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Forecasting criteria for sulphide PGE-copper-nickel deposits of the Noril'sk province

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Research subject. World-class sulphide platinum-group-element (PGE)-Cu-Ni deposits occur within the Noril'sk-Talnakh region of northern Siberia, Russia. The significance of these deposits presents opportunities to determine the most effective approaches for the search of similar deposits using commercial PGE-Cu-Ni deposit examples. *Materials and methods*. Petrological and geochemical analysis of the ultramafic-mafic intrusions of the Noril'sk province ranks them into three types in terms of sulphide mineralization style and economic significance: 1) economic intrusions containing unique and large sulphide PGE-Cu-Ni deposits (Oktyabr'sk, Talnakh and Noril'sk-1); 2) subeconomic intrusions that contain small- to medium-sized Cu-Ni sulphide deposits, and medium-sized to large PGE deposits (Chernogorsk, Zub-Marksheider, Vologochan, etc.); 3) uneconomic intrusions that contain low-grade disseminated Cu-Ni ores with ≈0.2 wt % of Cu and Ni, and low Cr and PGE (Nizhny Talnakh, Zelyonaya Griva, etc.). *Results and conclusions.* Principal sources used in exploration for rich sulphide PGE-Cu-Ni ores include structural, magmatic, stratigraphic-lithological, geochemical, mineralogical, metamorphic and some others. Based on an analysis of isotope-geochemical data, new indicators for locating sulphide PGE-Cu-Ni mineralization are suggested. A restricted range of S-isotope values, and a negative trend for coupled S-Cu isotope compositions can be employed as useful guides to assess the economic potential of a PGE-Cu-Ni sulphide deposit. It is proposed that the Chernogorsk ultramafic-mafic intrusion of the Noril'sk province is the most promising target in a search for rich PGE-Cu-Ni ores. It is suggested that the previously known mineralogical-geochemical and novel isotope-geochemical characteristics of sulphide and silicate minerals are important indicators in assessing the potential ore content of ultramafic-mafic intrusions of the Noril'sk province.

Keywords: *ultramafic-mafic intrusions, sulphide PGE-Cu-Ni deposits, forecasting criteria, Noril'sk province*

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Критерии прогноза сульфидных платиноидно-медно-никелевых месторождений Норильской провинции

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Объект исследований. С ультрамафит-мафитовыми интрузивами Норильской провинции на северо-западе Сибирской платформы связаны уникальные месторождения платиноидов, никеля и меди. Промышленное значение сульфидных платиноидно-медно-никелевых (ЭПГ-Cu-Ni) месторождений предопределяет необходимость выявления на их примере наиболее эффективных предпосылок и признаков прогноза для поиска подобных им месторождений. *Материалы и методы*. Петролого-геохимический анализ ультрамафит-мафитовых интрузивов Норильской провинции позволил ранжировать их по степени перспективности на платиноидно-медно-никелевые руды в составе трех геолого-экономических типов: 1) промышленно-рудоносного, вмещающего уникальные и крупные месторождения (Октябрьское, Талнахское и Норильск-1); 2) рудоносного, с которым ассоциируют мелкие (резервные) месторождения с забалансовыми запасами сульфидных платиноидно-медно-никелевых руд (Черногорское, Зуб-Маркшейдерское, Вологочанское и др.); 3) слаборудоносного с Cu-Ni сульфидной минерализацией без платиноидов (интрузивы Нижнеталнахский, Нижненорильский, Зеленогривский и др.). *Результаты и выводы*. В ста-

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тье рассмотрены глубинные, магматические, минералогические, геохимические, литолого-стратиграфические и метаморфические критерии и признаки прогноза сульфидных платиноидно-медно-никелевых месторождений. На основе анализа изотопно-геохимических данных предложены новые индикаторы масштабности сульфидного ЭПГ-Cu-Ni оруденения при прогнозировании богатых (массивных) сульфидных руд. На основе сочетания изотопных составов осмия, серы и меди впервые выявлены интрузивные тела с вкрапленными сульфидными ЭПГ-Cu-Ni рудами, обладающими параметрами рудного вещества, за счет которых были сформированы массивные руды платиноидно-медно-никелевых месторождений Норильской провинции. Высокие перспективы обнаружения богатых сульфидных платиноидно-медно-никелевых руд для Черногорского рудоносного интрузива обусловлены сходством S-Cu изотопных характеристик для вкрапленных сульфидных ЭПГ-Cu-Ni руд данного интрузива с таковыми промышленно-рудоносного Талнахского интрузива Норильской провинции. Обосновывается, что ранее известные минералого-геохимические и вновь предлагаемые изотопные характеристики рудного и силикатного вещества являются ключевыми индикаторами при оценке рудоносности ультрамафит-мафитовых интрузивов Норильской провинции.

Ключевые слова: *ультрамафит-мафитовые интрузивы, сульфидные платиноидно-медно-никелевые месторождения, критерии прогноза, Норильская провинция*

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INTRODUCTION

The ultramafic-mafic Noril'sk-type intrusions in the northern part of Siberia (Russia) host one of the world's major economic platinum-group-element (PGE)-Cu-Ni sulphide deposits. Despite the fact that PGE-Cu-Ni ores in the Noril'sk area have been explored since the early 1920s (Sotnikov, 1919; Rogover, 1959; Godlevsky, 1959; Korovyakov et al., 1963), it was the discovery of the Oktyabr'sk and Talnakh deposits within the Talnakh ore junction that brought the former USSR to a leading position in the world platinum and nickel industry in early 1960s (Egorov, Sukhanova, 1963; Vaulin, Sukhanova, 1970; Kravtsov, 2003). Along with the Sudbury ore district, the Noril'sk-Talnakh deposits dominate the global resource of sulphide-hosted Ni and contain a significant proportion of the global Pd resource. Russia was the world's leading producer of Pd in 2019 (www.statista.com/statistics/273647/global-mine-production-of-palladium), with about 40% of production coming from the Noril'sk-Talnakh deposits (State report on..., 2019). According to JSC Norilsk Nickel, the Oktyabr'sk deposit contains balanced reserves of 3930.4 t of platinum-group metals in category A + B + C_1, and 1537.5 t in category C_2, with a mean PGE grade in sulphide ore of 5.02 ppm, the Talnakh deposit contains balanced reserves of 3174.2 t of platinum-group metals in category A + B + C_1, and 1156.3 t in category C_2, with a mean PGE grade in sulphide ore of 4.8 ppm (State report on..., 2019). According to JSC Norilsk Nickel and PLC Russian Platinum, the Noril'sk-1 deposit contains balanced reserves of 1283 t of platinum-group metals in category A + B + C_1, and 1170.1 t in category C_2, with a mean PGE grade in sulphide ore of 5.7 ppm (State report on..., 2019). Five mines exploit ores of the Oktyabr'sk and Talnakh deposits (Oktyabr'sk, Taimyr, Komsomol, Mayak and Skalisty), whereas disseminated ore of the Noril'sk deposit is mined in the Zapolyarny underground mine and the Medvezhy Creek open pit. The Oktyabr'sk and Talnakh deposits within the Talnakh ore junction have no analogues in the world, featuring a unique combination of large scale and high-grade ores (see Table 1 in (Barnes et al., 2020)).

Since the discovery of economic sulphide PGE-Cu-Ni deposits within the Noril'sk province (as in other ore districts globally), there has been a continuous search for reliable criteria and indicators for forecasting these deposits (Map of prospective evaluation…, 1976, 1979; Lyakhnitskaya, Tuganova, 1977; Exploration criteria…, 1978; Malitch et al., 1987; Likhachev, 1986; Metallogenic map…, 1984, 1987; Principles and methods…, 1987; Stepanov, 1989; Dyuzhikov et al., 1988; Tuganova, 2000; Naldrett, 2004; Rad'ko, 2016, Malitch et al., 2018b, among others). These criteria include a wide range of structural, deep-seated, magmatic, geochemical, mineralogical, metamorphic, stratigraphic and hydrogeochemical indicators. Recent radiogenic and stable isotope studies of variously mineralized Noril'sk-type ultramafic-mafic intrusions used new approaches and expanded our knowledge for predicting sulphide PGE-Cu-Ni ores (Malitch et al., 2014, 2018a, b, 2020; Sluzhenikin et al., 2014, 2018, 2020a, b; etc.). In this article I attempt to review earlier known prediction criteria together with a novel set of key isotopic-geochemical indicators that can be used in exploration for sulphide PGE-Cu-Ni rich ores.

GEOLOGICAL BACKGROUND

Sulphide PGE-Cu-Ni deposits related to the Noril'sk-1, Talhakh and Kharaelakh (also known as Oktyabr`skoe deposit) mafic-ultramafic intrusions are located in the northwestern part of the Siberian Craton (Russia). The intrusions are controlled by a long-lived intracontinental paleorift (Tuganova, 2000) and have a

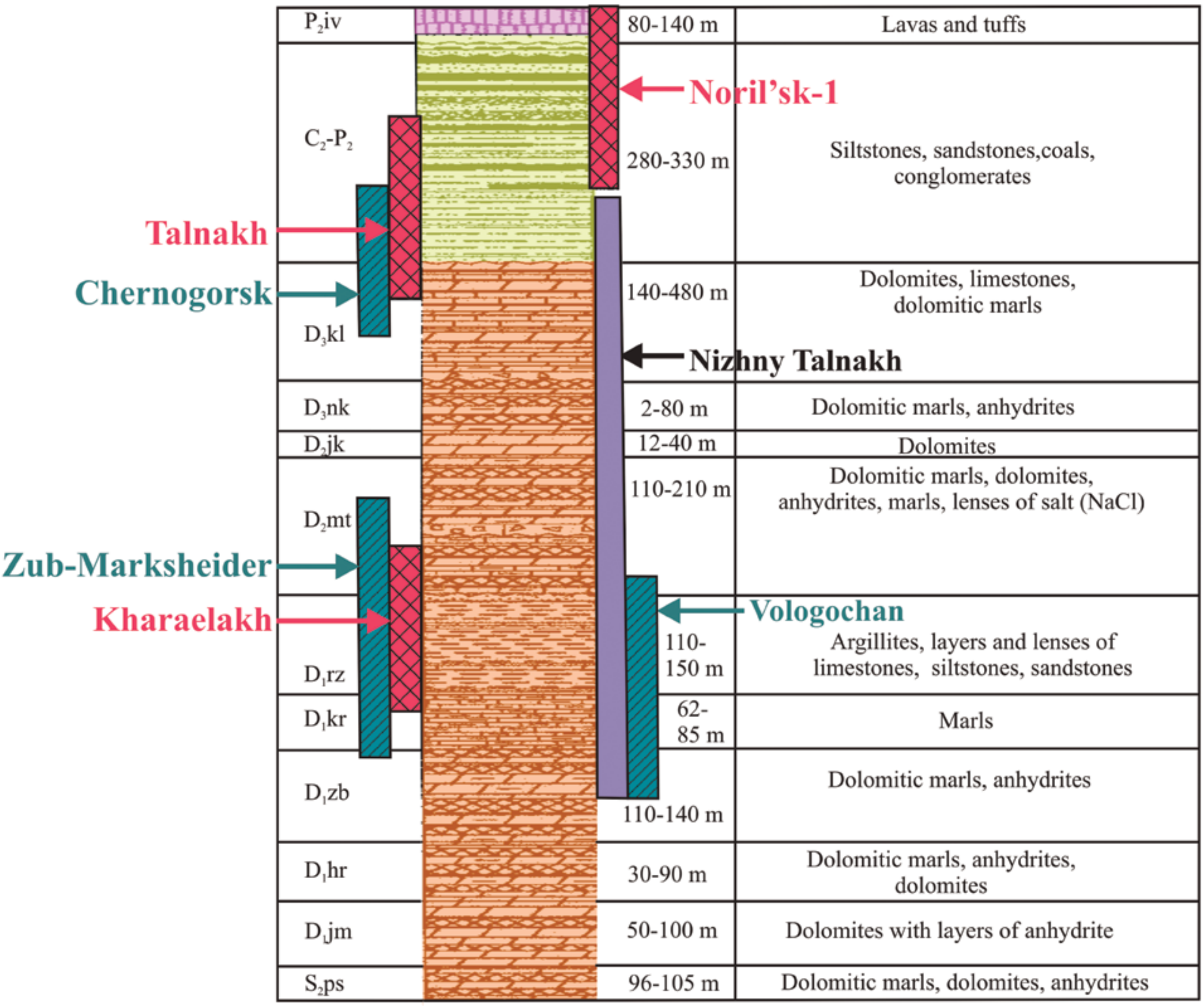

Fig. 1. Stratigraphic section showing the positions of economic, subeconomic and non-economic ultramafic–mafic intrusions (modified after Dyuzhikov et al., 1992; Czamanske et al., 1995).

