3D inversion of a subsurface magnetic anomaly: study case of Lucialva anomaly (SW of Mato Grosso, Brazil)

Divanir Conego Junior*, Vanessa B. Ribeiro, Marta S. M. Mantovani, Vinicius Hector Abud Louro, IAG/USP.

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Abstract

In the southwest region of the Parecis Basin it is observed the presence of several magnetic anomalies, most of them parallel to the Indiavaí-Lucialva and Pitas Shear Zone. Considering the great volume of mineral occurrences in this area (cooper, zinc, gold, diamond, etc.), a better knowledge of these magnetic sources behavior is important to understand the exploratory potential of the area. In this work, it was analyzed the characteristics of Lucialva magnetic anomaly. The results obtained for the borders delimitation techniques and the total magnetization inclination and declination, obtained by a reduction to the magnetic pole algorithm, were applied as constraints for the 3D inversion. The susceptibility contrast recovered by the 3D model suggests that the magnetic source is composed by diorite-like or porphyry-like intrusions.

Introduction

The southwestern portion of the Parecis Basin shows several known deposits of copper, zinc, gold and diamonds (associated with kimberlites) in concentrations and characteristics that make their exploitation economically viable.

The aeromagnetic data of this region shows a number of magnetic anomalies parallel to the Indiavaí-Lucialva and Pitas Shear Zones. These anomalies present a large variation in size, intensity and direction of magnetization (depending on the remanent component) and may be associated to geological structures linked to mineral deposits. Many of these magnetic sources do not show any evidence of outcropping and, consequently, no signs in surface of their exploration potential. Therefore, it is of great interest to better understand the characteristics of these structures as top depths of bodies, lateral limits, apparent magnetic susceptibility and volumes.

Several anomalies associated with this arc had been studied in relation to their geophysical characteristics as Rio Juína, Rio Juruena, Jauru 1 to 5 and Córrego do Bugre (Louro et al. 2013), Palmital 1 to 5 (Ribeiro et al., 2012).

In this work it was studied the magnetic signature of the Lucialva anomaly, contributing to the understanding of the magnetic structures observed in the region. The border limits and its top depths of the magnetic source were estimated through the Enhanced Horizontal Derivatives (EHD – Fedi and Florio, 2001) technique. The characteristics of magnetization were analyzed by two different reduction to the magntic pole (RTP) filters. All these results were used as constraints to the interpretation of the 3D inversion of the data.

The 3D model generated indicated a magnetic body with susceptibility between 0.02 and 0.035 S.I., located at 400 m depth. This susceptibility indicates that this source could be associated with a porphyry-like or diorite-like lithology, which may represent a potential scenario for the mineral exploration. However, it is important to highlight the importance of borehole analysis for a conclusive/unique answer for the lithological type of the anomaly.

Magnetometry

Due to the presence of rocks containing magnetic minerals, the Earth Magnetic Field (EMF) suffers a distortion in the region the rocks are emplaced. This distortion (anomaly) occurs because the EMF induces a magnetization (Mi) on the rock's minerals proportional to the susceptibility contrast between the rock and its host-rock.

However, ferromagnetic materials can retain a magnetization from EMF in their moment of (re)crystallization, the remanent magnetization (Mr – Blakely, 1995). Consequently, the total magnetization of a rock is the vector sum of the induced and remanent components.

The Reduction to the magnetic Pole (RTP), defined by Baranov (1957), uses a filter operator that adjusts the magnetic data to a state of vertical polarization, observed only in the magnetic poles. The formula used by Oasis Montaj 6.4.2 to this filtering is given by:

$$L(\theta)=\frac{\left[sen(I)-i.\cos(I).\cos(D-\theta)\right]^2}{\left[sen^2(Ia)+\cos^2(Ia).\cos^2(D-\theta)\right].\left[sen^2(I)+\cos^2(I).\cos^2(D-\theta)\right]} \quad (1)$$

where *I* is the magnetic inclination, *Ia* the slope of the amplitude correction, *D* is the magnetic declination and θ is the direction of the wave number.

According to Cooper and Cowan (2005), the RTP produces erroneous results when applied to magnetic anomalies with remanent magnetization of unknown direction. As alternative, this filtering was calculated through an algorithm developed by Fedi et al. (1994).

