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# Platinum-Copper-Nickel and Platinum Ores of Norilsk Region and Their Ore Mineralization

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**Abstract**—The latest data on the material structure, ash value, and emplacement of platinum-copper-nickel and platinum ores in deposits of Norilsk Region were discussed. The concentrations of nonferrous and noble metals in ores were reported. The cryptic layering of sulfide ores was described. The information on the mineral forms of noble metals was presented.

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## INTRODUCTION

Platinum-copper-nickel sulfide deposits of Norilsk Region constitute a set of ore horizons with diversified compositions and internal structures, which occupy a specific position relative to the productive differentiated basite-hyperbasite Norilsk intrusions (Fig. 1).

The two deposits that are known to exist within Talnakh ore cluster, the Talnakh and Oktyabr'skoe deposits, are confined to Talnakh and Kharaelakh intrusions, respectively. In the Norilsk ore cluster, along with Norilsk I deposit (the first exploited platinum–copper–nickel deposit), there exist Maslovskoe, Chernogorskoe, Norilsk II, and Zubmarksheiderskoe deposits that are off-balance sheet now.

The Norilsk deposit group accommodates 30, 12, 8, and 35% of the world reserves of nickel, cobalt, copper, and platinum group metals (PGMs), respectively. The ores from Talnakh ore cluster are exploited by Mayak, Komsomol'skii, Oktyabr'skii, Taimyrskii, and Skalistyi mines, and disseminated ores from Norilsk I deposit, by Medvezhii Ruchei (open pit mining) and Zapolyarnyi mines (underground mining).

The Norilsk deposits and their mineralogy have been the subject of numerous publications out of which only three summarizing studies [1–3] will be discussed in this short article, along with the new relevant data obtained by the author.

Based on the degree of saturation with sulfides, position relative to the intrusion, and prevailing value of individual metals, it is possible to differentiate among several types of ores that will be discussed below.

### Disseminated Ores

Disseminated ores are confined to the lower differentiates of the corresponding intrusive massifs, picritic and taxitic gabbrodolerites. In Norilsk deposits, disseminated ores from account for ca. 84% of the resources available.

The structure of the disseminated ore bodies is determined entirely by the morphology of the corresponding host rock horizons. The thickness of these ores is the largest (up to 40–50 m) at the intersection points with the maximal thicknesses of stratified massifs.

The sulfide mineralization of picritic gabbrodolerites differs from that of taxitic ones both in the morphology of their segregations and in the parageneses of sulfides.

In picritic gabbrodolerites sulfides form: (1) small (no larger than 2 mm) interstitial phenocrysts and (2) larger (up to 2–3 cm) ovoids ("drops," often stratified). They are composed by chalcopyrite on the top, and by pyrrhotite, on the bottom. Taxitic gabbrodolerites are dominated by relatively large (1–3 cm) xenomorphic segregations of sulfides. Also, well-developed fine interstitial impregnations are observed, along with irregular, lenticular, and veinlike schlieren up to 10–15 cm in size.

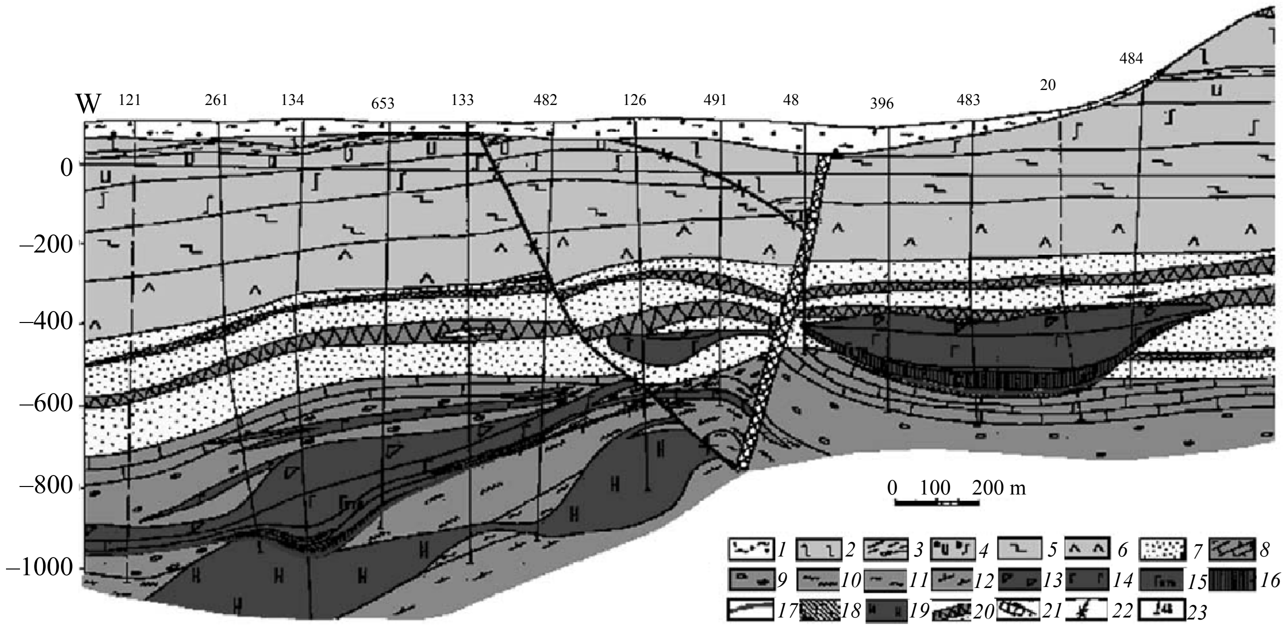


**Fig. 1.** Emplacement of ore-bearing intrusions (Talnakh and Kharaelakh) and their associated ores in the Talnakh ore field section: (*1*) Quaternary sediments; (*2–6*) $P_2$–$T_1$ basalts: (*2*) porphyritic, (*3*) tuff, (*4*) picritic, (*5*) tholeitic, and (*6*) labradorite; (*7*) $C_2$–$P_2$ Tunguska series terrigenous massifs; (*8–12*) terrigenous-carbonate and sulfate-carbonate rocks of the Devonian Formation for different formations: (*8*) Kalorgonskaya, (*9*) Manturovskaya, (*10*) Razvedochninskaya, (*11*) Kureiskaya, and (*12*) Zubovskaya; (*13–15*) ore-bearing intrusion (Talnakh and Kharaelakh) rocks: (*13*) eruptive breccias, contact gabbrodolerites, gabbrodiorites, and leukogabbro; (*14*) nonolivine, olivine-bearing, and olivine gabbrodolerites; (*15*) picritic, taxitic, and contact gabbrodolerites; (*16–18*) Pt–Cu–Ni ores: (*16*) disseminated, (*17*) massive, (*18*) veinlet-disseminated in exocontact rocks; (*19*) Low-Talnakh intrusive rocks; (*20*) dolerites; (*21, 22*) faults: (*21*) the main Norilsk-Kharaelakh fault suture and (*22*) other; and (*23*) detailed-exploration boreholes.

An important feature of disseminated ores is their zoning as manifested in variation of the proportions of the major ore minerals and their composition. It is typical especially for ores in picritic gabbrodolerites. Ideal zoning in vertical sections of picrites can be described as follows. In the central part of ultrabasites the sulfides are represented by troilite, cubanite, ferrous pentlandite, and talnakhite (Table 1). The latter mineral is naturally intergrown with thin chalcopyrite plates. Cubanite occurs in both lamellar and granular forms.

