Geophysical study of the Sertãozinho, Rio Aguapeí and Nova anomalies (SW of Mato Grosso, Brazil)

Vanessa B. Ribeiro*, Vinicius H. A. Louro, Marta S. M. Mantovani, IAG/USP.

Abstract

The southwest region of the Parecis Basin (Mato Grosso state, Brazil) is marked by the presence of several mineral occurrences of copper, zinc, gold and diamonds (associated with kimberlites). In this region the presence of several magnetic anomalies is observed, most of them parallel to the Indiavaí-Lucialva and Pitas Shear Zones. Beside these anomalies, three magnetic dipoles were identified within the Santa Helena batholith, and are the focus of this work. Considering the possible presence of remanent magnetization in the three anomalies, it was applied techniques with low dependence of the magnetization direction to isolate the magnetic contribution, associated to each source, preceding the 3D inversion. The susceptibility contrast obtained between the anomalous sources and the embedding rock (batholith) was compared with data in the literature to restrict the possible lithologies associated with the sources of the anomalies. Results indicate contrasts of susceptibility that suggest that the anomalies are composed by diorite-like or porphyry-like intrusions.

Introduction

In the southwestern portion of the Parecis Basin lies the Alto Jauru Gold District, where deposits of copper, zinc and gold are known. In this district several cretaceous kimberlites are also observed, presenting occurrences of diamonds, 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 Shear Zone and three anomalies within the limits of Santa Helena batholith. These anomalies present a large variation in size, intensity and direction of magnetization.

Geophysical characteristics of several anomalies associated with this arc have been studied: 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 is studied the geophysical response of three magnetic anomalies observed within the limits of Santa Helena batholith. Considering the presence of an intense remanent component associated with these intrusions, the Enhanced Horizontal Derivative (EHD – Fedi and Florio, 2001) and the Amplitude of Anomalous Magnetic Field (AAMF – Shearer, 2005) were applied for their weak dependence of the magnetization direction.

The resultant inverted models indicate the presence of three magnetic bodies with susceptibility varying from 0.02 to 0.08 S.I. The overall results show a complex of structures that may represent a potential scenario for the mineral exploration, depending only on a borehole analysis for a conclusive/unique answer for the lithological type of anomalies.

Magnetometry

Due to the presence of rocks containing ferromagnetic minerals, the Earth Magnetic Field (EMF) presents a distortion proportional to the susceptibility contrast between these rocks and their host-rocks. This distortion (anomaly) occurs because the EMF induces a magnetization (M_i) on the rocks' minerals.

However, the ferromagnetic materials can retain part of magnetization from the moment they (re)crystallize, recording the EMF from that moment. This component is called remanent magnetization (M_r). Consequently, the total magnetization of a rock, gathered in magnetic surveys, is the vector sum of the induced and remanent components.

The complexity of the magnetic signature and the lack of samples require the use of mathematical techniques to allow the isolation of the contribution of the magnetic body. Due the presence of significant remanence, it is necessary the use of procedures of little dependence of the direction of magnetization prior to an eventual 3D inversion. For this purpose, the technique of amplitude of the Anomalous Magnetic Field (AAMF – Shearer, 2005) was applied.

The AAMF is defined by the relation:

$$B_a = \left\| \overrightarrow{B_a} \right\| = \sqrt{B_x^2 + B_y^2 + B_z^2} \quad (1)$$

where B_x, B_y and B_z are the three components of the magnetic field in the Cartesian coordinate system.

Fedi and Florio (2001) proposed the EHD method expanding the residual magnetic field into a Taylor series $\varphi(x,y,z_0)$:

$$\varphi(x,y,z_0) = f(x,y,z_0) + f^{(1)}(x,y,z_0) + \ldots + f^{(n)}(x,y,z_0) \qquad (2)$$

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 to 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 borders and EHD_n is the Enhanced Horizontal Derivative of *n-th* order.

Gamaspectrometry

The disintegration of radioactive elements can release energy by emitting alpha (α) and beta (β) particles and gamma rays (γ). This disintegration is caused by the instability of these elements under natural conditions.

