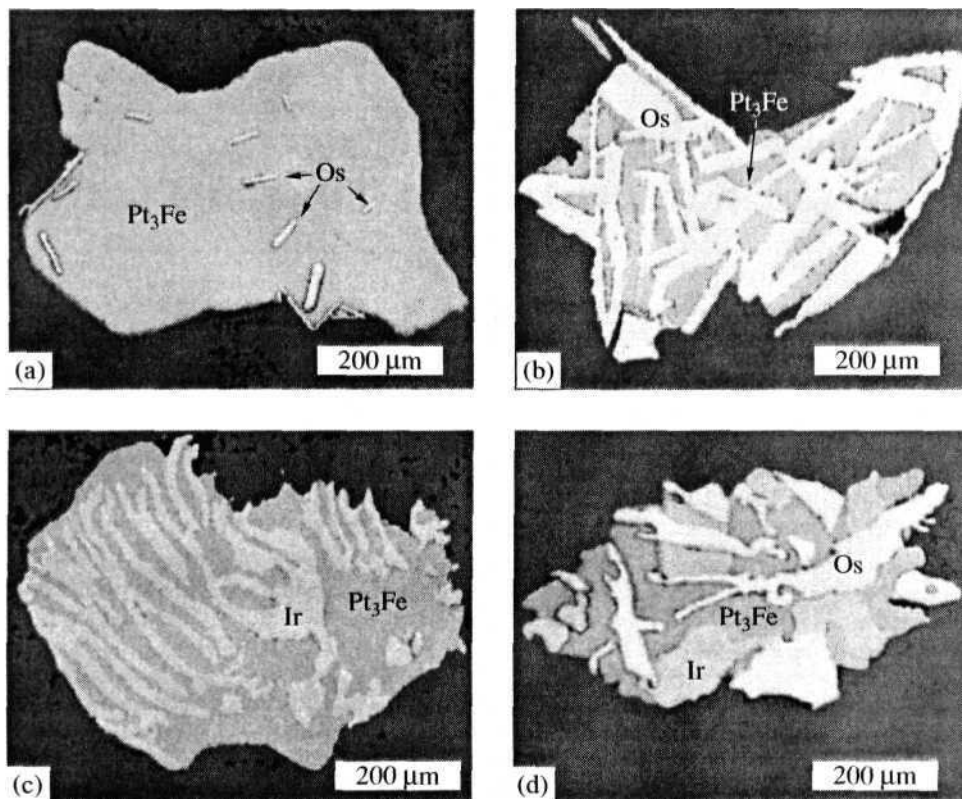
Fig. 1. Polymineral PGM intergrowths from the Inagli placer.
(a) Isoferroplatinum (Pt_3Fe) with rare lamella of native osmium (Os); (b) platy grains of native osmium in isoferroplatinum; (c) mirmekitic ingrowths of native iridium (Ir) in isoferroplatinum; (d) three-phase aggregate composed of isoferroplatinum, native iridium and native osmium.

Placers begin at the source of the Inagli River, where a deep funnel-like crater was formed due rapid erosion at the massif outcrop. Platinum in alluvial sediments was traced down the river for approximately 30 km. In placers within the massif or in the direct vicinity, PGM occur mainly as rolled agglomerate-like and rounded irregularly-shaped grains of 0.5 to 3 mm in size. Small and medium-sized nuggets were rarely found.

Degree of roundness and flatness of grains increases down the Ignali River and with an increase in distance from the massif, while grain sizes (on average up to 0.2-0.5 mm) decrease. Sulfides and arsenides of platinum group metals disappear in the same direction. This is explained by their instability under exogenic conditions. An increase of the magnetic isoferroplatinum fraction up to 5-10% is found, while nearly all platinum within the massif is concentrated in magnetic and nonmagnetic fractions. The Fe content in isoferroplatinum does not change along the placer. Some decrease of the Ir content in this mineral is observed. Taking into account the high stability of Ir to physical and chemical changes, this trend may have resulted from a vertical zonality of primary sources of platinum. If this is true, ore bodies in the upper part of the massif contained isoferroplatinum with a low Ir content, which migrated to the most distant area of the placer.

PLATINUM GROUP MINERALS

Isoferroplatinum with a narrow range in Fe content from 20 to 30 at. % and a profound mode at 25 at. % is the principal mineral in the Inagli placer. The Ir content in isoferroplatinum varies mainly from 1 to 4 wt % (rarely up to 8 wt % and more) with an average content of 2.87 wt % (Table 1). The iridium trend is most characteristic of platinum deposits of the Uralian (Alaskan) and Aldanian types related to zonal mafic-ultramafic intrusives found in both orogenic (Urals, Columbia and others) and platform (Inagli, Konder and others) regions. A strong tendency of the isomorphic substitution of Pt for Ir (correlation coefficient, $r_0 = -0.78$) is established for isoferroplatinum from the Inagli placer.

Mirmekitic and emulsion exsolution products, which are native iridium, occur in isoferroplatinum with a high Ir concentration of up to 4 wt % and more. Sometimes, tiny-lamellar and fine-tabular inclusions of native osmium are found in isoferroplatinum grains. Tabular lamella of native osmium, cemented by native iridium-isoferroplatinum aggregates, are sporadically observed (Fig. 1). Native iridium and native osmium are characterized by a low Ru content (usually below 5 wt %) and higher Pt content (up to 15 to 20 wt % in native iridium and up to 2 to 4 wt % in native osmium).

