https://doi.org/10.33271/nvngu/2025-5/023

A. N. Kopobayeva,
orcid.org/0000-0002-0601-9365,
K. E. Toleubek*,
orcid.org/0000-0003-2126-8084,
A. Amangeldikyzy*,
orcid.org/0000-0002-6665-8804,
N. S. Askarova,
orcid.org/0000-0002-2103-6198

Abylkas Saginov Karaganda Technical University, Karaganda, Republic of Kazakhstan
* Corresponding authors e-mail: toleubekkymbat69@gmail.com; a.amangeldykyzy@ktu.edu.kz

MINERAL AND GEOCHEMICAL FEATURES OF THE PORPHYRY COPPER ORES AT KOKTASZHAL DEPOSIT, CENTRAL KAZAKHSTAN

Purpose. To study mineralogical and geochemical characteristics of Koktaszhal porphyry copper deposit in order to reveal regularities of porphyry copper ore formation and develop exploration criteria.

Methodology. The research applies modern mineralogical and geochemical approaches including XRF (X-ray fluorescence), optical emission spectrometry (ICP-OES), X-ray diffraction analysis (XRD), chemical analysis and phase analysis, as well as analysis of literature and library materials.

Findings. Complex mineralogical and geochemical studies of ores of Koktaszhal deposit revealed a complex structure conditioned by porphyry copper mineralization and zonal distribution of its components. Geochemical analysis revealed the prevalence of SiO_2, Al_2O_3 and Na_2O in the ore composition. Comparison of oxide and sulphide ore analyses determined a clear spatial and geochemical differentiation of ore components, which reflects different stages of ore formation. It was found that in oxide ore 79.5 % of copper is associated with malachite and azurite, and in sulphide ore, 79 % of copper is associated with bornite. The supergene alteration zone is enriched in Bi, Pb, Co, Ni, which indicates the migration of these elements in the weathering zones, while the sulphide zone is characterized by stable content of Mo, Sb and Ag, which confirms the primary-sulphide nature of the studied mineralization and its formation under low temperature conditions. X-ray diffraction and electron microscopic analyses revealed predominance of quartz, albite, muscovite and other silicates, which confirms the presence of intensive processes of argillisitization and sericitization. The results of thermogravimetric analysis showed high thermal stability of the ore and predominance of thermally stable minerals. The results obtained make it possible to clarify the morphology of ore bodies, to identify geochemical criteria for exploring and evaluating porphyry copper objects, as well as to substantiate directions for ore processing optimization.

Originality. The porphyry copper mineralization of Koktaszhal deposit was comprehensively researched using modern analytical and statistical methods. For the first time, a complex interpretation of mineralogical and geochemical characteristics of ores was performed taking into account their spatial variability and influence of tectonic faults. The research identified new genetic features reflecting the stages of fluid mineralization, as well as diagnostic parameters allowing reliable differentiation of ore types.

Practical value. The obtained results can be used in ore bodies modelling and planning of exploration works at the stage of assessment and revaluation of reserves of porphyry copper deposits of Central Kazakhstan.

Keywords: *porphyry copper ores, Koktaszhal, geochemistry, mineralogy, clarke, oxide ores, sulphide ores*

Introduction. Porphyry copper deposits play a key role in the global economy since they provide more than 60 % of the world's copper production, which is used in electronics, construction and high-tech manufacturing [1]. For example, in Chile, copper ores account for up to 15 % of the country's GDP (gross domestic product) [2], which demonstrates the importance of these resources for the economic growth. With the growing demand for copper, especially in relation to the development of electric vehicles, strategic value of porphyry copper deposits grows [3]. It is important to note that up to 100 kg of copper is required to produce one electric vehicle [4], which emphasizes their role in new technologies. Current research shows that successful operation of these fields shall take into account social and environmental aspects to minimize the negative impact on the environment [5]. Thus, porphyry copper deposits are not only a major source of copper, but also a key component for sustainable economic development.

Kazakhstan occupies a strategically important position as a key region with large porphyry copper deposits that play a significant role in the global mining industry. The country has one of the largest copper reserves, making it an important player in the international market [6]. Deposits such as Bozshakol, Aktogay and Koktaszhal attract investors' attention due to their potential, which can be estimated based on exploration operations and high-grade mineralogy [7]. According to the study, Kazakhstan ranks 11th in the world in terms of copper reserves and *5th* in terms of its production level [8]. The importance of this sector of the economy is also emphasized by the fact that copper ores constitute a significant part of the country's export potential [9]. The lack of detailed mineralogical and geochemical research in a number of deposits hampers effective exploration and reserve assessment [10], which emphasizes the need for further research and involvement of modern technologies in exploration and production. Kazakhstan, with its rich porphyry copper reserves and growing importance in the global economy, is therefore a strategically important region for sustainable development of the mining industry. Data on genetic, mineralogical and geochemical features of ores allowed for determining the sequence of ore formation, and for describing the most favourable conditions for the deposition of Au, Ag, Cu minerals.

The obtained data will be used as exploration criteria for effective operational assessment of specific promising objects, which will contribute to increasing the mineral resource base of the country. The research has fundamental and theoretical value, as it allows for better understanding of the processes associated with migration of chemical elements that occurred during the ore formation in porphyry copper deposits.

The main purpose of this work is to highlight the features of mineralogical and geochemical characteristics of copper ores of Koktaszhal porphyry copper deposit for the development of exploration criteria of porphyry copper mineralization.

Literature review. In recent decades, scientific interest in issues related to geochemistry and the conditions of formation of copper–porphyry deposits has increased both on a global and regional level. A significant portion of research focuses on clarifying geological prerequisites for formation of these deposits, including their relationship with magmatism and composition of ore-bearing magmatic complexes as well as tectonic settings primarily involving subduction zones and island arcs [11–15]. Special attention is paid to the mineralogical and geochemical characteristics of copper-porphyry systems. The study of the mineral composition of ores reveals the presence of typical sulfide minerals such as chalcopyrite, bornite and molybdenite, as well as a wide range of secondary and related minerals that play an important role in assessing ore formation conditions [16–19]. Geochemical studies make it possible to determine the characteristic concentrations and distribution of elements such as copper, molybdenum, gold and silver in both ores and host rocks. This contributes to the reconstruction of ore genesis processes and the identification of productive geochemical associations [11, 15, 20, 21]. In addition, the study of their spatial arrangement makes a significant contribution to understanding the features of copper-porphyry systems. In particular, large deposits have been studied and described in detail in Kazakhstan, including Aktogai, Aidarli, Kounrad, Bozshakol, Nurkazgan, and Koksai. These objects serve as important models for analyzing regional patterns of formation and localization of copper porphyry ore systems [6–10, 22–27].

