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Petrophysical properties of rocks from the Bargilt iron ore deposit, Mongolia

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Abstract. Iron ore deposits play a significant role in Mongolia's mineral-based economy and require detailed geological and geophysical investigation for effective exploration and resource evaluation. This study focuses on the Bargilt iron ore deposit located in Khentii Province, Mongolia, within the MV-016657 license area operated by the state-owned enterprise Mongolrostsvetmet. The main objective of the study is to characterize the mineralogical composition, rock properties, and subsurface distribution of ore-bearing zones for better understanding of the deposit's structure and potential. A combination of field geological mapping, petrographic analysis, and petrophysical interpretation was used to determine the mineral composition and textural relationships. Representative samples of ore-bearing (59 samples) and host rocks (440 samples) have been collected, measured and analyzed. Magnetite was identified as the dominant ore mineral accompanied by minor accessory minerals, while the host rocks are mainly composed of silicate gangue minerals. Petrophysical data were interpreted to identify subsurface anomalies associated with iron-enriched zones and to identify structural factors influencing mineralization. The study results indicate that the iron ore mineralization is structure-controlled and exhibits a variable spatial distribution influenced by lithological boundaries and fault systems. Integration of geological and petrophysical datasets provides a more reliable model of ore body geometry and its continuity. The study results demonstrate the effectiveness of combined methods for improving exploration accuracy and can serve as a basis for further detailed assessment of the Bargilt iron ore deposit for future development planning.

Keywords: density, magnetic susceptibility, chargeability, resistivity, geostatistics

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Научная статья
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Петрофизические свойства горных пород железорудного месторождения Баргильт, Монголия

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Аннотация. Месторождения железной руды играют важную роль в экономике Монголии, основанной на добыче полезных ископаемых, и требуют детального геологического и геофизического изучения для эффективной разведки и оценки ресурсов. Данное исследование посвящено месторождению железной руды Баргильт, расположенному в провинции Хэнтий в Монголии на лицензионном участке MV-016657, эксплуатируемом государственным предприятием «Монголросцветмет». Основная цель исследования заключалась в том, чтобы охарактеризовать минералоги-

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ческий состав, свойства горных пород и глубинное распределение рудоносных зон, чтобы лучше понять структуру и потенциал месторождения. Для определения минерального состава и текстурных взаимосвязей были использованы методы полевого геологического картирования, петрографического анализа и петрофизической интерпретации. Были собраны и измерены петрофизические параметры, проанализированы репрезентативные образцы рудоносных (59 образцов) и вмещающих (440 образцов) пород. Магнетит был идентифицирован как доминирующий рудный минерал, сопровождаемый второстепенными акцессорными минералами, в то время как вмещающие породы в основном состоят из силикатных жильных минералов. Петрофизические данные были интерпретированы для определения подземных аномалий, связанных с зонами обогащения железом, и для выявления структурных факторов, влияющих на минерализацию. Результаты исследования показывают, что минерализация железной руды контролируется структурой и имеет переменное пространственное распределение, на которое влияют литологические границы и системы разломов. Интеграция геологических и петрофизических наборов данных обеспечивает более надежную модель геометрии рудного тела и его непрерывности. Результаты проведенного исследования демонстрируют эффективность комбинированных методов для повышения точности разведки и могут являться основой для дальнейшей детальной оценки железорудного месторождения Баргильт с целью планирования будущей разработки.

Ключевые слова: плотность, магнитная восприимчивость, поляризуемость, удельное сопротивление, геостатистика.

Финансирование. Исследование проводилось при поддержке и сотрудничестве горно-обогатительного комбината «Бор-Ундур» (провинция Хэнтий, Монголия) и финансовой поддержке геологического факультета Монгольского университета науки и технологий (г. Улан-Батор, Монголия).

