DOI: 10.31643/2028/6445.26
Earth and Planetary Sciences: Earth-Surface Processes

Mineralogical characteristics of oxidized copper-porphyry ores at the Koktaszhal deposit

[1]Toleubek K.E., [1*]Kopobayeva A.N., [1]Amangeldikyzy A., [1]Askarova N.S., [2]Zengin E., [1]Zhunusbekova G.Ye., [1]Mazakh B., [1]Battalova A.S.

[1]*Abylkas Saginov Karaganda Technical University, Karaganda, Kazakhstan*
[2]*Istanbul Technical University (ITU), Istanbul, Turkey*

**Corresponding author email*: *a.n.kopobayeva@gmail.com*

Received: *April 27, 2026*
Peer-reviewed: *May 21, 2026*
Accepted: *July 24, 2026*

ABSTRACT
This paper presents the results of a comprehensive mineralogical study of oxidized copper-porphyry ore from the Koktashal deposit. Optical microscopy, silicate analysis, and quantitative phase analysis were used to characterize the mineral composition and forms of copper occurrence in the oxidation zone. The ore contains 0.735% total copper, of which 89.8% occurs in oxidized form, 6.39% in primary sulfides, 2.72% in secondary sulfides, and 1.09% in water-soluble form. The principal ore minerals are malachite (1.5–2.0%) and azurite (0.3–0.4%), accompanied by hematite with magnetite (0.5%), goethite (0.2%), and pyrite (0.2%), whereas copper sulfides and native copper occur only in trace amounts. The integration of classical mineralogical methods with quantitative phase analysis provides new insights into the distribution of copper occurrence forms and their relationship to oxidation processes. Malachite and azurite occur as well-crystallized vein and nest aggregates as well as colloform earthy masses developed along microcracks in association with iron hydroxides. Their close association with iron hydroxides and the near absence of copper sulfides represent a diagnostic feature of the oxidation zone in copper-porphyry systems. These findings improve the assessment of supergene alteration during exploration and support the classification of oxidation-zone ores as a distinct geological and industrial type for reserve estimation, ore body delineation, and processing scheme selection.

Keywords: Koktaszhal, copper-porphyry deposits, oxidized ores, phase analysis of copper, malachite, azurite, forms of gold, material composition.

Information about authors:

Toleubek Kymbat Esmakhaikyzy	*PhD student at the Geology and Exploration MD Department of Abylkas Saginov Karaganda Technical University, 100027, Ave. Nursultan Nazarbayev, 56, Karaganda, Kazakhstan. E-mail: toleubekkymbat69@gmail.com; ORCID ID: https://orcid.org/0000-0003-2126-8084*
Kopobayeva Aiman Nygmetovna	*PhD, associate professor of the Geology and Exploration MD Department of Abylkas Saginov Karaganda Technical University, 100027, Ave. Nursultan Nazarbayev, 56, Karaganda, Kazakhstan. E-mail: a.n.kopobayeva@gmail.com; ORCID ID: https://orcid.org/0000-0002-0601-9365*
Amangeldikyzy Altynay	*PhD, associate professor of the Geology and Exploration MD Department of Abylkas Saginov Karaganda Technical University, 100027, Ave. Nursultan Nazarbayev, 56, Karaganda, Kazakhstan. E-mail: a.amangeldykyzy@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-6665-8804*
Askarova Nazym Srazhadinkyzy	*PhD, associate professor of the Geology and Exploration MD Department of Abylkas Saginov Karaganda Technical University, 100027, Ave. Nursultan Nazarbayev, 56, Karaganda, Kazakhstan. E-mail: n.askarova@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-2103-6198*
Zengin Enes	*PhD, Associate Professor, Department of Geological Engineering, Faculty of Mines, Istanbul Technical University (ITU), Ayazağa Campus, 34469 Maslak, Istanbul, Turkey. E-mail: eneszengin@itu.edu.tr; ORCID ID: https://orcid.org/0000-0002-5740-7763*
Zhunusbekova Gulden Yermukhanovna	*Senior Lecturer of the Geology and Exploration MD Department of Abylkas Saginov Karaganda Technical University, 100027, Ave. Nursultan Nazarbayev, 56, Karaganda, Kazakhstan. E-mail: zh.gulden@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-6578-5959*
Mazakh Bakytzhan	*PhD student at the Geology and Exploration MD Department of Abylkas Saginov Karaganda Technical University, 100027, Ave. Nursultan Nazarbayev, 56, Karaganda, Kazakhstan. E-mail: 06.06.2005@mail.ru; ORCID ID: https://orcid.org/0009-0007-5390-298X*
Battalova Arai Sayakhatovna	*Master's student of the Geology and Exploration MD Department of Abylkas Saginov Karaganda Technical University, 100027, Ave. Nursultan Nazarbayev, 56, Karaganda, Kazakhstan. E-mail: a84207553@gmail.com; ORCID ID: https://orcid.org/0009-0009-3192-1367*

Introduction

The importance of copper globally is determined not only by its wide range of industrial applications, but also by the steady increase in demand for the metal over time. According to the International Copper Association (ICA) [1], approximately 28 million tons of copper are consumed annually worldwide, with nearly 70% used in electrical and communication applications, which directly relates to the metal's excellent electrical properties. At the same time, the International Copper Study Group (ICSG) [2] reports that global consumption of refined copper has increased more than threefold over the last 50 years, reflecting a long-term trend in growing demand from energy, construction, mechanical engineering, transportation, and electronics industries.

In these conditions, copper deposits with large reserves and resources, capable of providing a stable long-term raw material base, are particularly important. Among them, porphyry copper deposits play a leading role, considered the world's largest source of copper and an important source of molybdenum, gold, and silver [[3], [4]]. Their industrial value stems from the combination of enormous ore masses, significant total reserves, the possibility of open-pit mining, and integrated extraction of several valuable components. Even with relatively low copper grades, these deposits form the basis of the modern global copper mining industry [[3], [4]].

A key feature of porphyry copper deposits is the combination of relatively low average metal grades with extremely large ore systems. The United States Geological Survey (USGS) [3] emphasizes that the average copper content in porphyry deposits was approximately 0.44% in 2008, but their economic significance remains exceptionally high due to the large scale of mineralization, which is often measured in hundreds of millions and even billions of tons of ore [1]. It is this combination of low content and gigantic volumes that makes porphyry copper a unique type of mineral resource and determines its special role in global metallurgy [[1], [3]].

