SATBAYEV UNIVERSITY

Engineering Journal of Satbayev University

Volume 146 (2024), Issue 4, 34-40

https://doi.org/10.51301/ejsu.2024.i4.05

Metasomatic zoning and features of mineralization of porphyry copper deposits of the North-Eastern Balkhash region

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Abstract. The study is devoted to the analysis of metasomatic zoning and features of mineralization of porphyry copper deposits of the North-Eastern Balkhash region, comparing them with other analogs around the world. Based on geological, mineralogical, and hydrothermal changes, the key characteristics of the Aktogay, Aidarly and Kyzylkiya fields were identified. Methods included rock and mineral analysis, geochemical studies, and comparative analysis with global deposits. The results showed the uniqueness of Kazakhstan deposits in terms of mineral composition and zoning structure. The conclusion emphasizes the importance of these deposits for understanding the formation of porphyry copper systems and the potential for further research in this direction. The copper ore deposit of North-Eastern Balkhash region is located 450 km northeast of Almaty, within the Balkhash-Ili suite of the Central Asian Orogenic Belt, an orogenic structure over 800 million years old. The porphyry formations are found within the Koldar plutonic massif, which dates from the Late Devonian to the Early Carboniferous period. Laccolith intrusions of diorite-granodiorites extend 17 km in an east-west direction here. The Koldar plutonic massif includes plates of volcanogenic sedimentary rocks consisting of Carboniferous andesites and dacite-rhyolites. The Aktogay deposit occupies the central plate, composed of volcanic rocks and bounded by magmatic formations. The stocks of porphyritic granodiorites that intrude into the volcanic layers date from the Middle Carboniferous period.

Keywords: *porphyry copper deposits, metasomatic zoning, hydrothermal changes, mineralogical composition, North-Eastern Balkhash region, Aktogay, Aidarly, Kyzylkiya.*

1. Introduction

Porphyry copper deposits occupy an important place in geological science and industry due to their great economic potential. However, despite extensive studies of deposits around the world, many aspects of their formation remain poorly understood. In particular, the metasomatic zoning and mineralization features of porphyry copper deposits in the Northeastern Balkhash region, including Aktogay, Aidarly, and Kyzylkiya, require detailed consideration for a better understanding of these unique systems. The purpose of this study is to analyze the metasomatic zoning and mineralization features of these deposits, considering the comparison with world analogs and identifying their unique characteristics. At the Aktogay deposit, drilling data identifies three main groups of rocks:

Keregetas suite rocks consist of volcanogenic sandstones with interlayers of siltstones, tuffs, and conglomerates, overlain by a layer of rhyolite-dacite tuffs and tuffaceous sandstones.

Diorites of the Koldar massif extend southwest from the Aktogay fault within the open pit, as well as to the west and north of the deposit. These rocks are mostly porphyritic, ranging from fine- to medium-grained. The Koldar massif is characterized by intermediate to acidic intrusions (granodiorites, porphyritic granodiorite-plagiogranites, monzogranites), which are primarily described as granodiorites in the drill core data. Additionally, sheet-like intrusions of diabase porphyry of later origin are present. Small intrusions of quartz-dacite porphyry are found in the northwest section of the area.

The central part of the massif consists of silicified volcanic rocks and granodiorites, surrounded by a dense stockwork of barren quartz veins and a thin zone of sericite-quartz metasomatism. The silicified zone intersects a large potassic alteration zone, which consists of early potassium feldspar and biotite. Localized zones of quartz-sericite-pyrite alteration are represented as narrow linear sections along the contacts of granodiorite porphyries. The periphery of the copper-porphyry system is bounded by a large propylitic halo containing epidote-amphiboles and albite-chlorite.

Mineralization extends in zones from the central part of the deposit to the periphery. In the center, bornite-chalcopyrite zones dominate, transitioning to chalcopyrite-pyrite zones, while a pyrite halo is observed at the outer boundaries. In the central part of the deposit, copper and molybdenum ores overlap, while lead-zinc mineralization is confined to the edges of the ore body. The main vein mineral is quartz, although early-period veins also contain potassium feldspar and biotite [1-5].