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Introduction

Iron deposits are indeed a critical component of Mongolia's mineral resources and a key driver of its economic development, often ranking as the third or fourth largest export contributor behind coal and copper. This study focuses on the Bargilt iron ore open-pit mine, operated by Mongolrostsvetmet State-Owned Enterprise, located in Khentii Province, Mongolia. The deposit is part of mining license MV-016657, covering an area of approximately 133.08 hectares. The site represents an important iron deposit within the regional metallogenic framework of eastern Mongolia (Fig. 1). The deposit area contains two iron ore bodies of industrial significance, oriented in a latitudinal direction (central ore body) and a longitudinal direction (ore body no. 1). During the 1987 exploration expedition, these ore bodies were investigated through 10 surface trenches and 10 boreholes. In the subsequent detailed exploration conducted in 2009, additional investigations included seven small-scale surface trenches (totaling 364.8 m^3) and seven boreholes (total drilling length of 825.5 m). In parallel with these works, geophysical surveys were also carried out. As a result, the 1987 exploration expedition is considered to have produced relatively comprehensive and well-constrained data, allowing for more reliable geological interpretations compared to earlier studies. In 2020 and 2021, a total of 31 boreholes (5,906.5 m) were drilled as part of a deep drilling aimed at increasing the resource quantity and upgrading its classification. Geophysical exploration is based on measuring variations in the physical properties of rocks and minerals, including density, magnetic susceptibility, electrical resistivity, and chargeability. These physical contrasts generate detectable anomalies that can be used to infer subsurface geological structures, lithological boundaries, and ore mineralization zones [1–4]. As well, petrophysical characterization provides a fundamental basis for the interpretation of geophysical data and improves the understanding of lithological variability, geological structures, and ore-forming processes. The integration of petrophysical measurements with geophysical observations enhances the reliability of mineral exploration and resource evaluation[1, 2] [5–7]. Magnetite-rich skarn deposits exhibit distinct petrophysical contrasts relative to the surrounding country rocks, including elevated density, magnetic susceptibility, and, in some cases, chargeability. These contrasts produce measurable geophysical anomalies, making magnetic, gravity, and induced polarization methods effective tools for the exploration and delineation of skarn-hosted iron ore deposits [8–11]. In the field area, these investigations refined the previously obtained results by providing additional information on the morphology, geological structure, grade, quality, and spatial distribution characteristics of the ore bodies, there by improving the overall geological model of the deposit.

In 2023, the petrophysical properties of the drill core samples were determined using four parameters: density, resistivity, chargeability, and magnetic susceptibility.

The main objective of the rock physical property study is to determine the fundamental physical parameters of iron ore-bearing and non-ore host rocks, and to investigate their spatial distribution, interrelationships, and underlying correlations with geological structures and formations.

In future, this provides a fundamental database for identifying the distinctive physical property characteristics of ore and non-ore rocks, improving the detailed characterization of deposit structure and morphology, and enhancing the processing and interpretation of multi-borehole geophysical data across the study area.

