MINING SCIENCE AND TECHNOLOGY (RUSSIA)
ГОРНЫЕ НАУКИ И ТЕХНОЛОГИИ
eISSN 2500-0632
https://mst.misis.ru/
2024;9(4):352–386

GEOLOGY OF MINERAL DEPOSITS

Review paper

https://doi.org/10.17073/2500-0632-2024-05-248
UDC 553.04:553.43

Mineral resource base of Russia's copper: current state and development prospects

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Abstract
This study addresses the need for a comprehensive understanding of current state of Russia's cupper mineral resource base. *Its objective* is to assess Russia's copper reserves (balance reserves and forecast resources), analyze the spatial distribution of copper deposits by ore formation types and across ore provinces, and evaluate prospects for sustaining national copper production. Methods: The study employs statistical, graphical, and logical analysis methods. *Results:* The research presents a consolidated map of Russia, highlighting 25 copper provinces and 150 significant copper deposits across various ore formations, as well as prospective sites and areas. Key characteristics of Russia's main ore formations, copper ore provinces, and outlying copper deposits are detailed. Copper production in Russia is currently concentrated in sulfide copper-nickel and copper-pyrite deposits, with emerging mining operations in copper-porphyry and copper-skarn formations. In 2021, copper production in Russia reached 1,147 Kt. Upcoming projects to develop copper deposits could increase annual production by 635–1,053 Kt, equivalent to a 55–91% rise over 2021 levels. The total estimated balance reserves and forecast resources amount to 102.7 million tons, with conditional reserves accounting for 16.1 million tons. The largest copper reserves are found in copper-nickel formations (34.4%), copper-porphyry formations (23.9%), copper sandstones formation (19.6%), and copper-pyrite formation (14.5%), with all other formations contributing 7.6%. Key provinces include Norilsk-Kharayelakh (30.9% Russian reserves), Kodar-Udokan (20.3%), and the Urals (18.9). The share of reserves is growing in newer provinces: Primorsky (8.29%), Okhotsk-Chukotka (6.23%), and East Tuvinian (3.7%). Remaining copper mining provinces account for 11.68% of reserves. Current reserves are estimated to suffice for at least 47 years of optimal extraction. The most substantial reserves are associated with copper-nickel, copper-porphyry, and copper sandstone formations, whereas balance ore reserves in copper-pyrite and copper-skarn formations are nearly exhausted. Sufficient reserve security is available in the Norilsk-Kharayelakh, Kola, and Rudny Altai provinces. However, significant reserve is observed in the traditional Ural and emerging East Trans-Baikal provinces. In the North Caucasus province, a high security results in low production levels and underutilized reserve deposits. The copper-nickel formation's reserve availability remains low, though new rich ore deposits may exist at greater depths within the Kharaelakh and Tangaralakh ore-bearing intrusions. Copper-pyrite formation reserves may expand with further exploration of deep horizons and the periphery of known deposits in the Ural province, alongside new deposits discoveries in the Circumpolar and Polar Urals. For copper-polymetallic formation, extensive deposits exist in old Ore-Altai, Salair, and North Caucasian provinces, with promising potential in the new East Tuvinian and Okhotsk-Chukotka provinces. Exploration for porphyry copper has intensified in the East Tuvinian, Primorsky, and Okhotsk-Chukotka provinces, indicating strong potential for discovering new large porphyry copper deposits. Additional reserves of copper sandstone formation may be developed within the Kodar-Udokanskaya, Igarskaya, Bilyakchan-Kolyma, and Shoria-Khakass provinces. New technology for underground copper leaching opens opportunities for exploring and utilizing smaller copper sandstone deposits in the Pre-Ural and Donetsk provinces. The recorded cooper balance reserves in Russia do not yet account for native copper deposits in basaltoid formations within the Shoria-Khakass, Norilsk-Kharayelakhskaya, and Bilyakchan-Kolyma provinces.

Keywords
copper, ore, strategic raw materials, ore formations, deposit, province, region, reserves, resurce, mining, forecasting, national projects, Russia

For citation
Boyarko G.Y., Lapteva A.M., Bolsunovskaya L.M. Mineral resource base of Russia's copper: current state and development prospects. *Mining Science and Technology* (*Russia*). 2024;9(4):352–386. https://doi.org/10.17073/2500-0632-2024-05-248

eISSN 2500-0632
https://mst.misis.ru/

ГЕОЛОГИЯ МЕСТОРОЖДЕНИЙ ПОЛЕЗНЫХ ИСКОПАЕМЫХ

Обзорная статья

Минерально-сырьевая база меди России: состояние, возможности развития

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Аннотация

Актуальность работы обусловлена необходимостью получения максимально полной картины состояния минерально-сырьевой базы меди по Российской Федерации. *Цель*: изучение состояния минерально-сырьевой базы меди России (балансовых запасов, прогнозных ресурсов), пространственного размещения месторождений меди по типам рудных формаций и в пределах рудных провинций, перспектив национального производства добычи меди. *Методы*: статистический, графический, логический. *Результаты*: Представлена сводная карта-схема России, включающая 25 меднорудных провинций и выборку из 150 наиболее значимых месторождений меди различных рудных формаций, перспективных объектов и площадей. Даны характеристики основных рудных формаций, месторождения меди которых имеются в России, а также меднорудных провинций и медных месторождений вне провинций. В России основная добыча сконцентрирована на сульфидных медно-никелевых и медно-колчеданных месторождениях, а также начата добыча на медно-порфировых и медно-скарновых месторождениях. В 2021 г. уровень добычи меди в Российской Федерации составил 1147 тыс. т. Реализация новых подготавливаемых проектов разработки медных месторождений может увеличить уровень годовой добычи России на 635–1053 тыс. т (на 55–91 % от уровня добычи 2021 г.). В России по состоянию на 01.01.2022 г. учтено 102,7 млн т балансовых запасов и прогнозных ресурсов в пересчете на условные запасы – 16,1 млн т. Наибольшие объемы запасов меди приходятся на медно-никелевую (34,4 % от российских запасов), меднопорфировую (23,9 %) формации, формацию медистых песчаников (19,6 %) и медно-колчеданную формацию (14,5 %) и 7,6 % на все остальные рудные формации. По провинциям на Норильско-Хараелахскую приходится 30,9 % от российских запасов, на Кодаро-Удоканскую – 20,3 % на Уральскую – 18,9 %. Отмечается увеличение показателей долей запасов меди для новых провинций: Приморской – 8,29 %, Охотско-Чукотской – 6,23 % и Восточно-Тувинской – 3,7 %. На остальные меднорудные провинции приходится 11,68 % российских запасов меди. В целом имеющихся запасов меди Российской Федерации хватит минимум на 47 лет оптимальной эксплуатации. Наиболее обеспечены запасами разрабатываемые месторождения медно-никелевой и медно-порфировой формаций, а также формации медистых песчаников. Для месторождений медно-колчеданной и медно-скарновой формаций имеет место срабатывание имеющихся запасов балансовых руд. По эксплуатационным регионам достаточная обеспеченность имеется лишь для Норильско-Хараелахской, Кольской и Рудно-Алтайской провинций. В старой горнопромышленной Уральской и новой Восточно-Забайкальской провинциях отмечается серьезное срабатывание запасов балансовых руд. В старой горнопромышленной Северо-Кавказской провинции имеет место высокий уровень обеспеченности, что является следствием малого уровня добычи и наличия невостребованных запасов резервных медных месторождений. Обеспеченность запасов прогнозными ресурсами медно-никелевой формации невысокое, но возможны открытия новых месторождений богатых сливных руд на глубине в пределах Хараелахского и Тангаралахского рудоносных интрузивов. Для медно-колчеданной формации прирост запасов возможен за счет оценки глубоких горизонтов и периферии известных месторождений Уральской провинции, а также поиска новых месторождений на территории Приполярного и Полярного Урала. Для медно-полиметаллической формации известно множество месторождений в старых горнопромысловых Рудно-Алтайской, Салаирской и Северо-Кавказской провинциях, а также при исследовании новых Восточно-Тувинской и Охотско-Чукотской провинций. Для медно-порфировой формации увеличились масштабы геологоразведочных работ в Восточно-Тувинской, Приморской и Охотско-Чукотской провинциях, где имеются все предпосылки к обнаружению новых, в том числе крупных медно-порфировых месторождений. Для формации медистых песчаников возможен прирост запасов в пределах Кодаро-Удоканской, Игарской, Билякчанско-Приколымской и Шорско-Хакасской провинциях. В условиях развития новых технологий подземного выщелачивания меди становятся привлекательными поиски, разведка и вовлечение в эксплуатацию небольших месторождениий медистых песчаников в Приуральской и Донецкой провинциях. В учтенных балансовых запасах меди России отсутствуют объекты месторождений формации самородной меди в базальтоидах, известные в пределах Шорско-Хакасской, Норильско-Хараелахской и Билякчанско-Приколымской провинций.

Ключевые слова

медь, руда, стратегическое сырье, рудные формации, месторождение, провинция, регион, запасы, ресурсы, добыча, прогнозирование, национальные проекты, Россия

Для цитирования

Boyarko G.Y., Lapteva A.M., Bolsunovskaya L.M. Mineral resource base of Russia's copper: current state and development prospects. *Mining Science and Technology* (*Russia*). 2024;9(4):352–386. https://doi.org/10.17073/2500-0632-2024-05-248

Introduction

Copper ranks third in global production and consumption among base industrial metals, following iron and aluminum [1]. It is widely used in electrical applications as a conductor, in various alloys (such as brass, bronze, and nickel silver), in copper compounds for producing antiseptics, micronutrients, and catalysts for oxidative processes, among other applications [2]. Copper is designated as a strategic mineral in Russia's national list of essencial raw materials (Decree of the Russian Federation Government, 30.08.2022 No. 2473-r). It is also classified in the first group of minerals in Russia's Mineral and Raw Material Base Development Strategy, with reserves that are expected to meet national demand under any economic scenario through 2035 and beyond (Decree of the RF Government, 22.12.2018 No. 2914-r) [3]. Copper holds a similar strategic status in the USA, the European Union, Canada, China, and India [4]; in some countries (e.g., Japan, South Korea, and Australia), it is even included in the list of critical, import-dependent commodities [5, 6].

Global consumption – and, accordingly, the supply – of primary copper increased by 60% from 2000 to 2021, while global reserves grew by a factor of 2.6. This growth primarily reflects the rapid expansion of the Chinese economy and the shift toward a global "green" economy, marked by a greater reliance on renewable energy sources and efforts to reduce carbon dioxide emissions from industrial and human activities [1, 2, 7]. Copper is essential in low-carbon energy technologies, including wind turbines and electric vehicle engines. The growth in copper consumption remains robust, even amid global economic downturn and political uncertainties, while supply has shown signs of lagging due to delays in commissioning new large-scale extraction operations [8].

Russia possesses a substantial copper resource base, ranking 2nd worldwide in terms of reserves, 6th in production, and 3rd-4th in exports[1]. In the 1990s, with the transition economy leading to reduced domestic consumption, Russian copper production declined from 800 Kt in 1991 to 500–580 Kt/year between 1995 and 2012. However, following the rise in global prices starting in 2013, production began to increase, reaching 1,028 Kt in 2019[2]. This growth in extraction and production of refined copper was accompanied by a significant rise in exports shares from 20–30% in 2011–2013 to 60–70% in 2015–2020. Russia's cooper mineral resource base and production facilities fully cover domestic needs and hold considerable export potential. Given global trends toward increasing copper consumption in the near future, expanding national production to boost Russia's share in the global copper market appears highly promising.

Methods

To analyze Russia's copper mineral resource, data on Russian copper production for the period 2002–2021, as well as reserves and forecast resources of copper deposits as of 01.01.2021, were collected. The data sources include state reports from the Ministry of Natural Resources and Ecology of Russia[3], certificates on the state and prospects of mineral resource use across Russian regions[4], state cadastral passports of deposits and mineral occurrences in Russia[5] and publications on copper resources available in the public domain. Copper reserves and production are measured in metric tons of 100% Cu. The volumes of forecasted copper resources are given by category in the stated absolute values, and, when aggregated, in terms of conditional reserves of category C_2, accounting for correction factors for different

[1] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[2] I bid.

[3] I bid.

[4] Information on the state and prospects of using the mineral resource base of the regions of the Russian Federation (as of 01.01.2022). St. Petersburg: VSEGEI, State Assignment No. 049-00018-22-01, 2022 dated 14.01.2022. URL: http://atlaspacket.vsegei.ru/?v=msb2021#91474d2e700eb6c90

[5] Passports of copper deposits. Russian Federal Geological Fund. The unified fund of geological information about the subsurface. The register of primary and interpreted information. 2023. URL: https://efgi.ru/

categories. A consolidated schematic map of Russia is presented, summarizing significant copper deposits across various ore formations, promising sites for copper exploration, previously designated copper ore provinces, and proposed new copper ore provinces. The paper identifies environmental restrictions on new copper deposit development. The authors also examine opportunities for advancing the copper mining industry by implementing innovative technologies for copper ores extraction and processing. Additionally, the paper provides an analysis of the state of balance reserves and forecast resources across ore formations and copper provinces.

State of the Russian mineral resource base of copper

Russia ranks 2nd globally in cooper reserves (after Chile), 6th in mining (following Chile, Peru, China, Congo, and the USA), 5th in refined copper production (after China, Chile, Japan, and DR Congo), and 3rd–4th in terms of exports (alongside Japan) after Chile and DR Congo[6] [9]. The foundation of Russia's copper resource base consists of deposits in sulfide copper-nickel, copper-porphyry, copper-pyrite, and stratiform geological-industrial types. Major mining operations are concentrated in sulfide copper-nickel and copper-pyrite deposits, with increasing production volumes at copper-porphyry sites[7].

Based on the collected data, the following was compiled:

– An overview map of Russia's copper ore provinces and primary copper deposits (see Fig. 1);

– Charts of copper production volumes and shares from 2002 to 2021 by types of ore formations (Fig. 2) and copper provinces (Fig. 7);

– Charts showing the shares of copper reserves and production (2021) by ore formation type (Fig. 3) and copper provinces (Fig. 6);

– A chart on the volume of balance reserves and forecast resources by ore formation type (Fig. 4);

– Charts on the volume of copper reserves and production by province (Fig. 6).

The paper also provides descriptions of the copper ore formations found within the Russian Federation and details on copper deposits both within and outside the designated copper ore provinces.