2. Materials and methods

The study is based on field work, laboratory analysis of rock and mineral samples, as well as a comparative analysis of data on porphyry copper deposits around the world. Methods of petrography, mineralogy, geochemistry, and structural geology were used [6-7, 9-16]. Spectral analysis and microscopy data were used to assess metasomatic zoning. Analysis of hydrothermal changes included the study of the miner-

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

alogical composition and textures of the rocks. The comparison with the fields of Kazakhstan and the world was carried out based on a comparison of geochemical indicators and structural features. The use of statistical analysis made it possible to identify patterns in the distribution of elements and their correlation with types of mineralization [8].

2.1. Geological structure of the Aktogay, Aydarli, and Kyzlkiya fields

The Aktogay field and the ore field of the same name are located in the southeastern part of the side of the Bakanas synclinorium, which belongs to the northeastern segment of the andesite herzin Pribalkhash-Ilei of the intrusive volcanic belt (Figure 1).

Analysis of the geological features of the Aktogay, Aydarli, and Kyzylkiya fields revealed their complex structure, in the center of which is the Koldar intrusive massif. This massif, laccolith, composed of diorite and granodiorite, is a key element in the architecture of the region, stretching 17 km from west to east and covering an area of 75 km^2. It is surrounded by younger volcanogenic and sedimentary rocks of a variety of geological formations. Of interest is the geophysical profile of the massif, showing its expansion to 216 km² at a certain depth and subsequent narrowing, which indicates an active magmatic origin. The depth of the laccolite neck reaches 4.7 km, and its root part at a depth of about 4 km forms an ellipse with an area of about 4 km^2, projected to the surface between Aktogay and Aydarly. Below 3 km, the massif acquires a subconsonant position in the volcanics of the Keregetas formation with a thickness of up to 2500-2600 m. Two additional shallow troughs are also visible in the east and west of the laccolith. A particularly noticeable decrease in the depth of the intrusion is observed near Aktogay, where it decreases from 3 to 2 km and possibly reaches 500 m to the east.

The Aktogay ore field, together with the adjacent Aydarli and Kyzlkiya deposits, is located at the intersection of important tectonic faults, which indicates the decisive role of tectonic processes in their development. The influence of magmatic uplift led to the creation of horst-anticline and caldera structures filled with volcanic and sedimentary layers of the Keregetas Formation. The structural position of the Koldar Intrusive Massif, coupled with its hydrothermal activity, has been determined by a network of faults, including the key Aktogay fault zone with an orientation of 290°, and other faults with a direction of approximately 60°. The Aktogay fault zone encompasses the Aydarli and Aktogay fields, while the Kyzylkiya fault zone is located in the area of the Ikbass faults directed to the northeast. The magmatic activity led to the deformation of the upper part of the massif, forming horst-anticlinal structures. Closer to the eastern part of the vein, a caldera-like depression with an area of 5.5 km^2 appeared, covering most of the Aktogay deposit and filled with volcanic and sedimentary rocks of the Keregetas formation up to 600 m thick, known as the Central Aktogay xenolith.

The geological picture of the deposits is also determined by significant geological faults with a long history of activity, including the Aktogay (sub-latitudinal), Koldar (northeastern) and northwestern directions. The faults of the Koldar direction demonstrate the greatest amplitudes of vertical displacements, reaching hundreds of meters, while the displacements along the Aktogay faults, although less pronounced, are confirmed by satellite images with the width of the fault zones of 200-400 m and additional cracks that expand this zone to 600-1000 m, making these zones more ancient compared to the Koldar ones.

