ASSOCIATIONS OF PLATINUM-GROUP MINERALS FROM THE ZOLOTAYA GOLD PLACER, PRIMORYE, RUSSIAN FAR EAST

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ABSTRACT

The platinum-group minerals (PGM) and chromite composition of the Zolotaya River gold placer, in the Russian Far East, indicate a genetic relationship to poorly exposed Late Permian dunite – hornblende – gabbro intrusions of Uralian–Alaskan type. Ninety percent of the PGM grains studied consist of Pt–Fe alloy, typically with a rhodium content in the 1–2 wt.% range. Pt-bearing Os–Ir–Ru alloy occurs in three variants: (1) heterogeneous grains with an exsolution texture, (2) intergrowths of Os–Ir alloy with Pt–Fe alloy, and (3) homogeneous grains. Minerals of the erlichmanite–laurite series are relatively rare. Their composition varies from pure laurite through Os-bearing laurite to erlichmanite. Cooperite occurs in multiphase inclusions (in association with cuprorhodsite and chalcopyrite) in Pt–Fe alloy, and as a secondary rim (occasionally intergrown with platarsite and sperrylite) around Pt–Fe grains. Heterogeneous aggregates of Pt–Fe and Ru–Pt–Ir alloy have inclusions of arsenides of rhodium, iridium and ruthenium (cherepanovite, iridarsenite, ruthenarsenite) and a sulfarsenide-rich rim (irarsite).

Keywords: Pt–Fe alloy, platinum-group minerals, Uralian–Alaskan-type complex, gold-bearing placers, platinum-group elements, Primorye, Russia.

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SOMMAIRE

D’après les minéraux du groupe du platine (MGP) et la composition du spinelle chromifère présents dans les placers aurifères de la rivière Zolotaya, dans la partie extrême orientale de la Russie, il y aurait un lien génétique avec des massifs intrusifs permiens tardifs à piétre affleurement de dunite – hornblende – gabbro du type Ourale–Alaska. Quatre-vingt dix pour cent des grains de MGP que nous avons étudié sont un alliage Pt–Fe, typiquement avec une teneur en rhodium de 1–2% (poids). Un alliage Os–Ir–Ru platinifère y figure en trois variantes: (1) grains hétérogènes ayant une texture d’exsolution, (2) intercroisements d’un alliage Os–Ir avec l’alliage Pt–Fe, et (3) grains homogènes. Les minéraux de la série erlichmanite–laurite semblent relativement rares. Leur composition varie de laurite pure, passant par laurite osmifère, jusqu’à erlichmanite. La cooperite se présente en inclusions multiphasées (en association avec cuprorhodsite et chalcopyrite) dans l’alliage Pt–Fe, et en liseré secondaire en bordure (ici et là en intercroisement avec platarsite et sperrylite) autour des grains de l’alliage Pt–Fe. Des agrégats hétérogènes des alliages Pt–Fe et Ru–Pt–Ir contiennent des inclusions d’arsénures de rhodium, iridium et ruthénium (cherepanovite, iridarsenite, ruthenarsenite) et une bordure riche en sulfarsénium (irarsite).


(Traduit par la Rédaction)
Platinum-group minerals (PGM) in southwestern Primorje, in the Russian Far-East (Fig. 1), were discovered at the end of the 19th century during gold placer mining on the territory of the Sof'e-Alexeevskoe Cosacks. Over the interval 1900–1912, exploration for gold was carried out at four fields: Zolotaya and Baykal river (former Dzhunikha) valleys and their northern tributaries (Annett 1928). In 1931, S.G. Vaulin, mining engineer with the “Dal’zoloto” company, evaluated the platinum potential. He confirmed the presence of small amounts of PGM in the gold placers (up to 3 mg PGE/m³) and noted the occasional occurrence of nuggets with a weight of more than 50 mg. Only about sixty years later, the composition and secondary transformation of the PGM from the Fadeevka placer were studied by researchers from the Far East Geological Institute in Vladivostok (Shcheka et al. 1991).

