

## THE PLATINUM-GROUP MINERALS OF THE BAIMKA PLACER DEPOSITS, ALUCHIN HORST, RUSSIAN FAR EAST

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### ABSTRACT

An Alpine-type mafic-ultramafic complex and several Alaskan-Ural type (AUT) plutons are exposed in the Aluchin horst, Chukotka, Russian Far East. Platinum-group element (PGE) mineralization is observed in placer deposits associated with the occurrence of a local stratigraphic unit (Volga) of Late Jurassic sediments. The platinum-group minerals (PGM) in these placer deposits consist mainly of native platinum and grains of Pt-Fe alloy, with Fe contents ranging from 0.3 to 36.15 at.% and, rarely, iridium, cooperite and sperrylite. Minerals present as inclusions in the grains of Pt-Fe alloy are: bowieite, cooperite, kashinite, erlichmanite, hollingworthite, irarsite, cuprorhodite, laurite, Ir oxide (or hydroxide), osmium, prassoite, guanglinitite, rhodarsenide, magnetite, plagioclase, silicate glass inclusions and unnamed PGE phases. Some PGM inclusions occur in assemblages of two or three phases indicative of a high-temperature origin for these nuggets. The data on PGM and other mineral inclusions in the grains of Pt-Fe alloy as well as their distribution and occurrence suggest that the primary source for the majority of PGM placer grains studied are AUT mafic-ultramafic complexes.

*Keywords:* platinum-group minerals, electron-microprobe analysis, Alaskan-Ural type complex, nuggets, placers, Chukotka, Russia.

### SOMMAIRE

Le horst d'Aluchin, à Chukotka, dans la partie orientale de la Russie, expose un complexe mafique-ultramafique de type alpin et plusieurs plutons de type Alaska-Oural. La minéralisation en éléments du groupe du platine est associée à l'érosion d'une formation conglomératique (Volga), d'âge jurassique tardif. Parmi les minéraux du groupe du platine dans ces placers, on trouve surtout le platine natif et des grains d'un alliage Pt-Fe, dont la teneur en Fe va de 0.3 à 36.15% (pourcentage atomique) et, plus rarement, iridium, cooperite et sperrylite. On trouve en inclusions dans ces grains de l'alliage Pt-Fe: bowieite, cooperite, kashinite, erlichmanite, hollingworthite, irarsite, cuprorhodite, laurite, oxyde (ou hydroxyde) d'iridium, osmium, prassoite, guanglinitite, rhodarsenide, magnétite, plagioclase, inclusions de verre silicaté et d'autres phases contenant des éléments du groupe du platine, mais encore sans nom. Certaines des inclusions se présentent en assemblages de deux ou trois phases, ce qui concorde avec une origine de ces pépites à température élevée. D'après les données sur ces minéraux et autres inclusions dans les grains d'alliage, de même que leur distribution et leur mode de gisement, la source primaire de la majorité des grains des alluvions serait les complexes mafiques-ultramafiques de type Alaska-Oural.

(Traduit par la Rédaction)

*Mots-clés:* minéraux du groupe du platine, analyse à la microsonde électronique, complexe de type Alaska-Oural, pépites, placers, Chukotka, Russie.

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## INTRODUCTION

The first report on platinum-group minerals (PGM) in the Baimka River area, Aluchin horst, Chukotka, Russian Far East was made in 1964 by V.D. Klimov (unpubl. data) after regional geological mapping and evaluation of lode and placer gold deposits in the vicinity of the Aluchin horst. Since that time, exploration programs have led to discovery of numerous PGM occurrences in alluvial deposits of the Baimka River, Omchak Creek and their tributaries. In 1981, V.S. Varzin & A.G. Mochalov (unpubl. data) studied gold concentrates obtained from the Priisk Anyuisky State Mining Company and reported that the PGM in the Baimka placers are mainly present in grains of Pt-Fe alloy.

In order to determine the possible sources of PGM discovered in Baimka River, Omchak Creek and tributaries, detailed electron-microprobe studies ( $n = 265$ ) of 79 grains have been carried out at the N-E Complex Research Institute of the Russian Academy of Sciences (74 grains studied) and at CANMET, Ottawa, Canada (five grains studied). A complete list of the analytical results is given in Gornostayev (1994). Detailed SEM studies have also been done at the Brockhouse Institute of Materials Research, McMaster University, Canada, the National Mining University of Ukraine and the Institute of Electron Optics, University of Oulu, Finland.

The results of our work at McMaster and CANMET have been reported at the Seventh International Platinum Symposium, Moscow (Gornostayev *et al.* 1994) and were briefly reviewed by Cabri *et al.* (1996). In this paper, we present the first detailed description of platinum-group element (PGE) mineralization in the Aluchin horst region utilizing all the data available.

## GEOLOGICAL SETTING AND LOCATIONS OF THE SAMPLES

The Baimka and Omchak gold-PGM placers (Gornostayev 1993) are located in the Aluchin horst, located about 180 km southwest of Bilibino, Chukotka, Russian Far East (Fig. 1). This region was one of the most important producers of placer gold in Chukotka up to 1991. The Aluchin horst includes (Fig. 1) ophiolitic rocks of Permian (or Triassic) age, various sedimentary and volcanic terranes of Jurassic and Cretaceous age, Mesozoic gabbro-clinopyroxenite plutons, and various hypabyssal intrusive bodies surrounded by hornfels (Dovgal 1964, Gorodinskii *et al.* 1982, Lychagin 1985, Surnin & Okrugin 1989). Ophiolitic rocks make up the mafic and ultramafic rocks of the Aluchin complex and include three separate north- to northwest-trending bodies of some 100 km in length, which are controlled by a regional system of faults. The largest body (~250 km<sup>2</sup>) extends for about 40 km along strike. The complex consists mainly of harzburgite, subordinate dunite and pyroxenite. Dunite and harzburgite

commonly include segregations of disseminated and, rarely, podiform and massive chromitites, which are most abundant in the Southern body (Aksenova *et al.* 1970). The cumulate part of the Aluchin complex forms an irregularly shaped body containing a layered sequence of wehrlite, dunite, gabbro, pyroxenite and hercynite (Lychagin 1985).

The gabbro-clinopyroxenite plutons are considered to belong to the early intrusive sequence of the Yegdegkychsky complex, of Late Jurassic age (Berlimble & Gorodinskii 1978, Volchkov *et al.* 1982, Kaminskii 1987, 1989). These plutons occur as roundish bodies, some displaying concentric patterns of zonation, and are composed of gabbro and clinopyroxenite (Gornostayev 1994). They are cut by monzonite and syenite of the late intrusive sequence of the Yegdegkychsky complex. The Ti- and Fe-rich varieties of clinopyroxenites of the Yegdegkychsky complex contain Pt (0.001–0.48 ppm), Pd (0.003–0.35 ppm) and

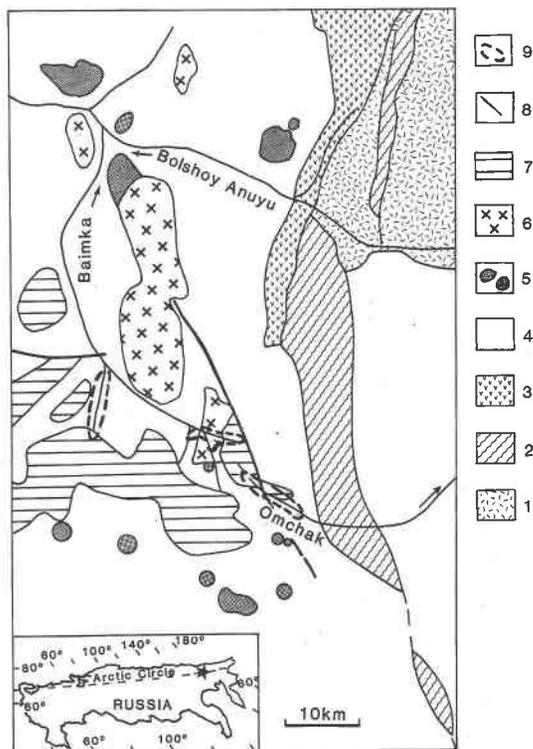


FIG. 1. Map illustrating the geology of the Aluchin Horst and location of the Baimka and Omchak gold-PGM placers. 1: Permian Group, 2: dunite, harzburgite, 3: basaltic sheeted dyke complex, 4: Mesozoic Group, 5: Alaskan-Ural type intrusions (gabbro, clinopyroxenite of the Yegdegkychsky complex), 6: syenite, syenodiorite, 7: Volga (Late Jurassic) sediments, 8: faults, 9: gold-PGM placers. Modified after Gornostayev (1994).

