SATBAYEV UNIVERSITY
Engineering Journal of Satbayev University
Volume 147 (2025), Issue 5, 35-41

https://doi.org/10.51301/ejsu.2025.i5.05

Petrogenesis and mineralogical characteristics of copper-bearing rocks in the Koldar massif, Central Kazakhstan

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Abstract. This paper analyzes the increasing global demand for mineral resources, particularly non-ferrous metals, and the growing challenge of finding new deposits as easily accessible ones are depleted. The study focuses on copper-porphyry deposits, which are crucial for meeting this demand. It highlights the importance of improving exploration methods and integrating various geological, geophysical, and geochemical techniques. The research emphasizes the unique metallogenic potential of Kazakhstan, specifically the Dzungar-Balkhash folded region, which hosts significant copper deposits like Kounrad, Bozshakol, Koksai, Aktogay, and Aidarly. The study uses the Koldar massif as a reference site to analyze the geological and mineralogical characteristics of these deposits. The methodology involved field studies, sample collection, and macro- and microscopic mineralogical analysis. A key finding of the study is the identification of widespread kalishpatization and argillitization zones within the Kyzylkiya deposit, which were confirmed through both spectral analysis and micromineralogical studies. The research also details the mineralogical and geochemical characteristics of different types of copper-porphyry ores, linking them to specific petrological features of the ore-bearing plutonism. The paper concludes by presenting prospect and prospecting signs for copper-porphyry deposits in various geological settings.

Keywords: *petrogenesis, copper, mineralogy, metallogenic models, non-ferrous metal ores.*

Received: 23 January 2025
Accepted: 16 October 2025
Available online: 31 October 2025

1. Introduction

The increasing demand for mineral raw materials, and especially for non-ferrous metal ores, determines the further strengthening and expansion of their mineral resource base and an increase in exploration reserves, primarily in the areas of existing mining enterprises and newly created territorial production complexes, for the long term. Currently, the fund of easily discoverable deposits located on the surface or at shallow depths is mostly exhausted. This requires constant improvement of the genetic and geological foundations of regional, small- and medium-scale and local forecasting, the formation of geological prospecting models of different metallogenic categories, the rational use and combination of geological, geophysical, geochemical and mining methods based on the development of their effective complexes.

1.1. Geological context of non-ferrous metal deposits

Recent research in the Chinese Altai highlights the significance of integrating zircon U–Pb geochronology with isotopic and geochemical data to better understand the petrogenesis and tectonic settings of granitic complexes associated with mineralization [1]. In Eastern Kazakhstan, studies of Early Triassic magmatism reveal a genetic link between monzonite–granite intrusions and the activity of the Siberian Large Igneous Province, suggesting a broader geodynamic control on ore formation processes [2]. Investigations in Central Lhasa further demonstrate that Cretaceous magmatic events played a key role in the development of Fe–Cu skarn systems, emphasizing the metallogenic potential of post-collisional magmatism [3]. Meanwhile, data from Northwestern Mongolia provide insight into the evolution of orogenic belts and show how regional tectonic regimes influence the emplacement and mineralization of granitoid massifs [4].

The expansion and strengthening of the raw material base of non-ferrous metals in the Republic of Kazakhstan is primarily possible due to the discovery and study of deposits of the leading geological and industrial types-copper-nickel, copper-porphyry, copper-pyrite, copper sandstones and shales. The specifics of deposits are determined by their paleotectonic and geological position, spatiotemporal and genetic relationships with various structural and material complexes (formations), the size and morphology of mineralization zones and ore bodies, the quality, mineral and material composition of ores. Copper deposits are quite widespread around the globe and are found on almost all continents. They are also diverse in time of formation (from the Precambrian to the Cenozoic), and each age epoch is characterized by the predominance of one or two geological and industrial types. In the Mesozoic, unlike the PaleoTriassicterozoic, there was a slight decrease in copper reserves, and the main reserves of this period were concentrated in copper-porphyry and copper-nickel deposits, which were developed mainly in the CIS

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Engineering Journal of Satbayev University. eISSN 2959-2348. Published by Satbayev University

countries, being associated with the Triassic trap formation. The Cenozoic era is characterized by a sharp increase in copper accumulation due to copper-porphyry deposits, confined mainly to the Pacific (94% of reserves) and partly to the Mediterranean (6% of reserves) folded belts [5].