In the present study, we give a description of the primary and secondary PGM mineralization, on the basis of sample material from a heavy-mineral concentrate taken from the Zolotaya River. Grains of chromian spinel were analyzed from the Zolotaya and Fadeevka River placers.

GEOLOGICAL SETTING

The Zolotaya and Fadeevka rivers are located in the Pogranichnaya gold belt, which is part of the southern Laoelin–Grodkev fold belt, Primorje (Figs. 1, 2). The fold belt strikes N–S and stretches along the China–Russia border, southwest of Lake Khanka. This area represents an island-arc terrane that accreted to the west of the Sino-Korean platform during the Late Paleozoic (Khanchuk et al. 1996). The stratigraphic sequence of the study area consists of an Early Paleozoic basement of muscovite–chlorite schist overlain by Permian black shale. Late Permian folding and thrusting were accompanied by basic to ultrabasic magmatism. Shallow gabbroic sills and stocks and granitic rocks with dominantly albitized common rock-units. This complex is concentrically zoned and is regarded as of Uralian–Alaskan-type (Shcheka et al. 1990). A large part of it was intruded by Late Permian granites and now occurs as xenoliths and large blocks (roof pendants) within the granitic rocks. Larger occurrences are in the upper Baykal valley and in the upper reaches of the Kamenska river west of Veranda Mountain (Fig. 2).

The hornblende suite of the dunite – hornblendite – gabbro complex has a composition similar to peridotites and hornblende-rich pyroxenites of the zoned ultrabasic intrusions of southwestern Alaska (Taylor & Noble 1969, Himmelberg & Loney 1995). A minor amount of hornblende also is present in some concentrically zoned massifs of the Uralian Platinum Belt (Ivanov 1997). All massifs mentioned above have similar petrochemical and mineralogical characteristics, although the proportion of hornblende-bearing ultrabasic rocks in individual intrusive complexes is highly variable.

The Permian black shale hosts a number of quartz veins with pyrite – arsenopyrite – gold; they formed in connection with the felsic intrusions, and are considered to be the source of the alluvial gold placers (Shcheka et al. 1991). The alluvial gold from the Zolotaya River consists of dominantly (1) low-silver Au–Ag alloy with <8 wt.% Ag, and (2) high-silver Au–Ag alloy with up to 25 wt.% Ag. Occasionally, a complex Au–Ag–Hg–Pd alloy occurs, with up to 8 wt.% Pd and 4 wt.% Hg. The palladium component in this variant is considered to be related to remobilization from dunitic rocks during the widespread felsic magmatism (Mulchanov et al. 2001).

ANALYTICAL METHODS

Both quantitative electron-microprobe analysis with wavelength-dispersion spectrometers (WDS) and energy-dispersion X-ray spectrometry (EDS) were done with a CAMECA SX100 electron microprobe at the Institute of Mineralogy and Mineral Resources of Technical University of Clausthal (Germany). The PGM were analyzed with a voltage of 20 kV and a beam current of 20 nA, with a beam 1 μm in diameter. The duration of the analyses varied from 10 to 30 s. Nineteen elements were determined using the following standards: FeS₂, PbTe, SnO₂, InAs and pure osmium, bisulfide, ruthenium, rhodium, palladium, silver, antimony, gold, platinum, iridium, nickel, cobalt, iron and copper. The X-ray Ka lines were used for Ni, Co, Fe; La for Ru, Rh, Sn, Sb, Te, Au, Pt, Ir, Cu; Lβ for Pd and Ag, and Mn for Os, Pb, Bi. The following detection-limits were obtained (in wt.%): 0.15 for Os, 0.15 for Ir, 0.16 for Ru, 0.12 for Rh, 0.24 for Pd, 0.27 for Pt, 0.27 for Au, 0.32 for Ag, 0.23 for Pb, 0.04 for Fe, 0.02 for Ni, 0.09 for Cu, 0.03 for Co, 0.18 for Bi, 0.08 for Sb, 0.08 Sn, 0.09 for Te, 0.05 for As, and 0.06 for S.

