Aeromagnetic Data Analysis: A Case Study of Igarapé-Bahia and Alemão Mining Deposits in Carajás Province, Pará State

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Abstract

The southeastern region of the state of Pará is known worldwide for its metallogenic potential, it is home to several deposits of the Iron-Oxide-Copper-Gold type, including the Igarapé-Bahia and Alemão Body mines, the largest gold mine in the Amazon. Magnetometry is one of the most used tools to discover these types of deposits. The Geological Survey of Brazil has a database of free-access aeromagnetic projects throughout Brazil. In this context, this present work consists of processing aerogeophysical data from the mineral Province Carajás region of Carajás, focusing on structural geological characterization and the search for bodies with mineral potential in the region.

Introduction

The Brazilian mineral industry makes a significant economic contribution to the country's trade balance. Brazil is known worldwide for its high potential in hosting large mineral reserves. Among the regions producing mineral commodities in Brazil, the Mineral Province of Carajás (MPC) stands out. Located in the southwest of the state of Pará, it is recognized worldwide for its world-class deposits of iron ore, copper-gold, manganese, nickel, and others. The MPC is characterized by various authors as a volcano-sedimentary sequence associated with granitic rocks ranging in age from the Archean to the Proterozoic, which justifies its prospective potential.

In this context, the MPC hosts several deposits related to the Iron-Oxide-Copper-Gold (IOCG) system. Among these, notable deposits include the Cu-Au-Ag Salobo, Cu-Au Sossego, and Sequeirinho, as well as the Cu-Au Igarapé-Bahia and Alemão deposits. The latter, located approximately 120 km from Parauapebas, represents the largest gold mine in the Amazon, with an estimated annual production of over 11 tons. According to Almada and Villas (1999), these concentrations are due to supergene processes that formed a lateritic-Gossan crust with average thicknesses of 100m. The location of these reserves is illustrated in the following map.

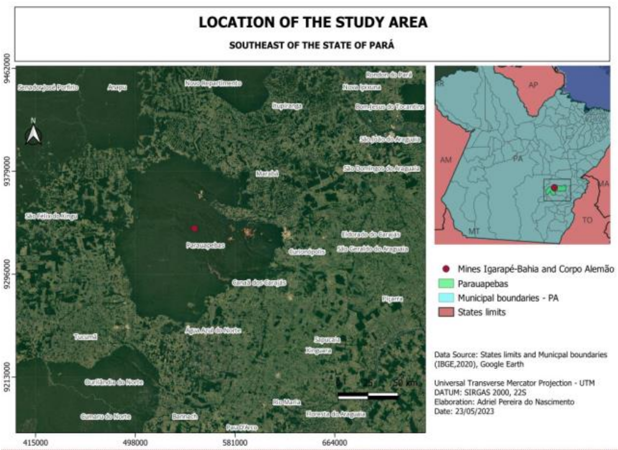

Figure 1 – Location map of the study area.

For the identification of reserves of this type, magnetometry is widely used mainly due to its speed and low cost compared to other methods. It measures the anomalies of the Earth's magnetic field when it is influenced by rocks in the subsurface, increasing or decreasing depending on the contrast of the magnetic susceptibility present in the rocks. The Geological Service of Brazil (SGB) has a database with geological and geophysical information on a large part of the country, this data is publicly accessible and available on its website (www.cprm.gov.br).

Therefore, using aero geophysical surveys available in the SGB, the objective of this present work focuses on the treatment of data in the PMC region, where after the geological understanding and the geophysical signature of the area, it becomes possible to identify metallogenetic horizons with mineral potential when comparing similar responses to those found in the Igarapé Bahia and Corpo Alemão deposits.

