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Structural-formational zones with porphyry copper mineralization – A promising mineral resource base for copper in Eastern Kazakhstan

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Abstract

Purpose. The article is dedicated to the informational analysis of the geological-genetic systematization of all known porphyry copper mineralization sites within the territory of Eastern Kazakhstan, with a focus on refining their structural and chronological position, magmatic association, material composition of the mineralization, and its zonality.

Methods. A prospective assessment of porphyry copper deposits is considered within four structural-formational zones (SFZs) – Rudny Altai, Zharma-Saur, Chingiz-Tarbagatai, and Dzungaro-Balkhash, where various types of porphyry mineralization are documented. During the desk study phase, an informational analysis was conducted, which involved collecting, summarizing, and analyzing archival, fund, and literature data on all known porphyry-type occurrences recorded since the previous century within the aforementioned SFZs. The compilation and analysis of geological, geophysical, and geochemical data were based on reports from prospecting and evaluation studies conducted in the study area.

Findings. The informational analysis allowed for the specification of prospecting and evaluation criteria, classification of the mineralization with comparison to global analogs, and refinement of the mineralization scale. Based on this, objects with potential for industrially significant mineralization were identified. A thorough review of archival data led to the creation of a geological database covering 23 major occurrences, each with its respective evaluation.

Originality. The study results indicate that despite the generally low ore grades in these deposits, their reserves, compared to other industrial copper deposit types (volcanogenic massive sulfide, skarn, and vein-type), are exceptionally large. This makes them economically viable for open-pit mining. Moreover, the low cost of open-pit copper extraction and the complex nature of the ores explain the industry's interest in this deposit type as a primary copper source, both at present and in the future.

Practical implications. The study provides an assessment of the practical significance of molybdenum-copper porphyry and gold-copper-polymetallic porphyry-type deposits. These findings serve as a foundation for decision-making regarding further exploration of porphyry occurrences in Eastern Kazakhstan.

Keywords: *opper-bearing sandstones, ore occurrence, ore zone, porphyry copper, Eastern Kazakhstan*

1. Introduction

More than 20 porphyry occurrences of various scales, including gold, copper, and molybdenum-copper types, have been identified in Eastern Kazakhstan. However, their potential for industrially significant mineralization remains insufficiently studied. Over the past three decades, the Republic of Kazakhstan has been experiencing the depletion of its mineral resource base for non-ferrous and noble metals [1]-[3]. This is primarily due to the intensive extraction of ore reserves known since the previous century, including both large deposits and small, subeconomic, easily accessible near-surface gold occurrences. At the same time, no new significant discoveries have been made in this period, largely due to the dismantling of essential geological exploration infrastructure.

The prospective assessment of porphyry copper deposits was carried out within four structural-formational zones (SFZs): Rudny Altai, Zharma-Saur, Chingiz-Tarbagatai, and Dzungaro-Balkhash, where various types of porphyry mineralization have been identified [4]-[7].

Based on an analysis of geological materials, the following occurrences were selected for study: Sugatovskoe, Rulevskoe, Rossypnoy Belok, Krestovsky I and II, and Listvenitovoe, Novo-Khairuzovskoe, Greisen-type occurrences within the Rudny Altai SFZ; Kensai, Kyzyl-Kain, Shorskoe, and Arsenievskoe in the Zharma-Saur SFZ; Bala-Urpek, Kanshoky, Karasu, and Argynbaysyz in the Chingiz-Tarbagatai SFZ.

This study presents a geological-genetic systematization of all known porphyry mineralization sites in Eastern Kazakhstan, with a refined classification of their structural and

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chronological position, magmatic association, material composition of the mineralization, and its zonality. Based on this systematization, prospecting and evaluation criteria have been specified, and the mineralization has been typified in comparison with global analogs. The scale of mineralization has been reassessed, leading to the identification of targets with potential for industrially significant ore deposits.

Recent international studies emphasize the relationship between geodynamic conditions of flat-slab subduction and the formation of large porphyry copper provinces. For example, the study by Lamont et al. (2024) on the Laramide Province (Arizona, USA) demonstrates that volatiles from the edge of the subducting Farallon Plate facilitated the melting of the lower crust, which was enriched in copper, without significant contribution from the mantle wedge. This explains the formation of giant deposits such as Resolution under conditions lacking classical island arc magmatic activity [8], [9]. Similar processes have been identified in the Andes (Chile), where the migration of magmatic arcs during the Cenozoic is associated with episodes of flat subduction and the formation of deposits such as Río Blanco-Los Bronces [8], [10].

A study published in EGUsphere (2024) highlights that the balance between exhumation and preservation of ore bodies is critical to their economic significance. Global mo-deling (goSPL) has allowed researchers to estimate exhumation rates (0.01-0.1 km per million years) and formation depths (1-6 km) for porphyry deposits. For instance, in the Central Andes, deposits older than 60 million years were found to be buried at depths exceeding 6 km, reducing their accessibility for mining. These findings help optimize exploration strategies in regions affected by active tectonic and climatic processes [11].

The study by Migachyov et al. (2022) distinguishes two types of porphyry copper systems [12]:

– Gold-copper systems, associated with basaltoid volcanic-plutonic belts (e.g., the Maricunga Belt in Chile);

– Molybdenum-copper systems, forming within andesitic belts of continental margins (e.g., the North American Cordillera).

These differences arise from the composition of magmatic sources and geotectonic settings, aligning with the conclusions of Schwartz (2024) on the role of crustal melts in ore enrichment [13].

In studies of the Laramide Province, Sr-Nd-Pb and Hf-in-zircon isotopic systems were used to confirm the crustal origin of magmas. For example, εNd(t) values ranging from -0.2 to -18.4 and a modeled source age of 1.1-2.6 billion years indicate remelting of Proterozoic copper-enriched crust [10].

Research in Azerbaijan (Goshgarchai OMS) has revealed a vertical elemental zonation: Mo→Cu→Co→Ni→Cr→Ag→Pb→Zn, which correlates with data from Chilean deposits. Metasomatic columns (e.g., secondary quartzites, propylites) serve as indicators for concealed mineralization [13]. Similar patterns have been described for deposits in the Lesser Caucasus and the Urals, where the combination of petrochemical and geophysical methods enhances exploration accuracy [13], [14].

Based on international research findings, the following practical conclusions can be drawn for Eastern Kazakhstan:

– The Dzungaro-Balkhash Zone may serve as an analogue to the Laramide Province, where flat-slab subduction facilitated the formation of crust-derived magmas;

– the classification of occurrences into gold-copper and molybdenum-copper types [12] will help refine exploration criteria.

The studies discussed above confirm that even low-grade ores in porphyry copper deposits can be economically viable when subjected to comprehensive geological and economic assessments, which is particularly relevant for Eastern Kazakhstan.

2. Methodology

For the petrological-geochemical characterization of ore-bearing and host rocks, drill core samples were selected as the most representative, unaltered by supergene processes. A total of 23 samples were collected to compare the chemical composition of the main magmatic rocks of the ore-bearing Sarykol complex from various intrusive massifs – Baimbet, Shet, and Katay, corresponding to the Bala-Urpek, Kanshoky, and Argynbaysyz sites.

In total, 35 km of reconnaissance-evaluation traverses were completed, and 199 samples were collected for various types of analyses. Samples for silicate analysis were taken from host rocks, while spectral, spectro-goldometric, and chemical analyses were performed on mineralized zones. All samples were analyzed using semi-quantitative spectral analysis for 27 elements, including Cu, Pb, Zn, As, Sb, Bi, Mo, Ag, Co, Ni, Cr, Ti, W, V, Sn, Ta, Ga, In, Ge, Ba, Mn, Sc, Zr, Cs, Ta, Nb, and Y. Samples with elevated concentrations of Cu, Mo, Au, and Ag (exceeding five times the clarke values of the Earth’s crust) underwent additional analysis using atomic absorption spectroscopy (AAS) and spectro-goldometric methods.

The collection of materials and the prospective assessment of porphyry copper deposits were conducted within four structural-formational zones (SFZs): Rudny Altai, Zharma-Saur, Chingiz-Tarbagatai, and Dzungaro-Balkhash, where various types of porphyry mineralization are documented.

2.1. Rudny Altai structural-formational zone (SFZ)

Within the territory of East Kazakhstan Oblast (EKO), the following metallogenic belts are distinguished: Greater Altai, Chingiz-Tarbagatai, and the northwestern fragment of the Dzungaro-Balkhash segment of the Earth’s crust. Within these regions, structural-formational zones (SFZs) are delineated, corresponding to ore-bearing metallogenic belts, which differ significantly in their geological structure and metallogenic specialization.

Within Greater Altai (GA), five SFZs are identified: Beloubinsk-Sarymsaktinsk Lead-Zinc SFZ, Rudny Altai Gold-Copper-Polymetallic SFZ, Kalba-Narym Rare Metal SFZ, Western Kalba Gold SFZ, Zharma-Saur Multimetallic SFZ [15]-[17] (Fig. 1).

The Rudny Altai SFZ is characterized by high tectonomagmatic activity, with intense basaltoid volcanism during the early riftogenic-island arc stage (D_{1-3}) and extensive intrusive magmatism during the middle collisional and late post-collisional stages (Fig. 2).

