In-depth imaging of an iron orebody from Quadrilatero Ferrífero using 3D gravity gradient inversion

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SUMMARY

We have interpreted the airborne gravity gradiometry data from Quadrilátero Ferrífero, an iron ore province in southeastern Brazil. Aiming at retrieving the geometry of the iron body, we have used a fast and novel gravity inversion method for estimating a 3D density-contrast distribution defined on a grid of prisms. This inversion approach combines robust data-fitting with an iterative procedure that does not require the solution of a large equation system. By using a systematic search algorithm, the estimated mass grows around prismatic elements called "seeds". The interpreter specifies the locations and the associated density contrasts of the seeds. Automatically, the inversion method fits the observations and favors compact gravity sources closest to the seeds. To produce a more robust data fitting than least-squares fit, the inversion method minimizes the L_1–norm of the residuals. Hence, it allows the presence of large residuals, so that outliers produced by non-targeted bodies can be handled. By using 126 seeds which were assigned density contrasts of 0.5 g.cm^{-3} and whose locations were based on our knowledge about the QF area, we have retrieved a continuous elongated iron body that fits the observed components of the gravity gradient. Our inversion result agrees reasonably with previous geophysical interpretations. In addition, our result honors the borehole information about the iron body depth.

INTRODUCTION

The Earth's largest iron reserves are composed of Banded Iron Formations (BIFs), which are altered sedimentary deposits with laminated rocks formed by alternating layers of silica and hematite-magnetite, as well as carbonates and iron silicates. One of the most important iron provinces in Brazil is the Quadrilátero Ferrífero (QF), located in the São Francisco Craton, southeastern Brazil. The QF is recognized for its high volume of iron reserves, the high quality of the ore produced and the cumulative production. Most of the iron orebodies in the QF are hosted in the oxided, metamorphosed and heterogeneously deformed BIF of the Cauê Formation, so-called itabirites. The itabirites are associated with the Minas Supergroup, more precisely the Itabira Group of the Cauê Formation, and they contain iron ore oxide facies, such as hematites, magnetites and martites.

Recent technological developments of the moving-platform gravity gradiometers made it feasible to accurately measure the independent components of the gravity gradient tensor. Thus, airborne gravity gradiometry has come to be a useful tool for interpreting orebodies in a mining district. Gravity gradiometry has the advantage, compared with other gravity methods, of being extremely sensitive to localized density contrasts within regional geological settings (Zhdanov et al., 2010). Recently, some gravity gradient inversion algorithms have been adapted to interpret field data from mineral exploration targets. All these methods parameterize the Earth's subsurface into prismatic cells and estimate the 3D density-contrast distribution which retrieves an image of orebodies (e.g., Martinez et al., 2010; Zhdanov et al., 2004; Li 2001; Jorgensen and Kisabeth, 2000).

We show the interpretation of the iron body from the Quadrilátero Ferrífero (Brazil) by using a 3D robust gravity gradient inversion developed by Uieda and Barbosa (2011). We are interpreting a large study area that extends itself by 95 km^2 with dimensions of approximately 19 km by 5 km. Uieda and Barbosa's (2011) method estimates a discrete 3D density-contrast distribution from gravity gradiometry data. The subsurface region containing the geologic sources is discretized into an $m_x \times m_y \times m_z$ grid of 3D rectangular prisms with constant but unknown density contrasts. Uieda and Barbosa's (2011) method uses "seeds" around which the density anomalies grow, as in the 2D gravity inversion proposed by Renè (1986). To estimate a sharp image of multiple and adjacent bodies Uieda and Barbosa (2011) impose a compactness constraint on the estimated bodies by using a regularizing function adapted from the 3D gravity inversion through an adaptive learning strategy developed by Silva Dias at al. (2009). In Uieda and Barbosa's (2011) method each seed can be assigned a different density contrast, based on the interpreter's knowledge about the geology of the study area. It allows the interpretation of multiple bodies with different density contrasts producing interfering gravity effects. The estimated mass grows by the accretion of neighboring prisms of the current solution. The prisms for the accretion are chosen by systematically searching the set of current neighboring prisms.

