Geology of Ore Deposits, Vol. 45, No. 4, 2003, pp. 287–308. Translated from Geologiya Rudnykh Mestorozhdenii, Vol. 45, No. 4, 2003, pp. 329–352.

The PGE Ore Mineralization in the Monchegorsk Magmatic Layered Complex (Kola Peninsula, Russia)

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Received February 18, 2003

Abstract—The paper contains new data on low-sulfide PGE occurrences related to the Early Proterozoic (~2450–2503 Ma) plutons within the Monchegorsk ore district (the northeastern part of the Baltic Shield). The most important PGE occurrences relate to the conjugation zone of the Monchetundrovsk massif and Monchegorsk pluton and to some intrusives at the southern frame of the Monchegorsk pluton. It was found that platinum and palladium bismuthotellurides are predominant in the vein and veinlet–disseminated Cu–Ni ores of the Monchegorsk pluton, while niggliite, sopcheite, and sperrylite are more rare. Sperrylite, hollingworthite, irarsite, and palladoarsenite occur in the marginal rock series, except for compounds of the system Pt–Pd–(Ag)–Te–Bi. The minerals of the braggite–cooperite-vysotskite row, bismuthotellurides of Pt and Pd, and sperrylite are common in the ore-bearing horizons of the rhythmically layered zone within the Monchetundrovsk massif. The most variable assemblage of PGE minerals was found in ore occurrences at the conjugation zone of the massifs and in intrusives of the southern frame of the Monchegorsk pluton. This assemblage includes alloys, sulfides, bismuthotellurides, and arsenides of Pt and Pd, as well as minerals of the systems Pd–As–Sb, Pd–As–Te–(Sn), Pd–Ni–As, Pd–Ag–Te, Pd–Pb–(S, Se), Pd–As-O and sulfarsenides of PGE, Ni, and Co. The PGE minerals associate with minerals of Au and Ag. Most of these minerals were found for the first time in the Monchegorsk district. The evolution of PGE assemblages in the process of the massifs crystallization is shown for the studied ore occurrences.

INTRODUCTION

The geology of the Monchegorsk ore district has been studied from the 1920s. The beginning of the research is associated with the names of K.I. Viskont, G.D. Rikhter, A.E. Fersman, V.K. Kotul'skii, N.S. Zontov, I.Ya. Kholmyanskii, M.F. Shestopalov, B.M. Kupletskii, G.M. Sheshukova, N.A. Eliseev, P.V. Lyalin, S.M. Rutshtein, E.K. Kozlov, and some others. All Cu–Ni deposits found in those and the following years relate to the Monchegorsk pluton, which is the reason for the sharp difference in the degree of investigation of the layered Monchegorsk and Monchetundrovsk massifs. While the nickel-bearing Monchegorsk pluton was explored with many hundreds of boreholes, the geological structure of the Monchetundrovsk massif remained insufficiently studied. Investigations of the latter were limited with data collected from surface outcrops and cores of three deep boreholes. According to these data, the vertical structure of the layered series at the massif was estimated and the presence of ultrabasic layers under the gabbro–anorthosites and gabbronorites was confirmed. Thus, a suggestion was made postulating a genetic relationship between the Monchegorsk pluton and Monchetundrovsk massif (Sokolova, 1976; Sharkov, 1980). However, the hypothesis that the two intrusions formed probably from the same magma source but emplaced in various tectonic structures is preferable according to geophysical, geodynamic, and petrologic investigations of recent years (Amelin *et al.*, 1995; Filatova, 1995; Sedykh *et al.*, 1995; Tevelev and Grokhovskaya, 1999).

PGE were found in vein ores at the Monchegorsk pluton at the very beginning of mining, but the first data concerning mineral forms of their occurrence in ores were published only in the 1960s (Genkin *et al.*, 1963; Yushko-Zakharova and Chernyaev, 1966). The Central Kola Enterprise, together with the Institute of Geology of Ore Deposits, Petrography, Mineralogy, and Geochemistry (IGEM), studied low-sulfide PGE in the Monchetundrovsk and Monchegorsk massifs in the late 1970s. As a result, increased PGE contents were found in rocks composing the rhythmically layered series of the Monchetundrovsk massif (total PGE content reaches 1.5 ppm) and higher PGE contents were confirmed in the vein and veinlet–disseminated ores of the Monchegorsk pluton (total PGE content reaches 25 ppm). PGE minerals (merenskyite, kotulskite, sperrylite, vysotskite, braggite, and cooperite) were found for the first time in some layers of low-sulfide PGE mineralization of the Monchetundrovsk massif (Grokhovskaya and Laputina, 1988).

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A systematic study of the low-sulfide PGE mineralization within the described massifs began from the mid-1990s. As a result of exploration by the Central Kola Enterprise, a PGE deposit was found in gabbronorites of the Vuruchuaivench intrusion (Bakaev, 1995; Shelepina *et al.*, 1998). Many ore occurrences were found at the eastern part of the Monchetundrovsk massif within its conjugation with the Monchegorsk pluton and in the massifs Nyud, Poaz, and the so-called Gabbro 10 anomaly as well. This study confirmed a high probability of discovery of the noble metal deposits in a large part of the Monchegorsk ore district (Sholokhnev *et al.*, 1998; Kliment'ev *et al.*, 1999). The low-sulfide PGE occurrences in the studied massifs show a great diversity of PGE minerals (Grokhovskaya, 1998; Grokhovskaya *et al.*, 1995, 2000, 2002).

GEOLOGIC STRUCTURE OF THE MONCHEGORSK MAGMATIC COMPLEX

The Early Proterozoic gabbro–labradorite intrusion of the Glavnyi Range crossing the Monche-Chuna-Volch'i and Losevy Tundras (area, more than 500 km^2), the adjoining Monchegorsk pluton (~50 km^2), and several smaller layered massifs occur in the southern part of the transform zone joining the Imandra and Pechenga segments of the Pechenga–Imandra–Varzuga rift system (Fig. 1a). We consider all these massifs as intrusions genetically related to each other and call them the Monchegorsk magmatic complex. Magmatic bodies of the Monchegorsk complex intrude gneisses of the archean Belomorsk and Kol'sk series and are overlapped with volcano–sedimentary rocks of the Middle-Proterozoic Imandra–Varzuga series (Fig. 1b). The geology and petrology of the layered massifs of the complex are described in detail in some publications (Eliseev *et al.*, 1956; Kozlov *et al.*, 1967; Sokolova, 1976; Sharkov, 1980; *Petrologiya…*, 1988; Chashchin, 1999; Chashchin *et al.*, 2002; and others). The geologic structure of the Monchegorsk complex is very complicated and debatable. Thus, detailed description of the structural relations between intrusions composing it is beyond the scope of this paper.

The Monchegorsk magmatic complex is an example of a long-evolving Paleoproterozoic ore–magmatic system. The time interval between periodic magma intrusions is no less than 50 Ma. The isotopic age of the Monchegorsk pluton varies from 2504.4 ± 1.5 Ma (Amelin *et al.*, 1995) to 2493 ± 7 Ma (Balashov *et al.*, 1993). The Monchetundrovsk massif was formed in the interval from 2488 ± 3 Ma (rocks of the rhythmically layered series) to 2453 ± 4 Ma (gabbro–anorthosites) (Smol'kin *et al.*, 2001; Mitrofanov *et al.*, 1993).

The Monchegorsk Pluton

The Monchegorsk pluton consists of two branches: meridional (Nittis, Kumuzh'ya, and Travyanaya massifs) (NKT) and latitudinal (Sopcha, Nyud, and Poaz massifs). These branches conjugate in the southwest part, in an area of so-called "plutonic roots" (Eliseev *et al.*, 1956). Massifs are trough-shaped and show a gently dipping initial layering and trachitoid crystal orientation (dip angles 10°–25°) but more steeply dipping contacts (angles to 45°). In general, the plutonic rocks plunge to the SW. The pluton is broken into tectonic blocks by faults.

The NKT massifs and the Sopcha massif are predominantly composed of ultrabasic rocks and show a similar structure. The following zones are distinguished in the vertical section of the layered series (upward): 1) the zone of poikilitic and granular peridotites with layers of dunites and olivine pyroxenites; 2) the zone of rhythmical alternation of pyroxenites and olivine pyroxenites; and 3) the zone of pyroxenites (bronzitites). Vertical veins of massive Cu–Ni sulfide ores (now worked out) and accompanying gabbronoritic pegmatites occur in the central part of the layered series.

The Sopcha massif contains several thin discontinuous layers of alternating dunites, peridotites, olivine pyroxenites, and pyroxenites with disseminated Fe–Cu–Ni sulfides and chromespinel (so-called "peridotitic layer 330") occurring among massive ortopyroxenites at the level of 300 to 330 m.

The structure of the ultramafic zone of the Monchegorsk pluton is disturbed in the SW part of the pluton (near the Sopchinsk lakes) with an enormous platelike body of layered ultrabasic rocks (the so-called "dunite block") gently dipping to the SW at an angle of 10°–15°. The body consists of rhythmically alternating peridotites, olivine pyroxenites, and dunites enclosing the Sopcheozersk chromite deposit. The dunite block is separated from the Monchegorsk pluton by a partly brecciated gabbronoritic zone. These rocks were formerly considered as the oldest in the Monchegorsk pluton (Eliseev *et al.*, 1956; Kozlov, 1973); however, recently, they are usually related to the ultrabasic zone of the Monchetundrovsk massif. This is confirmed by recent exporation drilling. According to these data, the rhythmically layered ultrabasic rocks of the Monchetundrovsk massif in the zone of the Monchetundrovsk fault contain chromite ores similar to those of the Sopcheozersk deposit.

The lower marginal rock series of the Sopcha and NKT massifs varies in thickness from 50–100 m to 5–10 m in the periphery. It consists of plagioperidotites, plagiopyroxenites, olivine norites, norites, quartz–biotite norites, and gabbronorites at the base of the section. The rocks of the marginal series have a taxitic fabric due to the alternation of pegmatoids, thin- and coarse-grained rocks with varying content of sulfides, and granophires and pegmatites. In the marginal series, disseminated Cu–Ni sulfide ores occur, composing the so-called "bottom ore body" (Eliseev *et al.*, 1956; *Petrologiya…*, 1988). In the marginal series of the NKT massifs, pocket and veinlet–disseminated mainly

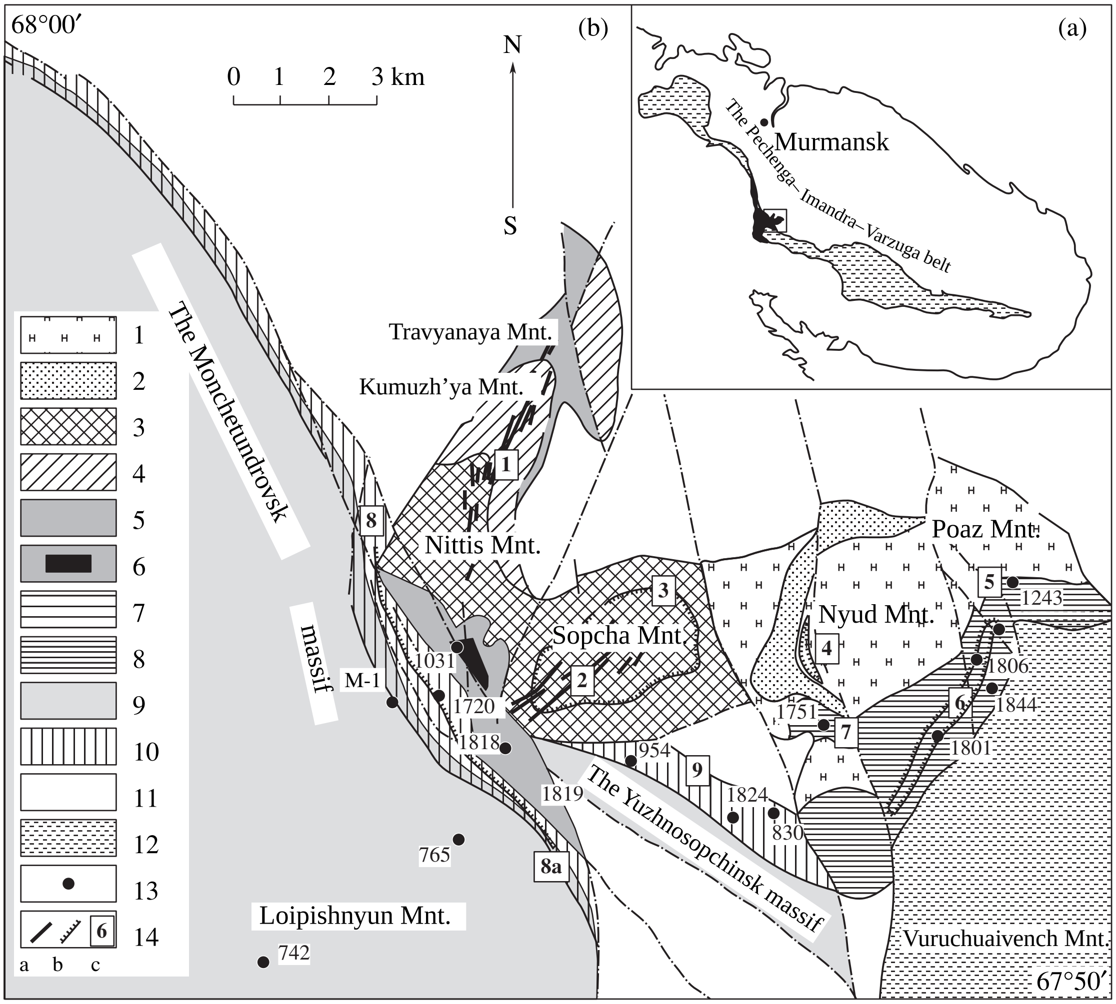

Fig. 1. Situation map (a) and schematic geological map (b) of the Monchegorsk magmatic complex. Made by V.V. Sholokhnev in 2001 using data of the Northwestern Geological Survey, the Kola Scientific Center of the Russian Academy of Sciences, the mining enterprise Severonikel', and the Central Kola Enterprise obtained in the period 1930–2000, with supplements of the authors.

