Geophysical Exploration of the Buraco da Velha Deposit (RO, Brazil)

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Abstract

Near the Alto Alegre dos Parecis city is located the Buraco da Velha copper deposit. This deposit reveals magnetic and radiometric anomalies, representing a considerable amount of ferromagnetic minerals in its structure and a concentration of radiometric elements in shallow depths. These behaviors permitted the geophysical study of the deposit through the magnetic and gammaspectrometric methods. This study, allied to previous geological works, indicated the overall spatial distribution of the magnetic and radiometric minerals/elements, an approximation of the age of the source of the magnetic anomaly and the area of hydrothermalization in which can be found the mineralized copper. This information can be crucial for the local mining industry, for an enhanced and more effective copper exploitation.

Introduction

The Rondônia state (Brazil) has been arousing the interest of mining companies, due the increasing discoveries of gold, copper and Platinum Group Elements (PGE) deposits in recent years. The southeast portion of this state reveals a complex structural scenario marked by several compressional and distentional events, indicating a possible origin and evolution compatible to a complete Wilson cycle (Rizzotto, 1999).

Near the Alto Alegre dos Parecis city lies the Buraco da Velha deposit (BVD). This deposit presents occurrences of copper, limestone and manganese at south of the major gold and copper known district of the state.

In 2006, the Brazilian Geological Service (former Company of Mineral Resources Researches - CPRM) performed an airborne magnetic and gammaspectrometric survey over the southeast Rondônia. This survey revealed in the BVD location a magnetic anomaly with evidences of significant remanence. Its location corroborates with a radiometric distribution that can be associated to a hydrothermal alteration.

The inversion of the magnetic anomaly revealed an elongated model in the E-W direction and its susceptibility distribution, along the indirectly calculated remanence, allowed estimating its crystallization at 123 ± 4 Ma.

The geophysical information, bound to the geological, indicates a promising scenario for the mineral exploration, revealing the horizontal and top limits of the probable magmatic intrusion and the extension of the hydrothermal alteration associated to the percolation of its fluids. The knowledge of these characteristics may direct to a more efficient exploitation of the target minerals.

Geological Context

The BVD is located in the northern Colorado Graben, where it makes frontier with the Nova Brasilândia Terrain (Fig. 01; Dardenne *et al*, 2005). The first is the southern extension of the Parecis Basin in the Rondônia state,

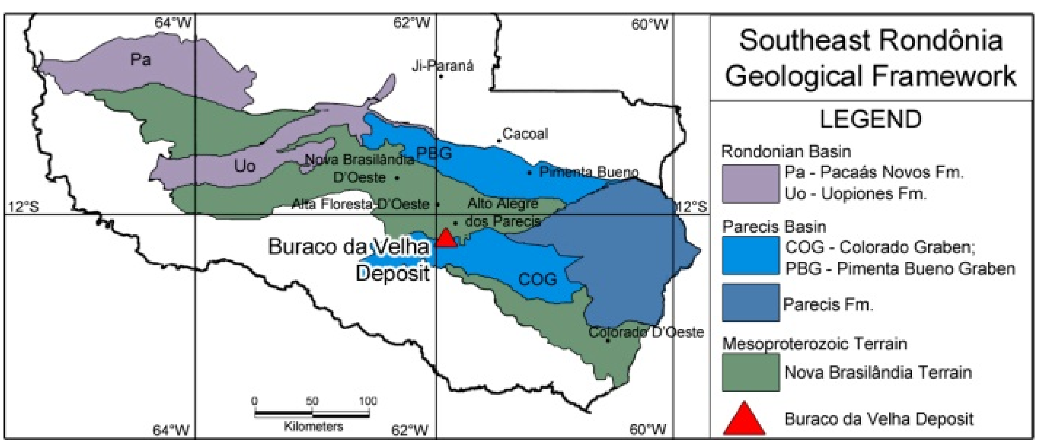

Fig. 01 – Southeast Rondônia geological framework (modified from Dardenne *et al.,* 2005).

being identified in this region as conglomerates, dolomitic limestone, sandstones and claystones, from the granodioritic basement to the surface. Dardenne *et* al. (2005) links the copper mineralization to the dolomitic limestone, in strata-bound occurrences. The same authors date this sequence from 180 Ma to 100Ma.