Rh (0.003–0.1 ppm); as we noted earlier (Gornostayev 1993, 1994, 1998, Barkov *et al.* 1998), these plutons are considered to belong to the Alaskan or Ural type. Ultramafic plutons mainly composed of dunite, wehrlite, clinopyroxenite and melanocratic gabbro and commonly displaying concentric patterns of zonation are known in western literature as Alaskan-type massifs (*e.g.*, Cabri 1981, Nixon *et al.* 1990). However, in Russia, ultramafic massifs of similar composition and metallogenic specialization are known as Ural type (*e.g.*, Tolstykh & Krivenko 1997) or Alaskan–Ural type (Malich & Augé 1998). Here we use the term Alaskan–Ural type (AUT) for description and reference to this type of ultramafic complex.

Of particular interest are basal conglomerates and gravels in the sedimentary rocks of Triassic to Cretaceous age. The conglomerates within a local stratigraphic unit (Volga) of Late Jurassic sediments have a thickness of about 30 m and contain numerous remnants of rocks of the early intrusive sequence of the Yegdegkychsky complex (Gulevich 1974, Gornostayev 1994).

No PGM have been observed to date in samples of mafic and ultramafic rocks in the Baimka area. All currently known PGM from the area are placer grains located in the alluvial sediments (Fig. 1) related to the disintegration of conglomerates of the Volga unit. These Late Jurassic conglomerates are considered to have previously concentrated PGM grains, and in this sense are regarded as intermediate collectors for PGM in the region (Gornostayev 1994, Gornostayev *et al.* 1994).

The other mineralized zones in the Baimka and nearby areas are very diverse and seem in most cases to be related to the late intrusive sequence of the Yegdegkychsky complex. They include porphyry copper and Au–Ag-bearing polysulfide ores in quartz-bearing monzonite and related hypabyssal rocks, and (quartz)–Mo–Cu–(Au) mineralization in altered monzonite (Berlimble & Gorodinskii 1978, Kaminskii 1987, Volchkov *et al.* 1982). The polysulfide ores are, in some cases, enriched in Rh and other PGE (V.G. Kaminskii, unpubl. data). In addition, they are considered the source of the gold placers (Kaminskii 1987) and associated rare minerals (Barkov *et al.* 1998).

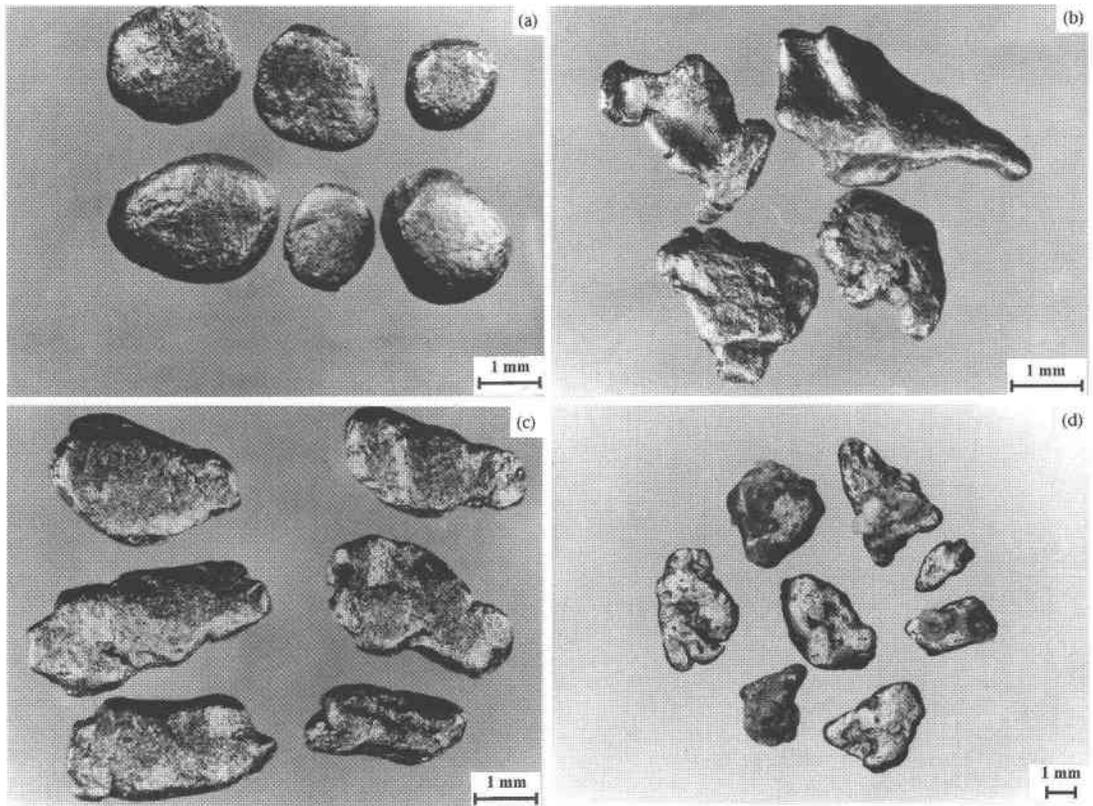


FIG. 2. Morphology of the PGM nuggets from Baimka. (a) Rounded grains. (b) Anhedral grains with bays and cavities. (c) Flake-like grains. (d) Shells of clastic minerals on nugget surfaces.

## ANALYTICAL TECHNIQUES

## PLATINUM-GROUP MINERALS

The PGM grains were first examined with a stereo microscope, and a selection of 79 grains was mounted in resin for reflected-light investigations and electron-microprobe analysis (wavelength-dispersion spectrometry). The analyses were carried out with a JEOL 733 electron microprobe at CANMET, Ottawa using techniques similar to those described by Nixon *et al.* (1990), and with a Cameca Camebax electron microprobe at the N-E Complex Research Institute, Russian Academy of Sciences, Russia following techniques described by Dmitrenko *et al.* (1987).

## MORPHOLOGY OF THE NUGGETS

The PGM grains inspected measure between 5–7 and 0.1–1 mm across, with the majority around 1 mm across. The shape of the nuggets varies considerably (Fig. 2). The majority occur as anhedral (Fig. 2b), flake-like (Fig. 2c) and oblate, well-rounded (Fig. 2a) grains. Some are coated by a thin shell of clastic minerals (Fig. 2d), showing the influence of lithification of the early host sediments. Other grains are knobby, with many rounded bays and cavities. A notable feature of Pt–Fe alloy grains in the Baimka area is the range in size, shape and degree of abrasion of grains coexisting within the placers, a feature that may reflect a long history of placer-forming processes.

A Pt–Fe alloy is the main PGM, encountered as discrete grains and nuggets. The grains of Pt–Fe alloy host a variety of inclusions, including PGM, PGE-bearing arsenides and sulfides, and silicate glass and oxide minerals. Rarely, other discrete placer grains were observed, including iridium, cooperite and sperrylite.

*Pt–Fe alloy*

Electron-microprobe studies (Table 1) have established that the concentration of Fe (*i.e.*, Fe + Ni + Cu) in these alloys (Gornostayev *et al.* 1994) ranges from 0.3 up to 36.15 at.%, and that the distribution of Fe is approximately bimodal (Fig. 3), with most samples falling in compositional fields with 16–20 (65.9% of grains studied) and 24–28 at.% Fe (9.8% of grains studied). These data suggest that the grains of Pt–Fe alloy in the Baimka area are represented by native platinum and a phase close in composition to isoferroplatinum. The average composition of grains with 16–20 at.% of Fe is given by the formula  $(Pt_{3.06}Rh_{0.10}Ir_{0.08}Pd_{0.03}Os_{0.01}Ru_{0.01})_{\Sigma 3.29}(Fe_{0.65}Cu_{0.05}Ni_{0.01})_{\Sigma 0.71}$ .