1–5—the Monchegorsk pluton rocks: 1—norites; 2—olivine norites; 3—pyroxenites; 4—alternating pyroxenites, olivine pyroxenites, and peridotites; 5—peridotites; 6—alternating dunites, peridotites, and chromitites at the dunite block; 7—gabbronorites at the Vuruchuaivench massif; 8—the Gabbro 10 anomaly massif rocks; 9—coarse-grained gabbros and anorthosites at the Monchetundrovsk massif; 10—rocks of the conjugation zone of the Monchegorsk pluton and the Monchetundrovsk massif; 11—Archean biotite, garnet–biotite, and amphibole gneisses and dioritic gneisses; 12—the volcanogenic–sedimentary rocks of the Imandra–Varzuga suite; 13—boreholes; 14—ore fields, zones, and deposits (figures in squares): 1, 2—fields of Cu–Ni sulfide ores at the NKT (1) and Sopcha (2) massifs; 3, 4—disseminated Cu–Ni ores at peridotite layer 330 (3) and the critical horizon (4); 5–9, disseminated PGE–Cu–Ni low-sulfide ores in rocks of the lower endocontact of the Monchegorsk pluton (5) and in gabbronorites of the Vuruchuaivench massif (6); gabbros and diorites of the Gabbro 10 anomaly massif (7); rhythmically layered rocks of the Vostochno-Monchetundrovsk ore zone (8, Pentlandite Creek; 8a, southern part of the zone around Arvarench Mtn.) and of the Yuzhnosopchinsk ore zone (9).

chalcopyritic "deep-level copper" ores occur. Some sulfide concentrations occur in gneisses underlying the pluton.

In the Nyud and Poaz massifs, basic rocks predominate. At the base of the section, plagiopyroxenites with rare interlayers of plagioperidotites occur. The main part of the section consists of poikilitic and olivine norites. The olivine norites of the Nyud massif contain a "critical horizon," which consists of alternating of norites, gabbronorites, olivine norites, cordierite-bearing fine-grained rocks, anorthosites, and pyroxenites with varying structure and fabrics. The disseminated and veinlet–disseminated Cu–Ni ores relate to olivine norite, rocks of the critical horizon, and rocks of the lower marginal series.

The massifs of the Monchegorsk pluton are bordered on the south with gabbronorites and anorthosites of the Vuruchuaivench massif gently dipping to the SW under volcano–sedimentary rocks of the Imandra–Varzuga series. Rocks of these massifs are intensely metamorphosed in contrast with rocks in the Monchegorsk

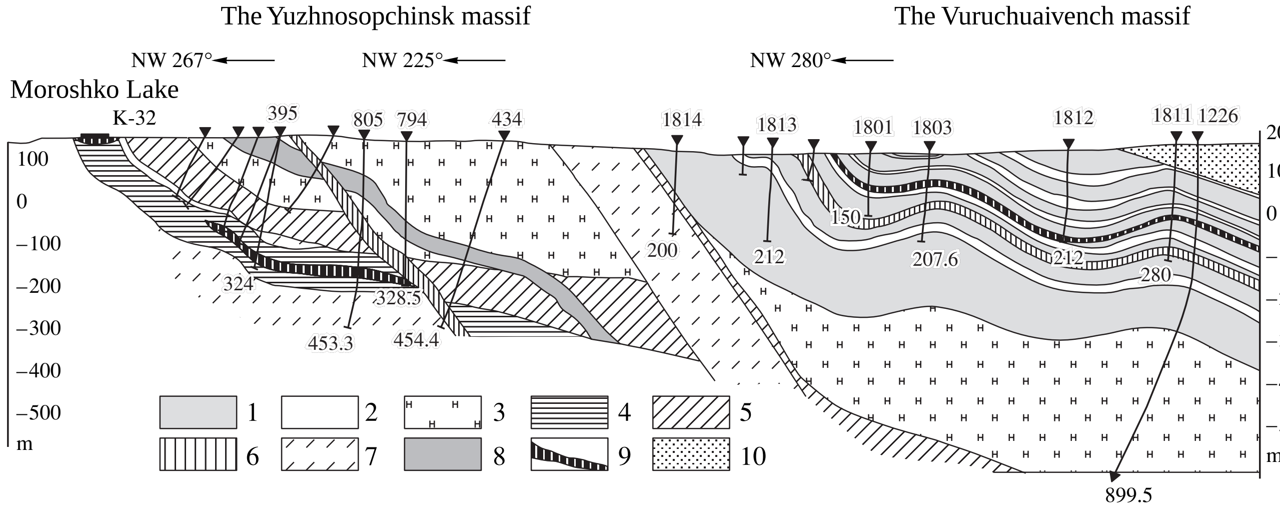

Fig. 2. Schematic vertical section of the eastern part of the Yuzhnosopchinsk and Vuruchuaivench massifs.
1—leucocratic gabbronorites; 2—anorthosites; 3—amphibolized norites; 4—metamorphosed gabbros; 5—poikilitic norites and plagiopyroxenites; 6—taxitic gabbronorites; 7—dioritic gneisses; 8—dolerite dike; 9—strata and areas of low-sulfide ores; 10–volcano–sedimentary rocks of the Imandra–Varzuga zone.

pluton, which experienced no autometamorphic alteration at all.

The Vuruchuaivench Massif

This massif contains the recently found deposit of the low-sulfide PGE ores (Shelepina *et al.*, 1998). It consists of alternating gabbronorites and anorthosites varying from medium-grained to pegmatoid (Fig. 2). Extensive layers and irregular bodies of disseminated sulfide ores with high PGE content are found in the study of the surface exposures and borehole cores (Grokhovskaya *et al.*, 2000). The isotopic age of the gabbro–norites in the Vuruchuaivench massif is not determined, and geological relationships with the Monchegorsk pluton are not yet clear.

The Monchetundrovsk Massif

The Monchetundrovsk massif is a part of the Glavnyi Range massif in the Chuna–Monche–Volch'ya and Losev tundras; it is lopolite-like and has steep tectonic contacts with host rocks, and its central part gently dips SW. The length of the massif is around 30 km; the thickness increases from 0.5–1 km to 3–4 km at the southeast (Sokolova, 1976). The Monchetundrovsk massif joins at the East with the Monchegorsk pluton, but is separated from it by a thick zone of cataclastic rocks of the Monchetundrovsk fault. The massif is mostly composed of basic rocks (anorthosites, gabbro, and gabbronorites) alternating with thinly layered rocks. The latter commonly occur at the zone boundaries inside the massif. Cryptic rhythmical layering is common in rocks of the massif (*Petrologiya…*, 1988).

A lower marginal series, consisting of thin-grained gabbronorites, and layered series are distinguished within the Monchetundrovsk massif. The layered series consists, in turn, of the following four zones varying in the composition of cumulus parageneses: ultramafic, rhythmically layered, gabbronoritic, and upper gabbroic.

The ultramafic zone is crossed by several deep boreholes in the central part of the massif and is exposed at the surface as separate tectonic fragments in the conjugation zone with the Monchegorsk pluton. The rocks composing the zone are pyroxenites, olivine pyroxenites, peridotites, and, more rarely, dunites. The rocks of the ultrabasic zone occur only in the southern part of the massif according to geophysical data. Thus, some authors consider them as a prolongation of the ultrabasic zone of the Monchegorsk pluton. However, the regular variations of the rock-forming silicates in composition from the ultrabasic to the upper gabbroic zones and the general trend of differentiation in the layered series rocks suggest that the described ultrabasic rocks are differentiates of the Monchetundrovsk massif (*Petrologiya…*, 1988).

*The rhythmically layered zone h*as a thickness of 300–400 m and consists of alternating gabbronorites, olivine gabbronorites, plagiopyroxenites, bronzitites, peridotites, and dunites. The ore-free rocks alternate with layers containing sulfide PGE–Cu–Ni dissemination. Ultrabasic rocks contain disseminated chrome spinel.

The gabbronoritic zone has a thickness of 400–600 m and consists of predominant trachitoid and massive gabbronorites. They alternate in the upper part of the zone with coarse-grained gabbros, norites, bronsitites, and olivine gabbronorites.

The upper gabbroic zone has a thickness of 600–1000 m and consists of alternating of massive coarse to medium-grained gabbros and subordinate anorthosites and gabbronorites.

The conjugation zone of the Monchetundrovsk Massif and the Monchegorsk pluton deserves more attention. The contact between the Monchetundrovsk massif and the Monchegorsk pluton coincides with the zone of Monchetundrovsk fault striking SE—NW. Within this zone, narrow linear blocks of less-altered rocks are separated from each other by intensely brecciated rocks, milonites, and cataclasites. The fault zone has a width of 0.5–1 km and an amplitude of 1.5–2 km and steeply dips (70°–80°) to the NE according to geophysical data (Sedykh *et al.*, 1995; Muradymov *et al.,* 2000). The tectonic plates composing the fault zone dip steeply (45°–80°) to the NE and consist of basic and ultrabasic rocks initially formed at various depths.

The rhythmically layered rocks occur along the whole eastern border of the Monchetundrovsk massif, where they compose the Yuzhnosopchinsk massif. The last occurs to the south of the Monchegorsk pluton and plunges under the Sopcha massif (Figs. 1b, 2). Formerly, the rhythmically layered rocks in the southwestern part of the Monchetundrovsk massif were considered as roots of the Monchegorsk pluton (Eliseev *et al.*, 1956; Kozlov, 1973). However, the U–Pb isotopic age of these rocks in the core of the borehole 1720 is 2488 ± 3 Ma (Smol'kin *et al.*, 2001).

The main PGE mineralization in the Monchegorsk magmatic complex relates to the conjugation zone and associates with disseminated sulfide Cu–Ni–Fe ores. The three platinum-bearing ore zones were distinguished after prospecting works: the Vostochno-Monchetundrovsk and the Yuzhnosopchinsk ore zones and the Vuruchuaivench massif.

The Vostochno–Monchetundrovsk ore zone consists of massive coarse-grained gabbros and gabbronorites alternating with rhythmically layered rocks. The layered rocks of the Monchetundrovsk massif formed at various depth and later were uplifted toward the Earth's surface by tectonic movements. Norites, pyroxenites, dunites, and peridotites alternating with massive chromite layers 2–3 m thick (similar to those at the Sopcheozersk deposit) occur in the eastern border of the Monchetundrovsk massif at the contact with the dunite block. The rhythmically layered rocks form several megarythms, in the base of which either dunites or peridotites occur. They change upward to pyroxenites and basic rocks.

The PGE nineralization relates to peridotites of the ultrabasic zone; to rhythmically layered pyroxenites, norites, peridotites, and dunites; and to pegmatoid norites and gabbronorites in the Pentlandite canyon exposures. Elevated PGE content is determined in rocks stratigraphically higher than the chromite layer in boreholes crossing massive chromite ores (Fig. 3).

The Yuzhnosopchinsk ore zone occupies the whole Yuzhnosopchinsk massif, which has an area of 7 × 1.5 km^2 and thickness around 300 m. Probably the massif plunges to NW under the Sopcha massif, but the trachitoid textural elements of the Yuzhnosopchinsk magmatic bodies show a dip to the SW. The Yuzhnosopchinsk massif is autonomious and structurally intermediate between the Monchetundrovsk and Sopcha massifs on the one side and the Nyud massif on the other. The massif is differentiated from gabbro and gabbronorites at the southwestern border to norites, pyroxenites, and peridotites at the northeastern border, where the tectonic contact of the massif with hypersthene diorites is observed. The rocks of the massif are strongly metamorphosed and brecciated. The rocks of the Yuzhnosopchinsk massif were intruded along some tectonic lines into ultrabasic rocks of the Monchegorsk pluton and the dunite block. These intrusions complicate the geological structure of the conjugation zone. The PGE mineralization of the Yuzhnosopchinsk ore zone is spatially related to the Cu–N sulfide dissemination and occurs in the autometamorphically altered gabbronorites, norites, and plagiopyroxenites.

The relationship between separate massifs of the conjugation zone is very complicated, and the degree of their tectonic alteration is strong; thus the geological position and structure of these massifs are not clear. The rocks of the Vostochno–Monchetundrovsk and Yuznosopchinsk ore zones have similar composition and type of rhythmical mineral and cryptic layering with some differentiates of the rhythmically layered ultrabasic zones in the central part of the Monchetundrovsk massif. Thus, these rocks can be fragments of the latter emplaced in the fault zone.