Рис. 1. Стратиграфический разрез, показывающий положение промышленно-рудоносных, рудоносных и нерудоносных ультраосновных-основных интрузивов, по (Dyuzhikov et al., 1992; Czamanske et al., 1995), с изменениями.

thickness of up to 360 m and length of up to 25 km. The geologic setting (Fig. 1) and the morphological, lithologic, petrographic, and isotopic-geochemical features of ultramafic-mafic intrusions and closely linked PGE-Cu-Ni deposits have been described in detail among others by Godlevsky (1959), Dodin and Batuev (1971), Zolotukhin et al. (1975), Distler et al. (1988, 1999), Likhachev (1994), Lyul'ko et al. (1994, 2002), Walker et al. (1994), Czamanske et al. (1992, 1995), Tuganova (2000), Komarova et al. (2002), Latypov (2002, 2007), Turovtsev (2002), Arndt et al. (2003), Cabri et al. (2003); Ripley et al. (2003), Naldrett (2004), Yakubchuk and Nikishin (2004), Petrov et al. (2009), Arndt (2011), Malitch and Latypov (2011), Malitch et al. (2014, 2018a, b, 2020), Ryabov et al. (2014), Sluzhenikin et al. (2014, 2018, 2020a, b), Krivolutskaya (2016), Barnes et al. (2019, 2020), Krivolutskaya et al. (2019), Tolstykh et al. (2020), Yao and Mungall (2021). A correlation scheme of ore-bearing intrusive formations in the north-western part of the Siberian Craton with respect to its geotectonic setting, as well as mineralogical, petrological, and geochemical features and ore content is given in Table 1.

Ultramafic-mafic intrusions of the Noril'sk area were subdivided (Petrov et al., 2009) into three types in terms of sulphide mineralization style and economic significance.

1. Economic ultramafic-mafic intrusions that host commercial reserves (Noril'sk-1, Talnakh and Kharaelakh intrusions) contain well-defined horizons of

Table 1. Correlation scheme of ore-bearing PGE-Cu-Ni intrusive formations of the Siberian Craton with respect to its geotectonic setting, petrological features and ore content (modified after (Tuganova, 2000))

Таблица 1. Кореляционная схема рудоносных платиноидно-медно-никелевых интрузивных формаций Сибирской платформы с учетом геотектонической позиции, петрологических особенностей и рудогенеза, по (Туганова, 2000), с дополнениями

Intrusive formations		Olivinite-gabbroic	Gabbro-melanotroctolitic	Troctolite-doleritic
Rock series composing the formation		Ore plagioclase-bearing dunites (olivinites) and wehrlites, melanotroctolites, troctolites, olivine, olivine-bearing and olivine-free gabbro, gabbro-diorites (hybrid), leucogabbro	Melanotroctolites, troctolitic, olivine, olivine-free gabbro-(dolerites), gabbro-diorites; rare discontinuous horizons and lenses of plagioclase-bearing peridotites	Troctolitic, olivine and olivine-free dolerites, rare melanotroctolites, quartz dolerites, ferrodolerites
Intrusion thickness		100–360 m (200 m in average)	10–400 m, more often 20–100 m	20–260, rare up to 400 m
Olivine-rich *vs* olivine-poor rocks ratio		25–30 (up to 50): 50–75	50м70: 30–50	5–10: 90–95
Inner structure of intrusions		Discrete rock series	Discrete rock series	Continuous rock series
Intrusion shape		Chonolith, complex gently (rare steeply) cross-cutting bodies	Complex and sheet-like bodies	Sills, rare gently cross-cutting intrusions and dykes
Petrological features	Geochemical	Olivine-rich rocks exhibit a high content of MgO (up to 29), low content of TiO_2 (<0.7) and Na_2O + + K_2O (less than 1.5) (all in wt %). Increased contents of chromium (up to 0.8 wt %), nickel, copper, cobalt, PGE. Increased content of Ni in olivine (0.2–0.3 wt %), increased content of chromium in clinopyroxene (up to 1.05 wt % Cr_2O_3), cromite (32–44 wt % Cr_2O_3). Olivine-bearing and olivine-free gabbro exhibit average contents, as follows (wt %): MgO – 7.5, TiO_2 – 1.5–3.0, Na_2O + K_2O – more than 2.5. The amount of Cr, Ni, Cu, PGE is 2 orders lower	Melanotroctolites exhibit increased contents of MgO (14–16 wt %), in ultramafic rocks (up to 27 wt %), low contents of TiO_2; and P_2O_5 (0.5 and 0.06 wt % in average respectively), low contents of Cr_2O_3, CaO and Al_2O_3, as well as Na_2O + + K_2O (≈1 wt %). Elevated contents of iron (up to 18 wt %) owing to sulphides (of troilite, pyrrhotite), magnetite and ilmenite, as well as increased contents of nickel, copper and cobalt (owing to chalcopyrite and pentlandite). The petrogeochemical composition of gabbroic rocks is similar to that of common intrusive dolerites	Typically, high contents of MgO in melanotroctolites and troctolitic dolerites (wt %): (up to 12–16), TiO_2 (>1.0) and Na_2O + K_2O (2.5–3.0). The content of MgO in olivine and olivine-free dolerites is ≈6–7 wt %
	Mineralogical	There are two mineral generations: deep-seated and shallow. The former contains high-pressure minerals: chromite, chrome-bearing augite and orthopyroxene, magnesian olivine (Fa 5–8 and 18–25), anorthite. Ores contain djerfisherite, Si and Wo carbides, sulphides with refractory PGE (Ir, Os, Ru); the latter generation contains common doleritic minerals: titanium-bearing augite (TiO_2 up to 0.9 wt %), more Fe-rich olivine (Fa 30–55), less mafic plagioclase (An 60–78)	Clinopyroxene of a slightly varied composition occurs all over the section. The iron content in it increases up- and downwards (along the section) from melanotroctolites and plagioperidotites. The composition of olivine in ultramafic rocks is more magnesian (Fa 20–25) than in gabbroic rock (Fa > 30); in the former it is replaced by serpentine, in the latter it is replaced by bowlingite. In the former plagioclase is represented by anorthite (An 90–100), in the latter it is represented by labrador-bytownite (An 60–80). In upper gabbro and contact dolerites plagioclase is albitized, pelitized; olivine is replaced by bowlingite, clinopyroxene is replaced by amphibole and chlorite	The content of chromium in clinopyroxenes and the content of nickel in olivines (0.04–0.08 wt %) is close to their amount in a shallow association of rocks in gabbro in the upper parts of the olivinite-gabbroic formation. Typically, high contents of cobalt in sulphides (in particular, up to 11 wt % in pentlandite), low contents of nickel and PGE
Morphological types of rocks associated with intrusive formations		Disseminated (interstitial, spheroidal, palmate) and disseminated-veined sulphide ores confined to the bottom of intrusions (to ultramafic and taxitic-textured basic rocks that replace them). Deposits and veins of massive ores in lower (rarely upper) endo- and exocontact intrusions. Brecciated ores occur in the upper exocontact. Massive ores are accompanied by an areole of disseminated-veined copper-rich ores. Disseminated low-sulphide PGE mineralization confined to upper "taxites"	Disseminated mineralization (interstitial, rare spheroidal dissemination) is mainly confined to olivine-rich rocks	Scattered dissemination of sulphides over the whole section of intrusions, rare sulphide-rich horizons (and schlierens) as hanging ore bodies

Table 1. Ending

Таблица 1. Окончание

<table>
<tr><td colspan="2">Intrusive formations</td><td colspan="2">Olivinite-gabbroic</td><td colspan="2">Gabbro-melanotroctolitic</td><td colspan="2">Troctolite-doleritic</td></tr>
<tr><td colspan="2">Ore body parameters</td><td colspan="2">Sheet-like bodies of disseminated sulphide nickel-copper ores as long as first tens of km and up to 90 m thick; deposits of massive ores are up to first km with the thickness of up to 45 m, more often 19–20 m</td><td colspan="2">Sheet-like bodies of disseminated mineralization with the thickness of up to 50–70 m, first tens of km long</td><td colspan="2">Discontinuous horizons and lens-like bodies are rich in disseminated (up to 15–20%, commonly 1–5%) sulphides (pyrrhotite mainly) up to 0.5–1.5 m thick and several km long</td></tr>
<tr><td rowspan="5">Ore content</td><td>Main ore content</td><td colspan="2">Nickel-copper (with cobalt, PGE and gold)</td><td colspan="2">Copper-nickel (with cobalt)</td><td colspan="2">Cobalt-copper (with nickel)</td></tr>
<tr><td>Major elements</td><td>Cu, Ni, Co, S, Pt, Pd.</td><td rowspan="2">Higher than clark Ko = = 50–200. Ko is up to 2000 in massive ores</td><td>Ni, Co, Cu, S</td><td rowspan="2">Ko for Ni is up to 8, Cu is up to 4, Co is up to 3</td><td>Cu, Co, S</td><td rowspan="2">Close to clark, Ko is up to 2–8</td></tr>
<tr><td>Secondary elements</td><td>Rh, Ru, Ir, Os, Se, Fe, Ag, Au, As, Zn, Pb, etc.</td><td>Pd, Pt, etc.</td><td>Ni, Pt, Pd, etc.</td></tr>
<tr><td>Major minerals</td><td colspan="2">Pyrrhotite, troilite, chalcopyrite, pentlandite, cubanite, magnetite, platinum group mineral (PGM)</td><td colspan="2">Troilite, pyrrhotite, chalcopyrite, cubanite, cobalt pentlandite (Co is up to 3.7 wt %)</td><td colspan="2">Pyrrhotite, chalcopyrite, magnetite, ilmenite</td></tr>
<tr><td>Secondary minerals</td><td colspan="2">Ilmenite, millerite, talnakhite, mooihoekite, pyrite, sphalerite, galenite, etc. (>100 ore minerals in total)</td><td colspan="2">Mooihoekite, talnakhite, PGM, etc.</td><td colspan="2">Pyrite, rare cobalt pentlandite (Co is up to 11 wt %); cubanite, PGM and other are rare</td></tr>
<tr><td colspan="2">Retrospective geotectonic setting</td><td colspan="4">Within rift systems. Associated with mantle faults and their intersection with major regional and local faults that often associated with the former ones</td><td colspan="2">In the framework of rift systems. Along zones of transverse faults (or tectonic sutures) above the junction of major structures of the platform cover and associated minor fractures</td></tr>
<tr><td colspan="2">Deep structure</td><td colspan="4">Typically, high-gradient downfolds in the basement; the crust is saturated with horst-graben structures, dense fault systems, including mantle faults; large amount of erupted masses of the mantle matter (including deep seated at >200 km and shallow); increased thickness of the “basaltic” layer, presence of the intermediate layer between the Earth crust and the mantle with an increased (regarding the crust) velocity of longitudinal waves (Vp = 7.3 km/s)</td><td colspan="2">Typical structure of stabilized blocks of the platform with similar (≈20 km) thicknesses of granitic and basaltic layers, gentle downfolds and minor fragmentation of the crust. No intermediate layer between the Earth’s crust and the mantle</td></tr>
<tr><td colspan="2">Primary magma composition</td><td colspan="2">Peridotite-komatiitic + tholeiite-basaltic</td><td colspan="2">Tholeiite-basaltic + probably, peridotite-komatiitic</td><td colspan="2">Mainly tholeiite-basaltic</td></tr>
<tr><td colspan="2">Intrusion types and deposits</td><td colspan="2">Talnakh-Noril’sk (Noril’sk)*, Mt. Zub*; Oktyabr’skoye, Talnakh, Noril’sk-1, Chernogorsk, Mt. Zub, Noril’sk-2, etc.</td><td colspan="2">Nizhny Noril’sk** (Nizhny Talnakh**), Morongo***, etc.</td><td colspan="2">Kureika***, Degensk***, etc.</td></tr>
</table>