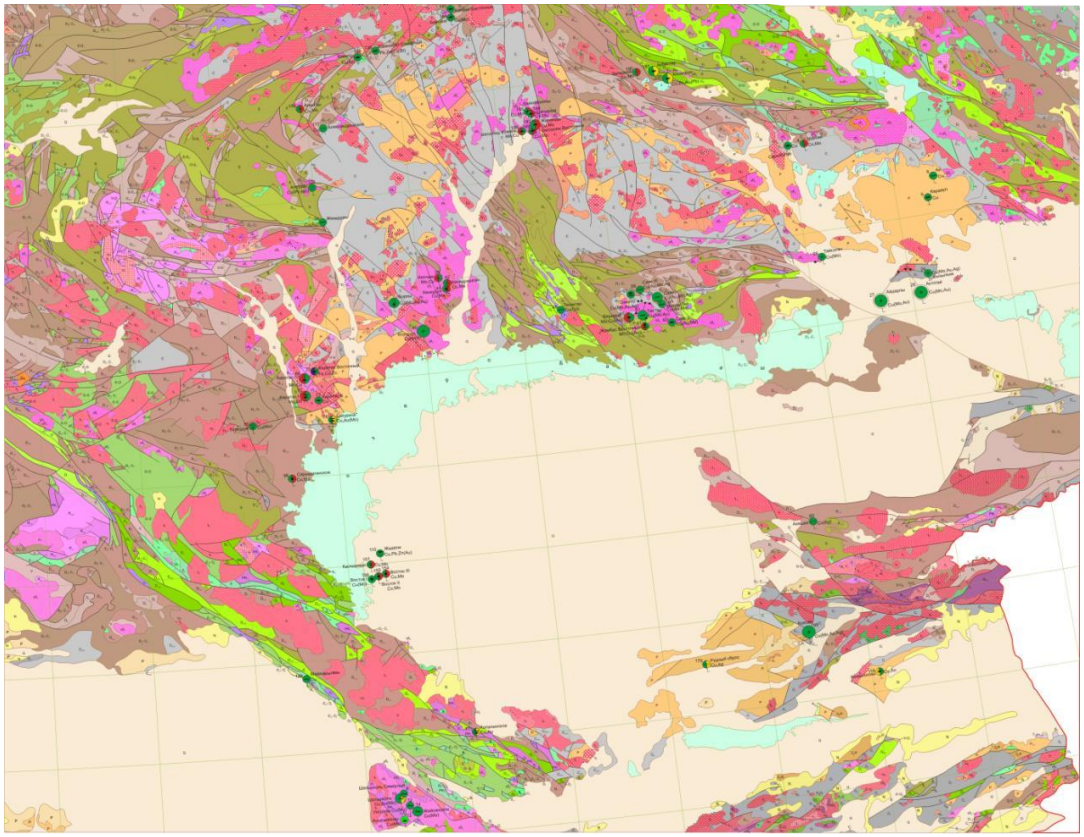

Figure 1. The map of the Dzungarian-Balkhash folded system (fragment of the state geological map [3])

In the context of mineralogy and petrology, vein rocks are noteworthy, among which diorite and diabase porphyrites, quartz and dacite porphyries, as well as special formations of granodiorite-porphyries stand out. These rocks enrich the mineralogical spectrum of the area and testify to the multi-stage activity of magma. The Koldar massif demonstrates magmatic connections with the volcanic complex of Keregetas. Among the intrusive rocks of the Koldar massif are:

Gabbro-diorites in the Northwest Block.

A variety of diorites, from uneven-grained and porphyritic to fine- and medium-grained, are found in the Central, Southern, Geophysical, Southeastern, and Far blocks. In some blocks, diorite with prismatic grain and needle hornblende are found, as well as porphyrites based on diorite and diabase, while quartz and dacite porphyries are also present in the Northwest block.

Medium-grained diorites and granodiorites, as well as porphyritic granodiorites in the eastern parts of the Central and Southern Blocks, as well as in the Diagonal and Eastern Blocks.

«Porphyry» subphase, which includes small formations and dikes of granodiorite porphyries with a fine-grained base, as well as porphyry plagiogranites with a vitreous base.

In addition, thin ore dikes of granite-aplites and fine-grained granites are common within the territory, which may be associated with the granites of the second phase of the Aktogay complex.

Post-ore dikes with almond-shaped diabase and andesite porphyrites stand separately.