The research is devoted to the study of the mineralogical and geochemical characteristics of the ores of the Koktaszhal deposit, taking into account their spatial variability and the influence of tectonic disturbances. Copper-porphyry ores are spatially associated with Mesozoic intrusions and deep faults that control the localization of mineralization [6, 7].

Geological and structural characteristics of the deposit. Koktaszhal deposit (Fig. 1) is located in Central Kazakhstan and is characterized by a complex structure and unique ore-bearing features. It is associated with magmatic intrusions and hydrothermal systems that have ensured formation of economically significant ore zones [11, 12].

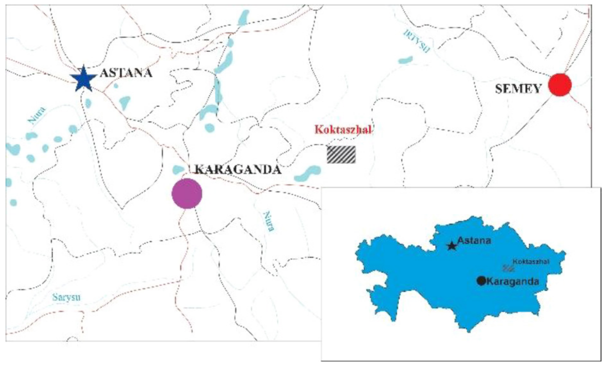


Fig. 1. Location of Koktaszhal porphyry copper deposit

Koktaszhal zone belongs to the ridge of the same name, which stretches in the north-western direction. The deposit is made of effusive and tuffogenic rocks of the Caradocian Stage of the Ordovician period, which are broken by plagiogranite porphyry intrusions. Vein rocks are widespread: diorite and diabase porphyrites, albitophyres, quartz diorites and plagiogranites (Fig. 2). The main rocks of the host strata are represented by lithic-crystal and crystal tuffs, with plagioclase and amphibole fragments predominating in the fragmental material. Fragments and groundmass have been exposed to intensive hydrothermal processing (chloritization, sericitization, carbonatization) [13, 14].

Intrusive rocks of the deposit include plagiogranite porphyries of Karazhal-Koktaszhal massif, which can be traced along the strike for more than 1.3 km with thickness of 10 to 70 meters. The basic structure of the intrusions is porphyritic, with microcrystalline and thin-crystalline groundmass. Secondary alterations are expressed in the development of sericite, epidote, chlorite and carbonates. In the contact zones, the rocks are enriched with dark-coloured minerals, and locally change to granodiorite porphyries and quartz diorite porphyries [11].

Hydrothermal activity associated with intrusion conditioned formation of a dense network of veins with varying thickness. Quartz and quartz carbonate veins range from fractions of a millimetre to several meters. Quartz chalcopyrite and quartz chalcopyrite bornite veins are widespread in the northwest of the mineralization zone [15]. Structural and mineralogical features of Koktaszhal deposit indicate its belonging to the porphyry copper type. The zonal distribution of the minerals and hydrothermal alteration emphasizes complexity of ore-forming processes that occurred under the conditions of intense tectonic activity.

Research methods. For more detailed research on the mineralogical and geochemical features of the Koktaszhal deposit, field research was carried out, which included sampling of oxide and sulphide ores, and host rocks in total amount of 40 samples using furrow and core methods with XRF. Sample preparation operations was performed for the taken field samples to ensure high quality of the samples for further analysis. These operations included treatment, grinding, and separation of the samples, which facilitated production of homogeneous test samples. The chemical and elemental com-

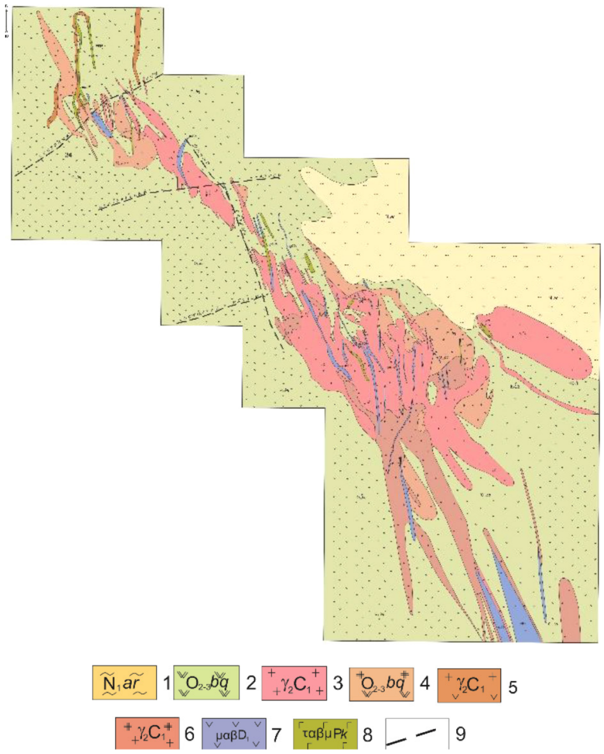


Fig. 2. Geological Map of Koktaszhal Deposit

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

position was determined using the following methods: XRF (X-ray fluorescence), optical emission spectrometry (ICP-OES), chemical analysis, phase analysis, X-ray diffraction analysis (XRD), and to obtain a more complete characterization of the ore composition and its features, the thermogravimetric studies were performed using simultaneous thermal analysis device by METTLER TOLEDO. The research was conducted in the laboratories of the branch of RSE "National Centre for Complex Processing of Mineral Raw Materials of the Republic of Kazakhstan", State Scientific and Production Association for Processing and Treatment of Minerals "Kazmekhanobr", DAWSON METALLURGICAL laboratories FLSmidth subdivision of FLSmidth company, and in the research centre Outotec (ORC) in Pori (Finland).

A Zeiss Axioplan2 optical microscope equipped with an AxioCam ECs 5 s camera, which recorded the optical images, was used to establish mineralogical features. A JEOL 6940LV scanning electron microscope (SEM) equipped with an energy dispersive (EDS) spectrometer was used to analyse the chemical composition of the mineralogical phases and to obtain high-resolution images of these phases. The mineralogical composition of the studied material was determined based on the information and observations obtained by means of optical microscope and electron scanning microscope with energy dispersive spectrometry during the analysis of identifiable phases and minerals, and also as a result of chemical analyses of samples using both total and selective dissolution methods. Mineralogical calculations were performed using a HSC-Geo material balance calculation software application, version 7.0.