Oxides and silicates were analyzed for twelve elements using the following standards and spectral lines: kaersutite, Cr₂O₃ (synthetic), rutile, sphalerite, Fe₂O₃ (synthetic), rhodonite, forsterite, albite. The SiKα, Kα, CaKα, CrKα, TiKα, SKα, FeKα, MnKα, ZnKα, NaKα, MgKα, and AlKα lines were used. For the data reduction, we employed the approach of Pouchou & Pichoir (1984).
SOURCE OF THE PGM

In an earlier study of the PGM and associated minerals from the Fadeevka River placer, Shcheka et al. (1991) suggested that the PGM mineralization is related to the dunite – hornblende – gabbro complex. Since then, black shale was found that also could be a source of the platinum-group elements. The chemical composition of chromian spinel is often used for both the petrogenetic characterization of basic-ultrabasic igneous complexes and their related mineralization (e.g., Barnes & Roeder 2001). We studied the chromian spinel from the Fadeevka and Zolotaya placers both as inclusions in PGM and in individual grains of chromian spinel in heavy-mineral concentrates, and compared it to chromian spinel from the Late Permian dunite –
FIG. 2. Geological sketch-map of the study area.
hornblende – gabbro complex within the same area. All three sample groups studied have a similar composition, suggesting a common source (Table 1). The chromian spinel has a high content of chromium, a low content of titanium, and a low oxidation state. The plot of \( \frac{\text{Fe}^{3+}}{(\text{Cr}^{3+} + \text{Fe}^{3+} + \text{Al}^{3+})} \) versus \( \frac{\text{Cr}^{3+}}{(\text{Cr}^{3+} + \text{Fe}^{3+} + \text{Al}^{3+})} \) for chromian spinel from the Zolotaya and Fadeevka areas shows a compositional field similar to Uralian–Alaskan-type occurrences and different from the ophiolitic trend (Fig. 3).

The composition of an olivine inclusion (Fo 91) within a PGM grain is similar to olivine in dunite and further confirms the connection of PGM mineralization from the Zolotaya River to the dunite – hornblende – gabbro intrusions.

**ASSOCIATIONS OF PLATINUM-GROUP MINERALS**

About 40 grains of PGM from the Zolotaya gold placer have been studied by electron-microprobe analysis. Ninety percent of the grains consist of a Pt–Fe alloy; the remaining grains consist of Os–Ir–Ru–Pt alloy. Other PGM occur as inclusions within or a rim on the main alloy phases. The grain size of the PGM seldom exceeds 2 mm (maximum is 4.4 mm across) and normally varies from 0.2 up to 1.4 mm. The grain shape is isometric or tabular, commonly irregular and angular. Usually, the PGM are poorly rounded, with euhedral outlines preserved, which indicates relatively little transport. Occasionally, the PGM are intergrown with silicates, such as forsterite, quartz, chamosite, white mica, and clay minerals.

**Pt–Fe alloy**

The Pt content in the Pt–Fe alloy varies from 80.0 up to 91.8 wt.\% (Table 2, Fig. 4). The most common minor elements are rhodium (from 0.55 to 2.51 wt.\%) and palladium (from 0.26 to 1.07 wt.\%). Some grains are rich in iridium (up to 7.14 wt.\%). Copper ranges from 0.26 to 1.12 wt.\%, and was found in all grains analyzed.

**Os–Ir–Ru–Pt alloy**

The grains of Os–Ir–Ru–Pt alloy have an extremely heterogeneous texture and consist of up to four different mineral phases, reflecting various stages of exsolution of the primary solid-solution (Table 3, Fig. 5). Sample ZL22 was found to be the most interesting because it allowed us to define the composition of the primary grains and to correlate it with the composition of its products of exsolution. The grain matrix consists of a micrographic intergrowth of iridium-rich Pt-Fe alloy with Os–Ir–Ru–Pt alloy phases of composition: Pt0.65Ir0.65Rh0.05Pd0.05Ru0.05Os0.05 (Fig. 6a). Numerous inclusions of cherepanovite (RhAs) and irarsite (IrAs2) are located in the matrix. The grain has a homogeneous rim of Pt0.46Ir0.25Fe0.18Ru0.08Rh0.01Os0.01Cu0.01 with graphic inclusions of cherepanovite characterized by a high Ru content (up to 20 wt.\%), in association with irarsite (Ir,Rh,Pt)AsS (Fig. 6b). We analyzed the matrix of the micrographic grain with a defocused beam (50 \( \mu \text{m} \)) in order to obtain its bulk composition. The
composition, Pt_{0.49}Ir_{0.23}Fe_{0.17}Ru_{0.07}Rh_{0.02}Os_{0.01}, is nearly identical to that of the rim, suggesting a variable degree of exsolution from a homogeneous primary phase for both rim and core.

