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Geological Structure Investigation Using Magnetometry and Geoelectrical Data in Aqda Area, Yazd Province

Omid Robatjazi, Alireza Arab-Amiri* and Keyvan Khayer

Faculty of Mining, Petroleum & Geophysics Eng., Shahrood University of Technology, Shahrood, Iran

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Abstract

Accurate delineation of subsurface controlling structures within complex geological settings is critical for reliable targeting of hematite mineralization, yet remains challenging. Interpretations relying on a single geophysical dataset typically suffer from limited structural resolution and interpretation ambiguity. This study integrates magnetic and geoelectrical datasets to investigate subsurface structures controlling hematite mineralization in the Aqda area, Yazd Province, Iran. Magnetic data were processed using reduction to the IGRF and several enhancement filters, including vertical and horizontal derivatives, analytic signal, and the Centre for Exploration Targeting (CET) technique. The results revealed five major magnetic anomalies trending northeast–southwest and northwest–southeast, interpreted as fault controlled intrusive bodies. Two dominant structural trends identified by CET, NE–SW and NW–SE correspond to the magnetic lineaments and delineate zones of high mineral potential. To validate these structures, seven IP RS profiles were acquired and inverted using the smooth model approach in RES2DINV software. The integrated resistivity and chargeability sections confirmed the position of the inferred faults and highlighted zones of elevated chargeability consistent with hematite mineralization. The combination of both datasets improved the structural resolution and significantly reduced interpretation ambiguity. This integrated approach demonstrates that the magnetic and geoelectrical methods complement each other and provide an effective tool for delineating mineralized zones in complex geological environments.

1. Introduction

In modern societies, a large proportion of industrial demand and many aspects of daily life rely on the use of mineral resources, which play a fundamental role in the economic structure of countries. However, to meet the increasing demand for these materials, targeted mineral exploration is required to identify new ore deposits [1]. On the other hand, the global trend of intensified exploitation of mineral reserves, together with a simultaneous increase in mining costs, has highlighted the need for greater accuracy in the identification and evaluation of these resources. For this reason, numerous exploration projects and programs have been developed and expanded in recent decades, focusing on delineating areas with high mineralization potential [2]. Given the

importance of achieving sustainable development goals in the mining industry, it is necessary to employ exploration methods that are both cost-effective and minimally destructive (non-destructive) [3,4]. Among mineral-producing countries, Iran is recognized as one of the key holders of diverse and abundant mineral resources in the Middle East. The mining sector in Iran is therefore of strategic importance, contributing to national economic growth and supplying a large share of domestic demand for raw materials. This significance is largely due to the presence of rich and diverse mineral reserves, including hematite-bearing ore deposits, which offer substantial capacity for further development and investment in the country's mineral industries.



Corresponding author: alirezaarabamiri@yahoo.com (A. Arab-Amiri)

Understanding subsurface geological structures is fundamental for advancing mineral exploration strategies. Faults, folds, and lithological contacts control ore emplacement and must be precisely mapped to reduce exploration risk and improve resource assessment. Geophysical methods, particularly magnetometry and geoelectrical resistivity, provide complementary datasets that can reveal both deep-seated and near-surface structures. A thorough examination of geological structures and their impact on Earth sciences is of paramount importance [5, 6]. To understand Earth's formation and its changes, as well as to evaluate mineral resources, it is necessary to identify subsurface features such as folds, faults, and intrusive rocks. This information enhances understanding of geological processes and facilitates more efficient resource utilization [7, 8, 9]. The use of geophysical data is highly effective for examining geological structures and identifying mineral-potential zones. It offers valuable insights into subsurface structures, significantly contributing to the mineral exploration process [10, 11, 12, 13]. Geophysical studies have a notable impact on mineral exploration worldwide. Methods such as magnetic and electrical resistivity surveys assist in verifying and investigating geological structures and faults [14, 15, 16, 17]. Magnetic surveys aid in identifying structural features, alteration zones, and mineralization [18, 19]. Electrical resistivity surveys can also provide information about subsurface characteristics and the potential presence of minerals by analyzing resistivity variations at depth and near the surface [20, 21, 22, 23]. In this study, these two methods were combined to identify fault and fracture trends in the region, as well as potential zones of hematite mineralization.

Magnetometry detects variations in the Earth's magnetic field arising from contrasts in rock magnetization, enabling the identification of intrusive bodies, faults, and alteration zones. Geoelectrical resistivity methods offer high sensitivity to lithological changes and mineralization, mapping faults and contact zones with meter-scale precision. Recent advances in computational image analysis techniques (e.g., CET and phase symmetry filters) have enhanced the structural interpretation of magnetic data, permitting systematic extraction of lineaments and structural networks from complex datasets [24, 25].

Despite their proven potential, integrated applications of these methods remain underreported for iron ore systems in central Iran. The Aqda hematite deposit, located within

Carboniferous sedimentary sequences intruded by basic magmatic bodies, presents an ideal case for testing such a methodology. By coupling magnetic texture analysis with targeted geoelectrical profiling, this study aims to:

1. Map the fault and fracture systems controlling ore bodies;
2. Characterize lithological contacts at depth;
3. Evaluate the relationship between structural trends and hematite mineralization.

The research provides a reproducible framework for structural geology investigations in mineral-rich settings, offering new insights into the tectonic and mineralization controls of the Aqda area. Prevec and Morris [26] studied geological structures concealed by north-south-trending diabase dykes in the Destor-Porcupine Deformation Zone (DPDZ) of the Abitibi greenstone belt, northern Ontario, Canada, using airborne magnetic data and the horizontal gradient technique. Oruç and Selim [27] identified and characterized subsurface linear features in the Sinop region, located in the middle of the Black Sea, Turkey, employing magnetic methods and techniques such as Total Derivative, Euler deconvolution, and Discrete Wavelet Transform (DWT). Selim and Abdel-Raouf [17] utilized magnetic and geoelectric data in the southern part of the Sinai Peninsula to determine subsurface structures and investigate groundwater potential. In addition to geoelectric surveys, two-dimensional spectral analysis, analytic signal, and Euler deconvolution techniques were applied to the magnetic data in this study. Akinlalu et al. [10] employed magnetic surveys, two-dimensional electrical resistivity, and Euler deconvolution to delineate geological structures in the Iwaraja area, southwestern Nigeria.

Lawal [28] used airborne magnetic and radiometric data to map lithology, structures, and hydrothermal alteration zones in southwestern Nigeria. Vertical gradient, power spectrum, analytic signal, and CET were applied to analyze and interpret the data. Sultan Araffa et al. [29] conducted magnetic and geoelectric geophysical surveys in the Wadi El-Sehu area, Egypt, to determine the depth and extent of mineral bodies. Integrating magnetic and geoelectric data reduces ambiguity and uncertainty in geophysical exploration. In the Shillman area of the southeastern Egyptian desert, Eldosouky and Mohamed [30] employed airborne magnetic data and various techniques, including the first vertical

derivative, total gradient, and theta, to enhance magnetic edges and understand the structural framework. Okpoli and Akinbulejo [31] investigated geological structures, lithological discrimination, faults, folds, and contacts in the Ijanu area, southwestern Nigeria, using airborne magnetic and vertical electrical sounding (VES) geophysical methods. Furthermore, various geophysical filters were applied during data interpretation to enhance resolution and effectively delineate structural and lithological components. Abdelrady et al. [32] used airborne magnetic data, the CET technique, and several filters to analyze subsurface structures in the Dungash area, which significantly influence mineralization zones.

Additionally, data fusion techniques are commonly used in other geophysical methods to improve results; for example, Khayer et al. [33] introduced a new attribute for identifying salt dome geobodies by combining seismic attributes. Using ground magnetic surveys and dipole–dipole DC resistivity imaging along five traverses orthogonal to the suspected structure in Ogbomoso, Bayowa et al. [34] delineated three magnetic lineaments (D1–D3) and their geoelectrical counterparts (R1–R3). Table 1 summarizes the literature on geological structure investigation using magnetometry and geoelectrical data, including susceptibility analyses, magnetic derivatives, geoelectrical methods, applications, and results.

Table 1. Tabulated literature review of geological structure investigations using magnetometry and geoelectrical data

Author(s) / Year	Key Results
Sultan and Santos (2008) [35]	Integrating 2D resistivity and ground magnetics effectively resolves faults, sediment thickness variations, bedrock surface, and lithological boundaries.
Gönenç et al. (2013) [36]	Integrated magnetometry and geoelectrical surveys in Koçarlı–Demirtepe delineated hematite-zone geometry and depth; 2D inversion revealed strong magnetic–electrical correlation, confirming joint interpretation effective for subsurface characterization.
Oyedele et al. (2016) [37]	Integrated aeromagnetic and geoelectrical datasets delineate BIF-hosted iron ore in the Ero area, Nigeria, constraining body boundaries and depths and highlighting NE–SW, E–W, and NW–SE trends.
Joel et al. (2019) [38]	Integrated aeromagnetic and electrical resistivity imaging in the Ado-Odo/Ota coastal-plain sands shows that groundwater potential is chiefly controlled by lineament-network connectivity.
Khayer and Ansari (2023) [39]	Integrated magnetometry, gravity, and induced polarization–resistivity (IP–RS) data from the Aqda iron-ore mine delineated contacts, intrusions, and probable faults, defining hematite targets that underpin a 3D mineralization model.
Irfan et al. (2024) [40]	Integrated magnetic–geoelectrical surveys, validated by modeling, mapped iron–granitoid boundaries from anomaly patterns tracking Fe grade, sharpening subsurface interpretation, and iron ore exploration efficiency.
Akinlalu (2025) [41]	Airborne magnetic data, integrated with ASTER imagery, delineated geological structures and iron-ore zones in Kogi State, Nigeria, demonstrating structurally controlled mineralization and the value of multi-sensor geophysical data integration.
Rey et al. (2025) [42]	Integrated magnetometry, TDEM, and electrical resistivity tomography (ERT) mapped fault-parallel trends, resolving PbS-vein displacement and discontinuity via coincident magnetic–electrical anomalies in Linares–La Carolina.