Research results. The results of the complex mineralogical and geochemical studies of ores of Koktaszhal deposit indicate a complex structural organization conditioned by the processes of porphyry copper mineralization and zonal distribution of the components. Ore minerals are represented by malachite, azurite, and sulphides. The upper horizons are characterized by the predominance of oxidized minerals such as malachite and azurite, while there are predominantly primary sulphides in the deeper horizons.

The research allowed for a detailed assessment of the mineralogical composition and geochemical characteristics of the ores, which is an important basis for further research on porphyry copper deposits. The geochemical analysis showed that ore samples consist predominantly of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3) and sodium oxide (Na_2O), and contain a number of other components.

It was found that the sulfur content amounts to 0.026 % in oxide ore and 0.301 % in sulphide ore, and carbon content is 0.07 and 0.22 %, respectively (Table 1). Significant excess of bulk earth values according to A. P. Vinogradov (1962) [16] if compared to clarkes of V. I. Serykh, [17] was registered for Mo, Au, Ag and a nuber of other elements. In general, oxide ore is characterized by higher Cu content, whereas sulphide ore shows higher Fe, Mg, Ca and S content, which indicates differences in their mineralogical composition and formation conditions.

For detailed comparison of the obtained data with background values of the lithosphere, as well as for the purpose of complex geochemical assessment of the ore samples, the authors constructed diagrams (Figs. 3, 4, 5) reflecting the distribution of the chemical elements content and their compounds in oxide and sulphide forms. To increase analytical significance, the results were compared with the clarkes of Vinogradov A. P. [16] and Serykh V. I. [17], which made it possible to more clearly identify abnormal concentrations of ore-forming and associated components. Selection of clarkes of Serykh V. I. is conditioned not only by their geographical validity, but also by their practical applicability that is confirmed by large-scale studies exclusively within the territory of Central Kazakhstan, strict analytical verification and approbation [18–20]. This makes them the most reasonable basis for geochemical calculations and interpretations under the conditions of Central Kazakhstan. Such a comparative approach provides an opportunity to trace the migration features of the chemical elements, assess the degree of their enrichment relative to the lithospheric background.

The diagrams show the comparison of the chemical elements and compounds content in oxide and sulphide forms with the clarks by Vinogradov A. P. and Serykh V. I. [16, 17], which allows for the comprehensive geochemical interpretation of the studied samples.

The oxide form demonstrates significant enrichment with such elements as Co, Ni, Pb and, in particular, Bi, if compared to background values of their clarkes, at the same time difference with the clarkes by Serykh V. I. is expressed more significantly. This indicates the migration and accumulation of these elements in the zones of

Table 1

Composition of Oxide and Sulphide Copper Ore Samples That is Identified by the Methods of X-Ray Fluorescence, g/t

Elements and Compounds	Clarkes acc. [16], g/t	Regional Clarkes acc. [17], g/t	Oxide Ore, g/t	Sulphide Ore, g/t	Elements and Compounds	Clarkes by [16], g/t	Regional Clarkes acc. [17], g/t	Oxide Ore, g/t	Sulphide Ore, g/t
Ni	58	11	30	40	Mn	1,000	–	40	400
Co	18	5.0	*170	*70	Mg	18,700	–	4,800	13,100
Zn	83	50	20	50	Ca	29,600	–	3,390	1,660
Pb	16	13	*70	*80	Ba	12	1,403	*17	*25
Sb	0.5	–	<50	<50	S	470	50	260	301
Bi	0.009	–	<50	<50	C	230	–	*700	*2,200
Te	0.001	–	*60	*60	Au	0.0043	0.0068	*0.83	*0.58
Y	29	20	<10	16	Ag	0.07	0.077	*4.97	*3.15
Nb	20	9	*27	*38	SiO_2	–	70.14	76.8	70.0
Mo	1.1	1.4	*5.3	*4.2	TiO_2	–	0.31	0.246	0.63
Sn	2.5	1.7	<20	<20	Al_2O_3	–	14.81	12.7	13.7
W	1.3	–	<20	<20	Cr_2O_3	–	–	0.039	0.029
Ga	19	17	<30	<30	V_2O_3	–	–	0.0094	0.011
Cl	170	–	90	70	FeO	–	2.15	1.19	3.00
Th	13	–	<10	<10	MnO	–	0.06	0.005	0.052
U	2.5	2.0	<5	<5	MgO	–	0.99	0.79	2.18
Cs	3.7	4.1	<10	20	CaO	–	2.12	0.475	2.33
La	29	37.3	20	20	Rb_2O	–	–	<0.001	<0.001
Ce	70	36.5	10	40	SrO	–	–	0.022	0.016
Ta	2.5	0.8	*20	*10	BaO	–	–	0.018	0.027
Si	295,000	–	359,000	327,000	Na_2O	–	4.49	5.49	6.10
Ti	4,500	–	1,470	3,790	K_2O	–	2.48	0.61	0.52
Cr	83	19	*260	*200	ZrO_2	–	–	0.212	0.021
V	90	46	60	80	P_2O_5	–	0.12	0.038	0.187

* *contents exceeding the clarke for igneous rocks by Vinogradov A. P. (1962)* [16] *and Serykh V. I.* [17]

hypogene transformation and weathering [21, 22]. At the same time, such elements as Zn and Ag are within or below background values, which may be due to their mobility and instability in the oxidized environment [23].

Comparison of the sulphide form shows more stable and higher content of the ore components, which is characteristic of primary hydrothermal systems. The enrichment with Mo, Zn, Sb and Bi is particularly pronounced, as well as the persistent presence of Ag. This confirms the primary sulphide nature of the studied mineralization and its formation under the low temperature conditions rich in volatile components [24, 25].

Study of compounds in oxide form reveals high concentrations of SiO_2, Al_2O_3, Na and Ti, which indicates the predominance of acidic alteration – argillisitization, sericitization and superimposed weathering processes [25, 26]. The presence of carbonate and ferruginous phases is confirmed by the increased content of MgO, CaO and FeO, as well as P_2O_5. These features indicate the formation of oxidation zones and alteration of parent rocks under the conditions of acidic fluids [26].