Upward and downward from these horizons, which comprise low-sulfur sulfide assemblage, the ores are represented by troilite + cubanite + chalcopyrite + ferrous pentlandite paragenesis. In going further toward the upper and lower picrite contacts, the changes in sulfide assemblages appears as a decrease in the amount of cubanite till complete disappearance and as variations in the species and chemical compositions of iron monosulfides. Initially, troilite–hexagonal pyrrhotite intergrowths in different proportions appear instead of homogeneous troilite; further, homogeneous hexagonal pyrrhotite is observed, and it is followed by hexagonal pyrrhotite–monoclinic pyrrhotite intergrowths. Homogeneous monoclinic pyrrhotite in picrite horizons is observed rarely and only in their periphery (along the vertical and lateral). The nickel concentration in iron monosulfides increases from that in troilite, in which it is contained in negligible amounts, to that in monoclinic pyrrhotite (up to 2.5 wt %). In the hexagonal pyrrhotite–monoclinic pyrrhotite intergrowths, nickel occurs in these phases in a typical ratio of 1:2. Such an ideal zoning is a rare phenomenon; it is fully manifested in segments characterized by maximal thicknesses, both in ore-bearing intrusion proper and in ultrabasites. Typically, picrites contain a (troilite + hexagonal pyrrhotite) + lamellar cubanite + chalcopyrite + medium-iron pentlandite assemblage in the central parts. Taxitic gabbrodolerites exhibit sulfide assemblages that are richer in sulfur. Only the uppermost parts of the taxitic horizon ores can be comprised by associations with troilite and cubanite. Iron monosulfides are typically represented by monoclinic pyrrhotite–hexagonal pyrrhotite intergrowths. The nickel concentrations in these pyrrhotite

**Table 1.** Major, minor, and rare ore minerals in the platinum-copper-nickel and platinum ores of Norilsk deposits. The table summarizes data for the following ores: (*3*) pyrrhotite, (*4*) copper-rich, (*5*) Norilsk I deposit, (*6*) Talnakh and Oktyabr'skoe deposit, (*7*) those in exocontact rock intrusion, (*8*) those in intrusive rocks, and (*9*) low-sulfide platinum

| Mineral name | Formula | Ore type[a] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | massive | | disseminated | | veinlet-disseminated | | |
| | | *3* | *4* | *5* | *6* | *7* | *8* | *9* |
| $M_{ss}$ | $(Fe,Ni)_{1-x}S$ | | | | | | | |
| $Cp_{ss}$ | $(Fe,Cu,Ni)_2S_2$ | | | | | | | |
| $Cub_{ss}$ | $(Fe,Cu,Ni)_3S_3$ | | | | | | | |
| Troilite | $FeS$ | | | | | | | |
| Hexagonal pyrrhotite | $Fe_{1-x}S$ | | | | | | | |
| Monoclinic pyrrhotite | $Fe_{1-x}S$ | | | | | | | |
| Pentlandite | $(Fe,Ni,Co)_9S_8$ | | | | | | | |
| Chalcopyrite | $CuFeS_3$ | | | | | | | |
| Talnakhite | $Cu_9(Fe,Ni)_8S_{16}$ | | | | | | | |
| Mooihoekite | $Cu_9(Fe,Ni)_9S_{16}$ | | | | | | | |
| Putoranite | $Cu_9(Fe,Ni)_9S_{16}$ | | | | | | | |
| Ni-putoranite | $Cu_{16}(Fe,Ni)_{19}S_{32}$ | | | | | | | |
| Fe-chalcopyrite | $(Fe,Cu,Ni)_2S_2$ | | | | | | | |
| Cubanite | $CuFe_2S_3$ | | | | | | | |
| Titanomagnetite | $(Fe,Ti)_3O_4$ | | | | | | | |
| Magnetite | $Fe_3O_4$ | | | | | | | |
| Ilmenite | $FeTiO_3$ | | | | | | | |
| Chromite | $(Fe,Mg)(Cr,Fe,Al)_2O_4$ | | | | | | | |
| Al–Mg-Fe spinel | $(Fe,Mg,Al)_3O_4$ | | | | | | | |
| Perovskite | $CaTiO_3$ | | | | | | | |
| Millerite | $NiS$ | | | | | | | |
| Pyrite | $FeS_2$ | | | | | | | |
| Marcasite | $FeS_2$ | | | | | | | |
| Heazlewoodite | $Ni_3S_2$ | | | | | | | |
| Violarite | $(Ni,Fe,Co)_3S_4$ | | | | | | | |
| Polydimite | $Ni_3S_4$ | | | | | | | |
| Siegenite | $(Ni,Co,Cu)_3S_4$ | | | | | | | |
| Bornite | $Cu_5FeS_4$ | | | | | | | |
| Chalcocite | $Cu_2S$ | | | | | | | |
| Digenite | $Cu_{2-x}S$ | | | | | | | |
| Sphalerite | $ZnS$ | | | | | | | |
| Hawleyite | $CdS$ | | | | | | | |
| Mackinawite | $(Fe,NI,Co)_{1+x}S$ | | | | | | | |
| Galena | $PbS$ | | | | | | | |

**Table 1.** (Contd.)

| Mineral name | Formula | Ore type[a] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | massive | | disseminated | | veinlet-disseminated | | |
| | | *3* | *4* | *5* | *6* | *7* | *8* | *9* |
| Clausthalite | $PbSe$ | | widespread | | | widespread | | |
| Alabandine | $MnS$ | | widespread | | | widespread | widespread | |
| Djerfisherite | $(K,Te,Pb,Ba)_2(Fe,Cu,Ni)_{25}S_{26}Cl_{0\text{-}1}$ | | widespread | | | rare | | |
| Talfenisite | $Tl_6(Fe,Ni,Cu)_{25}S_{26}Cl$ | | widespread | | | | | |
| Rasvumite | $KFe_2S_3$ | | | | | widespread | | |
| Tochilinite | $2FeS\cdot 1,67\{[Mg,Fe,Al][OH]_2\}$ | | | | | widespread | | |
| Valleriite | $2(Cu,Fe)S\cdot n\{[Mg,Fe,Al][OH]_2\}$ | | widespread | | | rare | | |
| Vyalsovite | $FeS\cdot Ca(OH)_2\cdot Al(OH)_3$ | | | | | widespread | | |
| Godlevskite | $Ni_9S_8$ | | widespread | | | | | |
| Parkerite | $Ni_3(Bi,Pb)_2S_2$ | | widespread | | | | | |
| Shandite | $Ni_3Pb_2S_2$ | | widespread | | | | | |
| Hauchecornite | $Ni_9Bi_2S_8$ | | | | | widespread | | |
| Shadlunite | $(Cu,Fe)_8(Pb,Cd)S_8$ | | widespread | | | | | |
| Manganshadlunite | $(Cu,Fe)_8(Mn,Pb,Cd)S_8$ | | widespread | | | | | |
| Thalcusite | $Cu_3Tl_2FeS_4$ | | widespread | | | | | |
| Molybdenite | $MoS_2$ | | widespread | | | | | |
| Stannite | $Cu_2FeSnS_4$ | | widespread | | | | | |
| Tilleyite | $(Sn,Pb)S$ | | widespread | | | | | |
| Cassiterite | $SnO_2$ | | widespread | | | | | widespread |
| Altaite | $PbTe$ | | rare | | | | | |
| Hedleyite | $Bi_7Te_3$ | | widespread | | | | | |
| Native bismuth | $Bi$ | | widespread | | | | | |
| Nickeline | $NiAs$ | widespread | widespread | | widespread | | | widespread |
| Maucherite | $Ni_{11}As_8$ | widespread | widespread | | widespread | | | widespread |
| Lollingite | $FeAs_2$ | widespread | widespread | | | | | |
| Safflorite | $CoAs_2$ | widespread | widespread | | | | | |
| Rammelsbergite | $NiAs_2$ | widespread | widespread | | | | | |
| Nikelskutterudite | $NiAs_3$ | widespread | widespread | | | | | |
| Skutterudite | $CoAs_3$ | widespread | widespread | | | | | |
| Ferroskutterudite | $FeAs_3$ | widespread | widespread | | | | | |
| Gersdorffite | $NiAsS$ | widespread | widespread | | | | | rare |
| Cobaltite | $CoAsS$ | widespread | widespread | | | | | rare |
| Breithauptite | $NiSb$ | widespread | widespread | | | | | widespread |
| Ullmannite | $NiSbS$ | widespread | | | | | | |
| Native arsenic | $As$ | widespread | | | | | | |

