Magnetization Vector Inversion Application in Quadrilatero Ferrifero Region, MG, Brazil

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Abstract

This paper presents the results obtained with the application of Magnetization Vector Inversion (MVI) technique in the CPRM – Brazilian Geological Survey aeromagnetometric data over the Quadrilatero Ferrifero (QF) region, MG, Brazil. The MVI technique was applied for four areas in QF region: Nova Lima, Santa Bárbara, Lamego Gold Mine and Pará de Minas. In all areas MVI provided good solutions of the magnetic bodies, which could be correlated with the structural control of gold mineralized bodies and their host rocks. When possible, these results were integrated with the Helicopter Transient Electromagnetic (HTEM) and airborne radiometric data available in this region.

Introduction

The QF region is a metallogenetic province, with many important world class gold and iron deposits. Because of this economic relevance and seeking the improvement for the mineral exploration on the region, CPRM executed an airborne magnetic, HTEM and radiometric surveys in QF region during the early 1990's and 2010's.

These surveys can be integrated to minimize the inherent ambiguities of each method. HTEM method has been used successfully in mineral exploration around the world since the early 2000's, with excellent results to find mineralized bodies in sulfides zones (Allard, 2010). However, there are many cases where the adjacent rocks are very conductive, which causes an ambiguity to distinguish mineralized and non-mineralized rocks. This is the case of many orogenic gold deposits in QF region (Lobato *et al.*, 2001), where they are stratabound type and the gold mineralization is located between graphite-schists and/or banded iron formations (BIFs). The graphite-schists are very good conductors and could mask the HTEM response from the mineralized sulfides zones.

This is where the integration with airborne magnetic data could help. The MVI technique can solve the magnetic bodies possibly associated with BIFs and zones rich in magnetite and other magnetic minerals, providing structural information about these magnetic bodies and, in many cases, about the structural framework of the mineralization. In addition, it solves the problem of remanent magnetization that is not addressed in susceptibility inversions. This is a key issue, because QF region has many areas where remanent magnetization is relevant. Integrated with the airborne radiometric data, the mineralized potassic zones associated with the hydrothermal processes could be also identified in some areas, providing a better characterization of the gold deposits.

This work presents the results of the MVI technique integrated with HTEM and radiometric data for the QF region. It is part of the CPRM ongoing project: "Geology and Metallogeny of Quadrilátero Ferrífero Province".

Method

The MVI technique implemented in VOXI is based on the paper of Ellis *et al.* (2012). Consider a magnetic source with volume V and magnetization $\boldsymbol{M}(\boldsymbol{r})$. The magnetic flux density $\boldsymbol{B}$ in a position $\boldsymbol{r}_j$ caused by this magnetic source is given by:

$$\boldsymbol{B}(\boldsymbol{r}_j) = \boldsymbol{\nabla} \int_V \boldsymbol{M}(\boldsymbol{r})\, \boldsymbol{\nabla} \frac{1}{|\boldsymbol{r} - \boldsymbol{r}_j|} dr^3 \quad (1)$$

If the volume V is dicretized in v_k ($k = 1,2, \dots, N$) volumes with $\boldsymbol{m}_k$ constant magnetization, assuming 3D spatial components, equation (1) could be rewritten as:

$$B_\beta(\boldsymbol{r}_j) = \sum_{k,\alpha}^{N,3} m_{k,\alpha} \int_{v_k} \partial_\alpha \partial_\beta \frac{1}{|\boldsymbol{r} - \boldsymbol{r}_j|} dr^3 \quad (2)$$

which defines the forward problem for a magnetic source. (α, β) indexes indicate the spatial components of the vectors. The discretization of equation (1) based on equation (2) leads $\boldsymbol{B}$ to be represented as:

$$\boldsymbol{B} = \bar{\bar{\boldsymbol{G}}}\boldsymbol{M} \quad (3)$$

where $\bar{\bar{\boldsymbol{G}}}$ is the sensitivity matrix. The inverse magnetic problem is based on the solution of equation (3) for $\boldsymbol{M}$, when $\boldsymbol{B}$ is given. This solution demands the regularization of the problem. VOXI MVI applies the Tikhonov minimum gradient regularizer (Aisengart, 2015), which solve $\boldsymbol{M}$ minimizing the distance of the calculated and measured magnetic field in the minimum square sense.