Formations of copper deposits

The development of copper deposits has been known since the Bronze Age, and throughout the history of copper mining, geological copper ore formations have been studied in terms of their attractiveness and relevance for the copper mining industry.

Initially, copper ore exploration focused on near-surface, copper-rich ores in copper-skarn, copper-pyrite formations, and of copper sandstone formations. It also possible to identify a significant *formation of the secondary enrichment zone with supergene copper*, with rich ores formed in near-surface conditions in deposits of almost all copper ore formations, often evolving from low-grade and ordinary ores. Previously, these secondary, copper-rich ores were the primary targets for development; however, they are now rare, and this ore formation has, in fact, become exotic. Due to the initial predominance of small-scale, near-surface artisanal mining, numerous small deposits were mined for copper, while medium and large copper deposits were locally damaged by mining operations that selectively extracted the available, most copper-rich fragments.

With growing copper demand, larger deposits of copper-pyrite and copper-nickel formations began to be put into operation. A notable unique and exotic deposit of native copper in basaltoids (Lake Superior deposit, USA) was entirely mined out.

The development of flotation enrichment technologies for sulfide ores has enabled the exploitation of deposits with disseminated copper mineralization, even those with relatively low-grade copper ores, provided they have a significant ore mass. Production has included deposits from the porphyry copper formation, which currently leads in supplying copper to the market. Flotation technologies have also enabled the to extraction of copper concentrate from deposits in other ore formations with associated copper mineralization (polymetallic, low-sulfide platinum-metal, quartz-sulfide, carbonatite, etc.). New enrichment technologies (flotation, hydrometallurgy) have also made it possible to mine porphyry copper from formations where previously only rich ores (copper-nickel, copper-pyrite, copper sandstones) were developed.

Hydrometallurgical technologies, such as heap and in-situ leaching, enable the development of fundamentally new formations, including technogenic deposits (e.g., dumps, drainage waters of mine workings), as well as previously unattractive small copper deposits and copper-bearing formations.

[6] U.S. Geological Survey (USGS). URL: http://minerals.usgs.gov/minerals/pubs/commodity/

[7] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

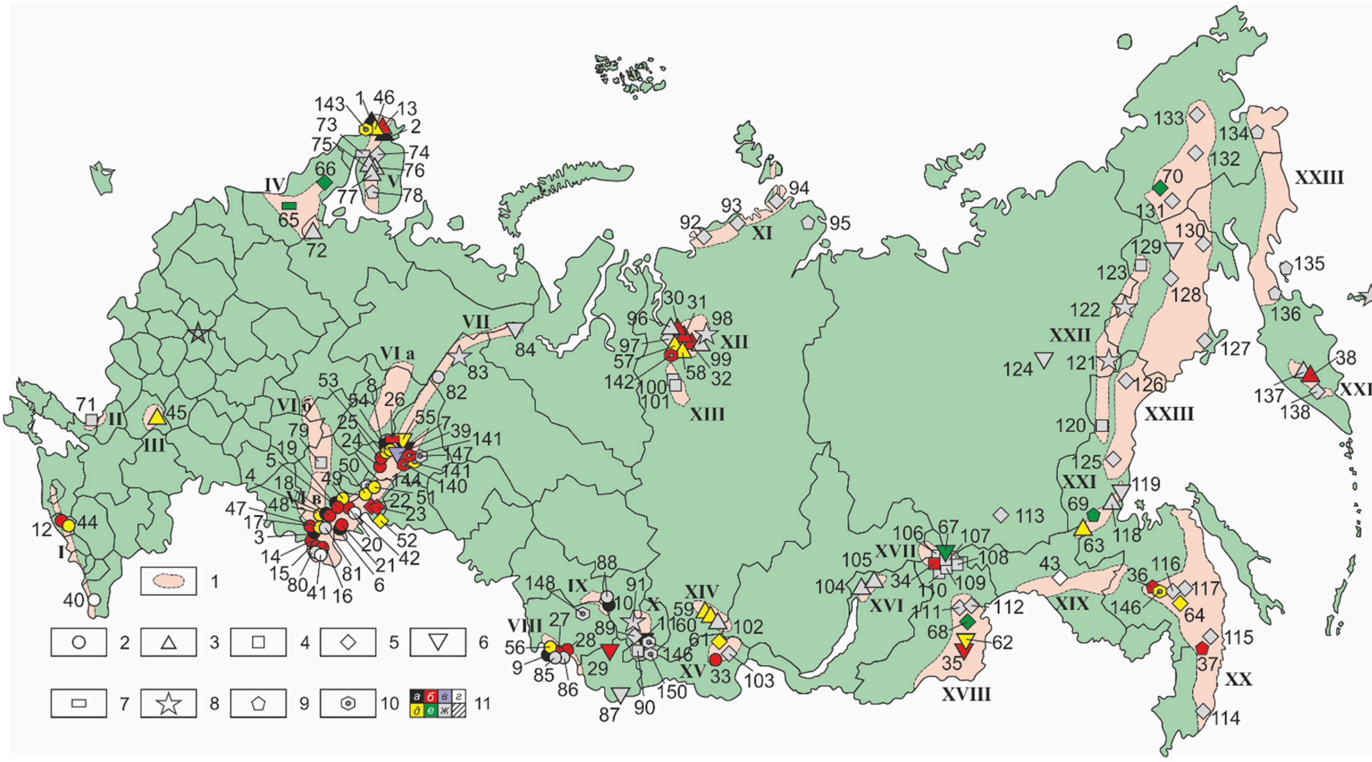


Fig. 1. Copper ore provinces, copper deposits by geological and technological types, and their status in production: 1 – copper ore provinces; 2–10 – geological and technological types of copper deposits (2 – copper-pyrite and pyrite-polymetallic, 3 – copper-nickel, 4 – copper sandstones, 5 – copper-porphyry, 6 – copper-skarn, 7 – copper-iron, 8 – native copper, 9 – with associated copper mineralization; 10 – technogenic); 11 – the status of copper deposit involvement in production: a – exhausted and suspended/shutdown mines (mothballed), b – developed by open-pit and underground methods, c – geotechnological development, d – unallocated subsoil fund, e – prepared for development, g – at the geological exploration stage, h – at the prospecting evaluation stage for sites and areas. Copper provinces: I – North Caucasus, II – Donetsk, III – Voronezh, IV – Karelian, V – Kola, VI – Pre-Ural (VIa – Ufa Stage, VIb – Kazan Stage, VIc – Tatar Stage), VII – Ural, VIII – Rudny Altai, IX – Salair, X – Shoria-Khakass (Mrassu-Batenev), XI – Central Arctic, XII – Norilsk-Kharayelakh, XIII – Igarka, XIV – Sayan, XV – East Tuvan, XVI – North Baikal, XVII – Kodar-Udokan, XVIII – East Trans-Baikal, XIX – Umlekan-Ogoja, XX – Primorsky, XXI – Jugjur, XXII – Bilyakchan-Kolyma; XXIII – Okhotsk-Chukotka, XIV – Koryak, XV – Kamchatka. Copper deposits: 1–11 – exhausted and suspended: 1 – Kotselvaara-Kammikivi, Semiletka, 2 – Tundra, Zapolyarnoye, 3 – Dergamyshskoye, 4 – Sibayskoye, 5 – Uchalinskoye, 6 – Aleksandrinskoe, 7 – Mednorudyanskoye, Turyinsky group, 8 – Tarnyerskoe, 9 – Zmeinogorskoye, 10 – Kamenushinskoye, 11 – Keyalykh-Uzen, Glafirinskoye, Julia; 12–38 – deposits under development: 12 – Urupskoye, 13 – Zhdanovskoye, 14 – Gayskoye, 15 – Osennee, 16 – Vesenne-Aralchinskoye, Dzhusinskoye, 17 – Yubileynoye, 18 – Kamagan, 19 – Ozernoye, Zapadno-Ozernoye, 20 – Talganskoye, Uzelginskoye, Molodezhnoye, 21 – Chebachye, 22 – Tominskoye, 23 – Mikheevskoye, 24 – Safyanovskoye, 25 – Novo-Shemurskoye, 26 – Volkovsky, 27 – Karbalikhinskoye, Zarechenskoye, 28 – Stepnoye, 29 – Sinyukhinskoye, 30 – Oktyabrskoye, 31 – Talnakhskoye, 32 – Norilsk-I, 33 – Kyzyl-Tashtyg, 34 – Udokan, 35 – Bystrinskoye [Cu–Fe], 36 – Pravourminskoye, Festivalnoye, Sobolinoye, Perevalnoye, 37 – Vostok-2, 38 – Shanuch; 39 – geotechnological development (Gumeshevskoye); 40–43 – undistributed reserve deposits: 40 – Kizil-Dere, 41 – Komsomolskoye, 42 – Novoye, Yuzhnoye, 43 – Ikanskoye; 44–64 – deposits prepared for development: 44 – Khudesskoye, Skalistoye, Pervomayskoye, 45 – Elanskoye, Elkinskoye, 46 – Bystrinskoye [Cu–Ni], Verkhneye, Sputnik, 47 – Podolskoye, Severo-Podolskoye, 48 – Vishnevskoye, 49 – Novo-Uchalinskoye, 50 – Sultanovskoye, 51 – Maukskoye, 52 – Tarutinskoye, 53 – Saumskoye, 54 – Severo-Kaluginskoye, 55 – Severnoye-3, 56 – Talovskoye, 57 – Maslovskoye, 58 – Chernogorskoye, 59 – Kingashskoye, 60 – Verkhnekingashskoye, 61 – Ak-Sugskoye, 62 – Kultuminskoye, 63 – Kun-Manye, 64 – Malmyzh; 65–70 –deposits at the exploration stage: 65 – Viksha, 66 – Lobash-1, 67 – Chineyskoye (Rudny site), 68 – Lukagonskoye, 69 – Konder-Rudny, 70 – Peschanka; 71–136 – promising areas, prospecting and evaluation sites: 71 – Bakhmutskaya, 72 – Voloshovskoye, 73 – Kolvitskoye, 74 – Pellapakhk, 75 – Poaz, Nyud, 76 – Nittis-Kumuzhya-Travyanaya, Sopcha (ore horizon 330), 77 – Arvarench, Moroshkovoye-Ozero, 78 – Fedorovo-Pan Tundra 79 – Belebeevskaya (Karsak mines), 80 – Blyavinskaya, 81 – Membetovskaya-Karagayskaya, Novopetrovskaya, 82 – Volinskaya, Grubeinsko-Tykotlovskaya, 83 – Khultymyinskaya, 84 – Novogodnee-Monto, 85 – Novonikolskaya, 86 – Kholodnaya, 87 – Ulandryk, 88 – Uskandinskoye, 89 – Bazinskoye, 90 – Taymetskoye, 91 – Malo-Labyshskoye, 92 – Uboininskoye, 93 – Verkhnetareyskoye, 94 – Porfyrovaya, 95 – Nadezhda, Pavlovsky, Koshka, 96 – Morongovskaya, 97 – Bolgokhtokhskoye, 98 – Arylakhskoye, 99 – Samoyedovskaya, 100 – Graviyskoye, 101 – Sukharikhinskoye, 102 – Kakhtarminskaya, 103 – Kyzyk-Chadrskoye, 104 – Yoko-Dovyrenskoye, 105 – Chayskoye, 106 – Unkurskoe, 107 – Krasnoe, 108 – Burpalinskoye, 109 – Sakinskoye, 110 – Pravoingamakitskoye, 111 – Zapadno-Mostovskaya, 112 – Borovaya, 113 – Ryabinovoe, Yllymakhskoye, Morozkinskoye, 114 – Lazurnoe, 115 – Malakhitovoe, 116 – Central Anajak, 117 – Ponyskaya, 118 – Nyandominskaya, 119 – Malokomuyskoye, 120 – Bilyakchanskoye, Severny-Uy, Borong, 121 – Rosomakha, Jalkan, Kharat, 122 – Batko, 123 – Oroek, Luchistoye, Vesnovka, 124 – Agylkinskoye, 125 – Chelasinskaya, 126 – Darpirchanskaya, 127 – Shkhiperskaya, 128 – Bebekan, 129 – Med-Gora, 130 – Mechiveemskaya, 131 – Nakhodka, 132 – Kavralyanskaya, 133 – Tanyurerskaya, 134 – Mainitskaya, 135 – Valaginsko-Karaginskaya, 136 – Snezhnoye, 137 – Kvinum, Kuvalorog, 138 – Kirganik, 139 – Beregovoe; 140–149 – technogenic deposits: 140 – slag dump of the Sredneuralsky Copper Smelter (CS), 141 – Cheremshansk sludge storage of the Vysokogorsky mine, 142 – tailings storage of the Norilsk Processing Plant (PP), 143 – dumps of the Allarechensk deposit, 144 – escorial of the Karabash CS, 145 – waste dump of the Kirovgrad CS, 146 – dumps of the Solnechniy PP, 147 – tailings dump of the Krasnouralsky concentrating plant (CP), 148 – slag dump of the Loktevskiy Silver Smelter, 149 – dumps of the Tuim CP, 150 – dumps of the Mainsky CP

eISSN 2500-0632
https://mst.misis.ru/

The copper-nickel formation is a specific mafic-ultramafic magmatic formation in which, during magma intrusion, melt differentiation and segregation occurred, producing silicate and sulfide liquids, with the sulfide melt concentrating in the lower parts of magmatic intrusions [10, 11, 12]. This process forms stratum-, plate-, and lens-shaped deposits of rich ores and horizons (reefs) of copper-nickel mineralization nodules. Melt differentiation and crystallization may occur repeatedly, but the largest deposits of predominantly rich copper-nickel ores form during a prolonged cycle in structures long platform margins (Norilsk type) and cratons (Pechenga type) [13]. Under conditions of multiple cycles of melt differentiation and segregation, beds and horizons are formed, predominantly with disseminated copper-nickel mineralization, as well as platinum-metal mineralization with associated copper-nickel ore [14]. Such copper-nickel deposits are found in platform margin structures on craton (Monchegorsk type in ultramafic rocks) and are primarily located in metallogenic orogenic zones of mobile belts within mafic complexes [13]. It should be noted that in deposits with predominantly disseminated copper ores, the nickel-to-copper ratio can increase from 0.5–1.0 to much higher values (up to 6.5 at the Shanuch deposit), reducing the economic significance of copper while increasing the concentration and economic importance of platinum group metals. Copper-nickel mineralization also appears as an associated component in deposits of the *low-sulfide platinum-metal formation*.