[a] Designations stand for the following minerals: not detected; widespread; rare; major.

phases are in a 1:1 ratio. Homogeneous monoclinic pyrrhotite is often the sole iron monosulfide in these ores. Another distinguishing feature of disseminated ores in taxitic horizons is a high enrichment in copper, and, consequently, in chalcopyrite.

Pentlandite-chalcopyrite-pyrrhotite ores, both disseminated and massive, exhibit a common structural pattern shown in Fig. 2: Around pyrrhotite (pyrrhotite I) blocks (area *1* in Fig. 2) there are rims of chalcopyrite with the latter flown into the pyrrhotite development

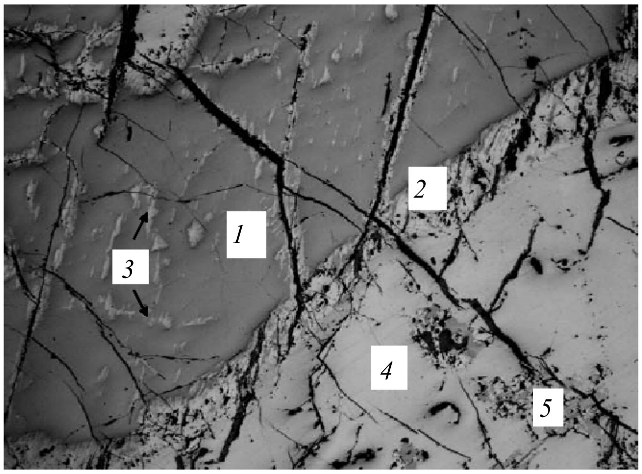


**Fig. 2.** Structure of disseminated pentlandite-chalcopyrite-pyrrhotite ore: Talnakh deposit, Komsomol'skii mine. Polished section. For designations (*1*–*5*) see the text.

field. At the pyrrhotite blocks–chalcopyrite contacts there are pentlandite I rims (area *2*) whose individual sections pass into porphyritic segregations. In pyrrhotite proper there are small lamellar, lenticular, and flame-shaped segregations of pentlandite II (area *3*), oriented along the fractures and joints of pyrrhotite I or perpendicular to the fractures therein (pentlandite II). The same orientation is observed for lenticular segregations of chalcopyrite. The chalcopyrite field (area *4*) is characterized by the appearance of pyrrhotite II grains which are either directly adjacent to pyrrhotite I blocks, in which case their optical orientation is identical to that of pyrrhotite I, or form irregularly shaped rectangular and hexagonal grains at some distance from pyrrhotite I (Fig. 2). Thin stripes of silicates can be observed between the pyrrhotite II grains and chalcopyrite. Occasionally, pyrrhotite II contains small equant or sharp-cornered pentlandite III grains (area *5*), but most often it is represented by numerous round or oval chalcopyrite inclusions solely. All the three pyrrhotite modifications can contribute to formation of both pyrrhotite I and pyrrhotite II.

In disseminated ores of Pyasino-Vologochanskii and Zubmarksheiderskii massifs the chalcopyrite group minerals are also represented by iron-rich chalcopyrite in which Fe prevails over copper in terms of atomic ratios. Ore oxides in disseminated ores are represented by titanomagnetite, magnetite, ilmenite, and chrome-spinelides (Table 1). Titanomagnetite underwent decomposition into magnetite and ilmenite; titanium, magnesium, and manganese are primarily concentrated in ilmenite, and aluminum, vanadium, silicon, calcium, and zinc, in magnetite, although the titanium concentration in magnetite reach 11 wt %. There are ilmenite prisms and xenomorphic grains in interstices of ore-forming minerals. Magnetite substitutes primary sulfides and is yielded by olivine serpentinization.

Chrome-magnetite and chromite in disseminated ores are primarily observed in picritic gabbrodolerites. They form segregations which range in size from several millimeters to several decimeters and may contain up to 40% chrome-spinelides. The chromium content in chrome-magnetite does not exceed 20 wt %, and that in darker in reflected light euhedral small (≤20 μm) chromite grains reaches 36 wt %. In these chromites the alumina and magnesia content increase to 13–21 wt %. These chromites often have a zonal structure, in which the central part is richer in alumina and magnesia, and the periphery, in iron and titanium.

The main ore components of disseminated ores occur in fairly persistent concentrations; the total content of nonferrous metals is close to 1.5 wt %, copper and nickel are in a ratio of 2:1, and the sulfur content is 2.0–3.7 wt %. The absolute concentrations of platinum group elements (PGEs) in disseminated ores are the lowest among all the ore types, though the highest in terms of the sulfide mass. The absolute PGE concentrations, g ton$^{-1}$, are as follows: 0.4–1.5 Pt; 3.0–5.0 Pd; 0.02–0.41 Rh; and 0.003–0.06 Ir; SPGE, g ton$^{-1}$/S, % = 0.8–1.9. The Pt/Pd ratio is 0.25–0.35. Disseminated ores are characterized by the highest enrichment in rare PGEs. The (Pt+Pd)/(Rh+Ir+Ru+Os) ratio is 7.6–22.4. Like in all types of ores, in disseminated ores PGEs occur in two forms: scattered, as solid solutions in sulfides, and as their own mineral phases. The role of each form of occurrence in the overall PGE balance is different for different elements. In disseminated ores of Talnakh deposits, 90–95% of the total amount of platinum is represented by its own mineral sperrylite, and in that of Norilsk-I, by Fe–Pt alloys (mainly isoferroplatinum, more rarely tetraferroplatinum and $Pt_2Fe$ alloy), rustenburgite, Pt-atokite, and cooperite (Table 2). The platinum concentration in pyrrhotite and pentlandite is no higher than 1.2 g ton$^{-1}$; 90–95% palladium is concentrated in pentlandite, where its content is 50–1000 g ton$^{-1}$. In pyrrhotite and chalcopyrite, the palladium concentration does not exceed 0.1 g ton$^{-1}$. Arsenide, arsenostibnides, and arsenostannides are palladium minerals that have a rare occurrence in disseminated ores (Table 2). Rhodium, iridium, and