Generally, the main task in the solution of inverse magnetic problems is to determine the spatial distribution of the characteristic physical property associated, i.e., the magnetic susceptibility k, which is related to $\boldsymbol{M}$ by:

$$\boldsymbol{M} = k\boldsymbol{H}_e \quad (4)$$

where $\boldsymbol{H}_e$ is the external magnetic field. The VOXI MVI algorithm solves the inverse problem considering the anisotropic nature of the magnetic susceptibility in the geological environment, i.e., the anisotropic magnetic susceptibility k is represented as a 3D vector. This is a generalization in 3D space of the conventional scalar magnetic susceptibility. Using this generalization, equation (4) is rewritten as:

$$\boldsymbol{M} = \boldsymbol{k}H_e \quad (5)$$

where $H_e = |\boldsymbol{H}_e|$. Besides this generalization, VOXI MVI also considers the normal remanent magnetization (NMR, represented as $\boldsymbol{M}_{NMR}$). In this paper, we are not interested in the nature of $\boldsymbol{M}_{NMR}$, only how to calculate it. $\boldsymbol{M}_{NMR}$ is represented as a component in effective magnetization and it is proportional to H_e, i.e.:

$$\boldsymbol{M}_{eff} = \boldsymbol{M} + \boldsymbol{M}_{NMR} \quad (6)$$

where:

$$\boldsymbol{M}_{NMR} = \boldsymbol{k}_{NMR}H_e \quad (7)$$

$\boldsymbol{M}_{eff}$ is the effective magnetization and $\boldsymbol{k}_{NMR}$ is a pseudo magnetic susceptibility caused by NMR. Using equations (5) and (7) in equation (6), $\boldsymbol{M}_{eff}$ is rewritten as:

$$\boldsymbol{M}_{eff} = \boldsymbol{k}_{MVI}H_e \quad (8)$$

where:

$$\boldsymbol{k}_{MVI} = \boldsymbol{k} + \boldsymbol{k}_{NMR} \quad (9)$$

Equation (9) shows the magnetic susceptibility used in the inverse problem solved by VOXI MVI. As can be seen in this equation, the spatial inclination and declination of the "effective" magnetic susceptibility of a magnetic source can be estimated (Aisengat, 2015), which could be a very helpful information to estimate structural parameters in geological investigations.

Examples

The four areas where the MVI were conducted (Figure 1) are:

- Lamego Gold Mine;
- Nova Lima;
- Santa Barbara; and
- Pará de Minas,

Each area is detailed bellow. The results are presented in the next section.

1) <u>Lamego Gold Mine</u>

Lamego Gold Mine is an important mine in QF region, which belongs to AngloGold Ashanti company. The main Lamego's structure is a rootless, reclined, isoclinal, cilindrical fold (Martins *et al.*, 2015) – Figure 2. There are four ore bodies: Queimada, Cabeça de Pedra, Arco da Velha and Carruagem. The gold mineralization is located in stratabound bodies between carbonaceous schist and BIF's (Figure 2-A), and the orebodies have dip angles between 22-29° (Martins *et al.*, 2015). Lamego presents a significant magnetic trend to NE and many conductors aligned with it (Figure 2-B).

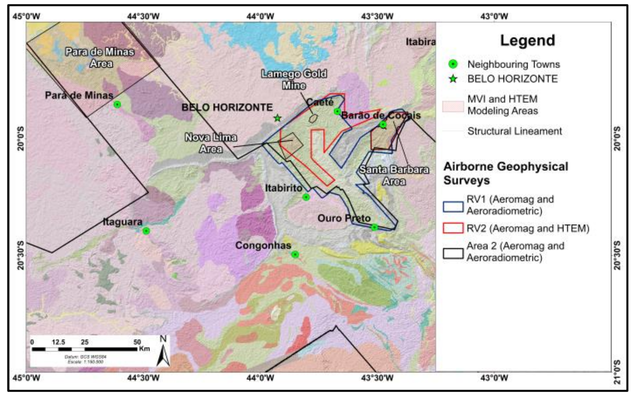

Figure 1: Location of the areas where MVI technique was conducted: Lamego Mine, Santa Bárbara, Nova Lima and Para de Minas areas. Three airborne geophysical surveys were used: RV1, RV2 and Area 2.