Other samples consist of aggregates of (i) zonal intergrowths of iridium, Ir_{0.40}Ru_{0.22}Os_{0.20}Pt_{0.11}Rh_{0.04}Fe_{0.02}, with two variants of rutheniridosmine, Ir_{0.39}Ru_{0.30}Os_{0.28}Rh_{0.02}Pt_{0.01} and Os_{0.42}Ir_{0.30}Ru_{0.23}Pt_{0.02}Rh_{0.02}, and iridium-bearing Pt–Fe alloy (Pt_{2.66}Rh_{0.15}Pd_{0.03})/Fe_{0.89}Ni_{0.07}Cu_{0.04}/H_{9018}^2.36 (sample ZL–1/6), (ii) iridium Ir_{0.41}Os_{0.28}Pt_{0.11}Rh_{0.09}Ru_{0.07}Pd_{0.03} with numerous spotted inclusions of Ir- and Rh-rich Pt–Fe alloy (Pt_{2.66}Rh_{0.15}Pd_{0.03}).

FIG. 3. Plot of Fe^{3+}/(Cr^{3+} + Fe^{3+} + Al^{3+}) versus Cr^{3+}/(Cr^{3+} + Fe^{3+} + Al^{3+}) for chromian spinel from the Zolotaya and Fadeevka areas. Evolution trends of chromian spinel in the Nizhni Tagil, Fifield (FIF), Goodnews Bay and Papua New Guinea (PNG) Uralian–Alaskan-type complexes, as well as for ophiolitic chromitites, according to Johan (2002).

FIG. 4. Composition of Pt–Fe alloy from the Zolotaya River placer (at.%).
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Ir₀.₁₀Pd₀.₀₅ (Fe₀.₉₄Cu₀.₄₄Ni₀.₃₂) and ribbon-like osmium Os₀.₇₁Ir₀.₂₆Rh₀.₀₂Pt₀.₀₁ (Fig. 6c, sample ZL2), and (iii) Ir-rich Pt–Fe alloy (Pt₂.₅₇Ir₀.₁₂Rh₀.₁₀) (Fe₀.₉₄Cu₀.₄₄)₁₆ (Fig. 6d, sample ZL14). Only one homogeneous grain of iridium was found, with the composition of Ir₀.₅₇Os₀.₂₆Pt₀.₀₈Rh₀.₀₂. In addition to these mineral associations, there are intergrowths of Pt–Fe alloy with plates of osmium Os₀.₇₁Ir₀.₃₂Rh₀.₀₄Pt₀.₀₁, and submicrometric inclusions of native osmium Os₀.₉₆Pt₀.₀₄ in Pt–Fe alloy.

On the basis of these observations, the refractory PGM of the Zolotaya placer can be subdivided into three groups: (1) heterogeneous Os–Ir–Ru–Pt grains (most common) formed as a result of breakdown of the solid...
solution (Figs. 6a, c), (2) Pt–Fe alloy and Os–Ir alloy intergrowths, and (3) homogeneous grains.

**Cooperite, PtS, and cuprorhodsite, Cu(Rh,Ir)₂S₄**

Cooperite from the Zolotaya placer occurs in two different varieties. Primary cooperite intergrown with cuprorhodsite and chalcopyrite forms roundish multiphase inclusions in Pt–Fe alloy (Fig. 7). The inclusions are not more than 10–20 µm across. Cuprorhodsite from the multiphase inclusions contains up to 30.8 wt.% Pt, whereas the Ir content does not exceed 0.81% (Table 4). Chalcopyrite contains up to 5.12 wt.% Pt and 1.13% Pd. Secondary cooperite forms a rim around Pt–Fe grains (Fig. 8). The distinctive feature of primary cooperite is its palladium content, up to 1.98 wt.%, whereas secondary cooperite commonly has a Pd content below the detection limit and only rarely attains 0.66 wt.% (Table 4).