METHODS OF STUDY

The PGE contents in rocks and ores were determined at IGEM RAN by chemical–spectral, kinetic, and chromatographic analyses performed by V.A. Sychkova, G.E. Belousov, and N.N. Nikol'skaya. Assemblages of the PGE minerals, ore-forming sulfides and oxides were studied in polished samples from surface exposures, open pits, and boreholes in the Monchegorsk magmatic complex. Heavy mineral concentrates are prepared from the crushed core samples to estimate the quantitative relations of the minerals. More than 500 grains of noble metal minerals were found there, and most of these grains were concentrated in a fine fraction –0.1 ± 0.06 mm.

Mineral analyses and photographs in the backscattered electron regime (contrast in relation to the mean atomic number, COMPO) were operated with the scanning electron microscope (SEM) JSM–5300 equipped with a LINK ISIS x-ray energy dispersion spectrome-

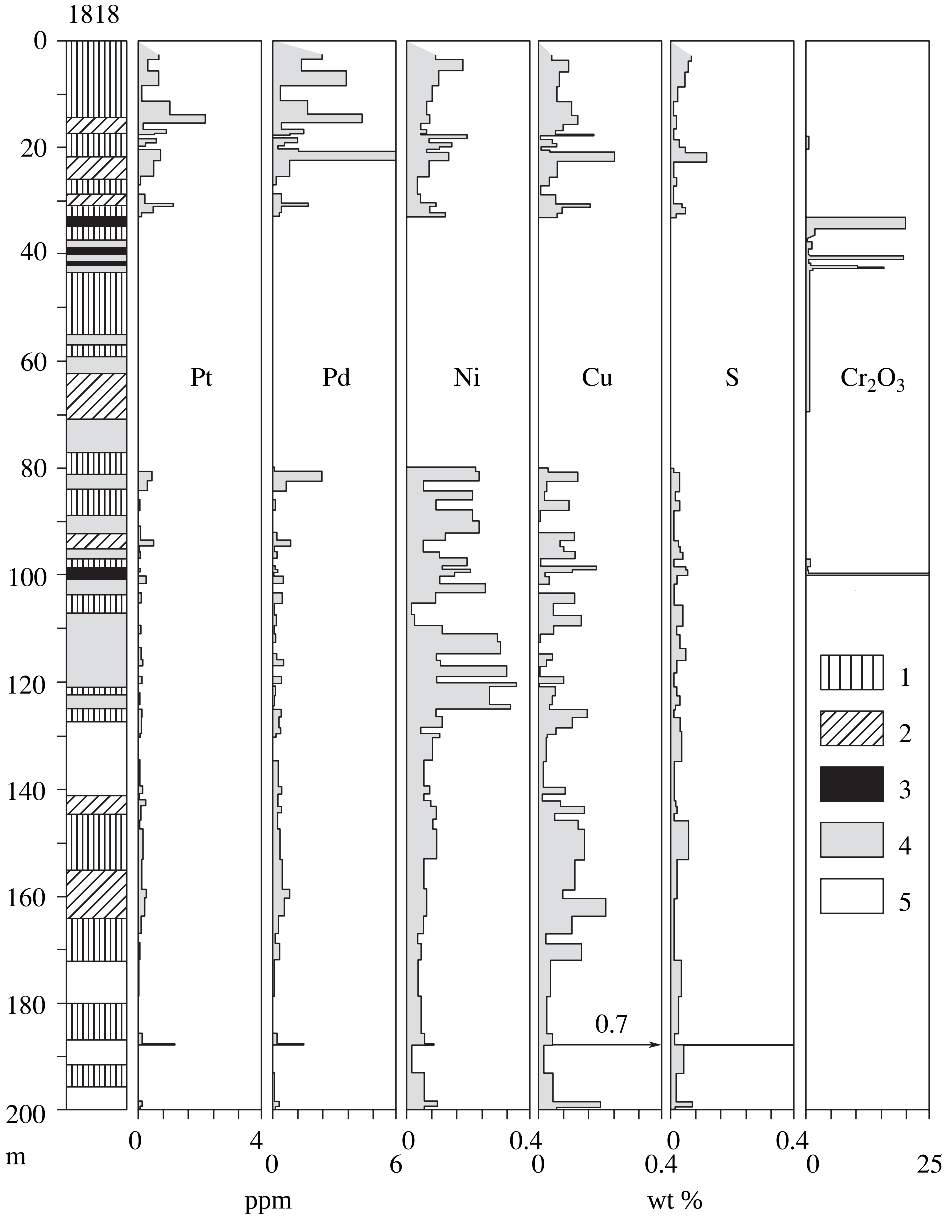

Fig. 3. Rhythmical layering and variation of Pt, Pd, Cu, Ni, S, and Cr along the core of borehole 1818 at the Vostochno-Monchetundrovsk ore zone.

1—Orthopyroxenites; 2—norites; 3—chromitites; 4—alternation of peridotites and dunites; 5—gabbronorites.

ter. Pure metals, MnS_2, GaAs, Ag_2Te, and HgTe were used as standards. The x-ray structural analysis of minerals did not fit, because mineral grains were too small and often finely intergrown. Thus, minerals were identified according to their optical features and chemical composition. The composition of the smallest grains (less than 5 μm) was estimated only qualitatively, because their dimensions were at the lower limit of the microprobe beam resolution. The minerals of the noble metals were united in some groups with similar chemical compositions.

THE PGE DISTRIBUTION IN LAYERED MASSIFS OF THE MONCHEGORSK MAGMATIC COMPLEX

The rhythmically layered rocks of the Monchegorsk pluton have hightened PGE background contents, the lowest content being in dunites. The PGE content is higher in the zones of alternating pyroxenites, peridotites, and olivine pyroxenites, where the ratio Pd/Pt < 1. The PGE contents in rocks of the marginal series, norites, pyroxenites, and gabbronorites of the complex strongly vary (Table 1).

Table 1. The content of PGE (ppm) and ore elements (wt %) in rocks of the Monchegorsk magmatic complex

Borehole numbers	Sample numbers	Rocks	Pt	Pd	Rh	Ni	Cu	Co	Cr
The Sopcha massif									
791	53	Peridotite	0.019	0.088	0.003	0.19	0.01	0.014	0.253
"	41	Pyroxenite	0.016	0.053	0.003	0.15	0.007	0.012	0.264
1195	34	Olivine pyroxenite	0.014	0.063	0.003	0.129	0.012	0.012	0.337
"	15	Gabbronorite	0.014	0.028	0.002	0.034	0.011	0.006	0.046
The Nittis massif and the dunite block									
898	29	Peridotite	0.022	0.071	0.004	0.202	0.005	0.018	0.314
904	23	Dunites	0.011	0.009	0.001	0.317	0.002	0.016	0.171
"	11	Peridotite	0.027	0.068	0.003	0.199	0.006	0.01	0.497
"	24	Pyroxenite	0.026	0.097	0.004	0.096	0.005	0.01	0.337
The Nyud massif									
1393	52	Norite	0.033	0.124	0.007	0.124	0.06	0.011	0.198
1394	25	Norite	0.034	0.2	0.006	0.087	0.06	0.007	0.196
The Monchetundrovsk massif									
765	19	Dunites	0.02	0.017	0.001	0.263	0.008	0.015	0.585
"	11	Pyroxenite	0.025	0.069	0.002	0.043	0.01	0.008	0.107
"	23	Gabbronorite	0.039	0.031	0.003	0.033	0.011	0.006	0.038
742	46	"	0.014	0.018	0.001	0.012	0.009	0.005	0.006
"	25	Pyroxenite	0.12	0.096	0.005	0.086	0.038	0.009	0.238

A heightened PGE content is found in all types of Cu–Ni sulfide ores of the Monchegorsk pluton. The vein, pocketlike, and veinlet–disseminated ores of the NKT massifs contain from 3–5 to 35 ppm total PGE. The pyrrhotite ores, which are most common in the NKT veins, contain 3–4 ppm total PGE. The highest PGE content relates to the vein and veinlet–disseminated pentlandite–(*magnetite*)–chalcopyrite ores. A high PGE content was first estimated by authors in limonitic ores that form an oxidation zone of sulfide veins at the Nittis massif (Table 2).

The PGE content in disseminated Cu–Ni ores of the Monchegorsk pluton massifs is rather constant and no higher than 2–3 ppm. The lowest PGE content (0.5–2.5 ppm) was estimated in disseminated ores of the "bottom body" (marginal series in the Sopcha and NKT massifs) and of the critical horizon in the Nyud massif. The disseminated and veinlet–disseminated ores with PGE content to 3–5 ppm in the marginal series of the Nyud–Poaz and Gabbro 10 anomaly massifs relate to the pegmatoid norite and plagiopyroxenite bodies (somewhere with massive Ti-magnetite) and to the quartz norites and diorites.

The content of ore components is rather constant throughout the section of the "Peridotite layer 330," and its mean values are PGE—1.4 ppm, Ni—0.3–0.7 wt %, and Cu—0.15–0.4 wt %. High total PGE content (to 8 ppm) was estimated only in the lump samples of pegmatoid pyroxenites from the roof of the so-called Peridotite layer 330."

The total PGE content in the disseminated sulfide ore of the rhythmically layered zone at the Monchetundrovsk massif does not exceed 5 ppm, and the mean value is around 1.2 ppm.

The total PGE content in the Vostochno–Monchetundrovsk ore zone varies from 1 to 32 ppm, but the mean value does not exceed 5–6 ppm (Table 3). The thickness of ore-bearing layers containing 2–3 ppm total PGE varies from 30 to 50 m in different boreholes. The layers with economic PGE content are from 1 to 3 m thick (Fig. 3).

Recently, platinum group elements were found in the Yuznosopchinsk ore zone, but they have to be additionally studied. The mean PGE content is 2–3 ppm a in 10 m thick zone in metamorphosed gabbronorites, norites, and pyroxenite. Higher total PGE contents (6–8 ppm) were estimated in some lump samples and in intervals having thickness to 0.5–1 m.

The PGE deposit in the gabbronorites of the Vuruchuaivench massif relates to the low-sulfide type (Grokhovskaya *et al.*, 2000). The mean total PGE content in ore body is 4–6 ppm, but in some places the content reaches 24 ppm.

Table 2. The PGE content (ppm) in the Cu–Ni ores and at the PGE occurrencies of the Monchegorsk magmatic complex

Sample numbers, borehole/depth, m	Ore types or host rocks	Pt	Pd	Rh	Ir	Total PGE content
The Monchegorsk pluton *The Nittis, Kumuzh'ya, and Travyanaya massifs*						
928/432.9	Disseminated of the bottom layer	0.14	1.5	0.02	0.005	1.67
9532, Shaft 5	Cp veinlet–disseminated	0.8	11.5	0.25	0.024	12.57
821/335.0	Po–Cp vein	0.7	5.4	0.005	N.e.	6.11
821/337.7	Mt–Cp vein	1.1	19.5	0.008	″	20.61
Vein 41	Mt–Cp vein	2.1	13.2	0.1	0.02	15.42
998/209.0	Po–Pn–Cp vein	1.6	7.5	0.04	0.01	9.15
Nittis Mtn.	Limonitic ores	1.42	12.8	0.3	N.e.	14.5
Disseminated Cu–Ni ores of peridotite layer 330 at the Sopcha massif						
MN-54	Pyroxenite	0.1	2.2	0.06	0.02	2.38
MN-56	″	0.8	6.9	0.22	0.05	7.97
MN-45	Peridotite	0.35	1.6	0.04	0.01	2.0
4443	″	0.1	0.8	0.02	0.01	0.93
Mean of 30 samples		0.17	1.41	0.04	0.01	1.63
Disseminated Cu–Ni ores of the critical horizon at the Nyud massif						
1244/420–422	Olivine norite	0.3	1.2	0.05	0.008	1.56
MN-6	Pyroxenite	0.25	1.4	0.03	N.e.	1.68
MN-15	Olivine pyroxenite	0.16	2	0.06	″	2.22
MN-17	Microanorthosite	0.1	1.1	0.01	″	1.2
MN-18	Micronorite	0.08	1.7	0.04	″	1.82
MN-68	Microgabbronorite	0.24	1.8	0.1	0.01	2.15
Mean of 18 samples		0.08	0.73	0.02	N.e.	0.82
The conjugation zone of the Monchetundrovsk massif and the Monchegorsk pluton *Vostochno-Monchetundrovsk ore zone*						
M1/780.2–781.6	Norite	1.2	3.3	0.14	N.e.	4.64
2702	Gabbronorite	1.35	5.45	0.19	0.03	7.02
3047	Peridotite	4.1	13.5	0.51	0.11	18.22
1819/101.2–101.4	Norite	4.7	24.9	0.13	0.05	29.78
1818/27.8–28.5	″	0.76	6.1	0.16	N.e.	7.02
Mean of 48 samples		0.62	2.9	0.07	0.001	3.6
The Yuzhnosopchinsk ore zone						
954/86.5	Gabbronorite	1.2	3.3	0.11	N.e.	4.61
10114	Gabbronorite	0.9	4.9	0.08	″	5.88
10202	Norite	0.8	6.2	0.27	″	7.27
Mean of 34 samples		0.44	2.28	0.08	″	2.80
The Vuruchuaivench massif						
6041	Gabbronorite	0.77	15.2	0.06	″	16.03
13708	″	0.71	6.02	0.06	″	6.79
1844/35.2–35.9	″	0.8	6.15	0.07	″	7.02
1844/32.5–39.2	″	0.40	3.50	0.03	″	3.93

Note: N.e., not estimated; Cp, chalcopyrite; Mt, magnetite; Pn, pentlandite; Po, pyrrhotite.

