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Validation of magnetic exploration in the iron deposit as an exploration key for decision making to continue the operation (a case study)

Reza Ahmadi*
*Assistant Professor, Arak University of Technology, Arak, Iran
Email: Rezahmadi@gmail.com; R_ahmadi@arakut.ac.ir

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*Corresponding Author's Email Address:
Rezahmadi@gmail.com
R_ahmadi@arakut.ac.ir

Abstract

In the southern part of Alijan-Divandarreh in the Kurdistan Province, magnetic survey has been carried out to explore iron in two phases for two separate zones called A and B. The magnetic surveys of the first and second phases in the eastern part of zone A have some overlaps, so that the western part of the area surveyed in the first stage is the eastern part of zone A. Six vertical boreholes have also been drilled on the anomalies of the first phase in the eastern part of zone A. To make a decision on continuation of detailed exploration in the second phase, especially deciding about drilling of 16 new proposed boreholes in zones A and B, the results of the first stage were evaluated using the drilling data. Based on the results of drilling conducted in the eastern part of zone A, the probability of technical success obtained 60% and probability of economic success compared to similar iron deposits in Kurdistan province is predicted to be 95%. Therefore, the probability of exploration success is 0.57 which is acceptable in the current conditions. In other words, at the moment the possibility of converting the deposit into ore is not very high and drilling of the new proposed boreholes in zones A and B is needed. However, it is suggested that the specifications of the new proposed boreholes be revised through the geology of the region and mineralization type. Whereas, new boreholes can be drilled based on the trend of mineralization in the contact between schist and amphibolite.

Introduction

Iron ore deposits are considered valuable metallic mineral deposits due to the high economic value and extensive industrial applications of iron. Also, magnetic survey as non-direct exploration method is the fastest, cheapest, most common and suitable method for exploring iron ore deposits. Direct exploration of these types of deposits through drilling is costly and time-consuming, making the determination of optimal drilling locations crucial. Therefore, in order to save time and costs, in semi-detailed exploration stage, magnetic anomalies are typically identified as the most suitable drilling targets based on the results obtained from the processing and interpretation of magnetic exploration data (Ahmadi and Rezapour, 2019; Ahmadi and Baharlouei, 2021).

In general, determining the location of anomaly sources and any other information relevant to exploration studies is the objective of geophysical exploration studies. The most significant characteristic of these methods is their potential ability to provide information about variations in subsurface physical properties and their relationship with the surrounding environment. If the desired physical property is more pronounced in the target than host rock, geophysical targets can be successfully identified (Reynolds, 2011; Curry et al., 2002; Milson, 1996; Parasnis, 1996; Telford et al., 1990; Griffiths and King, 1983).

In many geophysical exploration methods, the acquired raw data are not directly usable requiring a series of processing and modeling steps. Raw geophysical data are often contaminated with various types of noise, making it challenging to obtain comprehensive, accurate, and valid information about the actual burial depth, size and physical properties of subsurface masses. Therefore, corrections are necessary (Alilou et al., 2018; Khomutov et al., 2017).

Since the variations of subsurface physical properties is vast and geophysical data acquisition is influenced by numerous factors such as diverse and complex geological conditions, topography and

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various geological, thermal and human made noise sources (Samy and Arafa-Hamed, 2023; Reynolds, 2011; Norouzi, 2009), in many cases, even after applying various corrections and filters to geophysical data, the final results do not align well with reality (Rezapour, 2018; Baharlouei, 2019). Studies and investigations on the validation of geophysical results using different methods can be helpful in decision-making and determining the correct path for the process. In the present research, magnetic survey data in the Alijan Divandarreh district of Kurdistan were evaluated after necessary processing. Six drilled boreholes were used to assess the magnetic anomalies on the eastern part of the area, and decisions were made regarding the continuation of the exploration process, especially the new proposed drilled boreholes.

Regarding the processing and modeling of magnetic data and the validation of results from geophysical exploration operations using drilling data, a few notable research studies have been conducted in recent years. Saada (2016) utilized various processing techniques such as slope angle derivatives, horizontal derivatives and Euler's method to detect anomalies on airborne magnetic data in the Galala El Bahariya Plateau, Alborz, Iran. Ahmadi and Rezapour (2019) carried out data modeling of magnetic, induced polarization and resistivity data in the North Narbaghi porphyry copper deposit, Saveh. They demonstrated the correlation between mineralization profiles derived from geophysical data and drilling assay data, indicating that some drilling operations lacked proper design, logic and purpose, were not based on geophysical results, resulting in mineral-deficient zones. They also examined the qualitative correlation between geoelectrical survey results and assay data from mineralized profiles, revealing a general average qualitative correlation between the two datasets. Ahmadí and Shariati Zarch (2020) performed 2D and 3D synthetic modeling of various geological structures using Encom ModelVision software. They also investigated the influence of survey grid size on magnetic anomaly responses through magnetic surveys conducted on buried metallic pipes at the Arak University of Technology campus. Ahmadi and Baharlouei (2021) performed inversion processing and modeling of magnetic, resistivity, and induced polarization data, as well as quantitatively and qualitatively comparing them with assay data from mineralized profiles. The representation of magnetic survey anomaly profiles corresponding to four geoelectrical profiles revealed that many magnetic anomalies were associated with high chargeability and low resistivity, indicating a good qualitative correlation between magnetic and geoelectrical data and implying an increased likelihood of mineralization in the area. Furthermore, investigating the linear correlation between inverted geophysical data and assay data within a specific and uniform area, after a predetermined and equal grid layout and interpolation of their values, generally showed a relatively good quantitative match (between 0.4 and 0.7). Ahmadi and Ehsan Nejad (2021) performed processing, comparison and analysis of magnetic, resistivity and induced polarization data along geophysical profiles in the Aliabad-Yazd copper deposit, determining their relationship with mineralization. The results indicated a good overall agreement between magnetic and geoelectrical data, suggesting that the existing anomalies in the area were mostly related to metallic mineralization.

In previous studies, after completing the exploration process, the overall evaluation of geophysical results has been carried out but in the current study, the evaluation and validation of exploration activities have been used as an exploration key to make decisions for another part of the Alijan iron deposit, both analytically and based on the theory of exploration success probability.

Geographical and geological setting

The study area is located in Kurdistan province, approximately 30 kilometers west of Divandarreh city and south of Alijan village, between the geographical longitudes of 46°39'7" to 46°42'25" East and geographical latitudes of 35°54'20" to 35°54'45" North. Figure 1(a) shows the geographical location of the study area and the access roads to it on a Google Earth image.

The study area is situated within the 1:250,000 Sanandaj geological map (Zahedi and Hajian, 1985) and the 1:100,000 Bayenjoob geological sheet (Shahpasand Zadeh, 2006). This area is part of the Sanandaj-Sirjan tectonic zone, which is located in the southwestern part of the Urmia-Dokhtar magmatic belt and parallel to the general trend of the Zagros mountain range. The main lithological units in the region include gray-green slates and phyllites, schists, quartzites, metamorphosed gravel sandstones, crystalline dolomitic limestone of the Lower Paleozoic era (PZ^{sl}), and Paleozoic rocks (PZ^{vc}) consisting of metamorphosed acidic volcanic rocks in color ranging from white to light green and metamorphosed rhyolite-rhyodacite tuffs in color ranging from pink to white with distinct porphyry textures. In terms of structural and tectonic geology, the area is tectonically active, characterized by major faults with an east-west, northeast-southwest, and northwest-southeast orientation.