The width of the secondary rim of cooperite reaches 50 µm. One of the Pt–Fe grains studied is surrounded by a complex rim, which consists of cooperite intergrown with a Pb–Ir–Cu–Rh sulfide (Table 4, Fig. 8). The Pb content varies from 1.60 to 7.54 wt.%. The Pb-bearing phase could be either xingzhongite, (Ir,Pt)(Cu,Pb)S₄, or konderite, PbCu₃Rh₈S₁₆.

In another sample, patchily intergrown aggregates of cooperite with sperrylite form a several-µm-wide rim on Pt–Fe alloy. Cooperite contains up to 3.02 wt.% Ir, and both cooperite and sperrylite contain up to 1.30 wt.% Rh.

**The erlichmanite–laurite solid-solution series**

Members of the erlichmanite–laurite solid-solution series, OsS₂–RuS₂, occur both in the form of idiomorphic inclusions (up to 15 µm across) in Pt–Fe alloy and as an intergrowth with Os–Ir–Ru–Pt alloy (Fig. 9). Pure laurite has been found as an intergrowth with a zoned grain of ruthenicidomine. Erlichmanite, with up to 12.1 wt.% Ru (Table 6), occurs as an intergrowth with iridium. Idiomorphic inclusions of Os-bearing laurite of hexagonal habit (up to 20.2 wt.% Os) occur within Pt–Fe alloy. The euhedral laurite is evidence of its primary formation and subsequent entrapment by Pt–Fe alloy.

**The cheerepanovite–ruthenarsenite solid-solution series**

Minerals of the cheerepanovite–ruthenarsenite solid-solution series, RhAs–(Ru,Ni)As, form irregular inclusions (up to 20 µm; Table 4) mainly close or within the rim of heterogeneous grains with a lattice-like intergrowth of Ir-bearing Pt–Fe and Ir–Ru–Pt alloy (Fig. 6a). In some cases, cheerepanovite occurs as an intergrowth with iridosmene (Ir,Rh,Pt)As₂. In the rim zone, cheerepanovite has a high Ru content (up to 19.2 wt.%). This phase probably is an intermediate member of the cheerepanovite–ruthenarsenite solid-solution series. Ru-rich cheerepanovite forms a graphically intergrown aggregates with irarsite (Ir,Rh,Pt,Ru)As₅.
PGE arsenides and sulfarsenides

As-bearing PGM are relatively rare. They are commonly represented by sperrylite and occur as rim phases around grains of Pt–Fe alloy or fill cavities after leached magmatic Os–Ir lamellae in Pt–Fe alloy. There are also inclusions of irarsenite and irarsite in association with minerals of the cherepanovite–ruthenarsenite solid solution (Table 4).

DISCUSSION AND CONCLUSIONS

The Zolotaya River placer contains primary (magmatic) and secondary PGM (Table 7). The primary minerals are Pt–Fe alloy, Os–Ir–Ru alloy, cooperite (in multiphase inclusions), laurite, erlichmanite, cuprorhodsite, cherepanovite and iridarsenite. The secondary minerals are distinguished by their occurrence in reaction rims around grains of Pt–Fe alloy and are represented by cooperite, irarsite, platarsite and sperrylite.

Pt–Fe alloy is the main PGM in the Zolotaya River placer. The Fe content (including Ni and Cu) varies from 14 to 30 at.%, which is characteristic of native platinum and ferroan platinum alloy (Cabri & Feather 1975). Its average composition \( n = 21 \) is: 87.84 ± 3.25 wt.% Pt (73.35 ± 5.89 at.%), 6.88 ± 2.37 wt.% Fe (19.69 ± 5.72 at.%), 0.85 ± 0.73 wt.% Os, 0.09 ± 0.09 wt.% Ru, 1.58 ± 0.65 wt.% Rh, 0.47 ± 0.31 wt.% Pd, 0.67 ± 0.12 wt.% Ir, 0.13 wt.% ± 0.11 wt.% Ni, and 0.61 ± 0.21 wt.% Cu.