Interest in the copper-nickel formation was initially driven by the significance of its nickel content, with copper often a secondary or by-product. However, following the development of large Norilsk deposits of rich ores in the 1960s and 1970s, the copper-nickel formation became the leading source of national copper production, accounting for 60–65% of Russian output in the 2000s. However, due to a slight decline in copper-nickel ore production (from 500 Kt/year to 430 Kt in 2021) and the commissioning of new copper deposits from the porphyry copper and skarn copper formations, the of the copper-nickel formation's share of Russian production declined to 36.5% by 2021 (see Fig. 2, 3). Nevertheless, based on the recorded reserves and resources, the copper-nickel formation accounts for 34.4% of balance reserves and 15.8% of forecasted resources, reduced to conditional reserves [9]. Thus, this formation retains a leading position in reserves (see Fig. 3, 4).

Deposits of rich copper-nickel ores are located in the Norilsk-Kharayelakh and Kolskaya provinces, deposits of mainly disseminated copper-nickel ores are in the Voronezh, Kola, Sayan, North Baikal, and Jugjur provinces, and deposits of the low-sulfide platinum-metal formation with associated copper-nickel mineralization are found in the Karelian, Karyak, and Kamchatka provinces.

The copper-pyrite formation is a diverse group of deposits characterized by volcanogenic hydrothermal-sedimentary and hydrothermal-metasomatic origins, consisting of sulfide ores with pyrite and copper sulfides playing a dominant role [15, 16].

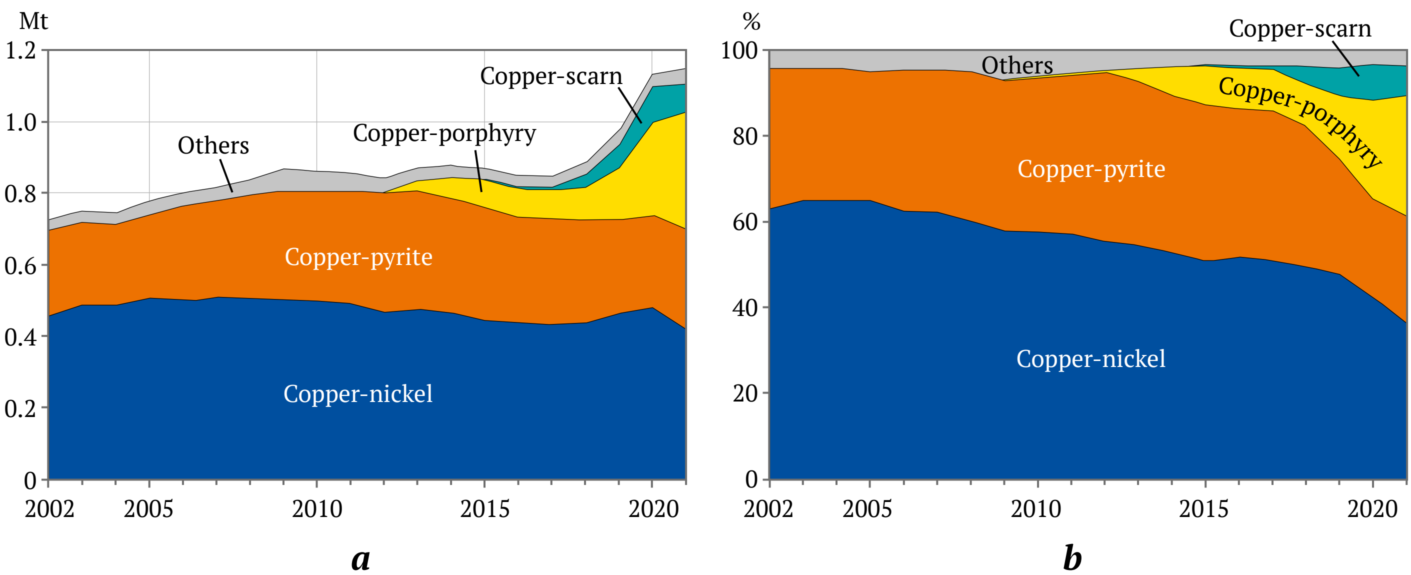


Fig. 2. Dynamics of copper production in Russia (2002–2021) by copper ore formation types:
a – production volumes, million tons; *b* – shares of total production in the Russian Federation, %
Source: Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

Morphologically, these deposits appear as plate- and lens-shaped formations of massive sulfide ores, often accompanied by halos of disseminated sulfide mineralization. Distinguished within this formation are the copper-pyrite deposits in basaltoid formations of eugeosynclines, the copper-zinc-pyrite deposits in rhyolite-basalt formations of eugeosynclines, and the unique Cypriot type of cobalt-bearing copper-pyrite deposits [17]. It is notable that there is both a similarity and a paragenetic relationship between the copper-pyrite and copper-nickel formations [18].

From the 19th century until the 1950s, products from copper-pyrite deposits formation led Russian copper mining, before yielding leadership to the copper-nickel formation. In the 2000s and 2020s, production from copper-pyrite deposits has ranged from 230–330 Kt/year (23–38% of Russian production), reaching 285 Kt (24.8%) in 2021 (see Fig. 2, 3). According to recorded copper reserves and resources, the copper-pyrite formation accounts for 14.5% of balance reserves and 36.3% of forecasted resources (reduced to conditional reserves) [9] (see Fig. 3, 4). This distribution indicates both the utilization of high-grade massive ores and the potential for additional reserves in the form of previously undeveloped disseminated copper-pyrite ores. Due to the depletion of many near-surface copper-pyrite ores, there has been a shift toward developing deep horizons of massive ores and utilizing disseminated ores on the flanks of established deposits.

The majority of copper-pyrite deposits are located in the Ural province, which accounts for over 90% of the ore production of this formation; deposits are also found in the North Caucasus, Karelia, Rudny Altai, Salair, and Eastern Tuva provinces.

The copper-polymetallic formation is essentially a genetic counterpart of the volcanogenic copper-pyrite formation, where the main components are zinc and lead, with copper mineralization as a secondary element [19, 20]. The volume of associated copper production at Russian polymetallic deposits is small, amounting to 12–30 Kt/year (1.1–3.5% of Russian production) and, in 2021, reaching 12.3 Kt (1.1%) (see Fig. 2, 3). According to recorded reserves and resources of copper, the copper-polymetallic formation accounts for 0.9% of balance reserves and 8.3% of forecasted resources, reduced to conditional reserves [9] (see Fig. 3, 4). This imbalance between reserves and resources arises from a critical view of copper as an associated component, which often complicates the enrichment process and may not always be efficient or cost-effective. Consequently, at the geological assessment stage, associated components are accounted for as fully as possible; however, during the exploration and planning of a mining enterprise, these components are often transferred

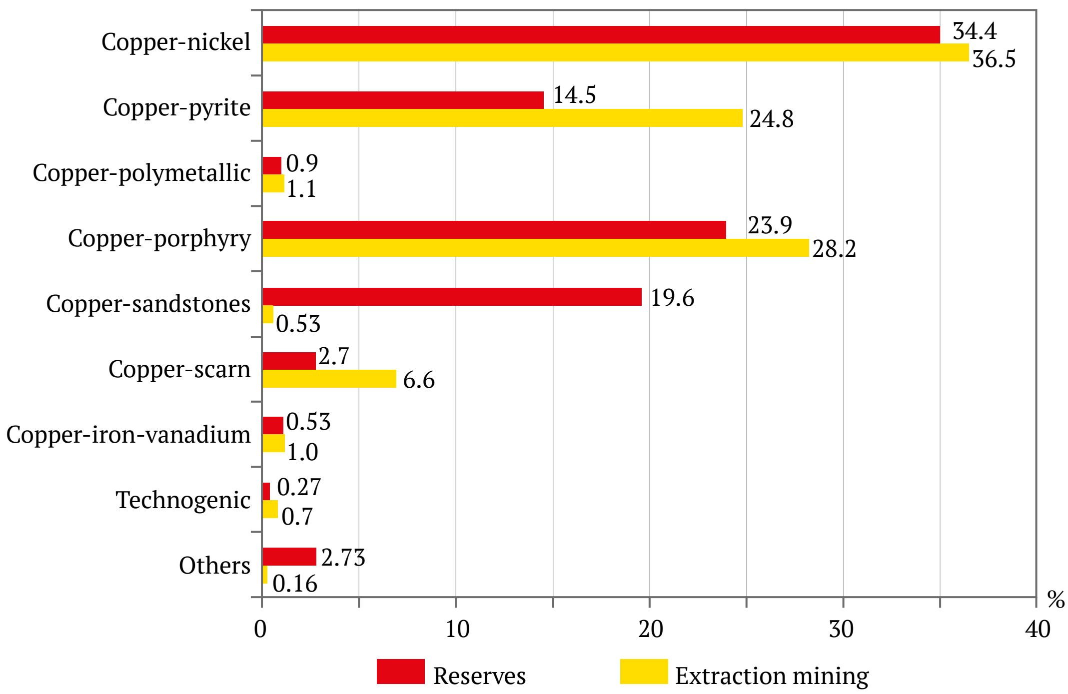


Fig. 3. Shares of copper reserves and production (2021) by copper ore formation types as a percentage of total indicators for the Russian Federation, %

Source: State Reports of the Ministry of Natural Resources (https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/), Information on the state and prospects of mineral resource base in the regions of the Russian Federation (http://atlaspacket.vsegei.ru/?v=msb2021#91474d2e700eb6c90) and Y.V. Alekseev [9]

to off-balance reserves. Copper-polymetallic deposits dominate in the Salair and Rudno-Altai provinces and are also present in the North Caucasus, Karelia, Eastern Tuva, and Okhotsk-Chukotka provinces.

The porphyry copper formation is the undisputed global leader in copper and molybdenum production, as well as in their reserves and forecast resources. Porphyry-type deposits are large-volume bodies of veined- disseminated sulfide copper-molybdenum formations associated with intrusive bodies, often displaying a porphyry texture (the origin of the formation's name) which acts as a substrate for mineralization [21, 22]. Interest in these relatively low-grade, but resource-abundant deposits grew with advancements in enrichment technologies – initially gravity-based, followed by highly effective flotation enrichment of sulfides. As a result, porphyry deposits of copper and molybdenum have become the primary source for the extraction of these metals [23]. In addition to copper and molybdenum, significant volumes of associated components, including Au, Ag, and Re, are extracted from mined ores in deposits of this type. The porphyry copper formation is often interpreted as the Mo–Cu–Au formation [24]. Within the porphyry formation, several ore-forming types are identified: gold-copper-porphyry in basaltoid volcanogenic-plutonic belts (island-arc and riftogenic) and molybdenum-copper-porphyry in andesite volcanogenic-plutonic belts, formed through activation on a substrate of various composition and age [25, 26].

In the Soviet-era joint economy, Russia did not developed its porphyry copper deposits due to sufficient production from the Kounrad (Kazakhstan) and Almalyk (Uzbekistan) GOKs. Nonetheless, porphyry deposits were known in Russia and, where possible, exploited, with ongoing exploration, evaluation, and development of new porphyry copper deposits. According to the recorded reserves and resources, the porphyry copper formation accounts for 23.9% of balance reserves and 32.3% of forecasted resources, reduced to conditional reserves [9] (see Fig. 3, 4). Since 2013, the exploitation of porphyry copper deposits in the Ural province has begun, and by 2021 production from these deposits reached 323 Kt (28.2% of Russian production) (see Fig. 2, 3). A cross-border porphyry copper deposit in the Chelyabinsk Region (bordering Kazakhstan), as well as deposits in the Eastern Tuva and Primorsky provinces, are being prepared for operation. Geological exploration is underway in East Trans-Baikal and northern Okhotsk-Chukotka provinces. Additionally, many areas and within these and other provinces – Kola, Central Arctic, Umlekan-Ogoja, and Kamchatka– show promise for further prospecting and evaluation.

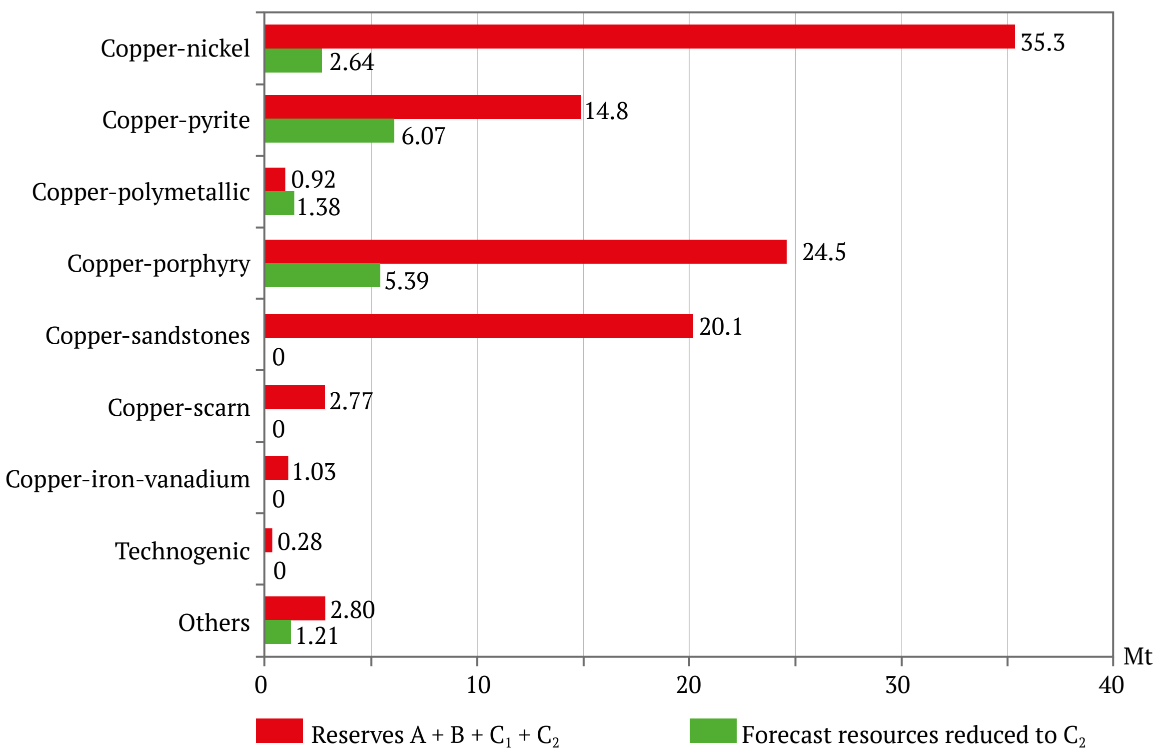


Fig. 4. Volumes of balance reserves and forecast resources of copper by ore formation types as of 2021, million tons

Source: State Reports of the Ministry of Natural Resources (https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/), Information on the state and prospects of mineral resource base in the regions of the Russian Federation (http://atlaspacket.vsegei.ru/?v=msb2021#91474d2e700eb6c90) and Y.V. Alekseev [9]

The copper sandstone formation includes stratiform deposits in sedimentary rocks with copper sulfide formations occurring on geochemical barriers with sources of exhaled copper in seawater or released through leaching of copper-bearing rocks by infiltrated reservoir waters [27, 28, 29, 30]. In terms of production volumes and reserves, the copper sandstone formation ranks second globally after the porphyry copper formation.