Table 3. Chemical composition of the PGE sulfides at the ore occurrences of the Monchegorsk magmatic complex (wt %)

No.	Borehole numbers	Minerals	Pd	Pt	Ni	Ru	Ir	Rh	Os	Cu	Fe	S	Total
1	830/400.5	Braggite	20.52	60.09	2.35	N.e.	N.e.	N.e.	N.e.	N.e.	N.e.	16.46	99.42
2	954/166	Vysotskite	62.26	N.e.	8.53	″	″	″	″	″	1.31	25.9	98.0
3	954/173.2	Braggite	24.55	52.54	5.12	″	″	0.23	″	″	N.e.	17.13	99.57
4	1031/51.0	Laurite	0.21	0.78	0.20	40.05	4.28	0.27	14.10	″	0.43	37.92	98.24
5	2702	Vysotskite	60.98	N.e.	12.19	N.e.	N.e.	N.e.	N.e.	″	0.87	25.51	99.55
6	″	Braggite	6.58	65.88	9.52	″	″	″	″	0.3	0.81	17.69	100.78
7	2703	Cooperite	4.97	76.05	3.0	″	″	0.03	″	N.e.	0.94	15.29	100.28
8	M1/777.8	Braggite	35.14	41.15	4.96	″	″	0.12	″	0.02	0.09	19.85	101.33
9	765/1000	″	13.87	57.37	8.23	″	0.8	0.22	1.08	0.24	0.27	17.39	99.47
10	765/1000	″	57.43	9.23	8.6	″	0.17	0.03	0.67	N.e.	0.14	23.58	99.85
11	3/188	(Cu, Pt, Pd)$_2$S	17.82	40.95	0.35	″	N.e.	N.e.	N.e.	24.0	2.59	11.85	97.58
12	″	″	13.6	41.88	1.73	″	″	″	″	23.5	7.78	12.2	100.69
13	″	″	6.87	42.56	0.39	″	″	″	″	30.94	6.32	13.4	100.48
14	″	(Cu, Pt, Pd)S	14.14	47.17	N.e.	″	″	″	″	19.94	N.e.	21.65	102.90
15	″	″	13.61	44.60	″	″	″	″	″	17.45	1.6	18.70	95.96

Note: 1–3, the Yuzhnosopchinsk ore zone; 4, the Sopcheozersk deposit; 5–15, the Vostochno-Monchetundrovsk ore zone (5–7: samples from open pits). Sample 15 contains 1.35 wt % Ag.
N.e., not estimated.

THE ORE COMPOSITION AND MINERALS OF PGE, SILVER, AND GOLD

The main ore-forming minerals of the Cu–Ni sulfide and low-sulfide PGE mineralization at the Monchegorsk magmatic complex are pentlandite, pyrite, magnetite, chalcopyrite, and pyrrhotite. The primary assemblages are replaced by secondary minerals in various degree. Pyrrhotite predominates in vein ores of the Sopcha and NKT massifs. Disseminated and veinlet–disseminated ores strongly vary in the quantitative relation of main ore-forming sulfides. Some later sulfides (millerite, that is in some places the main ore mineral, bornite, linneite group minerals, marcasite, covellite, and chalcocite) are common at the PGE occurrences, as well as the primary mineral assemblages.

The subordinate minerals and accessories in ores of the Monchegorsk magmatic complex are sphalerite, galena, mackinawite, argentopentlandite, molibdenite, heazlewoodite, altaite, hessite, bismuth and copper tellurides, zircon, and native metals (Bi, Pb, and Cu). Sulfides are spatially related to magnetite, titanomagnetite, ilmenite, and chromspinelides in the Cu–Ni sulfide ores of the PGE occurrences. The upper near-surface part of sulfide veins of the NKT massifs is occupied with an oxidized zone consisting of iron hydroxides. In the PGE occurrences, some minerals of silver and gold, nickel arsenides, cobaltite, gersdorffite, and arsenopyrite are common in assemblages with PGE minerals. The PGE minerals and ore-forming sulfides either occur in the intercumulus of magmatic silicates or intergrow with quartz and hydrosilicates (amphiboles, micas, chlorite, and serpentine).

The PGE minerals form solid solutions in the ore-forming sulfides, arsenides, and sulfoarsenides. The Pd content (wt %) in pentlandite varies form some hundredhs fractions to 0.12, and in cobaltite and gersdorffite it reaches 2–3. The nickel arsenides and minerals of the cobaltite–gersdorffite series are quite common in all of the studied PGE-bearing zones. The nickeline in the Vuruchuaivench massif and the mineral Ni_2As (orcelite?) in the Vostochno–Monchetundrovsk ore zone intergrow with PGE minerals. The cobaltite and gersdorffite either form metacrystals in the ore-forming sulfides or intergrow with PGE minerals. Some of observed structural relations between minerals suggest synchronous crystallization of PGE minerals and nickel arsenides. The genetic relationships between minerals of the cobaltite–gersdorfite series are not clear enough: sulfarsenides commonly replace sulfides, but this can be a result either of the magmatic fluid–hydrothermal activity or of metamorphic rock alterations.

Variable assemblages of the noble metal minerals (including all six PGE, gold, and silver) are found in the PGE occurrences of the Monchegorsk magmatic complex. These minerals occur in sulfides, at the contact between sulfides and silicates, and in rock-forming silicates as monomineral aggregates or polyphase intergrowths varying in size from submicronic to 100–200 μm.

There are some regularities in distribution of the PGE minerals in various ore types of the complex. The

Cu-Ni ores of the Monchegorsk pluton contain a uniform PGE mineral assemblage with predominance of the Pd and Pt bismuthotellurides and occasional occurrence of niggliite, stannopalladinite, sperrylite, sopcheite, and electrum. The main platinum mineral in ores of the Monchegorsk pluton is moncheite. In ores of the marginal series, hollingworthite and minerals of the cobaltite–gersdorffite series with an admixture of PGE are found, as well as minerals of the system Pt–Pd–Te–Bi. In the low-sulfide PGE mineralization at the central part of the Monchetundrovsk massif, minerals of the braggite–cooperite–vysotskite are common and palladium bismuthotellurides and sperrylite are scarcely found.

The most variable mineral assemblages of PGE, Au, and Ag are found at the Vostochno–Monchetundrovsk and Yuzhnosopchinsk ore zones and the Vuruchuaivench massif. Some of these minerals were found in the Monchegorsk complex for the first time (Fig. 4). Composition of the PGE mineral assemblages (as primary ones or later) strongly varies both within ore zones and in ore occurrences and even in separate samples. For example, more than 20 grains of the palladium arsenotelluride $Pd_5(Te, As)_2$ were found in one sample from the Yuzhnosopchinsk ore zone, though this mineral is not common in other ore occurrences. In some samples from the Vostochno–Monchetundrovsk zone, the main Pt mineral is sperrylite (more than 100 grains in individual samples), but, in other occurrences, Pt alloys with varying composition are the main Pt concentrators.

In the PGE occurrences of the Vostochno–Monchetundrovsk ore zone, rhythmically layered rocks enriched with PGE and related to various depth levels are spatially combined. Thus the distribution of the PGE minerals was influenced by the intensive and prolonged fluid-hydrothermal activity.

PGE minerals in the ultrabasic rocks from the lower part of the section are sperrylite, isoferroplatinum, Pd bismuthotellurides, and sulfides and alloys of Pt, Pd, Ni, Cu, and Fe. In the rhythmically layered rocks, sperrylite, isoferroplatinum, alloys of Pt–Pd–Fe–Ni–Cu with varying composition, and minerals of the PdS–PtS–NiS, Pt–Pd–Te–Bi–(Ag), Pd–Pb, Pd–As–Sb, Pd–Ni–As, PGE–(Ni, Co, Fe)–As–S, and Pt–Fe–As–O systems occur. In the pegmatoid norites and gabbronorites, as well as in the rhythmically layered zone of the Monchetundrovsk massif, minerals of the braggite–cooperite–vysotskite series, Pt–Pd–bismuthotellurides, and sperrylite occur.

Laurite rich in osmium was found in chromspinelides of massive chromite ores at the Sopcheozersk deposit. This rather unusual mineral assemblage was found in the intercumulus of metasomatically altered chromitites. It includes a solid solution of Pt and Pd with Au and Ag, native Ag, Cu with an admixture of PGE, argentite, millerite, heazlewoodite, galena, KCl, and $BaSO_4$.

PGE assemblages in ores of the Yuzhnosopchinsk ore zone also vary (Fig. 4). Palarstanide and minerals of Pd–Te–As and Pd–Pb-S–Se composition were found there for the first time.

In the PGE ores at the Vuruchuaivench massif, minerals of the systems Pd–As–Sb and Pd–Ni–As occur along with common Pd–bismuthotellurides and sperrylite. Complicate polymineral intergrowths of the platinum metal minerals are characteristic. They contain minerals replaced by Pd-bearing cobaltite and gersdorffite in various degree (Grokhovskaya *et al.*, 2000).

Minerals of the Pt–Pd–Te–Bi System

Platinum and palladium bismuthotellurides are common in all ore types in the Monchegorsk magmatic complex and are predominant over other PGE minerals in the Cu–Ni ores of the Monchegorsk pluton. In the rich Cu–Ni ores, PGE minerals are the most common in chalcopyrite and at the contacts between sulfides and silicates. The minerals form relatively large (to 200 μm) monomineral aggregates and polymineral intergrowths in association with bismuthotellurides and hessite. In low-sulfide PGE ores, platinum and palladium bismuthotellurides occur among the rock-forming silicates as well (Fig. 5).

Moncheite ($Pt(Te, Bi)_2$) is the main platinum mineral in the Cu–Ni ores of the Monchegorsk pluton. It also occurs in the Vostochno–Monchetundrovsk ore zone and the “Gabbro 10 anomaly” massif. Froodite ($PdBi_2$) and michenerite (PdTeBi) are most typical for ores of the NK. Kotulskite (Pd(TeBi) and merenskyite ($(Pd, Pt)(Te, Bi)_2$) occur in all ore types at the Monchegorsk magmatic complex (Figs. 5a–c). In the low-sulfide PGE ores of the Monchegorsk complex, kotulskite and merenskyite intergrow with PGE minerals of other systems (arsenides, antimonides, sulfarsenides, and alloys with varying composition).

The chemical compositions of the bismuthotellurides of platinum and palladium in various ore types and occurrences are shown in a diagram (Fig. 6). The isomorph substitutions of Te and Bi in kotulskite and merenskyite are common in all types of ores at the Monchegorsk pluton, Yuzhnosopchinsk ore zone and the Vuruchuaivench massif (Figs. 6a–c). Pt and Pd tellurides with low bismuth content occur in the ores of the Vostochno–Monchetundrovsk ore zone and the “Gabbro 10 anomaly” massif. The Pt and Pd isomorph substitutions in the series merenskyite–platinum merenskyite occur in Cu–Ni ores at the NKT and “Gabbro 10 anomaly” massif occurrences (Figs. 6d).

