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*Журнал также включён в международную реферативную и наукометрическую базу данных Emerging Sources Citation Index (ESCI) платформы Web of Science (Clarivate Analytics, 2018).*

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# PETROPHYSICAL MODEL OF THE ZHAIREM DEPOSIT

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**Abstract.** *Relevance*. As mineral exploration extends to greater depths, geophysical methods become increasingly important, and their effectiveness depends on the accurate interpretation of rock physical properties. Because geological constraints are often limited by sparse drilling, integrated approaches to the analysis and interpretation of geophysical data are essential. Petrophysical modeling links geological structure, lithological composition, and rock physical properties, thereby improving the reliability of geophysical interpretation and refining exploration criteria for ore deposits. The integrated approach adopted in this study is consistent with the methodological traditions of the Kazakhstan geological scientific school established by K.I. Satpayev, which emphasizes the comprehensive integration of geological and geophysical information in mineral exploration. *Objective*. To develop a petrophysical model of the Zhairem deposit based on the analysis and integration of available geological information, published petrophysical data, and well logging results, and to evaluate its applicability for improving geophysical data interpretation. *Methods*. The study was based on the analysis of the geological structure of the deposit, drill core descriptions, well logging data, and published laboratory measurements of rock physical properties. The model integrates data on rock density, magnetic susceptibility, and electrical resistivity. Statistical analyses included descriptive statistical evaluation, comparative assessment of lithological units, and correlation of petrophysical properties with geological characteristics to identify systematic patterns in the spatial distribution of rock physical properties. *Results and Conclusions.* Variations in petrophysical properties were found to be controlled by lithology, hydrothermal alteration, weathering, metamorphism, deformation, porosity, and stratigraphic characteristics. The integrated analysis established characteristic ranges of physical properties for the principal rock types and their relationships with geological factors, improving the interpretation of geophysical anomalies. The developed petrophysical model systematizes available geological and published petrophysical data and can be applied to refine exploration criteria and develop similar models for deposits with comparable geological settings.

**Keywords:** polymetal, geological structure, intrusive massif, petrophysical model, density, magnetic permeability, apparent resistivity

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## ЖӘЙРЕМ КЕН ОРНЫНЫҢ ПЕТРОФИЗИКАЛЫҚ МОДЕЛІ

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**Аннотация.** *Өзектілігі*. Пайдалы қазбалар кен орындарын іздеу мен барлау жұмыстарының тереңдеуіне байланысты геофизикалық әдістердің маңызы артып келеді, ал олардың тиімділігі тау жыныстарының физикалық қасиеттерін сенімді интерпретациялауға тікелей тәуелді. Бұрғылау тығыздығының жеткіліксіздігінен геологиялық ақпараттың шектеулі болуы геофизикалық деректерді кешенді талдау мен интерпретациялауды талап етеді. Петрофизикалық модельдеу геологиялық құрылым, литологиялық құрам және тау жыныстарының физикалық қасиеттері арасындағы өзара байланысты анықтап, геофизикалық материалдарды түсіндірудің сенімділігін арттыруға және кен орындарын іздеудің критерийлерін нақтылауға мүмкіндік береді. Зерттеуде қолданылған кешенді тәсіл академик Қ.И. Сәтбаев негізін қалаған Қазақстанның геологиялық ғылыми мектебінің әдіснамалық дәстүрлеріне сәйкес келеді және пайдалы қазбалар кен орындарын зерттеу мен болжауда геологиялық және геофизикалық деректерді кешенді пайдалануға негізделген. *Зерттеудің мақсаты*. Геологиялық ақпаратты, жарияланған петрофизикалық деректерді және ұңғымалардың геофизикалық зерттеулері нәтижелерін біріктіру негізінде Жәйрем кен орнының жалпыланған петрофизикалық моделін әзірлеу және оның геофизикалық деректерді интерпретациялау сенімділігін арттырудағы қолданылу мүмкіндіктерін бағалау. *Әдістері*. Зерттеу Жәйрем кен орнының геологиялық құрылымын, бұрғылау керндерінің сипаттамаларын, ұңғымалардың геофизикалық зерттеулері материалдарын және тау жыныстарының физикалық қасиеттері бойынша жарияланған зертханалық өлшеулер нәтижелерін талдауға негізделген. Петрофизикалық модельге тау жыныстарының тығыздығы, магниттік қабылдағыштығы және меншікті электрлік кедергісі туралы деректер енгізілді. Тау жыныстарының физикалық қасиеттерінің кеңістіктік таралу заңдылықтарын анықтау үшін сипаттамалық статистика әдістері, литологиялық бірліктерді салыстырмалы талдау және петрофизикалық қасиеттер мен геологиялық сипаттамалар арасындағы корреляциялық талдау қолданылды. *Нәтижелері мен қорытындылары*. Петрофизикалық қасиеттердің өзгергіштігі литологиялық құраммен, гидротермалық өзгерістермен, үгілу, метаморфизм және тектоникалық деформация процестерімен, сондай-ақ жыныстардың кеуектілігі мен стратиграфиялық ерекшеліктерімен анықталатыны белгіленді. Кешенді талдау негізгі жыныс түрлерінің петрофизикалық параметрлерінің сипаттамалық диапазондарын

анықтауға және олардың геологиялық факторлармен байланысын айқындауға мүмкіндік берді, бұл геофизикалық аномалияларды интерпретациялаудың сенімділігін арттырады. Әзірленген петрофизикалық модель қолда бар геологиялық және жарияланған петрофизикалық деректерді жүйелейді және іздеу критерийлерін нақтылау, сондай-ақ геологиялық құрылысы ұқсас кен орындары үшін ұқсас модельдерді құру кезінде қолданылуы мүмкін.

