State of the Art Techniques for Iron Oxide Exploration

James Mataragio (Bell Geospace Inc), Greg Jorgensen (Flat Irons), Dionisio Uendro Carlos, Marco Antonio Braga (Vale S.A.)

This paper was prepared for presentation during the 12th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, August 15-18, 2011.

Abstract

Geological and geophysical characteristics of the Maquiné Rocinha property located in Quadrilátelo Ferrífero, (QF) area, Minas Gerais, Brazil were investigated particularly to locate iron oxide deposits, estimate their volumetric tonnage and map features of interest associated with oxides mineralization. Airborne full tensor gradiometry in conjunction with magnetic surveys was flown over an area covering approximately 600 square kilometers.

Gravity gradient and magnetic methods are used to delineate structures, lithological units and iron ore bodies in the QF area both at local and regional scale levels. The ore body in Iron Quadrangle is associated with positive, high-amplitude gravity anomalies that are related to elevated abundances of high-density iron minerals, including magnetite and hematite.

This paper presents the interpretation results for the integration of geophysical and geological data in mapping, detection and volume estimation of iron oxide deposits in the QF area.

Introduction

Airborne gravity gradiometry surveys have been successfully flown in the past for iron formation hosted hematite and magnetite in different parts of the world including Northern Canada, West Africa and South America. In South America alone over 100,000 line kilometers of full tensor gravity data have been flown in the last 5 years. Over 90% of the data that has been acquired during this period has been essentially used for iron oxide exploration and the remaining 10% has been used for targeting base metals, precious minerals and, hydrocarbons in Brazil and Uruguay.

The application of airborne gradiometry in iron oxide exploration is viable due to the fact that iron oxide ore is extremely dense compared to the host rock; hence they become ideal gravity targets. The combination of two geophysical methods, namely gravity gradiometry and magnetics is considered an important exploration tool in the QF area as the ore occurs in two different physical properties. The compact, dense and high grade ore is lacking magnetite therefore not a magnetic target on the other hand the friable, less dense and relatively low grade ore presents both magnetic and gravity target. However, the presence of quartzite units associated with oxide ore could bring a challenge if gravity alone has to be used to resolve low grade friable ore. Quartzite tends to have small density contrast with the itabiritic ore.

In addition to mapping and direct detection of the hematite and magnetite ore deposits, the joint Inversion of the full tensor gravity gradiometry, magnetic and ground gravity could be instrumental for approximate resource tonnage estimation prior to embarking on the costly drilling phase. Such approximate tonnage resource estimation might be especially useful in remote Greenfield locations where ground access is limited by rugged terrain or dense forest areas like the Amazon jungle.

Regional Geological Setting

The QF is located in the southern part of the São Francisco Craton and is made up of Archean granite-gneissic terrains, Greenstone Belt (Rio das Velhas Supergroup); Paleoproterozoic (Minas Supergroup and Itacolomi Group) and Paleoproterozoic-Mesoproterozoic (Espinhaço Supergroup) supracrustal units see figure 1 (Adalene Moreira da Silva al 2003).

The Quadrilátero Ferrífero (QF) district is located roughly between latitudes 19° - 20° S and between longitudes 43° - 44° W (Figure 1). The iron ore deposits are hosted within the Cauê and Batatal Formations, similar to the typical Banded Iron Formation such as the Algoma type Banded Iron Formation around Lake Superior area. The geology of Quadrilátelo Ferrífero has previously been discussed by the following authors, Dorr 1969; Renger and Others, 1994, Machado and Others 1992; Machado and Carneiro 1992; Bekker and Others 2003.

The iron ore in QF is comprised of the intermediate chemical member of the Minas Supergroup, which is a Paleoproterozoic meta-sedimentary sequence. The banded iron formations, locally known as itabirites, are metamorphosed and strongly oxidized. On the western border of the QF, the Minas Supergroup is less deformed and preserves some original sedimentary structures. The metamorphism at this region reached the green schist facies.

Mineralization Controls

The iron ore bodies occur as discontinuous lenses of varied sizes and shapes within the itabirites (Figure 2). Iron ore in QF can be classified into two main types of iron ores: the high-grade ore (Fe > 64%), called hematite ore or hard hematite and intermediate-grade ore (64% < Fe < 52%), called itabiritic ore. The intermediate-grade itabiritic ore is typically friable and generally grades to hard itabirite with low iron content.