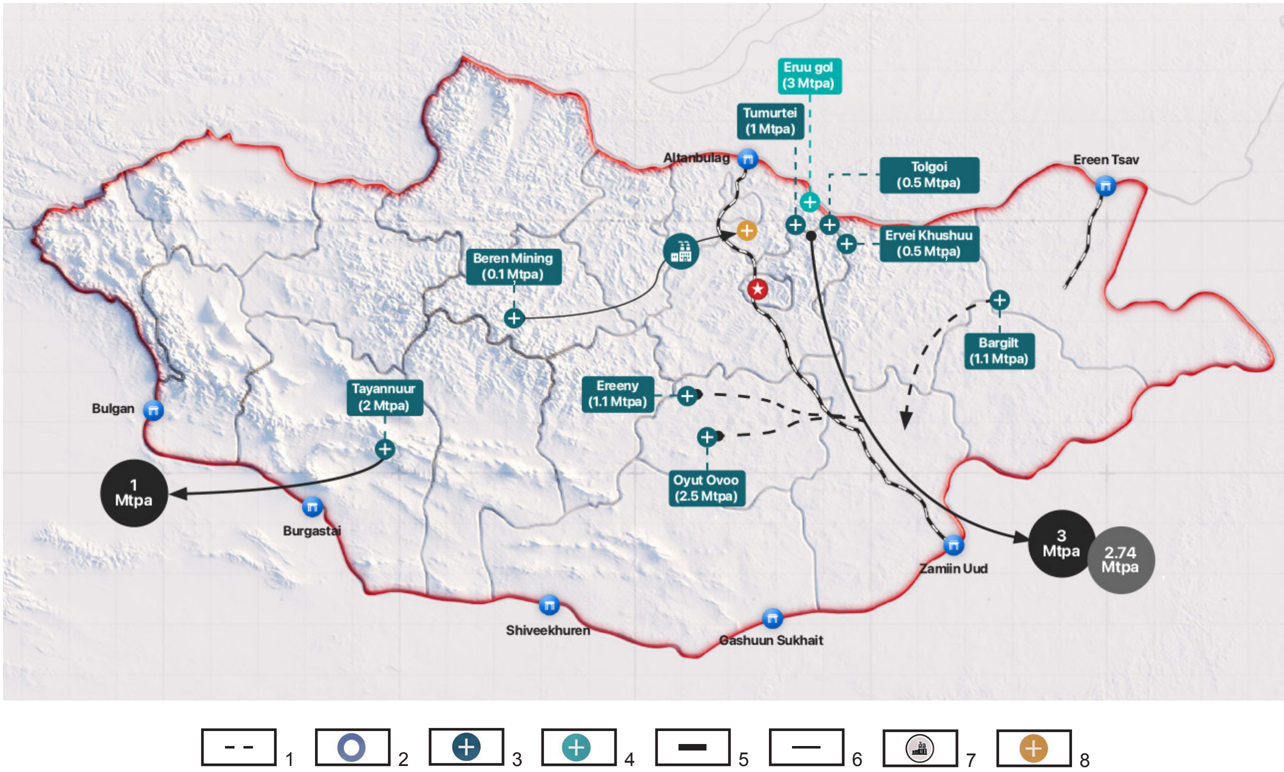

Fig. 1. Location map of the Bargilt iron ore deposit (according to the Economic Research Institute data, 2014):
1 – railway; 2 – border crossing; 3 – iron ore mine; 4 – iron concentrate mine; 5 – export direction; 6 – domestic direction; 7 – mineral processing plant; 8 – metallurgical plant

Рис. 1. Карта расположения месторождения Баргильт (по данным Института экономических исследований, 2014 г.):
1 – железная дорога; 2 – пограничный переход; 3 – железорудный рудник; 4 – рудник железного концентрата; 5 – экспортное направление; 6 – внутреннее направление; 7 – обогатительная фабрика; 8 – металлургический завод

[1] Carmichael R.S. *Practical handbook of physical properties of rocks and minerals.* New York: CRC Press; 2017, 756 p.
[2] Dobrynin V.M., Vendel'shtein B.Yu., Kozhevnikov D.A. *Petrophysics: a textbook for university students.* Moscow: Nedra; 1991, 367 p.

Materials and methods

The physical properties of the rock samples from the study area were systematically characterized through of laboratory measurements and detail procedures. Magnetic susceptibility reflects the ability of a rock to become magnetized in the presence of an external magnetic field and is largely controlled by the abundance of ferromagnetic minerals. This property is widely used in geophysical exploration to distinguish rock types and identify mineralized zones [12–16]. All analyses were conducted using calibrated instruments and facilities of the Geophysics Laboratory, Department of Geology, Mongolian University of Science and Technology (Ulaanbaatar, Mongolia). Prior to measurement, the samples were prepared following standard laboratory protocols to ensure consistency and reliability of the results. The experimental work was performed at the sample repository of the Bor-Undur Mine over the period from June 5 to June 20, 2023.

Sample preparation. The core samples used in this study were obtained from drilling conducted in 2020 and 2021. Samples selected for laboratory measurements accepted the required criteria in terms of dimensions and surface condition to ensure measurement accuracy and reproducibility. Each sample was systematically classified and labeled according to its lithological characteristics prior to analysis.

Magnetic susceptibility measurement. The magnetic susceptibility of the rock samples was determined using an MPP probe (MPP-EM2S+, serial no. MP1131) manufactured by GDD Instruments, Canada. All measurements were carried out under standard laboratory conditions. For each sample, measurements were taken on three orthogonal faces to minimize directional bias and improve the reliability of the results.

Electrical resistivity and chargeability measurements. The electrical resistivity and chargeability *M* characteristics of the rock samples were determined using a Sample Core IP Tester (SCIP), TDLV model (serial no. SC2053), manufactured by GDD Instruments. Measurements were conducted under controlled laboratory conditions employing a standard four-electrode configuration. A constant direct current was injected into the sample, and the resulting potential difference was measured across the inner electrodes.