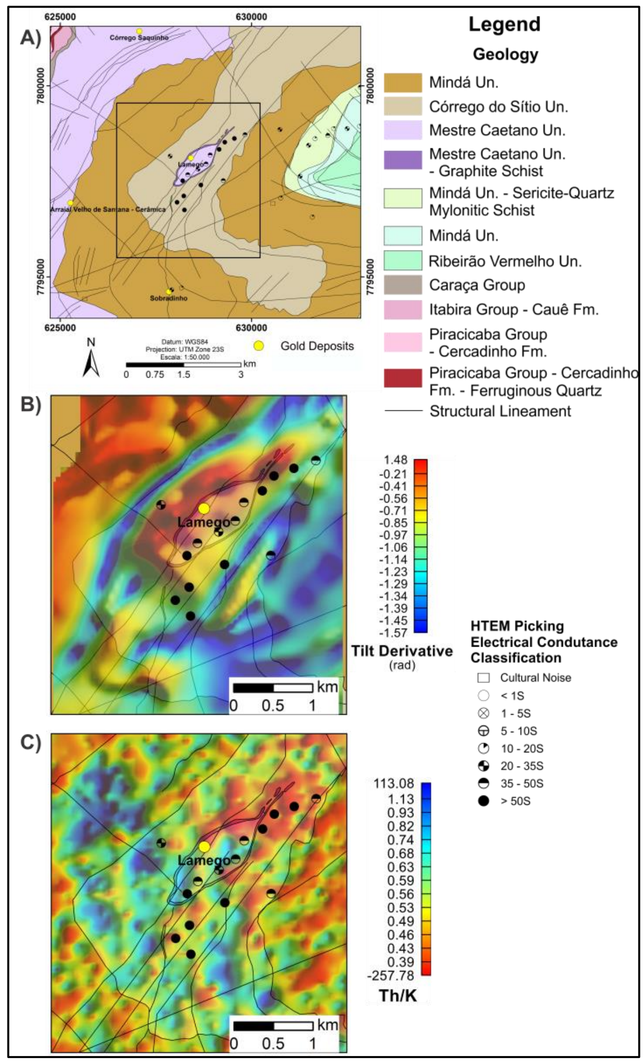

Figure 2: Lamego Mine area detail. A) Geological map of the area. B) Tilt derivative map. C) Th/K ratio map. The black square in Figure 2-A is the area zoomed in geophysical maps.

Possibly, the magnetic anomaly could be correlated with anomalous concentration of magnetite inside BIF layers or with the metamafic rocks enveloping around the mineralized structure. The MVI technique and HTEM plate modeling was applied seeking to understand the relation of gold mineralization and its host rocks.

The HTEM data over Lamego structure show many conductors pickings aligned with the NE-SW direction of the mineralized structures (black points in Figure 2). Some of these pickings could be correlated with sulfide zones (mainly pyrrhotite and/or chalcopyrite) and could be associated with gold mineralization. Those pickings were modeled and are presented in the next section.

The airborne radiometric data for Lamego mine show significant concentration in the NE portion of folding structures (Figure 2-C), where the limbs are very close, indicating the strong potassic hydrothermal process. This part of the mineralized structure is coincident with the Carruagem orebody, which presents the highest gold grades at Lamego Mine.