In modern conditions, interest in porphyry copper systems is growing due to the energy transition and the rising demand for copper as a key metal for electrification. According to the International Energy Agency (IEA) [[5], [6]], total copper demand may rise from 25.855 million tons in 2023 to 36.379 million tons by 2040, with the need for clean energy technologies growing particularly rapidly [[5], [6]]. In this context, porphyry copper deposits are considered among the most promising types of mineralization capable of significantly increasing copper reserves. This area is particularly important for the Republic of Kazakhstan, which has high potential for porphyritic copper mineralization [[7],[8],[9],[10],[11]] within the Central Asian fold belt. Moreover, a significant portion of known deposits is in mature stages of exploitation, making detailed study urgent and the identification of new deposits, including hidden and deep ore bodies, a priority [[12],[13],[14]]. State policy in the field of subsoil use focuses on addressing these problems. Geologists face a range of interrelated scientific and applied issues in developing geological and genetic models for porphyry systems, identifying criteria for predicting concealed mineralization, and integrating geophysical and geochemical techniques into detailed exploration of the geological characteristics of porphyritic copper mineralization [[2],[5]]. These trends underscore the importance of both searching for new porphyritic deposits and conducting in-depth exploration of known ones, including their mineral composition, mineralogical properties, and the forms of occurrence of valuable components. Accordingly, this work aims to conduct a detailed mineralogical study of oxidized copper-porphyry ores from the Koktaszhal deposit, determining their material composition, the forms of copper occurrence, and the ratios among oxidized, secondary, and primary forms.

Geological settings

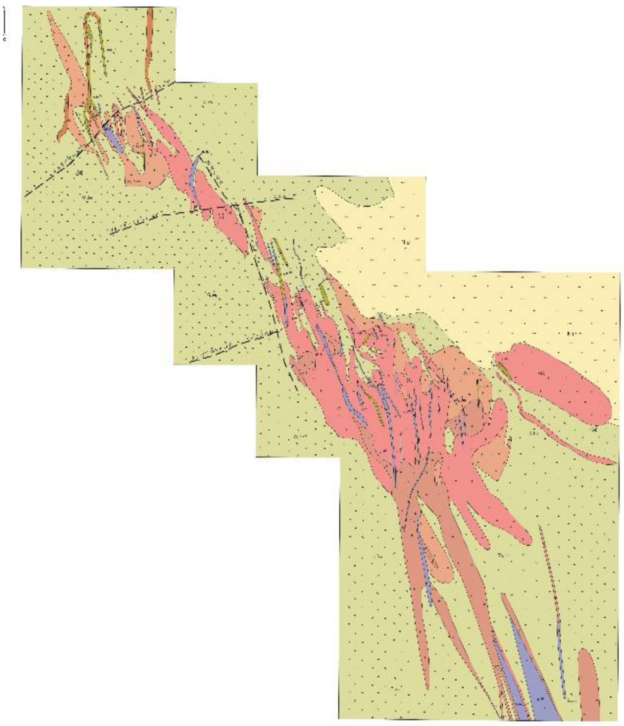
The Koktaszhal deposit is located in the Egindybulak district of the Karaganda region (Fig. 1), 30 km northwest of the district center of Eginbulak [[15],[16]]. In regional-geological terms, it is confined to the eastern part of the Spassky anticlinorium. It is associated with an anticlinal fold composed of andesite-basalt porphyrites and their tuffs, with interlayers and lenses of rhyolite, dacite, siliceous tuffite, sandstone, siltstone, and limestone from the Middle Devonian period. The aforementioned volcanogenic-sedimentary formations have been universally cataclased, sheared, and propylitised, indicating significant tectonic reworkings and hydrothermal-metasomatic transformations of rocks [[15], [16]].

Intrusive magmatism is represented by the granitoids of the Koktaszhal Massif, which belong to the tonalite-granodiorite-plagiogranite suite and exhibit a three-phase structure. The first phase consists of gabbro and diorite; the second includes quartz diorites, tonalites, and granodiorites, which make up the main part of the massif; and the third comprises additional intrusions of plagiogranitic and granitic porphyries.

Ore-bearing structures are sill-like apophyses of the Koktaszhal Massif, formed by third-phase plagiogranitic porphyries and traced over about 1.300 meters (see Fig. 2).

Figure 1 – Location of the Koktaszhal Copper-Porphyry Deposit

Mineralization in the volcanic rocks is predominantly found at contact zones, indicating a close spatial relationship between ore mineralization and late-stage porphyritic intrusions.



1 – weakly brownish bladed clays; 2 – quartzites over porphyrites and their tuffs; 3 – plagiogranit porphyry and granodiorite porphyry; 4 – secondary quartzite over porphyrite; 5 – albitophyres; 6 – secondary quartzite over plagiogranit porphyry; 7 – diorite porphyry; 8 – diabase porphyrite; 9 – tectonic faults

Figure 2 – Geological map of Koktaszhal Deposit [7]

The structural control of mineralization is evident in the development of a quartz-sulfide stockwork, which is concentrated primarily in the hanging wall of an apophysis. This stockwork is accompanied by intense quartzization, resulting in the formation of monocrystalline quartz rocks. Quartz veins are located along schistose planes and sometimes constitute up to 60-80% of rock volume, with the spaces between them filled with chlorite-sericite aggregates. The main ore mineralization associated with this vein system is represented by quartz-chalcopyrite and quartz-chalcopirite-bornite veins [15]. Thus, the Koktaszhal ore field is characterized by distinctly expressed vein-disseminated and stockwork-type mineralization that is structurally controlled by schistification zones and contact zones of intrusive bodies.

An essential feature of the deposit is the extensive development of the oxidation zone, which can be clearly traced to a depth of 20-50 meters. Malachite, azurite, chrysocolla, native copper, and goethite are found within this zone. At the same time, the leaching zone and the zone of secondary sulfide enrichment are virtually absent, with only occasional grains of covellite and chalcopyrite being observed up to a depth of about 90-95 meters [[15],[16],[17],[18],[19]]. This characteristic of the structure of the upper portion of the ore body suggests that the predominant processes involved are oxidative transformation of copper mineralization without formation of a distinct horizon of secondary sulphide enrichment [[18],[19]].

According to mineralogical and petrographic studies, ore-bearing rocks are represented by silicified acidic intrusive rocks, monocrystalline quartz formations, and layered schistose quartz-mica-chloritic rocks, often with interlayers of injected intrusive rock [[18],[19]].

Rock-forming minerals include quartz (43-45%), acidic plagioclase (31-33%), chlorite (9-11%), hydrophlogite (8-10%), and dolomite (2-3%). In some varieties of rock, intense fracturing is noted, with the development of microfractures, sericite, and impregnation with iron hydroxide, with fine inclusions of ore minerals and free gold grains [18]. This allows us to consider microfracturing and schistosity as the most significant structural and textural characteristics that control the distribution of mineralization within the deposit [[19],[20]].

In general, the geological and structural features of Koktaszhal are determined by a combination of the anticlinal position of the ore field, mineralization associated with silicate apophyses of the Koktaszhal massif, widespread development of quartz-sulfide veins and intense processes of calcification, schistosity and propylitisation of host rocks [15]. This combination reflects the complex structure of the ore-magma system and creates structural and lithological conditions for the formation of vein-interspaced and oxidised copper-gold mineralisation at the Koktaszhal deposit.

