KPU International Journal of Engineering & Technology
Volume 6, Issue 1, Mar. 2026
e-ISSN:2790-0819, p-ISSN:2790-0800

Date Received: 2026-01-07
Date Accepted: 2026-03-07
Date Published: 2026-03-30

Investigation of Iron Ore Deposits, Using Magnetic and Gravity Methods: Case Study from Yakawlang District, Bamyan Province, Afghanistan

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Abstract

The Syadara area of the Yakawlang district of Bamyan province is located near the unique Hajigak iron mine, and previous geological investigations have confirmed numerous mineral deposits with a high percentage of iron. Geophysical studies, which are done after geological studies, are a key part of geological exploration. In this study, two geophysical methods, gravity and magnetic, were used to determine the distribution and depth of the location of iron mineral deposits under the sediments. According to the interpretation of the magnetic and gravity anomalies, iron deposits extend horizontally beneath the sediments in the southwest part of the study area from northeast to the southwest and in the northeast part of the study area from north to the south and southwest. Finally, the depth of iron ore deposits in the vertical direction at different locations has been determined using the Euler deconvolution approach; the majority of these deposits in the central and northeastern parts of the research area are expected to be between 500 and 1000 meters deep.

Keywords: Geophysical Methods, Iron Ore Deposits, Magnetic and Gravity Anomalies, Yakawlang.

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1. Introduction

Surkhab, Jawi, Faizabad, Western Hindukush, Bamyan, and Hazrat Sultan are the zones that can be identified in the Afghan portion based on the type of folded structures, the nature of the rock sequence, and the properties of magmatism. [1]. Also [1], citing H. Hayden, said that the Bamiyan zone is located in the south and southwest of the western Hindu-Kush zone. The rocks that make up this zone's basement are from the Ordovician to Devonian eras. Permian limestones, which range in thickness from 960 to 1150 meters, are characteristic of this zone.

Two conformable units make up the Miocene sequence in the Yakawlang-Bamyan Graben, which runs along the southern edge of the northern Afghan plate. There is a region with severe faults southwest of the Yakawlang-Bamyan Graben that exhibits a fault system that is nearly parallel to the northwest trend. It is evident that the processes responsible for the construction of the Yakawlang-Bamyan Graben also created these faults. These faults are considered to be Late Neogene since many of them cut through Neogene strata. Some of the faults are still active [1].

The Syadara mineral area is part of the central Afghan iron belt, which extends from the Iranian border to the Panjshir Valley and contains iron deposits from Proterozoic and Paleozoic rocks. Its most important part is the Hajigak deposit along with Syadara in Bamyan Province [2]. The study area, about 30 square kilometers of Syadara, is located south of Yakawlang District, Bamyan Province, with an elevation of about 2,7°0-3550 meters, as shown in the topographic map (Figure 1). The iron ore deposit at Syadara in central Afghanistan is located about 110 kilometers west of Hajigak.

In the study area, the Gemstones Team of the Survey Department of the Ministry of Mines and Petroleum of Afghanistan has conducted a 1:25,000 mapping of an area of 42 square kilometers. In an area of 17 square kilometers, 21 iron ore masses have been confirmed, and laboratory results have shown that, in addition to the presence of a high percentage of iron, the mineral appearances of galena, barite, and zinc are in the form of sulfides [3].

The study area is composed of metamorphic, intrusive, and sedimentary rocks, and deposits of the Upper Proterozoic, Paleozoic, Mesozoic, and Quaternary periods have been more widespread. The Upper Proterozoic deposits consist of schist, rhyolite, greenish schist, gravelite, and sandstone. In addition to limestone, the Paleozoic rocks in the Upper Dion-Carboniferous system are mostly composed of black schists that have been crushed by tectonic movements and are observed in some parts as thick layers and in some areas as thin layers. The red-colored layers correspond to the Jurassic period (J_{1-2}). On both sides of the Syadara, there is a Paleogene sedimentary valley consisting of travertine. The Quaternary deposits cover all the older rocks and are mostly spread along the foothills and along the paths of temporary water flows, consisting of Proluvial and Diluvial sediments [3].

