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PLATINUM-GROUP MINERALS IN LODE AND PLACER DEPOSITS ASSOCIATED WITH THE URAL-ALASKAN-TYPE GAL'MOENAN COMPLEX, KORYAK–KAMCHATKA PLATINUM BELT, RUSSIA

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Abstract

Mineralization in the platinum-group elements occurs in lodes in the dunite – clinopyroxenite – gabbro Gal'moenan complex, in the Koryak–Kamchatka Platinum Belt of Russia, and in associated placers, namely those along the Levtyrinyvayam River and Ledyanoy and Penistiy creeks at different distances from the source. The grains of Pt–Fe alloy in lode deposits are isoferroplatinum and have Pt_3Fe compositions, whereas those in the Levtyrinyvayam River placer range in composition from native to ferroan platinum and having iron contents generally higher than in the lodes (30–35 at.% Fe). Platinum grains from the Ledyanoy Creek placer are larger and more commonly intergrown with chromite than those from the Levtyrinyvayam River. Minor elements, which are indicators of conditions of formation of the Pt–Fe alloy, exhibit different concentrations in lodes and in the nearby placers. Platinum–iron alloy from the Levtyrinyvayam placer, the farthest from the source, represents the eroded upper apical part of the intrusion, and contains mainly Pd. The Penistiy placer receives platinum from dunite and pyroxenite of a marginal facies of the complex, and thus platinum–iron alloy bearing Rh–Ir and Pd–Rh. Placer isoferroplatinum deposited in the Ledyanoy Creek, which drains dunite and chromite-bearing rocks in the south of the intrusion, is rich in Ir (up to 6.98 wt.%), as is the Pt–Fe alloy in the Gal'moenan complex (4.34 wt.% Ir). Most grains contain also a relatively high Rh content. Isoferroplatinum + iridium and isoferroplatinum + osmium are two main primary magmatic parageneses revealed in both placers and lodes, though the first is more commonly found in lodes and in the Ledyanoy Creek placer, and the latter in the Levtyrinyvayam River placer. Lodes mostly contain laurite, RuS_2, and the Levtyrinyvayam placer bears all varieties of $(Ru,Os)S_2$, including Ru-free Rh-rich erlichmanite $(Os,Rh)S_2$. The irarsite – hollingworthite series predominates in lodes, and the irarsite – platarsite and osarsite – platarsite series predominate in the Levtyrinyvayam placer. Sperrylite in lodes may contain up to 6.94 wt.% Sb, and thus differs from that in placers. The phase $(Pt_{0.96}Fe_{0.02})_{\Sigma 0.98}(As_{1.17}Sb_{0.75}S_{0.09})_{\Sigma 2}$, a member of the sperrylite – geversite solid solution, has been found in a lode. Complete solid-solution between RuS_2 and RuAsS on one hand, and PtAsS and $PtAs_2$ on the other, is demonstrated. In the Gal'moenan complex, concentrations of Ir decrease, and those of Pd and Os increase, toward the upper or apical parts of the complex.

Keywords: lode and placer deposits, platinum-group minerals, Gal'moenan massif, Koryak–Kamchatka Platinum Belt, Russia.

Sommaire

La minéralisation filonienne en éléments du groupe du platine du complexe de Gal'moenan (dunite – clinopyroxénite – gabbro), dans la ceinture platinifère de Koryak–Kamchatka, en Russie, a été disséminée dans les placers associés, en particulier ceux de la rivière Levtyrinyvayam et des ruisseaux Ledyanoy et Penistiy, à des distances variables de la source. Les grains de l'alliage Pt–Fe prélevés dans les roches sont de l'isoferroplatine, avec une composition Pt_3Fe, tandis que ceux des placers de la rivière Levtyrinyvayam varient en composition entre le platine natif et le platine ferreux, avec une teneur en fer supérieure (30–35 at.% Fe) à celle des grains provenant des gîtes filoniens. Les grains provenant du ruisseau Ledyanoy sont plus gros et plus aptes à montrer une intercroissance avec la chromite que ceux de la rivière Levtyrinyvayam. Les éléments mineurs, qui peuvent servir d'indicateurs des conditions de formation de l'alliage Pt–Fe, ont des concentrations différentes selon leur milieu de prélèvement.

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Les grains provenant des placers de la rivière Levtyrinyvayam, prélevés à plus grande distance de la source, représenteraient donc la partie supérieure érodée du massif, et sont palladifères. Les placers du ruisseau Penistiy reçoivent les grains de platine de la dunite et la pyroxénite de faciès du complexe près de la bordure, et donc un alliage contenant Rh–Ir et Pd–Rh. L'isoferroplatine des placers du ruisseau de Ledyanoy, contribué par la dunite et les roches à chromite dans la partie sud du massif, est riche en Ir (jusqu'à 6.98%, poids), tout comme l'alliage Pt–Fe prélevé des gîtes filoniens du complexe de Gal'moenan (4.34 wt.% Ir). La plupart de ces grains ont aussi une teneur relativement élevée en Rh. Isoferroplatine + iridium et isoferroplatine + osmium sont deux associations primaires recouvertes dans les placers et dans le complexe, quoique la première est plus commune dans les roches et les placers du ruisseau Ledyanoy, et la seconde, plus répandue dans les placers de la rivière Levtyrinyvayam. Les gîtes filoniens contiennent davantage de laurite, RuS_2, et dans les placers de la rivière Levtyrinyvayam, on peut trouver toutes les variétés de $(Ru,Os)S_2$, y compris l'erlichmanite $(Os,Rh)S_2$ dépourvue de Ru et enrichie en Rh. La série irarsite – hollingworthite prédomine dans les roches, tandis que les séries irarsite – platarsite et osarsite – platarsite prédominent dans les placers de la rivière Levtyrinyvayam. La sperrylite des roches peut contenir jusqu'à 6.94% Sb (poids), et diffère donc de celle des placers. Nous avons trouvé la phase $(Pt_{0.96}Fe_{0.02})_{\Sigma 0.98}(As_{1.17}Sb_{0.75}S_{0.09})_{\Sigma 2}$, membre de la solution solide sperrylite – geversite, dans le complexe. Nous démontrons une solution solide complète entre RuS_2 et RuAsS d'une part, et entre PtAsS et $PtAs_2$ de l'autre. Dans le complexe de Gal'moenan, les concentrations d'iridium diminuent, et celles de Pd et Os augmentent, en s'approchant des parties apicales.

(Traduit par la Rédaction)

Mots-clés: gîte filonien, placers, minéraux du groupe du platine, complexe de Gal'moenan, ceinture platinifère de Koryak–Kamchatka, Russie.

Introduction

The composition of Pt–Fe alloys and of solid-solution series of platinum-group minerals (PGM) records specific features of ore-forming systems in igneous complexes (Johan *et al.* 1990, 2000, Tolstykh *et al.* 2002). However, the conditions of mineralization in the platinum-group elements (PGE) and the evolution of ore-forming systems are usually inferred from minerals in spatially associated placers (Legendre & Augé 1992, Evstigneeva *et al.* 1992, Weiser & Schmidt-Thomé 1993, Tolstykh *et al.* 2000). Only in a few cases were both placer and lode samples available, as in the Tulameen complex (Nixon *et al.* 1990) and the Nizhny Tagil intrusion (Cabri & Genkin 1991). Pt–Fe alloys from placers and lodes were noted to have somewhat different compositions, but it remains unclear how much of this difference is caused by the zonal distribution of PGE mineralization in intrusions and by supergene alteration in placers.