The CET grid analysis extension for Oasis Montaj™ was developed by the University of Western Australia to automate the detection of structural lineaments and areas of geological complexity within gridded potential-field data. The CET algorithm combines Texture Enhancement and Phase Symmetry (PS) filters to highlight discontinuities and boundaries, providing a rapid, unbiased first-pass interpretation workflow. In this study, magnetic data were processed using various filters and the CET technique. Magnetometer data were utilized to identify geological lineaments and faults, as well as to differentiate between lithologies. To accurately locate faults identified previously, geoelectric methods were employed. The resulting data provided insights into subsurface electrical properties and facilitated the correlation of faults with magnetic data.

Accordingly, this study develops the first integrated structural model of the Aqda area, derived from combined magnetometry and geoelectrical data interpretation, emphasizing the innovative application of magnetic lineament analysis using the CET algorithm along with subsurface electrical resistivity imaging to enhance mineral potential assessment.

2. Methodology

In this study, subsurface geological structures at the hematite iron ore mine in Aqda were analyzed using magnetometry and geoelectric geophysical methods. The methodological workflow adopted in this research is summarized in the flowchart presented in Figure 1, providing a concise overview of the successive stages of data

acquisition, processing, and integrated interpretation.

The methodological framework was designed to maximize the complementary capabilities of magnetometry and geoelectrical resistivity surveys in delineating subsurface structural controls on hematite mineralization in the Aqda deposit. This integrated approach was selected to reduce interpretational ambiguity common when using a single method by exploiting the sensitivity of magnetic data to lithological and alteration contrasts, and the high spatial resolution of resistivity data for detecting faults and contact zones.

Magnetometry was deployed primarily to characterize spatial variations in the Earth's magnetic field caused by differences in rock

magnetization, thereby enabling the detection of intrusive bodies, fault zones, and lithological boundaries. The acquisition grid was designed to balance coverage and resolution, with denser sampling in areas of strong magnetic gradients. This method is particularly advantageous in carbonate-hosted iron ore systems where magnetic anomalies often coincide with mineralized contacts. Geoelectrical resistivity surveys were implemented to resolve ambiguities in magnetic interpretation and to map subsurface discontinuities with meter-scale precision. Seven IP-RS profiles were strategically aligned along magnetic lineaments identified in the preliminary stage to characterize resistivity anomalies associated with fault planes and potential mineralization zones.

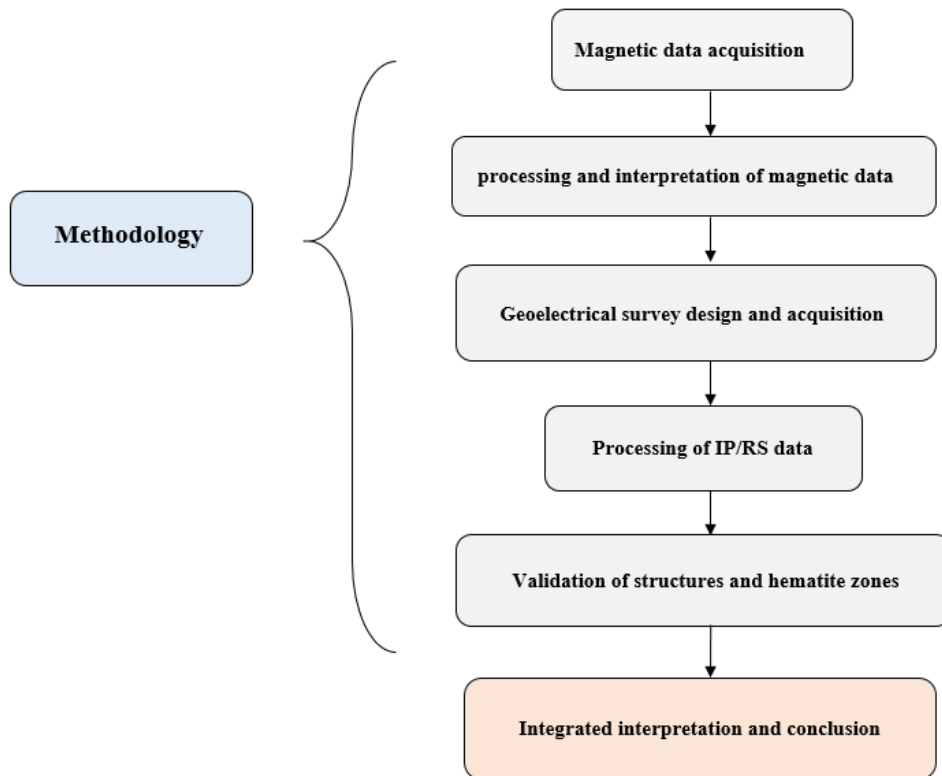


Figure 1. Flowchart illustrating the integrated magnetometry and IP-RS workflow applied in this study to delineate subsurface geological structures and hematite mineralization.

Magnetic texture analysis using the CET and PS filters was applied to enhance lineament visibility and quantify structural complexity. CET facilitates automatic detection of discontinuities within total magnetic intensity data, transforming them into vectorized lineament networks, while PS filtering isolates lateral discontinuities by assessing signal symmetry. These outputs provided a reproducible dataset of structural trends, which was then cross-referenced with resistivity anomalies to confirm their geological significance. This workflow

emphasizes methodological reproducibility and scientific rigor, providing a transferable framework for combined geophysical surveys in structurally complex mineral systems.

There is a set of algorithms that provide the ability to enhance, identify lineaments, and analyze the structural complexity of potential field data [43]. The main goal of CET is to provide a comprehensive understanding of geological processes and mineralization patterns to help improve efficiency in exploration activities [24].

This method, using the total magnetic intensity, automatically determines geological structures to identify potential mineral deposit locations. By analyzing magnetic data and detecting discontinuities, this method provides a more accurate picture of subsurface structures [44,45]. This process involves key steps that assess structural complexities, identify lineaments, analyze texture, and apply lineament vectorization techniques. These methods can be used in various fields such as network texture analysis, edge detection, boundary determination, lineament identification, and locating areas with complex structures [25,46].

This method identifies intersections, connections, or contact points, as well as changes in the direction of impact, first identifying magnetic discontinuities and then determining their location, which ultimately examines the links (communication connections) of the structure. This process helps in selecting high-potential areas for exploration [47]. This process consists of the following steps:

1. Texture Enhancement: Using the standard deviation (SD), areas with complex textures related to discontinuities in magnetic data are identified and calculated as follows:

$$\sigma = \sqrt{\frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2} \quad (1)$$

For a window, where (N) is the number of cells, the mean value is $\mu=1$, the cell values are (x_i), and σ is the standard deviation. The standard deviation (SD) method provides a clearer picture of the randomness of the data, which helps in reducing internal noise.

2. PS: At this stage, the improved texture results are employed to identify lateral discontinuity zones. The PS filter is applied to the SD network's magnetic data, and the output data is presented as a normalized grid ranging from 0 to 1, indicating the level of signal symmetry in each grid cell.
3. Structure Detection: PS results are used to transform discontinuities into linear structures. PS analysis of the SD filter identifies the desired regions. The trends obtained from the PS filter can be improved by reducing noise and background signals through threshold determination. The output of this stage is used to identify skeletal structures. Finally, these skeletal structures are converted into vectors to define trends.

In this study, the CET process was performed using the following parameters and filter settings:

Filter window size: 15 × 15 pixels ($\approx 300 \times 300$ m),

Phase symmetry threshold: 0.6,

Edge wavelength cutoff: 250 – 350 m,

Vector-linking tolerance: 10°.

These parameters were determined through trial iterations to optimize the balance between edge sharpness and background noise reduction. The selected values allowed reliable extraction of medium-scale structural lineaments consistent with observed magnetic anomalies and geological fault positions.

3. Geology

The study area is situated approximately 35 kilometers east of Aqda County in Yazd Province, Iran. The geographic location relative to Aqda County is illustrated in Figure 2.