Diorites with varying degrees of granularity, from irregular to fine to medium, are distinguished by their diversity in composition and the presence of structures characteristic of gabbro, ophite, and subophyte. Their appearance resembles hypabyssal rocks, and they occupy more than half of the site.

Diorite porphyrites stand out as an important geological component, forming a ring structure in the south of the site. They form several large masses and several adjacent apophyses and independent dike formations, especially near the southern edge of the orebody.

Diabase porphyrites are relatively gentle formations located mainly along the C33 direction, with a slope to the south. Their thickness usually reaches about 20 meters. These rocks, which have a fine and fine grain, are colored in dark gray and almost black tones with a greenish tint, and are younger compared to diorite porphyrites, but also contain ore minerals.

Quartz and dacitic porphyries are found mainly in northwestern and northern blocks, with the dike direction from sublatitudinal to northwestern. Their incidence angles vary from 55 to 75 degrees in south-westerly directions, increasing to 75-85 degrees near the Small Koldar Fault, which indicates their ore-bearing nature.

Medium-grained full-crystalline diorites and granodiorites, which form the third phase of development, are distributed in the northeastern part and most of the eastern half of the Koldar massif. These rocks correspond to quartz diorites and biotite-hornblende granodiorites.

Porphyritic granodiorites form separate small masses in the eastern part of the Central and Southern Blocks, as well as in the Diagonal and Eastern Blocks, covering an area of about 0.4 km^2. Their location emphasizes the closure of the annular ore-bearing structure with the pinkish-gray color of the rocks.

Granodiorite porphyries with a fine-grained base create a chain of significant vein formations and dikes running along the Aktogay deep fault, passing through the central, drilling, and northwestern parts of the site. Their shape varies from isometric to elongated, resembling dikes with various thickenings and narrowings. The total length of such structures is approximately 1500 meters, with a steep slope in the northeastern direction and a pinkish tint, while granodiorite porphyries are distinguished by the absence of hornblende among the disseminated ones.

Plagiogranite-porphyry forms extensive dike structures of a light gray hue, which demonstrate the western boundary of the ore-bearing formations of the deposit. Extend in a northwesterly direction, tilting at angles of 65 to 75 degrees to the northeast. Their thickness varies between 18 and 41 meters, with some dikes containing little or no ore. Plagiogranite porphyries also form compact masses in the area of the Central and Drilling blocks and are also embedded in the form of dikes among porphyritic granodiorites and granodiorite porphyries in the eastern part of the Central Block with a thickness of up to 40 meters. In areas where stockwork is most rich in ores, porphyry plagiogranite dikes can be heavily mineralized. In general, porphyritic granodiorites, granodiorite porphyries, and plagiogranite porphyries are tightly interrelated, forming a complex geological structure.

Metasomatic processes, which are especially active in the deep layers of intrusions, where the process of «granodioritization» due to siliceous-alkaline metasomatic occurs, are key to understanding the development of deposits. These phenomena, which cause changes in the mineral and chemical composition of rocks, play an important role in the formation of ore-bearing systems and their metallogenesis.

In the Aktogay deposit, there is a classic concentric zoning in the distribution of metasomatic rocks to ore formations. Propylites, biotite and quartz-potassium, quartz-sericite metasomatites predominate, surrounding the inner zone of strong quartz up to monoquartzites. These metasomatites, formed against the background of orogenization of volcanogenic-sedimentary rocks of the Keregetas formation, affect all known rocks of the deposit, except for tourmalinized breccia and late basite dikes. Quartz-potassium metasomatites, together with the surrounding biotite metasomatites, are typical of the center of the deposit, where they create an oval field elongated in a northwesterly direction, denoting the zone of the main distribution of copper and molybdenum mineralization. In zones of tectonic activity, these metasomatites turn into migmatites with characteristic structures.

On the periphery, sericite-quartz metasomatites predominate, crossing the central part. The outer zone, mainly outside the field, is represented by propylites, in the north by the epidote-amphibolite facies, and in the south by mainly the albite-prehnite-chlorite facies.

