Analysis of structure and material in the southwest of the Talnakh ore cluster

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Abstract. The issues of metallogenetic modeling of ore-forming systems for search purposes when studying sides and deep horizons of the mined deposits are considered. The object of the study is the geological and geochemical conditions of ore accumulation of various mineral composition and the concentration of useful components in various sections of the Talnakh ore-forming system. Mineral and geochemical zoning of the deposits reflect the degree of contamination of primary silicate and magmatic melts with crustal material. On the western and southern sides of the ore-forming system, ore mineralization is represented by low-sulfur associations of chalcopyrite minerals and is specialized in Cu–Ni–Co. The geochemical analysis of isotopes $\delta^{34}S$, $^{40}\text{Ar}/^{36}\text{Ar}$, $\delta^{65}\text{Cu}$, $^{87}\text{Sr}/^{86}\text{Sr}$ suggests that the process of ore formation on the sides of the Talnakh ore cluster occurs under intense influence of the crust (sulfur source evaporite rocks) and near-surface water on the fluid in melting-fractionated sulphide magma enriched with copper, which results in the formation of chalcopyrite ore.

1. Introduction
The Taimyr–Norilsk ore province contains unique resources and reserves of copper, nickel, platinum and palladium (Norilsk–Kharaelakh cluster), as well as other but less studied plutonic magmatic platinum-bearing mineralization bodies. Analyses of the structure, material, geochemistry, age and genesis of orogenic system can help create a reference metallogeny model containing signs and criteria usable in the studies of platinoid/copper/nickel-promising sides of deposits under mining or other potentially ore-bearing areas [1–5].

The Taimyr–Norilsk ore province lies in the far northwest of the ancient Pre-Sinian Siberian Platform at the joint with the pericratonic Yenisei–Katanga downfold and West Siberain Plate. Between the Proterozoic and Mesozoic ages, the edges of the platform formed under conditions of pericratonic downfolding. The Late Paleozoic subduction of the West Siberian oceanic plate under the Siberian Plate activated mantle plume, which caused origination of trappean plato-basaltic formation 251 million years ago and the associated deposits of sulfide platinum-bearing copper–nickel ore [6]. Furthermore, in the course of subduction, sedimentary cover of the platform mantle was entered by water which later interacted with fluid-saturated magmatic melting and enriched it with sulfur and halide [2].

Focal magmatic zones stand out in the range of the metallogenic zones: Norilsk–Kharaelakh, Khantai–Gorbyiacha, Kureika–Severnaya, etc. Structurally, these zones are downfolds and bowls.

The Norilsk–Kharaelakh metallogeny (NKM) in the southwest of the Taimyr–Norilsk ore province occurs within the limits of junction of three continental reefs and features disjunctive dislocations of extreme density, which governs extremely high fluid–magmatic permeability of the crust.
2. Structural features of the Talnakh ore cluster

The basic ore-bearing structure in this zone is the Norilsk–Kharaelakh downfold—a small rift trough currently mapped as a trough-like depression between listric faults. As a result of tension-and-compression alteration, the downfold is cut by cross-wise upfolds into a series of smaller bowls, including the largest Kharaelakh Bow (KB) and Norilsk Bowl (NB) separated by the dome-like Kayerkan–Pyasina Swell (KPS). Each listed structure contains two troughs: Kharaelakh and Ikon in (KB) and Norilsk and Vologocha in NB. The unique deposits of sulfide platinum-bearing copper–nickel ore occur in the southwest of KB and in the northwest of NB.

The disjunctive bordering of the Norlisk–Kharaelakh Metallogeny (NKM) zone is represented by a long-lived and deep-seated fault traceable along the axis of the downfold adjoined with ore-bearing intrusions. The grouped intrusions shape ore-forming systems—bundled ore fields. NKM zone is composed of two ore fields—Norilsk ore cluster and Talnakh ore cluster which concentrate the most differentiated trappan intrusions of high alkalinity. The sulfide platinoid-bearing copper–nickel mineralization is spatially and genetically connected with the ore-enclosing structures—differentiated intrusions of gabbro dolerites of the Norilsk–Talnakh type. A geological equivalent of the deposits is the completely differentiated zone of the ore-bearing intrusion containing picritic and taxitic gabbro dolerites in the section.

