Modeling HTEM Data Anomalies for Mineral Exploration in the Quadrilatero Ferrifero

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This paper was prepared for presentation during the 16th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 19-22 August 2019.

Abstract

We present a preliminary analysis of the modeling of data from a Helicopter Transient Electromagnetic survey acquired by CPRM – Geological Survey of Brazil, for the project Rio das Velhas II, over the Quadrilateral Ferrifero, MG, Brazil. The integration of the airborne magnetic data was important for the analysis and selection of conductive anomalies for modeling, in order to understand their structural control.

For the conductors modeling, we used EMIT Maxwell thin sheet modeling in this research, for the purpose of extracting geometrical parameters of the main conductive bodies.

Introduction

The Quadrilátero Ferrífero (QF) area is an important geological province of Precambrian due to significant mineral deposits, mainly gold, iron and manganese. The QF region extends over an area of 7000 km^2, in the central portion of Minas Gerais State.

The QF region was the most important Brazilian area of gold production in the beginning of XVIII century until the late 1970s. Represents a world-class gold province, with historical production that exceeds 1000 tons of gold, totaling more than 40% of the total Brazilian production (Lobato et al., 2001).

The use of geophysics in the search for mineral deposits is internationally recognized and has become routine in geophysical exploration programs for small and large companies in the mining market (Oliveira, 2014). Among the most used geophysical methods is the time domain electromagnetic (TDEM) or Transient Electromagnetic (TEM) method, due to its high depth of investigation in relation to electromagnetics frequency domain methods and sensitivity to conductive bodies at greater depths.

According to (Allard, 2007), the mining industry has successfully used the airborne electromagnetics methods (AEM) for about 60 years, especially due to the possibility of studying large areas in a short period of time. In the 2000s, the HTEM (*Helicopter Transient Eletromagnetic*) gained prominence due to its good spatial resolution of conductors, low cost in relation to the fixed wings systems for surveys in small areas and greater depth of research in relation to frequency domain systems.

Although the region is covered by several geophysical surveys, both air and terrestrial, carried out by public and private initiative, there are few published studies dealing with auriferous deposits in the Quadrilatero Ferrifero with the geophysical approach. Among existent works stand out Silva (2005), Guimarães (2011), Oliveira (2014), Couto Jr. et al (2017) and Couto Jr. et al (2018).

Silva (2005) integrated aerogeophysical magnetic, electromagnetic and gamma spectrometric data of Rio das Velhas project with the goal of determining prospective zones in the auriferous deposits of Quadrilatero Ferrifero.

Guimarães (2011) used aerogeophysical magnetic, electromagnetic and ground induced polarization data in order to obtain tridimensional models and determine prospective gold zones. The author took into account the lack of EM response in the case of gold deposits in disseminated sulphides, where there is a predominance of the IP effect response.

Oliveira (2014) integrated aerogeophysical magnetic, electromagnetic and gamma spectrometric data with the objective of developing an exploration model of the auriferous deposits found in the Complex of Corrégo do Síto mines, owned by *AngloGold Ashanti* company, in the Quadrilatero Ferrifero.

Couto et al (2017) present the results of the integration of HTEM, radiometric data and of the inversion techinique called “Magnetization Vector (MVI)”, in areas of Quadrilátero Ferrifero, with the objective to provide a better understanding of auriferous deposits, as part of the project of CPRM called “Geology and Metalogenesis of Quadrilatero Ferrifero”.

Couto el al (2018) present the IP modelling of AEM signals in areas with disseminated sulphides associated to gold mineralization in the Lamego mine, owned by *AngloGold Ashanti* company, in Quadrilatero Ferrifero. The AEMIP modelling was performed using MPA reparameterization (Maximum Phase Angle) of the Cole-Cole model, introduced by (Fiandaca et al., 2018).

In this context, the development of researches using modelling of airborne geophysical data can contribute to improve the understanding of physical responses of electromagnetic methods in different types of gold deposits and to determine their geometries, as will contribute to Brazilian mineral sector, assisting future mineral prospecting campaigns.

Geology

The QF presents a granite-greenstone terrain covered by proterozoic supracrustal sequences and is located in the Southern portion of the São Francisco Craton (Almeida, 1967; Almeida and Hasui, 1984; Marshak et al., 1992).