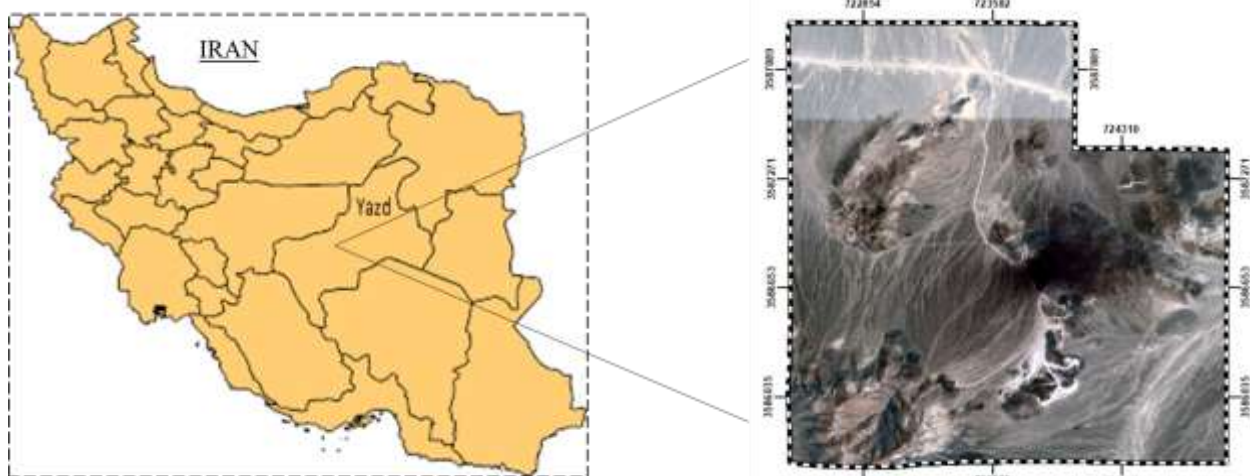


Figure 2. Location of the study area relative to Aqda County in Yazd Province, central Iran, with the dashed polygon marking the investigated area.

Geologically, this area is located within the 1:100,000 scale geological map of Sarve Bala, and Figure 3 shows the location of the study area on the Sarve Bala geological map [48]. As seen in Figure 3, shale, sandstone, and carbonate rocks of Carboniferous age are recognized as the dominant lithologies. A significant portion of this area is covered by recent alluvial sediments. According to field observations, hematite mineralization is mostly observed at the contact of lithologies, usually accompanied by barite.

In the geology of this region, the limestones of the Aqda Formation, composed of algal and dark-colored limestones, create significant prominences. These limestones are extensively characterized by stromatolitic and nodular algae and have turned brown in some areas due to dolomitization. In zones where basic intrusive rocks have intruded into the Aqda Formation, contact effects such as baking and whitening are observed.

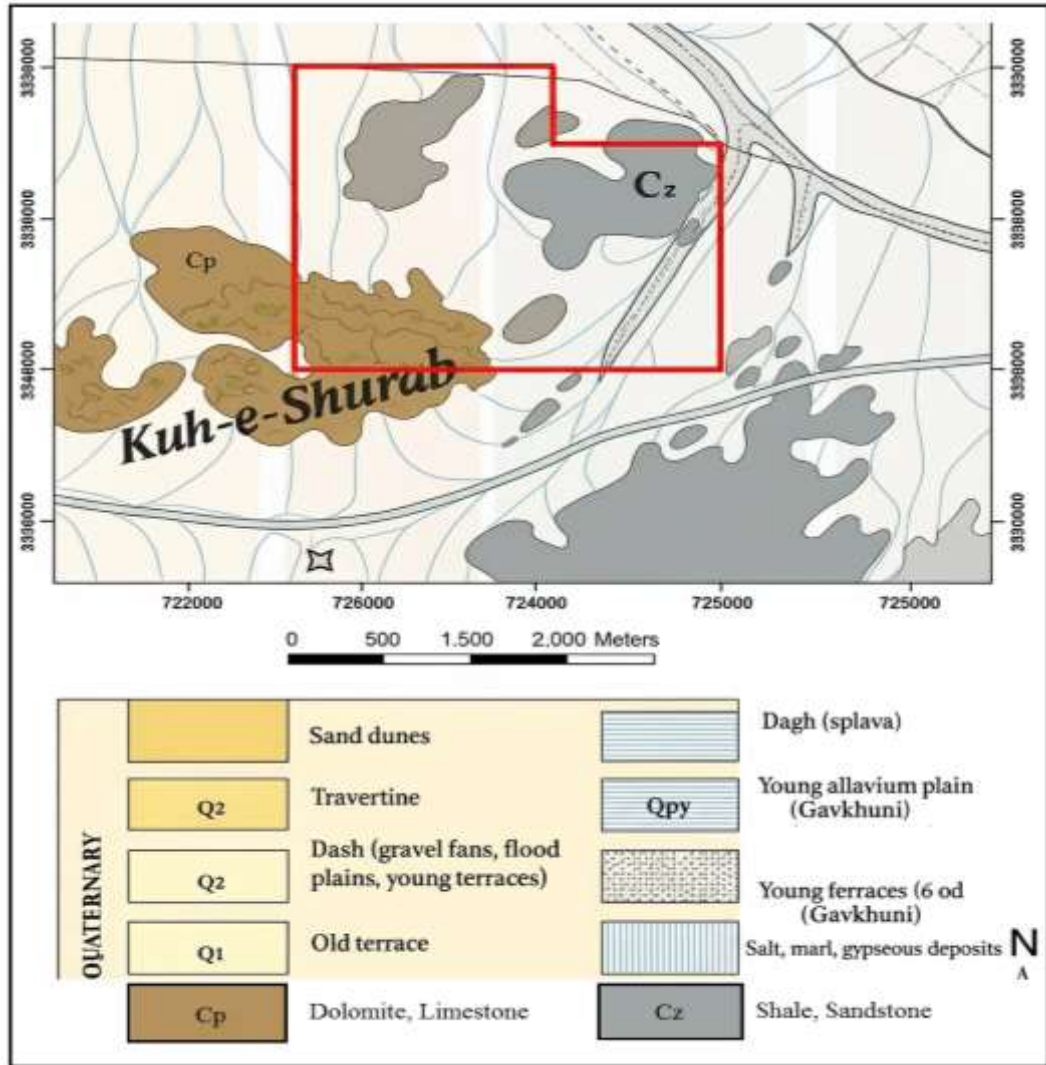


Figure 3. Location of the study area on the 1:100,000 geological map of Sarve Bala

4. Results and discussion

To achieve the study's objectives, the dimensions of the magnetic data acquisition grid were initially set at 40 x 20 meters. In areas with high magnetic field variation intensity, the grid dimensions were reduced to 20 x 10 meters to allow for a more detailed investigation (Figure 4).

Following the acquisition of magnetic data and application of diurnal corrections, a total magnetic intensity (TMI) map (Figure 5) was produced using Geosoft software. The minimum and maximum magnetic field intensities recorded within the study area were 46,753 and 48,021 nT, respectively. Thus, the difference between the minimum and maximum recorded field intensity is approximately 1,268 nT.

