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Gold-rare metal and associated mineralization in the western part of Bolshevik Island, Severnaya Zemlya archipelago

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Abstract. The presented studies are aimed to determine the formation patterns of the gold-rare metal mineralization within one of the most inaccessible Arctic islands of the Russian Federation, Bolshevik Island of the Severnaya Zemlya archipelago. The relevance of the work is determined by the high probability of discovering a significant in terms of metal reserves deposit, which is proved by many researchers on the example of known large deposits to be a typical feature of sites with gold-rare metal formation. Obviously, only the possibility of discovering and subsequent development of a deposit of a highly liquid type of mineral, gold, can ensure the profitability of mining production on Severnaya Zemlya. It is established that the main geological, mineralogical, and geochemical features of the gold-rare metal mineralization in the Kropotkinsko-Nikitinskaya metallogenic zone of Bolshevik Island correspond to that of similar ore sites in Russia and the world. The occurrences of other formation types revealed in this metallogenic zone suggest a certain zoning in their distribution: mineralization is located in the apical parts of granitoids and in the nearest halo of hornfelses. At a distance, with an exit from the hornfelsed zone, there are occurrences of a cassiterite-sulphide formation with elevated gold and silver content at the top of the ore column, together with an increased amount of polymetallic ores. Occurrences of gold-quartz and gold-sulphide-quartz formations are localized in fault zones, as a rule, farther from granitoids. The total vertical range of gold mineralization exceeds 300 m. The assignment of all types of mineralization in the Kropotkinsko-Nikitinskaya metallogenic zone of Bolshevik Island to a single hydrothermal process is emphasized by the similar isotope composition of lead galena from heterogeneous occurrences, which determines the age of all mineralization at 200-300 Ma.

***Keywords*:** gold-rare metal mineralization; Taimyro-Severozemelskaya province; Bolshevik Island of the Severnaya Zemlya archipelago; granitoids; hornfelses; polymetallic ores

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The article is dedicated to the blessed memory of Professor of Empress Catherine II Saint Petersburg Mining University Sergey Vyacheslavovich Sendek

Introduction. Numerous oil and gas fields [1-3], as well as new ore mineral sites [4-6], are found in the Arctic zone of Russia. In this regard, many scientists raise the question of studying and developing gold deposits of a relatively new type, large sites attributed to the gold-rare metal formation [7].

The gold-rare metal formation as an independent one was identified by N.A.Shilo in 1978 [8], subsequently studied by many researchers: A.V.Volkov, A.A.Sidorov [7, 9, 10], A.P.Osipov, N.E.Savva [9], G.N.Gamyanin [11-13] and others [14-16]. A generalized description of gold-rare metal deposits (GRM), based on the study results of sites of this type in the north-east of Russia, as well as considering the data of foreign researchers who studied the Tintin metallogenic belt deposits in Northern Canada (Yukon) and Alaska is given in [7, 18, 19]. All publications note a feature of the GRM – localization within granitoid intrusions or in zones of contact-altered rocks [17, 20, 21].

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The ore bodies of deposits of this type are represented by veins 0.1-0.6 m thick and 2-100 m long, stockwork areas with an area of up to 1-2 km^2. They contain more than 10-20 % of quartz material per m. Separate crushing zones reach a thickness of 2-3 m and a length of 200-300 m with different amounts of quartz material. The main ore minerals include arsenopyrite. Pyrite, pyrrhotite, molybdenite, cassiterite, as well as bismuth minerals – bismuthine, joseite-A, B, other sulphotellurides and bismuth sulphosalts, as well as native bismuth are often present in appreciable amounts in ores. Fine gold with a grain size of 1-30 μm in association with bismuth tellurides, according to researchers, is the most characteristic feature of the ores in these deposits [7]. Fineness of gold in GRM ores varies widely, from 650 to 970 ‰. The admixtures include silver, copper, antimony, bismuth, mercury, and traces of tin. The content of ore minerals in GRM ores varies from 1-2 to 50 %. Most of the deposits are characterized by low gold content with a large volume of ore mass and metal reserves, the vertical range of mineralization exceeds 300 m.

Mining operations at large deposits allowed a number of researchers [22, 23] to build a generalized ore magmatic column for rare metal sites. Greisen veins and stockworks occur directly in granitoids. Up the section, in terrigenous hornfelsed rocks, there are cassiterite-quartz veins, and even farther from the granitoids, often already in unaltered rocks, there are cassiterite-sulphide veins with abundant mineralization in the apical parts of the veins. Similar zoning, described by G.N.Gamyanin and et al. [24], was revealed at the large polymetallic silver deposit Prognoz in Yakutia. Here gold-rare metal mineralization is located on the deepest horizons. Cassiterite-sulphide and silver-polymetallic mineralization are superimposed on gold-rare metal ores and are hypsometrically higher.