**Түйінді сөздер**: полиметалл, геологиялық құрылым, интрузивті массив, петрофизикалық модель, тығыздық, магниттік өтімділік, меншікті кедергі

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## ПЕТРОФИЗИЧЕСКАЯ МОДЕЛЬ ЖАЙРЕМСКОГО МЕСТОРОЖДЕНИЯ

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**Аннотация.** *Актуальность*. По мере увеличения глубины поисков и разведки месторождений полезных ископаемых возрастает роль геофизических методов, эффективность которых во многом определяется достоверностью интерпретации физических свойств горных пород. Ограниченность геологической информации, обусловленная недостаточной плотностью бурения, требует применения комплексных подходов к анализу и интерпретации геофизических данных. Петрофизическое моделирование позволяет установить взаимосвязи между геологическим строением, литологическим составом и физическими свойствами горных пород, повысить надёжность интерпретации геофизических материалов и уточнить поисковые критерии рудных месторождений. Применённый комплексный подход соответствует методологическим традициям казахстанской геологической научной школы, сформированной академиком К. И. Сатпаевым и основанной на интеграции геологических и геофизических данных при изучении и прогнозировании месторождений полезных ископаемых. *Цель.* Разработать обобщённую петрофизическую модель Жайремского месторождения на основе анализа и интеграции геологической информации, опубликованных петрофизических данных и материалов геофизических исследований скважин, а также оценить возможности её применения для повышения достоверности интерпретации геофизических данных. *Методы.* Исследование основано на анализе геологического строения месторождения, описаний керна, материалов геофизических исследований скважин и опубликованных результатов лабораторных измерений физических свойств горных пород. В основу петрофизической модели положены данные о плотности, магнитной восприимчивости и удельном электрическом сопротивлении пород. Для выявления закономерностей пространственного распределения петрофизических параметров применялись методы описательной статистики, сравнительный анализ литологических подразделений и корреляционный анализ взаимосвязей между физическими свойствами пород и их геологическими характеристиками. *Результаты и выводы.* Установлено, что изменчивость петрофизических свойств пород контролируется их литологическим составом, гидротермальными изменениями, процессами выветривания и метаморфизма, тектоническими деформациями, пористостью и стратиграфическим положением. Комплексный анализ позволил определить характерные диапазоны основных петрофизических параметров для главных литологических разновидностей и установить их взаимосвязь с геологическими факторами, что способствует повышению достоверности интерпретации геофизических аномалий. Разработанная петрофизическая модель систематизирует имеющиеся геологические материалы и опубликованные петрофизические данные и может быть использована для уточнения поисковых критериев, интерпретации геофизических материалов, а также построения аналогичных моделей месторождений со сходным геологическим строением.

**Ключевые слова:** полиметаллическое оруденение; геологическое строение; интрузивный массив; петрофизическая модель; плотность; магнитная восприимчивость; удельное электрическое сопротивление.

**Introduction**. Petrophysical modeling is a key tool for investigating geological structures and supporting mineral exploration. It establishes quantitative relationships among geological structure, lithology, and the physical properties of rocks, thereby improving the interpretation of geophysical data and the understanding of ore-forming processes. In Kazakhstan, the development of petrophysical methods continues the scientific tradition established by Academician K.I. Satpayev, whose work laid the foundation for the integrated investigation of mineral deposits and the rational exploration of the country's mineral resources (Istekova, 2024:8, Togizov, 2019: 7, Issayeva, 2025: 27).

The integrated analysis of geological structure, ore composition, petrophysical properties, and geophysical fields has become a defining methodological feature of Kazakhstan's geological scientific school. This approach, originally advocated by K.I. Satpayev, views mineral deposits as components of broader geological and metallogenic systems rather than as isolated ore bodies. Its methodological strength lies in the combined interpretation of stratigraphic, structural, mineralogical, petrophysical, and geophysical data. The present study follows this concept by integrating information on the geological structure, ore-bearing stratigraphy, rock physical properties, and geophysical characteristics of the Zhairem deposit.

The aim of this study is to develop a generalized petrophysical model of the Zhairem deposit through the integration of geological information, drill-core descriptions, well-log data, and published and archival petrophysical datasets. Specific objectives include identifying the principal stratigraphic units responsible for density, magnetic, and electrical anomalies and evaluating the applicability of the integrated geological and geophysical methodology developed within Kazakhstan's geological scientific school.

This study is scientific and methodological in nature. It does not involve reserve re-estimation, techno-economic evaluation, mine design, or an independent reassessment of the industrial significance of the Zhairem deposit. Instead, it synthesizes the available geological and petrophysical evidence into a generalized model, identifies the principal anomaly-forming stratigraphic units, and demonstrates the application of an integrated geological approach to petrophysical interpretation.

