Structurally constrained lithology characterization using magnetic and gravity gradient data over an iron ore formation

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SUMMARY

It is often desirable to extract meaningful lithologic information directly from geophysical data. Here, we describe a multi-faceted approach that combines the known geologic sections of a site from borehole data with recovered density and magnetic susceptibility distributions from 3D inversion of airborne gravity gradient and magnetic data. The technique can produce end-member solutions based on average property values extracted from literature and well records; or, it can be implemented using the geologic sections to extract an appropriate range of property values to address the model smoothing common to modern 3D generalized inversions. To demonstrate our approach, we present results utilizing magnetic and gravity gradient data over part of the Gandarela Syncline iron formation in the Quadrilátero Ferrífero, Brazil.

Key words: Gravity gradient data, magnetic data, inversion, lithologic differentiation.

INTRODUCTION

There has been much work in exploiting the potential field relationships to extract information from the data. Kanasewich and Agarwal in 1970 explored the validity of examining the magnetization to density ratio in the wavenumber domain as an interpretation tool. Directly combining magnetic and gravity derived gravity gradient data in the spatial domain through the Poisson relation has been accomplished by Dransfield et. al. (1994) in order to generate psudolithology maps based on the ratio of apparent susceptibility to density.

Inversion of the potential field data for a susceptibility and density distribution can be explored for lithologic differentiation. Lane and Guillen (2005) have explored inversion guided by lithologic categories with density and susceptibility properties being ancillary information. In 2007, Williams and Dipple explored estimating mineral abundance through drill data and 3D property distributions obtained by inversion of magnetic and gravity data utilizing geologic reference models.

More recently, Kowalczyk et. al. (2010) utilized 3D inversion of magnetic and gravity data to obtain regional susceptibility and density contrast models that were used to divide the region into class distributions based on a scatterplot of the physical properties.

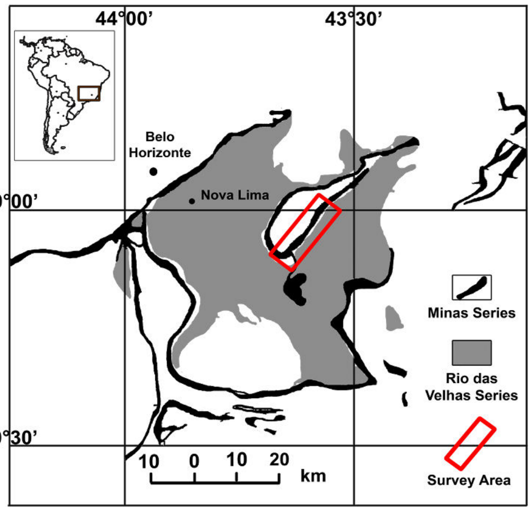

Figure 1. Geologic map of the Quadrilátero Ferrífero, with red lines indicating where the Minas Series is present; modified from Dorr, 1965.

Here, we utilize a similar approach to obtain a 3D lithologic model by combining susceptibility and density distributions obtained via inversion of magnetic and gravity gradient data.

FIELD SITE

The Quadrilátero Ferrífero, or Iron Quadrangle, is an area of significant mineral resources in the state of Minas Gerais, Brazil. The Quadrilátero Ferrífero covers approximately 7,000 km^2. The area has rugged terrain with canyons, plateaus, and valleys composing the landscape. The climate is semitropical with an average annual rainfall of nearly 250 cm.

The iron bearing formation occurs within the Minas Series, which is composed of metasedimentary rocks thought to be Precambrian in age. The Minas Series is characterized by folding structures and is present today in regional synclinal features such as the Gandarela Syncline. The structurally controlled occurrence of the Minas Series is shown in Figure 1. The eastern flank of the Gandarela syncline has been overturned while the western flank remains upright.

Within the Minas Series, the Cauê Itabirite hosts the majority of the iron mineralization and is sandwiched between the overlying Gandarela Formation and underlying Batatal formation.