The sulphide form of the compounds shows higher contents of FeO, MgO and CaO, which suggests the presence of primary minerals – carbonates and sulphides, formed under the conditions of metasomatosis and hydrothermal activity [27]. Taken together, the obtained results emphasize the presence of pronounced geochemical zone sequence, which reflects the stages of ore body formation and confirms industrial potential of the studied object [27, 28].

As a result of the research, the methods of optical microscopy found that the main copper mineralogical phases are malachite ($Cu_2(OH)_2CO_2$) and azurite ($Cu_3(CO_3)_2(OH)_2$) with inclusions of copper sulphides, chalcocite. (Cu_2S) and chalcopyrite ($CuFeS_2$) (Figs. 6, 7).

In the sulphide ore sample, bornite and chalcopyrite were identified as the main copper sulphides (Fig. 8).

A number of associated minerals were identified and their chemical composition was determined using scanning electron microscopy. Additional silicates identified by SEM are albite, quartz, chlorite, biotite, K-feldspar, hornblende, rutile, titanite, apatite, and calcite (Fig. 9).

The mineralogical compositions of the samples were calculated (Table 2). Both samples consisted mainly of albite, quartz and mica (chlorite and biotite). Since the oxide ore contained both copper oxides, namely mala-

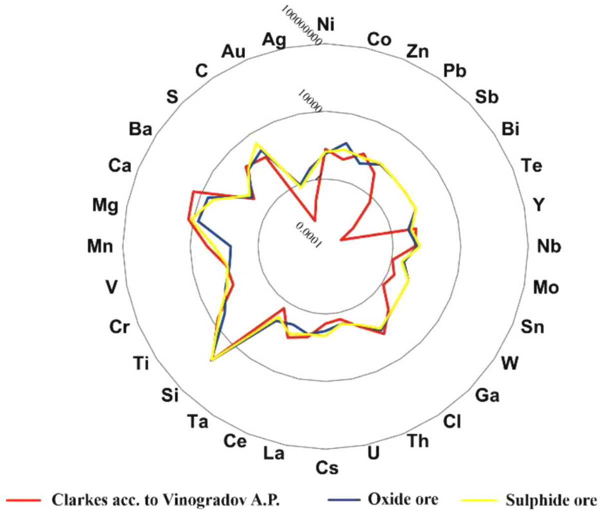


Fig. 3. Comparative Analysis of Chemical Elements Content in Oxide and Sulphide Ore with the Clarkes by Vinogradov A. P.

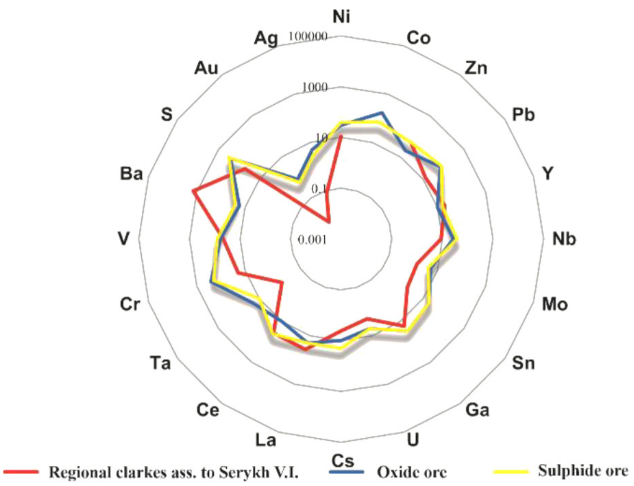


Fig. 4. Comparative Analysis of Chemical Elements Content in Oxide and Sulphide Ore with the Regional Clarkes by Serykh V. I.

chite and azurite, it was not possible to calculate their exact weight percentages separately. Their total estimated weight percentage in the oxide ore sample was 1.46 %, which, given the very low copper sulphide content (<0.1 % by weight), suggested that the main part of the copper (79.5 %) was naturally distributed among the copper oxides. The major copper sulphide in the sulphide ore was bornite (0.75 % by weight), with 79 % of total copper. Chalcopyrite was the second most copper-rich sulphide (0.34 % by weight) and contained 19.5 % of total copper. The remainder of the copper (1.3 %) was contained in copper oxides.

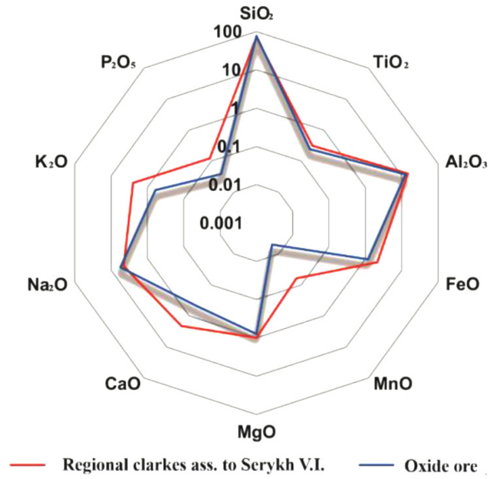
Based on the phase analysis, the research identified the zone sequence of mineralization characterized by the transition from the oxide zone to the primary sulphide zone (Fig. 8). The obtained data allow for clarifying the boundaries of the zones and their mineralogical composition. Detailed analysis of mineral compounds allowed for quantitative assessment of copper distribution in different zones of Koktaszhal deposit.

In the sulphide ore, the total copper content is 0.62 %, and most of it is in the primary form (0.43, or 70.17 % of the total copper content). Secondary copper accounts for 0.15 % (28.07 %), while oxidized and water-soluble compounds account for only 0.04 and 0.0002 %, respectively. This indicates the predominance of primary copper minerals, which may indicate a low degree of weathering and little secondary processing of the ore under natural conditions.

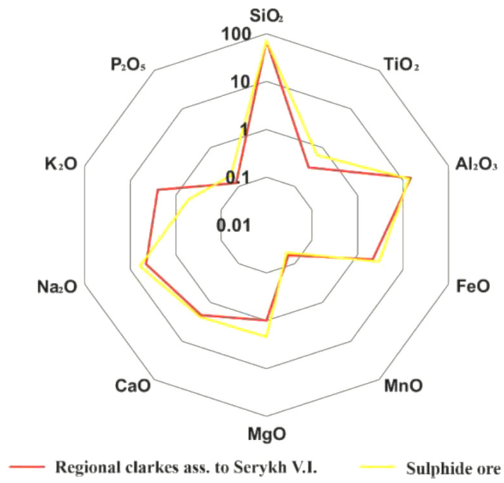
The oxidized ore has a total copper content of 0.49 %, with 79.90 % being oxidized forms (0.39 %), while secondary copper amounts to only 0.02 % (3.67 %). This indicates a high level of copper oxidation in this sample.

