Interpretation of magnetic data in the Chenar-e Olya area of Asadabad, Hamedan, Iran, using analytic signal, Euler deconvolution, horizontal gradient and tilt derivative methods

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ABSTRACT The main goal of the present work is delineating and estimating the depth of a magnetic anomaly in the Chenar-e Olya area of Asadabad, Hamedan, Iran. Ground magnetic data were acquired north of the region, every 15 m along lines that were spaced 10 m apart. Then, methods were used to estimate the depth and shape of the body causing the anomalies. Our pattern recognition criteria were based on analytic signal, Euler deconvolution, horizontal gradient, and tilt derivative obtained from magnetic data. Various steps were taken to decide, among the four methods, on the depth estimation and contact location of the magnetite body. The best contact location was found where the horizontal gradient contacts were isolated. Comparing parallel contacts of horizontal gradient with analytic signal methods, the analytic signal contacts were deemed more accurate, and discontinuity of the contact location was supplemented with tilt derivative and Euler deconvolution contacts. For depth estimation, in addition to the Euler deconvolution on the surface and tilt-depth estimation, upward continuation was applied, with a reduction to pole approach at heights of 10, 20, 30, and 40 metres, and then the Euler deconvolution method was performed on them. Ultimately, the results were compared with borehole data. There are six drilled boreholes in this area to validate the magnetic survey results for depth estimation and contact location. After calculating the contact location and depth of the magnetite body, the results show good agreement with the borehole data obtained within the calculated contact location.

Key words: magnetic data, Chenar-e Olya, Iran.

1. Introduction

A quick look at magnetic field maps tells much about the location and shape of buried complicated features. However, a careful study of a map can provide extra details about the depth and edges of magnetic materials that are underground.

In magnetic surveying, by delineating lateral changes in magnetic susceptibilities, information about structural trends and lithological changes are provided. To distinguish between different sizes and different depths of the geological structures, edge detection
techniques are used. To delineate structural features from magnetic data, many techniques have been developed. Also, estimation of the depth of magnetic sources using different methods can be applied to gridded magnetic data sets.

Nabighian (1972) used the concept of the analytic signal for magnetic interpretation, and showed that the analytic signal amplitude yields a Gaussian-shaped function over each corner of a 2D body with polygonal cross section. Roest et al. (1992) used the total magnetic intensity, which required the 3D analytic signal to approximately estimate the positions of magnetic contact corners and obtain depth estimates from gridded data. Reid et al. (1990) ushered in the Euler deconvolution as an interpretive tool in the magnetic potential field for locating magnetic anomalies and the determination of their depths by deconvolution using Euler’s homogeneity relation. Cordell and Grauch (1985) proposed a method for locating the horizontal extents of the anomalous sources from the maxima of the horizontal gradient of the pseudogravity computed from the gridded magnetic data. Verduzco et al. (2004) developed tilt derivative from the potential magnetic field anomaly map and used the horizontal gradient of the tilt derivative as an edge detector for magnetic anomaly. Salem et al. (2007) have applied a new method for interpretation of gridded magnetic data based on the tilt derivative. The tilt derivative method, by providing a means for estimating the depth to the basement, is a useful technique for interpreting magnetic data.

To estimate the positions of structural lineaments and magnetic anomaly depth in the study area from total field data, analytic signal, Euler deconvolution, horizontal gradient, and tilt derivative methods were applied.

2. Geological setting

The study area is located approximately 3 km SE of Chenar-e Olya village in the Chaharduli Rural District, in the Central District of Asadabad County, Hamadan Province, Iran. The study area is located approximately 3 km SE of Chenar-e Olya village in the Chaharduli Rural District, in the Central District of Asadabad County, Hamadan Province, Iran. The study

Fig. 1 - Geological map of Chenar-e-Olya area accomplished with iron lenses and boreholes.
area lies between latitude 48° 04’ 58” N and 48° 05’ 19” N and longitude 34° 52’ 04” E and 34° 51’ 10” E.

The study area is underlain by metamorphosed rock covered with meta-limestone, marmorized dolomitic limestone, schist, calc-schist, and amphibole schist (Eghlimi, 2000). There are some small and large iron lenses that have outcrops in this area and have orientation from SW to NE (Fig. 1). These deposits of iron do not have significant layering and lie on the north-western end of the Sanandaj-Sirjan structural zone. In the Zagros Orogenic Belt, the Sanandaj-Sirjan Zone (Stöcklin, 1968) represents one of the main basement tectonic blocks and is located between the NW-Iran Block (Allen et al., 2011) and the Arabian Plate. The main ore in this area is Magnetite (Fe₃O₄) and is modified to Hematite in some regions (Jafarzade et al., 1995). The origin of this deposit is Skarn. The Mesozoic and Cenozoic sedimentary rocks in this Skarn area containing limestones, marls, sandstones, conglomerates, and Cenozoic volcanic rocks, are in the central part of the study area (Nadimi and Konon, 2012).