Usually an inversion method for estimating a 3D density-contrast distribution leads to a linear system of N equations in M unknowns, where N is the number of dada and M is the number of parameters to be estimated. This system demands a huge computational effort to be solved if M and N are large. An important advantage of Uieda and Barbosa's (2011) method is its low computational demand, in terms of both memory and processing time, because it does not solve linear systems. Furthermore, the sensibility matrix of the linear system is not fully calculated at any single time during the inversion, because the systematic search algorithm is limited to neighboring prisms of the current solution. This means that each column of the sensitivity matrix only needs to be calculated when a prism of the interpretative model is tentatively accreted to a seed. Once a neighboring prism is permanently added to the solution, its corresponding column is no longer needed and can be discarded. Hence, by applying Uieda and Barbosa's (2011) method, it is feasible to interpret a huge set of gravity gradient data by setting up a fine interpretation model composed of small 3D prisms. Additionally, Uieda and Barbosa's (2011) method uses a robust data-fitting procedure by minimizing the L_1–norm of the residuals. This allows the presence of large residuals, so that outliers produced by non-targeted bodies can be handled.

We present a 3D interpretation of a large set of gravity gradient data (greater than 45,500) from an economically important iron ore province in southeastern region of Brazil, named Quadrilátero Ferrífero. We inverted this data set by applying Uieda and Barbosa's (2011) method. The study area is 95 km^2 in extent. We discretized the subsurface into a grid composed by a large number of 3D prisms (greater than 237,000). Our interpretation aims at delineating in depth the geometry of the iron body. By applying the 3D robust gravity gradient inversion (Uieda and Barbosa, 2011) to the data from the QF, we obtained a depth image of the iron body consistent with the available borehole data.

GEOLOGIC SETTING

The Quadrilátero Ferrífero is located at the southeastern border of the São Francisco Craton, southeastern Brazil. Since the 17th century, the QF has been known as a major gold- and iron-rich province in the Precambrian region of Brazil (Klein and Ladeira, 2000). A simplified stratigraphic sequence of the QF includes (Klein and Ladeira, 2000): (1) a granite-gneiss basement; (2) the Archean Rio das Velhas Supergroup, which includes the Rio das Velhas greenstone belt, and hosts the major gold deposits of the region, many of which are associated with banded iron formations; (3) the Proterozoic Minas Supergroup, which overlies the older rocks with a tectonically transposed angular and erosional unconformity, and includes the Cauê Formation or Cauê Itabirite that hosts the hematite-rich iron ore deposits of the region; and (4) the Itacolomi Group, which rests on the Minas Supergroup with a slight angular and profound erosional unconformity.

Most of the major iron mines in the QF are associated with Precambrian banded iron formations, locally known as itabirites, that are part of the Proterozoic Minas Supergroup. The Minas Supergroup consists of three metamorphic sequences: (1) the Caraça Group, (2) the Itabira Group, and (3) the Piracicaba Group. The Caraça Group, the lowest unit of the Minas Supergroup, consists of clastic sedimentary rocks (e.g., phyllites and quartzites). The Itabira Group, the middle unit of the Minas Supergroup, comprises the Cauê and Gandarela Formations, which mostly consists of chemical sedimentary rocks. The Cauê Formation is economically important because it contains the huge iron deposits of the QF. The Cauê Formation comprises a thick sequence of itabirites (BIFs) intercalated with hematitic phyllites and dolomitic phyllites. The Gandarela Formation, which conformably overlies the Cauê Formation, comprises mainly calcitic and dolomitic marbles with subordinate phyllites. The Piracicaba Group, the upper unit of the Minas Supergroup, consists of clastic sedimentary rocks with dolomites. Part of this unit is the Sabará Formation which consists of mica-chlorite schist, thin interbedded mafic volcanic quartzose rocks, BIFs, and fragmental quartzose schists.

RESULTS

The airborne gravity gradiometry survey covered the Gandarela Syncline, located in east region of the Quadrilátero Ferrífero where we can find the Minas and Rio das Velhas Supergroups. Figure 1 shows the digital terrain model and the airborne survey flight lines.