The main minor PGE present is rhodium. Pt–Fe alloy of similar composition is typical of Uralian–Alaskan-type deposits (Cabri et al. 1996).

Ir-bearing Pt–Fe alloy forms three different morphological types: (1) lattice-like intergrowths (exsolution fabric) with Ir–Os–Ru–Pt alloy (Fig. 6a), (2) irregular patchy inclusions in Ir–Os–Ru–Pt alloy (Fig. 6c), and (3) a grain matrix with subhedral inclusions of iridium (Fig. 6d).

Fig. 7. Cooperite inclusions in Pt–Fe alloy. Sample ZL–1/7.

Fig. 8. Secondary rim of cooperite (a) intergrown with Pb–Ir–Cu–Rh sulfide (xingzhongite or konderite) and of cooperite (b) on Pt–Fe alloy.
The triangular diagram (Pt + Fe) – (Os + Ru) – (Ir + Rh) of Slansky et al. (1991) allows an estimate of the temperature of formation and was applied to the Uralian–Alaskan-type intrusions at Fifield, Nizhni Tagil and Durance River (Slansky et al. 1991), Inagli (Tolstykh & Krivenko 1997), Salmon River (Tolstykh et al. 2002), and Kondyor and Guli (Malitch & Thalhammer 2002). The composition of multiphase assemblages from the Zolotaya River is plotted in relation to temperature of formation (Fig. 10). Grain ZL22 shows the highest temperature, >850°C. Sample ZL2 shows step-like exsolution, with an Ir content corresponding to 800°C. The formation of iridium and Ir-rich Pt–Fe alloy (3.72 wt.% Ir) took place at a temperature slightly below 750°C (sample ZL14). In sample ZL-1/6, native osmium formed first, followed by phases rich in Ir (at temperatures >850°C). The textural evidence of the multiphase associations of minerals and the interpretation of the compositional data with the help of the diagram of Slansky et al. (1991) point to high-temperature formation of the Ir–Os–Ru–Pt alloy, similar to that for the Inagli, Kondyor and the Alaskan intrusions.

Cooperite is the most common PGE sulfide mineral, and occurs both as a primary inclusion phase enriched in Pd, and as a secondary rim. The absence of nickel in cooperite from the Zolotaya River placer is typical of Uralian–Alaskan-type deposits.

Cuprorhodsite belongs to the group of PGE-bearing thiospinels, i.e., cuprorhodsite – cuproiridsite – malanite – ferrorhodsite solid solution. These minerals are most abundant in Uralian–Alaskan-type deposits (Cabri et al. 1981, Rudashevsky et al. 1985a, Nekrasov et al. 1994, Augé et al. 2002, Garuti et al. 2002), but they occur also in ophiolitic complexes (Corrivaux & Laflamme...
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1990, Augé & Maurizot 1995, Garuti et al. 1995), Alpine-type complexes (Garuti et al. 1995), and in layered mafic-ultramafic intrusions (Barkov et al. 1997, 2000). The cuprorhodsite–cuproiridsite series shows complete solid-solution, whereas pure malanite is not described in the literature. The cuprorhodsite from the Zolotaya placer is similar to occurrences in eastern Madagascar, Burma, Borneo, Ecuador, India (Baula), and Russia (Chukotka) (Fig. 11). In general, the Ir content of minerals of the cuprorhodsite–cuproiridsite solid-solution series from these occurrences is very low. Judging from the distribution of minerals at the different localities, there is no visible correlation between type of deposit and cuprorhodsite – cuproiridsite – malanite mineral composition. Rather, a compositional control is exerted by the saturation of the ore-forming system in a mineral phase containing Rh, Ir, and Pt.

