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, cuprorhodsite, laurite, Ir oxide (or hydroxide), osmium, prassoite, guanglinite, 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’erosion d’une formation conglomératique (Volga), d’âge jurassique tardif. Parmi les minéraux du groupe du platine dans ces placer, 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 d’un alliage Pt–Fe: bowieite, cooperite, kashinite, erlichmanite, hollingworthite, irarsite, cuprorhodsite, laurite, Ir oxide (ou hydroxide), osmium, prassoite, guanglinite, 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.

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). 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 zoning, 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 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 lherzolite (Lychagin 1985).

The gabbro–clinopyroxenite plutons are considered to be composed of gabbro–clinopyroxenite 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 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 lherzolite (Lychagin 1985).

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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

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), flakelike (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 (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.

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<th>Ru</th>
<th>Rh</th>
<th>Pd</th>
<th>Cu</th>
<th>Ni</th>
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* 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).

PLATINUM-GROUP MINERALS

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 iruperoiridium. The average composition of grains with 16–20 at.% Fe is given by the formula (Pt3.66Rh6.11Ir6.65Pd6.3Os6.01Ru0.61Os6.71). 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-
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 \((\text{Ir}_{0.80}\text{Os}_{0.20}\text{Ru}_{0.04}\text{P}_{0.01})\) and \((\text{Ir}_{0.65}\text{Os}_{0.35}\text{P}_{0.06}\text{Ru}_{0.06}\text{Rh}_{0.04})\). The composition of a third grain (Table 1, anal. 19) is different from these: \((\text{Ir}_{0.70}\text{Os}_{0.18}\text{P}_{0.08}\text{Ru}_{0.01})\).

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 × 115 μm and (2) a rounded component (Fig. 5d) about 12 × 25 μm (Table 3, anal. 26) in three-phase inclusions along with cooperite and cuprorhodsite. Compositions for these two varieties of bowieite gave formulae of \((\text{Rh}_{1.07}\text{Ir}_{0.65}\text{P}_{0.03}\text{Ru}_{0.02}\text{Os}_{0.01}\text{Ni}_{0.01}\text{S}_{2.01}\text{S}_{3.00})\) and \((\text{Rh}_{1.36}\text{Ir}_{0.53}\text{P}_{0.04}\text{Ru}_{0.01}\text{Os}_{0.01}\text{Ni}_{0.01}\text{S}_{2.99}\text{S}_{3.02})\).

Kashinite constitutes six inclusions of 30 × 130, 30 × 40, 20 × 20, 15 × 15, 10 × 60, 15 × 130 μm 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 \((\text{Ir}_{1.11}\text{Rh}_{0.83}\text{Ru}_{0.02}\text{P}_{0.02}\text{S}_{1.98}\text{S}_{3.02})\) (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
The first sample listed is GS1-2-4, the second is GS1-7-6, and so on.