**Materials and Methods.** At the Zhairem deposit, economically significant ore bodies are concentrated within three principal sectors: the Far Western, Western, and Eastern areas. Although these sectors share a common geological framework, they exhibit local structural variations that become evident at a detailed scale. The deposit is situated within the Zhailmin synclinal structure, which is composed of a Middle Paleozoic marine sedimentary succession. This succession comprises a transgressive sequence of carbonate and clay-siliceous-carbonate rocks overlain by a regressive sequence of carbonate-siliceous and sandy-argillaceous strata, with a cumulative thickness exceeding 2,000 m (Brusnitsyn, 2018: 10, Kembayev, 2023:6).

The basement and marginal parts of the Zhailmin structure consist of Givetian- and Frasnian-age continental to shallow-marine volcano-sedimentary successions that belong to the Devonian marginal volcanic belt separating the Dzhungar–Balkhash synclinal zone from the Caledonian consolidated terranes. These successions are characterized by repeated alternations of volcanic rocks ranging in composition from diabase to rhyolitic porphyry, together with their reworked volcaniclastic derivatives, including conglomerates, sandstones, and siltstones.

Stratified iron-manganese and lead-zinc ores of the Atasuy-type deposits are hosted in Famennian siliceous-carbonate and clay-siliceous-carbonate sediments, which approach the surface in the limbs of the Zhailmin syncline and in several second-order brachyanticlinal structures that complicate its central parts (Leach, 2005,47). One of these is the Zhairem brachyanticline, to which the deposit is directly related. The Paleozoic deposits are overlain by a cover of loose Cenozoic formations (sands, loams, and clays) ranging in thickness from 5 to 60 meters, averaging around 30 meters (Kuz'mina, 2013: 12). Beneath the overburden, the ore-hosting rocks and ores have undergone intense weathering, resulting in the formation of loose pelitolitic material that preserves the primary stratification of the original rocks. The thickness of the weathering profile ranges from 30–60 m above barren zones to 150–170 m over ore-bearing areas and locally reaches 300 m above major ore bodies.

The principal anticline trends northeastward before curving toward the southeast. Its core is composed predominantly of Lower Famennian strata and, locally, rocks of the Daryan Formation. The southeastern limb consists of Lower Famennian sedimentary rocks with bedding dips of up to 45° (Antonenko, 2020, 7). In contrast, the northwestern limb exhibits a simpler and more gently inclined geometry, with bedding dips generally ranging from 20° to 30°. Toward the central part of the deposit, this limb is disrupted by a series of minor fault-related folds (Fig. 1).

The anticline core is characterized by a system of narrow, steeply dipping folds accompanied by tectonic shear zones, along which pervasive albitization, dolomitization, and silicification of the siliceous-carbonate rocks have developed.

Tectonic Structure of the Deposit. From a tectonic perspective, the Zhairem deposit (according to geological and geophysical data) is associated with the Zhairem block, located at the intersection zone of the deep faults of Kyzylzhar, Shashty, Kynek, and Eastern Zhomart, as well as secondary block structures such as Karaoba–Taszhargan and Zhairem (Kovalev, 2019,13).

The main fold structure of the deposit is the eponymous brachyanticline, which is presumed to have formed within a horn-shaped structure of the lower structural tier. The core of the brachyanticline is composed of Lower Famennian stage deposits and is complicated by higher-order folds.

Geological and Stratigraphic Structure of the Deposit**.** The stratigraphic section of the deposit includes marine clayey-siliceous-carbonate deposits of the Famennian and Visean-Tournaisian ages, overlain by water-bearing Cenozoic formations (Fig. 2).

The lower substage of the Famennian stage ($D_3fm_1$) is subdivided into three blocks: massive (D3fm1a), rhythmic ($D_3fm_1b$), and flyschoid ($D_3fm_1c$). The massive block consists of brachiopod reef limestones, as well as clayey-siliceous-carbonate rocks that form the aggregate of the rhythmic block. Overall, their petrophysical parameters are similar: the average density is 2.55–2.60 t/m³, magnetic susceptibility reaches $30–50\times10^{-6}$ SI, and the average electrical resistivity is about 6500 Ohm·m. (Emsbo, 2016,148)

