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 Pt3Fe 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, RuS2, and the Levtyrinyvayam placer bears all varieties of (Ru,OoS)2, including Ru-free Rh-rich erlichmanite (Os,Rh)S2. 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 [(Pt0.96Fe0.02)H9018(As1.17Sb0.75S0.09)S2], a member of the sperrylite – geversite solid solution, has been found in a lode. Complete solid-solution between RuS2 and RuAsS on one hand, and PtAsS and PtAs2 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.

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 ont été isoferroplatine, avec une composition Pt3Fe, 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.
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 to 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 Penisty 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).
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, CuFeS₂ for Cu, Fe, and S, FeNiCo for Ni, InAs for As, and CuSbS₂ for Sb. The following X-ray lines were used: Lα for Pt, Ir, Pd, Rh, Ru, As, and Sb, Kα for S, Fe, Cu, and Ni, and Mα 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.

**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,Fe) compositions (Fig. 3A), whereas the Levyrinyvayam 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
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 PtFe – CuPt 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 (Evsitinaeva et al. 1992), Goodnews Bay (Tolstykh et al. 2002), Gusevogorsky (Cabi & 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 isoferronplatinum deposited in Ledyanoy Creek, which drains dunite and chromitite 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). The composition of Pt–Fe alloy (at.%) in lode deposit of the Gal’moenan complex (A) and in the Levtyrinyvayam River placer (B).
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 Levtryrinyvayam placer.

**Ru and Os sulfides**

Ruthenium and osmium sulfides vary in composition from laurite (RuS₂) to erlichmanite (OsS₂). The lodes mostly contain laurite (Fig. 2G), and the Levtryrinyvayam 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)S₂, 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 Levtyrynivayam 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 occurring 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.

**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 – 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.

![Diagram](image)

**Fig. 6. Contents of trace elements in Pt–Fe alloy from lode deposits of the Gal’moenan complex, Ledyanoy, Penisty 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.**

**TABLE 1. SELECTED COMPOSITION OF GRAINS OF Pt–Fe–Co ALLOY, GAL’MOENAN COMPLEX, RUSSIA**

<table>
<thead>
<tr>
<th></th>
<th>Pt</th>
<th>Ir</th>
<th>Rh</th>
<th>Pd</th>
<th>Ru</th>
<th>Os</th>
<th>Fe</th>
<th>Cu</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>99.98</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>8.59</td>
<td>0.00</td>
<td>100.38</td>
</tr>
<tr>
<td>2</td>
<td>98.79</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>10.23</td>
<td>0.00</td>
<td>100.02</td>
</tr>
<tr>
<td>3</td>
<td>99.36</td>
<td>0.31</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>9.01</td>
<td>0.38</td>
<td>100.38</td>
</tr>
<tr>
<td>4</td>
<td>88.81</td>
<td>2.35</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>8.22</td>
<td>0.00</td>
<td>100.22</td>
</tr>
<tr>
<td>5</td>
<td>87.56</td>
<td>3.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>8.27</td>
<td>0.18</td>
<td>99.60</td>
</tr>
<tr>
<td>6</td>
<td>87.57</td>
<td>3.21</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>8.53</td>
<td>0.20</td>
<td>99.82</td>
</tr>
<tr>
<td>7</td>
<td>86.61</td>
<td>4.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>8.58</td>
<td>0.21</td>
<td>99.86</td>
</tr>
<tr>
<td>8</td>
<td>86.72</td>
<td>4.34</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>8.36</td>
<td>0.14</td>
<td>100.40</td>
</tr>
<tr>
<td>9</td>
<td>76.40</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>22.83</td>
<td>0.56</td>
<td>102.01</td>
</tr>
<tr>
<td>10</td>
<td>75.51</td>
<td>0.35</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>11.65</td>
<td>4.28</td>
<td>98.40</td>
</tr>
<tr>
<td>11</td>
<td>76.07</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>10.88</td>
<td>10.52</td>
<td>98.51</td>
</tr>
<tr>
<td>12</td>
<td>75.99</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>11.70</td>
<td>12.76</td>
<td>99.74</td>
</tr>
<tr>
<td>13</td>
<td>70.72</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>11.14</td>
<td>16.76</td>
<td>98.62</td>
</tr>
<tr>
<td>14</td>
<td>63.20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>4.68</td>
<td>28.62</td>
<td>95.85</td>
</tr>
<tr>
<td>15</td>
<td>44.97</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>2.00</td>
<td>47.43</td>
<td>99.77</td>
</tr>
</tbody>
</table>