**Table 2.** Noble metal minerals in the platinum-copper-nickel and platinum ores of the Norilsk deposit. The table summarizes data for the following ores: (*3*) pyrrhotite, (*4*) copper-rich, (*5*) Norilsk I mine, (*6*) Talnakh and Oktyabr'sky deposits, (*7*) those in exocontact rocks intrusions, (*8*) those in intrusive rocks, and (*9*) low-sulfide platinum

| Mineral name | Formula | Ore type[a] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | massive | | disseminated | | veinlet-disseminated | | |
| | | *3* | *4* | *5* | *6* | *7* | *8* | *9* |
| | $Au_3Cu$ | | | | | | | |
| Auricupride | $Cu_3Au$ | | | | | | | |
| Pt–Pd tetraauricupride | $(Au,Pd,Pt)Cu$ | | | | | | | |
| Argentoauricupride | $(Ag,Au,Pd,Pt)Cu$ | | | | | | | |
| | $Cu_3(Pt,Au)$ | | | | | | | |
| Au, Cu, Ag, Pt, Pd alloys | | | | | | | | |
| Native gold | $Au_{75–100\ wt\ \%}Ag_{0–25\ wt\ \%}$ | | | | | | | |
| Electrum | $Au_{25–75\ wt\ \%}Ag_{25–75\ wt\ \%}$ | | | | | | | |
| Kustelite | $Ag_{75–95\ wt\ \%}Au_{5–25\ wt\ \%}$ | | | | | | | |
| Native silver | $Ag_{95–100\ wt\ \%}Au_{0–5\ wt\ \%}$ | | | | | | | |
| Acanthite | $Ag_2S$ | | | | | | | |
| Naumanite | $Ag_2Se$ | | | | | | | |
| | $(Ag,Au,Cu,Pt,Pd)_2S$ | | | | | | | |
| | $Ag_2PdS$ | | | | | | | |
| | $(Pd,Ag)_5BiS_2$ | | | | | | | |
| | $(Pd,Cu)_7Ag_4Pb(Te,Se,S)_4$ | | | | | | | |
| Telargpalite | $(Pd,Ag)_3Te$ | | | | | | | |
| Sopcheite | $Ag_4Pd_3Te_4$ | | | | | | | |
| Stromeyerite | $CuAgS$ | | | | | | | |
| Hessite | $Ag_2Te$ | | | | | | | |
| Argentopentlandite | $(Fe,Ni,Ag)_9S_8$ | | | | | | | |
| Ni-argentopentlandite | $(Ni,Fe,Ag)_9S_8$ | | | | | | | |
| | $(PdAg)_2Pb$ | | | | | | | |
| Kerargirite | $AgCl$ | | | | | | | |
| Native platinum | $Pt$ | | | | | | | |
| Isoferroplatinum | $Pt_3Fe$ | | | | | | | |
| Fe–Pt alloy | $Pt_2Fe$ | | | | | | | |
| Tetraferroplatinum | $PtFe$ | | | | | | | |
| Tulameenite | $Pt_2FeCu$ | | | | | | | |
| Pd–Cu alloys | $Pd_{5–10}Cu_{90–95}$ | | | | | | | |
| Pt–Pd alloys | $Pt_{10–20}Pd_{80–90}$ | | | | | | | |
| Rustenburgite | $Pt_3Sn$ | | | | | | | |
| Atokite | $Pd_3Sn$ | | | | | | | |
| Zvyagintsevite | $Pd_3Pb$ | | | | | | | |
| Guanglinite | $Pd_3As$ | | | | | | | |
| | $Pd_3Sb$ | | | | | | | |
| Vincentite | $Pd_3(As,Te)$ | | | | | | | |
| | $Pd_3(Sn,As,Sb,Pb)$ | | | | | | | |
| | $Pd_5(Sn,As,Sb,Pb)_2$ | | | | | | | |
| Arsenopalladinite | $Pd_5As_2$ | | | | | | | |

**Table 2.** (Contd.)

| Mineral name | Formula | Ore type[a] | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | massive | | disseminated | | veinlet-disseminated | | |
| | | *3* | *4* | *5* | *6* | *7* | *8* | *9* |
| Arsenopalladinite | $(Pd,Ni)_5As_2$ | | widespread | | | widespread | | |
| | $Pd_3Ni_2As_3$ | | widespread | | | widespread | | |
| Majakite | $PdNiAs$ | | rare | widespread | | widespread | widespread | widespread |
| Palladoarsenide | $Pd_2As$ | widespread | widespread | widespread | rare | widespread | widespread | rare |
| Paolovite | $Pd_2Sn$ | | major | widespread | widespread | | widespread | widespread |
| | $Pd_2(Sn,Sb)$ | widespread | widespread | widespread | rare | widespread | widespread | rare |
| | $Pd_4SnSb$ | | rare | | | | | widespread |
| | $Pd_2(Sn,As)$ | widespread | widespread | widespread | rare | widespread | widespread | rare |
| | $Pd_2(As,Sb)$ | widespread | widespread | widespread | rare | widespread | widespread | rare |
| | $(Pd,Ni)_2As$ | widespread | widespread | widespread | rare | widespread | widespread | rare |
| | $(Pd,Ni)_2(Sn,As)$ | widespread | widespread | widespread | rare | widespread | widespread | rare |
| | $(Pd,Ni)_2(As,Sb)$ | widespread | widespread | widespread | rare | widespread | widespread | rare |
| Pd-orcelite | $(Ni,Pd)_2As$ | | widespread | | | | | |
| Pd-melonite | $(Ni,Pd)Te_2$ | | | | | | | widespread |
| Stannopalladinite | $Pd_5Sn_2Cu$ | widespread | major | rare | widespread | | rare | widespread |
| Taimyrite | $(Pd,Cu,Pt)_3Sn$ | widespread | major | | widespread | | rare | widespread |
| Tatyanite | $(Pd,Pt,Cu)_3Sn$ | | widespread | | | | | |
| Cabriite | $Pd_2SnCu$ | | rare | | | | | |
| Palarstanide | $Pd_8(Sn,As)_3$ | | widespread | | | | | |
| Mertieite-II | $Pd_8(Sb,As)_3$ | | | | | widespread | | |
| Stibiopalladinite | $Pd_5Sb_2$ | | widespread | widespread | widespread | | widespread | |
| Sobolevskite | $PdBi$ | widespread | major | rare | rare | widespread | rare | widespread |
| Kotulskite | $PdTe$ | widespread | | widespread | widespread | major | widespread | major |
| | $Pd(Bi,Te,Pb)$ | | widespread | | | | rare | |
| Sudburyite | $PdSb$ | | widespread | | | | | |
| Polarite | $Pd(Bi,Pb)$ | | rare | | | | rare | |
| Plumbopalladinite | $Pd_3Pb_2$ | | widespread | | | | widespread | |
| Niggliite | $PtSn$ | | widespread | | | | | |
| Insizwaite | $PtBi_2$ | | rare | | widespread | | | |
| Maslovite | $PtBiTe$ | | rare | | widespread | | | |
| Michenerite | $PdBiTe$ | widespread | rare | | | | | |
| Geversite | $PtSb_2$ | | widespread | widespread | | | widespread | |
| Moncheite | $PtTe_2$ | | rare | widespread | widespread | major | widespread | widespread |
| Merenskyite | $PdTe_2$ | | widespread | | | rare | | |
| Froodite | $PdBi_2$ | | rare | | | | widespread | |
| Urvantsevite | $Pd(Bi,Pb)_2$ | | widespread | | | | | |
| Cooperite | $PtS$ | | | major | | major | | rare |
| Braggite | $(Pt,Pd,Ni)S$ | | widespread | widespread | | major | | widespread |
| Vysotskite | $(Pd,Ni)S$ | | widespread | | | major | | major |
| Kharaelakhite | $(Pt,Cu,Pb,Fe,Ni)_9S_8$ | | | | | rare | | widespread |
| Laflammeite | $Pd_3Pb_2S_3$ | | | | | rare | | |
| Sperrylite | $PtAs_2$ | major | rare | rare | major | widespread | rare | major |
| Hollingworthite | $RhAsS$ | widespread | widespread | | widespread | | | widespread |
| Platarsite | $PtAsS$ | widespread | | | | | | |
| Irarsite | $IrAsS$ | widespread | | | | | | |
| Laurite | $RuS_2$ | widespread | | | | | | widespread |
| | $Pd_4Bi_5Cl_3$ | | widespread | | | | | |
| | $PdBiO$ | | widespread | | | | | |