The more ancient Nova Brasilândia Terrain (aprox. 1100 Ma; Rizzotto, 1999), is described as a meta-plutonic-sedimentary sequence of varied metamorphosed lithologies, due its complex tectonic evolution comporting a complete Wilson Cycle.

The known copper mineralization is attributed to a mixing of hot and cold fluids from different sources. Dardenne *et al.* (2005) indicate that the cold fluids are originated from a hydration of sediments due the presence of paleo-ocean. These authors also infer the origin of the hot fluids as from the basal portion of the Colorado Graben, however without clear evidences.

Radiometric Method

The radioactive elements disintegration releases energy through the emission of alpha (α) and beta (β) particles and gamma (γ) radiation. This process accrues from the atoms' nuclei instability in natural conditions.

The main sources of gamma radiation detected in the Earth's surface comes from the natural disintegration of the potassium (^{40}K), and the elements from the uranium (^{238}U) and thorium (^{232}Th) series present in the rocks.

Several factors influence the gammaspectrometric signal, attenuating it. The main is the absorption of the energy by the own layer of rock or soil above the source limiting the reach of airborne gammaspectrometric data to the first 30 to 40 centimeters depth. Other factors also influence the airborne gathered signal attenuating or interfering in it, as the local vegetation, the soil humidity, thermal inversion phenomenon, topographic variation and directional effects.

The Buraco da Velha Deposit radiometric data showed two distinct distributions of the radiometric elements: the eastern portion presents high values of the three elements interspersed to Th and U predominance. This behavior is generally observed in the region at north to the BVD anomaly and can be associated to the superficial meta-volcano-sedimentary lithology from the Nova Brasilândia Terrain (Fig. 02-A).

The southern region of the Fig. 02-A indicate two more radiometric domains, in the southwest and south having a high concentration of the three elements with tendencies to predominance of K and Th. As it is possible to observe in Fig. 02-B, this characteristic is associated to a topographic depression, which can be interpreted as a trap for the eroded/weathered sediments from rocks in higher topographies around the depression.

The central and western portion reveals a concentration of K and U, prevailing over the Th. The F factor, proposed by Efimov (1978, *apud* Gnojek and Prichystal, 1985), relates the concentrations of U and Th with the K's. Biondi *et al*. (2001) affirm that this normalization indicates efficiently hidrothermalized zones. The Fig. 02-C presents the F Factor map of BVD. This map shows high values for the same central and west zone of the deposit, what can be interpreted as a target for mineral exploration due the known association of copper mineralization with hydrothermal environments.

