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GEOLOGICAL AND GEOPHYSICAL CRITERIA FOR ASSESSING PORPHYRY COPPER PROSPECTIVITY IN THE SHYNGYS-TARBAGATAI STRUCTURAL-FORMATIONAL DOMAIN, KAZAKHSTAN

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Abstract. *Relevance.* Mining is one of the most important segments of the Kazakhstan economy. The country possesses significant mineral resources, and their optimal utilization is key to future development. *Objective.* To effectively explore for new ore mineral deposits, it is necessary to systematize existing theoretical understanding of the distribution patterns of various ore systems and refine exploration criteria, taking into account the development of modern technologies. *Methods.* Porphyry copper deposits occupy a significant place in the mineral production structure, representing the largest source of copper, molybdenum, and gold reserves. Due to their unique geological structure, deposits of this type possess a number of well-studied diagnostic geological features. With the development of modern geophysical technologies, it is now possible to more accurately record anomalies in physical fields caused by geological structures and features. As part of the exploration program, an integrated set of geophysical methods was carried out within the study area, including ground magnetic surveying and induced polarization (IP) surveys. *Results.* The authors chose the Shyngys-Tarbagatai structural-formational zone as their research object. The results of magnetic and electrical surveys indicate that the study area is a structurally and geophysically distinct system, consistent with the model of a prospective porphyry copper mineralization system, manifested at the surface by silicified rocks forming part of an advanced argillic lithocap. The high-resistivity zone is located within an area of slightly elevated anomalous magnetic field values with a low total gradient, which coincides with the projection of the deep source (intrusion stock) based on 3D inversion data. *Conclusions.* Based on comprehensive geophysical studies conducted at one of the region's promising sites, the authors identified a set of geological and geophysical criteria applicable to ranking promising sites for porphyry copper mineralization within the Shyngys-Tarbagatai structural-formational zone.

Key words: geological and geophysical search criteria, silicified rocks, porphyry copper mineralization, magnetic survey, electrical prospecting, electrical resistivity tomography, induced polarization, chargeability, electrical resistivity

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ЧИНГИЗ-ТАРБАҒАТАЙ ҚҰРЫЛЫМДЫҚ-ФОРМАЦИЯЛЫҚ АЙМАҒЫНДА (ҚАЗАҚСТАН) МЫС-ПОРФИРЛІК МИНЕРАЛДАНУДЫҢ ПЕРСПЕКТИВАЛЫЛЫҒЫН БАҒАЛАУДЫҢ ГЕОЛОГИЯ-ГЕОФИЗИКАЛЫҚ КРИТЕРИЙЛЕРІ

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Аннотация. *Өзектілігі.* Тау-кен өндірісі Қазақстан экономикасының негізгі құрамдас бөлігі болып табылады. Елде айтарлықтай минералды ресурстар бар, және оларды оңтайлы пайдалану болашақ дамудың кілті болып табылады. *Мақсаты.* Жаңа кен минералды кен орындарын тиімді барлау үшін әртүрлі кен жүйелерінің таралу заңдылықтары туралы теориялық түсініктерді жүйелеу және заманауи технологиялардың дамуын ескере отырып, барлау критерийлерін нақтылау қажет. *Әдістері.* Порфирлік мыс кен орындары елдің минералды өндірісінде маңызды рөл атқарады, мыс, молибден және алтын қорларының ең ірі көзі болып табылады. Геофизикалық технологиялардың жетістіктері геологиялық құрылымдар мен нысандардан туындаған физикалық өрістердегі ауытқуларды дәлірек тіркеуге мүмкіндік береді. Перспективалы учаскедегі барлау жұмыстарының бөлігі ретінде жер үсті магниттік зерттеуі мен индукцияланған поляризация әдісін қолдана отырып, электрлік барлауды қамтитын кешенді геофизикалық зерттеу жүргізілді. *Нәтижелері.* Авторлар зерттеу нысаны ретінде Шыңғыс-Тарбағатай құрылымдық-формациялық аймағын таңдады. Магниттік барлау және электрлік барлау нәтижелері зерттелетін перспективалық учаскенің екінші реттік кварциттер (литокап) арқылы бетінде көрінетін мыс-порфирлік іздеу нысанының моделіне сәйкес келетін құрылымдық және геофизикалық тұрғыдан өрнектелген жүйе екенін көрсетеді. Жоғары кедергілі аймақ 3D инверсия деректеріне сәйкес терең көздің (интрузиялық қор) проекциясымен сәйкес келетін жалпы градиенті төмен аномальды магнит өрісінің сәл жоғары мәндері бар аймақта орналасқан. Жоғары кедергілі аймақ және жоғары поляризациялық мәндері бар аномальды аймақ кен-магмалық жүйенің беткі бөлігінің элементтері ретінде түсіндіріледі. Кен жүйесінің үстіңгі бөлігі литокапты (интенсивті кремнийлену аймағы) және терең ерекшеліктің (интрузия) проекциясымен кеңістіктік сәйкес келетін локализацияланған сульфидтену аймақтарын қамтиды. *Қорытынды.* Авторлар аймақтағы перспективалы учаскелердің бірінде жүргізілген кешенді геофизикалық зерттеулерге сүйене отырып, Шыңғыс-Тарбағатай құрылымдық-формациялық аймағындағы порфирлік мыс минералдануы бойынша перспективалы учаскелерді рейтингтеуге қолданылатын бірқатар геологиялық және геофизикалық критерийлерді анықтады.