As a result of geochemical analysis, it was found that the ore samples show differences in the forms of copper present. This indicates not only differences in ore types, but also reflects a two-stage genesis: hypogene formation of sulphide minerals with their subsequent oxidation in the zone of hypogenesis. Such zone sequence can serve as an indirect indicator of the presence of a secondary enrichment zone that is characteristic of porphyry copper deposits, where chalcosine formation is possible in the cementation zone [29–31].

Fig. 11 shows the diffractogram and results of mineral composition analysis for carbonate and igneous rocks.



a



b

Fig. 5. Comparative Analysis of Compounds Content in a) Sulphide and b) Oxide Ore with the Regional Clarkes by Serykh V. I.

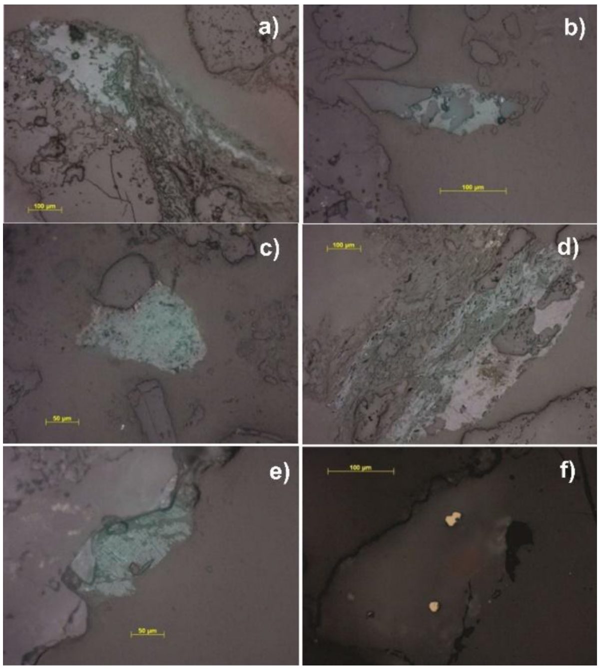


Fig. 6. Optical Microscopy Images of Cu Oxide Ore Sample:

a–f – Turquoise – Malachite/Azurite; f – a Pair of Yellow Grains of Chalcopyrite Blocked by Silicate

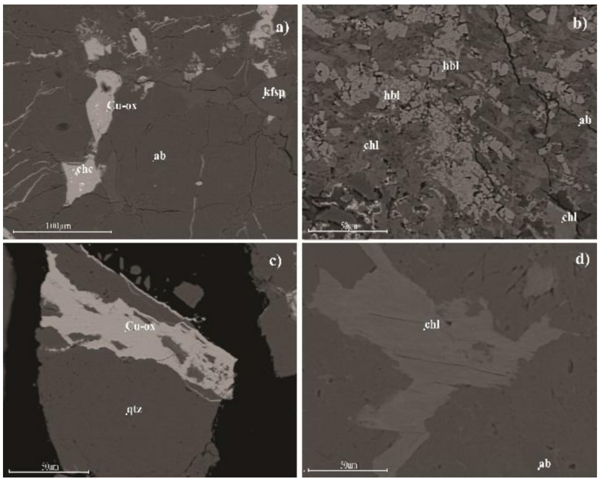


Fig. 7. Back Electron Scattering Microscopy Images of Cu Oxide Ore Sample:

a–d – cu-ox = malachite/azurite; chc = chalcocite; ab = albite; kfsp = K-feldspar; hbl = hornblende; qtz = quartz; chl = chlorite

As a result of the analysis, several key minerals have been identified based on their diffraction characteristics:

- quartz (SiO_2): one of the most intense peaks in region 2θ around 26° belongs to quartz. This shows its significant content in the sample, indicating the presence of this mineral as a major component; – albite ($NaAlSi_3O_8$): indicates the presence of clay minerals or other silicate compounds;

- clinochlore ($(Mg_5Al_6(Si_3Al)_8O_{10}(OH)_8)$): indicates the presence of aluminum silicates in the tested material;

- muscovite ($K_2Al_3Si_6O_2$-$2H_2O$): as a mineral with high potassium and aluminum content, also has corresponding peaks in the X-ray diffractogram, which confirms its presence.

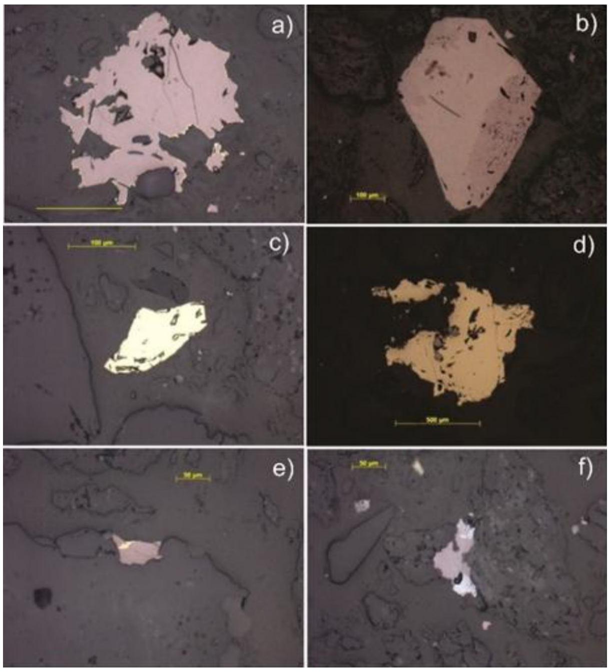


Fig. 8. Optical Microscopy Images of a Cu Sulphide Ore Sample:

a–e – Large Grains of Bornite; c–d – Large Grains of Chalcopyrite; e – Bornite (Purplish Brownish) Blocked by Silicate. Bornite Blocks Chalcopyrite; f – Bornite (Purplish Brownish) Blocked by Silicate. Bornite Blocks Chalcocite