3. Materials and methods

3.1. Analysis of magnetic data

Ground magnetic data were acquired in the region every 15 m along lines in the north, spaced 10 m apart. An interpretation difficulty with total magnetic intensity anomalies is that they are dipolar (anomalies have positive and negative components), such that the shape of the anomaly depends to some extent on the presence of any residual magnetization and the magnetic inclination. Because the magnetic anomaly depends on the inclination and declination of the

Fig. 2 - Total magnetic intensity map with survey points and study area.
body magnetization, the inclination and declination of the local Earth’s magnetic field (Baranov, 1957) and total field are calculated.

Baranov and Naudy (1964) proposed a mathematical approach called “reduction to pole” for simplifying anomaly shape estimates. The reduction to pole technique transforms total magnetic intensity anomalies into anomalies that would be measured if the field were vertical (meaning there is only an inducing field). This reduction to pole transformation makes the shape of the magnetic anomalies more closely related to the true location of the source structure and allows easier interpretation of the magnetic anomaly, as the location of the anomaly maxima will be centered over the body (assuming there is no residual magnetization). Thus, the reduction to pole reduces the effect of the Earth’s ambient magnetic field and provides a more accurate interpretation for the position and shape of anomalous sources.

Total magnetic field strength (Fig. 2), as well as geomagnetic inclination and declination of the study area (Table 1), which are prerequisite parameters in computing the apparent magnetic susceptibility, was derived for the study area (NOAA, 2013). Before applying the methods, the total field anomaly data were reduced to pole using a magnetic inclination of 53.149° and a declination of 4.497° (Fig. 3).

Table 1 - Result of the calculated Earth’s magnetic field for Chenar-e Olya area using Geomagix Model.

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iran</td>
<td>34°51'01.787&quot;</td>
<td>48°05'09.207&quot;</td>
<td>2036 m</td>
<td>September 2013</td>
<td></td>
</tr>
<tr>
<td>Calculated Parameters</td>
<td>Total field</td>
<td>47342 nT</td>
<td>Inclination</td>
<td>53.149°</td>
<td>Declination</td>
</tr>
</tbody>
</table>

Fig. 3 - Reduction to pole map of Chenar-e Olya area.
The reduction to pole signature of the Chenar-e Olya is marked by a rugged relief with positive and negative anomalies of various wavelengths and amplitudes. The reduction to pole anomaly, in the central portion of the study area, shows an important gradient zone elongated approximately in NE-SW direction, specified by much longer wavelength.

3.2. Borehole data

Another method of investigating subsurface geology is, of course, drilling boreholes. For a more accurate conclusion concerning contact location and depth estimation, the results of the magnetic survey are compared with borehole data.

There are six boreholes drilled in this area that are used for comparing depth estimation with results obtained from boreholes. The drilled boreholes (Fig. 1) analyzed provided data about the magnetite ore and its thickness in each of the boreholes (Fig. 4).

![Lithology of boreholes and their thickness in metres.](image)

3.3. Depth estimation and contact location

In the study area, the magnetic signature has anomalies of different wavelengths and amplitudes. To estimate the positions of structural lineaments in this region from total field data, several methods have been suggested in the literature, including the amplitude of the analytic signal (Nabighian, 1972; Roest et al., 1992), Euler deconvolution method (Reid et al., 1990), the magnitude of the horizontal gradient (Cordell and Grauch, 1985; Blakely and Simpson, 1986) and tilt derivative method (Salem et al., 2007). In each case, we can estimate the source depths at the contact locations derived from peaking over the contacts.

3.3.1. Analytic signal method

The analytic signal method is a well-known technique for locating the edges of magnetic anomalies. Nabighian (1972) developed the notion of 2-D AS of magnetic anomalies. In 2D, the amplitude of the analytic signal is independent of the direction of magnetization, and represents
both the vertical and horizontal derivatives over all possible directions of the Earth’s field and source magnetization. In 3D, Roest et al. (1992) introduced the total gradient of magnetic data as an extension of the 2D case. The function used in the analytic signal method is the analytic signal amplitude (absolute value) of the observed magnetic field at the location \((x, y)\), defined by three orthogonal gradients of the total magnetic field using the expression:

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

where \(A(x, y)\) is the amplitude of the analytic signal at \((x, y)\), and \(M\) is the observed magnetic field at \((x, y)\).