Түйін сөздер: геологиялық және геофизикалық іздеу критерийлері, екіншілік кварциттер, мыс-порфирлік минералдану, магниттік барлау, электрлік барлау, электрлік кедергі томографиясы, индукцияланған поляризация, зарядталғыштық, меншікті электрлік кедергі

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ГЕОЛОГО-ГЕОФИЗИЧЕСКИЕ КРИТЕРИИ ОЦЕНКИ ПЕРСПЕКТИВНОСТИ МЕДНО-ПОРФИРОВОГО ОРУДЕНЕНИЯ В ЧИНГИЗ-ТАРБАГАТАЙСКОЙ СТРУКТУРНО-ФОРМАЦИОННОЙ ЗОНЕ (КАЗАХСТАН)

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Аннотация. *Актуальность.* Добыча полезных ископаемых является одним из ключевых секторов экономики Казахстана. Страна обладает значительными минеральными ресурсами, рациональное освоение которых имеет стратегическое значение для её дальнейшего социально-экономического развития. Медно-порфировые месторождения занимают важное место в структуре минерально-сырьевой базы, являясь крупными источниками меди, молибдена и золота. Эффективный поиск новых рудных объектов требует систематизации современных представлений о закономерностях размещения рудных систем и совершенствования геологических и геофизических поисковых критериев. *Цель.* Выявить комплекс геолого-геофизических критериев оценки перспективности медно-порфирового оруденения в пределах Чингиз-Тарбагатайской структурно-формационной зоны на основе результатов магнитной съёмки и электроразведки методом вызванной поляризации. *Методы.* Объектом исследования являлся перспективный участок, расположенный в пределах Чингиз-Тарбагатайской структурно-формационной зоны. На участке проведён комплекс наземных геофизических исследований, включавший магнитную съёмку и электроразведку методом вызванной поляризации. Выполнены анализ пространственного распределения аномального магнитного поля, удельного электрического сопротивления и поляризуемости, а также интерпретация результатов трёхмерной инверсии.

Полученные геофизические данные сопоставлены с геологическим строением участка и прогнозно-поисковой моделью медно-порфировой рудно-магматической системы. *Результаты.* Результаты магнитной съёмки и электроразведки показали, что исследуемый участок представляет собой структурно и геофизически выраженную систему, соответствующую прогнозно-поисковой модели медно-порфирового объекта, проявленного на поверхности вторичными кварцитами, образующими литокап. Высокоомная зона расположена внутри области умеренно повышенных значений аномального магнитного поля, характеризующейся низким полным градиентом. Её положение совпадает с проекцией глубинного источника, интерпретируемого как интрузивный шток по результатам трёхмерной инверсии. Зона повышенного удельного электрического сопротивления и аномалия высокой поляризуемости интерпретируются как элементы приповерхностной части рудно-магматической системы. Надинтрузивная часть системы включает литокап, представленный зоной интенсивной силицификации, и локальные участки сульфидизации, пространственно совпадающие с проекцией глубинного интрузивного объекта. *Выводы.* На основе комплексных геофизических исследований выделен набор геолого-геофизических критериев, которые могут использоваться для оценки и ранжирования перспективных участков медно-порфирового оруденения в пределах Чингиз-Тарбагатайской структурно-формационной зоны. К таким критериям относятся сочетание высокоомных зон с аномалиями повышенной поляризуемости, их пространственная приуроченность к областям умеренно повышенного магнитного поля с низким полным градиентом, а также совпадение приповерхностных зон силицификации и сульфидизации с проекцией глубинных интрузивных тел.

Ключевые слова: геолого-геофизические поисковые критерии, вторичные кварциты, медно-порфировое оруденение, магниторазведка, электроразведка, электротомография, вызванная поляризация, поляризуемость, удельное электрическое сопротивление

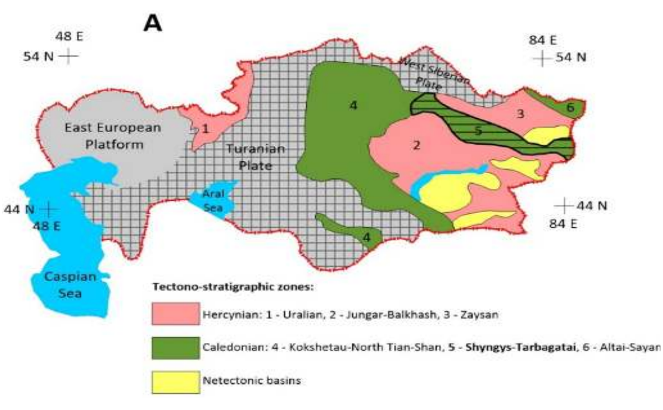
Introduction. Mineral extraction is a priority for Kazakhstan's economy. The country possesses significant ore reserves, which determines its position in the global market and facilitates investment inflow. Expanding the mineral resource base is a top priority. However, the scope of regional metallogenic research is extremely uneven, with some areas having been studied only in the last century.