Research methodology

For a more detailed study of the mineralogical features of the oxidized copper-gold ores from the Koktaszhal deposit, results of laboratory studies on representative technological samples of ore and mining material were used.

Samples were taken from central parts of ore bodies - Center-1 and Center-2 sites from upper horizons of the oxidation zone within the 2nd layer at 694m. A total of 8 samples of oxidized ore weighing up to 100 kg, including 6.4 kg, were sent to the FLSmidth Dawson Metallurgical Laboratories for analysis. The research involved sample preparation, mineralogical description, chemical, phase, and spectral analyses.

These studies included sample preparation, mineralogical descriptions, chemical, phase, rational, and spectral analyses. Main factual data were obtained during research carried out by the State Scientific and Production Association of Industrial Ecology "Kazmekhanobr" (Subsidiary State Enterprise SSAPIE "Kazmekhanobr"), Kazzink LLP, East Research Mining and Metallurgical Institute of Nonferrous Metals "VNIITSVETMET", and FLSmidt Dawson Metallurgical Laboratories.

Sample preparation for analysis involved mixing the source material, reducing it by quartering, crushing, screening, and separating it into subsamples for individual analysis methods. Loose samples and a medium-sized sample were collected for mineralogical study. Individual subsamples were sent for chemical, fire assay, phase analysis, and mineralogy analysis.

The mineralogical study of ores was conducted using optical-mineralogical methods on transparent and polished thin sections, immersed in liquids, and on polished artificial briquettes made from a medium sample and its heavy fraction. This approach allowed us to determine the composition of the ore and rock-forming minerals as well as the morphological features of malachite and azurite.

The mined material was studied using an Olympus BX51 Pol microscope, a Simagis 2P-2C video camera and SIAMS Mineral C7 software for oxidized primary and secondary copper sulfide deposits in polished sections. Additional information about finely dispersed phases and spatial relationships between copper-bearing minerals and host rock was provided by FLSmidth mineralogical data, including optical microscopy, backscatter electron microscopy, and QEMSCAN analysis.

The chemical and material characteristics of the ores were refined based on the results of semi-quantitative atomic emission spectral analysis, chemical analysis, and phase analysis of copper. Phase analysis was used to determine the ratio of water-soluble, oxidized, secondary, and primary forms of copper, which made it possible to determine the degree of oxidation of the ore and characterize it as an oxidized type of ore. Rational analysis was used to assess the forms of gold and silver, revealing free forms, aggregates with sulfides, rock grains coated with iron hydroxide films, as well as difficult-to-extract forms associated with rock.

Results and Discussion

To characterize the Koktaszhal ore sample, a chemical analysis was performed to determine the main useful components. The results are presented in Table 1. As can be seen from the presented data, the original ore contains 1.0% Cu, 0.8 g/t Au, and 2.0 g/t Ag, making it a porphyry copper deposit with significant commercial copper and precious metal content. Lead and zinc are present in low concentrations, and iron at 1.51% indicates that these elements play a subordinate role in the overall composition of the ore.

Table 1 – Chemical composition of the ore sample from the Koktaszhal deposit

Name	Content, %					g/t	
	lead	zinc	copper	iron	S_{pyr}	gold	silver
Ore	0.07	0.02	1.0	1.51	0	0.8	2.0

According to Table 1, copper is the leading mineral component of the ore, with associated gold and silver. Combined with subsequent mineralogical and phase data, this allows us to consider the sample as oxidized copper porphyry ore.

To characterize the host mineral mass, a silicate analysis of the sample for rock-forming elements was performed. The results are presented in Table 2. The table shows that silicon dioxide (SiO_2) predominates in the ore composition at 69.82%, with a subordinate aluminum oxide (Al_2O_3) content of 12.78%. The contents of the remaining components are significantly lower: Fe_2O_3 – 2.08%, BaO – 1.63%, MgO – 1.35%, and CaO – 0.66%.

Table 2 shows that the ore is dominated by siliceous and aluminosilicate components. The elevated SiO_2 content indicates a significant proportion of siliceous material in the ore structure and may indicate increased strength of the host rocks, while the Al_2O_3 content reflects the presence of aluminosilicate [[20],[21]]. This establishes the significant role of silicate material in the structure of the ore mass, which is important for characterizing its composition and interpreting the properties of the host rocks.

Table 2 – Chemical analysis of the ore sample from the Koktaszhal deposit for rock-forming elements

Name	Content, %					
	BaO	Fe_2O_3	CaO	MgO	Al_2O_3	SiO_2
Ore	1.63	2.08	0.66	1.35	12.78	69.82

To clarify the elemental composition of the studied process sample and assess the role of rare and trace components, a semi-quantitative atomic emission spectral analysis was performed. The results are presented in Table 3. These analysis data allow us to characterize the general geochemical background of the ore and clarify the composition of the host mineral mass.

As can be seen from Table 3 and Fig. 3, the sample is dominated by silicon, aluminum, calcium, magnesium, iron, and sodium, confirming the significant role of the quartz-plagioclase and aluminosilicate host mass. Among the minor components, titanium, barium, and strontium are characterized by relatively elevated contents. Most rare and trace elements are present at low concentrations or below the detection limit.

To determine the mineral composition of the sample, a quantitative mineralogical analysis was performed. Microscopic examination was conducted on the original sample, its heavy fraction, and crushed material. The observation results were compared with data from previous analytical studies, which allowed us to refine the sample's mineral composition and the quantitative ratios of individual minerals.

The results are presented in Table 4 and additionally presented as a histogram (Fig. 4). Analysis of the table and histogram data shows that the main industrially valuable minerals are malachite and azurite, while associated and minor minerals include hematite, magnetite, goethite, pyrite, and limited copper sulfides.

Table 3 – Results of semi-quantitative atomic emission spectral analysis of the sample

Elements	Concentration, %	Elements	Concentration, %
Au	<0.00005	Cd	<0.0005
Cu	<1.0	Ni	0.005
Ag	0.001	Co	0.002
Si	>>1.0	Cr	0.007
Fe	>1.0	Sr	0.1
Ca	>1.0	Sn	0.0003
Al	>>1.0	Ti	0.5
Mg	>1.0	Bi	<0.0002
Pb	0.01	Y	0.003
Zn	0.01	Ge	<0.0002
Na	≥1.0	Tl	<0.0005
Mo	0.0007	Te	<0.003
Hg	<0.003	As	<0.01
Ba	0.15	Be	0.0001
Ga	0.004	W	<0.003
Ta	<0.01	Yb	0.00025
Se	<0.1	Nb	0.001
Re	<0.0003	Sc	0.002

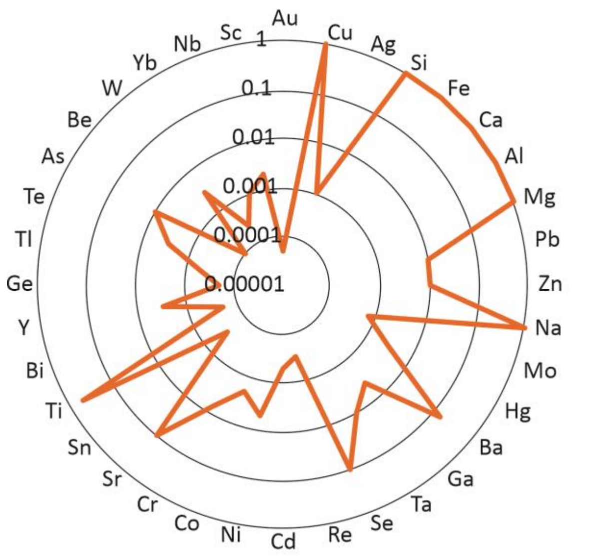


Figure 3 – Element distribution in the sample based on semi-quantitative atomic emission spectral analysis

The rock-forming component is represented primarily by quartz, plagioclase, chlorite, mica, and dolomite.