In the Syadara area, iron ore mineralization is seen in Proterozoic rocks similar to the Hajigak area. Based on geological mapping (Figure 2), the mineralization is in the form of a layer of compact magnetite that is embedded in chlorite-sericite schist, metadolomite, and quartz-sericite phyllite. Its composition is mostly magnetite with small amounts of hematite, pyrite, and minor traces of chalcopyrite. At the surface, intense oxidation with goethite, martite, hematite, and small amounts of malachite and azurite is seen [4].

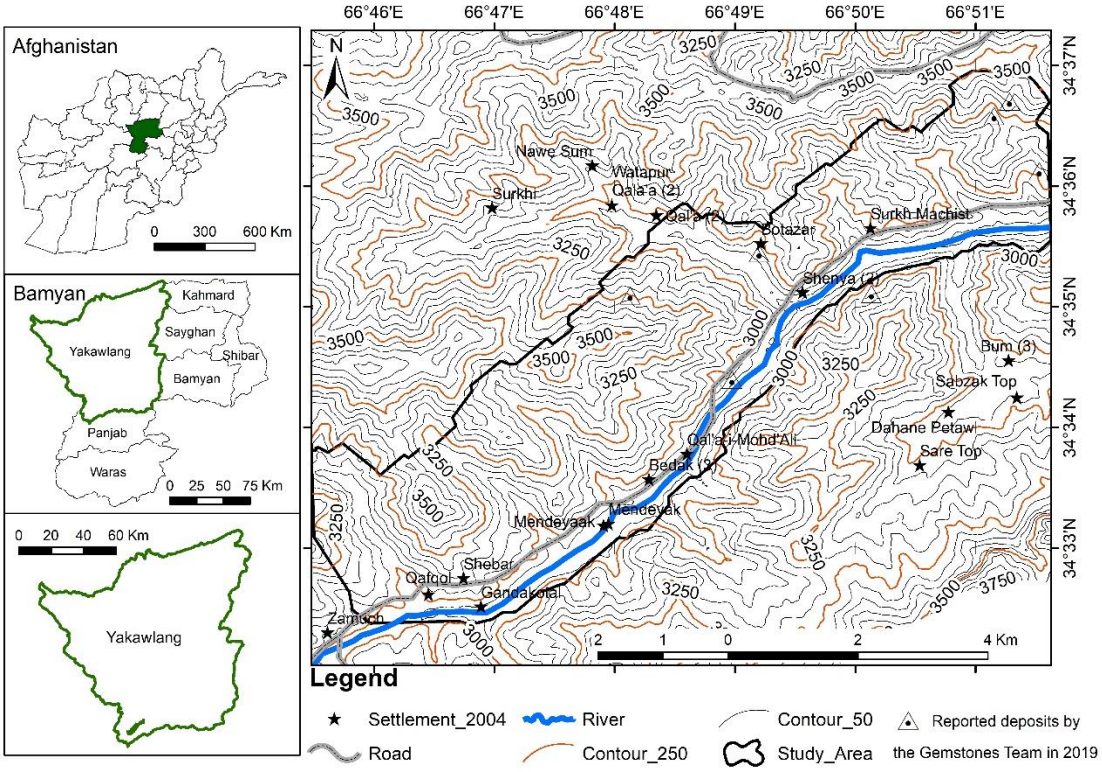


Fig. 1. Topographic map of the study area

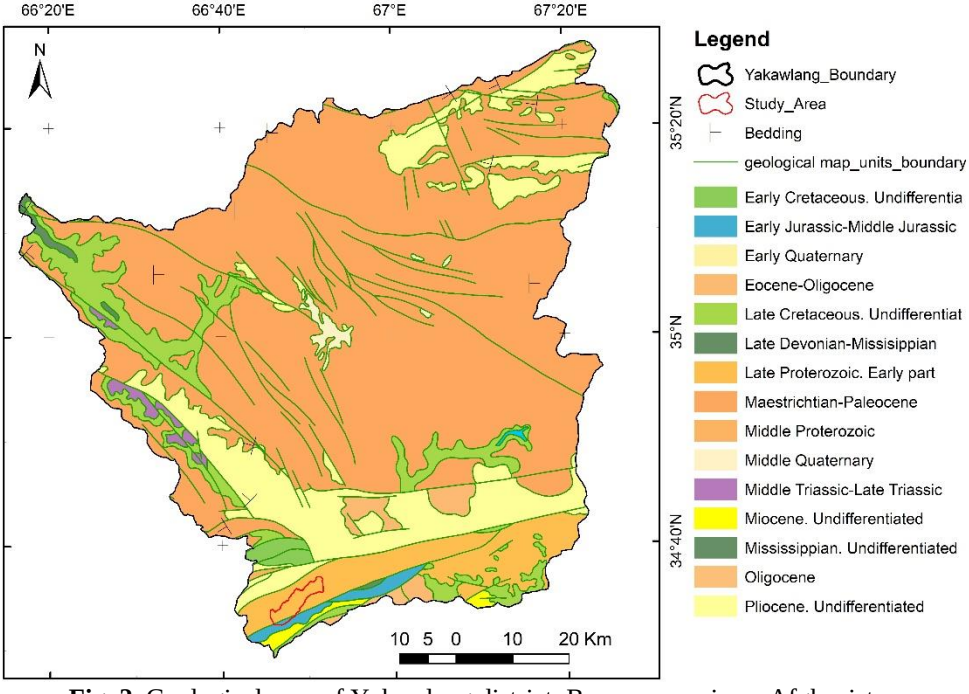


Fig. 2. Geological map of Yakawlang district, Bamyan province, Afghanistan

Despite extensive geological studies in the Syadra area, integrated gravity and magnetic investigations remain limited. Due to the extensive coverage of mineral masses, geophysical methods such as gravity and magnetic fields are considered very useful for identifying geological structures and determining the location of deposits, because the structures and magmatic activities related to mineralization have obvious differences in density and magnetic properties. Conducting this research, the following issues will be able to be clarified: (1) the quantity and distribution of metallic minerals, especially iron ore deposits, in the area; (3) mapping subsurface iron ore distribution (2) estimating depth; and (3) identifying drilling targets.

2. Research Methodology

In this study, two geophysical methods, magnetic and gravity, were used to investigate the distribution of iron ore masses under sediments in the Syadara area of the Yakawlang district of Bamyan province. Fieldwork was done on 44 parallel profiles that ranged in length from 1500 to 2500 meters. Because the rock masses were between 150 and 1500 meters in length, the space between the profiles was about 200 meters. The Ministry of Mines and Petroleum's geophysical team conducted a four-and-a-half-month geophysical field survey, in which I participated for about twenty days.