[a] Designations stand for the following minerals: (white box) not detected; (dark grey box) widespread; (light grey box) rare; (black box) major.

osmium form exclusively solid solutions in pyrrhotite and pentlandite, in which Rh and Ir occur in the concentrations of 1.1 and 0.2 g ton$^{-1}$, respectively. Also, these elements occur as impurities (up to 1.5% Rh) in sperrylite. Rhodium and iridium very rarely form tiny hollingworthite and irarsite crystals.

The average content of gold in disseminated ores of Norilsk I, Talnakh, and Oktyabr'skoe deposits is 0.23, 0.26, and 0.17 g ton$^{-1}$, respectively, and that of silver, 8.0, 4.18, and 3.15 g ton$^{-1}$. In these ores, gold mainly occurs as high-grade alloys with silver. The Au content in native gold is no lower than 75 wt % (Table 2); also known are solid solutions of silver in sulfides, mainly, in chalcopyrite. Copper-gold alloys that have a widespread occurrence in disseminated ores of Norilsk I deposits include: $Au_3Cu$, aurocupride, and Pt and Pd-tetrauricupride (Table 2). Also, gold is contained in amounts of up to 6 g ton$^{-1}$ in some platinum group minerals (PGMs): atokite, rustenburgite, and zvyagintsevite.

### Massive Ores

Massive ores represent the most economically valuable type of crude ores of today. They account for 8.5% of ore reserves of Norilsk deposits. In Talnakh ore cluster the area over which massive ores are spread is comparable to that for intrusive massifs themselves and the disseminated ores horizons confined thereto. Along the lateral the deposits of solid ores has a stretch of up to several hundreds of meters. The ore body thickness exhibits broad variations, from tens of centimeters to 45 m. The largest thickness is characteristic of intersections confined to the axial zones of intrusions.

The typical localization site for massive ore bodies are the metamorphic and metasomatic rocks in the near exocontact zone of ore-bearing intrusions. Between the intrusion base and massive ore deposit roof the thickness of sedimentary metamorphic rocks ranges from several centimeters to 7 m. The massive ore bodies in the sedimentary-metamorphic rocks have a tabular or a flattened-lenticular shape. In more rare cases the massive ore bodies are located among the rocks of ore-bearing intrusions, where they form veins appearing either as cavity fillings or those clearly indicative of an active impact exerted on the host rocks. Massive ores form blocks and stockwork veinlet zones, along with tabular and lenticular bodies.

A complete series of paragenetic sulfide assemblages, covered by the Fe–Ni–Cu–S system, was established for the Norilsk massive ores, especially for those in Talnakh deposits. They form individual segments of ore bodies and are responsible for their zoning and cryptic layering. Most of the ore bodies are composed of pyrrhotite ores with Cu/Ni ratios of ca. 0.8 (which is nearly half that in disseminated ores). The percentage composition of these ores can be represented as follows: 60–65 pyrrhotite minerals, 15–20 chalcopyrite, 10–15 pentlandite, and ~5 magnetite. Among highly pyrrhotite ores, two types are differentiated on the basis of the textural features. One type is characterized by a loopy texture: Among the blocks formed by pyrrhotite group minerals, there are chalcopyrite loops of variable thickness, in which the number of hornfels xenoliths does not exceed 5%. The second type is represented by fine-grained ores that are rich in magnetite and silicate inclusions, of which the latter account for up to 30% of the ore volume.

Mineral zoning of pyrrhotite ores is manifested in a relative increase (up to 30–40%) of the proportion of chalcopyrite in the near-contact and peripheral areas and in a change from homogeneous hexagonal pyrrhotite and troilite–hexagonal pyrrhotite intergrowths to monoclinic pyrrhotite or monoclinic pyrrhotite–hexagonal pyrrhotite intergrowths. This zoning is stressed by the nickel concentration in pyrrhotite increasing in going to the ore body periphery.

Ore bodies with a clear zonal structure are localized in the lower endocontact of ore-bearing massifs. The most pronounced zoning is observed for the western part of Kharaelach mine of the Oktyabr'skii deposit. In the central part (along the lateral) and in the cut in the upper contact there are ores with the following percentage composition: chalcopyrite group minerals (talnakhite, mooihoekite, and putoranite) 55–60; cubanite 10–15, pentlandite 20–25, troilite up to 5; and magnetite 5. These ores are rimmed by several types of ores comprising ore minerals in highly variable proportions, though invariably containing cubanite (30–50%), chalcopyrite group minerals (20–40%), troilite (5–20%), chalcopyrite (10–40%), pentlandite (15–10%), and magnetite (5%). This is followed by disappearance of chalcopyrite group minerals poor in sulfur, and only tetragonal chalcopyrite becomes stable, while iron monosulfides are represented by iron-rich hexagonal pyrrhotite in intergrowths with, and further without, troilite. Typical for these segments are chalcopyrite-cubanite, cubanite-chalcopyrite, pyrrhotite-chalcopyrite, and cubanite-chalcopyrite-pyrrhotite ores. They are replaced by ores containing sulfide assemblages described for ore bodies having a simple structure. Such zoning is stressed by cryptic layering which is manifested in variations of the chemical composition of pentlandite and nickel concentration in iron monosulfides.

In the case of ores comprising low-sulfide assemblages, the nickel concentration in pentlandite decreases to 28 wt %, and in pyrrhotite ores, increases to 36 wt %. The nickel content in pyrrhotite varies from several hundredth fractions of percent (in troilite) to 1.6 wt % in monoclinic pyrrhotite.

The change in the mineral composition of ores characterizes the variations in the copper concentration at nearly unvaried nickel content. The Ni/Cu ratio is 0.23–0.45, 0.11, and 0.20 in cubanite, mooihoekite, and talnakhite ores, respectively.

The distribution of PGMs in massive ores is determined by the set of ore mineral types available. Pyrrhotite ores are characterized by a relatively stable content of PGMs, g $ton^{-1}$: 1.5–20 Pt; 7.0–9.0 Pd; 0.6–1.2 Rh; 0.2–0.3 Ru; 0.06–0.10 (up to 0.2) Ir; and 0.03–0.05 Os. The bodies formed by these ores undergo platinum and palladium enrichment toward the contact and periphery in parallel with an increase in the copper concentration. Pyrrhotite ores contain the maximal amounts of rhodium, iridium, ruthenium, and osmium. The rhodium content in the ores is sometimes comparable to that of platinum. The(Pt+Pd)/(Rh+Ir+Ru+Os) ratio lies within 1–20; ΣEPG/S = 0.4, which is 3 times lower than that in disseminated ores at identical Pt/Pd ratios (0.23–0.35).