The described features of the distribution and morphology of copper minerals are clarified by the results of microscopic studies shown in Figures 5 and 6. Microscopic examination of a sample of copper oxide ore allowed us to establish the forms of separation of malachite and azurite, the nature of their distribution in the ore mass, and the features of accretion with rock-forming minerals. It was established that malachites and azurites are represented by two main morphological differences. The first difference is expressed by well-crystallized translucent and transparent formations observed in the form of nests, 1-5 mm in size; veins, 1-3 mm thick; as well as secretions along microcracks and between grains of rock-forming mineral. The second difference is represented by earthy, slightly crystallized collomorphic formations forming inclusions, 0.07-0.2 µm or more, which form cracks and sometimes form accretions with iron hydroxide.

Malachite is characterized by the development of radially fibrous aggregates and kidney-shaped forms.

Table 4 – Mineral Composition of the Ore Sample

Product	Mineral Composition, Mass Fraction, %											
	Ore							Rock-Forming Materials				
Sample	Malachite	Azurite	Gold*	Hematite, Magnetite	Goethite	Sulfides Cu, Cu itself	Pyrite	Quartz	Plagioclase	Chlorite	Mica	Dolomite
	1.5-2.0	0.3-0.4	*SCE*	0.5	0.2	*SCE*	0.2	43-45	31-33	9-11	8-10	2-3

*Note: * – content of gold, copper sulfides, and native copper – SCE (significant concentrations not established). These minerals are present in the sample in quantities below the detection limit; therefore, their mass fraction cannot be quantitatively determined. The absence of significant concentrations of copper sulfides confirms that the sample belongs to the oxidation zone, where primary sulfide minerals are completely replaced by secondary copper oxides and carbonates (malachite, azurite) [[18], [19]].*

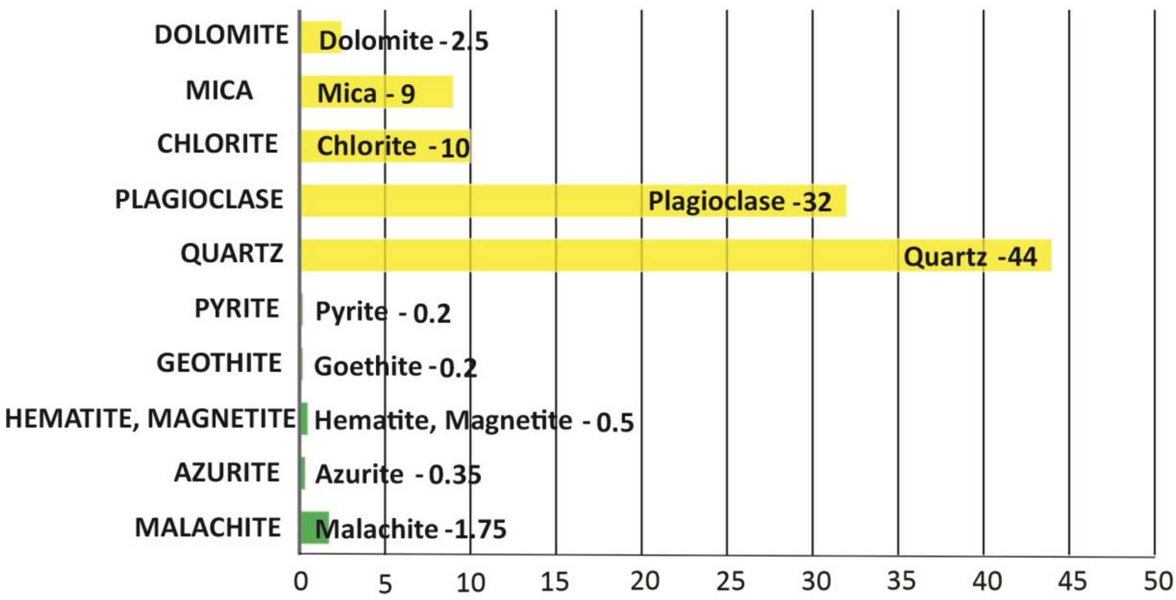


Figure 4 – Distribution of Ore and Rock-Forming Minerals in the Koktaszhal Deposit Ore

The results of rational analysis presented in Table 5 were used to characterize copper species in a sample. Based on phase analysis, copper was found to be extremely unevenly distributed among various compound forms in the Koktashal deposit sample. The total copper content was 0.735%, with the vast majority concentrated in the oxidized form – 0.66% or 89.8% of the total content. Primary copper content was found at 0.047% (6.39%) and secondary copper at 0.2% (2.72%). Water-soluble copper was also found at a concentration of 0.8%.

The predominance of the oxidized form of copper indicates a significant degree of transformation of the original ore mineralization in the hypergenesis zone [22]. According to modern concepts, the formation of powerful oxidation zones in porphyry copper systems requires long-term exposure to oxidation processes in a semi-arid climate and tectonic uplift, resulting in a lowering of the groundwater level [[22],[23]]. The low content of primary and secondary sulfides (around 9% in total) indicates that they are largely destroyed and replaced by oxidation products. Similar processes have been described for hypergenesis zones in the Southern Urals and Lesser Caucasus, where oxidized ores form full-profile zonal patterns with subzones of oxidation, leaching, and secondary sulfide enrichment [[24], [25]]. This allows us to interpret the studied ore samples as material formed under conditions of intense hypergenic oxidation and copper redistribution [[22], [24], [25]].