In Russia, small copper sandstone deposits were mined in the Pre-Ural province until the mid-19th century. During the USSRs collaborative economy, with the large Dzhezkazgan copper sandstone deposit in Kazakhstan already in operation, exploration in Russia focusede only prospecting and exploration of deposits within this formation. The ultra-large Udokan copper sandstone deposit in the Kadaro-Udokan province, discovered in 1949, was initially located far from well-developed infrastructure in mountainous tundra (before the construction of the Baikal-Amur Mainline). The deposit was not put into operation until 2023, and geological exploration is ongoing in nearby prospective areas. Copper production at the Udokan deposit reached 6.1 Kt in 2021 (0.5% of Russian production), with plans to increase output to 65 Kt (6–7%) by 2027 and, in the future, up to 175 Kt/year (up to 15–17%). According to copper inventory, the copper sandstone formation represents 19.6% of balance reserves, but no officially approved forecast resources are listed for this formation [9]. In addition to the aforementioned provinces, deposits and indications of copper sandstones are also known in the Donetsk, Igarka, Shoria-Khakass, and Bilyakchan-Kolyma provinces.

The copper-skarn formation consists of metasomatic (skarn) deposits at the contact between intrusive rocks (ranging from basic to acidic in composition) with calcareous sedimentary rocks, where newly formed skarns serve as the substrate for overlapping copper mineralization [31, 32]. Copper skarn deposits are typically high in grade but limited in reserves (primarily in the Ural and Shoria-Khakass provinces), and nearly all have been exhausted. Some skarn deposits with associated copper mineralization are still being mined, but their contribution to copper production remains minor (1–2 Kt/year). The copper-iron skarn type has the highest potential, with vein-disseminated cooper mineralization superimposed on on the substrate of iron ore bodies [33]. Exploitation of copper-iron skarn deposits in the East Trans-Baikal province began in 2013, with annual production at these deposits rising from 3 to 94 Kt by 2020, accounting for 8.3% of Russian output (see Fig. 2, 3). New copper-skarn deposits are being prepared for exploitation in the Ural and East Trans-Baikal provinces, while exploration is underway, and new areas are being explored in the Ural, Kadaro-Udokan, and Okhotsk-Chukotka provinces, as well as in regions the established provinces. Based on recorded copper reserves, the copper-skarn formation accounts for 2.7% of balance reserves, though no approved forecast resources are available for this formation [9] (see Fig. 3, 4).

The copper-iron-vanadium magmatic formation in Russia is represented by the unique Volkovsky deposit, which contains complex apatite- and vanadium-bearing titanomagnetite and copper sulfide ores, along with associated gold-palladium mineralization formed during the differentiation and crystallization of the Volkovsky gabbroid massif. This process resulted in lenses of dessiminated sulfide and titanomagnetite mineralization [34]. Copper production at the Volkovskoye deposit ranges from 4–12 Kt/year (0.5–1.1% of Russian production), reaching 12.6 Kt (1.1%) in 2021 (see Fig. 2, 3). Cu–Fe–V magmatic formations are relatively rare, but the Veksha deposit and the Pudozhgorskoye manifestation in the Karelian province, the Kolvitskiy deposit on the Kola Peninsula, and the Pogorelovskoye manifestation in the Chelyabinsk region are similar to the Volkov-type of iron-copper ores. The Cu–Fe–V formation reserves in Russia are small, totaling 1.03 million tons (0.53% of Russian reserves) (see Fig. 3, 4), and there are no forecasted resources of this formation.

The formation of native copper is of interest due the historical significance of the Lake Superior deposit in the USA, a unique, large, and high-grade native copper deposit in amygdaloidal diabases of blanket effusions, which was mined out in the 19th century, producing over 4.5 million tons of copper [35]. The discovery of such high-grade copper deposits has been a goal in many countries, including Russia, though with limited success [36]. Nevertheless, deposits and occurrences of native copper in volcanogenic settings are known in Russia, located of the Ural, Shoria-Khakass, Norilsk-Kharayelakh, and Bilyakchan-Kolyma provinces, with some sizeable deposits such as Taymetskoye (Gornaya Shoria, Kemerovo region) and Arylakhskoye (North of the Krasnoyarsk Territory).

Ore formations with associated copper mineralization include several different types of ore formations, where copper is only a secondary associated component.

The most economically significant among them is *the formation of low-sulfide platinum-metal ores with associated copper-nickel mineralization* in the form of disseminated mineralization within mafic and ultramafic magmatic rocks in orogenic zones, ranging from Archean to Neogene age [13, 37, 38, 39]. Deposits and occurrences of this type are mainly targeted for platinum exploration and are found in the Voronezh, Karelian, Kola, Norilsk-Kharayelakh, Sayan, North Baikal, Jugjur, Okhotsk-Chukotka, Koryak, and Kamchatka provinces. Currently, the balance reserves and forecast resources of the low-sulfide deposits are included within traditional copper-nickel formations.

The quartz-sulfide formation with associated copper mineralization includes genetically diverse ore formations of non-ferrous (tin, tungsten) and precious metals (gold, silver). Copper concentrate is extracted as a by-product at tin [40] and tungsten [41] deposits in the Primorsky Province, as well as at numerous gold deposits [41] outside the known copper provinces.

Copper mineralization may also occur within carbonatite formations, such as the Palabora copper-zirconium-phosphate carbonatite deposit currently under development in South Africa [42]. In Russia, occurrences of carbonatite formations with disseminated copper-sulfide mineralization are known on the Taimyr Peninsula and in the carbonatite massifs of the Maymech-Kotui province.

The technogenic formation results from anthropogenic impact on the subsurface, creating new deposits of technogenic raw materials (e.g., dumps of overburden and substandard ores, tailings and intermediate products storage from processing plants, slag heaps, residues from metallurgical ore conversion, and mineralized mine waters) [43, 44]. Copper extraction from slag is underway at the dumps of the Sredneuralsky copper smelter {No. 140} and the sludge storage at the Cheremshansky facility of the Vysokogorsky mine {No. 141} in Sverdlovsk region (up to 16 Kt/year), as well as from the tailings of the Norilsk processing plant (PP) {No. 142} (up to 1.5 Kt/year)[8], (for the numbering of sites, see Fig. 1). Sabstandard ore dumps of the Allarechensk deposit {No. 143} in Murmansk region [45], slag heaps at the Karabash Copper smelter (CS) {No. 144} in Chelyabinsk region, and residues at the Kirovgrad CS {No. 145} in Sverdlovsk Region [43], and dumps at the Solnechniy PP {No. 146} in Khabarovsk Territory are being prepared for operation[9]. The potential for dump mining is also being evaluated for the Krasnouralsky concentrating plant (CP) {No. 147} in Sverdlovsk region, the dumps of the Loktevskiy Silver Smelting Plant {No. 148} in Altai Territory, as well as dumps of the Tuim CP {No. 149} and Mainsky CP {No. 150} in Khakassia. Estimated copper reserves in technogenic deposits in Russia total 270 Kt, with an annual production of 8–16 Kt/year (0.7–1.9% of Russian production), reaching 8.5 Kt (0.7%) in 2021 (see Fig. 3, 4). Resources of technogenic deposits are undervalued due to limited exploration at tailings dumps of processing plants (only 4 out of 36 operating and closed PP) and limited surveys at individual substandard ore dumps in developed and mothballed deposits [46].

Copper provinces

The North Caucasian province includes volcanogenic-sedimentary structures of the Peredovoy Ridge and Privodorazdelnaya Area along the border of the Scythian Platform and folded rock of the Great Caucasus. Numerous *copper-pyrite deposits* found here. Since the 1950s, the Urupskoye deposit {No. 12} [47] has been mined, though now significantly depleted, with production in 2021 reached 5.4 Kt. The Khudesskoye, Skalistoye, and Pervomaiskoye deposits {No. 44} are being prepared for exploitation, with over 100 ore occurrences recorded. The Kizil-Dere deposit {No. 40}, with copper reserves of 1.17 Mt of 100% at an average grade of 2.14% Cu, has been explored and is held in reserve [48]. Altogether, the North Caucasus province accounts for 2.23 million tons of balance copper reserves (2.17% of Russian reserves), with an annual production of 5.4 Kt (0.47% of Russian production) in 2021 (see Fig. 5, 6).

The Donetsk province contains copper sandstone deposits of the Kartamyshinsky formation from the Lower Permian within the Dnieper-Donetsk trough on the East European platform. Copper mining in this area dates back to the Bronze Age (e.g., Kartamyshskoye, Vyskrivka, Pilipchatino) and continued into the 19th century [49]. promising areas for the discovery of significant copper sandstone deposits include the Bakhmutskaya ({No. 71}, with 28 occurrences) and Kalmius-Toretskaya (with 3 occurrences) [50]. In the 1960s, the «Artemgeologia» searched for mineralized zones in the Kartamyshinsky syncline, identificating copper-rich layers (e.g., Berestyanskoye, Sour Hill), along with indications of copper, lead, and zinc mineralization (e.g., Serebryanskoye, Sukhodolskoye, Odnobokovskoye) [51]. The Donetsk province represents only a portion of copper sandstone distribution along the periphery of the Ukrainian shield, extending to the Pridobrudzhsky trough in the west [52].

[8] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[9] I bid.

The Voronezh province includes the well-known Voronezh Crystalline Massif (VCM), where deposits and occurrences of *sulfide platinum-copper-nickel ores of the Elan type* (e.g., Elan and Elkinskoye deposits, as well as over 20 ore occurrences) are found. These are genetically related to norites of the subvolcanic orthopyroxenite-norite-diorite formation, and the *Mamon type* (e.g., Nizhnemamonskoye, Podkolodnovskoye deposits, Jubilee, with numerous occurrences in the Nizhnemamonsky and Anninsky ore districts), associated with ultramafic dunite-peridotite-pyroxenite-gabbronorite formations [53]. The Elan and Elkinskoye PGE-copper-nickel deposits {No. 45} are the most prepared for exploitation, with copper reserves of 58.8 and 17.3 Kt, respectively. However, despite favorable conditions, a significant obstacle to their development is the potential alienation of fertile lands and the proximity of protected areas. Balance copper reserves in the Voronezh Province are recorded at 0.08 Mt (0.08% of Russian reserves) (see Fig. 5, 6).

The Karelian province is situated in the eastern part of the Fennoscandian Shield. Copper mining in this region dates back to the 18th century, when small copper-pyrite deposits were mined (Voitskoe, Voronovoborskoe, Pyalozerskoe mines, etc.), with further development continuing into the 19th century. Geological studies, have since identified deposits of various ore formations. Known deposits *of the copper-pyrite ore formation include those* in the Central Karelian (Vedlozerskoe, Hautavaarskoye, Chalkinskoye, etc.), Sumozersko-Vygozerskaya (Parandovskoye), and West Karelian (Yalonvaarskoye) mineragenic zones. The province also hosts *copper-nickel sulfide ultramafic-mafic formation*, including the Vostochno-Vozhminskoye deposit (associated with theVozhminskoye ultrabasite massif) and the Lebyazhin deposit (within the Kumbuksin ultramafic massif), as well as komatiite formations (Zolotoporozhskoye, Leshchevskoye, Rybozerskoye occurrences in the basalt and komatiite sequences of the Sumozero-Kenozero greenstone belt). Additionally, deposits of *the copper-molybdenum-porphyry formation* (Lobash, Pyayavaara, Yalonvara), *the low-sulfide platinum-metal-titanium-vanadium formation* in the Koikar-Svyatnavolok mineragenic zone (Viksha deposit in the Koikar gabbro-dolerite sill), and the copper sandstone formation (the mined-out Voronov Bor deposit and other occurrences) are present [54]. Exploration work has been conducted at the Viksha {No. 65} [55] and Lobash-1 {No. 66} [56] deposits, with cooper reserves of 125 and 56.4 Kt, respectively. Additionally, over 50 copper-nickel occurrences were recorded in the southeastern part of