A number of researchers suggested a significant role in the introduction into GRM of ore components, in particular gold, from black shale strata with finely dispersed sulphidization [7, 25], which were cut through by intrusions [26, 27]. Such confinement of gold deposits to terrigenous rocks with a high content of organic carbon and increased background gold content is known in many regions of Russia and the world [28, 17].

Let us consider in detail the rare metal mineralization with gold within the Taimyro-Severozemelskaya gold province, discovered in the 70-80s of the last century [7]. This discovery was the result of long-term (since 1972) thematic and industrial work of the following institutions: NIIGA [29-31] – VNIIOkeangeologia [29], PGO Sevmorgeologia, NOMTE-TsAGRE, SNIIGGiMS, PGO Krasnoyarskgeologia [32].

The province covers the northern part of Taimyr and part of the islands of the Severnaya Zemlya archipelago: October Revolution Island, Bolshevik Island. The first occurrences of gold and its placer concentrations were found on the islands of the archipelago in 1973-1980 during the geological mapping by the Norilsk expedition NOMTE – Sevmorgeo. In 1975-1980, special studies by geologists from NIIGA – VNIIOkeangeologia and SNIIGGiMS in the northern Taimyr also revealed a number of promising gold mineral occurrences, Konechnoye, Zhilnoye, Izvitistoye, its placer concentrations [33, 34]. In subsequent 1981-1992, as a result of special, geological prospecting, and survey work on Bolshevik Island, the discovery of numerous gold sites, as well as gold-bearing mineral occurrences of rare metal – W, Mo, Sn, Bi – mineralization continued [33, 34]. In 1983, occurrences of the Martovsky-Nikitinsky ore cluster were revealed [35]. As a result of special studies and generalization of all available material on the mineralogeny of the province, the leading experts from of VNIIOkeangeologia – N.K.Shanurenko [36], V.G.Kuzmin [37, 38], V.F.Proskurnin [31, 39] distinguished metallogenic taxa and a number of metallogenic zones of rare metal mineralization with gold. Metallogenic zones are distinguished by the highest concentration of mineral occurrences and mineralization points of gold and rare metals.

Problem statement. In the northeast of the Taimyro-Severozemelskaya gold province, three metallogenic zones with rare metal mineralization are found: the East Oktyabrskaya molybdenum-tungsten-tin-bearing zone on October Revolution Island, the Kropotkinsko-Nikitinskaya molybdenum-tungsten-tin-bearing zone, and the Solnechninsko-Akhmatovskaya molybdenum zone on

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Bolshevik Island. In all these zones, rare metal mineralization is accompanied by an elevated gold content up to independent gold occurrences. The most studied is the Kropotkinsko-Nikitinskaya metallogenic zone. It is oriented nearly from north to south and extends along the southwestern part of Bolshevik Island from the coast of the Vilkitsky Strait in the south to the Semenov-Tyan-Shansky Glacier in the north (see Figure). In terms of richness in various types of ore formations, it differs significantly from other metallogenic zones of Bolshevik and October Revolution islands.

The host rocks of heterogeneous mineralization in this zone are terrigenous Riphean-Vendian rocks, in some areas hornfelsed by granitoids of the C_{1-2} granite-leucogranite formation that cut through them. Granitoids are represented by weakly eroded Nikitinsky and Kropotkinsky massifs. The granitoid massifs are confined to the near-longitudinal zone, bounded by the Severozemelsky and Antsevsko-Akhmatovsky deep faults. The typomorphic rocks of the complex are biotite, amphibole-biotite, two-mica granites, leucogranites, less often granodiorites, granite-porphyries, aplites.

A characteristic and metallogenically important feature of granitoids is the wide development of greisenization, with the formation of zones of silicification, muscovitization, tourmalinization, and albitization in them. The main geochemical feature of the Kropotkinsky granites is high concentrations of Mo, Sn, W, Cu, Ag. The upper age limit of the complex is determined by the presence of gresenized granite pebbles in the Upper Carboniferous-Permian conglomerates. The Kropotkinsko-Nikitinskaya metallogenic zone is divided by the Kropotkin glacier into two areas: the northern part is the Studeninsko-Ozerninsky ore cluster, the southern part is the Tora-Kamensky ore placer region (OPR) [31]. Characteristics of these areas: Tora-Kamensky OPR is identified as an area with increased concentration of ore placers and covers an area of about 500 km^2. It covers the basins of the Tora, Kamenka, Kamenistaya rivers, including the mouth parts of the Burlivaya and Porozhistaya rivers.