Table 1. Compositions of isoferroplatinum, native iridium, native osmium and their polyphase intergrowths from the Inagli placer, wt %

Grain no.	Pt	Ir	Os	Ru	Rh	Pd	Fe	Ni	Cu	Total
					Isoferroplatinum					
109	89.07	0.03	0.00	0.00	0.00	0.78	7.60	0.08	1.11	98.67
118	84.18	1.65	0.24	0.37	0.80	2.61	7.56	0.20	1.56	99.17
67/5*	86.37	2.26	0.00	0.04	0.39	0.00	9.26	0.26	0.62	99.21
125	86.93	2.86	0.06	0.00	0.00	0.17	8.57	0.19	0.67	99.45
					Isoferroplatinum + native iridium					
119m	86.51	3.49	0.36	0.07	0.08	0.19	8.25	0.15	0.54	99.64
119I	21.84	44.63	29.04	2.47	0.98	0.00	0.96	0.05	0.01	99.98
001*	83.14	5.84	0.30	0.28	0.59	0.02	8.86	0.37	0.43	99.81
001I*	14.29	61.51	17.33	4.54	1.63	0.00	0.36	0.11	0.18	99.95
127m	82.86	6.57	0.00	0.22	0.14	0.77	7.90	0.05	0.83	99.33
127I	12.17	74.80	3.88	2.85	1.62	0.00	0.76	0.01	0.00	96.09
67/2*	81.57	8.12	0.31	0.21	0.41	0.13	8.50	0.20	0.60	100.05
67/2I*	10.26	56.60	26.71	4.46	1.06	0.00	0.18	0.07	0.23	99.57
					Isoferroplatinum + native osmium					
114m	87.03	0.37	0.00	0.07	0.12	1.58	8.71	0.09	0.54	98.51
114I	1.88	7.41	90.26	0.00	0.56	0.00	0.03	0.00	0.02	100.16
14Im	87.44	1.02	1.52	0.00	0.08	0.57	8.56	0.07	0.28	99.54
141I	2.01	14.03	79.78	2.31	0.61	0.00	0.04	0.00	0.01	98.79
151m	86.00	2.79	0.00	0.28	1.14	0.15	7.82	0.14	0.55	98.87
151I	4.32	14.93	73.92	5.08	0.86	0.00	0.04	0.05	0.04	99.23
155m	86.92	3.70	0.52	0.19	0.00	0.12	8.43	0.09	0.30	100.26
155I	2.80	26.67	66.52	2.86	0.21	0.00	0.07	0.00	0.00	99.13
					Isoferroplatinum + native iridium + native osmium					
	84.84	3.53	0.17	0.23	1.00	0.21	8.41	0.22	0.42	99.03
10in	15.78	49.21	25.06	7.98	1.37	0.10	0.38	0.07	0.19	100.14
10in	2.29	29.76	62.73	4.94	0.22	0.17	0.05	0.02	0.11	100.29
24in	84.35	3.67	0.07	0.04	0.82	0.06	8.94	0.20	0.30	98.46
24in	14.13	50.44	29.13	4.56	0.99	0.06	0.22	0.04	0.17	99.74
24in	2.85	29.32	64.11	3.31	0.37	0.08	0.05	0.03	0.11	100.23
					Native iridium					
138	7.28	62.53	24.58	3.17	0.42	0.00	0.26	0.00	0.00	98.24
24/86	7.57	73.68	13.09	3.96	0.98	0.02	0.38	0.06	0.90	100.64
15/86	4.28	84.58	5.16	1.97	0.54	0.16	0.35	0.05	0.99	98.08
					Native iridium + native osmium					
14/86m	24.15	40.38	24.19	5.30	2.84	0.03	0.99	0.07	0.60	98.55
14/86I	0.96	33.40	61.25	1.25	1.16	0.10	0.00	0.03	0.43	98.58
13/86m	18.81	43.25	29.68	3.88	1.37	0.13	0.73	0.04	0.70	98.59
13/86I	1.82	24.60	67.74	3.41	0.42	0.17	0.01	0.01	0.32	98.50

Note: m—matrix, I—inclusion, in—growths, *—analyses of nuggets.

Fine regular crystalline inclusions of laurite and erlichmannite as well as grains of native osmium and native iridium are observed in the isoferroplatinum matrix. Inclusions of other sulfides and sulfoarsenides (cooperite, cuproiridsite, cuprorhodsite, inagliite, irar-site, hollingworthite, etc.) are present in isoferroplatinum as well. Sometimes fine irregular inclusions are confined to contacts between native osmium and native iridium with isoferroplatinum or occur at grain margins.
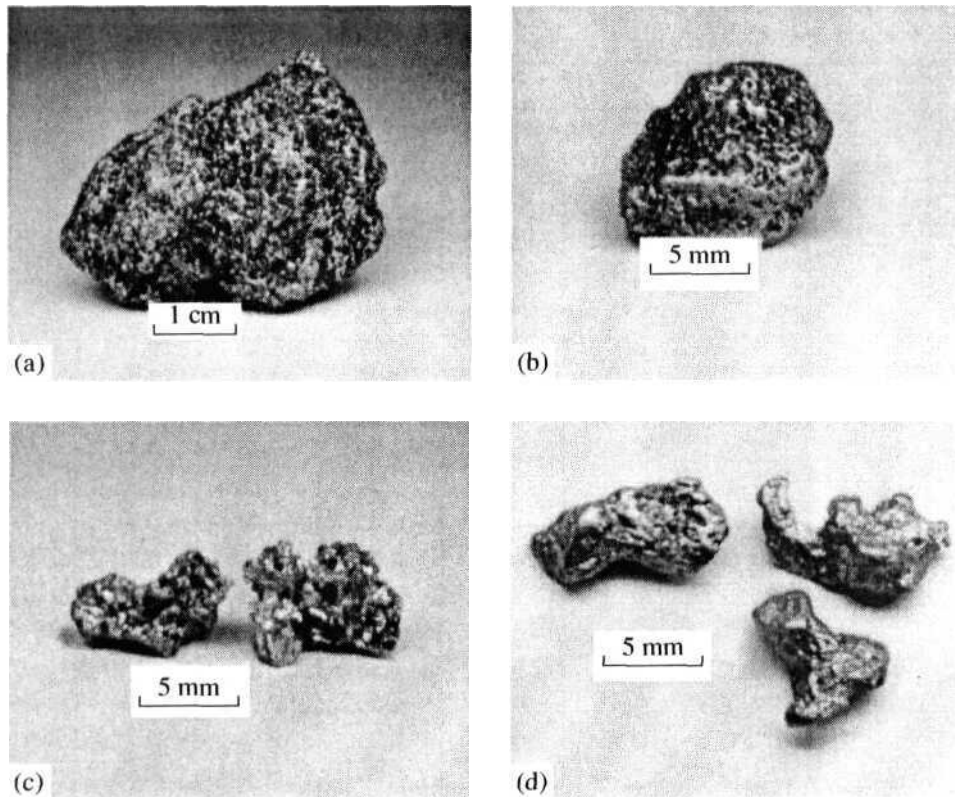
Fig. 2. Nuggets of isoferroplatinum from the Inagli placer.
(a) Nugget with abundant inclusions of chrome-spinelide (weight of 100.22 g); (b) well-rounded nugget with impregnations of chrome-spinelide (weight of 4.59 g); (c) nonrounded grains of isoferroplatinum intergrown with chrome-spinelide grains; (d) rounded monomineralic nuggets of isoferroplatinum.