Talnakh ore cluster hosts two ore bodies: Oktyabrsky ore body adjoining the Kharaelakh intrusion and Talnakh ore body adjoining the Talnakh intrusion. Norilsk ore cluster hosts Norilsk I and Norilsk II ore bodies delineated within the limits of the Norilsk intrusion. With respect to the absolute age of the intrusions, the K–Ar method determines their origination sequence as follows: Talnakh 249.4 ± 1.5, Kharaelakh 248.0 ± 1.6 and Norilsk I 246.2 ± 2.2 million years, which is the Early Triassic period [5, 7]. So, we suppose that each deposit featured its own magmatism and had its own focal zones of ore regeneration.

The major ore system of the ore cluster is the plutonic magmatic system hosting sulfide platinum-bearing copper–nickel ore deposits containing around 60% and 15% of the global Pd and Pt resources, respectively, and large resources of Cu, Ni, Co, Se, Ag and Au in Russia [3]. The ore zone has a multi-level structure. Commercial types of ore occur as dissemination, solid (massive) ore bodies with content of sulfides more than 70% and as vein-disseminated ore.

The disseminated ore originated after segregation of sulfides from the magmatic sulfide–silicate meting during gravitational differentiation and crystallization in the magmatic cell, and is localized in the lower intrusive differentiates: picritic, taxitic and contact gabbro dolerites. The solid ore source was the sulfide fluidized magmas. The vein-disseminated ore in the sulfide platinoid-type copper–nickel mineralization has the metamorphic–metasomatic genesis.

Structurally, Norilsk and Tanakh ore-forming systems adjoin high walls of the dome-like Pyasina Swell. Externally the ore forming systems are limited by uplifted sides of flexures and axial lines of upfolds across the strike of the Norilsk–Kharaelakh fault and Kharaelakh trough axis. The main magma and ore control structure is the Norilsk–Kharaelakh fault. The comparison of extension of the invariant lines of maximum thicknesses of intrusions and their morphostructures with the axes of compressive dislocations shows that the latter were the most active magma-controlling structures, and the curves of the syncline folds are the magma-locating structures. The Middle–Paleozoic–Lower Mesozoic upfolds limited propagation of magmas. The ore bodies occur at different depths, from subsurface to a depth of 1400 m.

The NKM zone ore bodies occur in the strata of different lithology: Norilsk cluster is localized in the Carbonic–Permian terrigene sediments of the Tungusska series and at the bottom of the Upper Permian–Lower Triassic basalts; the Oktyabrsksy ore body in the Talnakh cluster, at the Kharaelakh intrusion occurs within the Devonian sulfate–carbonate strata; the Talnakh ore body—in the Cabonic–Permian terrigene coal-bearing strata and, partly, in the Devonian chemogenic rocks. Despite common genesis of ore formations, their sections feature different geochemistry. It follows from the analysis of isotope geochemistry that contamination in the mantle magmas is higher in the Talnakh ore cluster than in the Norilsk ore cluster (Table 1). The properties of ore mineralization in the Talnakh cluster change from the center sideways of the ore-holding intrusions (Table 2).
The Kharaelakh intrusion occurs on the west wall of the Norilsk–Kharaelakh fault and is localized in the Lower to Middle Devonian dropped side of flexure oriented normally to the fault. The Talnakh intrusion adjoins the Lower Devonian trough traceable along the Norilsk–Kharaelakh fault. The Talnakh intrusion mostly lies eastward of the fault (Northeast branch), and its Southwest branch occurs in the Central graben in the zone of the fault. Enclosing rock mass is composed of Carbonic–Permian aluminosilicate terrigene sediments and Upper Devonian carbonate rocks.