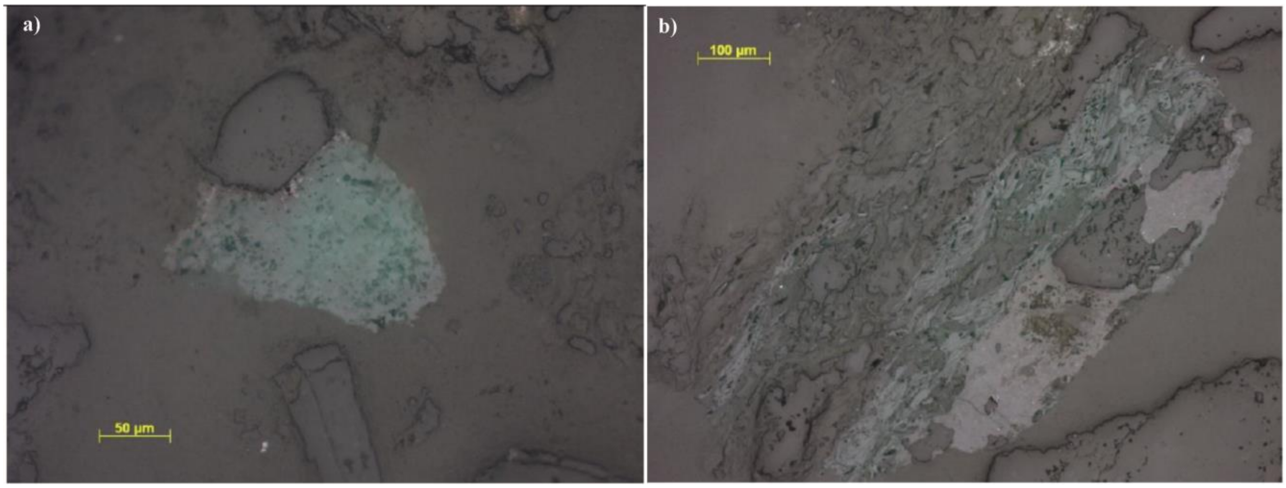


Figure 5 – Optical microscopy images of Cu oxide ore sample: turquoise – malachite /azurite

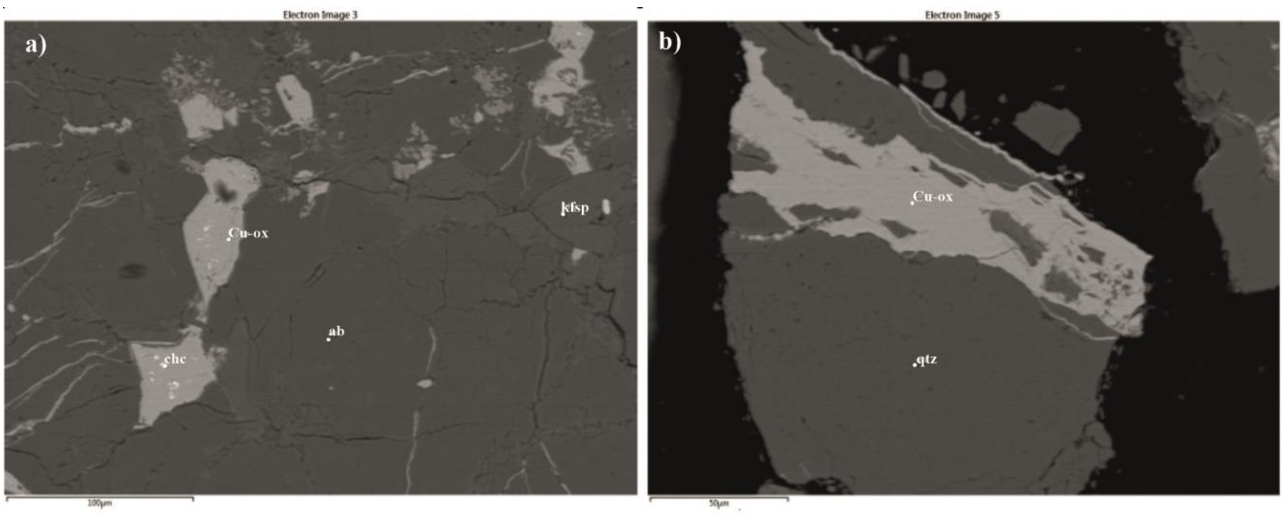


Figure 6 – Electron backscatter microscopy images of a Cu oxide ore sample: Cu-ox = malachite/azurite, chc = chalcocite, ab = albite, kfsp = K-feldspar, qtz = quartz

The results of copper phase analysis in the sample were further visualized as a histogram (Fig.7). This representation allows for a more visual assessment of the ratio of primary, secondary, oxidized, and water-soluble forms of copper, as well as identification of its dominant type in ore. Analysis of the data presented in Table 5 and the resulting histogram (Fig.7) shows that the sample belongs to the oxidized ore type.

Table 5 – Phase analysis of an ore sample from the Koktaszhal deposit (copper)

Minerals	Compounds	Content, %	
		abs.	rel.
Copper	Primary	0.047	6.39
	Secondary	0.02	2.72
	Oxidized	0.66	89.80
	Water-soluble	0.008	1.09
	Total	0.735	100

This is entirely consistent with its mineralogical characteristics, according to which the main ore minerals are malachite and azurite, while primary sulfide forms of copper are subordinate. Determining the oxidized type of ore is of significant scientific and practical importance. On the one hand, this confirms the significant role of hypergenic processes in the transformation of primary copper mineralization [[25], [26]]. On the other hand, it allows us to predict technological features of ore processing, since the predominance of oxidized copper minerals determines specifics of its enrichment and extraction of valuable components [[27], [28]].

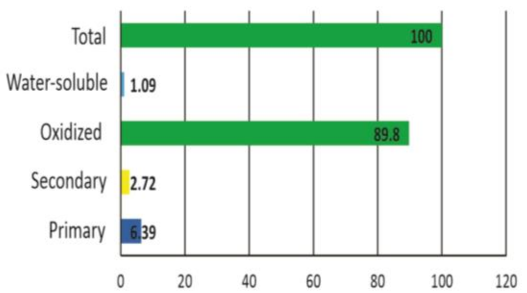


Figure 7 – Phase analysis of ore from the Koktaszhal deposit (copper)

The obtained analytical data indicate that the Koktaszhal ore belongs to the oxidized copper porphyry type with a well-developed supergene alteration zone. Copper is predominantly represented by secondary minerals such as malachite and azurite, which determines favorable conditions for hydrometallurgical processing. The high silica content reflects a strong quartz–aluminosilicate host matrix, which may increase ore hardness and influence comminution characteristics. At the same time, low contents of carbonate components suggest reduced acid consumption during leaching. The presence of finely disseminated copper mineralization and its association with iron hydroxides may negatively affect metal recovery and should be taken into account when selecting processing technology. Overall, the ore is characterized by a favorable composition in terms of valuable components and relatively low concentrations of harmful impurities, making it a promising object for further technological evaluation.

Conclusions

The study revealed that the oxidized copper porphyry ores of the Koktaszhal deposit are characterized by a complex composition and pronounced mineralogical heterogeneity. The main ore minerals in the studied samples were malachite and azurite, while primary and secondary copper sulfides were present in subordinate amounts. The host mineral mass is predominantly siliceous-aluminosilicate in nature and consists primarily of quartz, plagioclase, chlorite, and mica, reflecting the significant role of the silicate matrix in the structure of the ore strata.