Economically, the iron mineralization in the Divandarreh, Qorveh and Hamadan regions is mainly of volcanic-sedimentary or skarn type (Ghorbani, 2008; Rostami Paydar et al., 2010; Zamanian and Radmard, 2016). The hydrothermal iron deposits also occur as vein-type or lens-shaped deposits, formed due to the activity of hydrothermal fluids at different depths (Azizi et al., 2009). The main mineral in these type of deposits is magnetite and hematite (Barati and Gholipour, 2014). In the study area, mineralization has mainly occurred in the schist-amphibolite sequence, limited and lens-shaped, parallel to them. Figure 1(b) shows the geological map of the study area.

Materials and methods

The present research consists of several steps and in the following, each step of the research is described in detail.

Data acquisition, processing and interpretation

In order to obtain information about promising areas with exploration potential, identification of mineralized veins and fractures, as well as the investigation of surface and subsurface anomalies in the Alijan iron deposit, magnetic surveys were conducted in two phases. In the first stage, magnetic surveying was carried out in an approximate area of 1.5 km^2 in the eastern part of the target area, with 5,104 measurement stations distributed in a grid with station interspacing of 5-15 m and profile interspacing of 10-30 m. Then, to expand the coverage, in the second stage as Figure 2, surveys were conducted in zones A and B, with an approximate aerial distance of 2,947 m between them. The magnetic surveys of the first and second stages have some overlapping in the eastern part of Zone A. In other words, the western part of the surveyed area in the first stage, with an approximate horizontal length of 480 m in the east-west direction, corresponds to the eastern part of Zone A. Following these stages, drilling operation was carried out in the eastern part of Zone A, specifically on the western section of the magnetic anomalies surveyed in the first stage. The study area in the present research includes Zones A and B, which encompass the magnetic surveys conducted in the second stage and the western part of the area surveyed in the first stage. The magnetic data acquisition was carried out in the investigated area in two separate zones, A and B (Doulati-Ardehjani and Amirkhani, 2021). As shown in Figure 3, 8,321 and 4,836 stations were measured in Zones A and B, respectively, and a total of 13,157 in the entire area. The data acquisition points were mostly obtained using 10 by 10 m grid, using a single proton magnetometer. However, in locations where magnetic field variations indicated possible mineralization, the acquisitions were conducted with a higher density to determine the boundaries of anomalies with more accuracy.

The data processing was performed using Geosoft Oasis Montaj software. Figure 4 shows the total magnetic intensity map in the zones A and B of the Alijan iron deposit. The potentially areas in this map are represented by blue and red dipoles, indicating sections with the highest and lowest magnetic field intensity values, respectively. These variations are possibly related to the presence of magnetic minerals at different depths.

The magnetic field intensity in Zone A ranges from 46430 to 56558 nT with a variation range of approximately 10128 nT. The background magnetic limit in the area (IGRF) was also calculated 48021 nT, indicating a significant variation in this region due to the presence of magnetic dipoles, suggesting a potential occurrence of suitable minerals in this zone.

The most important anomaly of zone A is located at the center of the map. Considering the magnitude of the magnetic field intensity variations and the magnetic dipoles, this section has a potential for suitable iron minerals. In the southwestern part of the region, scattered anomalies are also observed, which have a lower magnetic intensity compared to the central part. In the southern part, the intensity of the magnetic field with pink color is relatively significant, which may be caused by the effect of igneous rocks.

The intensity of the magnetic field in Zone B ranges from 47004 to 62107 nT with a variation range of 15103 nT. The background magnetic limit in this area was calculated 48017 nT, indicating a significant portion of the area may be caused by the effect of igneous rock formations, especially in the parts that do not have blue and pink colors together or potential mineralization due to the presence of magnetic dipoles. A distinct trend of potential mineralization is observed as a zone with a northeast-southwest extent.

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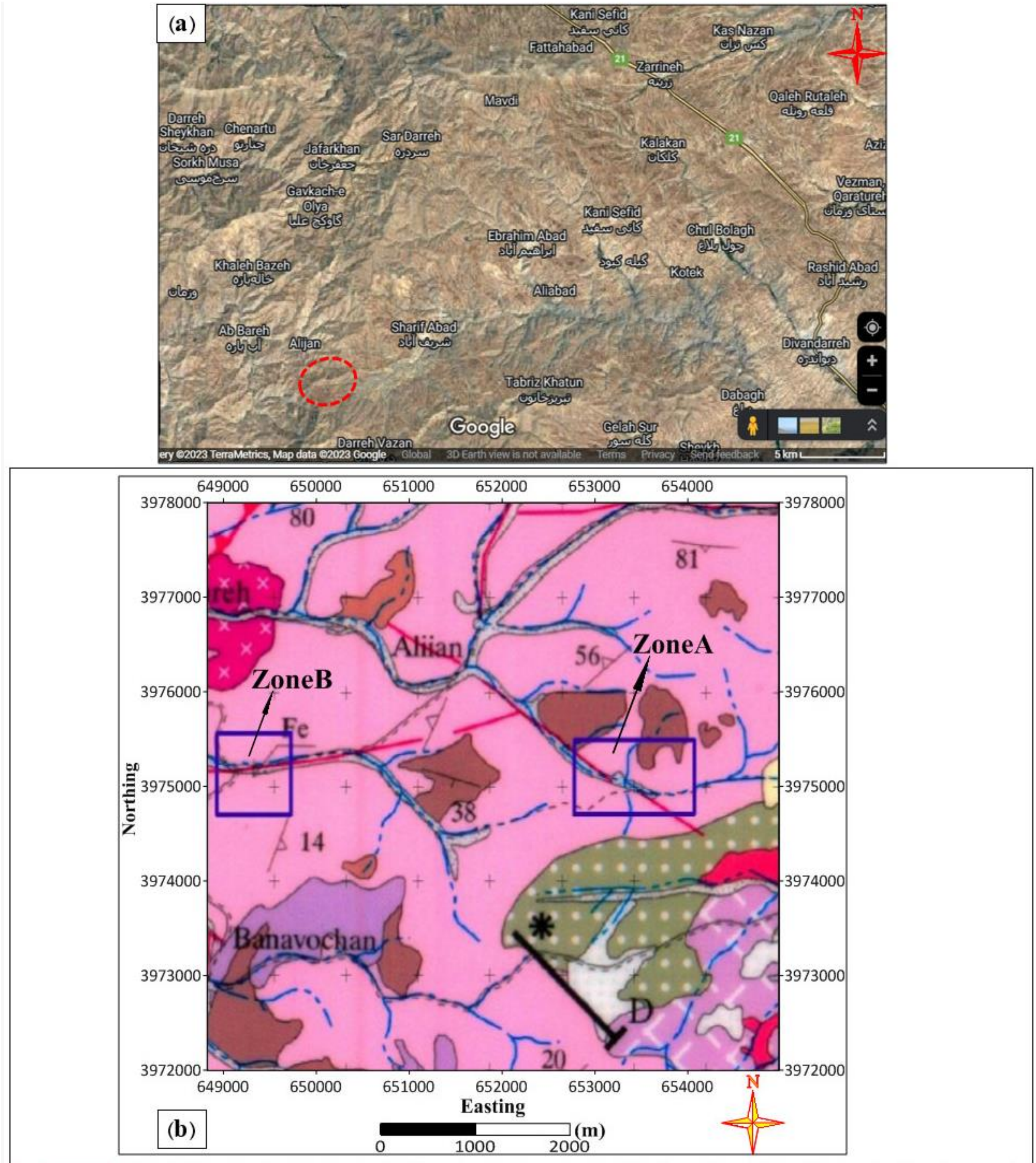