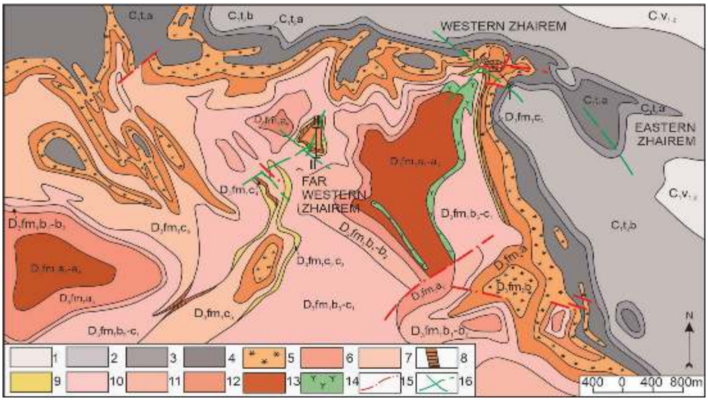



Figure 1. Geological Map of the Zhairem Deposit
1 – argillites with sandstone interlayers ($C_1v_{1.2}$); 2 – siliceous-carbonate rocks ($C_1t_2b$); 3–6 – limestones: 3 – siliceous nodular limestones ($C_1t_2a$), 4 – wavy-bedded carbonaceous limestones (C1t1a), 5 – red-colored siliceous nodular-bedded limestones ($D_3fm_2b$), 6 – wavy-bedded gray-colored limestones ($D_3fm_2a$); 7 – interbedding of organogenic-detrital limestones and clayey-siliceous-calcareous rocks ($D_3fm_1c_5$); 8 – interlayers of low-grade iron ores in clayey-siliceous-carbonate deposits ($D_3fm_1c_4$); 9 – rhythmites of clayey-siliceous-calcareous, pyritic, carbonaceous, and sphalerite composition; carbonate–K-feldspar–siliceous rocks ($D_3fm_1c_{2-3}$); 10 – interbedding of carbonaceous–siliceous–calcareous layers, carbonaceous and pyritic rhythmites, and tuffaceous–sedimentary rocks ($D_3fm_1b_3$–$c_1$); 11 – rhythmic alternation of siliceous–calcareous concretion-bearing rocks, pyrite–sphalerite ores, and organogenic–detrital limestones ($D_3fm_1b_{1-2}$); 12 – thin-bedded clayey–siliceous–carbonate deposits ($D_3fm_1a_5$); 13 – carbonaceous–clayey–calcareous bedded rocks ($D_3fm_1a_{1-4}$); 14 – trachytic porphyries; 15 – fault zones; 16 – hinges of intersecting folds.

The Flyschoid Unit ($D_3fm_1c$) is represented by five horizons: flyschoid–concretional rocks with barite–sulfide rhythmites ($D_3fm_1c_1$); nodular carbonate–feldspar–siliceous rocks ($D_3fm_1c_2$); flyschoid rocks of horizon ($D_3fm_1c_3$) are lithologically similar to the rocks of horizon ($D_3fm_1c_1$); the banded iron ore horizon ($D_3fm_1c_4$) is composed of albite–carbonate and carbonate–siliceous rocks with interlayers and lenses of magnetite–hematite ores; flyschoid siliceous–calcareous rocks ($D_3fm_1c_5$) in Eastern Zhairem contain the first zinc ore layer with a thickness of 20 m. (Zeinedinov, 2021: 11) The overall average density of the flyschoid unit, due to the presence of barite–sulfide and magnetite–hematite ores, is 2.97 t/m³, and the magnetic susceptibility ($\chi$) is $730 \times 10^{-6}$ SI.

The Ore-Hosting Gray-Colored Unit of the Upper Famennian Substage ($D_3fm_2a$) consists of four horizons. In the Western and Far Western Zhairem deposits, these are barren gray-colored nodular–bedded siliceous limestones with interlayers of carbonaceous clayey–siliceous rocks. In Eastern Zhairem, this unit hosts hydrothermal–sedimentary iron–manganese and lead–zinc, as well as hydrothermal–metasomatic barite–polymetallic mineralization and consists of four horizons: the horizon of carbonate nodular–bedded siliceous limestones ($D_3fm_2a_1$) composed of interlayers of hematite, magnetite, and jaspers; the horizon of clayey–siliceous–calcareous rocks ($D_3fm_2a_2$); the horizon of nodular–bedded and siliceous limestones ($D_3fm_2a_3$) is represented by barite–lead–zinc mineralization with interlayers of hematite–magnetite ores; the horizon of rhythmically interbedded carbonaceous–clayey–siliceous–carbonate rocks ($D_3fm_2a_4$) is mainly composed of zinc-bearing ore layers. The weighted average density of the ore-hosting gray-colored unit is 2.99 t/m³, magnetic susceptibility is $550\times10^{-6}$ SI, and electrical resistivity (ρ) is 600 Ohm·m (Togizov K, 2020:5).

The Red-Colored Unit of the Upper Famennian Substage ($D_3fm_2b$) is composed of wavy–bedded, coarse–grained siliceous–calcareous rocks interbedded with magnetite–hematite ores and lies above barite metasomatites. Due to the presence of ores, its density (weighted average) is 2.94 t/m³. It is also characterized, due to the magnetite–hematite ores, by the highest value of magnetic susceptibility - $11698\times10^{-6}$ SI - and represents the main anomaly-forming layer in the deposit section.

