Geobody Estimation by Bhattacharyya Method Utilizing Nonlinear Inverse Modeling of Magnetic Data in Baba-Ali Iron Deposit, NW Iran

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Highlights:

Bullet Points

- More accurate and realistic geobody estimation.
- Optimized target function using the Bhattacharyya method in MATLAB software.
- 3D modeling of geomagnetic anomalies.
- Anomalous field values from a 3D distribution of magnetized rectangular block.
- Cost-saving method via the early magnetic approach implementation.
Geobody Estimation by Bhattacharyya Method Utilizing Nonlinear Inverse Modeling of Magnetic Data in Baba-Ali Iron Deposit, NW Iran

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Abstract

One of the essential geophysical concerns is the estimation of the physical and geometrical parameters of the reserve (geobody), which is done by exploiting the nonlinear inverse modeling of magnetic data. The present study includes preparing and modeling magnetic data to suggest drilling sites in the Baba Ali Iron ore deposit, NW Iran. The area is covered with 1000 points of geomagnetic reading with an almost 5×10 m$^2$ regularly spaced grid trending WE. The areal and depth extent of the iron ore geobody was unknown. The Bhattacharyya method by MATLAB software coding was used to minimize the misfit function and re-construct potential field data providing the best fit with measured magnetic data. In this order, the residual calculated anomaly exhibited an excellent two-dimensional conformation with forward modeling. Also, 3D modeling correctly reconstructs properties of the productive resources of anomalies. After preparing full magnetic maps, the magnetic lenses distinguished in four anomalies of surface depths, 20, 50, and deeper than 50 meters for this zone. This magnetite lens for the first zone was estimated based on analytical signal filters applied on the entire magnetic map so that the lens's depth is trivial and almost zero. Due to specific gravity calculated as 4.77 t/m$^3$, initial storage capacity is suggested to be about 95,400 tons of magnetite, pyrite, and hematite minerals at most in an area about 6 Km$^2$. Finally, to complete the preliminary explorations of the specified area, exploratory drilling is suggested for three points by inverse modeling. Regarding this study as the first try in magnetic reconnaissance step of Iron mineral exploration in the study area, there is no geological constraints available based on drilling evidences. However, the model is well satisfies the surface anomalies considering residual magnetic property.

Keywords

Magnetometry, Nonlinear Inversion, Bhattacharyya Modeling, Upward Filter, Baba Ali Iron Ore Deposit

1. Introduction

In a few decades, geophysical studies are often one of the main steps in mining and petroleum exploration which would be considered before any exploratory excavations [1-4]. Applying the geophysical methods, reduces the high cost of excavation and related heavy machinery required [5-10]. Geophysical methods differ based on the physical properties and geological conditions of minerals. For example, the magnetic method is best for their direct exploration regarding the exploration of iron reserves due to magnetite [11-14] and hematite with magnetic properties. Meanwhile, the gravity method is also auxiliary and complementary [15-22]. Often, in the studied areas, due to the outcrops of magnetite seen on the earth's surface and their relationship with existing tectonic systems, the pursuit of these iron-
bearing zones in-depth, as well as the extent of their expansion in different directions, has necessitated the performance of magnetic operations [5,6,11,23-27].

In addition, the magnetic method is used as a geophysical method with high and inexpensive survey efficiency in most mineral potentials, especially in iron-bearing areas, so it is before other geophysical methods in this regard [18,28-30].