The ore stockwork of the Aktogay deposit is part of a large zone of sulfide (mainly pyrite) mineralization, which also unites the Aydarli ore stockwork, covering an area of 15 km^2.

The changes affected all the rocks around the orebody except the later main. The central empty space is occupied by a siliceous zone with quartz formations surrounded by a dense network of quartz stockwork and a zone of shallow sericite-quartz transformations. As it approaches the edges, this siliceous zone is replaced by an extensive layer of early

potassium variations of potassium feldspar and biotite surrounding the main orebody. In this potassium zone, there are several lines with low mineralization but strong changes in potassium feldspar, surrounded by a broad biotite halo. The zoning of the stockwork: the presence of the epicenter (quartz stockwork), the closure of the structure, and the concentric-zonal plan of the structure, fragmentarily manifested in the position of the pre-ore geological formations, but quite clearly in the spatial distribution of copper and molybdenum, and to a lesser extent sulfuric, gold-silver and lead-zinc mineralization, the mineral composition and technological properties of the ores, as well as the metasomatic zoning of the altered rocks of the region.

Phyllite transformations, distinguished by the presence of quartz, carbonates, chlorite, and sericite, occur as ephemeral, narrow bands located along the boundaries of granodiorite-porphyry apophyses and along fracture zones along the sides of the orebody. The surrounding zone of the porphyry copper system is represented by an extensive propylite halo, including epidote-amphibole and albite-chlorite-prehnite.

The orebody as a whole is an elliptical overturned cone with thick walls, the base of which is framed by jagged, jagged edges that break up into a series of disappearing conductors with small and irregular cross-sections. The boundary of this body at depth in the southern and eastern parts inclines to the east at an angle of 25 to 40 degrees. The axis of the cone is inclined to the south-southwest at an angle of 75 to 80 degrees, and the angles of inclination of the outer surface vary from 40 to 65 degrees in the south, 80 to 85 degrees in the north, 20 to 40 degrees in the west, and 70 to 85 degrees in the east.