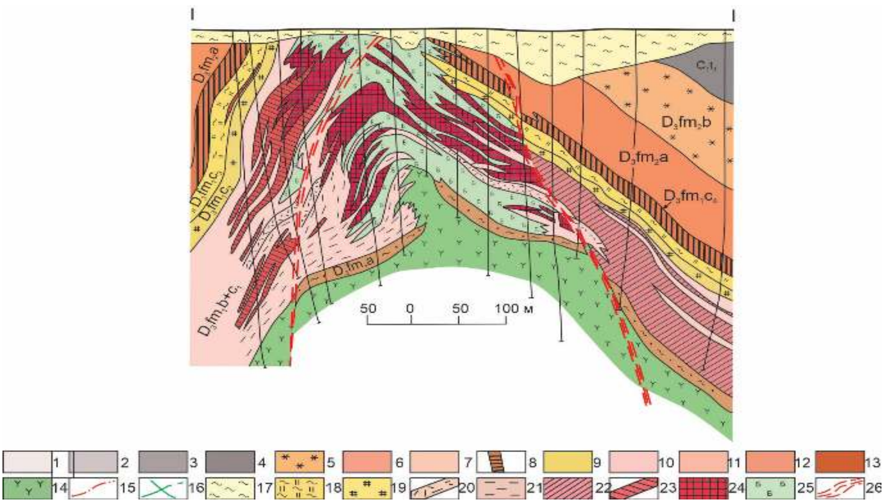



Figure 2. Geological Cross-Section of the Zhairem Deposit.
1 – argillites with sandstone interlayers ($C_1v_1.2$); 2 – siliceous-carbonate rocks ($C_1t_2b$); 3–6 – limestones: 3 – siliceous nodular ($C_1t_2a$), 4 – wavy-bedded carbonaceous ($C_1t_1a$), 5 – red-colored siliceous nodular-bedded ($D_3fm_2b$), 6 – wavy-bedded gray-colored ($D_3fm_2a$); 7 – interbedding of organogenic-detrital limestones and clayey-siliceous-calcareous rocks ($D_3fm_1c_5$); 8 – interlayers of low-grade iron ores in clayey-siliceous-carbonate deposits ($D_3fm_1c_4$); 9 – rhythmites of clayey-siliceous-calcareous, pyritic, carbonaceous, and sphalerite composition; carbonate–K-feldspar–siliceous rocks ($D_3fm_1c_{2-3}$); 10 – interbedding of carbonaceous–siliceous–calcareous layers, carbonaceous and pyritic rhythmites, and tuffaceous-sedimentary rocks ($D_3fm_1b_3$–$c_1$); 11 – rhythmic alternation of siliceous–calcareous concretion-bearing rocks, pyrite–sphalerite ores, and organogenic–detrital limestones ($D_3fm_1b_{1-2}$); 12 – thin-bedded clayey–siliceous–carbonate deposits ($D_3fm_1a_5$); 13 – carbonaceous–clayey–calcareous bedded rocks ($D_3fm_1a_{1-4}$); 14 – trachytic porphyries; 15 – fault zones; 16 – hinges of intersecting folds; 17 – Cenozoic sandy-clayey sediments; 18 – clayey–siliceous–calcareous deposits ($D_3fm_1c_3$); 19 – carbonaceous carbonate–K-feldspar–siliceous rocks ($D_3fm_1c_2$); 20 – tuff interlayers; 21 – barren rocks of the ore-bearing unit ($D_3fm_1b+c_1$); 22–23 – syngenetic lead–zinc mineralization: 22 – subeconomic, 23 – commercial-grade; 24–25 – regenerated hydrothermal–metasomatic ores: 24 – zinc–lead–barite, 25 – copper–barite; 26 – cleavage zones of anticline folds.

Mineralization at the Zhairem deposit formed during a complex geological evolution involving sedimentary, hydrothermal, and, to a lesser extent, magmatic processes that affected carbonate and volcanogenic–sedimentary rocks. As a result, the deposit contains a diverse mineral assemblage, with more than 110 mineral species identified (Table 1).

The Zhairem deposit is a stratiform polymetallic deposit whose economic mineralization is dominated by lead, zinc, barite, iron, and manganese ores. The principal ore minerals are galena, sphalerite, pyrite, marcasite, barite, hematite, magnetite, and manganese-bearing minerals. The main gangue minerals include calcite, dolomite, quartz, and subordinate fluorite. Sulfide mineralization occurs predominantly as stratiform, disseminated, and vein-type ores hosted by carbonate and volcanogenic–sedimentary rocks.

Magmatic rocks are represented by four varieties. At the Far Western site, a stock-shaped body of amygdaloidal trachytic porphyrites intrudes the deposits of the Lower Famennian substage and the base of the ore-bearing unit. Drilling has revealed its apical part at depths down to 90 meters. At the Western and Eastern sites, a complexly constructed laccolith-like body of specific magmatic rocks lies at the base of the ore-bearing unit. It includes fully sericitized fluidal varieties hosting large blocks and fragmental segregations of potassic-altered porphyrites, quartz–potassium feldspar metasomatites, felsite porphyries, and amygdaloidal porphyrites similar to those at the Far Western site. The thickness of this body reaches approximately 200 meters, with lateral dimensions exceeding 1.5×1.5 km. At the Eastern site, a concordant body of spilites, locally amygdaloidal, is intersected in the upper part of the iron ore horizon. The contacts of the body are parallel to the bedding of the host rocks. Endocontact alterations are manifested by the brightening and "quenching" of the spilites, while exocontact alterations are not developed (Table 1).

In all ore zones and beyond, at various stratigraphic levels, zones of explosive breccia are intersected. The cement and part of the clastic material of these breccias are composed of a fine-grained quartz–albite aggregate. The clasts also abundantly include host rocks of various stratigraphic levels. The breccias form both concordant and cross-cutting dikes and vein-like bodies (Oitseva, 2023: 7).

*Petrophysical Model of the Deposit.* Petrophysical datasets are usually summarized and presented in the form of numerical tables, using some average values with or without indicating statistical measures of dispersion/range. Although this approach allows for basic conclusions, we consider it insufficient for a complete understanding of the significance of internal variability within a petrophysical dataset.

The variability of petrophysical properties and the fact that the data often reflect the combined influence of various geological factors suggest that a more suitable method of analysis is to study the data in terms of populations using frequency histograms and cumulative distribution plots (Amralinova, 2025: 24).