The compositions of Pt–Fe alloy from Baimka indicate a PGE source enriched in Cu and Rh (Table 1). Copper and Rh enrichment was suggested by Johan *et al.* (1990, and references therein) as a feature typical of PGE mineralization related to AUT intrusive com-

TABLE 1. ELECTRON-MICROPROBE DATA ON SELECTED NUGGETS OF ALLOY FROM BAIMKA, RUSSIAN FAR EAST

Nugget	Weight %										Atomic %									
	Pt	Ir	Os	Ru	Rh	Pd	Cu	Ni	Fe	Total	Pt	Ir	Os	Ru	Rh	Pd	Cu	Ni	Fe	
1 GSI-2-4	88.18	0.00	0.14	0.01	0.61	0.13	1.66	0.00	6.75	97.48	74.48	0.00	0.12	0.02	0.98	0.20	4.30	0.00	19.92	
2 GSI-7-6	83.14	4.27	0.00	0.07	2.24	0.43	3.37	0.07	6.16	99.75	66.66	3.47	0.00	0.11	3.40	0.63	8.29	0.19	17.25	
3 GSI-9-9	85.05	5.97	1.19	0.00	1.90	0.11	0.24	0.08	5.26	99.80	73.61	5.24	1.06	0.00	3.12	0.17	0.64	0.23	15.90	
4 GS2-1-2	90.89	0.00	0.53	0.00	1.33	1.02	0.50	0.04	5.78	100.09	77.23	0.00	0.46	0.00	2.14	1.59	1.30	0.11	17.16	
5 GS2-2-2	85.25	6.10	0.45	0.13	1.64	0.50	0.35	0.15	5.38	99.95	73.15	5.31	0.40	0.22	2.67	0.79	0.92	0.43	16.13	
6 K1*	88.36	3.71	0.20	0.02	1.60	0.32	0.43	0.10	5.16	99.90	74.51	3.17	0.17	0.03	2.56	0.49	1.11	2.75	15.20	
7 K2*	83.59	1.39	0.11	0.06	0.64	0.25	6.06	0.05	6.86	99.01	64.48	1.09	0.09	0.09	0.94	0.35	14.35	0.13	18.49	
8 K5-core*	88.63	4.07	0.29	0.09	1.27	0.18	0.45	0.09	4.97	100.04	77.07	3.59	0.26	0.15	2.09	0.29	1.20	0.26	15.10	
9 K5-rim*	93.60	4.17	0.00	0.03	1.37	0.18	0.11	0.00	0.00	99.46	92.54	4.18	0.00	0.06	2.57	0.33	0.33	0.00	0.00	
10 K7*	84.33	5.87	0.84	0.07	1.90	0.75	0.55	0.19	5.63	100.13	71.32	5.04	0.73	0.11	3.05	1.16	1.43	0.53	16.63	
11 II-1	88.10	0.85	0.24	0.00	0.78	1.12	0.55	0.00	7.41	99.05	73.22	0.72	0.20	0.00	1.23	1.71	1.40	0.00	21.51	
12 II-2	90.20	1.74	0.69	0.16	1.53	0.58	0.42	0.11	4.85	100.28	78.05	1.53	0.61	0.27	2.51	0.92	1.12	0.32	14.66	
13 XIII-1	80.70	10.30	0.06	0.00	1.85	0.44	0.47	0.10	4.66	98.58	71.05	9.20	0.05	0.00	3.09	0.71	1.27	0.29	14.33	
14 XIII-6	91.10	0.47	1.10	0.00	0.87	0.78	0.32	0.13	4.15	98.92	81.57	0.43	1.01	0.00	1.48	1.28	0.88	0.39	12.98	
15 XIII-8	85.60	5.58	0.00	0.00	1.67	0.42	0.52	0.08	4.61	98.48	75.65	5.01	0.00	0.00	2.80	0.68	1.41	0.24	14.23	
16 XIV-8	82.20	2.31	0.08	0.10	4.26	1.15	0.55	0.19	8.14	98.98	65.36	1.86	0.07	0.15	6.42	1.68	1.34	0.50	22.61	
17 GSI-3-1	90.85	0.30	0.34	0.11	1.28	0.53	0.33	0.07	4.81	98.62	80.28	0.27	0.31	0.19	2.14	0.86	0.90	0.21	14.85	
18 GSI-3-6	85.74	3.90	0.39	0.05	2.15	0.53	0.49	0.08	5.52	98.85	73.72	3.40	0.34	0.08	3.50	0.84	1.29	0.23	16.58	
19 II-16	8.19	72.50	18.30	0.77	0.25	0.23	0.00	0.08	0.36	100.68	7.84	70.45	17.97	1.42	0.45	0.41	0.00	0.26	1.20	
20 XIII-15	1.37	60.70	36.50	2.02	0.00	0.00	0.00	0.11	0.17	100.87	1.30	58.52	35.56	3.71	0.00	0.00	0.00	0.35	0.56	
21 XIV-10	9.70	52.30	31.10	3.55	2.51	0.00	0.00	0.07	0.25	99.48	9.03	49.43	29.70	6.38	4.43	0.00	0.00	0.22	0.82	

\* K1 (n=8), K2 (n=7), K5-core (n=3), K5-rim (n=3), K7 (n=7). Pt–Fe alloy (1–18), osmium (19–21).

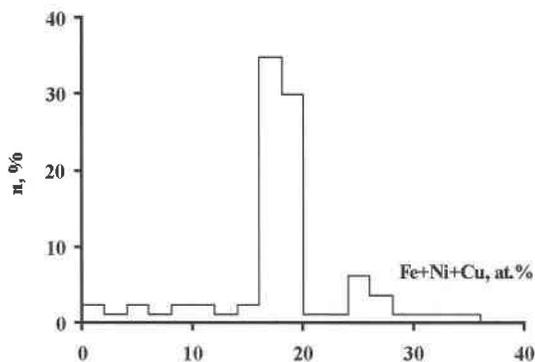


FIG. 3. Histogram illustrating the ranges of Fe + Ni + Cu content in grains of Pt-Fe alloy from Baimka.

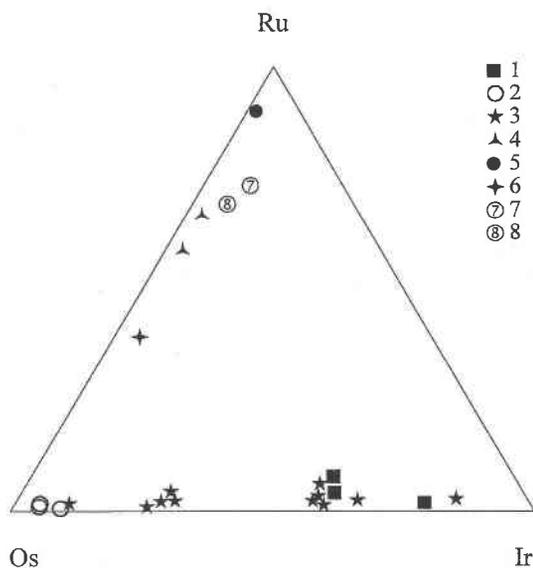


FIG. 4. Plot of chemical composition of Os-Ir-Ru alloys and laurite-erlichmanite. (1) Inclusions of iridium in Pt-Fe alloy from Baimka. (2) Single placer grains of osmium from Baimka. (3) Inclusions of osmium and iridium in Pt-Fe alloy from Fifield, Australia (Slansky *et al.* 1991). (4) Inclusions of laurite in Pt-Fe alloy from Baimka (Table 3, anal. 10, 15). (5) Inclusions of laurite in Pt-Fe alloy from Fifield, Australia ( $n = 3$ , Slansky *et al.* 1991). (6) Inclusion of erlichmanite in Pt-Fe alloy from Baimka (Table 3, anal. 9). (7) Inclusions of laurite in chromite from the Oman ophiolite ( $n = 11$ , Augé 1986). (8) Laurite from chromites of Othrys, Greece ( $n = 13$ , Garuti *et al.* 1999).

plexes. However, recent data on PGM associated with the Veluče ophiolite complex in Yugoslavia (Krstić & Tarkian 1997) have revealed that the level of Cu encountered is not atypical of Pt-Fe alloy from ophiolitic complexes.

### Iridium

Three discrete grains of iridium were found (Fig. 4). The composition of two of them (Table 1, anal. 20, 21) is close to the immisibility field for Os-Ir-Ru alloys. Their compositions correspond to  $(\text{Ir}_{0.58}\text{Os}_{0.36}\text{Ru}_{0.04}\text{Pt}_{0.01})$  and  $(\text{Ir}_{0.49}\text{Os}_{0.30}\text{Pt}_{0.09}\text{Ru}_{0.06}\text{Rh}_{0.04})$ . The composition of a third grain (Table 1, anal. 19) is different from these:  $(\text{Ir}_{0.70}\text{Os}_{0.18}\text{Pt}_{0.08}\text{Ru}_{0.01})$ .

