Application of the Euler deconvolution 2D and 3D at the Pari syncline, internal area of the Paraguay Belt, Mato Grosso, Brazil

Aplicação da deconvolução de Euler 2D e 3D sinclinal do Pari, zona interna da Faixa Paraguai, Mato Grosso, Brasil

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Abstract

Among the several techniques that allow the estimation of mean depths from airborne geophysical magnetic data, the Euler deconvolution became popular due to the high level of reliability in the generated data. With the use of this tool, it is possible to study structures remotely at different crustal levels that may or may not contain mineralization, consequently being able to determine potential targets for mineral exploration or to study better its relation with the structural background. With the analysis of the magnetic susceptibility of subsurface and the inversion profiles of the magnetic data (Euler deconvolution 2D) were interpolate a 3D model of the region, that allowed to generate a descriptive suggestion of the geometry of the Pari syncline, located in the Cuiabá Group, in the northwestern portion of the Paraguay belt. It has a strong structural control in the context of the Pari River basin and a great auriferous potential, as evidenced by updated research and exploration data. The data applied in this paper were extract from the Cuiabá aerogeophysical project and previous mappings and have their mean depths correlated with the Cuiabá group.

Keywords: Aerogeophysics; Cuiabá group; Pari syncline; Magnetic data; Mineral prospecting.

Resumo

Entre as várias técnicas que permitem a estimativa de profundidades médias a partir de dados magnéticos aerolevantados, a deconvolução de Euler se popularizou pelo alto nível de confiabilidade dos dados gerados. Com a utilização dessa ferramenta é possível estudar remotamente estruturas em diferentes níveis crustais que portam, ou não, mineralizações, podendo assim determinar alvos potenciais de exploração mineral ou estudar melhor a sua relação com o arcabouço estrutural. Com a análise da susceptibilidade magnética de subsuperfície e dos perfis de inversão dos dados de magnetometria (deconvolução de Euler 2D) foram feitas interpolações que configuram um modelo 3D da região, permitindo assim, gerar uma menção descritiva da geometria da sinclinal do Pari, localizada no Grupo Cuiabá, na porção noroeste da Faixa Paraguai. Ela apresenta um forte controle estrutural no contexto da bacia hidrográfica do Rio Pari e um grande potencial aurífero, comprovado por dados de pesquisas e exploração atualizados. Os dados aplicados neste trabalho foram extraídos do Projeto Aerogeofísico Cuiabá e de mapeamentos prévios, tendo suas profundidades médias correlacionadas ao Grupo Cuiabá.

Palavras-chave: Aerogeofísica; Grupo Cuiabá; Sinclinal do Pari; Dados magnéticos; Exploração mineral.

INTRODUCTION

The Paraguay Belt, located in the southeast of the Amazonian Craton, is composed of folded metasediments that progressively evolve into sedimentary coverages (Alvarenga and Trompette, 1993), directly affected by the Brasiliano tectonic cycle (Alvarenga, 1988). Three structural zones, defined and characterized by Almeida (1984) for the Paraguay Belt and for the adjacent craton portion: Sedimentary platform cover; External folded zone with slightly or no metamorphism; and Internal metamorphic zone with granitic intrusions (Figure 1). Afterward, Lacerda Filho et al. (2004) divides the Upper Paraguay Belt into two domains: Passive margin with remnants of oceanic crust (initial stage of rift, with corresponding metavulcano-sedimentary in the Cuiabá Group) and Foreland Basin (transgression with deposition of carbonates of the Diamantino and Araras formation).

The Pari syncline (Oliveira, 2011) acts as a structural control of the Pari river basin, being part of the Cuiabá Group foliation band, composed of meta-sedimentary rocks of low metamorphic degree, folded, with their formation correlated with the tectonic unit Alto Paraguay Belt (Evans, 1894).

The Pari River Basin occupies an area of 753 km²; following from SW to NE about 70 km to the Cuiabá River, its water springs are in quotas that do not exceed 450 m (Thomé Filho et al., 2006). It lies on the border between two tectonically active sedimentary basins, Paraná and Pantanal.

The first records of gold exploration in the Pari river basin occurred in the 1980s (Santos, 1984), when an intensive exploration of secondary deposits began in the entire Cuiabana depression (Miranda, 1997). In tributaries of the Pari River, in the stream Pirapora, a strong gold anomaly occurs (Thomé Filho et al., 2006). Nowadays, it is possible to verify in real time, through the Mining Geographic Information System (*Sistema de Informação Geográfica da Mineração* — SIGMINE) portal of the National Mining Agency (ANM), all the permitting processes opened by the agency around the Pari syncline.