The deviation of the petrophysical characteristics of the ore-bearing zones of the Lower and Upper Famennian formations of the Zhairem deposit was assessed in relation to a reference model from the Atasuy district, which is composed primarily of normal, unaltered rocks.

According to the obtained petrophysical parameters, the nature of the gravity and magnetic anomalies at the Zhairem deposit is primarily determined by the ore-bearing layers of the Lower and Upper Famennian substages. Moreover, the ore layers are characterized by both normal and anomalous physical properties.

The widely distributed Tournaisian deposits in the region are represented by marine carbonates, siliceous carbonates, and to a lesser extent, sandy-clayey rocks. The average density of the nodular-bedded shells of the Lower Tournaisian ($C_1t_1$) sublayer at the deposits ranges from 2.0 to 2.50 t/m³, and for the siliceous-carbonate rocks and siliceous coarse-grained limestones of the upper formations ($C_1t_2$) with an ash-gray shell – from 1.90 to 2.40 t/m³ (Reed, 2021: 6).

Analogous layers in the generalized section of the region have the following density values: $C_1t_1$ – 2.62 t/m³ and $C_1t_2$ – 2.55 t/m³. The lower density values of the studied deposits compared to the generalized section are explained by the intense development of the weathering crust, which in some places reaches a thickness of up to 300 meters.

The anomalous petrophysical characteristics of the ore-hosting units represented by the Lower and Upper Famennian rock sequences of the Zhairem deposit were evaluated relative to the generalized stratigraphic section of the Atasu district, which is composed predominantly of unaltered sedimentary rocks.

As discussed above, the mean densities of the flyschoid ($D_3fm_1c$), gray-colored ($D_3fm_2a$), and red-colored ($D_3fm_2b$) units of the Famennian Stage at the Zhairem deposit are 2.97, 2.99, and 2.94 g/cm³, respectively.

In the generalized stratigraphic section of the Atasu district, the corresponding units have mean densities of 2.62 g/cm³ for $D_3fm_1c$, 2.68 g/cm³ for $D_3fm_2a$, and 2.68 g/cm³ for $D_3fm_2b$. Comparison of these values revealed excess density anomalies of 0.35, 0.31, and 0.26 g/cm³, respectively. These values indicate that the ore-bearing sequences exhibit anomalously high density compared with equivalent stratigraphic horizons in the regional generalized stratigraphic section.

The obtained results indicate that the gravity anomaly of the Zhairem deposit is primarily controlled by the increased density of the ore-hosting Lower and Upper Famennian strata of the Upper Devonian ($D_3fm$).

The lateral zonation of the hydrothermal-sedimentary iron-manganese mineralization mirrors that of the lead-zinc mineralization. The central part of the deposit, which is spatially associated with potassium feldspar porphyries, is characterized by elevated silica and iron contents. Outward from the center, hematite-magnetite ores grade into magnetite-hematite ores, which are succeeded by iron-manganese ores and, ultimately, by mineralized siliceous limestones.

Analysis of the petrophysical parameters (density, magnetic susceptibility, and induced polarization) of ores from different lateral zones shows that these parameters adequately reflect the physical state of the mineralized zones and are consistent with the observed geophysical field patterns.

The Pearson correlation coefficient between magnetic susceptibility ($\chi$) and density ($\rho$) is 0.54 for the red unit ($D_3fm_2b$), 0.41 for the gray unit ($D_3fm_2a$), and 0.48 for the flyschoid unit ($D_3fm_1c$).

The statistical significance of these correlations was evaluated using Student's *t*-test. The results indicate that the correlations between density and magnetic susceptibility are statistically significant for the red and gray units, whereas the correlation observed for the flyschoid unit does not reach statistical significance.

Relationships between the petrophysical properties of the ore-hosting units and the corresponding geophysical fields were also examined. The calculated Pearson correlation coefficients are as follows:

$\rho$–$\Delta g$: 0.597

$\chi$–$\Delta Z$: 0.512

These results demonstrate a positive linear relationship between geophysical anomalies and the anomalous petrophysical properties of both the ores and the hydrothermally altered host rocks. This relationship is expressed in both the vertical and lateral distributions of the ore-bearing sequences.

A distinctive feature shared by all three ore bodies of the Zhairem deposit is the occurrence of lens-shaped magmatic bodies within the footwall. In the Far Western sector, these bodies are composed predominantly of amygdaloidal porphyries, whereas in the Western and Eastern sectors they are represented by potassium feldspar porphyries.

In general, these intrusive bodies are concordant with the surrounding host rocks, although their upper contacts locally display cross-cutting relationships. They are considered to be genetically associated with the ore-forming processes. Throughout the district, even the felsic varieties of these magmatic rocks exhibit relatively high magnetic susceptibility and are associated with pronounced magnetic anomalies.

Density. Rock density is one of the principal petrophysical parameters used in mineral exploration because it provides important constraints on the composition and internal structure of ore bodies and facilitates the identification of anomalous mineralized zones. At the Zhairem deposit, density measurements reveal significant departures from regional background values, indicating an elevated abundance of ore minerals within the ore-hosting stratigraphic units.

The mean densities of the flyschoid ($D_3fm_1c$), gray ($D_3fm_2a$), and red ($D_3fm_2b$) units are 2.97, 2.99, and 2.94 g/cm³, respectively. These values are substantially higher than those of the corresponding units in the generalized stratigraphic section of the Atasu district, where the mean densities are 2.62 g/cm³ for $D_3fm_1c$ and 2.68 g/cm³ for both the $D_3fm_2a$ and $D_3fm_2b$ units (Mabiala, 2025,10).