2) <u>Santa Bárbara Area</u>

This area is located at the Northeastern portion of QF region, nearby the Santa Bárbara Town (Figure 3). The main rock units comprise a metamorphosed succession of schistose sediments of the Nova Lima Group, Rio das Velhas greenstone belt, which host lode-gold mineralization associated with BIF's (Pilar and Córrego do Sítio II deposits) and quartz-carbonate-sulfide-sulfosalt veins (Córrego do Sítio I deposit). The gold deposits are controlled by a series of NE-SW regional lineaments, known as Córrego do Sítio, Cristina and São Bento-Donana shear zones (Lima, 2012). The regional structure was previous defined by Moore (1957) as Conceição anticline, but recent mapping identified an overturned synformal structure in the nucleus of this major fold. The Conceição syncline (Malouf and Corrêa Neto, 1996) trends northeast and is defined by bedding surfaces of the greenstone.

Some gold mineralization are hosted in very magnetic BIF's, as can be seen their good correlation with the linear magnetic anomalies in Figure 3 detail. The HTEM data also show alignment of the conductors pickings with the magnetic BIFs bodies, which may indicates the high association of sulfide zones with the Córrego do Sítio lineament and the BIFs bodies. The MVI technique was applied to understand the extension and geometry of these magnetic structures in the underground, and its correlation with the Conceição syncline.

3) <u>Nova Lima Area</u>

This area is nearby the Nova Lima Town, in the central part of QF region. It is characterized by regional fold with Z pattern, where important gold deposits are located, like Morro da Glória, Gabirobas and Gaia (Figure 4). This Z pattern structure has a strong magnetic signal (Figure 4 detail) and the MVI technique to understand its extension in the underground.

The HTEM data over Nova Lima region presents many conductors picking along the Z pattern structure, which tends to follow its contour. Those conductors pickings seems to be correlated with the magnetic BIF's in the area and also could indicate sulfide zones possibly associated with the magnetic anomalies.

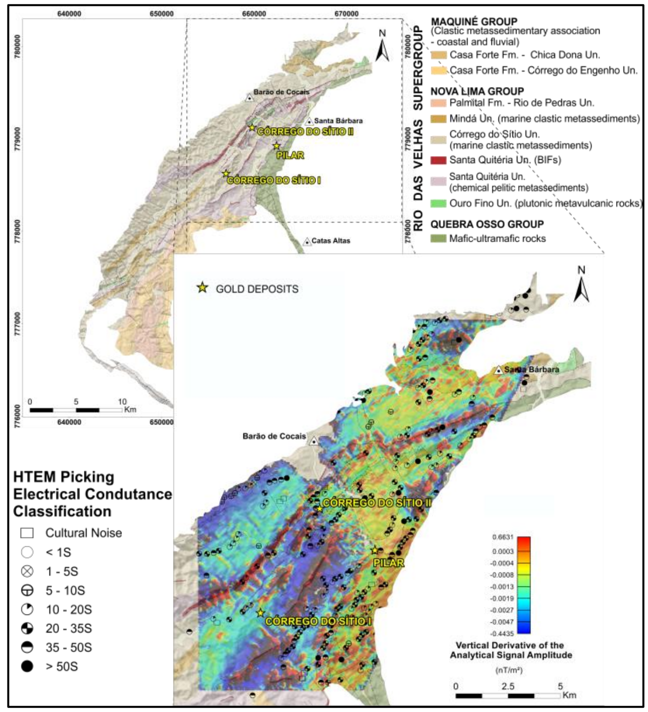

Figure 3: Detail of the Santa Bárbara area. The geological map is shown upper part. The bottom part shows the vertical derivative of the analytical signal amplitude for the area. Observe the good correlation between the BIFs bodies, magnetic anomalies and HTEM conductors pickings.

4) <u>Pará de Minas Area</u>

This area is located in the NW portion of QF region. Its geology is composed by Archean TTG basement and metavolcanic-sedimentary sequences of the Pitangui Greenstone Belt, which could be correlated to the Rio das Velhas Greenstone Belt in the central part of QF region. Gold is the main mineral resource in the area, but there are also quartz and algamatolite deposits.