The highest variability in PGE concentrations is observed in the case of ore-body zoning. Talnakhite and mooihoekite ores are characterized by sharply increased concentrations of platinum and palladium and by decreased concentrations of rhodium, iridium, osmium, and ruthenium. The (Pt+Pd)/(Rh+Ir+Ru+Os) ratio is 285–470; ΣEPG/S = 1.8–4.2, which level is the highest among all types and kinds of ores. The absolute content of platinum and palladium in these ores is 10–25 and 40–100 g $ton^{-1}$ and over, respectively; the Pt/Pd ratio remains constant at 0.24–0.30.

Cubanite ores exhibit medium PGE levels and geochemical characteristics. The absolute content, g $ton^{-1}$, of PGE in them is as follows: 3.40–4.90 Pt; 19.0–23.0 Pd; 0.05–0.10 Rh; 0.01–0.08 Ir; 0.09–0.14 Ru; and 0.01–0.08 Os. The Pt/Pd ratio is 0.23–0.24.

The role of scattered and mineral forms of occurrence of PGEs in the overall balance of these metals in massive ores is also determined by the mineral composition of ores. Rhodium, iridium, ruthenium, and osmium are nearly entirely represented by solid solutions in sulfides, mainly in pyrrhotite and pentlandite. Pyrrhotite and pentlandite contain 0.2–1.6 and 0.4–1.8 g $ton^{-1}$ rhodium, respectively, with high-sulfide pyrrhotites being richer in rhodium than are low-sulfide ones. A sharp decrease in the rhodium concentration for copper-rich ores is associated with a change from high-sulfide pyrrhotites to troilite, which is followed by complete disappearance of iron monosulfides in the ores. Rhodium is also concentrated in sperrylite (up to 1.5%) and very seldom forms its own mineral, hollingworthite.

The iridium concentration in pyrrhotite and pentlandite is within 0.05–0.25 g $ton^{-1}$ and, like in the case of rhodium, the iridium levels in ores containing low-sulfur sulfide assemblages is significantly reduced.

The ruthenium concentration, g $ton^{-1}$, in sulfides is as follows: 0.13–0.45 in pyrrhotite, 0.06–0.32 in pentlandite, and 0.06–0.43 in chalcopyrite (cf. 0.06–0.25, 0.02–0.05, and 0.03–0.08 g $ton^{-1}$, respectively, for osmium). Because of partial solubility of ruthenium and osmium in chalcopyrite group minerals, their levels in ores containing low-sulfur sulfide assemblages tend to decrease less sharply compared to the case of pyrrhotite ores.

Palladium forms both solid solution in sulfides, mostly in pentlandite, and its own minerals. These two forms of occurrence make quantitatively different contributions to the overall balance of palladium in ores containing low- and high-sulfur sulfide assemblages. In pyrrhotite-containing ores, like in disseminated ores, pentlandite is the main palladium concentrator; the palladium content in pentlandite is 50–300 g $ton^{-1}$, and in other sulfides it does not exceed 5 g $ton^{-1}$. These ores very rarely contain the own palladium minerals: arsenides, stibioarsenides, and stannoarsenides (Table 2).

Ores comprising low-sulfide chalcopyrite group minerals (talnakhite, mooihoekite, putoranite) and cubanite are characterized by a drastically reduced palladium concentration in pentlandite, 5–30 g $ton^{-1}$. A high total content of palladium in these ores is contributed by numerous minerals: the Pd–Pt–Cu–Sn system (stannopalladinite, taimyrite, cabriite); a number of $Pd_3Sn$–$Pt_3Sn$ series minerals (atokite-rustenburgite); palladium plumbides (zvyagintsevite and plumbopalladinite); tellurides and bismuthides (kotulskite, sobolevskite, froodite, michnerite, merenskiite); stibnides (stibiopalladinite, mertieite, sudburyite); plumbobismuthides (polarite, urvantsevite); arsenides (majakite, palladoarsenide, vincentite); and stannides (paolovite); and $Pd_2M$ minerals, where M = Sn, As, Sb (Table 2).

Platinum in massive ores exhibits a minimal solubility in sulfides; its concentration in pyrrhotite and pentlandite does not exceed 0.5 g $ton^{-1}$. Platinum forms its own minerals: sperrylite in pyrrhotite ores and tetraferroplatinum, rustenburgite, maslovite, moncheite, and niggliite, in copper-rich ores. Sperrylite and tetraferroplatinum invariably contain rhodium, iridium, and ruthenium impurities.

The content of gold and silver, as well as that of PGEs, is determined by the content of copper and the mineral composition of ores. The minimal content of these elements is observed for highly pyrrhotite ores (the average values for Au are 1.58, 0.26, and 0.11 g $ton^{-1}$ for Norilsk I, Talnakh, and Oktyab'rskoe deposits, respectively, and those for Ag, 33.0, 7.52, and 4.51 g $ton^{-1}$, respectively), and the maximal, in chalcopyrite and talnakhite ores (the average values for Au are 11.1, 5.5, and 6.0 g $ton^{-1}$, respectively, and those for Ag, 66.0, 83.0, 115.3 g $ton^{-1}$, respectively). Like in the case of disseminated ores, the main form of occurrence of gold is represented by its own minerals (Au–Ag alloys, native Au, electrum, kustelite). In Talnakh deposit there are also Au–Cu alloys: $Au_3Cu$, aurocupride, and Pt and Pd-tetrauricupride (Table 2). Silver forms, along with solid solutions in sulfides, alloys with gold, whose segregations are typically confined to PGM grains. In highly pyrrhotite ores, argentopentlandite can be the main silver mineral.

Massive loop pyrrhotite ores from Oktyabr'skoe deposits (Komsomol'skii mine, west plot) are cut by subvertical calcite veins (substitution veins) with a thickness of up to 40 cm. Along with the main nonmetallic material, the substitution is contributed by chalcopyrite, galena, sphalerite, and nickel, cobalt, and iron arsenides, stibnides and sulfoarsenides, and native arsenic (Table 1).

Massive fine-grained pyrrhotite ores, along their contact with the host rocks, also show replacement, with pyrrhotite replaced by pentlandite and pyrite, which leads eventually to unusual pyrite-pentlandite ores.

*Pegmatoid Galena-Chalcopyrite (Talnakhite, Bornite) Massive Ores*

In the top selvage of copper-rich ore deposits (pit no. 1 of Oktyabr'skii mine) and the abandoned southern deposit of the eastern section of the Komsomol'skii mine there are sporadic pegmatoid schliers of galena-rich ores (up to 30% of the ore volume). Galena forms symplectites intergrown with ore-forming minerals chalcopyrite, talnakhite, and (less frequently) bornite. Also, these ores invariably contain pentlandite and, less frequently (in chalcopyrite and talnakhite ores), cubanite and fine-grained pyrrhotite. The schliers range in size from several centimeters to several tens of decimeters and are well-isolated from their host ores. The shape of these isolations varies from irregular to spherical. These ores are rich in rare minerals: argentopentlandite, parkerite (often this is the lead-bearing species), Pb–Tl-djerfisherites, thalfenisite, hessite, altaite, thalcusite, stannite, cassiterite, tilleyite, tellurobismuthides, maucherite, and breithauptite (Table 1). The PGE concentration in galena-rich ores reaches several kilograms per ton. Platinum group metal minerals are represented by various classes of compounds, of which the most abundant ones include platinum and palladium bismuthides, tellurides, and tellurobismuthides (sobolevskite, moncheite, michenerite, insizwaite, maslovite), characterized by broad isomorphism of platinum-palladium and bismuth-tellurium; palladium stannides and stannostibnides [mineral with the composition $Pd_4(Sn,Sb)$, paolovite, Sb-paolovite) and Pd–Pt–Cu–Sn system minerals (cabriite, taimyrite, stannopalladinite, tatyanite); often formed are zonal segregations. Less abundant species include Pt-atokite, niggliite, sudburyite, Te–Bi-geversite; gold and silver minerals are represented by native silver, kustelite, and electrum.