The identification of promising areas of porphyry copper mineralization is traditionally based on the analysis of a combination of ore-forming factors, including the composition, age, and structural position of geological complexes. Within the framework of metallogenic studies, a formational (structural-compositional) approach has become widely used, allowing for the consideration of a territory as a hierarchically organized system of geological formations formed under specific geodynamic conditions. Prospective ore deposits are identified based on objective exploration indicators: their association with volcano-plutonic and volcanogenic-sedimentary complexes, structural features, and evidence of magmatic and hydrothermal activity. Furthermore, patterns in the spatial distribution of alteration zones and mineralization play a key role in forecasting. These factors form the basis for successful mineral exploration.

The effectiveness of formation analysis is enhanced by the use of geophysical methods of prospecting and exploration. Geophysical data allow the tracing of the boundaries of lithological variations, tectonic structures, and hidden structural elements that are not always accessible to direct geological observation. The comparison of geological criteria with stable geophysical features increases the reliability of the ranking of prospective sites, allows for a high accuracy in determining the location of target zones and ensures optimal planning of the next stages of prospecting. Thus, geophysics acts not only as a tool of geological exploration, but also as a full-fledged stage for testing and refining formative metallogenic hypotheses.

Copper occurrences were discovered in the Shyngys-Tarbagatai region in the middle of the 20th century. Since that moment, this region of Kazakhstan is significant and promising in terms of mineral resources. Territorially it is adjacent to the Shyngys-Tarbagatai Folding System of the Central Asian Folding Belt in the eastern part of Kazakhstan. This structure is located between the Zaysan and Dzungaro-Balkhash Hercynian fold systems and extends for several hundred kilometers with a width of tens to hundreds of kilometers (Abdullin, 1981; Seitmuratova et al., 2025).

Geodynamically, the region is considered as part of the former active continental margin (island-arc) of the Paleozoic, where successive stages of subduction and further development of the continental margin arc were manifested, which determined the complex structural framework (including the role of large shear zones) and the widespread development of volcanogenic-sedimentary and intrusive complexes, creating favorable conditions for the formation and preservation of ore-bearing magmatic-hydrothermal systems (Figure 1A).



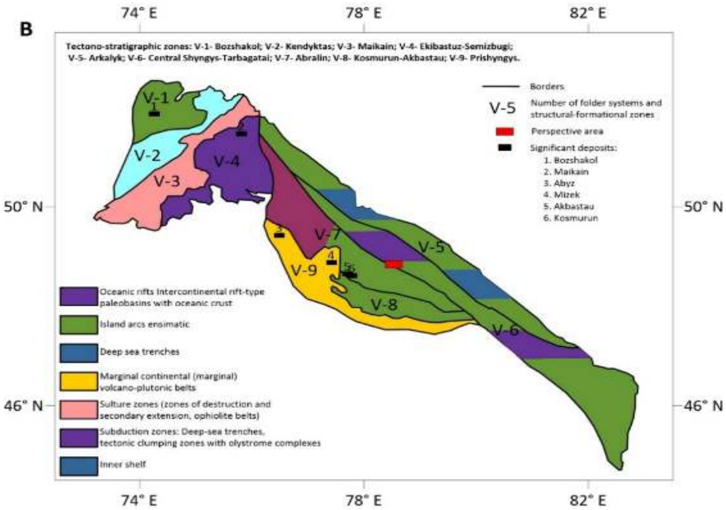


Figure 1. (A) position of the Shyngys–Tarbagatai folded system within the Kazakh Paleozoic Orogen; (B) Tectono-stratigraphic zoning scheme of the Shyngys–Tarbagatai folded system; modified after Abdullin, 1981 and Seitmuratova, 2025.

The Shyngys-Tarbagatai region is characterized by a long and multistage evolution of magmatism and tectonics. The initially formed island-arc structures of the active margin were transformed into a continental margin volcano-plutonic belt. This is reflected in the wide combination of various ore elements and the diversity of genetic types of mineralization in the region.