Details on the structural occurrence and properties of the iron ore bodies are given by Dorr (1965). The ore bodies tend to be shallow and can range anywhere from 25 to 150 m below the surface. The high-grade ore typically contains an average of 66% Fe with the intermediate grade ores containing an average of 63% Fe. The high-grade deposits are easily differentiated from the dolomitic and quartz-rich country rock by the stark density contrast. The host rocks contain average densities close to the typical 2.67 g/cc, while target ore densities can range from 3 g/cc to 5 g/cc.

Gravity Gradient and Magnetic Data

The gravity gradient and magnetic data were collected in August-September 2005 in the Quadrilátero Ferrífero. The 93 km^2 survey was acquired with 100 m line spacing trending northeast-southwest at roughly 32 degrees from the north. The survey was semi-draped and has flight heights ranging from 60 to 500 m above the ground surface. Only a subset of the collected dataset is presented here and covers approximately a 4 km by 5 km area.

The acquired gravity gradient data underwent routine proprietary processing and corrections for the centripetal force and self-gradient, acceleration compensation, and demodulation by the acquisition company. Before data delivery, the lines were leveled and filtered to attenuate noise.

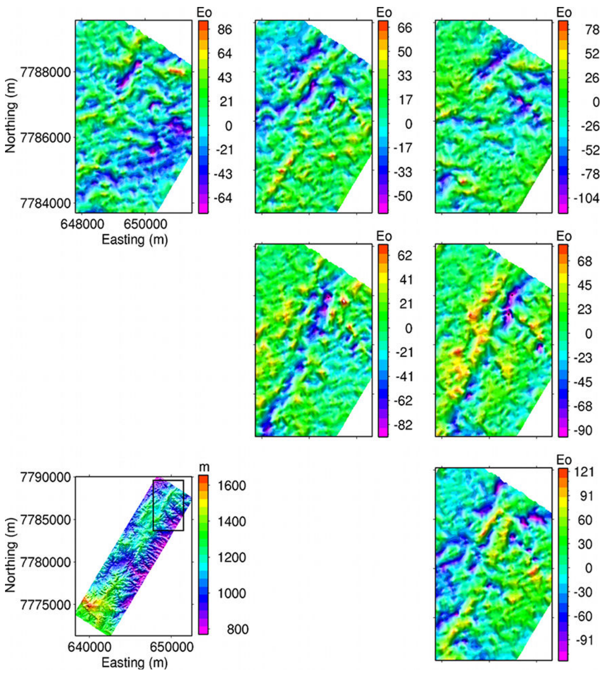

Figure 2. Observed gravity gradient data, with lower left plot showing topography of the entire survey area and location of subset data.

Though the gravity gradient satisfies Laplace's equation and there are only five independent components, six components were measured within this survey area. The extracted data are shown in Figure 2. The geologic feature of interest, the Gandarela Syncline, runs through the middle of the data parallel to the long axis of the survey area. To obtain the displayed gradient anomaly of Figure 2, a density value of 2.67 g/cc was used to acceptably remove the terrain effect.

For the magnetic data, three tie lines were flown over the survey area. Prior to delivery, the service company applied a parallax correction, height correction, removed the diurnal variation, and removed the International Geomagnetic Reference Field. The magnetic observations were upward and downward continued to maintain a constant terrain clearance of 250 m. To prepare the magnetic data for inversion, the data was levelled and gridded at 20 m spacing. The data subset used for inversion after removal of the regional field is shown in Figure 3. Before the data could be inverted, removal of the regional field was a necessity. Removal of the regional field took place by implementing an inversion methodology not discussed here.

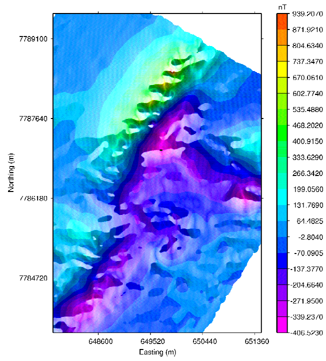

Figure 3. Magnetic anomaly data over the same subset area as the gravity gradient data after regional-residual separation

Density Contrast and Susceptibility Model

Inversion of the magnetic data was carried out based on the original methodology set forth by Li and Oldenburg in 1996. The algorithm was then adapted for use with gravity gradiometry data by Li in 2001.