The genesis of intermediate-grade itabiritic ore is thought to have been formed by residual concentration of the iron oxides after leaching of the gangue minerals during the Cenozoic weathering. The genesis of the hard high-grade is more complex and not well understood. This ore type generally preserves the original banding of the hosted itabirite and shows hematite re-crystallization.

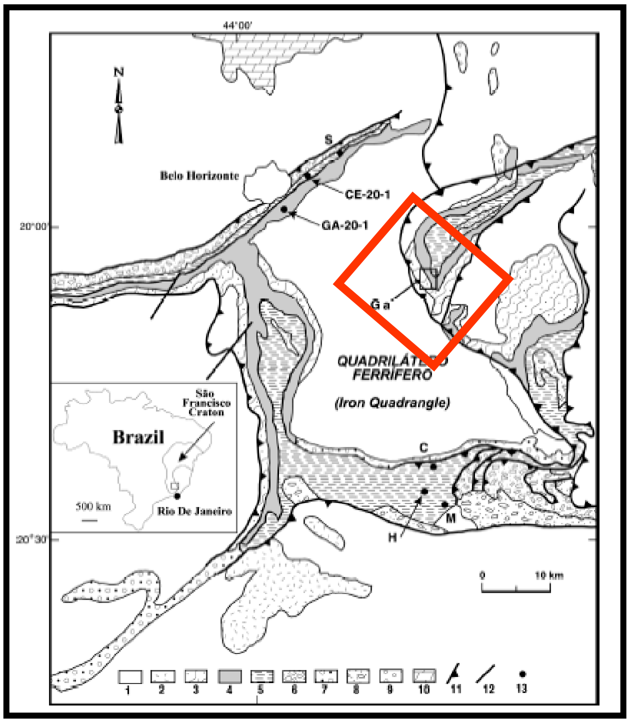

Figure 1. Regional Geological map (modified from Dorr, 1969) of the Quadrilátero Ferrífero area with survey area shown in red. 1 – Archean terrain; 2 –Paleoproterozoic granitoids; 3 – Caraca Group; 4 – Itabira Group; 5 – Piracicaba Group; 6 – Sabara´ Group; 7 - Minas Supergroup undivided; 8 – Itacolomi Group; 9 – Mesoproterozoic Espinhac¸o Supergroup; 10 – Neoproterozoic Bambui Group; 11 – thrust; 12 – fault. Inset shows location of the Quadrilatero Ferrıfero area in Brazil.

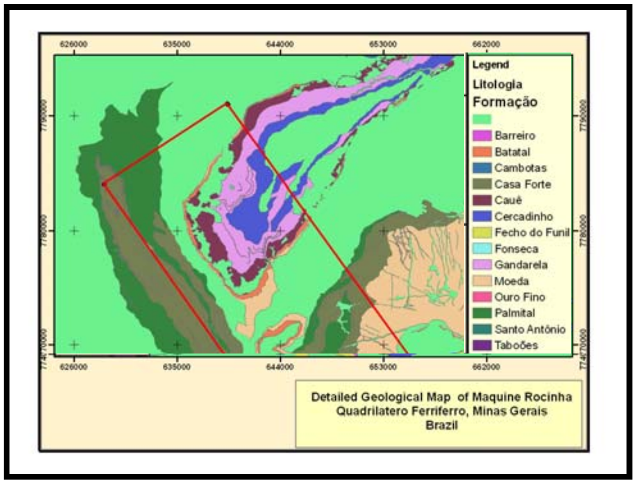

Figure 2. Detailed Geological map (modified from Dorr, 1969) over the survey area shown in red.

Data Preparation and Results

Gravity Gradient Data

The measured gradient free air data was leveled, full tensor noise reduced (FTNR) and terrain corrected prior to evaluation and interpretation. Optimum density for terrain correction is critical to accurately separate geological signals from terrain related signals. A range of density corrections from 2.0 g/cc - 4.5g/cc was analyzed to determine the best density value which closely removes the effect of terrain in the free air measured data.

The terrain correction was computed using a proprietary 3-D prism modelling package which uses grids and prisms to compute the gravity effect of each defined layer. For this particular study the density of 2.6g/cc was chosen as the optimum density to be used throughout the interpretation

Magnetic Data

The measured magnetic data was reduced to pole before interpretation because the total magnetic field (TMI) incorporates the geometric effect of the earth's magnetic field. So, it was necessary prior to interpretation to remove this effect from the data. The process of reducing TMI to the pole (RTP) simplifies interpretation and makes the location of the anomaly more accurate. The first vertical derivative and analytical signal of the RTP were then computed and used for Interpretation as well.