*Intrusive formations are associated with unique and major sulphide PGE-copper-nickel and low-sulphide PGE deposits.
**Associated with copper-nickel occurrences disseminated over sections of intrusions.
***Occurrences and mineralization.

*С интрузивными формациями ассоциируют уникальные и крупные сульфидные платиноидно-медно-никелевые и малосульфидные платиноидные месторождения.
**Ассоциируют сульфидные медно-никелевые рудопроявления, рассеянные по разрезу интрузивов.
***Рудопроявления и минерализация.

plagioclase-bearing peridotites (plagiodunite and plagiowehrlite) with elevated contents of chromium and taxitic textured rock assemblage. The disseminated, vein-disseminated, and massive ores forming large and unique PGE-Cu-Ni deposits (with cobalt, gold, silver, etc.) are associated with these rock lithologies. In the upper part of these intrusions a PGE-rich low sulphide horizon is hosted by leucogabbro with lenses of ultramafic rocks. According to Sr-Nd isotope systematics, lithologies show a distinct heterogeneity in the radiogenic strontium component ($^{87}Sr/^{86}Sr = 0.7055–0.7075$) at rather constant initial isotope composition of neodymium (εNd values of about +1).

2. Subeconomic intrusions with disseminated PGE-Cu-Ni ores that form uncommercial reserves are represented by ultramafic-mafic intrusions of Chernogorsk

(Chernogorsk intrusion) and Zubovsky (Zub-Marksheider and Vologochan intrusions) types. The mineralogy, geochemistry, Nd-Sr isotope systematics and rock lithologies are closely match those of the economic intrusions. Subeconomic intrusions have disseminated, or more rarely vein-disseminated, sulphide ores and may contain small to medium size Cu-Ni sulphide deposits, and medium to large size PGE deposits.

3. Weakly mineralized uneconomic mafic-ultramafic intrusions of "Lower Talnakh type" are represented by the Nizhny Talnakh, Nizhny Noril'sk and Zelyonaya Griva intrusions. They contain low-grade disseminated Cu-Ni mineralization (up to 0.2 wt % of Cu and Ni). In contrast to the above-mentioned intrusions, lithologies of the uneconomic intrusions show low contents of chromium and PGE (≈0.005 ppm, rarely up to 0.02 ppm). Rocks of the uneconomic intrusions have more radiogenic initial Sr values ($^{87}Sr/^{86}Sr$ = 0.7076–0.7086) together with negative εNd values of about −5.

Sulphide ores associated with economic intrusions occur as (1) massive or vein-like ores at the lower contacts, (2) vein-like and disseminated ores in host rocks, and (3) disseminated ores in ultramafic and taxitic-textured rocks in the lower parts of the intrusions. Each type contributes differently to the total resources of base metals and PGE (Table 2), and each has distinct PGE concentrations and modes of occurrence of platinum-group minerals (PGM).

Lens-like massive orebodies can extend for several kilometers with thickness up to 30 m; they also penetrate the host rocks as thin apophyses and veins. Massive ores vary in composition spanning from a pyrrhotite-rich variety containing 2 to 3 wt % of Cu with subordinate chalcopyrite, pentlandite, and PGM to a Cu-rich variety (27–32 wt % of Cu) with dominant chalcopyrite, cubanite, and mooihoekite over other sulphides and PGM (Sluzhenikin et al., 2014). Subordinate chalcopyrite-rich ores usually have a zoned structure from pyrrhotite, through chalcopyrite and cubanite, to mooihoekite. Chalcopyrite-rich ores are more enriched in Pt and Pd than pyrrhotite-rich ores (Tuganova, Malich, 1990). Vein-like and disseminated ores occur as haloes around massive ores with thicknesses ranging from 1 to 16 m. Disseminated ore bodies are the main repository of PGE (Lyul'ko et al., 2002); they occur in taxitic-textured and ultramafic horizons and are 30 to 90 m thick.

The "low-sulphide" horizon in the upper part of the intrusions is a relatively new economic ore variety in the Noril'sk-type deposits (Sluzhenikin et al., 1994). The low-sulphide horizon is 0.1–30 m thick, and occurs exclusively in the taxitic-textured rocks, with lenses of chromitite and chromite-olivine segregations (e.g., dunite) within leucogabbro in the upper parts of parts of the intrusions. The low-sulphide horizon contains up to 3 vol. % of sulphides with Cu and Ni ranging from 0.2 to 0.3 wt %, and PGE concentrations (up to 60 ppm) comparable with or sometimes higher than for PGE-Cu-Ni disseminated ores (Table 2).

The most promising targets for the PGE-Cu-Ni prospecting within the Taimyr Province (Fig. 2) are linked to the Dyumtaley and Binyuda mafic-ultramafic intrusions located in the Binyuda-Tarey and Luktakh ore districts, respectively (Dyuzhikov et al., 1995; Komarova et al., 1999; Geology and mineral resources…, 2002; Romanov et al., 2011). The prospective Dyumtaley intrusion consists mostly of ferrogabbro (i.e., gabbro abnormally high in Fe) with titanomagnetite ores in the upper part and troctolitic ferrogabbro with PGE-Cu-Ni sulphide mineralization in the lower part (Komarova et al., 1999; Geology and mineral resources…, 2002). The prospective Binyuda intrusion is composed of dunite, plagioclase-bearing dunite, and plagioclase-bearing wehrlite in the upper and middle parts and of melanocratic troctolite in the lower part of intrusion (Geology and mineral resources…, 2002; Malitch et al., 2016). The rocks from both intrusions have distinct initial Nd-Sr signatures (εNd = 4.2 ± 0.7 and $^{87}Sr/^{86}Sr$ = 0.70474 ± 0.00020 at Dyumtaley and εNd = 3.8 ± 0.4 and $^{87}Sr/^{86}Sr$ = 0.70588 ± 0.00013 at Binyuda (Malitch et al., 2016)).

Table 2. Proportions of total reserves of various ore types in the Noril'sk area

Таблица 2. Качество и структура запасов различных типов руд эксплуатируемых месторождений Норильского района

Ore type	Reserves, %				Average metal contents in ores		
	Total ore	Ni	Cu	PGE	Ni, %	Cu, %	PGE, ppm
Massive	10.3	41.7	31.8	20.6	3.2	4.6	10.8
Vein/disseminated	7.4	8.1	16.4	13.3	0.9	3.3	9.8
Cu-dominant, Disseminated	82.3	50.2	50.2	66.1	0.5	0.9	4.3
PGE-dominant, Low sulphide horizon					0.3	0.2	3–6

Note. Data compiled from (Lyul'ko et al., 2002); ore from the low sulphide horizon has not been adequately evaluated to include in reserves but 2700 and 3600 metric tons of PGE may occur in this setting at Noril'sk-1 and Talnakh-Oktyabr'sk (combined), respectively.

Примечание. Данные из работы (Люлько и др., 2002); руды малосульфидного горизонта не были оценены и включены в подсчет запасов, тем не менее по предварительным оценкам в них может находиться 2700 и 3600 т ЭПГ в месторождениях Норильск-1 и Талнахское-Октябрьское (объединенно), соответственно.

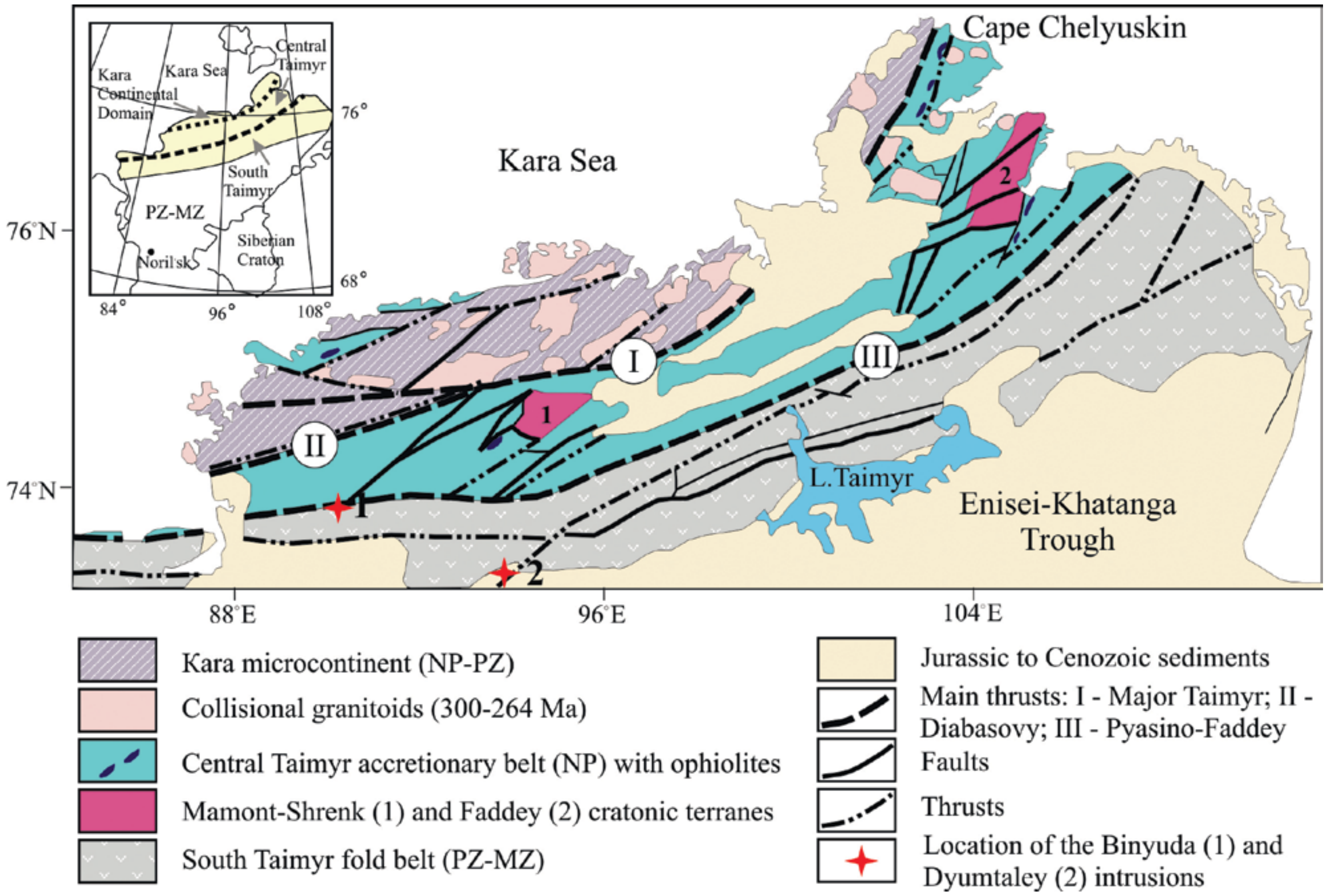

Fig. 2. Geological sketch map of the Taimyr Peninsula (modified after Vernikovsky, Vernikovskaya, 2001; Proskurnin et al., 2014). NP – Neoproterozoic.