Six measured components (Txx, Txy, Txz, Tyy, Tyz, and Tzz) were simultaneously inverted to obtain a representative density contrast model of the target subsurface geology (Martinez et. al., 2010). The mesh used for both gravity gradient and magnetic data inversion is composed of rectangular prisms or cells with constant density contrast within each cell. The mesh has cell sizes of 25 m in the easting by 25 m in the northing by 20 m in depth in the central region of the mesh, with padding cells beyond the data area and at large depth. The rectangular mesh has dimensions of 156 cells in the easting by 241 cells in the northing by 45 cells in depth giving a total of 1,691,820 cells.

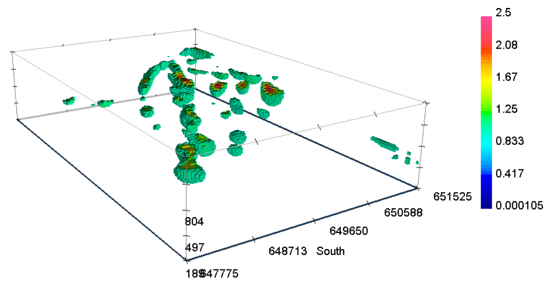

Figure 4. Density contrast distribution with cells less than 1.0 removed; units are g/cc. Distance is in meters.

The density contrast model was obtained by blind inversion of the 18,102 data points. Generic inversion parameters were used with little a priori information incorporated into the inversion. A zero reference model was used with an initial model of 2.0 g/cc. Lower and upper bounds on the density contrast were set as 0.0 g/cc and 4.0 g/cc using the knowledge that a positive density contrast is expected from the dense ore body in the less dense host rock. The length scales in each direction are two times the cell size such that Lx = Ly = 50 m and Lz = 40 m, requiring an equal amount of feature elongation in each direction. A volume rendered image of the density contrast distribution is shown in Figure 4 with model cells below 1.0 g/cc removed for clarity.

The susceptibility contrast model was obtained by blind inversion of the 12,037 data points. A zero reference model was used with an initial model of 0.001 (SI). Lower and upper bounds of 0.0 and 1.0 were placed on the model to keep the recovered values within a reasonable range of susceptibilities. Coefficients that control the smoothness derivative in each direction were 0.0001 for the smallest model and 1.0 for the easting, northing, and vertical directions. A volume rendered image of the recovered susceptibility distribution is shown in Figure 5 with model cells below 0.15 (SI) removed for clarity.

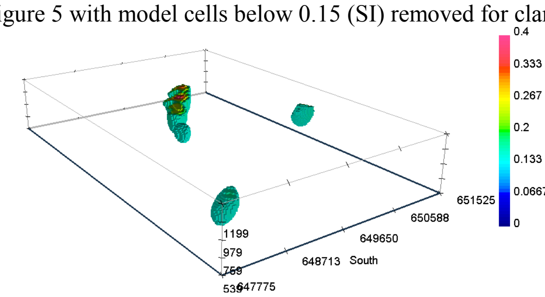

Figure 5. Susceptibility distribution with cells less than 0.15 removed; units are SI. Distance is in meters.

Lithologic Mapping

Lithology assignment using general petrophysical data

With a 3D density and susceptibility model, it is possible to examine the correlation that the two physical properties have with each other. A cross-plot of the corresponding model cells susceptibility versus density is generated in order to assign lithologic units based on these rock properties. Lithology types can then be assigned based on the susceptibility and density values according to generally known rock properties. We have used the general density and susceptibility values from Ahrens (1995).