Within the limits of the Tora-Kamensky OPR, in addition to the outcrops of granitoids of the Kropotkinsky complex, the Nikitinsky massif, dikes of diorites, kersantite dolerites were found. Within this OPR, the Martovsko-Nikitinsky ore cluster is distinguished with the predominant development of rare metal mineralization with gold [36, 38, 39]. Within its limits, hornfelsed to a various degree terrigenous Precambrian rocks of the Krasnorechenskaya and Slozhnenskaya formations predominate. Greisenized biotite granites of the apical protrusion of the granitoid massif are exposed among hornfelses in the southwestern part of this cluster in an area of about 700 m^2. By composition, they belong to the C_{1-2} granite-leucogranite formation. In total, within the Tora-Kamensky OPR, according to the data of prospecting and geological surveys at 1:200,000 and 1:50,000 scales, six gold occurrences were identified: three gold-quartz and three gold-sulphide-quartz formations; 25 points of mineralization and geochemical anomalies of gold. Three gold-rare metal occurrences and ten points of rare metal mineralization, as well as geochemical anomalies and points of mineralization of a number of ore elements (20 copper, 4 arsenic, 2 lead) were found in the area. In addition to primary sites, numerous gold placers were found in this area along the Tora, Kamenka with tributaries, Porozhistaya rivers, as well as the $₽_3$-N_1 placer Vodorazdelnaya in the interfluve of the lower reaches of the Tora and Kamenistaya rivers.

The Martovskoye, Nikitinskoye, and Mordovinskoye occurrences are at a distance of six to seven km from each other [38]. Ore formations are represented by zones of veins and veinlets 15-20 m thick and 1500-1600 m long. The Martovskoye occurrence consists of two northeast-trending zones with significant rare metal mineralization and a near-latitudinal zone 800 m long with polysulphide mineralization. The thickness of individual veins is small, 0.1-0.7 m, the maximum is 1-2 m, and the debris length is 15-20 m. In some places, small, a few hundred m^2 in size, stockworks are noted. The localization of ore bodies is different. In the Martovsky and Mordovinsky areas, the veinlet-vein zones are in hornfelses, and in the Nikitinsky area, both in hornfelses and in greisenized granites [38].

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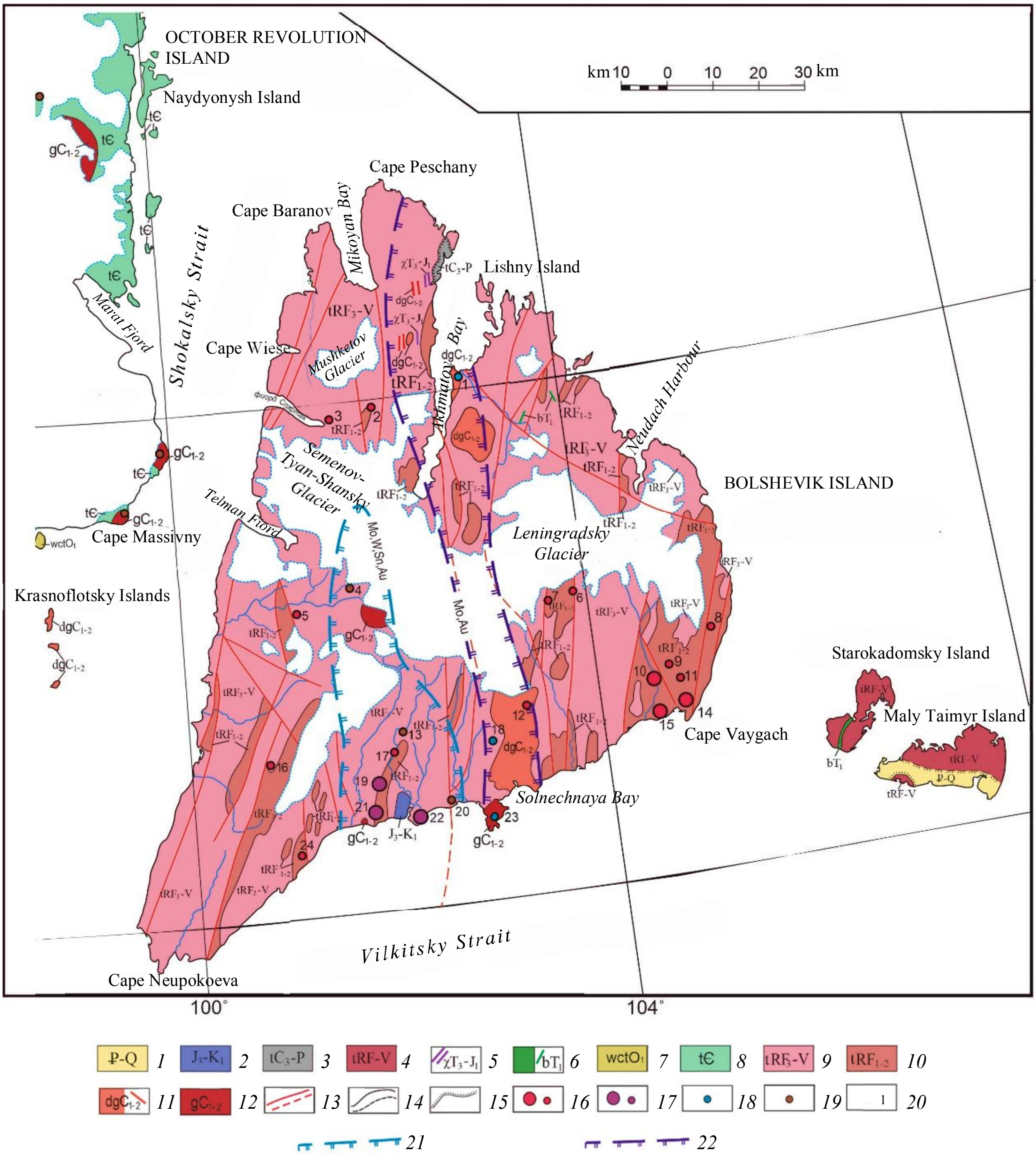