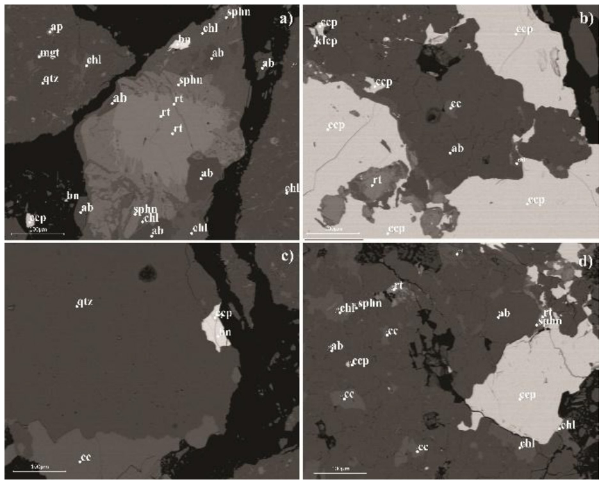


Fig. 9. Back Electron Scattering Microscopy Images of a Cu Sulphide Ore Sample:

a–d – ab = Albite; chl = Chlorite; sphn = Titanite (Sphene); rt = Rutile; ccp = Chalcopyrite; bn = Bornite; cc = Calcite; mgt = Magnetite; ap = Apatite; kfsp = K-feldspar; hbl = Hornblende; qtz = Quartz

Thermogravimetric tests were performed to obtain a more complete characterization of the ore composition and its features. The results are presented in Fig. 12.

Experimental works were performed at 30 °C up to 1,050 °C with a heating rate of 15° per minute in an air stream. During the heating process, the thermal effects on the DSC (differential scanning calorimetry) curve and the sample mass changes on the TGA (thermogravimetric curve) curve were recorded in parallel. Within the temperature range of 569 to 582 °C, polymorphic transformation of quartz minerals occurs. Within the tem-

Table 2

Elemental Composition of Oxide and Sulphide Ore Minerals Determined by Scanning Electron Microscopy

Oxide Ore		Distribution, %								
Mineralogy	% by weight	Cu	S	C	Al	Si	Fe	Mg	Ca	Na
Malachite/Azurite	1.46	93.20	–	100.00	–	–	–	–	–	–
Chalcopyrite	0.09	3.34	79.49	–	–	–	2.23	–	–	–
Chalcocyte	0.04	3.45	20.51	–	–	–	–	–	–	–
Albite	43.38	–	–	–	71.11	41.58	–	–	–	100.0
Quartz	32.38	–	–	–	-	45.14	–	–	–	–
Mica (chlorite + biotite)	15.63	–	–	–	20.64	8.16	30.93	100.00	–	–
K-feldspar	3.37	–	–	–	5.20	3.04	–	–	–	–
Hornblende	3.33	–	–	–	3.04	2.08	66.84	–	88.80	–
Rutile+titanite	0.25	–	–	–	–	–	–	–	–	–
Apatite	0.09	–	–	–	–	–	–	–	11.20	–
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Sulphide ore										
Mineralogy	% by weight	Cu	S	C	Al	Si	Fe	Mg	Ca	Na
Bornite	0.75	79.19	61.92	–	–	–	3.20	–	–	–
Chalcopyrite	0.34	19.48	38.08	–	–	–	3.93	–	–	–
Malachite/Azurite	0.01	1.33	–	0.34	–	–	–	–	–	–
Albite	49.22	–	–	–	73.25	50.69	–	–	–	100.0
Quartz	22.35	–	–	–	-	33.48	–	–	–	–
Mica (chlorite+biotite)	13.02	–	–	–	15.61	7.31	80.67	100.0	-	–
K-feldspar	8.47	–	–	–	7.03	5.68	12.20	–	45.50	–
Hornblende	2.93	–	–	–	4.11	2.84	–	–	–	–
Calcite	1.83	–	–	99.66	–	–	–	–	43.93	–
Rutile+titanite	0.63	–	–	–	–	–	–	–	–	–
Apatite	0.44	–	–	–	–	–	–	–	10.57	–
Total	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Table 3

Phase Analysis of Sulphide and Oxidized Ore

Minerals	Compounds	Contents, %			
		Sulphide ore		Oxidized ore	
		abs.	rel.	abs.	rel.
Copper	Primary	0.43	70.17	0.00	0.02
	Secondary	0.15	28.07	0.02	3.67
	Oxidized	0.04	1.75	0.39	79.90
	Water-soluble	0.00	0.052	0.08	16.33
	Total	0.62	100	0.49	100

perature range of 569 to 582 °C, an exothermic effect that is rearrangement of mineral phases is observed. The total weight loss amounted to 1.18 %, which corresponds to losses during torrefaction. The low mass loss value indicates the limited presence of volatile components, suggesting a high content of stable minerals. The ore has high thermal stability and does not contain significant amounts of thermally degradable compounds.

Conclusion. The results of the complex mineralogical and geochemical studies of ores of Koktaszhal deposit indicate a complex structural organization conditioned by the processes of porphyry copper mineralization and zonal distribution of the components. The research allowed for a detailed assessment of the mineralogical composition and geochemical characteristics of the ores, which is an important basis for further research on porphyry copper deposits. Ore minerals are represented by malachite, azurite, and sulphides. The upper horizons are characterized by the predominance of oxidized minerals such as malachite and azurite, while

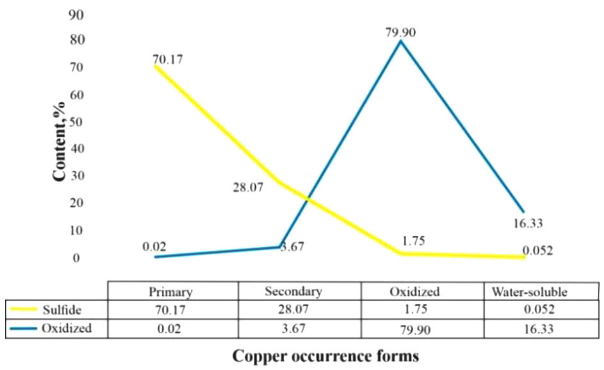


Fig. 10. Diagram of copper forms distribution in sulphide and oxidized ore

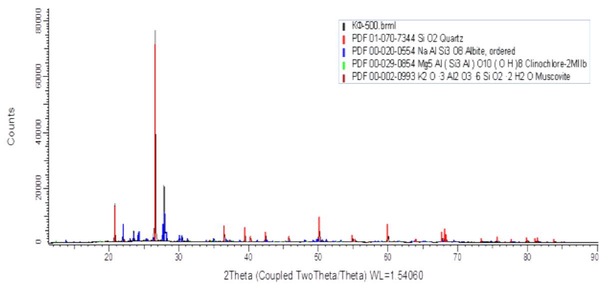


Fig. 11. X-ray diffractogram of the sample КФ-500 (Base Ore)