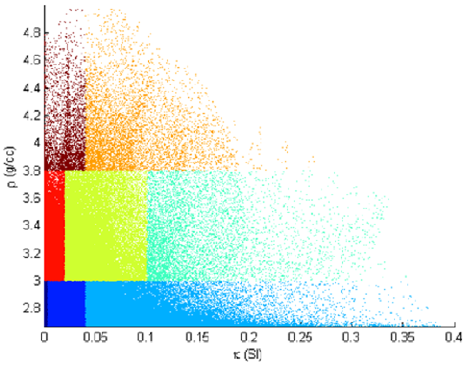

Figure 6. Cross-plot of susceptibility model versus density with lithologic units colour coded.

A cross-plot for the susceptibility and density model described above is shown in Figure 6. The background density of 2.67 g/cc was added back into the density contrast model to restore the original density range. Note that reference is made to the density contrast model.

We next assign colours to collections of points within the cross-plot to better visualize the relationships. With these colour assignments, we are then able to generate a 3D model to see the lithologic representations. The geologic section given in Figure 7 provides information for evaluating our lithologic assignments. A cross section through our constructed lithologic model, corresponding to the geologic section of Figure 7, is shown in Figure 8.

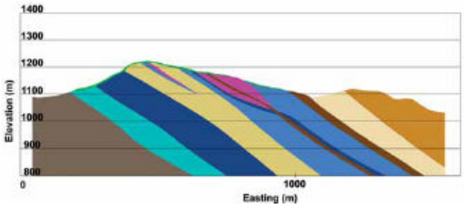

Figure 7. Geologic cross section generated from bore hole data showing itabirite in blue and hematite in pink

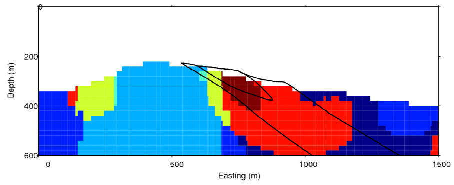

Figure 8. Cross section through lithologic model using general physical property values; maroon is hematite, red is soft itabirite.

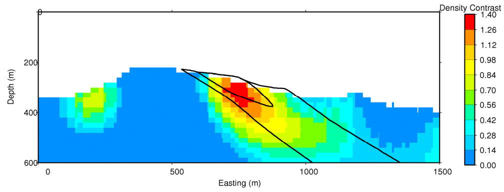

Figure 9. Cross section through density contrast model corresponding to geologic cross section of Figure 7; units are g/cc.

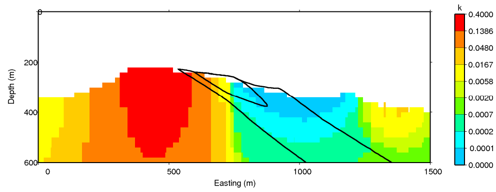

Figure 10. Cross section through susceptibility model corresponding to geologic cross section of Figure 7 plotted on a logarithmic scale; units are SI.

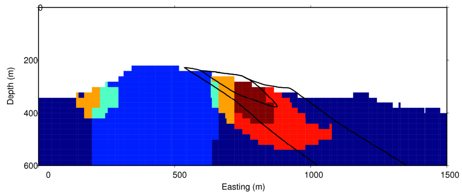

Figure 11. Cross section through lithologic model using geologic section and 3D physical property distributions; maroon is hematite, red is soft itabirite.

For additional comparison, the corresponding cross section from the separate density contrast and susceptibility models are shown in Figures 9 and 10, respectively. From the susceptibility, density, and lithologic models it is observed that the high density iron ore within the Caue Itabirite is identified by low susceptibility.

Lithology assignments using structure information

Another approach to assigning lithologic units is to use the known geologic structure together with petrophysical data. We use the geologic cross section provided in Figure 7 to obtain physical property bounds based on the density contrast and susceptibility model values. Assigning lithologic units in this manner addresses an overlooked aspect of inversion. The 3D generalized inversion formulation results in a smooth model. Assigning lithologic units based on the physical properties recovered in the inverted models accounts for the smoothing of the model.