Nearly all major polymetallic deposits of Eastern Kazakhstan are located within the Rudny Altai SFZ and are spatially associated with volcanogenic-sedimentary deposits of the basalt-rhyolite carbonate-siliceous-terrigenous formation [17], [18].

The polymetallic deposits of Rudny Altai are localized within chemogenic-sedimentary formations of the Middle and Upper Devonian and are spatially associated with post-volcanic magmatic formations.

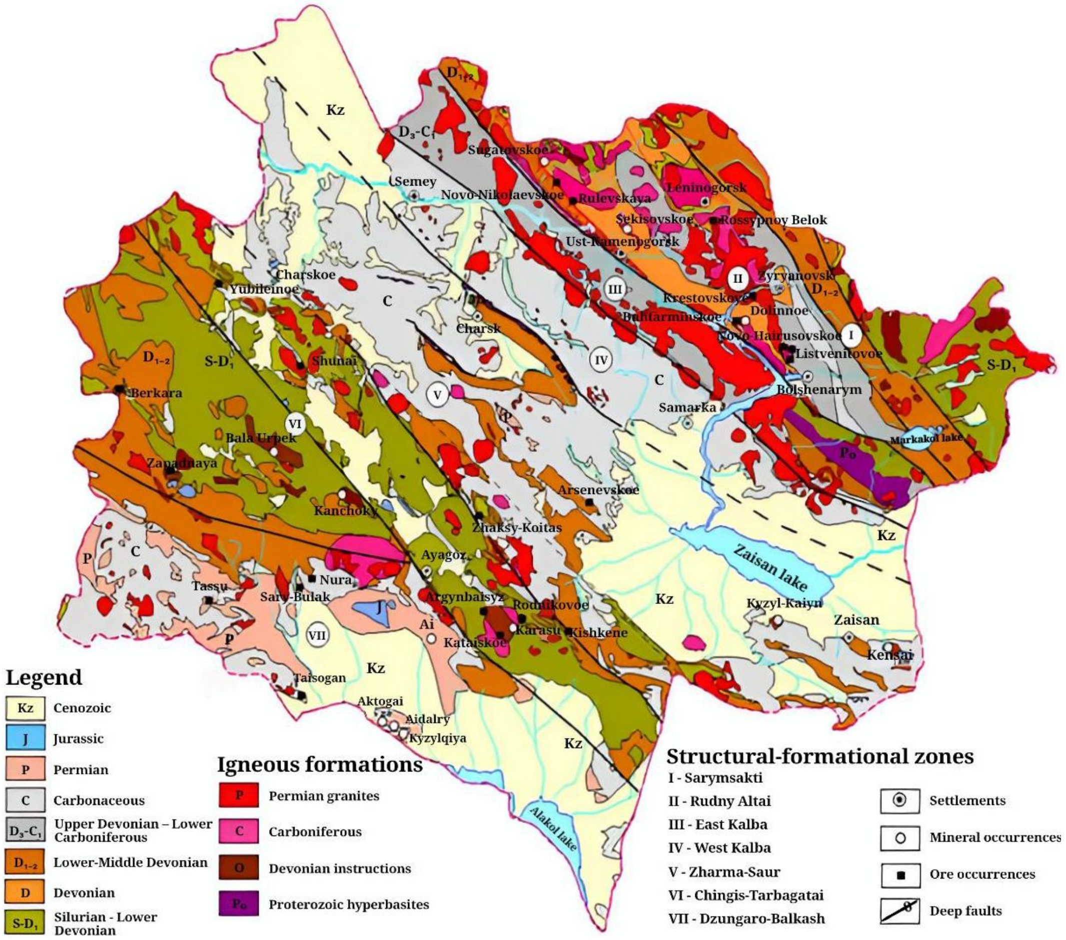

Figure 1. Geological structure map of East Kazakhstan Oblast

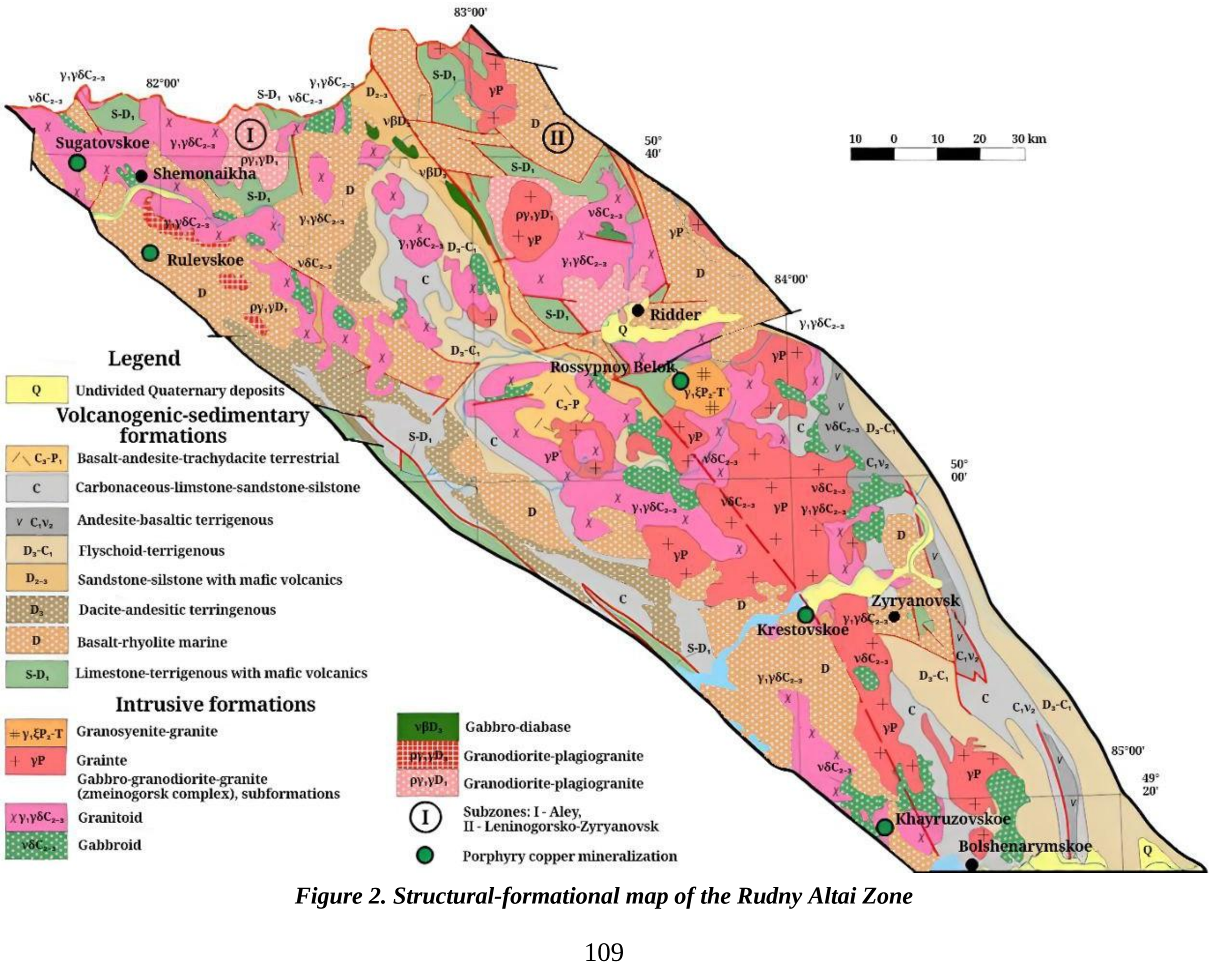

Figure 2. Structural-formational map of the Rudny Altai Zone

The ore-hosting rocks are exclusively sedimentary formations, filling intervolcanic depressions, or the ores are confined to the apical parts of Devonian porphyritic intrusions, emplaced within tuffogenic-terrigenous sequences (e.g., Nikolaevskoe, Novoleninogorskoe, Dolinnoe, and Strezhanskoe deposits).

The completion of the postmagmatic hydrothermal-metasomatic process at all identified stratigraphic levels is associated with Devonian porphyritic rock [19]. The metal sources, in our view, were postvolcanic secondary (residual) magmatic foci, which generated hydrothermalites, ores, and various porphyritic and porphyry rock facies. The relationship between mineralization and volcanism is merely paragenetic, stemming from a common primary magmatic source, which formed both the ore-bearing Devonian basalt-rhyolite volcanogenic rock complex and the ores [7], [20].

The formation of gold-copper porphyry occurrences in the Rudny Altai SFZ is primarily associated with formations of the Middle Hercynian stage and granitoids of the Zmeinogorsk magmatic complex. The Zmeinogorsk magmatic complex (C_{2-3}) reflects the late collisional epoch in the geological evolution of Greater Altai, marking the final stage of collisional compression. This complex is characterized by the extensive development of gabbro-granodiorite-granite intrusions, which are spatially distributed within the axial part of the Rudny Altai deep mobile zone. These intrusions are represented by large, multiphase, and heterogeneous plutonic bodies, including stocks and irregularly shaped masses [15]. The gold-porphyry subformation is genetically linked to rocks of this formation, hosting deposits such as Sekisovskoe and Sugatovskoe, along with gold-copper porphyry-type occurrences, including Novo-Khairuzovskoe, Listvenitovoe, Greisenovoe, and Krestovskoe-I, II, III.