The results for the full tensor gravity data together with the magnetic data are displayed below (Figure 3 and 4).

The vertical component of the gravity gradient Tzz (Figure 3) is closely related to the sub surface geology; it directly delineates long linear itabirites units of the Caue and Batatal as well as hard hematite. Tyz and Txz outline central axes of the itabirites in north-south and east-west directions. Txx and Tyy delineate edges of the itabirites as well as hematite ores in east-west and north-south directions respectively. Txy maps all other features within the itabirites that are oriented at an angle with respect to north-south.

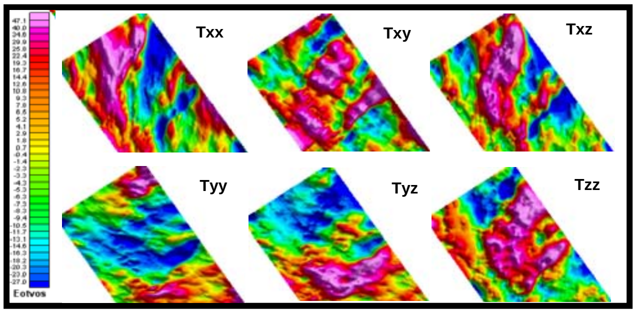

Figure 3. Terrain corrected (at 2.60g/cc) and full tensor processed images. Each tensor outlines different attributes of geology as explained above.

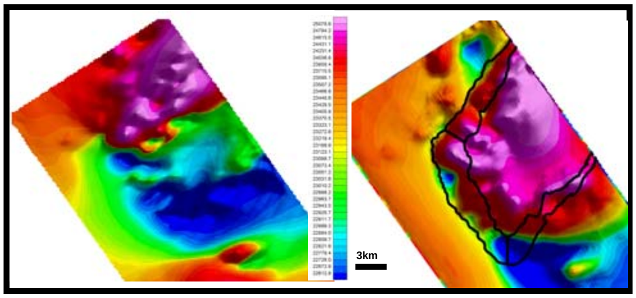

Figure 4. A. Total magnetic field (TMI) and B. pole-reduced magnetic field (RTP), shaded at 45 degree from the north.

Rotational Invariants and Data Enhancement

Rotational invariants are computed from terrain corrected full tensor noise reduced and filtered tensor data. The data for this study was low pass filtered at 500m wavelengths in order to remove high frequency signals that are not necessarily related to the geology of interest.

The technique is primarily intended to improve the data quality by highlighting the density contrast between different geological features. In addition to highlighting density contrast, the rotational invariants provide an alternative way to visualize all six tensor components from a single image. Information such as contacts, lithological units, and 3D-shaped targets such as the intrusive bodies is greatly improved.

The enhancement technique computes the rotational invariant-1 (R-1) and rotational invariant-2 (R-2). The invariant tensors are rotated about the Z-axis and the computed response retains its shape and orientation regardless of the direction rotated. The technique was first described by Pederson & Rasmussen (1990). In their paper Mataragio and Kieley (2009) discuss in detail the use of rotational invariants citing an example of the massive sulphide hosted in steeply dipping ultramafic intrusions.

Figure 5 and 6 show R-2 and its first vertical derivative. Tzz image clearly outline the itabirite, this case the Caue formation which forms part of the southern tip of the regional Gandarela fold (Figure 2). The R-2 enhances hematite and some high grade itabiritic ore within the itabirite. The first vertical derivative of the Rot-2 further enhances shallow ore bodies providing good drill targets.

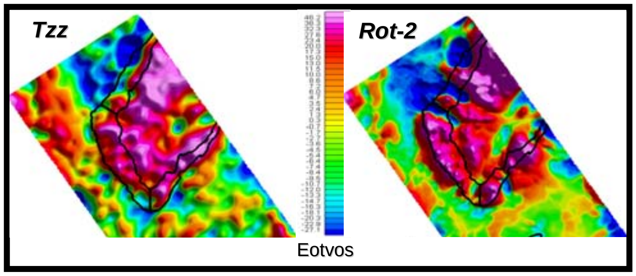

Figure 5. Terrain corrected Tzz maps the outline of the itabirite (Banded Iron Fromation) where as R-2, enhances shapes of various small individual hematite ore bodies within the itabirite.