Four lithostratigraphic units comprise the QF: Archean crystal basement, Rio das Velhas Supergroup, Minas Supergroup and Itacolomi Group (Alkmin & Marshak, 1998). The figure 1 presents the stratigraphic column of the QF:

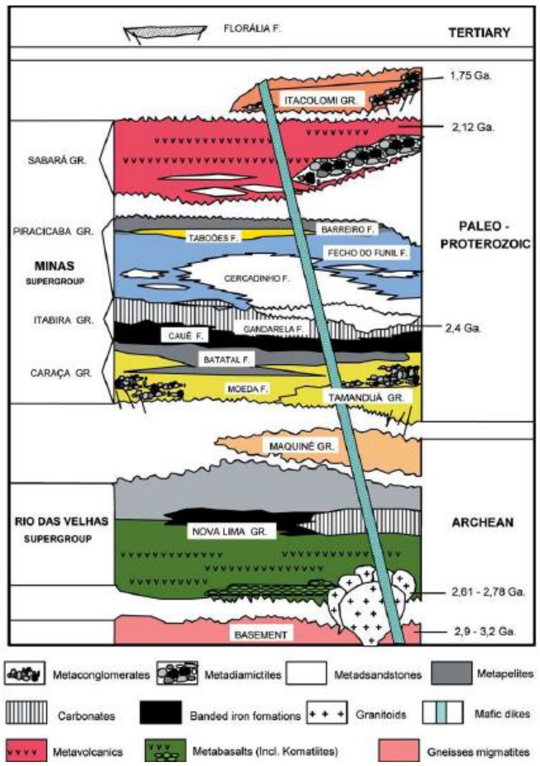

Figure 1: stratigraphic column of the Quadrilatero Ferrifero (Alkimim & Noce, 2006).

Rocks of the Archean Rio das Velhas Supergroup (Lobato et al., 2001) host the orogenic gold deposits. The Rio das Velhas Supergroup is characterized by a typical greenstone-belt-type succession, known as Rio das Velhas greenstone belt (GBRV) (Schorscher, 1976). The GBRV encompass two groups: Nova Lima e Maquiné.

The Nova Lima Group, basal unit of GBRV, consists of volcanic, chemical and clastic metasedimentary rocks. The group is known worldwide for its deposits and auriferous occurrences in BIF's (banded iron formations). These deposits are structurally controlled and occur associated with hydrothermal alterations along Archean thrust shear zones (Baltazar & Zucchetti, 2007). The mineralization hosts mainly in BIF's, mafic volcanic rocks and quartz veins associated with Nova Lima Group.

TEM Method

The electromagnetic geophysical methods are all based upon the fact that a magnetic field varies in time (the primary filed) and thus, according to the Maxwell equations, induce an electrical current in the surroundings. This current and the associated electrical and magnetic fields are often called the secondary fields (Christiansen et al., 2006).

The TEM arose from the need to investigate targets at great depths and high resistivity contrast. Its advantage in relation to frequency domain methods is that the measures can be performed in the absence of the primary field.

The TEM method is used to obtain the electrical resistivity (or conductivity) variation depending on the depth. For this, a direct current is injected into an ungrounded transmitter loop. According to Ampere's Law, this current has an associated static magnetic field:

$$\oint_c \vec{B}.\vec{dl} = \iint_s \mu_0.\vec{j}.\vec{n}.dS \qquad (1)$$

Where:
$\vec{B}$ – Associated magnetic field.
μ_0 – Magnetic permeability in vacuum.
$\vec{j}$ – Current density.

The current is shutted down abruptly, which due to the Faraday's Law induces an electrical field in the surroundings.

$$\oint_c \vec{E}.\vec{dl} = \iint_s \left(-\frac{\partial \vec{B}}{\partial t}\right).\vec{n}.dS \qquad (2)$$

Where:
$\vec{E}$ – Associated electrical field.

$\frac{\partial \vec{B}}{\partial t}$ – Variation of the magnetic field over time.

The primary electrical field varying in time will induce electrical currents known as "eddy currents" or "induction current", which will be attenuated by the subsurface according to Ohm's Law, i.e., according to the underground electrical resistivity, resulting in a non-static decaying magnetic field, the secondary field.

