# The PGE-Bearing Sulphide Ores of the Kingash Mafic-Ultramafic Differentiated Intrusion and Ore Processing Characteristics, East Sajan, Russia

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The Kingash PGE-bearing Cu-Ni deposit occurs in the Kingash layered intrusion located within the eastern part of the Kansky greenstone belt, East Sajan Mountain land of the East Siberia. The metamorphic host rocks belong to the Karagan series (AR-$PR_1$) and are represented by mica, amphibole and garnet-bearing gneisses with interbeds of amphibolites, marbles, quartzites and amphibole schists.

The intrusion has a lenslike shape and, in its present plane of erosion, covers an area of 2.5 $km^2$, being confined to the north-eastern flank of a large anticline and controlled by faults striking north-west. The intrusive body has tectonic contacts with host rocks. Within the layered intrusion, three zones have been recognized: 1) the lower peridotite zone, 2) the intermediate pyroxenite zone, and 3) the upper gabbro zone, having a cumulative thickness of more than 1000 m. The peridotite zone is porly layered and consists of serpentinized dunite and wehrlite. The pyroxenite zone is a transition zone from ultramafic rocks to gabbroic ones and is distinctly layered, consisting of frequently inter-bedded rhythmic units represented by pyroxenites, peridotites and gabbro. The upper gabbro zone is composed of metamorphic rocks, which belong to the epidote-amphibolite facies. The igneous rocks underwent four stages of metamorphic alteration: autometamorphism, regional metamorphism, contact metamorphism and hydrothermal meta-morphism. The intrusion is cut by the numerous dikes of acid (granite, granodiorite, albitite, plagioclase granite), intermediate (diorite, plagioclase diorite) and basic (microgabbro, hornblendite, spessartite) compositions. Moreover, the acid dikes are youngest and prevailing in amount.

The Cu-Ni mineralization occurs in mafic-ultramafic layered rocks and, to a much lesser degree, in exocontact gneisses and amphibolites, but Cu-Ni sulphide ores are confined to peridotites. The gabbro zone carries fine, weak dissemination mostly of pyrite and magnetite.

The sulphide ores are represented by disseminated, breccia and massive ore types. The disseminated ore is dominant and occurs in the lower and middle portions of the peridotite zone composed of dunite, wehrlite and serpentinite. The thickness of the orebodies ranges from 5 m to 270 m, and the sulphide content increases downward from 1-2 vol.% to 15-20 vol.%. On the textural basis, disseminated ores are subdivided into weakly-disseminated, strongly-disseminated, schlieren-disseminated, and stringer-disseminated varieties. The sulphide-dissemination size ranges from tenths of millimeter to 2-3 cantimeter in diameter. The major ore minerals are pyrrhotite (50%), pentlandite (up to 20%) with subordinate amount of chalcopyrite and magnetite (up to 10%); minor and accessory minerals include chrome spinel, valleriite, violarite, cubanite, mackinawite, altaite, melonite, gersdorffite-cobaltite, nickeline, millerite, ilmenite, sphalerite, galena, clausthalite, bornite, pyrite, markasite, molibdenite, talnakhite, Co- and Cu-bearing pentlandite, awaruite, native Cu, Au-Ag alloys and PGM. In the disseminated ores, three mineral varieties are recognized: pyrrhotite-valleriite-pentlandite, pyrrhotite-pent-landite and chalcopyrite-pentlandite-pyrrhotite. The disseminated ore grades 0.3 to 1.4% Ni, 0.1 to 0.7 % Cu and 0.005 to 0.3 % Co.

The massive ore occurs as veins with thickness ranging from a few to eighty centimeters. The major ore minerals are pentlandite, chalcopyrite and pyrrhotite; minor and accessory minerals include magnetite, ilmenite, cubanite, bornite, mackinawite, valleriite, pyrite, sphalerite, millerite, molibdenite, gersdorffite, maucherite, nickeline and PGM. The ore grades 6.05% Ni, 2.46% Cu, and 0.14% Co. Together with the massive ore, breccia-matrix ores occur in ultramafic rocks, with thickness ranging from 0.8 to 3.1 m. These ores are most abundant in various ore-mineral species: major minerals are represented pyrrhotite (10 to 35%), pentlandite (15 to 20%), chalcopyrite and cubanite (10%, each); minor minerals are mackinawite, pyrite, magnetite, bornite, ilmenite, valleriite, sphalerite: rare minerals are represented by various arsenides, sulpharsenides, tellurides, Au-Ag alloys and PGM.

The breccia-matrix ore grades up to 3.95% Ni, 0.95% Cu, and 0.094% Co. The massive and breccia ores are mainly confined to the interlayer slip faults, steeply-dipping normal faults and exocontact zones of the acid dikes.