The observed density contrasts of 0.35, 0.31, and 0.26 g/cm³, respectively, indicate anomalous enrichment of the ore-hosting strata in high-density metallic minerals. These petrophysical contrasts account for the positive gravity anomaly observed over the Zhairem deposit and demonstrate the close relationship between ore mineralization and the corresponding geophysical response.

Thus, the conducted studies confirm that the gravity anomaly of the Zhairem deposit is specifically due to the ore layers of the Lower and Upper Famennian substages ($D_3$fm). These results demonstrate the importance of geophysical methods, such as density analysis, in the study of deposits, their structural characterization, and the prediction of prospective ore zones.

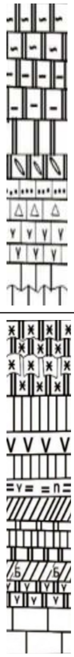
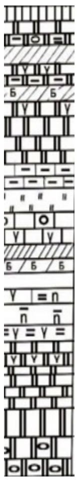
Magnetic susceptibility (χ) is one of the principal petrophysical parameters used to characterize ore-bearing rocks and to distinguish mineralized bodies from the surrounding country rocks. At the Zhairem deposit, magnetic susceptibility measurements reveal pronounced contrasts between the ore-hosting stratigraphic units and the enclosing sedimentary succession, indicating that the observed magnetic anomalies are controlled primarily by the mineralogical composition of the ores (Ma, 2021,19).

The mean magnetic susceptibility values of the principal ore-hosting units are $730 \times 10^{-6}$ SI for the flyschoid unit ($D_3fm_1c$), $550 \times 10^{-6}$ SI for the gray unit ($D_3fm_2a$), and $11{,}628 \times 10^{-6}$ SI for the red unit ($D_3fm_2b$), the latter exhibiting the highest magnetic susceptibility. These values are substantially higher than those of the corresponding units in the generalized stratigraphic section of the Atasu district, where magnetic susceptibility typically ranges from 40 to $50 \times 10^{-6}$ SI.

The pronounced contrast in magnetic susceptibility demonstrates that the ore-hosting units possess distinctive petrophysical characteristics that clearly differentiate them from the surrounding sedimentary rocks. Potassium feldspar porphyries associated with the deposit exhibit intermediate magnetic susceptibility values of 120–$180 \times 10^{-6}$ SI, exceeding the regional background but remaining markedly lower than those of the ore-bearing horizons.

Across the surrounding area, the magnetic susceptibility of most rocks generally ranges from 20 to $50 \times 10^{-6}$ SI, reflecting the relatively uniform petrophysical properties of the regional geological succession. In contrast, the exceptionally high magnetic susceptibility of the ore-hosting units at the Zhairem deposit accounts for the prominent magnetic anomalies and provides an effective geophysical criterion for delineating mineralized zones during exploration. The high magnetic susceptibility values of the ore horizons suggest that they are the main source of the gravity-magnetic anomalies characteristic of this deposit.

Table 1. Petrophysical Model of the Zhairem Deposit.

| System | Series | Subseries | Formation | Lithological characteristics | Layer | Column | Power | Density (g/cm³) | Magnetic Susceptibility (×10⁻⁶ SI) | Polarizability η (%) | Apparent Resistivity $\rho_k$ (Ohm) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Carboniferous System | Lower Series | Tirhvin Subseries | Upper series | $C_1t_2b$ | ash grey |  | 265<br>225 | 2,70 | 5 | | 430 |
| | | | | $C_1t_2a_2$<br>$C_1t_2a_1$ | Zhelvakovist | | 75-162 | 2,62 | 20 | | 385 |
| | | | Lower series | $C_1t_1a_2$<br>$C_1t_1a_1$ | Dark grey | | 242-320 | 2,64 | 50 | | 830 |
| Devonian System | Upper series | Famennian | Upper series | $D_3fm_2b$ | Red colored | | 886<br>180 | 2,94 | 11699,14 | 5,58 | 1088 |
| | | | | $D_3fm_2a_4$ | Gray - colored | | 260 | 280 | 550,58 | 3,95 | 5 |
| | | | | $D_3fm_2a_3$ | | | 210<br>150<br>180<br>240<br>143<br>260 | 3,04<br>3,05 | | | 225<br>275 |
| | | | | $D_3fm_2a_2$ | | | 310 | 3,03 | | | |
| | | | | $D_3fm_2a_1$ | |  | 180 | | | | 450 |
| | | | Lower series | $D_3fm_1a_5$<br>$D_3fm_1c_4$<br>$D_3fm_1c_3$<br>$D_3fm_1c_2$<br>$D_3fm_1c_1$ | Flyschoid | | 240<br>215<br>230<br>180<br>215<br>191<br>152<br>215<br>210<br>190 | 2,86<br>3,03<br>2,97<br>3,07<br>2,35 | 726,98 | 5,12 | 183<br>350<br>30<br>100<br>230 |
| | | | | $D_3fm_1b_4$<br>$D_3fm_1b_3$<br>$D_3fm_1b_2$<br>$D_3fm_1b_1$ | Rhythmically layered | | 245<br>305<br>216 | 2,63 | 20 | | 100 |
| | | | | $D_3fm_1a_5$ | non-layered | | 380<br>370 | 2,62 | 20 | | |

Electrical Resistivity. Electrical resistivity is an important petrophysical parameter for characterizing the composition, structure, and fluid content of rocks and for delineating mineralized zones in geophysical investigations. At the Zhairem deposit, the primary (unweathered) rocks generally exhibit relatively high electrical resistivity, reflecting their compact nature and the presence of poorly conductive rock-forming and ore minerals.