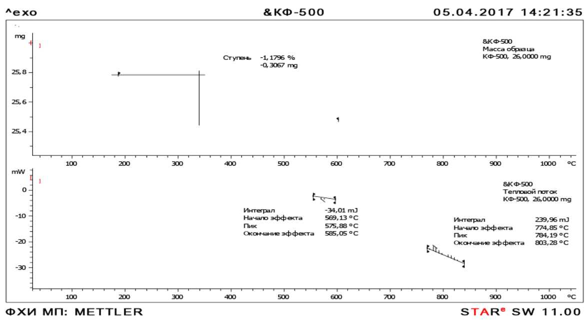


Fig. 12. Results of thermogravimetric tests performed using synchronous thermal analysis device by METTLER TOLEDO

there are predominantly primary sulphides in the deeper horizons. Moreover, the geochemical analysis showed that the ore is dominated by SiO_2, Al_2O_3 and Na_2O, and a number of other components. Results of the performed comparative analysis between oxide and sulphide mineralization forms showed a clear spatial and geochemical differentiation of ore components, which reflects different stages of ore formation. Mineralogical and chemical characteristics indicate the predominance of argillisitization, sericitization and carbonatization processes in different parts of the section.

As a result of mineralogical tests performed by optical microscopy, it was found that the main copper mineralogical phases were malachite ($Cu_2(OH)_2CO_3$) and azurite ($Cu_3(CO_3)_2(OH)_2$) with inclusions of copper sulphides, chalcocite (Cu_2S) and chalcopyrite ($CuFeS_2$). In the sulphide ore, bornite and chalcopyrite were identified as the main copper sulphides. A number of associated minerals were identified and their chemical composition was determined using scanning electron microscopy.

Based on the phase analysis, the research identified the zone sequence of mineralization characterized by the transition from the oxide zone to the primary sulphide zone. The obtained data allow for clarifying the boundaries of the zones and their mineralogical composition. Detailed analysis of mineral compounds allowed for quantitative assessment of copper distribution in different zones of Koktaszhal deposit. According to the results of X-ray diffraction analysis, the following main minerals were identified in the sample: quartz (SiO_2), albite ($NaAlSi_3O_8$), clinochlor ($Mg_5Al_6(Si_3Al)_8O_{10}(OH)_8$), and muscovite ($K_2Al_3Si_2O_2 \cdot 2H_2O$).

The identified features can be used for further development of patterns for profitable ore processing, and they contribute to the improvement of approaches to the identification and assessment of porphyry copper objects in this region, which, in its turn, increases the efficiency of geological prospecting and reveals the ore potential of the territory

References.

1. Bai, Y., Hu, W., & Wu, Y. (2021). Strategic significance of copper porphyry deposits in global economic development. *Resources*, *10*(3), 34. https://doi.org/10.3390/resources10030034

2. Calderón, C., & López, R. A. (2020). The impact of copper exports on economic growth: Evidence from Chile. *Resources Policy*, *68*, 101782. https://doi.org/10.1016/j.resourpol.2020.101782

3. Lee, J., Chen, K., & Liu, X. (2019). Emerging trends in copper demand: Implications for copper porphyry mining. *Minerals*, *9*(10), 322. https://doi.org/10.3390/min9100322

4. Wang, H., Zhang, X., & Wu, Y. (2018). Global copper supply and demand forecast: The economic implications of copper mining. *Mineral Economics*, *31*(2), 199-206. https://doi.org/10.1007/s13563-018-0156-9

5. Arnaud, L., & Gaillard, F. (2020). Sustainable development in copper mining: Challenges and opportunities. *Journal of Cleaner Production*, *261*, 121161. https://doi.org/10.1016/j.jclepro.2020.121161

6. Kurmangaliyev, A., Baimukhanov, A., & Zharikov, A. (2017). The role of Kazakhstan in global copper production. *Resources Policy*, *52*, 189-196. https://doi.org/10.1016/j.resourpol.2017.03.004

7. Baimukhanov, A., Zharikov, A., & Turgumbayev, A. (2020). Geological overview of major copper deposits in Kazakhstan. *Geological Journal*, *55*(7), 3656-3668. https://doi.org/10.1002/gj.3750

8. Zharikov, A., Turgumbayev, A., & Kovalev, I. (2020). The development of the copper mining industry in Kazakhstan. *Minerals*, *10*(5), 444. https://doi.org/10.3390/min10050444

9. Turgumbayev, A., Kovalev, I., & Zhukov, N. M. (2018). Analysis of copper exports from Kazakhstan: Economic implications. *Economic Studies Journal*, *47*(2), 246-261.

10. Kovalev, I., Zhukov, N. M., & Abdulin, A. A. (2021). Climate change and sustainable mining practices in Kazakhstan. *Journal of Cleaner Production*, *285*, 124812. https://doi.org/10.1016/j.jclepro.2020.124812

11. Zhukov, N. M., Abdulin, A. A., Bespaev, Kh. A., Votsalevsky, E. S., Daukeev, S. Zh., & Miroshnichenko, L. A. (1997). *Copper deposits of Kazakhstan: Reference book*. Almaty: [b.i.].

12. Duzhnikova, Y. V., Kryazheva, T. V., & Toleubek, K. Ye. (2020). Koktaszhal ore field (Central Kazakhstan) research results. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (3), 5-12. https://doi.org/10.33271/nvngu/2020-3/005

13. Geologiya Kazakhstana (2001). *Geology of Kazakhstan*, (1), 41-58.

14. Duzhnikova, Ye. V., Kryazheva, T. V., & Kenzhin, B. M. (2019). The mineral composition of the ores and the conditions of their formation at the Koktaszhal deposit. *Bulletin of the East Kazakhstan State Technical University named after D. Serikbayev*, *1*(83), 3-8. Retrieved from https://www.ektu.kz/files/vestnik/geo1_2019.pdf

15. Chitalin, A. V., Grigoriev, S. V., Korolkova, N. V., & Shcherbakov, D. V. (2024). Porphyry copper and epithermal gold-silver mineralization of the Baemskaya zone. *IGEOTECH*, (2), 5-25. Retrieved from https://igeotech.ru/wp-content/uploads/2024/06/chitalin-i-dr_baimskaya-zona_2024.pdf

16. Vinogradov, A. P. (1962). Average content of chemical elements in igneous rocks of the Earth. *Geokhimiya*, (7), 555-571.