The algorithm of RTP by Fedi et al. (1994) performs the filtering in a pre-defined number of iterations, varying both the inclination and declination. For each group of thirty directions, the one presenting the most negative amplitude values is discarded and, then, the process is reinitiated. At the end of the last iteration, the best solution is presented, with its inclination and declination (I_M, D_M). This pair of values will compose the total magnetization vector direction, which will be used in the inversion stage.

Fedi and Florio (2001) proposed the Enhanced Horizontal Derivatives (EHD) technique presenting a weak dependency on the magnetization direction and allowing estimating the location of the horizontal boundaries of a given magnetic source. They expanded the residual magnetic field into a Taylor series $\varphi(x,y,z_0)$:

$$\varphi(x,v,z_0) = f(x,v,z_0) + f^{(n)}(x,v,z_0) + \cdots + f^{(n)}(x,v,z_0) \quad (2)$$

where $f(x,y,z_0)$ is a function of the residual magnetic field and $f^{(n)}(x,y,z_0)$ is the subsequent vertical derivative of *n-th* order. As a result, the series is derived to *n*-th order in the x and y components and their module are expressed by the relation:

$$EHD_n(x,y) = \sqrt{\left(\frac{\partial^n \varphi}{\partial^{n-1} z \partial x}\right) + \left(\frac{\partial^n \varphi}{\partial^{n-1} z \partial y}\right)} \quad (3).$$

Fedi and Florio (2001) also proposed an extrapolation for the EHD, aiming the estimative of the depth of the top of the borders determined by the EHD. This extrapolation was based on the Enhanced Analytic Signal proposed by Hsu et al. (1998) and it is expressed by:

$$EHD - depth(x,y) = \frac{|EHD_n(x,y)|}{|EHD_{n+1}(x,y)|} \quad (4),$$

where EHD-depth is the depth of the top of the borders defined through the EHD, and EHD_n is the Enhanced Horizontal Derivative of n-th order.

3D Inversion

The 3D inversion technique used in this work was developed by Li and Oldenburg (1996) through the software UBC-GIF MAG3D. The relation between the magnetic anomaly generated by a specific source related to the host rock can be expressed by a linear function defined by:

$$d = W \cdot p \quad (5)$$

where $d = (d_1, \cdots, d_N)^T$ represents the vector of observed data, *W* is the matrix NxM of sensitivity and $p = (p_1, \cdots, p_M)^T$ is the vector containing the magnetic susceptibility of each cell of the mesh.

The inverse problem is formulated as an optimization process, where the objective function of the susceptibility (6) is minimized under a set of constraints to reproduce the data within a pre-defined error. The model fit is obtained by minimizing this objective function:

$$\phi = \phi_d + \mu \phi_m \quad (6)$$

In (6), *Φ* represents the objective function and *μ* is the "regularization parameter". The positivity is implemented by using a primal logarithmic barrier method (MAG3D, 2003). The fitting accuracy (ϕ_d) is calculated by:

$$\phi_d = \left\| W_d \left(G\vec{\kappa} - \vec{d}^{\,obs} \right) \right\| \quad (7)$$

where d^{obs} represents the vector with the observed data, κ is the vector with the model parameter generated and *G* is the sensitivity matrix. W_d is a diagonal matrix whose *i*-th element is given by $w_i = 1/\sigma_i$, being σ_i the standard deviation of the *i*-th data. This equation also subjects to susceptibility ≥ 0.

From (6), the Φ_m is the regularization function, given by:

$$\begin{aligned}\phi_m = {} & \alpha_s \int_v w_s \{w(r)[m(r) - m_0]\}^2 dv + \\ & \alpha_x \int_v w_x \{[\partial w(r)/\partial x][m(r) - m_0]\}^2 dv + \\ & \alpha_y \int_v w_y \{[\partial w(r)/\partial y][m(r) - m_0]\}^2 dv + \\ & \alpha_z \int_v w_z \{[\partial w(r)/\partial z][m(r) - m_0]\}^2 dv \end{aligned} \quad (6)$$

where m is the magnetic model elements, m_0 is the reference model, w_x, w_y, w_z and w_s are the weighting functions, $w(r)$ is the depth-weighting function. The details of the objective function are problem-dependent and can vary according to the priori available information but, generally, the objective function should have the flexibility of constructing a model close to a reference model p_0, and to produce a model smooth in the three spatial directions.