Rare individual grains of native iridium, sperrylite, cooperite, and mertierite occur in the nonmagnetic fraction. In contrast to dim silver-white isoferroplatinum grains, grains of native iridium have steel-gray coloring with a sleek surface and sometimes contain fine native osmium inclusions. Intergrowths of native iridium with a high Os content and native osmium are observed less often. Individual particles of native osmium have not been encountered in the Inagli placer.

Sperrylite usually composes cubic-octahedral- and octahedral-shaped crystals. Insufficient admixtures of Rh (up to 0.28 wt %), Os (up to 0.22 wt %), and S (up to 1.26 wt %) are found in this mineral. Inclusions of hongshiite-PtCu, irarsite-IrAsS, osmian laurite-$(Os,Ru)S_2$, covellite-CuS, chalcopyrite, and pyrrhotite are present in sperrylite. Cooperite occurs as isolated irregular clot-like grains with a dark gray granular surface or as intergrowths with sperrylite, Pd isoferroplatinum and Pd intermetallides. The Pd, Rh, and Ni content in cooperite amounts to 10 wt %, 2 wt %, and 1 wt %, respectively. Clot-like grains with bronze coloring compositionally corresponding to mertierite and isomertierite contain 63.2–73.5 wt % Pd, 15.3–25.0 wt % Sb, 2.9–9.8 wt % As, and 1.0–5.1 wt % Cu.

Besides, tiny phases containing As, Bi, Sb, Te, Sn, Pd, and Au, for which precise identification is impeded, are found in isoferroplatinum from the Inagli placer. Chrome-spinelides (44–62 wt % Cr_2O_3), chrome-bearing (up to 6 wt % Cr_2O_3) diopside, olivine (Fa_{2_5}), serpentine, phlogopite, Ni-bearing (up to 5 wt % NiO) vermiculite, K-feldspar, pectolite, apatite and incompletely identified Ti-bearing K- and Ca-silicates occur in intergrowths with PGM and as inclusions. An inclusion of K-Ti-silicate ($K_2TiSi_3O_9$) in isoferroplatinum has been described (Kim and Pankov, 1998).

ISOFERROPLATINUM NUGGETS

In addition to fine metal sand, the author has examined 100 nuggets obtained from the placer deposit. After Razin's (1989) classification, monomineral or polycrystalline aggregates more than 3 mm in size containing more than 100 mg of a metal are referred to as platinum nuggets. Samples studied by the author are defined as small nuggets. They have sizes and weights from 5 to 15 mm and 0.5 to 4.5 g, respectively. The largest nugget (No. 001) of 45 x 30 x 22 mm in size weighs 100.22 g. It is an aggregate of the metal with

Table 2. Volumes and weights of chromite inclusions and metal in isoferroplatinum nuggets from the Inagli placer

Sample no.	P, g	P_1, g	V, cm^3	d, g/cm^3	V_{incl}, vol%	V_{Pt}, %	P_{Pt}, %
001	100.220	88.267	11.953	8.385	72.845	27.155	58.298
23-1	4.593	4.288	0.305	15.059	22.280	77.720	92.898
67-5	4.342	4.038	0.304	14.283	28.160	71.840	90.536
23-2	2.650	2.417	0.233	11.373	50.202	49.798	78.813
23-5	2.142	1.971	0.171	12.526	41.467	58.533	84.110
23-4	1.959	1.779	0.180	10.883	53.914	46.086	76.222
23-3	1.812	1.632	0.180	10.067	60.101	39.899	71.343
67-3	1.730	1.574	0.156	11.111	52.187	47.813	77.456
5	1.630	1.508	0.122	13.361	35.147	64.853	87.373
67-1	1.016	0.958	0.058	17.423	4.372	95.628	98.795
67-2	0.965	0.901	0.063	15.261	20.749	79.251	93.474
67^4	0.767	0.701	0.067	11.526	49.047	50.953	79.574

numerous impregnations of chrome-spinelide (Fig. 2) and may be considered as a nugget of middle class.