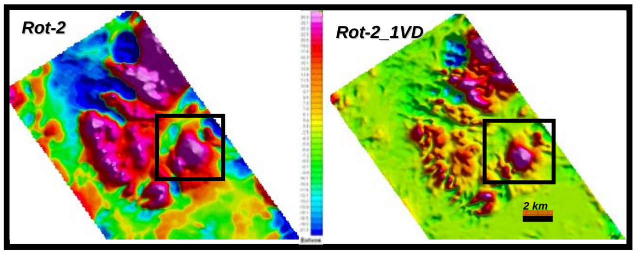

Figure 6. Rot-2_1VD enhances shallower and even smaller ore bodies, separating them from deep sourced bodies.

Ore Estimation using Inversion of Full Tensor Data

The inversion process is a space domain inversion method. The inversion simultaneously inverts on all channels in the tensor matrix (the sensitivity matrix in the inversion is controlled by each tensor channel). The degree of fit between the input data and the model data is controlled by a filter function that operates on the model (not the data). The filter function has a depth weighting parameter (the greater the distance between model inversion boundary and the observed data, the greater the filter effect).

In the ore body inversion method (Figure 7) the inversion model starts as a “thin ribbon” model. The upper surface of the thin ribbon is the Shuttle Radar Topography Mission (SRTM) surface. The lower boundary (Ore Base) of the starting thin ribbon model is a slightly downward shifted STRM surface (~10 meters). The space between the two boundary surfaces is populated with a cell network (cell size user designed). Each cell is assigned a density, and each cell can have a unique density. The inversion process migrates the lower boundary of the cell network to obtain a fit between the model response and input data.

In using a “thin ribbon” starting model, the input data must be a terrain corrected version. Density values used in each cell then becomes a contrast density, with the contrast defined by the rock density assigned to each cell minus the terrain correction value.

Convergence of the model can be demonstrated by comparison of the input data and the final model forward field (Figure 8 and 9).

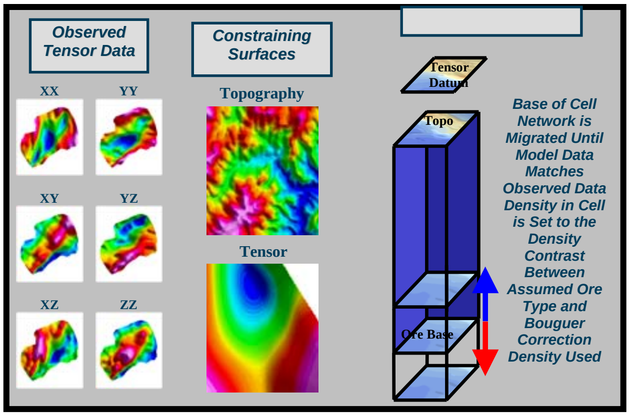

Figure 7. Inversion Model construction overview. The left hand side images are observed tensor data. The centre two images are the constraining surfaces, the topography (SRTM) and tensor datum. The right image shows a schematic diagram of the inversion process.

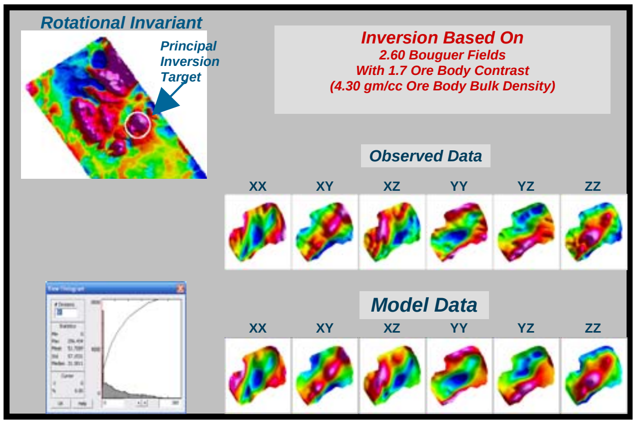

Figure 8. Inversion target location and the display of input tensor data and the output model field

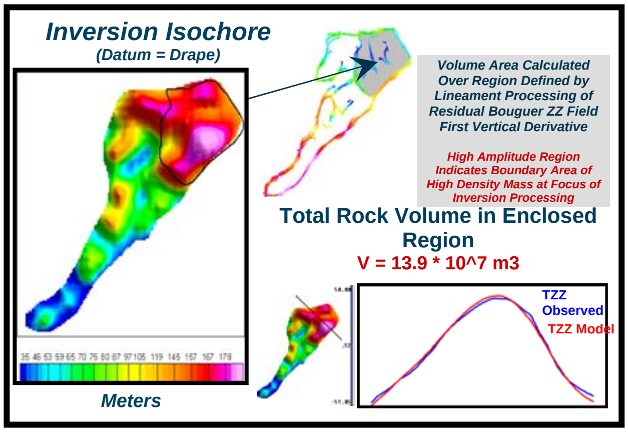

Figure 9. The volume of the ore was computed based on the inversion of a gray area. The graph shows the comparison between input data and the model forward field.