Рис. 2. Геологическая схема п-ва Таймыр, по (Vernikovsky, Vernikovskaya, 2001; Proskurnin et al., 2014), с изменениями. NP – неопротерозой.

FORECASTING CRITERIA FOR DISCOVERY OF ECONOMIC INTRUSIONS WITH RICH SULPHIDE ORES

Comparative analysis of sulphide PGE-Cu-Ni deposits, including those in Polar Siberia, suggests identical criteria for their regional (and partially local) prospecting, regardless of their location and time of emplacement. Structural, magmatic and lithological-stratigraphic criteria are considered to be the main features, whereas geochemical, mineralogical, isotope-geochemical, metamorphic, lithogeochemical and other signatures are also important (Map of prospective evaluation…, 1976, 1979; Lyakhnitskaya, Tuganova, 1977; Exploration criteria…, 1978; Metallogenic map…, 1984, 1987; Likhachev, 1986; Malitch et al., 1987; Principles and methods…, 1987; Stepanov, 1989; Tuganova, 2000; Naldrett, 2004; Petrov et al., 2009; Rad'ko, 2016, Malitch et al., 2018, b, among others). The study of various ore-bearing intrusions and sulphide PGE-Cu-Ni ores in Polar Siberia allows us to refine already known prediction criteria and specify additional indicators useful for prospecting similarly rich ores.

Structural criteria. Structural criteria include data from regional and local levels. The analysis of the deep structure of the Noril'sk area suggests a connection between the formation of PGE-Cu-Ni deposits in paleorift structures (Malitch et al., 1988) and particular geological and geophysical parameters (Fig. 3). These include: (i) high-gradient downfolds in the basement represented by thick (12–15 km) sequences of sedimentary and volcanogenic rocks, (ii) a high abundance of horst-graben structures in the crust, (iii) increased density of faults in the Earth's crust, and (iv) large volumes of intruded mantle-derived material between the crust and mantle, in agreement with gravitational anomalies (Vaulin et al., 1978). Using seismic data (Egorkin et al., 1984; Malitch et al., 1989), a transition zone has been identified at the base of the crust in the Noril'sk region, with higher velocities of longitudinal waves (Vp; 7.3 km/s) compared to those typical of the crust (Fig. 3). This zone has been considered as a manifestation of ultramafic material injected in the subcrustal levels of the

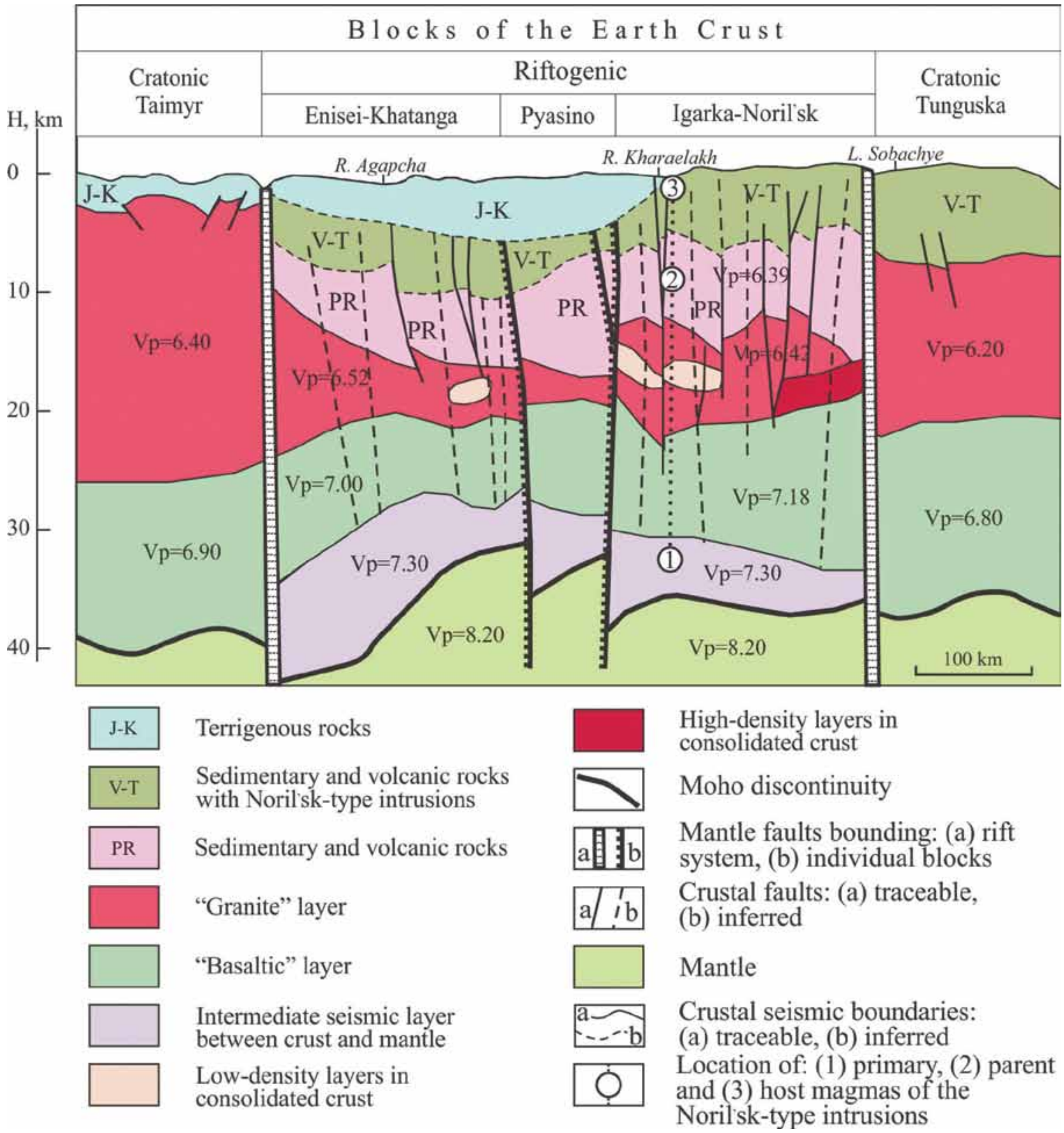

Fig. 3. Geoseismic section along the northern part of the profile Dikson–Khilok, illustrating a three-stage evolution model for the PGE-Cu-Ni sulphide deposits (modified after (Malitch et al., 2020)).

Рис. 3. Геосейсмический разрез вдоль северной части профиля Диксон–Хилок, иллюстрирующий трехступенчатую модель эволюции сульфидных месторождений PGE-Cu-Ni по (Malitch et al., 2020 с изменениями).

lithosphere. The thickness of this zone is 5–10 km, with a spatial extent of about 500 km at depths of 32–43 km. Most likely, a large volume of sulphide-rich ultramafic-mafic material preceded the tholeiite-basaltic volcanism, which contributed to the removal of these bodies to form relatively small hybrid layered intrusions. It was proposed (Malitch et al., 2020) that the sulphide ores had a prehistory responsible for the concentration of sulphides from the large volume of ultramafic-mafic magmas (Fig. 3, stage 1). This was followed by partial assimilation of crustal material and isolation of significant amounts of sulphide liquid in staging chambers (Fig. 3, stage 2), resulting in its capture by a later magma that served as the vehicle facilitating their passage to the surface (stage 3). It is noteworthy that economic intrusions are restricted to the region above this transition zone, which is considered as a typical feature of the basal part of the crust in oceanic and continental paleorifts (e.g., Krylov, 1976; Belousov, 1982; Ramberg, Morgan, 1984; Malitch et al., 1987). In general, the deep structure of the Noril'sk area shows non-cratonic features of a transitional type differentiated crust (Malitch et al., 1989). Therefore, identification of deep structures as exemplified at Noril'sk is an important criterion for regional tectonic forecasting.

An important indicator of increased mobility of the Noril'sk region in the Precambrian is a linear downfold, which is clearly observed on the Dikson-Khilok seismic profile (Fig. 3). Judging by the velocity of longitudinal waves, the downfold is composed of 5–8 km thick sedimentary and volcanogenic rocks. Tholeiitic, trachybasaltic and picritoid formations of the Early Proterozoic age exposed in the Igarka Swell, located south-eastwards from the downfold, also implies rifting settings in the Igarka-Noril'sk region in the early Proterozoic (Tuganova, 1992). The factual basis for in-depth criteria is provided by petrological research confirming the association of magmatic and ore formations with the Earth's deep-seated horizons (Deep conditions..., 1986; Metallogenic map…, 1987; Tuganova, 1992; etc.) and indicating interaction of the mantle material at different levels during evolution of paleorift systems.

The key structural elements that contributed to the transfer of sulphide-rich ore from the abyssal mantle are regional deep-seated units (paleorift systems, mantle faults). Meanwhile, local disjunctive and plicative units (crustal faults, troughs, saddles, domes) contributed to emplacement of ore areas, fields, ore-bearing intrusions and ores at the near-surface levels of the Earth's crust. Regional units predetermine the content and scale of the ore genesis, while local units define only the shape of ore-bearing intrusions and to a lesser extent the content of rocks and ores (during assimilation).

Major regional long-lived transcrustal faults are typical of all Ni-bearing provinces (Staritsky et al., 1960; Lyakhnitskaya, Tuganova, 1977; Condie, 1983; Metallogenic map…, 1987; Naldrett, 1984; Principles and methods…, 1987; Geology of copper-nickel..., 1990; Chernyshev, 1991; etc.). In the Noril'sk province, economic PGE-Cu-Ni deposits are confined to the extended Noril'sk-Kharaelakh and Lamsko-Letninsky faults controlling the metallogenic zones of the same name associated with the even larger Enisei and Enisei-Kotui faults. The long-lived Noril'sk-Kharaelakh fault striking north-east inherits the main direction of Precambrian units. The fault is located at the junction of a narrow (≈60 km), long (>200 km) downfold of the same name (complicated by the Noril'sk, Vologochan, Kharaelakh, and Icon troughs and transverse uplifts and saddles separating them) with the Khantai-Rybninsk uplift (Staritsky et al., 1960). Ore accumulations are constrained by the intersection of regional and minor (local) faults. They are confined to plicative units such as transverse uplifts, saddles, folds, and grabens that complicate larger plicative units (depressions, troughs). These areas have cavities and zones of fractured and crushed rocks increasing permeability favorable for localization of ore-bearing intrusions (Metallogenic map..., 1987). Another feature of economic intrusions is their occurrence along subhorizontal shear zones, lying on interformational surfaces (Lyakhnitskaya, Tuganova, 1977). In particular, the intrusions of Noril'sk-1 and in part the Talnakh intrusions were emplaced between Late Paleozoic continental sediments and Early Mesozoic volcanogenic formations. Major sulphide deposits and veins of sulphide ores are located along shear fractures in the lower (less often in the upper) contacts of economic intrusions, in bottom downfolds of the latter, as well as in contract cracks (Tarasov, 1983).