The composition of alluvial platinum-group minerals also depends on the remoteness and erosion level of the source, as the most distant placers contain material from its uppermost part. More control comes from the proportion of intrusive units (dunites, chromitites, and pyroxenites) subjected to erosion and placer generation. In this study, we investigate the chemical and mineralogical zonation of the Gal'moenan complex, of Ural-Alaskan type, by comparison of Pt–Fe alloys, platinum-group sulfides and sulfarsenides in lodes and placers at variable distances from the source. The data presented here pertain to lode deposits in chromite veins and in dunites containing chromite schlieren in the southern part of the complex and also to some placers in adjacent rivers.

Geological Setting

The Gal'moenan complex belongs to the zone of Ural-Alaskan-type layered intrusions that make up the Koryak–Kamchatka Platinum Belt. The dunite – clinopyroxenite – gabbro complex includes currently worked economic PGM placers (Fig. 1) and numerous lode deposits (Zaitsev *et al.* 1998). Its structure, origin, and composition are discussed in several papers (*e.g.*, Batanova *et al.* 1991, Astrakhantsev *et al.* 1991, Kozlov & Sidorov 2000, Melkomukov & Zaitsev 1999, Batanova & Astrakhantsev 1994, Sidorov *et al.* 2001). Dunites occupy 70% of the area in the center, and clinopyroxenite, wehrlite and gabbro occur near the periphery. Chromian spinel forms layers, veinlets and schlieren up to 30 cm thick in dunite and also is associated with a Pt–Fe alloy. The complex as a whole is a tectonic nappe making the core of an inverted synform.

Streams draining the intrusion have formed placers of alluvial platinum around it. Economic placer deposits were discovered by Zaitsev *et al.* (1998). The placer along the Levtyrinyvayam River is the longest. It originates from the eastern part of the complex, where dunite coexists with wehrlite, clinopyroxenite, and gabbro. Placers of the Ledyanoy and Penistiy creeks, which drain the complex in the west and southwest, are mostly derived from the dunite core, *i.e.*, clinopyroxenite and wehrlite are less important source-rocks than in the Levtyrinyvayam placer. The first data on platinum-group minerals in the region were reported by Kutyev *et al.* (1991). A detailed description of Levtyrinyvayam River placer PGM was presented by Tolstykh *et al.* (2001).

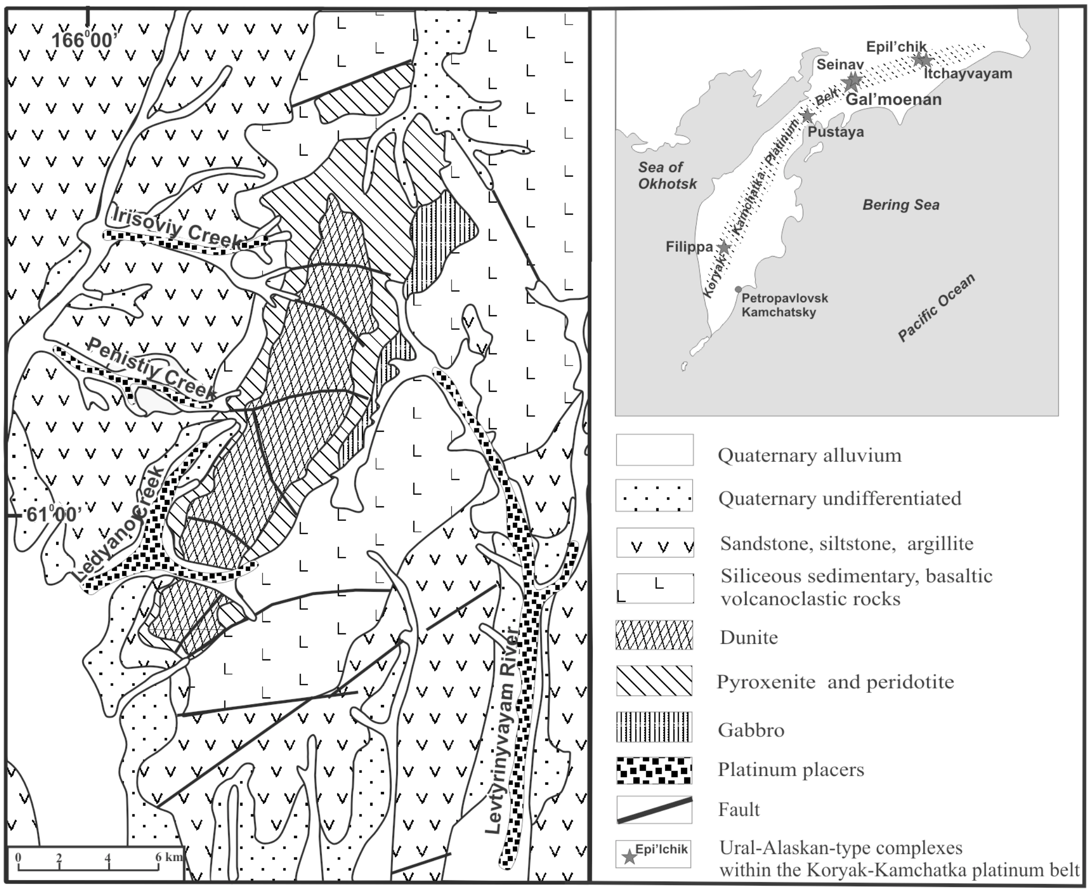

FIG. 1. Location map of Gal'moenan complex and surrounding placers. Modified from Batanova *et al.* (1991).

Analytical Methods

The composition of the PGM was determined with a Camebax–Micro electron microprobe, using the RMA–92 program (L.N. Pospelova and V.M. Chubarov, analysts). The acceleration voltage was 20 kV, the probe current 20–30 μA, and the counting time, 10 seconds for each analytical line. Standards used during analyses include: Pt, Ir, Os, Pd, Rh, and Ru metals, $CuFeS_2$ for Cu, Fe, S, FeNiCo for Ni, InAs for As, and $CuSbS_2$ for Sb. The following X-ray lines were used: $L\alpha$ for Pt, Ir, Pd, Rh, Ru, As, and Sb, $K\alpha$ for S, Fe, Cu, and Ni, and $M\alpha$ for Os. The interference of lines was corrected with the help of a file of experimentally calculated coefficients (Lavrent'ev & Usova 1994). The detection limits for the elements sought are (wt.%): Pt 0.17, Ir 0.15, Os 0.04, Pd 0.04, Rh 0.04, Ru 0.04, Fe 0.03, Cu 0.06, Ni 0.06, S 0.02, As 0.05, and Sb 0.06.

