Qualitative and Quantitative Magnetization Vector Inversion applied to the Pirapora Anomaly

Telma Aisengart, Geosoft Latinoamérica

Abstract

The Pirapora magnetic anomaly is located at the North of the Quadrilatero Ferrifero Area in Minas Gerais, Brazil and has been object of several studies (Borges, 2013; Borges and Drews,, 2009), but its source was not already defined. The general sense from observing the anomaly is that it is a very deep source with strong remanence.

In this paper we have performed Magnetization Vector Inversion both on the total and residual magnetic fields confirming the strong remanence. We have also estimated the depth to the top and the apparent Inclination and Declination of the main source.

Several coincidences, as the geological context, depth of the main source and very strong remanence, have lead us to propose further investigation to verify the possibility of a geological model for Pirapora similar to the one that represents the anomaly in the Cobar Area, central western New South Wales, Australia.

The Cobar area is very well covered in scientific literature (Emerso, 1980; Clark and Tonkin, 1994), and there are three main types of sulphide mineralisation: a copper + gold-rich deposits southeast of the town; a copper + lead + zinc-rich deposit 10 km north of the town (CSA mine); and the silver + lead + zinc-rich Elura deposit 40 km north of Cobar. The Cobar regional magnetic anomaly is essentially produced by Pyrrothite with strong remanence and anisotropy.

We have also applied the Magnetization Vector Inversion for the Cobar area, using publicly available regional data as well as calculated an estimate for the inclination and declination of the area. Follow up studies need to be applied to corroborate the proposed geological model.

Introduction

The Pirapora magnetic anomaly is located at the Occidental part of the Sao Francisco Craton at the North Center of the Minas Gerais State. Basically the area is extensively covered by alluvial deposits unconsolidated to semi-consolidated with varying thickness of gravel, sand and clay, some of the deposits being stratified, and from sedimentary and meta-sedimentary rocks from the Neoproterozoic, mostly representative from the Bambui group.

Some siltstone and silt occurrences from the Três Marias and Terra da Saudade formations are also observed at some points at the North and South of the region, respectively (CODEMIG, 2013.). This extensive occurrence from alluvial and sedimentary rocks from recent deposition is an indication that the Pirapora magnetic signature is almost exclusively due to crystalline rocks from the basement (Santos, 2006).

Although the Pirapora magnetic anomaly is being studied for more than 40 years (Borges, 2013) its sources are not yet fully understood. According to this report, a seismic line surveyed over the anomaly could indicate the basement rock at about 1000m depth that was not confirmed by drilling as it reached 2000m depth having intercepted only sediments with gas without any trace of magnetic rocks.

It is also interesting to observe that over the anomaly, the magnetic data shows a big NE lineament, truncated by a NW lineament that ends in another lineament almost NS, coincident with the bedding of the Das Velhas river that flows into the São Francisco river also in the Pirapora Anomaly. (Borges and Drews, 2001).
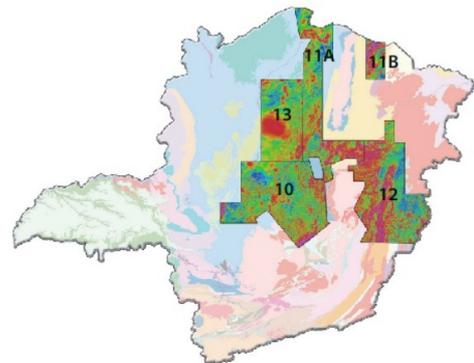
Figure (1) – Minas Gerais State showing the Analytic Signal of Magnetic Surveys from CODEMIG Program 2008/2009, including Area 13 and the Pirapora anomaly that dominates this area (Source: Codemig – www.codemig.com.br)

Method

Measuring the magnetic field B in a series of locations r gives the forward equation for the Magnetic Vector (Ellis et al, 2012):

$$B_\beta(r_J) = \sum_{k,\alpha}^{N,3} m_{k,\alpha} \int_{v_k} \partial_\alpha \partial_\beta \frac{1}{|r - r_j|} dr^3 \qquad (1)$$

Discretization of equation (1) gives the equation for the direct problem

$$B(r) = \nabla \int_V M(r') \cdot \nabla' \frac{1}{|r - r'|} dr'^3 \quad (2)$$

That can be simply represented as:

$$B = Gm \quad (3)$$

The Magnetization Vector Inversion problem is to solve for **m**, given **B**. To be able to resolve this inverse problem, it is necessary to subject B to regularization conditions.