Density measurement. The bulk density of the rock samples was determined using an MZ-Z600 electronic densitometer manufactured in China. The measurements were performed using a direct mass–volume determination method. The mass of each sample was measured using a precision electronic balance, while the volume was obtained directly from the densitometer under controlled laboratory conditions.

Data processing methodology. To evaluate the relationships between the physical properties of the iron ore samples from the Bargilt deposit and to classify the samples based on their physicochemical characteristics, a combination of correlation analysis and cluster analysis was applied. Correlation analysis was used to quantify the strength and direction of relationships among the measured physical parameters, while cluster analysis was employed to group samples with similar property patterns [17–19]. This integrated statistical approach enabled the identification of underlying associations between variables and facilitated an objective classification of the samples according to their physical property similarity. The methodological approaches employed in this study are summarized in the table below, which provides an overview of the statistic techniques used for data processing and interpretation (Table 1).

Sample classification of the deposit. The rock samples collected from the study area were systematically classified based on their mineralogical composition, spatial distribution of ore minerals, and iron grade. Based on these criteria, the samples were categorized into two principal groups: iron ore-bearing samples and non-ore (host) rock samples. This classification was used as a basis for subsequent physicochemical analysis and statistical evaluation. Classification of rock samples from the study area according to mineralogical composition, showing ore and non-ore mineral assemblages in iron ore-bearing and host rocks (Table 2).

During the statistical processing stage, all sample data were systematically organized and entered into a structured database to ensure data consistency and traceability. The compiled

Table 1. Comparison of correlation and cluster analysis method
Таблица 1. Сравнение методов корреляционного и кластерного анализа

Property	Correlation analysis	Cluster analysis
Objective	To identify statistical relationships between variables	To classify samples into homogeneous groups based on similarity
Output	Correlation coefficient *r*, indicating the strength and direction of relationships	Cluster membership and cluster centroids representing group characteristics
Data type	Bivariate analysis (pairwise relationship between two variables)	Multivariate analysis (simultaneous consideration of multiple variables)
Methodological approach	Classical statistical method	Multivariate statistical analysis/ unsupervised machine learning technique

dataset was subsequently pre-processed and prepared for further statistical analysis.

Results and discussion

Iron ore-bearing samples. Correlation analysis shows that the strong positive correlations (r = 0.48–0.611) between density, chargeability, and magnetic susceptibility are consistent with the presence of iron ore mineralization, particularly magnetite-rich zones. The elevated magnetic susceptibility and density values suggest significant concentrations of ferromagnetic minerals, while the increased chargeability may indicate the presence of associated sulfide minerals. The weak negative correlation with resistivity further supports that the mineralized zones are relatively conductive compared to surrounding host rocks (Fig. 2).

Results of K-means clustering applied to resistivity and chargeability data of 58 iron ore samples. Blue dots represent individual measurements, while the red marker indicates the centroid (mean value) of the dataset. The distribution shows a weak negative correlation (r = -0.699), where lower resistivity values are generally associated with higher chargeability, reflecting the influence of mineralization. This trend suggests that combined resistivity and induced polarization parameters can effectively distinguish mineralized zones from non-mineralized host rocks (Fig. 3).

Non-ore (host) rock samples. The correlation heatmap indicates generally weak relationships among density, resistivity, chargeability, and magnetic susceptibility, with all correlation coefficients ranging from -0.117 to 0.248 (Fig. 4). The strongest positive correlation is observed between density and magnetic susceptibility (r = 0.248), while resistivity and chargeability show a weak negative correlation (r = -0.117).

Overall, the absence of strong correlation patterns implies that each physical parameter contributes relatively independent information to the dataset. This independence is advantageous for multivariate statistical analysis (e.g., clustering or classification), as it reduces redundancy and enhances the ability to discriminate lithological or mineralization-related variations.