2.2. Zharma-Saur structural-formational zone (SFZ)

The Zharma-Saur SFZ is characterized by the extensive development of sedimentary and effusive-sedimentary deposits from the Middle and Upper Paleozoic, which are represented by andesites, basalts, and plagioclase porphyrites, interbedded with carbonate-terrigenous sediments. The intrusive rocks of the region are grouped into four complexes: the gabbroid complex (Upper Devonian – Lower Carboniferous), the Saur intrusive complex (Visean age), and the Manrak intrusive complex (Middle – Upper Carboniferous) [21]

The Zharma-Saur SFZ is characterized by diverse mineralization, with copper-gold deposits being the predominant type. It is subdivided into two structural-metallogenic subzones (SMSZs): the Sirektas-Sarsazan Subzone and the Zharma-Saur Subzone (Fig. 3).

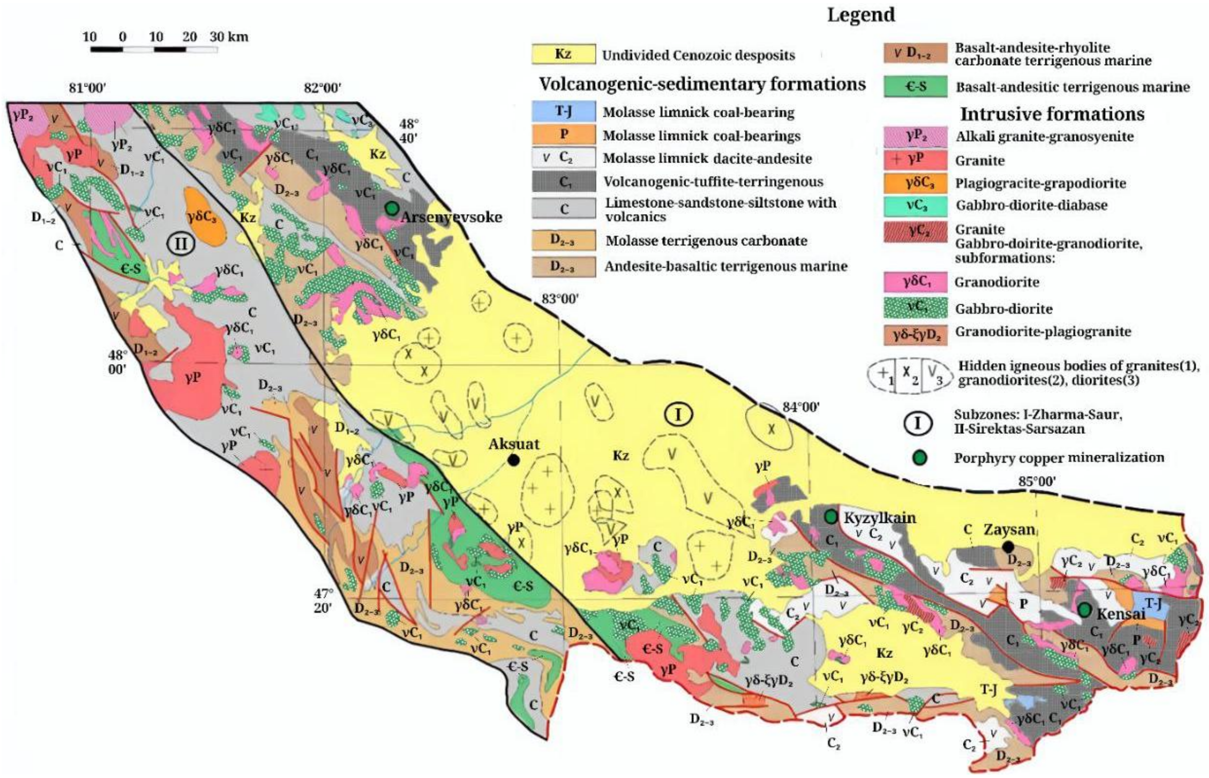

Figure 3. Structural-formational map of the Zharma-Saur Zone

The Sirektas-Sarsazan Subzone borders the Caledonides of Chingiz-Tarbagatai and extends northwestward for 530 km. Within this subzone, two metallogenic districts are distinguished: the Sirektas Gold-Rare Metal-Rare Earth District and the Sarsazan Copper-Polymetallic District. This subzone is characterized by weak copper-molybdenum and polymetallic mineralization. The Shorskoe Copper-Molybdenum Deposit, which closely resembles the molybdenum type, is known here, along with the Kishkine and Zhaksu-Koytas occurrences, located in the junction zone with the Chingiz-Tarbagatai SFZ and associated with the Zharma Intrusive Complex. In general, the metallogenic profile of this region is copper-gold-rare metal-rare earth [21]. The Zharma-Saur Subzone is characterized by high tectonomagmatic mobility during both the early (riftogenic) and middle (collisional) stages, with an abundance of basaltoid geological formations. The metallogenic profile is predominantly siderophile-chalcophile, including Cu, Ni, Co, Au, Ag (Fe, Mn, W, Mo).

The most productive level for porphyry copper mineralization in the Zharma-Saur SFZ is the Saur Ore-Bearing Horizon (C_1), represented by gabbro-diorite-granodiorite formations, which are associated with the Kyzyl-Kain and Kensai deposits. These intrusions formed in an early collisional environment during the final stages of the Saur folding phase and are considered syn-inversion in origin.

The most significant porphyry copper occurrences within this SFZ are linked to formations of the Middle Hercynian stage, primarily represented by rocks of the Saur Complex. This complex is genetically associated with porphyry copper mineralization (Kyzyl-Kain, Kensai, Shorskoe deposits, and the Arsenievskoe occurrence) as well as hydrothermal gold-quartz mineralization (Bugaz occurrence). The most ore-bearing zones are the apical parts of layered intrusions, which have undergone tectonic deformation (stockwork fracturing, veining) and metasomatic alterations (propylitization, sericitization, silicification, etc.).

The age of porphyry copper mineralization is estimated as Middle Carboniferous – Early Permian. In Saur-Tarbagatai, based on lead isotope composition analysis, the absolute age is determined to be 280-320 million years [22].

The distribution of diorite-granodiorite formations, which are prospective for porphyry copper occurrences, is controlled by deep-seated fault zones and shows a spatial association with andesite-basalt volcanism. The mineralization is linked to low-temperature postmagmatic hydrothermal alterations, including argillization, carbonatization, secondary quartzites, and quartz-carbonate veinlets.

2.3. Chingiz-Tarbagatai structural-formational zone (SFZ)

The SFZ represents a Caledonian block-fold system, bounded by Hercynian structures of the Dzungaro-Balkhash region to the southwest and the Zaisan region to the northeast. This structure is likely a fragment of Ordovician island arcs and corresponds to an accretionary-fold zone by its nature. It is located in eastern Central Kazakhstan, extending northwestward for 700 km beyond the submeridional Central Kazakhstan deep fault. It lies north of Northern Pribalkhash and is separated from it by the Chingiz-Balkhash fault, with the Kalba-Chingiz fault marking its northeastern boundary. The fold system under consideration represents a terrane, consisting of a series of anticlinoria and synclinoria (Fig. 4).

According to modern interpretations, the Chingiz-Tarbagatai Early Paleozoic system represents an island-arc volcanic-plutonic belt [23]. The geological structure of this belt includes volcanogenic-sedimentary formations of the Lower-Middle Paleozoic, along with intrusive complexes of varying age and composition [24], [25]. Based on its internal development characteristics and deep structure, the Chingiz-Tarbagatai fold system is subdivided into two structural zones: Western Chingiz and Eastern Chingiz [26]-[28]. The Western Chingiz Zone includes two subzones: Akbastau and Abralin, which are separated by the Zhuyrtagin Fault. This zone is characterized by intensive basaltoid volcanism and copper-massive sulfide (VMS) mineralization [29]-[31].

The Chingiz-Tarbagatai SFZ is recognized as a volcanogenic massive sulfide (VMS) province with polygenic and polychromatic gold-copper-zinc mineralization. During the early stage, VMS mineralization associated with volcanogenic rocks was predominant, while in the middle and late stages, copper-molybdenum and quartz-gold mineralization became dominant, forming in connection with intrusive complexes.