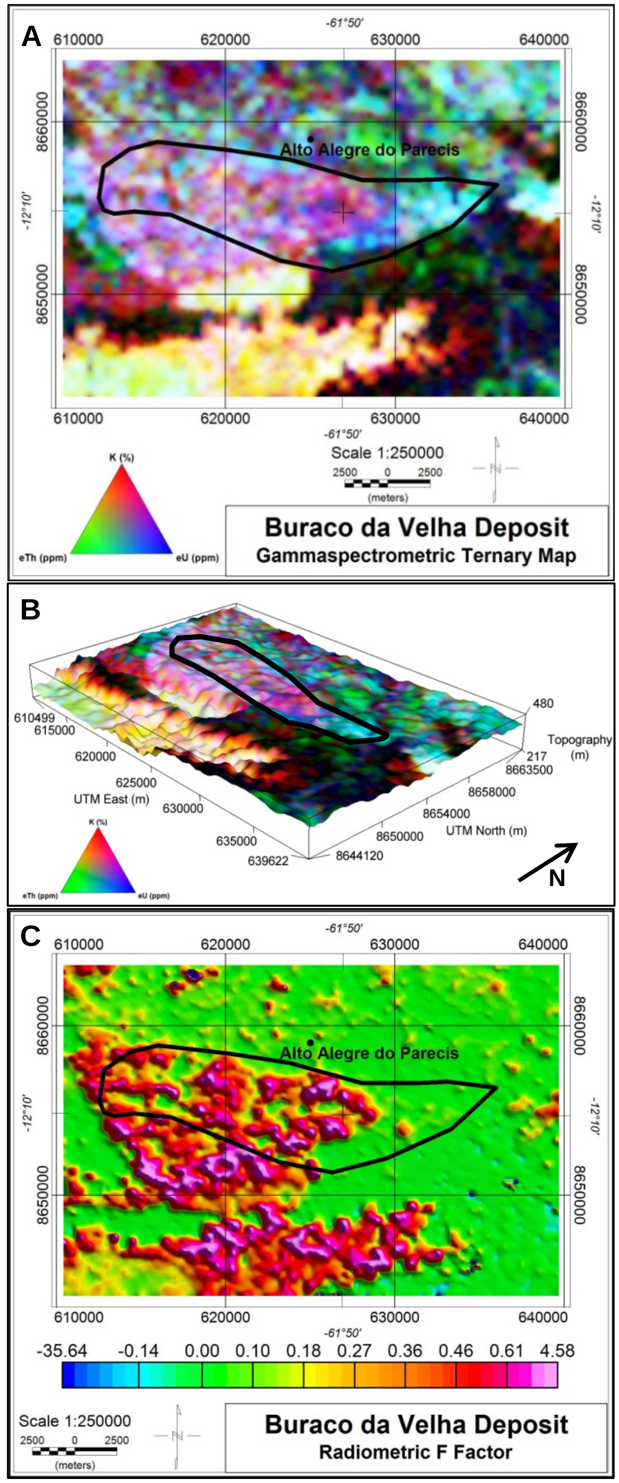

Fig. 02 – (A) Radiometric ternary map of BVD; (B) Surface map of the regional topography around BVD; (C) F factor map of BVD. The black contour refers to the possible borders of the source of the BVD anomaly.

Magnetic Method

The magnetic method is based on the contrast of magnetic susceptibility of a body and its environment. Geologically this contrast may occur between an intrusion and its host-rock, for an example.

The values obtained by the airborne collected data represent the vector sum (Total Magnetization, $\overrightarrow{M_T}$) of the components of the induced ($\overrightarrow{M_I}$) and the remanent ($\overrightarrow{M_R}$) magnetizations:

$$\overrightarrow{M_T} = \overrightarrow{M_I} + \overrightarrow{M_R}$$

The BVD is located at low magnetic latitudes, what implies instabilities to the use of several magnetic processing techniques. Furthermore, the magnetic anomaly related to the deposit also shows evidences that the source of the signal may contain a significant remanent magnetization (Fig. 03). These evidences indicate the need of the use of techniques that have either small or no dependence of the magnetization direction.

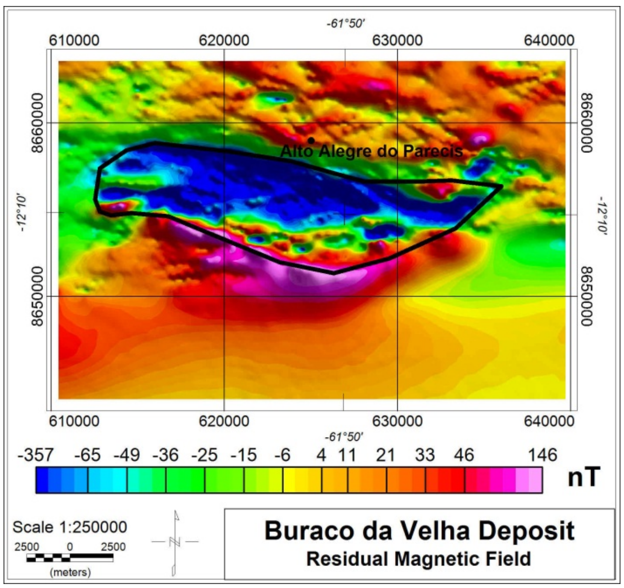

Fig. 03 – Residual magnetic field of the Buraco da Velha deposit.

Borders Delimitation

The lateral delimitation of the BVD's source was obtained by the Amplitude of the Analytic Signal (AAS; Roest *et al.*, 1992) that is defined by the equation:

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

where *M* is the magnetic anomaly field and *∂x*, *∂y* and *∂z* are the derivatives in x, y and z directions.

The AAS showed an E-W structure, following the direction of the normal faulting that separates the Nova Brasilândia Terrain and the Colorado Graben (Fig. 04). This also may indicate a possible structural control for the magma emplacement that resulted in the source of the magnetic signal.