Table 2. Rock sample classification
Таблица 2. Классификация образцов горных пород

Category	Образцы, содержащие железную руду		Non-ore (host) rock samples
	Ore minerals	Нерудные минералы	
Primary	Magnetite, bismuthinite, native bismuth	Pyroxene, forsterite, plagioclase, phlogopite, chondrodite, brucite, tremolite, chlorite, graphite	Limestone, diorite gneiss, granite gneiss, strongly skarn-altered rocks, fine-grained vein granite
Secondary and rare	Hematite, chalcopyrite, bismutite, malachite, arsenopyrite, pyrite, marcasite, pyrrhotite, ilmenite	Calcite, epidote, chlorite, muscovite, grossular, sericite, leucoxene, serpentine, tremolite	

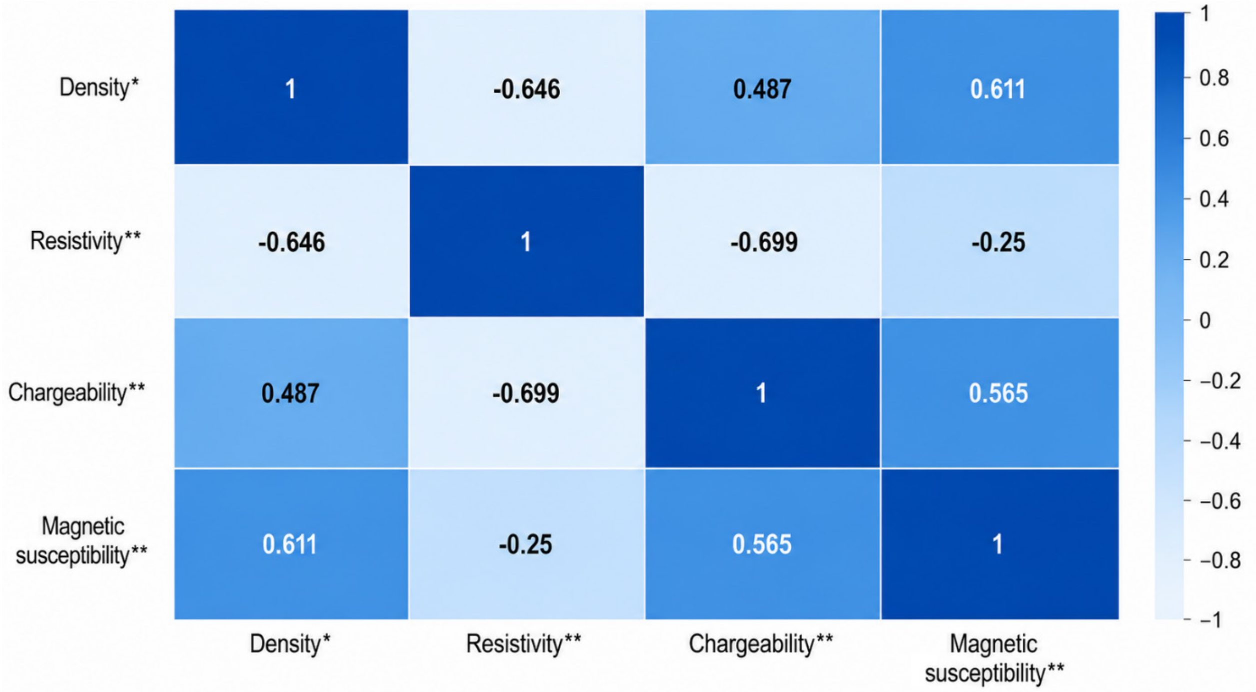

Fig. 2. Correlation coefficient between the physical properties of iron ore samples
*Distribution law: * – normal; ** – lognormal*
Рис. 2. Коэффициент корреляции между физическими свойствами образцов железорудных материалов
*Закон распределения: * – нормальное; ** – логнормальное*