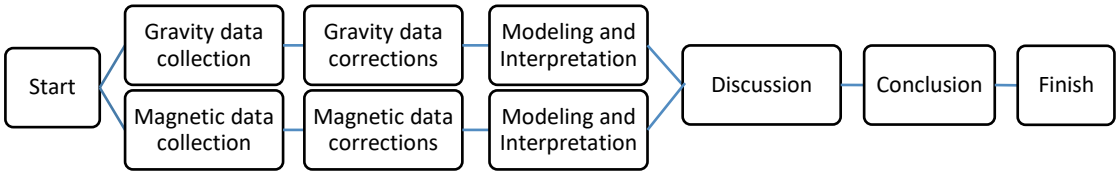


Fig. 3. Research Flowchart

2.1 Magnetic method

The study of magnetic anomalies, which arise from differences in the magnetization of adjacent rocks, provides valuable information about geological structures. These anomalies may indicate economic mineralization, petroleum-related structures, plate tectonics, or the polarity history of the Earth. At each geomagnetic field measuring station, magnetic surveying is carried out by measuring, correcting, and comparing the actual field value with the expected value. The difference between the observed value and the expected value, determined at any point based on the International Geomagnetic Reference Field (IGRF), is called the magnetic anomaly [5].

In the study area, the magnetic field was measured using a survey instrument (G-858 cesium vapor magnetometer) manufactured by Geometrics Company with an accuracy of 0.01 nT. This device recorded data in a periodic manner at a rate of one reading per second. Compared to gravity data, magnetic survey data require few corrections. The most important correction is for the daily variations in the strength of the Earth's magnetic field, which are caused by an external field originating in the ionosphere [5]. To obtain the residual or local field, an additional correction known as regional magnetic gradient removal is carried out using the International Magnetic Reference Field (IGRF) model [6]. During the measurement, in order to correct for daily changes in the Syadara area of

Yakawlang district, a specific location was considered as the base station outside the study area. The magnetic field intensity at this site was measured using a base station instrument for diurnal correction (G-856 proton magnetometer), which took a reading every thirty seconds.
After making the necessary corrections and leveling using the tie-line leveling method, an anomaly map of the area was prepared using Geosoft software, which shows the changes in the intensity of the magnetic field within the study area (Figure 5A).