The solution for minimizing the objective function as well as a description of other restrictions imposed at the inversion algorithm, such as the use of a positive bound are described in Li and Oldenburg (1996).

The non-uniqueness characteristic of the modeling of potential fields permits the achievement of models of high susceptibility in great depths with small volume, or even a low susceptibility model in small depth with greater volume. The measures taken to minimize these limitations were to bond the inversions with as many results and local geological features as possible (Louro and Mantovani, 2012). Consequently, the boundaries and depths found through EHD and its extrapolation to depth were detected and used as constriction to the obtained model.

Geology

The Lucialva magnetic anomaly (Figure 1) is located inside the limits of the Parecis Basin, being totally covered by the sediments of the Utiariti formation. For a better visualization, the contour of the anomaly (black polygon in Figure 1) was traced based on the magnetic map (Figure 2) and displayed over the geologic map.

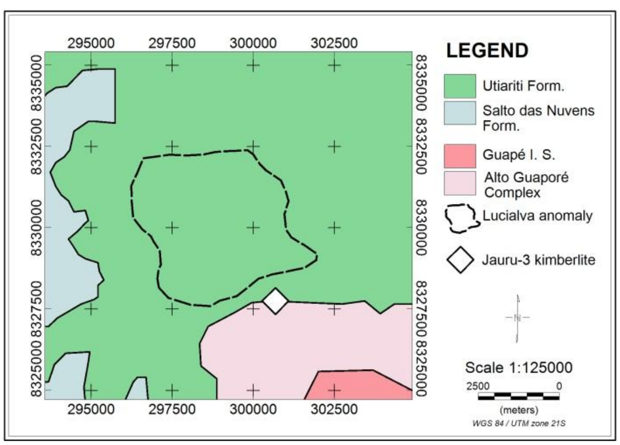

Figure 1. Simplified geological map of the studied region. The black polygon indicates the location of the Lucialva magnetic anomaly and white diamond the Jauru-3 kimberlite intrusion.

The Cretaceous Sequence of the Parecis basin is restricted to the Parecis Group (composed by Salto das Nuvens and Utiariti Formations – Figure 1), dating from the mid to upper Cretaceous. This sequence consists of conglomerates and sandstones, deposited in fluvial and aeolic environments (Lacerda Filho, 2004).

The magnetic anomaly of Lucialva (15º09'S, 58º92'W) has a significant magnetic contrast in relation to the basin sediments, being the center of this anomaly nearly 3 km distant of Jauru-3 kimberlite (white diamond in Figure 1).

The results obtained for the analysis of magnetic data and the 3D model is present below.

Lucialva magnetic anomaly

The isolation the regional contribution from the studied area was performed by the application of an upward continuation technique with 2000 m (Figure 2). This value was chosen based on a series of tests performed using a range of several values.

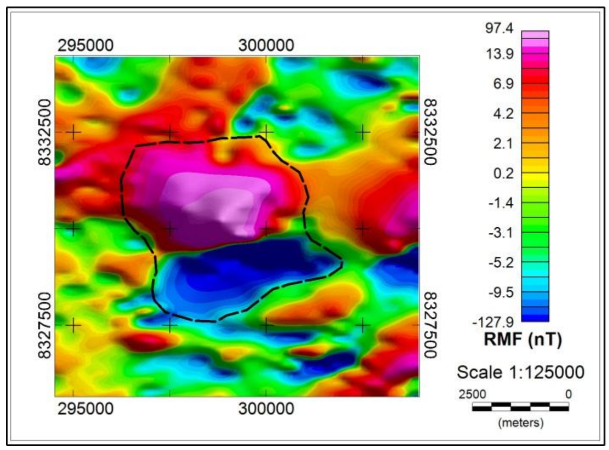

Figure 2. Residual magnetic field (RMF) of the studied region. The black polygon indicates the contour of the Lucialva anomaly.

The Lucialva anomaly presents a normal magnetic polarization for the south hemisphere, with its intensity ranging from -127.9 to 97.4 nT and lateral extension of approximately 3 km (Figure 2).

Yet, despite the anomaly does not provide clear evidence of a strong remnant magnetization, the RTP proposed by Baranov (1957) did not present good results, considering the inclination and declination of the induced magnetic field for the region (-11.78º, -14.03º - Figure 3).