The main sources of gamma radiation detected in the surface comes from the natural decay of potassium (^{40}K) and the elements of the uranium (^{238}U) and thorium series (^{232}Th) present in the composition of most rocks. However, their emission can be detected only for a limited thickness (30 to 40 cm) due the loss of energy of the gamma ray crossing the most superficial layer of rocks.

Different lithologies may show great variations in their composition, which are directly reflected in their radiometric signatures. Besides the composition, the gamma spectrometric response can also vary due to the presence of faults, magma differentiation, action of erosion and weathering, etc.

Among the main applications of this method it can be cited: the characterization of undifferentiated intrusions, set of possible points of lithology outcropping, to assist the demarcation of geological limits, the identification of areas of hydrothermal alteration (often associated with mineralization of Cu-Pb-Zn and gold) etc.

3D Inversion

The 3D inversion technique used in this work was developed by Shearer (2005) through the software AMP3D. The relation between a magnetic anomaly, generated by the susceptibility contrast of 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 *N*x*M* 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 is minimized under a set of constraints to reproduce the data within a pre-defined error. The details of the objective function are problem-dependent and can vary according to the a priori available information but, generally, the objective function should have the flexibility of constructing a model that is close to a reference model p_0 and producing a model that is smooth in the three spatial directions.

The fitting accuracy (ϕ_d) is calculated by:

$$\phi_d = \left\| W_d \left(G\vec{\kappa} - \vec{d}^{\,obs} \right) \right\| \quad (6)$$

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.

The model fit is obtained by minimizing the objective function:

$$\phi = \phi_d + \mu \phi_m \quad (7)$$

being (7) subject to susceptibility ≥ 0.

In (7), ϕ represents the objective function and μ is the regularization parameter that allows to control data adjustment. The positivity is implemented by using a primal logarithmic barrier method (WRIGHT, 1997; Li and Oldenburg, 2003). The Φ_m is the regularization function, expressed by:

$$\begin{aligned}\phi_m = {} & \alpha_s \int_v w_s \{w(r)[m(r)-m_0]\}^2 dv + \\ & \alpha_x \int_v w_x \{[\partial w(r)/\partial x][m(r)-m_0]\}^2 dv + \\ & \alpha_y \int_v w_y \{[\partial w(r)/\partial y][m(r)-m_0]\}^2 dv + \\ & \alpha_z \int_v w_z \{[\partial w(r)/\partial z][m(r)-m_0]\}^2 dv \end{aligned} \quad (8)$$

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 solution of minimizing the function as well as a description of other restrictions imposed by the inversion algorithm, such as the use of a positive bound are described in Shearer (2005).

Geology

The Santa Helena batholith presents an elongated shape in the N-S direction, with 75 km of extension by 35 km of wide (Figure 1). According to Lacerda Filho (2004), this batholith is composed by porphyroid granites with granodiorites, tonalites and subordinates pegmatites. The alkali feldspar is abundant in granites, ranging from 40% to 50% with quartz and plagioclase from 20% to 25%, and biotite and hornblende about 5% to 10%. The accessory minerals include allanite, apatite, zircon and magnetite.

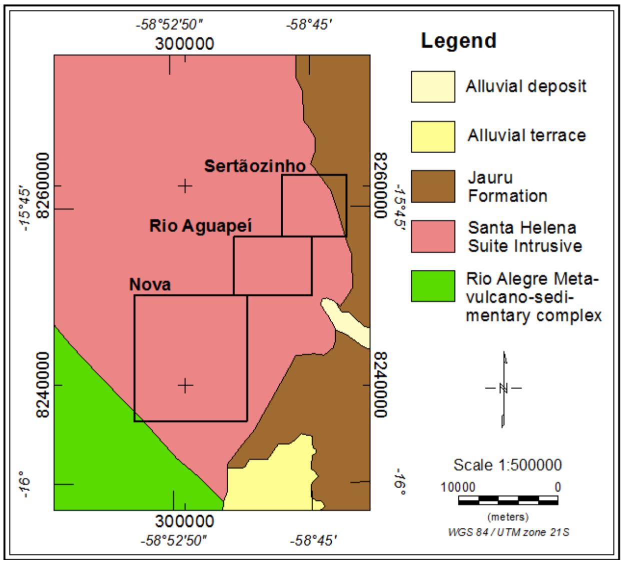

Figure 1. Simplified geological map of southern portion of Santa Helena batholith. The black squares indicate the location of the magnetic anomalies studied.