Airborne geophysical maps analysis allows the individualization of lithofacies, visualization of structural lineaments and kinematic movements (faults, fractures, and shear zones), thus estimating possible areas with hydrothermal alteration that support mineral exploration (Madeira et al., 2015). The inversion of magnetic data (Euler Deconvolution 2D) provides structural sections at different depth intervals, allowing the identification of planar structures up to 5,000 m (Madeira et al., 2015).
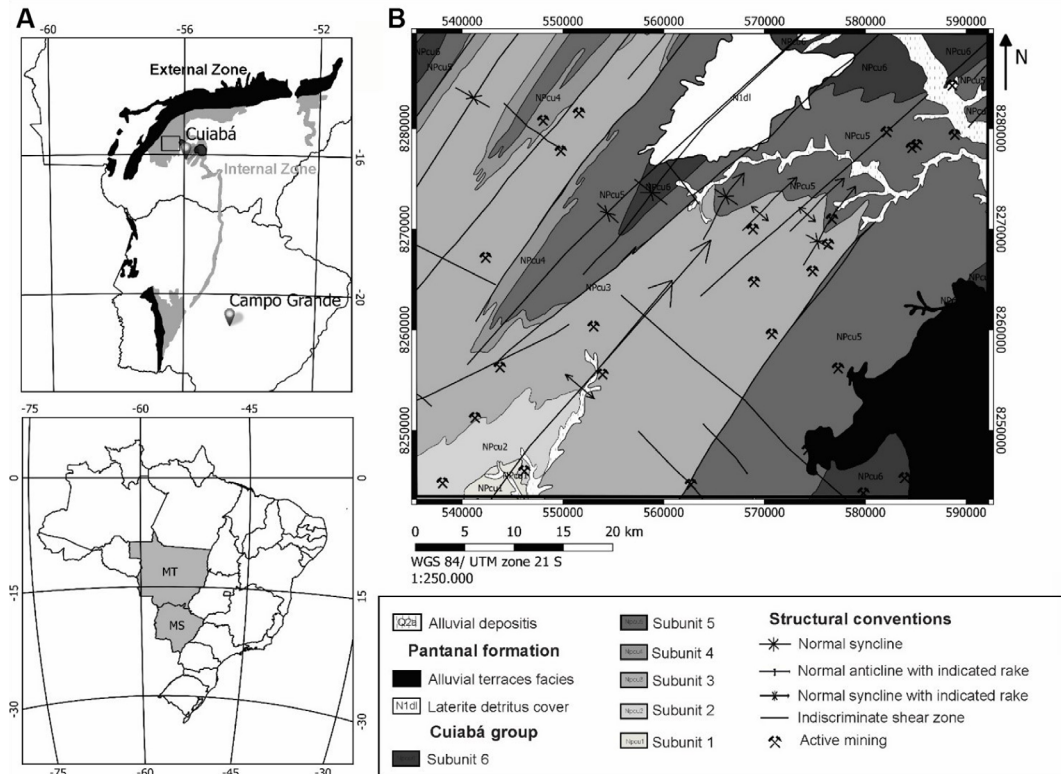
Source: (A) adapted from Alvarenga (1988).

Figure 1. (A) Location map of the Paraguay Belt in the Cuiabá region. (B) Lithostratigraphic map of Thomé Filho et al. (2006), specifying the units present in the area of studies and their structural and cartographic conventions.

The objective of this paper was, based on data from the Cuiabá aerogeophysical project (Lasa, 2014), to establish an estimate of the mean depth of the Pari syncline using the magnetic data inversion technique (Euler 2D and 3D Deconvolution). Therefore, reaching a level of crustal investigation on a local scale that allows correlating the magnetic anomalies and the depth data with the processes and models generated until the present moment of concentration of auriferous deposits.

GEOLOGICAL CONTEXT

The rocks of the Cuiabá Group fit in the tectonic unit of the Upper Paraguay Belt, of neoproterozoic age (Thomé Filho et al., 2006). This belt has a curvature in the NE-SW direction, with the concavity facing southeast. It extends approximately for 1,500 km and has an average width of 300 km (Thomé Filho et al., 2006).

The Cuiabá slate was the first designation made by Evans (1894) for what Almeida (1964) would individualize in the Jangada and Cuiabá Groups. From the work developed by Luz et al. (1980) and Souza (1981), it was proposed the division of the Cuiabá Group into 8 litho-stratigraphic sub-units from the mappings made during the Coxipó project with 1:50,000 and 1:250,000 scales.

Thomé Filho et al. (2006) and Tokashiki and Saes (2008) also divide the Cuiabá Group into 8 subunits, in which there would be 7 subunits and 1 undivided one, where the undivided subunit correlate genetically with subunits 6 and 7.

The region studied during the execution of the present paper is in the Folha SD.21-Z-C-V-2-Cuiabá (Figure 1). The database comes from the works of Thomé Filho et al. (2006) and Tokashiki and Saes (2008).