Mineralogy

Pt–Fe alloy

PGE mineralization in the Gal'moenan complex and associated placers occurs mostly as Pt–Fe alloy. Anhedral crystals of isoferroplatinum up to 1.5 cm across are interstitial to chromite (Figs. 2A–D) or form small euhedral grains (20–50 μm) in chromite and olivine (Figs. 2E, F). Lode deposits contain isoferroplatinum (Pt_3Fe) compositions (Fig. 3A), whereas the Levtyrinyvayam River placer contains small rounded grains of platinum, with few inclusions of chromite, ranging in composition from native platinum to ferroan platinum (Fig. 3B) and having iron contents generally higher than in lodes (30–35 at.% Fe). Ferroan platinum is restricted to fractures and margins of isoferroplatinum grains, which is evidence for later saturation in iron. Platinum grains from the Ledyanoy placer (Fig. 4A) are

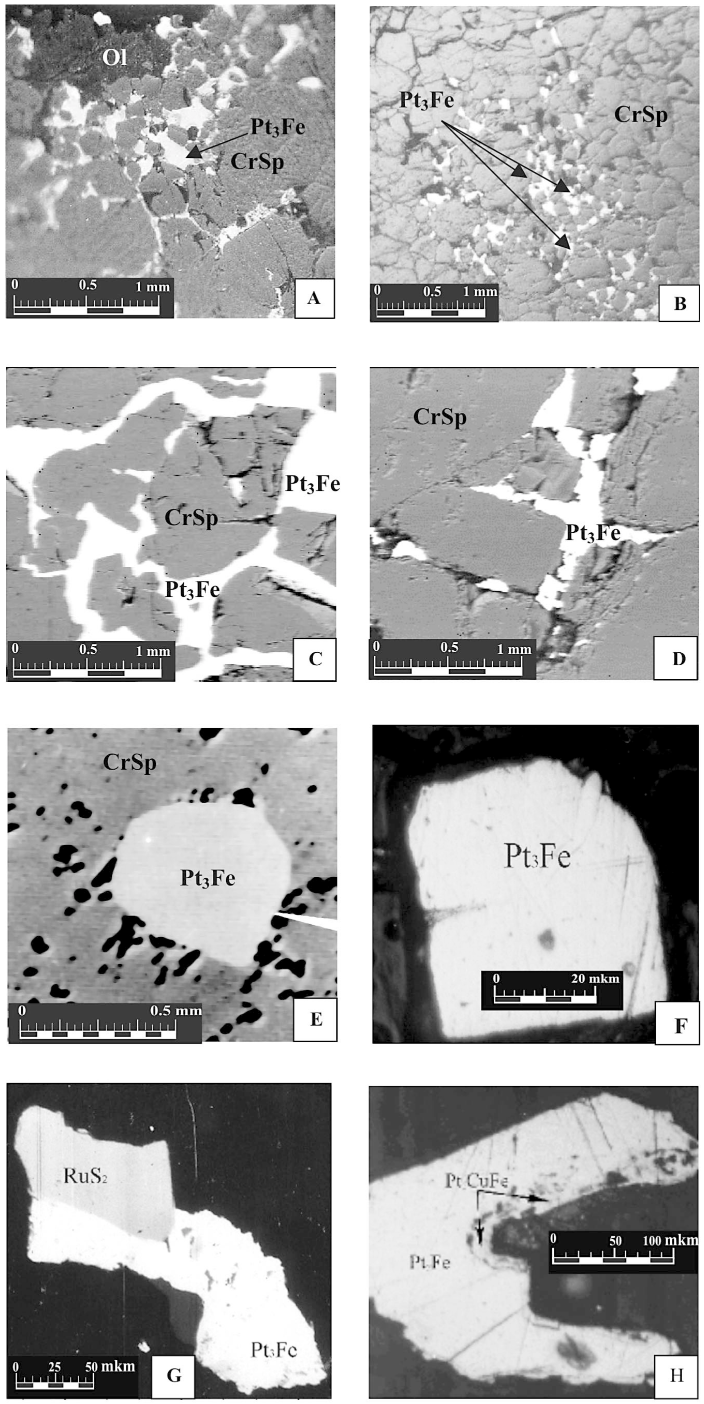

FIG. 2. Reflected-light photomicrographs from lode deposits of the Gal'moenan complex. A. Anhedral grains of Pt–Fe alloy in chromite developing at the borders of olivine. B. Impregnation of chromite by anhedral grains of platinum. C. A grain of isoferroplatinum in intergranular space among grains of chromite. D. Pt–Fe alloy in fractures of chromite grains. E, F. Euhedral grains of isoferroplatinum in chromite (E) and olivine matrix (F). G. Laurite crystal is intergrown with isoferroplatinum. H. The replacement of isoferroplatinum by an irregular rim of tulameenite.

larger than those from the Levtyrinyvayam Creek (Fig. 4B) and are generally intergrown with chromite (Fig. 4C) or olivine (Fig. 4D).

Grains of primary Pt–Fe alloy are altered to produce Pt–Fe–Cu varieties belonging to the tetraferroplatinum – tulameenite series, encountered both in lodes and in placers (Figs. 2H, 5A, C–F). Lode deposits show two trends of alteration of Pt–Fe alloy: in dunite, the grains are replaced by a member of the tetraferroplatinum – tulameenite series, and in chromitite, by tulameenite and a Cu-rich alloy whose composition plots along the Pt_3Fe – Cu_3Pt line (Fig. 3A). The replacement of a primary cubic Pt–Fe alloy by tetragonal Cu-rich tetraferroplatinum – tulameenite at the final stage of mineralization is known in a few Ural-Alaskan-type intrusions, namely Tulameen (Nixon *et al.* 1990), Yubdo (Evstigneeva *et al.* 1992), Goodnews Bay (Tolstykh *et al.* 2002), Gusevogorsky (Cabri & Genkin 1991), and the Utkus and Kytlim complexes (Garuti *et al.* 2002).

Minor elements, which are indicators of conditions of formation of the Pt–Fe alloy, exhibit different concentrations in lodes and in the surrounding placers. Most (70%) of the analyses of lode Pt–Fe alloy from the Gal'moenan complex show up to 4.34 wt.% Ir (Table 1), with enhanced compositions of Os, Rh in a few grains, whereas Pd is virtually absent (Fig. 6A). Placer isoferroplatinum deposited in Ledyanoy Creek, which drains dunite and chromite in the south of the intrusion, has a constant composition, and Ir is likewise the predominant minor element (up to 6.98 wt.%.). Most grains contain between 1 and 4 at.% Ir and a relatively visible Rh content (Fig. 6B). The Penistiy alluvium receives platinum from dunite and pyroxenite. It contains Rh-bearing and Ir-rich Pt–Fe alloys (Fig. 6C). For the most part, the platinum–iron alloy in the Levtyrinyvayam placer contains Pd and Rh only, without Ir; a Ir-rich Pt–Fe alloy (up to 11.59 wt.%, Table 1) is encountered infrequently, however (Fig. 6D).

The levels of minor elements in grains of Pt–Fe alloy reflect geochemical features of the ore-forming system at the source. They indicate a strong fractionation of PGE in the ore-forming system (Johan *et al.* 2000) and a difference in temperature of ore deposition, which decreases in the direction (Ir + Rh)-rich to Pd-rich PGE alloy (Slansky *et al.* 1991). Minor-element concentrations and their relationships in the grains of Pt–Fe alloy vary from one occurrence to another. Grains of Pt–Fe alloy in various Ural-Alaskan-type intrusions are either Ir-rich (Goodnews Bay and Inagli placers), or Ir–Rh-rich (Fifield, Yubdo placers), or Pd-rich (Pustaya River placer) as a function of thermal conditions of mineralization (Tolstykh *et al.* 2002). Iridium-rich platinum is a high-temperature alloy that formed together with Pt-rich iridium at near-critical temperatures (~850°C) on the solvus. If the temperature decreases from (Ir + Rh)-rich to Pd-rich nuggets, we can conclude that the lode-derived Pt–Fe alloy of the Gal'moenan complex and the alloy from the Ledyanoy placer crystallized at higher temperatures than was typical of material in the Penistiy and Levtyrinyvayam placers.