Geraldes *et al.* (2001) obtained U-Pb ages from 1.42 Ma to 1.45 Ma for the batholith. It was interpreted by the authors as an indicative that the diverse phases of the batholith were emplaced as part of a major magmatic episode.

The magnetic anomalies of Sertãozinho (15º45'S, 58º44'W), Rio Aguapeí (15º48'S, 58º47'W) and Nova (15º53'S, 58º51'W) are placed internally to the Santa Helena batholith (Figure 1) and have a significant susceptibility contrast in relation to it.

The results obtained for the analysis of gamma ray spectrometric and magnetic data of each anomaly is presented below.

Sertãozinho magnetic anomaly

The magnetic anomaly of Sertãozinho has a reverse polarization with approximately 3 km of extension and inclination about N45E (Figure 2). This anomaly is located over the batholith geological boundary and has no visible radiometric response.

To isolate the residual component, the regional magnetic field contribution was removed by an upward continuation filtering technique considering a height of 2500 m (Figure 2). This height was chosen based on a series of tests performed using several values (ranging from 1000 to 5000 m).

Aiming to obtain a better definition of the magnetic source's lateral limits, it was applied the EHD to the data (Figure 3). The analysis of the positive peaks of EHD and their relation with the depth estimation through the Eq. 4, permitted to estimate an approximately 5 km elongated source in NE-SW direction with the depths of the top of its borders at 182.64 ± 53.87 m.

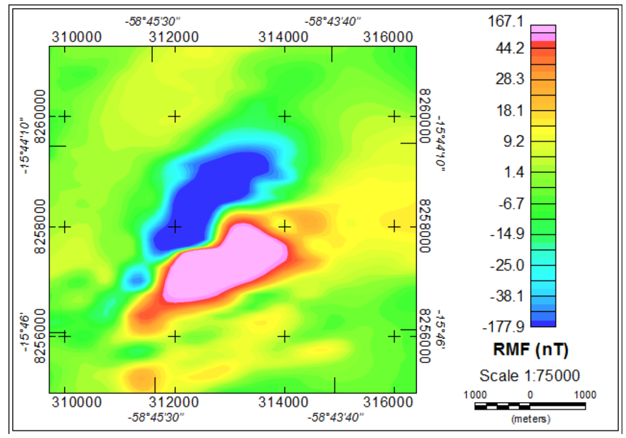

Figure 2. Residual magnetic field (RMF) of the region of Sertãozinho magnetic anomaly.

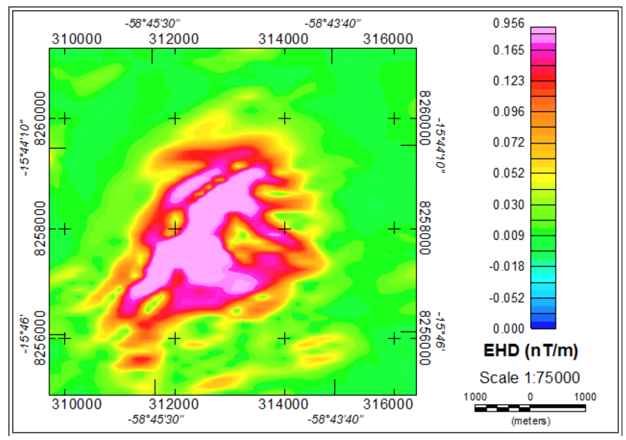

Figure 3. Map of the Enhanced Horizontal Derivative (EHD) obtained for the Sertãozinho anomaly.