Kazakhstan is a unique ore province, which contains deposits of non-ferrous and ferrous metals that are diverse in composition and origin [6]. In the Balkhash ore province, copper deposits are developed in the form of a sublatitudinal strip extending along the Northern Balkhash region for more than 500 km with a width of 40-50 km [5].

Copper porphyry deposits are characterized by large masses of calcified rocks with a veined-interspersed, stockwork character of mineralization and are mainly suitable for mining by large quarries. By origin, these deposits are hydrothermal: plutogenic and volcanogenic, which indicates a fairly wide range of temperatures at which their formation took place. Ore-bearing rocks can be coarse- and fine-grained diorites, granodiorites, granodiorite porphyries and plagiogranite porphyries, which break through older (from Silurian to Carboniferous) formations, both volcanogenic-sedimentary and intrusive. The main ore components are copper and molybdenum. The primary ore minerals are pyrite, chalcopyrite, bornite, molybdenite, and magnetite. Malachite and azurite develop in the oxidation zone, and chalcosine ores with bornite develop in the secondary enrichment zone. Hydrothermal changes consist of calypathization and biotitisation [5].

Mineralization, as a rule, is located on the contact of the intrusions that caused it with the host rocks (Aktogay, etc.) or on the periphery of granitoid massifs (Aksu, Koksai). At the same time, ore-bearing intrusions are confined to deep fault zones, as well as the widespread development of hydrothermal changes, up to the transformation of rocks into secondary quartzites. There are a number of areas within the Dzungar-Balkhash folded region where a combination of deep fault zones with manifestations of intrusive activity is favorable for mineralization, especially at its junction with the Teniz and Zhezkazgan depressions in the west, the Kokshetau block in the west and northwest, the Zharkyn synclinor structure in the east, and the Shu syneclise and Ili depression in the south. Studying various research cases of copper deposits around the world, it was interesting to review the case of the Shagai belt, Pakistan, with the resulting RSG picture of the massif [7] (Figure 1).

Figure 1. RSG of the Reko Dik copper and sapphire deposit, Pakistan

On the territory of the Republic of Kazakhstan, the research group accepted the copper deposits of the Koldar massif as the reference study site.

1.2 Geological description of the research object

The Dzungar-Balkhash folded region is located to the north, northwest and southeast of the lake. Balkhash, on three sides (except the southeast), it represents a trough formed by precipitation from the Middle Devonian to Permian inclusive. Folding, accompanied by intrusions, manifested itself in the Middle and Late Carboniferous; in its first stage, moderately acidic granitoid intrusions were introduced, and in the second, potassium granites mainly along faults. During the consolidation process in the Late Permian-Early Mesozoic, intense terrestrial volcanic activity was manifested along the periphery of the region in connection with the above-mentioned deep faults, which led to the development of not only tuff-effusive formations but also subvolcanic intrusions. The latter are associated with the formation of secondary quartzites and molybdenum-copper deposits of the stockwork type near volcanic apparatuses [8]. The formation of subgeosynclinal and skarn polymetallic deposits is associated with late Carboniferous small intrusions, and stockwork and vein deposits of tungsten and molybdenum are associated with early Carboniferous and late Carboniferous intrusions.

Five Paleozoic deposits are known in the Dzungara-Balkhash folded region in Central Kazakhstan: Kounrad, Bozshakol, Koksai, Aktogay, and Aidarly. The Aktogay deposit is located to the east of the lake. Balkhash is associated with volcanogenic formations of the Upper Paleozoic age, broken near the axis of the anticlinal fold by a number of small subvolcanic intrusions of the Upper Carboniferous age, represented by granodiorites and quartz diorites. The copper mineralization is confined to the apical part of one of the massifs and partially extends into its roof. In the central part of the deposit there is an oreless quartz core surrounded by a zone of kalishpatization, which is associated with the main mineralization [9]. The ore body has a horseshoe shape with a maximum width of up to 800 m. Mineralization has been traced to a depth of 400-600 m. It has a veined-interspersed character. Ore minerals are chalcopyrite, pyrite and less commonly bornite and molybdenite. Magnetite, pyrrhotite, sphalerite and galena are even rarer. The copper content in the ores is low and does not exceed 0.6%. Molybdenum is low. The Aidarly field is located next to the Aktogay field and is similar in structure to it.