In 1980, a 3-D distribution of magnetization was presented by Bhattacharyya; moreover, it was generated to delineate the magnetized region responsible for the observed anomalous magnetic field [31-33]. In 1987, it was shown by Sharma that Quantitative interpretation had advanced, mainly through the development of computerized multiparameter inversion methods [34]. In 1990, it was mentioned by Hinze and Von Frese that Sedimentary rocks are known to be the source of magnetic anomalies under special conditions, such as Proterozoic sedimentary iron formations and clastic sedimentary rocks rich in magnetite nearby sources of magnetite that are concentrated by the action of moving water [35,36]. Wang and Lilley (1999) presented a method to invert observed geomagnetic induction data regarding the surface conductance distribution of a thin-sheet model developed and carried through a basic testing procedure. The method uses conjugate gradient relaxation in solving an equation that optimizes a balance between a model misfit function and a model roughness function [35,37-39]. In 2011, an inversion method was introduced based on a geostatistical approach (co-kriging) for three-dimensional inversions of total magnetic field data by Shamsipour et al. [40]. The method was adapted to include the depth weighting matrix approach to reduce the lack of resolution in depth [9,10,40]. An efficient algorithm for 3D inversion of magnetic data over a porphyry-Cu deposit located in the Kerman Province of Iran was presented by Abedi et al. [16]. The main characteristic of that study was the implementation of joint sparsity constraints for simultaneously preserving the smooth and rough edges of model parameters [16,41,42]. In 2016, 3D geophysical inversion modeling was performed by Wittert et al. in three different ways to explore the possible distribution of density within the model: unconstrained, geologically constrained with homogeneous density rock units, and geologically constrained with heterogeneous density rock units [43]. In 2017, Occam's inversion technique was described by Ghanati et al. to retrieve the magnetic parameters of simple geometric structures such as thin sheets and cylinder-like bodies, using two automatic ways of estimating the regularization parameter the L-curve and weighted generalized cross-validation (W-GCV) criteria [44,45]. The integrative use of the Very Low-Frequency Electromagnetic (VLF-EM) and geoelectrical resistivity sounding techniques was found effective by Youssef et al. in 2018 for imaging the typical shallow stratigraphic sequence in the study area. There are some direct indications of iron ore accumulations [46-48]. In 2019, Giraud et al.’s approach enabled the integration of probabilistic geological modeling in geophysical inversion without petrophysical information sufficient to calculate petrophysical constraints. It uses geophysical measurements to optimize the inverse problem by updating the physical property model, preferably in geologically uncertain parts of the studied area during what is called uncertainty-guided inversion [49-52]. An optimized combination of geophysical survey methods was capable by Fu et al. [36] for taking single-point, continuous measurements (e.g., the high-precision ground magnetic survey (HPGMS), the transient electromagnetic (TEM), and the magnetotelluric (MT) methods) can be employed to accurately determine the anomalous planar spatial locations, anomalous profile morphologies, and burial depths of concealed iron ore bodies such as banded iron formation (BIF)-type [36,53], and the survey helped to characterize subsurface geology better [54,55]. Furthermore, magnetic data were used to improve neighboring bodies' resolution and densify the information, profile, and 2D survey by Sampaio et al. [24].

As the application of magnetic inversion methods in recent years, a transient electromagnetic induction was used to detection of near-surface horizontal anisotropy in weathered metamorphic schist at Llano Uplift, Texas [56]. Then, an inverse method was presented to describe the 3D geometry of geological objects [57]. Moreover, a three-dimensional magnetotelluric inversion program was developed for the vertical magnetic transfer functions (VTFs) and parallelization of the code, which was most appropriate for small clusters [58,59]. After that, a simple and fast numerical method was developed to determine simultaneously the depth and shape of a buried structure from second-horizonal derivative anomalies obtained from magnetic data with filters of successive window lengths [60].

Afterward, a new approach was presented based on the Genetic-Price hybrid Algorithm (GPA) proposed for the inversion of potential-field data, specifically of self-potential signals [61]. Furthermore, an algorithm for 2D inversion of the potential magnetic field was developed in regions with rugged topography [62,63]. Moreover, an inverse
modeling analysis on the interpretation of magnetic anomalies induced by 2D dyke-shaped bodies was accomplished by employing the differential search algorithm (DSA), a novel metaheuristic roused by the migration of superorganisms \[64-66\].

A new imaging method has been developed based on calculating the correlation coefficient of the analytic signals of the measured magnetic anomaly and the calculated response of some geometrically simple interpretive models of sheets, cylinders, and spheres \[21,22,67\]. Furthermore, another new method using variance analysis has been developed by Essa et al. \[68\] for the interpretation of a magnetic anomaly profile by idealized-geometrical bodies \[67,68\]. Deep learning neural networks (DNNs) were used to recover the distribution of the physical properties of buried magnetic orebodies from the surface and airborne magnetic anomaly data \[39,69-72\]. The application of the total intensity magnetic and reduced-to-pole maps, power spectrum, analytic signal, tilt-angle, and local wavenumber maps were used to allocate and describe the structural elements and mineralization zones such as uranium, gold, and sulfide in recognizing magnetic sources distribution, lineament features, and mineral zones \[21,22,38,73-75\].