The region is known for a combination of porphyry copper, volcanogenic-massive sulfide and gold ore occurrences, with each type of mineralization confined to specific stratigraphic and structural zones, reflecting the complex paleotectonic and magmatic evolution of the Shyngys-Tarbagatai fold system. Key deposits include the large Bozshakol porphyry copper (Cu-Au-Pt) deposit, which is considered one of the largest porphyry-type objects within the system. A high concentration of porphyry copper mineralization is characteristic of the Maikain zone, where the Maikain group of porphyry copper/barite-polymetallic deposits (Au-Ag-Cu-Zn-Pb) and a large number of ore occurrences of various sizes are distinguished. For the Kosmuryn-Akbastau zone, the Akbastau and Kosmuryn porphyry copper deposits are noted, as well as large gold ore objects Abyz (Au-Ag) and Mizek (Au-Cu-Zn), which emphasizes the mixed specialization (Cu-Au-Mn and gold-copper associations) within a single structural system (Berger et al., 2010; Seedorff et al., 2005).

The purpose of this study is to identify and substantiate geological and geophysical criteria for assessing the prospects of porphyry copper mineralization within the Shyngys-Tarbagatai structural-formational system based on a comprehensive interpretation of the results of geophysical work and analysis of available geological data.

To achieve this goal, the authors solved the following tasks:

1. Collection, synthesis, and analysis of prior geological information to identify the geological structure of the prospective area.
2. Planning and execution of comprehensive geophysical surveys.
3. Processing and interpretation of geophysical data.
4. Analysis of the results to refine the geological structure of the area and identify geological and geophysical criteria for assessing the prospects of porphyry copper mineralization.

Literary review *(Modern concepts of porphyry copper ore systems).* Porphyry copper deposits (ore systems) are accumulations of veinlet-disseminated copper ores containing molybdenum or gold, associated with intermediate and felsic porphyry intrusions of normal and subalkaline series. Despite their relatively low element concentrations, porphyry copper deposits account for over 50% of global copper production, over 90% of molybdenum production, and are the primary gold deposit type (based on materials from the MGRI-RGGRU seminar, March 10, 2015, lecture: "Porphyry Copper Deposits: Criteria and Features." K.I. Voskresensky).

The generalized forecast and exploration model of the porphyry copper ore system (Sillitoe, 2010; Lowell and Guilbert, 1970; Seedorff et al., 2005) includes the following elements:

1. A deep intrusive magmatic center that is a source of heat and fluid flow.
2. Vertical and horizontal zoning reflecting hydrothermal alteration of rocks, including pyrite halos.
3. Stockwork (veinlet-disseminated) mineralization, characterized by a dense network of variously oriented veins and small veinlets of several generations containing ore minerals.
4. A significant volume of metasomatic alteration, exceeding the volume of the ore bodies themselves

Modern concepts of the structure of porphyry copper deposits and the analysis of ore-forming factors make it possible to formulate general exploration criteria of porphyry copper ore systems (Krivtsov et al., 2001; Sillitoe, 2010).

Structural and tectonic control. Deposits form within volcano-plutonic belts, typically associated with subduction zones, including volcanic arcs, as well as within intraplatform intrusive complexes. A clear spatial relationship with intrusive bodies of intermediate to felsic composition is noted. The distribution of intrusions is associated with large linear structures, extensional structures and faults.

Lithology. Mineralization is typically associated with porphyry intrusions, breccias, and surrounding volcanics. Structurally, mineralization zones are controlled by fractures, faults, and intrusion contacts with host rocks.

Hydrothermal zoning. Hydrothermal alteration (vertical and lateral), including potassic, phyllic, and advanced argillic assemblages, constitute a key exploration criterion. An important feature is the spatial association of porphyry intrusions with surface volcanics and silicified rocks (secondary quartzites) forming part of an advanced argillic lithocap. The large extent of surface hydrothermal alteration makes these features an important exploration guide.

The characteristic geological and tectonic exploration guides of porphyry copper ore systems make them a promising object for research using geophysical methods and allow the formation of a set of geological and geophysical criteria for ranking promising areas of porphyry copper mineralization.

The authors identified and substantiated geological and geophysical criteria for assessing the prospects of porphyry copper mineralization within the promising mining region of Kazakhstan – the Shyngys-Tarbagatai structural-formational system – based on a comprehensive interpretation of the results of geophysical work and an analysis of available geological data for the site.

Materials and Methods. The study area is located in the Abay District, Abay Region, and corresponds to the southern part of geological map sheet M-44-XXV (scale 1:200,000).

The geological structure of the study area comprises stratigraphic complexes of all series of the Cambrian and Ordovician, the Lower Silurian, all series of the Devonian, and the Lower Carboniferous. Mesozoic and Cenozoic deposits are of limited distribution and occur mainly within topographic depressions. All these units are involved in complex relationships resulting from multiple phases of folding and paleotectonic reorganization, which have led to the fragmented occurrence of individual stratigraphic units in the form of xenoblocks, tectonic slices, olistoliths and olistostromal blocks within suture zones. The complexity of the geological structure of the area is controlled by its spatial association with different structural–formational zones (GRK "Topaz" LLP, 2010)

On the geological map, the boundary of the prospective area is shown by a yellow contour (Figure 2).