PZ^{vc}: White-pink, rhyolitic to rhyodacitic meta-volcanic and volcaniclastites with undifferentiated mylonitic micro granite-granodiorite
PZ^{b}: Dark green, massive, pillow-structured, meta-basaltic lava and volcaniclastites
D^{m}: Gray, laminated, medium-thick bedded, crinoid-bearing recrystallized limestone (Devonian)
PZ^{sl}: Green-gray, medium-thin bedded slate, phyllite, meta-graywacke and quartzite with minor arinoid-bearing recrystallized limestone (Ordovician–Devonian)
E^{s}: Massive to thick-bedded, moderately sorted, polymitic basal conglomerate, coarse pebbly sandstone with minor dark gray, medium thick-bedded, calcareous sandstone and argillitic nummulite bearing limestone

Fig 1. a) Geographic location of the Alijan iron deposit on the Google Earth image (red dashed ellipse), b) geological map of the study area.

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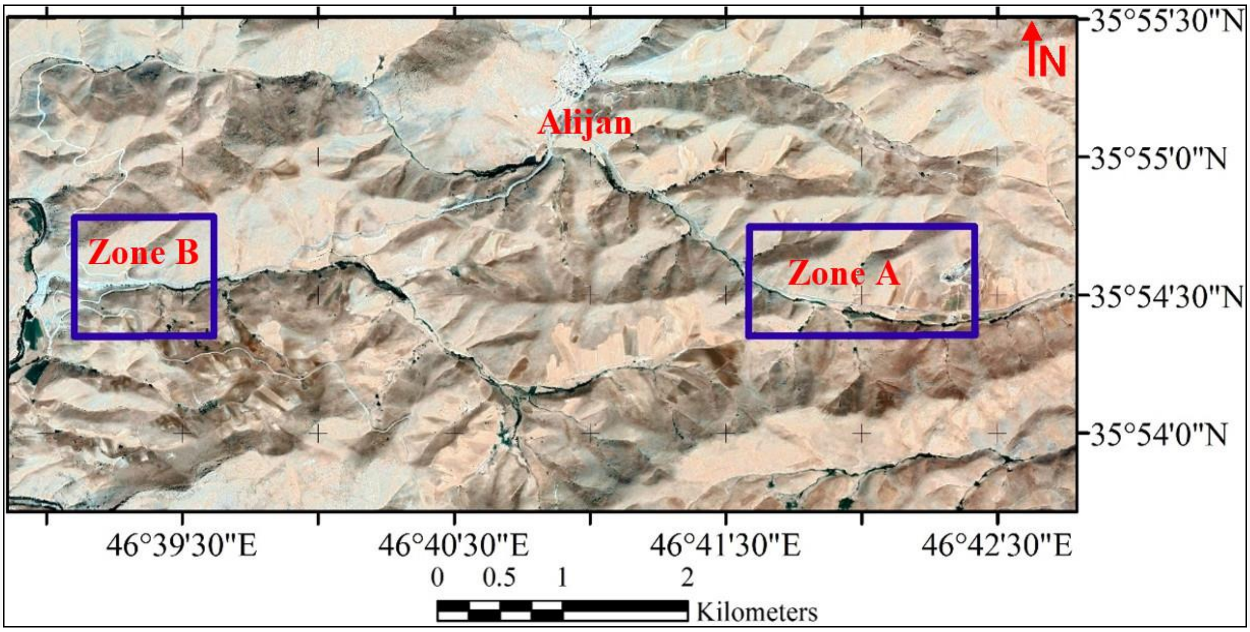

Fig 2. The location of geophysical survey zones A and B (blue rectangle and square, respectively) by magnetic method in Alijan area.

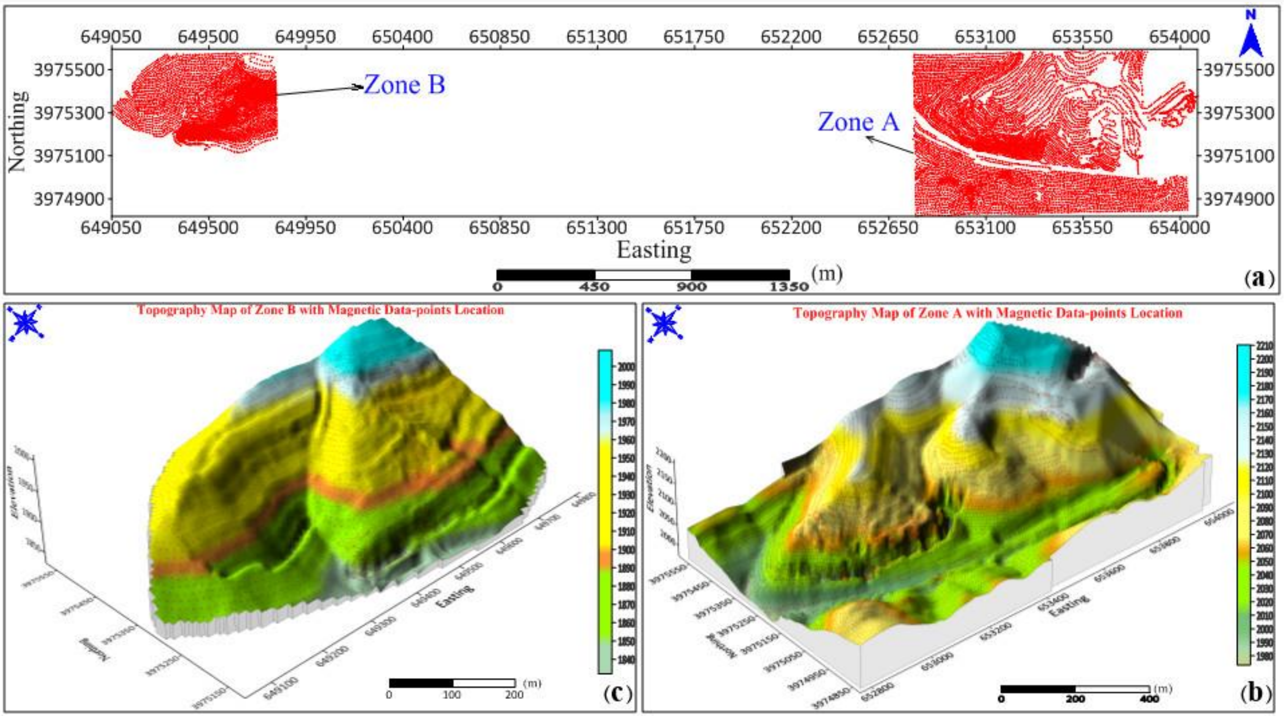

Fig 3. a) 2D scatterplot of magnetic stations (red multiplication signs) in zones A and B, b and c) the location of magnetic data points of zones A and B on the 3D topographic map of the Alijan area, respectively.