Recently, Standard Particle Swarm Optimization (SPSO) and Genetic Algorithm (GA) have been commonly used in the geophysical inversion. A novel bio-inspired algorithm called Barnacles Mating Optimizer (BMO) was presented for the inversion of magnetic anomalies \[19,76,77\]. The Bat Algorithm Optimization (BAO) technique based on bat echolocation performance was applied to magnetic data to scan the data space to appraise sources parameters \[78\]. After that, the global optimizing bat algorithm (GOBA) approach was implemented to interpret the magnetic data measured along 2D profiles using specific elementary geometric forms in the category of spherical-shaped models, infinitely long horizontal cylinders, thin sheets, as well as the source of multiple models \[79\]. Furthermore, the Social Spider Optimization (SSO) algorithm mimicked social spiders' cooperative behavioral style. It was applied in the inversion of magnetic data to assess the distribution of magnetic properties over simple geometrical causative sources \[80\].

A new stabilizing function called minimum support gradient (MSG) was used as a stabilizer in 3D magnetotelluric (MT) inversion. It developed a Gaussian-Newton (GN) algorithm based on the edge-based finite-element method (FEM) to invert the MT data and obtain clear and sharp boundaries \[81\]. Also, a three-dimensional (3-D) MT inversion code was developed, considering electrical anisotropy \[82\]. The inversion procedure was completed with a well-developed subroutine of the non-linear conjugate gradient method \[9\]. A very fast simulated annealing (VFSA) global optimization algorithm was carried out using inverse modeling of the magnetic anomalies produced by a 2D dyke like structure \[51,83,84\]. Finally, as new research, a 3D inverse modeling procedure was applied to the Charmaleh Iron deposit magnetic data in Iran to obtain a valid anomaly edge perimeter. It focused on investigating the simultaneous application of 3D inversion and edge-detecting methods \[21,22,38,72,75,85-88\].

The broad pursuit of conducting this study is to prepare and model magnetic data for proposed drilling sites in the Baba Ali Iron ore deposit in the Hamedan province of NW Iran, which iron ore geobody characteristics were not known heretofore. This article uses the capabilities of MATLAB coding to minimize the misfit function and potential field data to create the best fit for magnetic data for the first time; finally, 3D modeling, performed on all map profiles simultaneously, is our next innovation.

2. Geological settings

Structurally, the Baba Ali iron skarn deposit forms part of the Sanandaj-Sirjan (S-S) zone. Three main rock units surround the Almoughlagh Batholith, namely the Songhor Series (Triassic-Jurassic), the Hamadan Schists (Jurassic), and the Limy Formations (Oligo-Miocene) (Fig. 1a, Fig. 1b and Fig. 1c). The Songhor Series is a volcano-sedimentary sequence. This series consists of alternating schistose and limy units with interbedded meta-morphosed spilitic volcanic rocks and andesitic tuff \[41,89-92\]. The studied area consists of several metasedimentary and metavolcanic rocks. The oldest metasedimentary rocks are exposed around Almogholagh batholith and contain dolomitic to calcitic marble and intermediate-felsic metavolcanic rocks, in which some parts are metamorphosed to greenschist facies. In the field research, three groups of intrusive rocks were observed based on their lithological features, including (1) gray to greenish-gray monzodiorite and diorite, (2) light gray monzonite and syenite, and (3) light gray to pink granite. The first group comprises coarse- to medium-grained monzodiorite and diorite with a granular texture, mainly in the northeastern part of the Almogholagh batholith. The second and third groups include medium- to fine-grained
monzonite and syenite, and granite with granular and porphyritic textures mainly occurring in the southeastern, west, and central parts of the Almoghologh batholith [53,90]. An age equivalent to 148 to 143 Ma for the Almoghologh batholith was reported by Jamshidibadr et al. [93]. More than five iron ore bodies have been recognized in the Almoghologh batholith, which seem spatially and temporally associated with each other, most of which occur within the limestone. However, they are uneconomic (Fig. 1b). Only vein-type magnetite ores hosted within the dioritic rocks are economically more critical for being Iron ore. The vein-type iron deposit contains 6 Mt Fe ore reserves with an average grade of 38% Fe. The main Baba Ali iron deposit is a sub-vertical vein-type magnetite body that consists mainly of magnetite with minor gangue minerals and pyrite. The banded and massive iron ores commonly occur in veins filling the fractures of the dioritic rocks with sharp contacts. In addition, rare brecciated dioritic host rock ore also occurs within the deposit. Gangue minerals mainly consist of actinolite, epidote, tourmaline, biotite, calcite, quartz, minor titanite, and apatite distributed as veins and veinlets. They vary in thickness from a few millimeters to a few centimeters along cracks of magnetite. Magnetite is the most dominant iron mineral in the deposit; although, due to the effects of oxidation and supergene processes, local magnetite has been martitized along grain boundaries and fractures [46,94-99].