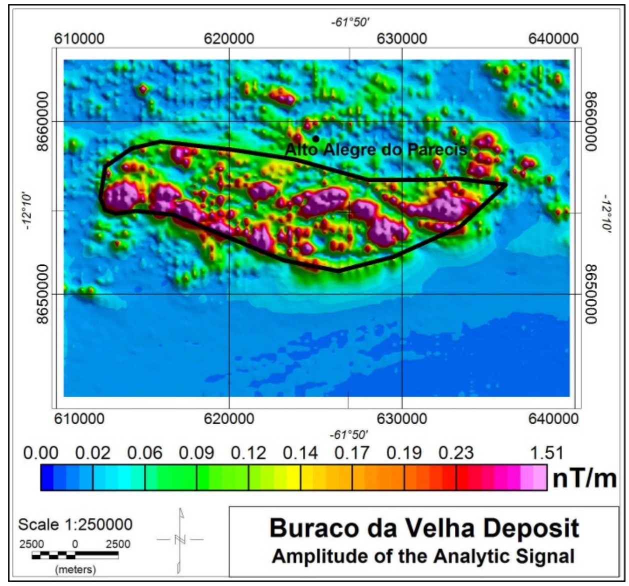

Fig. 04 – Amplitude of the Analytic Signal of BVD.

The Fig. 04 shows a contrast marked in black contour that can be related with a deeper structure, possibly the main body. The smaller peaks of higher amplitudes (in red and pink, inside the black contour) may be linked to shallower bodies related to a hidrothermalization process.

Depth Estimative

The depth estimative of the magnetic sources was provided by the Euler Deconvolution (Fig. 05; Reid *et al.*, 1990). This technique comes from the Euler's homogeneous differential equation:

$$(x - x_0)\frac{\partial M}{\partial x} + (y - y_0)\frac{\partial M}{\partial y} + (z - z_0)\frac{\partial M}{\partial z} = \eta(R - M)$$

being x_0, y_0 and z_0 the magnetic signal source's coordinates, *M* is the magnetic anomaly, *η is* the structural index and *R* is the total field regional value.

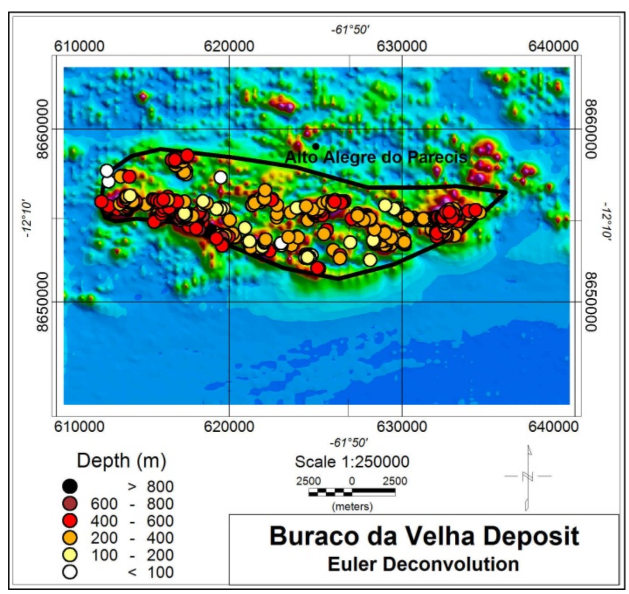

Fig. 05 – AAS map with the estimated depths from the Euler Deconvolution of the BVD anomaly.

The Euler Deconvolution revealed a possible magmatic intrusion with its topmost part varying from 100 to 400 meters

Estimative of Directions of Total Magnetization

In cases of significant magnetic remanence, especially in locations inside the range of the South Atlantic Anomaly, the estimative of the components of the total magnetic field is crucial for a successful inversion of the magnetic data. So it was used the MaxiMin technique of reduction to the magnetic pole (RTP) from Fedi *et al.* (1994), for a first approach of the directions of inclination and declination of the total magnetic field, simulating the anomaly in the vertical field of the magnetic pole.

The MaxiMin technique selects randomly 30 pairs of inclination and declination and it performs a RTP filtering with each one. The worst reduction is then discarded and the process is reinitiated until the values of the pairs inclination/declination do not exceed a pre-defined reliability value. This value must be small enough to does not permit a proper reduction to the pole and large enough to allow the convergence in the n-defined iterations. The value of reliability and number of iterations used were 2 and 4000, respectively.