**Table 1.** Isotopes He, Ar and S in ore-bearing intrusions of Norilsk and Talnakh clusters

| Intrusion     | Age, mln yr | $^{3}$He/$^{4}$He mantle helium | Atmospheric argon fraction | $^{34}$S crust |
|---------------|-------------|---------------------------------|---------------------------|---------------|
| Norilsk I     | 246.2 ± 2.2 | 3.7                             | 98.9                      | 7.5–9.5       |
| Kharaelakh    | 248.0 ± 1.6 | 0.17                            | 88.3–92                   | 12–14         |
| Talnakh       | 249.4 ± 1.5 | 2.7                             | 94–98                     | 9.5–12        |

The contrast geochemical zonality at the scale of the clusters and deposits is based on the distribution patterns of ratios Ni / Cu, S / Cu and fractionation factor Ff = (Pt + Pd) / (Ru + Ir + Os), reflective of the ore formation process in the conditions of sulfide melting fractioning typical of sulfide copper–nickel ore with platinoids in the Norilsk Region [8].

**Table 2.** Mineral and geochemical zonality of ore-bearing zone in different sections of Talnakh ore-forming system

| Ore bodies | Ni / Cu | Ff | Mineralogy and geochemistry |
|------------|---------|----|------------------------------|
| Northern front, Talnakh intrusion, Talnakh ore body | 0.9 | 23 | Intermediate association. Pyrrhotine–cubanite mineralization. Specialization: Ni = Cu – Co |
| Central zone, Talnakh intrusion, Talnakh ore body | 1.6 | 10 | Highly sulfuric association (S / Cu = 7.0–9.0): pyrrhotine (monoclinic and hexagonal) + chalcopyrite + pentlandite. Specialization: Ni – Cu – Co |
| Southwestern front, Talnakh intrusion, Talnakh ore body | 0.2 | 120 | Low-sulfuric association (S / Cu = 1.8): chalcopyrite, bornite, covelline, chalcocine. Specialization: Cu – Ni – Co |
| Central zone, Kharaelakh intrusion Oktyabrsky ore body | 0.9 | 40–70 | Intermediate association (S / Cu to 4.2): chalcopyrite + pyrrhotine (monoclinic and hexagonal) + pentlandite + cubanite. Specialization: Ni – Cu – Co (Cu = Ni – Co) |
| Southwestern front, Kharaelakh intrusion Oktyabrsky ore body | 0.2–0.7 | 167–1750 | Low-sulfuric association (S / Cu to 2.7): cubanite + chalcopyrite + pentlandite → talnakhite (moikhukite) + cubanite + pentlandite. Specialization: Cu – Ni – Co |

The mineral composition and geochemistry of contact envelopes of the ore-bearing intrusions in rocks of different lithology differ greatly. The upper contact envelope of the Talnakh intrusion is composed of quartz–feldspar hornfels marked with Zr anomalies. The upper contact envelope of the Kharaelakh intrusion in the Mantur sulfate–carbonate sediments is marked with anomalies [9].

In the west of Oktyabrsky ore body, the high-contrast anomalies of (Ff = 35) spatially adjoin the anomalies of Ag – Cu – Ni (or Cu – Ag – Ni) of chalcopyrite-type mineralization with the extremely high contents of Pt to 9–12 g/t, Pd 43–60 g/t and Ag to 13.34 g/t, which form the metamorphic–hydrothermal mineralization of Ag – Pd – Pt [10, 11].
The strontium anomalies in the upper contact envelope of the intrusion in sulfate–carbonate rocks are conditioned by the formation of hydrothermal-origin minerals at the post-magmatic hydrothermal stage [12]. It is supposed that the mineral-forming fluids formed under the higher influence of subsurface water from enclosing sediments around the intrusion.