It was found that malachite and azurite exhibit significant morphological diversity and are represented by both well-crystallized veinlet-nested formations and colloform earthy aggregates. Their development along microcracks, between grains of rock-forming minerals, and in association with iron hydroxides indicates a significant role for hypergene processes in the transformation of the original copper mineralization. At the same time, the presence of preserved sulfide forms of copper indicates signs of an earlier stage of mineral formation.

The phase composition of copper confirms that the studied ores belong to the oxidized type, as the majority of the metal is associated with oxidized forms.

Therefore, the oxidized ores of the Koktaszhal deposit represent a mineralogically complex product of the processing of a copper-porphyry system under conditions of intense hypergenesis. The combined data obtained allow Koktaszhal to be considered a representative object for the study of the mineral composition, morphology of secondary copper minerals, and the forms of copper occurrence in oxidized copper-porphyry ores.

Conflicts of interest. The authors declare that they have no conflicts of interest regarding the publication of this paper.

CRediT author statement: **K.Toleubek:** Conceptualization, Investigation, Data curation, Writing – original draft; **A. Kopobayeva:** Supervision, Methodology, Validation, Writing – review & editing; **A. Amangeldikyzy:** Investigation, Formal analysis, Data curation; **N. Askarova:** Laboratory analyses, Validation, Data interpretation; **E. Zengin:** Methodology, Software, Formal analysis; **G. Zhunusbekova:** Visualization, Data processing, Writing – review; **B. Mazakh:** Validation, Data curation, Investigation; **A. Battalova:** Resources, Project administration.

Cite this article as: Toleubek KE, Kopobayeva AN, Amangeldikyzy A, Askarova NS, Zengin E, Zhunusbekova GYe, Mazakh B, Battalova AS. Mineralogical Characteristics of Oxidized Copper-Porphyry Ores at the Koktaszhal Deposit. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2028; 346(3):28-39. https://doi.org/10.31643/2028/6445.26

Көктасжал кен орнының тотыққан мыс-порфирлі кендерінің минералогиялық ерекшеліктері

[1] **Төлеубек К.Е.**, [1*] **Копобаева А.Н.**, [1] **Амангелдіқызы А.**, [1] **Асқарова Н.С.**, [2] **Zengin E.**, [1] **Жунусбекова Г.Е.**, [1] **Мазах Б.**, [1] **Батталова А.С.**

[1] *Әбілқас Сағынов атындағы Қарағанды техникалық университеті, Қарағанды, Қазақстан*
[2] *Ыстанбұл техникалық университеті (ITU), Ыстанбұл, Түркия*

Мақала келді: *27 сәуір 2026*
Сараптамадан өтті: *21 мамыр 2026*
Қабылданды: *24 шілде 2026*

ТҮЙІНДЕМЕ

Мақалада Көктасжал кен орнының тотыққан мыс порфир кендерін егжей-тегжейлі зерттеу нәтижелері ұсынылған. Оптикалық микроскопияны, силикатты және фазалық талдауды кешенді қолдану негізінде тотығу аймағының негізгі минералогиялық ерекшеліктері анықталды. Кендердің материалдық құрамы анықталды: мыстың жалпы мөлшері 0,735% құрайды, оның ішінде 0,66% (89,8%) тотыққан түрінде, 0,047% (6,39%) бастапқы, 0,02% (2,72%) екінші реттік және суда еритін 0,008% (1,09%) болды. Анықталған жетекші кен минералдары малахит (1,5-2,0%) және азурит (0,3-0,4%), сондай-ақ қосымша минералдар: магнетит қосылған гематит (0,5%), гетит (0,2%) және пирит (0,2%) бар; мыс сульфидтері және табиғи мыс анықтау шегінен төмен мөлшерде кездеседі. Бұл жұмыстың ғылыми жаңалығы классикалық минералогиялық зерттеулердің сандық фазалық талдау деректерімен үйлесімінен туындайды, бұл бізге кендердің минералды құрамы туралы ақпаратты жүйелеуге ғана емес, сонымен қатар мыстың пайда болуының әртүрлі формалары арасындағы байланысты анықтауға мүмкіндік берді. Малахит пен азуриттің морфологиялық ерекшеліктері сипатталады: олар жақсы кристалданған тамырлы ұялы түзілімдермен және темір гидроксидтерімен байланысты микрожарықтар бойымен дамыған коллоформды жер агрегаттарымен ұсынылған. Алынған нәтижелерді ұқсас объектілерді болжау және іздеу кезінде пайдалануға болады, себебі мыс сульфидтері болмаған кезде малахит пен азуриттің темір гидроксидтерімен байланысы мыс-порфирлік жүйелердің тотығу аймағының диагностикалық ерекшелігі болып табылады, ал мыстың пайда болу формалары туралы сандық деректер бір жағынан барлаудың алғашқы кезеңдерінде кендерді гипергенмен өңдеу тереңдігін бағалауға, ал екінші жағынан, тотығу аймағының кендерін тәуелсіз геологиялық және өнеркәсіптік түрге бөлуге мүмкіндік береді, бұл қорларды есептеуде, кен денелерін анықтауда және өңдеу схемасын таңдауда маңызды болып табылады.

Түйін сөздер: Көктасжал, мыс-порфир кен орындары, тотыққан кендер, мыстың фазалық талдауы, малахит, азурит, алтынның пайда болу формалары, заттық құрамы.

Авторлар туралы ақпарат:

Төлеубек Қымбат Есмахайқызы — *Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Геология және пайдалы қазбалар кен орындарын барлау кафедрасының докторанты, 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: toleubekkymbat69@gmail.com; ORCID ID: https://orcid.org/0000-0003-2126-8084*

Копобаева Айман Нығметовна — *PhD, Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Геология және пайдалы қазбалар кен орындарын барлау кафедрасының қауымдастырылған профессоры, 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: a.n.kopobayeva@gmail.com; ORCID ID: https://orcid.org/0000-0002-0601-9365*

Амангелдіқызы Алтынай — *PhD, Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Геология және пайдалы қазбалар кен орындарын барлау кафедрасының қауымдастырылған профессоры, 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: a.amangeldykyzy@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-6665-8804*

Асқарова Назым Сражадинқызы	*PhD, Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Геология және пайдалы қазбалар кен орындарын барлау кафедрасының қауымдастырылған профессоры (доценті), 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: n.askarova@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-2103-6198*
Zengin Enes	*PhD, Ыстанбұл техникалық университетінің (ITU) Тау-кен факультетінің Геологиялық инженерия кафедрасының қауымдастырылған профессоры, Аязаға кампусы, 34469, Маслак, Ыстанбұл, Түркия. E-mail: eneszengin@itu.edu.tr; ORCID ID: https://orcid.org/0000-0002-5740-7763*
Жунусбекова Гулден Ермухановна	*Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Геология және пайдалы қазбалар кен орындарын барлау кафедрасының аға оқытушысы, 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: zh.gulden@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-6578-5959*
Мазах Бакытжан	*Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Геология және пайдалы қазбалар кен орындарын барлау кафедрасының докторанты, 100027, Қарағанды, Қазақстан. E-mail: 06.06.2005@mail.ru; ORCID ID: https://orcid.org/0009-0007-5390-298X*
Батталова Арай Саяхатовна	*Әбілқас Сағынов атындағы Қарағанды техникалық университетінің Геология және пайдалы қазбалар кен орындарын барлау кафедрасының магистранты, 100027, Нұрсұлтан Назарбаев даңғ. 56, Қарағанды, Қазақстан. E-mail: a84207553@gmail.com; ORCID ID: https://orcid.org/0009-0009-3192-1367*

Минералогические особенности окисленных медно-порфировых руд месторождения Коктасжал

[1]Төлеубек К.Е., [1*]Копобаева А.Н., [1]Амангелдіқызы А., [1]Асқарова Н.С., [2]Zengin E., [1]Жунусбекова Г.Е., [1]Мазах Б., [1]Батталова А.С.