Rio Aguapeí magnetic anomaly

The Rio Aguapeí anomaly is at 8 km from the eastern geologic limit of the Santa Helena batholith (Figure 4) and has a reverse polarization, with intensity ranging from -128 to 35 nT and lateral extent of 3 km

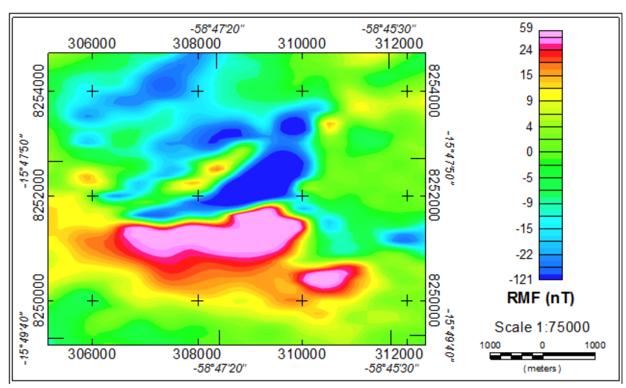

Figure 4. Residual Magnetic Field (RMF) of the region of Rio Aguapeí magnetic anomaly.

Like Sertãozinho, the Rio Aguapeí anomaly does not present a specific radiometric signature, indicating that its source may be completely located in sub-surface.

The contribution of the residual component has been isolated through the upward continuation technique at 2500 m (Figure 4). As for the Sertãozinho anomaly, the lateral limits of the Rio Aguapeí source were obtained with the EHD technique (Figure 5), being E-W elongated, almost 4 km long, and with the depth of its source's lateral limits calculated by EHD-depth to 168.00 ± 46.25 m.

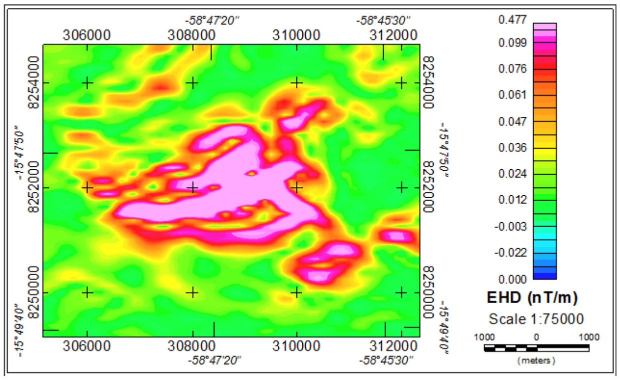

Figure 5. Map of the Enhanced Horizontal Derivative (EHD) obtained for the Rio Aguapeí anomaly.

Nova magnetic anomaly

The Nova anomaly is the innermost of the three identified in this study. Located at approximately 9 km from the eastern geological limit of the batholith, this anomaly presents a reverse polarization, with intensity ranging from -252 to 260 nT and lateral extent of 4.5 km (Figure 6). The contribution of the residual component has been isolated by the upward continuation to a height of 5000 m (Figure 6).

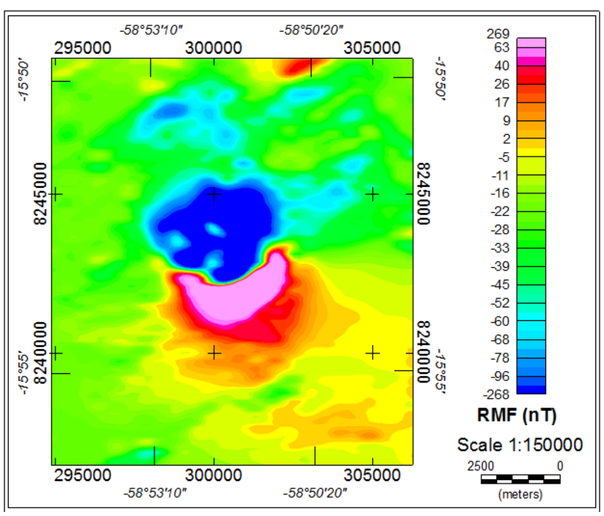

Figure 6. Residual Magnetic Field (RMF) of the region of Nova magnetic anomaly.

For a better analysis of the radio elements distribution, the contour of the anomaly limits traced from EHD map (Figure 7) was overlaid on the ternary map and the (Figure 8). The EHD filtering showed a circular-shaped source, with the topmost parts of its limits outcropping (as obtained by the EHD-depth).