The electrical resistivity of the rocks ranges from approximately 600 to 6,500 $\Omega \cdot m$, indicating considerable heterogeneity in lithology and physical properties. Higher resistivity values are typically associated with compact carbonate rocks and silicified lithologies, whereas lower values may reflect fractured, weathered, or water-saturated rocks. The observed variations in resistivity therefore record differences in both lithological composition and post-depositional alteration.

The broad range of electrical resistivity values emphasizes the structural and lithological complexity of the deposit and demonstrates the importance of integrated interpretation of geophysical and geological data for identifying anomalous ore-bearing zones.

The methodological framework of this study is based on an integrated geological interpretation in which petrophysical properties are evaluated in conjunction with stratigraphy, lithology, mineral composition, structural setting, hydrothermal alteration, weathering, and the corresponding geophysical response. This systems-based approach is consistent with the methodological traditions of Kazakhstan's geological scientific school established under the influence of the scientific principles of Academician K.I. Satpayev.

**Results.** The integrated analysis enabled refinement of the geological model of the Zhairem deposit and identification of prospective mineralized zones based on established metallogenic models of Central Kazakhstan. The results demonstrate a clear spatial correspondence between the principal gravity and magnetic anomalies and the Lower and Upper Famennian stratigraphic units that host the ore-bearing horizons (Spiridonov, 2017, 13; Wellmann, 2018, 121).

These results confirm that the main ore bodies are concentrated specifically within these horizons, making them key targets for further geological exploration. The identified patterns emphasize the need for more detailed investigation of the deposit using additional geophysical and geochemical methods.

Thus, the conducted research plays an important role in refining the industrial reserves of mineral resources as well as in strategic mining planning. Further detailed investigations will not only improve the delineation of the ore bodies but also provide a basis for optimizing future exploration and mining strategies (Oldenburg, 2012, 9).

The obtained result is not limited to the compilation of individual physical-property values. The integration of stratigraphic, lithological, mineralogical, and geophysical data enabled the development of a unified interpretative framework for identifying the principal anomaly-forming units of the Zhairem deposit. This framework represents a contemporary application of the integrated geological methodology characteristic of Kazakhstan's geological scientific school.

**Discussion.** The petrophysical model of the Zhairem deposit plays a key role in optimizing exploration work, assessing ore bodies, and planning their development. The use of the obtained data allows the creation of predictive models that help not only in refining the deposit boundaries but also in improving the efficiency of mineral extraction.

Future research will concentrate on refining the lithological characterization of the host rocks and evaluating the influence of structural controls on the distribution of ore bodies. These investigations will provide a more comprehensive understanding of the deposit's geological architecture and facilitate the identification of additional prospective mineralized zones.

The resulting model demonstrates the continuity of the integrated research methodology characteristic of Kazakhstan's geological scientific school. The joint interpretation of geological structure, stratigraphy, mineralization, physical rock properties, and gravity, magnetic, and electrical responses develops the system-based approach associated with K.I. Satpayev's scientific legacy. This approach requires that a mineral deposit be interpreted not as an isolated anomalous body, but as a component of a stratigraphic, structural, lithological, and metallogenic system.

Instead, it contributes to the analysis, systematization, and present-day application of the methodological traditions of Kazakhstan's geological scientific school and prepares the obtained results for integration into research and university education.

Therefore, the development and refinement of petrophysical models contribute to more accurate forecasting of ore-bearing horizons and improvement of exploration and production strategies in the region.

**Conclusion.** In the course of the research, such petrophysical characteristics of the Zhairem deposit as density, magnetic permeability, and apparent resistivity were determined. Based on these data, a petrophysical model of the deposit was developed, which allowed updating information on its geological structure and identifying the most promising ore-bearing horizons.

These studies are of great importance for the further exploration of the deposit. The results not only improve the delineation of the deposit and its internal geological architecture but also provide a robust foundation for subsequent geological investigations. The refined petrophysical model supports more reliable geological interpretation, improves exploration targeting, and contributes to the optimization of future exploration programs.

Overall, the integrated dataset provides a reliable basis for further research and more detailed investigations of the Zhairem deposit. It also contributes to more accurate prediction of ore-bearing zones and to the continued refinement of exploration models for similar hydrothermal-sedimentary deposits.

The integrated interpretation adopted in this study reflects the methodological continuity of Kazakhstan's geological scientific school and the scientific legacy of Academician K.I. Satpayev. The results demonstrate the contemporary application of a systems-based approach that integrates geological structure, stratigraphy, mineralization, petrophysical properties, and geophysical responses within a unified interpretative framework. The proposed petrophysical model may serve as a reference for future scientific investigations and as an educational resource in university courses on petrophysics, exploration geophysics, geological modeling, and economic geology, thereby promoting the continued development of the integrated geological methodology established by K.I. Satpayev.

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