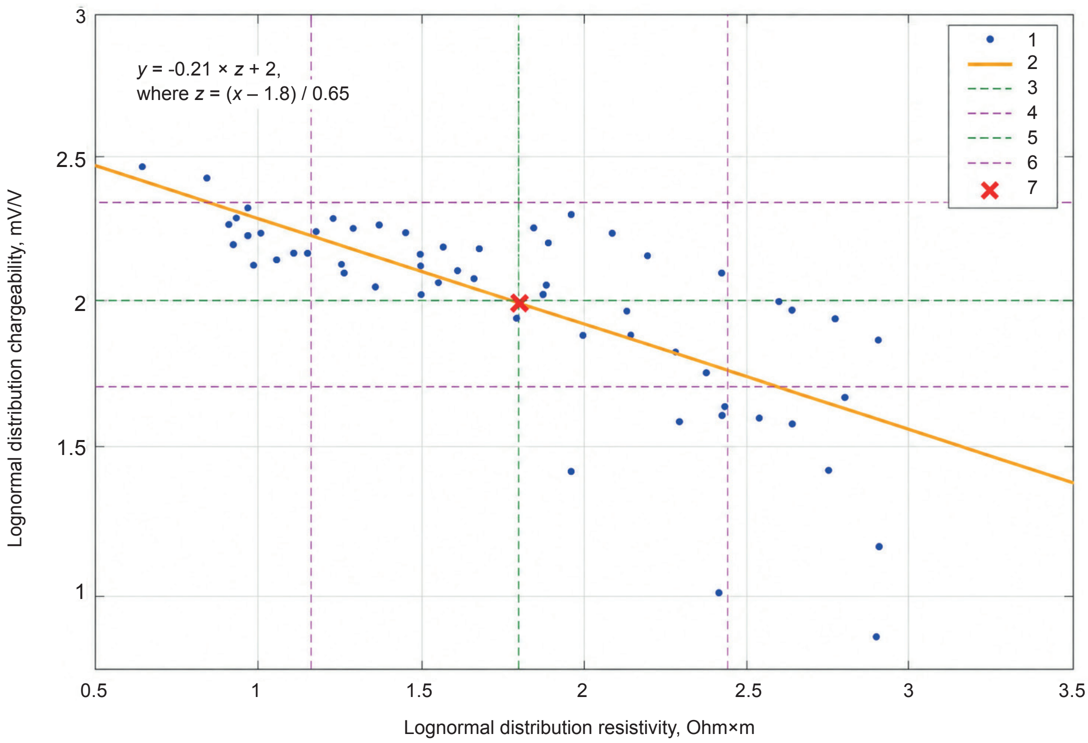

Fig. 3. Cluster analysis results of resistivity and chargeability for iron ore samples:
1 – ore-bearing samples; 2 – linear dependence; 3 – X mean value; 4 – X standard deviation; 5 – Y mean value; 6 – Y standard deviation; 7 – cluster centroid
Рис. 3. Результаты кластерного анализа удельного сопротивления и поляризуемости для образцов железосодержащих руд:
1 – рудоносные образцы; 2 – линейная зависимость; 3 – среднее значение X; 4 – стандартное отклонение X; 5 – среднее значение Y; 6 – стандартное отклонение Y; 7 – центроид кластера