[1]Карагандинский технический университет имени Абылкаса Сагинова, Караганда, Казахстан
[2]Стамбульский технический университет (ITU), Стамбул, Турция

Поступила: *27 апреля 2026*
Рецензирование: *21 мая 2026*
Принята в печать: *24 июля 2026*

АННОТАЦИЯ
В статье представлены результаты детального изучения окисленных медно-порфировых руд месторождения Коктасжал. На основе комплексного применения методов оптической микроскопии, силикатного и фазового анализов выявлены ключевые минералогические особенности зоны окисления. Установлен вещественный состав руд: общее содержание меди составляет 0,735%, из которых 0,66% (89,8%) приходится на окисленную форму, 0,047% (6,39%) – на первичную, 0,02% (2,72%) – на вторичную и 0,008% (1,09%) – на водорастворимую. Идентифицированы ведущие рудные минералы: малахит (1,5-2,0%) и азурит (0,3-0,4%), а также второстепенные: гематит с магнетитом (0,5%), гетит (0,2%) и пирит (0,2%); сульфиды меди и самородная медь присутствуют в количествах ниже предела обнаружения. Научная новизна работы обусловлена сочетанием классического минералогического изучения с количественными данными фазового анализа, что позволило не только систематизировать сведения о минеральном составе руд, но и уточнить соотношение различных форм нахождения меди. Охарактеризованы морфологические особенности малахита и азурита: они представлены как хорошо окристаллизованными прожилково-гнездовыми образованиями, так и колломорфными землистыми агрегатами, развитыми по микротрещинам в ассоциации с гидрооксидами железа. Полученные результаты могут быть использованы при прогнозировании и поисках аналогичных объектов, поскольку установленная ассоциация малахита и азурита с гидрооксидами железа при отсутствии сульфидов меди является диагностическим признаком зоны окисления медно-порфировых систем, а количественные данные о формах нахождения меди позволяют, с одной стороны, оценивать глубину гипергенной переработки руд на ранних стадиях разведки, а с другой – выделить руды зоны окисления в самостоятельный геолого-промышленный тип, что важно при подсчёте запасов, оконтуривании рудных тел и выборе технологической схемы переработки.

Ключевые слова: Коктасжал, медно-порфировые месторождения, окисленные руды, фазовый анализ меди, малахит, азурит, формы нахождения золота, вещественный состав.

Информация об авторах:

Толеубек Кымбат Есмахайкызы	*Докторант кафедры Геология и разведка месторождений полезных ископаемых Карагандинского технического университета имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: toleubekkymbat69@gmail.com; ORCID ID: https://orcid.org/0000-0003-2126-8084*
Копобаева Айман Ныгметовна	*Доктор PhD, ассоциированный профессор кафедры Геология и разведка МПИ, Карагандинский технический университет имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: a.n.kopobayeva@gmail.com; ORCID ID: https://orcid.org/0000-0002-0601-9365*

Амангелдіқызы Алтынай	*Доктор PhD, ассоциированный профессор кафедры Геология и разведка МПИ, Карагандинский технический университет имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: a.amangeldykyzy@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-6665-8804*
Аскарова Назым Сраджадиновна	*Доктор PhD, ассоциированный профессор (доцент) кафедры Геология и разведка МПИ, Карагандинский технический университет имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: n.askarova@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-2103-6198*
Zengin Enes	*PhD, ассоциированный профессор кафедры геологической инженерии горного факультета Стамбульского технического университета (ITU), кампус Аязага, 34469, Маслак, Стамбул, Турция; E-mail: eneszengin@itu.edu.tr; ORCID ID: https://orcid.org/0000-0002-5740-7763*
Жунусбекова Гулден Ермухановна	*Старший преподаватель кафедры Геология и разведка кафедры МПИ, Карагандинский технический университет имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: zh.gulden@ktu.edu.kz; ORCID ID: https://orcid.org/0000-0002-6578-5959*
Мазах Бакытжан	*Докторант кафедры Геология и разведка месторождений полезных ископаемых Карагандинского технического университета имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: 06.06.2005@mail.ru; ORCID ID: https://orcid.org/0009-0007-5390-298X*
Батталова Арай Саяхатовна	*Магистрант кафедры Геология и разведка месторождений полезных ископаемых, Карагандинский технический университет имени Абылкаса Сагинова, 100027, пр. Нурсултана Назарбаева, 56, Караганда, Казахстан. E-mail: a84207553@gmail.com; ORCID ID: https://orcid.org/0009-0009-3192-1367*

References

[1] International Copper Association. Copper Environmental Profile. URL: https://copperalliance.org/wp-content/uploads/2021/08/ICA-EnvironmentalProfileHESD-201803-FINAL-LOWRES-1.pdf

[2] International Copper Study Group. The World Copper Factbook 2024. Lisbon: International Copper Study Group, 2024. URL: https://icsg.org/download/2024-09-23-the-world-copper-factbook-2024/

[3] Ayuso RA, Barton MD, Blakely RJ, Bodnar RJ, Dilles JH, Gray F, Graybeal FT, Mars JL, McPhee D, Seal RR, Taylor RD, Vikre P. Porphyry copper deposit model. Reston, VA: U.S. Geological Survey. Scientific Investigations Report 2010-5070-B. 2010, 169. https://doi.org/10.3133/sir20105070B

[4] Sillitoe RH. Porphyry copper systems. Economic Geology. 2010; 105(1):3-41. https://doi.org/10.2113/gsecongeo.105.1.3

[5] International Energy Agency. Global Critical Minerals Outlook 2024. Paris: IEA. 2024.

[6] International Energy Agency. Copper. Paris: IEA. 2024.