Magmatic criteria. An important indicator is the presence of significant volumes of mantle material in the form of (i) volcanogenic and intrusive formations of ultramafic-mafic composition (volcanogenic-intrusive belts) or (ii) thick (up to 5–6 km) plutons and dykes (intrusive dyke belts), equivalent in scale to erupted volcanics (Polferov, 1979), which are often found by large gravitational anomalies. Economic intrusions in the Noril'sk region are an integral part of magmatic formations represented by the trachybasaltic, tholeiitic, picritic and compositionally similar intrusions. The presence of such formations is an important search criterion (Urvantsev et al., 1973; Petrological features..., 1983; and others).

One of the main magmatic criteria is the close association of PGE-Cu-Ni deposits with ultramafic magmatic rocks (Geology of copper-nickel..., 1990). For example, sulphide-bearing peridotites are found only in economic intrusions associated with massive (up to 20–40 m thick) sulphide PGE-Cu-Ni ores that form world-class deposits. Therefore, the presence of such rocks is another main search criterion for the discovery of rich PGE-Cu-Ni ores.

Economic intrusions are commonly composed of two main units: gabbroic rocks (gabbro-diorite, gabbro, olivine-bearing and olivine gabbro) at the top and ultramafic (the so-called "picrite", composed of plagioclase-bearing dunite and wehrlite, and partially melanotroctolite) and recrystallized taxitic-textured rocks (so called "taxites") of predominantly mafic composition at the bottom. The layering of the upper unit is due to the characteristic differentiation of intrusions that are derivatives of basaltic magma. Gabbroic rocks are characterized by a coarse- or irregular-grained gabbro-ophytic, gabbroic or prismatic-grained structure. Compositionally, gabbroic rocks are saturated with SiO_2, enriched with Al_2O_3, CaO, TiO_2 and alkalis, and contain the paragenesis of rocks and ore minerals characteristic of tholeiites (plagioclase $An_{50\text{-}65}$, clinopyroxene with increased TiO_2, olivine containing 30–50% of the fayalite component, usually replaced by iddingsite; among the ore minerals are titanomagnetite, ilmenite, pyrite, rarely pyrrhotite). The contents of copper, nickel, and cobalt in the rocks are negligible, and PGE are nearly absent.

The lower unit differs from the upper unit in chemical, mineralogical, and geochemical composition (Tuganova, 1988, 1991, 2000; etc.). The rocks are composed of olivine, up to 70–80% ($Fa_{15\text{-}26}$), clinopyroxene and orthopyroxene (up to 15–20%), and an insignificant amount of xenomorphic plagioclase ($An_{90–100}$) filling the gaps between olivine, less often clinopyroxene. The presence of chromite (up to 7%) forms accumulations and discontinuous chains making these ultramafic rocks similar to dunite. A distinctive feature of ultramafic rocks is their structure – panidiomorphic-grained, poikilite, sideronite, cataclastic. The latter is the result of strong pressure, that probably took place during the movement of ultramafic rocks in the solid-plastic state from considerable depths. Strong fracturing of ultramafic rocks was previously noted by V.V. Zolotukhin (1964) and M.K. Ivanov et al. (1971). The lower unit is associated with disseminated sulphide PGE-Cu-Ni mineralization, and whose rocks always have high H_2O content (3.5–5.6 wt %) and undersaturated in SiO_2 (40–44 wt %). The lower part of the ultramafic unit underwent uneven metasomatism ("debasification") with the formation of taxitic-textured rocks, characterized by a wide variation of chemical and mineralogical compositions. A close relationship to ultramafic rocks is indicated by SiO_2 undersaturation (40–44%), an increase in chromium (up to 0.58 wt %), and relics of plagioclase-bearing peridotite. The rocks also contain a significant amount of disseminated PGE-Cu-Ni sulphide mineralization.

Petrochemically, the discrete pattern of rocks in the Noril'sk-type intrusions is shown in a vector diagram by A.N. Zavaritsky (Fig. 4) and a triple plot AFM (Fig. 5), which fix the separated fields for ultramafic and gabbroic rocks. Notably, the field of taxitic-tex-

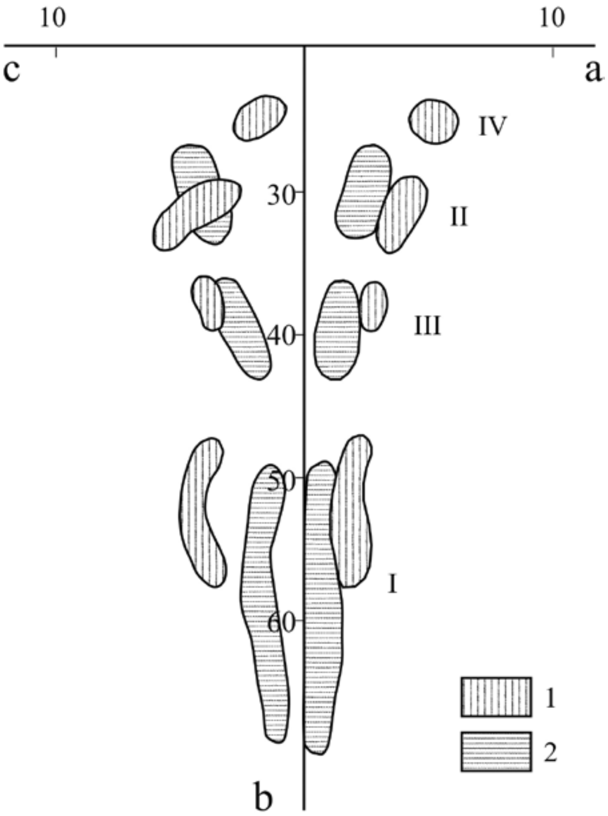

Fig. 4. Vector diagram by A.N. Zavaritsky for composition of rocks from economic ultramafic-mafic intrusions of the Noril'sk (1) and Kola (2) regions (modified after (Malitch et al., 2018a)).

I – ultramafic rocks; II – upper gabbroic rocks; III – lower gabbroic rocks, pyroxenites of the Pechenga ore area; IV – leucogabbro.

Рис. 4. Векторная диаграмма А.Н. Заварицкого, иллюстрирующая состав пород промышленно-рудоносных ультрамафит-мафитовых интрузивов Норильского (1) и Кольского (2) регионов, по (Малич и др., 2018а), с изменениями.

I – ультраосновные породы; II – верхние габброиды; III – нижние габброиды, пироксениты Печенгского рудного района; IV – лейкогаббро.

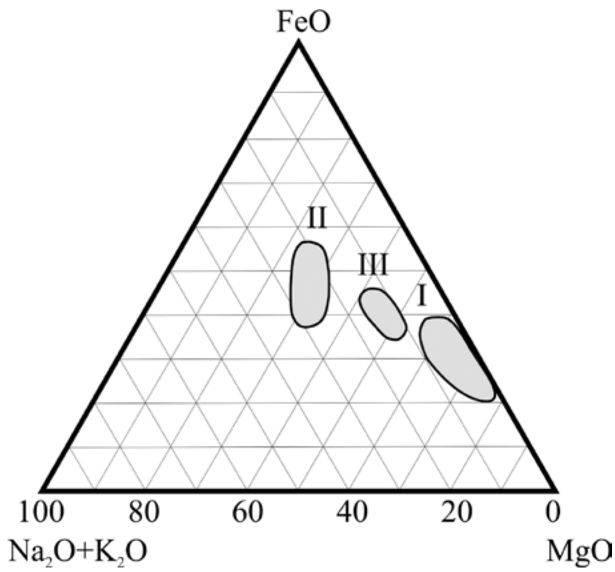

Fig. 5. Triple diagram MgO–FeO–(Na_2O + K_2O) in rocks of economic intrusions of the Noril'sk region (modified after (Malitch et al., 2018a)).

I – ultramafic rocks (plagioclase-bearing peridotite, melanotroctolite); II – upper gabbroic layered sequence rocks; III – lower taxite-textured gabbroic rocks.

Рис. 5. Тройная диаграмма MgO–FeO–(Na_2O + + K_2O) в породах промышленно-рудоносных интрузивов Норильского региона, по (Малич и др., 2018а), с изменениями.

I – ультраосновные (плагиоклазсодержащий перидотит, меланотроктолит) породы; II – габброиды расслоенной серии (верхние); III – габброиды такситового горизонта (нижние).

tured gabbroic rocks lies in a gap between them, though the latter underlie ultramafic rocks. The unique petrochemical features of ultramafic and gabbroic rocks of the Noril'sk type intrusions are illustrated by the A–S diagram (Fig. 6), which clearly shows that plagioclase-bearing ultramafic rocks are compositionally close to peridotitic komatiites, whereas the gabbroic rocks are located at a significant distance, partly overlapping the field of clinopyroxenite.

The mineralogical criterion to be used in exploration for sulphide PGE-Cu-Ni rich ores is the presence of shallow and abyssal mineral parageneses in the Noril'sk-type intrusions (Distler et al., 1988; Tuganova, 1991). The abyssal paragenesis includes magnesian olivine ($Fa_{15–25}$), chrome spinel (Cr_2O_3 – 32–44 wt %), chrome-bearing augite (Cr_2O_3 – ≈1 wt %) and orthopyroxene (Cr_2O_3 – 0.2 wt %) associated with the plagioclase-bearing peridotite. The listed minerals are similar in composition to the minerals of ultramafic inclusions in kimberlites, and probably formed in similar deep physical and chemical conditions. A less deep-seated mineral association occurs in gabbroic rocks containing plagioclase ($An_{58–78}$), olivine – hyalosiderite ($Fa_{30–46}$), clinopyroxene – titanium-bearing augite (TiO_2 0.7–0.9 wt %) with a high FeO content (FeO ≈8 wt %), and no orthopyroxene and chromite. Minerals of shallow association are confined to gabbroic rocks above and below the plagioclase-bearing peridotite; they are like minerals from common ore-free dolerites widespread in the Siberian Platform. Two types of melt inclusions (MI) differing in composition, homogenization temperature, degree of crystallization and correlation of phases were found in chrome- and titanium-bearing augites of the Noril'sk-type intrusions (Ore formation and genetic..., 1988; among others). Chrome-bearing clinopyroxene display a constant ratio between phases, which is not observed in titanium-bearing clinopyroxene. This suggests that the former was crystallized from a homogenous melt, while the latter originated from a heterogeneous melt. Different homogenization temperatures and fluid saturation of MI in these clinopyroxenes testify to an independent nature of magmas from which they crystallized.