Regarding strontium isotopes, $\varepsilon_{\text{Sr}}$ for Norilsk anhydrites in the enclosing rock mass of the intrusion fits the Devonian sea water with $\varepsilon_{\text{Sr}}$ from +45 to +60, which differs from $\varepsilon_{\text{Sr}}$ (+20) in the Norilsk intrusions at the type of intrusion. Ratios $\text{Sr}^{87}/\text{Sr}^{86}$ from 0.707 downward are observed in the ultraalkaline rocks of the intrusions. In sulfides in the west of the Kharaelakh intrusion, ratios $\text{Sr}^{87}/\text{Sr}^{86}$ vary from 0.708–0.709 to 0.7116 and exceed $\text{Sr}^{87}/\text{Sr}^{86}$ in intrusive rocks. It can be supposed that during ore formation, the crust (evaporate rocks) with high concentrations of radiogenic strontium has a great influence on the mantle fluid, i.e., at the post-magmatic stage of the hydrothermal process, radiogenic strontium is brought from enclosing rocks into the contact zones of the intrusion after crystallization of magmatic rocks, which induces formation of strontium anomalies with high concentrations of Zn, Mo and Sn in the contact envelopes [9].

The zonal distribution of sulfur, argon and copper isotopes in magmatic rocks of intrusions and ore bodies in the Talnakh system is analyzed in the northwest to the southeast direction, along the strike of the Kharaelakh intrusion.

From the isotopic research [7], at the top section on the west side of the Kharaelakh intrusion, in hornfelses and metasomatic rocks with anhydrite and calcite, the content of heavy sulfur isotopes $\delta^{34}$S vary from 11.4‰ to 12.8‰. In the vein-disseminated ore, $\delta^{34}$S = 11.4‰, in the disseminated ore, 12.6‰ and in the solid ore, 12.6‰ to 12.8‰, which is close to the values of $\delta^{34}$S 15–18‰ (average 16.5‰) in anhydrite. These data point at the essential contribution of sedimentary sulfate sulfur in the process of ore formation. Farther to the southeast from the west of the Kharaelakh intrusion with copper ore, the values of $\delta^{34}$S in sulfides somewhat decrease (from 12.8 to 11.5‰) and approach $\delta^{34}$S = 11.2‰, typical of the Talnakh intrusion ore in the Carbonic–Permain terrigene strata.

The stable isotope compositions of sulfur and copper ($\delta^{65}$Cu/$\delta^{63}$Cu) in ore-bearing intrusions correlate negatively, i.e. copper lightens with heavier sulfur. In the Kharaelakh intrusion with copper ore, $\delta^{65}$Cu (–1.55‰), in Norilsk I intrusion containing more mantle sulfur, $\delta^{65}$Cu (+0.25‰). The lower values of $\delta^{65}$Cu are observed in the conditions of ore mineralization at post-magmatic stage of low-temperature hydrothermal process as against the high-temperature and magmatic conditions of ore formation (Norilsk ore cluster) [7].

In different cross-sections of the deposits and the whole Talnakh system, the different conditions of ore formation are illustrated by patterns of argon isotope ratios $\text{Ar}^{40}/\text{Ar}^{36}$, which allow revealing the atmospheric component of argon in subsurface sedimentation and infiltration water which participate in the ore formation process [7].

In the west of Oktyabrsky deposit, the isotopic abundance of argon in disseminated and solid ore is the same, 89–98%. In the center and south of the deposit, the disseminated ore contain much less air argon (63‰) as compared with the solid ore (77–97%), which means lower impact of subsurface water on the formation of the magmatic disseminated ore.

3. Conclusions

The ore-generating factor in the Norilsk–Kharaelakh Metallogeny zone is the mantle plume. Sulfide platinum-bearing copper–nickel ore in the Norilsk and Talnakh ore clusters belong to plutonic magmatic formation enclosing different types of ore mineralization. Mineralogy and geochemistry is nonuniform per cross-sections of the Talnakh ore cluster, which is conditioned by different mineralization factors, for instance, different structure and tectonics of ore bodies. The center of Oktyabrsky deposit occurs in the deepened part of the Kharaelakh trough (at a depth to 1400 m), the southwest and the west sides of the deposit adjoin stepfold walls of the trough (the occurrence depth of the ore bodies is to 750 m), while the east side of the deposit is adjacent to the stepfold of the long-lived Norilsk–Kharaelakh Fault, which is a natural flexural normal fault.
Magmatic melt in the Kharaelakh Trough flew from the north to the south. The increased fractionation of sulfide magmatic melt and its enrichment with Cu, Pt and Pd is observed in the lines from the east to the west and from the north to the south, i.e. from the center sideways of the deposit, up-dip of the ore-bearing intrusion.