**Lode deposits of the Gal’moenan massif**

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Placer deposit of the Levtyrinyvayam River**

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Placer deposit of Ledyanoy Creek**

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Placer deposit of Penisty Creek**

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Placer deposit of Penisty Creek**

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**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 isoferronplatinum. 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 (Pt0.96Fe0.02)O0.98(As1.17Sb0.75S0.09)2.01 belongs to a sperrylite – geversite solid-solution series in which PtSb2 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-

### TABLE 2. SELECTED COMPOSITION OF GRAINS OF Os–Ir PT ALLOY, GAL`MOENAN COMPLEX, RUSSIA

<table>
<thead>
<tr>
<th>Pt</th>
<th>Ir</th>
<th>Os</th>
<th>Rh</th>
<th>Ru</th>
<th>Cu</th>
<th>Fe</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.15</td>
<td>6.8</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>2</td>
<td>1.25</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>3</td>
<td>1.35</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>4</td>
<td>1.45</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>5</td>
<td>1.55</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>6</td>
<td>1.65</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>7</td>
<td>1.75</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>8</td>
<td>1.85</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>9</td>
<td>1.95</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>10</td>
<td>2.05</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
<tr>
<td>11</td>
<td>2.15</td>
<td>6.75</td>
<td>95.0</td>
<td>0.37</td>
<td>0.07</td>
<td>0.00</td>
<td>99.75</td>
</tr>
</tbody>
</table>

### TABLE 3. COMPOSITIONS OF SULFIDES, ARSENIDES, AND SULFOSILASBENITIDES OF PGE, GAL`MOENAN COMPLEX, RUSSIA

<table>
<thead>
<tr>
<th>Pt</th>
<th>Os</th>
<th>Ir</th>
<th>Ru</th>
<th>Fe</th>
<th>Cu</th>
<th>Sb</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>56.5</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>2</td>
<td>56.4</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>3</td>
<td>56.3</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>4</td>
<td>56.2</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>5</td>
<td>56.1</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>6</td>
<td>56.0</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>7</td>
<td>55.9</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>8</td>
<td>55.8</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
<tr>
<td>9</td>
<td>55.7</td>
<td>0.12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.75</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Compositions are expressed in wt.%.
Nevertheless 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. 8. Composition of laurite–erlichmanite (mol.%).](image)

![Fig. 9. Compositions of PGE sulfarsenides (mol.%).](image)

![Fig. 10. Solid-solution series of PGE sulfides, sulfarsenides and arsenides from lode deposits and placers associated with the Gal’moenan complex.](image)
most distant from the source, represent the eroded upper part of the intrusion, those in the Penisty 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 (OsS2) and osarsite (OsAsS) inclusions in Pt–Fe alloy in the Levtryrinyvayam placer. The same placer contains isoferronplatinum + osmium, unlike the isoferronplatinum + iridium paragenesis encountered in lodes where native alloys also are rich in iridium.

Grains of Pt–Fe alloy from lodes and most placers have isoferronplatinum compositions (PtFe). Judging by their morphology, the alloys of the Levtryrinyvayam 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 RuS2–OsS2 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 Penisty placer, corresponding to the marginal facies, contains Rh- and Pd-rich platinum. Palladium contents are relatively high in the Levtryrinyvayam 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.

ACKNOWLEDGEMENTS

The authors are grateful to Drs. Yu.G. Lavrent’ev, L.N. Pospelova and V.M. Chubarov for reliable analytical tests of PGE minerals. The authors greatly acknowledge the constructive comments by Federica Zaccarini, an anonymous referee, and Robert F. Martin. The work was partly supported by research grant of the scientific school, #1573.2003.5.

REFERENCES


FURUSETH, S., SELTE, K. & KIERSHUS, A. (1967): The solid solubility and structural properties of PtAs2–Sb, PtP2–Sb2, PtP3–Sb, PtAs3–Sb2, PtAs2–Sb, PtSb2–Bi, PtSb3–Bi, Pd1–mPt2As2, Pd1–mPt2Sb, Pt1–mAu0Sb2 and Pt1–mAu0Sb2. Acta Chem. Scand. 21, 527-536.


Received February 25, 2003, revised manuscript accepted February 22, 2004.