Nuggets consist mainly of isoferroplatinum. However, as compared with the fine fraction of the metal, they are characterized by a higher Ir content, ranging from 2.26 to 8.12 wt % and averaging 4.58 wt %. Mirmekitic ingrowths of native iridium occur frequently in the majority of isoferroplatinum nuggets.

Small nuggets are monomineralic or polyphase aggregates of irregular shape. Mineral inclusions are chrome-spinelides and more rarely diopside, serpentinite, phlogopite, and vermiculite. Most nuggets are well rounded during the placer formation process, when fragile minerals disappeared from the surface of polymineralic aggregates and metal lugs were flattened and forge-rolled from mineral inclusions. Quite often, hollows on the nugget surface are observed. They are imprints of minerals broken off. Poorly rounded nuggets with fractured dendritic lug occur less often. Most small nuggets (3 to 5 mm) consist of metal with rare inclusions. The fraction of mineral inclusions in nuggets is increased as their size increases.

To determine the fraction of mineral inclusions, nuggets with inclusions were suspended in air and in distilled water. According to the equation of d_{H2O} $V = P - P_1$ at water density (d_{H2O}) equal to unity, the volume of a nugget (V, cm^3) is equal to its weight difference in air (P, g) and in distilled water (P_1, g). Further, using the equation:

$$P = d_{Incl}V_{incl} + d_{Pt}(V - V_{incl}),$$

a volume fraction of inclusions (V_{ind}) in the nugget can be calculated after the equation:

$$V_{incl} = (d_{Pt} V - P)/(D_{Pt} - d_{incl}).$$

The metal density (d_{Pl}) is assumed to be equal to 18.5 g/cm^3 (the calculated density of isoferroplatinum), while the density of an inclusion (d_{incl}) is considered to be equal to 4.8 g/cm^3 (the calculated density of chromite), because 90 vol % of inclusions are composed of a spinelide with a high Cr content. Results of calculations given in Table 2 show that the percentage of the inclusion volume (V_{incl}) in isoferroplatinum nuggets varies within a wide range and can amount to 60 vol % and more. In the nugget No. 001 weighing 100 g, chrome-spinelide inclusions occupy nearly 73 vol % of the bulk volume of the mineral aggregate. This value is probably critical for the existence of the nugget, because in the closest packing of balls their volume occupies 74.05 vol % of the space. With a greater content of inclusions, there will apparently be a breakup of the integrity of the cemented metallic framework, resulting in the disintegration of the nugget into separate pieces. With the increase of the inclusion amount, the percentage of the isoferroplatinum weight (P_{Pl}) in the nugget is respectively reduced. This causes an abrupt decrease of its average density. For example, the density of the nugget No. 001 is 8.4 g/cm^3. Hence, similar chromite-native platinum aggregates can be concentrated in tailings even at large sizes because of a rather low density.

PGM PARAGENESES

Chrome-spinelides, which often occur as inclusions or ingrowths in the isoferroplatinum grains more than 1 to 2 mm in size, are the most widespread minerals associated with PGM in the Inagli placer deposit. Nearly all isoferroplatinum nuggets from the Inagli placer are chromite-native platinum aggregates. In this connection, it is useful to consider in detail the composition of chrome-spinelides (Fig. 3) intergrown with PGM in the placer and in rocks of the Inagli massif.

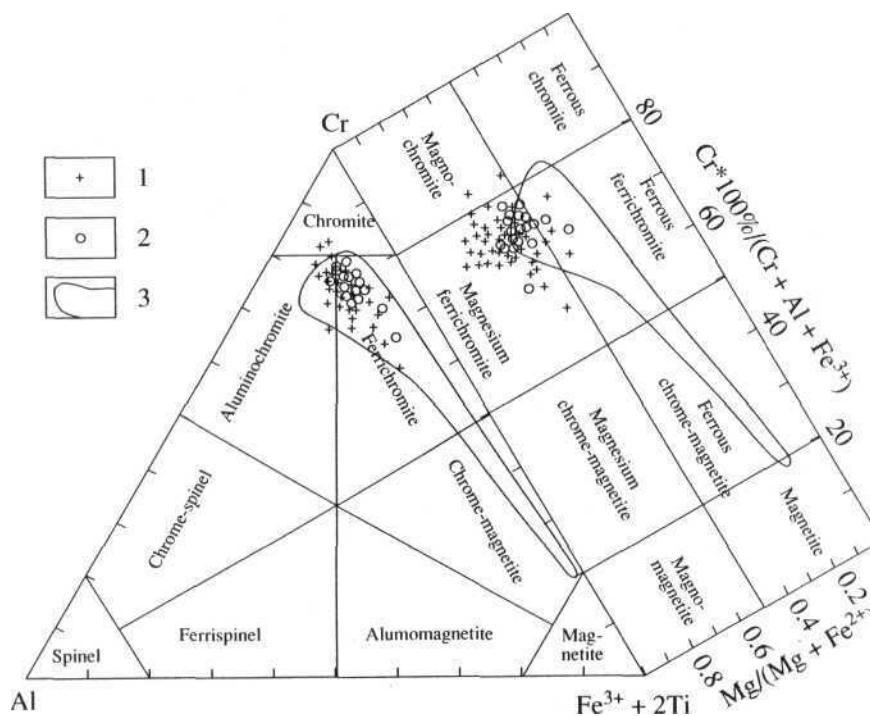The chrome-spineliide composition from magmatic and metamorphic rocks varies within wide ranges.

Fig. 3. The Al-Cr-Fe^{+3}-Mg/(Mg + Fe^{+2}) diagram of spinelides from the Inagli massif.
(1) Chrome-spinelides intergrown with isoferroplatinum from the placer; (2) schlieren-veinlets chromitites in dunite; (3) accessory spinelides from dunite.