The geochemical criterion for prospecting the Noril'sk-type deposits is the discrete pattern of trace elements distribution in ultramafic and gabbroic rocks, as emphasized by M.N. Godlevsky, G.V. Nesternko, A.I. Al'mukhamedov, A.I. Arkhipova and many others. The ultramafic rocks have high contents of chromium, nickel, cobalt, copper, silver, gold, bismuth, platinum,

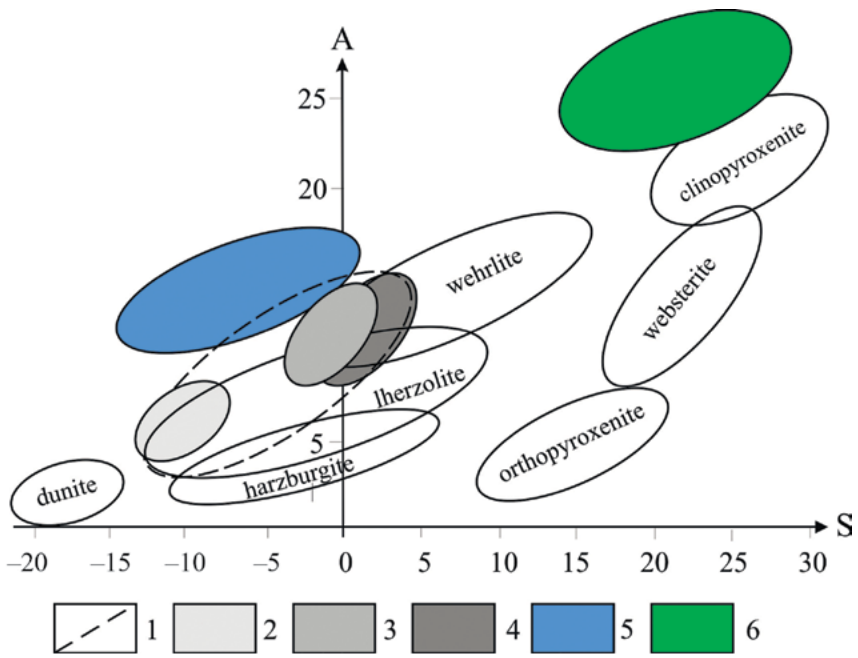

Fig. 6. Chemical composition of rocks in the coordinates A = Al_2O_3 + CaO + Na_2O + K_2O and S = SiO_2–(Fe_2O_3 + + FeO + MgO + MnO + TiO_2), wt % (modified after (Malitch et al., 2018a)).

1 – different picritic rocks; 2 – meimechites; 3 – picrites; 4 – peridotite komatiites; 5, 6 – rocks of the Noril'sk-type intrusions: 5 – plagioclase-bearing peridotites, melanotroctolites, 6 – gabbroic rocks.

Рис. 6. Химический состав горных пород в координатах A = Al_2O_3 + CaO + Na_2O + K_2O и S = SiO_2–(Fe_2O_3 + + FeO + MgO + MnO + TiO_2), мас. %, по (Малич и др., 2018а), с изменениями.

1 – различные пикритовые породы; 2 – меймечиты; 3 – пикриты; 4 – перидотитовые коматииты; 5, 6 – породы интрузивов норильского типа: 5 – плагиоклаз-содержащие перидотиты, меланотроктолиты; 6 – габброиды.

etc., and are depleted in titanium, vanadium, strontium, barium, zirconium, and lithium. Gabbroic rocks have an order of magnitude lower content of elements of the first group and higher of the second. Cr/Ti and Cr/V ratios are especially indicative, which sharply increase in ultramafic rocks. At the same time, in gabbroic rocks, these ratios are equal to those in conventional sulphide-free dolerites.

One of the important ore and geochemical signatures is the combination of a wide range of elements such as nickel, cobalt, platinum, palladium, rhodium, iridium, ruthenium, osmium, gold, silver, copper, selenium, titanium, sulphur extracted during the processing of ores, with tin, antimony, bismuth, lead, arsenic, etc., forming intermetallic compounds with PGE in complex sulphide ores of the Noril'sk type (Ore formation and genetic..., 1988; Geology of copper-nickel..., 1990). Such a wide range of elements in the Noril'sk type sulphide PGE-Cu-Ni ores suggests that the ore-bearing magmas separated at different levels of the Earth's tectonosphere. A particularly important geochemical criterion for the detection of Noril'sk-type deposits is an increased amount of IPGE (Iridium-group PGE: ruthenium, iridium, osmium) in sulphide ores, which is comparable to (and even higher than) the content of these PGE in dunites and chromitites of the clinopyroxenite-dunite massifs (Tuganova, Malich, 1990; Malitch, 1999). The presence of IPGE indicates a deep-seated source underlying continents at depths of up to 500 km (Shcheglov, Govorov, 1985).

A typical feature of the Noril'sk deposits is the significant amount of Cu, which is uncommon for other copper-nickel deposits in the world. The source of Cu is one of unresolved questions of the Noril'sk-type deposits. The upper mantle, judging by inclusions of ultramafic rocks in kimberlites (Distler et al., 1987; Garanin et al., 1988; and others), is rich in nickel sulphides, whereas copper sulphides occur in subordinate amounts. It is very likely that there was an intermediate "reservoir" of copper, which may be associated with stratiform Proterozoic copper deposits found in the Igarka uplift (Rzhevskii et al., 1980; Gablina, 1986).

Based on these lines of evidence, the economic intrusions are considered to have distinct sources, both for the silicate and ore components. It has been suggested that high-magnesium fluid-saturated ore-bearing melts of a peridotite-komatiitic composition, separated at significant depths, interacted with basaltic magmas formed at shallower depths (Tuganova, 1991; etc.). All the above data point to a significant role of hybrid-metasomatic processes in formation of ore-bearing intrusions and ores, presumably as a result of both (i) mixing of magmas with participation of intratelluric fluids, and (ii) assimilation of the host rocks.

Lithological-stratigraphic criteria for prospecting the Noril'sk-type deposits are related to an injection of the ore-bearing magma in weakly lithified deposits or in subhorizontal and gently inclined interformational (rarely intraformational) sutures and displacements, constraining different environments. In the Noril'sk region, intrusions are found in sediments of the Middle Paleozoic evaporite clayey limestone anhydrite formation or Upper Paleozoic carbonaceous sandy clayey rocks, shielded by Early Triassic lava (Metallogenic map..., 1987; and others).

Direct prediction criteria involve the presence of the sulphide mineralization and detection of primary dispersion halos with anomalously elevated concentrations of nickel, copper, cobalt, chromium, silver, zinc, etc. Deeply eroded ore horizons with exposed plagioclase-bearing peridotite and taxitic-textured gabbroic rocks (e.g., Noril'sk-1 intrusion) or massive ore deposits in tectonic shifts are promising indicators to locate rich mineralization. Primary geochemical dispersion halos in rocks that host PGE-Cu-Ni mineralization have anomalously high concentrations of nickel, cobalt, copper, chromium, silver, sulphur and trace elements such as lead, zinc, arsenic, fluorine, boron, selenium, and tellurium. The dispersion halos are characterized by a distinct zonation, indicating the distance to the ore body (Lyakhnitskaya, Tuganova, 1977; etc.). Elements such as nickel, cobalt, copper, zinc, lead, sulphur, and chromium are positive indicators of economic intrusions and ores in the Noril'sk region. Arsenic, scandium, tellurium, fluorine and uranium are classified as indirect indicators, while titanium, vanadium, and niobium are considered to be negative indicators.

Indirect prediction criteria are secondary dispersion halos, ore boulder trails, as well as metamorphic and other indicators. For example, secondary dispersion halos with elevated contents of copper, nickel, cobalt, chromium, zinc, barium and molybdenum indicate ore-bearing bodies within widespread eluvial-deluvial sediments, as well as in soils and plants above mineralization as "blind" shallow deposits (15–20 m). The halos may be dispersed along slopes away from the source, and are considerably larger in size compared to ore bodies (Samoylov, 1983; etc.). One of the indirect signs in the search for these deposits are trails of ore boulders, which, according to V.G. Chuvardinsky (1990), were associated with neotectonic movements. It is considered that the tectonic breccia formed along faults under compressive stress and later migrated from depths of up to several hundred meters and finally transferred laterally to a distance of several kilometers. The direction of movement is determined by the extent of faults, grooves, sliding planes, ridges or a pattern of a boulder trail. It should be taken into account that in the Noril'sk region boulders could have been rearranged due to solifluction.

Metamorphic criteria are valued prospecting indicators for the contact and regional metamorphism. The Noril'sk-type intrusions are surrounded by zonal halos of contact-metamorphic and metasomatic rocks studied in detail by D.M. Turovtsev (1970, 1986; etc.), V.V. Yudina (1973), B.N. Batuev (1972) and others. The most reliable indicator of the ore content in the Noril'sk-type intrusions is the presence of magnesian skarns and alkaline (K-Na) metasomatites in the halos. In contrast to uneconomic and subeconomic intrusions, halos in economic intrusions show a prominent thickness comparable with that of the intrusions (Turovtsev, 1970; Dodin, Batuev, 1971; Batuev, 1972; Lyakhnitskaya, Tuganova, 1977; etc.).

For ancient (AR, PR) copper and nickel deposits that experienced regional metamorphism, the prospects for the discovery of rich ores depend on the type of metamorphism and redox conditions. Metamorphism of the green schist facies (partially amphibolite facies) contributes to the re-deposition, recrystallization and concentration of primary mantle sulphides (Allarechensk and Pechenga districts in Russia, Thompson and Ungava belts in Canada, etc.), whereas regional metamorphism of the granulite facies commonly destroys and disperses nickel sulphides (Lyakhnitskaya, Tuganova, 1977; and others).

Isotope-geochemical criteria. Based on comparative isotope-geochemical data for the economic, subeconomic, uneconomic, prospective intrusions, and associated PGE-Cu-Ni sulphide ores and accumulations (Table 3), the key isotope-geochemical indicators to be used in exploration for PGE-Cu-Ni deposits can be suggested. These comprise (i) isotope signatures of sulphur (i.e., $\delta^{34}S$ = 8–13 along with a dispersion value of $\delta^{34}S$ < 1) and osmium ($^{187}Os/^{188}Os$ = 0.131–0.144, Re/Os = 1.0–8.8 and γOs = 4–14) in Cu-Ni sulphides; (ii) a radiogenic Hf-isotope composition of zircon (εHf > 5 along with a significant range in εHf values from +5 to +16), and (iii) initial isotopic compositions of neodymium (εNd = +1 ± 0.5) and strontium ($^{87}Sr/^{86}Sr$ from 0.7055 to 0.7080) in rocks.