Subunits 1 and 2 present devastated soils, with thicknesses of 300 to 350 m in the stratigraphy and intercalations of seritic phyllites, phylites, meta-sandstones, and lenses of calcitic marble. Subunit 3 presents several structural indicators, such as normal, inverse, and thrust faults; well-preserved primary structures; and micro-folds. It is composed of phyllites with conglomerate lenses, meta-arkose, meta-sandstone, quartzites, and lenses of calcium metasediments. Subunit 4 is composed of meta-diamictites with rare intercalations with other rocks of the group and has a thickness of 150 m, not very representative in the stratigraphic column. It has no quartz veins. Subunit 5 is the largest subunit of the Cuiabá Group in terms of area of distribution. The predominant rocks are sericitic phyllites and phyllites, with intercalations of meta-arkose, meta-sandstones, quartzites, and meta-conglomerates. This is the subunit that most bears quartz veins, faults and fractures, so this unit shows the majority of wells for groundwater exploration registered in the national system (SIAGAS/CPRM) and most

occurrences of gold mines are in the Cuiabá Group. Subunit 6 shows slightly higher reliefs than the other subunits (1, 2, 3, 4, and 5), with dimensions above 200 m of altitude. It is composed of conglomerate phyllites with intercalations of meta-sandstones and quartzites.

METHODOLOGY

The Euler 2D deconvolution algorithm was developed with the purpose of estimating depths of magnetic sources or magnetic bodies (Oliveira et al., 2005). Developed by Thompson (1982), this technique is based on the homogeneous differential equation of Euler (Equation 1), considering the cartesian coordinates x, y, z and the function described by $T (x, y, z)$. It allowed $T (x, y, z)$ to be a homogeneous function of degree n, if:

$$(x - x_0)\frac{\partial T}{\partial x} + (y - y_0)\frac{\partial T}{\partial y} + (z - z_0)\frac{\partial T}{\partial z} = nT \qquad (1)$$

The equation expresses the anomaly of the total field $\partial T (x, y, z)$ created by a three-dimensional point source situated by the x_0, y_0, z_0 coordinates of the Cartesian System which is subjected to a decrease in intensity at a rate n, distanced between the source and the measured point (Madeira et al., 2015). The structural index n is an indication of the geometry of the source (or magnetic body) generating the observed magnetic field.

The Euler deconvolution is a least squares inversion process in which the values of the total magnetic field anomalies and the chosen structural index aim to solve the Euler equations, producing solutions for the depth and geographical position of all magnetic sources in the selected area (Reid et al., 1990; Reid et al., 2014).

Processing and interpretation were applied in the magnetic database of the Cuiabá aerogeophysical project (Lasa, 2014). Some parameters defined for the data collection as direction N-S for the flight lines with spacing between the lines of 250/500 meters; direction E-W for the control lines with spacing between 5/10 kilometers.

The survey was carried out by two aircrafts of the same model (Cessna Caravan 208B), equipped with the aeromagnetometer Scintrex CS-3. The average aircraft flight speed is between 266/269 km/h and the sample spacing of 74.6/73.8 meters.