There is no generally accepted nomenclature for these minerals. Taking into account the classifications suggested by A.K. Boldyrev, A.G. Betekhtin, S.A. Vakhromeev, N.V. Pavlov, G.A. Sokolov and others, a more simplified scheme of a definition of chrome-spinelides was used by the author for the description of chrome-spinelides and for further discussion of their genesis. Besides end-members of the isomorphic series, chromite, spinel, and magnetite containing more than 20 mol % of other components were related to three major groups of chrome-, alumo-, and ferri-spinelides. In this case, a prefix after the name of the isomorphic component was added to the name of the end-member. Depending on the ratio of divalent cations, all varieties of spinelides were subdivided into ferrous and magnesian ones, adding a relevant adjective to their name. The historically used names were preserved for some varieties. For example, names of hertsinite and magnochromite were used instead of ferrous spinel and magnesian chromite; spinel and magnetite are suggested for magnesian spinel and ferrous ferri-spinel, respectively. Such a definition somewhat corresponds to natural boundaries between spinelides from relevant types of rocks or mineral parageneses. For example, chromites or chrome-spinelides containing more than 80 mol % of the chromite member occur in meteorites or kimberlites in association with diamond. If ferrous chromite is characteristic of meteorites, the magnesian variety is peculiar to kimberlites (Sobolev, 1974). Alumochromite and

chrome-spinel are typical for alpinotype ultrabasites (Pavlov *et al.*, 1979), while ferrichromite and chrome-magnetite are characteristic of rocks of alkaline-ultra-basic massifs, including the Inagli massif.

Chrome-spinelides in dunites of the Inagli massif occur as accessory octahedral crystals or rounded grains. The amount of minerals usually does not exceed 1 % of the rock volume, and their sizes vary from 0.1 to 1.0 mm. Locally, chrome-spinelide content is increased, and more large isolated crystals (up to 3 to 5 mm) occurred. The densely impregnated accumulations of chrome-spinelide, sometimes schlieren aggregates of 4 to 5 cm and of irregular isometric shape and veinlets of massive chromitites up to 2-3 cm, are present in these sites as well. Some of these aggregates are strongly deformed.

Accessory chrome-spinelides are represented by ferrichromite and alumochromite, less often by chromite and chrome-magnetite, forming an uniform trend (Fig. 3). The content of chrome oxide in them varies from 58 to 13 wt % (Table 3). Their majority is defined as the ferrous variety. Schlieren aggregates consist mainly of ferrichromite. They (as opposed to accessory chrome-spinelides) are richer in manganese. As a rule, the mole fraction of the magnesium component in them prevails over bivalent iron. Chrome-spinelides intergrown with isoferroplatinum belong to magnesian ferrichromite, less often to magnochromite. A complete concurrence of fields of chrome-spinelides

Table 3. Composition of chrome-spinelides from rocks and placer of the Inagli massif, wt %

Grain no.	TiO$_2$	Al$_2$O$_3$	Cr$_2$O$_3$	Fe$_2$O$_3$	FeO	MnO	MgO	Total
Accessory chrome-spinelides in dunite								
24	0.59	3.93	58.28	7.88	21.16	0.35	7.51	99.70
48	0.40	5.24	56.53	9.70	18.86	0.49	8.50	99.72
77	0.87	6.80	54.98	10.82	13.75	0.24	13.06	100.52
28	0.33	10.34	52.86	6.35	22.98	0.33	6.99	100.18
19	0.76	3.62	50.21	16.95	20.56	0.36	8.04	100.50
20	0.83	3.96	48.89	16.80	22.27	0.40	6.90	100.05
21	0.48	5.40	45.37	20.32	19.27	0.43	8.71	99.98
31	0.88	3.32	43.89	23.28	21.25	0.53	7.30	100.45
32	0.74	3.77	40.44	24.89	24.21	0.54	5.34	99.93
97-3	0.83	2.02	37.50	30.06	23.99	0.45	5.45	100.30
97-4	0.59	0.74	13.32	54.04	26.89	0.23	2.84	98.65
Chrome-spinelides from schlieren-veinlets chromitite in dunite								
4	0.75	4.69	58.53	8.52	15.74	0.19	11.35	99.77
62	0.59	5.85	57.45	7.88	17.16	0.33	10.29	99.55
17	0.72	5.17	56.86	10.12	15.21	0.23	11.74	100.05
10	0.67	5.54	56.58	9.50	16.62	0.33	10.76	100.00
11	0.72	4.49	55.89	11.73	15.31	0.23	11.56	99.93
6	0.80	6.46	54.92	11.31	13.12	0.28	13.22	100.11
79	0.78	5.93	53.52	12.67	14.15	0.30	12.42	99.77
91	0.82	6.30	52.63	12.19	16.28	0.42	10.99	99.63
93	0.50	3.97	50.26	16.92	20.13	0.59	8.06	100.43
97	0.76	4.37	48.12	20.95	12.76	0.26	13.21	100.43
Inclusions and intergrowths of chrome-spinelides with isoferroplatinum from placer								
28	0.38	4.90	62.37	5.70	12.42	0.14	13.26	99.17
28-1	0.44	5.38	60.44	7.04	11.73	0.18	13.69	98.90
24	0.55	5.75	58.06	8.76	12.46	0.14	13.36	99.08
10	0.65	7.38	57.74	6.55	15.10	0.11	12.01	99.54
29-1	0.43	5.14	56.69	.11.82	11.59	0.25	13.84	99.76
9-2	0.54	6.07	54.45	12.97	10.39	0.02	14.81	99.25
15	0.71	4.26	51.21	16.78	16.33	0.20	10.94	100.43
35-32	0.45	9.16	49.65	11.74	19.62	0.43	8.95	100.00
8-2	0.79	5.22	43.80	23.09	16.20	0.23	11.09	100.42
Chrome-spinelides from nuggets								
001	0.55	5.50	58.86	10.28	8.66	0.40	15.86	100.11
001	0.68	6.21	54.47	12.93	9.11	0.32	15.57	99.28
GKh5	0.64	5.38	58.16	9.61	12.20	0.40	13.56	99.94
67\3	0.71	5.79	55.93	10.62	14.01	0.44	12.42	99.93
67\2	0.60	7.33	59.32	5.24	12.57	0.49	13.23	98.78