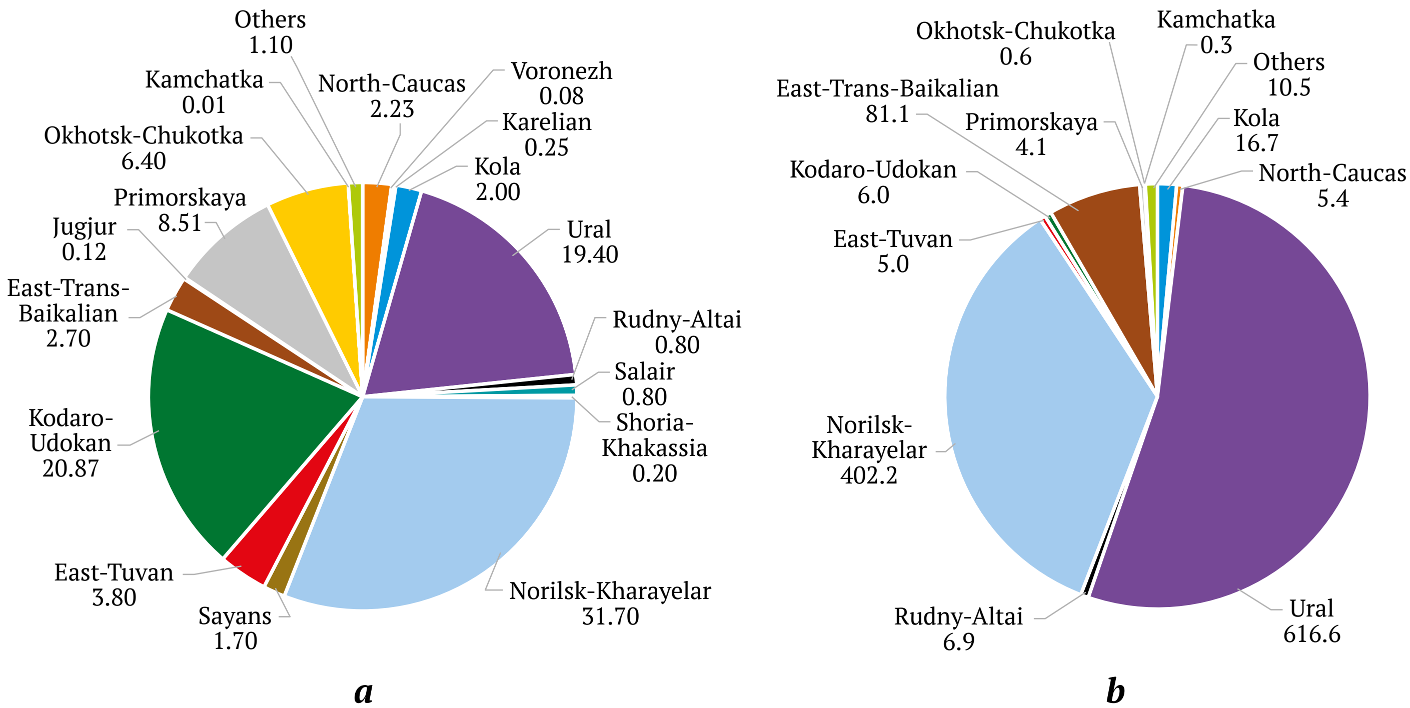


Fig. 5. Cooper reserves, million tons – *a*, and annual production, Kt – *b* by province as of 2021

Source: State Reports of the Ministry of Natural Resources (https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/), Information on the state and prospects of mineral resource base in the regions of the Russian Federation (http://atlaspacket.vsegei.ru/?v=msb2021#91474d2e700eb6c90) and Y.V. Alekseev [9]

the province, specifically in the Astrakhan region. However, prospecting efforts have primarily focused on two massifs within the Kamennoozersky kamatiite complex, associated with the Voloshovskoye copper-nickel deposit {No. 72}, where drilling evealed disseminated sulfide mineralization was uncovered, resources of 277 Kt of copper were calculated with an average content of 0.15% Cu [57]. 0.25 Mt of balance reserves of copper (0.24% of Russian reserves) were calculated for the Karelian province, see Fig. 5, 6.

The Kola province is situated in the northern part of the Fennoscandian Shield. Within the riftogenic Pechenga-Imandra-Varzug greenstone belt, numerous Paleoproterozoic stratified intrusions are present, including several ore-bearing (PGE–Cu–Ni) intrusions that are part of the Pechenga, Monchegorsk, and Fedorovo-Panskiy ore districts. These areas contain deposits of *copper-nickel sulfide ore formations* and *low-sulfide platinum-metal ores with associated copper-nickel mineralization* [58].

In *the Pechenga ore district*, two main ore nodes are recognized, featuring deposits of the stratified sulfide copper-nickel formation of mafic and ultramafic rocks [59]: the Western Node (Kotselvaara-Kammikivi and Semiletka deposits) and the Eastern Node (Zhdanovskoye, Zapolyarnoye, Bystrinskoye [Cu–Ni],

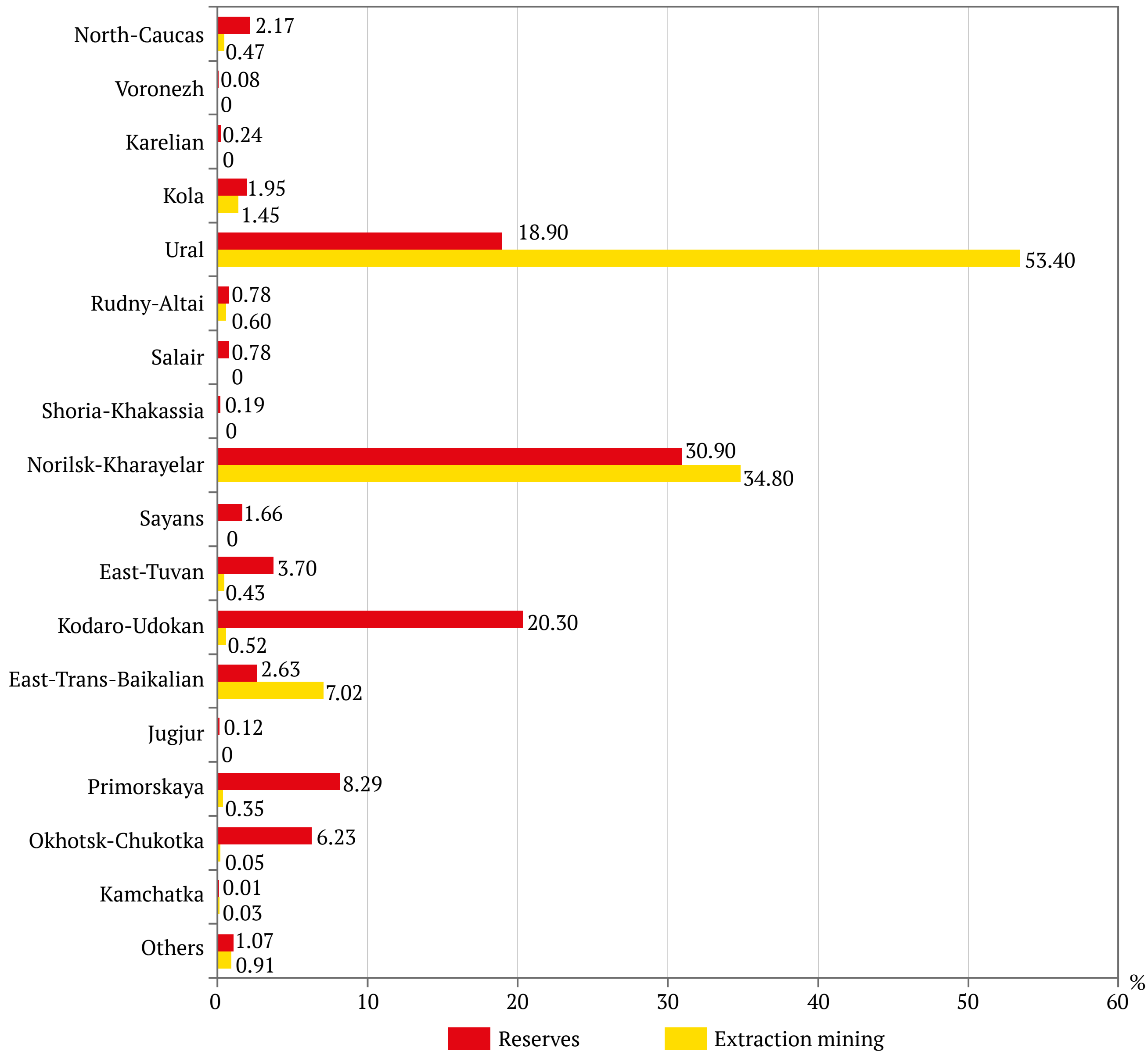


Fig. 6. Share of copper reserves and production by provinces (as of 2021) from total figures for the Russian Federation. No reserves and production recorded in Donetsk, Pre-Ural, Central Arctic, and Bilyakchan-Kolyma provinces

Source: State Reports of the Ministry of Natural Resources (https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/), Information on the state and prospects of mineral resource base in the regions of the Russian Federation (http://atlaspacket.vsegei.ru/?v=msb2021#91474d2e700eb6c90)

Tundra, Sputnik, and Verkhnoye). Mining of the Western Node deposits began in the 1930s, with the Eastern Node following in the 1960s. Nowdays, richest copper-nickel ores reserves at Kotselvaara-Kammikivi, Semiletka, Tundra, and Zapolyarnoye have been depleted and preserved. Currently, the Zhdanovskoye deposit, containing disseminated copper-nickel ores with reserves of 840.5 Kt at an average grade of 0.31% Cu, is under active development, while the Bystrinskoye, Sputnik, and Verkhneye deposits are being prepared for exploitation.

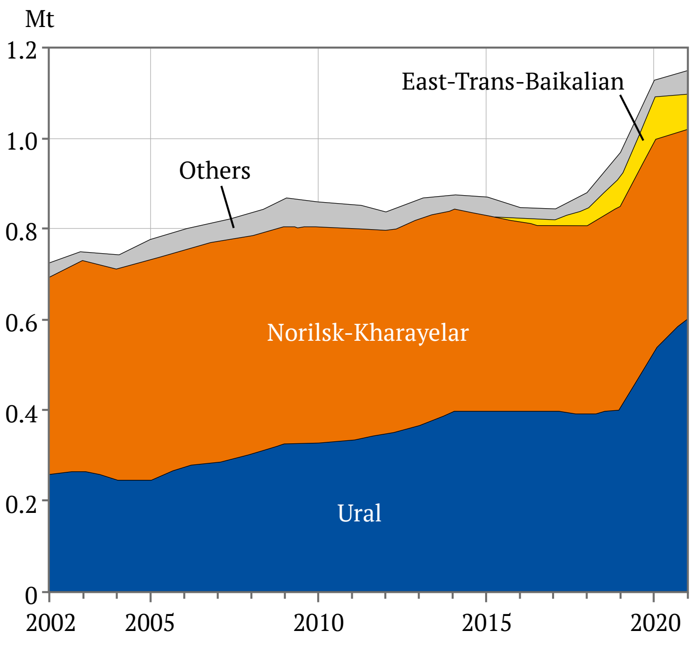
The Monchegorsk ore district, with deposits and occurrences known since the 1930s, contains both sulfide cooper-nickel ores and low-sulfide platinum-metal ores (PGM) with minor copper-nickel mineralization [60]. Major sulfide copper-nickel deposits here include Poaz (443 Kt, average grade of 0.13% Cu), Nyud (188 Kt, 0.24% Cu) {No. 75}, Nittis-Kumuzhya-Travyanaya (229 Kt, 0.16% Cu), Sopcha (ore horizon 330) (109 Kt, 0.23% Cu) {No. 76}, Arvarench (246 Kt, 0.26% Cu), and Moroshkovoye-Ozero (172 Kt, 0.20% Cu) {No. 77}. Notable low-sulfide platinum-metal deposits with minor copper-nickel mineralization include Loypishnyun [61], Yuzhnaya Sopcha, and Wuruchuaiwench, each containing 30–50 Kt of copper resources.

The Fedorovo-Panskiy ore district {No. 78} is primarily known for low-sulfide platinum-metal ores with minor copper-nickel mineralization. Deposits in this district, such as Fedorovotundra and Kievey [62] and Eastern Chuavry [63], were initially evaluated for platinum group metals, with copper and nickel as secondary components. These deposits represent reef horizons in stratified mafic rocks.

Among other copper ore formations in the Kola province, the Pellapakhk deposit {No. 74} contains *copper-molybdenum-porphyry ores* of 203 Kt at 0.15% Cu and has been deemed economically viable [64]. Additionally, the Kolvitskoye deposit {No. 73} represents the *copper-iron-vanadium magmatic formation* [65].

Altogether, the Kola province holds 2.0 million tons of copper reserves (1.95% of Russia's reserves), with an annual production in 2021 of 16.7 Kt (1.48% of Russian production) (see Fig. 5, 6).

The Pre-Ural province lies within the Pre-Ural foreland basin of the East European Platform, where numerous deposits and occurrences of *copper sandstones formations are present within* the Upper Permian strata of the Ufa, Kazan, and Tatar Stages [66]. These formations have been mined since the Bronze Age until the mid-19th century. Archaeological data indicate that over 500 sites with copper sandstone deposits were under development in this region [67]. Due to their small size and limited reserves, these copper sandstone occurrences are not attractive for traditional open-pit mining methods but hold significant potential for geotechnological methods of underground copper leaching [68].



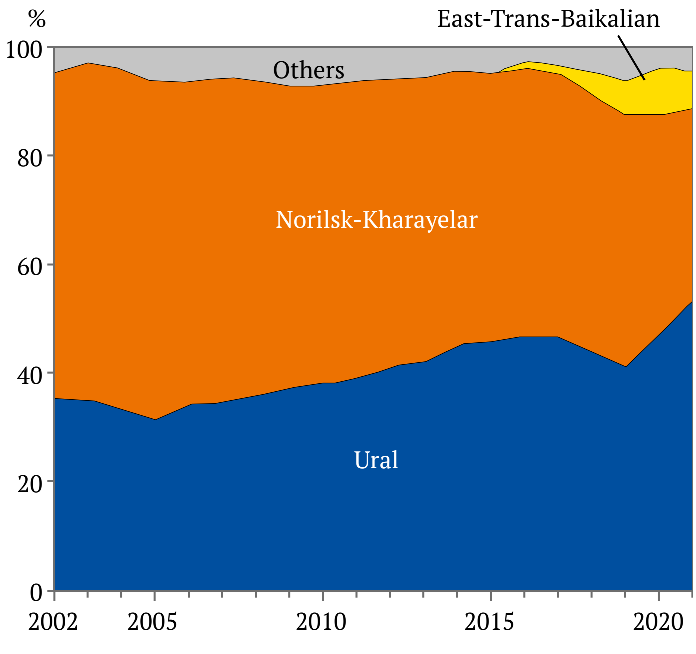


Fig. 7. Dynamics of copper production in Russia (2002-2021) by ore provinces: *a* – production volumes, million tons; *b* – percentage shares of total production in the Russian Federation, %

Source: Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

The Ural province is located within the Ural Orogenic System and contains hundreds of deposits and occurrences of copper-pyrite, copper-porphyry, copper-skarn, vanadium-bearing copper-iron magmatic formations, as well as formations of copper sandstone and native copper [69]. The Ural province holds 19.4 million tons of prepared copper reserves (18.9% of Russian reserves), with 707 Kt of copper extracted, or 52.5% of national production (see Fig. 5, 6). There is a trend toward toward increasing production over time, raising the Ural province's share in Russia's cooper output (see Fig. 7). In addition, Ural plants process up to 490 Kt/year of copper concentrate imported from Kazakhstan[10].