Distribution scheme of the main mineral occurrences on Bolshevik Island on a geological basis (compiled by Yu.D.Shulga and V.K.Dorofeev according to [38])

1 – unstratified Cenozoic deposits – sands, pebbles, silts, clays, conglomerates; *2* – Late Jurassic-Early Cretaceous lacustrine-marsh deposits – clays, sands with clay interlayers; *3* – Late Carboniferous-Permian lagoonal-continental formation – sandstones, mudstones, siltstones, conglomerates, gritstones, limestones; *4* – unstratified Riphean-Vendian deposits; *5* – lamprophyre formation (dikes); *6* – gabbro-diabase formation (massifs and dikes); *7* – Early Ordovician volcanic-carbonate formation; *8* – Cambrian molassoid formation, sandstones, mudstones, siltstones; g $Є_{1-2}$ formation; *9* – Late Riphean-Vendian flyschoid variegated formation – sandstones, siltstones, mudstones; *10* – Riphean flyschoid dark-coloured formation – sandstones, siltstones, mudstones, carbonaceous shales; *11* – diorite-granodiorite formation; *12* – granite-leucogranite formation, Kropotkinsky massif; *13* – faults (reliable and supposed); *14* – geological limits (reliable and intended); *15* – limits of unconformable occurrence; *16* – gold occurrences (large and ordinary); *17* – rare metal occurrences (large and ordinary); *18* – molybdenum occurrences; *19* – tin occurrences; *20* – occurrence number (1 – Mo, Cape Palets; 2 – Au, Bazovaya River; 3 – Au, Lake Zakrytoye; 4 – Sn, Ag, Zn, Studencheskoye; 5 – Au, Gryaznukha; 6 – Au, Lagernaya River; 7 – Au, Ruslovoye; 8 – Au, Groznenskoye; 9 – Au, Gravelitistoye; 10 – Au, Golysheva-1; 11 – Au, Litke River; 12 – Au, Solnechny massif; 13 – Sn, Au, Daikovoye; 14 – Au, Nizhnelitkenskoye; 15 – Au, Fokinskoye; 16 – Au, Kropotkin Glacier; 17 – Au, Torinskoye; 18 – Mo, Mount Ploskaya; 19 – W, Sn, Au, Ag, Martovskoye; 20 – Sn, Zn, Zhuravlev Bay; 21 – W, Mo, Sn, Nikitinskoye; 22 – W, Bi, Sn, Au, Mordovinskoye; 23 – Mo, W, Cape Taimyr; 24 – Au, Pervoye); *21* – Kropotkinsko-Nikitinskaya Mo, W, Sn, Au metallogenic zone; *22* – Solnechninsko-Akhmatovskaya Mo, Au metallogenic zone

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During geological survey and prospecting at the Martovskoye occurrence, eight prospecting and one mapping wells were drilled. Prospecting wells were drilled to a depth of 120 m within the tin halo previously identified by lithogeochemistry. The mapping well was drilled to a depth of 300 m; the roof of the intrusion was not reached anywhere. In a number of wells at depths of 35-104 m from the surface, zones of thin quartz veining and individual quartz veins with elevated contents of a number of ore elements, W, Sn, Mo, Bi, Ag, Au were found. Gold content in these intervals reaches 0.08-4.0 g/t. The intervals with gold content in the core are 1-6 m. More than 80 % of elevated gold values are accompanied by the presence of Bi ($2\text{-}30\cdot10^{-3}$ %).

The Nikitinskoye occurrence was estimated based on core sampling data from six wells 120 m deep, which were drilled in granites and one in hornfelses. The gold content in them is mainly 0.05-0.5 g/t. At the Mordovinskoye occurrence, geochemical sampling was carried out in the primary scattering haloes and grab sampling in the vein debris, the gold content in which does not exceed 1.3 g/t [38].

Methodology. Mineralization in the Nikitinsko-Kropotkinskaya metallogenic zone was studied in the field in 1989 by samples and polished sections selected by the authors from ore sites. The collection was supplemented by rock materials taken in the area over several years by other employees of the PGO Sevmorgeo subdivisions.