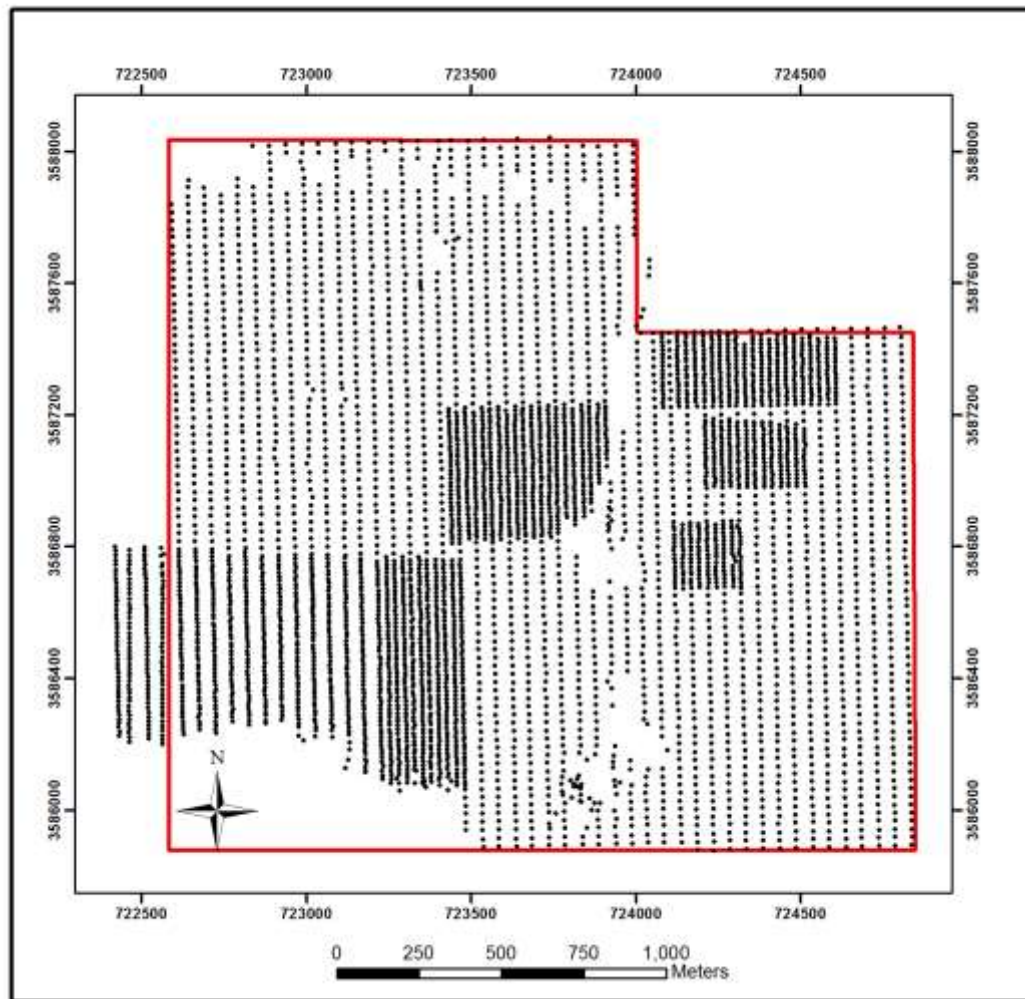


Figure 4. Location of data acquisition points

As shown in Figure 5, the survey data identified five anomalies, labeled 1 through 5, which are referred to by these numbers throughout the study. In the northern part of the study area, an east-west trending magnetic dipole has appeared, associated with the Esfahan-Yazd water pipeline, indicating the high accuracy of the data. A cursory examination of the TMI map suggests that the potential mineralization trend within the study area follows a northeast-southwest direction. This trend is segmented by a fault, with anomaly 5 separating it from the other anomalies and anomaly 4 separating it from anomalies 1, 2, and 3. Among the observed anomalies, anomalies 4 and 5 exhibit higher magnetic field intensities and greater lateral extents. Anomaly 4 trends northwest-southeast and appears to be separated from anomalies 1 and 2 by a fault, as depicted on the map. Anomaly 3, located south of anomalies 1 and 2, displays a stronger magnetic field intensity compared to the other anomalies.

Anomaly number 5, located in the southern part of the study area, exhibits a significant lateral

extent and an incompletely closed bipolar shape. Based on the east-west variation in magnetic field intensity, the source body of the anomaly appears to dip eastward. One of the most crucial steps in detecting local anomalies is removing the background field and generating a residual anomaly map. Therefore, it is necessary to identify the background level in the study area, which is approximately 47,328 nT based on the IGRF map, and subtract its effect from the measurements. Various methods are employed in magnetometry studies to produce residual anomaly maps. In this study, the local magnetic field reference map, IGRF, was utilized to determine the characteristics of the Earth's main field. Based on this, a residual anomaly map was generated and presented in Figure 6. To produce this map, variations in the trend of the reference field, particularly in the north direction, were applied. The minimum and maximum magnetic field intensities obtained were -574 and +693 nT, respectively.

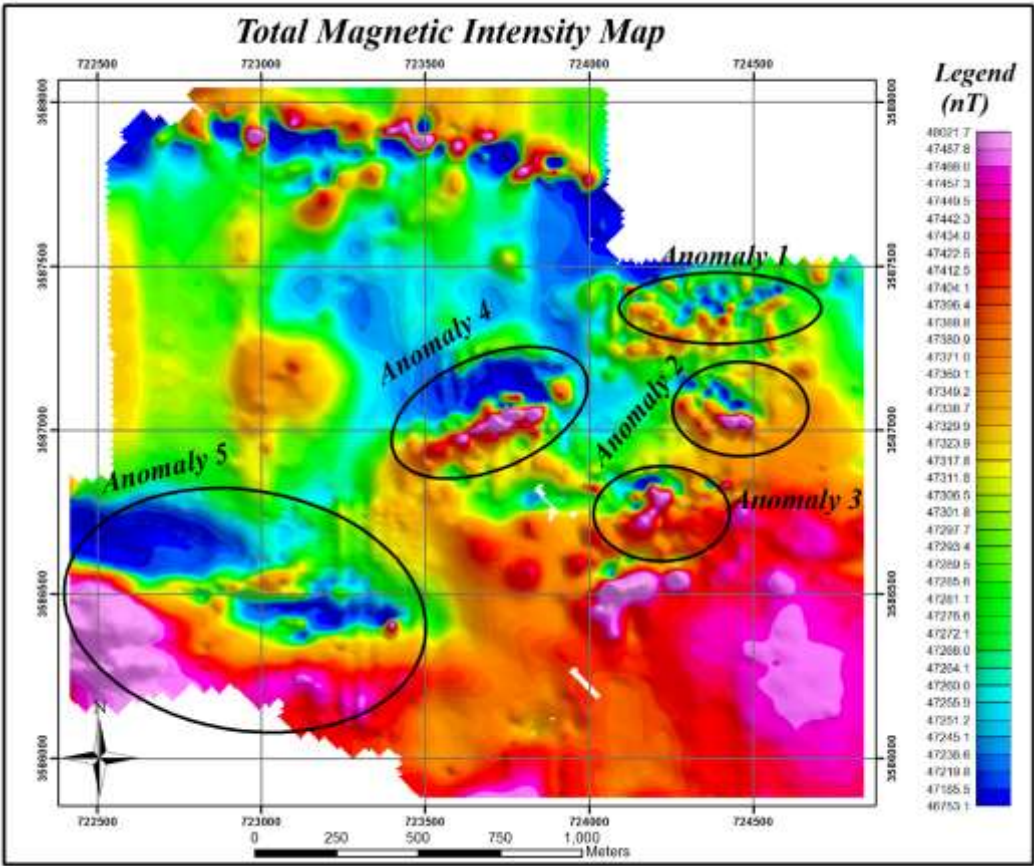


Figure 5. Total magnetic intensity map

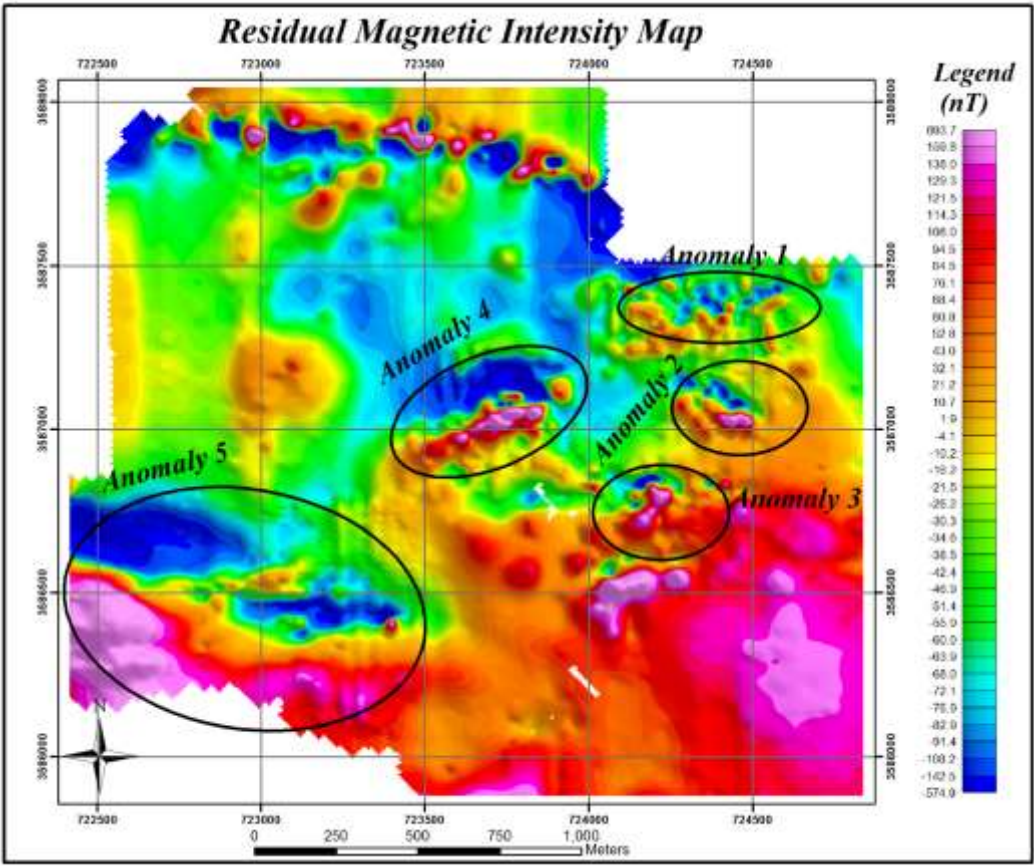


Figure 6. Residual magnetic intensity map

The magnetic anomalies identified in the TMI and residual maps reveal distinct NE–SW and NW–SE trends that correspond closely to the regional fault pattern observed in the Sarve Bala geological map. These orientations are consistent with the structural grain imposed by pre-existing tectonic phases, suggesting that hematite mineralization is likely structurally controlled. In particular, anomalies 4 and 5, with their high amplitudes and extensive lateral continuity, coincide with zones of intersection or bending between NE–SW and NW–SE lineaments, which are known to act as favorable pathways for hydrothermal fluids. The eastward dip inferred from anomaly 5's bipolar geometry indicates possible alignment with subsurface fault planes, an interpretation supported by field observations of lithological contacts.

Among the processes applied to magnetometry data, vertical and horizontal derivative filters, analytic signal, and CET can be mentioned.