Physical property values are extracted based on the geometry of the geologic section. This geometry is compared to the density contrast and susceptibility model cross sections through the model. The resulting lithologic section using this approach is shown in Figure 11. The difference in the two techniques is noted by the change in the structure of the red unit (soft itabirite). The volume rendered hematite distribution is shown in Figure 13.

As seen by the constrained distribution of hematite, taking into account the smoothing of the inversion has a significant impact on differentiation of the lithologic units. The distribution is further impacted by the method used to assign units based on the cross plot. Early analysis of both methods and corresponding lithologic models suggest the lithology units can potentially be better defined by taking the model smoothing into account and using the known geologic structure to define units.

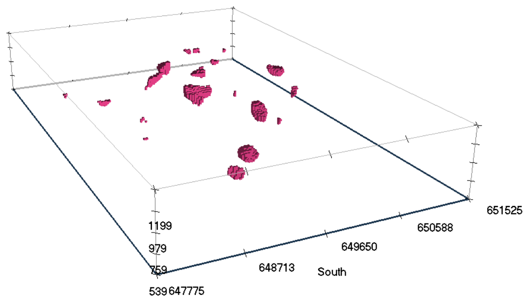

Figure 12. Hematite distribution with density and susceptibility constraints applied using geologic section.

CONCLUSIONS

Susceptibility and density models have been generated from airborne magnetic and gravity gradient data in the Quadrilátero Ferrífero. As a means of further utilizing inversion for interpretation, it is possible to combine physical property models. The two physical property distributions can be grouped into geologically representative units via known rock properties or geologic cross sections. These lithologic units can then be organized into a 3D model in order to help characterize subsurface structure.

While general petrophysical information can be used to identify lithologic units, it can be beneficial to incorporate geologic knowledge into the identification process. Incorporating known geologic structure and utilizing recovered physical property models address model smoothing characteristic of the inversion algorithm.

Utilizing inverse models has the potential to be a powerful interpretation tool, particularly combined with other general geologic information. Preliminary models such as the susceptibility distribution, density distribution, and lithologic character may prove useful in planning further exploration.

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REFERENCES

Ahrens, T.J., 1995, Rock Physics & Phase Relations, A Handbook of Physical Constants: American Geophysical Union.

Dorr, J. V. N., 1965, Nature and origin of the high-grade hematite ores of Minas Gerais, Brazil: Economic Geology and the Bulletin of the Society of Economic Geologists, 60, no. 1, 1–46.

Dransfield, M.H., M.J. Buckingham, and F.J. van Kann, 1994, Lithological Mapping by Correlation Magnetic and Gravity Gradient Airborne Measurements: Exploration Geophysics, 25, 25-30.

Kanasewich, E.R., and R.G. Agarwal, 1970, Analysis of Combined Gravity and Magnetic Fields in Wave Number Domain: Journal of Geophysical Research, 75, 5702-5712.

Kowalczyk, P., D. Oldenburg, N. Phillips, T.N. Hai Nguyen, and V. Thomson, 2010, Acquisition and Analysis of the 2007-2009 Geoscience BC airborne data: Australian Society of Exploration Geophysicists – PESA Airborne Gravity Workshop.

Lane, R., and A. Guillen, 2005, Geologically-inspired Constraints for a Potential Field Litho-inversion Scheme: Proceedings of IAMG: GIS and Spatial Analysis, 181-186.

Li, Y., and D.W. Oldenburg, 1996, 3-D inversion of magnetic data: Geophysics, 61, 394-408.

Li, Y., 2001, 3-D inversion of gravity gradiometer data: SEG Technical Program Expanded Abstract, 20, 1470–1473.

Martinez, C., Y. Li, R. Krahenbuhl, M. Braga, 2010, 3D Inversion of airborne gravity gradiometry for iron ore exploration in Brazil: SEG Technical Program Expanded Abstract, 29, 1753-1757.

Williams, N., and G. Dipple, 2007, Mapping Subsurface Alteration Using Gravity and Magnetic Inversion Models: Proceedings of the Fifth Decennial International Conference on Mineral Exploration, 461-472.