2.2 Gravity method

The Earth's gravitational field is simple, single-polar, and nearly vertical. The average gravity at the Earth's surface is about 980,000 mGal, or 9.8 meters per second squared. In mineral exploration, gravitational anomalies are typically only a few hundred mGal. Denser rocks increase gravity and create positive anomalies, while lighter rocks decrease gravity and create negative anomalies [7]. Gravity measurements are used to ascertain density changes within the Earth, which is used in the environmental and mining fields to detect lithologies, structures, and occasionally even mineral masses as well [8].
In the gravimetric survey of the Syadara area of Bamyan Province, a Scintrex CG-5 gravimeter with an accuracy of ±1 µGal was used, which is one of the new technological gravimeters produced in Canada. A network of stations was established in the form of 44 parallel profiles with northwest-southeast (NW-SE) and north-south (N-S) directions, which are 1 to 1.5 km long. Regarding the length of the rock masses (150 to 1500 m), a space of about 200 m was chosen between the profiles. The distance between the stations on each profile was decided to be 100 meters because, on the one hand, the area had a very steep slope, and on the other hand, the rock masses were exposed in the direction of the profile, around 100 meters on the surface. Due to the extreme mountainous nature of the area, the profiles vary in length, resulting in a total of 720 surveyed points throughout all profiles (Figure 4).
Gravity measurements are not the same all over the Earth. After removing known effects such as Earth's rotation, polar flattening, and diurnal variations due to tides, gravity differences are attributed to variations in the density of local rocks. In Bouguer reduction, which is considered in this study, for land areas, factors such as Earth's rotation, latitude, station elevation, and the gravitational attraction of rocks between the station and sea level are corrected. In rugged areas, terrain correction is also applied [7]. After the research area's gravity data were gathered, the terrain and Bouguer corrections (Figure 9B) were prepared for interpretation using Geosoft software. The terrain correction was applied based on the station elevation data (obtained by a Garmin Rino 520HCx handheld GPS) with an estimated vertical accuracy of approximately ±5 m, and no external digital elevation model (DEM) was used.

3. Data Processing and Interpretation

For mineral exploration, interpreting variations in the Earth's magnetic and gravitational fields is a common geophysical issue. These two sets of data are usually analyzed together because the principles of their interpretation are similar. The location, depth, and form of the resource are calculated by modeling (forward and inverse) after a qualitative

investigation of the anomalies is completed [9]. The first step in processing and interpreting magnetic data is to apply a reduction to pole (RTP) filter to locate anomalies exactly above their source. Then, enhancement techniques such as horizontal and vertical derivatives, analytic signal, and Euler deconvolution are applied to the reduced magnetic maps and residual gravity maps. These techniques help to better resolve anomalies, accurately define geological boundaries (such as faults and contacts), and estimate the depth of sources [6], [9].