Geographic information and petrology of mineral area
Baba Ali iron ore span is adjacent to Baba Ali village, 35 km northwest of Hameda. This iron ore deposit is located 500 meters from the northwest of this exploration area. This range is located in the Sanandaj-Sirjan structural zone (S-S Zone), consisting of two northern and southern lenses. Country rocks of the iron ore in these two lenses are igneous rocks with a combination of diorite and granodiorite. Paragenesis mainly comprises magnetite, pyrite, and hematite, along with small amounts of copper minerals such as chalcopyrite, bornite, and malachite. Gangue minerals accompanying the storage include epidote, actinolite, chlorite, quartz, feldspar, and calcite. There is no significant outcrop of magnetite in this area, and there is only the debris of varying sizes here; Fig. 2a and Fig. 2b show an aerial photograph of the geographical position of Hamedan and its access path.

3. Methodology
3.1. Magnetic effect of a 3D mass in a forward method
One of the essential measures in magnetometry is the magnetic susceptibility of the rocks. The magnetism observed in each rock consists of inductive and residual components. In the inversion, one of the calculations required is forward modeling [18,25,28,100]. The magnetization depends on the contrast of the magnetic susceptibility of the mass with surrounding rocks for an inductive magnetic field [15,17,21,22]. When the susceptibility contrast is minimal, the magnetization is proportional to the magnetic susceptibility contrast and equal to its product in the inductive magnetic field. In practice, under the earth's surface, as depicted in Supplementary Fig. A. 1, it is divided into tiny prisms. The cell is given a constant value of the magnetic susceptibility contrast, and the magnetic field obtained from them is computed [101-103].

The magnetic field resulting from the size of magnetic material is calculated as follows [7,8,104,105] (Eq. (1)):

\[
B = -C_m \nabla \frac{M \nabla}{r} \, d\nu
\]  

(1)

where: \(M\) is the magnetization and \(r\) is the distance from the observation point of \(P\) to the volume element \(d\nu\) of the mass. The constant value \(C_m\) in the SI system is \(10^{-7}\) H/M. However, in most magnetic surveying, the anomaly of the entire field is measured, which approximately is calculated as follows [7,106,107] Eq. (2):

\[
\Delta T = -C_m \hat{F} \nabla \frac{M \nabla}{r} \, d\nu
\]  

(2)

In which, \(\hat{F}\) is a unit vector in the direction of the earth’s magnetic field.

One of the main tasks in forwarding modeling is the volumetric integral solution. In practice, the volume of magnetic mass can be estimated by a set of more specific elements, such as magnetic polygons, rectangular prisms, or polygonal sheets. The relation between calculating the magnetic field due to a rectangular prism is presented by Bhattacharyya [31,33] (Eqs. (3) and (4)):
where
\[
\begin{align*}
\Delta T &= C_n M \\
&= -\frac{1}{2} \log \left( \frac{r-x}{r+x} \right) + \frac{1}{2} \log \left( \frac{r-y}{r+y} \right) - \log (r+z) + M_x \hat{F}_x \arctan \left( \frac{y}{r + z^2} \right) - M_y \hat{F}_y \arctan \left( \frac{x}{r + z^2} \right) + M_z \hat{F}_z \arctan \left( \frac{x}{r + z^2} \right) \\
&= x = x_1 \quad y = y_1 \quad z = z_1
\end{align*}
\]
of magnetization computed 1 A/m. The position of maximum points and the shape of this signal can be used to identify the regular fountain's boundaries and estimate its depth. In Fig. 5, analytic signal processing is another approach that can significantly help detect abnormalities. This process amplifies the anomaly edges and displays the magnetic bipolar as outstanding anomalies to model the surveyed data.

3.3. Analytical signal (AS)
Analytical signal (AS) is a modern gradient technique, which is linked to magnetic fields by the derivatives. Roest et al. [12] explained that the amplitude of the AS can be determined from the three orthogonal derivatives of the magnetic data using the following expression (Eq. (5)):

$$A(x,y) = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2 + \left(\frac{\partial M}{\partial z}\right)^2}$$

where $A(x,y)$ is the AS amplitude at $(x,y)$.