By analyzing the map of the radioelement ternary distribution (Figure 8), it is observed an anomaly with average to highs counts of thorium, low to medium scores of uranium and low of potassium at the coordinates of the magnetic anomaly. The contrast between the radiometric response of the intrusion and the batholith is evident mainly in the K counts map (Figure 9).

The Santa Helena batholith has a radiomentric response characterized by high level of K (Ribeiro and Mantovani, 2012). According to Dickson and Scott (1997), mafic and ultramafic rocks present lower counts of K than granites, which is consistent with the difference in the observed counts.

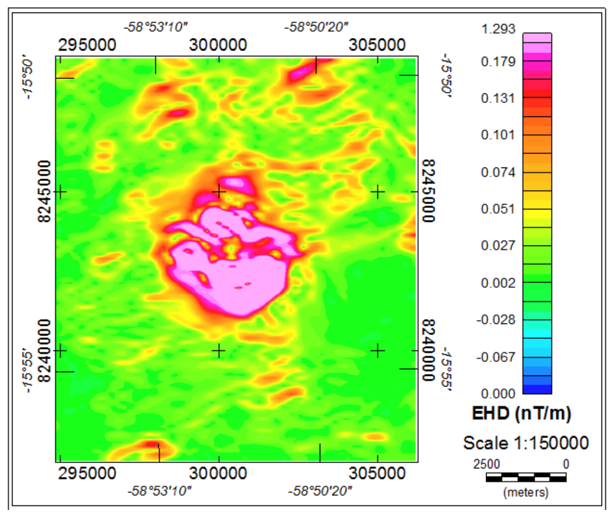

Figure 7. Map of the Enhanced Horizontal Derivative (EHD) obtained for the Nova anomaly.

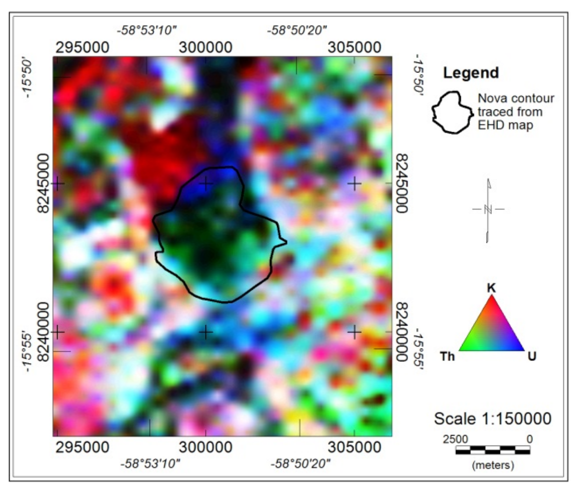

Figure 8. Ternary map of the K, Th and U counts distribution in the region of Nova magnetic anomaly (indicated by the black polygon).

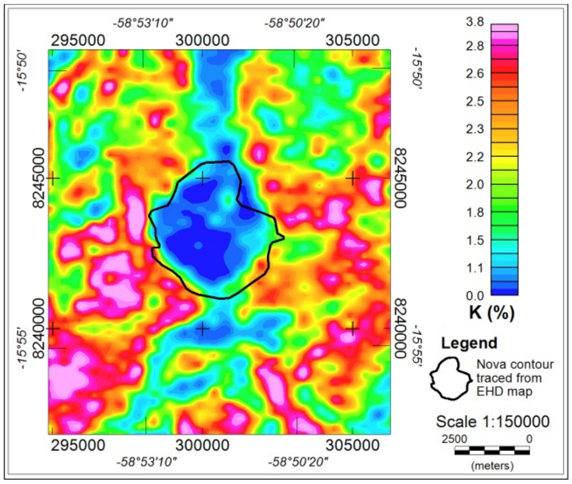

Figure 9. Distribution of K counts (%) along the Nova magnetic anomaly (indicated by the black polygon).

3D magnetic model

The models recovered by 3D inversion have an apparent susceptibility contrast of 0.026 to 0.067 (S.I.) for Sertãozinho anomaly, 0.023 to 0.035 (S.I.) for Rio Aguapeí and 0.027 to 0.086 (S.I.) for Nova (Figure 10).