All these data, already corrected, were processed by the Geosoft Oasis Montaj software. The magnetometry maps (Figure 2) were originated from a gridding by a bidirectional method with cells of 100 x 100 meters of the anomalous magnetic field (AMF) channel (subtracted from the International Geomagnetic Reference Field — IGRF). Thereafter, they were reduced to the pole (RTP) by the average date in which the area was surveyed (03/06/2014) with a magnetic inclination of -16.83° and magnetic declination of -16.57°, and continued upward at 500 m.
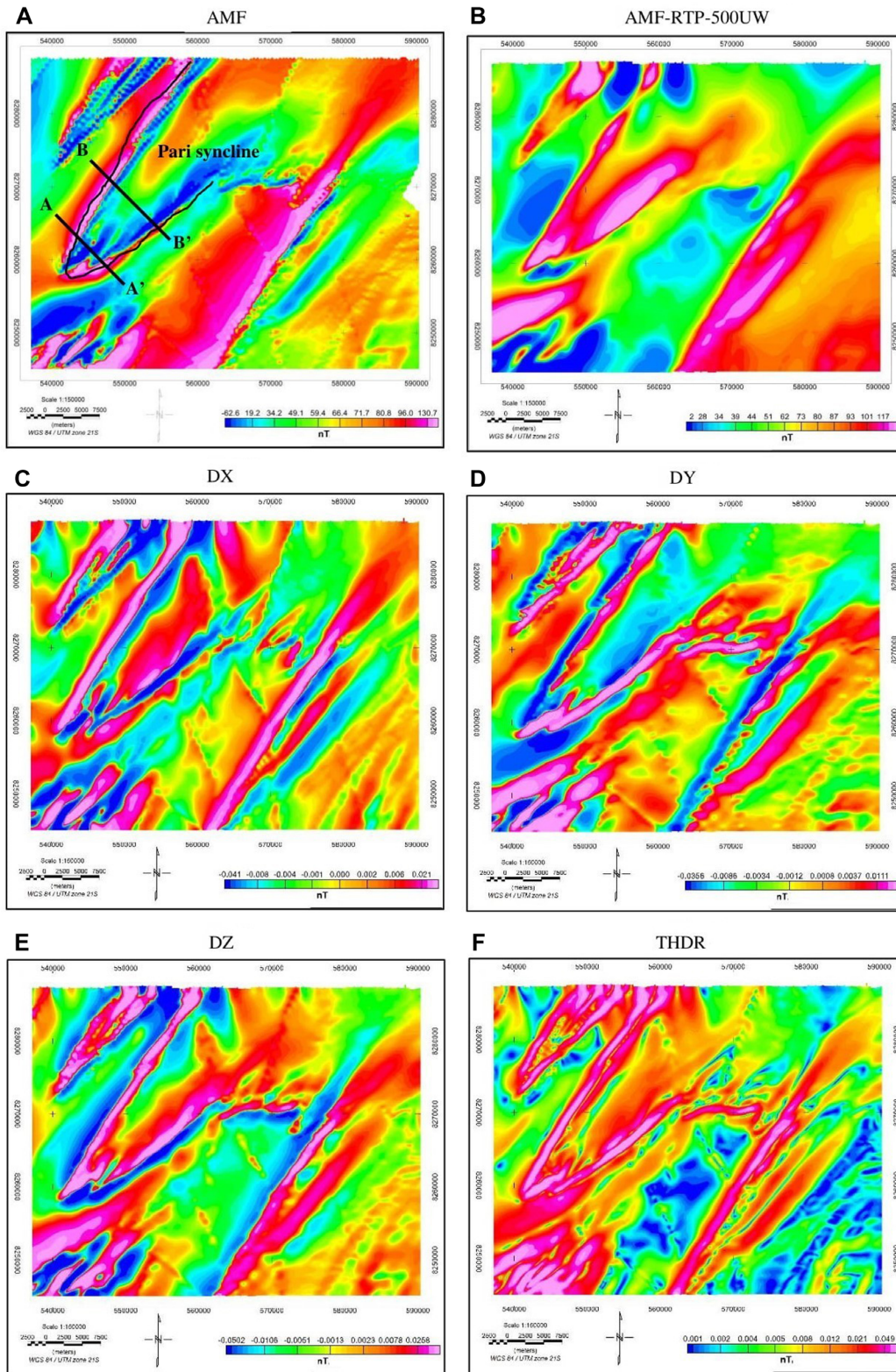
DZ: vertical derivative; THDR: total horizontal derivate.
Figure 2. Flowchart of the adopted methods from the magnetic data. Location of the AA' and BB' profiles in the map of the; (A) Anomalous Magnetic Field (AMF); (B) AMF-RTP-500UW =: Reduced to the pole and Upward Continuation of 500 m; Horizontal Derivatives; (C) Dx - E/W; (D) Dy - N/S); (E) DZ; (F) THDR.

The following enhancement methods were applied to the AMF-RTP-500UW gridding data: horizontal derivative (Dx and Dy), vertical derivative (Dz), and total horizontal derivative (THDR) (Figure 2). This method was applied, using the upward continuation grid maps, to allow the structural analysis of crustal deeper levels (Figure 2).

Directional derivatives of magnetic maps are useful for delimiting the boundaries of bodies and structures that cause major anomalies. Anomalies of short wavelength and greater gradient (generally associated with shallower sources) are highlighted. It is also common to use these derivatives after reduction to the magnetic pole, in order to highlight the center of the magnetic sources.

The upward continuation is widely used to attenuate or remove the influence of the magnetic signal from more superficial sources and sources of noise, constituting a very useful tool for the regional-residual magnetic field filtering. The filter recalculates the magnetic signal, simulating that the measurements taken were located at a greater distance from the earth's surface.

For the 2D magnetometric inversion two profiles (AA' and BB') were selected along the Pari syncline (Figure 2). For this step, two database files (.dta extension) were generated with AMF gridding information, with sampling interval of 1.5 and 2 m respectively, total field strength of 23,215.8 nT, magnetic inclination of -16.83°, magnetic declination of -16.57°, and average flight height of 100 m.

The Euler 2D deconvolution was obtained through the free version of the Euler software, School of Geosciences, University of the Witwatersrand (Figure 3). The deconvolution does not generate geological models by the magnetic field, but limited attempts to be applied in some geological situations.

In order to determine the values of tolerance and window size to be used for the construction of the 3D view of the Euler deconvolution more compatible with the reality, grids of the minimum curvature were made.

Euler 3D solutions (Figure 4) were obtained from the gridded of the anomalous magnetic field reduced to the pole and upward continuation of 500 m (AMF-RTP-500UW), with the relief surface corresponding to the Euler depth solutions.