Discussion and Results

The improved geological knowledge can help exploration geoscientist target new areas for mineral exploration. Recognize patterns of geophysical anomalies that correspond to geological targets for mineral potential, such as the banded iron formations and associated volcanic clastic rocks.

The interpretation of high-resolution gravity has provided both an overview of the regional structure as well as further insight into structural controls of the iron oxide deposits. Particularly important gravity gradient data has proved to be a useful tool in identifying high grade hematite ore, which could not be resolved magnetically.

Qualitative comparison of terrain corrected Tzz and RTP (Figure 4 and 5) shows a clear difference in terms of features the two methods can resolve. The marked box indicate areas where gravity data resolves hematite bodies and other high frequency features whereas RTP data map those features as magnetic lows and provide a relatively smooth data dominated by low frequency features.

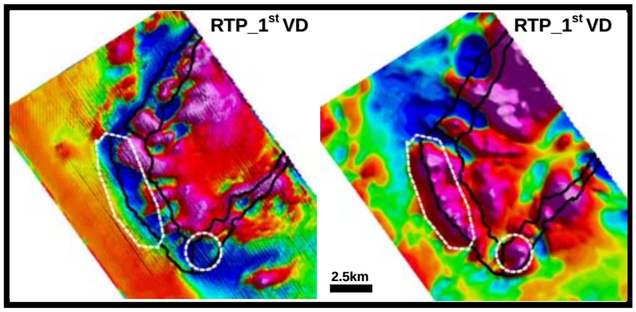

Figure 10. Two images show the advantage of using integrated approach in mapping oxide ores. The left image is RTP_1VD, it resolves the magnetic itabiritic ore,

however the data fails to resolve the non magnetic hematite as indicated in the white dashed line. On the other end the gravity resolve both itabirite and hematite ore.

The results from the inversion of full tensor data is within the error of previously calculated tonnage in this location based on limited drilling information. There is good fit between the input data and the output data (Figure 8 and 9), the data in figure 8 and the graph in figure 9, giving more confident for the final volume estimation based on the inversion.

Conclusions

The interpretation of high resolution airborne gravity gradient combined with magnetic and geological data provides new insights into:

i. The knowledge of the lithologies and structure for the Maquiné Rocinha property,
ii. The understanding of the property's regional and local setting,
iii. Detection of possible new iron ore targets for ground follow-up and,
iv. Ore estimation based on the inversion of full tensor data provides an estimate of the exploration budget and helps in decision making for the next exploration phase. It minimizes risks and costs that may be involved in undertaking further exploration program

References

Bekker, A., Sial, A. N, Karhu J. A., Ferreira, V. P., Nocc. M. E.,
Kaufman, A. J., A. Romano, W., and Pimentel, M. M. 2003, American Journal of Science, Vol. 303, P. 865–904.

Dorr, J. V. N.d., 1969, Physiographic, stratigraphic and structural development of the Quadrila´tero Ferrı´fero, Minais Gerais, Brazil: United States Geological Survey Professional Paper 641-A, 110 p

Machado, N., and Carneiro, M. A., 1992, U-Pb evidence of late Archean tectono-thermal activity in the southern Sa˜o Francisco shield, Brazil: Canadian Journal of Earth Sciences, v. 29, p. 2341–2346.

Machado, N., Noce, C. M., Ladeira, E. A., and Belo de Oliveira, O., 1992, U-Pb geochronology of Archean magmatism and Proterozoic metamorphism in the Quadrila´tero Ferrı´fero, southern Sa˜o Francisco craton, Brazil: Geological Society of America Bulletin, v. 104, p. 1221–1227.

Mataragio J., and Kieley J., 2009, Application of full tensor gradient invariants in detection of intrusion-hosted sulphide mineralization: implications for deposition mechanisms.

Pedersen, L. B., and. Rasmussen, T. M., 1990, The gradient tensor of potential field anomalies: Some implications on data collection and data processing of maps. Journal of Geophysics, v. 55, No. 12, p. 1558-1566