The main structural features are E to NW shear zones, which could be the main way for the hydrothermal mineralizing fluids. One of these NW structures (called Pequi shear zone, Romano 2007), is characterized by a strong remnant magnetic anomaly (Figure 5) associated with magnetic BIFs aligned to this shear zone. The MVI technique was applied to understand the extension and geometry of these BIFs bodies and to evaluate their potential to host gold deposits

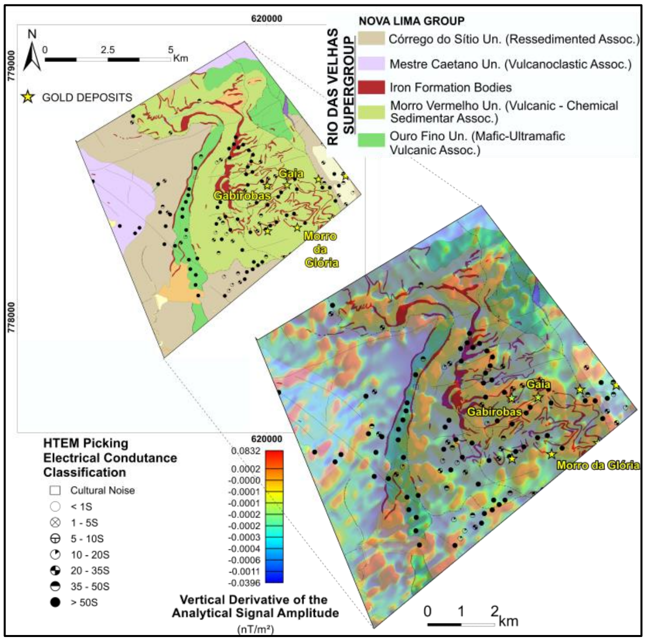

Figure 4: Nova Lima area detail. The geological map is shown in the upper part of the figure. The detail shows vertical derivative of the analytical signal amplitude map for the area. Observe the good correlation between the BIFs bodies, magnetic anomalies and HTEM conductors pickings.

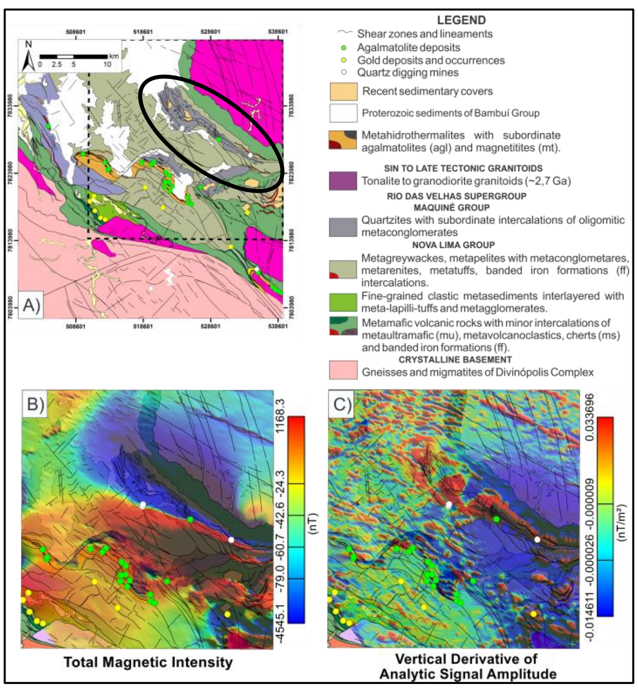

Figure 5: Para de Minas area detail. A) Geological map of the area with the main gold, algamatolite and quartz deposits. B) Total magnetic intensity map. C) Vertical derivative of the analytical signal amplitude. The black square in Figure 5-A is the area zoomed in geophysical maps. The black elipse shows the region of the Pequi shear zone. Observe the strong remanent magnetic anomaly associated with this structure.