The structural index used for the adjustment of contacts was 1.0 (option suggested by the software used to generate the profiles) and the window size to control the absorption of magnetic sources was between 1,000 and 2,000 m. Furthermore, it was possible to demarcate structural lineaments corresponding to edges and/or centers of magnetic sources (Figure 5).

The following parameters adopted were the same for both the grids and the view (maximum tolerance of 5 and 10% and window size of 1,000 and 2,000 m), where it was possible to determine the depth intervals to compare with the geology (Figure 6).

RESULTS AND DISCUSSION

In the geophysical anomalies maps, the most evident structure is the Pari syncline, showing a distinct structural pattern in the central region of the area, having its edges and nucleus composed of subunits 4 and 5 of the Cuiabá Group, respectively, corresponding to the basal sequence of the Paraguay Belt.

With the application of the vertical and horizontal derivatives (Figure 2), it was possible to observe magnetic anomalies with positive amplitudes of homogeneous and elongated geometry throughout the studied area.

Two preferred structures with perpendicular directions were identified. The first one (L1), more profuse and predominant, corresponding to 90% of the structural interpretations, with NE-SW direction, correlated with the preferential trend of structures mapped in the Cuiabá Group, where the contacts, plane axial foliations to folds and faults related to folds have an orientation of 30°N – 40°E (Luz et al., 1980; Migliorini, 1999). The second direction (L2), less abundant, has a preferential NW-SE direction and is correlated to relief fractures, filled by discordant veins, with predominant orientation 50°N – 70°W, structures already mapped in previous works (Miranda, 1997; Migliorini, 1999; Lacerda Filho et al., 2004).

With the upward continuation grid of 500 m, it was possible to attenuate the noises, thus being able to circumvent more successfully the geophysical maps. Which allows the previous analysis of the anomalies that prevail in depths below the surface, thus suggesting which structures would have the most consistent results in the Euler 2D and 3D solution.

The choice of the position of the 2D profiles AA' and BB' was made with the intention of intercepting the Pari syncline, which presents the largest amplitudes of the recorded magnetic data, with predominant direction NE-SW, which allowed the analysis of the subsurface geometry.

In the AA' profile, the SE flank is deeper in relation to the NW flank, reaching depths closer to 1,100 m, yet it shows a greater slope which shows the likely direction of the dive, based on surface data.

In the BB' profile, the flanks have a lower depth than the maximum observed in the AA' profile, reaching approximately 650 m, but present similar geometry, with the SE flank deeper than the NW flank, and inclined indicating the dive.

From the minimum curvature grids of the depth channels (Figure 4), it was analyzed as the window size decreases, the number of solutions increases, and small windows can visually pollute and complicate the interpretation of bodies
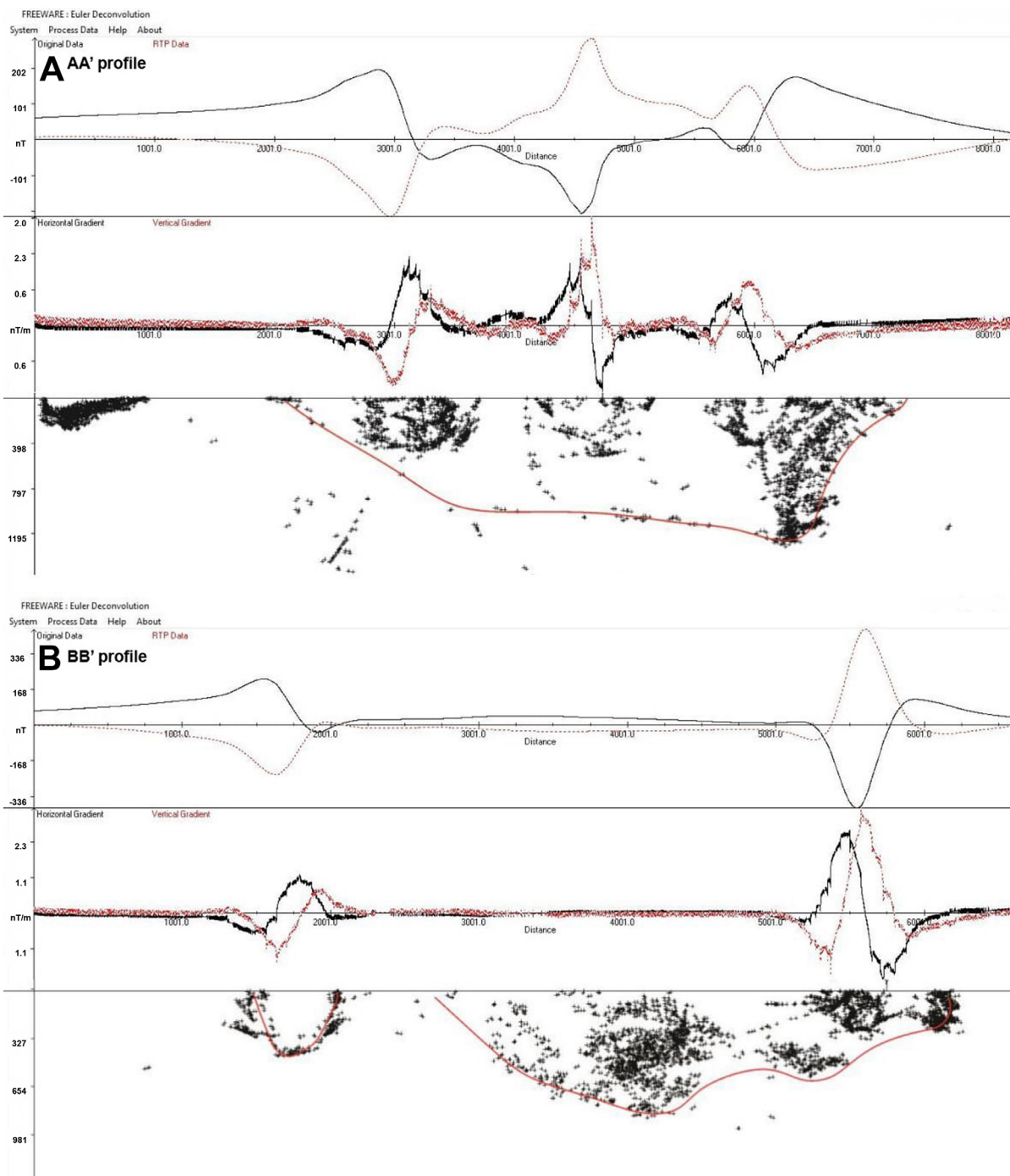
Figure 3. (A) Euler solutions of the AA' profile (window size 1,100 m, x separation 40.95 m, y separation 20.47 m, maximum depth 1,594.50 m); (B) Euler solutions of the BB' profile (window size 1,100 m, x separation 33.08, y separation 16.54, maximum depth 1,308 m). See locations of the profiles in Figure 2A.