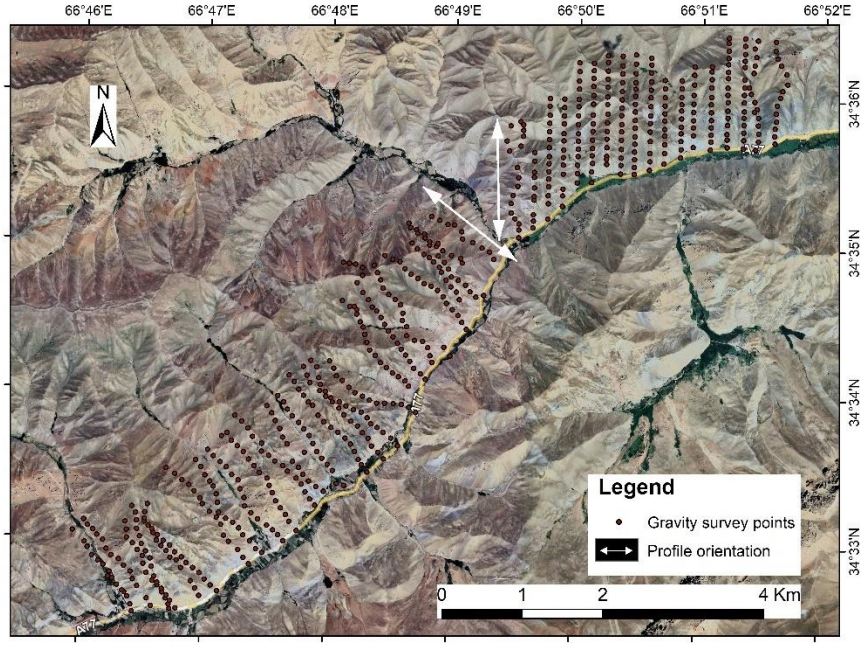


Fig. 4. Gravity survey lines and gravity stations with the orientation of (N–S, NW–SE) in the research area

Baranov developed a technique known as "reduction-to-the-pole," which transforms magnetic anomalies so that they appear monopolar and directly above the source, like polar regions, improving the resolution of nearby sources. However, this technique is only effective when the rocks contain induced magnetization that is aligned with the Earth's field, making interpretation easier [9], [10]. To more accurately match the total magnetic field anomalies with their actual sources in the study area, the reduction to the pole process has been performed. As RTP effectively focuses magnetic anomalies on their sources, shallow magnetic sources may be found in the western part, while deeper magnetic sources may be found in the northeastern part of the study area. This phenomenon is most likely caused by deeper magnetic rock depths or more sedimentary cover in the northeast, and vice versa in the west (Figure 5B).

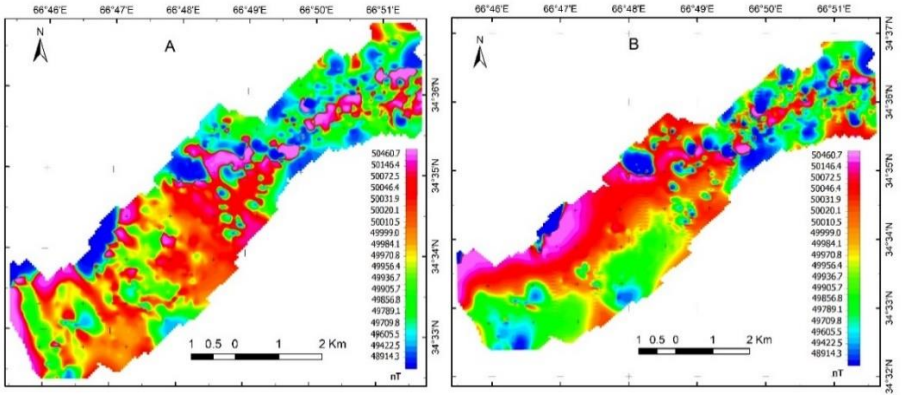


Fig. 5. (A) Total magnetic intensity (TMI) map before correction and (B) magnetic anomaly map following the change of reduction to the pole (RTP)

Magnetic data is divided into two parts: regional and residual. The most common method for separating them is the upward continuation filter. In this filter, the desired height is entered manually, and as the height increases, a large part of the noise is removed. In geomagnetic data processing, upward continuation removes irrelevant topographic effects and shows the main anomalies more clearly [11]. To separate the impacts of near-surface noise and anomalies related to iron mineralization in the research area, an upward continuation filter was applied to the data at 20 m and 100 m. Furthermore, this filter was used to assess the depth distribution of the iron deposit (Figure 6). The upward continuation at 20 m mainly reduces the very shallow effects and near-surface noise (Figure 6A). On the other hand, the upward continuation at 100 m improved the long-wavelength magnetic responses linked to deeper sources and significantly decreased the short-wavelength anomalies (Figure 6B). The fact that magnetic anomalies are still present at a depth of 100 meters suggests that iron mineralization is deep-rooted and not limited to sources near the surface.