On the magnetic data obtained in both zones, corrections such as IGRF (to remove the background and prepare the residual magnetic field map), RTP (reduction to the pole), and various filters such as first and second-order vertical derivatives, analytic signal and upward continuation (Norouzi, 1388; Heinz et al., 2013) were applied for levels of 5, 10, 20, 30, 40, 50, 60, and 70 m. Based on these corrections and filters, the depth and potential mineralization were qualitatively and semi-quantitatively examined.

The Euler deconvolution method was used to estimate the depth of buried anomalies in these zones. This method is based on calculating the vertical and horizontal gradients at each point and plotting their diagrams. Figure 5 illustrates the

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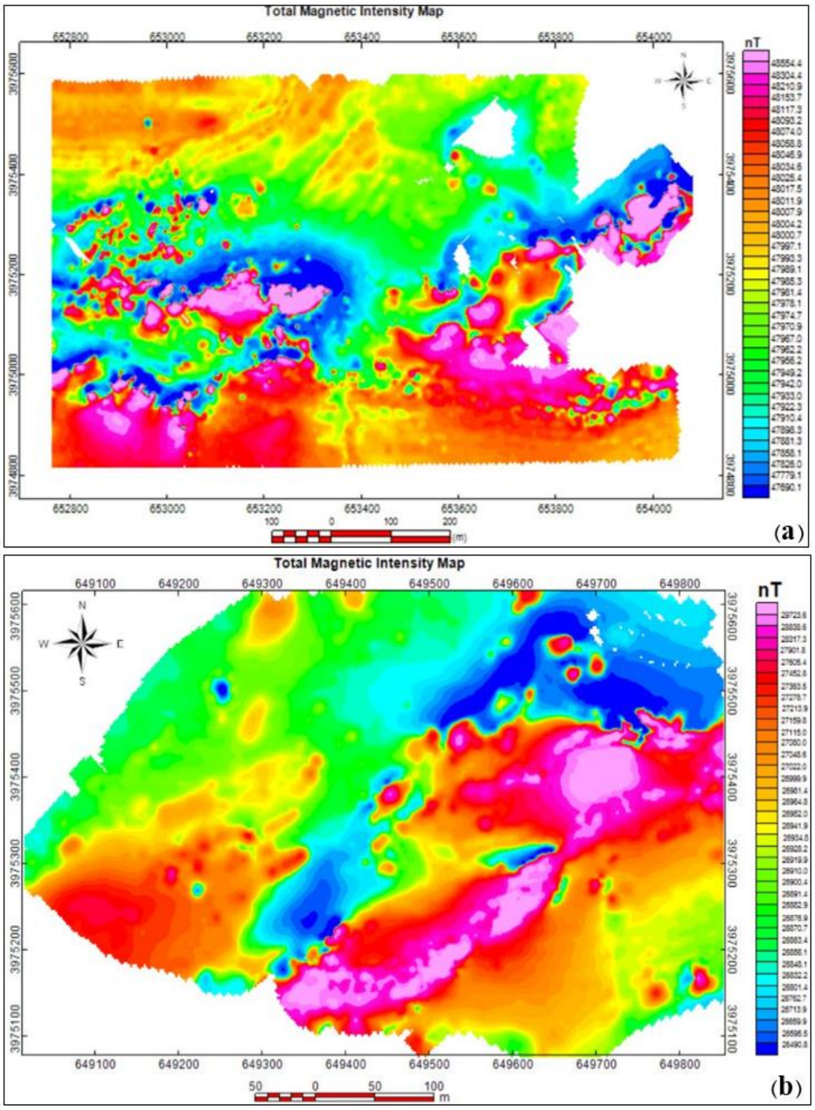

Fig 4. Total magnetic intensity map of: a) zone A, b) zone B.

determination of depth using the Euler's method, implemented on the analytic signal map. On these maps, anomalies are classified into four categories based on their depth: yellow, red, green and blue circles are standing for anomalies with depths less than 10 m, 10-20 m, 20-30 m and exceeding 30 m, respectively.

In Zone A, as shown in Figure 6, a total of eight vertical boreholes called BH1 to BH8 with a minimum depth of 30 m are proposed on the magnetic anomalies. The numbering of the boreholes is based on the priority of drilling. It is evident that drilling should continue as long as the mineralized extracted cores. Drilling of the borehole should be stopped at the depth of 30 m, if no mineralization is present at that depth.

In Zone B, as shown in Figure 7, a total of eight vertical boreholes called BH1 to BH8 with a minimum depth of 30 m are also proposed. The numbering of the boreholes in this zone is also based on the priority of drilling. Similarly, drilling should continue as long as mineralized samples are obtained from inside the borehole. If the borehole is drilled to a depth of 30 m and no mineralization is present at that depth, drilling should be stopped.

Verification of geophysical results with drilling operation

According to Figure 8, approximately one-fourth of the western section of the magnetic survey area in the first phase (with a horizontal aerial length of about 480 m) is located in the eastern part of Zone

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A, namely the Alijan area (inside the blue box). In this figure, the magnetic anomalies are indicated by white dashed lines. Currently, based on the results of the geophysical operations in the first phase, six boreholes called BH1, BH2, BH1Old to BH4Old with different depths have been drilled in two designated sections indicated by white dashed lines in the bottom left part of the map in Figure 8(a), i.e., in the eastern part of Zone A (between UTM geographical longitudes 653600 m to 654080 m East), as shown in Figure 8(b), the locality of these boreholes are also shown on the magnetic anomalies.

In Figure 9, the 3D geological-mining strip-logs of the boreholes in the Alijan iron deposit using the obtained data from drilling is presented, where the unit of measurement for horizontal and vertical axis numbers is meter. In this figure, depth intervals without any mineral deposit, regardless of the lithology, are labeled as gangue. According to the color legend of this figure, can be observed that BH3Old, BH4Old, and BH1Old are entirely waste or contain a very negligible thickness of irony schist.