The low latitudes where the BVD anomaly is found make the RTP filtering unstable. However the resultant pair of the MaxiMin technique indicated approximately the total magnetization inclination and declination. This pair, when used in an RTP algorithm that considers the low latitudes effects as the one from Grant and Dodds (1972 *apud* Mcleod *et al.*, 1993), may filter the anomaly successfully with slight adjustments to the angles of inclination and declination. This RTP filter is given by the relation:

$$L(\theta) = \frac{[\sin(I) - i\cos(I).\cos(D-\theta)]^2}{[\sin^2(Ia) + \cos^2(Ia).\cos^2(D-\theta)].[\sin^2(I) + \cos^2(I).\cos^2(D-\theta)]}$$

where θ is the wavenumber direction, I is the inclination, D is the declination and Ia is the inclination for amplitude correction to stabilize the RTP filtering at low latitudes.

The regional induced inclination and declination were defined through the International Geomagnetic Reference Field (IGRF), being -3.9° and -11.9° respectively. The MaxiMin technique indicated an inclination of 25.5° and a declination of 2.8°. This pair however did not reduce the anomaly properly, resulting in a distortion of the field instead a vertical signal.

When applied the RTP filter from Grant and Dodds (1972), attempting small variations for the inclination and declination angles, it was possible to achieve a filtering resulting in a vertical representation of the anomaly, with an inclination of 16° and a declination of -12° (Fig. 06-A).

In order to confirm the RTP results it was calculated the reduction to the magnetic equator through the algorithm of Grant and Dodds (1972), similarly to the RTP:

$$L(\theta) = \frac{[\sin(I) - i\cos(I).\cos(D-\theta)]^2.[-\cos^2(D-\theta)]}{[\sin^2(Ia) + \cos^2(Ia).\cos^2(D-\theta)].[\sin^2(I) + \cos^2(I).\cos^2(D-\theta)]}$$

The same directions of total magnetic field permitted to successfully reduce to the magnetic equator (Fig. 06-B) confirming the results.

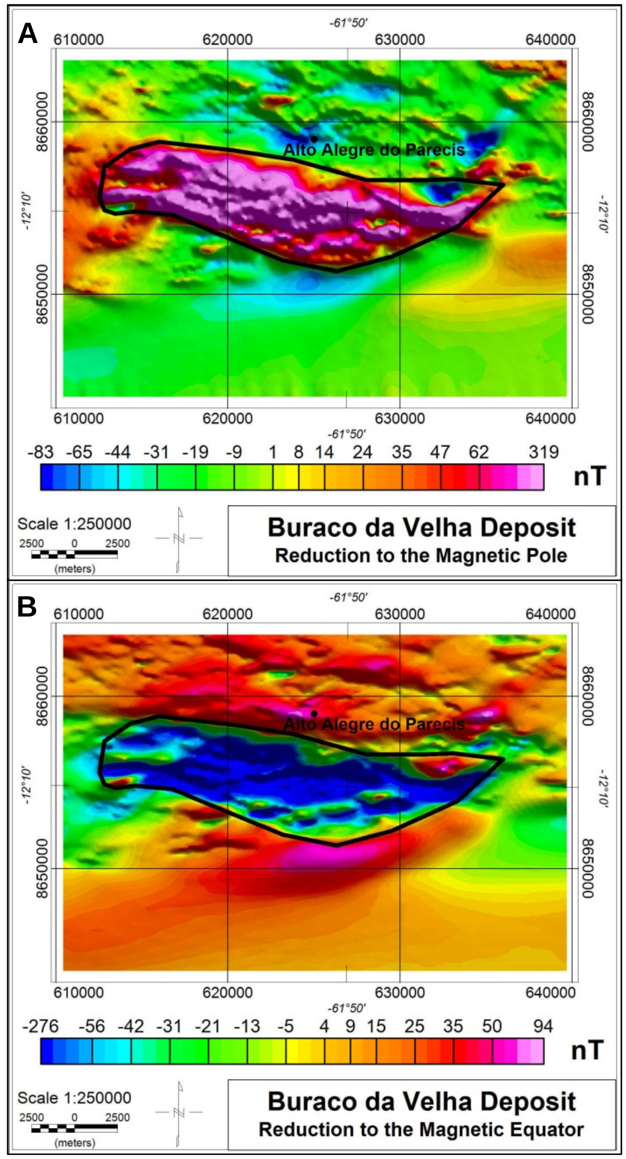

Fig. 06 – (A) Reduction to the magnetic pole of the BVD anomaly; (B) Reduction to the magnetic Equator of the BVD anomaly.