The implementation that has been used in this work applied the Tikhonov minimum gradient regularizer (Zhdanov, 2002) to solve the inverse magnetic problem for the magnetic vector by minimizing the difference of the calculated and measured field.

Up until quite recently the physical property used to describe magnetic material in the earth, particularly for inversion, was the susceptibility. Susceptibility is related to Magnetization:

$$\vec{M} = k\vec{H}e \quad (4)$$

Therefore the Magnetization Vector target equivalent to the Susceptibility target is a collection of magnetic dipole sources. The assumption by using susceptibility is that the magnetization vector is aligned with the inducing field direction that is the Earth's field direction.

However the complex nature of rocks demands a more general description of their magnetic properties. To accomplish this we introduce the anisotropic susceptibility. The anisotropic susceptibility generalizes the scalar susceptibility to a vector susceptibility with three components (kx, ky, kz), with the amplitude of the anisotropic susceptibility being just the scalar susceptibility.

The term normal remanent magnetization NRM is used to describe at least five types of remanent magnetization, including chemical, detrital, isothermal, thermo remanent and viscous remanent magnetizations.

We will not concern ourselves with the origin of the NRM. For our purposes we will denote the NRM by the vector R and we show how it contributes to the magnetization. The units of NRM are the same as those of the magnetization vector, namely A/m. However we find it convenient to represent NRM as a pseudo-susceptibility which allows us to add it to the anisotropic susceptibility to form the MVI susceptibility.

VOXI-MVI is based on this effective susceptibility which includes anisotropic magnetization and remanent magnetization.

Denoting NRM as $\vec{R}$ [A/m] , we may write:

$$\vec{M} = (\vec{k} H_e + \vec{R}) \quad (5)$$

Define NRM "pseudo-susceptibility":

$$R = \vec{k}_R He \quad (6)$$

$$\vec{M} = (\vec{k} + \vec{k}_R) H_e = \vec{k}_{MVI} H_e \quad (7)$$

Equation (6) shows how the MVI susceptibility relates to the magnetization vector, and is based on $\vec{k}_{MVI}$ the "effective" (anisotropic + remanent) susceptibility.

This equation can be used to estimate the Inclination and Declination of the "effective" susceptibility of a source based entirely on the Magnetization Vector Inversion of a magnetic survey.

Examples

As part of the CODEMIG program to cover the Minas Gerais State with Airborne Magnetic and Radiometric Surveys, the area 13 that covers almost completely the Pirapora Anomaly was part of the 2008/2009 geophysical program and was kindly provided by Antonino Juarez Borges from CPRM - Brazilian Geological Survey to be used in this work.

The data was acquired in 2009 with a 500 m line spacing and 100 m flight height. The TMI data used for the Magnetization Vector Inversion is shown in Figure (2).
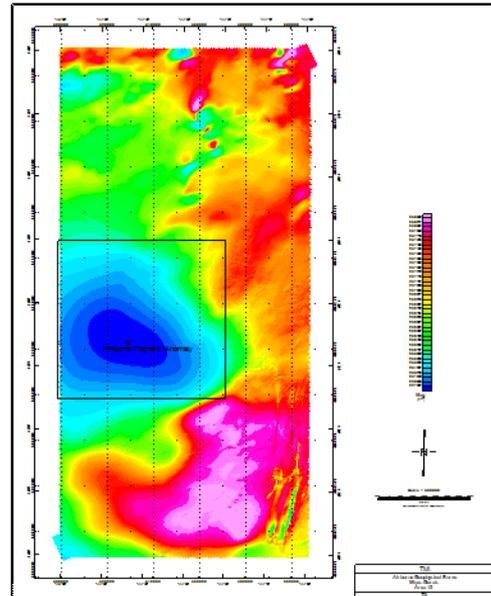
Figure (2) – TMI of Area 13 of Minas Gerais with the area of the inversion presented in this work