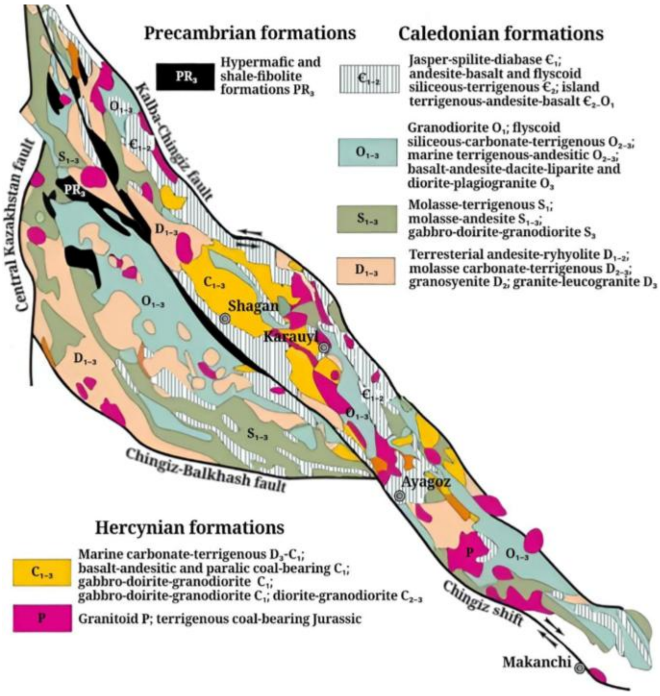

Figure 4. Distribution of the main formations of the Chingiz-Tarbagatai fold system

The largest deposits, including Akbastau, Kosmuron, Mizek, and the Koskuduk occurrence, formed during the post-Caledonian epoch and are localized within volcanogenic-sedimentary formations of the Cambrian and Ordovician. These deposits contain one to four ore bodies, which are arranged either in chains or en echelon. The length of ore bodies ranges from 200 to 400 m, with thicknesses varying from 10 to 50 m. Gold is present in all ore types, with concentrations ranging from trace amounts to several tens of grams per ton.

Copper-molybdenum mineralization is widespread in the Chingiz-Tarbagatai Zone and is associated with the Upper Silurian gabbro-diorite-granodiorite intrusive complex. This type of mineralization is represented by the Bala-Urpek and Kanshoky deposits, as well as the Jelanda, Yuzhnoe, Ush-bala, and Zapadnoe occurrences, among others. Mineralization in these areas is associated with large, compositionally differentiated intrusive bodies. These deposits are localized at structural intersections of positive massifs (domal uplifts, apophyses) with deep-seated faults, which are expressed as fracture zones and dyke swarms.

In recent decades, Late Caledonian mineralization has been attributed to a group of copper-molybdenum occurrences within the Katay granitoid massif (Karasu, Katayskoe, Belbastau, Argynbaysyz, Karabay, and Altuyt), which are confined to contact zones of the massif.

The Hercynian granitoid complex is associated with molybdenum-type mineralization, including the Zhaman-Koytas, Zhaksu-Koytas, and Kishkine occurrences, which are spatially and genetically linked to the Zharma Intrusive Complex (C-P) at the boundary with the Zharma-Saur SFZ.

Subordinate mineralization types in the Chingiz-Tarbagatai structures include gold-quartz and gold-sulfide mineralization, which formed during the Late Caledonian, Early Hercynian, and Late Hercynian stages. These mineralization types are represented by the Kant-Chingiz, Malva, and Maibulak deposits.

2.4. Dzungaro-Balkhash structural-formational zone (SFZ)

Within the Dzungaro-Balkhash megasynclinorium, the Bakanas Synclinorium occupies the study area in East Kazakhstan. Within this structure, the Kalmakemel-Bakanas structural-formational subzone (SFSZ) is distinguished, corresponding structurally to the Bakanas Synclinorium, which represents the marginal structure of the North Balkhash megasynclinorium and, as a whole, the Hercynides of the Dzungaro-Balkhash fold system. The zone is bounded to the northeast by the Caledonides of the Chingiz-Tarbagatai system, separated by the Chingiz-Balkhash, Main Chingiz, and Ayazuz-Urjar faults, while to the southwest, it is delimited by the Kalmakemel fault. The synclinorium has an arcuate shape, extending over 300 km with a width of 100-120 km. In the northwest, its orientation shifts from northwest-trending to sublatitudinal, while in the southeast, its structures subside and are overlain by Cenozoic deposits of the Alakol Depression (Fig. 1).

From a metallogenic perspective, within the studied area of the Balkhash Province, located in East Kazakhstan Oblast, the Katanemel-Bakanas structural-metallogenic zone (SMZ) is identified, which includes the Katanemel, Kalmakemel-Aktogay, Bakanas, and Prichingiz SMPSZs.

Within the Katanemel SMPSZ, the Kokdalin-Zhilandin ore zone has been distinguished, which is prospective for hydrothermal quartz-adularia gold mineralization. This zone extends westward beyond the studied area. The mineralization is confined to felsic volcanics, explosive breccias of tectonovolcanic structures, and second-order faults associated with regional fault systems (Kalmakemel, Tassuy). Beyond the boundaries of East Kazakhstan, deposits such as Tuz and occurrences like Uzuntas and Kokdala are known.

In the Kalmakemel-Aktogay SMPSZ, the Koldar ore cluster is highly prospective for copper, comprising the Aidarli, Aktogay, and Kyzylkiya deposits, which are located within 3 km of each other, forming a single Aktogay ore field. This ore field is structurally controlled by the sublatitudinal Koldar horst-anticline, whose core is composed of volcanics of the Koldar Formation (C_{2-3}) intruded by granitoids of the Koldar Intrusion. These formations are interpreted as a volcanic-plutonic complex of intermediate composition, with an intense overprint of metasomatic transformation processes. The ore-hosting rocks include medium-grained quartz diorites, granodiorites, granites, and host rocks within the exocontact zones.

All three deposits exhibit similar geological settings and ore formation conditions. Molybdenum-copper mineralization within ore stockworks is characterized by irregular but continuous distribution patterns. Copper grades decrease from the central part of the ore ring toward its periphery and with depth. The ore stockworks exhibit the typical supergene zonation of porphyry copper deposits, including oxidation, leaching, secondary sulfide enrichment, and primary sulfide zones.

The average metal grades are as follows:

– oxidized ores: Cu – 0.3%;

– sulfide ores: Cu – 0.38%, Mo – 0.01%, Au – 0.014 g/t, Ag – 1.4 g/t, Re – 0.2 g/t, Se – 1.8 g/t.

Direct indicators of mineralization include secondary dispersion halos of molybdenum and copper, which are often associated with lead, zinc, and other metal anomalies.

In addition to the porphyry copper deposits of the Aktogay ore field, three blind stockworks – Western, Intermediate, and Eastern – have been identified, which have only been intersected by isolated drill holes. Taking these stockworks into account, the Aktogay ore field, along with the Aktogay, Aidarli, and Kyzylkiya deposits, is classified as a world-class porphyry copper system, comparable to Bingham, Butte, and Cananea.

The Koldar ore cluster has estimated P2 + P3 resources of up to 15 million tonnes of copper, 276 thousand tonnes of molybdenum, and 60 tonnes of gold.

Within the Kalmakemel-Aktogay SMPSZ, the Taisogan ore zone has been identified, including the Zharyk ore field, which is confined to the core of the Taisogan anticline. This structure is composed of sedimentary-volcanogenic formations of the Kalmakemel Formation, intruded by granitoids of the Taisogan intrusive massif of the Aktogay Complex. The structural position of the Taisogan ore zone is determined by its location within a transitional suture belt, marking the convergence of two distinct structural-formational zones. The Taisogan occurrence is known within this zone, which is prospective for porphyry copper mineralization, analogous to the Aktogay type.

Hydrothermal porphyry copper occurrences such as Taisogan and Jerek have been identified beneath Neogene unconsolidated cover, where quartz diorites and porphyrites have been exposed. The geological structure of the occurrences includes quartz diorites, monzonites, and granodiorites of the Taisogan Massif. The average metal grades in sulfide ores are Cu – 0.3%, Mo – 0.001-0.008%, with some samples containing notable zinc and lead concentrations.

The Zharyk I, II, and III occurrences, located north of the Taisogan occurrence, are situated within the Zharyk ore field, which belongs to the same structural-metallogenic zone as the Aktogay ore field. The geological structure, ore characteristics, and mineral composition of these occurrences are similar to those at Aktogay, indicating high exploration potential at depth.

The Prichingiz Subzone represents the junction belt of the Dzungaro-Balkhash structure with the Chingiz-Tarbagatai meganticlinorium. This subzone is characterized by a high concentration of Late Hercynian intrusive massifs, which are genetically associated with most of the copper mineralization. Two metallogenic areas are distinguished within this subzone: the Nurbai ore district and the Kaindy ore-bearing area.

The Nurbai ore district is notable for the presence of porphyry copper occurrences, represented by quartz-copper stockworks within intrusive rocks. The Nurbai occurrence, identified in this district, is classified as a hydrothermal plutonogenic type, forming a porphyry copper-gold-molybdenum stockwork-disseminated formation within monzonitoids.

The Kaindy area contains numerous copper mineralization points of various formational types. However, skarn-hosted copper occurrences are limited, primarily within the Sarybulak ore cluster, where the Sarybulak occurrence is known. The overall copper potential of this area is considered low.

Within the Prichingiz SMPSZ, the Koytas ore district is distinguished by hydrothermal gold-quartz vein mineralization, associated with granites. Thus, the Dzungaro-Balkhash segment of the Earth's crust is considered highly prospective for the discovery of porphyry copper deposits and hydrothermal gold-quartz vein occurrences within volcanogenic formations associated with small Late Carboniferous diorite intrusions.