Note: Separation of Fe$_2$O$_3$ and FeO was yielded by recalculation on stoichiometric formula of spinelides.

from schlieren aggregates and PGM from placers suggests that chromitite segregations in dunite are one of the major primary sources of platinum group metals of the Inagli placer.

Olivine intergrown with isoferroplatinum consists of small (less than 1.0 mm) rounded colorless grains of forsterite (Fa$_{2-5}$), containing 0.10-0.35 wt % CaO and 0.25-0.42 wt % NiO. Its composition corresponds to

Table 4. Compositions of clinopyroxene from rocks and placer of the Inagli massif, wt %

Grain no.	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MgO	CaO	Na_2O	Total
				Dunite					
40	55.91	0.18	0.29	0.55	2.01	17.10	23.32	0.15	99.51
54	53.34	0.36	1.58	0.40	5.65	16.11	21.21	0.52	99.17
55	53.98	0.33	1.29	0.35	5.34	16.07	21.16	0.55	99.07
61	53.68	0.28	1.05	0.31	5.64	16.07	22.48	0.34	99.85
				Shonkinite					
7	53.03	0.49	1.34	0.01	7.37	15.33	22.68	0.54	100.79
46	52.53	0.55	2.00	0.11	7.11	14.73	20.90	0.55	98.48
57	53.93	0.46	0.67	0.09	5.88	14.94	22.09	1.00	99.06
63	53.45	0.31	0.94	0.34	5.57	16.39	22.09	0.48	99.57
				Chrome-diopside					
92	55.61	0.21	0.07	0.36	2.22	17.23	24.18	0.44	100.32
133	54.88	0.21	0.19	0.36	2.57	17.29	23.72	0.45	99.67
107	54.61	0.37	0.41	0.52	3.20	17.62	23.68	0.52	100.93
121	55.34	0.09	0.05	0.39	2.09	17.79	23.12	0.07	98.94
171	55.85	0.13	0.26	0.87	1.56	17.86	23.86	0.27	100.66
155	55.22	0.21	0.29	0.75	1.74	17.48	24.19	0.16	100.04
				Intergrowths with isoferroplatinum					
19	55.02	0.17	0.14	0.48	2.42	16.71	23.51	0.56	99.01
53	55.63	0.00	0.01	0.51	0.64	18.53	24.85	0.21	100.38
30	54.22	0.17	0.30	0.62	2.15	17.62	23.44	0.50	99.02
37	54.23	0.11	0.64	0.62	1.02	18.44	24.83	0.28	100.17
34	56.01	0.08	0.25	0.69	1.90	17.72	22.75	0.48	99.88
19	54.19	0.11	0.20	0.79	2.41	16.61	23.56	0.48	98.35
17	52.68	0.28	1.56	0.90	4.90	15.74	22.36	0.67	99.09
42	54.85	0.04	0.30	1.05	2.44	17.30	22.66	0.88	99.52
41	55.29	0.00	0.01	1.48	1.17	17.85	23.34	0.07	99.21
13	55.65	0.00	0.00	1.56	3.57	15.90	22.40	1.41	100.49
40	54.82	0.01	0.37	6.14	2.81	13.60	18.61	3.50	99.86
				Inclusions in nugget No. 001					
30\1	55.33	0.03	0.04	0.06	0.43	18.55	24.44	0.00	98.88
32\1	57.10	0.12	0.58	0.04	2.85	16.14	22.13	0.00	98.96

olivine (Fa$_{3-7}$) in dunite containing densely impregnated and veinlet-schlieren chromitites. In dunite with accessory chromite mineralization, olivine is usually richer in iron (Fa$_{5-10}$, less often to Fa$_{18}$), while olivine from peridotites, pyroxenites, and shonkinites contains 20 to 30 mol % of the fayalite component.

Clinopyroxene associated with isoferroplatinum is represented by diopside usually containing 0.5–1.5 wt % Cr_2O_5. Diopside from nugget No. 001 is characteristic of a lower Cr content and a practical absence of Na (Table 4). One intergrowth of an irregular clotlike grain of isoferroplatinum with bright-green chrome-diopside

contains 6.14 wt % Cr_2O_3 and 3.5 wt % Na_2O. Clinopyroxene of similar composition with a high content (up to 10 mol %) of the juriite component ($NaCrSi_2O_6$) is known in the intergrowth with diamond from kimberlites (Sobolev, 1974). A higher $A1_2O_3$ content up to 3-8 wt % is also found in the mineral from the diamond assemblage. This is caused by an increase of the role of $A1^{VI}$ with an increase in pressure (Sobolev, 1965).

The composition of clinopyroxene intergrowths with isoferroplatinum is generally similar to that of pyroxene from the monomineral chrome-diopside nodules and veinlets in dunites as well as of pyroxene from the well-known deposit of jewel-grade chrome-diopside from the Inagli massif. Pyroxene from dunites and shonkinites is different due to a higher FeO content (usually more than 5 wt %) and a low Cr_2O_3 content (less than 0.5 wt %).