The absence of superficial or near surface magnetic sources stands for the lack of correlation of the geological map with the magnetic data. As usually, the ternary radiometric map provides very good superficial information as shown in Figure (3).
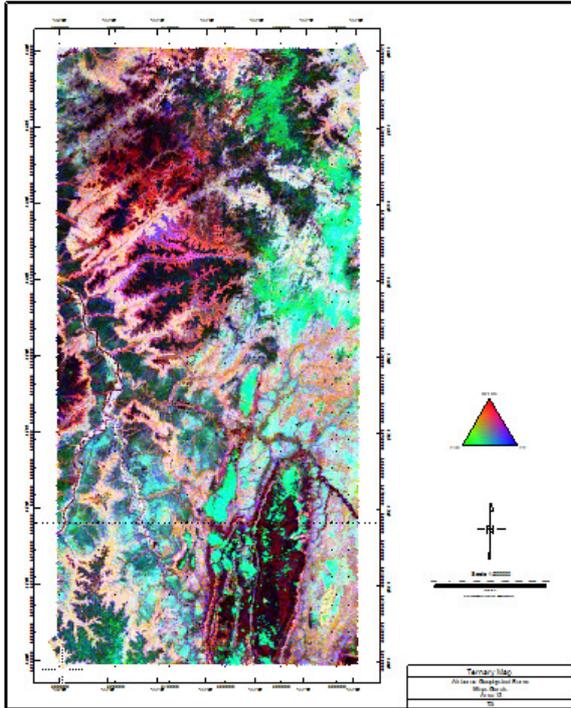
Figure (3) – Ternary map for Area 13 – R=Potassium; G=Thorium; B=Uranium
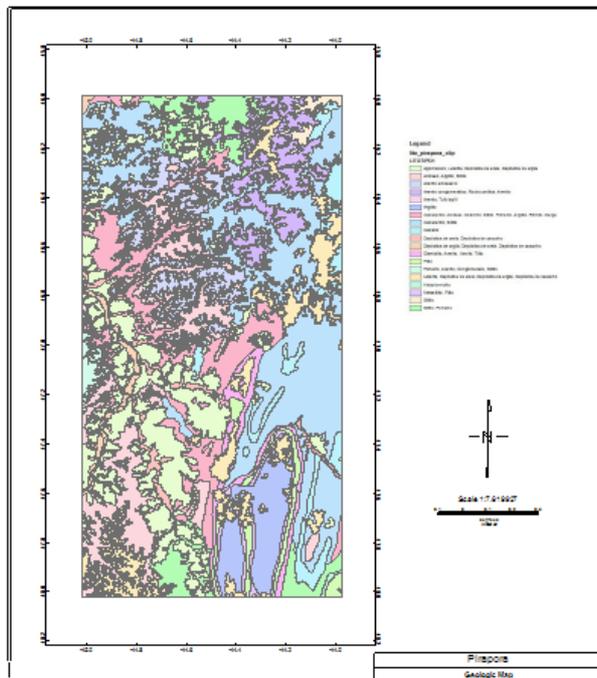
Figure (4) – Geological map for Area 13 – Source CODEMIG