17. Glukhan, I.V., & Serykh, V.I. (1996). The Mean Chemical Compositions (Regional Clarkes) of Igneous Rocks of Central Kazakhstan.

In V. Shatov, & R. Seltman (Eds.) (1996). *Granite-Related Ore Deposits of Central Kazakhstan and Adjacent Areas*, (pp. 269-286). SPb.
18. Serykh, V. I., & Kopobayeva, A. N. (2019). Patterns of distribution of rare metal deposits in Central Kazakhstan. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, 143-150. https://doi.org/10.32014/2019.2518-170X.18
19. Portnov, V. S., Kopobayeva, A. N., Amangeldikyzy, A., & Askarova, N. S. (2019). Patterns of beryllium distribution in rocks of Central Kazakhstan. *Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu*, (6), 5-10. https://doi.org/10.29202/nvngu/2019-6/1
20. Portnov, V. S., Kopobayeva, A. N., Amangeldikyzy, A., & Askarova, N. S. (2019). The distribution of beryllium in magmatic rocks of Central Kazakhstan. *News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences*, *2*(434), 150-158. https://doi.org/10.32014/2019.2518-170X.49
21. Lerman, A., & Meybeck, M. (Eds.) (1988). *Physical and Chemical Weathering in Geochemical Cycles*. (NATO Science Series C, Vol. 251). Springer Dordrecht. https://doi.org/10.1007/978-94-009-3071-1
22. Rollinson, H. R. (1993). *Using Geochemical Data: Evaluation, Presentation, Interpretation*. London: Longman. ISBN: 9780582060713.
23. Pirajno, F. (2009). *Hydrothermal Processes and Mineral Systems*. Springer Dordrecht. https://doi.org/10.1007/978-1-4020-8613-7
24. Groves, D. I., & Santosh, M. (2024). *Mineral Systems, Earth Evolution, and Global Metallogeny* (*1st* ed.). Elsevier. https://doi.org/10.1016/C2022-0-02818-X
25. Guilbert, J. M., & Park, C. F. (2007). *The Geology of Ore Deposits*. Waveland Press. ISBN: 9781577666605.
26. Colman, S. M., & Dethier, D. P. (Eds.) (1986). *Rates of Chemical Weathering of Rocks and Minerals*. Academic Press. ISBN 9780121814908.
27. White, W. M. (2013). *Geochemistry*. Wiley-Blackwell. ISBN: 9780470656686.
28. Heinrich, C. A. (2005). The chemistry of hydrothermal tin(-tungsten) ore deposition. *Economic Geology*, *100*(7), 1287-1312. https://doi.org/10.2113/gsecongeo.100.7.1287
29. Guilbert, J. M., & Park, C. F. Jr. (1986). *The Geology of Ore Deposits*. W. H. Freeman. https://doi.org/10.1007/BF01041818
30. Ridley, J. (2013). *Ore Deposit Geology*. Cambridge: Cambridge University Press. ISBN: 9780521869510.
31. Sillitoe, R. H. (2010). Porphyry copper systems. *Economic Geology*, *105*(1), 3-41. https://doi.org/10.2113/gsecongeo.105.1.3

Мінерально-геохімічні особливості мідно-порфірових руд родовища Коктасжал, Центральний Казахстан

А. Н. Копобаєва, *К. Е. Толеубек**, *А. Амангельдикизи**, *Н. С. Аскарова*

Карагандинський технічний університет імені Абилкаса Сагінова, м. Караганда, Республіка Казахстан
* Автор-кореспондент e-mail: toleubekkymbat69@gmail.com; a.amangeldykyzy@ktu.edu.kz

Мета. Вивчити мінералогічні й геохімічні характеристики Коктасжалського мідно-порфірового родовища з метою виявлення закономірностей утворення мідно-порфірових руд і розробки критеріїв розвідки.

Методика. Дослідження використовує сучасні мінералогічні й геохімічні підходи, включаючи рентгенофлуоресцентний аналіз, оптико-емісійну спектрометрію (ICP-OES), рентгеноструктурний аналіз (XRD), хімічний аналіз і фазовий аналіз, а також аналіз літератури та фондових матеріалів.

Результати. Комплексні мінералого-геохімічні дослідження руд родовища Коктасжал виявили складну будову, обумовлену мідно-порфіровою мінералізацією і зональним розподілом її компонентів. Геохімічний аналіз виявив переважання SiO_2, Al_2O_3 і Na_2O у складі руди. Порівняння результатів аналізу оксидних і сульфідних руд виявило чітку просторову й геохімічну диференціацію рудних компонентів, що відображає різні стадії рудоутворення. Було виявлено, що в оксидній руді 79,5 % міді пов'язано з малахітом і азуритом, а в сульфідній руді 79 % міді пов'язано з борнітом. Зона гіпергенних змін збагачена Bi, Pb, Co, Ni, що вказує на міграцію цих елементів у зонах вивітрювання, у той час як сульфідна зона характеризується стабільним вмістом Mo, Sb і Ag, що підтверджує первинно-сульфідну природу досліджуваного орудfestнення та його формування за низьких температур. Рентгеноструктурний та електронно-мікроскопічний аналізи виявили переважання кварцу, альбіту, мусковіту та інших силікатів, що підтверджує наявність інтенсивних процесів аргілітизації й серицитизації. Результати термогравіметричного аналізу показали високу термічну стабільність руди та переважання термостабільних мінералів. Отримані результати дозволяють уточнити морфологію рудних тіл, визначити геохімічні критерії для розвідки й оцінки мідно-порфірових об'єктів, а також обґрунтувати напрями оптимізації переробки.

Наукова новизна. Мідно-порфірове орудення родовища Коктасжал було всебічно досліджено з використанням сучасних аналітичних і статистичних методів. Уперше була проведена комплексна інтерпретація мінералогічних і геохімічних характеристик руд з урахуванням їх просторової мінливості та впливу тектонічних розломів. У ході дослідження були виявлені нові генетичні ознаки, що відображають стадії флюїдної мінералізації, а також діагностичні параметри, що дозволяють надійно диференціювати типи руд.

Практична значимість. Отримані результати можуть бути використані при моделюванні рудних тіл і плануванні геологорозвідувальних робіт на етапі оцінки й переоцінки запасів мідно-порфірових родовищ Центрального Казахстану.

Ключові слова: *мідно-порфірові руди, Коктасжал, геохімія, мінералогія, кларк, оксидні руди, сульфідні руди*

The manuscript was submitted 11.06.25.