### Placer grains of cooperite and sperrylite

Placer grains of cooperite and sperrylite have been found by V.S. Varzin & A.G. Mochalov, (unpubl. data) during investigations of gold concentrates obtained from the Priisk Anyuysky State Mining Company.

### INCLUSIONS IN THE Pt-Fe ALLOY

Eighteen of 79 grains of Pt-Fe alloy studied contain inclusions of other minerals or phases, among which are the following: bowieite, cooperite, kashinite, erlichmanite, hollingworthite, irarsite, cuprorhodsite, laurite, Ir-oxide (or hydroxide), osmium, prassoite, guanglinite, rhodarsenide, unnamed PGE phases, silicate glass inclusions, magnetite and plagioclase. As can be seen from Table 2, the majority of the grains are host to one or two mineral species and, in rare cases, up to five (nuggets K7 and II-1).

### Bowieite-kashinite solid solution

Bowieite occurs in nuggets GS1-9-9 (Table 1, anal. 6) and K7. In nugget K7, it forms (1) anhedral crystals (Table 3, anal. 27) approximately  $35 \times 115 \mu\text{m}$  and (2) a rounded component (Fig. 5d) about  $12 \times 25 \mu\text{m}$  (Table 3, anal. 26) in three-phase inclusions along with cooperite and cuprorhodsite. Compositions for these two varieties of bowieite gave formulae of  $(\text{Rh}_{1.27}\text{Ir}_{0.65}\text{Pd}_{0.03}\text{Pt}_{0.02}\text{Ru}_{0.02}\text{Os}_{0.01}\text{Ni}_{0.01})_{\Sigma 2.01}\text{S}_{3.00}$  and  $(\text{Rh}_{1.36}\text{Ir}_{0.53}\text{Pd}_{0.04}\text{Pt}_{0.03}\text{Ru}_{0.01}\text{Os}_{0.01}\text{Ni}_{0.01})_{\Sigma 1.99}\text{S}_{3.02}$ .

Kashinite constitutes six inclusions of  $30 \times 130$ ,  $30 \times 40$ ,  $20 \times 20$ ,  $15 \times 15$ ,  $10 \times 60$ ,  $15 \times 130 \mu\text{m}$  in nugget XIII-1 (Table 3, anal. 16) and occurs as a single inclusion in nugget GS2-2-2 (Table 3, anal. 8). The formula describing the composition of kashinite in nugget XIII-1 is  $(\text{Ir}_{1.11}\text{Rh}_{0.83}\text{Ru}_{0.02}\text{Pt}_{0.02})_{\Sigma 1.98}\text{S}_{3.02}$  (average result of six analyses). It should be noted that minerals of the bowieite-kashinite solid solution are considered typical of AUT ultramafic complexes (Begizov *et al.* 1975, Desborough & Criddle 1984, Slansky *et al.* 1991).

### Cooperite

Cooperite is very common in base-metal sulfide (BMS) associations in stratiform intrusions (Brynard *et al.* 1976, Cabri *et al.* 1978, Kingston & Dosuky 1982, Mostert *et al.* 1982, Alapieti & Lahtinen 1986), and

TABLE 2. LIST OF PGM AND OTHER MINERALS INCLUDED IN Pt-Fe ALLOY NUGGETS FROM BAIMKA, RUSSIAN FAR EAST

	GS1			GS2		K			II		XIII	XIV	GS1	GS7				
	2	7	9	1	2	1	2	5	7	1	2	1	6	8	8	3	3	1
	4	-6	-9	-2	-2											-1	-6	-1
Bowseite (Rh,Ir) <sub>2</sub> S <sub>3</sub>				•						•								
Cooperite PtS					•					•								
Cuprorhodsite CuRh <sub>2</sub> S <sub>4</sub>	•					•				•								
Erlichmanite OsS <sub>2</sub>										•								
Guanglinitite Pd <sub>2</sub> As										•								
Hollingworthite RhAsS										•								
Irarsite IrAsS																		•
Ir oxide (or hydroxide)								•										
Kashinite (Ir,Rh) <sub>2</sub> S <sub>3</sub>					•													
Laurite RuS <sub>2</sub>										•								
Osmium (Os)										•								
Prassoite Rh <sub>17</sub> S <sub>15</sub>																		
Rhodarsenide (Rh,Pd,Pt) <sub>2</sub> As								•										
(PGE) <sub>23,4</sub> (Cu,Fe) <sub>20,6</sub> As <sub>0,9</sub>																		
Pt <sub>3</sub> (Cu,Fe)																		
(Cu,Rh,Pt,Fe,Ir)S	•																	
(Pt,Rh,Pd)S																		
Magnetite																		•
Plagioclase																		•
Silicate glass																		•

The first sample listed is GS1-2-4, the second is GS1-7-6, and so on.

rarely occurs in AUT complexes (Begizov *et al.* 1975, 1976, Zhdanov & Rudashevskii 1980, Nixon *et al.* 1990).

Cooperite inclusions have been found in four nuggets [GS2-1-2 (Table 3, anal. 7), XIII-8 (Table 3, anal. 19), K1 (Table 3, anal. 21) and K7 (Table 3, anal. 28)], where they show different textural relationships with the host and other coexisting minerals. In one case, in nugget K7, the cooperite is found as a component of a three-phase assemblage with bowseite and cuprorhodsite (Fig. 5d). The formula of the cooperite in this nugget is  $(\text{Pt}_{0.98}\text{Pd}_{0.03}\text{Rh}_{0.01})_{\Sigma 1.02}\text{S}_{0.99}$ . In nugget K1, cooperite forms euhedral crystals (Fig. 5c) within droplet-like inclusions of cuprorhodsite. The formula calculated for these euhedral crystals (average result of four analyses) is  $(\text{Pt}_{0.99}\text{Pd}_{0.01}\text{Fe}_{0.01}\text{Rh}_{0.01})_{\Sigma 1.02}\text{S}_{0.98}$ .

Cooperite included in nugget K1 contains 0.15–0.22 wt.% Fe, which is similar to the Fe content in cooperite from the Tulameen River (Cabri & Laflamme 1981). The cooperite associated with the BMS in stratiform intrusions contains a significant amount of Ni, the concentration of which is usually higher than 1 wt.%. In contrast, Ni concentrations are characteristically low in AUT complexes (Johan *et al.* 1989, and references therein). The cooperite in grains of Pt-Fe alloy at Baimka contains 0.01–0.11 wt.% Ni, which would suggest an origin in an AUT complex.

#### Osmium

Osmium (Fig. 4) was observed in two inclusions in nuggets XIII-6 (Table 3, anal. 17, 18) and II-1 (Table 3,

anal. 13), where it occurs as crystals between  $20 \times 250$  and  $70 \times 120 \mu\text{m}$  in size.

#### Hollingworthite and irarsite

Hollingworthite has been identified in nugget II-1 (Table 3, anal. 11) in association with erlichmanite and guanglinitite (Table 2). The composition of the hollingworthite is  $(\text{Rh}_{0.56}\text{Ir}_{0.23}\text{Ru}_{0.15}\text{Pd}_{0.11}\text{Os}_{0.02})_{\Sigma 1.10}\text{As}_{0.85}\text{S}_{1.04}$ . Irarsite was observed in two inclusions in nugget GS7-1-1 and occurs as grains 1–2  $\mu\text{m}$  in size, which could not be analyzed quantitatively.