Os–Ir alloy

Grains of Os–Ir alloy, typically included in Pt–Fe alloy, occur mostly as native osmium in the Levtyrinyvayam and Penistiy placers (Figs. 5A, B, D)

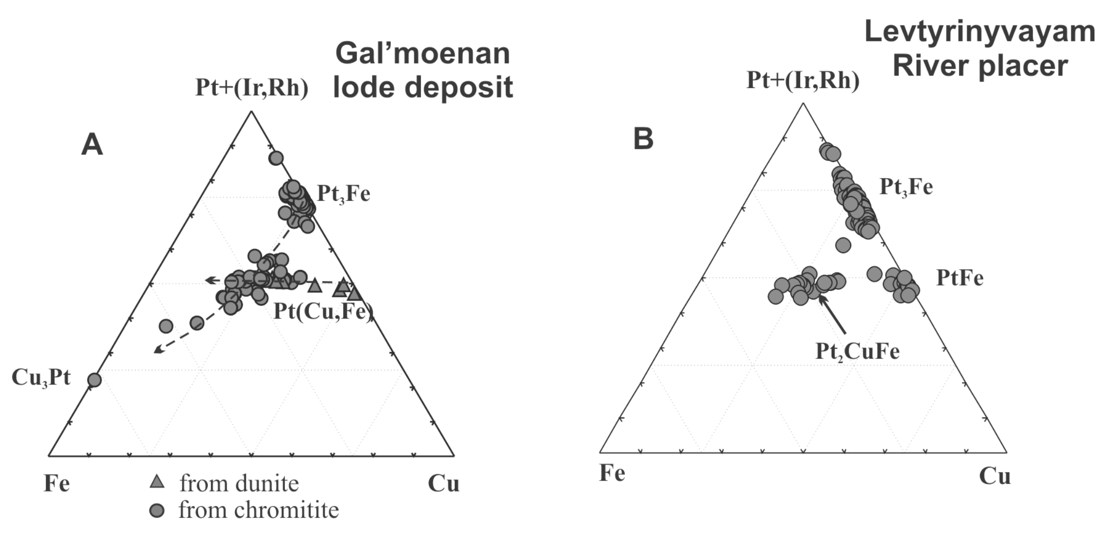

FIG. 3. Composition of Pt–Fe alloy (at.%) in lode deposit of the Gal'moenan complex (A) and in the Levtyrinyvayam River placer (B).

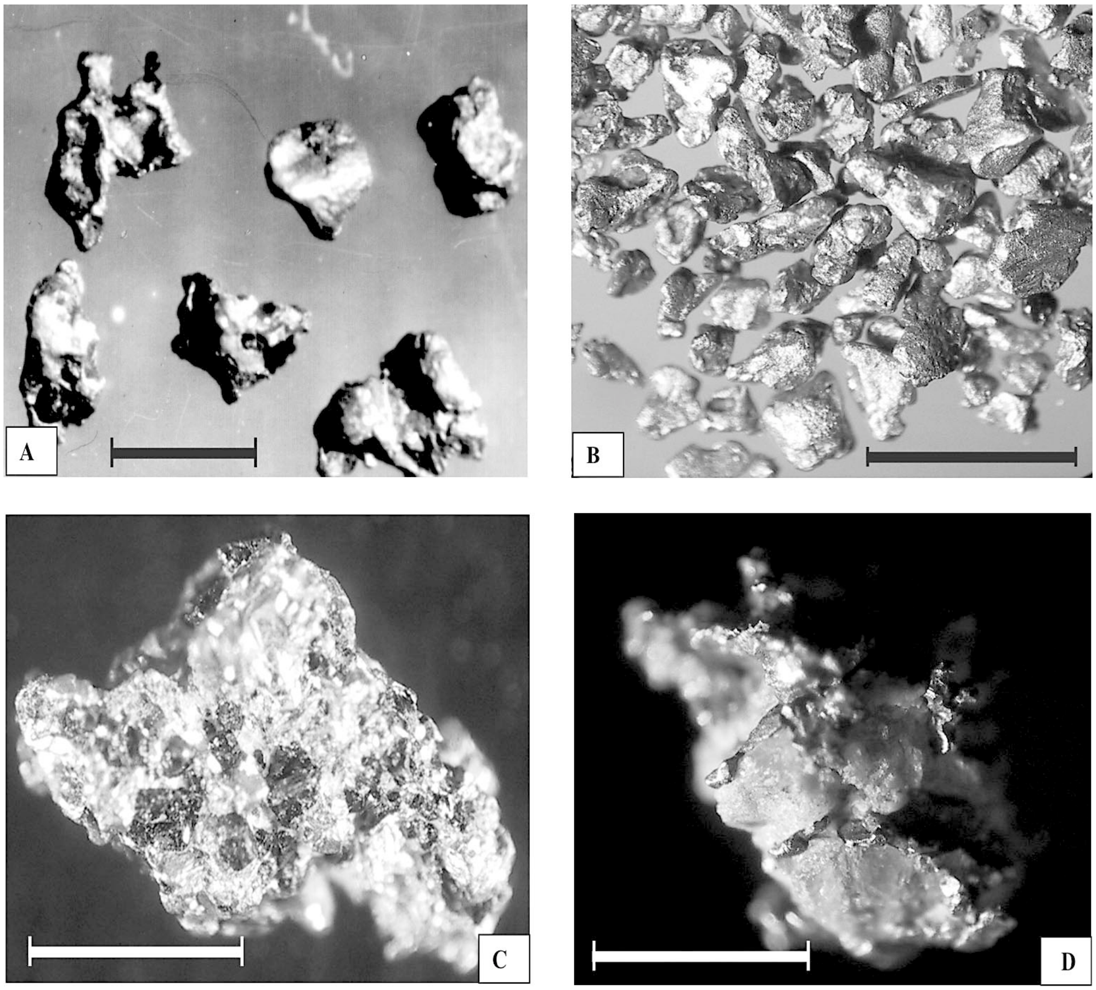

FIG. 4. SEM photomicrographs grains of Pt–Fe alloy. A. Angular grains from Ledyanoy Creek. B. Rounded grains from undercurrent Levtyrinyvayam River. C, D. Grains of isoferroplatinum intergrown with chromite (C) and olivine (D). Scale bars are 0.5 mm.

and as native iridium in Pt–Fe alloy in lodes and in the Ledyanoy placer. There is a lack of Ru in the Os–Ir alloy (Table 2). High contents of Pt in the Ir–Os alloy indicates a broad range in temperature of their exsolution from isoferroplatinum (from 750 to 850°C. Isoferroplatinum – iridium and isoferroplatinum – osmium are two main primary magmatic parageneses revealed in both placers and lodes (Fig. 7), though the former is more generally found in lodes and in the Ledyanoy placer, and the latter in the Levtyrinyvayam placer.