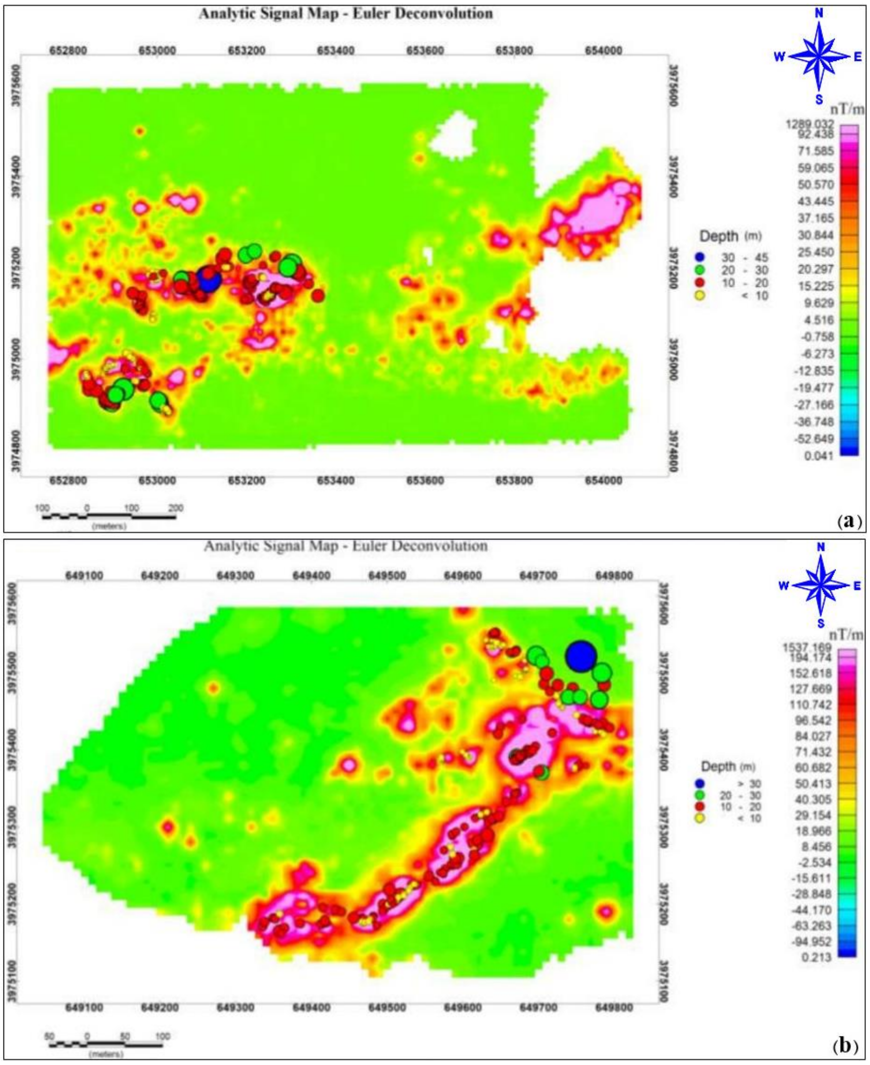

Fig 5. The variations range map of anomalies estimated depth for: a) zone A, b) zone B of the Alijan iron deposit using Euler's method on the analytic signal map.

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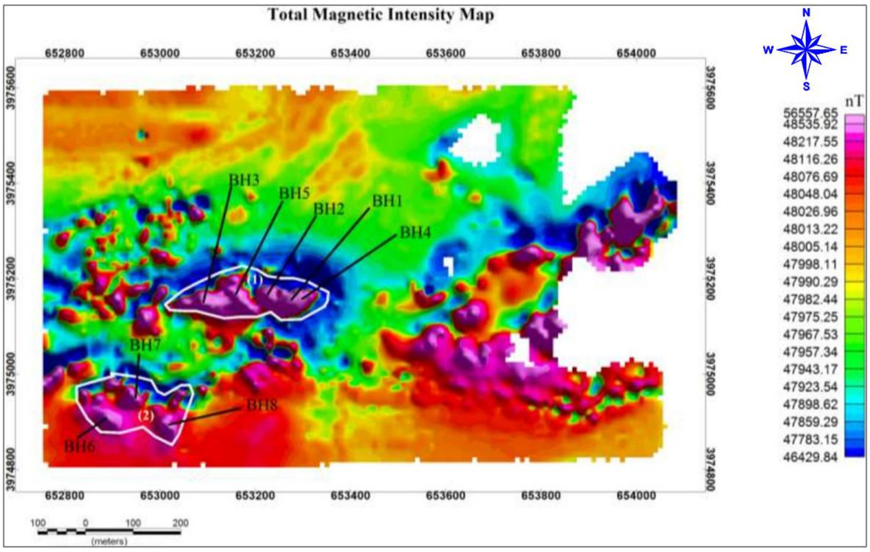

Fig 6. Drilling location of proposed boreholes in zone A of the Alijan deposit on the total magnetic intensity map.

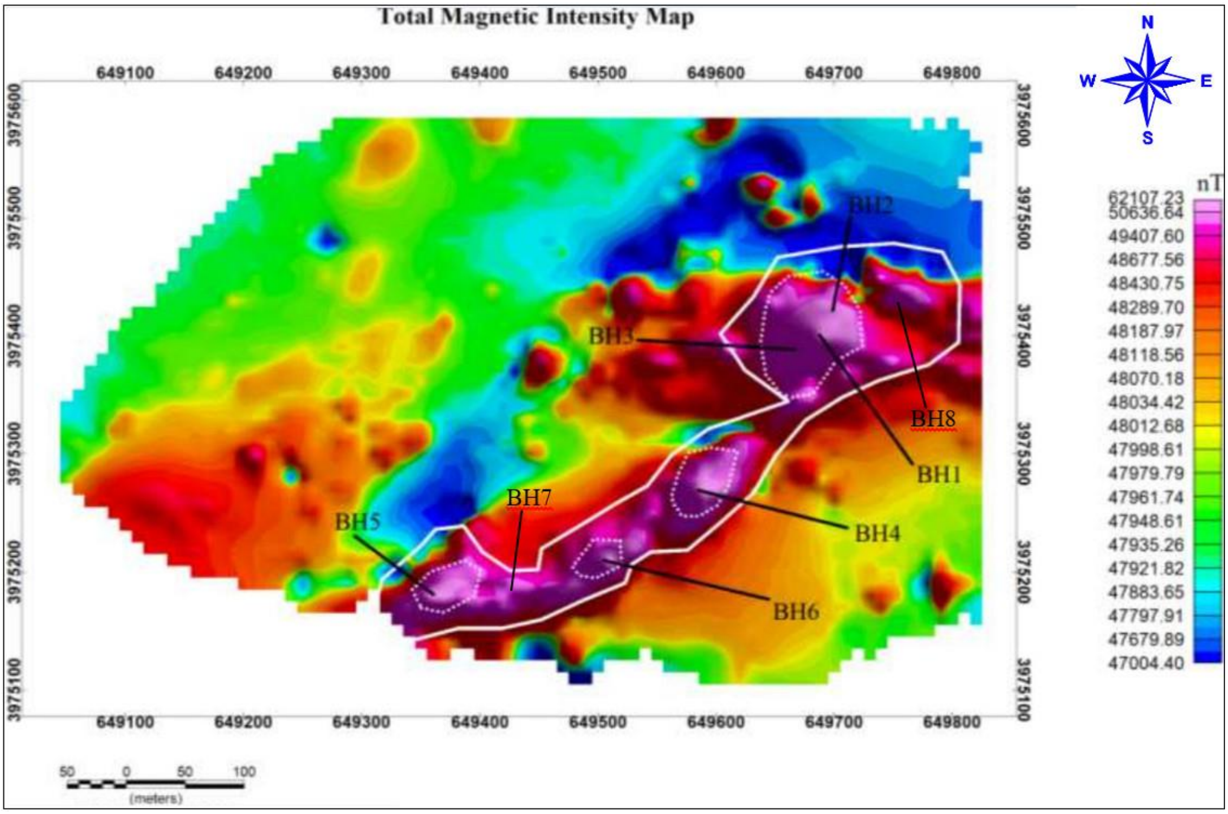

Fig 7. Drilling location of proposed boreholes in zone B of the Alijan deposit on the total magnetic intensity map.

In other words, 50% of the six drilled boreholes did not encounter any mineral deposit and are devoid of that. However, all boreholes except BH4Old have been drilled within the magnetic anomaly zones. It was expected that at least five of the six boreholes would intersect with mineral deposit.

BH4Old with a drilling length of 100 m, did not encounter any mineral deposit as expected, because it was drilled outside the magnetic anomaly zones, and it only showed a 30 cm thickness of iron rich schist at a depth of 70 m. However, selection of this borehole location was initially incorrect and was drilled without any logical and scientific basis. BH1Old with a drilling length of 105 m, which was drilled at the boundary of the magnetic anomaly, only had a one-meter thickness of irony schist at a depth of 73 m. The entire length of BH3Old with 55 m drilling length is also waste.