#### Cuprorhodsite

Cuprorhodsite (Fig. 6), a thiospinel of the platinum-group elements (Rudashevskii *et al.* 1985), has been observed in the Baimka area as inclusions in three nuggets, GS1-2-4 (Table 3, anal. 1), K1 and K7. In nugget K7 (Fig. 5d), this mineral occurs as (1) euhedral crystals 25  $\mu\text{m}$  across (Table 3, anal. 29) and (2) as an anhedral crystal of 60  $\mu\text{m}$  across (Table 3, anal. 30) in a three-phase association with bowseite and cooperite. The third variety (3) of cuprorhodsite,  $(\text{Cu}_{0.49}\text{Fe}_{0.41}\text{Ni}_{0.05})_{\Sigma 0.95}(\text{Rh}_{1.57}\text{Pt}_{0.29}\text{Ir}_{0.13}\text{Pd}_{0.03}\text{Ru}_{0.02})_{\Sigma 2.04}\text{S}_{4.01}$  observed in nugget K1 (Table 3, anal. 22), is the droplet-like inclusion (Fig. 5c) that hosts cooperite, as described above. This inclusion is considerably enriched in Rh and Pt, with lower Ir in comparison with the other cuprorhodsite examined: (1)  $(\text{Cu}_{0.54}\text{Ni}_{0.44}\text{Fe}_{0.03})_{\Sigma 1.01}(\text{Rh}_{1.23}\text{Ir}_{0.50}\text{Pt}_{0.21}\text{Pd}_{0.03}\text{Os}_{0.01})_{\Sigma 1.98}\text{S}_{4.00}$ , and (2)  $(\text{Cu}_{0.54}\text{Ni}_{0.42}\text{Fe}_{0.02})_{\Sigma 0.98}(\text{Rh}_{1.24}\text{Ir}_{0.51}\text{Pt}_{0.20}\text{Pd}_{0.04}\text{Os}_{0.01})_{\Sigma 2.00}\text{S}_{4.01}$ .

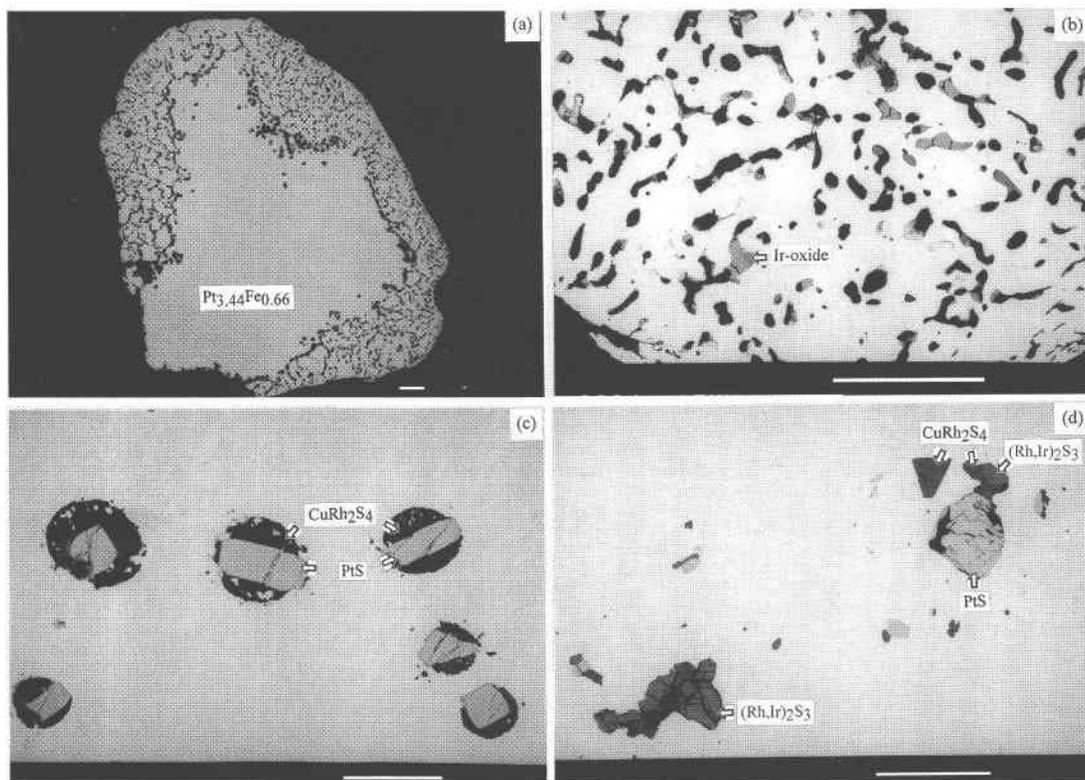


FIG. 5. Inclusions in Pt-Fe alloy from Baimka. (a) Nugget K5. Zoned grain of Pt-Fe alloy (core,  $\text{Pt}_{3.44}\text{Fe}_{0.66}$ ) and native platinum (rim) filled with Ir-oxide (or hydroxide). (b) Nugget K5, rim area. Inclusions of Ir-oxide (or hydroxide). (c) Nugget K1. Euhedral crystals of cooperite (PtS) in droplet-like inclusions of cuprorhodsite ( $\text{CuRh}_2\text{S}_4$ ). (d) Nugget K7. Euhedral crystal of cuprorhodsite ( $\text{CuRh}_2\text{S}_4$ ) and complex inclusion of cooperite (PtS), cuprorhodsite ( $\text{CuRh}_2\text{S}_4$ ) and bowieite ( $\text{Rh,Ir}_2\text{S}_3$ ). Scale bars: 100  $\mu\text{m}$  in Figures 5a, 5b and 5d; 10  $\mu\text{m}$  in Figure 5c.

As can be seen from formulae (1) and (2), the compositions of the two types of cuprorhodsite hosted by the same grain are very close. The similarity in composition may reflect very stable temperature conditions of the formation of the grains. It should be noted that this rare mineral has also been observed in clinopyroxenites of the AUT Owendale complex, Australia (Johan *et al.* 1989) and placer deposits associated with the AUT intrusions of the Aldan Shield (Mochalov *et al.* 1992). Cuprorhodsite also is found in the Finero Alpine-type peridotite massif, Italy, but in this case it occurs as a single-phase grain included in unfractured chromite (Garuti *et al.* 1995).

#### Laurite and erlichmanite

Laurite–erlichmanite solid solution represents a mineral species widely known in various mafic–ultramafic complexes (Augé 1986, 1988, Talkington & Lipin 1986,

Augé & Johan 1988, Nixon *et al.* 1990, Slansky *et al.* 1991, Tarkian *et al.* 1992, 1996). In the Baimka placers, inclusions of laurite (Fig. 4) have been identified in nuggets II–1 (Table 3, anal. 10) and II–2 (Table 3, anal. 15). In nugget II–1, laurite occurs in association with erlichmanite, hollingworthite and guanglinite (Table 2). The composition of this inclusion is described by the formula  $(\text{Ru}_{0.54}\text{Os}_{0.35}\text{Rh}_{0.04}\text{Ir}_{0.03}\text{Pt}_{0.01})_{\Sigma 0.97}\text{S}_{2.02}$  (average result of seven analyses). The coexisting erlichmanite is  $(\text{Os}_{0.52}\text{Ru}_{0.36}\text{Rh}_{0.05}\text{Ir}_{0.05}\text{Pt}_{0.02})_{\Sigma 1.00}\text{S}_{2.00}$  (Table 3, anal. 9). The single inclusion of laurite in nugget II–2 corresponds to  $(\text{Ru}_{0.62}\text{Os}_{0.29}\text{Rh}_{0.03}\text{Ir}_{0.03}\text{Pt}_{0.01}\text{Pd}_{0.01})_{\Sigma 0.99}\text{S}_{2.01}$ . These data show that inclusions of laurite from the Baimka area have a  $(\text{Os/Ir})_{\text{at}}$  ratio (4.51 to 12.14) remarkably in excess of the chondritic value (0.586: Slansky *et al.* 1991) and high concentrations of Rh (up to 3.86 wt.%). The latter compositional property is assumed to be an intrinsic attribute of this mineral in Alaskan-type complexes (Slansky *et al.* 1991).