3. Results and discussion

3.1. Comparative formation-metallogenic analysis of various types of porphyry deposits and their comparison with global analogues

Based on the material composition of the mineralization and its association with specific magmatic complexes, several typical porphyry occurrences have been identified: Altai, Zharma, Saur, Chingiz, and Aktogay types. A generalized classification of these types is reflected in the formation-based typology of mineralization (Table 1), their mineralogical-geochemical characteristics (Table 2), as well as the composition of ore-hosting rocks, morphology of porphyry mineralization in Eastern Kazakhstan, and its comparison with global analogues (Table 3).

In the Rudny Altai SFZ, porphyry gold-quartz-polymetallic occurrences (Altai type) include the Sugatovskoe and Sekisovskoe deposits, as well as the Krestovskoe I, II, III, Novo-Khairuzovskoe, Listvenitovoe, and Greisenovoe occurrences. Additionally, the region is home to the Bukhtarma porphyry copper deposit and the Dolinnoe polymetallic porphyry deposit, both of which were mined in the 1950-1960s.

All of these porphyry occurrences are spatially associated with the junction of the Aleisk Anticlinorium and the Irtysh Shear Zone. They are closely related to intrusions of quartz-feldspar porphyries and are expressed as disseminated pyrite, chalcopyrite, less commonly gold, galena, and sphalerite, occurring within hydrothermally altered porphyries and host rocks.

Rudnoaltai porphyry gold occurrences, in terms of base and precious metal ratios, are represented by mineralization types similar to those found in the Ridder-Sokolnoe deposit. However, the absolute concentrations of valuable metals in these occurrences are 1-2 orders of magnitude lower. This difference is due to the fact that at the uniquely large-scale Ridder-Sokolnoe deposit, over more than 200 years of mining, more than 520 tonnes of gold have been recovered alongside base metals. Consequently, the Rudnoaltai SFZ is classified as a gold-copper-lead-zinc province with accompanying elements Ag, Mo, Bi, As, Sb, Se, Te, Re, Hg, W, Sn, and pathfinder elements Co, Ni, Ti, V, Tl, Ga, In, Ge [17].

Mineralization refers to the process of introducing and depositing chemical elements into a specific space, resulting in "anomalous" concentrations of the introduced components, i.e., exceeding at least three times their concentrations in certain rocks of the Earth's crust [32]. It should be noted that for commercial gold-polymetallic ores, industrially "anomalous" concentrations of Cu, Zn, Pb, and Au must exceed 200 times the Clarke values of the Earth's crust for porphyry copper ores and 300 times for polymetallic ores. Gold-polymetallic mineralization, based on the sequential-spatial differentiation of chalcophile elements, is divided into five mineralogical-geochemical associations corresponding to the types of mineralization: gold, copper, polymetallic, gold-copper, and gold-polymetallic [20].

Gold mineralization is characterized by anomalous concentrations of the noble metal (more than 20 times the Clarke value), accompanied by background contents of all chalcophile elements. It formed during the early hydrothermal stage of rock metamorphism and is associated with unevenly dispersed gold mineralization, which is superimposed on all granitoids and metasomatic formations developed within them. The practical significance of this mineralization is currently low due to the low metal concentrations and extremely irregular distribution of gold-bearing intervals in space. The noble metal content in this type of mineralization usually ranges from 0.08 to several grams per ton.

Gold-copper mineralization differs in that anomalous concentrations of gold are associated with above-Clarke (10-20 times) concentrations of copper. The latter is present in amounts ranging from 250 to 800 g/t. The noble metal content in samples of this association usually varies within the first tenths of a gram per ton, while higher gram-level concentrations of gold are typically associated with gold-polymetallic mineralization.

Table 1. Systematics (formational classification) of porphyry occurrences within the territory of Eastern Kazakhstan

Structural-formational zone	Subformation	Type of porphyry occurrence	Ore-bearing magmatic complex	Ore-hosting geological formation	Spatial association with other ore formations	Examples of deposits (occurrences)
Rudnoaltai	Gold-quartz-polymetallic	Altai	Zmeinogorsk gabbro-granodiorite-granite (C_{2-3})	Contrasting basalt-rhyolite siliceous-carbonate-terrigenous (D_{1-3})	With copper-lead-zinc VMS basalt-rhyolite	Sugatovskoe, Sekisovskoe (Krestovskoe I, II, III, Novo-Khairuzovskoe, Listvenitovoe)
Zharma-Saur	Copper-molybdenum	Zharman	Zharman gabbro-diorite-granodiorite-granite (P_1)	Andesite-basalt formation (P_1)	With rare-metal, rare-earth	Shorskoe, Kishkine, Zhaksu Koytas
	Molybdenum-copper	Saur (Aktogay)	Saur gabbro-diorite-granodiorite-granite (C_1)	Andesite-basalt formation	With VMS-polymetallic and rare-metal	Kyzyl-Kain, Kensai
Chingiz-Tarbagatai	Molybdenum-copper	Chingiz	Sarykol gabbro-diorite-granodiorite-granite	Andesite-basalt formation	With copper-zinc VMS rhyolite-basalt	Bala-Urpek, Kanshoky, Karasu (Argynbaysyz, Bel-bastau, Katayskoe, Zapadnoe)
Dzungaro-Balkhash	Molybdenum-copper	Aktogay (Kounrad)	Aktogay gabbro-diorite-granodiorite-plagiogranite (C_3)	Contrasting andesite-rhyolite Keregetas Formation (C_{2-3} kg)	With VMS-polymetallic	Aktogay, Aidarly, (Kyzylkiya, Toisagan, Tassu)
	Copper-molybdenum	Sayak	Balkhash intrusive complex (C_3)	Andesite-rhyolite-dacite formation (D_{1-2})	With VMS copper-zinc	Nurbai

Table 2. Mineralogical-geochemical characteristics of porphyry occurrences

Subformation	Main ore (secondary) minerals	Main gangue (secondary) minerals	Main (secondary) components	Pathfinder elements	Mineral ore associations	Stages of metasomatic alterations
Altai	Py, Cp, Gn, Sf, Zn, Bn, Mo, Az (Mo, Py, Lim, Cv, Mag, El, Agt, Bi)	Qz, Ser, Chl (Ba, Cal, Bt, Fl, Ab, Or, Dol)	Au, Ag, Cu, Pb, Zn, Mo (As, Sb, Se, Te, Ba, Re, Bi, W)	Tl, Ga, In, Ge, Sn, Hg, Co, Ni, Mn, Sr, Cr, V, Ti	Pyrite-gold, pyrite-chalcopyrite, gold-quartz, pyrite-chalcopyrite-galena-black ore	Propylitization, silicification, sericitization, K-feldspar alteration, chloritization
Zharman	Mo, Cp, Py, Ml, Az (Po, Cup, Pow, Hem, Lim, Mag)	Qz, Ser, Chl (Cal, Bt, Ab, Or)	Mo (Cu, Au, Ag, Se, Te, Re)	Cu, Pb, Zn, As, Sb, Co, Ni, W	Quartz-molybdenite, pyrite-molybdenite-chalcopyrite	Beresitization, argillitization, propylitization, sericitization, pyritization
Saur	Cp, Py, Mx, Az (Mo, Lim, Kup, Mag, Vis)	Qz, Ser, Chl (Cal, Bt, Ab, Or, Tur)	Cu, Pb, Zn, As, Sb, Co, Ni, W	Se, Te, Re, Pb, Zn, As, Sb, Co, Ni, W	Pyrite, gold-chalcopyrite-molybdenite, chalcopyrite-molybdenite	Propylitization, pyritization, K-feldspar alteration, epidotization, chloritization
Chingiz	Cp, Py, Mx, Mo, Bn (Hem, Cv, Cup)	Qz, Ser, Chl, Ab (Qvc, Cal, Bt, Or)	Cu, Mo (Au, Ag, Pb, Zn, Ba)	Pb, Zn, Ba	Quartz-chalcopyrite, chalcopyrite-molybdenite, chalcopyrite-bornite	Quartzite formation, propylitization, sericitization, pyritization, K-feldspar alteration
Aktogay	Qz, Ser, Chl, Ab (Qvc, Cal, Bt, Or)	Qz, Kfs, Pr, Ep, Cal, Ser, Ts (Mus, Ap, Ab, Sf, Ru)	Cu, Mo (Au, Ag, Pb, Zn)	As, Bi, Se, Te, Re	Quartzite, quartz-sericite-sulfide	K-feldspar alteration, biotitization, argillitization, tourmalinization, propylitization

Note:

Ab – albite	Chl – chlorite	Hem – martite (hematite variety)	Mt – magnetite	Ru – rutile
Act – acanthite	Cp – chalcopyrite	Kfs – potassium feldspar	Mus – muscovite	Sch – scheelite
Agt – argentite	Cv – covellite	Kup – cuprite	Or – orthoclase	Ser – sericite
Au – native gold	Dol – dolomite	Lim – limonite	Po – pyrrhotite	Sf – sphalerite
Az – azurite	El – electrum	Mag – magnetite	Pow – powellite	Sp – sphalerite
Ba – barite	Ep – epidote	Mar – marcasite	Pr – prehnite	Ttm – titanomagnetite
Bi – bismuthinite	Fcs – fuchsite (fengite)	Mo – molybdenite	Py – pyrite	Ts – zeolite (clinoptilolite)
Bn – bornite	Fl – fluorite	Ml – malachite	Qvc – quartzite	Tur – tourmaline
Bt – biotite	Gn – galena	Msh – mischetovite	Qz – quartz	Ttn – tetrahedrite-tennantite
Cal – calcite				