The mineral Pd_5Te_2 is found in pegmatoid gabbronorites at the Pentlandite canyon in intergrowths with braggite and vysotskite (Fig. 5e). Its grain dimensions are too small for the x-ray diffraction study of the mineral. Thus, it can be one of the following phases with similar composition: the unknown in nature phase

Minerals and unknown mineral phases	Monchegorsk pluton			Vuruchuaivench massif	Gabbro 10 anomaly massif	Monchetundrovsk massif		
	Nittis–Kumuzh'ya–Travyanaya*	Sopcha**	Nyud–Poaz***			Yuzhnosopchinsk ore zone	Vostochno-Monchetundrovsk ore zone	rhythmically layered ore zone
Isoferroplatinum (Pt_3Fe)							○	
Pt-Pd-Cu-Ni-Fe ± (Au-Ag)							○	
Cu_3Pt, Cu_3Pd						○	○	
Native gold				○			○	
Native silver				○		○	○	
Electrum (AuAg)	○ 1		○	● 2		●	●	○
Cooperite [(Pt, Pd, Ni)S]						○	●	○
Braggite [(Pd, Pt, Ni)S]						○	●	●
Vysotskite[(Pd, Ni)S]						○	●	○
Zvyagintsevite (Pd_3Pb)						○	○	
$(Pd, Pb)_2(Se, S)$						○		
Palladoarsenide (Pd_2As)				○				○
$Pd_3(Te, As)$						○		
Guanglinite (Pd_3As)				○		○	○	
Palarstanide [$Pd_8(As, Sn)_3$]				○		○		
Izomertieite ($Pd_{11}As_2Sb_2$)				○		○	○	
Mertieite [$Pd_8(Sb, As)_3$]							○	
$Pd_3(As, Sb)_2$				○				
$Pd_2(As, Sb)$				○				
Stibiopalladinite (Pd_5Sb_2)				○				
Mayakite (PdNiAs)				○				
$Ni_6Pd_2As_3$							○	
Menshikovite ($Ni_3Pd_2As_3$)				○				
Stannopalladinite (Pd_8Sn_3)	□ 3						○	
Niggliite (PtSn)	□ ○							
Kotulskite [Pd(Te, Bi)]	◆ 4 ●	●	●	●	●	●	●	●
Michenerite (PdTeBi)	◆ ●			○				○
Merenskyite [(Pd, Pt)(Te, Bi)]	◆ ●	○	●	●	●	●	●	●
Moncheite [$Pt(Te, Bi)_2$]	◆ ●			○	○		○	○
Sobolevskite [Pd(Bi, Te)]		5		○				
Sopcheite ($Ag_4Pd_3Te_4$)		◇	○	○			○	
Pd_6AgTe_4				○		○	○	
Froodite ($PdBi_2$)	□ ●							
Telluropalladinite (Pd_9Te_4)							○	
Pd_5Te_2								○
Sperrylite ($PtAs_2$)	○	○	○	●	●	●	●	●
Laurite (RuS_2)							○	
Hollingworthite (RhAsS)			○	○	○	○	○	
Platarsite (PtAsS)				○				
Irarsite (IrAsS)				○		○	○	
Pd_3Tl							○	
(Pd, Pt, Ni, Fe)-As-O				○			○	
Cobaltite [(Co, Ni, Fe, Pd)AsS]			●	●		●	●	

Fig. 4. Minerals of the platinum metals at the Monchegorsk magmatic complex.

1, 2—data of (Grokhovskaya *et al.*, 1988, 1995, 2000, 2002) and from this paper: subordinate (1) and main (2) minerals; 3—data of (Yushko–Zakharova *et al.*, $1966_{1,2}$; 4—data of (Genkin *et al.*, 1963); 5—data of (Orsoev *et al.*, 1982).

* vein, pocket, and veinlet–disseminated sulfide Cu–Ni ores; ** vein Cu–Ni and disseminated ores of layer 330; *** disseminated PGE–Cu–Ni ores in the marginal series of the pegmatoid and poikilitic norites and of the diorites underlying the Monchegorsk pluton.

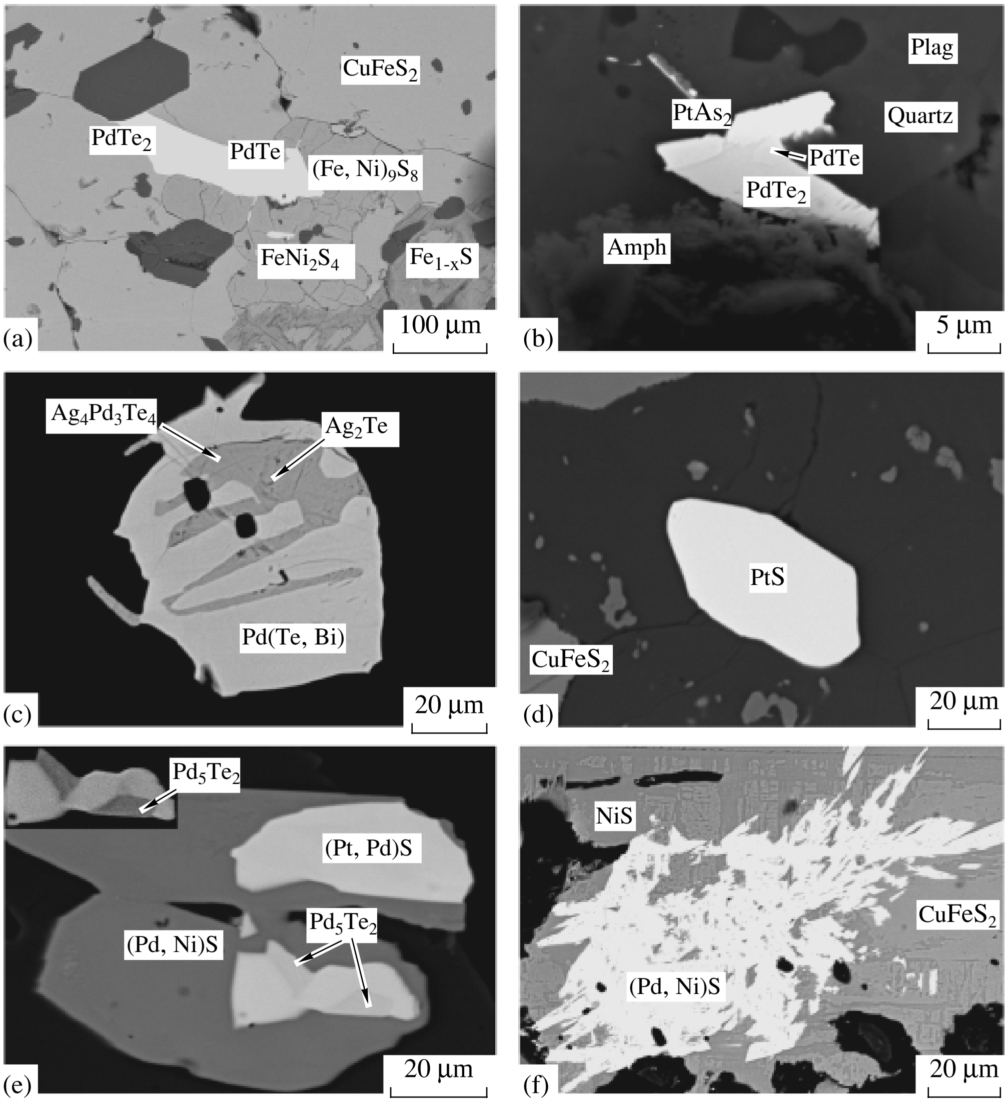

Fig. 5. Bismuthotellurides of Pt and Pd and minerals of the cooperite–braggite–vysotskite series from the low-sulfide PGE ore occurrences at the Monchegorsk magmatic complex. Images in backscattered electrons, JSM-5300 SEM. (a) Intergrowths of kotulskite with merenskyite hosted by chalcopyrite and pentlandite replaced in some degree by violarite, Pentlandite Creek; (b) sperrylite, merenskyite, and kotulskite grains in quartz–amphibole–plagioclase rock, the Yuzhnosopchinsk ore zone; (c) replacement of kotulskite with sopcheite and hessite, the Vuruchuaivench massif;(d–f) the Vostochno-Monchetundrovsk ore zone: (d) cooperite grain in rock-forming silicates hosting disseminated chalcopyrite; (e) intergrowth of the mineral (Pd_5Te_2) (inset in the upper left corner) with braggite and vysotskite hosted by chalcopyrite (black); (f) vysotskite grain in the millerite+chalcopyrite symplectite.

(Pd_5Te_2), or telluropalladinite (Pd_9Te_4), or keitkonite (($Pd_{3-x}Te$).

The telluropalladinite forms complicate intergrowths with Pt and Pd alloys that are found in heavy fractions of the PGE ores from the peridotites at the Vostochno–Monchetundrovsk ore zone.

Minerals of the System PtS–PdS–NiS

The Pt, Pd, and Ni sulfides occur in the disseminated ores related to the rhythmically layered zone of the Monchetundrovsk massif and in ore occurrences of the Vostochno–Monchetundrovsk and Yuzhnosopchinsk ore zones—from Pentlandite Creek at the north to Moroshko Lake at the SE (Fig. 1b).

Cooperite (PtS) occurs rarely as small grains (20 μm) in chalcopyrite, pentlandite, millerite, and the silicate matrix of the norites and gabbronorites (Fig. 5d). Braggite ((Pd, Pt)S) and vysotskite (Pd, Ni)S) form zonal aggregates or small irregular grains in silicates, chalcopyrite, and millerite (Fig. 5e). Vysotskite is common in pegmatoid gabbronorites at Pentlandite Creek as big intergrowths (100–150 μm) of platy grains in chalcopyrite, millerite, and rock-forming silicates

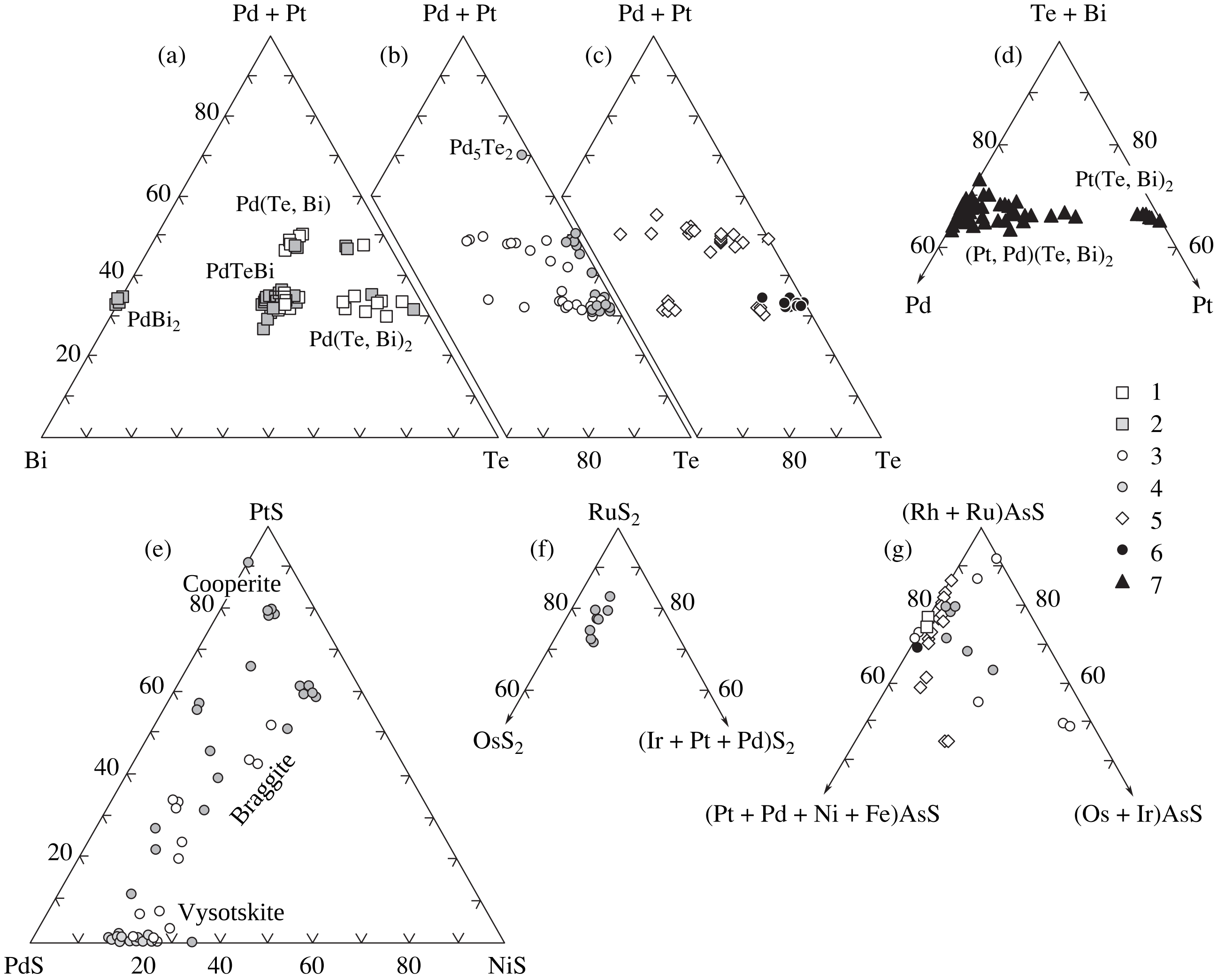

Fig. 6. Composition diagram of the PGE minerals in layered massifs at the Monchegorsk magmatic complex (wt %). (a–c) Palladium bismuthotellurides: (a) the Monchegorsk pluton; (b) the Vostochno-Monchetundrovsk and Yuzhnosopchinsk ore zones; (c) the Vuruchuaivench and Gabbro 10 anomaly massifs; (d) merenskyite, platinum merenskyite, and moncheite at the NKT massifs; (e) minerals of the braggite–cooperite–vysotskite series; (f) laurite from the Sopcheozersk deposit; (g) hollingworthite from the NKT occurrences. (1) disseminated PGE–Cu–Ni ore from the marginal series of the Monchegorsk pluton; (2) vein and veinlet–disseminated Cu–Ni ores from the NKT massifs; (3)–(6) PGE ores of the Yuzhnosopchinsk (3) and Vostochno-Monchetundrovsk (4) ore zones and the Vuruchuaivench (5) and Gabbro 10 anomaly (6) massifs; (7) PGE–Cu–Ni ores and PGE ores of the NKT massifs.

(Fig. 5f). The mineral composition varies, and an admixture of Os and Rh is estimated in braggite from the rhythmically layered zone of the Monchetundrovsk massif (Table 3; Fig. 6).