TABLE 3. ELECTRON-MICROPROBE DATA ON PGM\* INCLUSIONS IN Pt-Fe ALLOY NUGGETS FROM BAIMKA

Nugget	Weight %															Atomic %														
	Pt	Ir	Os	Ru	Rh	Pd	Cu	Ni	Fe	S	As	Total	Pt	Ir	Os	Ru	Rh	Pd	Cu	Ni	Fe	S	As							
1	GS1-2-4	31.24	0.87	0.87	0.39	25.90	0.07	12.64	0.09	0.57	28.97	0.15	101.76	10.39	0.29	0.30	0.25	16.33	0.04	12.90	0.10	0.66	58.61	0.13						
2	GS1-2-4	11.59	1.47	0.15	0.09	9.66	0.18	42.99	0.06	1.87	27.02	0.00	95.08	3.46	0.45	0.05	0.05	5.46	0.10	39.38	0.06	1.95	49.05	0.00						
3	GS1-7-6	18.88	3.31	0.01	0.00	32.14	22.00	0.99	0.00	0.18	0.00	21.27	98.78	10.34	1.84	0.01	0.00	33.37	22.09	1.66	0.00	0.34	0.00	30.34						
4	GS1-7-6	81.32	5.62	0.43	0.17	1.39	0.21	7.95	0.06	1.71	0.01	0.17	99.04	66.71	4.68	0.36	0.27	2.16	0.32	20.02	0.16	4.90	0.05	0.36						
5	GS1-7-6	45.73	7.23	0.00	0.00	16.86	9.22	5.70	0.00	0.52	0.01	10.43	95.70	30.80	4.94	0.00	0.00	21.53	11.38	11.79	0.00	1.22	0.04	18.29						
6	GS1-9-9	1.72	33.54	0.08	0.59	36.18	0.06	0.05	0.10	0.08	27.29	0.00	99.69	6.63	12.49	0.03	0.42	25.17	0.04	0.06	0.12	0.10	60.93	0.00						
7	GS2-1-2	82.98	0.00	0.00	0.10	0.35	3.27	0.01	0.02	0.00	14.90	0.36	101.99	45.72	0.00	0.00	0.11	0.37	3.30	0.02	0.04	0.00	49.94	0.52						
8	GS2-2-2	1.29	52.09	0.00	0.45	20.58	0.10	0.11	0.01	0.13	24.52	0.03	99.31	0.53	21.64	0.00	0.36	15.97	0.08	0.14	0.01	0.19	61.06	0.03						
9	II-1	1.39	4.08	44.90	16.50	2.45	0.00	0.05	0.03	0.12	29.00	0.00	98.52	0.52	1.56	17.36	12.01	1.75	0.00	0.06	0.04	0.16	66.53	0.00						
10	II-1	0.87	3.16	33.80	27.30	2.01	0.00	0.03	0.09	0.09	32.40	0.00	99.75	0.30	1.09	11.83	17.98	1.30	0.00	0.03	0.10	0.11	67.26	0.00						
11	II-1	9.12	17.70	1.53	5.96	23.60	1.35	0.04	0.05	0.11	13.50	26.00	98.96	3.83	7.55	0.66	4.84	18.81	1.04	0.05	0.07	0.16	34.53	28.46						
12	II-1	18.70	0.70	0.66	0.14	2.76	58.60	0.16	0.08	0.21	0.00	14.30	96.31	10.89	0.41	0.39	0.16	3.05	62.55	0.29	0.15	0.43	0.00	21.68						
13	II-1	3.92	4.76	89.90	0.66	0.71	0.00	0.19	0.00	0.00	0.00	0.00	100.14	3.76	4.64	88.52	1.22	1.29	0.00	0.56	0.00	0.00	0.00	0.00						
14	II-2	50.40	0.57	0.00	0.13	17.50	14.40	1.16	1.39	0.00	16.60	0.00	102.15	22.91	0.26	0.00	0.11	15.08	12.00	1.62	2.10	0.00	45.91	0.00						
15	II-2	0.82	2.95	27.40	31.50	1.79	0.30	0.00	0.00	0.05	32.20	0.00	97.01	0.28	1.02	9.60	20.77	1.16	0.19	0.00	0.00	0.06	66.92	0.00						
16	XIII-1	0.86	53.32	0.00	0.50	21.45	0.00	0.00	0.00	0.00	24.22	0.00	100.35	0.35	22.18	0.00	0.40	16.67	0.00	0.00	0.00	0.00	60.40	0.00						
17	XIII-6	1.87	9.50	91.20	0.10	0.32	0.00	0.00	0.04	0.07	0.00	0.00	103.10	1.76	9.08	88.05	0.18	0.57	0.00	0.00	0.13	0.23	0.00	0.00						
18	XIII-6	1.52	5.17	94.10	0.30	0.41	0.00	0.00	0.04	0.09	0.00	0.00	101.63	1.45	4.99	91.84	0.55	0.74	0.00	0.00	0.13	0.30	0.00	0.00						
19	XIII-8	86.20	0.00	0.00	0.00	0.00	0.40	0.00	0.06	0.03	14.20	0.00	100.89	49.65	0.00	0.00	0.00	0.42	0.00	0.11	0.06	49.76	0.00	0.00						
20	XIV-8	3.34	3.45	0.00	0.00	69.14	0.00	1.52	1.17	0.23	20.48	0.00	99.33	1.23	1.29	0.00	0.00	48.21	0.00	1.72	1.43	0.30	45.83	0.00						
21	K1	84.08	0.00	0.00	0.00	0.26	0.39	0.00	0.05	0.19	13.60	0.00	98.57	49.79	0.00	0.00	0.00	0.29	0.42	0.00	0.10	0.39	49.00	0.00						
22	K1	13.00	5.70	0.00	0.48	37.00	0.83	7.10	0.70	5.30	29.50	0.00	99.61	4.15	1.85	0.00	0.30	22.37	0.49	6.95	0.74	5.91	57.25	0.00						
23	K2	20.17	0.38	0.00	0.00	33.63	19.97	0.55	0.00	0.00	0.00	25.20	99.90	10.72	2.20	0.00	0.00	33.87	19.45	0.90	0.00	0.00	0.00	34.86						
24	K5	1.80	77.10	0.17	0.42	3.90	0.00	0.00	0.00	0.30	0.00	0.00	83.69	2.01	87.45	0.19	0.91	8.26	0.65	0.00	0.11	0.00	59.93	0.00						
25	K5	1.40	76.50	0.00	0.59	4.00	0.07	0.00	0.00	0.37	0.00	0.00	82.93	1.57	87.06	0.00	1.28	8.50	0.14	0.00	0.00	1.45	0.00	0.00						
26	K7	1.70	29.10	0.37	0.33	39.70	1.10	0.00	0.09	0.00	27.50	0.00	99.89	0.61	10.66	0.14	0.23	27.16	0.73	0.00	0.11	0.00	60.37	0.00						
27	K7	1.30	33.90	0.47	0.44	35.60	0.95	0.00	0.09	0.00	26.20	0.00	98.95	0.49	12.94	0.18	0.32	25.37	0.65	0.00	0.11	0.00	59.93	0.00						
28	K7	84.00	0.00	0.00	0.00	0.22	1.20	0.00	0.11	0.00	14.00	0.00	99.53	48.79	0.00	0.00	0.00	0.24	1.28	0.00	0.21	0.00	49.47	0.00						
29	K7	8.80	20.70	0.58	0.08	27.50	0.70	7.40	5.60	0.31	27.90	0.00	99.57	2.97	7.09	0.20	0.05	17.60	0.43	7.67	6.29	0.37	57.32	0.00						
30	K7	8.30	21.10	0.54	0.08	27.20	0.91	7.40	5.30	0.26	27.50	0.00	98.59	2.84	7.33	0.19	0.05	17.65	0.57	7.77	6.03	0.31	57.26	0.00						
31	K7	13.43	0.56	0.00	0.13	33.03	25.27	0.32	0.14	0.00	0.00	25.87	98.75	7.00	0.30	0.00	0.13	32.61	24.13	0.51	0.24	0.00	0.00	35.08						

\* Bowicite (6, 26, 27); Cooperite (7, 19, 21, 28); Cuprorhodsite (1, 22, 29, 30); Erlichmanite (9); Guanglinitite (12); Hollingworthite (11); Ir-oxide (24, 25); Kashinite (8, 16); Laurite (10, 15); Osmium (13, 17, 18); Prassoite (20); Rhodarsenide (3, 23, 31); (PGE)<sub>Σ3</sub>(Cu,Fe)<sub>Σ20</sub>As<sub>0.9</sub>(5); (Cu,Rh,Pt,Fe,Ir,S) (2); (Pt,Rh,Pd,S) (14); Pt<sub>3</sub>(Cu,Fe) (4).