Table 3. Ore-hosting rocks and morphology of mineralization in various deposits and occurrences of eastern Kazakhstan and abroad

Composition of ore-hosting rocks, age	Morphology of mineralization	Examples of deposits	
		Eastern Kazakhstan	Foreign countries
Plagiogranite-porphyries and their breccias in the sub-intrusive zone of a granitoid massif (P_1)	Steeply dipping stockworks with dykes forming linear zones near the junction of NW and SW-trending faults	Shorskoe, Kishkine, Zhaksu Koytas, Rossypnoy Belok	Sorskoe (Yakutia) [33], Kajaran (Armenia) [34], Climax (Canada) [35], Shalkiya, Tologoy (Kazakhstan)
Granodiorites, plagiogranite-porphyries, granite-porphyries, and their host rhyolites and andesite-dacites (C_{2-3})	Stockworks in plagiogranite-porphyries and their breccias with vein bodies	Sugatovskoe, Sekisovskoe, Krestovskoe 1, 2, 3	Fort Knox (USA) [36], aul, Ryan Lode (USA), Breven Creek
	Stockwork-like mineralized zones with quartz-gold-sulfide veins in granitoids and andesite-basalts	Novo-Khairuzovskoe, Listvenitovoe, Greisenovoe	Petropavlovskoe, Yubileinoe, Bereznyakovskoe, Shkolnoe
Quartz diorites, granodiorites, granite-porphyries, plagiogranites, and their host intermediate-mafic volcanics (C-P)	Steeply dipping ore stocks with isometric and elliptical shapes in granitoids	Aktogay, Aidarly, Kyzylkiya, Taisogan, Kyzyl-Kain	Bingham [37], Butte (USA), Cananea (Canada)
	Steeply dipping stock-shaped zones oriented NW	Kensai	Tsagansuburga [38], Erdenetuin-Obo, Gulan, Sary-Chemche
Granodiorites, diorites, plagiogranites, monzonites, and their host andesite-basalt formation deposits (O-S)	Steeply dipping ore stocks with lenticular and elliptical shapes in granitoids	Bala-Urpek, Karasu	Ajo
	Stockwork-like zones of lenticular bodies in the endo- and exocontact of granitoids and volcanics	Kanshoky, Katayskoe, Argynbaysyz	Chuquicamata [39], Kalmakyr [40], Dalnee, Sary Cheku [41]

Gold-polymetallic mineralization is characterized by a close spatial relationship between increased (anomalous) concentrations of gold and chalcophile elements (Cu, Bi, Ag, Pb, As, Zn, Sb, Mo, R). This mineralization resulted from hydrothermal activity manifested in the final stage of the process. This geochemical association does not have widespread areal distribution, but it is associated with high-grade gold ore deposits preferentially localized on the periphery of mineralized zones.

Copper mineralization is represented by anomalous copper concentrations exceeding 10 times the Clarke values of the Earth's crust, while maintaining background (Clarke-level) contents of all associated chalcophile elements, including noble metals. The spatial distribution of copper mineralization coincides with the contour of gold mineralization.

Polymetallic mineralization, unlike copper mineralization, has a fragmented distribution and occurs only in the form of small-scale (up to 2 m thick) mineralized formations among barren rocks, where the intervals between polymetallic zones range from several meters to tens and hundreds of meters.

Thus, during the post-magmatic stage, from hydrothermal fluids entering the ore-localizing structure, gold is initially deposited, associated with silica, pyrite, and arsenopyrite. It then becomes finely dispersed and isomorphically incorporated into the crystal lattices of base metal sulfides, while excess concentrations form native gold. In the final stage, gold crystallizes in an intermetallic form (electrum) in association with sulfides and sulfosalts of Bi, Ag, Pb, and Cu.

3.2. Criteria for the localization of porphyry mineralization in ore-bearing structures of Eastern Kazakhstan

In Eastern Kazakhstan, Au-Cu-Mo porphyry deposits were formed during the Middle and Late Paleozoic. The Middle Paleozoic deposits include Bala-Urpek, Kanshoka, Karasu, and ore occurrences such as Zapadnoye, Shunay, Yubileynoye, Argynbaisaz, Katayskoye, and Belbastau, which are located within the Caledonides. All other deposits and ore occurrences belong to Late Paleozoic formations and are localized within Hercynian structures.

Porphyry-type deposits are associated with volcanoplutonic belts, which are known in all Phanerozoic fold systems. The connection of such deposits with intrusive magmatism is recognized by all researchers of these mineralizations. In all provinces of Eastern Kazakhstan, gold-copper porphyry mineralization exhibits stable spatial-temporal associations with products of volcanism and plutonism. The volcanic formations of the Paleozoic belts belong to the andesite-dacite-rhyolite group of normal alkalinity, which are subsequently replaced by comagmatic plutonic formations of a similar composition.

Porphyry-type mineralization represents a part of the ore-magmatic system, with the final stage of its evolution being the formation of deposits during the late phases of fully differentiated magmatic complexes of multiphase and polychronous plutons. Concentrated ore formation marks the culmination of long-lived magmatic systems, characterized by multi-stage activity and multi-impulse magma intrusions at each stage. During the early (volcanogenic) stage, massive sulfide-polymetallic mineralization was formed, associated with post-volcanic basalt-rhyolite magmatism. At a later stage, granitoid massifs were emplaced, followed by the intrusion of porphyries in the form of stock- and dike-like bodies, accompanied by vein-disseminated mineralization of quartz-vein and porphyry types. The emplacement of ore-bearing porphyry stocks was controlled by deep-seated faults, while the deposits themselves are located in tectonic blocks between zones of deep faults and are associated with the intersection nodes of faults of different orders.

The ore-hosting intrusive granitoid bodies consist of rocks of the gabbro-diorite-granodiorite-granite association, with granodiorites of the calc-alkaline series dominating. The granitoids represent late differentiates of the initial basaltic magma, while leucogranites (granite-porphyries) constitute residual granitoid melt accumulations, in which a significant portion of volatiles and ore components were concentrated. These melts served as sources of ore-bearing fluids that led to the formation of porphyry-type mineralization.

Porphyry deposits are mainly localized in the upper dome-like sections of granitoid massifs, where fracturing and crushing zones develop due to heterogeneous thermal decompression in the crystallized frontal parts of porphyry stocks. The ores were formed simultaneously with the late phases of near-surface intrusions and were accompanied by intense hydrothermal activity, manifesting as extensive metasomatism under conditions of rhythmically pulsed influxes of metal-bearing solutions.

Gold-molybdenum-copper porphyry deposits are integral parts of their respective magmatic systems and consist of several interrelated elements that serve as exploration criteria and indicators. The primary regional ore localization factors are structural-tectonic and magmatic.

From a geotectonic perspective, porphyry-type occurrences are known within the Hercynian and Caledonian structures of Eastern Kazakhstan. The most favorable structures for the identification of industrial-scale deposits are the Hercynian structures [22], [23]. The spatial position of the most prospective sites is determined by the structural-tectonic framework of Eastern Kazakhstan, which encompasses the Hercynian fold belt.

Magmatic factors reflect the relationship between mineralization and specific magmatic rock complexes and certain intrusion phases. A characteristic feature of the distribution of copper-porphyry deposits within volcanoplutonic belts is the close association of ore-bearing porphyry intrusions with volcanogenic formations. The genetic unity of volcanic and intrusive rocks and their connection with successive stages of magmatic evolution is confirmed by the structural framework, certain petrographic and petrochemical characteristics, and the metallogenic specialization of the intrusions.

The most promising fold systems for gold-porphyry and molybdenum-copper-porphyry industrial mineralization are the Hercynian fold systems of the Rudny Altai, Zharma-Saur, and Dzhungaro-Balkhash metallogenic zones (MFZ).

In the Rudny Altai MFZ, the formation of gold-copper-porphyry occurrences is associated with granitoids of the Zmeinogorsk magmatic complex of Carboniferous – Permian age (Sugatovskoye, Sekisovskoye deposits, and the Krestovskaya and Bolshenarim ore occurrences). The granitoids of this complex are represented by granodiorites, tonalites, quartz diorites, plagiogranites, and granites.

In the Zharma-Saur MFZ, the most productive complex for copper-porphyry mineralization is the Saur complex (C1), which includes ore-bearing massifs formed in an early collisional setting during the final stages of the Saur folding phase [22]. The rocks of this complex are generally characterized by molybdenum-copper specialization, with which copper-porphyry mineralization is genetically associated (Kyzyl-Kain, Kensay, Shorskoye deposits, and the Arsenyevskoye ore occurrence).

The Dzhungaro-Balkhash MFZ is the most promising region for molybdenum-copper-porphyry mineralization in Kazakhstan. It hosts the largest industrial deposits, Aktogay and Aydarly, which are associated with Late Carboniferous granitoids of the Aktogay complex. The ore mineralization is concentrated in uplifted areas located at the margins of an anticlinorium. Mineralization is typically localized within zones of concealed deep-seated faults of various orientations, which serve as ore-conducting structures. Within these structures, deposits are associated with small porphyry intrusions, pipe-like bodies of hydrothermal-explosive breccias, and intersections of major zones of fine fracturing. At these deposits, ring and semi-ring dikes are widely developed, clearly delineating the boundaries of volcano-tectonic structures.