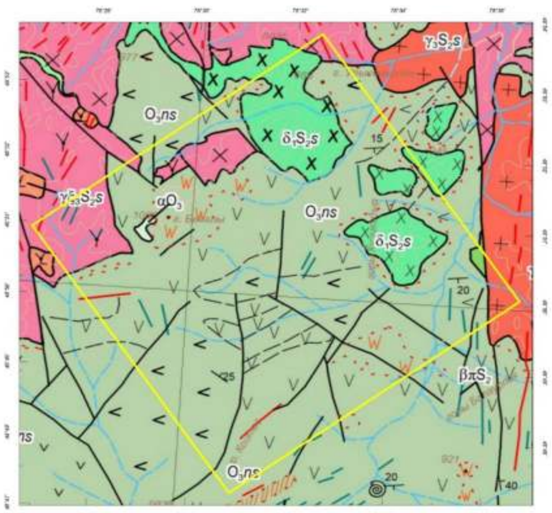


Figure 2. Geology map of the study area modified after GRK "Topaz" LLP (2010).

Within the study area, the Namas Formation (O_3ns) is the most widely distributed unit. It is composed of volcanic and volcaniclastic rocks, dominated by andesites and basaltic andesites, their tuffs, as well as terrigenous varieties (sandstones and siltstones). A large body of silicified rocks (unit W on the map) is distinguished within the area. According to previous studies, their formation may be associated with intrusions of the Sarykol complex, in whose exocontact zone they occur. These silicified rocks are interpreted as manifestations of intense hydrothermal alteration and are used as an exploration indicator in assessing the porphyry copper potential of the area.

In addition to the Namas Formation, within the prospective area and its immediate surroundings, according to the 1:200,000 scale geological map, subvolcanic and intrusive formations of the late Ordovician and early Silurian ages, as well as intrusive rocks of the Sarykol complex, are distinguished.

The Late Ordovician subvolcanic complex (αO_3 according to the M-44-XXV index) is represented by small bodies of isometric and irregular shapes, and less commonly, elongated dike-like bodies with sharply sinuous contours. Individual bodies are confined to zones of tectonic disturbances and have localized contact relationships with volcanogenic-sedimentary strata. The complex is characterized by a limited area of distribution within the area.

The Silurian subvolcanic intrusion complex of the area ($\beta\pi S_2$) is represented by small intrusive bodies (subvolcanics) intruding into host volcanic and terrigenous sediments. Intrusions of this complex form dike-shaped bodies with smoothly curved contours. The orientation of the dike-shaped bodies coincides with the general direction of the host sediments. Intermediate rocks are most common, with mafic rocks being less common.

1. The Sarykol intrusive complex (δ1S2s, gIt is less dependent on the direction of rock magnetization and geomagnetic field parameters than the TMI map;

2. It more clearly identifies the boundaries and contacts of magnetic bodies, as well as linear features such as dikes and fault zones;

3. It enables the identification of zones with elevated magnetic field gradients, interpreted as potential structural lineaments.

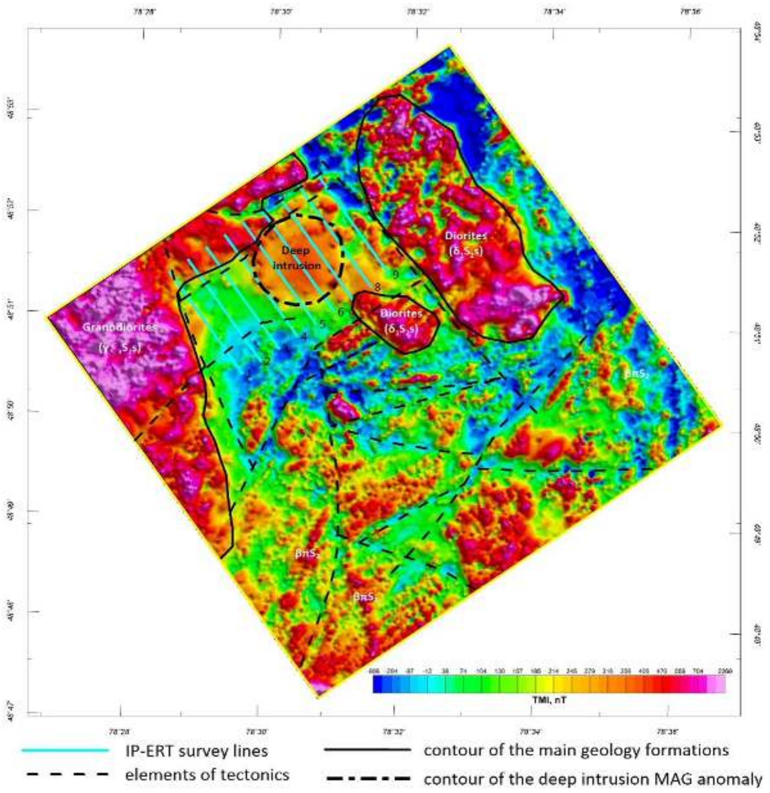


Figure 4. Map of the analytic signal amplitude (ASIG of the RTP magnetic field).