Results

1) Lamego Gold Mine

The Lamego Mine MVI solution (Figure 6) presents a magnetic body underneath main structure, with $> 0.0025\,SI$ magnetic susceptibiltiy. The geometry of the solved body by MVI (Figures 6-C and 6-D) suggests the association of magnetic anomaly with a metamafic rocks envelop around the main structure of Lamego. The NW limb of the magnetic body presents structural attitude of 135/32. This result is in agreement with the Queimada orebody plunge (102/29), the nearest one, which apparent dip along the flight line direction (135°) is 27.9°. The HTEM plate models show compatible dip angles between 20-35° to SE and depth of top plate about 10-40 m. These results could indicate the position of sulfide zones (possibly pyrrhotite and chalcopyrite).

Apparently, the hinge zone (Cabeça de Pedra orebody area) is well marked by the MVI result. The profile for the flight line L20810 (RV2) located at SW portion of Lamego structure shows the closing of the hinge zone (Figures 6-B and 6-C), which do not occurs in the NE portion of the fold, where the Carruagem ore body is well marked by a magnetic body (Figure 6-D). It could suggest that the axial fold has a plunge to SE and partly rotates to counter clockwise direction during the QF tectonic evolution, as proposed by Martins *et al.* (2016).

2) Santa Bárbara Area

The MVI solution for Santa Bárbara region shows a strong magnetic body ($k > 15\,SI$) associated with BIFs well correlated with the linear magnetic anomaly along NE-SW direction (Figure 7). The magnetic body shows a strong remanent magnetization (see the magnetization vectors directions) and presents a synformal structure (NE view in Figure 7), with depth extension about 1000 m and length 5 km along NE direction, approximately. Possibly, this magnetic body is correlated to the Conceição syncline, associated with the Córrego do Sítio Lineament, as discussed in (Malouf and Corrêa Neto, 1996). Further studies with MVI technique and integration with the HTEM modeling could help to better understand this structure and its association with gold deposits along this lineament.

3) Nova Lima Area

In this area, MVI solution shows many strong magnetic bodies ($k > 0.15\,SI$) associated with the Z pattern structure (Figure 8), possibly correlated with the BIFs bodies in the region. In the SE portion of the area, there is a magnetic body with smooth dip angle to SE about 20°, with variable thickness (1200 – 2000 m) between its NW and SE portion and extension about 3.7 km in NW-SE direction. Apparently, the magnetic bodies show a folding pattern along NW direction, which suggests to be correlated with the folded BIFs in the area.

This magnetic body is directly associated with the Morro da Glória, Gabirobas and Gaia gold deposits. Further integration with the available HTEM data (in current stage of development) in the area could provide better information about the relation of these magnetic structures and gold mineralization. However, HTEM data presents very noisy in this area and has to be carefully processed to avoid misinterpretations. Further works intend to solve this problem and present the integration.