4. Results
4.1. Survey grid design
Due to the extent of the area and the mineralization debris and tectonic conditions that are the main mineralization factors in each region, the survey grid was first selected in the form of profiles of 20 m and survey points at a distance of 10 m. Given the evidence and the structural appearance of the mineral mass, the eastern-western (E-W) data mining direction was selected to discontinue the mineralization of the exploration area. While the survey, according to the range of magnetic field changes during the measurement and according to the priorities in the area, the distance between the survey profiles was reduced by up to 10 m, and the distance between the stations was reduced by up to 5 m. With the performed design, there are 1000 reading measurement points, and this exploration network covers an area of approximately 21 hectares. In Supplementary Fig. A. 2, the survey grid is shown for the first zone. The magnetometer used in this survey is GEM made in Canada. The sensitivity of this device is up to one-tenth nanotesla (1/10 nT), and it is equipped with DGPS. The earth's magnetic field changes with latitude, longitude, and time are calculated by the complete empirical computational equations known as the International Geomagnetic Reference Fields (IGRFs). This information is very useful in obtaining actual field values and regional corrections. Due to time changes in this data, IGRF must be updated every few years. Therefore, it must change when air or land surveys within a few months or years. The magnetic field parameters in the study area are obtained using the coordinates of a point in the region of the IGRF system, as shown in Table 1. The geomagnetic field equals a magnetic dipole field with a 1025×8 electromagnetic unit in the earth's center. The survey's magnetic field intensity measurement unit is nanotesla (nT). The magnetic anomalies on the earth's surface can cause changes in magnetic field intensity up to a few hundred nanoteslas. The topographic map of the exploration area is illustrated in Supplementary Fig. A. 3. After preparing magnetic data and modeling them, drilling sites can be proposed on the map, which is one of the goals of the present geophysical study.

4.2. Data preparation and processing
Generally, in the magnetic method analyses, the map of the intensity of the entire magnetic field in the vertical axis direction is first provided after the corrections on the survey data, known as raw data. Magnetic anomalies appear in solid and weak poles in the total magnetic field intensity map. Magnetic flow around the earth is affected by magnetic gradient and field deviation angles. These two parameters affect the intensity of the entire field. The amount of this effect changes with the change in latitude and longitude. Also, the two parameters make the magnetic anomaly precisely not be placed on its causative agent. Therefore, it is necessary to reduce pole correction for areas not precisely on the pole (like Iran). IGRF is used for this, and this amount is reduced from the surveyed data. It means that by doing this, it is thought that the surveys are taken in pole; as a result, the anomalies are exactly on its causative factors. Another critical factor affecting the intensity of the earth's magnetic field is residual magnetism in the presence of rocks. The residual magnetism in rocks sometimes causes excessive kurtosis of anomalies or, conversely, a very slight decrease in anomalies. Suppose this correction in the
region does not cause excessive data kurtosis or excessive deformation of anomalies. This map will be a base for other processes, such as upward continuation and field derivative methods. Otherwise, the map of the magnitude of the total magnetic field will be used as the base map in the direction of the vertical component. Another process that can significantly help detect anomalies is analytical signal processing (Eq. (5)). This process amplifies the anomaly edges and displays the magnetic dipoles as outstanding ones.

5. Discussion

5.1. Modeling and interpretation of magnetic data

After data preparation, magnetic field intensity and different processing maps were designed by data networking through appropriate cells. The surveyed field data were networked using the least-squares method and according to their frequency to minimize the minimums and maximums to frame maps.

As seen in Supplementary Fig. A. 4 and Fig. 6, this map has four distinct anomalies, with two western anomalies that are very superficial and insignificant. However, in the east of the first zone, there are two notable anomalies. From these two eastern anomalies, southern anomalies appear as a complete dipole with a more significant negative pole. The very high-intensity variations indicate its proximity to the data acquisition surface. However, only the positive pole has been recorded from the north anomaly, and its negative pole is likely to be seen in the north direction if data acquisition is continued. This anomaly has a relatively more significant but less intense extent and is probably related to high-depth mineralization. Of course, another possibility is the presence of magnetic rocks like gabbro-diorite, etc., with little magnetization. However in the total magnetic maps, the anomalies in the Western part of area are not considerable, removing the regional trend highlights these areas as anomaly comparing the surrounding parts. It is noteworthy to consider these small anomalies are related to skarn rock units adjacent to quartz-diorite units which differ in magnetic properties from surrounding rock units. The occurrence of this anomaly must be determined by exploratory excavation, indeed.