As a rule, the ASIG maxima are spatially confined to the marginal parts of magnetic sources and their contact zones, whereas deep-lying volumetric sources are characterized by a smoother morphology of the anomalous field, expressed in reduced ASIG values in the central part of the anomaly with their relative increase at the periphery.

Within the area, the ASIG map refines the contours of the main magnetic inhomogeneities: contact and linear zones are manifested by chains of local maxima in the analytical signal, typically in the range of ~4-9.4 nT/m, while the area interpreted as a deep source projection (Deep Intrusion) is characterized by lower ASIG values of ~0.5-1.6 nT/m and smoothed gradients. This distribution is consistent with the deep nature of the anomaly-forming object (a decrease in the high-frequency component of the field) and complements the interpretation based on the TMI-RTP map, where the source is expressed primarily by the amplitude of the anomalous field.

The results of 3D magnetic field inversion (Figure 5) indicate the presence of a compact deep source of the anomaly, interpreted as an intrusive body (stock) of increased magnetic susceptibility.

The volumetric model's isosurface displays values greater than 0.01 SI units of magnetic susceptibility. The depth of the upper edge of the submerged body according to the model is 600-700 m. The model's projection is spatially consistent with a local magnetic anomaly on the daylight surface, associated with a massif of silicified rocks.

Thus, the joint analysis of TMI-RTP and ASIG allows to separate volumetric anomalies (associated with deep sources) and contact-linear manifestations (body boundaries, dikes, faults), which increases the reliability of identifying structural elements and contours of potential ore-controlling zones.

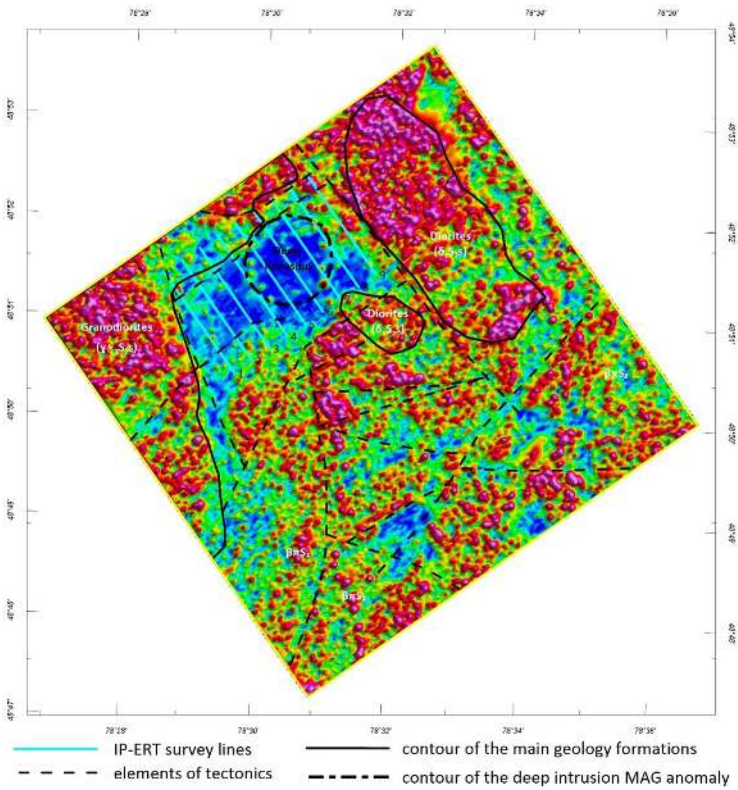


Figure 5. 3D-model of the magnetic body under the silicified rocks area.

Based on the results of induced polarization electrical resistivity tomography (ERT-IP), a joint 2D inversion was performed for each of the nine profiles intersecting the silicified rocks distribution area, and geoelectric cross-sections were constructed. Typical resistivity and chargeability cross-sections for one of the typical profiles are shown as an example (Figure 6).

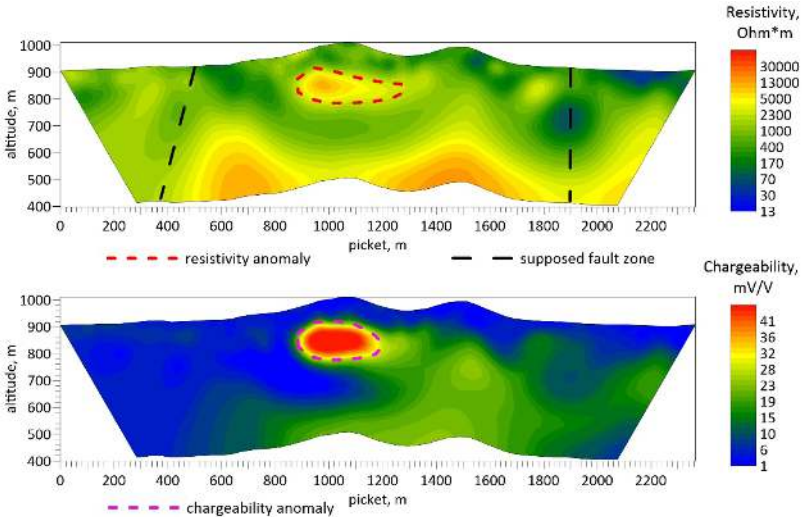


Figure 6. Resistivity and chargeability sections under the silicified rocks area.