Copper-skarn deposits were among the earliest targets of development Ural mining region, including those of the Turyinsky group, which are now depleted [70], as well as the Gumeshevskoye [71] and Mednorudnyanskoye deposits [72] {No. 7}. These deposits, though small in size and reserves, were highly attractive due to rich ore and the secondary enrichment zones developed along them. Currently, new copper-skarn deposits are being prepared for development, including the Severnoye-3 deposit {No. 55}. The Novogodnee-Monto gold-iron skarn deposit {No. 84} in the Polar Urals is also being evaluated for its copper mineralization [73]. At the Gumeshevskiy copper-skarn deposit {No. 39}, redeposited oxidized copper ores in loose karst sediments, known as "copper clays", have been identified as a separate industrial type [74]. Since 2004, these ores have been extracted via underground copper leaching, with annual production of 1.0–3.5 Kt/year [75] and with estimated resources of 455 Kt [9].

Copper-pyrite deposits are widespread in the Paleozoic paleovolcanic belts (Shchuchinsko-Tagilskiy, Sakmarskiy or Krakinsko-Mednogorskiy, West and East Magnitogorsk, Kamenskiy, Kateninskiy, Oktyabrsko-Denisovskiy, and Irgizskiy) and zones (Bolshakovsko-Reftinskaya, Birgildinsko-Polyanovskaya, Kolpakovskaya, Elenovsko-Kumakskaya, Buryktalsko-Kundybaevskaya) of the Southern and Middle Urals [69]. Copper-pyrite deposits have been a traditional cooper source for mining enterprises in these regions for many decades [76]. Many deposits are now decommissioned or mothballed, including Dergamyshskoye {No. 3}, Sibayskoye {No. 4}, Uchalinskoye {No. 5}, Aleksandrinskoye {No. 6}, and Tarnyerskoye {No. 8}. Active development continues at the Gayskoye deposit {No. 14} I4.37 Mt of reserves at 1.32% Cu, producting 93 Kt of Cu in 2021) [77], as well as Osennee {No. 15}, Vesenne-Aralchinskoye, Dzhusinskoye {No. 16}, Novo-Sibayskoye, and Yubileynoye {No. 17} (1.24 Mt at 1.65% Cu, 22 Kt in 2021) [78]. Other active deposits include Kamaganskoye, Ozernoye, and Zapadno-Ozernoye {No. 19} (373 Kt, producing 11 Kt in 2021) [79], Talganskoye, Uzelginskoye, Molodezhnoye, Chebachye, and Novo-Shemurskoye[11]. The Podolskoye and Severo-Podolskoye copper-pyrite deposits are being prepared for development {No. 47}, along with Vishnevskoye {No. 48}, Novo-Uchalinskoye {No. 49} (1.09 Mt at 0.98% Cu) [80], Sultanovskoye {No. 50} (67 Kt at 3.25% Cu), Maukskoye {No. 51} (47 Kt at 1.58% Cu), Tarutinskoye {No. 52} (64 Kt at 1.33% Cu), Saumskoye {No. 53} (21 Kt at 2.78% Cu), and Severo-Kaluginskoye[12]. The Komsomolskoye copper-pyrite deposit {No. 41}, with reserves of 504 Kt at 1.78% Cu), is held in the Reserve Fund. Prospecting for copper-pyrite deposits is ongoing in the promising Blyavinskaya {No. 80}, Membetovskaya-Karagayskaya (520 Kt of resources), and Novopetrovskaya {No. 81} areas of the Southern and Middle Urals[13], as well as in the Circumpolar Urals (Volinskiy and Grubeinsko-Tykotlovskiy ore districts) {No. 82} [81].

The second most significant *formation* in the Ural province is *the porphyry copper formation*, represented by deposits within the North Sosvinskiy, Volinskiy, and Grubeinsko-Tykotlovskiy volcanic belts of the Southern Urals, prinarily in its eastern part [82]. Key copper-porphyry deposits include Tominskoye {No. 22} with reserves of 3.85 Mt at an average grade of 0.34% Cu, producting 212 Kt of Cu in 2021, and Mikheevskoye {No. 23} with reserves of 1.8 Mt at 0.37% Cu, producing103 Kt in 2021) copper-porphyry deposits [83]. Appraisal work is ongoing at the Birgildinsky, Zapadny, and Tarutinsky sites near the Tominskiy deposit. Copper-porphyry occurrences within the North Irendyk, Verkhneuralskaya, Dombarovsko-Aschebutakskaya [84], and Alapaevsko-Sukholozhskaya [85] metallogenic zones of the Middle Urals also require further assessment.

The unique Volkovsky deposit {No. 26}, an igneous *copper-iron ore formation containing* vanadium [86], is also located in the Ural province, with reserves of 805 Kt at an average grade of 0.63% Cu, producting 13 Kt of Cu in 2021. Many occurrences of the igneous copper-iron ore vanadium formation exhibit transitional characteristics toward copper-skarn formations of similar composition.

[10] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[11] I bid.

[12] I bid.

[13] I bid.

In the Circumpolar region of the Ural province, within the Lyapinskiy mineragenic zone, there are *occurrences of copper sandstone formations*, including stratiform hydrosluidic copper sandstones (Musyurskoye, Kosyunskoye, and Tesninoye) and polymetallic sandstones (Kozhimskoye) [87].

In the Northern Urals, occurrences of *native copper formation* are known in the Khultymya mineralized zone, associated with amygdaloidal olivine basalts and their ash tuffs in the Tournaisian Stage volcanics of the Lower Carbonierous [88].

The Rudny Altai province within the Russian Federation is part of a larger polymetallic province of the same name, with the main and most significant deposits located in Kazakhstan (Kolba-Narym metallogenic region). However, numerous deposits and occurrences of the *polymetallic pyrite formation*, including copper components, are found within the Russian part of the Rudny Altai province. Like the Ural province, Rudny Altai is an orogenic structure formed by arc magmatism, characterized by basaltoid formatons in the Urals and rhyolite formations in the Altai, resulting in distinct metallogenic specialization – copper-zinc in the Urals and copper-polymetallic in the Altai [20].

Polymetallic deposits in the Zmeinogorsk ore district have been exploited since the Bronze Age, with industrial development starting at the Zmeinogorskiy deposit in the 18th century. While the Zmeinogorskoye deposit is now depleted, the Karabalikhinskoye pyrite-polymetallic deposit {No. 27}, with cooper reserves of 316 Kt at an average grade of of 1.5% Cu, remains active, producting 6.3 Kt in 2021. Other polymetallic deposits with associated copper mineralization, such as Zarechenskoye (Cu 3.1 Kt, 0.17% Cu) {No. 27} and Stepnoye {No. 28} (25 Kt, 1.18% Cu), are also in operation. The Talovskoye copper-polymetallic deposit {No. 56} is being prepared for exploitation, while exploration continues in the Ural province at the promising Novonikolskaya (resources of 91 Kt) {No. 85} and Kholodnaya (resources of 82 Kt) {No. 86} sites with potential to expand search areas within the Altai Republic. The Rudny Altai province has 0.8 million tons of balance copper reserves (0.78% of Russian reserves), with annual production in 2021 totaling 6.9 Kt (0.6% of Russian production) (see Fig. 5, 6).

The Salair province corresponds to the Salair mineragenic zone, an orogenic arc structure with basalt-andesite-rhyolite magmatism from the Salair phase of folding, featuring numerous pyrite-polymetallic deposits [89]. This historical mining area has been exploited since the early 19th century, though active mining has since ceased. The Kamenushinskiy copper-polymetallic deposit is preserved, and the province still contains various *copper-pyrite polymetallic occurrences* (Uskandinskoye, Prichumyshskaya group), including those overlain by the sedimentory cover of the West Siberian Plate. Copper reserves in the Salair province amount to 0.8 million tons (0.78% of Russian reserves)[14] (see Figs. 5, 6).

The Shoria-Khakass province is located in the southern part of the Kuznetsk Alatau orogenic within the Mrassko-Batenev anticlinorium structural-formational zone. This area features thick deposits of Riphean-Cambrian-Ordovician age enriched with volcanic rocks of the basalt-andesite-trachyte-liparite group, formed during Early Paleozoic diorite and plagiogranite magmatism of the Salair or Early Caledonian tectogenesis cycle [90]. Deposits and occurrences of copper-skarn, copper-porphyry formations, and formations of native copper and copper sandstones are present here. *Copper-molybdenum-skarn* deposits are associated with Early Paleozoic granitoids, the largest of which – Kiyalykh-Uzen, Glafirinskoye [91], and Julia [92] {No. 11} – have now been mined out. The Malo-Labyshskoye deposit {No. 91} belongs to the *copper-molybdenum-porphyry formation*, with cooper resources 264 Kt at 0.12% Cu [93]. Mauntain Shoria is home Russia's largest *native copper deposit*, Taymetskoye {No. 90}, with copper resources totaling 1.57 million tons at an average grade of 0.76% Cu [94]. In Khakassia, occurrences of *copper sandstone formations*, such as Bazinskoye and Kharajulskoye, are also recorded. The Shoria-Khakass province contains 0.2 million tons of cooper reserves[15].

The Central Arctic province encompasses the relatively unexplored areas of the Taimyr Peninsula and the Severnaya Zemlya islands. This province was identified through geological surveys, which recorded occurrences and deposits of the *copper-porphyry formation* within the Central Arctic gold-bearing Late Paleozoic-Early Mesozoic copper-molybdenum-porphyry belt [95]. Numerous copper-molybdenum occurrences have been documented here, with the most promising being Uboininskoye {No. 92}, Verkhnetareyskoye {No. 93}, and Porphyrovoye {No. 94}, with the province's potential copper resources estimated at 2.5 million tons [95].

[14] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[15] I bid.

The Norilsk-Kharaelakh province, located in the far northwest of the Dorifeian Siberian Platform near the pericratonal Yenisei-Khatanga Trough [96], host unique copper-nickel deposits with substantial reserves and high quality. The province also contains copper-porphyry and native copper deposits. This area holds 30.9% of Russia's copper reserves (31.7 million tons) and accounts for 34.8% of Russian copper production (402 Kt), (see Fig. 5, 6). However, due to increasing production in the Ural and East Trans-Baikal province, the share of copper production in the Norilsk-Kharayelakh province within Russia's overall production balance is gradually decreasing (see Fig. 7).

The unique Norilsk *copper-nickel* deposits are products of Mesozoic trappean activity in the pericratonic cover of the Siberian Platform [13]. Key deposits include Oktyabrskoye {No. 30}, with reserves of 18.34 Mt of Cu at an average grade of 1.61% Cu, producting 273 Kt in 2021; Talnakhskoye {No. 31}, with reserves of 9.90 Mt at 1.09% Cu, producing 121 Kt in 2021); and Norilsk-1 {No. 32} with reserves of 2.57 Mt at 0.47% Cu, producing 9 Kt in 2021. Additional deposits, Maslovskoye {No. 57} with reserves of 1.10 Mt at 0.53% Cu [97] and Chernogorskoye {No. 58} with 400 Kt, at 0.29% Cu [98], are being prepared for development. Exploration is underway in the promising Morongovskaya {No. 96} and Samoyedovskaya {No. 99} areas[16], and further discoveries of copper-nickel deposits in the Kharaelakh depression, where some deposits may be concealed at depth [99, 100].

In the 1960s, the Bolgokhtokhskoe deposit, a porphyry copper formation with cooper resources of 462 Kt at 0.27% Cu, was discovered on the western flank of the Norilsk-Kharayelakh province [101].

In the 1970s, *native copper deposits* were identified in the North Kharayelakh ore zone, with prospecting conducted at the Arylakhskoye deposit {No. 98} with cooper resources of 600 Kt at 0.41% Cu [102].

The Igarka province is notable for *copper sandstone formations found* in the sediments of the Gravian Vendian formation and the Sukharikhinskaya Vendian – Lower Cambrian formation, located in the horst of the Igarka baykalid uplift in the northwest of the Siberian Platform [103]. In the 1970s, Graviyskoye {No. 100} deposit, with cooper resources of 359 Kt at 2.42% Cu, and Sukharikhinskoye {No. 101}, with 120 Kt at 1.08% Cu, discovered and preliminarily assessed within this cratonic area [104].

The Sayan province lies in the southwestern part of the Siberian Platform, where serpentinized ultrabasic rocks of the gabbro-peridotite-dunite magmatic formation, bearing disseminated platinum-copper-nickel mineralization, are found within Early Proterozoic metamorphites of the Karagan series along the western periphery of the Kansk block [13]. The Kingashskoye {No. 59}, with cooper reserves of 1.1 Mt at 0.17% Cu [105], and Verkhnekingashskoye {No. 60}, with 632 Kt at 0.24% Cu [106], are being prepared for development. Further copper-nickel deposits may be found in the adjacent areas surrounding the Kingash massif, including the promising Kakhtarminskaya {No. 102}, Berezovskaya, Erminskaya, and Agulskaya sites [107]. The Sayan province has recorded copper reserves of 1.7 million tons, or 1.66% of Russian reserves[17] (see Fig. 5, 6).

The Eastern Tuvan province encompasses early Caledonian (Salair) and Baikalian rocks of the Tuvan-Mongolian massif and East Sayan rigid block. Within these areas, metal-bearing volcanic-plutonic complexes from the Cambrian-Devonian period host numerous copper occurrences across the Aksug-Kandat, Khamsarin, Ozhinsko-Derzyg, Balyktyghem-Bilinsky, East Tannuol, Central Sayan, Khemchik, and Mongun-Taiga metallogenic zones [108]. The Ak-Sugskoye deposit {No. 61}, a *copper-porphyry formation* with cooper reserves of 3.63 Mt at 0.67% Cu, is being prepared for operation [109]. Other copper-porphyry sites include Kyzyk-Chadrskoye deposit {No. 103} with reserves of 2.35 Mt at 0.29% Cu) [110], and the Kyzyl-Tashtyg deposit {No. 33}, *pyrite-polymetallic formation with associated copper mineralization*, which is already operational with reserves of 37 Kt at 0.65% Cu [111]. The Eastern Tuva province has recorded cooper reserves of 3.8 million tons, accounting for 3.7% of Russian reserves[18] (see Fig. 5, 6).

The North Baikal province is situated in the southeastern folded margin of the Siberian Platform, where rift-related dunite-troktolite-gabbro intrusions (Yoko-Dovyrenskiy, Avkitskiy, Chayskiy, Hasan-Dyakitskiy, and Nyurundukan) with platinum-copper-nickel mineralization formed within the Riphean Baikal-Muya island arc [112]. Since the 1980s, studies have been conducted on the *PGE-copper-nickel* deposits and occurrences within this

[16] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[17] I bid.