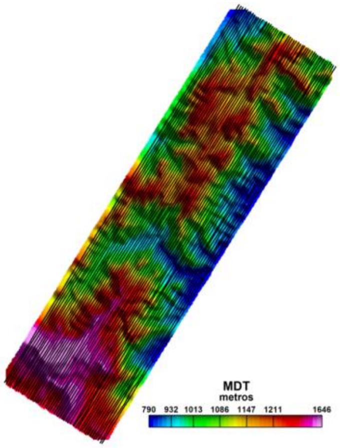

Figure 1: Digital Terrain Model of the study area. Superimposed are the flight lines.

Figure 2 shows the three observed components of the gravity gradient tensor (Gyy^o , Gyz^o e Gzz^o) over the study area in QF. The choice of using these three components in the inversion takes into account the elongated southwest-

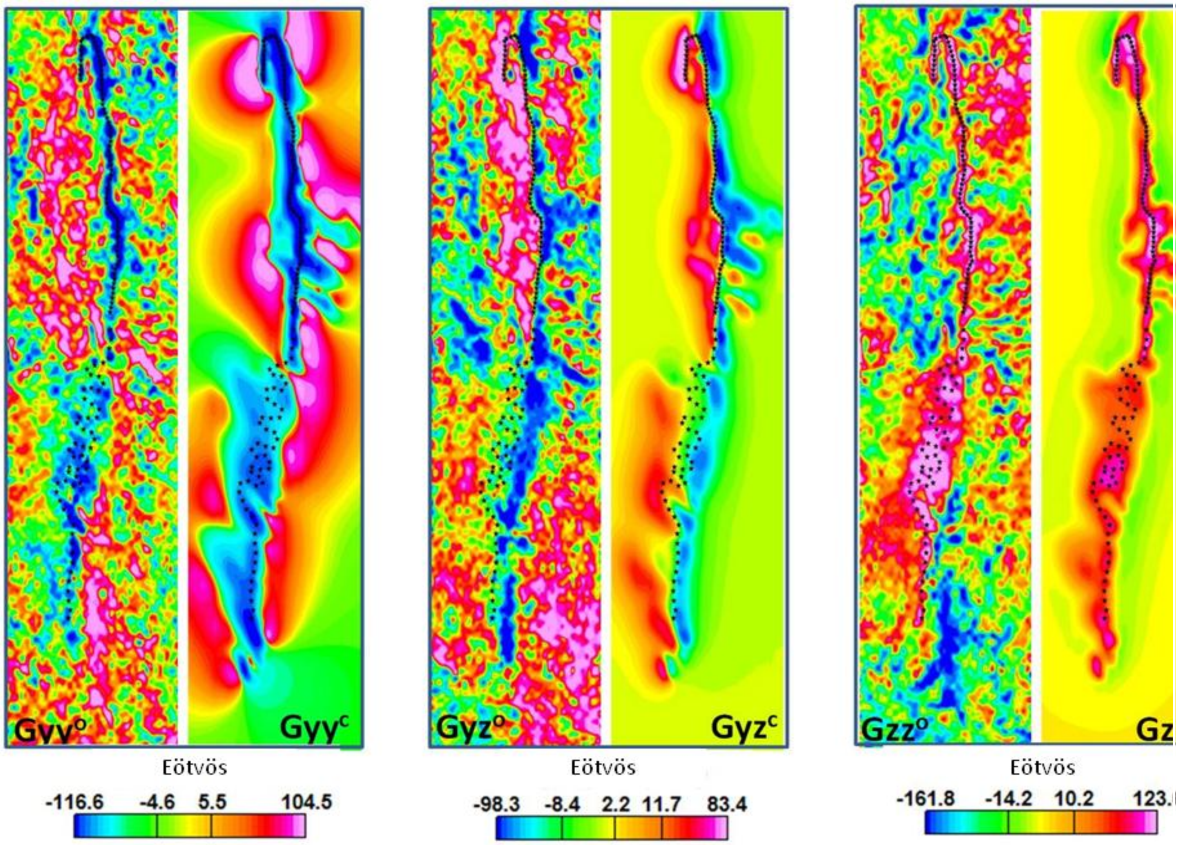

Figure 2: Observed (Gyy^o , Gyz^o e Gzz^o) and computed (Gyy^c , Gyz^c e Gzz^c) components of the gravity gradient tensor; the latter were produced by the estimated iron orebody shown in Figure 3. The black dots pinpoint the horizontal projection of the positions of the seeds specified in our inversion. All components were rotated to improve the visualization.

northeast feature related to the iron orebody. The gravity gradient data set used in this study contains 45,798 observations. The data were corrected for the effect of topography, assigning a density of 2.67 $g.cm^{-3}$. Figure 2 shows in black dots the horizontal projections of the positions of the 126 seeds used in the inversion. We assign to all seeds a density contrast of 0.5 $g.cm^{-3}$. The specification of the set of seeds defining the iron orebody framework was based on our knowledge about the studied area. Such knowledge has been provided by drilling hole information.