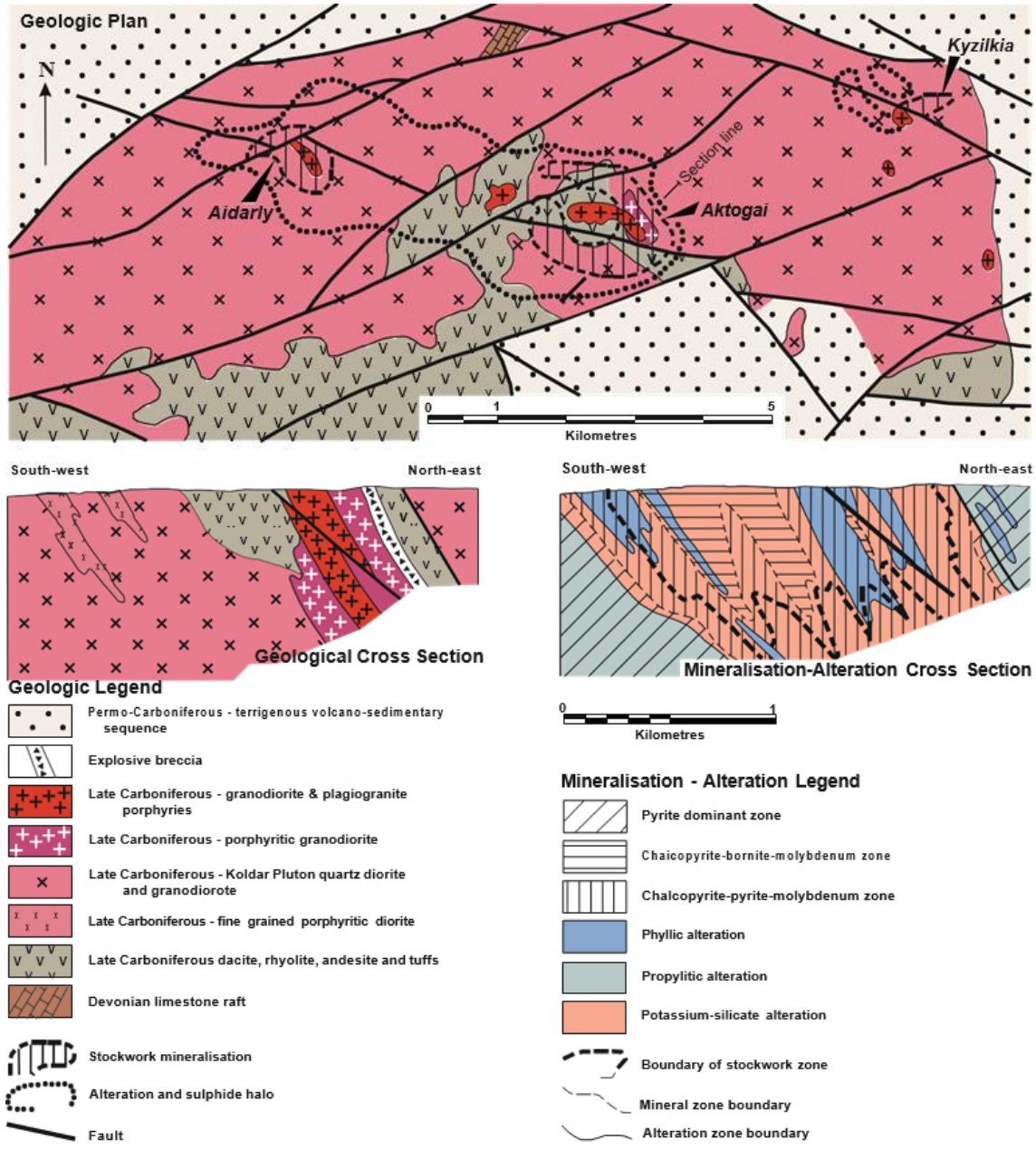

Figure 2. Geology, alteration and mineralisation at the Aktogai Group of porphyry Cu-Au deposit in southeastern Kazakhstan. The geology and alteration-mineralisation are also separately shown on a NE-SW oriented section through the Aktogai deposit. After Zvezdov, et al., (1993)

In the eastern part, the complexity of the stockwork configuration is due to the presence of a branched apophysis filled mainly with ores with low grades.

Tectonic shifts have little or no effect on the shape and integrity of the ore stockwork as an open-pit mining object. The only separate part is the balance section of the stockwork in the north-western block, which is also adjacent to the Drilling block in its eastern part along the Small Koldarsky fault.

The internal structure of the ore stockwork is characterized by a high degree of homogeneity of mineralization and well-defined vertical and lateral zoning, both in sulfide and oxidized ores.

The Aktogay deposit is characterized by vertical mineralogical zoning of ores, including:

– leaching subzone;
– zone of oxidized ores;
– subzone of mixed ores;
– secondary sulfide subzone;

Primary sulfide ore zone.

The zoning of the stockwork exhibits a complex structure, starting from the central quartz core, through concentrically arranged layers to the peripheral zones, where the distribution of mineralization from copper and molybdenum to gold, silver, and base metals changes gradually, emphasizing the stepwise change in mineral composition and enrichment of the ore bodies. The predominance of primary sulfide ores in the zone provides the bulk of the resources, with a high concentration of copper over wide areas.

The level of copper in the ores shows stability, with a coefficient of variation not exceeding 40% for copper, indicating the uniformity of mineralization within the stockwork, considered as a homogeneous object in three-dimensional space when mining methods are chosen.

A distinctive feature of stockwork is its lateral and vertical mineral zoning, which is reflected in a decrease in the concentration of copper from the center to the periphery and with depression, as well as a change in the amount of pyrite and other sulfides in different zones. This zoning confirms the gradient decrease in copper content with depth and the change in mineral composition from the outer to the inner layers of the stockwork.

The oxidized ores above the sulfide ores form a stable layer that occupies about 5% of the reserves and is expressed in separate «windows» on the surface, where the contours of the oxidized and sulfide ores do not coincide. This indicates the distribution of copper mineralization and its movement along the slopes and into the lowlands in the central parts of the stockwork.

