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Case study

Optimizing depth estimates from magnetic anomalies using spatial analysis tools

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ABSTRACT

We offer a methodology to analyze the spatial and statistical properties of the tilt derivative of magnetic anomalies, thus facilitating the mapping of the location and depth of concealed magnetic sources. This methodology uses commonly available graphical information system (GIS) software to estimate and interpolate horizontal distances between key attributes of the tilt derivative, which then are used to estimate depth and location of causative bodies. Application of the method to synthetic data illustrates its reliability to determine depths to magnetic contacts. We also achieved consistent depth results using real data from the northwest portion of the Paraná Basin, Brazil, where magnetic anomaly interpretations are complicated by low geomagnetic inclinations and rocks with remanent magnetization. The tilt-derivative method provides more continuous and higher resolution contact information than the 3D Euler deconvolution technique.

1. Introduction

Various methods are available to automatically and rapidly analyze magnetic anomalies in order to estimate the locations and depths of geologic sources over large, regional areas (Spector and Grant, 1970; Syberg, 1972; Phillips, 2001; Salem et al., 2007; Curto et al., 2014). Regional and residual components of the potential fields can be identified based on the wavenumber in the radial power spectrum, where their respective depths estimates are equivalent to the half of the straight lines slope in the power spectrum (Spector and Grant, 1970). Modern methods generally use gridded magnetic data and focus on the depth to geologic contacts, such as concealed faults, intrusive margins, and sedimentary basins. A simple method to isolate the residual component of the gridded data is the removal of a regional trend surface, calculated from the polynomial fit of 1st or 2nd order (Nabighian et al., 2005). A popular example is the Euler deconvolution technique, which is based on Euler's differential equation and provides estimates of depths to two-dimensional (Thompson, 1982) and three-dimensional (Reid et al., 1990) sources. The Euler method requires assumption of a “structural index”, a parameter characteristic of the source geometry, and provides a scatter of depth solutions that must be evaluated by additional assumptions (Thompson, 1982; Fairhead et al., 1994; Kuttikul, 1995; Barbosa et al., 1999).

Here we discuss the tilt–depth method (Salem et al., 2007), which is based on the ratio of the vertical and horizontal gradients of magnetic anomalies caused by vertical contacts (Miller and Singh, 1994; Verduzco et al., 2004; Salem et al., 2010). This method yields depth solutions along and adjacent to the contact, thus largely overcoming the problem of scattered solutions characteristic of the Euler approach. We further demonstrate a methodology of spatial and statistical analysis of the tilt derivative within a geographic information system (GIS) platform, which leads to more accurate estimates of the depth to the magnetic contact. Finally, we provide examples of our methodology by applying it to synthetic anomaly data and to field data from the northwest region of the Paraná Basin, Brazil, where major magnetic sources are concealed beneath sedimentary deposits. The Paraná Basin provides a particularly stringent test of the method because low geomagnetic inclinations and subsurface rocks with unknown remanent magnetizations complicate interpretation of magnetic data from this region (e.g., Curto et al., 2014).

2. Theoretical review

Many methods for edge detection and depth-to-source estimation rely on horizontal and vertical derivatives of magnetic anomalies (Nabighian, 1984; Blakely and Simpson, 1986; Thurston and Smith, 1997; Fedi and Florio, 2001; Phillips, 2000; Ferreira et al., 2013). The

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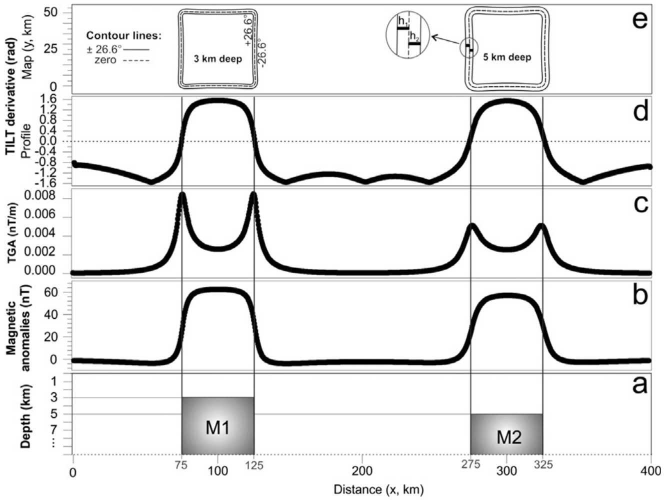

Fig. 1. (a) Synthetic Model A, consisting of two magnetic prisms, M1 and M2, with same magnetization values (0.13 A/m), dimensions, infinite depth extent, and tops at depths of 3 and 5 km, respectively. Anomalies calculated with the method of Bongiolo et al. (2013). (b) Profile calculated from Model A assuming geomagnetic inclination 90°. (c) Total gradient amplitude of profile b. (d) Tilt derivative of profile b in radians. (e) Contour maps of the tilt derivative for Model A. Solid contours are the zero value of the tilt angle, which is correspondent to the limit of the bodies. Dashed lines are equivalent to 26.54° or 0.46 rad, where h_1 and h_2 is the horizontal distance between 0 and +0.46 rad and −0.46 rad, respectively.

total-gradient method, for example, calculates the analytic signal by combining horizontal and vertical derivatives of magnetic anomalies, calculated from either profile or gridded data. Maxima of the total gradient are centralized over causative sources and have shapes indicative of the source depth (Nabighian, 1972; Roest et al., 1992; MacLeod et al., 1993). However, the amplitude of the total gradient attenuates with increasing depth to source, thus hampering interpretations when both shallow and deep sources (Fig. 1c) are present.