The RTP filtering calculated through the algorithm developed by Fedi et al. (1994) presented a better behavior when it applied the filter with the values of total magnetization inclination and declination of -27.0º and -40.7º, respectively. The RTP map generated by this procedure is presented in Figure 4.

Considering the presence of a significant remanent component (evidenced by the RTP) it is important to use a technique to estimate the lateral boundaries of the source. This technique shall present little dependence of the magnetization direction, and for this reason, the EHD was applied to the region (Figure 5).

The EHD allowed a very good estimation of the Lucialva borders, showing a strong correlation with the reduced to the pole anomaly by the algorithm developed by Fedi et al. (1994 – Figure 4).

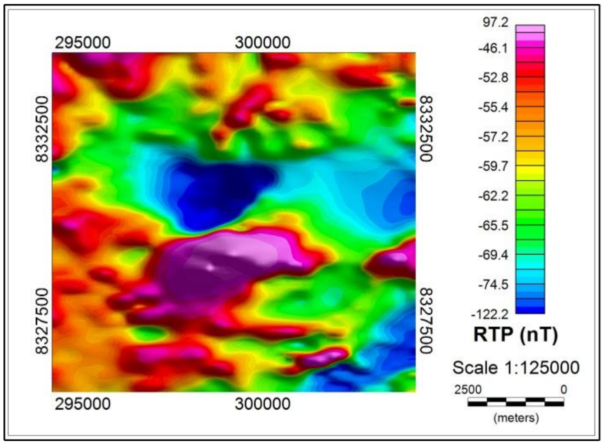

Figure 3. RTP map calculated by the filtering from Baranov (1957) implemented by the Oasis Montaj 6.4.2.

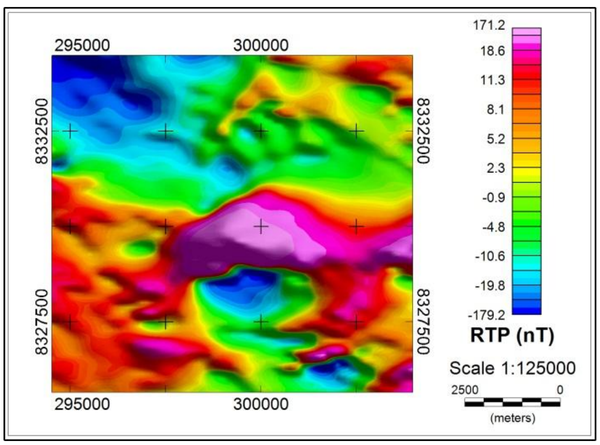

Figure 4. RTP map calculated through the algorithm developed by Fedi et al. (1994).

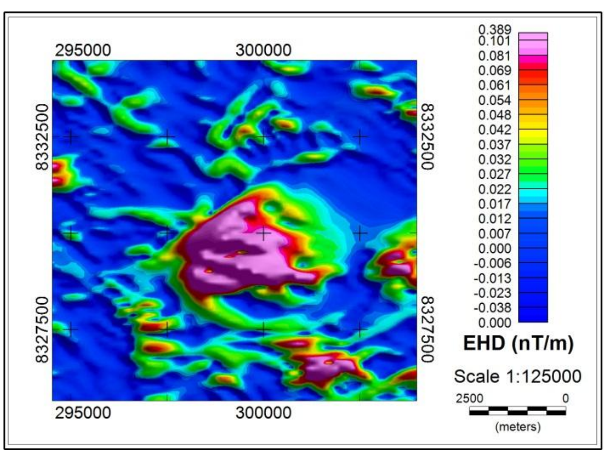

Figure 5. Map of the enhanced horizontal derivative (EHD) obtained for the Lucialva anomaly.

Conducting an analysis of the positive peaks of EHD and relating them to the depth estimation through the Eq. 4, it was possible to localize the depth of the anomalous body borders at 249 ± 64 m.

3D magnetic model

The models recovered by 3D inversion obtained an apparent susceptibility contrast from 0.023 to 0.035 (S.I. – Figure 10).

According to Telford et al. (1990), the magnetic susceptibility of sediments rocks is varies from 10^{-4} to 10^{-5} (S.I.). Still according to these authors, the average magnetic susceptibility for igneous basic intrusion is 0.025 (S.I.; being the susceptibility of the diorite from 6.000×10^{-3} to 0.120 S.I. and the porphyry's goes from 0.3×10^{-3} to 0.200 S.I.). Therefore, the susceptibility contrast obtained between the 3D model and the Parecis Basin sediments is consistent with that expected by the literature.