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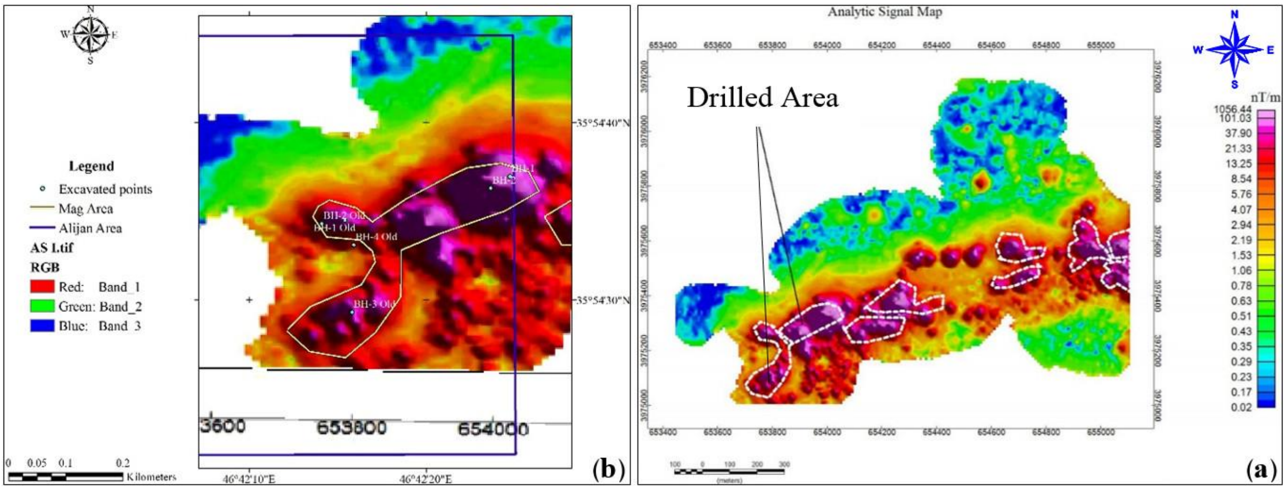

Fig 8. a) Anomalous areas on the analytical signal map from the magnetic survey of the first phase in the east of zone A, b) drilling location of 6 boreholes in the anomaly surface on the lower left part of the map (a).

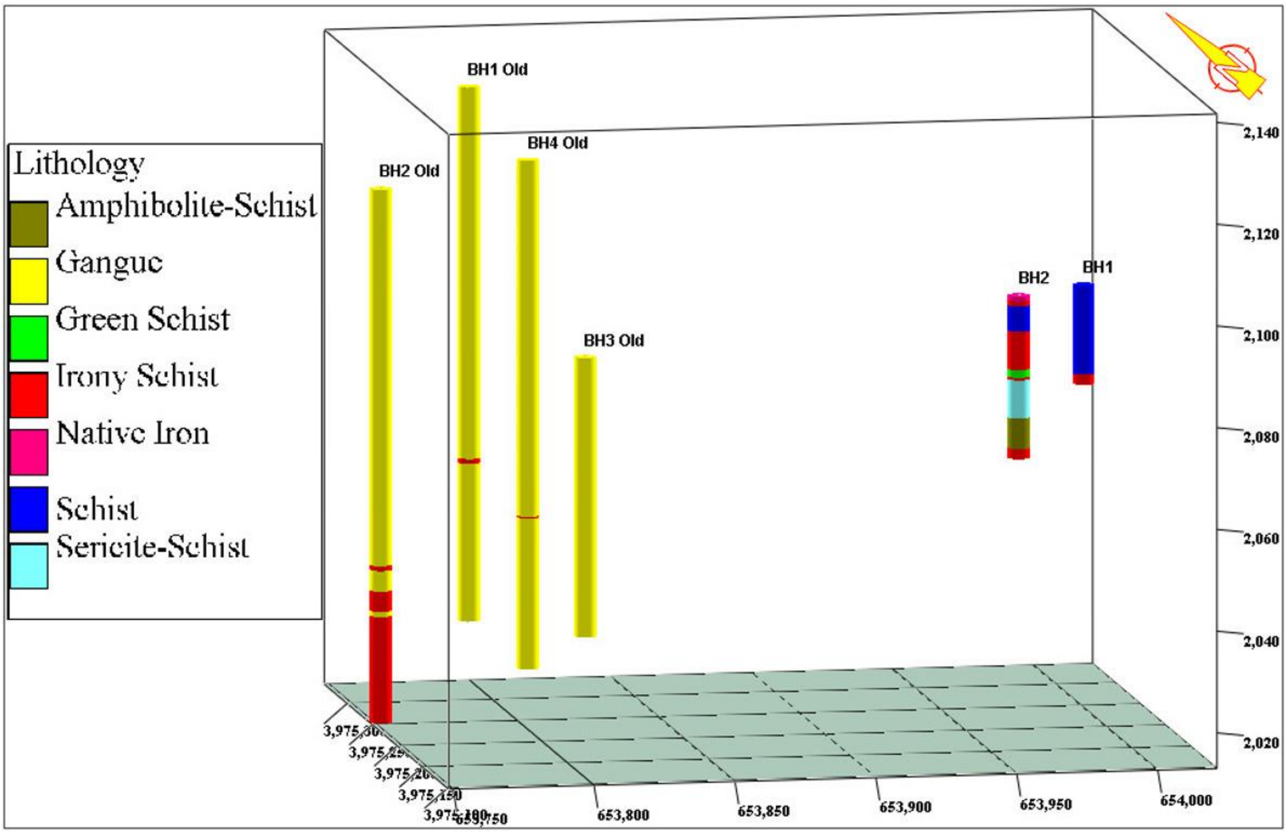

Fig 9. 3D geological-mining strip-logs of the boreholes drilled in the Alijan iron deposit area (the numbers unit of the horizontal and vertical axes is meter).

In Figure 10, 2D strip-logs of the mineralized boreholes in Alijan is shown, separately. In BH1, the shortest borehole with a drilling length of 19.5 m, only the final two meters consist of mineral deposit (irony schist). Drilling was not possible to continue in this borehole, therefore, drilling of BH2 was initiated in its vicinity. BH2 with a length of 32 m, is the most promising borehole in this area. It starts with mineral deposit from the ground surface where a total of 12 m of the borehole consist of mineral deposit, including iron ore and irony schist. However, drilling operation encountered difficulties in this borehole, so that drilling was stopped in the mineralized zone (irony schist) at this depth. BH2Old with a length of 105 m, is one of the deepest drilled boreholes in the area, and 26 m of

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the borehole consist of mineral deposit (irony schist). Based on Figure 10, can be observed that in all three boreholes (BH2, BH2Old, and BH1) where a portion of the borehole length consists of mineral deposit, iron is somehow associated with schist, making the separation of the mineral from the waste somewhat challenging.

Also, Figure 11 shows the indicator geological-mining cross-section of the Alijan deposit containing four boreholes of BH1, BH2, BH1 Old and BH2 Old. To plot this cross-section in order for lithoblending, randomize blending algorithm was used with the interpolation of outlier values.