Geological Context

Regional Geology

In the regional geological context, the Carajás Mineral Province (CMP) is located within the Archean-age Amazonian Craton, which was initially divided into three blocks: the Itacaiúnas Belt, the Rio Maria Granite-Greenstone Terrain (RMGGT), and the Pau D'Arco Belt (Araújo & Maia, 1991; Costa et al., 1995). Later, it was reduced to only two domains: the RMGGT and the Carajás Block (Souza et al., 1996; Dall'Agnol et al., 1997, 2006; Althoff et al., 2000). Numerous studies have been carried out on tectono-stratigraphic concepts related to the evolution of the CMP, the most notable works being

Araujo & Maia (1991), Oliveira et al. (1994), Costa et al. (1995) and Pinheiro & Holdsworth (2000). According to Venziani et al. (2004), despite some differences among these authors, they converge on the following points:

1) The region is located within the Itacaiúnas Shear Belt, oriented in a WNW-ESE direction.

2) Shear of a ductile nature affected the infracrustal rocks (Pium and Xingu complexes and the Monte Bacajaí Suite) and part of the cover sequences represented by the Itacaiúnas Supergroup. This deformation is associated with a set of oblique sinistral movements (imbricate thrusts), related to regional transcurrent events.

3) The development of this movement occurred during the Archean era.

4) A dextral transtensive episode (in the WNW/ESE direction) was recognized, also occurring during the Archean era, which resulted in the formation of a series of basins.

5) From the Neoproterozoic period (1.9 - 1.8 Ga), Pinheiro & Holdsworth (2000) reported a predominance of extensional movements, which were responsible for the emplacement of granites.

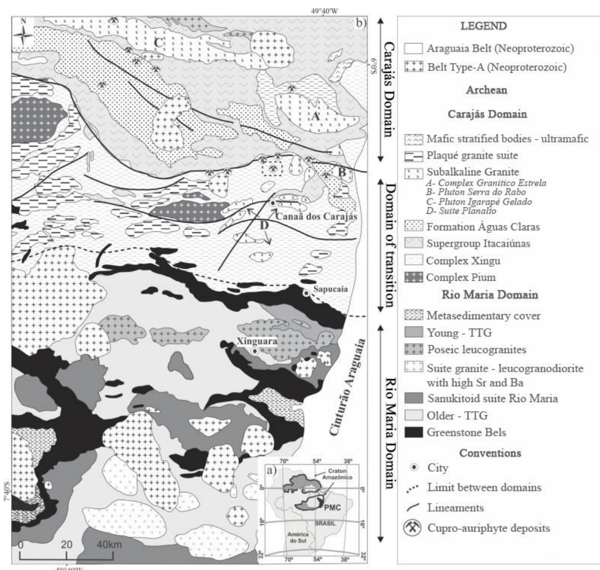

Figure 2 – Simplified geological map adapted from Craveiro et al., 2012.

The figure above illustrates the geological distribution of the region, both in the regional and local context, which will be summarized below.

Local Geology

The study area covers the geology surrounding the Igarapé Bahia and Corpo Alemão mines. In this context, the rocks belonging to the volcanic-sedimentary sequences that vary in age from the Archean to the Paleoproterozoic stand out. These rocks underwent metamorphism at the greenschist facies and are composed of mafic volcanic rocks at the base and metapelite rocks at the top, indicating a metapelite sequence. Below is a summary of the main lithostratigraphic units found in the region:

1) Igarapé Bahia Group: It consists of a volcanic-sedimentary sequence, with the Grota do Vizinho Formation at the base and the Sumidouro Formation at the top. The Grota do Vizinho Formation is described as containing pyroclastic, clastic, and chemical sedimentary rocks, and subordinate metabasaltic rocks. The Sumidouro Formation is composed of sandstones with intercalations of basic volcanic rocks (Ferreira Filho, 1985).

2) Águas Claras Formation: This terminology was defined by Araújo et al. (1991) to replace the term "Rio Fresco Formation" due to difficulties in faciological correlations. DOCEGEO (1988) initially attributed a Paleoproterozoic age to it, but Dias et al. (1996) determined a Pb/Pb age of 2645±12 Ma for intrusive metagabbro sills within the Águas Claras Formation, indicating an Archean age. Nogueira et al. (1995) described this unit as siliciclastic sedimentary rocks, including sandstones, claystones and siltstones, deposited in coastal to fluvial environments that outcrop in the central portion of the Carajás Transcurrent System.