Vertical and horizontal derivative filters are employed to delineate the boundaries of magnetic anomalies. Theoretically, the vertical derivative value is zero at the edges of subsurface bodies, while the horizontal derivative reaches its maximum value above these edges. Consequently, vertical and horizontal derivative maps play a significant role in delineating faults and magnetic lineaments. Figure 7a presents the vertical derivative map, and Figure 7b displays the horizontal derivative map of the study area. These maps enhance the visibility of anomaly boundaries, enabling their precise identification and differentiation. The major faults identified through the magnetometry method are marked as black lines in Figure 7a.

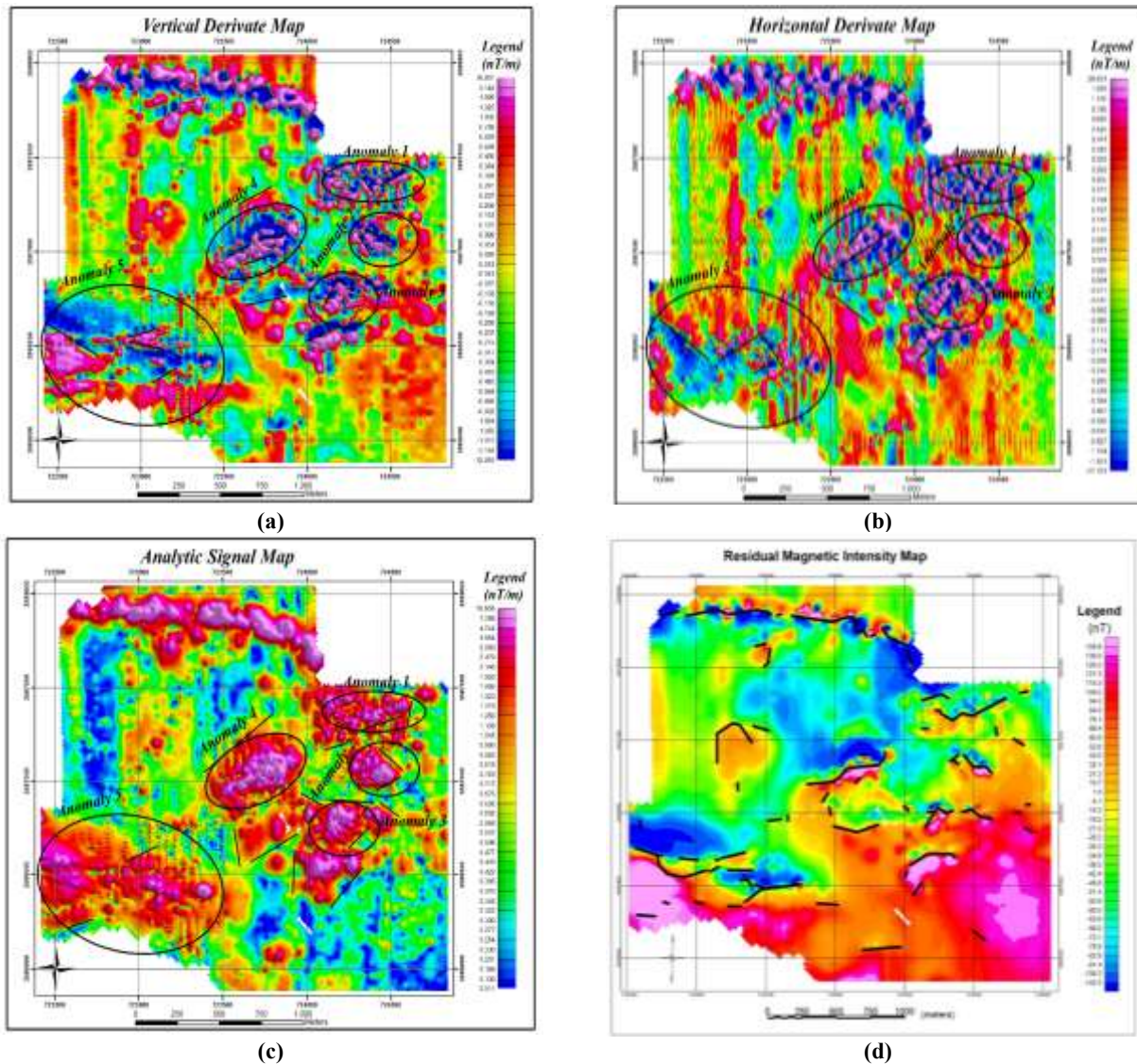


Figure 7. a) Vertical derivative map, along with the boundaries of intrusive bodies and the locations of identified faults on the map; b) Horizontal derivative map, along with the boundaries of intrusive bodies and the locations of identified faults on it; c) presents an analytic signal map highlighting faults and intrusive body boundaries; d) results obtained from CET using residual data.

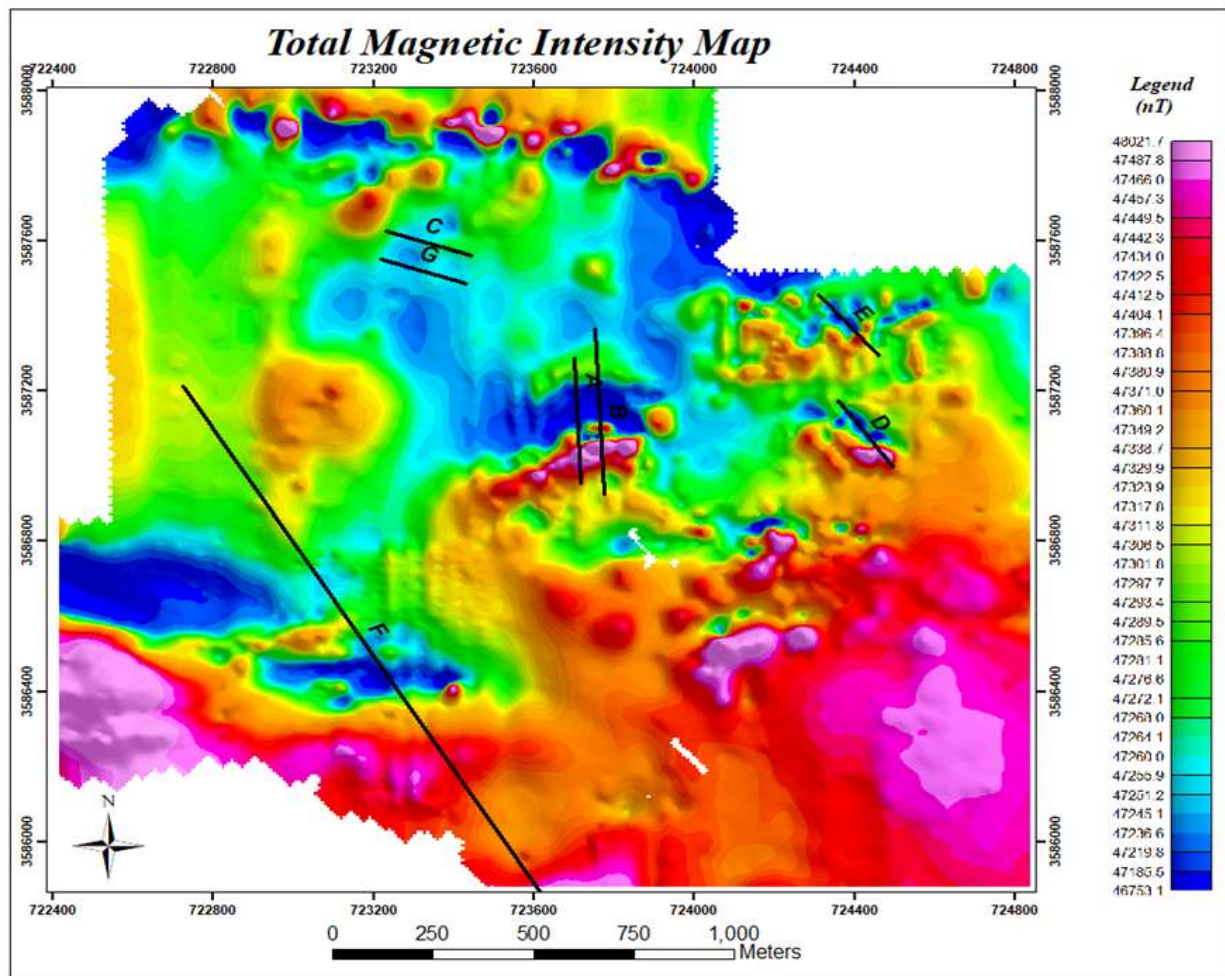


Figure 8. The location of acquired IP-RS profiles within the study area, highlighted in black on the total magnetic intensity map

These profiles were acquired using a dipole-dipole array with an electrode spacing of 10 meters. Figure 9 shows the location of the designed profiles on the Google Earth map.

After the data survey, the collected data were processed using the 2D smooth inversion method with RES2DINV software. Considering the significance of the survey profiles, the following sections analyze the chargeability and resistivity sections of the five main profiles. Figure 10 presents the resistivity, chargeability, and interpreted geological model sections derived from the magnetometry and IP-RS data for profile A. The maximum recorded chargeability along this profile is approximately 30 milliseconds. An anomalous zone is observed between 0 and 80 meters from the profile's starting point, characterized by relatively low resistivity and high chargeability values. This anomaly is likely associated with an intrusive body, suggesting the need for further exploration studies in this area.