According to this figure, it can be seen that the mineral deposit is often located between the schist and amphibolite units. Since the length of the four boreholes of this cross-section are not equal, thus, the mineral deposit is seen as a continuous layer in the depths which created by interpolation incorrectly, due to the lack of enough data. Therefore, for example if two boreholes are drilled one vertically and the other azimuthally at the location of X (shown as dashed line arrow with light purple color in the figure), the azimuthal borehole will more likely encounter the mineral deposit.

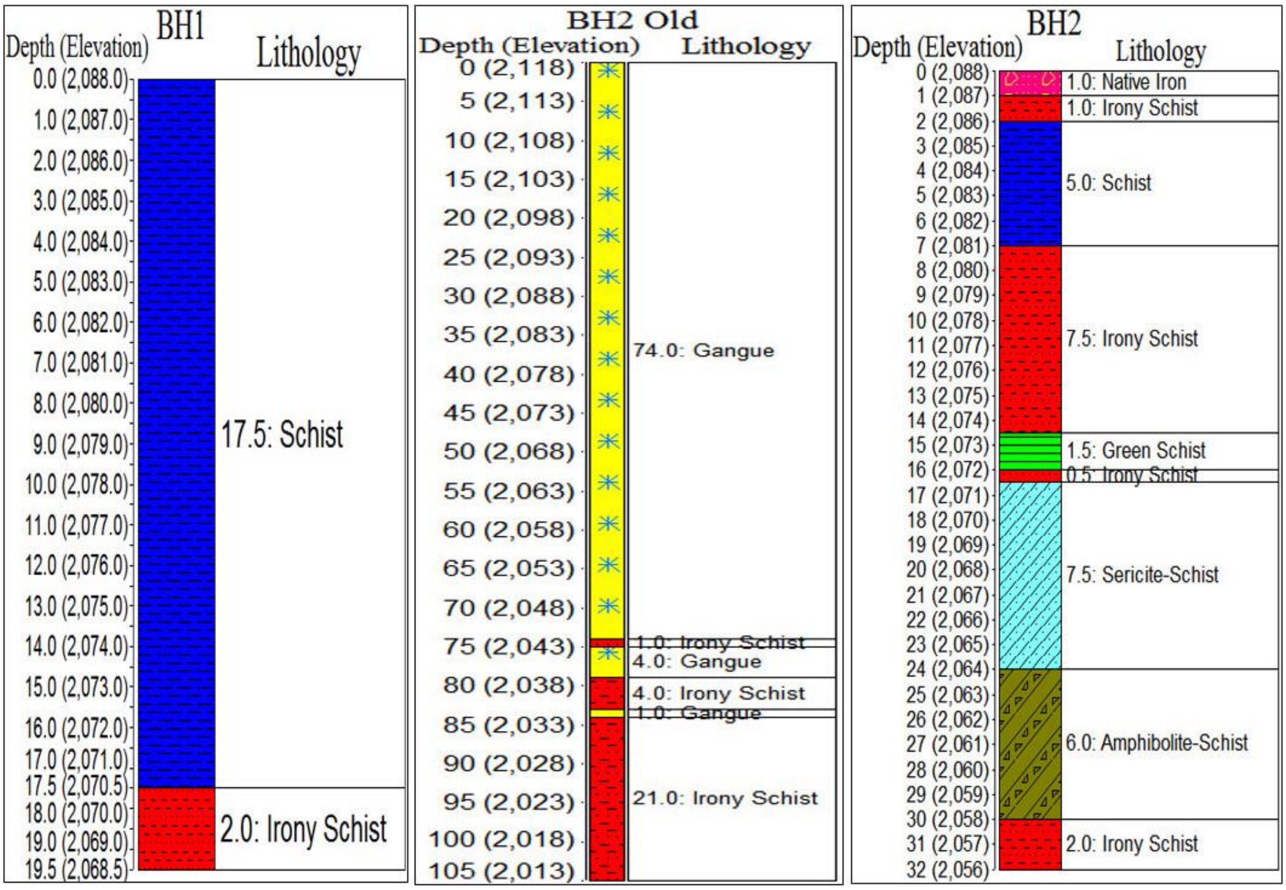

Fig 10. 2D strip-logs of BH2, BH2Old and BH1 boreholes in the Alijan deposit.

The map of Figure 12, shows the distribution of previously drilled and new proposed boreholes in Zone A of the Alijan deposit. Based on this figure, it can be observed that the location range of the drilled boreholes in the first magnetic anomaly phase is relatively close to the proposed ones in the second magnetic anomaly phase in Zone A, with an approximate horizontal aerial distance of 450 m.

Discussion

In general, the process of mineral exploration is a probabilistic phenomenon and always accompanied by a certain level of risk. Therefore, probability-related issues, especially geometric probabilities, have applications in mineral exploration, and this exploration probability is quantifiable (De-Geoffroy and Wignal, 1985). The probability of success in the exploration of mineral deposits, especially metallic deposits, is defined as the product of technical and economic success probabilities. The technical success probability is equal to the product of the

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probability of deposit formation or target mineralization under geological conditions and environment as well as the probability of acceptable target discovery with the selected exploration method. The minimum acceptable discovery probability refers to 0.5, and values smaller than that are considered as unsuccessful or failure. A discovery probability of 0.95 is always desirable (Hasani Pak, 2015; Ahmadi, 2018; De-Geoffroy and Wignal, 1985).

Based on the results of previous drilling in the eastern part of Zone A, out of the five boreholes drilled in the magnetic anomalies location, only three encountered mineralization. Therefore, the technical success probability is 60% ($\frac{3}{5} \times 100$), which is not a high probability.