In the central part of the resistivity section (in the interval of approximately 900-1400 m along the profile), a zone of elevated resistivity (thousands of Ω·m and higher) is distinguished within a depth range of approximately 100-250 m. Localized low-resistivity regions, interpreted as fault zones, are observed on the left and right flanks of the profile. In the chargeability section, the largest anomaly, with an intensity of up to 45 mV/V, is located in the central part of the profile and spatially coincides with the resistivity anomaly. This anomaly is localized, with fairly distinct boundaries, which is typical of zones of localized sulfidization (including pyritization).

To facilitate the identification of patterns in the spatial distribution of resistivity and chargeability anomalies, depth sections reflecting the anomaly positions were constructed along each ERT-IP profile (Figures 7 and 8). A combined analysis of the sections and maps (slices) of electrical parameters allows for the most comprehensive use of the data for interpretation. An absolute elevation of 820 m was chosen for the slices, corresponding to a depth range of 100 to 250 m. This interval of the geological section contains the most contrasting anomalies, reflecting the geological structure of the site with sufficient resolution of the electrical exploration array.

The resistivity map within profiles 5-7 reveals a large anomalous zone of high resistivity, which shows the distribution of silicified rocks and corresponds to the contour of a magnetic anomaly interpreted as a deep-seated intrusive body (stock). Correlated areas of low resistivity between the profiles, interpreted as inferred fault zones, outline this large anomalous zone. On the chargeability map, the most obvious anomalous zone coincides with the zone of high resistivity, with several other small local anomalies noted to the west.

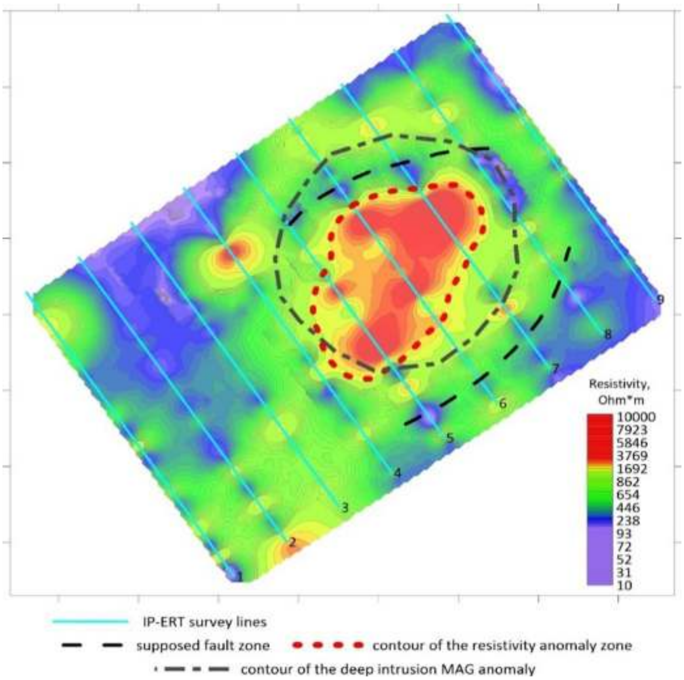


Figure 7. Resistivity map.

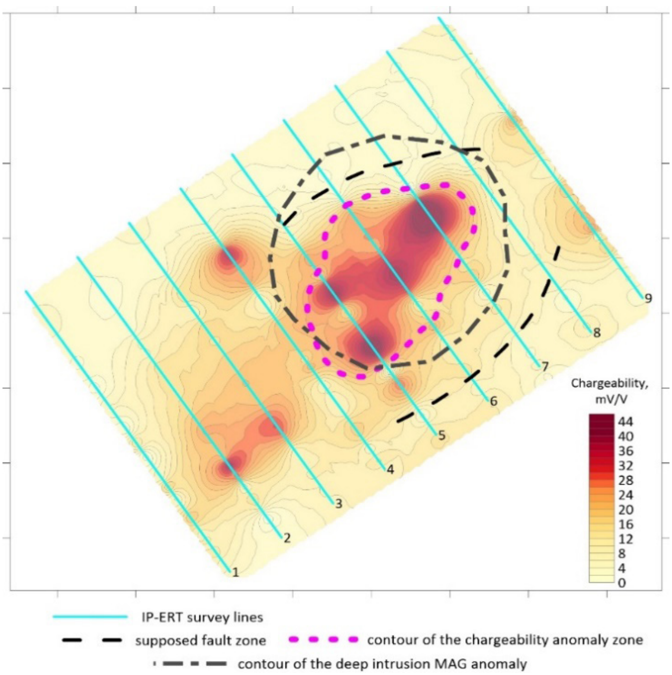


Figure 8. Chargeability map.