The structures limiting spreading of the fluid-saturated magmatic melt became the sides of the paleo uplifts. There, in the barrier zone of displacement of upward and pore solutions, conductive heat exchange too place and fluid-and-heat bags formed, where intense hydrothermal processes run. The composition of the ore mineralization was governed by the primary composition of the ore-generating magmatic melt and by its secondary alteration in the course of intense assimilation by the crust as a result of metasomatic processes at the geothermally–infiltration stage. The proof of the ore formation at the sides of the Kharaelakh intrusion under impact of the crust (sulfur is sourced by evaporate rocks) and subsurface water on the fluid component in the melting-fractionated sulfide magma enriched with copper, which results in the formation of chalcopyritic ore with Cu–Ni–Co geochemical specialization is the nonuniform distribution of isotopes $\delta^{34}S$, $^{40}\text{Ar} / ^{36}\text{Ar}$, $\delta^{65}\text{Cu}$, $^{87}\text{Sr} / ^{86}\text{Sr}$.

References

[1] Dodin DA 2002 *Metallogeny of the Taimyr–Norilsk Region* Saint-Petersburg: Nauka (in Russian)

[2] Nikulin II and Radko VA 2019 Metallogeny of basic magmatic complexes on the example of the Norilsk province *Minerageny, Economic Geology and Mineral Resources: Smirnov’s Lectures* Part I Moscow: MaksPress pp 147–176 (in Russian)

[3] Spiridonov EM 2019 Genetic model of deposits of the Norilsk ore field *Minerageny, Economic Geology and Mineral Resources: Smirnov’s Lectures* Part I Moscow: MaksPress pp 41–115 (in Russian)

[4] Tarasov AV and Petrov OP 1983 Zonality of commercial copper–nickel deposits in the Norilsk Region as an ore occurrence prediction criterion *Forecasting and Appraisal of Nickel Content in New Areas in the North of the Siberian Platform* Leningrad: PGO Sevmorgeologiya pp 30–41 (in Russian)

[5] Dodin DA and Tarnovetsky LL 1992 Geodynamic model of sulfide–copper–nickel-bearing ore-magmatic systems of the Taimyr–Norilsk province *Geologiya Geofizika* No 12 pp 40–51

[6] Kamo SL, Czamanske GK, Amelin Yu, Fedorenko VA, Davis D and Trofimov VR 2003 Rapid eruption of Siberian flood-volcanic rocks and evidence for coincidence with Permian–Triassic boundary and mass extinction at 251 Ma *Earth and Planetary Science Letters* Vol 214 pp 75–91

[7] Adamskaya EV, Badinova VP, Belyatsky BV et al 2017 *Isotopic Geology of the Norilsk Deposits* Saint-Petersburg: VSEGEI (in Russian)

[8] Miroshnikova LK 2014 The study of ore-geochemical zonality of ore bodies of deposits of the Norilsk Region *Izv. vuzov. Geologiya i Razvedka* No 2 pp 31–36

[9] Miroshnikova LK The relationship of strontium anomalies in contact aureoles of ore-bearing intrusions with anomalies of mineralogenic trace elements in commercial horizons of sulfide ores *Vestnik IrGTU* No 7 (47) pp 46–52

[10] Spiridonov EM, Serova AA, Kulikova IM, Korotaeva NN and Zhukov NN 2016 Metamorphic-hydrothermal Ag–Pd–Pt mineralization in the Norilsk sulfide ore deposit, Siberia *Canad. Mineral* Vol 54 pp 429–452

[11] Spiridonov EM, Belyakov SN, Yapaskurt VO, Korotaeva NN and Krivitskaya NN 2019 Norilsk ore field: Direct evidence of the pneumolithic genesis of palladium minerals in solid sulfide ores *New Ideas in Earth Sciences* Vol II pp 380–383 (in Russian)

[12] Turovtsev DM 2000 *Contact Metamorphism of Intrusions in the Norilsk Region* Moscow: IGEM RAS (in Russian)