Ru and Os sulfides

Ruthenium and osmium sulfides vary in composition from laurite (RuS_2) to erlichmanite (OsS_2). The lodes mostly contain laurite (Fig. 2G), and the Levtyrinyvayam placer bears all varieties, but erlichmanite is dominant (Figs. 5C, D, F), including Ru-free Rh-rich erlichmanite (Fig. 8, Table 3). The latter has a different morphology than the Ru-rich variety (Ru,Os) S_2, which may be of magmatic origin, and belongs to a later generation of sulfides formed after the crystals of

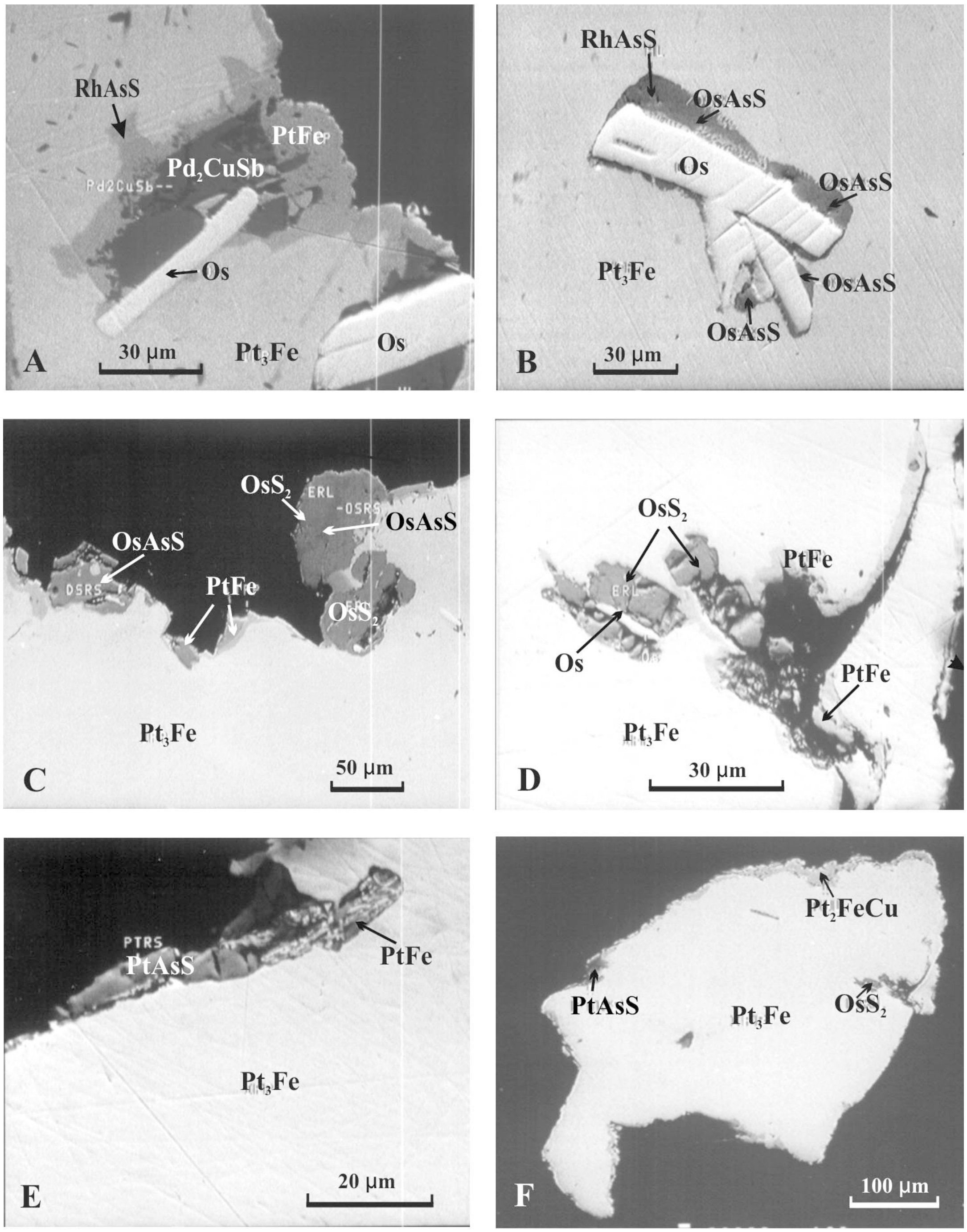

FIG. 5. Back-scattered electron images of PGE minerals from the placer deposit of the Levtyrinyvayam River. A. Osmium crystals with hollingworthite, which is rimmed by tulameenite in a grain of isoferroplatinum. B. Osarsite and hollingworthite occurring at the margin of osmium crystals in a grain of isoferroplatinum. C. Osarsite and erlichmanite associated with tetraferroplatinum occuring at the margin of a grain of isoferroplatinum. D. Osmium is intergrown with a erlichmanite in isoferroplatinum. Tetraferroplatinum rims the host isoferroplatinum. E. Platarsite with tetraferroplatinum replaces isoferroplatinum along the periphery. F. Isoferroplatinum grain with erlichmanite inclusion rimmed by tulameenite.

osmium. The abundance of euhedral inclusions of laurite – erlichmanite in the Pt–Fe matrix may explain the low concentration of Ru in the Pt–Fe alloy, which is extracted at early stages of the ore-forming system at conditions of high activity of sulfur. According to diagram log S_2 activity *versus* temperature (Ohnenstetter *et al.* 1991), magmatic PGE mineralization in the Gal'moenan complex was formed at a fugacity of sulfur $f(S_2)$ greater than –4.

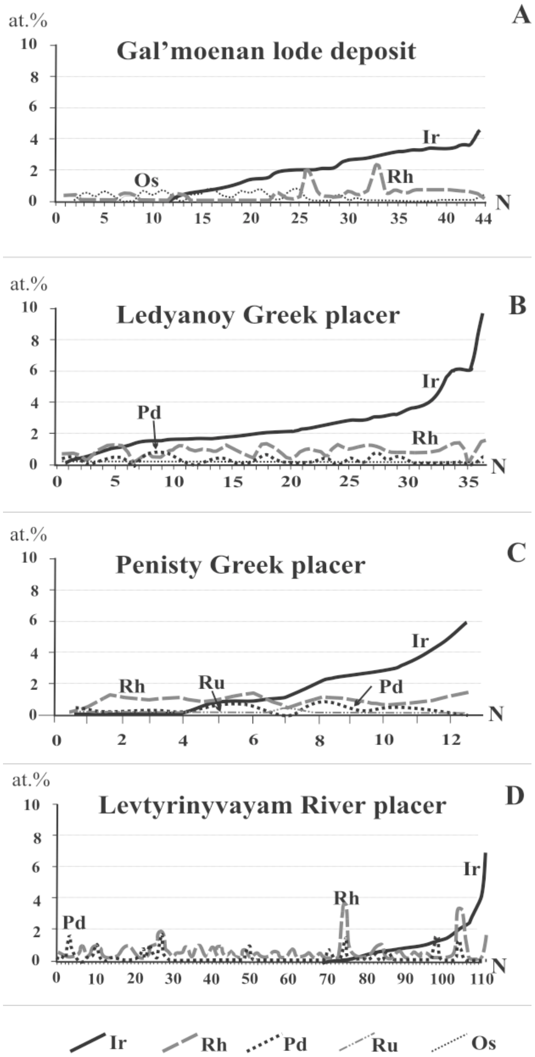

FIG. 6. Contents of trace elements in Pt–Fe alloy from lode deposits of the Gal'moenan complex, Ledyanoy, Penistiy Creek placers, and Levtyrinyvayam River placer. N: total number of analyzed grains. Compositions are ordered according to increasing concentration of Ir in the Pt–Fe alloy.