According to Telford *et al.* (1990), the average susceptibility of a granite is 2.5×10^{-3} (S.I.), ranging from 0 to 0.05 (S.I.). Considering the granitic composition of the Santa Helena batholith, and the presence of magnetite as an accessory mineral, the magnetic susceptibility of this batholith is expected to be larger than the average value. Still according to these authors, the average magnetic susceptibility for igneous basic intrusion is 0.025 S.I. (being susceptibility of the pyroxenite of about 0.125 S.I. and peridotite ranging from 0.090 to 0.200 S.I.). Therefore, the susceptibility contrast obtained between the 3D models and the batholith is consistent with that expected from the literature.

The depth to the sources lateral limits obtained by the 3D models (Figure 10) was 200 meters to the Sertãozinho and Rio Aguapeí, presenting a good correlation with the depth estimated through the EHD-depth. Note that the imprecision in the 3D model estimation corresponds to at least half the size of the cell used in the mesh, which is 100 m, therefore, the value of models 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 bottom part 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.

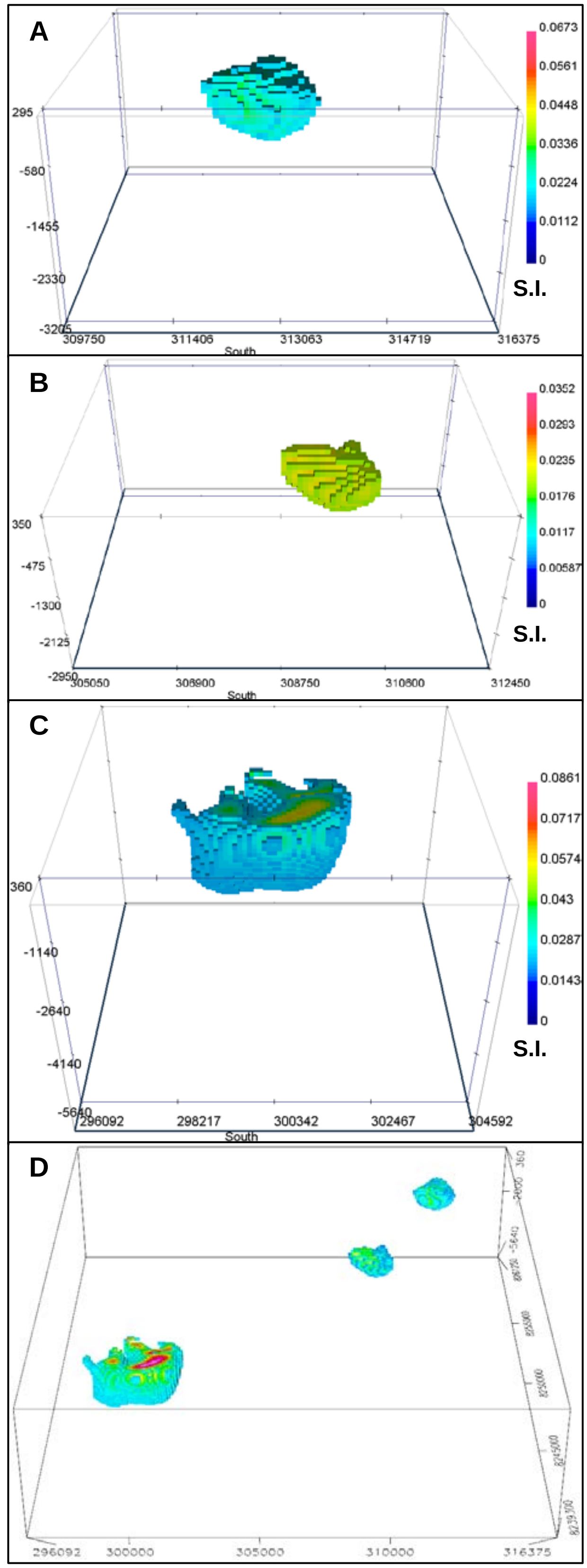

Figure 10. 3D model obtained for the inversion of the AAMF data of (A) Sertãozinho, (B) Rio Aguapeí, (C) Nova anomaly and (C) view of three bodies together.