*Millerite-Bornite-Chalcopyrite Massive Ores*

The millerite-bornite-chalcopyrite massive ores occur either at tailing-out of zoned (laterally) veins from the pyrrhotite to chalcopyrite ones, or form individual veins and stringers in the lower exocontact of Kharaelakh massive ore deposits and Norilsk I intrusive. In the latter case, another vein material is calcite; frequently, there is chalcosine along with bornite. Nickel sulfides in these ores are represented by godlevskite, along with millerite. Millerite-bornite-chalcopyrite ores are rich in palladium-containing nickel, cobalt, and iron arsenides and sulfoarsenides, as well as in parkerite, altaite, hessite, and PGMs.

*Pentlandite (Heazlewoodite)-Bornite-Chalcosine Massive Ores*

The pentlandite (heazlewoodite)-bornite-chalcosine massive ores either result from replacement of copper-rich massive chalcopyrite and talnakhite ores, whose most prominent occurrences exist in Mayak mine, or form individual veins at the base of the massive ore deposit of Oktyabr'skoe deposit. In the latter case, the vein material is often represented by calcite as well. The replacement leads to pentlandite coarsening and enrichment in nickel and cobalt. In some sections, instead of pentlandite, there is heazlewoodite which forms large (up to 2 cm) spherical porphyritic phenocrysts. There is millerite over pentlandite and heazlewoodite, as well as thin rims of composition (Ni, Fe, Cu) (S, Cl) mineral around heazlewoodite. Heazlewoodite-chalcosine ores contain long shendite prisms. Copper sulfides are represented by digenite, along with chalcosine.

Similar to copper-rich massive ores, bornite-chalcosine ores contain diverse PGMs: polarite, plumbopalladinite, sobolevskite, taimyrite, froodite, and niggliite. Also, there are some gold and silver minerals: platinum and palladium tetraauricupride and gold and silver alloys custelite and electrum.

**Morozov mine massive ores.** Morozov mine (northern cape of Rudnaya mountain) existed prior to 1953; most likely, the first copper-nickel ore sample taken by merchant K.M. Sotnikov was that from the enrichment zones of this deposit which is composed by subvertical veins with a thickness of no larger than 0.5 m, extending down to 90 m. At the top, the veins are confined to a subhorizontal deposit of massive ores at the lower exocontact of the Norilsk I intrusion and are composed by normal pentlandite-chalcopyrite-pyrrhotite ores. In going from top to bottom they are replaced by fine-grained ores, and further by fines, which is paralleled by an increase in their copper content. Ores from vertical sulfide veins are rich in both copper (15–19 wt %) and nickel (6–7 wt %). At the bottom of these veins, monosulfide (MSS) (iron-nickel) and intermediate (CpSS and CubSS) (iron-copper) solid solutions were detected for the first time in copper-nickel ores (Table 1). The content of platinum group metals in these ores reaches 2 kg ton$^{-1}$. Palladium is mostly concentrated in pentlandite in amounts of up to 3 wt %, which value is the highest observed in the solid solutions it forms in pentlandite. Platinum forms its own minerals: tetraferroplatinum, iron-platinum alloy $Pt_2Fe$, palladium rustenburgite, and cooperite.

**Veinlet-Disseminated Ores**

In metamorphic and metasomatic rocks of the exocontact of ore-bearing intrusions, veinlet-disseminated ores form a halo around them, especially in the lower, less frequently in the upper, exocontact, as well as around massive ore bodies. They form lenticular and sheetlike bodies, typically with a thickness of no larger than 2–3 m, which are generally consistent with the host rocks.

Combined with brecciform ores of Oktyabr'skoe deposit (commercially termed "cupriferous" ores), the veinlet-disseminated ores in the intrusive massif exocontact account for ca. 4% of ore reserves of Norilsk deposits.

The texture pattern of veinlet-disseminated ores is determined by the structures and textures of the host rocks for the mineralization and by the intensity of the occurrence of mineralization. Banded textures originate from alternation of mineralized and barren or weakly-mineralized layers. The thickness of the massive ore veinlets varies within 1–20 mm and reaches several centimeters. A particular type is represented by brecciform ores occurring in rocks of the roof of the western end of the Kharaelakh intrusion. "Fragments" in these ores are fine-impregnated with sulfides, and the cementing mass is most often formed by the massive sulfides.

Veinlet-disseminated ores are superior to all types of ores in the diversity of the mineral composition. Bodies composed by these ores exhibit distinctly zonal patterns. Complete zoning appears as follows. Ores in zones adjacent to massive pyrrhotite ores or to intrusion base are represented by a pyrrhotite + chalcopyrite + pentlandite assemblage. With increasing distance from this zone, the content of chalcopyrite relative to the pyrrhotite group minerals tends to increase. Subsequently, these ores are replaced by pyrrhotite-free ores, initially, by a chalcopyrite + pentlandite and, further, by a chalcopyrite + millerite + pyrite assemblage. The outlying areas of such exocontact ores are constituted by a chalcopyrite + millerite + bornite assemblage. In some segments the outer zone is represented by a pyrrhotite + pyrite + sphalerite + galena assemblage. Galena and sphalerite are competitive in their abundance with the major ore minerals of this assemblage. Such an ideal column is observed only in segments characterized by maximal thicknesses of the veinlet-disseminated ores (at the base of the north-eastern branch of the Talnakh intrusion and in the roof of the Kharaelakh intrusion) in the metasomatic rocks over the upper Devonian carbonate formations. In most cases the column is reduced, being limited to pentlandite-chalcopyrite parageneses.

The changes in the mineral composition of ores are associated with those in the chemical composition of the major ore minerals, pyrrhotite and pentlandite. Pyrrhotite in the rear part of the zonal column of the veinlet-disseminated ores is very rarely represented by homogeneous hexagonal pyrrhotite; the dominant role belongs to hexagonal pyrrhotite–monoclinic pyrrhotite intergrowths or homogeneous segregations of monoclinic pyrrhotite, formed by iron monosulfides. With increasing distances from the massive ores and the contact with the intrusion, the nickel concentration in pyrrhotites tends to increase, being 1.6 wt % at the maximum. The content of nickel in pentlandite tends to increase as well; in pentlandite from pentlandite-chalcopyrite ores it reaches 46 wt %. These pentlandites are enriched in nickel to the greatest extent among those in all types and kinds of ores.

The veinlet-disseminated ores localized in sedimentary-metamorphic rocks fairly rarely comprise associations of sulfides with cubanite. They are observed only in the vicinity of massive bodies of cubanite ores. The veinlet-disseminated ores are enriched in sphalerite, galena, and djerfisherite; they are very prone to secondary changes, through which the primary sulfide assemblages are often replaced entirely. Pyrite, marcasite, magnetite, and valleriite are formed over pyrrhotite; pyrite, valleriite, and valsovite, over chalcopyrite; and violarite, polydymite, millerite, and pyrite, over pentlandite (Table 1). Also, sulfides are often replaced by secondary nonmetallic minerals: chlorite, serpentine, prehnite, vesuvianite, and hydrogarnet. The composition of djerfisherite and valleriite group minerals is determined by the primary chemical composition of ores.