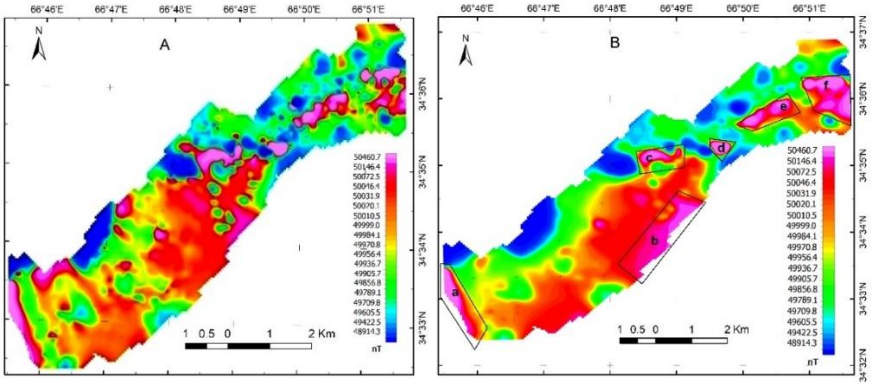


Fig. 6. shows the high-frequency near-surface noise elimination, where (A) is the upward continuation in altitude of 20 meters and (B) is the upward continuation in altitude of 100 meters of the study area

Also, as shown in Figure 6A, in the upward continuation at a height of 20 meters, part of the anomaly in the total magnetic field intensity map has disappeared, and a number of

them that had larger dimensions still exist. In the upward continuation map at a height of 100 meters, a number of anomalies that originated near the surface of the earth have disappeared, but the large anomalies in the center and their extension to the southwest and south, shown in Figure 6B as letters a to f, are clearly visible. In this study, it is observed that anomalies b and f have larger dimensions and will continue at depths of more than 100 meters. Furthermore, anomalies a, c, d, and e might disappear below a depth of 100 meters.

The horizontal (x) and vertical (z) derivatives are another filter used on the magnetic data that improves the edges of magnetic anomalies and highlights the difference between geological units and effective structures like faults. These derivatives were used to minimize long wavelengths (deep and regional sources) while highlighting shallow characteristics that are hidden by the larger effects of deep and widespread structures in the gridded TMI data [12]. As shown in Figure 7, a significant depth extension is expected for the masses creating this anomalous zone in the eastern and central regions of the map. In the western portion of the map, no specific trend is expected to develop, and the depth of extension is most likely not very great. Analyzing these maps reveals that in certain areas, the magnetic field map displays continuous magnetic anomalies due to the deep continuity of the iron masses. These maps have been confusing in certain places due to the surface appearance of these masses and their lack of expansion at large depths.

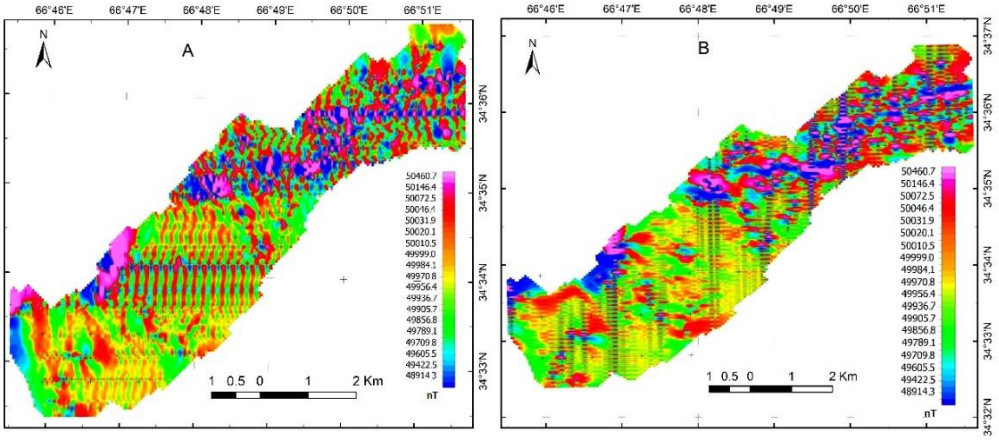


Fig. 7. illustrates the first-order derivative (A) in the X-direction ($\partial P/\partial x$) and (B) Y-direction ($\partial P/\partial y$) for additional clarification and reinforcement of the shallow sources of the research area's magnetic field anomaly

When identifying geological boundaries and separating closely spaced objects, the analytical signal filter works very well. Because the magnetic analytical signal depends only on the magnitude of the magnetization, not its direction, it is particularly useful for data from tropical regions and sources with strong remanent magnetization, where TMI provides limited spatial resolution [10]. As shown in Figure 8B, the location of the main anomaly zones identified in this area is clearly visible.