The time-decay of the secondary magnetic field or, according to Faraday's Law, the electromotive force (EMF), depends on the resistivity of the medium. Consequently, the resistance of the underground will decrease the amplitude of the induction current. This attenuation will induce more currents in the underground, with similar geometry of the transmitter loop, but with crescent area, known as the smoke ring effect (Nabighian, 1979). Finally, the signal of EMF is sampled by the receiver coil, as a function of the time in the receiver, in specific time-gates.

From this recorded signal, which is converted, to a decay curve of the secondary magnetic field by time is possible to obtain the resistivities of the subsurface materials.

The whole process described above is summarized in figure 2:

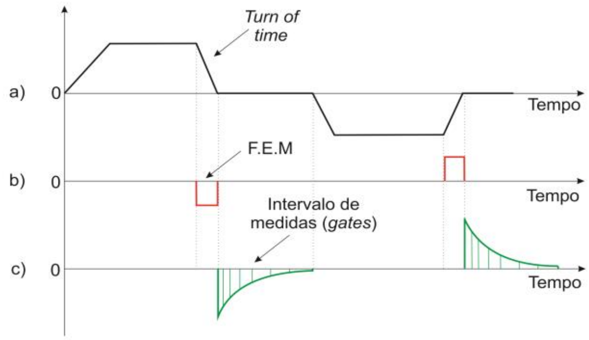

Figure 2: Diagram of the sequence of events of a TEM survey (adapted from McNeill, 1994).

The airborne TEM systems (ATEM) have been used for more than 50 years. The development was driven by the exploration for minerals with its needs for surveying large areas within reasonable cost (Christiansen et al., 2006).

The Helicopter Transient Electromagnetic (HTEM) systems most well-known and develop are the AeroTEM, VTEM, NEWTEM, Hoistem and SkyTEM. All were developed especially for the mineral exploration, except SkyTEM, which was initially developed for groundwater exploration, but today there are versions specific for both applications.

The system used in this research was the AeroTEM^{HD}. This system is based on a geometric concentric loop and a receiver coil located inside the transmitter loop. According to Balch et al. (2003) the advantages of this configuration are: maximum coupling of all the geometric targets regardless of depth, clearer anomalies with simpler shapes compared to fixed wings systems and anomalies shapes independent of the direction of the flight line.

The figure 3 shown an AeroTEM^{HD} system:

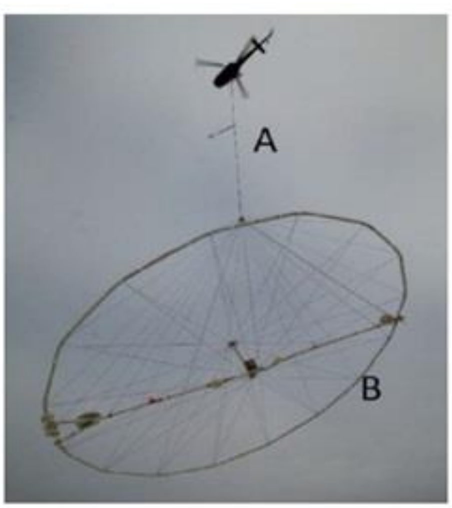

Figure 3: AeroTEM system. In a) Magnetometer bird and in b) Transmitter loop (Adapted from CPRM).

Data acquisition

The data was acquired by CPRM (Brazilian Geological Service) for the Rio das Velhas II project. The detailed study area is located in Santa Barbara and Barão de Cocais municipalities, Minas Gerais state, Brazil. The survey comprises magnetic and time domain electromagnetic airborne data acquired with the AeroTEM^{HD} system.

The figure 4 shown the location of the project:

Figure 4: Rio das Velhas – Stage 2 location (Adapted from CPRM).

The project occurred in the period of 08/08/2011 until 27/09/2011. and it is composed by 755,45 km of flight lines, with spacing of 250 m between the lines and the N45°W orientation.

Geophysical Modeling Methodology

The forward modeling of geophysical exploration methods is useful for purposes such as planning acquisitions, to understand the method, especially for students, and as part of an iterative inversion process of the measured data (Butler & Zhang, 2015).

The qualitative interpretation of the data was performed through EMIT Maxwell software, using thin sheet plate modeling or rectangular prisms, which allows direct 3D modeling, with the objective of determining geometry and the physical properties (conductivity) of conductive bodies. Various mineral deposits are characterized by a vertical extension much larger than the its thickness, such as the gold deposits of the QF region, making valid approximation by plates with negligible thickness.