The analytic signal amplitude peaks over isolated magnetic contacts. Fig. 5 shows the analytic signal map, along with identified crests of the analytic signal amplitude.

![Fig. 5 - Analytic signal map with identified crests of the analytic signal amplitude, which can be used for contact location.](image)

3.3.2. Euler deconvolution method

The reason for employing the Euler deconvolution method is that the results are not affected by the presence of remanent magnetization (Ravat, 1996). By applying the Euler deconvolution method equation, we relate the magnetic field and its gradient components to the location and depth of the source (Yaghoobian et al., 1992). The 3D Euler equation is written as (Reid et al., 1990):

\[
(x-x_0)\frac{\partial M}{\partial x} + (y-y_0)\frac{\partial M}{\partial y} + (z-z_0)\frac{\partial M}{\partial z} = N(B-M)
\]

where \(x, y, \) and \(z\) are the coordinates of a point of observation, \(x_0, y_0, \) and \(z_0\) are the coordinates...
of the source location, and $B$ is a base level. The structural index $N$ (or degree of homogeneity) is a measure of the decaying rate of the field with distance from the source. It provides a way to discriminate between different source shapes by defining the anomaly attenuation rate at the observation point and depends on the geometry of the source (Thompson, 1982). For a homogeneous point source $N=3$, a linear source (line of dipoles or poles, and for a homogeneous cylinder, rod, etc.) $N=2$, for extrusive bodies (thin layer, dike, etc.) $N=1$, for a contact, vertex of a block and a pyramid with a big height $N=0$. The choice of a proper structural index is a function of the geometry of causative bodies. Estimation of the correct structural index is crucial for the successful application of the Euler deconvolution method. Reid (1995) showed that the optimum structural index usually yields the tightest clustering of the solutions. In order to prevent repetition for finding the best structural index, and to preserve the most attractive feature of the Euler deconvolution method and automatic interpretation of large amounts of data, we chose to implement the algorithm of Stavrev (1997) using an unprescribed structural index, which allows simultaneous estimation of the coordinates and the structural indices of the singular points. As is well known, two important parameters of the Euler deconvolution are the choice of window and $N$. The $N$ value must be assumed as a priori information. By applying this program (Gerovska and Arauzo-Bravo, 2003), the value of averaged structural indices is calculated as 0.9.

Note the Euler deconvolution that yielded the best results to resolve source depths and indicated the source edges, as shown in Fig. 6. The depth of edges is clarified with colored points. Euler deconvolution calculates location and depth below survey points. The basement depths estimated through the Euler deconvolution technique vary from 3.2 km to 32 m.

![Image](image-url)  
**Fig. 6 -** Applied Euler deconvolution method to resolve source depths and edges. The depth of edges is clarified with colored points. The Euler depth solution map shows the cluster of source depth locations positioned at the boundaries.
3.3.3. Horizontal gradient method

Using the horizontal gradient of pseudogravity for locating the edges of magnetic sources was developed by Cordell and Grauch (1985). The steepest gradients of pseudogravity anomaly are located just beyond the edges of the body. Thus, crests of the horizontal gradient magnitude of the pseudogravity field are used as a tool for locating the edges of magnetic bodies.

We can use this technique for edge detection in a window moving across the grid of reduction to pole, whenever a linear trend (for example a contact or fault) is found within the window. Using pseudogravity data, the method gives results assuming edges of thin horizontal sheets (Phillips, 2000). From empirical observations made during other studies, this method are not reliable for sources deeper than about 150 m (Grauch and Bankey, 2003).

The method requires calculation of the two first-order horizontal derivatives of the magnetic field. If \( M(x, y) \) is the pseudogravity field, then the horizontal gradient magnitude is given by:

\[
HG(x, y) = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2}
\]  

Edges in the horizontal gradient magnitude can be searched for maxima by passing a small 5-by-5 windows grid that contains grid values over the horizontal gradient grid (Blakely and Simpson, 1986). Only depth estimates with standard errors of 15% or better remain in the final interpretation.

Fig. 7 shows the horizontal gradient map with color-coded horizontal gradient edge estimates in pink.