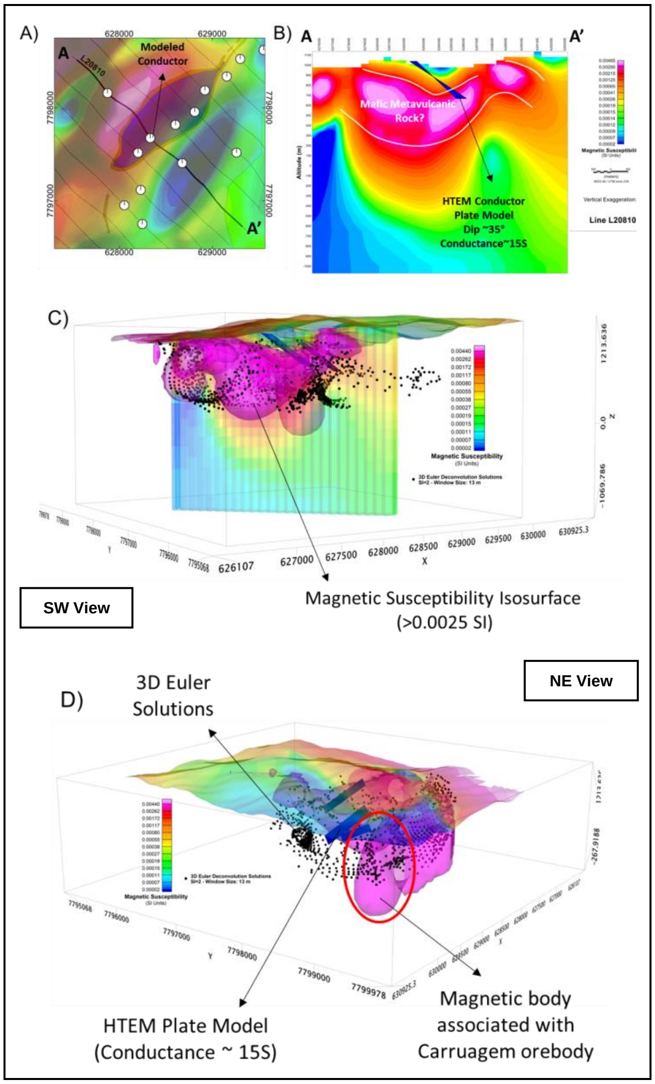

Figure 6: MVI result for Lamego Gold Mine. The blue plates indicate the HTEM plate models for the conductors pickings. A) Detail for the Lamego structure with TMI map overlayed. B) A-A' profile of the magnetic model for Lamego structure, with the plate model for the conductor indicated in Figure 6-A. C) SW view of the magnetic model. D) NW view of the magnetic model.

4) <u>Pará de Minas Area</u>

The MVI results in Pará de Minas area shows a huge magnetic body associated with strong remanent magnetization (inverted dipole anomaly) - Figure 9. The dimensions of the magnetic body are almost 5.2 km in depth extension and 14 km in the NW-SE direction.

The solution presents a strong remanent magnetization, with mostly magnetization vectors pointing to South-SW direction, which explains the strong inverted Total Magnetic Intensity (TMI) anomaly in Figure 5. The NW portion of this magnetic body is probably correlated with magnetic BIFs in this region, which seems prolate-oblate shape plunging 40-45° to NW. This magnetic body has a great prospectivity importance, because its structural and position model could contribute to the metallogenic and structural understanding of the area.

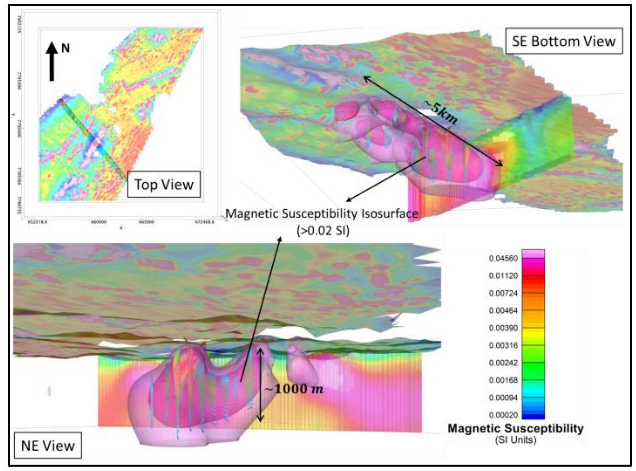

Figure 7: MVI results for the Santa Barbara area by many perspectives. Observe the synformal pattern associated with the linear magnetic body along NE-SW direction. The colored arrows indicate the direction of the magnetization vectors.

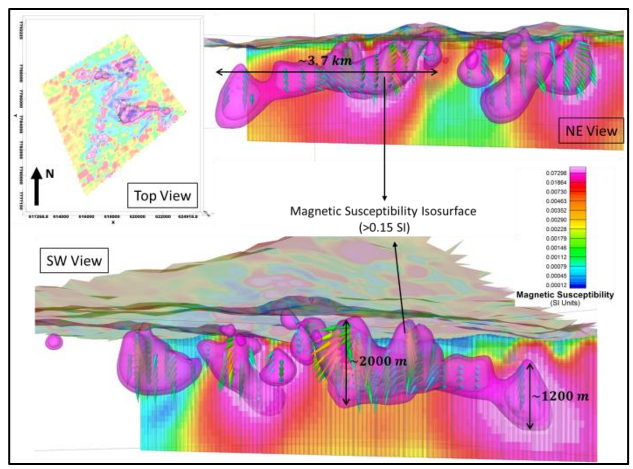

Figure 8: MVI results for the Nova Lima area by many perspectives. Observe the strong magnetic body which deps to SE. probably associated with BIF bodies. The colored arrows indicate the direction of the magnetization vectors.