The mixed ores underlying the oxidized ores are distinguished as a thin layer of variable thickness, where sulfides make up a significant portion of the copper mineralization, accompanied by cuprite and native copper.

The zone of secondary sulfides, located at the boundary of oxidized and primary sulfide ores, is characterized by uneven thickness and is represented by coulis zones of sulfide veins, accompanied by complex rock changes.

The small Kyzylkiya field, located near Aktogay, shows deeper erosion, indicating the diversity of erosion processes in the region. Copper-molybdenum mineralization is associated with granodiorite-porphyry rod penetrating through the granodiorites of the Koldar massif and is accompanied by potassium-silicate and phyllite changes (Figure 2).

3. Results and discussion

In general, the geological characteristics of the Aktogay, Aidarly, and Kyzylki deposits represent a complex network of processes covering magmatic activity, metasomatic changes, and volcanic-sedimentary events. This makes them valuable for the study of the geodynamics and mineral resources of the Carboniferous period in a given region.

The richness of molybdenum and copper in these deposits emphasizes their importance as molybdenum-copper objects, while the relatively low presence of gold, silver, and selenium is noted.

The relationship of the structure of these sites to deep tectonic faults indicates their importance in understanding the region's long-term tectonic activity, including shallow intrusions and explosive breccias.

A well-defined zonality in the distribution of mineralization confirms the complex interaction of geological processes at different depths and in different parts of the deposits.

Changes in the stockwork structure at different depth levels emphasize the dynamic development of these geological formations.

The vertical gradient of the distribution of molybdenum-copper mineralization is indicative of the complexity of the region's geological history and mineral potential.

Differences in erosion levels between the Aydarli and Kyzylkiya fields reflect variations in the geological development of the region.

Deep tectonic activity in the region affects the formation and preservation of mineral resources, which requires additional study for effective development.

The diversity of minerals and unique structures in these deposits, including prehnite and quartz with unique structural features, provide an important source of information on the geological processes and conditions of mineral deposits in this region.

Thus, the study of these deposits opens up broad prospects for understanding the mechanisms of the formation of molybdenum-copper deposits and the influence of tectonic processes on mineralization during the Carboniferous period.

The discussion of the results highlights the importance of metasomatic zoning for understanding the processes of field formation and suggests that these fields may contain untapped potential for exploration.

4. Conclusions

The study confirmed the hypothesis of complex metasomatic zoning and unique features of mineralization of porphyry copper deposits in the North-Eastern Balkhash region. The results can be used to refine the models for the formation of such fields and develop new approaches to prospecting and exploration. The analysis showed that a thorough understanding of metasomatic processes and hydrothermal changes is key to assessing the economic potential of the region.

Given the significant technological breakthrough in recent years, particularly in the quality and availability of satellite imagery, we recommend integrating modern remote sensing data into our research on metasomatic zonality and associated minerals. Current methods for mineral exploration and geological mapping often fail to fully utilize the potential of these advanced digital technologies. By incorporating a spectral signature library and developing a predictive explo-

ration model based on the processing and interpretation of remote sensing data, we can optimize our approach.

We propose using a comprehensive method that combines geological, geophysical, and aerospace data, including multi- and hyperspectral sensors, into a unified exploration model. This will significantly reduce time and labor costs while enhancing the efficiency and accuracy of our exploration and research efforts. Incorporating these methods into traditional methods would provide a unique solution for mineral deposit discovery and geological mapping, particularly for ore-bearing zones.

Acknowledgements

The study was carried out with the financial support of the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (grant No. BR21882179).