The Euler deconvolution method Figure 8A was used to estimate the depth of the magnetic anomaly in the study area. This method is a semi-automatic technique for

estimating the depth of the magnetic source, which is used for rapid analysis of large volumes of data. This method works based on anomaly gradients and assumes a specific source geometry and is applied sequentially to all points of a profile [10]. The Euler convolution method may not correctly represent the complex iron mineralization system because it is subject to data noise, structural index selection, and source geometry assumptions. Based on the geological setting and expected geometry of the magnetic sources, the structural index (SI) is taken to be 1 for estimating depth using the Euler deconvolution approach. While the selection of this index eliminates ambiguity, uncertainties are a natural part of Euler deconvolution and are (~20–25%) in this study.

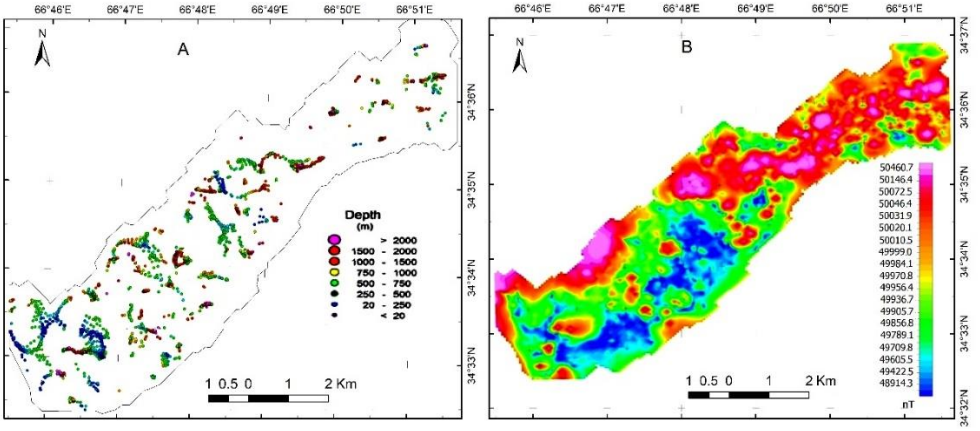


Fig. 8. (A) Source depth estimation using the Euler dissociation method (SI=1), which displays the relative depth ranges and is prone to ambiguity, and (B) the amplitude of the analytic signal of magnetic data of the study area.

In addition to the interpretation of magnetic anomalies, the gravity field is also a crucial part of mineral exploration, as the principles of interpretation are similar in both data sets; they are usually analyzed together. Gravity measurements are made to obtain information about the density within the Earth, the geometric distribution, and the depth of subsurface objects. Gravity provides just a limited amount of information. For instance, the entire mass of an anomalous object can be directly determined, but its depth is very difficult to ascertain due to ambiguity until additional information is provided from other sources. The logical process involves determining the target, making measurements at specific stations, extracting anomalies, and interpreting them using previous information. Gravity measurements alone provide little information, and their interpretation is always accompanied by uncertainty, but the accuracy and clarity of the data and additional information can increase their informative value [13].

In the gravimetric data processing, first, the coordinates of the observation points obtained by a Garmin handheld GPS were combined with the data and arranged. Then various corrections, including the Bouguer correction, were made using Geosoft software. The Bouguer anomaly is computed using a standard reference density of 2.67 g/cm^3, reflecting the typical density of the continental crust (Figure 9A and B).

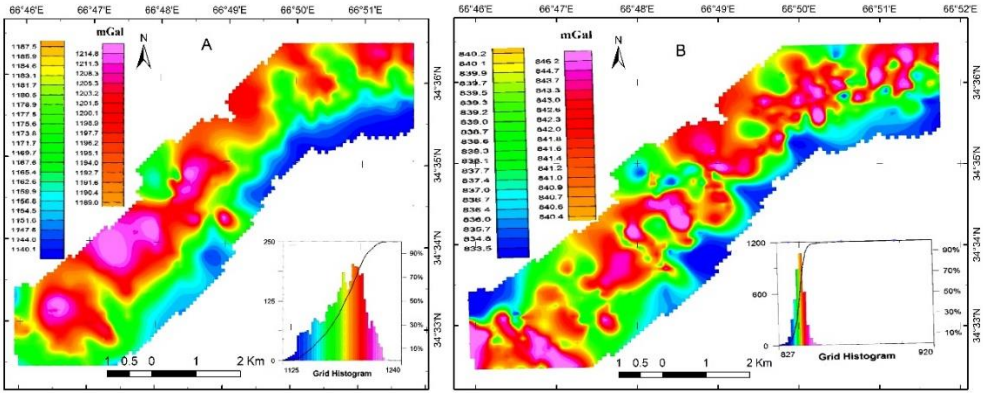


Fig. 9. (A) Free air gravity anomaly map and (B) Bouguer correction of the study area