Two faults are observed in the resistivity section at 120 and 160 meters from the profile's beginning, where a high-resistivity formation is juxtaposed with a low-resistivity formation. Furthermore, between 170 and 230 meters from the profile's starting point, a zone with a chargeability ranging from 5 to 7 milliseconds is observed, which also exhibits moderate resistivity. Given the range of chargeability and resistivity values recorded, there is a possibility that this zone is associated with hematite mineralization. To gather more comprehensive data, gravity surveys should be conducted in this area. It is worth noting that the location of the aforementioned anomaly coincides with the dipolar boundary in the total magnetic field intensity map, indicating the presence of an intrusive body or mineralization. This observation further corroborates the results obtained from the chargeability and resistivity sections. The results of profile B are similar to those of profile A; therefore, to avoid repetition, its presentation was omitted.

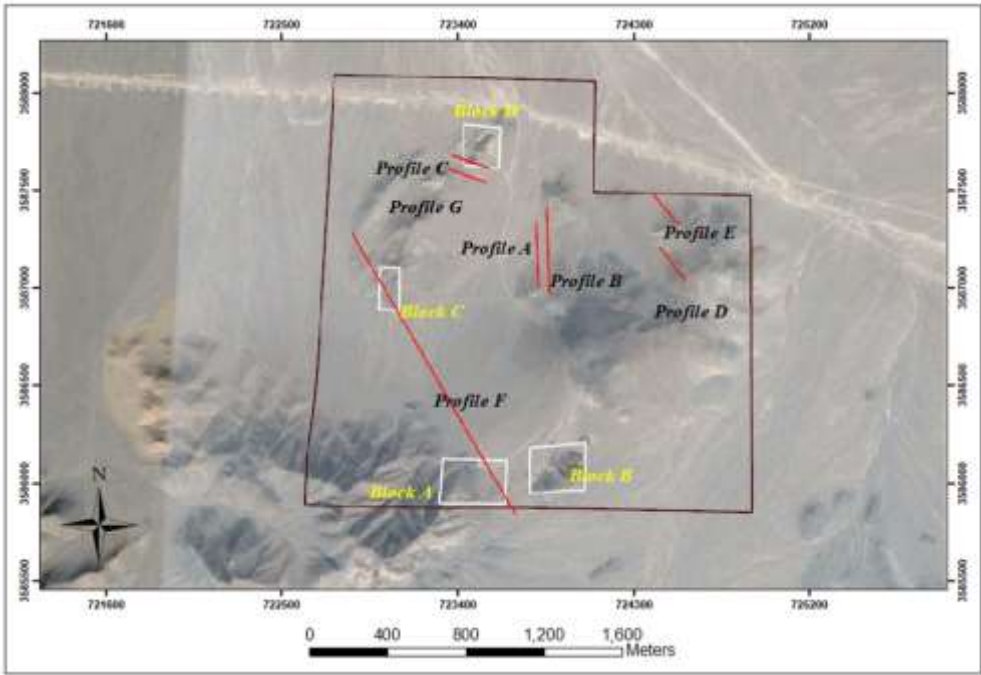


Figure 9. Location of IP-RS profiles on Google Earth map

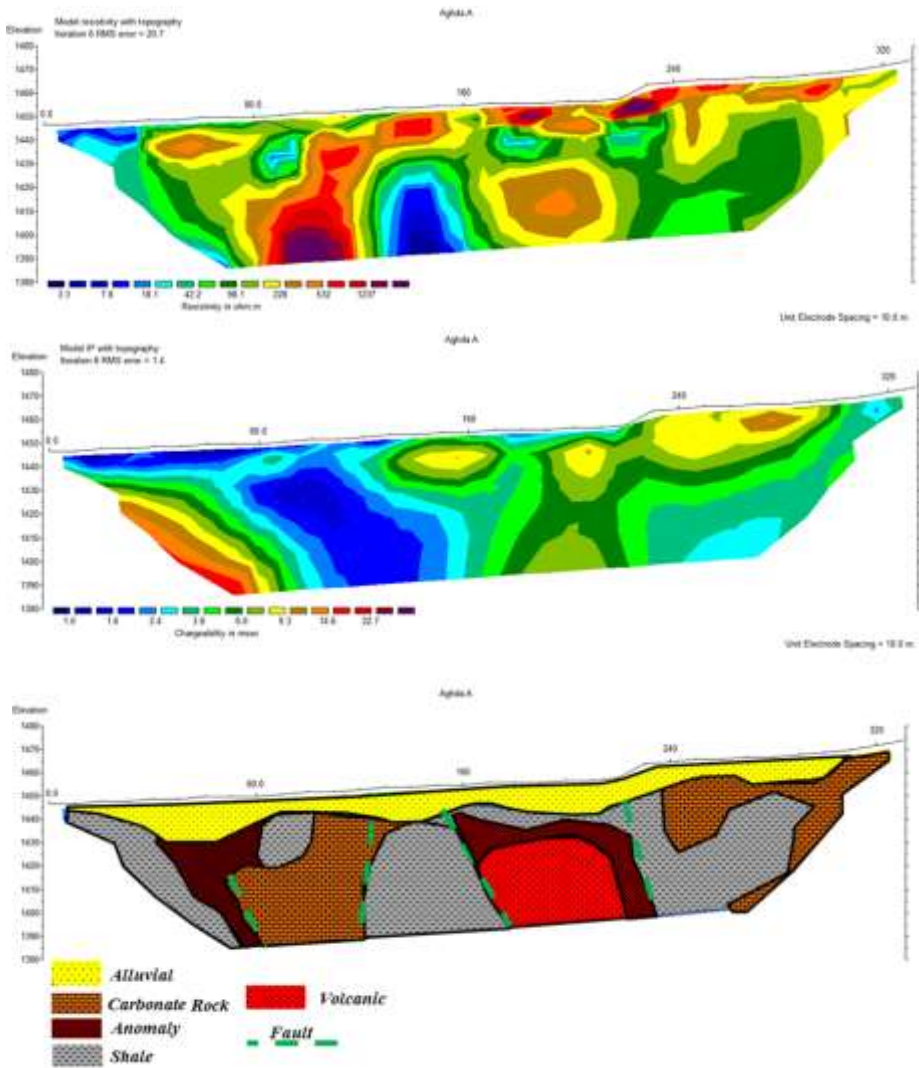


Figure 10. Resistivity, chargeability, and geological model sections derived from profile A

In Figure 11, the chargeability and resistivity section related to profile C is illustrated. Based on the observed changes, the geological section corresponding to profile C has also been prepared. As shown in Figure 11, from the 0 to 90 meters position from the start of the profile, a zone with low resistivity and high chargeability appears, which is associated with shale formations. The local position of this zone on the ground is shown in Figure 12a. Additionally, in the 120 to 220

meters range from the start of the profile, a zone with high resistivity and low chargeability appears, which is associated with carbonate formations. The local position of this zone on the ground is shown in Figure 12b. In the range of 90 to 120 meters from the start of the profile, a zone with medium to low resistivity characteristics and a chargeability of about 5 to 7 milliseconds has appeared, which could be related to hematite mineralization. Its local position on the ground is shown in Figure 12c.