Results

The Magnetization Vector Inversion of the TMI data shown in Figure (2) provided a magnetic model showing the top of the magnetic source at a depth of approximately 4500m, in accordance with previous estimates (Borges, 2011) as well as strong remanence. Comparing the component projected in the direction of the induction field with the one perpendicular to the field, or comparing the susceptibility inversion with the Magnetization Vector Inversion (MVI) it can be clearly seen that the remanent component plays a very important role in the model.
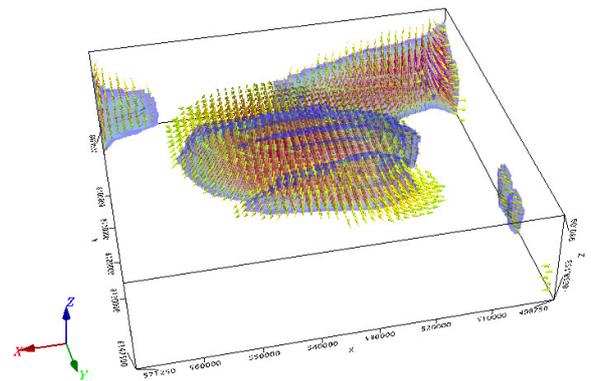
Figure (5) – Magnetization Vector Inversion results for TMI Area 13, Amplitude and magnetization vectors clipped at 0.025 SI
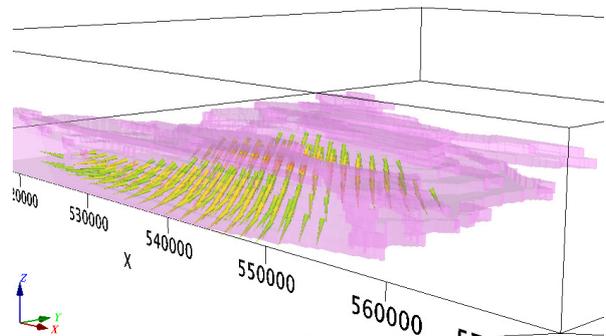
Figure (6) – Magnetization Vector Inversion results for TMI Area 13, Amplitude and magnetization vectors clipped at 0.05 SI

Following the methodology described above, we have first qualitatively observed that the larger Magnetization vectors over the main source appear to be focused in a predominant direction, while the smaller vectors are oriented "mathematically", not geophysically.
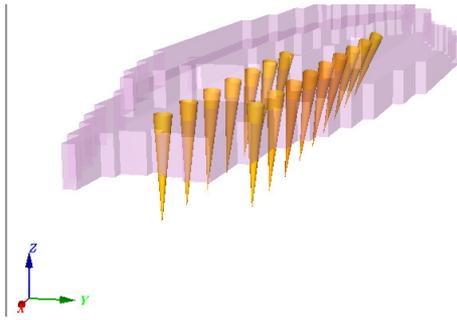
Figure (7) – Magnetization Vector Inversion results for TMI Area 13, Amplitude and magnetization vectors clipped at 0.06 SI

We have conducted a statistical analysis on the distribution of the amplitude model and have noticed that the top 20% of the amplitude values were coherently distributed over the main source, validating its use. We have calculated the Inclination and Declination angles based on those samples and obtained the values of 77.00o $\pm$ 6.51o and -119.86 o $\pm$ 13.78 o respectively.

In order to be able to see the shallowest sources, we have applied a high pass filter to the TMI, obtaining the residual magnetic that was also inverted indicating where there is a potential for shallower sources and would need further investigation.

The TMI data was filtered using a cutoff of 8300m and the filtered data was then inverted for the Magnetization Vector to seek shallower sources that could be further investigated. We have found a particular target that is certainly worth a more thorough analysis, including acquisition of more detailed surveys.
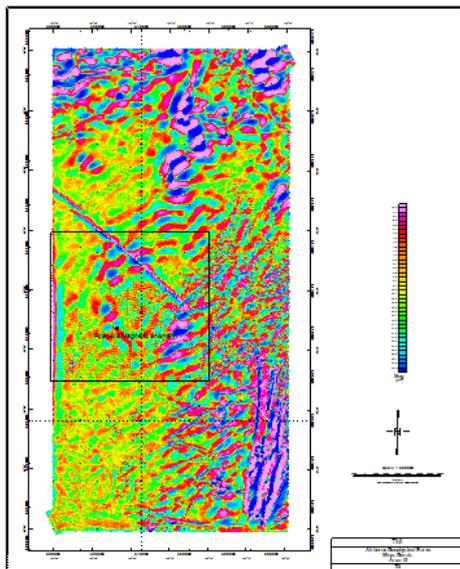
Figure (8) – Area 13 Residual - High Pass filter cutoff of 8300m
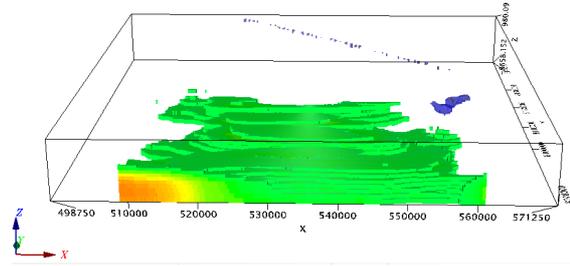
Figure (9) – Area 13 MVI results TMI (Green-orange) and Residual (Blue)