in regional-sized grids, whereas in smaller areas the method has higher resolution. The inverse occurs with the tolerance, in which the greater the tolerance defined, the greater the number of solutions found.

Thus, after the analysis, the generated data were adopted as the most reliable model for the real quantitative interpretation of the Euler solution, the grid of tolerance 10% and window size of 2,000 m. From it, a 3D view of the Euler
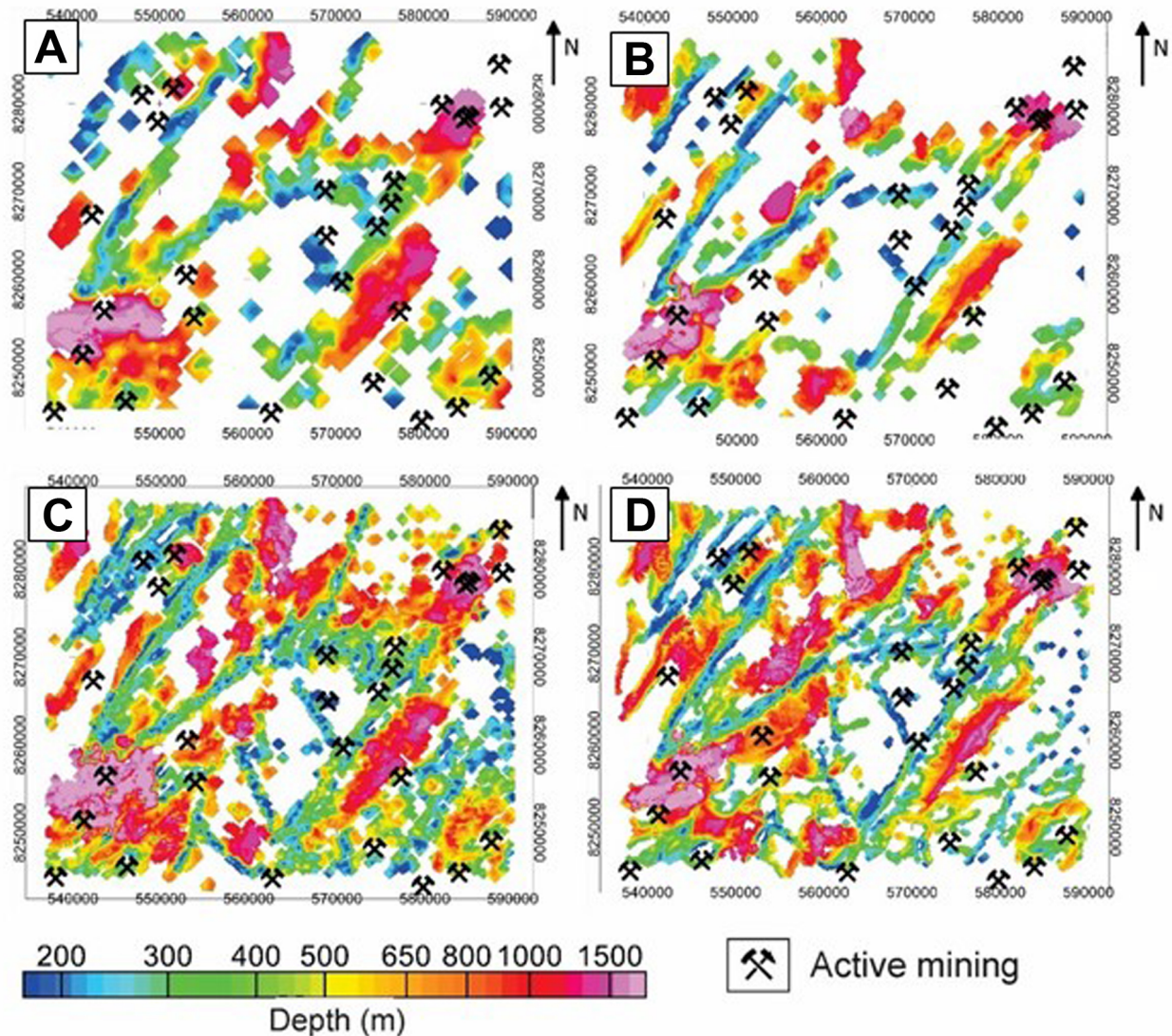
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Figure 4. Grids generated from the solution of the Standard Euler solutions with structural index n = 1, with values of: (A) Tolerance 5% and window size 1,000 m; (B) tolerance 5% and window size 2,000 m; (C) tolerance 10% and window Size 1,000 m; (D) tolerance 10% and window size 2,000 m. Active mining according Brazilian National Mining Agency (ANM).