Oasis Montaj (Geosoft) software was used for viewing the electromagnetic profiles and for the magnetic data processing. The magnetic data was used to assist in the interpretation of results. Moreover, sattelite images and (Instituto Brasileiro de Geografia e Estatística) IBGE infrasctructure database were used to analyze the two sets of data on the area, in order to identify powerlines and man-made structures (railroads, buildings, industrial pipes, etc) that could be sourve of electromagnetic couplings in the data.

Preliminary results

The electromagnetic and magnetic anomalies were selected and processed, respectively, in the Oasis Montaj software. For electromagnetic data, shown below, the channel 7 for the turn-off times (intermediate times) was chosen to visualize the distribution of anomalies over the area.

The anomalies selected for modeling were chosen from the combined analysis of the electromagnetic and magnetic data, in order to associate the conductive zones with the structural control of the gold deposits.

According to Lobato (2011b), the gold mineralization in this region occurs with disseminated sulfide minerals and/or quartz boudins in bedding-parallel shear zones within the sedimentary rocks.

The figure 5 shows the vertical derivative of analytical signal amplitude for the area. The strong magnetic anomalies follow a linear trend that can be interpreted as the structural lineaments of the region, known as Córrego do Sítio, Cristina and São Bento-Donana shear zones (Lima, 2012).

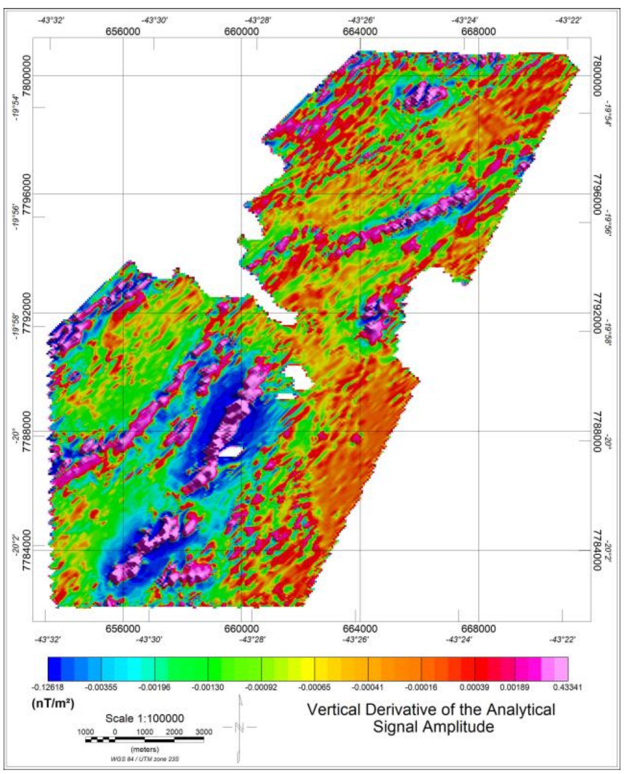

Figure 5: Vertical derivative of the analytical signal amplitude of the anomalous magnetic field for the area.

The figure 6 shows the distribution of HTEM anomalies in the region.

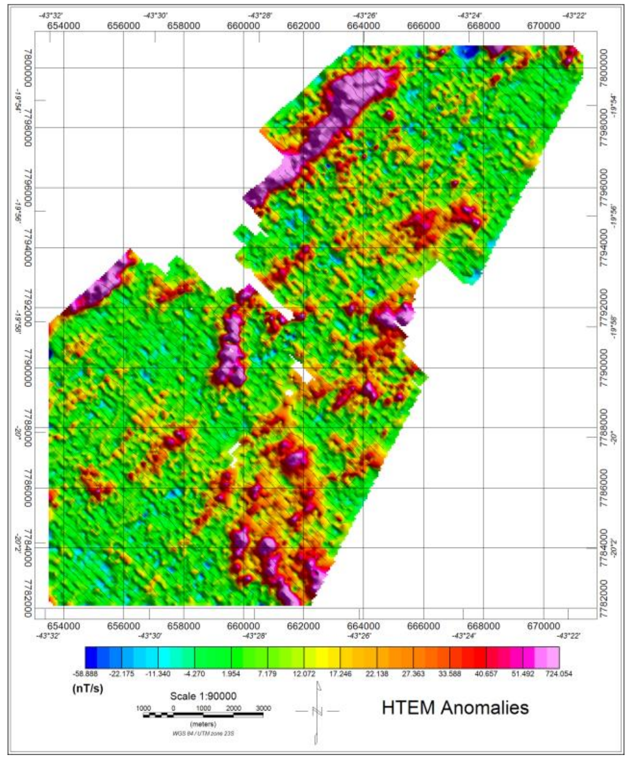

Figure 6: Distribution of HTEM anomalies. The map presents the 7th channel of the turn-off times regime.