### Iridium oxide (or hydroxide)

An unidentified oxide or hydroxide of Ir (the presence of oxygen was confirmed by energy-dispersion spectrometry) was found in nugget K5, which shows a distinct zonal structure (Fig. 5a). The core of this grain is Pt-Fe alloy (generally Pt<sub>3.44</sub>Fe<sub>0.66</sub>) close in composition (Table 1, anal. 8) to isoferroplatinum, whereas the rim zone of about 300 µm across consists of native platinum (Table 1, anal. 9) full of vermicular holes (Fig. 5b) filled with Ir oxide (or hydroxide). The presence of a major oxygen-rich phase leads to a deficit in the analytical total (Table 3, anal. 24, 25). This rare mineral is a possible analogue of the phase (Ir,Os,Ru,Pt)O(OH)•H<sub>2</sub>O described by Mochalov *et al.* (1992).

### Prassoite

The stoichiometry of prassoite is not known exactly (Cabri & Laflamme 1981, Augé 1988, Garuti *et al.* 1995, Daltry & Wilson 1997, Mandarin 1999). Two inclusions of this rare mineral have been observed in

nugget XIV-8 (Table 3, anal. 20). The inclusions are 50 µm and 40 × 100 µm and are associated with osmium and laurite-erlichmanite. The average result of five analyses calculated on the basis of 32 atoms (Cabri & Laflamme 1981) corresponds to the formula (Rh<sub>15.43</sub>Cu<sub>0.55</sub>Ni<sub>0.46</sub>Ir<sub>0.41</sub>Pt<sub>0.39</sub>Fe<sub>0.10</sub>)<sub>Σ17.34</sub>S<sub>14.66</sub> or, ideally, Rh<sub>17</sub>S<sub>15</sub>.

### (Pd,Pt)<sub>Σ3.13</sub>As<sub>0.87</sub>, probably guanglinitite

A mineral having a low analytical total (Table 3, anal. 12) and close to the stoichiometry of guanglinitite (Pd<sub>3</sub>As) or stillwaterite (Pd<sub>8</sub>As<sub>3</sub>) has been observed in nugget II-1 in association with erlichmanite, laurite, hollingworthite and osmium. The formula, calculated on the basis of four atoms, can be written as (Pd<sub>2.50</sub>Pt<sub>0.44</sub>Rh<sub>0.12</sub>Fe<sub>0.02</sub>Ir<sub>0.02</sub>Os<sub>0.02</sub>Cu<sub>0.01</sub>)<sub>Σ3.13</sub>As<sub>0.87</sub>. An occurrence of guanglinitite has been also noted in placer deposits related to AUT complexes of the Aldan Shield (Mochalov *et al.* 1992). In the alluvial deposit of the Durance River, France, where dismembered AUT intrusions were also considered as a probable source of

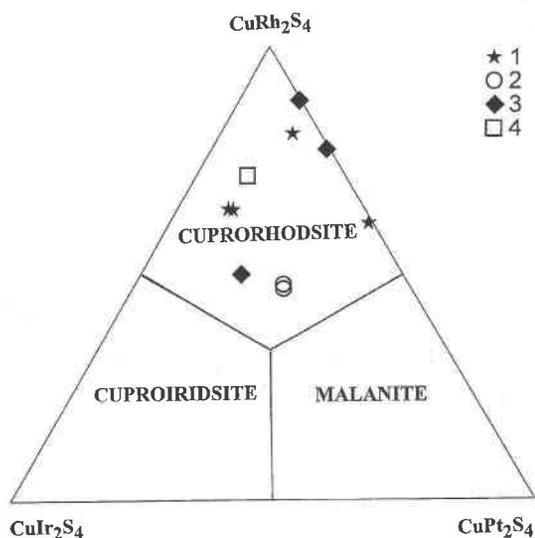


FIG. 6. Plot of chemical composition of cuprorhodsite. (1) Inclusions in grains of Pt-Fe alloy from Baimka. (2) Single grain in clinopyroxenites of the Owendale intrusion, Australia (Johan *et al.* 1989). (3) Inclusions in grains of Pt-Fe alloy from the Durance River, France (Johan *et al.* 1990). (4) Single-phase grain in unfractured chromite, Finero massif, Italy (Garuti *et al.* 1995).

PGM (Johan *et al.* 1990), a phase with a composition compatible with guanglinite was encountered as an inclusion in Pt-Fe alloy. In contrast to guanglinite, stillwaterite is known as a phase typical for BMS associations in layered intrusions (*e.g.*, Cabri *et al.* 1975, Hänninen *et al.* 1986).

#### Rhodarsenide

We reported the occurrence of an unnamed mineral close in composition to rhodarsenide in 1994 (Gornostayev *et al.* 1994). Recently, rhodarsenide from Srebrenica River, central Serbia, was approved as a new mineral species (Tarkian *et al.* 1997). Nuggets GS1-7-6 (Table 3, anal. 3), K2 (Table 3, anal. 23) and K7 (Table 3, anal. 31) contain irregularly shaped inclusions (Fig. 7) of variable sizes (from  $4 \times 22$  to  $15 \times 20 \mu\text{m}$ ) and composition that corresponds closely to the ideal formula  $(\text{Rh,Pd,Pt})_2\text{As}$ .

#### Other PGE phases

Several PGE- and Cu-bearing arsenides and PGE sulfides have been observed as minute ( $4\text{--}30 \mu\text{m}$ ) inclusions within various nuggets of Pt-Fe alloy, including GS1-7-6, II-2 and GS1-2-4. In nugget GS1-7-6, in association with rhodarsenide, there are also inclusions of other PGM whose composition (Table 3, anal. 5) corresponds to the formula  $(\text{Pt}_{1.54}\text{Rh}_{1.08}\text{Pd}_{0.57}\text{Ir}_{0.25})_{\Sigma 3.44}(\text{Cu}_{0.59}\text{Fe})_{\Sigma 0.65}\text{As}_{0.91}$ . In addition, an unusual Pt-Cu-Fe alloy (Table 3, anal. 4) with a formula  $(\text{Pt}_{2.67}\text{Ir}_{0.19}\text{Rh}_{0.09}\text{Os}_{0.01}\text{Pd}_{0.01}\text{Ru}_{0.01})_{\Sigma 2.98}(\text{Cu}_{0.80}\text{Fe}_{0.20}$

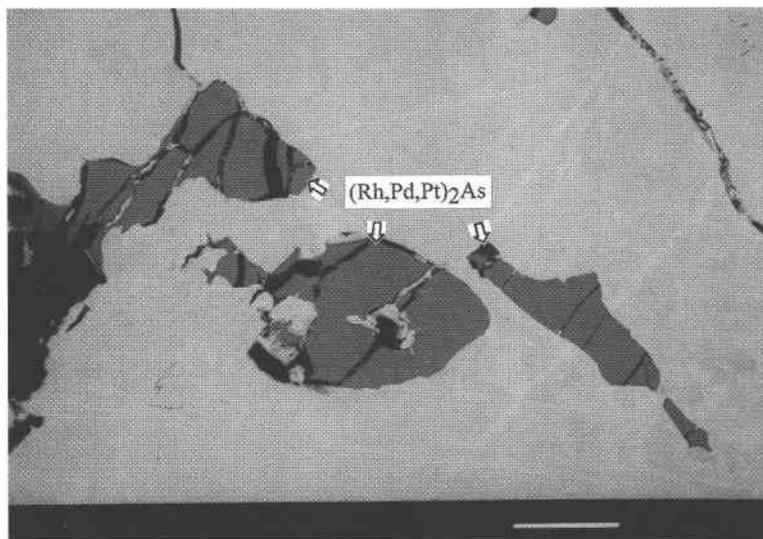


FIG. 7. Inclusions of rhodarsenide,  $(\text{Rh,Pd,Pt})_2\text{As}$ , in grains of Pt-Fe alloy from Baimka, nugget K2. Scale bar:  $10 \mu\text{m}$ .

$\text{Ni}_{0.01}\text{S}_{1.01}$ , close to the stoichiometry of isoferroplatinum, has also been identified in this nugget. In nugget II-2, an inclusion of PGE sulfide (Table 3, anal. 14) with a high concentration of Rh (17.5 wt.%), a ratio *Me/S* close to 1, and a composition corresponding to  $(\text{Pt}_{0.46}\text{Rh}_{0.30}\text{Pd}_{0.24}\text{Ni}_{0.04}\text{Cu}_{0.03}\text{Ir}_{0.01})\text{S}_{1.08}\text{S}_{0.92}$  has been identified. Finally, in nugget GS1-2-4, another Cu-rich phase (Table 3, anal. 2) was found with *Me/S* near unity and a formula corresponding to  $(\text{Cu}_{0.79}\text{Rh}_{0.11}\text{Pt}_{0.07}\text{Fe}_{0.04}\text{Ir}_{0.01})\text{S}_{1.02}\text{S}_{0.98}$ . The host of this inclusion is a Pt-Fe alloy containing 1.66 wt.% Cu (Table 1, anal. 1).