Magnetic flow around the earth is affected by magnetic gradient and field deviation angles. These two parameters affect the intensity of the entire field. The amount of this effect changes with the latitude and longitude alteration. Also, the two parameters make the magnetic anomaly precisely not to be placed on the causative agent. Therefore, reducing-to-pole correction for areas not precisely on the pole (like Iran) is necessary. As the anomalies must be transferred to the actual location, the reduction-to-pole filter was applied to the initial data, which is significant in Fig. 7a. Due to the application of this filter, anomalies have somewhat shifted to the north. The reduced-to-pole (RTP) magnetic anomaly map is calculated for a regular grid of the total intensity map to minimize the dipolar nature of the field. A MATLAB function was used to deskewed the field based on the Fourier transform. The filter transformed a regular gridded total-field anomaly (extracted from the original map) into new anomalies with new directions of magnetization and ambient field.

Another processing that can significantly help to detect abnormalities is analytical signal processing. This process amplifies the anomalous edges and displays the magnetic dipoles as outstanding ones (Eq. (5)). Fig. 7b portrays the analytical signal map of zone one. In this map, the horizontal extension of mineralization is determined and limited. The proposed drilling points of zone one will be picked according to this map. Fig. 8 reveals upward continuation filter maps from 5 to 40 m of zone one. The maps show that the western anomalies are trivial and almost eliminated in an upward continuation of 10 m. However, the eastern anomalies continue to depths of 30 to 40 m. Therefore, due to the changes in the anomaly's intensity and shape, the southern mineralization's final depth in the eastern part of the first zone is expected to be at most 15 m.

Euler's method was not used for the eastern part (zero tailing depth) due to the outcrops in this part. Of course, it should be remarked that the low-intensity northeast anomaly extends to the north and depths of more than 40 m. Thus, the tailing thickness of this part seems to be more than 10 m.

5.2. 2D and 3D inverse modeling

The interpretation of magnetic data in the Baba Ali iron ore deposit field was performed to identify the status of anomalies. Given the relatively low exploratory costs, the magnetic method can identify the area effectively at the beginning of the work. By modeling and interpreting anomalies and integrating geological and existing information,
valuable and usable outcomes will be fetched to drill structures. In Fig. 9a, the magnetic intensity map of the ore span is shown.

For further identification and interpretation of anomalies and structural conditions of the area, it was necessary to deduct the regional's anomaly effects from the magnetic anomalies employing proper methods to obtain the residual anomalies and which can be used for exploratory purposes.

Foremost, choosing the second-order surface process filter, the region effects seen in Fig. 9b are plotted. Afterward, the residual map (Fig. 9c) utilized for modeling was obtained by removing the regional effects from the magnetic intensity anomaly.

Modeling should be done to determine geometric parameters (such as depth, shape, structure, etc.), physical parameters (density, etc.) and interpret residual magnetic anomalies. Regarding the separation of the anomalies made by the anomaly separation filters, the best answer was the residual magnetic anomaly of the second-order surface process. According to Supplementary Fig. A.5, profiles are drawn perpendicular to the region's anomaly spread for this pursuit.

A polygon was plotted on each anomaly as the first assumption, according to Fig. 10. As the interpretation of the magnetic anomaly and the separation is given, it can be caught how the density of these anomalies will be close to each other.

Using Fig. 10, a polygon is plotted on each anomaly in the residual map of the second-order surface process, and its answer is calculated with a 3D forward modeling. After evaluating the modeling error, it was found that it is greater than the target Root Mean Square Error (RMS = 2 nT). Hence, parametric inverse modeling is used to confirm the curve of the answer model and the measured value curve of magnetic data and lessen the error. For uncertainty analysis to demonstrate the reliability of the results obtained after several repetitions, the error modeling operation was reduced to RMS = 1.94 nT, which was satisfactory to the target error. As a result, 3D modeling by Fig. 13 has been able to revamp the properties of the productive resources of anomalies correctly.

In Fig. 11 and Fig. 12, the modeling results are shown for anomalies A and B. In this modeling, the graphs of the residual anomaly and the model graph delivered an excellent two-dimensional conformation (Table 2). As it could be seen in Fig. 11, a shallow magnetic anomaly in depth about 50 m covering more than half the area caused magnetic anomaly as more steep in left hand side of the anomaly.