2. Materials and methods

The sites were studied and sampling points were identified for macro- and microscopic mineralogical analysis of the selected sites (Figure 2). The general requirements for the cartographic foundations of predictive research are determined by the need to display a set of direct and indirect signs of predicted objects on graphic materials. The places of birth, attributed to the copper-porphyry family by a complex of geological, genetic and geological industrial characteristics, are located in specific geostructures – volcanic-plutonic belts of two types:

1) Basaltoid rocks formed in the outer (barrier) zones of island arcs, at the end of the early stages of the development of eugeosynclines;

2) Andesitoids, which are formed in the orogenic activation regime on a substrate of various compositions and times of occurrence.

The allocation of provinces or regions requires determining the position of the corresponding volcanic-plutonic belts in the general zonality of geosynclinal folded systems.

Basaltoid volcanic-plutonic belts in marginal continental geosynclinal folded systems are naturally located between the frontal troughs adjacent to the troughs and the inner or rear zones of the island-arc space.

In intracontinental geosynclinal folded systems, basaltoid belts are located either directly above the actual eugeosynclinal bends or on their flanks. This situation is typical for Central Kazakhstan and the Central Ural uplift, which have experienced the regeneration of the geosynclinal regime [10].

In the basaltoid volcanic-plutonic belts, the copper-porphyry and gold-copper-porphyry deposits themselves are associated with a volcanic-plutonic association formed by basalt-andesite-basalt volcanogenic and gabbro-diorite-quartz-diorite (plagiogranite) plutogenic formations. This association occurs after an undifferentiated basalt, contrasting basalt-rhyolite, and continuous basalt-andesite-dacite-rhyolite formation. After productive association, volcanogenic molassoids of Grauwacke and carbonate strata usually accumulate.

The appearance of copper-porphyry deposits is preceded by the formation of pyrite family deposits associated with differentiated volcanogenic formations and located in adjacent metallogenic zones [11]. Copper-porphyry deposits arose after ferromanganese volcanogenic ores. Vein polymetallic deposits are formed synchronously with copper-porphyry ores or somewhat later.

In andesitoid volcanic-plutonic belts, the composition of ore-bearing volcanic-plutonic associations depends on the nature of the substrate. In epicraton belts, molybdenum-porphyry deposits are associated with the diorite-granodiorite-granite formation, which is preceded by the usually sparsely distributed dacite-rhyolite. In epimiogeosynclinal belts, copper-molybdenum-porphyry deposits accompany associations formed by andesite-dacite-rhyolite and diorite-granodiorite-monzonite formations [12]. In the epicheosynclinal belts, molybdenum-copper-porphyry deposits are associated with volcanic-plutonic associations, which include andesite volcanogenic and gabbro-diorite-granodiorite plutogenic formations. These associations belong to the initial stages of the formation of volcanic-plutonic belts. Later formations are represented by ignimbrite, liparitoid, trachytoid, and trachyte volcanogenic formations accompanied by granite-leucogranite, subalkaline, alkaline, and alaskite intrusive complexes.

The epicraton-type birthplace is characterized by a significant amount of molybdenum, less often copper-molybdenum ore composition and is most similar to molybdenum-porphyry objects according to classification V. Popov. In the ores of these deposits, the ratio of copper to molybdenum varies from 0.4 to 20 (about 13 on average) with non-industrial copper contents [13]. The deposits contain practically no gold and silver.

The gold-bearing ores of epimiogeosynclinal type deposits have a molybdenum-copper composition; the Cu ratio: The Mo ranges from 15 to 40 with a weighted average of about 23. The ores are weakly gold-bearing and silver-bearing [14].