Minerals of the Systems Pd–Pb and Pd–Pb–S-Se

Minerals of these systems were found in the Monchegorsk magmatic complex for the first time. Zvyagintsevite (Pd_3Pb) was found as monomineral grains and intergrowths in chalcopyrite, bornite, and cobaltite and along fissures in pentlandite at the Yuzhnosopchinsk and Vostochno–Monchetundrovsk ore zones. Previously unknown palladium and lead sulfides and sulfoselenides $(Pd, Pb)_2S$ and $(Pd, Pb)_2(S, Se)$ occur in the veinlet–disseminated millerite–bornite–chalcopyrite ores at eastern part of the Yuzhnosopchinsk ore zone. The minerals form some complicated intergrowths with electrum and zvyagintsevite. Very small dimensions of grains and fine mutual intergrowths made impossible their x-ray diffraction study. The composition of the minerals is in good correspondence with the formula $(Pd, Pb)_2(S, Se)$ with some heightened metal content and variation of the S/Se ratio due to isomorphic substitution (Table 4; Figs. 7a–c).

Minerals of the System Pd–Ag-Te

The following silver and palladium tellurides were found in the Monchegorsk magmatic complex:

Table 4. Chemical composition of zvyagintsevite and mineral [$(Pd, Pb)_2(S, Se)$], wt %

No.	Sample numbers	Minerals	Fe	Cu	Pd	Pb	Se	S	Total
1	1819/105	Pd_3Pb	N.e.	0.47	62.29	38.0	N.e.	N.e.	100.76
2	10114	Pd_3Pb	″	1.19	62.49	37.97	″	″	101.65
3	″	$(Pd_{1.24}, Pb_{0.8})_2S_{0.97}$	0.53	2.54	40.57	48.44	″	9.43	101.51
4	″	$(Pd_{1.27}, Pb_{0.79})_{2.06}S_{0.94}$	0.59	2.76	39.87	48.35	″	8.94	100.51
5	″	$(Pd_{1.3}, Pb_{0.7})_2(S_{0.76}, Se_{0.2})_{0.96}$	0.93	3.1	39.5	44.89	4.49	7.07	99.98
6	″	$(Pd_{1.27}, Pb_{0.79})_{2.07}(S_{0.66}, Se_{0.28})_{0.93}$	0.69	2.51	38.24	46.44	6.16	5.94	99.98
7	″	$(Pd_{1.29}, Pb_{0.76})_{2.05}(S_{0.77}, Se_{0.17})_{0.95}$	N.e.	2.11	39.49	45.25	3.88	7.13	97.86

Note: 1, the Vostochno–Monchetundrovsk ore zone; 2–7, the Yuzhnosopchinsk ore zone, zvyagintsevite intergrowths with [$(Pd, Pb)_2(S, Se)$] and electrum (Figs. 7a–7c).
N.e.—not estimated.

sopcheite ($Ag_4Pd_3Te_4$) and mineral Pd_6AgTe_4. Latter was found in the Lukkulaisvaara massif (Grokhovskaya *et al.*, 1992). Sopcheite forms complicated intergrowths with merenskyite, kotulskite, and hessite in ores at the Nyud–Poaz and Vuruchuaivench massifs (Fig. 5c). The mineral Pd_6AgTe_4 occurs in intergrowths with kotulskite, sperrylite, and palarstanide, and the alloy Cu_3Pd from the PGE occurrences at the Vostochno–Monchetundrovsk and Yuzhnosopchinsk ore zones (Table 5; Figs. 7e, 7f).

Minerals of the Systems Pd–As–Sb and Pd–As-Ni

The following minerals related to these systems were found in the Monchegorsk complex: guanglinite, mayakite, menshikovite ($Ni_3Pd_2As_3$), a mineral $Ni_6Pd_2As_3$, and the unknown previously in nature $Pd_2(As, Sb)$ and $Pd_3(As, Sb)_2$. The minerals form monomineral grains and complicated intergrowths composed the same minerals (Fig. 8).

Guanglinite (Pd_3As) forms small grains (1–5 μm) in chalcopyrite, millerite, and cobaltite in gabbronorites of the Vuruchuaivench massif. It contains an admixture of Hg and Au (Grokhovskaya *et al.*, 2000). In the Yuzhnosopchinsk and Vostochno–Monchetundrovsk ore zones, this mineral intergrows with kotulskite, sperrylite, and palarstanide. In heavy mineral concentrates it was found as monomineral grains (up to 40 μm).

In the PGE ores at the Vuruchuaivench, massif, polymineral intergrowths of palladoarsenide (Pd_2As), the mineral $Pd_2(As, Sb)$, and menshikovite ($Ni_3Pd_2As_3$) are common. This paragenesis was found in polished samples (Grokhovskaya *et al.*, 2000) and in heavy fractions of rich PGE ores (30 intergrowths). Nickeline, kotulskite, stibiopalladinite (Pd_5Sb_2), isomertieite ($Pd_{11}As_2Sb_2$), sobolevskite, and electrum occur in such intergrowths. The majority of grains of the intergrowths are oval or spherical and are bordered with replacing rims composed of cobaltite and gersdorffite (Figs. 8a, 8c). These intergrowths concentrate in chalcopyrite and at its contacts with millerite, pentlandite, bornite, sphalerite, pyrite, and rock-forming silicates. Probably, the intergrowths of menshikovite with PGE minerals at the Chineisk massif have similar composition and structure (Barkov *et al.*, 2002). The mineral $Pd_2(As, Sb)$ appears to be an antimony variety of palladarsenide.

The polymineral intergrowths of PGE minerals of the Vostochno–Monchetundrovsk ore zone form irregular grains consisting of isomertieite, sperrylite, kotulskite, and hollingworthite and associate with pentlandite and chalcopyrite (Fig. 8e), but the matrix of these intergrowths is composed at an unknown mineral corresponding in composition to $Ni_6Pd_2As_3$.

An unknown previously mineral $Pd_3(As, Sb)_2$ was found in heavy fractions of the PGE ores from the Vuruchuaivench massif as irregularly shaped white grains and in some places in intergrowths with kotulskite. The mineral is replaced along fissures by palladium and iron arsenate (Table 5; Fig. 8d).

The composition of the studied minerals of these systems is shown in diagrams (Figs. 9a, 9b). Minerals of the system Pd–As–Sb have similar compositions and optical characteristics, but separate groups of arsenides and arsenoantimonides are distinctly visible in the diagram (Fig. 9a).

Arsenotellurides were found for first time at the Moroshko Lake occurrence of the Yuzhnosopchinsk ore zone and have to be studied. In the heavy fractions, 14 grains of the minerals varying from 5 to 80 μm were found both as monomineral and in intergrowths with sperrylite and chalcopyrite (Fig. 8e). The stoichiometric composition of the minerals varies, but tightly corresponds to the formulas $Pd_3(As, Te)$ and $Pd_5(As, Te)_2$ (Table 5, Fig. 9c).

Minerals of the Systems Pt–Sn and Pd–Sn-As

Niggliite, stannopalladinite, and palarstanide occur at the Monchegorsk magmatic complex. Niggliite (PtSn) has a constant composition and forms inter-

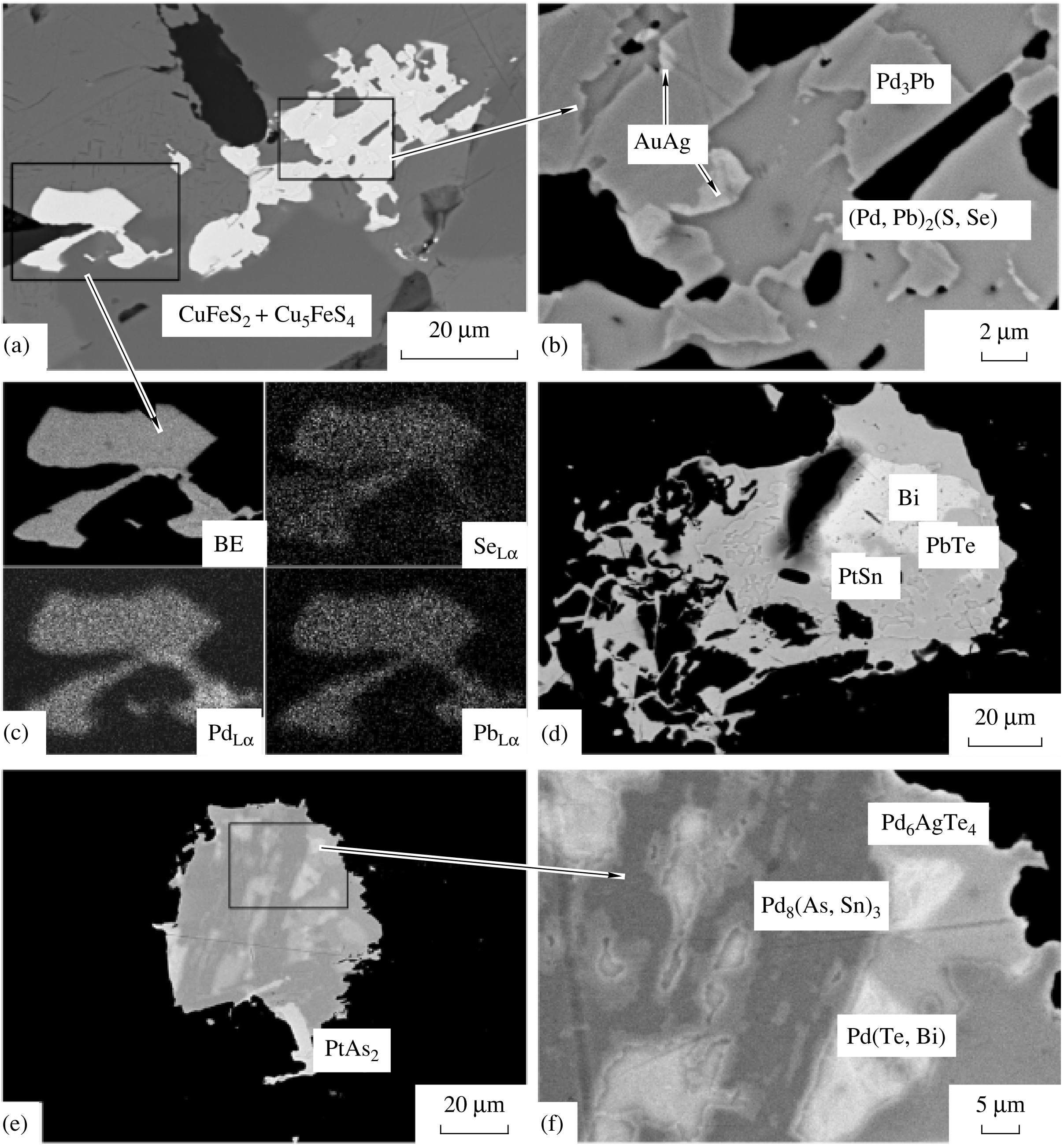

Fig. 7. Microphotographs of the platinum metal minerals in backscattered electrons and in characteristic x-ray radiation, JSM-5300 SEM. (a–c) Polymineral intergrowths of zvyagintsevite with electrum and unknown phase (Pd_6AgTe_4) hosted by the bornite–millerite–chalcopyrite assemblage from the Yuzhnosopchinsk ore zone (polished lump 10114): (a) general view; (b) enlarged fragment; (c) fragment in characteristic x-ray radiation; (d) intergrowth of niggliite with altaite and native Bi hosted by chalcopyrite (black) vein ore from the NKT massif; (e) intergrowth of sperrylite, kotulskite, palarstanide, and mineral (Pd_6AgTe_4) hosted by the bornite–millerite–chalcopyrite assemblage from the Yuzhnosopchinsk ore zone (polished lump 954/166); (f) enlargement of fragment e.

growths with native bismuth and altaite in vein ores of the NKT occurrences (Table 5; Fig. 7d). Stannopalladinite (Pd_8Sn_3) was known in the vein ores of the NKT occurrences (Yushko–Zakharova *et al.*, 1966). Stannopalladinite forms intergrowths with telluropalladinite, pentlandite, and alloys (Cu, Fe)$_3$(Pt, Pd) in peridotites of the Vostochno–Monchetundrovsk ore zone. Palarstanide ($Pd_8(As, Sn)_3$) forms complicated polymineral intergrowths with kotulskite, sperrylite, guanglinite, Cu_3Pd, and Pd_6AgTe_4 hosted by chalcopyrite and millerite at the Vostochno–Monchetundrovsk and Yuzhnosopchinsk ore zones (Figs. 7d, 7e).