### Hollingworthite and irarsite

Hollingworthite has been identified in nugget II-1 (Table 3, anal. 11) in association with erlichmanite and guanglinite (Table 2). The composition of the hollingworthite is \((\text{Rh}_{0.56}\text{Ir}_{0.23}\text{Ru}_{0.13}\text{Pt}_{0.11}\text{Pd}_{0.09}\text{Os}_{0.02})_{2.10}\text{As}_{0.03}\text{S}_{1.06}\). Irarsite was observed in two inclusions in nugget GS7-1-1 and occurs as grains 1-2 μm 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 μm across (Table 3, anal. 29) and (2) as an anhedral crystal of 60 μm across (Table 3, anal. 30) in a three-phase association with bowieite and cooperite. The third variety (3) of cuprorhodsite, \((\text{Cu}_{0.39}\text{Fe}_{0.41}\text{Ni}_{0.03})_{2.05}\text{(Rh}_{1.59}\text{Pt}_{0.29}\text{Ir}_{0.17}\text{Pd}_{0.02})_{2.00}\text{S}_{4.01}\) 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) \((\text{Cu}_{0.34}\text{Ni}_{0.44}\text{Fe}_{0.03})_{2.11}\text{(Rh}_{2.23}\text{Ir}_{0.50}\text{Pt}_{0.27}\text{Pd}_{0.03}\text{Os}_{0.01})_{2.29}\text{S}_{4.00}\), and (2) \((\text{Cu}_{0.34}\text{Ni}_{0.42}\text{Fe}_{0.02})_{2.08}\text{(Rh}_{1.24}\text{Ir}_{0.51}\text{Pt}_{0.20}\text{Pd}_{0.03}\text{Os}_{0.01})_{2.26}\text{S}_{4.01}\).
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 \((Ru_{0.54}Os_{0.35}Rh_{0.04}Ir_{0.06}Pt_{0.01})_{20.97}S_{2.02}\) (average result of seven analyses). The coexisting erlichmanite is \((Os_{0.52}Ru_{0.38}Rh_{0.05}Ir_{0.05}Pt_{0.02})_{21.00}S_{2.00}\) (Table 3, anal. 9). The single inclusion of laurite in nugget II–2 corresponds to \((Ru_{0.50}Os_{0.25}Rh_{0.03}Ir_{0.03}Pt_{0.01})_{20.99}S_{2.01}\). These data show that inclusions of laurite from the Baimka area have a \((Os/Ir)_{rel}\) 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).
inclusions of this rare mineral have been observed in Prassoite (Cabri & Laflamme 1981, Aug6 1988, Garuti et al. 1995, Daltry & Wilson 1997, Mandarino 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$_{15.43}$ Cu$_{0.55}$Ni$_{0.46}$Ir$_{0.41}$Pt$_{0.39}$Fe$_{0.10}$)$_{21.34}$S$_{14.66}$ or, ideally, Rh$_{15}$S$_{15}$.

(Pd, Pt)$_{25.13}$As$_{0.87}$, probably guanglinite

A mineral having a low analytical total (Table 3, anal. 12) and close to the stoichiometry of guanglinite (Pd$_x$As$_y$) or stillwaterite (Pd$_x$As$_y$) 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$_{6.58}$Pt$_{0.44}$Rh$_{0.12}$Fe$_{0.20}$Ir$_{0.25}$Os$_{0.29}$Cu$_{0.01}$)$_{27.31}$As$_{14.66}$. An occurrence of guanglinite 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 inclusions were also considered as a probable source of...
CuRh₂S₄

CUPRORHODSITE

CUPROIRIDSITE

MALANITE

PGM (Johan et al. 1990), a phase with a composition compatible with guanginite was encountered as an inclusion in Pt–Fe alloy. In contrast to guanginite, 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 × 22 to 15 × 20 μm) and composition that corresponds closely to the ideal formula (Rh,Pd,Pt)₂As.

**Other PGE phases**

Several PGE- and Cu-bearing arsenides and PGE sulfides have been observed as minute (4–30 μm) 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 (Pt₁.₅₄Rh₁.₀₈Pd₂.₅₇Ir₀.₂₅)₂₃.₄₄(Cu₀.₉₀Fe)₂₀.₆₅As₂.₀₁. In addition, an unusual Pt–Cu–Fe alloy (Table 3, anal. 4) with a formula (Pt₂.₆₇Rh₀.₁₉Os₀.₀₅Pd₀.₀₁Ru₀.₀₁)₂₂.₉₈(Cu₀.₇ₐFe₀.₂₀

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**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).