In order to determine the crystallization temperatures of vein minerals, quartz was decrepitated in the laboratory of VNIIOkeangeologia under the guidance of V.S.Aplonov. The equipment and methods for studying decrepitation correspond to the standards adopted in the 1980s and 1990s. The results of geothermal determinations were used in special developments of VNIIOkeangeologia and publications of the institute. To study the composition and admixtures of ore minerals, spectral, spectrochemical, and X-ray microspectral analyses were performed in VSEGEI and VNIIOkeangeologia laboratories.

Ore occurrences of the cluster are characterized by similar mineral composition. They belong to the vein topaz-muscovite-quartz greisen subformation with complex rare metal, as well as polysulphide gold and silver mineralization with cassiterite.

According to semi-quantitative spectral and chemical analyses of grab, furrow, and core samples taken during special and prospecting investigations (including mining and drilling operations during a geological survey at 1: 50,000 scale), the ores in all three considered occurrences are very close in the content of the main ore components [38]. All mineral occurrences contain vein formations of three types. As a rule, veinlets and veins of granular quartz to 10-30 cm thick with biotitized rock inclusions are manifested along the periphery of the ore zones. In vein quartz, sulphide mineralization is noted mainly as pyrrhotite, pyrite, melnikovite-pyrite, less often chalcopyrite, marcasite, and single grains of galena and sphalerite. Ilmenite is sometimes found in selvages of veins. Quartz decrepitation shows the almost complete absence of gas-liquid inclusions in these veins. Cases of their crossing by veins with greisen rims are noted. All this can testify to their pre-granite formation. In this type of vein, the following elements are observed in elevated concentrations: copper (to 0.2 %), polymetals Zn, Pb (in thousandths of a percent), silver (to 1 g/t), and gold (to 0.074 g/t).

The second type of vein formations has an albite-K-feldspar-muscovite-quartz composition and is accompanied by mineralization typical of greisens, represented by muscovite, micaceous lithium, fine rare segregations of topaz, beryl, tourmaline, and sometimes apatite. The generations of veined quartz are predominated by coarse-grained varieties with mining bags filled with small crystals of transparent quartz, less often smoky crystal.

Micaceous selvedges usually contain medium scaly molybdenite-I, and molybdenite-II, which forms rosettes, interstitials quartz. Sometimes wolframite crystals to four cm long are noted, which arose simultaneously with quartz or somewhat later. Scheelite is often associated with wolframite, forming nested clusters. It was isolated later than wolframite, since cases of cementation of wolframite crystals by it were noted [39]. The veins occasionally contain arsenopyrite, pyrite, and chalcopyrite, cassiterite, and bismuthine with native bismuth and joseite-A [40].

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Molybdenite-II, bismuthine, native bismuth, joseite-A, and gold are most closely related to each other in this type of vein formations. The temperature of ore deposition of minerals, according to decrepitation data, was 320-500 °C.

The following minerals are recorded in elevated contents in this type of veins: Mo 0.1 % (to 1 % in single samples), W 0.1-0.3 %, Bi 0.02-0.2 % (to 1 %), Sn to 0.08 %, silver to 3.0 g/t and gold to 0.32-1.3 g/t.

The third type of vein formations, as a rule, is represented by thin veins and veinlets of medium-grained, sometimes columnar quartz, sometimes with xenoliths of host rocks. They contain developed arsenopyrite-polysulphide mineralization, varying in different veins from single inclusions to 50 % of the volume. Arsenopyrite predominates among the ore minerals. Arsenopyrite is represented by dissemination of small (to 1-1.5 mm) crystals and their aggregates, forming strip-like segregations parallel to selvedges. Usually it is 30-80 % of ore mineralization. There are small (0.004-0.1 mm) inclusions of chalcopyrite, pyrrhotite, sphalerite, in isolated cases, stannite, bismuthine, native gold and bismuth. Larger segregations of chalcopyrite, sphalerite, pyrite, less often stannite, galena, and bismuthine grow on arsenopyrite crystals, which proves their later segregation. In many cases, cassiterite is also noted in these veins, in individual cases bournonite and antimonite. The temperature of mineral deposition in this type of veins is 180-480 °C. The content of the main ore elements reaches the following values: As 2 %, Zn 1 %, Cu 0.7 %, Bi 0.2 %, Mo 0.02 %, Pb 0.1 %, silver 400 g/t, gold 4 g/t.

Decrepitation of vein quartz gave a temperature range from 180 to 500 °C. X-ray microspectral analysis showed the content of "invisible" gold in arsenopyrite 0.31 %, silver to 0.07 % [29]. Elevated contents of a number of other elements are also recorded: antimony to 0.33 %, tin to 0.11 % and tellurium to 0.03 %. The content of bismuth and silver according to the spectral analysis of the mineral monofractions is 0.004-0.02 and 0.01-0.1 %, respectively. The detection of tellurium in arsenopyrite may indicate the presence of ultra-fine dissemination of gold, silver, and bismuth tellurides. Elevated contents of characteristic elements were also found in galena from veins of this type: Ag 0.32-1.0 %, Bi 0.94-1.9 %, Te to 0.08 %, Se 0.03-0.09 %. In individual cases, small (4-5 μm) inclusions of native silver are found in galena.