[18] I bid.

province. The most researched sites are Yoko-Dovyrenskoye {No. 104}, with 51 Kt of copper resources, and Chayskoye {No. 105}, with resources of 260 Kt at 0.18% Cu [112, 113, 114].

The Kodar-Udokan province is located in the marginal Udokan trough in the southern Siberian Platform, comprising Early Proterozoic carbonate-terrigenous deposits of the Udokan series, which include *copper sandston formations* [115]. The largest deposit in Russia, the Urdocan copper sandstone deposit {No. 34}, was commissioned in 2023 with reserves of 20.09 Mt at an average grade of 1.44% Cu, and produced 6 Kt of cooper inpilot operations in 2021. Additional promising sites in the Udokan basin include Burpalinskoye {No. 108} with 739 Kt at 1.17% Cu, Pravoingamakitskoye {No. 110} with 608 Kt at 0.88% Cu [117], Sakinskoye {No. 109} with 404 Kt at 0.98% Cu [118], Unkurskoe {No. 106} with 320 Kt at 0.57% Cu) [119], and Krasnoe {No. 107} with 933 Kt at 1.81% Cu [120]. On the northeastern flank of the Kodar-Udokan province is the Chinaian gabbro-norite massif of Late Proterozoic age, which intrudes the Early Proterozoic carbonate-terrigenous deposits of the Udokan series. In its middle stratified part, it includes mineralization of the *copper-skar formation* (noble metal-copper-sulfide) within the Rudny area of the Chineyskoye deposit {No. 67}, with cooper reserves of 775 Kt at an average grade of 0.52% Cu [121]. The resource potential of this formation could be further expanded by copper ore occurrences in the adjacentLukturskу and Mailava massifs of the Chiney complex [118].

In total, in the Kodar-Udokan province has recorded balance copper reserves of 20.87 million tons (20.3% of Russian reserves), with annual pilot production in 2021 amounted to 6.0 Kt, or 0.52% of Russian output (see Fig. 5, 6).

The East Trans-Baikal province is rich in multimetal deposits and occurrences of Mo, W, Sn, Au, Cu, Bi, Pb, Zn, As, Sb, Hg, U, rare, and rare earth elements, located within the stagnant oceanic slab of the Dalainor-Gazimuro-Olekminsky mineragenic zone, formed from the Aalenian (J2) to Cenomanian (K2) [122]. Copper deposits in this province are represented by copper-iron ore-skarn and copper-porphyry formations. The Bystrinskoye [Cu-Fe] deposit {No. 35}, of the *copper-iron-skarn formation*, is currently under development with cooper reserves of 2.04 Mt at an average grade of 0.74% Cu, producting 79 Kt in 2021 [123]. Another deposit in this formation, the Kultuminskoye site {No. 62}, is being prepared for operation with reserve of 587 Kt at 0.91% Cu [124]. Geological exploration is ongoing on the periphery of this site, specifically at the Ochunogdinsky, Preobrazhensky, and Engineering sites, with cooper resources of 487 Kt. The explored Lukagonskoye deposit {No. 68} is a complex structure, where the upper section shows classical copper-skarn mineralization [125], which transitions at depth to typical *copper-porphyry formation* mineralization [126], with cooper reserves of 604 Kt at 0.40% Cu [127]. To expand the resource base of the Bystrinsky GOK, exploration is also underway at the Zapadno-Mostovskaya {No. 111} and Borovaya {No. 112} promising sites for copper-porphyry formations. There are also favorable conditions for identifying copper-porphyry deposits within the Uronai ore node and in the Gazimuro-Zavodsky, Mogochinsky, and Verkhne-Olekminsky ore regions of the East Trans-Baikal province. The recorded copper reserves in this province total 2.7 million tons (2.63% of Russian reserves), with production in 2021 reaching 81.1 Kt (7.0% of Russian production)[19] (see Fig. 5, 6).

The Umlekan-Ogoja province encompasses the volcanic-plutonic belt of the same name in the Amur region [128], featuring Late Mesozoic basalt-andesite volcanic rocks and gabbro-diorite plagiogranitic plutonic formations with copper-porphyry mineralization [129]. In the central part of this province, the Ikanskoye deposit {No. 43} is in reserve as a *porphyry-copper formation* with cooper reserves of 459 Kt at an average grade of 0.21% Cu, along with nearby occurrences at Borgulikan and Eastern Double [130]. The Umlekan-Ogoja province has a recorded total of 0.8 million tons of copper reserves[20].

The Primorsky Province, like the Trans-Baikal province, contains abundant multimetal deposits and occurrences of Sn, W, Au, Mo, Cu, Pb, Zn, rare elements, and other minerals, spanning a wide geological timeframe from the Paleozoic to the Meso-Cenozoic. This province is part of the Pacific Ore Belt [131]. Copper deposits are here represented by the porphyry-copper formation and deposits with associated copper mineralization. Sites under development *include* Pravourmiyskoye (Cu reserves of 37.2 Kt), Festivalnoye (124.5 Kt), Sable (53.6 Kt), and Perevalnoye (25.1 Kt) tin ore deposits {No. 36}, which produced 916 t of cooper in 2021 [132], and the Vostok-2 tungsten deposit {No. 37} with 7.3 Kt of cooper [133]. The Malmyzh deposit {No. 64}, a *copper-molybdenum-porphyry formation* with coper

[19] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[20] I bid.

reserves of 8.31 Mt at an average grade of 0.35% Cu, located in the northern part of the Zhuravlevo-Amur terrane of the Early Cretaceous Sikhote-Alinsky orogenic belt, is being prepared for operation [134]. There is potential for identifying copper-porphyry deposits within the Central Anajak {No. 116} area, with cooper resources of 800 Kt, and the Ponyskaya {No. 117} area, with 714 Kt) of cooper, both adjacent to the Malmyzh field [135]. Additionally, the Lazurnoe {No. 114} deposit, with187 Kt at 0.48% Cu [136, 137], and the Malakhitovoe {No. 115} deposit, with 1.94 Mt at 0.30% Cu [138], are located in the southern part of the Zhuravlevo-Amur terrane [139]. The recorded copper reserves in the Primorsky Province total 8.51 million tons (8.29% of Russian reserves), with production in 2021 reaching 4.1 Kt (0.35% of Russian output)[21] (see Fig. 5, 6).

The Jugjur province is located on the eastern flank of the Dzhugdzhur-Stanovy mobile belt, formed through Proterozoic and Mesozoic tectonic activities [140]. This belt contains deposits of copper-nickel, copper-skarn and low-sulfide formation with associated copper mineralization.

The Kuhn-Manye deposit {No. 63} of the *PGE-copper-nickel formation* is the most advanced for development, with reserves of 31.5 Kt at an average grade of 0.21% Cu [141]. At the eastern end of the province lies the Nyandominskaya perspective area {No. 118} within the Early Archean gabbro-anartosite of the Lanthar section of the Dzhugdzhur anorthosite massif [142], where PGE–Cu–Ni occurrences such as Batomg and Nyandomi, as well as PGE–Cu occurrences like Skeletal and Mukdakindya, have been recorded. The Nyandoninsky area is estimated to hold cooper resources totaling 235 Kt.

The Konder magmatic massif, located in the western part of the Jugjur province, is a complex, multi-age structure with a Proterozoic dunite core surrounded by a Mesozoic syenite ring intrusion. The dunites hosts known schlieren PGE-chromite mineralization, along with fields of Late Cretaceous alkaline pegmatites, where sulfide copper mineralization enriched with platinoids (*low-sulfide formation with associated copper mineralization*) is spatially confined [143]. This mineralization is the focus of geological exploration at the Konder-Rudny deposit {No. 69}, with estimated copper reserves of 61 Kt.

In the easten part of the Jugjur province, the Malokomuyskoye deposit {No. 119} contains copper-lead-zinc ores within the Late Cretaceous granodiorites of the Jugjur complex. in the structure of [144]. Copper reserves at this *copper-skarn deposit* are estimated at 33 Kt, with additional forecast resources of 100 Kt.

Overall, the recorded copper reserves in the Jugjur province total 0.12 million tons (0.12% of Russian reserves)[22] (see Fig. 5, 6).

The Bilyakchan-Kolyma province is a Proterozoic metallogenic belt rich in copper-bearing sedimentary rocks and native copper in basalts, stretching from the Bilyakchansk seam zone in the Khabarovsk Territory to the Oriek ore zone within the Prikolymsky terrane in the Magadan region. This belt hosts known occurrences and deposits of Proterozoic age *copper sandstone formations, such as* Bilyakchanskoe [145], Severny-Uy [146], and Borong [147] {No. 120}, as well as Oroekskoye [148] and Luchistoye [149] {No. 123}, with additional occurrences from the Early Paleozoic era, like Vesnyanka {No. 123} [147]. Occurrences and deposits of the of the Middle Proterozoic *native copper formation* age found in the Sette-Daban ore zone, including Jalkan, Rosomakha, and Hurat [150] {No. 121} and the Urultinsky ore zone – the Batko ore mineralization point {No. 122} [147].

The Okhotsk-Chukotka province aligns with the Late Jurassic-Early Cretaceous Okhotsk-Chukotka volcanic belt, a segment of the global Pacific ore belt [131]. This region contains deposits and occurrences of both copper-porphyry and copper-skarn formations. Noteworthy among the *copper-porphyry deposits* is a group of ore bodies in the Baim ore zone [151], including the largest explored deposit, Peschanka {No. 70}, with reserves of 6.4 Mt at an average grade of 0.53% Cu) [151, 152], and its satellite, Nakhodka {No. 131}, with reserves of 3.1 Mt at 0.34% Cu [151, 153], both dated to the Late Jurassic-Early Cretaceous. Northward, exploration is active in promising areas such as Kavralyanskaya {No. 132} [154] and Tanyurerskaya {No. 133} [155] for potential copper-porphyry mineralization. In the southern part of the Okhotsk volcanic belt, within the Khabarovsk Territory, lies the Late Cretaceous Chelasinskoye copper-(Au)-porphyry deposit {No. 125}, with cooper reserves of 2.0 Mt [156], as well as the promising Darpirchanskaya area {No. 126},

[21] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

[22] I bid.

containing resources of 324 Kt. Within the Magadan region, exploration is ongoing for copper-porphyry deposits in the promising areas like Shkhiperskaya {No. 127}, which hosts Early Cretaceous deposits and occurrences such as Nakhatanjinskoye, Lora, Osennoye, Etanja, and Muromets, totaling 1.0 Mt in resources [157], and Mechiveemskaya {No. 130}, with Late Cretaceous deposits such as Dvoustnaya, resources also totaling 1.0 Mt in resources [158]. The Bebekan molybdenum-copper deposit {No. 128}, from the Early Cretaceous and located in the Levo-Omolon ore zone [158], is also within this province. Additionally, this zone includes the Early Cretaceous *copper-skarn deposit*, Med-Gora {No. 129} [159]. Overall, the Okhotsk-Chukotka province contains an estimated 6.4 million tons of copper reserves (6.23% of Russian reserves), though this figure is likely conservative (see Fig. 5, 6).

The Koryak province is located in the northern part of the Koryak-Kamchatka Mesozoic-Cenozoic volcanic belt [160]. Known deposits and occurrences of *low-sulfide platinoid formations with associated copper mineralization* are found in alpine-type mafic-ultramafic complexes here. Prospecting and evaluation are also underway in the Mainitskaya {No. 134} [161] and Valaginsko-Karaginskaya {No. 135} [162] promising areas for low-sulfide-PGE formations with associated copper mineralization. In the southern part of the province, the Late Cretaceous Snezhnoye low-sulfide PGE-chromite deposit, also with associated copper mineralization, is identified {No. 136} [163].

The Kamchatka Province is situated in the southern part of the Koryak-Kamchatka Mesozoic-Cenozoic volcanic belt. Here deposits of the *copper-nickel formation* are associated with hornblende peridotites and gabbroids in the Late Cretaceous-Paleocene Kvinum-Kuvalorog ore zone. This includes the substantially developed Shanuch nickel deposit with associated copper mineralization {No. 38}, holding reserves of 7.4 Kt of cooper at an average grade of 0.3% Cu) [139, 164], with its copper-nickel ores designated fro export. The Kvinum and Kuvalorog copper-nickel deposits {No. 137} [165, 166] are also found under this ore zone. The southern part of the province hosts the Kirganik *copper-porphyry deposit* {No. 138} from the Late Cretaceous [167]. Altogether, the Kamchatka province holds 0.01 Mt of copper reserves, with an annual production of 0.3 Kt in 2021 (see Fig. 5, 6).

In regions without defined provinces, copper deposits are found in poorly explored territories, where the classification of certain deposits by ore formation type remains unclear.

Noteworthy among these is the associated copper mineralization at the Sinyukhinskoye *gold-skarn deposit* {No. 29}, currently under development, with recorded copper reserves of 28 Kt [168, 169] and annual output reaching up to 1 Kt of extracted copper concentrate from the Vesely mine.

The Ulandryk iron-copper-rare earth deposit {No. 87}, an IOCG-type (iron-oxide-copper-gold) deposit, lies in the southern Altai Mountains, containing 1.2 Mt of cooper at an average grade of 0.70% Cu [170]. This deposit exhibits copper-gold and rare earth mineralization overlaying iron ore within Silurian-Devonian rhyolitic volcanic rocks and their tuffs in contact, in contact with Devonian subvolcanic leucogranites of the Ulandryk massif. This unique deposit may be part of a larger copper province extending into the Xinjiang Altai region in China, where the Chacha iron-copper and Minke copper deposits are located [171].

Potential analogs to the Palabora copper-zirconium-phosphate carbonatite deposit [42] include occurrences copper-sulfide mineralization occurrences within the Dumtaley carbonatite massif [172 and the Nadezhda, Pavlovsky, and Koshka massifs [173] {No. 95} in Eastern Taimyr. Notable sulfide mineralization in these carbonatite complexes suggests a rare opportunity for industrial copper mining and warrants further assessment.