#### Inclusions of silicate glass and an oxide mineral

Besides various PGM, inclusions of silicate glass and an oxide mineral were identified in some Pt-Fe alloy nuggets. The silicate glass inclusions hosted by nuggets K2, K5 and K7 are generally between  $5 \times 5$  and  $10 \times 40$   $\mu\text{m}$ . Electron-microprobe analyses have established  $\text{SiO}_2$  concentrations from 34.10 to 64.30 wt.% and considerable variations in the proportion of  $\text{Al}_2\text{O}_3$ ,  $\text{MgO}$ ,  $\text{CaO}$ ,  $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$  (Table 4). The majority of the inclusions are characterized by low analytical totals, and some of them are partly devitrified. Despite the difficulties of precise interpretation of the compositions of the glass inclusions, we suggest that they indicate a range of basaltic to more felsic parent melts.

Two nuggets (GS1-3-1 and GS1-3-6) contain euhedral crystals of magnetite (Fig. 8), a common inclusion in PGM associated with AUT complexes (Nixon *et al.* 1990). The occurrence of silicate glass and magnetite inclusions in the Baimka nuggets is a feature simi-

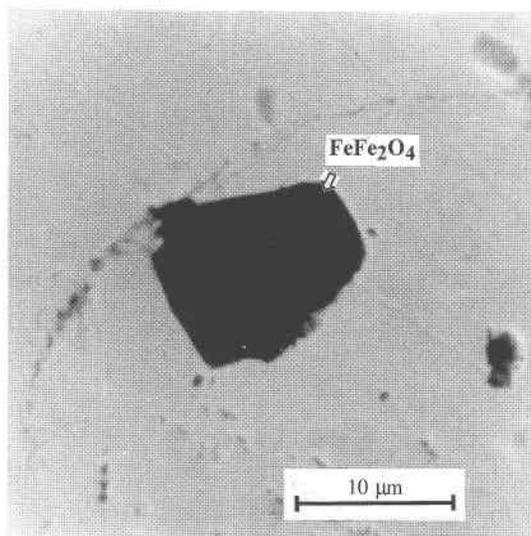


FIG. 8. Magnetite ( $\text{FeFe}_2\text{O}_4$ ) inclusion in grain of Pt-Fe alloy from Baimka. Nugget GS1-3-6.

TABLE 4. ELECTRON-MICROPROBE DATA ON SILICATE GLASS INCLUSIONS IN Pt-Fe ALLOY NUGGETS FROM BAIMKA, RUSSIAN FAR EAST

Nugget	$\text{SiO}_2$	$\text{TiO}_2$	$\text{Al}_2\text{O}_3$	$\text{FeO}$	$\text{MnO}$	$\text{MgO}$	$\text{CaO}$	$\text{Na}_2\text{O}$	$\text{K}_2\text{O}$	Total
K2	64.30	0.33	19.10	0.57	0.00	0.00	0.72	1.60	11.90	98.52
K2	44.60	1.40	31.60	1.20	0.00	0.16	0.40	0.00	3.00	82.36
K2	48.90	0.35	26.90	4.10	0.00	1.90	1.00	0.00	1.70	84.85
K5	44.00	0.00	35.00	2.50	0.00	0.53	0.53	0.00	0.61	83.17
K7	56.40	0.20	22.70	0.48	0.00	0.00	5.70	4.90	1.60	91.98
K7	34.10	2.10	1.30	26.80	1.30	24.80	3.90	0.43	0.51	95.24
K7	43.50	0.28	38.40	1.60	0.00	0.00	0.12	0.00	0.07	83.97

The data are expressed in weight %.

lar to nuggets in other regions (Johan *et al.* 1990, Nixon *et al.* 1990), and suggests comparable genetic processes.

#### DISCUSSION

The PGM nuggets of the Baimka area consist of Pt-Fe alloy hosting inclusions of other PGM, PGM-bearing arsenides and sulfides, magnetite, plagioclase and silicate glass. They are characterized by considerable variation in size, shape and degree of abrasion, and commonly are coated by a layer or shell of clastic minerals. These properties, together with an intimate spatial association with the Volga conglomerate of Late Jurassic age, support the hypothesis that the nuggets were a detrital component of these conglomerates, *i.e.*, the nuggets were previously concentrated in these conglomerates prior to their dispersal in the Quaternary alluvial sediments of the Baimka area. Hence, the nuggets have probably been subject to a protracted history of placer-forming processes.

The grains of Pt-Fe alloy show a bimodal distribution of compositions, with most grains ranging from 16 to 20 or 24 to 28 at.% (Fe + Cu + Ni). This compositional variation, together with textural characteristics, especially euhedral crystals of cooperite within droplet-like or spherical inclusions of cuprorhodsite (Fig. 5c), suggest a multistage origin for these nuggets. We suggest that under high-temperature magmatic conditions, two immiscible liquids were present in the system Pt-Fe alloy - PGE sulfides. Platinum was distributed between both the sulfur-poor and sulfur-rich liquids, but other PGE and Cu were preferentially partitioned into the sulfur-rich phase. With cooling, the sulfur-poor liquid crystallized as a Pt-Fe alloy, forming a matrix to the Cu-Pt-Rh-rich sulfide liquid. This liquid finally crystallized PtS and  $\text{CuRh}_2\text{S}_4$ , probably at subsolidus temperatures.

Whereas textural features of high-temperature origin are considered predominant, the very distinctive vermicular texture seen in nugget K5 (Fig. 5a) may represent a feature due to relatively low-temperature alteration. The unidentified oxygen-rich Ir phase, a possible

analogue of a H<sub>2</sub>O-bearing Ir mineral described by Mochalov *et al.* (1992), is present as a rim around the Pt-Fe alloy. An origin during burial diagenesis or low-grade metamorphism in a sedimentary host is a distinct possibility. Hence, a protracted history of mineralogical modification in response to liquidus and subsolidus temperatures in an igneous regime was probably followed by further mineralogical adjustments in a sedimentary environment at a much lower temperature.

A magmatic source for the Baimka nuggets in AUT intrusions is favored by the assemblage of PGM and especially their composition, as reflected in high levels of Cu and Rh and low levels of Ni. This compositional feature is characteristic of the Pt-rich Pt-Fe alloy compositions. It is also reflected in the presence of cupro-rhodsites, magnetite and plagioclase in some samples, the high Rh contents of the laurite (Slansky *et al.* 1991), and the high concentration of Rh + Cu with a low level of Ni in several PGE- and Cu-bearing PGE sulfides. Further, the (Os/Ir)<sub>at</sub> of Baimka laurite exceeds the chondritic value by as much as 20, favoring (Slansky *et al.* 1991) an AUT source rather than an ophiolitic parent. The high (Os/Ir)<sub>at</sub> ratio in laurite at Baimka is an indicator of low Ir content (close to 1 at.%) in comparison to that (Fig. 4) from ophiolites of Oman (2.88 at. %, calculated from Augé, 1986) and Othrys, Greece (2.21 at. %, calculated from Garuti *et al.* 1999). In general, most of these compositional features are best explained by equilibration of high-temperature immiscible PGE-bearing melts with strongly fractionated silicate magmas as would be the case in the AUT source rocks. In addition, both the presence of PGE-bearing AUT intrusions in the Baimka area and their preservation as clasts in conglomerates of the Volga unit add support to the suggestion that AUT rocks were the predominant source of PGM-bearing alluvial sediments.

### CONCLUSIONS

The main conclusions drawn from this study of Baimka PGM-bearing alluvial sediments are:

1. Grains of Pt-Fe alloy of the Baimka area, along with their inclusions of other PGM, arsenides, sulfides, oxides and silicates, were derived from Alaskan-Ural-type plutons.
2. The Pt-Fe alloy crystallized at magmatic temperatures from a sulfur-poor liquid, whereas other PGE-bearing phases crystallized from a sulfur-rich liquid. Both liquids coexisted immiscibly.
3. The mineralogy of the Baimka nuggets reflects a protracted history of cooling in an igneous environment, followed by continued modification during burial as components of detrital sediments.

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