Mineral associations productive for gold in the occurrences of the Martovsko-Nikitinsky ore cluster are early arsenopyrite-polysulphide with cassiterite and late molybdenite-bismuth with native bismuth and joseite-A [38]. The second one is superimposed on earlier associations or forms independent small segregations in quartz fractures. Gold, according to mineragraphic studies, is finely dispersed and pulverized, the maximum size of gold grains is 0.12 mm, while the bulk of the observed segregations is smaller, from a few tens of microns to 1-50 μm. Gold is present, as in quartz, but mainly in bismuth minerals – bismuthine, native bismuth, joseite-A. From 40 to 70 % of the identified gold particles in various veins are associated with bismuth minerals. These data are also confirmed by spectral analysis of bismuthine monofractions, in which gold contents to 0.1 % are recorded. Much less often, gold is observed in arsenopyrite and galena. The fineness of gold, determined for the molybdenite-bismuth association with native bismuth, is low, 693-703 ‰. Of the impurities, in addition to silver, it contains copper and mercury in the amount of hundredths to tenths of a percent.

The isotopic composition of galena from veins of diverse occurrences in the Kropotkinsko-Nikitinskaya metallogenic zone was studied in eight samples by the isotope ratio of lead on the order of VNIIOkeangeologia on the M1201 mass spectrometer in the VSEGEI laboratory by L.A.Neimark in 1984 and A.P.Chukhonin in 1991. The model age of this mineralization was determined in the range of 200-300 Ma, i.e., Late Carboniferous to Early Jurassic. Modern research, as a rule, is based on statistically significant samples of analyses. Nevertheless, similar datings are also known for a number of other gold occurrences of Bolshevik Island, including the occurrences of Lake Zakrytoye north of the Spartak Fjord on the beam of the Kropotkinsko-Nikitinskaya metallogenic zone. Similar age

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limits were established for gold occurrences in the north of Taimyr: gold-rare metal formation of the Walter Bay, gold-quartz formation Zhilnoye, gold-sulphide-quartz formation Konechnoye, etc. [29, 36]. All these data allow us to assert that the obtained determinations of the absolute age of mineralization on Bolshevik Island are very probable.

Points of mineralization with gold on the northern extension of the Kropotkinsko-Nikitinskaya metallogenic zone behind the Semenov-Tyan-Shansky Glacier were identified at altitudes from 50 to 350 m.

Discussion of the results. All the described mineral and geochemical features of the mineralization on the western part of Bolshevik Island make it related to the gold-rare metal formation identified in the northeast of Russia [22, 23], as well as in other regions of the world [7, 9, 11], which was noted in previous works [29, 36]. In addition to the listed mineralization features of the Martovsko-Nikitinsky cluster, the fact that, both as the GRM, a significant mobilization of gold and other metals by granitoids from the sedimentary rocks with gold-sulphide mineralization intruded by them is supposed [7]. On Bolshevik Island, the most ancient strata, the Golyshevskaya of Riphean age, contains elevated concentrations of gold [29, 41, 42]. When VNIIOkeangeologia employees studied the gold content of black shale deposits in the Taimyr-Severnaya Zemlya region in the 70-90s, they found a number of strata with elevated gold content (from 7 to 16 mg/t). And in some parts of the section of the Golyshevskaya strata on Bolshevik Island, its anomalous contents were revealed, to 198 mg/t. Estimations on the possible amount of gold extracted from the black shale strata in the region during contact metamorphism by granitoids, based on data obtained by V.A.Buryak [43], V.A.Zlobin [44], A.I.Zabiyaka [45, 46], can be tens and hundreds of tons of metal in one cubic km in a number of stratigraphic units in the region [41]. These data suggest a significant role of the Golyshevskaya strata in the supply of gold to hydrothermal fluids during the Paleozoic tectonic-magmatic activation of the region [38, 39, 41].

In addition to gold-rare metal and gold occurrences, two occurrences of the cassiterite-sulphide formation were revealed in the western part of Bolshevik Island: Daikovoye occurrence in the Tora-Kamensky OPR area, and Studeninskoye occurrence in the Studeninsko-Ozerninsky ore cluster. The Daikovoye occurrence is interesting in that rare metal mineralization is superimposed on a layered dike of T_{1-2} gabbro-dolerites four to five m thick with a traced length of two km. The mineral occurrence is 10 km north of the Mount Eighth of March and is confined to the crumpling-foliation zone on the right bank of the Tora River [38, 39].