The identification of a zone of increased electrical resistivity is consistent with the distribution of silicified rocks. This is due to the low effective porosity and, consequently, the high electrical resistivity of intensely silicified rocks. At the same time, increased chargeability indicates the presence of electron-conducting (polarizable) phases, most likely finely disseminated sulfides (primarily pyrite), disseminated within the quartz matrix or confined to veinlet-breccia structures.

Discussion. The results of magnetic and electrical surveys (ERT-IP) indicate that the study area is a structurally and geophysically distinct system, consistent with the model of a prospective porphyry copper mineralization system, manifested at the surface by silicified rocks forming part of an advanced argillic lithocap. The high-resistivity zone is located within an area of slightly elevated anomalous magnetic field values with a low total gradient, which coincides with the projection of the deep source (intrusion stock) based on 3D inversion data.

The high-resistivity zone and the anomalous zone of high chargeability, within a depth range of 100-250 m, are interpreted as elements of the near-surface part of the ore-magmatic system. The above-intrusive portion of the ore system includes an advanced argillic lithocap (a zone of intense silicification) and localized areas of sulfidization, spatially coincident with the projection of the deep intrusive body. Vertical zoning is observed, corresponding to the classical model of a porphyry copper system, including a deep magmatic source (intrusion), an advanced argillic lithocap (characterized by intense silicification), and deeper local mineralization zones.

Spatial correlation of the following geophysical features is observed:

1. local isometric magnetic field anomaly with low-gradient boundaries;
2. local high-resistivity anomalous zone corresponding to the silicified rocks massif;
3. local chargeability anomalies, partially coinciding with the high-resistivity zone and its boundaries.

High resistivity values (thousands of Ω·m) at depths of 100-250 meters are interpreted as evidence of intense silicification and the predominance of a siliceous matrix (interpreted as vuggy silica). High resistivity is typical for such rocks due to low effective porosity and, as a rule, limited participation of conductive pore solutions. Localized chargeability anomalies within and at the boundaries of the high-resistivity zone indicate the presence of polarizable phases, likely disseminated pyrite or other sulfides, in a quartz matrix or a system of veinlets and breccias. The intensity of the IP anomaly can serve as a criterion for prospectivity.

The structural factor is also important. Localized subvertical zones, interpreted as faults, are identified in resistivity sections at the margins of the profiles. These zones, characterized by increased permeability, facilitate the migration of hydrothermal fluids and, consequently, the localization of sulfide mineralization. The location of zones of anomalous chargeability between fault zones reflects the association of mineralization with zones of increased fracturing (contact and fault zones, brecciation).

Magnetic survey, as a rapid and relatively low-cost method, is performed at the early stage of exploration. Magnetic exploration enables mapping of structural and geological elements and identification of local magnetic anomalies, including those associated with deep intrusions. Based on the anomalous magnetic field distribution map, a preliminary area ranking is performed and areas of detail research are identified.

The next recommended step is to perform electrical exploration using the median gradient method (IP-SG) or vector measurements (Vector IP). These methods allow for highly reliable mapping of resistivity and chargeability anomalies. The relationship of the anomalies to known and magnetic survey identified structural-geological elements is assessed. If a spatial correlation is identified between the interpretation elements of magnetic and electrical surveys, it is appropriate to perform electrical survey using the IP electrical tomography (ERT-IP) method as the next step. In this case, information obtained from previous stages of geophysical surveys ensures optimal profile planning. Electrical resistivity tomography (ERT-IP) allows for a more precise lateral and depth-dependent determination of anomalous resistivity and chargeability zones, supplementing the interpretation concept with information on the deep structure of the site. The interpretation scheme obtained from comprehensive geophysical surveys provides the necessary information for choosing the optimal location, depth, and azimuth of exploration wells.

Conclusion. Within the study area, which is associated with the silicified rocks zone, ERT-IP data revealed a zone of high electrical resistivity (thousands of Ω·m and higher) at depths of approximately 100–250 m. This area corresponds to the development of silicification. The data also revealed localized maxima (up to 45 mV/V) within the chargeability sections, located within the high-resistivity zone, which are interpreted as a mineralization zone. Anomalous resistivity and chargeability zones are located within a large isometric magnetic anomaly. Results of 3D inversion of the anomalous magnetic field reveal the deep source of the anomaly, most likely a deep intrusion. The combined manifestation of the described geophysical anomalies forms a set of geological and geophysical criteria applicable for ranking promising areas for porphyry copper mineralization within the Shyngys-Tarbagatai structural-formational zone.

Practically, a phased exploration scheme is recommended: initial areal ranking based on magnetic exploration data, followed by IP-SG or Vector IP to identify zones of chargeability and structural control, and at the final stage - profile work with ERT-IP to clarify the geometry of target zones and optimal drilling. In the near future, the planned core drilling is a key stage in verifying the proposed forecast and exploration model and refining the deep geological interpretation.

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