According to geological studies, the Syadara area consists of sedimentary, metamorphic, and magmatic rocks, with sedimentary rocks being more widespread. Iron mineral zones are mostly composed of magnetite masses and, in some parts, hematite masses, which are surrounded by sediments. The density of iron mineral masses is higher than that of the nearby rocks, indicating a positive anomaly. Higher density is indicated by pink, red, and orange regions on the gravity anomaly map (Figure 9).

The findings from the analysis of gravity (Bouguer) and magnetic (upward continuation and Euler deconvolution) anomalies at various points in the research area show either strong or weak conformity. In general, there is a strong agreement between these two anomalies in the northeast and continuously towards the southwest and the central parts of the study area. These areas are thought to have substantial iron resources because of the strong magnetic anomaly that overlaps with a high density, which suggests the presence of magnetized mineral bodies (magnetite). However, there is a weak conformity between the magnetic and Bouguer anomalies in the southwest part of the research area, which may be because of the existence of magnetite-containing shallow or thin-body ore minerals. There may also be a contradiction, like in the study area's south, which could be due to mineralogical changes or low body thickness.

According to this magnetic and gravity analysis and other previous geological studies, the Syadara iron ore's mineralization is comparable to that of the Hajigak iron deposit. Similar to the Hajigak deposit area, the iron deposit of Syadara is located in Neoproterozoic metavolcano-sedimentary rocks. Compared to Hajigak, its deposits are smaller and include less iron; they are all stratified masses of magnetite and hematite with small amounts of siderite and pyrite [14] [2].

4. Conclusion

First, the Syadara iron ore deposit in Bamyan province's Yakawlang district is close to the Hajigak mine. However, according to the geological research and laboratory sample analysis, iron makes up about 62% of the deposit along with trace elements like manganese, magnesium, zircon, titanium, molybdenum, barium, uranium, and titanium. Additionally, there are roughly 21 iron ore deposits in the research area that contain the minerals hematite, magnetite, martite, pyrite, siderite, and malachite. Therefore, it has

been suggested that geophysical research is of extreme importance for more in-depth studies.

Two geophysical methods, gravity and magnetic, were considered in this investigation. The magnetic method in the research area exhibits a strong and persistent anomaly, which confirms the existence of an iron source. On the one hand, magnetic sources are found at depths larger than 100 meters, according to the upward continuation technique applied to the magnetic data. However, the extended pattern of anomalies was obtained by using the Euler deconvolution method with a structural index of 1, where the source's depth is approximately 500–1000 meters, and the approach's uncertainty is assessed to be between 20% and 25%. Because the Euler deconvolution and upward continuation procedures complement one another, the accuracy of the magnetic data interpretation outputs is acceptable. Additionally, by applying the Bouguer correction and comparing it with the magnetic responses, the study has found the actual mineral resources in the subsurface.

Finally, the central and northeastern areas exhibit the strongest geophysical anomalies and are given priority for additional studies. For more in-depth research, this geophysical study suggests seven exploration drilling sites (Table 1) at various depths and 3D modeling.

Table 1. Suggested sites in the study area for exploratory well drilling

DH ID	Latitude (DD)	Longitude (DD)	Indination	Estimated Depth
DH 1	34.604735	66.854842	Vertical	600
DH 2	34.603719	66.849455	Vertical	1000
DH 3	34.599079	66.842893	Vertical	1000
DH 4	34.594653	66.834684	Vertical	1000
DH 5	34.5883	66.827331	Vertical	800
DH 6	34.586708	66.811684	Vertical	600
DH 7	34.55281	66.760057	Vertical	200

5. Acknowledgment

The geophysical data analyzed in this study were used with the permission of the Ministry of Mines and Petroleum of Afghanistan. We would like to sincerely thank our colleagues at the Ministry of Mines and Petroleum for their support during this research and for providing the gravity and magnetic data. In particular, we are grateful to the geophysics team for providing the necessary datasets.

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