We invert the data set using an interpretation model consisting of 237,770 prisms juxtaposed in the vertical and horizontal directions. This interpretation model includes the topography of the area. Figure 3 shows the estimated 3D density-contrast distribution using Uieda and Barbosa's (2011) method. The inversion method recovers an elongated compact iron orebody (red prisms in Figure 3). Figure 4, a cross section of the estimated density-contrast distribution, shows that the iron orebody is compact, continuous and has variable thickness. The estimated depths of the iron orebody are in agreement with the depths of the mineralization found in the drilling holes. Furthermore, our result shows good agreement with the results reported by Braga (2009), Martinez at al. (2010) and Uieda and Barbosa (2011). Figure 2 shows the fitted components of the gravity gradient tensor (Gyy^c, Gyz^c and Gzz^c) produced by the estimated density-contrast distribution (Figure 3) obtained via robust inversion using L1 norm of residuals. The most striking feature of the robust data fitting is that it allows an acceptable fit of the main anomalies of the gravity gradient data (related with the iron orebody) and allows large residuals associated with the spurious and small amplitude anomalies.

CONCLUSIONS

We have used a robust 3D gravity gradient inversion for inverting gravity gradient data produced by an iron orebody from the Quadrilátero Ferrífero (Brazil). This method estimates a 3D density-contrast distribution by combining a systematic search algorithm with a robust data-fitting procedure. By using a systematic search algorithm, the estimated mass grows around user-specified prismatic elements called “seeds”. By using a robust data fitting, the method allows large residuals associated with the spurious and small amplitude anomalies produced by non-targeted bodies. Because this inversion method does not solve linear systems, we can quickly interpret a huge set of parameters and gravity gradient data. This is an important advantage because it eliminates the need for time-consuming optimization methods and data-compression procedures.

We have inverted a large set of data and the estimated iron orebody from the Quadrilátero Ferrífero showed close agreement with previous in-depth iron orebody imaging reported in previous interpretations.

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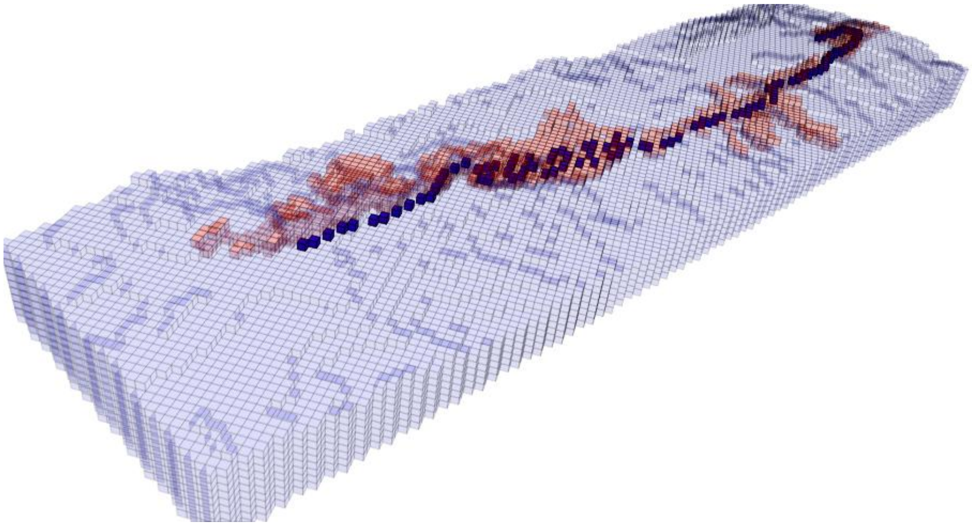

Figure 3: Quadrilatero Ferrífero iron orebody. Perspective view of the 3D estimated density-contrast distribution obtained using Uieda and Barbosa's (2011) method. Prisms with zero density contrast shown in blue and prisms with density contrast of 0.5 $g.cm^{-3}$ shown in light red; the latter are representing the iron orebody from the Quadrilátero Ferrífero. Dark blue prisms represent the seeds used in the inversion.