PGE sulfarsenides

Platinum-group sulfarsenides, also found among the PGM associations, are represented by all varieties except for ruarsite; as the most chalcophile of the PGE, Ru becomes bound with S at early stages of mineralization. Members of the irarsite – hollingworthite series in lodes and irarsite – platarsite and osarsite – platarsite series in placers (Table 3, Fig. 9) are most commonly encountered. Platinum-group sulfarsenides constitute either subhedral (IrAsS) or anhedral (OsAsS, RhAsS) crystals (Figs. 5A, B, C, E), attributed to contacts with other phases.

TABLE 1. SELECTED COMPOSITION OF GRAINS OF Pt–Fe–Cu ALLOY, GAL'MOENAN COMPLEX, RUSSIA

	Pt	Ir	Rh	Pd	Ru	Os	Fe	Cu	Ni	Total
Lode deposits of the Gal'moenan massif										
1	90.98	0.00	0.00	0.00	0.00	0.81	8.59	0.00	0.00	100.38
2	89.76	0.00	0.00	0.00	0.00	0.63	10.23	0.00	0.00	100.62
3	90.36	0.31	0.10	0.00	0.00	0.00	9.01	0.38	0.22	100.38
4	88.81	2.35	0.00	0.00	0.00	0.84	8.22	0.00	0.00	100.22
5	87.50	3.12	0.21	0.00	0.00	0.06	8.47	0.18	0.06	99.60
6	87.57	3.23	0.23	0.00	0.00	0.00	8.53	0.20	0.06	99.82
7	86.61	4.00	0.38	0.00	0.00	0.00	8.58	0.21	0.08	99.86
8	87.25	4.34	0.34	0.00	0.00	0.00	8.36	0.14	0.00	100.43
9	76.40	0.00	0.00	0.00	0.00	0.00	22.83	0.56	1.22	101.01
10	75.51	0.35	0.13	0.00	0.00	0.00	11.65	8.28	2.48	98.40
11	76.07	0.00	0.16	0.00	0.00	0.00	8.98	10.52	2.78	98.51
12	73.29	0.00	0.13	0.00	0.00	0.00	11.70	12.67	0.99	98.78
13	70.72	0.00	0.00	0.00	0.00	0.00	11.14	16.76	0.00	98.62
14	63.20	0.00	0.10	0.00	0.00	0.00	4.68	28.62	0.25	96.85
15	44.97	0.00	0.00	0.93	0.00	0.00	0.20	47.43	0.00	*97.35
Placer deposit of the Levtyrinyvayam River										
16	92.37	0.26	0.23	0.00	0.00	0.00	3.91	0.31	0.00	97.08
17	93.28	0.00	0.19	0.00	0.00	0.00	4.16	0.29	0.00	97.92
18	88.92	2.40	0.68	0.22	0.00	0.12	6.50	0.51	0.00	99.35
19	91.10	0.00	0.00	1.02	0.00	0.00	6.85	0.45	0.00	99.42
20	77.89	11.59	1.09	0.37	0.68	1.97	7.42	0.20	0.06	101.27
21	85.84	0.00	0.90	0.53	0.00	0.00	9.26	0.70	0.08	97.31
22	86.13	0.00	0.62	0.55	0.07	0.00	9.50	0.67	0.07	97.61
23	89.16	0.36	1.03	1.16	0.00	0.00	9.67	0.00	0.00	101.38
24	84.33	0.35	1.02	0.39	0.07	0.00	10.41	0.87	0.10	97.54
25	84.09	0.31	2.21	1.08	0.00	0.00	11.35	0.30	0.00	99.34
26	83.71	0.00	0.00	0.47	0.00	0.00	13.10	1.01	0.00	98.29
27	73.39	2.87	0.00	0.00	0.00	0.00	22.67	0.48	0.00	99.41
28	75.19	0.00	0.00	0.00	0.00	0.00	13.79	1.54	10.63	101.15
29	77.12	0.00	0.00	0.00	0.00	0.00	21.81	2.30	0.00	101.23
30	79.72	0.00	0.00	0.00	0.00	0.00	18.75	3.06	0.44	101.97
31	73.13	1.83	0.00	0.18	0.00	0.12	10.10	11.07	0.60	97.03
32	75.65	0.00	0.00	0.00	0.00	0.00	9.40	16.22	0.00	101.27
Placer deposit of Ledyanoy Creek										
33	87.86	4.99	0.57	0.06	0.08	0.24	6.23	0.32	0.07	100.42
34	87.75	3.92	0.58	0.39	0.09	0.23	7.49	0.37	0.07	100.89
35	82.19	6.98	0.36	0.00	0.13	0.33	7.65	0.10	0.07	97.81
36	85.99	1.97	0.69	0.25	0.07	0.00	8.00	0.34	0.00	97.31
37	90.52	0.23	0.47	0.26	0.00	0.00	8.30	0.32	0.00	100.10
38	85.50	1.75	0.10	0.00	0.00	0.08	10.51	1.48	0.35	99.77
39	77.24	0.00	0.08	0.00	0.00	0.00	10.80	11.24	1.06	100.42
40	75.08	0.00	0.00	0.00	0.00	0.00	9.07	15.85	0.17	100.17
Placer deposit of Penistiy Creek										
41	77.80	13.45	0.91	0.22	0.31	0.86	6.53	0.22	0.07	100.37
42	84.09	5.03	0.61	0.17	0.00	0.06	8.83	0.49	0.00	99.28
43	88.48	0.25	0.72	0.12	0.10	0.00	9.34	0.51	0.14	99.66
44	81.90	7.25	0.97	0.00	0.10	0.00	9.40	0.35	0.11	100.08
45	87.23	1.09	0.99	0.39	0.07	0.07	9.59	0.33	0.14	99.90
46	86.11	0.00	0.07	0.37	0.05	0.05	10.92	0.54	0.65	98.76
47	77.30	0.79	0.00	0.00	0.00	0.09	13.71	4.83	1.40	98.12
48	74.30	1.59	0.06	0.10	0.09	0.07	10.23	12.07	0.16	98.67

Compositions are expressed in wt.%. * Total includes 3.82 wt.% Sb.

Sperrylite

Sperrylite, one of the main minerals, crystallized at the final stage of PGE mineralization. It replaces Pt–Fe alloy at the grain margin, and commonly exists in epitaxic ingrowths with tulameenite or as an outer rim bordering an inner rim of tulameenite in isoferroplatinum. Rhodium is the most widespread minor element in placer sperrylite (up to 2.14 wt.%); arsenic is partially replaced by sulfur (S to 1.27 wt.%) and rarely by antimony (Sb to 5.63 wt.%). Lode sperrylite and placer sperrylite differ in their Sb content (0.22–6.94 wt.% Sb, Table 3). A phase $(Pt_{0.96}Fe_{0.02})_{\Sigma 0.98}(As_{1.17}Sb_{0.75}S_{0.09})_{\Sigma 2.01}$ belongs to a sperrylite – geversite solid-solution series in which $PtSb_2$ attains 37 mol.%. Antimony-rich sperrylite is known in mafic-ultramafic intrusions in northern Vietnam (Polyakov *et al.* 1999) and in pyroxenite at Fifield in Australia (Johan *et al.* 1989). According to experimental data on the system Pt–As–Sb (Furuseth *et al.* 1967), the extent of Sb-for-As substitution increases with temperature. The PtAsSb phase can exist at 1200°C, though Johan *et al.* (1989) described sperrylite – geversite solid solutions that fall into the miscibility gap at this temperature, but are nev-