Anomalies with high amplitude and direction consistent with the general direction of geology predominate the intermediate times and have a good correlation with the strong magnetic bodies, following a similar linear magnetic trend.

The anomalies of HTEM data could be associated with sulfide zones and the magnetic anomalies are well correlated with BIFs bodies.

The modeling of selected HTEM anomalies consists of obtaining a geophysical model which parameters could represent the structural behavior of the sulfides associated with mineralized zones. The parameters that control the model (thin sheet) are: spatial position (coordinate system), orientation, dimension and electrical property (conductance or conductivity). The figure 7 shows a model obtained from an anomaly located in the southeast portion of the area:

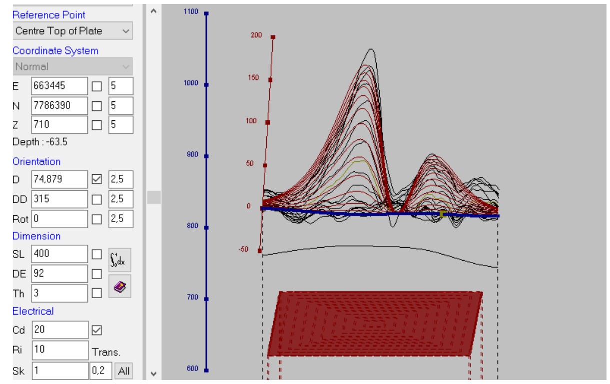

Figure 7: Modelled plate and parameters for line 30400 and Z component response (red) and field data (black). The view is to oriented to NW.

The figure 8 shows the components Z and X for line 30400 and the field data and responses for the modelled plate:

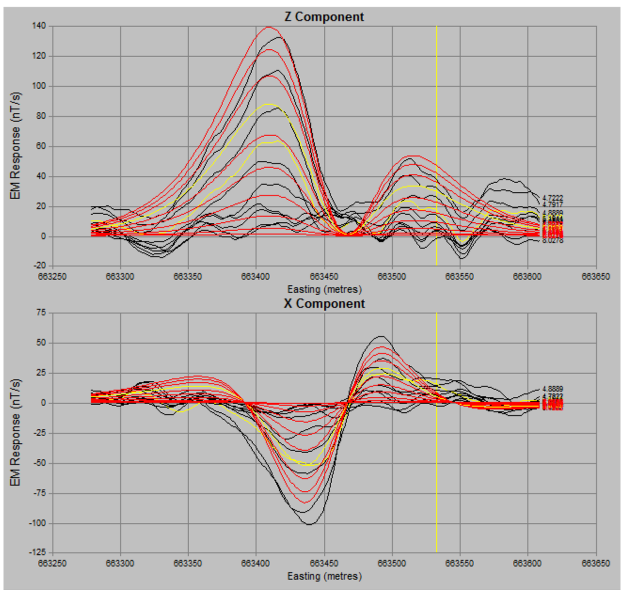

Figure 8: Components Z and X for line 30400 and the field data and responses for the modelled plate.

The plate represents a strong conductor and is not associated with anthropic noise. It presents 3 m of thickness, dips 25º towards to azimuth 315° and conductivity of 20 S/m.

These results are preliminary and further discussions will present integration with structural data and other geophysical data during the evolution of this research.

Conclusion

The Quadrilátero Ferrífero has a complex history of deformation that influence on the structural control of the gold deposits.

As seen in the preliminary results there are a correlation between the magnetic and eletromagnetic responses, as well as there is correlation between the conductive anomalies and the structural control of the region.

The modelled conductor presents a dip direction of 315/25 structural parameters, suggesting to be associated with the structural control of Conceição Syncline, as discussed in Malouf and Corrêa Neto (1996). However, this interpretation needs to be supported by structural data and further geophysical modeling for the magnetic data.

Acknowledgments

The authors would like to tkank CPRM for providing the data of Rio das Velhas project.

This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

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