In the Sr-Nd isotopic systematics, lithological units of economic and subeconomic intrusions manifest a clear increase in initial $^{86}Sr/^{87}Sr$ value, which varies from 0.7055 to 0.7080, at rather constant subchondritic Nd isotope values (εNd about +1). In contrast, the Nd-Sr isotope compositions of uneconomic intrusions show the least radiogenic εNd values (εNd = –5) and most radiogenic initial $^{87}Sr/^{86}Sr$, in the range of 0.7076–0.7086 (Table 3). We suggested that a radiogenic Hf-isotope composition of zircon along with a significant range in initial $^{176}Hf/^{177}Hf$ values can be employed as an effective fingerprint for identifying prospective intrusive host rocks (Malitch et al., 2010, 2013, 2018a, b). Consequently, Nd-Sr-Hf isotope signatures are use-

Table 3. Summary of isotopic-geochemical parameters for variously mineralized ultramafic-mafic intrusions from the Noril'sk and Taimyr Provinces (after (Malitch et al., 2018a))

Таблица 3. Сравнительная характеристика изотопно-геохимических данных для различно рудоносных ультрамафит-мафитовых интрузивов Полярной Сибири, по (Малич и др., 2018а)

Intrusion	εHf	εNd	$^{87}Sr/^{86}Sr_i$	$\delta^{65}Cu$	$\delta^{34}S$	γOs
Noril'sk-1	6.0 ± 2.1 –2.9…+15.5	0.7 ± 0.2 –1.9…+2.0	0.70591 ± 0.00005 0.70552–0.70625	0.23 ± 0.28 –0.10…+0.61	8.6 ± 0.6 7.5–9.4	
Talnakh	4.9 ± 3.4 –4.3…+12.0	0.3 ± 0.3 –3.3…+1.2	0.70638 ± 0.00010 0.70584–0.70709	–0.55 ± 0.41 –1.1…+0.0	10.9 ± 0.6 7.8–12.1	6.6 ± 0.3 5.3–8.2
Kharaelakh	9.7 ± 0.7 2.3–16.3	1.0 ± 0.1 0.8–1.4	0.70666 ± 0.00026 0.70555–0.70798	–1.56 ± 0.27 –2.3…–0.9	12.7 ± 0.5 11.5–13.6	7.5 ± 1.1 –5.7…+5.8
Chernogorsk	4.4 ± 2.9 –1.2…+10.9	1.4 ± 0.3 0.9–2.6	0.70711 ± 0.00033 0.70640–0.70898	–0.03 ± 0.06 –0.1…+0.0	10.9 ± 0.4 10.4–11.2	9.6 ± 0.1 9.5–9.6
Zub-Marksheider	1.0 ± 5.1 –6.7…+13.4	1.2 ± 0.1 0.4–2.1	0.70685 ± 0.00037 0.70570–0.70908	–0.1 ± 0.0 –0.1…–0.1	0.4 ± 1.6 –0.7…+3.9	20.7 ± 11.0 9.7–31.6
Vologochan	5.5 ± 7.0 –3.0…+21.0	1.2 ± 0.2 –1.7…+2.4	0.70634 ± 0.00015 0.70560–0.70808	–0.72 ± 0.29 –1.1…–0.4	6.9 ± 1.2 5.1–8.5	6.2 ± 1.9 4.3–9.9
Binyuda	–3.4 ± 1.3 –1.9…–4.6	–3.8 ± 0.4 –4.4…–3.2	0.70588 ± 0.00013 0.70566–0.70609	–0.4 ± 0.1 –0.5…–0.3	1.5 ± 0.4 0.7–2.0	8.8 ± 0.7 8.1–9.5
Dyumtaley	9.5 ± 2.5 6.0–12.4	4.2 ± 0.7 2.7–4.7	0.70474 ± 0.00020 0.70451–0.70504	–0.66 ± 0.42 –1.24…–0.25	11.4 ± 0.6 9.9–12.9	
Nizhny Talnakh	–1.3 ± 2.7 –7.4…+5.6	–4.6 ± 0.2 –5.5…–1.2	0.70824 ± 0.00007 0.70765–0.70863	–0.60 ± 0.42 –1.0…0.0	6.4 ± 1.2 1.8–8.0	65.0 ± 14.9 35.6–117.8
Zelyonaya Griva	–1.4 ± 2.1 –3.8…+1.3	–5.2 ± 0.1 –5.9…–4.6	0.70836 ± 0.00008 0.70800–0.70867	0.28 ± 0.47 –0.26…+1.21	8.4 ± 0.6 6.8–9.7	54.5

Note. Average values of εHf, εNd, $^{87}Sr/^{86}Sr$, $\delta^{65}Cu$, $\delta^{34}S$ and γOs parameters are followed by their respective range value. The Binyuda and Dyumtaley intrusions as the most prospective targets of the Taimyr province are given for comparison.

Примечание. В верхней строчке ячеек указаны средние значения параметров, в нижней – соответствующие значения диапазона. Бинюдинский и Дюмталейский потенциально-рудоносные иннтрузивы – наиболее перспектвные объекты Таймырской провинции.

ful indicators in exploration for sulphide-rich ores associated with "Noril'sk-type" intrusions.

A more detailed description of the revealed features exemplified by isotope compositions of Os, S and Cu are provided below. One of the most effective indicators of the economic scale of a deposit is the initial isotopic composition of osmium. This is primarily because the massive Ni-Cu-PGE sulphide deposits are characterized by Os-isotope values corresponding to a mixture of mantle and crustal material with a predominance of the mantle component. In the disseminated ores of the same deposits, the mantle signature is somewhat diluted by the crustal component and the proportion of the mantle component is minimal in the uneconomic Nizhny Talnakh and Nizhny Noril'sk intrusions (Walker et al., 1994; Arndt et al., 2003; Petrov et al., 2009). Re-Os isotope-geochemical indicators to estimate the scale of sulphide PGE-Cu-Ni mineralization are characterized by three signatures (i.e., $^{187}Os/^{188}Os$, Re/Os and γOs values, Table 3). $^{187}Os/^{188}Os_i$ values in the range of 0.1283–0.1375 are typical of sulphides from disseminated ores from economic or subeconomic intrusions, while the $^{187}Os/^{188}Os_i$ value over 0.195 is typical for uneconomic intrusions. High Re/Os values of disseminated sulphides (Re/Os between 13.7 and 71.6) are typical for uneconomic intrusions, low Re/Os values (0.6–3.5) for subeconomic intrusions and intermediate Re/Os values (1.0–8.8) for economic intrusions. High γOs values of disseminated sulphides (γOs from 36 to 118) are typical for uneconomic intrusions, low γOs values (–6...+8) for economic intrusions and intermediate γOs values (4–32) for subeconomic intrusions.

The S isotope compositions of disseminated sulphide ores and ore occurrences in different intrusions of the Noril'sk and Taimyr provinces are highly variable. S isotopic values ($\delta^{34}S$) vary in economic intrusions from 7.5 to 13.6‰, subeconomic intrusions from –0.7 to 11.2‰, uneconomic intrusions from 1.8 to 11.4‰ and prospective intrusions from 0.7 to 12.9‰ (Fig. 7). Listed according to increasingly high $\delta^{34}S$, disseminated ores from ultramafic-mafic intrusions of Polar Siberia fall into the following sequence (Fig. 7): Zub-Marksheider (–0.7…+3.9‰, average 0.4 ± 1.6‰), Binyuda (0.7–2.0‰, average 1.5 ± 0.4‰), Nizhny

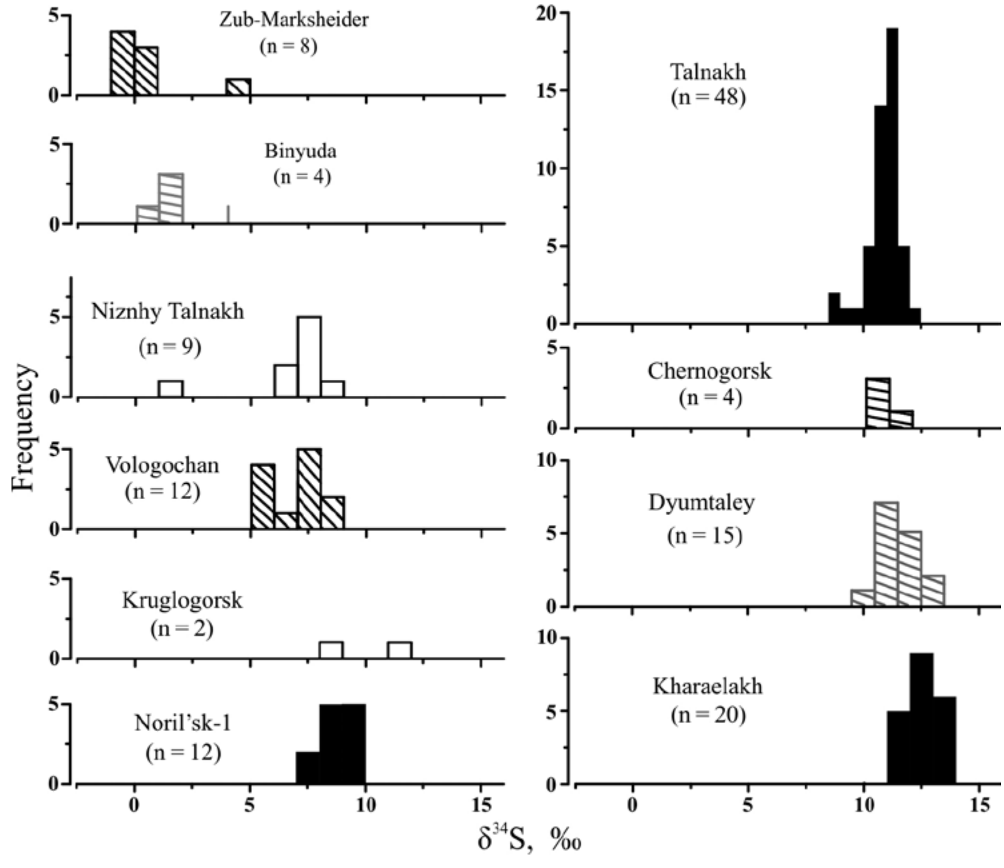

Fig. 7. Variations in the sulfur isotope composition in disseminated ores from economic (black), subeconomic (dashed in black), prospective (dashed in gray) and uneconomic (white) intrusions of Polar Siberia.

Рис. 7. Вариации изотопного состава серы во вкрапленных рудах промышленно-рудоносных (черное), рудоносных (черная штриховка), потенциально рудоносных (серая штриховка) и слаборудоносных (белое) интрузивов Полярной Сибири

Talnakh (1.8–8.0‰, average 6.4 ± 1.9‰), Vologochan (5.1–8.5‰, average 6.9 ± 1.2‰), Noril'sk-1 (7.5–9.4‰, average 8.6 ± 0.6‰), Kruglogorsky (8–11.4‰, average 9.7 ± 1.7‰), Talnakh (9.9–12.0‰, average 11.0 ± 0.4‰), Chernogorsk (10.4–11.2‰, average 10.9 ± 0.4‰), Dyumtaley (9.9–12.9‰, average 11.4 ± 0.6‰), Kharaelakh (11.5–13.3‰, average 12.6 ± 0.5‰). The crustal (sulphate) isotopic composition of S frequently postulated as evidence of high economic potential of a mafic-ultramafic intrusion is contradicted by mantle-like S isotopic compositions of disseminated PGE-Cu-Ni sulphide mineralization from the subeconomic Zub-Marksheider intrusion. The field evidence for latter intrusion also suggests that it has experienced significant assimilation of sulphate-rich Devonian sediments. Following (Kuz'min, Tuganova, 1977), we questioned the validity of isotopically-heavy sulphur as a feature indicative of economic sulphide PGE-Cu-Ni ore (Malitch et al., 2014). It has been noted (Malitch et al., 2009) that an increase in the range of S-isotope values correlates negatively with ore-deposit reserves. I suggest using the relationship between mean $\delta^{34}S$ and $\delta^{34}S$ dispersion values (Fig. 8) as an indicator of the scale of mineralization. Fig. 8 shows that sulphide ores from economic intrusions are restricted to the field of mean $\delta^{34}S$ values > 8 and $\delta^{34}S$ dispersion values of $\delta^{34}S < 1$. Notably, the larger the scale of economic deposit, the quantity of most abundant $\delta^{34}S$ values increases, whereas the variation range of these values decreases (Kharaelakh–Talnakh–Noril'sk-1, see Figs. 7 and 8).

Another promising isotopic indicator that can be used in exploration for sulphide PGE-Cu-Ni rich ores refers to a combined S-Os isotope study, which allows identifying intrusions with disseminated ores identical in isotopic parameters to those of economic deposits (Fig. 9). Based on this approach, the studied intrusions are divided into three groups.