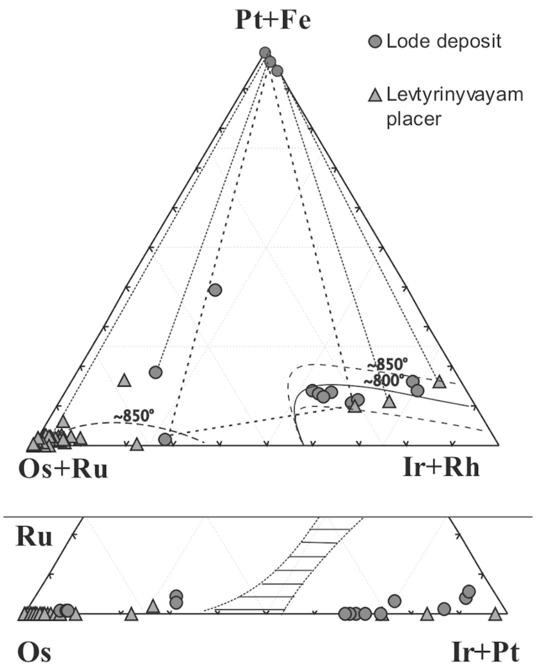

FIG. 7. Composition of Os–Ir alloy (at.%) and two-phase isoferroplatinum–osmium and isoferroplatinum–iridium parageneses in lode deposit of the Gal'moenan complex and placers.

TABLE 2. SELECTED COMPOSITION OF GRAINS OF Os–Ir–Pt ALLOY, GAL'MOENAN COMPLEX, RUSSIA

	Pt	Ir	Os	Rh	Ru	Cu	Fe	Total
			Lode deposits, Gal'moenan massif					
1	11.57	17.88	66.79	0.38	1.48	1.61	1.10	100.81
2	1.40	26.76	68.44	1.12	2.51	0.08	0.03	100.34
3	12.66	53.38	33.29	0.01	0.00	0.00	0.47	99.81
4	10.13	62.02	25.82	0.39	0.00	0.00	0.18	98.54
5	11.16	74.40	6.68	2.54	2.17	0.34	0.77	98.06
			Placer deposit, Levtyrinyvayam River					
6	1.34	0.00	97.76	0.00	0.00	0.00	0.00	99.10
7	0.56	0.00	99.54	0.00	0.00	0.00	0.00	100.10
8	1.64	0.89	95.79	0.00	0.00	0.00	0.00	98.32
9	0.98	1.44	98.45	0.00	0.00	0.00	0.00	100.87
10	2.01	1.76	96.83	0.34	0.43	0.00	0.06	101.43
11	1.74	2.57	96.55	0.00	0.00	0.00	0.00	100.86
12	5.14	3.05	89.87	0.28	0.50	0.00	0.30	99.14
13	2.28	4.11	91.99	0.33	0.52	0.00	0.07	99.29
14	1.42	6.01	90.47	0.00	0.00	0.00	0.00	97.90
15	1.38	9.08	88.47	0.00	0.00	0.07	0.16	99.16
16	14.84	11.34	74.95	0.40	1.09	0.16	0.77	103.55
17	0.00	21.83	76.70	0.00	0.00	0.19	0.00	98.72
18	9.98	63.41	25.63	0.20	0.00	0.06	0.00	99.28
19	11.17	69.98	16.04	0.28	0.80	0.00	0.00	98.27
20	10.54	79.80	2.44	2.92	1.37	0.53	1.57	99.17
			Placer deposit, Ledyanoy Creek					
21	2.45	1.73	93.90	0.43	0.56	0.00	0.00	99.07
22	1.25	6.75	90.78	0.37	0.35	0.07	0.00	99.57
23	33.43	23.33	36.59	0.51	0.83	0.00	3.33	98.02
24	12.04	41.59	45.77	1.13	0.51	0.00	0.88	101.92
25	24.16	53.29	20.83	2.30	0.51	0.00	1.54	102.63
26	12.42	59.61	24.14	1.80	2.55	0.00	0.37	100.89
27	11.72	59.77	23.36	1.72	2.46	0.00	0.39	99.42
			Placer deposit, Penistiy Creek					
28	2.61	1.77	94.92	0.27	0.21	0.00	0.00	99.78
29	1.79	2.08	93.48	0.29	0.41	0.00	0.00	98.05
30	2.04	8.20	87.26	0.54	0.22	0.00	0.00	98.26
31	1.51	12.01	83.45	0.60	1.81	0.00	0.00	99.38

Compositions are expressed in wt.%.

TABLE 3. COMPOSITIONS OF SULFIDES, ARSENIDES AND SULFOARSENIDES OF PGE, GAL'MOENAN COMPLEX, RUSSIA

	Pt	Os	Ir	Rh	Ru	Fe	Cu	S	As	Sb	Total
					Sb-bearing sperrylite						
1	56.59	0.12	0.00	0.00	0.00	0.75	0.31	0.18	39.28	1.17	98.40
2	56.03	0.06	0.00	0.00	0.00	1.93	1.36	0.86	38.75	2.90	101.89
3	53.52	0.00	0.00	0.12	0.00	0.10	0.00	1.13	39.10	6.94	100.91
4	53.93	0.00	0.00	0.22	0.00	0.16	0.20	1.57	39.11	8.38	103.57
5	49.31	0.00	0.00	0.00	0.00	0.30	0.00	0.72	23.37	23.87	97.57
					Rh-bearing erlichmanite						
6	0.00	67.63	1.23	3.46	0.00	0.00	0.00	26.13	0.00	0.00	98.45
7	1.40	65.10	0.00	4.20	2.50	0.36	0.00	26.70	0.00	0.00	100.26
8	4.86	57.02	2.47	4.40	0.00	0.00	0.00	25.03	7.42	0.00	101.20
9	4.00	64.50	0.00	4.80	0.00	0.00	0.00	25.10	0.60	0.00	99.00
10	1.27	63.76	1.74	5.19	0.00	0.26	0.08	28.89	0.00	0.00	101.19
11	0.29	47.21	1.23	10.34	9.52	0.11	0.06	29.12	2.51	0.00	100.39
12	1.15	48.57	5.36	12.15	0.00	0.43	0.09	25.18	5.86	0.00	98.79
					OsAsS–OsS_2 solid solution						
13	24.00	26.20	0.60	10.20	0.00	0.00	0.00	11.40	27.50	0.00	99.90
14	27.68	27.29	1.46	3.61	0.00	0.00	0.00	12.25	24.75	0.00	97.04
15	25.76	25.56	1.22	7.74	0.00	0.00	0.06	13.25	25.02	0.00	98.61
16	23.00	36.10	2.40	3.90	0.00	0.00	0.00	14.00	20.70	0.00	100.10
17	15.10	39.40	2.00	9.20	0.00	0.42	0.00	16.30	18.00	0.00	100.42
18	11.40	43.90	2.50	8.30	0.00	0.34	0.00	17.60	15.50	0.00	99.54
19	7.80	55.50	2.40	4.70	0.00	0.00	0.00	20.00	11.00	0.00	101.40
20	7.80	58.50	2.70	2.40	0.00	0.25	0.00	20.40	7.90	0.00	99.95
21	2.90	43.20	0.70	18.50	0.00	0.00	0.00	20.60	13.50	0.00	99.40

Compositions are expressed in wt.%. Grains 1–5: lode deposit of the Gal'moenan complex; grains 6–21: Levtyrinyvayam River placer.

ertheless later, lower-temperature phases crystallized at the stage of the postmagmatic process. Johan *et al.* mentioned a continuous solid-solution series, $PtAs_2$–$PtSb_2$, that originates at a late stage of mineralization in association with cobalt pentlandite at 670–710°C. A sperrylite sample from the Gal'moenan complex has a composition similar to the one reported by Johan *et al.* (1989). The morphology of sperrylite in the lodes of the complex also indicates its postmagmatic origin.