The depth of the magnetic source lateral limits obtained by the 3D models (Figure 10) was around 400 m. Note that this imprecision in the 3D model estimation corresponds to, at least, half the size of the cell used in the mesh (100 m), therefore, the value of the model's depth is a rough estimative. For better results, the inversion should use smaller cells, which represent a compromise between the precision and time of computational processing.

It is important to note that the inferior boundaries of the bodies that appear in the inversion (Figure 10) are not necessarily the geologic lower limits but rather the depth below which the data are no longer sensitive to magnetic material.

Conclusions

Beside the Lucialva magnetic anomaly presents a normal polarization for the south hemisphere, it has a significant remanent component, evidenced by the result of the reduction to the magnetic pole proposed by Baranov (1957). The implementation of Fedi et al. (1994) algorithm allow not only to successful reduced the anomaly to the magnetic pole, as estimated the total magnetization inclination and declination angles (-27.0º and 40.7º, respectively).

The EHD-depth results showed a good correlation with the 3D model obtained from the anomalies, but it is important to highlight that the model's depths are a rough estimative and are conditioned by the cells length used in mesh.

The susceptibility contrast recovered by the 3D model may be interpreted as diorite or porphyry-like intrusions. In both cases, there is the possibility for mineral exploration for gold, copper and zinc, especially in the region between the top of the inverted body and the surface, due hydrothermal process

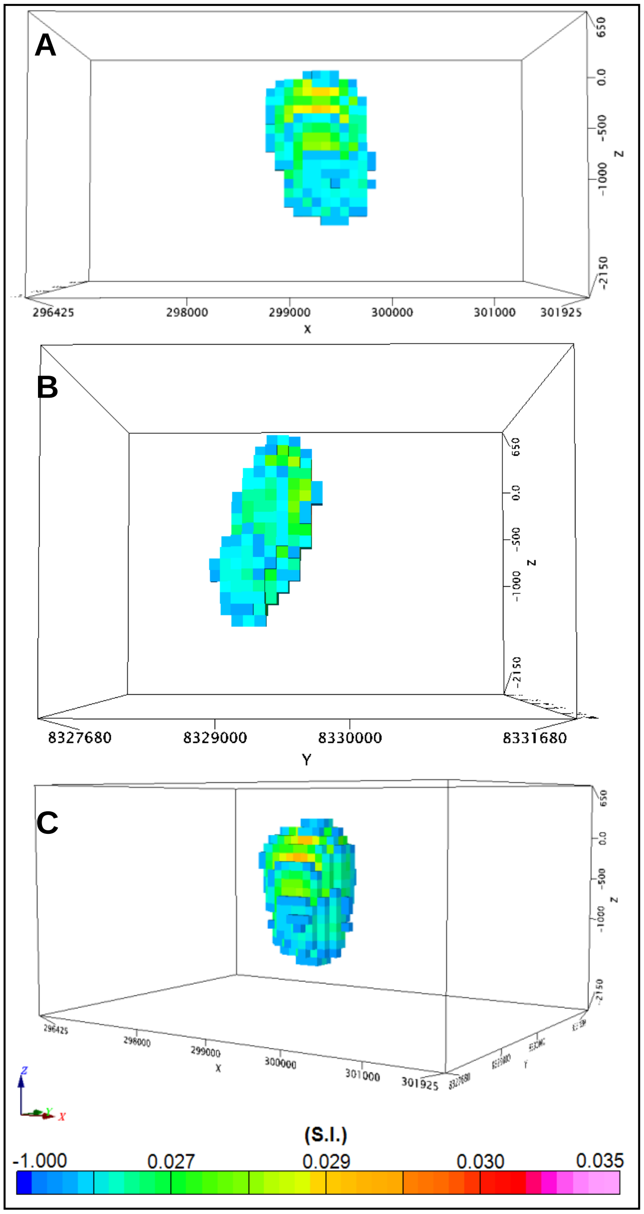

Figure 10. (A) View of south, (B) east and (C) perspective of the 3D model obtained through the inversion of Lucialva magnetic data.

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Either the hypothesis fits to the regional geology and to the magnetic data. A conclusive answer for the lithological type can only be achieved by borehole analysis.

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