3) Dikes and Sills: These are described as bodies in the form of dikes and sills that cut through a large part of the Serra dos Carajás. Silva et al. (1974) initially assigned an age of 550±30 Ma to these mafic bodies. However, other authors have reported U-Pb ages in zircon ranging from 2556±29 Ma to 2708±37 Ma (Mougeot et al., 1996), and a Pb-Pb age in zircon of 2645±12 Ma (Dias et al., 1996).

4) Ore Bodies: TAVAZA (1999) macroscopically characterizes the rocks that host the ore bodies of the Igarapé Bahia mine by a volcanic-sedimentary sequence described from base to top by: metavolcanic; siliceous metapyroclastic/volcanoclastic and hydrothermal breccias; and metasedimentary rocks. According to TAVAZA (1999), hydrothermal breccias present a matrix with varied proportions of chlorite, tourmaline, carbonate, quartz, magnetite, chalcopyrite, bornite and, more rarely, biotite and stilpnomelane and, based on this descriptive composition, described 3 types of breccias: breccias chloritic, sideritic and magnetitic, the last two being linked to Cu-Au mineralizations.

Materials and Methods

Magnetometry

Magnetometry is a geophysical technique that measures the magnetic susceptibility of minerals based on localized variations in the Earth's magnetic field and the magnetic characteristics of rocks and geological structures present underground. These variations are interpreted as anomalies that may indicate the presence of ores. In addition, the method has a varied investigation scale, and its interpretation is relatively easy, making it widely used in mineral exploration (SORDI,2007).

Being a property that originates in the atomic structure of materials, magnetism determines how a given material behaves in the presence of a magnetic field. In this sense, there are several types of designations for the behavior of these materials when exposed to a field, among them diamagnetic, paramagnetic, and ferromagnetic materials stand out (Pereira,2021).

Data acquisition for surface magnetometry is typically carried out in small areas where the targets have already been pre-determined, and the spacing between measurements generally ranges from 10 to 100 meters. However, for the investigation of large areas, aero magnetometry is used using small to medium-sized aircraft, and in these cases, the spacing between flight lines depends on the desired level of detail in the region. Higher levels of detail require smaller distances between flight lines. Greater levels of detail require smaller distances between the flight lines, that is, for reconnaissance surveys, the spacing can vary between 1 and 2 kilometers, while for detailed surveys, this distance decreases considerably to the range of 100 to 150 meters. It is noteworthy that the flight altitude is kept as low as possible in both cases (CPRM,2010).

This method is more compatible with plutonic magmatic rocks, particularly basic and ultrabasic rocks. On the other hand, the method has a limited affinity for sedimentary or metasedimentary rocks. In general, when working in areas dominated by the sedimentary or metasedimentary cover, the magnetic-contrast anomalies are commonly associated with the crystalline basement (CPRM,2010)

Aero Geophysical Projects

For this work, data from CPRM aero geophysical projects 1097 (Tucuruí aero geophysical project) and 1129 (Rio Maria aero geophysical project) were used. The first covers the central-eastern region of the state of Pará, this aerial geophysical survey covered just over 97,000 km of magnetic air profiles in high resolution using the city of Marabá-PA as the center of operations. The second focused on the southeast region of the state of Pará and a small northwest portion of the state of Tocantins in the northern region of Brazil, where the aerial survey covered more than 118,000 km of aero magnetometric profiles and had the cities of Marabá and Redenção in the state of Pará and the city of Araguaína in Tocantins as a base of operations (CPRM, 2010)

In both surveys, the flight and control lines had spaced of 500 km and 10 km, respectively, with flight lines oriented in the N-S and E-W directions. The flight altitude was set at 100 meters above the ground surface, although variations of up to 15 meters were allowed in the Rio Maria Project due to the region's topography. The data acquisition equipment used was the Scintrex CS-3, which was attached to the tail of the aircraft. The signal was received through a preamplifier located at the base of the tail cone and sent to the aeromagnetic acquisition and compensation system contained in the FASDAS system (CPRM, 2010).