In arsenopyrite monofractions, gold is present in small amounts (to 0.26 g/t according to spectrochemical analysis), and the following admixtures were established according to the results of X-ray microanalysis: Ag (to 0.04 %), Pt (to 0.15 %), Pd (to 0.07 %) [29]. According to the data of furrow sampling, in ores with exceptionally low tin contents, which are hundredths of a percent, there is gold (to 0.5 g/t), silver (to 400 g/t), copper (to 2 %), and zinc (to 1 %).

The Studeninskoye mineral occurrence is in weakly hornfelsed terrigenous rocks of the exocontact zone of the Kropotkin granitoid massif [38, 39]. Mineralization is controlled by a NE-trending fault zone 20-80 m wide, traced for 500 m. Ore mineralization is associated with a dense network of steeply dipping quartz veins and veinlets oriented across the strike of the rocks. Vein thickness does not exceed 5-20 cm. In the mineral occurrence limits, there are two areas with a dense network of veinlet-vein silicification, separated by a 200-m interval with single quartz veins. The western section, 140 m wide, is characterized by low contents of ore elements: Sn 0.02-0.04 %, Ag 100-400 g/t, Cu 0.1-0.6 %, Zn 0.1 %, sometimes Pb to 0.1%, Sb to 0.03 %. The eastern section, about 100 m wide, is distinguished by much richer mineralization: Sn 0.1 % (to 2-7 %), Ag 200-400 g/t (to 1 kg/t), Bi 0.01-0.2 %, Cu, Pb and Zn are tenths of a percent. Gold is rarely found, hundredths of grams per ton.

Gold occurrences and points of gold mineralization in the Tora-Kamensky OPR belong to gold-sulphide-quartz and gold-quartz formations. An example of a gold-sulphide-quartz formation in this area is the Torinskoye occurrence. The occurrence is represented by two vein-veinlet zones of northeast strike in the middle reaches of the Tora River downstream its sharp loop. The sampled part of

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the first zone is 60 m thick. Four types of vein formations are distinguished: 1 – lenticular near-concordant with the strike of host rocks gently dipping veins to 0.5 m thick without visible ore mineralization; 2 – near-concordant veinlets 2-4 cm thick with predominantly pyrite (2-4 %) mineralization and rare segregations of chalcopyrite and sphalerite; 3 – secant near-latitudinal thin (1-10 to 60 cm) veinlets and veins of carbonate-quartz composition, in which sulphides are much more (to 50 %); 4 – secant near-latitudinal thin veinlets of the same composition with a small amount of sulphides. Vein formations of the 3rd and 4th types contain gold (0.7-2.1 g/t), silver (87-104 g/t), elevated zinc contents are also observed (to 0.2 %), less often lead (to 0.06 %), arsenic (to 0.04 %), and copper (to 0.01 %). The ores are dominated by pyrite (70-90 % of the total amount of ore minerals), minor minerals are sphalerite, galena, and chalcopyrite, and rare are arsenopyrite, fahlore, native silver, acanthite, and gold.

The type of gold ore bodies attributed to the gold-quartz formation in this area is represented by an occurrence identified on the Kamenistaya River. The ore occurrence is represented by a zone of carbonate-quartz veining in the area of crumpling and fracturing, which accompanies the large Kamensky fault. The ore occurrence is on the right side of the Kamenistaya River, two km from its confluence with the Kamenka River. The veining zone strikes northeast, it is about six m thick. The frequency of veining is to 10-15 per m, the thickness of veinlets is from 0.2 to 5-10 cm. Often they are differently oriented, branching, the general dip of the zone is at an angle of 60° to the northwest. Quartz in veins and veinlets is white and white-grey compact, it contains 5-8 % chlorite and chloritized relics of the host rock and the same amount of white calcite. The total amount of sulphides in the vein formations is about one percent, in some places up to two or three. Sulphides are concentrated mainly along the selvedges in the form of lenticular pockets and veinlets, less often they are present in the veinlet centre, and also in the form of very scattered dissemination in the rock. The main ore minerals are arsenopyrite and pyrite in varying amounts relative to each other, but in general, arsenopyrite makes up 60-70 %, and pyrite 30-40 %, although in some cases it even prevails.

Gold is most commonly found in large crushed sulphide aggregates. In arsenopyrite, only 4 % of metal grains are found, the rest of the identified grains is confined to pyrite. Gold is fine, 5-10 μm, rarely more than 30 μm. The average content of a number of elements in the veinlets of this zone: As 0.11 %; Cu 0.002 %; Pb 0.02 %; Zn 0.004 %; Ag 3.4 g/t; Au 3.38 (maximum 11 g/t). At the same time, in the host sulphidized rocks: As 0.09 %; Cu 0.004 %; Pb 0.0006 %; Zn 0.004 %; Ag 0.17 g/t; Au 0.27 g/t. Many points of gold mineralization in this area can be classified as similar sites with poor mineralization.

Mineral occurrence similar in mineral composition, Pervoye, with thin gold and a slightly higher content of sulphides in veinlets and quartz metasomatites of the ore zone from one to three percent, in some places to 10%, and an average gold content of 1-5 g/t (maximum to 72 g/t) is located southwest of the limit of this metallogenic zone. Gold fineness within its limits is 810-926 ‰.