The distribution of PGE in sulphide ores is characterized by the following features: maximum concentrations of Pt, Os and Ir are observed in disseminated ores, whereas the Pd, Rh and Ru concentrations favor massive and breccia-matrix ores. As a result, the platinum shows a positive correlation with Ni and Fe, while palladium, with Cu, Co and S. The Ni/Cu ratio in sulphide ores attains 2-3:1, Ni/Co, 20-40:1, and Pt/Pd, from 4:1 to 1:2 (in average 2:1). The proportions of PGE in ores are defined by the ratio Pt:Pd:Os:Ru:Rh:Ir = 48:46:16:9:4:1.

The PGM are distributed unevenly in the ores types. The breccia-matrix cubanite-chalcopyrite ore occurring in the lower zone contains the maximum concentrations of various PGM, particularly Pd-bearing species. In the disseminated ore, practically only sperrylite was found with rare tetraferroplatinum and moncheite grains.

Among the PGM found, sperrylite and Pd bismuthotellurides such as michenerite, merenskyite and sobolevskite are dominant; kotulskite, froodite, moncheite, paolovite, stibiopal-ladinite and mertieite II are in subordinate quantities, while tetraferroplatinum, irarsite, irid-arsenite, erlichmanite, cabriite and unnamed $Pd_2(Bi,Sb)$ and $Pd_7Sb_2$ are of limited occurrence.

Sperrylite forms euhedral grains, up to 0.25 mm in diameter. It constitutes intergrowths with crome spinel, magnetite, chalcopyrite, pentlandite and other PGM. Sperrylite contains up to 0.18% Os, up to 4.4% Ir, up to 1.38% Rh, up to 0.42 Sb, and up to 0.39% S.

The main carriers of Pd are michenerite and merenskyite, which are abundant in sulphide ores. They frequently associate with each other and altaite, hessite and melonite. Both minerals form relatively large, up to 0.25 mm in diameter, equant and oval grains and contain Pt, up to 9.85 in michenerite and up to 4.97% in merenskyite. In addition, merenskyite constitutes an isomorphic series with melonite, members of which contain from 10.35 to 21.65% Pd and from 3.44 to 11.33% Ni.

Sobolevskite is the only PGM which was found not only in the ore confined to ultramafic rocks but also in the acid dike. It is frequently intergrown with hessite, altaite, nickeline and michenerite, as well as it forms single grains ranging up to 0.1 mm in diameter. Sobolevskite analyses sometimes show increased Sb, up to 7.67%.

Kotulskite and froodite are rare PGM and were found in breccia chalcopyrite ore, where they form minute grains, < 0.01 mm in diameter. Kotulskite, as a rule, contains high Bi, up to 38.4%. Stibiopalladinite forms relatively large equant grains ranging 0.025 to 0.55 mm in diameter. It is associated with Au alloys and, in places, with amphibole and contains 0.11 to 0.83% Pt, up to 1.58% Te and 0.34 to 1.63% As.

Mertieite II, moncheite and tetraferro-platinum are restricted, forming minute single grains. Mertieite II contains increased As, 1.73 to 3.23%, and moncheite contains up to 0.94% Pd.
The Pd stannides, paolovite and cabriite, are also of limited occurrence and were observed as minuscule grains (0.007x0.006 mm) in pyrrhotite of disseminated and breccia ores.

The high-temperature PGE, Ir, Os and Ru, occur as discrete minerals such as irarsite, iridarsenite and erlichmanite. These form equant grains, <0.01 mm in diameter, in disseminated and breccia ores as well as in the exocontact gneisses. Erlichmanite contains up to 13.44% Ru. Besides, the members of gersdorffite-cobaltite series carry high Os and Ru, 4.82% and 7.92%, respectively.

Several ore samples, which were obtained from sulphide-mineralized drill core representing the disseminated ores occurring in the lower zone ultramafics, were processed using a bulk flotation flow sheet. The flotation feed grades range 0.35 to 0.78% Ni, 0.17 to 0.47% Cu, 0.016 to 0.0195 % Co, 0.23 to 1.4 ppm Pd, 0.12 to 1.32 ppm Pt, 1.2 to 5.32 ppm Ag and up to 0.23 ppm Au. As a result of flotation, the final products contain 6.44 to 8.04 % Ni, 2.02 to 5.68% Cu, 0.17 to 0.28% Co, up to 10.6 ppm Pt, up to 13.1 ppm Pd, up to 54.7 ppm Ag and up to 1.5 ppm Au, with the metal recovery ranging 60.88 to 78.51%, 77.7 to 84.5%, 55.5 to 71.8%, 51 to 93.4%, 50 to 80.46%, 58 to 88.7% and up to 55%, respectively.

For mineralogical purposes, the flotation products were concentrated using gravity techniques. Examination of polished sections prepared from the sized gravity concentrates revealed that the absolutely dominant PGM in concentrates are sperrylite and the merenskyite-melonite series species, which account for 99% of total PGM. The other major PGM reported to the gravity concentrates include sobolevskite, mich-enerite and stibiopalladinite, whereas others are rare. The majority of PGM grains range from 20 to 60 μm in diameter and only few are > 200 μm.