In order to compare the Cobar results with the ones generated for the Pirapora anomaly and validate the methodology, the TMI as well as the digital terrain model were obtained using Seeker - the Search Mechanism within Oasis montaj. The magnetic data (400m resolution) was made available by the Australia government and published by Geosoft in the public DAP Server, while for the DTM we have used the SRTM (90 m resolution), provided by NASA and also published in DAP by Geosoft.
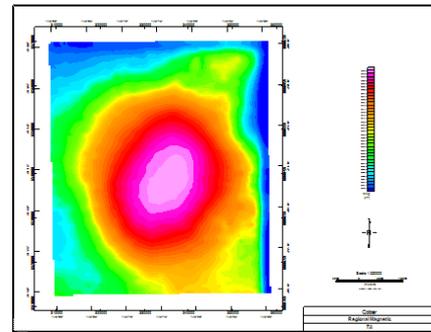
Figure (10) – Cobar Area TMI – Data used for inversion
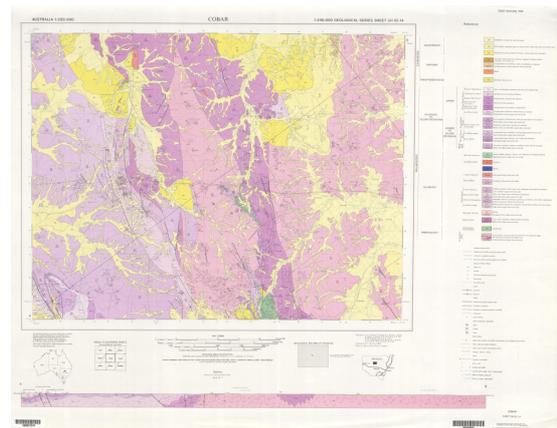
Figure (11) – Geological Map of the Cobar area – Source http://www.resourcesandenergy.nsw.gov.au/miners-and-explorers/geoscience-information/products-and-data/maps/geological-maps/1-250-000/cobar-250k-geological-map2
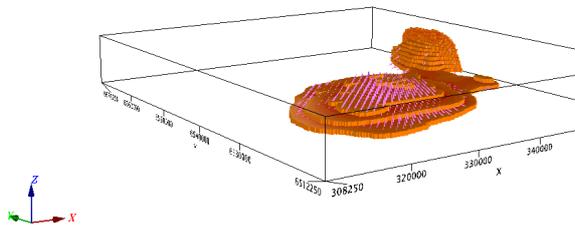
Figure (12) – Magnetization Vector Inversion results for Cobar Area TMI, Amplitude and magnetization vectors clipped at 0.0107 SI

We have applied the same methodology as described before to estimate the magnetic apparent inclination and declination obtaining the values of -66.06 ^{o} $\pm$11.37 ^{o} and 150.79 ^{o} $\pm$14.56 ^{o} respectively. Comparing the calculated values with published results (Clark and Tonkin, 1994) showed a very good agreement for the inclination value, but not for the declination value.
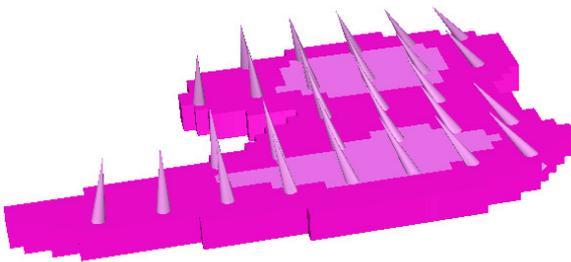
Figure (10) – Cobar Area MVI results – Samples used for the quantitative analysis.