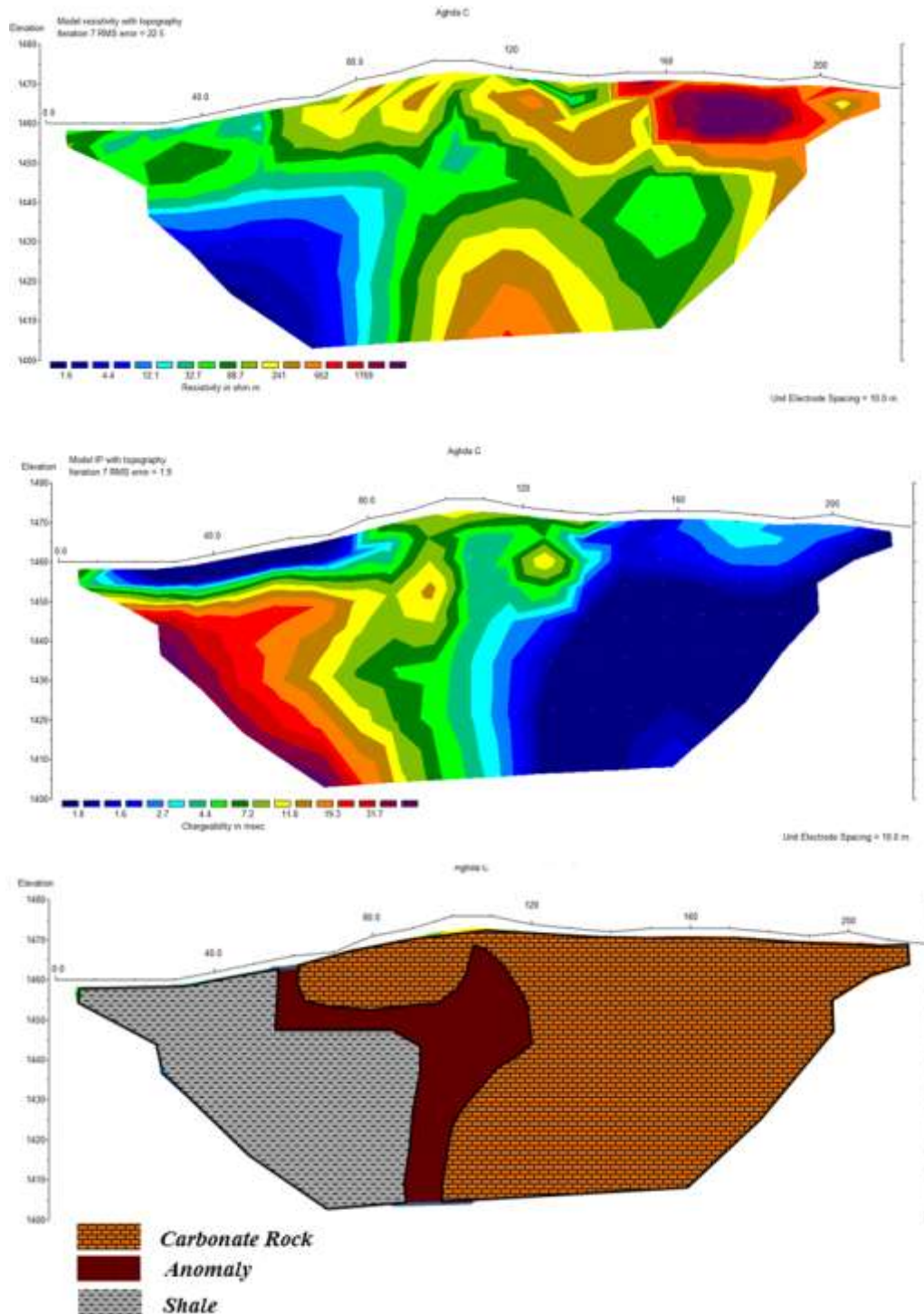


Figure 11. Resistivity, chargeability, and geological model sections derived from profile C



Figure 12. a) Shale formations located within the 0 to 90 meter interval of profile C; b) Carbonate formations located within the 120 to 220 meter interval of profile C; c) Hematite mineralization within the 90 to 120 meter interval of profile C, at the contact between the two lithologies

To investigate the geological conditions of the southwestern part of the study area, IP-RS studies were conducted in the form of profile F. In Figure 13, the chargeability, resistivity, and geological sections related to this profile are illustrated. As shown in "Figure 13", from 0 to approximately 400 meters from the start of the profile, data collection was carried out parallel to the existing benches and trenches. Geologically, the 80 to 330 meters range from the start of the profile corresponds to limestone formations. At the 220 meters position from the start of the profile, a hematite outcrop is observed among carbonate rocks, as shown in Figure 14a. Additionally, at 310 meters from the start of the profile, a trench has been excavated, and hematite mineralization is observed on the trench

wall, as depicted in Figure 14b. As shown in the figure, in some sections, variations in resistivity and chargeability correspond to the hematite mineralization zone, which is clearly visible in the geological section prepared and shown in the third part of Figure 13.

Integration of resistivity and chargeability sections provides a more precise understanding of the subsurface architecture. Low-resistivity/high-chargeability zones mapped in profiles A, B, and C align spatially with black shale formations, indicating lithological control over electrical properties. Importantly, contact zones between carbonate and shale units display intermediate resistivity coupled with elevated chargeability (5–7 ms), a signature typically associated with

hematite mineralization due to the conductive signature of Fe-oxides embedded within the host rock matrix. Profiles F and G further confirm that mineralized intervals occur preferentially along lithological boundaries and fault traces, consistent with the magnetic anomaly positioning.

The combined interpretation of magnetometry and geoelectric datasets has significantly reduced ambiguity inherent in single-method analyses. Magnetic mapping provided a regional-scale framework for structural trends, while geoelectric profiling refined the spatial definition of faults and

mineralized zones. The strong spatial correlation between magnetic lineaments, conductive horizons, and mapped hematite occurrences demonstrates that the integration strategy is both effective and scalable. This approach can be generalized to other carbonate-hosted iron systems, where multi-method geophysics may uncover mineralization patterns obscured by complex structural settings. The combined results of both methods are shown on the horizontal derivative map of the magnetic field in Figure 15.

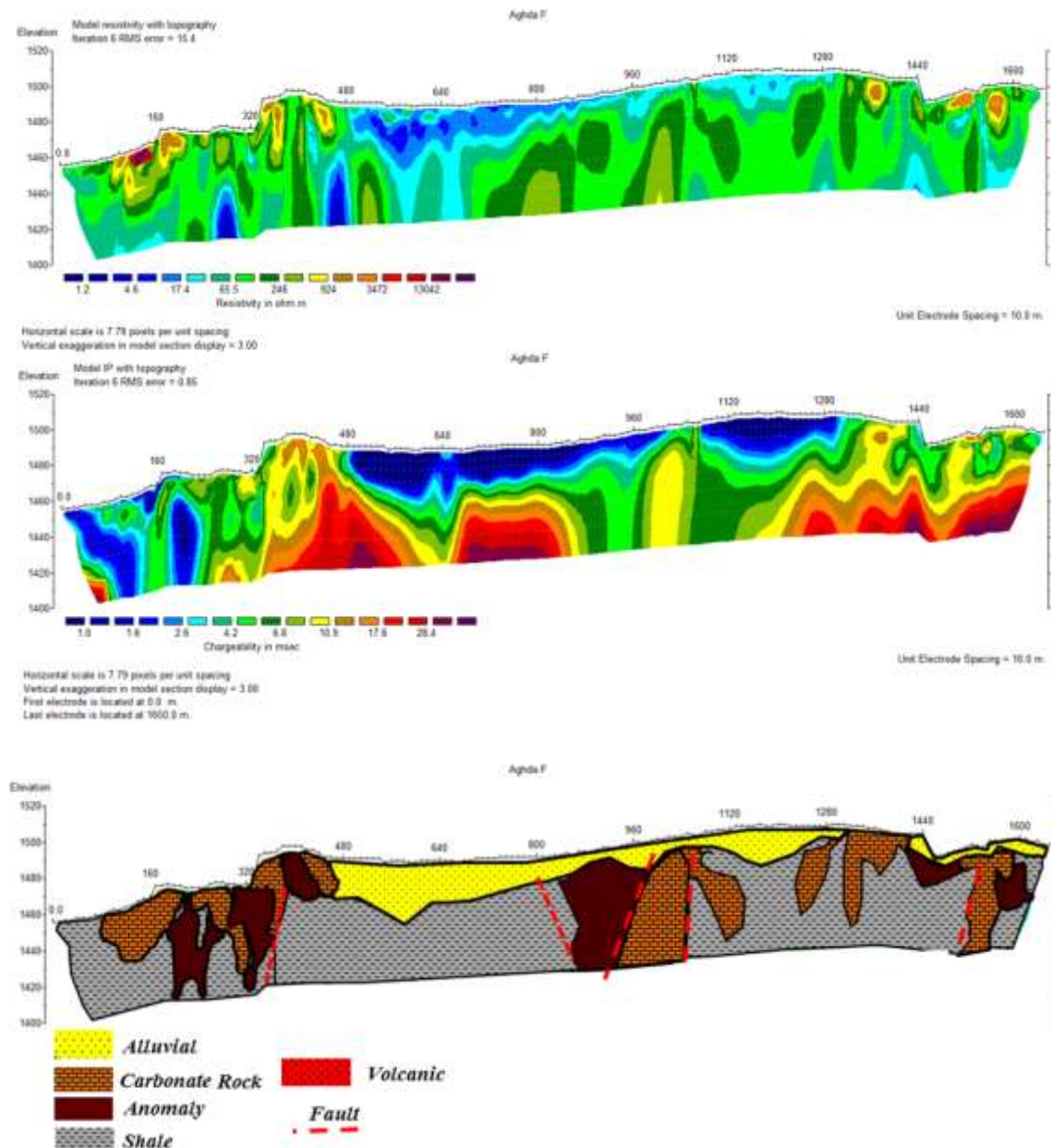


Figure 13. Resistivity, chargeability, and geological model sections derived from profile F