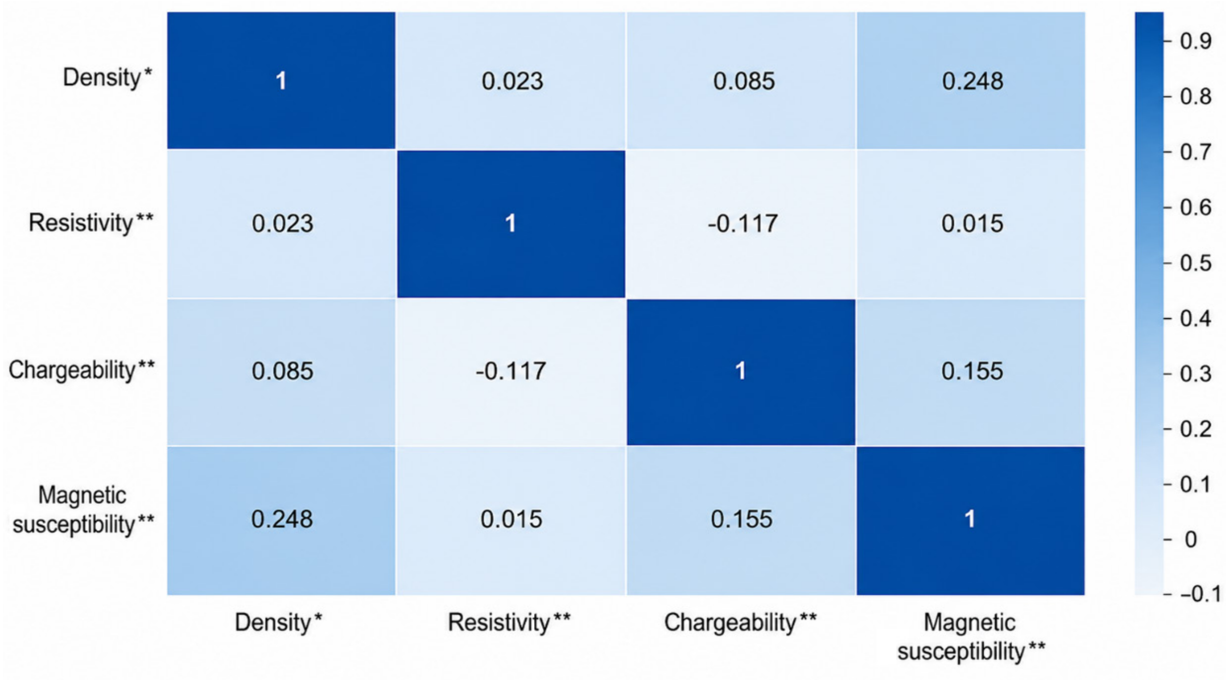

Fig. 4. Correlation coefficient between the physical properties of non-metallic (host) rock samples
*Distribution law: * – normal; ** – lognormal*
Рис. 4. Коэффициент корреляции между физическими свойствами образцов нерудных (вмещающих) пород
*Закон распределения: * – нормальное; ** – логнормальное*

In cluster analysis, the relationship between electrical resistivity and chargeability of the non-ore (host) rock samples shows a broad and scattered distribution, indicating significant lithological heterogeneity within the dataset. Resistivity values span a wide range, while chargeability remains relatively constrained within low to moderate levels, suggesting that the polarization response is not strongly controlled by resistivity alone (Fig. 5). The absence of a clear linear correlation between these two parameters implies that electrical conduction and induced polarization processes are governed by different petrophysical factors. Specifically, resistivity is primarily influenced by pore structure, fluid content, and mineral connectivity, whereas chargeability is more sensitive to the presence and distribution of disseminated conductive minerals such as sulfides and graphite.

The centroid of the dataset represents the average geoelectrical behavior of the host rocks and indicates a dominantly non-mineralized background signature. The clustering of most data points at relatively low chargeability values further supports the interpretation that sulfide mineralization is either absent or occurs in very minor concentrations within the host rock units. And, the geophysical response suggests that the host rocks are characterized by resistive but weakly polarizable properties, consistent with silicate-dominated lithologies with limited conductive mineral content. Based on the cluster centroid behavior, each cluster represents a distinct petrophysical properties with clear lithological and mineralogical implications.

Cluster 1 (iron ore-bearing samples). This cluster is defined by high magnetic susceptibility, high chargeability, relatively high density, and low resistivity. Petrophysically, it represents a strongly mineralized zone dominated by magnetite-rich iron ore. The very high magnetic response indicates a significant concentration of ferromagnetic minerals, while the low resistivity suggests enhanced electrical conductivity due to interconnected ore minerals. Elevated chargeability further supports the presence of disseminated metallic phases contributing to induced polarization effects.

Overall, this cluster corresponds to economically prospective iron ore zones.