The above data support a link of the platinum mineralization with dunite containing chromite and diopside segregations. The presence of phlogopite, serpentinite, vermiculite, K-feldspar, apatite and other K- and OH-bearing phases in isoferroplatinum as isolated inclusions is evidence for a high concentration of volatiles and mobile elements at the stage of platinum metal formation in the Inagli massif.

ORIGIN OF PGM FROM THE INAGLI MASSIF

The ore potential of basic-ultrabasic magma enriched with Cr and PGE is most evident at liquid separation of the oxide-ore melt from the silicate liquid. Though oxide-ore liquates dissolve a high amount of PGE, the latter are separated during the subsequent crystallization as individual phases, because the PGE solubility in oxide-ore minerals is abruptly dropped in the solid state. Under these conditions chromitite schlieren and veinlets and interspaced Ir-Pt segregations related to them originate.

Textures of most natural polyphase PGM aggregates are similar to those of artificial alloys obtained at a solidification of molten metals. Hence, the first are also crystallization products of multicomponent metal liquids. A large number of minerals, wide variations of trace elements, and the presence of various inclusions of parent crystals and exsolution products suggest a formation mechanism of paragenetic assemblages of PGM and their evolutionary trend.

The evolution of phase transformation of the multicomponent alloys can be traced using ternary diagrams. Unfortunately, at the present time ternary diagrams are known only for a limited group of elements and PGE. In this connection, the ternary Ir-Os-Pt diagram with a projection of binary systems was constructed from binary systems for platinum metals using the interpolation graphic technique (Okrugin, 2000). Binary diagrams were taken from handbooks on metallic systems

(Hansen and Anderko, 1957; Shunk, 1966; Platinum-group..., 1989 and others). On the ternary plot, isotherms, peritectic lines, and solidus isotherms are schematically shown as thin dashed, dashed, and dotted lines, respectively. The Pt solubility contours in Ir and Os are given after Slansky et al. (1991).

A comparison of chemical and phase compositions of natural polymineral aggregates with the artificial alloys on this plot shows a good agreement. At drawing points of the composition of natural minerals on the diagram, the Ru and Fe contents are added to that of Os and Pt, respectively, because these pairs have similar phase equilibrium diagrams with other PGE and cannot substantially change a trend of phase transformations. The author realizes that these diagrams characterize a key direction of phase transformations in the PGE systems and temperatures, which in dry artificial systems are much higher in comparison with those of the ore-magmatic processes. A considerable temperature drop in the crystallization of metal liquates is explained by their eutectic relationship with equilibrated silicate magma. Some diversions are also explained by the presence of impurities, including low-melting components in natural alloys. The latter not only essentially lower crystallization temperatures, but also detour the system on other trajectories of phase transformations at the final stage of solidification as a result of an abrupt increase in the impurity activity due to their accumulation in a residual melt.

The ternary diagram (Fig. 4) shows that three one-phase fields (a_1, a_2, and b), three two-phase fields ($a_1 + a_2$, $p + a_1$, and $b + a_2$), and one three-phase field ($a_1 + a_2 + b$) exist under the solidus of the Ir-Os(Ru)-Pt(Fe) system. If the trace element content does not exceed its limiting solubility, one-phase homogeneous solid solutions are formed on the base of Pt, Ir, and Os. Most grains from the Inagli placer, which are composed of homogeneous isoferroplatinum, and rare individual grains of native iridium are in such phases (Table 1).

Besides homogeneous metals, grains of isoferroplatinum with a high Ir content often occur at the placer (Fig. 1c). This indicates that homogeneous solid solutions were initially formed from the Ir-Fe-Pt liquids, the bulk composition of which lies within the two-phase field on the diagram. Two-phase intergrowths of isoferroplatinum and iridium were formed at exsolution of these solid solutions below 975°C.