A large proportion of tetragonal chalcopyrite in veinlet-disseminated ores is responsible for high concentrations of copper in these ores, on which grounds the latter are commercially qualified as of “cupriferous” ores. The Ni/Cu ratio for them is under 0.2.

In veinlet-disseminated ores the PGE content tends to increase in proportion to the degree of the ore enrichment in copper. Hence, at a lower total amount of sulfides the total PGE content is no less, and often even higher, than that in massive pyrrhotite ores, and ΣPGE/S is 0.9–1.9. Also, these ores exhibit downward trends (though less pronounced than those in the case of the copper-rich massive ores) in the relative proportions of rhodium, iridium, ruthenium, and osmium. The (Pt + Pd)/(Rh + Ir + Ru + Os) ratio is 20:60. In the case of vein-disseminated ores the own minerals of palladium and platinum are not only typical for copper-rich ores but also are frequently observed in pyrrhotite-containing ores. The latter contain palladium and nickel arsenides, stibioarsenides, arsenostannides, and stibiostannides (Table 2). Kotulskite and moncheite commonly occur in chalcopyrite-enriched ores. The ores richest in PGMs are millerite- and bornite-containing ores, the content of platinum and palladium sulfides being at a maximum, by contrast to pyrrhotite- and chalcopyrite-containing ores in which these sulfides are rare. Along with cooperite, braggite, and vysotskite, only these ores contain platinum, iron, copper, and lead sulfides of the kharaelakhite type with Pt, Fe, Ni, Cu, and Pb in variable proportions. Tellurides are represented not only by kotulskite but also by telargpalite and sopcheite, and silver sulfides and selenides are associated with silver and palladium, palladium, silver and lead, and palladium, silver, and bismuth selenosulfides (Table 2). All the species contain sperrylite as a passing mineral.

*Veinlet-Disseminated Ores in Intrusive Rocks*

Veinlet-disseminated ores in intrusive rocks are closely related to massive ores. They are localized near the base of ore-bearing massifs at 2–5-m distances from the lower contact of these massifs with the host rocks and in some sections are adjacent to massive ores. They have a lenticular and tabular shape and are extended in parallel to the massif contact. The thickness of the bodies composed by these ores reaches several meters; the content of sulfides in them very broadly varies from several per cent to 40% of the ore volume. The sulfide-rich ores acquire a sideronite-type texture. Sulfides form interstitial phenocrysts ranging from several fractions of millimeter to 2–3 mm in size and up to 5–15-cm-thick veinlets. These ores also exhibit zoning pattern in which pyrrhotite ores are replaced initially by pyrrhotite-chalcopyrite ores and further by chalcopyrite-cubanite or chalcopyrite ores. This zoning pattern can be symmetrical or unidirectional.

The PGE concentration in these ores exceeds in some sections that in copper-enriched massive ores. Generally, the species composition of PGE minerals is similar to that of massive ores enriched in copper minerals. However, there exist sections characterized by abundant $Pd_3L$ minerals with broadly varying proportions of ligands (L): As, Sn, Sb, and Pb (Table 2).

### Low-Sulfide Platinum Ores

Low-sulfide platinum ores are localized in chromite-bearing taxitic gabbroids, less frequently in leukogabbro and eruptive breccias of the upper endocontact of differentiated intrusions. A feature specific of the rocks hosting the ore mineralization is a highly variable petrographic composition. Along with plagioclase cumulates, they include picrites, troktolites, and gabbroids. Another feature characteristic of this horizon is the abundance of amygdules filled with $F^-$-, $Cl^-$-, and $OH^-$-bearing minerals prehnite, phlogopite, biotite, amphiboles, chlorite, analcime, zeolites, and apatite. The $Cr_2O_3$ content in taxitic gabbroids goes up to 6 wt %. Chromite forms segregations ranging from several fractions of millimeter to several centimeters in size. Sulfides account for no larger than 3% of the ore volume. The total content of nonferrous metals does not exceed 0.2–0.3 wt %. Sulfides are represented by the following assemblages: monoclinic pyrrhotite + nickel pentlandite + chalcopyrite; nickel pentlandite + chalcopyrite; and millerite + pyrite + chalcopyrite. These ores comprise abundant palladium-containing nickel, cobalt, and iron arsenides and sulfoarsenides. The absolute ΣPGE con-centrations are typically 6–10 and may reach 40 g $ton^{-1}$. The Pt/Pd ratio broadly varies but is typically 0.25–0.35; the ΣEPG/S ratio is 40 or even higher. The main forms of occurrence of PGE in these horizons are their own minerals: sulfides, tellurides, tellurobismuthides, stannides, arsenides, and platinum–iron alloys (Table 2). Gold and silver minerals are represented by high-grade gold and Pt–Pd-containing solid solutions of copper and gold. Noble metal minerals form small (no larger than 20 μm) segregations confined to the contact of sulfides and the secondary silicates that replace them and with sulfides and silicates proper. Platinum group elements also form solid solutions in pyrrhotite and pentlandite, as well as in iron, nickel, and cobalt sulfoarsenides and arsenides.

## CONCLUISONS

A unique feature of the Norilsk Industrial Region ores consists in that they comprise nonferrous metals in proportions and concentrations that are close to those characteristic for the largest world copper-nickel deposits and, simultaneously, platinum group metals in amounts comparable with those in platinum deposits. The discovery of low-sulfide platinum ores in the upper endocontact zones of ore-bearing basite-hyperbasite intrusions of the Norisk Region enhanced the value of the deposits [4]. At the present time, the occurrences of low-sulfide platinum ores were revealed for other differentiated intrusions as well. Disseminated ores that are traditionally interpreted as platinum-copper-nickel ores may be regarded as copper-nickel-platinum ones, considering the today's prices for platinum group metals. The abundance of platinum group metals in disseminated ores, as recalculated for the sulfide mass, is much higher than that in massive ores of the same composition. In processing of disseminated ores, account should be made of the fact that the mineral and impurity forms of platinum group metals in them are of identical value.

Metallurgical combines undertake processing of the above-described eight types of Norilsk ores to recover nickel, copper, cobalt, platinum, palladium, rhodium, iridium, ruthenium, osmium, gold, silver, selenium, tellurium, and sulfur. In the most productive years, ca. 550 thousand tons of copper, 380 thousand tons of nickel, 13 thousand tons of cobalt, and 120 tons of platinum group metals were extracted from ores of Norilsk deposits.

These ultralarge deposits of noble and nonferrous metals account for a significant proportion of Russia's economic potential. The metals recovered from Norilsk ores are extensively applied on the domestic market with the aim to satisfy the needs of Russia's industry; also they constitute a noticeable proportion of Russia's exports. Noble metals that are accepted for storage by Gokhran (Russia's State Repository for Precious Metals and Gemstones) significantly contribute to stability of the national currency (ruble) claiming for a status of a new world's reserve currency. The reserves of Norilsk noble and nonferrous metal ores will suffice for many decades. The Norilsk Nickel mining conglomerate undertakes to finance the prospecting activities for other deposits of the considered type on Kola Peninsula and Voronezh Crystal Massif and in East Sayan (East Siberia). A number of perspective occurrences of deposits have been found and are being explored with a view to replace in the future the currently exploited mines.

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