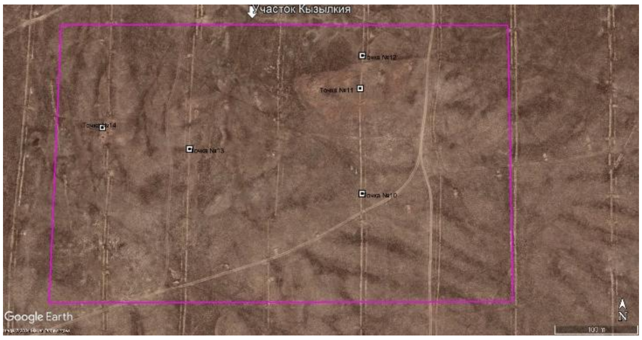
Epigeosynclinal deposits are characterized by gold-bearing molybdenum-copper ores. Cu Relations: Mo ranges from 30 to 235 at concentrations of Mo, sometimes of no industrial significance [15-24]. The gold content of ores is increased and can reach 20 g per 1 t of copper reserves.

Thus, copper-porphyry deposits are clearly divided into molybdenum-, gold-bearing copper-molybdenum-, gold-bearing molybdenum-copper and gold-copper-porphyry deposits, which correlates with the petrological characteristics of ore-bearing plutonism, depending on the types of metallogenic zones. Table 1 shows the conditions of occurrence of deposits of the copper-porphyry family.

Table 1. Conditions of occurrence of molybdenum-porphyry deposits

№	Metallogenic and geological characteristics of typical environments	Types of deposits and reference objects
	Molybdenum-copper-porphyry (deposits of the Balkhash region)	
1	Metallogenic provinces	Marginal and intracontinental orogenic-activated volcanic-plutonic belts on the eugeosynclinal basis
2	Metallogenic (structural and formation) zones:	
2.1	Paleotectonic position	The central parts of the epigeosynclinal volcanic-plutonic belts with the development of an association of formations: andesite-dacite and andesite-rhyodacite volcanogenic and gabbro-diorite-granodiorite and plutogenic. The central parts of the belts with the development of ore-bearing volcanic-plutonic associations
2.2	Formations containing ore-bearing plutogenic formations	Andesite-dacite, andesite-rhyodacite, and eugeosynclinal belt base complexes
2.3	Ore-bearing formations	Gabbro-diorite-granodiorite potassium-sodium (K_2O:Na_2O from 0.5 to 0.8)
3	The position of the ore regions	Multiphase plutons or areas of development of porphyritic phases of an ore-bearing formation corresponding to groups of magmatogenic-hydrothermal systems
4	Position of ore fields and deposits	Porphyry stocks and adjacent structures of their frames are controlled by inherited paleodepositions of the base of the belts (sometimes stratovolcanoes) and corresponds to single magmatogenic-hydrothermal systems
5	Ore-bearing structures and the position of ore bodies in ore-bearing formations and massifs	Apical parts of rod-shaped and dike-shaped porphyry intrusions, sometimes containing breccia tubes of granodiorite porphyries
6	Forms of ore bodies	Conformal to porphyry intrusions: cones, truncated cones, hollow thick-walled cones, straight and inverted, plates, wedges; disconformal: inverted vertical and inclined cones, groups of cones and funnel-shaped bodies
7	Geochemical characteristics of ores	Cu:Mo from 200:1 to 30:1
8	Ash content of hydrothermal-metasomatic changes (from the center to the periphery of the rods)	Biotitisation-sericitization-propylitization

In the course of the study, the rock sections and polished sections were taken from control points, prepared and studied (Figure 2). Rock sections are thin sections of rocks examined under a microscope in transmitted light to study their mineral composition and texture. Polished sections are polished samples that are examined under a microscope in reflected light, which makes it possible to analyze ore minerals and their relative positions.



(a)

(b)

Figure 2. Overview diagram of control points: (a) – initial condition of the study area before mining operations; (b) – open-pit view with control points where rock and polished sections were collected for mineralogical analysis

3. Results and discussion

An important result of the research was the identification of the zone of spread of kalishpatization, which is widespread in the Kyzylkiya deposit. The samples taken from this zone also confirmed the results of spectral analysis. Argillitization, widespread in the territory of Kyzyl Kiya, was clearly expressed on the map, compiled according to the results of the spectral method, and confirmed by microminerological studies.

Thin sections are magnified by 10X. From left to right, the top row contains grains of biotite, quartz, plagioclase, sericitized, and potassium feldspar, in crossed nichols; unchanged quartz in granodiorite, about 5 mm in size, in crossed nichols. From left to right, the bottom row shows hydrothermal changes in feldspar, in crossed nichols; a cryptocrystalline glassy mass with fragments of pyroclasts and quartz fragments, in crossed nichols (Figure 3).