Within the Studeninsko-Ozerninsky ore cluster, two outcrops of granitoids of the Kropotkinsky complex (C_{1-2}) were found. This is the Kropotkin massif and granite outcrop, identified later by the Dudinskaya Central Arctic Geological Exploration Expedition (DTsAGRE) near the glacier. It is assumed that this is a single massif, mainly covered by the Leningradsky Glacier. Along with granite intrusion, numerous dikes were identified in this area. They are represented by andesites and dacites of the Norinsky complex, rhyolites of the Kropotkinsky complex, dolerites of the Universitetsky and Blizhneostrovsky complexes, and single kersantite dikes of the Akhmatovsky complex.

According to the DTsAGRE data, the Studeninskoye mineral occurrence, a cassiterite-sulphide formation, and several occurrences and points with polysulphide mineralization, in some cases with elevated contents of gold, silver, and tin, were identified within the cluster. Mineralized veins are dominated by pyrite, arsenopyrite, galena, chalcopyrite, and sphalerite. There are almost monomineral pyrite and galena veinlets. Native gold was found in 10 veins in crushed samples.

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Gold is represented by small (from 0.05 to 0.9 mm) lumpy, interstitial, incompletely crystalline and partially faceted segregations. The fineness of gold from crushed samples of the Studeninsko-Ozerninsky ore cluster is from 700 to 980, 800 ‰ on average.

In total, according to spectral analysis, 28 complex polymetallic and silver-polymetallic mineralization points were identified in this area. Silver content is to 2 kg/t, including three points with gold to 20 g/t. Most are concentrated in the east of the area in biotite hornfelses and near them. In addition to noble metals, the samples showed elevated contents of Cu (to 0.8 %), Pb (more than 1 %), Zn (more than 1 %), As (to 0.2 %), Sn (to 0.6 %). The abundance of polysulphides in the Studeninskoye occurrence and the purely acicular nature of cassiterite [38, 39] suggest that this occurrence represents the top of the ore column and has a good depth prospect. Other quartz-sulphide occurrences of the Studeninsko-Ozerninsky ore cluster can be of the tin-silver-polymetallic type, which can also be considered as a positive moment in assessing the mineralization prospects in the Studeninsky-Ozerninsky area.

By analogy with the described cases of vertical zoning of mineralization in other regions of Russia, one can assume that gold-rare metal mineralization is located directly in the apical parts of granitoids and in the nearest hornfelses halos. At a distance from the exit from the hornfels zone, there are veins of cassiterite-sulphide formations, sometime with elevated contents of gold and silver. And, finally, occurrences of the gold-sulphide-quartz and gold-quartz types are localized in fault zones, as a rule, further from the granitoids than the previous ones. In a number of cases, cassiterite and other rare metal minerals (wolframite, molybdenite, scheelite, the Gryaznukha mineral occurrence) were found in crushed samples in the proper gold occurrences of the region [39]. All this speaks of the wide distribution of cassiterite in the ore formations of the metallogenic zone and emphasizes the connection of heterogeneous mineralization with granitoids.

Conclusion. All the given geological and mineralogical-geochemical characteristics of the rare metal mineralization with gold of the Kropotkinsko-Nikitinskaya metallogenic zone correspond to the characteristics of the GRM formation.

The occurrences of other formation types revealed in this metallogenic zone suggest a certain zoning in their distribution, gold-rare metal mineralization is located in the apical parts of granitoids and the nearest hornfelses halo. At a distance from the exit from the hornfelsed zone, there are veins of the cassiterite-sulphide formation with elevated content of gold and silver at the top of the ore column, together with an increased amount of polymetals. Proper gold occurrences of the gold-quartz and gold-sulphide-quartz formations are localized in fault zones, as a rule, farther from the granitoids. Although in a number of cases, the presence of rare metal minerals, such as cassiterite, wolframite, and molybdenite, is also established in the proper gold occurrences (for example, in the Gryaznukha occurrence) [39].

The assignment of all types of mineralization in this metallogenic zone to a single hydrothermal process associated with granitoids of the Kropotkinsko-Nikitinsky complex is emphasized by the similar Pb isotopic composition of galena, which determines the model age of all mineralization at 200-300 Ma.

For gold-rare metal deposits in Russia and the world, researchers assume the mobilization of a significant amount of gold from sedimentary strata with gold-sulphide mineralization intruded by granitoids. On Bolshevik Island, the most ancient strata, the Golyshevskaya of Riphean age, contains elevated metal concentrations and can serve as a base formation, a gold supplier for the subsequent hydrothermal process.

The Kropotkinsko-Nikitinskaya metallogenic zone is characterized as the most significant in this region and promising for the identification of industrial deposits, including gold-rare metal ones, during geological exploration.

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