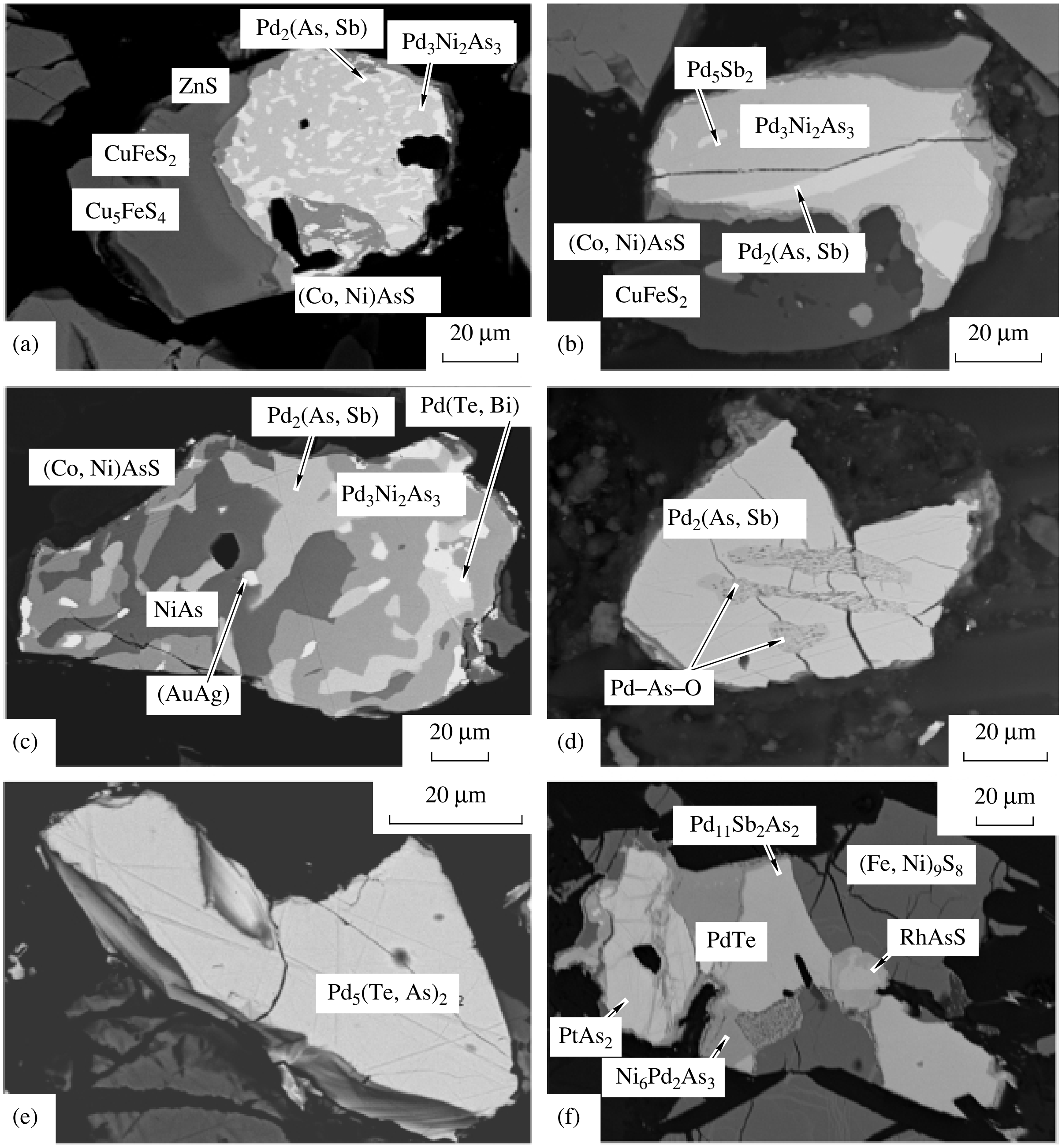

Fig. 8. Microphotographs of the platinum metal minerals from the PGE occurrences at the Monchegorsk magmatic complex in back-scattered electrons, JSM-5300 SEM. (a–d) The Vuruchuaivench massif: (a) intergrowths of menshikovite, mineral [Pd_2(As, Sb)] and cobaltite associated with bornite, chalcopyrite, and sphalerite; (b) intergrowth of menshikovite, mineral [Pd_2(As, Sb)], and stibiopalladinite with cobaltite rim hosted by amphibole (dark gray); (c) polymineral intergrowth of nickeline, menshikovite, mineral [Pd_2(As, Sb)], kotulskite, and electrum replaced by cobaltite; (d) grain of [Pd_2(As, Sb)] replaced by palladium arsenate; (e) grain of the mineral [Pd_2(As, Sb)] from the Yuzhnosopchinsk ore zone; (f) polymineral intergrowth of sperrylite, hollingworthite, kotulskite, isomertieite, [Pd_5(Te, As)$_2$], and pentlandite in the amphibole matrix of the rock from the Vostochno-Monchetundrovsk ore zone (polished lump 1819/101.4). (a–e) polished preparations from the heavy mineral fractions.

Minerals of the System Rh–Ir–Pt–(Os, Ru, Pd)–As–S

Hollingworthite ((Rh, Ir, Pt, Ru, Os, Pd)AsS) occurs in sulfides, nickel and cobalt sulfarsenides, and rock-forming silicates as separate grains and intergrowths with PGE minerals in all PGE occurrences of the Monchegorsk magmatic complex (Fig. 8f). Some hollingworthite crystals are heterogeneous, varying in PGE content and including irarsite (IrAsS) grains. Chemical heterogeneighty and especially variation in Pt, Rh, Ir, and Os contents are typical for the studied

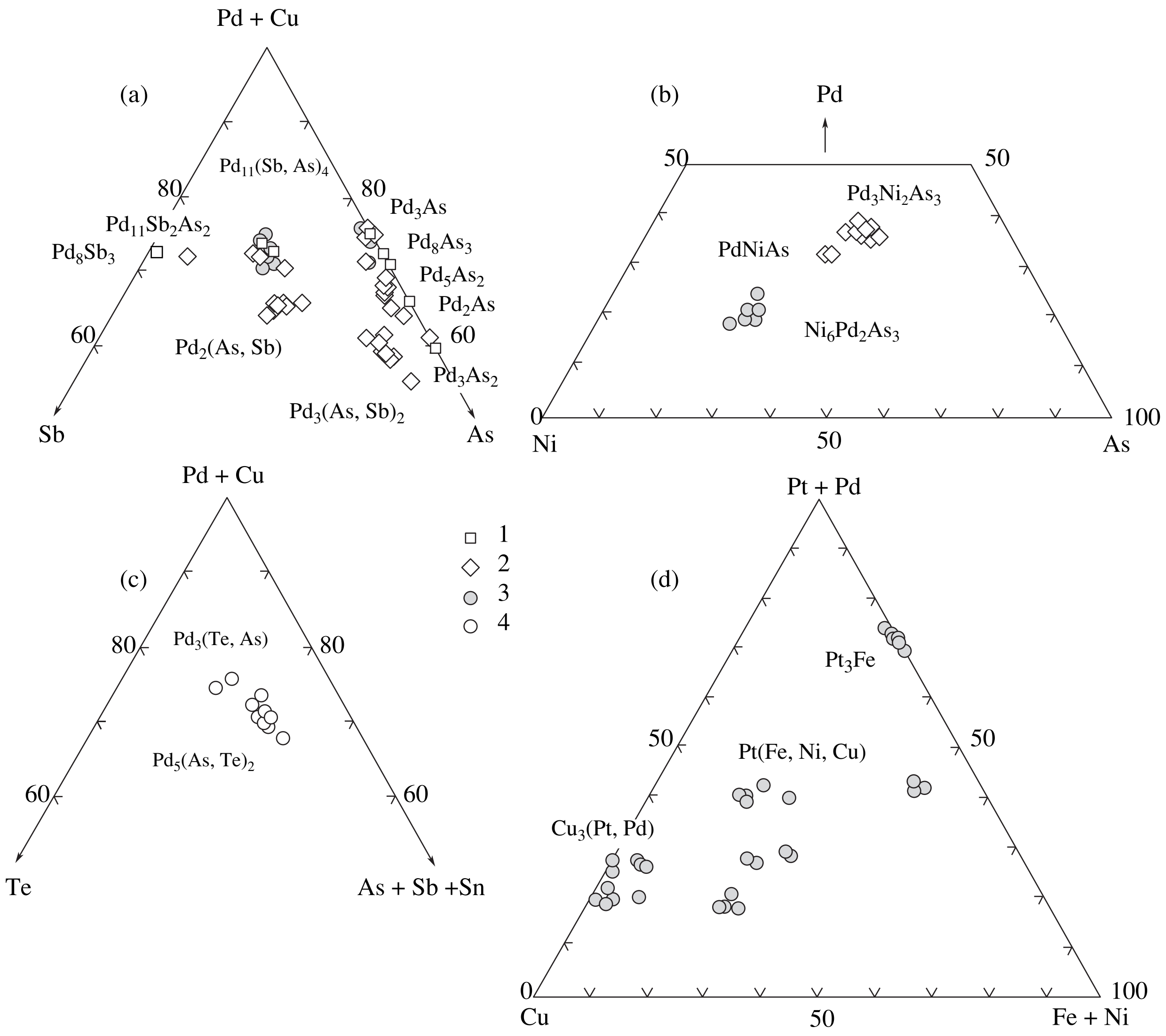

Fig. 9. Platinum metal mineral composition at the layered massifs of the Monchegorsk magmatic complex (at. %).
(a–c) Minerals of the systems (a) Pd(+Cu)–As-Sb, (b) Pd–Ni-As, and (c) Pd(+Cu)–As–Te; (d) alloys with varying composition Cu–(Pt + Pd)–(Fe + Ni). 1—ideal mineral compositions; 2—the Vuruchuaivench massif; 3—the Vostochno-Monchetundrovsk ore zone; 4—the Yuzhnosopchinsk ore zone.

hollingworthite. In the peridotites and chromitites interlayering at the Vostochno–Monchetundrovsk ore zone the mineral contains high Ru, that is not typical for other ore occurrences (Fig. 6–g).

PGE Minerals of Some Other Systems

Laurite ((Ru, Os)S_2) forms small inclusions in chromspinelides in chromitite layers at the Sopcheozersk deposit. It contains to 14 wt % Os (Table 4, Fig. 6f).

Sperryite ($PtAs_2$) is one of the main Pt phases in the low-sulfide PGE ores of the Monchegorsk magmatic complex. It forms numerous monomineral aggregates from 1–3 to 150 µm and polymineral intergrowths with PGE minerals hosted by sulfides and silicates (Figs. 5b and 8f). Sperryite commonly associates with hollingworthite and bismuthotellurides of Pd and other PGE. Sperryite is considered as a stable mineral, and its composition is rather constant, with a small admixture of Rh (up to 2 wt %). The authors found 80 grains of sperrylite in polished samples and heavy mineral concentrates from the ores at the Vostochno–Monchetundrovsk ore zone. The mineral intergrows with PGE minerals, and their relationships are uniform in all samples. Sperrylite in all studied intergrowths is fissured, and fissures are filled with nickel arsenide Ni_2As, alloys Fe–Ni–Pt, and Cu_3Pt (Table 6; Figs. 8f, 10a, 10b).

Isoferroplatinum (Pt_3Fe) was found in the PGE ores in peridotites, pyroxenites, and norites at the Vos-

Table 5. Chemical composition of minerals of Pd and Pt from the Monchegorsk magmatic complex

No.	Borehole numbers	Minerals	Pd	Pt	Ni	Cu	Fe	Ag	As	Sb	Te	Sn	O	Total
1	1819/101.4	Mertieite	67.71	N.e.	1.86	4.73	N.e.	N.e.	11.05	15.63	N.e.	N.e.	N.e.	100.98
2	″	Guanglinite	80.35	″	N.e.	2.14	″	″	16.63	N.e.	″	″	″	99.12
3	″	$Ni_6Pd_2As_3$	27.96	″	43.85	N.e.	″	″	28.19	″	″	″	″	100.01
4	1844/35	$Pd_3Ni_2As_3$	48.54	″	17.92	″	″	″	34.47	″	″	″	″	101.05
5	1803/65.8	Majakite	46.88	″	20.58	″	″	″	31.36	″	″	″	″	98.82
6	1844/35	Palladoarsenite	72.1	″	0.15	″	0.14	″	25.08	3.1	″	″	″	100.57
7	″	$Pd_2(As, Sb)$	67.56	″	N.e.	″	N.e.	″	14.47	18.85	″	″	″	100.88
8	″	$Pd_3(As, Sb)_2$	64.58	″	2.05	″	0.1	″	25.35	7.99	″	″	″	100.07
9	″	$Pd_2(As, Sb)$	65.45	″	0.78	″	″	″	13.49	20.69	″	″	″	100.41
10	″	$Pd_5(As, Sb)_2$	73.77	″	N.e.	″	″	″	23.46	2.99	″	″	″	100.22
11	″	Isomertieite	74.32	″	″	″	″	″	9.85	16.67	″	″	″	100.84
12	″	Stibiopalladinite	68.7	″	1.04	″	″	″	3.84	25.69	″	″	″	99.27
13	954/166	Guanglinite	80.16	″	N.e.	″	″	″	17	N.e.	″	4.39	″	101.55
14	″	Palladoarsenite	67.04	″	″	0.59	0.81	″	13.87	″	″	11.7	″	99.6
15	10202	Arsenopalladinite	75.88	″	″	1.5	N.e.	″	22.13	″	1.41	N.e.	″	100.92
16	10114	$Pd_3(As, Te)$	74.23	″	″	″	″	″	8.06	″	16.2	N.e.	″	98.49
17	3/188.0	Stannopalladinite	61.77	3.07	″	7.11	″	″	1.58	1.76	6.83	21.31	″	103.43
18	599/148.0	Niggliite	1.13	53.55	″	N.e.	″	″	N.e.	N.e.	N.e.	45.67	″	100.35
19	1296/274.5	Sopcheite	26.82	N.e.	″	N.e.	″	34.82	″	″	41.7	N.e.	″	103.34
20	954/166	Pd_6AgTe_4	50.99	″	″	0.69	″	7.19	″	″	42.06	″	″	100.93
21	1819/101.4	Pd_6AgTe_4	47.87	″	″	3.88	″	7.18	″	″	43.97	″	″	102.90
22	1844/35	(Pd, Fe)-As-O	62.07	″	0.58	0.94	8.19	″	13.70	″	N.e.	″	13.72	99.20
23	1844/35	″	68.41	″	N.e.	N.e.	3.24	″	15.90	″	″	″	8.39	95.93
24	1819/101.4	(Pt, Ni, Cu)-As-O	N.e.	23.51	41.14	6.14	1.85	″	14.67	″	″	″	10.86	98.16

Note: N.e., not estimated.
1–3, 17, 21, and 24, the Vostochno-Monchetundrovsk ore zone; 4–12, 19, 22, and 23, the Vuruchuaivench massif; 13–16 and 20, the Yuzhnosopchinsk ore zone (15 and 16: open pit samples); 19, the Nittis massif. In analysis 14, Au content is estimated to be 5.1 wt %. In analyses 24–26, the oxygen is directly determined with a JSM-5300 SEM.