**Fig. 7.** Inclusions of rhodarsenide, (Rh,Pd,Pt)₂As, in grains of Pt-Fe alloy from Baimka, nugget K2. Scale bar: 10 μm.
Ni_{0.01} \text{S}_{1.01}, close to the stoichiometry of isoferroro-
platinum, 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
(Pt_{0.46}Rh_{0.30}Pd_{0.24}Ni_{0.06}Cu_{0.03}Ir_{0.01})S_{1.08}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 (Cu_{0.78}Rh_{0.14}Pt_{0.07}
Fe_{0.03}Ir_{0.01})S_{1.02}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 X 5 and 10 X
40 μm. Electron-microprobe analyses have established
SiO\textsubscript{2} concentrations from 34.10 to 64.30 wt.% and con-
siderable variations in the proportion of Al\textsubscript{2}O\textsubscript{3}, MgO,
CaO, Na\textsubscript{2}O and K\textsubscript{2}O (Table 4). The majority of the in-
clusions are characterized by low analytical totals, and some
of them are partly devitrified. Despite the diffi-
culties 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 in-
clusion in PGM associated with AUT complexes (Nixon
et al. 1990). The occurrence of silicate glass and mag-
netite inclusions in the Baimka nuggets is a feature simi-
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-bear-
ing arsenides and sulfides, magnetite, plagioclase and
silicate glass. They are characterized by considerable
variation in size, shape and degree of abrasion, and com-
monly are coated by a layer or shell of clastic minerals.
These properties, together with an intimate spatial asso-
ciation 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 conglomer-
ates 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 distribu-
tion of compositions, with most grains ranging from 16
to 20 or 24 to 28 at.% (Fe + Cu + Ni). This composi-
tional 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 sug-
gest that under high-temperature magmatic conditions,
two immiscible liquids were present in the system Pt–
Fe alloy – PGE sulfides. Platinum was distributed be-
tween 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 liq-
uid crystallized as a Pt–Fe alloy, forming a matrix to
the Cu–Pt–Rh–rich sulfide liquid. This liquid finally
crystallized PtS and CuRh\textsubscript{2}S\textsubscript{4}, probably at subsolidus
temperatures.

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

**Table 4. Electron-Microprobe Data on
Silicate Glass Inclusions in Pt–Fe Alloy Nuggets
From Baimka, Russian Far East**

<table>
<thead>
<tr>
<th>Nugget</th>
<th>SiO\textsubscript{2}</th>
<th>TiO\textsubscript{2}</th>
<th>Al\textsubscript{2}O\textsubscript{3}</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>Na\textsubscript{2}O</th>
<th>K\textsubscript{2}O</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>K2</td>
<td>64.30</td>
<td>0.33</td>
<td>19.10</td>
<td>0.57</td>
<td>0.00</td>
<td>0.00</td>
<td>0.72</td>
<td>1.60</td>
<td>11.90</td>
<td>98.52</td>
</tr>
<tr>
<td>K2</td>
<td>44.60</td>
<td>1.40</td>
<td>31.60</td>
<td>1.20</td>
<td>0.00</td>
<td>0.16</td>
<td>0.40</td>
<td>0.00</td>
<td>3.00</td>
<td>82.36</td>
</tr>
<tr>
<td>K2</td>
<td>48.90</td>
<td>0.35</td>
<td>26.90</td>
<td>4.10</td>
<td>0.00</td>
<td>1.90</td>
<td>1.00</td>
<td>0.00</td>
<td>1.70</td>
<td>84.85</td>
</tr>
<tr>
<td>K5</td>
<td>44.00</td>
<td>0.00</td>
<td>35.00</td>
<td>2.50</td>
<td>0.00</td>
<td>0.53</td>
<td>0.53</td>
<td>0.00</td>
<td>0.63</td>
<td>83.17</td>
</tr>
<tr>
<td>K7</td>
<td>56.40</td>
<td>0.20</td>
<td>22.70</td>
<td>0.48</td>
<td>0.00</td>
<td>5.70</td>
<td>4.90</td>
<td>1.60</td>
<td>91.98</td>
<td></td>
</tr>
<tr>
<td>K7</td>
<td>34.10</td>
<td>2.10</td>
<td>13.00</td>
<td>26.80</td>
<td>1.30</td>
<td>24.80</td>
<td>3.90</td>
<td>0.43</td>
<td>0.51</td>
<td>95.24</td>
</tr>
<tr>
<td>K7</td>
<td>43.50</td>
<td>0.28</td>
<td>38.40</td>
<td>1.60</td>
<td>0.00</td>
<td>0.12</td>
<td>0.00</td>
<td>0.07</td>
<td>83.97</td>
<td></td>
</tr>
</tbody>
</table>

The data are expressed in weight %.

![Fig. 8. Magnetite (FeFe\textsubscript{2}O\textsubscript{4}) inclusion in grain of Pt–Fe alloy
from Baimka. Nugget GS1–3–6.](image-url)
analogue of a H₂O-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 cuprohodsite, magnetite and plagioclase in some samples, the high Rh contents of the laurite (Słansky 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)₉ of Baimka laurite exceeds the chondritic value by as much as 20, favoring (Słansky et al. 1991) an AUT source rather than an ophiolitic parent. The high (Os/Ir)₉ 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 Garutti 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 magma 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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