solution was generated, allied with drawn magnetic lineaments above structural elements corresponding to edges and/or centers of magnetic sources (Figure 5).

This grid showed Euler solutions correlated only with active mining in the area (according to data available in the ANM portal) and presents a greater amount of information about the average depth of the study area (Figure 4D).

With the analysis of the 3D view (Figure 5) and the 2D profiles (Figure 3), it was possible to observe an inclined fold with a NE vertical fold axis, shallow limb and hinge zone, with depths between 0 (outcrop) and 200 m.

The depths of the Pari syncline reach values between 1,100 and 1,500 meters for its core. In relation to profiles AA' and BB', they show a slight reduction of the anomaly generated by the structure in the SW to NE directions.

With the integration of data from Euler solutions and active mining in the area, it was possible to estimate that of the present 27 gold deposits: 15 of them (56%) have a correlative magnetic anomaly between 0 – 400 m depth; 8 of them (30%) present a correlated anomaly between 400 – 1,000 m of depth; and 4 of them (14%) did not present a directly correlated magnetic anomaly.

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From the data presented above, it is possible to correlate them with works already carried out in the Paraguay Belt, in the area of regional geology and metalogenesis, evidencing the consistency in the integration of the information generated by aerogeophysical surveys in relation to terrestrial studies.

Luz et al. (1980) characterized three modes of occurrence for the Cuiabana depression gold province: Gold associated with quartz veins; gold of the eluvial — colluvial coverings; and gold in the recent alluviums.

The origin of the deposits surrounding the Pari syncline is associated by Miranda (1997) and Gambier (1998) as the first Cuiabá Group deformation phase, characterized by reverse folds (D1) and reverse shear zones (Figure 6).

Souza (1988), Silva (1999), and Oliveira (2011) attributed the presence of gold deposits in the region to hydrothermal processes, generating Au-rich quartz veins with strong structural control. Oliveira (2011) confers on the preferential direction of the exploration of mineralized quartz veins in the Cuiabá Group with NW-SE direction, present in large folds, in the hinge zone.

As can be seen, some structures, after the formation of the Pari syncline, such as thrust faults and shear zones, corroborate with the data of Thomé Filho et al. (2006) and Oliveira (2011), which point out these structures as essential for the formation of first-order gold deposits (Figure 6).