5.3. Proposed exploration excavations

As the results of gravity anomaly modelings to calculate the volume of the mineral, the background density was calculated to be 3.5 g/cm³. Accordingly, 3D modeling was performed on all profiles of the map concomitantly. In this modeling, the background and polygon gravity is presumed to be 2.67 and 2.2 mGal, respectively.

According to the maps and interpretation of the filters applied on the entire magnetic map, a magnetite lens for the first zone is estimated so that the lens's depth is trivial and almost zero. According to the upward maps for different depths, the final depth is at most 20 m and, as a result, the maximum volume for this zone is about 20,000 m³ and with a specific gravity of 4.77 tons per m³, the reserve of this zone will be estimated at most 95,400 tons. Due to the low intensity of the signal in the broader North East (N-S) anomaly, it is necessary to initially ensure that the iron mineralization is attributed to this anomaly by drilling, and then the storage should be estimated. The following best sites are proposed for drilling considering the overlap of the maps, completing the data, and evaluating this area's technical and economic conditions (Table 3).

6. Conclusions

This study modeled magnetic data for proposed drilling sites in the Baba Ali Iron ore deposit in the Hamedan province of NW Iran, in which iron ore geobody characteristics were not known previously. It uses the capabilities of MATLAB coding to minimize the misfit function and potential field data to devise the best fit for magnetic data. Meanwhile, 3D modeling was performed on all map profiles simultaneously. Complete empirical computational equations known as the International Geomagnetic Reference Fields (IGRF) were used to reduce pole correction because this area was not exactly on the pole (like other parts of Iran), and this amount is reduced from the surveyed data, so the surveys were deskewed in the pole. The surveyed field data are networked to prepare maps utilizing the least-squares method and
according to their frequency to minimize the minimums and maximums. One of the southern anomalies east of the first zone appears as a complete dipole with a more significant negative pole. Very high-intensity variations indicate its proximity to the data acquisition surface and are probably related to high-depth mineralization, which must be determined by exploratory excavation. A reduction-to-pole filter was applied to the initial data to transfer the anomalies to the actual location, so anomalies have shifted to the north. The final depth of the southern mineralization in the eastern part of the first zone is expected to be at most 15 m due to the anomaly's intensity and shape changes. As the results of the analytical signal map of zone one on amplifies the anomalous edges and display the magnetic dipoles as outstanding ones, the horizontal extension of mineralization is determined and limited. The low-intensity northeast anomaly extends to depths of more than 40 m and extends to the north. Thus, the tailing thickness of this part is more than 10 m.

Regarding the separation of the anomalies made by the anomaly separation filters, the best answer is the residual magnetic anomaly of the second-order surface process. In this modeling, the background density was considered 3.5 g/cm$^3$; 3D modeling was performed simultaneously on all map profiles. The background and polygon gravity was calculated to be 2.67 and 2.2 mGal. After several repetitions, the error modeling operation reduced Root Mean Square Error (RMS) to 1.94 nT using parametric inverse modeling, which was acceptable to the target error. A magnetite lens for the first zone was estimated based on filters applied on the entire magnetic map so that the lens's depth is trivial and almost zero. It was concluded that magnetite is the most dominant iron mineral in the deposits of Baba Ali iron ore. However, magnetite has been martitized along grain boundaries and fractures due to local oxidation and supergene processes. According to maps for different depths, the final depth is at most 20 m, and, as a result, the maximum volume for this zone is about 20,000 m$^3$ with a specific gravity of 4.77 tons per m$^3$, so the reserve of this zone will be estimated at most 95,400 tons.

Nomenclatures

**$\rho$**: Density (gr/cm$^3$)
**A/m**: Ampere per Meter
**C_m**: Constant value in the SI system = $10^{-7}$ H/M
**dv**: Volume element
**$\hat{F}$**: Unit vector in the direction of the earth Magnetic field
**M**: magnetization
**$\vec{M}$**: Magnetization of each prism
**mGal**: Miligal (bouguer Anomaly Unit)
**nT**: Nanotesla
**r**: Distance from the observation point of P to the volume element dv of the mass.