3.3. General assessment of the prospectivity of Eastern Kazakhstan for porphyry-type mineralization

Currently, two deposits are being exploited in Eastern Kazakhstan – the Aktogay molybdenum-copper-porphyry deposit and the Sekisovskoye gold-porphyry deposit. A large deposit with substantial reserves of economic ores, Aydarly, has been explored in detail. Within the Rudny Altai metallogenic zone (MFZ), the Bukhtarma copper-porphyry and Dolinsk polymetallic porphyry-type deposits were fully mined out in the 1950-1970^{s}, while the Sugatovskoye gold-copper-porphyry deposit was exploited in the 18-19th centuries. In the 1980^{s}, the Rulevskoye copper-porphyry occurrence was explored, but it was classified as unpromising.

The Sugatovskoye deposit has been accessed by mining workings at seven levels down to a depth of 102 m, and the rich ores of the cementation zone have long been extracted. Approximately 30% of the ore-bearing plagiogranite-porphyries have been classified as conditionally economic ores, containing over 2000 kg of gold (Tables 4, 5). Due to the remaining ore reserves and the concentration of valuable components, the deposit has been classified as subeconomic. The deep horizons and flanks have been thoroughly studied, and the discovery of a large deposit in this area is considered unlikely. The remaining oxidized-zone reserves of gold and silver may be mined by open-pit methods.

Table 4. Average element content in porphyry ores of Eastern Kazakhstan

Ore type	Average element contents in g/t									Ag/Au
	Zn	Pb	Cu	Mo	Au	Ag	Se	Te	Re	
Rudny Altai MFZ										
Sugatovskoye deposit										
Oxidized gold-polymetallic	300	2600	1000	5	2.55	24.7	–	–	–	9.7
Sulphide gold-polymetallic	1000	2000	4600	5	0.62	30.3	–	–	–	48.8
Krestovskie 1, 2, 3 occurrences										
Sulphide gold-polymetallic	1560	600	2100	35.50	2.15	2.6	–	–	–	1.21
Novokhayruzovskoye occurrence										
Sulphide gold-polymetallic	800	1250	850	5	0.6	3.3	0.025	–	0.001	5.5
Listvenitovoye occurrence										
Oxidized gold-polymetallic	–	–	–	–	2.53	–	–	–	–	–
Sulphide gold-polymetallic	850	1200	650	2.4	0.8	2.1	0.02	–	0.003	2.6
Greisenovoye occurrence										
Sulphide gold-polymetallic	750	1500	1200	5	0.3	1.6	0.03	–	0.001	3.3
Zharma-Saur MFZ										
Kensay deposit										
Sulphide copper-molybdenum	350	250	1670	40	–	0.5	–	–	–	–
Kyzyl-Kain deposit										
Sulphide copper-molybdenum	–	–	2900	50	0.03	–	–	–	–	5.4
Shorskoye deposit										
Sulphide copper-molybdenum	–	–	590	1054	–	1.28	1.0	1.17	0.46	–
Sulphide copper-molybdenum	–	–	590	1054	–	1.28	1.0	1.17	0.46	–
Oxidized copper-molybdenum	–	–	480	720	–	–	–	–	–	–
Chingiz-Tarbagatai MFZ										
Bala-Urpek deposit										
Oxidized copper, Western ore zone			6200	15	0.06	1,1				18.3
Oxidized copper, Eastern ore zone			2000	10	0.2	1,5				7.5
Kanshoka deposit										
Sulphide copper-molybdenum	1500	75	3200	200	0.12	1.8				15.0
Oxidized copper-molybdenum			2600	55	0.025	1.8				72
Kataisky Massif occurrences (Karasu, Kataiskoye)										
Sulphide copper-porphyry	300	200	3500	<10	-					
Argynbaisaz occurrence										
Sulphide copper-porphyry	250	150	500	<10	-	0.35				
Dzhungaro-Balkhash MFZ										
Aktogay deposit										
Sulphide copper-molybdenum			3850	80	0.03	1.09	1.8		0.001	36.3
Aidarli deposit										
Sulphide copper-molybdenum			3840	100	0.009	1.42	1.79		0.243	157
Taysogan occurrence										
Sulphide copper-molybdenum	800	500	3000	45						
Nurbay occurrence										
Sulphide copper-molybdenum	600	200	5000	100	0/004					

Table 5. Reserves of valuable metals in porphyry ores of Eastern Kazakhstan

Ore types	Category	Ore reserves, million tons	Metal reserves: Zn, Pb, Cu, Mo in thousand tons, and Au, Ag, Se, Re in tons							
			Zn	Pb	Cu	Mo	Au	Ag	Se	Re
Rudny Altai MFZ										
Sugatovskoye deposit										
Oxidized gold-polymetallic	P_1	0.86	0.26	2.23	1.01	–	2.19	24.62	–	–
Sulphide gold-polymetallic	P_1	0.60	0.68	1.23	2.8	–	0.37	18.2	–	–
Krestovskoye 1, 2, and 3 occurrences										
Sulphide gold-polymetallic	P_1	2.34	–	–	–	–	0.46	–	–	–
Novo-Khayruzovskoye occurrence										
Sulphide gold-polymetallic	P_1	–	–	–	–	–	0.50	–	–	–
Listvenitovoye occurrence										
Oxidized gold-polymetallic	C_2	0.11	–	–	–	–	0.35	–	–	–
Sulphide gold-polymetallic	P_1	0.28	–	–	–	–	0/72	–	–	–
Greisenovoye occurrence										
Sulphide gold-polymetallic	P_2	0.097	–	–	–	–	0.095	–	–	–
Zharma-Saur MFZ										
Kensay deposit										
Sulphide copper-molybdenum	P_1	198.33	–	–	595	–	–	–	–	–
Kyzyl-Kain deposit										
Sulphide copper-molybdenum	P_1	542.8	–	–	1576	27,0	–	–	–	–
Shorskoye deposit										
Oxidized molybdenum	C_2	0.66	–	–	0.31	047	–	–	–	–
Sulphide molybdenum	C_2	13.23	–	–	7.82	13.94	–	16.7	13.1	6.0
Chingiz-Tarbagatai MFZ										
Bala-Urpek deposit										
Oxidized copper-porphyry	C_2	18.98	–	–	116.2	–	1.132	–	–	–
Oxidized copper-porphyry	P_1	4.65	–	–	9.65	–	0.98	–	–	–
Kanshoka deposit										
Sulphide copper-molybdenum	P_1	69.053	–	–	221.0	13.7	–	–	–	–
Karasu, Kataiskoye occurrences										
Sulphide copper-porphyry	P_1	177.23	–	–	797.5	–	–	–	–	–
Sulphide copper-porphyry	P_3	464.2	–	–	1021.3	–	–	–	–	–
Dzhungaro-Balkhash MFZ										
Aktogay deposit										
Sulphide copper-molybdenum	B + C_1	1528.278	–	–	5884.8	121.7	43.9	1576.4	2599.5	155.0
Oxidized	C_1	–	–	–	20.5	–	–	–	–	–
Aidarli deposit										
Sulphide copper-molybdenum	B + C_1	1529.25	–	–	5870.5	154.2	14.1	2168.8	2724.0	370.0
Oxidized copper-molybdenum	C_1	–	–	–	328.0	–	–	–	–	–
Taysogan occurrence										
Sulphide copper-molybdenum	–	–	–	–	–	–	–	–	–	–
Nurbay occurrence										
Sulphide copper-molybdenum	P_1	36.47	–	–	171.3	–	–	–	–	–

The Krestovskoye site occurrences (Krestovskoye I, II, III) have not been fully studied either along the flanks or at depth. The conducted exploration has confirmed the presence of industrial-grade gold ore bodies within the stockwork quartzification zone at depths of 150-200 m (Krestovskoye II).

On the flanks of the quartz-vein zones (Krestovskoye I, II), gold mineralization is predicted to be associated with steeply dipping porphyry bodies with stockwork quartzification and sulfide mineralization. The Krestovskoye site is considered promising for the discovery of a medium-scale gold deposit. Further exploration of the flanks and deeper horizons is recommended using a drilling grid of 50×25 m down to a depth of 300 m.

The Novo-Khayruzovskoye occurrence consists of two mineralized zones.

The eastern mineralized zone, in combination with quartz-vein mineralization, extends for 6.5 km with a width of up to 300 m. Surface trenching has been conducted along strike at intervals of 400 and 50 m, and 50 core boreholes have been drilled to a depth of 400 m.

The western mineralized zone is 3.8 km long and 120-750 m wide. It has been traced on the surface with trenches spaced at 400 m intervals, and 27 boreholes have been drilled to a depth of 400 m.

Each mineralized zone of the occurrence contains three columnar-shaped bodies with gold mineralization. Overall, out of 6052 core samples from the Novo-Khayruzovskoye occurrence, over 70% show gold contents between 0.13 and 0.4 g/t, 198 samples exceed 1 g/t, and only 22 samples contain more than 5 g/t.