Conclusions

The Santa Helena batholith tectonic history is marked by the action of several compressive stresses that would have fractured this intrusion. The presence of these faults would generate a weakness zone that could allow the emplacement of the magmatic intrusions associated with the studied anomalies. A second hypothesis that might explain the presence of these sources consists in the intrusion of these bodies before the batholith magma intrusion.

Either of the presented 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, what allied to the information gathered by this work will certainly present a secure scenario for the tectonic history of this region.

The estimated depths show a good correlation with the 3D models obtained for the three anomalies. But it is important to highlight that the models depths are a rough estimative and are conditioned by the cells length used in the mesh.

Analyzing the magnetic and gamma spectrometric results it was possible to conclude that the Nova anomaly has the greater exploratory potential of the three anomalies, being the only one to present outcropping indication.

The susceptibility contrast recovered by the 3D models may be interpreted as diorite-like or porphyry-like intrusions. In both cases, there is possibility for mineral exploration for gold, copper and zinc. To specify the lithological type of the magnetic sources it would be essential borehole analysis of these bodies.

Acknowledgments

Serviço Geológico Brasileiro (CPRM) for providing the data used in the study, and the National Council for Scientific and Technological Development (CNPq) for the award of a PhD scholarship to the first author.

References

DICKSON, B. L., SCOTT, K. M. Interpretation of aerial gamma-ray surveys – adding the geochemical factors. AGSO Journal of Australia Geology and Geophysics, vol. 17, n. 2, pg. 187-200. 1997.

FEDI, M., FLORIO, G. Detection of potential fields source boundaries by enhanced horizontal derivative method. Geophysical Prospecting, 49, p. 40–58. 2001.

GERALDES, M. C., VAN SCHMUS, W. R., CONDIE, K. C., BELL, S., TEIXEIRA, W., BABINSKI, M. Proterozoic geologic evolution of the SW part of the Amazonian Craton in Mato Grosso state, Brazil. Precambrian Research, v. 111, p. 91-128, 2001.

HSU, S., COPPENS, D., SHYU, C. Depth to magnetic source using the generalized analytic signal. Geophysics 63, 1947-1957. 1998.

LACERDA FILHO, J. V. Geologia e Recursos Minerais do Estado de Mato Grosso. Org. Joffre Valmório de Lacerda Filho, Waldemar Abreu Filho, Cidney Rodrigues Valente, Cipriano Cavalcante de Oliveira e Mário Cavalcanti Albuquerque. Esc. 1:1.000.000. Goiânia: CPRM, 200 p., 2004. (Convênio CPRM/SICME).

LOURO, V. H. A., RIBEIRO, V. B., MANTOVANI, M. S. M. Indirect estimation of the tectonic evolution of magnetic structures along the Indiavaí-Lucialva Shear Zone, Mato Grosso, Brazil.. In: AGU Meeting of the Americas, 2012, Cancun, México. AGU Meeting of the Americas 2013 - Scientific Program, 2013.

RIBEIRO, V. B., MANTOVANI, M. S. M. Contribuição geofísica ao estudo do Batólito Granítico Santa Helena, sudoeste do Cráton Amazônico. Geologia USP. Série Científica. , v.12, p.65 - 82, 2012.

RIBEIRO, V. B., LOURO, V. H. A., MANTOVANI, M. S. M. 3D Inversion of magnetic data of grouped anomalies whith different magnetizations study applied to Palmital intrusions In: AGU Fall Meeting, 2012, San Francisco. AGU Fall Meeting 2012 - Scientific Program. , 2012.

SHEARER, S. E. Three-dimensional inversion of magnetic data in presence of remanent magnetization. 2005. 148 f. Dissertação (Mestrado em Geofísica) – Departamento de Geofísica do Center for Gravity, Electrical and Magnetic Studies, Colotado School of Mines. 2005.

TELFORD, W. M.; GELDART, L. P.; SHERIFF, R. E.; KEYS, D. A. Applied Geophysics. 2. Edição. Nova Iorque: Cambridge University Press. 1990. 770 p.