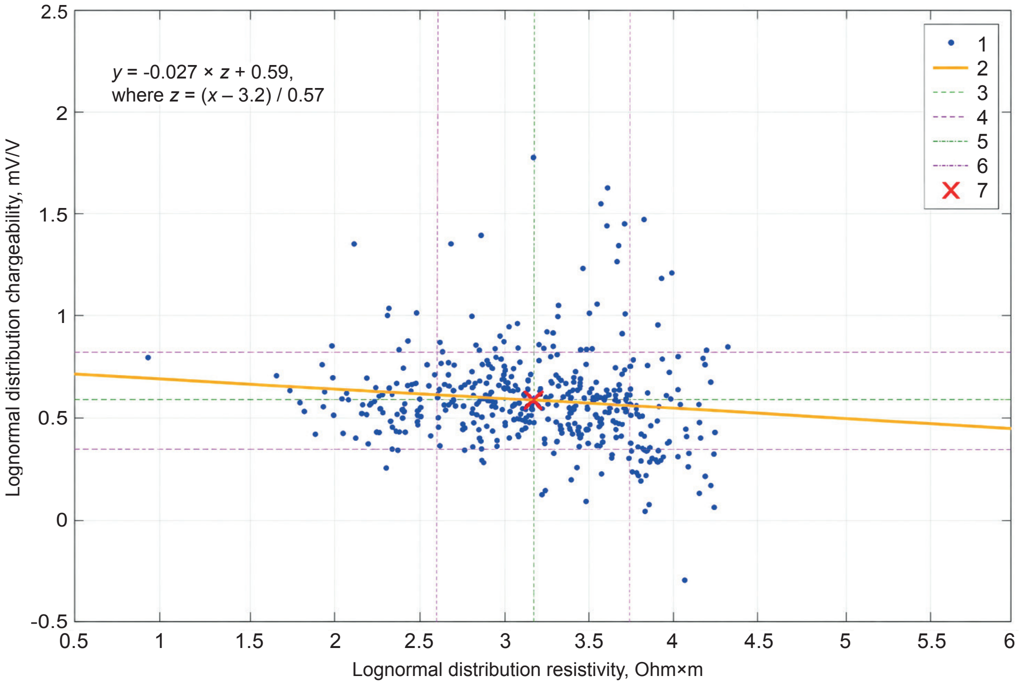

Fig. 5. Resistivity and chargeabilty clustering results for non-ore (host) rock samples:
1 – non-ore samples; 2 – linear dependence; 3 – X mean value; 4 – X standard deviation; 5 – Y mean value; 6 – Y standard deviation; 7 – cluster centroid
Рис. 5. Результат кластеризации удельного сопротивления и поляризуемости для образцов нерудных (вмещающих) пород:
1 – не содержащие руду образцы; 2 – линейная зависимость; 3 – среднее значение X; 4 – стандартное отклонение X; 5 – среднее значение Y; 6 – стандартное отклонение Y; 7 – центроид кластера

Cluster 2 (non-ore host rocks). This cluster is characterized by low magnetic susceptibility, low chargeability, low density, and high resistivity. It reflects weakly mineralized host rocks dominated by silicate and non-conductive minerals.

The weak magnetic response indicates minimal ferromagnetic content, while high resistivity suggests poor electrical conduction and limited metallic mineral presence. Low chargeability confirms the absence of significant disseminated ore minerals. This cluster represents background geological units with low exploration potential.

Finally, the clear petrophysical contrast between the two clusters demonstrates that magnetic susceptibility and resistivity are the most diagnostic parameters, while chargeability provides additional discrimination strength. This confirms that cluster analysis is an effective method for separating iron ore mineralization from host rock environments in the study area (Table 3).

Conclusion

The comparison of physical properties between iron ore-bearing samples and non-ore host rocks shows clear and consistent petrophysical contrasts. Iron ore-bearing samples exhibit significantly higher density, chargeability, and magnetic susceptibility, while showing much lower resistivity compared to host rocks. These differences strongly indicate the presence of magnetite-rich and conductive mineralization within the ore zones.

The elevated magnetic susceptibility confirms a strong ferromagnetic response, likely controlled by magnetite content. The reduced resistivity suggests enhanced electrical conductivity associated with ore mineral distribution, while the high chargeability reflects the presence of disseminated metallic minerals contributing to induced polarization effects. In contrast, the host rocks are characterized by lower density and weak petrophysical responses, indicating relatively barren or weakly mineralized lithologies.

Table 3. Centroid values of physical properties of ore and host rocks in Bargilt area
Таблица 3. Значения центроидов физических свойств руды и вмещающих пород в районе месторождения Баргилт

Rock type	*N*	Density (standard deviation), kg/m³	Resistivity (standard deviation), Ohm×m	Chargeability (standard deviation), mV/V	Magnetic usceptibility (standard deviation), $\times 10^{-5}$ SI
Non-ore (host) rock samples	440	2,727 (±204)	1,637 (×/÷3.72)	3.73 (×/÷1.7)	72 (×/÷4.26)
Iron ore-bearing samples	59	3,555 (±534)	63 (×/÷5.01)	139 (±64.4)	316,228 (×/÷3.98)

Note. N – number of samples participating in statistics.

Generally, the integrated physical property analysis demonstrates that magnetic, electrical resistivity, and induced polarization methods are highly effective in distinguishing iron ore mineralization from surrounding host rocks and provide a reliable basis for geophysical exploration and interpretation in the study area.

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