The local phase of the magnetic field, or tilt derivative (Miller and Singh, 1994; Verduzco et al., 2004), overcomes this attenuation problem by using the ratio of the vertical and horizontal gradients. The tilt angle is given by

$$\theta = \tan^{-1}\left(\frac{\frac{\delta M}{\delta z}}{\frac{\delta M}{\delta h}}\right) \tag{1}$$

where $\delta M/\delta h = \sqrt{(\delta M/\delta x)^2 + (\delta M/\delta y)^2}$, and $\delta M/\delta x$, $\delta M/\delta y$, $\delta M/\delta z$ are first-order derivatives of the magnetic field M in the x, y, and z directions, respectively. The tilt angle θ has values between $\pi/2$ and $-\pi/2$ (−90° and 90°). Salem et al. (2007, 2010) showed that, for magnetic anomalies caused by vertical contacts and reduced to the pole,

$$\theta = \tan^{-1}\left(\frac{h}{z}\right) \tag{2}$$

where z is the depth to the contact and h is the horizontal distance perpendicular to the contact. It is clear from Eq. (2) that $\theta=0$ directly over the contact. It also can be shown that the horizontal gradient of the tilt derivative in the vicinity of $\theta=0$ is a measure of the depth to the contact. One way to estimate the horizontal gradient of the tilt derivative (and thus the depth to source) is by measuring the horizontal distance between specific contours on opposite sides of the zero-contour (Fig. 1e). Using this as a rule of thumb, it is possible to conduct a simple qualitative interpretation of source depths. For example, $z=h$ when $\theta=\pm\pi/4$, so the horizontal distance between the $+\pi/4$ and $-\pi/4$ contours is a measure of $2z$.

Other tilt-derivative contours can be used as well. We empirically observed that anomaly interference for close or overlapping magnetic sources is greater for larger tilt angles, whereas much smaller tilt angles hamper the tilt visualization in 3D, consequently affecting our interpretations. Best results were found when we used angles between 20° and 30°. A simple relation between tilt angle and depth values was determined using two measurements:

- h_1, the horizontal distance between θ contours 0 and +0.46 rad (+26.6°), and
- $h_{2,}$ the horizontal distance between θ contours −0.46 and 0.

Each measurement provides an estimate of source depth; i.e., $z_1=2h_1$ and $z_2=2h_2$ (i.e., $\theta=0.46$ rad when $h=0.5z$; Fig. 1e).

3. Spatial analysis of the tilt–depth

In our methodology, tilt–depths are estimated with a four-step procedure: (1) We calculate the tilt derivative of the reduced-to-pole magnetic field; (2) display contour lines of the tilt in radians; (3) measure the variables h_1*and* h_2; and (4) calculate $z_1=2h_1$ and $z_2=2h_2$. The first two steps are achieved within Oasis Montaj® (Geosoft®), and we automate the last two steps using the ArcGIS® platform (Esri®) and adding two additional steps: (5) a statistical

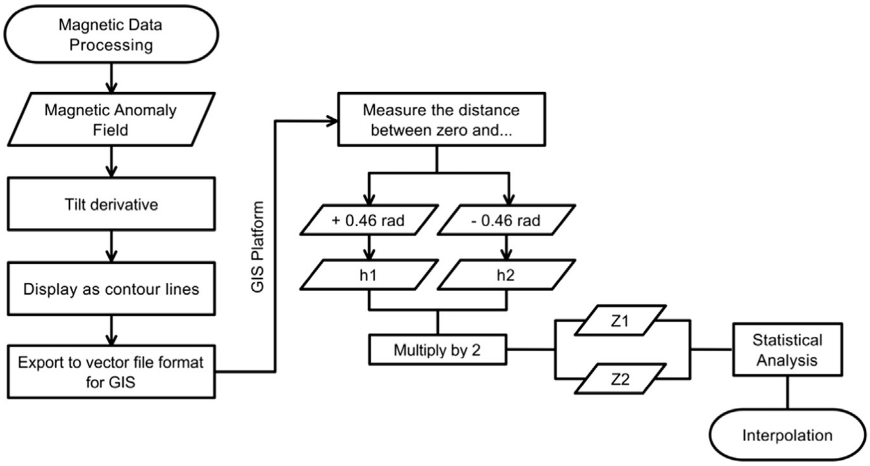

Fig. 2. The main steps and parameters used to produce our depth map of magnetic anomalies.