Inversion

The borders and depths estimation gave information about the spatial distribution of the ferromagnetic minerals of the BVD. The region where the BVD in inserted is known as the main concentration of mafic and ultramafic intrusions of the Rondônia state (Rizzotto, 1999) especially gabbroic lithologies. Counting with the average magnetic susceptibility for this lithology available in the accessible literature, it was possible to compose an initial model. It was also applied to the synthetic initial model the directions of the induced magnetic field (IGRF) and the angles of inclination and declination of the total magnetic field.

The magnetic data was inverted with the algorithm from Li and Oldenburg (1996). This algorithm considers the magnetization for the i-th cell (J_i) as:

$$J_i = \chi_i H_0$$

being χ_i the magnetic susceptibility for the i-th cell and $H_0$the Earth magnetic field for its position.

The objective function to be minimized by the algorithm is:

$$\phi = \phi_d + \mu\phi_m$$

where ϕ_d is the adjustment function, given by:

$$\phi_d = \left\| W_d \left(G\vec{\kappa} - \overrightarrow{d^{obs}} \right) \right\|^2$$

Being $\overrightarrow{d^{obs}}$ the gathered data from the survey, G the sensitivity matrix, $\vec{\kappa}$ the susceptibility vector and W_d is the diagonal matrix for which the i-th element is:

$$w_i = \frac{1}{\sigma_i}$$

being σ_i the standard deviation from the i-th data.

Finally, ϕ_m is the regularization function given by:

$$\phi_m(m) = \alpha_s \int_V w_s\{w(\vec{r}).[m(\vec{r}) - m_0]\}^2 dv + \alpha_x \int_V w_x \left\{ \frac{\partial w(\vec{r}).[m(\vec{r}) - m_0]}{\partial x} \right\}^2 dv + \alpha_y \int_V w_y \left\{ \frac{\partial w(\vec{r}).[m(\vec{r}) - m_0]}{\partial y} \right\}^2 dv + \alpha_z \int_V w_z \left\{ \frac{\partial w(\vec{r}).[m(\vec{r}) - m_0]}{\partial z} \right\}^2 dv$$

with α_s, α_x, α_y and α_z being the adjustable coefficients related to the importance of the components of the regularization function; w_s, w_x, w_y and w_z are spatially depending weighing functions. More information is available in Li and Oldenburg (1996).

The inverted model revealed an E-W elongated structure with lateral bounds and depths that corroborated with the results of previous magnetic techniques presented in this study indicated a possible intrusion without evidences of outcropping. The regional geology presents several gabbroic intrusions at north of BVD. Telford *et al.* (1990) present a magnetic susceptibility range from 0.3 to 0.9.

The magnetic field from the inverted model showed an approximated solution for the BVD anomaly. This field showed a good resemblance to the real data and it was confirmed by the histogram analysis of residues (Fig. 08).

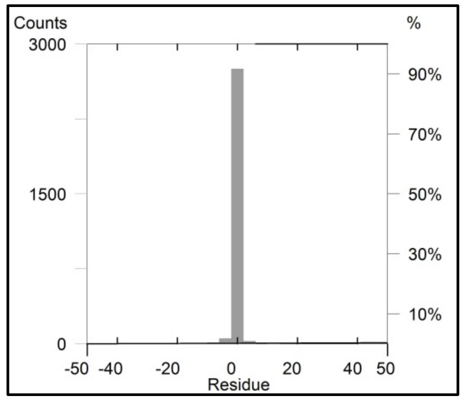

Fig. 08 – Histogram distribution of the residue.

Remanence Estimation

Once known the susceptibility distribution, the induced magnetization (through the IGRF) and the angles of inclination and declination of the total magnetization, it is possible to make a final modeling process to achieve the intensity of the total magnetization.

It was attributed to the distribution of susceptibility the known induced and total magnetization components. The unknown component at this stage is the intensity of the total magnetization, which was estimated by a forward modeling with the spatial parameters and the known components of magnetization fixed, varying the intensity until it is achieved an acceptable approximation from the modeled and real magnetic fields.

This estimation permitted, by vector subtraction of the induced and total magnetizations, to indicate the apparent remanence of the BVD anomaly, with inclination of 22.7°, declination of 168.0° and intensity of 42.2 A/m.