Table 6. Chemical composition of the Pt and Pd alloys at the Vostochno-Monchetundrovsk ore zone occurrences (wt %)

No.	Borehole numbers	Minerals	Pt	Pd	Cu	Fe	Ni	Total
1	1818/21.0	Pt_3Fe	88.76	N.e.	0.44	8.46	0.12	97.78
2	3/188	"	87.31	"	N.e.	10.07	N.e.	100.81
3	1819/101.4	Cu_3Pd	N.e.	30.55	54.94	1.12	1.53	92.13
4	"	PtCu	79.90	N.e.	11.66	4.34	6.28	102.18
5	"	Cu_3Pt	39.09	0.3	40.95	9.63	9.1	99.07
6	"	PtCuFeNi	64.06	N.e.	6.10	13.14	7.81	91.11
7	3/188	"	49.06	14.04	26.69	10.19	N.e.	99.99
8	"	"	44.33	15.85	25.74	8.68	0.68	95.28
9	"	"	34.38	4.29	56.19	2.96	0.09	97.91

Note: N.e., not estimated.
Analyses 3, 6, and 8 are semiquantitative, because the grain size is less than the microanalyzer beam diameter. Some additional components are estimated in the following analyses (wt %): 2, Ir (3.43); 3, Al (3.33) and Si (0.66); 5, Rh (0.64); and 6, Rh (1.32).

tochno–Monchetundrovsk ore zone. It forms large monomineral grains and intergrowths with bismuthotellurides of Pd hosted by sulfides, magnetite, and rock-forming silicates (Fig. 10c). Its composition is constant (Table 6; Fig. 9d).

Minerals Cu_3Pt, Cu_3Pd, and alloys of Pd and Pt with Cu, Fe, and Ni with varying composition were found in the heavy mineral concentrates and polished samples from the ores at the Vostochno–Monchetundrovsk zone. The minerals intergrow with sperrylite, Ni_2As, millerite, pentlandite, and amphybole (Table 6; Fig. 10). The phase Cu_3Pd forms thin plates in pentlandite and millerite and at contacts of sulfides with rock-forming silicates (Fig. 10d).

Polycomponent sulfides (Cu, Pt, Pd, Fe)S and $(Cu, Pt, Pd, Fe)_2S$ (Fig. 10e) were found in peridotites of the Vostochno–Monchetundrovsk ore zone. They replace Cu–Pt–Pd–Fe alloys from the grain boundaries and along fissures. The replacement is accompanied with removal of Pd, Cu, and Fe from the alloys with conservation of Pt (Tables 3 and 6).

Minerals (Pt, Fe)–As–O and (Pd, Ni, Fe)–As–O were found for the first time in the heavy mineral concentrates from samples at the Vostochno–Monchetundrovsk ore zone and the Vuruchuaivench massif. In the PGE ores of the Vuruchuaivench, the phase (Pd, Ni, Fe)–As–O intergrows with palladoarsenide, the mineral $Pd_3(As, Sb)_2$, and kotulskite and replaces $Pd_3(As, Sb)_2$ along fissures (Fig. 8d). The minerals vary in composition, and after direct determinations of oxygen, they were related to arsenates; however their systematics needs further study (Table 5). A mineral with similar composition was found earlier in intergrowths with arsenopalladinite and $(Pd, Cu)_7(As)_2$ from the Konttijarvi area (Northern Finland) (Vuorelainen *et al.*, 1982).

The mineral Pd_3Tl was found in hollingworthite at the Vostochno–Monchetundrovsk ore zone. Its grains are very small (less than 3 μm), and thus the microanalyzer beam takes the surrounding hollingworthite as well as the measured grain. Therefore, the mineral composition was estimated only qualitatively. A mineral with similar composition occurs in the Merensky Reef at the Bushveld Complex (Kinloch, 1982).

Gold and Silver Minerals

The Ag–Au minerals form close assemblages with PGE minerals and occur in all types of ores at the Monchegorsk magmatic complex. Native gold, silver, electrum, and kustellite occur in intergrowths with PGE minerals.

The alloys Pt–Pd–Au–Ag were found in metasomatically altered chromitites at the Sopcheozersk deposit. The minerals occur in the intercumulus of chromspinel as very small grains (1–3 μm) in an assemblage with argentite and native silver. The alloy composition was estimated qualitatively, because the measured grains are very small. The composition of one grain recalculated to 100% corresponds (in wt %) to Pd, 62.45; Ag, 27.01; Pt, 7.0; and Au, 2.47. Millerite, heazlewoodite, galena, argentite, and native copper with an admixture of PGE occur in altered chromitites as well.

Electrum (AuAg) is common in all ore types at the Monchegorsk complex. It occurs in chalcopyrite and pyrite as grains varying from 1–3 to 80 μm, and in intergrowths with PGE minerals (Figs. 7a, 7b, 8c).

Native silver forms many small monomineral grains in bornite and chalcopyrite in ores at the Yuzhnosopchinsk ore zone (Fig. 10g). At the Vostochno–Monchetundrovsk zone, occurrences of many grains of native silver, argentite, and silver chlorides associated with native bismuth were found in heavy mineral concentrates (Fig. 10f).

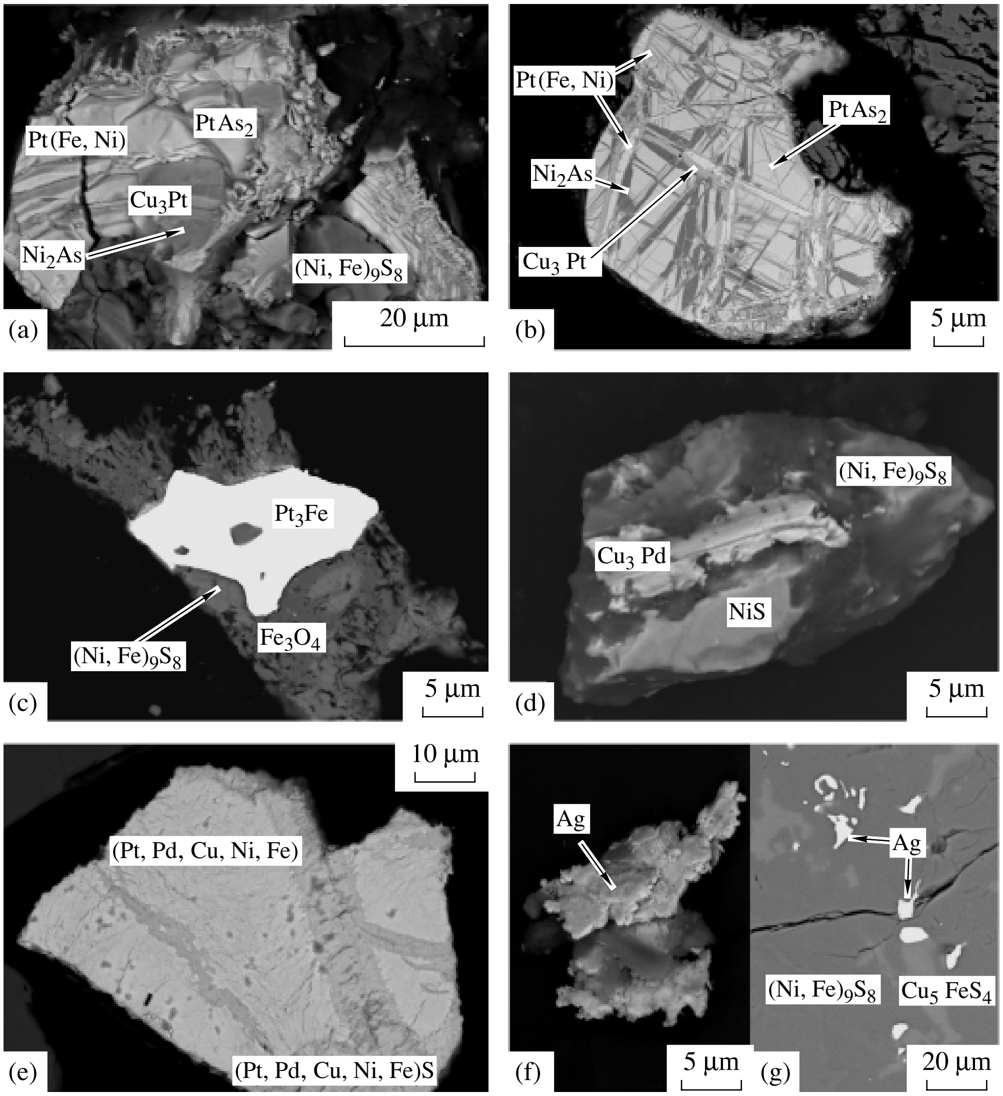

Fig. 10. Microphotographs of the noble metal minerals from the PGE occurrences at the Vostochno-Monchetundrovsk (a–f) and the Yuzhnosopchinsk (g) ore zones in backscattered electrons, JSM-5300 SEM. (a, b) Intergrowths of sperrylite, pentlandite, and minerals (Pt–Cu–Fe–Ni), (Cu_3Pt), and (Ni_2As); (c) isoferroplatinum grain in magnetite and pentlandite; (d) intergrowth of pentlandite, millerite, and (Cu_3Pd) in silicates (dark gray); (e) replacement of the alloy (Pt–Pd–Cu–Ni–Fe) by sulfide (Pt, Pd, Cu, Ni, Fe)S; (f) native silver; (g) native silver in pentlandite and millerite; (a, d, f) grains from the heavy mineral fraction mounted on carbonaceous scotch; (b, c, e) polished preparation from the heavy mineral fraction; (g) polished sample 1824/177.0.

CONCLUSIONS

The exclusively wide association of mineral species and assemblages of the PGE minerals found in the study relate to the complicated geological structure and tectonic evolution of the Monchegorsk magmatic complex area. The tectonic regime of the region in the Early Proterozoic defined its position in the inner angle of the rift–transform fault system. In such systems, tectonic conditions favored prolonged heating and repeated intrusions of magmatic melts, according to published data for recent continental and oceanic rifts. These environments are similar to those occurring in the plume geodynamics. According to Kazansky *et al.* (2002) such conditions could be the most important factor in formation of big base and noble metal deposits in the Pechenga volcano–tectonic structure.

In the low-sulfide occurrences at the Vostochno–Monchetundrovsk and Yuzhnosopchinsk ore zones, the PGE distribution is very irregular. The highest PGE contents relate to the metasomatically altered rocks. New PGE mineral types were found there: palladium and platinum arsenates and palladium and lead sulfoselenides.

The PGE mineralization was deposited at various stages of the layered intrusions of the Monchegorsk complex formation. Every stage was characterized with a specific association of predominant PGE mineral species. Tellurides and bismuthotellurides of Pt and Pd are common at the early stages, when other mineral groups scarcely formed. Thus, the main Pt mineral in disseminated and vein ores of the Monchegorsk pluton is moncheite, but sperrylite and niggliite are accessory minerals. In the rhythmically layered rocks of the Monchetundrovsk massif, the content of braggite–cooperite–vysotskite minerals increases, as well as that of palladium bismuthotellurides. At the late stages, especially in the tectonically permeable zones, physicochemical conditions changed and the fluid–hydrothermal solutions became enriched with As, Sb, Sn, Pb, and Se. In the Vostochno–Monchetundrovsk zone, PGE arsenides, antimonides, and alloys were formed. All rocks at all ore zones underwent the latest hydrothermal processes. As a result, heightened contents of silver and, in part, gold were formed and native silver, argentite, naumannite, and selenides of Pd and Pb were deposited. Uncommon for chromitite layers, alloys of Pd with Ag, Cu, and Au also probably relate to hydrothermal processes. They were found in chromitites at the Sopcheozersk deposit.

ACKNOWLEDGMENTS

The authors thank N.S. Bortnikov, A.D. Genkin, V.I. Kazansky, I.V. Murav'eva, and A.V. Tevelev for discussion and helpful remarks.

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