(i) The first group comprises the Chernogorsk intrusion and, with a certain degree of uncertainty, the Vologochan intrusion, in which disseminated sulphide ores are similar in S- and Os-isotope compositions to those in the Talnakh deposit. Notably, S- and Os-isotope compositions of sulphide mineralization from the Vologochan intrusion (our data) correspond to those from the Noril'sk-1 intrusion (Arndt et al., 2003). Hence, the Chernogorsk and likely Vologochan intrusions may also contain rich sulphide ores, and as such are the most promising for prospecting and exploration.

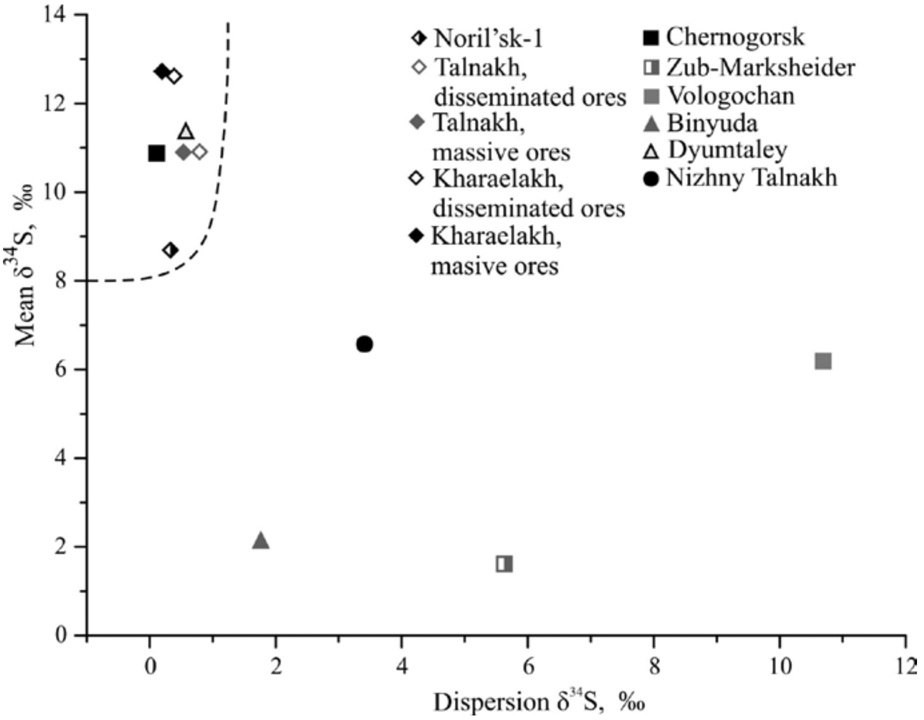

Fig. 8. Plot of $\delta^{34}S$ mean versus $\delta^{34}S$ dispersion in massive and disseminated ores from economic (Noril'sk-1, Talnakh, Kharaelakh), subeconomic (Chernogorsk, Zub-Marksheider, Vologochan), prospective (Binyuda, Dyumtaley) and uneconomic (Nizhny Talnakh) intrusions of Polar Siberia.

Рис. 8. Бинарная диаграмма среднее $\delta^{34}S$ – дисперсия $\delta^{34}S$ для массивных и вкрапленных руд промышленно-рудоносных (Норильск-1, Талнахском, Хараелахском), рудоносных (Черногорском, Зуб-Маркшейдерском, Вологочанском), потенциально рудоносных (Бинюдинском, Дюмталейском) и слаборудоносных (Нижнеталнахском) интрузивах Полярной Сибири.

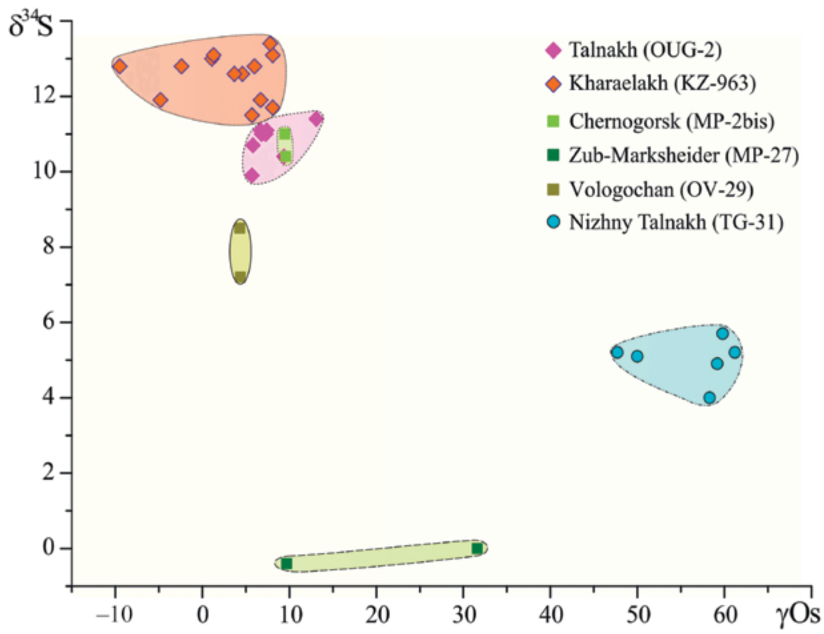

Fig. 9. Plot of $\delta^{34}S$ versus γOs values in sulphide PGE-Cu-Ni ores of economic (Talnakh, Kharaelakh), subeconomic (Chernogorsk, Zub-Marksheider, Vologochan) and uneconomic (Nizhny Talnakh) ultramafic-mafic intrusions of the Noril'sk province (modified after (Malitch et al., 2018a)).

Рис. 9. График зависимости $\delta^{34}S$ от γOs в сульфидных ЭПГ-Cu-Ni рудах в промышленно-рудоносных (Талнахском, Хараелахском), рудоносных (Черногорском, Зуб-Маркшейдерском, Вологочанском) и слаборудоносных (Нижнеталнахском) ультрамафит-мафитовых интрузивах Норильской провинции, по (Малич и др., 2018а), с изменениями.

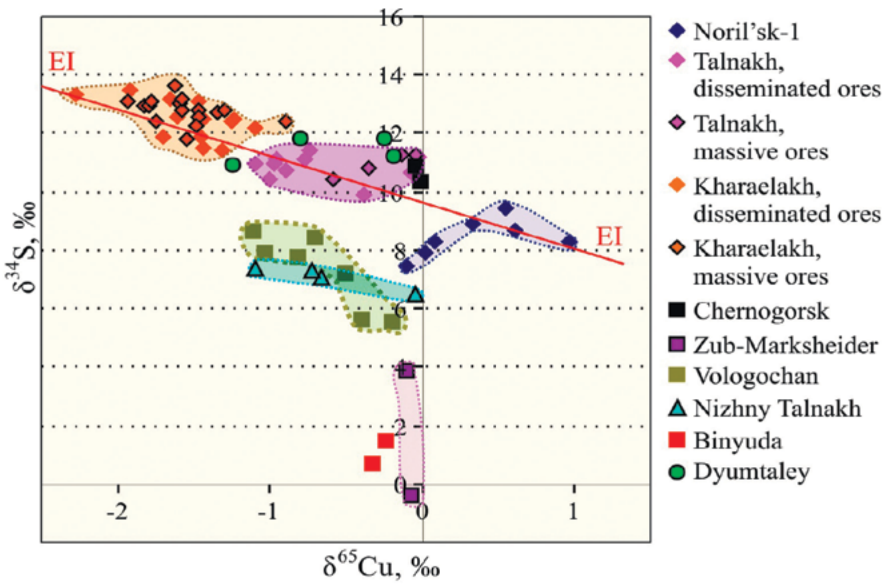

Fig. 10. $\delta^{34}S$–$\delta^{65}Cu$ systematics of sulphide PGE-Cu-Ni ores and accumulations from economic (Noril'sk-1, Talnakh, Kharaelakh), subeconomic (Chernogorsk, Zub-Marksheider, Vologochan), prospective (Binyuda, Dyumtaley) and uneconomic (Nizhny Talnakh) intrusions of Polar Siberia (modified after (Malitch et al., 2016)).

Рис. 10. Вариации изотопного состава серы и меди в координатах $\delta^{34}S$–$\delta^{65}Cu$ в ЭПГ-Cu-Ni рудах и сульфидной минерализации из промышленно-рудоносных (Норильск-1, Талнахском, Хараелахском), рудоносных (Черногорском, Зуб-Маркшейдерском, Вологочанском), потенциально рудоносных (Бинюдинском, Дюмталейском) и слаборудоносных (Нижнеталнахском) интрузивах Полярной, по (Malitch et al., 2014; Малич и др., 2016).

(ii) The Zub-Marksheider intrusion is partially similar in Os-isotope composition to economic deposits, but significantly differs from them in S-isotope composition. Notably, isotope composition of sulphides preserved features of a juvenile ore source, which was not affected by crustal contamination.

(iii) Uneconomic intrusions (Nizhny Talnakh and Zelyonaya Griva, see Table 3, Fig. 9) that host disseminated sulphides have significantly different Os isotope signatures from those of economic PGE-Cu-Ni deposits. This implies that there is no potential to find commercial ore reserves in uneconomic intrusions.

Another isotopic indicator for assessing the economic potential of a PGE-Cu-Ni sulphide deposit is associated with a negative correlation between $\delta^{34}S$ and $\delta^{65}Cu$ for sulphide ores of economic intrusions (trend EI–EI, Fig. 10). There is a gradual progression from lighter isotope compositions for the sulphides of the Kharaelakh (–2.3 to –0.9‰) and Talnakh (–1.1 to 0.0‰) intrusions to heavier compositions for those of the Noril'sk-1 intrusion (–0.1 to +1.0‰). Samples from the other intrusions show a decoupling of S and Cu isotopes (Fig. 10), with $\delta^{65}Cu$ ranging mainly from 0 to –1‰, but $\delta^{34}S$ between 0 and 13‰. The disseminated ores of the subeconomic Chernogorsk and prospective Dyumtaley intrusions have $\delta^{34}S$ and $\delta^{65}Cu$ values overlapping the trend EI-EI for the economic intrusions (Fig. 10); they therefore can be the next prospective targets for discovering massive ores. The other intrusions, in which stable isotope compositions do not correspond to those in economic deposits, show low potential for revealing of massive PGE-Cu-Ni sulphide ores.

CONCLUDING REMARKS

This article outlines previously known prediction criteria and several new isotope-geochemical indicators to be used for predicting the potential ore content of poorly studied mafic-ultramafic intrusions of Polar Siberia. The main forecasting criteria for sulphide PGE-copper-nickel deposits include structural, magmatic, stratigraphic-lithological, geochemical, mineralogical, isotope-geochemical, metamorphic and some others. A combined study of the isotopic composition of osmium, sulphur and copper revealed intrusive bodies with disseminated sulphide ores that have similar signatures to those from economic sulphide PGE-Cu-Ni deposits. It is suggested that the Chernogorsk intrusion of the Noril'sk province and the Dyumtaley intrusion of the Taimyr province are the most promising targets in search for rich PGE-Cu-Ni ores, whereas other studied intrusions are unlikely to be considered prospective targets for discovery of rich sulphide ores. It is proposed that the previously known forecast criteria supplemented by a set of novel isotope-geochemical indicators can be employed as useful guides for prospecting the Noril'sk-type deposits containing rich sulphide ores.

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