Uncommon occurrences of copper-sulfide mineralization have also been found in potassium-rich alkaline intrusions in the Central Aldan region, an area activated in the Late Mesozoic on the Aldan shield [174]. During geological exploration for gold, zones of copper and molybdenum sulfide mineralization were identified, with Au, Cu, and Mo mineralization zones independently distributed in space. This led to the development of the concept of a *molybdenum-copper-gold porphyry formation, characterized by a potassium* rather than sodium *profile of igneous rocks* [175]. The Ryabinovoe copper-gold-porphyry deposit {No. 113} is located on the igneous massif of the same name [175, 176], as is the Yllymakhskoye deposit {No. 113} [177]. Copper mineralization is also recorded in the central type massifs of Yakokutsky and Tommotsky. Additionally, copper mineralization has been identified in previously considered oreless syenite porphyry laccoliths, including the Morozkinskoye deposit within the Gora-Rudnaya laccolith [178] {No. 113} and the syenite porphyry of the Gloomy laccolith.

The Agylkinskoe *copper-tungsten skarn deposit* {No. 124} is unique, being the only large occurrence of copper and tungsten within the Verkhoyansk gold-dominant metallogenic province [179]. The deposit is a contact body in the zone of a yet undiscovered Late Mesozoic granitoid pluton, with registered copper reserves of 206 Kt at an average grade of 2.7% Cu and estimated resources of 84 Kt of Cu.

Among the copper occurrences in lesser-known provinces, the Beregovoye deposit {No. 139} on the northwestern tip of Cape Sulkovsky, Medny Island, in the Commander Islands archipelago, is noteworthy. Discovered by Russian industrialist E.S. Basov, who gathered substantial quantities of copper nuggets, it has since been the subject of geological studies. Research conducted in 1903 by I.A. Morozevich and L. Konyushevsky and in1958 byYu.V. Zhegalov and V.P. Vdovenko identified fine inclusions of native copper in the dikes of Cenozoic augite andesites (*native copper formations*). However, the residual bench placer of native copper has been depleted, and both I.A. Morozevich and Yu.V. Zhegalov classified this deposit as non-industrial [180]. Due to the limited land areas of the Commander Islands, it has not been possible to define a distinct province for native copper mineralization on Copper Island.

Reserves and forecast resources of copper in the Russian Federation

Accounting reserves and resources. As of January 1, 2022, the Russian Federation accounted for 102.7 million tons of balance reserves of categories A, B, C_1, and C_2, and 79.9 million tons of forecast resources of categories P_1, P_2, and P_3[23]. Forecast resources are additionally evaluated by conversion to conditional reserves. According to MPR Methodology (MPR Order No. 68250, April 18, 2022), the conditional reserves calculated by converting to C_2 as follows: $C_2 = 0.5P_1 + 0.25P_2 + 0.125P_3$, amount to 16.7 million tons. Another approach to copper resources, developed by Ya.V. By Alekseev, calculates C_2 conversion as $1.0P_1 + 0.6P_2$, yielding 16.1 million tons [9] – comparable to the MPR method's recalculations. The results from this latest method are used in assessing the resources of copper ore formations.

Mining reserve sufficiency. The existing balance of copper reserves in the Russian Federation is projected to support the current national production rate – including upcoming capacity expansions – sufficiently for at least 47 years of operation. Additionally, the Oktyabrskoye, Talnakhskoye, Norilsk-I, and Gaiskoe deposits have sustained copper production levels for over 100 years. Meanwhile, some deposits with limited remaining reserves and set for decommissioning, including Osennee, Dzhusinskoye, Vesenne-Aralchinskoye, Talganskoye and others.

Copper formations. In terms of the production-to-reserve ratio within Russia's total copper output, only the copper-nickel (1.06) and copper-porphyry (1.18) formations show a balance between production and reserves (see Fig. 3). Reserves supply concerns and potential depletion issues for these formations therefore not significant. In contrast, the copper-pyrite (1.96) and copper-carbonate (2.44) formations have a high production-to – reserve ratio, indicating an increased activation of ore reserves of these types. For copper sandstones, the production-to-reserves ratio stands as just 0.03, reflecting the early stage of exploitation for this type, as seen with Udokan.

Copper mining provinces. In terms of the production-to-reserves within Russia's copper mining regions, only the Norilsk-Kharayelakh (1.13), Kola (0.74), and Rudny Altai (0.77) provinces show a balanced relationship between production and reserves (see Fig. 3). In the well-established mining region of the Urals, this ratio is 2.85, indicating significant reserve activation in this area. A similar pattern is observed in the newer Eastern Trans-Baikal Province (2.67). Conversely, in the older North Caucasus province mining region, the production-to-reserves ratio is only 0.21, suggesting untapped copper reserves, including deposits like Kizil-Dere. In the newly developed regions, such as Primorsky (0.04), Okhotsk-Chukotka (0.01), and Eastern Tuva (0.12), the ratios remain low, as copper deposits are still in the initial stages of development.

Development plans for new copper deposits. In 2023, the Udokan copper sandstone deposit in the Kodar-Udokan province was put into operation, with an initial production capacity of 136 Kt annually, projected to increase to 542 Kt in the second stage. In the Ural province, two copper-pyrite deposits are in the final preparation stage: Podolskoye, with an expected production level of 85 Kt/year, and Novo-Uchalinskoye, with initial production in the first stage at16 Kt/year, reaching 28 Kt/year in the second stage. The Ak-Sugskoye porphyry-copper deposit is under prepared in the Eastern Tuva province, with an output of 151 Kt/year. Preparations for the Malmyzh porphyry-copper deposit in the Primorsky province also nearing completion, with an anticipated annual production level of 300 Kt. Of the explored depos-

[23] Ministry of Natural Resources and Environment of the Russian Federation. URL: https://www.mnr.gov.ru/docs/gosudarstvennye_doklady/o_sostoyanii_i_ispolzovanii_mineralno_syrevykh_resursov_rossiyskoy_federatsii/

its, the most advanced preparation is underway for the Peschanka porphyry-copper deposit in the Okhotsk-Chukotka province, with production projected to reach up to 350 Kt /year.

The implementation of these projects could increase annual cooper production in Russia by 635–1053 Kt, or 55–91% of the 2021 production level. With the commissioning of the Peschanka deposit, Russian copper production may rise by as much as118% compared to the 2021 level.

The state of forecast copper resource base. The prospects for developing the mineral resource best evaluated through the resources (converted to C_2) and reserves volumes. For the *copper-nickel formation*, the ratio is 0.46, reflecting a high exploration level for known deposits in the Norilsk-Kharayelakh and Kola provinces, primarily of drained ores, with relatively lower expectations for reserve growth from projected resources of disseminated copper-nickel ores. However, new deposits of rich drained ores could potentially be discovered at depths within the Kharaelakh and Tangaralakh ore-bearing intrusions [99, 100]. For the *copper-pyrite formation*, the resour-to-reserve ratio is very high at 2.5, due to significant exploration efforts in the Ural province for both drained and disseminated ores. Reserve growth for copper-pyrite ores remains possible through assessing deep horizons and the peripheries of known deposits, as well as by identifyng new deposits in the Circumpolar and Polar Urals regions [73, 81]. The *copper-polymetallic formation* has an even higher resources / reserves ratio of 9.2 as it includes numerous deposits and occurrences, most of which are medium or small and have not previously been prioritized for exploration. As demand for copper increases, these deposits are becoming attractive, especially in the traditional mining areas of Rudny Altai, Salair, and the North Caucasian provinces [19, 89], as well as in the newly studied regions of Eastern Tuva and Okhotsk-Chukotka. For the *porphyry-copper formation*, the resources-to-reserves ratio of stands at 1.35. With rapid engagement of deposits of this type (such as Tominskoye, Mikheevskoye, Malmyzh, and Peschanka), exploration and prospecting have intensified in the Eastern Tuva, Primorsky, and Okhotsk-Chukotka provinces, which offer favorable conditions for discovering new, potentially large, copper-porphyry deposits [151, 154, 155, 156, 157]. Other copper ore formations show low forecasted resources relative to balance reserves. For the *copper-skarn formation*, this is primarily because most of these objects are accounted for within the copper-polymetallic formation. In contrast, the low level of forecast resources form *copper sandstone formations stems* from the limited interest in the technologically complex ores they contain. Geological exploration has been limited primarily to the Udokan deposit, which is unique in its mineralization. Only low level assessments have been performed on nearby deposits and occurrences in the Kodar-Udokan province (Unkurskoye, Krasnoe, Burpalinskoye, Sakinskoye, Pravoingamakitskoye), as well as in the Igarka province (Graviyskoye, Sukharikhinskoye). Beyond these, exploration of these deposits in the newly identified Bilyakchan-Kolyma [148] and Shoria-Khakass provinces is also feasible. With new technologies for underground copper leaching, known and previously developed copper sandstone deposits in the Pre-Ural [68], Igarka [102], and Donetsk [51] provinces may become viable for exploration and exploitation. Currently, no *native copper deposits* in basaltoids formations are included in Russia's balance of recorded copper reserves. However, such deposits are known within the Shoria-Khakass, Norilsk-Kharayelakh, and Bilyakchan-Kolyma copper ore provinces. Unfortunately, the largest and most studied of their deposits (Taymetskoye [94] and Arylakhskoye [102]) lie within protected areas and are unlikely to be available for commercial exploitation.

Conclusions

1. A summary map of Russia has been compiled, including 25 copper ore provinces and the 150 most significant copper deposits of various ore formations, as well as promising sites and areas. Some copper-ore provinces contain only one type of ore formations: copper sandstones in the Pre-Ural, Igarka, and Donetsk provinces; others are dominated by a single primary formation, such as copper-nickel in the Norilsk-Kharayelakh and Kola provinces, copper sandstones in the Kadaro-Udokan provinces, and copper-polymetallic in the Rudny Altai and Salair provinces. In the Ural province, deposits of two formations – copper-pyrite and copper-porphyry – predominate. Many provinces contain deposits of various formations and ages, indicating a shared geochemical specialization within each province's territory, often irrespective of the geological features of ore-bearing complexes.

2. In contrast to the global distribution of copper ore formations, where the copper-porphyry formation leads in both reserves and production, Russia ranks the copper-nickel technological type of ores first in reserves and production. The main production focuses on copper-nickel sulfide depos-

its (419–508 Kt/year, or 36-65% of Russian production) and pyrite copper deposits (227-334 Kt/year, or 23–40%). Production is also expanding for copper-porphyry deposits (reaching up to 323 Kt/year, or 25%, since 2013) and copper-skarn deposits (since 2018, reaching up to 94 Kt/year, or 8.3%). In 2021, copper production in the Russian Federation totaled 1,147 Kt. In 2023, the ultra-large Udokan copper sandstone deposit, with a maximum production potential of 175 Kt/year, was put into operation. The comp letionof new cooper projects currently in preparation could further raise Russia's annual production by 635–1053 Kt, a 55–91% increase over the 2021production level.

3. As of January 2022, Russia's copper reserves include102.7 million tons of balance reserves and 79.9 million tons of forecast resources accross categories $P_1 + P_2 + P_3$, equivalent to 16.1 million tons in terms of conditional reserves in category C_2. The largest share of copper reserves are concentrated in copper-nickel formations (34.4% of Russian reserves), copper-porphyry formations (23.9%), copper sandstones (19.6%), and copper-pyrite formation (14.5%), with the remaining 7.6% distributed among other ore formations. By region, the Norilsk-Kharayelakh area holds 30.9% of Russia's cooper reserves, followed by the Kodar-Udokan region with 20.3%, and the Ural region with 18.9%. Newer provinces are also showing increases in their copper reserves: Primorsky (8.29%), Okhotsk-Chukotka (6.23%), and Eastern Tuva (3.7%). All other copper-producing provinces combined hold 11.68% of Russia's copper reserves. Overall, Russia's current copper reserves re projected to sustain 47 years of operation at current production levels.

4. In comparing the shares of copper reserves and production acroos ore formations, the copper-nickel (1.06) and copper-porphyry (1.18) formations show the most balanced and favorable security ratios. The production-to-reserves ratio is even more favorable for copper sandstones, reflecting the early stages of exploitation of deposits like Udokan. However, high production shares in copper-pyrite (1.96) and copper-skarn (2.44) formations indicate an intensive drawdown of reserves for these ore types. By region, only the Norilsk-Kharaelakh (1.13), Kola (0.74), and Rudny Altai (0.77) provinces maintain favorable ratios of production to reserves. In contrast, older mining provinces like the Ural (2.85) and newer ones like East Trans-Baikal (2.67) exhibit significant depletion of ore reserves. In the North Caucasus, an established mining region, the ratio of production to reserves is low at 0.21, indicating untapped copper potential, particularly at sites like Kizil-Dere.

5. Each ore formation has distinct prospects for expanding the copper mineral resource base. The copper-nickel formation shows a resource-to-reserve ratio of 0.46, indicating a high exploration density within the Norilsk-Kharayelakh and Kola provinces. However, additional reserves of high-grade ores could potentially be uncovered at depths within the Kharaelakh and Tangaralakh ore-bearing intrusions. The copper-pyrite formation (2.5) presents opportunities for reserve expansion through assessment of deeper horizons and periphery areas of known deposits within the Ural province, along with exploration in the Circumpolar and Polar Urals. Copper-polymetallic formation reserves (9.2) offer numerous known deposits, but most are medium and small, interest in this formation is growing, especially in the mature Rudny Altai, Salair, and North Caucasus provinces, as well as in the emerging Eastern Tuva and Okhotsk-Chukotka provinces. For copper-porphyry formation (1.35), and with the rapid operational engagement of deposits of this type, the scale of geological exploration for this mineralization has expanded in the Eastern Tuva, Primorsky, and Okhotsk-Chukotka provinces, where all conditions are favorable for discovering new, including large, copper-porphyry deposits. Copper sandstone formations, with relatively low forecast resources, have seen limited exploration due to the complex processing requirements for these ores. The Kodar-Udokan province hosts several underexplored deposits, such as Unkurskoe, Krasnoe, Burpalinskoye, Sakinskoye, and Pravoingamakitskoye, as does the Igarka provinc with Graviyskoye and Sukharikhinskoye deposits. In addition, the Bilyakchan-Kolyma and Shoria-Khakass provinces provinces present new prospects for this formation. New underground copper leaching technologies may also support development of smaller copper sandstone deposits within the Pre-Ural and Donetsk provinces. Although deposits of native copper in basaltoids are not currently included in Russia's recorded balance reserves, they are present within the Shoria-Khakass, Norilsk-Kharayelakh, and Bilyakchan-Kolyma copper ore provinces. Unfortunately, the largest and most studied deposits of this type, Taymetskoye and Arylakhskoye, are situated within protected areas, unlikely preventing their commercial exploitation.

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Received 14.05.2024
Revised 07.06.2024
Accepted 10.06.2024