Discussion and Conclusions

MVI technique shows excellent results to solve complex magnetic structures associated with gold mineralization in the QF region. The existence of remanent magnetization is an impediment to use susceptibility inversion and the MVI solution makes good sense of the structural behavior of the magnetic bodies. Furthermore, MVI demonstrated to be an important geophysical tool to understand structural and metallogenic evolution in geological studies.

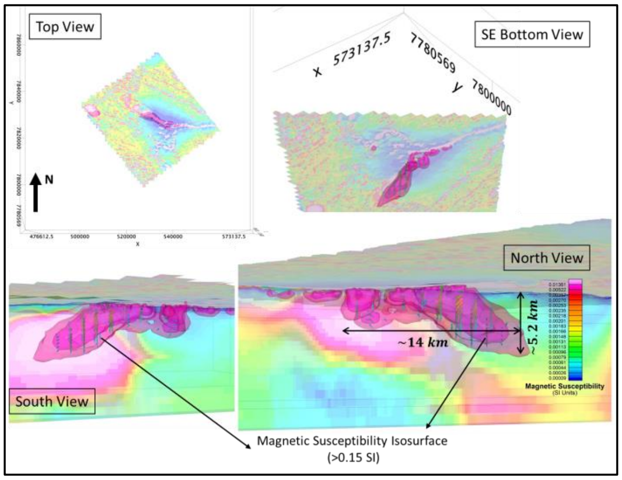

Figure 9: MVI results for the Pará de Minas by many perspectives. Observe the strong magnetic body associated with the NW lineament (Pequi shear zone). The colored arrows indicate the direction of the magnetization vectors. Mostly of the magnetization vectors points to SW-South direction, which can be seen the strong remanent nature of this magnetic body.

When possible, it is highly recommended integrate these results with many geophysical methods as possible, as presented in the Lamego Mine case. The association of HTEM, magnetometry and radiometric methods presented important characteristics of the gold deposit. In many cases, HTEM modeling probably indicates the position of sulfide zones, associated with pyrrhotite and/or chalcopyrite, while MVI technique presented a good solution for the magnetic envelopment of the main mineralized structure.

In the case of Santa Bárbara and Pará de Minas regions, the MVI results presented strong magnetic bodies associated with regional structures: Córrego do Sítio lineament and Pequi shear zone, respectively. These regional structures concentrate important mineralization along them. In Santa Barbara area, the MVI results show a magnetic synformal body, which could be correlated with the Conceição syncline. Also, there is HTEM data available and will be integrated in future works to understand the structural relation between this structure and the gold mineralization. In Pará de Minas region, besides the regional structure, there are many magnetic anomalies associated with other BIFs bodies nearest to gold and algamatolite deposits. However, unfortunately, there is not HTEM data at this area. Given the occurrence of these deposits, the mapping of these shear zones structures with HTEM method (or other EM methods) could be very helpful to reveal the important relation between these regional structures and gold mineralization.

In Nova Lima area, the MVI results show an important magnetic structure associated with the SE portion of Z pattern fold. Apparently, this magnetic body is associated with BIFs bodies in the region and could demonstrate structural features, as the BIF's folding to NW-SE direction. Such BIFs bodies are associated with gold mineralization in this area and the HTEM data presents many conductors picking and could help to understand the relation between the mineralized sulfide zones and the BIF's bodies. However, HTEM data presents a high noise level, which could difficult the modeling for these pickings. Further works intend to solve this problem and present the solution. Also, terrestrial geophysical follow up is highly recommended with electromagnetic, magnetic, resistivity and radiometric methods to enhance the geophysical anomalies occurrences.

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