![Fig. 7 - Horizontal gradient map with color-coded horizontal gradient depth estimates. Dots indicate crests of horizontal gradient achieved by passing a small 5-by-5 windows grid over the horizontal gradient grid.](image-url)
3.3.4. Tilt derivative method

Salem et al. (2007) developed the tilt derivative method, which provides a simple and rapid technique to estimate the depth of the magnetic basement for large areas. The tilt angle is a tool for locating magnetic sources of data and defined as:

\[
\theta = \tan^{-1} \left[ \frac{\partial M/\partial z}{\partial M/\partial h} \right]
\]  

(4)

where

\[
\frac{\partial M}{\partial h} = \sqrt{\left(\frac{\partial M}{\partial x}\right)^2 + \left(\frac{\partial M}{\partial y}\right)^2}
\]

(5)

where \(\frac{\partial M}{\partial x}\), \(\frac{\partial M}{\partial y}\) and \(\frac{\partial M}{\partial z}\) are first-order derivatives of the magnetic field \(M\) in the \(x\), \(y\), and \(z\) directions. The tilt angle has many interesting properties. For example, due to the nature of the arctan trigonometric function, all tilt amplitudes are restricted to values between \(-90^\circ\) and \(+90^\circ\), regardless of the amplitude of the vertical or the absolute value of the total horizontal gradient. Since the tilt angle consists of the ratio of the vertical and horizontal derivatives, the resulting tilt function, does not contain information about induced magnetization of the causative bodies.

Salem et al. (2007) showed that Eq. 4 can be written as:

\[
\theta = \tan^{-1} \left[ \frac{h}{z} \right]
\]

(6)

where \(h\) is the horizontal distance from the horizontal location of the contact, and \(z\) is the depth to the top of the contact. Eq. 6 indicates the value of the tilt angle above the edges of the contact that is equal to \(0^\circ\) \((h=0)\). This value is equal to \(45^\circ\) when \(h=z\) and \(-45^\circ\) when \(h=-z\). This clarifies that the contours of the magnetic tilt angle can identify both the location \((\theta=0^\circ)\) and depth (half the physical distance between \(\pm45^\circ\) contour lines) of contact-like structures (Salem et al., 2007). The negative contours suggest the outside of the region surrounding the source of the magnetic body. The positive contour values are above the source bodies, and edges are marked by zero contour value. This method uses the reduction to pole field and assumes a simple vertical 2D contact. In this section, we demonstrate the tilt derivative method on magnetic data over the metamorphosed rocks of the south-eastern Chenar-e-Olya area.

Before applying the tilt derivative method, for a better demonstration of the contact location, data are upward continued to a height of 50 m. After that, by applying the tilt derivative method on the magnetic tilt angle map, the contours of \(-0.78\), \(0\), and \(+0.78\) radian are displayed. The black contour line demonstrates the edge of the contact and localizes the contact location. Half of the physical distance between two white contour lines is equal to the depth of the body causing the anomalies (Fig. 7).
4. Results

4.1. Contact locations

In order to better interpret the results related to the contact locations, we compare the results obtained from the analytic signal with Euler deconvolution, horizontal gradient, and tilt derivative images. The four sets of contact locations resulting from the four methods can be combined and ranked as a composite image to aid in the final interpretation of contact locations.

To choose the best contact location, the following criteria were used. 1) The horizontal gradient method provides contacts that are continuous and parallel to the contours of the reduction to pole magnetic field. Therefore, where the horizontal gradient contacts are isolated, they represent the best contact location. 2) Where the horizontal gradient contacts are parallel to the analytic signal contacts with a slight offset, the analytic signal contact represents the true contact location and the horizontal gradient contact indicates the down dip direction (Phillips, 2002). 3) Where the analytic signal contacts are discontinuous due to noise effects, they may be supplemented with tilt derivative and Euler deconvolution contacts. The best results of these steps are displayed in Fig. 9. The final contact locations are shown in Fig. 10. The results suggest that the structural trends are elongated in the NE-SW direction.
Interpretation of magnetic data in the Chenar-e Olya area

Fig. 9 - The superimposed best contacts obtained by Euler deconvolution, tilt derivative, analytic signal and horizontal gradient methods. The best contact location is represented where horizontal gradient contacts are isolated. Where horizontal gradient contacts are parallel to analytic signal contacts with slight offset, the analytic signal contact represents the true contact location and the horizontal gradient contact indicates the down dip direction of the edge of the magnetic body. Elsewhere, they may be supplemented with tilt derivative and Euler deconvolution contacts.

Fig. 10 - The final contact location of magnetite body obtained by Euler deconvolution, tilt derivative, analytic signal, and horizontal gradient methods. The results suggest that the structural trends are elongated in the NE-SW direction.
4.2. Depth estimates

For the horizontal gradient and analytic signal methods, assuming thick sources, minimum depths to magnetic sources were obtained.