If the initial platinum melt was enriched with osmium, two-phase aggregates of the Ir-Pt solid solutions with inclusions of native osmium were formed after the peritectic reaction (Fig. 1a, 1b). In this case, osmium should peritectically react with a residual melt. However, high-temperature Os crystals are probably stable at the rapid nonequilibrium crystallization of the system and are preserved as metastable phases. The diagram shows that solid Pt should dissolve up to 20 at. % Os and more. A low Os content (usually not
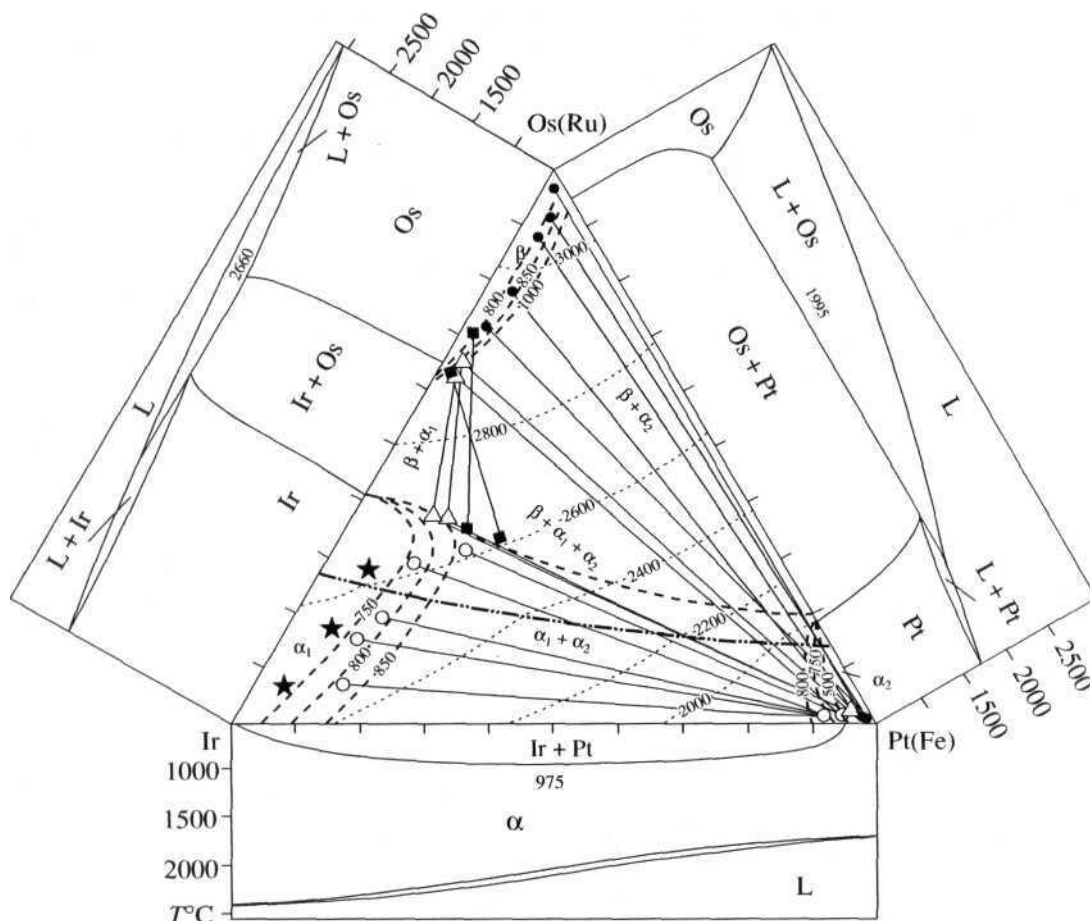
Fig. 4. Ternary Ir-Os-Pt plot of compositions of paragenetic assemblages of isoferroplatinum, native iridium and native osmium. The lines connect coexisting phases: not filled circles—isoferroplatinum + native iridium; filled circles—isoferroplatinum + native osmium; quadratics—native iridium + native osmium; triangles—isoferroplatinum + native iridium + native osmium; stars—individual grains of native iridium.

more than 1 to 2 wt %) in the natural Fe-Pt solid solutions can be explained by the low Os solubility (maximum 2.7 at. %) in 6-Fe (Shank, 1973). The exsolution of osmium from isoferroplatinum was probably also influenced by a small Cu admixture, as the Os solubility in solid copper is extremely limited.

Rare two-phase intergrowths of native iridium and native osmium found at the Inagli placer evolved as simple Os-Ir systems. In this case, osmium crystallized in the beginning, while Ir and impurity platinum accumulated in the residual melt. At low Pt content in such a melt, the latter was mainly isomorphically incorporated into iridium (Table 1). At an excess of the Pt content over the isomorphic capacity of Ir, a third platinum phase developed.

A three-phase field of coexisting Pt, Os, and Ir alloys occurs in the middle diagram. The crystallization of the Ir-Pt liquates enriched in Os begin with the osmium solidification above the peritectic field of the system. A reaction of Os with the residual liquid, with the formation of a solid Os-Ir-Pt solution with a high

Os content, proceeded at the crossing of a peritectic line. However, these conditions are not realized during the natural nonequilibrium processes. As a result, early Os crystals are cemented by Fe-bearing platinum with a higher Ir content. The complete solid solution exsolved to Ir and Pt below a critical point at 975°C. Textures of three-phase aggregates composed of corroded relics of lamellar parent crystals of osmium, cemented by isoferroplatinum with mirmekitic ingrowths of iridium (Fig. 1d) illustrate this crystallization trend of the polycomponent Os-Ir-Fe-Pt melts.

CONCLUSIONS

1. Studies of the PGM compositions from the Inagli placer demonstrate that the fraction of magnetic isoferroplatinum increases with distance from the Inagli massif, as well as that the Ir content in this mineral is decreasing, and that the Fe content remaining the same. This is probably caused by the vertical zonation of primary sources of PGE.

2. The Ir trend displayed due to continuous Ir concentration up to 8 wt % and more is characteristic of isoferroplatinum from the Inagli massif. The Ir specialization is inherent to the Uralian (Alaskan) type and Aldanian types of platinumferrous deposits related to zonal mafic-ultramafic intrusions in both orogenic (the Urals, Columbia and others) and platform (Inagli, Konder and others) regions. The correlation coefficient (r_0) of the isomorphic substitution of Pt for Ir in isoferroplatinum from the Inagli placer is -0.78.

3. The isoferroplatinum nuggets, which are mainly chromite-isoferroplatinum aggregates obtained from the Inagli placer, have been studied for the first time. The chrome-spinelides intergrown with isoferroplatinum are defined as magnesian ferrichromite, less often as alumochromite and magnochromite. They are identical to the chrome-spinelides from schlieren segregations and are different from accessory chrome-spinelides in dunites with a higher MgO content. This indicates that chromite segregations in dunites are major primary sources of PGE in the Inagli placer.

4. Textures of most natural polyphase MPG aggregates are similar to those of artificial alloys obtained by the solidification of molten metals. In this connection, mechanisms of the formation of similar polyphase multicomponent solid solutions displaying wide variation of trace element contents, numerous variable inclusions of parent crystals, and isolated exsolved lamella are considered based on the ternary Ir-Os-Pt diagram derived from binary systems for platinum metals using the interpolation graphic technique.

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