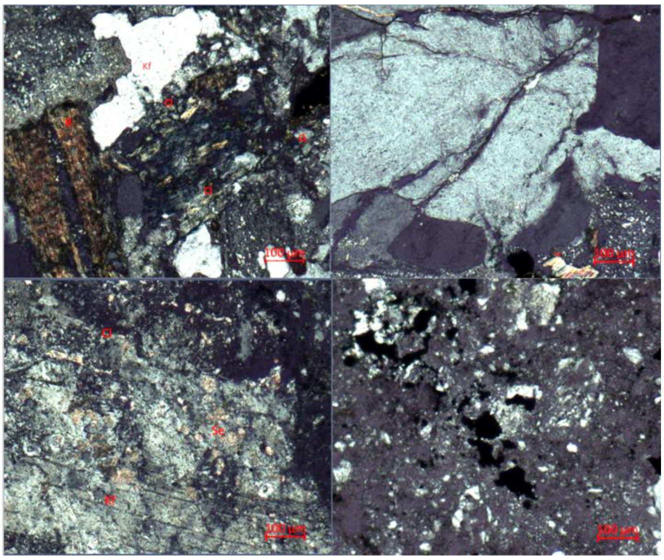


Figure 3. Microscopic images of rock thin sections showing mineral composition and key geological features of the rock samples

The mineralogical composition and geochemical features of ores from various types of copper-porphyry deposits are summarized in Table 2 where I-IV are types of deposits:

– I-molybdenum-porphyry,
– II-gold-bearing copper-molybdenum-porphyry,
– III-gold-bearing molybdenum-copper-porphyry,
– IV-gold-copper-porphyry

Table 2. Mineralogical and geochemical characteristics of the main types of ores of copper-porphyry deposits

Ore type	Minerals				Mineral associations	Impurity elements		The predominance in various types of deposits			
	Main	Secondary	Rare	Gangue		Main	Secondary	I	II	III	IV
Magnetite-pyrite	py, mag	hm, pyr	ilm, cub, chp, mo, rt	q, chl	py, mag-py	Co(py)*, Se(py)	Te, Re, Bi, Au, Ag	+	+	+	+ + +
Molybdenum	mo, py	chp, bn, pyr, hb, wf, mag	gal, sph, bit, hm, bl, cs	q, anh, bi	mo, q-mo, q-py-mo	Re(mo)	Se, Te	+ + +	+ +	+	+
Chalcopyrite-bornite	bn, chp, py	mo, chils, mag	sph, gal, ars, bl, bit, Au, el, Ag, an, tel, Au, Ag	q, pot, anh, bi, ser	mo-chp-bn, mo-py-chp-bn, bn-chp, py-chp-bn	Re(chp), Au(chp,bn), Ag(chp,bn, sph, gal)	Se, Bi, Pt(chp)	–	+ +	+	–
Pyrite-chalcopyrite	chp, py	bn, mo, mag, sph, chls	sph, gal, ars, bl, bit, Au, el, Ag, tel, Au, Ag, cv, an	q, pot, anh, bi, ser	mag-py-chp, mo-bn-py-chp, mo-py-chp, py-chp	Re(chp,mo), Au(chp,bn), Ag(chp,bn, sph, gal)	Se, Bi, Pt(chp)	+ +	+ + +	+ + +	+ + +
Polysulfide	py, chp, gal, sph, bl	an, Au, Ag, tel, u sel Au, Cu, Pb	gs, ars, pyr	q, car, bar, zl	py-chp-bl-gal-sph, py-chp-sph-ars, gal-sph-py-chp	Au(py, chp, gal, bl) Ag(chp, sph, gal, bl)	Se, Te Bi (gal, sph) In, Cd, Ga	+	+ +	+ +	+
Enargite-polysulfide	py, en	luz, ars, bn, rdhr, bl, S, gal, sph, chp	spec, cv	q, car, zl	en-chp-gal-sph, py-en-chls, en-ars-py, en-rdhr-cv-py-S, luz-en	Ag(bl, gal, sph)	–, – As	–	+	+	–
Hypergene	chlz, bn, cv, as	py, chp, mal, Au, Cu, mo		–	–	Au, Ag	–	+	+ +	+ +	+ +

*The minerals that carry the elements of impurities are indicated in parentheses

The prevalence of the main types of ores is characterized as follows: "+++" indicates occurrence in significant amounts, including at the level of major industrial concentrations; "++" denotes constant presence in various quantities; "+" marks rare occurrence in small volumes; "–" signifies absence.