The Listvenitovoye occurrence has been traced over a distance of 1000 m. It has been explored by 49 trenches at intervals of 25-50 m and 10-25 m, reaching depths of 20 m, and by 516 pneumatic drilling boreholes across 21 profiles. Deeper sections have been studied using 86 core boreholes in three cross-sections, and an exploratory trench has been excavated.

Additionally, nine small technological samples have been analyzed. Three gently dipping mineralized zones have been identified, with average gold contents ranging from 0.44 to 8.75 g/t. Cyanide leaching technology is recommended for gold extraction. The site has been studied in detail and is recommended for artisanal mining.

The Greisenovoye occurrence has been traced over a distance of up to 1500 m. It has been explored by 34 trenches and 26 core boreholes across three sections. More detailed drilling has been carried out using 1190 KGK boreholes to depths of 40 m and 164 pneumatic boreholes to depths of 20 m. Gold contents range from 0.1 to 1.35 g/t. The total estimated gold resources amount to 95.5 kg. This occurrence is not considered of practical economic interest.

The Kyzyl-Kain deposit remains underexplored. The author's estimation of reserves down to depths of 400-500 m (Tables 4, 5) allows this deposit to be classified as a medium-scale copper deposit. Reserves of gold, silver, and other associated components have not been calculated.

The Kensay deposit has an estimated copper reserve of 592 thousand tons, based on individual boreholes (Tables 4, 5). There is a high probability that ore zones extend further to the east and west, which could potentially increase the forecasted copper reserves by 1.5 times, reaching 850-900 thousand tons of conditional copper.

The Shorskoye deposit has ore and valuable metal reserves presented in Tables 4 and 5, classifying it as a small-scale deposit with economic-grade ores.

The Arsenyevskoye occurrence is assessed as a second-priority prospective site. The area has been explored through reconnaissance surveys with detailed studies and sampling of mineralized zones and host rocks. Several drilled boreholes have intersected ore mineralization with copper and molybdenum concentrations reaching 0.5-1% and 0.03-0.05%, respectively, accompanied by gold with concentrations ranging from 0.1 to 3.0 g/t.

The Karasu deposit is considered a promising site. Exploratory-evaluation drilling of boreholes 300-500 m deep is recommended to delineate previously identified ore bodies along the flanks and densify the drilling network along latitudinal profiles for correlation. The drilling should be accompanied by a suite of geophysical logging methods, including gamma logging, resistivity logging, induced polarization logging, and magnetic susceptibility logging. Based on the results of these studies, an increase in category P1 copper resources up to 1 million tons is expected.

The Nurbay occurrence is associated with the central part of a sericitic quartzite massif, formed from andesitic porphyrites and monzonites. Three zones have been identified at the deposit-oxidation, secondary enrichment, and primary sulfide ores. Two ore bodies have been delineated, extending up to 500 m in length and approximately 250 m in thickness. Ore reserve estimation indicates that at a cutoff copper grade of 0.3%, reserves down to 300 m depth amount to 36468.9 thousand tons of ore, containing 180 thousand tons of copper with an average grade of 0.47%.

The Bala-Urpek deposit site, located within the Chingiz Range and its southwestern slopes, covers approximately 3 km^2. Numerous copper mineralization points are known in this area, a significant portion of which including the Bala-Urpek deposit-belong to the copper-porphyry ore formation, which has considerable industrial significance in the region. However, these occurrences remain insufficiently studied to date. Nevertheless, the potential for identifying industrial-scale deposits among them is considered high.

4. Conclusions

The completion of these studies has enabled an assessment of the practical significance of molybdenum-copper-porphyry sites, which should serve as the basis for further exploration of porphyry occurrences in Eastern Kazakhstan.

The most important scientific and practical outcome of this research is the identification of the key geological characteristics of the predictive-exploration model for porphyry occurrences in Eastern Kazakhstan, which can be applied in prospecting and evaluation work.

This study consolidates all available geological and metallogenic data on porphyry-type occurrences in Eastern Kazakhstan and compares them with global analogs. Previously known exploration criteria have been refined and specified. Fundamentally new data have been obtained, allowing significant adjustments to the conventional sub-intrusive model without deviating from its general principles. Firstly, there is evidence linking mineralization to hydrothermalites and magmatites – porphyritic rocks associated with hydrothermalites and ores. Secondly, clear signs indicate the superposition of mineralization onto late intrusions and volcanites, as well as its coexistence with porphyries. Based on this, it is suggested that ores were formed from residual post-magmatic melts simultaneously with the late phases of near-surface intrusive magmatism and were accompanied by intense hydrothermal activity, resulting in strong metasomatism.

Prospective areas for the search for industrial-scale deposits should include regions with Lower Carboniferous – Early Permian granitoids of the Hercynian cycle, specifically: in the Dzhungaro-Balkhash MFZ: the Aktogay, Dzhaltyr-Taysogan, and Nurbay ore fields; in the Zharma-Saur MFZ: the Saur and Kensay ore districts; in the Altai MFZ: the Sekisovskoye and Krestovsko-Bolshenarim ore districts.

Among formations of the Caledonian cycle, the most promising are granitoids of Late Silurian – Early Devonian age (Chingiz-Tarbagatai MFZ), developed within the Katai, Baimbet, and Shet granitoid massifs, where small deposits and numerous mineralization points are known.

The authors see significant potential for discovering new porphyry-type deposits through further study and reassessment of previously identified highly prospective areas, particularly copper-porphyry, gold-polymetallic, and gold-quartz-vein epithermal occurrences. This will undoubtedly enhance the evaluation of the region's ore-bearing potential. In exploration, it is crucial to consider the coexistence of copper, gold, and polymetallic mineralization within the same ore district, field, or site.

The summarized data and insights presented in this article have broad relevance and will serve as a stimulus for rethinking the geological structure of ore districts and deposits associated with granitoids. They will also contribute to more effective geological exploration and predictive-exploration efforts for various types of mineralization in the region.

Thus, the authors believe that the territory of Eastern Kazakhstan continues to be a leading center for base and precious metal industries in Kazakhstan. Accordingly, further prospecting and evaluation work will enable the expansion of the resource base for this mineral-raw material complex.

Author contributions

Conceptualization: IM; Data curation: BA; Formal analysis: OF, KT; Funding acquisition: AD; Investigation: IM, OF; Methodology: IM, OF, KT; Project administration: BA; Resources: IM, BA, KT; Software: IM, BA; Supervision: AD; Validation: AD; Visualization: IM, OF; Writing – original draft: IM, OF, AD; Writing – review & editing: BA, AD, KT. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interests

The authors declare no conflict of interest.

Data availability statement

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

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Структурно-формаційні зони з мідно-порфіровим орудненням – перспективна мінерально-сировинна база міді Східного Казахстану

А. Рагданова, І. Матайбаєва, О. Фролова, Б. Агалієва, А. Долгополова, К. Тогізов

Мета. Стаття присвячена інформаційному аналізу геолого-генетичної систематизації всіх відомих на території Східного Казахстану об'єктів порфірового оруднення з уточненням їх структурного та вікового стану, зв'язку з магматизмом, речовим складом оруднення, його зональності.

Методика. Розглядається перспективна оцінка мідно-порфірових об'єктів у чотирьох структурно-формаційних зонах (СФЗ) – Рудно-алтайській, Жарма-Саурській, Чингіз-Таргабатайській та Джунгаро-Балхаській, у межах яких відомі різні типи порфірового оруднення. У камеральний період проводився інформаційний аналіз, що полягав у зборі, узагальненні та аналізі архівного, фондового й літературного матеріалу за всіма проявами порфірового типу, відомими з минулого століття, в межах чотирьох вищезгаданих СФЗ. Збір та аналіз геологічного, геофізичного, геохімічного, матеріалу здійснено за звітами пошуково-оціночних робіт, проведених у межах досліджуваної території.

Результати. Інформаційний аналіз дозволив конкретизувати пошуково-оціночні критерії та провести типізацію оруднення із зіставленням його зі світовими аналогами, уточнити масштабність оруднення та на цій основі виділити об’єкти, потенційно перспективні на промислово значуще оруднення. Здійснено аналіз фондових матеріалів зі створенням банку геологічних даних за основними 23-ма об’єктами з їх оцінкою.

Наукова новизна. Результати дослідження дозволили заявити, що попри те, що руди цих родовищ найчастіше досить бідні, запаси у порівнянні з іншими промисловими типами мідних родовищ (колчеданными, скарновыми, житловими) дуже великі і руди можуть рентабельно відпрацьовуватися відкритим способом. Більше того, низька собівартість відкритого видобутку міді, комплексний характер руд пояснюють інтерес промисловості до цього типу родовищ як до основного джерела отримання міді не лише в даний час, а й у майбутньому.

Практична значимість. Виконання робіт дозволило дати оцінку практичної значущості молібден-мідно-порфіровим та золото-мідно-поліметалевим порфіровим типам об’єктів, яка повинна бути основою для вжиття заходів щодо подальшого вивчення порфірових проявів на території Східного Казахстану.

Ключові слова: *медисті пісковики, рудопрояви, рудна зона, мідно-порфіровий, Східний Казахстан*

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