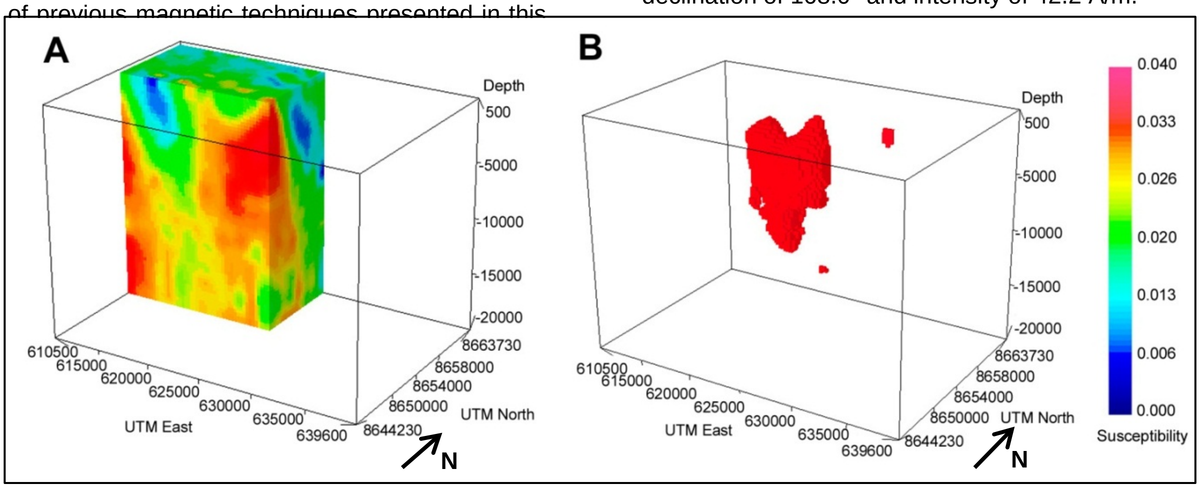

Fig. 07 – Perspective view of the 3D inversion of the BVD magnetic data with: (A) N-S and E-W cuts; and (B) the distribution of susceptibilities of values 0.4 or higher (in S.I.).

Virtual Paleopole and Dating

The estimation of the remanence of the source of the BVD anomaly allowed the calculation of its virtual paleopole (VPP) through the relations:

$$\tan(I) = 2.\tan(\lambda)$$

$$\sin(\lambda_P) = \sin(\lambda_X).\sin(\lambda) + \cos(\lambda).\cos(D)$$

being *I* and *D* the inclination and declination respectively, λ the paleolatitude of the source of the anomaly, λ_X the present latitude of the source of the anomaly and λ_P is the latitude of the paleopole. The paleopole longitude (ϕ_P) depends on a relation among λ, λ_X and λ_P, in which if:

$$\sin(\lambda) \geq \sin(\lambda_X).\sin(\lambda_P)$$

Then:

$$\sin(\phi_P - \phi_X) = \frac{\cos(\lambda).\sin(D)}{\cos(\lambda_P)}$$

Else:

$$\sin(180° + \phi_P - \phi_X) = \frac{\cos(\lambda).\sin(D)}{\cos(\lambda_P)}$$

In the BVD anomaly, the calculated VPP coordinates (XX, YY) can be compared to prior paleomagnetic studies and indirectly dated (Cordani and Shukowsky, 2009). In BVD case, the VPP coordinates (78.3ºS, 28.2ºE) accorded with the data from Mendía (1978), that dated through K-Ar sources in South America with this specific VPP coordinates to 123 ± 4 Ma.

Conclusions

The BVD is a recently discovered copper deposit in the southeast Rondônia state. Its magnetic data revealed a reverse polarity anomaly indicating presence of remanence.

The depths estimated for the top of the anomaly varies mainly from 100 to 400 meters. These depths also give margin for a metallogenic analysis, based on the magnetic and radiometric data, and previous works. The radiometric data showed an element distribution in the western portion of the magnetic anomaly relatable to hydrothermalized environments. The known copper deposit may be linked to hydrothermal processes of magmatic and meteoric fluid mixing in these depths.

It was performed an inversion of magnetic data, indicating an elongated source in E-W direction, permitting the inference that the magma injection was simultaneously favored and restrained by structural control with the normal faulting between the Colorado Graben (Parecis Basin) and the Nova Brasilândia Terrain.

Indirectly, it was possible to estimate the age of the intrusion through the magnetic data, locating its insertion in the upper crust in 123 ± 4 Ma.

The presented results, allied to a possible borehole data to confirmation, are of great value for the mineral exploitation, delimiting the area and calculating the exploratory potential for this target, defining it as economically viable or not.

Acknowledgments

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