Author contribution statement

**Pooria Kianoush**: Formal analysis, Conceptualization, Investigation, Methodology, Software (Writing MATLAB coding), Validation, Data curation, Visualization, Writing – original draft, Writing – review & editing. **Nasser Keshavarz Faraj Khah**: Investigation, Methodology, Software, Supervision, Formal analysis, Writing – review & editing. **Seyed Aliakbar Hosseini**: Investigation, Data curation, Software, Formal analysis. **Emad Jamshidi**: Data curation, Formal analysis, Writing – original draft. **Peyman Afzal**: Investigation, Data curation, Software, Formal analysis. **Arash Ebrahimabadi**: Investigation, Data curation, Writing – review & editing.

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**Data availability statement**
The authors do not have permission to share data.

**Additional information**
No additional information is available for this paper.

**Declaration of Competing 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.
Figure Captions

**Fig. 1.** a) Simplified geological of the Almoghollagh intrusive rocks after the Tuyserkan 1/100000 geological map modified, b) Geological map of the Baba Ali iron deposit, c) Geological profile from A–A’ [90].
Fig. 2. a) The geographical image of study area relative to Hamedan and access path, b) Baba Ali iron mine (green polygon), the target zone for data mining (red polygon) with about 6 Km² extend.
Fig. 3. Flowchart of the Bhattacharya nonlinear inverse modeling method applied in this study.
Fig. 4. Total magnetic field anomaly calculated on a 2D block located in magnetic fields with slopes 0, 30, 60, and 90 degrees (MATLAB Software).

Fig. 5. Total magnetic field anomaly of a square prism: a) 3D mass condition, b) Magnetic field of the entire 3D mass, c) analytical signal of the mass.
Fig. 6. Four anomalies location on the first zone magnetic map (nT).

Fig. 7. a) Map of magnetic data reduced-to-pole (nT) in the first zone, b) Analytical signal filter map (nT) of the first zone.
Fig. 8. Upward continuation filter map (nT) of the first zone at a) 5 m, b) 10 m, c) 15 m, d) 20 m, e) 30 m, f) 40 m.
Fig. 9. a) Magnetic intensity anomaly map (nT) of the first zone, b) Regional magnetic anomaly map (nT) with a second-order surface process filter, c) Residual magnetic anomaly map (nT) of the first zone.
Fig. 10. Four anomaly locations highlighted on forward modelled residual map (nT).

Fig. 11. 2D modeling map (nT) of anomaly A.
Fig. 12. 2D modeling map (nT) of anomaly B.
Fig. 13. 3D Residual anomaly modeling map (nT) of Zone 1, a) Inclination: 80 deg., b) Inclination: 65 deg.
Table Captions

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<th>Declination (D)</th>
<th>Inclination (I)</th>
<th>Total Intensity (F)</th>
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<td>53.25°</td>
<td>47390 (nT)</td>
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Table 1. Parameters of the geomagnetic field in the studied area.

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<th>Anomalies</th>
<th>Position</th>
<th>Type of building status</th>
<th>Density $\rho$ (gr/cm$^3$)</th>
<th>Depth of storage (m)</th>
<th>Volume (m$^3$)</th>
<th>Azimuth (deg.)</th>
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Table 2. 3D modeling results for four anomalies.

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<th>Y (UTM-WGS84)</th>
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<tbody>
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<td>1</td>
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<td>1</td>
<td>244370</td>
<td>3867784</td>
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<td>75° to north</td>
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<tr>
<td>2</td>
<td>B2</td>
<td>1</td>
<td>244277</td>
<td>3867866</td>
<td>50 m</td>
<td>60° to north</td>
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<tr>
<td>3</td>
<td>B3</td>
<td>1</td>
<td>244277</td>
<td>3867900</td>
<td>50 m</td>
<td>60° to north</td>
</tr>
</tbody>
</table>

Table 3. Best sites for drilling regarding overlapping of the results maps and evaluating this area’s technical and economic conditions.

Appendices

Appendix A: Supplementary figure captions

Supplementary Fig. A. 1. Discrete earth with several 3D cells [104,105].
Supplementary Fig. A. 2. First zone data acquisition network design.

Supplementary Fig. A. 3. Topographic map (m) of the study area.

Supplementary Fig. A. 4. Total magnetic map (nT) of the first zone.
Supplementary Fig. A. 5. Map of the profiles perpendicular to the spread of residual anomalies (nT).

Appendix B: MATLAB coding for magnetic data

Appendix C: Reference file of End Note software

Reference


Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- AppendixofMATLABCoding.docx
- Tectonophysicsreference2023.enl