In both surveys, the flight speed was approximately 266 km/h. In the Tucuruí Project, magnetometer readings were taken every 0.1 seconds, which corresponded to approximately 7.4 m on the ground. In the Rio Maria Project, one of the aircraft captured data at a rate of 0.01 seconds (100 Hz), equivalent to 0.736 m on the surface.

Data processing

Data processing was carried out using the Oasis Montaj Software, licensed by the Geosciences Department of UFRRJ, in which the XYZ coordinates of the aero geophysical projects of Tucuruí and Rio Maria were applied, where they were submitted to the filters that will be detailed below:

1) Directional filters: They are used to highlight structural features or mitigate undesirable effects (trends). It must be used with great caution because it can darken or eliminate important structures. They are used in conjunction with raster imaging systems to digitally illuminate datasets from a chosen direction (horizontal and vertical), creating lighter tones in the data gradients facing the direction of illumination and darker tones in the gradients facing away. away from the lighting direction (Isles & Rankin, 2019).

2) Correction of the geomagnetic field: As it is not useful for mapping, it is necessary to remove the influence that the magnetic field suffers from the Earth's core, this can be done by subtracting the IGRF (International Geomagnetic Reference Field) which are values generated by mathematical models that estimate the value of this influence (SORDI, 2007).

3) 3) ASA (Analytic Signal Amplitude): Comprises the combination of the vertical and horizontal gradients of the anomalies, it is commonly used when you want to map the edges of a given body. Generally, the results are very significant in regions where the remnant magnetization is relevant where the sources are shallow and the magnetic latitude is low since their results depend on factors such as depth, direction of the terrestrial magnetic field, and angle and extension of the immersed body. (Pereira, 2021).

4) Tilt Derivative: It is used to identify gross variations in the slope of the layers that can indicate the presence of flaws or folds. Normally, when the filter is applied, regions with high spatial variations of the field are amplified and regions with smooth variations are attenuated, highlighting edges and discontinuities in geological structures (Isles & Rankin, 2019).

5) Power spectrum: It is composed of the sum of individual time series that differ in their wavelengths and amplitude since they all have sinusoidal shapes, representing the variations of the harmonic sequences of the analytical signal. The discontinuities in the slope of the spectral

function allow organizing the sources that cause anomalies according to their depth (RAMOS, 2010).

Results

The first data obtained was the Geomagnetic Field Correction (TMI), which was processed by combining data from the aerogeophysical projects of Rio Maria and Tucuruí. However, upon initial processing, the data showed vertical trends, requiring the use of directional filters in the same direction to smooth these trends. After applying the filter, the TMI was generated, which is illustrated below along with its geographical distribution by region seen in the Figure 3.

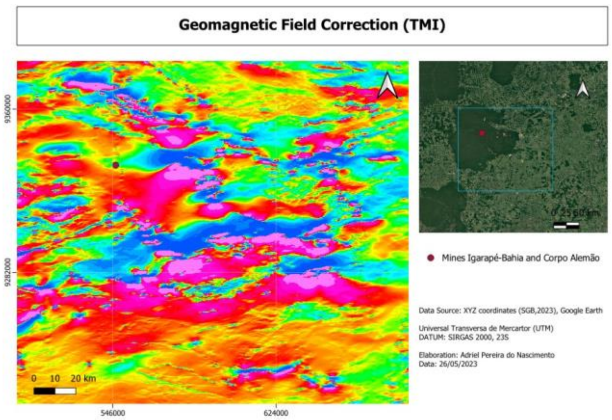

Figure 3 – Geomagnetic Field Correction.

From the generated TMI, we submitted the data to the Tilt Derivative and First Vertical Derivative filters, these results help in the identification of faults and geological structures, allowing a structural characterization of the region (Figure 4).