Conclusions

The application of the Magnetization Vector Inversion to the Pirapora magnetic anomaly using the regional aeromagnetic survey confirmed a strong remanence and allowed us to give an estimate of the depth to the main source. The quantitative analysis also provided an estimate for the inclination and declination of the apparent susceptibility and this study can be further developed to generate a reasonable geological model for the area.

The magnetization vector inversion of the residual field generated an interesting target to be further investigated with higher resolution magnetic surveys or using other geophysical methods to confirm the potential. We have not found references of detailed surveys over this area, although probably there are unpublished investigations.

We have noticed several coincidences between the Pirapora Anomaly and the Cobar area in North South Wales, Australia and have inverted the public available magnetic data, generating a model with strong remanence that is confirmed by numerous publications of this anomaly. The estimated Inclination calculated from MVI yields a very good agreement with the published results and although we did not have a good agreement for the declination estimate, the difficulties to orient the core sample to enable the declination estimation may be accountable for the differences.

The quantitative MVI analysis can help to build a geological model for the magnetic sources and further studies with higher resolution needs to be conducted in order to corroborate with the presented results.

Acknowledgments

References

Aisengart, T., 2013, 3D Inversion of Magnetic Data at Low Magnetic Latitudes, , Thirteenth International Congress of the Brazilian Geophysical Society, Rio de Janeiro

ALMEIDA, F.F.M., 1977. O Cráton do São Francisco. Revista Brasileira de Geociências, 7:349-364.

Barbosa, R.D & Pereira, J.G. 2013. Inversão 3D de dados Magnéticos na Região de Mara Rosa – Goiás, Brasil, utilizando Geosoft VOXI. Thirteenth International Congress of the Brazilian Geophysical Society, Rio de Janeiro.

Borges, A.J., 2013, Relatório Interno CPRM (não publicado)

Borges, A.J., Drews, M.G.P., 2009, Anomalias Aeromagnéticas Notáveis da Bacia do Rio São Francisco, Seventh International Congress of the Brazilian Geophysical Society, Rio de Janeiro

Codemig – www.codemig.com.br

CODEMIG, 2013. Mapa Geológico 1:1.000.000. Folha Pirapora - SE.23-X-C-I. Projeto Norte de Minas.

D.A. Clark, C. Tonkin, 1994, Magnetic anomalies due to pyrrhotite: examples from the Cobar area, N.S.W., Australia Journal of Applied Geophysics 32: 11-32

Ellis, R.G., Wet, B., and Macleod, I.N., 2012. Inversion of Magnetic Data from Remanent and Induced Sources,

22nd International Geophysical Conference and Exhibition, Australia

Ellis, R.G., 2015, Quantitative Analysis of MVI, Geosoft Presentation at ASEG

Emerson,D.W.,1980,The Geophysics of the Elura Orebody,COBAR,NewSouthWales.. The Proceedings of the Elura Symposium, Sydney. The Australian Society of Exploration Geophysicists.

http://www.resourcesandenergy.nsw.gov.au/miners-and-explorers/geoscience-information/products-and-data/maps/geological-maps/1-250-000/cobar-250k-geological-map2

SANTOS, M.H.L., 2006. Processamento, Nivelamento e Integração de Levantamento Aerogeofísicos Magnetométricos no Estado de Minas Gerais e sua contribuição à Geologia da Porção Sul do Cráton São Francisco. Dissertação de Mestrado Nº210. Universidade de Brasília. Instituto de Geociências. Brasília – DF.

Zdhanov, M. S., 2002, Geophysical Inverse Theory and Regularization Problems, Method in Geochemistry and Geophysics 36, Elsevier Science B.V., Amsterdam, The Netherlands.