Mineral designations:

Ad – native silver; ap – argentite; anh – anhydrite; ars – arsenopyrite; as – azurite; Ai – native gold; bar – barite; bi – biotite; bl – pale ore; bit – bismuthinite; bn – bornite; sag – carbonate; chl – chlorite; chr – chalcopyrite; chls – chalcosine; cs – cassiterite; Si – native copper; cub – cubanite; cup – cuprite; cv – covelline; el – electrum; en – enargite; gal – galena; gs – hessite; hb – hubnerite; hm – hematite; ilm – ilmenite; luz – luconite; mag – magnetite; mal – malachite; mo – molybdenite; pot – potassium feldspar; py – pyrite; pyr – pyrrhotite; q – quartz; rdhr – rhodochrosite; rt – rutile; S – native sulfur; sel – selenides (of gold, silver, copper, lead); ser – sericite; spec – specularite; sph – sphalerite; tel – tellurides; wf – wolframite; zl – zeolites.

The characteristics of the prospect and prospecting conditions are summarized in Table 3.

Table 3. Prospect and prospecting signs of copper-porphyry deposits in various settings

Elements of field models	Environments-according to the options for the position of the erosional truncation and the possibilities of detecting ore bodies		
	Favorable, I, II	Moderately favorable, III	Unfavorable, IV
Supramineral space: Propylitized rocks of the intrusive frame	+c	+c	-
Zones:			
Pyritization	+c	+c	-
Tourmalinization	+- u	+- u	-
Argillitization	+c	+c	-
brecciated tubes	+-a	+-a	-
Supramineral lithogeochemical envelope	+c	+c	-
Vein polymetallic mineralization	+c	+c	-
Vein and impregnated copper-arsenic mineralization	+-c	+c	-
Ore – hosting space			
Propylitized rocks of the intrusive frame	+c	-	-
Pyritization zones	+c	-	-
Porphyritic intrusive bodies	+c	-	-
Brecciated tubes	+-c	-	-
External lithogeochemical envelope	+c	-	-
Vein polymetallic mineralization	+-c	-	-
Zones:			
Argillitization	+-c	-	-
Silicification and sericitization	+c	-	-
Ore bodies	+u	-	-
K-feldspathization and biotitization	+-c	-	-
sub-ore lithogeochemical envelope	+-c	-	-
sub-ore space:			
Propylitized rocks of the intrusive frame	+-c	-	+-c
Pyritization zones	+-c	-	+-c
Porphyritic intrusive bodies	+c	-	+c
External lithogeochemical envelope	+c	-	+c
K-feldspathization and biotitization	+-c	-	+-c
Quartzy core	+-u	-	+-u
Internal lithogeochemical envelope	+-c	-	+c

The designations used in Table 3 are as follows: +" presence of a feature on the section; "–" absence of a feature; "+/–" possible presence of a feature; "u" unambiguous identification of the corresponding part of the geological space; "a" ambiguous identification; "c" identification in combination with other features.

4. Conclusions

An important result of the microminerological studies was the identification of the zone of spread of kalishpatization, which is widespread in the Kyzylkiya deposit. The samples taken from this zone also confirmed the results of spectral analysis. Argillitization, widespread in the territory of Kyzyl Kiya, was clearly expressed on the map, compiled according to the results of the spectral method, and confirmed by microminerological studies. Mineralogical and geochemical characteristics of the main types of ores of copper-porphyry deposits were identified. Prospect and prospecting signs of copper-porphyry deposits in various settings were detected.

Author contributions

Conceptualization: DEU; Data curation: AAB; Formal analysis: EOO; Funding acquisition: EOO; Investigation: AAB; Methodology: DEU; Project administration: DEU; Resources: AAB; Software: TLA; Supervision: EOO; Validation: TLA; Visualization: DEU; Writing – original draft: DEU; Writing – review & editing: EOO. All authors have read and agreed to the published version of the manuscript.