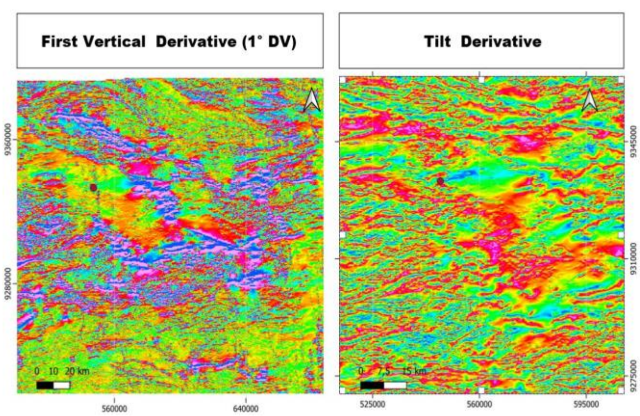

Figure 4 – 1DV and Tilt filters.

For the identification of bodies with mineral potential, we used the ASA filter (Analytical Signal Amplitude), from which we selected two areas of interest so that later some bodies with a possible mineral potential could be selected, the regions of these areas were submitted to other procedures (Power Spectrum and Euler Deconvolution) for a better detailing of them. The ASA along with selected areas are illustrated in Figure 5.

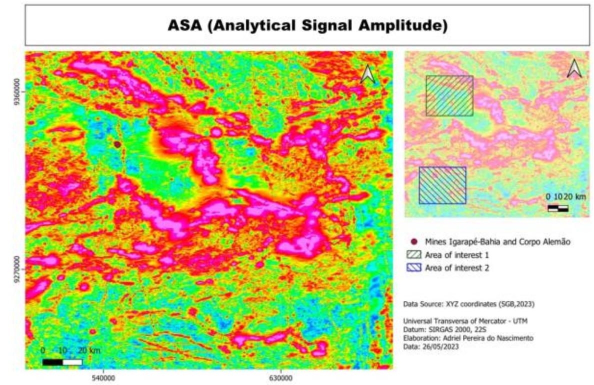

Figure 5 – ASA and selection of areas of interest.

Discussion

Comparing the results obtained with 1DV and Tilt, it was possible to identify that most of the faults that occur in the region have an E-W direction and the geological structures that occur in the N-S direction are mostly associated with gabbro or diabase dykes. Due to the low resolution of the data in 1DV and Tilt, the structures mapped in them were plotted using TMI as a base as shown in Figure 6:

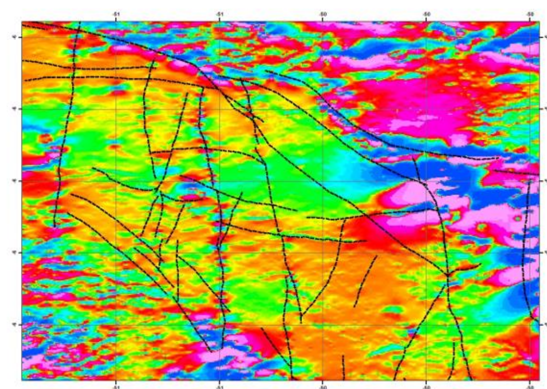

Figure 6 – Identified flaws and structures.

With the ASA it was possible to select some bodies with a possible potential mineral within the areas of interest, their distribution is shown in Figure 7.

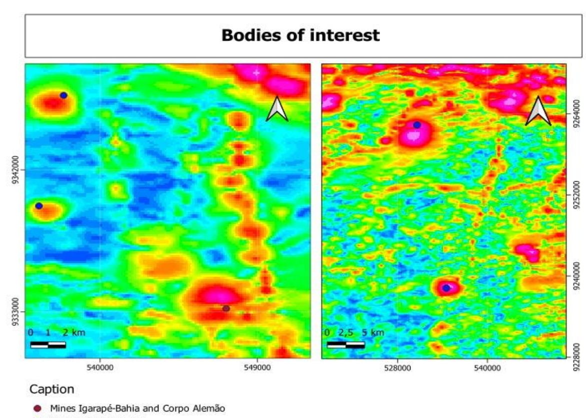

Figure 7 – Bodies of interest

With the choice of these bodies for a better deepening of these regions, we obtained the power spectra and the Euler Deconvolution of these areas to obtain the depth range of the anomaly sources and how they are spatially distributed, the best results will be illustrated below and correspond to the interest zone 2.