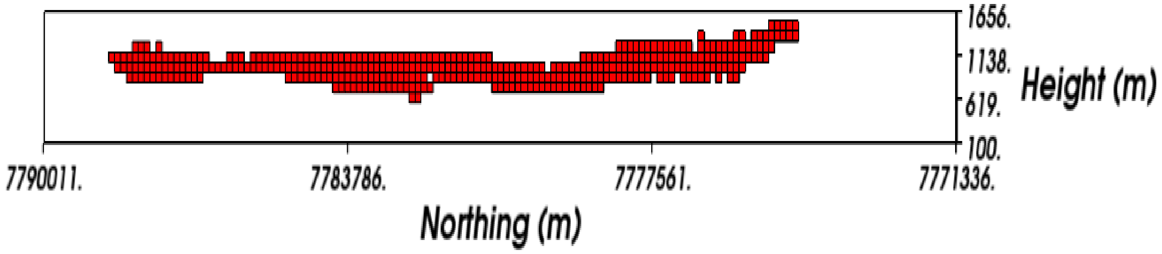

Figure 4: Quadrilatero Ferrífero iron orebody. View of the result from the eastern side. The “height” axis refers to height above the geoid. The iron orebody from the QF is shown in red prisms with density contrast of 0.5 $g.cm^{-3}$.

EDITED REFERENCES

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REFERENCES

Braga, M. A. S., 2009, Aplicação de Aerogradiometria Gravimétrica 3D-FTG na Prospecção de Minério de Ferro no Quadrilátero Ferrífero (MG) e Modelagem 2D e 3D para Estimativa de Massa do Depósito de Ferro de N1 em Carajás (PA): Ph.D. thesis, Universidade Federal do Rio de Janeiro.

Jorgensen, G. J., and J. L. Kisabeth, 2000, Joint 3D inversion of gravity, magnetic and tensor gravity fields for imaging salt formations in the deepwater Gulf of Mexico: 70th Annual International Meeting, SEG, Expanded Abstracts, 424–426.

Klein, C., and E. A. Ladeira, 2000, Geochemistry and petrology of some proterozoic banded iron-formations of the Quadrilátero Ferrífero, Minas Gerais, Brazil: Economic Geology and the Bulletin of the Society of Economic Geologists, **95**, no. 2, 405–427, doi:10.2113/95.2.405.

Li, Y., 2001, 3D inversion of gravity gradiometer data: 71st Annual International Meeting, SEG, Expanded Abstracts, 1470–1473.

Martinez, C., Y. Li, R. Krahenbuhl, and M. Braga, 2010, 3D Inversion of airborne gravity gradiometry for iron ore exploration in Brazil: 80th Annual International Meeting, SEG, Expanded Abstracts, 1753–1757.

René, R. M., 1986, Gravity inversion using open, reject, and “shape of the anomaly” fill criteria: Geophysics, **51**, 988–994, doi:10.1190/1.1442157.

Silva Dias, F. J. S., V. C. F. Barbosa, and J. B. C. Silva, 2009, 3D gravity inversion through an adaptive-learning procedure: Geophysics, **74**, no. 3, I9–I21, doi:10.1190/1.3092775.

Uieda, L., and V. C. F. Barbosa, 2011, 3D gravity gradient inversion by planting density anomalies: 73rd Annual International Conference and Exhibition, EAGE, Extended Abstracts, 1–5.

Zhdanov, M. S., R. Ellis, and S. Mukherjee, 2004, Regularized focusing inversion of 3-D gravity tensor data: Geophysics, **69**, 925–937. doi:10.1190/1.1778236

Liu, Z. M. S. X., and G. Wilson, 2010, Potential field migration for rapid 3D imaging of entire gravity gradiometry surveys: First Break, **28**, 47–51.