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Солтүстік–Шығыс Балқаш аумағының мыс порфир кенорындарының минералогиялық ерекшеліктері және метасоматикалық белдемдері

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Аңдатпа. Зерттеу Солтүстік-Шығыс Балқаш аймағындағы порфирлі мыс кенорындарының метасоматикалық белдемдері мен минерализация ерекшеліктерін талдауға, сондай-ақ оларды әлемнің басқа ұқсас кен орындарымен салыстыруға арналған. Геологиялық, минералогиялық және гидротермальдық өзгерістер негізінде Ақтоғай, Айдарлы және Қызылкия кен орындарының негізгі сипаттамалары анықталды. Әдістерге тау жыныстары мен минералдарды талдау, геохимиялық зерттеулер және әлемдік кенорындарымен салыстырмалы талдау кірді. Нәтижелер Қазақстанның кен орындарының минералдық құрамы мен зоналылық құрылымы тұрғысынан бірегей екенін көрсетті. Қорытындыда осы кен орындарының порфирлі мыс жүйелерінің қалыптасуын түсінудегі маңыздылығы және бұл бағыттағы зерттеулердің болашағы атап өтіледі. Солтүстік-Шығыс Балқаш аймағындағы мыс кен орны Алматыдан солтүстік-шығысқа қарай 450 км қашықтықта, жасы 800 миллион жылдан асатын Орталық Азия орогендік белдеуінің Балқаш-Іле қатпарлы кешенінде орналасқан. Порфирлі формациялар Колдар плутондық массивінде кездеседі, ол кейінгі девоннан бастап ерте карбон дәуіріне жатады. Мұнда диорит-гранодиоритті лакколиттік интрузиялар батыстан шығысқа қарай 17 км қашықтыққа созылған. Колдар плутондық массиві карбондық андезиттер мен дацит-риолиттерден тұратын вулканогендік-шөгінді жыныстар қабаттарын қамтиды. Ақтоғай кен орны орталық тақтаны алып жатыр, ол вулкандық жыныстардан тұрады және магмалық түзілімдермен шектелген. Вулкандық қабаттарға енетін порфирлі гранодиориттердің штоктары орта карбон дәуіріне жатады.

Негізгі сөздер: *мыс порфир кенорындары, метасоматикалық белдемдер, гидротермалық өзгерістер, минералалдық қосылыстар, Солтүстік-шығыс Балхаш аумағы, Ақтоғай, Айдарлы, Қызылқия.*

Метасоматическая зональность и особенности минерализации медно-порфировых месторождений Северо-Восточного региона Балхаша

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Аннотация. Данное исследование посвящено анализу метасоматической зональности и особенностей минерализации порфировых медных месторождений Северо-Восточного Балхаша, а также сравнению их с аналогичными месторождениями по всему миру. На основе геологических, минералогических и гидротермальных изменений были выявлены ключевые характеристики месторождений Актогай, Айдарлы и Кызылкия. В методах исследования использовались анализ пород и минералов, геохимические исследования и сравнительный анализ с мировыми месторождениями. Результаты показали уникальность месторождений Казахстана по составу минералов и структуре зональности. В заключении подчеркивается важность этих месторождений для понимания процессов формирования порфировых медных систем и потенциал для дальнейших исследований в этом направлении. Медное рудное месторождение Северо-Восточного Балхаша расположено в 450 км к северо-востоку от Алматы, в пределах Балхаш-Илийского комплекса Центрально-Азиатского орогенного пояса, орогенной структуры, возраст которой составляет более 800 миллионов лет. Порфировые формации обнаружены в пределах Колдарского плутоногенного массива, который относится к позднедевонскому — раннекарбоновому периоду. Здесь лакколитовые интрузии диоритов и гранодиоритов простираются на 17 км в направлении с запада на восток. Колдарский плутоногенный массив включает пласти вулканогенно-осадочных пород, состоящих из карбоновых андезитов и дацит-риолитов. Месторождение Актогай занимает центральную пластину, состоящую из вулканических пород и ограниченную магматическими образованиями. Штоки порфировых гранодиоритов, которые внедряются в вулканические слои, относятся к среднекарбоновому периоду.

Ключевые слова: *медно-порфировые месторождения, метасоматическая зональность, гидротермальные изменения, минералогические соединения, Северо-Восточный регион Балхаша, Актогай, Айдарлы, Кызылкия*.

Received: 29 April 2024
Accepted: 15 August 2024
Available online: 31 August 2024