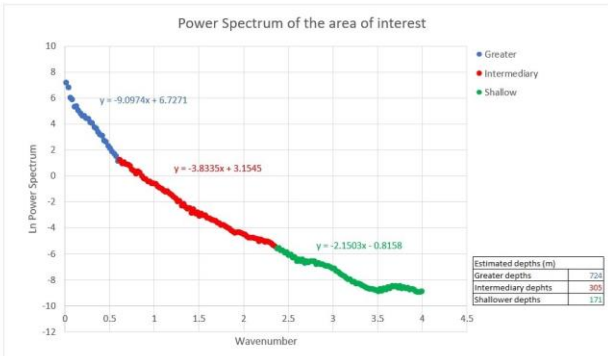

Figure 8 – Power Spectrum of the interest area 2.

With the power spectrum, it is possible to identify that the sources have depths of up to 724 meters. In addition, it can be observed that the largest distribution range corresponds to the depth zone with bodies located between 171 and 305 meters. The distribution of these depths is best visualized with Euler Deconvolution, which is illustrated in Figure 9.

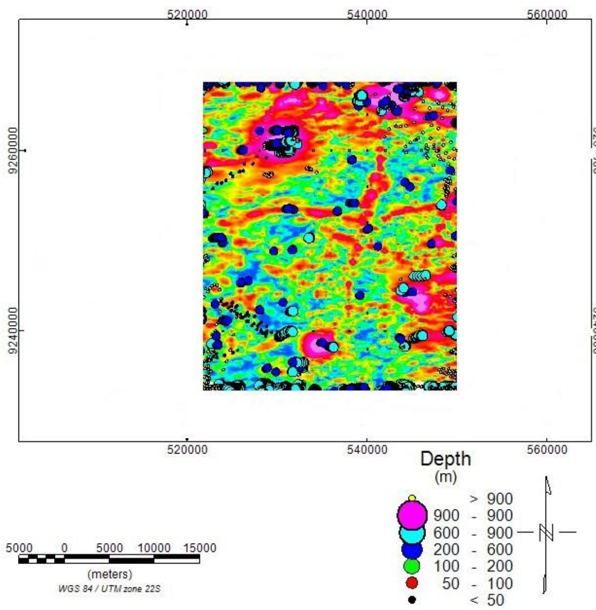

Figure 9 – Euler deconvolution of the interest area 2

Figure 9 shows the results of Euler deconvolution, near to the region of one of the selected bodies, which is further north of the area of interest 2, there is a high concentration of anomaly sources, which can be a good indicator of mineral potential. The body located further south has a geometry like that found in the Igarapé-Bahia Mine. However, the source concentration is less significant compared to the northernmost body. In addition, there is a behavior of other sources further west, which are directed towards the body under study. This behavior deserves further study for a better understanding of this body.

Conclusions

Magnetometry has proven to be a valuable tool in identifying geological structures and searching for mineral potential. The application of 1DV (First Vertical Derivative) and Tilt filters allowed us to identify E-W trending lineaments and diabase and gabbro dikes with preferred N-S orientations, which aligns perfectly with the regional geology of the area.

Regarding the search for bodies with mineral potential, the combination of the ASA filter, Power Spectrum and Euler Deconvolution allowed selecting and determining their respective depths, which mostly varied between 200 and 600 meters. The selected bodies in both areas of interest 1 and 2 are well defined and located, allowing to determine their dimensions in terms of area. Additionally, with the knowledge of their depths, we can calculate their respective volumes and estimate the amount of ore that can be extracted.

Finally, using the SIGMINE platform database available on the National Mining Agency (ANM) website, it was possible to discover that both bodies of interest in area 1 are located within the same polygon, which is under the requirement regime of mining carried out by Vale Metais Basicos SA for the extraction of the substance copper (Cu). Regarding the bodies of interest in area 2, the northernmost body, which showed better prospecting potential based on Euler deconvolution, is mostly located within a reserved area. However, the portion that does not belong to this reserve is under the research request regime by Vale SA for the substance manganese (Mn). On the other hand, the southernmost body, which shows geological similarity to the Igarapé-Bahia Mine, is within a polygon that is under the research authorization regime requested by Mineração Zaspir Ltda for the substance gold (Au).

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