The solid solutions OsS_2–OsAsS and PtAsS–$PtAs_2$

As a result of S-for-As substitution, erlichmanite, sulfarsenides, and sperrylite from the lodes of the Gal'moenan intrusion and the surrounding placers define a continuous solid-solution series from OsS_2 to OsAsS in the system S–PGE–As (Table 3). This series is extended by platarsite (PtAsS), whose composition shifts toward sperrylite ($PtAs_2$). Sperrylite, in turn, contains S, but natural platarsite and sperrylite phases show only partial solid-solution (Fig. 10). These solid solutions between natural sulfides and sulfarsenides on the one hand, and sulfarsenides and arsenides on the other, were earlier reported as intermediate RuS_2–IrAsS compositions in placers in the northwestern Salair Ridge in Russia (Tolstykh *et al.* 1999) and a $PtAs_2$–RhAsS solid solution in Mongolia (Izokh & Mayorova 1990).

Conclusions

Our study shows that the minor-element composition of the grains of Pt–Fe alloy, the nature of the PGM parageneses, and the mineral chemistry of sulfide and sulfarsenide solid-solutions are controlled by the composition of the source rocks and by the specific features of ore-forming systems.

The vertical zoning of the Gal'moenan complex, in the Koryak–Kamchatka region, was inferred on the basis of PGM geochemistry from compositions of alloys in lode and placer deposits. In our opinion, the platinum-group minerals in the Levtyrinyvayam placer, the

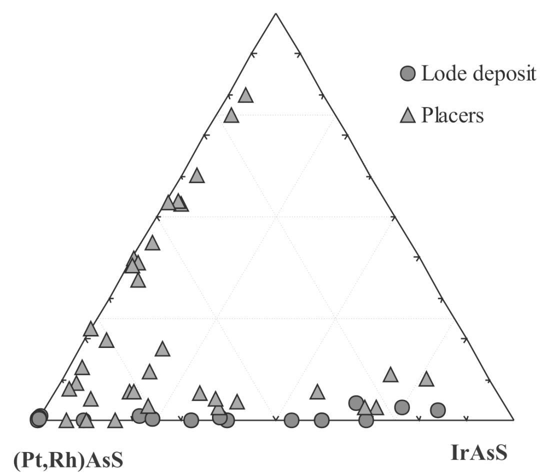

FIG. 9. Compositions of PGE sulfarsenides (mol.%).

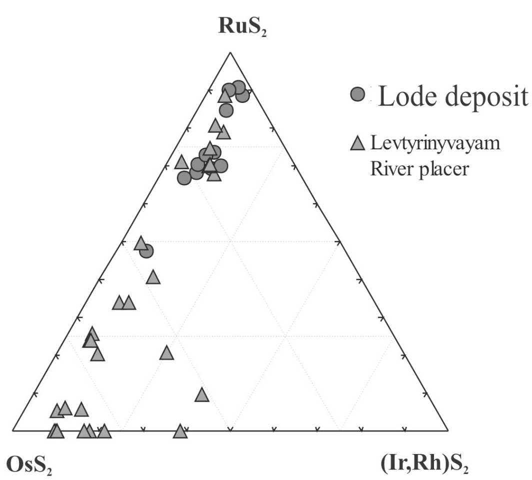

FIG. 8. Composition of laurite–erlichmanite (mol.%).

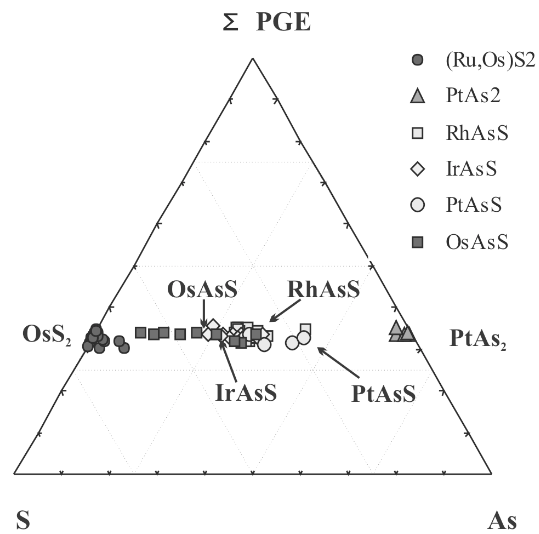

FIG. 10. Solid-solution series of PGE sulfides, sulfarsenides and arsenides from lode deposits and placers associated with the Gal'moenan complex.

most distant from the source, represent the eroded upper part of the intrusion, those in the Penistiy placer correspond to its intermediate part, and the PGM associated with Ledyanoy Creek are derived from dunite and chromitite of the core.

Platinum from the intrusion's apical part is Rh- and Pd-rich, unlike the Ir-rich platinum of lower- and higher-temperature layers. Pt–Fe alloy from the mostly pyroxenite periphery of the complex also contain more Rh–Pd-enriched platinum than the Rh- and Ir-bearing platinum alloys supplied to the placers from dunite. Concentrations of Ir decrease and Os increase toward the upper or apical parts of the complex, as is indicated by the presence of erlichmanite (OsS_2) and osarsite (OsAsS) inclusions in Pt–Fe alloy in the Levtyrinyvayam placer. The same placer contains isoferroplatinum + osmium, unlike the isoferroplatinum + iridium paragenesis encountered in lodes where native alloys also are rich in iridium.

Grains of Pt–Fe alloy from lodes and most placers have isoferroplatinum compositions (Pt_3Fe). Judging by their morphology, the alloys of the Levtyrinyvayam placer corresponding to the upper part of the complex have high iron contents (Pt,Fe), which were produced during postmagmatic metasomatism rather than during primary crystallization, because of the Fe-rich zones develop along the cracks in the Pt–Fe grains.

A relatively high fugacity of sulfur at an early stage of PGE mineralization is responsible for the abundance of RuS_2–OsS_2 inclusions and the resulting depletion of Ru in the Os–Ir alloy, as well as for the scarcity of native Os in lode deposits. A higher activity of As at a late stage has led to the formation of secondary sperrylite.

We have shown that in terms of minor elements, the composition of platinum in the Gal'moenan complex is dominated by Ir, which is, however, unevenly distributed. Platinum in the Ledyanoy placer, derived from the southern part of the complex, contains the highest concentrations of Ir, comparable to those in the lodes. The Penistiy placer, corresponding to the marginal facies, contains Rh- and Pd-rich platinum. Palladium contents are relatively high in the Levtyrinyvayam placer, which is the most distant from the source and represents the eroded upper part of the intrusion, but it is virtually absent in alloys from the lodes.

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