Funding

This research was funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. BR21882179).

Acknowledgements

The authors express their sincere gratitude to the editor and anonymous reviewers for their constructive comments and valuable suggestions, which have significantly improved the quality of this manuscript.

Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

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Орталық Қазақстандағы Қолдар массивінің мыс-кенді тау жыныстарының петрогенезисі және минералогиялық сипаттамалары

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Аңдатпа. Бұл жұмыс минералдық шикізатқа, әсіресе түсті металл кендеріне деген жаһандық сұраныстың артуын және оңай табылатын кен орындарының сарқылуына байланысты жаңа кен орындарын іздеудегі қиындықтарды талдайды. Зерттеу осы сұранысты қанағаттандыруда маңызды рөл атқаратын мыс-порфирлі кен орындарына бағытталған. Ол барлау әдістерін жетілдірудің және әртүрлі геологиялық, геофизикалық және геохимиялық әдістерді біріктірудің маңыздылығын көрсетеді.Зерттеу Қазақстанның бірегей металлогендік әлеуетін, атап айтқанда Қоңырад, Бозшакөл, Қоқсай, Ақтоғай және Айдарыл сияқты маңызды мыс кен орындары орналасқан Жоңғар-Балқаш қатпарлы аймағын ерекше атап көрсетеді. Зерттеу жұмысы осы кен орындарының геологиялық және минералогиялық сипаттамаларын талдау үшін Қолдар массивін эталонды зерттеу алаңы ретінде пайдаланады. Әдістеме далалық зерттеулерді, үлгілерді жинауды, сондай-ақ макро- және микроскопиялық минералогиялық талдауды қамтиды.Зерттеудің негізгі нәтижесі – Қызылқия кен орнында кең таралған калишпаттану және сазға айналу аймақтарын анықтау болып табылады, бұл спектрлік талдаулармен және микроминералогиялық зерттеулермен расталды. Жұмыс сондай-ақ мыс-порфирлі кендердің әртүрлі түрлерінің минералогиялық және геохимиялық сипаттамаларын, олардың кен түзуші интрузиялардың петрологиялық ерекшеліктерімен байланысын егжей-тегжейлі сипаттайды. Қорытынды бөлімде әртүрлі геологиялық жағдайлардағы мыс-порфирлі кен орындарының іздестіру белгілері ұсынылған.

Негізгі сөздер: *петрогенезис, мыс, минералогия, металлогендік модельдер, түсті металл кендері.*

Петрогенезис и минералогические характеристики медьсодержащих пород массива Колдар, Центральный Казахстан

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Аннотация. В данной работе анализируется растущий мировой спрос на минеральные ресурсы, особенно на руды цветных металлов, и усиливающаяся проблема поиска новых месторождений по мере истощения легкодоступных залежей. Исследование сфокусировано на медно-порфировых месторождениях, которые имеют решающее значение для удовлетворения этого спроса. Подчеркивается важность совершенствования методов разведки и интеграции различных геологических, геофизических и геохимических подходов.Исследование акцентирует внимание на уникальном металлогеническом потенциале Казахстана, в частности, на Джунгаро-Балхашском складчатом регионе, где расположены такие значимые медные месторождения, как Коунрад, Бозшаколь, Коксай, Актогай и Айдарыл. В качестве эталонного участка для анализа геологических и минералогических характеристик этих месторождений используется массив Колдар. Методология включала полевые исследования, отбор проб, а также макро- и микроскопический минералогический анализ.Ключевым результатом исследования стало выявление обширных зон калишпатизации и аргиллизации в пределах месторождения Кызылкия, что было подтверждено как спектральным анализом, так и микроминералогическими исследованиями. В работе также подробно описаны минералогические и геохимические характеристики различных типов медно-порфировых руд, связывая их с конкретными петрологическими особенностями рудоносного плутонизма. В заключении представлены поисковые признаки медно-порфировых месторождений в различных геологических обстановках.

Ключевые слова: *петрогенезис, медь, минералогия, металлогенические модели, руды цветных металлов.*

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