[7] Li C, Shen P, Seltmann R, Zhang D, Pan H, Seitmuratova E. Quartz textures, trace elements, fluid inclusions, and in situ oxygen isotopes from Aktogai porphyry Cu deposit, Kazakhstan. American Mineralogist. 2025; 110(2):272–292. https://doi.org/10.2138/am-2023-8931

[8] Serikbayeva E, Togizov K, Talgarbayeva D, Orynbassarova E, Sydyk N, Bermukhanova A. Application of Multispectral Data in Detecting Porphyry Copper Deposits: The Case of Aidarly Deposit, Eastern Kazakhstan. Minerals. 2025; 15:938. https://doi.org/10.3390/min15090938

[9] Ragdanova A, Mataibayeva I, Frolova O, Agaliyeva B, Dolgopolova A, Togizov K. Structural-formational zones with porphyry copper mineralization – A promising mineral resource base for copper in Eastern Kazakhstan. Min. Miner. Depos. 2025; 19:107-120. https://doi.org/10.33271/mining19.01.107

[10] Baibatsha A, Vikentyev I, Muratkhanov D, Bulegenov K. New Porphyry Copper-Molybdenum Ore Occurrence in Arganaty Granites of the Eastern Balkhash (Kazakhstan): Geology, Geochemistry, and Mineralogy. Geosciences. 2024; 14:237. https://doi.org/10.3390/geosciences14090237

[11] Kopobayeva AN, Zharylgapov YeYe, Ulgibayeva BS, Amangeldikyzy A, Askarova NS, Kabyken AB. A study of the geochemical features of the Nurkazgan copper-porphyry deposit. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2027; 340(1):67-76. https://doi.org/10.31643/2027/6445.07

[12] Kopobayeva A, Musabayeva M, Amangeldikyzy A, Askarova N, Issatayeva F, Toleubek K, & Mazakh B. Study of geochemical characteristics of the Bakyrchik ore zone. Kompleksnoe Ispolzovanie Mineralnogo Syra = Complex Use of Mineral Resources. 2026; 338(3):81–91. https://doi.org/10.31643/2026/6445.31

[13] Shah Z, Bayramov E, Neafie J, Seltmann R, Rahnama Z. Determination of geospatial criteria and prediction of potential areas for porphyry copper deposits in Kazakhstan. Sec. Geoinformatics. 2025; 13. https://doi.org/10.3389/feart.2025.1489969

[14] Feng H, Seltmann R, Shen P, Chu X, Suo Q, Seitmuratova E, Shatov V. Hydrothermal rutile chemistry and U-Pb age fingerprinting of the formation of the giant Nurkazgan porphyry Cu-Au deposit, Central Kazakhstan. Ore Geology Reviews. 2024, 174. https://doi.org/10.1016/j.oregeorev.2024.106293

[15] Bolatbekuly S, Umirova G, Zakariya M, Temirkhanova R, Togizov K. Formation of prospecting criteria for copper-porphyry deposits based on the construction of reference models. Nauk. Visnyk Natsionalnoho Hirnychoho Universytetu. 2024; 2:19-24. https://doi.org/10.33271/nvngu/2024-2/019

[16] Kopobayeva AN, Toleubek KE, Amangeldikyzy A, Askarova NS. Mineral and geochemical features of the porphyry copper ores at Koktaszhal deposit, central Kazakhstan. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu. 2025; 5:23-31. https://doi.org/10.33271/nvngu/2025-5/023

[17] Duzhnikova EV, Kryazheva TV, Kenzhin B M. Mineralnyy sostav rud i usloviya ikh obrazovaniya na mestorozhdenii Koktaszhal [Mineral composition of ores and conditions of their formation at the Koktaszhal deposit]. Vestnik VKGTU im. D. Serikbayeva. 2019; 1(83):3-8. (in Russ.).

[18] Duzhnikova Ye V, Kryazheva TV, Toleubek KYe. Koktaszhal ore field (Central Kazakhstan) research results. Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu. 2020; 3:5-12. https://doi.org/10.33271/nvngu/2020-3/005

[19] Otchet po rezultatam laboratornykh issledovaniy na obogatimost proby rudy mestorozhdeniya Koktaszhal [Report on the results of laboratory tests on the enrichment of ore samples from the Koktaszhal deposit]. Zyryanovsk. 2011. (in Russ.).

[20] Izucheniye prichin poter medi pri flotatsii okislennoy rudy na OF TKB i razrabotka rezhima povysheniya izvlecheniya eye iz srednikh klassov krupnosti (-0.125+0.04 mm): otchet o nauchno-issledovatelskoy rabote [Investigation of the causes of copper losses during flotation of oxidized ore at the Office of the TCB and the development of a mode for increasing its extraction from medium grades of fineness (-0.125+0.04 mm): research report] Ust-Kamenogorsk: VNIItsvetmet. 2017. (in Russ.).

[21] Pękala A. The Influence of Siliceous Mineral Phases on the Mechanical Properties of Transitional Rocks in the Belchatow Lignite Deposit. E3S Web of Conferences. 2015; 8:01018. https://doi.org/10.1051/e3sconf/20150801018.

[22] Sillitoe RH. Supergene oxidized and enriched porphyry copper and related deposits. Economic Geology 100th Anniversary Volume. 2005, 723-768. https://doi.org/10.5382/AV100.22.

[23] Sillitoe RH, McKee EH. Age of supergene oxidation and enrichment in the Chilean porphyry copper province. Economic Geology. 1996; 91(1):164-179. https://doi.org/10.2113/gsecongeo.91.1.164

[24] Belogub EV, Novoselov KA. Gipergenez sulfidnykh mestorozhdeniy Yuzhnogo Urala: novyye dannyye po stroyeniyu. mineralogii i izotopnomu sostavu sery i ugleroda. Rudogenez [Hypergenesis of sulfide deposits in the Southern Urals: new structural data. mineralogy and isotopic composition of sulfur and carbon]. 2020. (in Russ.).

[25] Azadaliyev DzhA. Guseynova EB. Mineralogo-geneticheskiye osobennosti zony gipergeneza Garadagskogo mestorozhdeniya medno-porfirovykh rud (Gyadabeyskiy rudnyy rayon Malogo Kavkaza, Azerbaydzhan) [Mineralogical and genetic features of the hypergenesis zone of the Garadagh deposit of copper porphyry ores (Gadabeysky ore district of the Lesser Caucasus. Azerbaijan)]. ANAS Transactions. Earth Sciences. (in Russ.).

[26] Atapour H, Aftabi A. The geochemistry of gossans associated with Sarcheshmeh porphyry copper deposit, Rafsanjan, Kerman, Iran: Implications for exploration and the environment. Journal of Geochemical Exploration. 2007; 93(1):47-65. https://doi.org/10.1016/j.gexplo.2006.07.007

[27] Chavez WX. Supergene oxidation of copper deposits: Zoning and distribution of copper oxide minerals. SEG Discovery. 2000; 41:1-21. https://doi.org/10.5382/SEGnews.2000-41.fea

[28] Feng Q, Yang W, Wen S, Wang H, Zhao W, Han G. Flotation of copper oxide minerals: A review. International Journal of Mining Science and Technology. 2022; 32(6):1351-1364. https://doi.org/10.1016/j.ijmst.2022.09.011.