Many investigators examining the PGM in Uralian–Alaskan-type deposits have given detailed descriptions of multiphase inclusions. In general, the inclusions consist of base-metal sulfides and (Pd,Pt,Rh) sulfides and tellurides. Pt–Pd mineral assemblages are characteristic of the PGM occurrences of the Durance River, France, and Pustaya River, Kamchatka, Russia (Johan et al. 1990, Tolstykh et al. 2000). Rh–Pd mineral assemblages are more common in the Santiago River, Ecuador (Weiser & Schmidt-Thomé 1993). Rh-bearing minerals are also most typical of multiphase inclusions from the Zolotaya River placer.

Such multiphase inclusions were described also in PGM from the ophiolitic complexes of northwestern Salair, Russia (Tolstykh et al. 1999), Troodos, Cyprus (McElduff & Stumpf 1991), and Kraubath, Austria (Malitch et al. 2001), as well as in the Alpine-type complex of Ronda, southern Spain (Torres-Ruiz et al. 1996). The most typical paragenesis of these complexes consists of laurite + (Pt,Ir,Rh,Ni,Fe,Cu)-bearing sulfides and base-metal sulfides (including millerite, NiS). The study of multiphase inclusions leads to the assumption that complex solid-solutions of Pt, Fe, Ir, Rh, Pd, Cu, Ni, Au and S exist at high temperature (Johan et al. 1990). Tolstykh et al. (2000) suggested that these inclusions form from vapor-saturated residual melt in a closed-system situation in gas-rich miroles.

Minerals of the erlichmanite–laurite solid-solution series vary from pure laurite (in association with ruthenarsenite), through Os-bearing laurite (in association with Pt–Fe alloy) to erlichmanite (in association with iridium). Rhodium is present up to 2.07 wt.%, which is one distinguishing feature of Uralian-Alaskan-type deposits (Johan et al. 1989).

Cherepanovite is a rare mineral. It was first described in the deposits of the Koryaksko–Kamchatkskiy Ultrabasic Belt (Rudashevsky et al. 1985b). Cherepanovite has also been found in New Zealand (Raitt & Watters 1990), Tasmania, Australia (Botrill 1993), and the Polar and Southern Urals of Russia (Garuti et al. 1999, Britvin et al. 1999). Cherepanovite occurs in two varieties in the Zolotaya River samples: (1) relatively poor in Ru in core zones, and (2) richer in Ru in rim zones. The high Ru content of cherepanovite leads to the inference that there is a wide range of solid solution between cherepanovite and ruthenarsenite at high temperature.

All mineralogical and chemical observations point to a connection of the Zolotaya and Fadeevka River placers to the Late Permian dunite–hornblende–gabbro intrusions of Uralian–Alaskan-type. The composition of the chromite from heavy-mineral concentrates and from inclusions within PGM from the Zolotaya placer is typical of Uralian–Alaskan-type intrusions, i.e., high chromium and iron content at relatively low titanium content. The primary PGM are dominated by Pt–Fe alloy (about 90%), and Os–Ir–Ru alloy is subordinate. All other PGM occur as rim or inclusion phases in the primary PGE alloys. Cooperite is impoverished in Ni. Rhodium and Cu are invariably present as minor elements of the Pt–Fe alloy, and the minerals of the laurite–erlichmanite solid-solution series have an elevated Rh content. Other Rh-bearing minerals present are cuprorhodsite and cherepanovite. The distinct rhodium-enrichment signature is one of the main features of Uralian–Alaskan type deposits.

### TABLE 6. SELECTED COMPOSITIONS OF LAURITE, ZOLOTAYA RIVER PLACER

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<td>0.04</td>
</tr>
<tr>
<td>Total</td>
<td>101.86</td>
<td>100.05</td>
<td>98.17</td>
<td>Total</td>
<td>3.00</td>
<td>3.00</td>
</tr>
</tbody>
</table>

**Note:** 1: intergrown with zonal ruthenarsenide; 2: inclusion inside Pt–Fe grain; 3: intergrown with grain of iridium. Pt, Bi, Pd, Sn, Sb, Te, Ir, Ni, Fe, Cu were not detected - below detection limit. The raw data are recalculated to metal-formula units (app).
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