These structures must be related to the third orogenic event of the Cuiabá Group, represented by faults and introduction of quartz veins, occurring in the intrusion of acid bodies, which generated a strong hydrothermalism, thus conferring the surrounding deposits of the Pari syncline directions in agreement with foliations S_2 and dives to NW and SE (Luz et al., 1980; Miranda, 1997).
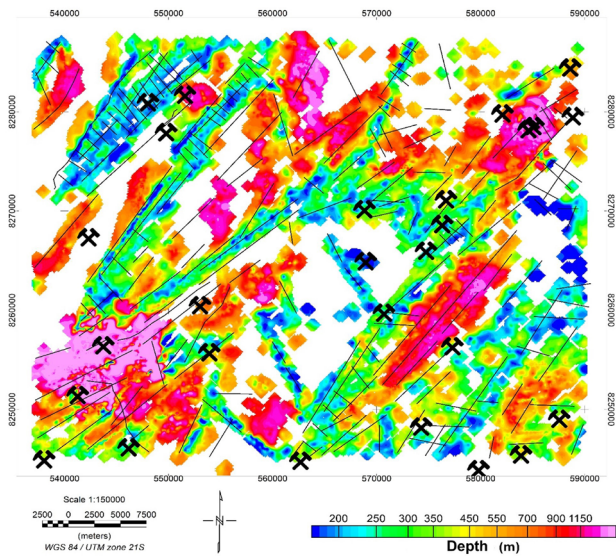

Figure 5. 3D view of Euler solutions of the data in Figure 4D (structural index SI = 1; tolerance = 10%; window size = 2,000 m) with magnetic lineaments above structural elements corresponding to edges and/or centers of magnetic sources.

CONCLUSIONS

By applying the Euler Deconvolution to the airborne geophysical data, together with the available geological and
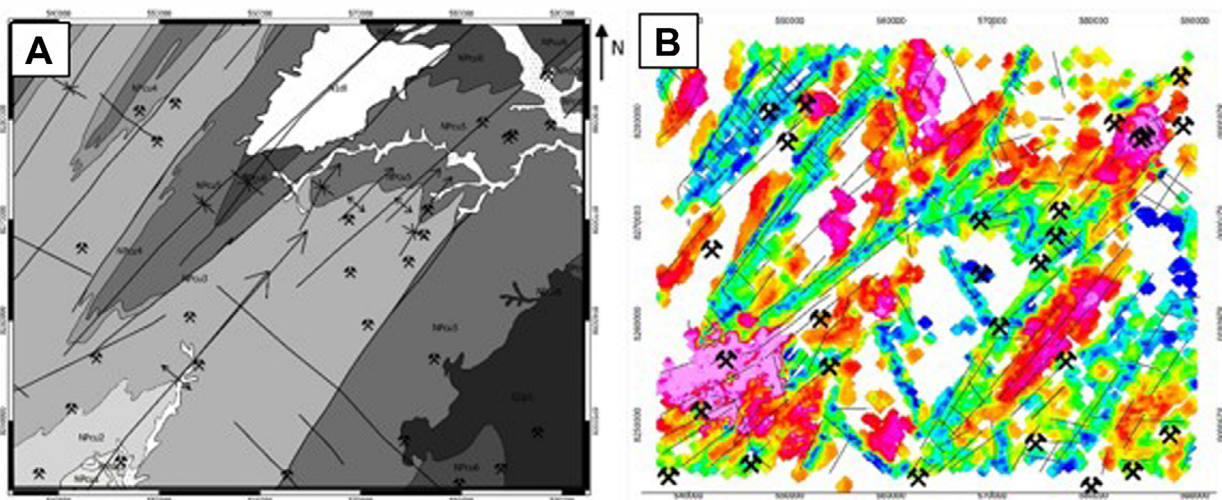

Figure 6. Comparison between (A) the lithostratigraphic map of Thomé Filho et al. (2006), and (B) Euler deconvolution map with magnetic lineaments above structural elements corresponding to edges and/or centers of magnetic sources. See the legends of each feature in (A) Figure 1B and (B) Figure 5.

mineral resources database, it was possible to estimate the average depth, the main geometric and the morphological elements of the Pari syncline.

The generated maps show strong indications that the magnetic anomalies of larger amplitudes are correlated with the deformation phases that occurred during the orogenesis of the Cuiabá Group in the formation of auriferous deposits associated with quartz veins of hydrothermal origin.

In addition, the maps of the Euler 2D and 3D solutions allowed to analyze the continuity and lateral extension of the Pari sycline in the subsurface, thus facilitating the analysis of the tectonism that occurred in the region and of the present megaestructures.

The gold extraction in the study area is concentrated around the Pari sycline, correlated, for the most part, with magnetic anomalies up to 400 m deep. In the Pari sycline inner region, up to the date of publication of this article, proceed through 12 research requests for gold inside the ANM, which shows the great economic potential of the area and the importance of understanding the subsurface features that host deposits.

In highly complex terrains, which present indicators of multiple deformation efforts, such as the Cuiabá Group, this tool proved to be quite feasible for the determination of the structural framework. It requires a relatively short time for the generation and interpretation of aerogeophysical maps and covering an area that hardly any other method would reach with better or similar precision, using the same financial resources, which in the case of the data used in the present work, was much more accessible than a campaign of drilling holes, for example.

The application of this tool opens a new perspective for the study of the magnetic bodies of the Paraguay Belt. As it is an extensive and complex region, this method has great potential, if used correctly, to support the determination of the structural framework and its metalogenetic relationships.

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