Depth estimates were calculated along contact location obtained from the tilt derivative method and then compared with the Euler deconvolution depths (Table 2). In magnetic surveys, upward continuation is particularly useful in tying together aeromagnetic surveys made from different flying altitudes (Allaby and Allaby, 1999). For calculating other depths apart from the edges of magnetic body to basement with Euler deconvolution technique, upward continuation was applied on reduction to pole field at heights of 10, 20, 30, and 40 m, and then the Euler deconvolution method with $N=0.9$ was performed on them. Comparisons of the depth estimates from the Euler deconvolution and tilt derivative methods are represented in Table 2. The locations of the tilt derivative points that were selected for depth estimation were compared with the nearest points obtained from Euler deconvolution maps of upward continuation at heights of 10, 20, 30, and 40 m, and also the surface. The best approximations for depth of contact location are derived. Euler deconvolution is the basis for estimating depth to basement, and then those depths are corrected with tilt derivative depth estimations. Finally, a 3D map for the body that is shown in Fig. 11 was derived for the area.

Table 2 - Results of the calculated depth using tilt derivative and Euler deconvolution methods.

<table>
<thead>
<tr>
<th>Label</th>
<th>X</th>
<th>Y</th>
<th>Tilt derivative depth (m)</th>
<th>Euler deconvolution depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>233719.9</td>
<td>3860290</td>
<td>30</td>
<td>24</td>
</tr>
<tr>
<td>B</td>
<td>233428.9</td>
<td>3860380</td>
<td>21</td>
<td>15.5</td>
</tr>
<tr>
<td>C</td>
<td>233476.5</td>
<td>3860253</td>
<td>27</td>
<td>29.5</td>
</tr>
<tr>
<td>D</td>
<td>233607.2</td>
<td>3860466</td>
<td>36</td>
<td>36</td>
</tr>
<tr>
<td>E</td>
<td>233547.9</td>
<td>3860347</td>
<td>18</td>
<td>16</td>
</tr>
<tr>
<td>F</td>
<td>233582.3</td>
<td>3860147</td>
<td>35</td>
<td>20</td>
</tr>
<tr>
<td>G</td>
<td>233401.9</td>
<td>3860297</td>
<td>15</td>
<td>16</td>
</tr>
</tbody>
</table>

Fig. 11 - The 3D map of the magnetite anomaly, showing the depth and volume of the magnetic source. To produce this figure, all of the depths from Euler deconvolution and tilt derivative methods and final contact location from Euler deconvolution, tilt derivative, analytic signal and horizontal gradient methods were used.
5. Conclusion

In this study, analytic signal, Euler deconvolution, horizontal gradient, and tilt derivative methods were applied to magnetic data, obtained from field surveys, to estimate the depth and contact location of a magnetite body in the Chenar-e Olya area of Asadabad, Hamedan, Iran. To apply these methods, the Geosoft software was used. To achieve the best contact location and depth estimation, the results of all of the methods were ranked and combined using ArcGIS software.

For a more reliable report about the magnetite deposit in this area, the results obtained in this study were compared with the six geological boreholes drilled in the study region. This provides the best approximation for depth estimation at shallow depths. Boreholes 1, 5, and 6 are inside the resulted contact location, and were compared with the final depth estimates. Borehole 4 is near the contact location and can be compared with Euler deconvolution depth estimates on the surface. Boreholes 2 and 3 are out of the estimated body, but evidence magnetite anomaly at shallow depths of about 8 m. Boreholes 1, 4, 5, and 6 show good agreement with the results of this study. The uncertainties of the borehole results are shown as percentages in Table 3. In conclusion, the shape and depth of the magnetite body for excavation were reported.

Table 3 - Uncertainty obtained from the comparison of borehole data and final depth estimates and contact location derived from Euler deconvolution, tilt derivative, analytic signal, and horizontal gradient methods.

<table>
<thead>
<tr>
<th>Borehole number</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>4.5</td>
</tr>
<tr>
<td>6</td>
<td>7</td>
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Acknowledgements. The authors are very indebted to the Research Committee of the Young Researcher Club (Islamic Azad University, South Tehran Branch), who provided magnetic and geological data of boreholes in the Chenar-e Olya area of Asadabad. The authors also acknowledge valuable discussions with Soheil Eyvazkhani and Mahyar Soltani from Rahpouyan Co., as well as their financial support and helpful suggestions.

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