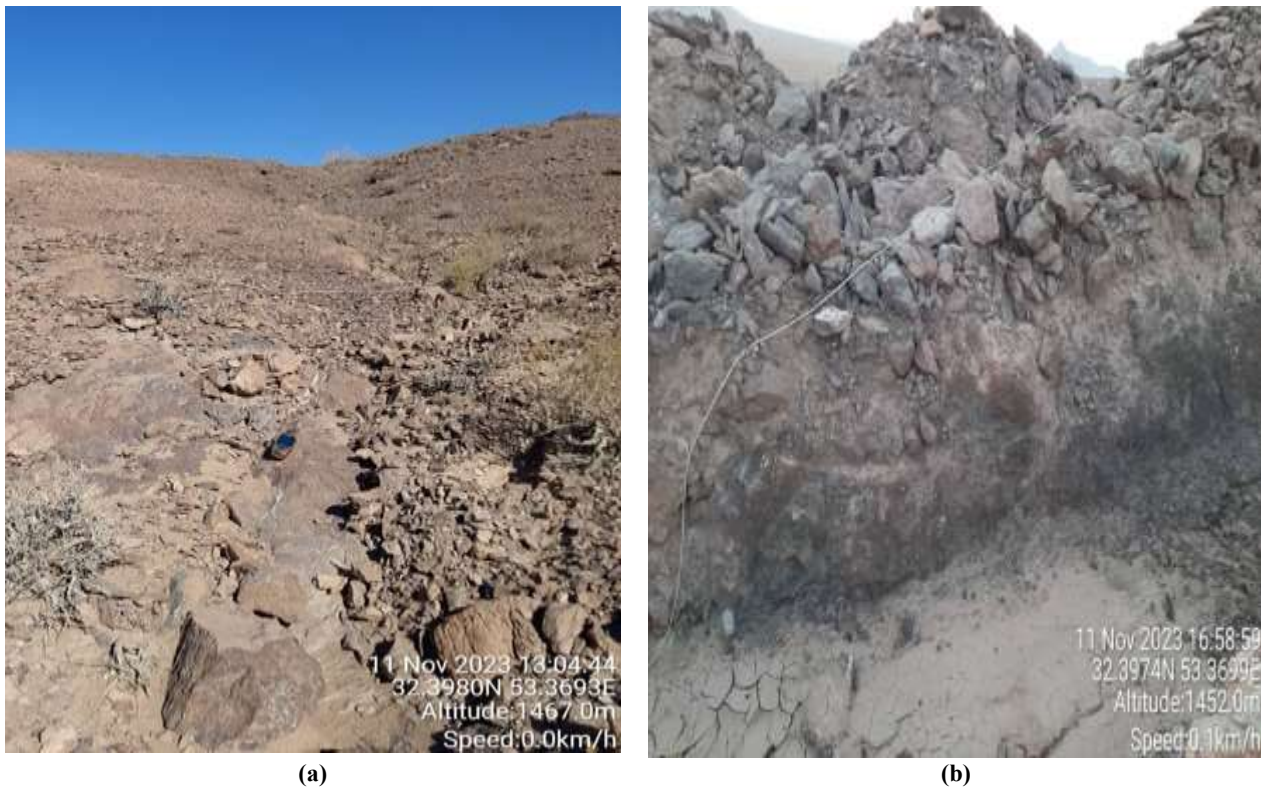


Figure 14. a) Hematite outcrop located 220 meters from the beginning of the profile; b) Evidence of hematite mineralization within a trench located 310 meters from the beginning of the profile

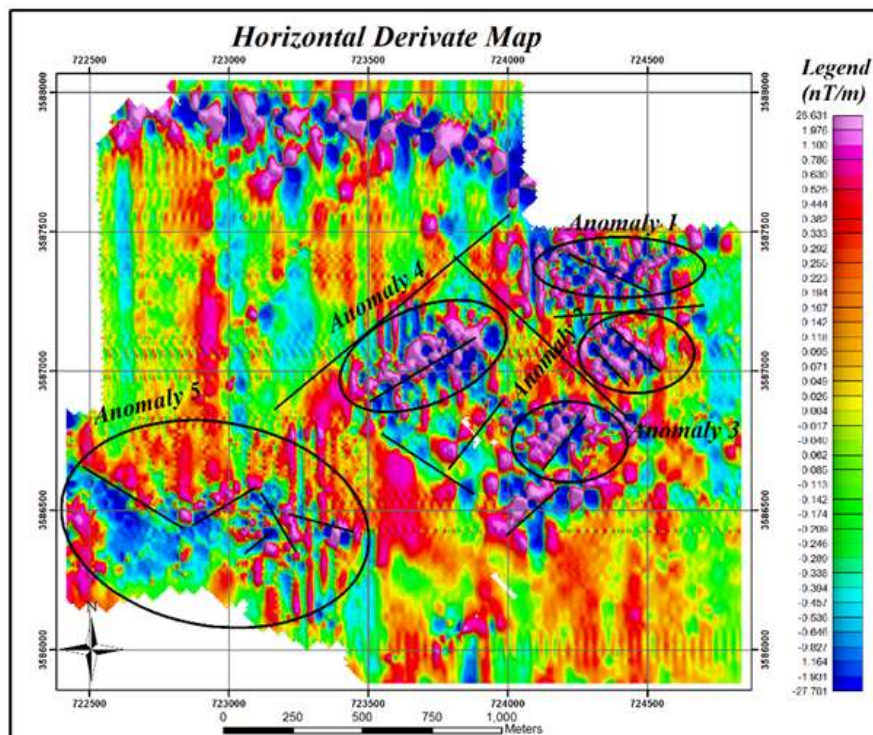


Figure 15. Map of fault locations derived from the combined results of resistivity and magnetometry

5. Conclusions

This study integrated magnetometry and geoelectric (IP-RS) methods to investigate the structural controls of hematite mineralization in the Aqda area, Yazd Province. The magnetic datasets

revealed NE–SW and NW–SE structural trends that closely align with the dominant tectonic pattern of the Sarve Bala region. Interpretation of residual anomalies and derivative maps indicated that intersections of these trends are strongly

associated with hematite-bearing zones. Complementary IP–RS profiles confirmed that mineralized intervals occur preferentially along lithologic contacts, especially between carbonate and shale formations, validating the structural origin of mineralization inferred from magnetic data.

The main contribution of this research lies in demonstrating the effectiveness of integrating magnetic and geoelectric techniques for delineating structurally controlled mineralization zones in carbonate-hosted iron deposits. Magnetic mapping provided a regional framework for trend detection, while IP–RS profiling refined fault geometry and detected conductive mineralized zones. The cross-validation between datasets significantly reduced interpretational ambiguity, resulting in a more robust and repeatable understanding of subsurface conditions compared to using either method alone.

The integrated approach presented here can be effectively applied to other structurally complex exploration targets, particularly those in sedimentary or carbonate environments where lithological and structural factors govern mineralization. The workflow proposed, comprising derivative magnetic analysis, CET-based structure detection, and targeted IP–RS profiling, offers a transferable exploration model for early-stage geophysical investigations. Thus, this study not only clarifies the subsurface structure of the Aqda deposit but also contributes a methodological framework to improve efficiency and reliability in mineral exploration campaigns. Future research could apply the integrated magnetometry and IP–RS workflow to other carbonate- and sediment-hosted iron deposits with different structural settings to test its robustness and limitations. Additionally, combining geophysical interpretation with drill-hole data, petrographic observations, and 3D inversion of the magnetic and IP datasets would enable a more quantitative assessment of ore geometry, grade, and tonnage in similar exploration projects.

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Declarations

Conflict of interest: The authors declare that they have no known competing financial interests

or personal relationships that could have appeared to influence the work reported in this paper.

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امید رابط جزی، علیرضا عرب امیری، کیوان خیر

دانشکده مهندسی معدن، نفت و ژئوفیزیک، دانشگاه صنعتی شاهرود، شاهرود، ایران

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کانه زایی هماتیت

عقدا

چکیده

در محیط های زمین شناسی پیچیده، شناسایی دقیق ساختارهای کنترل کننده زیرسطحی برای هدف گذاری مطمئن کانه زایی هماتیت ضروری است؛ با این حال همچنان کاری دشوار به شمار می آید. تفسیرهایی که تنها بر یک مجموعه داده ژئوفیزیکی تکیه دارند، معمولاً با محدودیت در تفکیک پذیری ساختاری و افزایش ابهام تفسیری همراه اند. داده های مغناطیسی و ژئوالکتریک در این پژوهش به صورت یکپارچه تلفیق شده اند تا ساختارهای زیرسطحی موثر بر کانه زایی هماتیت در منطقه عقدا، استان یزد، ایران بررسی شوند. داده های مغناطیسی با استفاده از کاهش به IGRF و چندین فیلتر تقویتی، شامل مشتق های قائم و افقی، سیگنال تحلیلی و تکنیک مرکز هدف گذاری اکتشافی (CET) پردازش شدند. نتایج وجود پنج ناهنجاری اصلی مغناطیسی را نشان داد که راستای غالب آن ها شمال شرق-جنوب غرب و شمال غرب-جنوب شرق است؛ این ناهنجاری ها به عنوان توده های نفوذی که توسط گسل ها کنترل می شوند تفسیر شدند. علاوه بر این، تکنیک CET دو روند ساختاری اصلی شمال شرق-جنوب غرب و شمال غرب-جنوب شرق را مشخص کرد که با خطواره های مغناطیسی هم راستا هستند و پهنه های با پتانسیل بالای کانه زایی را مرزبندی می کنند. برای اعتبار سنجی این ساختارها، هفت پروفیل IP-RS برداشت شد و با استفاده از رویکرد مدل هموار در نرم افزار RES2DINV وارون سازی گردید. مقاطع تلفیقی مقاومت ویژه و بارپذیری، موقعیت گسل های استنباط شده را تایید کردند و زون های با بارپذیری افزایش یافته را که با کانه زایی هماتیت سازگار هستند، برجسته کردند. ترکیب هر دو مجموعه داده تفکیک پذیری ساختاری را بهبود داد و ابهام تفسیر را به طور چشمگیری کاهش داد. این رویکرد تلفیقی نشان می دهد که روش های مغناطیسی و ژئوالکتریک مکمل یکدیگرند و ابزاری موثر برای مرزبندی زون های کانهدار در محیط های زمین شناسی پیچیده فراهم می کنند.