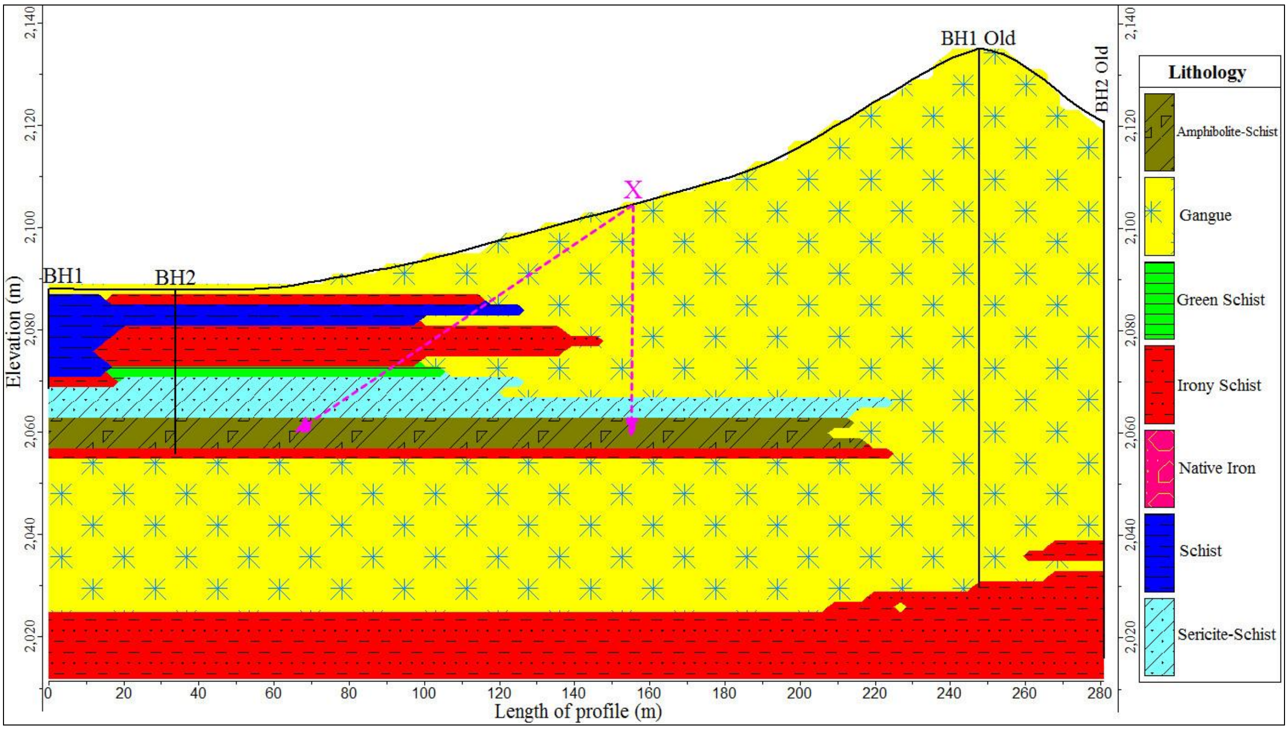

Fig 11. The indicator geological-mining cross-section of the Alijan deposit including four boreholes.

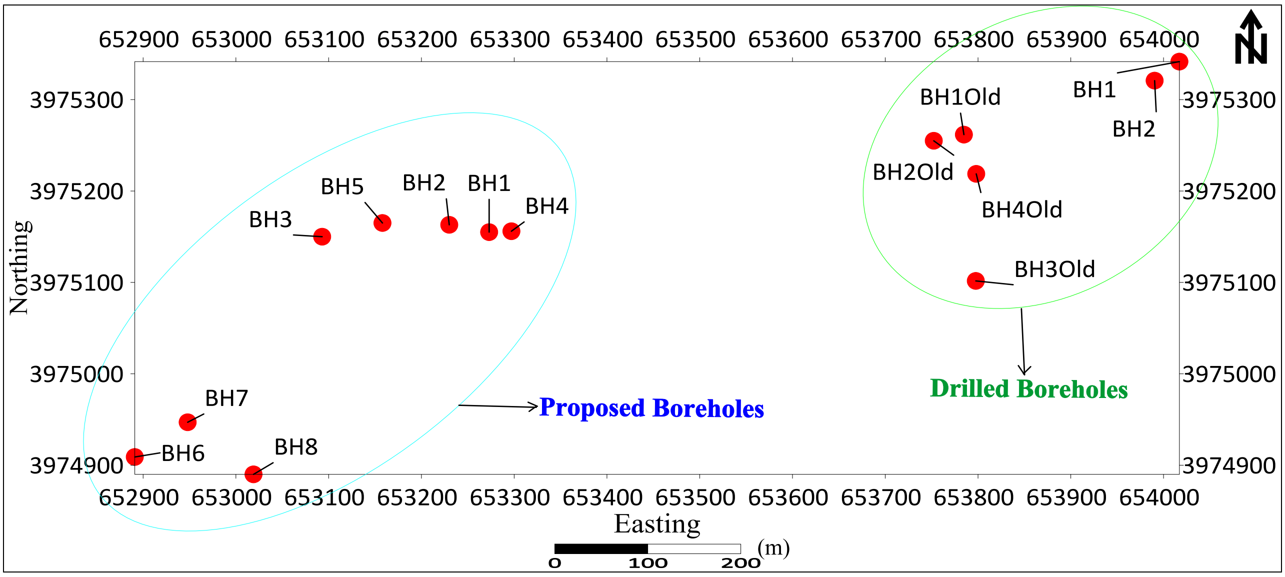

Fig 12. The distribution of previously drilled and new proposed boreholes in zone A of the Alijan iron deposit.

Furthermore, based on field observations of the study area, considering the type of mineralization and geological structure (schist and andesite enclosing iron), the 2D geological-mining strip-logs in Figure 10 and comparing with similar iron deposits, especially in the Kurdistan province (i.e. Hassan-Salaran, Zafarabad, Shahrak, Sarab, Sharif-Kandi, Qareh-Kand, Mimunabad, Galali, Khosroabad, and Ebrahimabad), the economic success probability of the studied deposit is predicted to be 95%.

Since the geological structure and deposit genesis in the entire Alijan area are almost the same, due to the small distance between the surveyed areas using magnetic method, based on the results of the conducted drilling, the overall exploration success probability of the studied deposit is approximately 57% (0.6 × 0.95×100). Therefore, if the results of the calculations of the discovery probability of deposits are taken into account and decisions are made based solely on them, the discovery probability of this deposit is acceptable under current conditions. However, in the future, with changing conditions, especially an increase in the value and price of the mineral deposit (iron), a decrease in the availability and accessibility of iron reserves, and the advancement of mining and processing technologies, this probability will be increased further. Although, the drilling results of the new proposed boreholes in Zones A and B will help in making decisions in this regard.

Furthermore, since the mineralization in the study area is mainly in the schist-amphibolite sequence, alongside them in a layered and lens-shaped manner, it is initially suggested to have an accurate understanding of the geology of the area and the characteristics of the mineral deposit. Then, in proposing the specifications of the boreholes (slope angle and direction), especially for the new proposed boreholes, more accuracy should be exercised. In other words, considering the geological conditions of the area and the type of mineralization, the boreholes should be drilled based on the trend of mineralization in the contact between schist and amphibolite.

Conclusions

In the present study, in order to explore iron deposit in the southern part of Alijan village, geophysical exploration were carried out using the magnetic method in two phases for two separate zones called A and B, adjacent to each other. Based on the results of the first stage magnetic survey, six vertical boreholes were drilled at the various depths on the magnetic anomalies where 2D geological-mining strip-logs were plotted and analyzed. After applying corrections and various filters to the acquisitioned magnetic data in the second stage, eight additional boreholes with a minimum drilling depth of 30 m were suggested for both zones A and B. In order to decide on continuing the exploration process of the magnetic surveyed areas in the second stage, the results of the first-stage by magnetic survey operation were evaluated using the drilling results. By using the drilling results obtained in the eastern part of zone A and the plotting of 2D geological-mining strip-logs of the mineralized boreholes, the overall success probability of the studied deposit was calculated to be approximately 0.57. Based on this, the probability of successful exploration is acceptable under current conditions. However, the probability is not very high and drilling of the newly suggested boreholes in zones A and B is needed. Also, field observations in the study area indicate that considering the regional geology and deposit formation conditions, a revision should be made in presenting the specifications of the new boreholes based on geophysical operations. In other words, the boreholes should be drilled azimuthally instead of vertically at the location of the mineral accumulation, i.e., in the contact of schist-amphibolite.

Although indirect geophysical exploration methods for mineral exploration, especially metallic minerals, are fast, relatively inexpensive and useful, these methods are influenced by various factors, including geological conditions and types of noise, and their results do not always fully coincide with the ground reality, even after applying various corrections and multiple processing steps. Therefore, before any action or decision is taken, the geological characterization of the area must be accurately identified, and based on that, the specifications of the boreholes should be proposed.

The evaluation of the results obtained from geophysical operations in line with the ground reality, similar to the drilling results, is feasible and beneficial in many practical cases, and it will be helpful in future decision-making. The results of this study will be useful for all researchers and practitioners in the field of mineral exploration.

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