Applicability of standard Euler deconvolution, modeling, and amplitude magnetic data inversion in Greenfield programs: The Leite target case study, Carajás Mineral Province, Brazil

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Abstract

The Leite target is located in Carajás Mineral Province and has a magnetic anomaly with 140 nT of amplitude, elongated in the northwest–southeast direction. Four exploratory drillholes were performed to test the magnetic anomaly. The test showed that the source of the anomaly is a narrow magnetite hydrothermal alteration zone bearing copper mineralization up to 2%. In addition, geologic and geochemical data, magnetic susceptibility (MS) measurements were collected to identify the lithotypes with ferromagnetic minerals. We use three different techniques to estimate the depth and geometry of the magnetic source: standard Euler deconvolution, total field magnetic anomaly modeling, and magnetic amplitude inversion. When visualized in 3D, the depth of solutions from Euler deconvolution crossed the real magnetic layer with less inclination. The modeling, using the solutions from Euler deconvolution, was performed, and the magnetic anomaly produced by the body modeled achieved a low misfit. The body used in the forward modeling is geometrically similar to the geologic magnetic layer. The magnetic amplitude inversion successfully recovered the MS distribution. Finally, we carried out a borehole magnetic survey in two drillholes to validate the obtained models and investigate the magnetic source. This survey confirmed that the models were intercepted and the magnetic anomaly was associated, a hydrothermal alteration zone, with magnetite intercepted by drillholes. In this study, we demonstrated that the use of those techniques was effective in Greenfield exploration programs.

Introduction

The target Leite is a magnetic anomaly located in Carajas Mineral Province (CMP) established due to an aeromagnetic survey over Águas Claras Formation sedimentary sequence in the Carajas basin. Due to the proximity and geologic similarity with the Alemão deposit, the Leite target has become an important area to host copper mineralization associated with magnetite breccias. For the first magnetic anomaly investigation, four drillholes were drilled along two north–south sections. These boreholes intercepted a narrow hydrothermal alteration zone with chalcopyrite and magnetite breccias, with almost 10 m of apparent thickness and copper mineralization up to 2%.

Magnetic susceptibility (MS) measurements on drillhole cores were performed for quantitative analysis of the lithotypes intercepted by drillholes and to check if the magnetic source was reached. The MS measurements show that the magnetic source, a hydrothermal alteration zone, with magnetite has an average susceptibility of 0.5 SI.

Usually, the mineralization at Carajás Province has a sigmoidal shape, creating narrow structures above or below the large hydrothermal zone (such as fingers in a hand). This situation could be occurring presently in the Leite target, and we decided to use the magnetic data set to estimate the geometry and depth of the anomaly source.

Standard Euler deconvolution (SED) (Nabighian et al., 2001) was the first method used to determined the geometry. Besides the location of the source (coordinates x, y, and z), extended Euler deconvolution can estimate the dip and susceptibility of magnetic sources (Mushayandebvu et al., 2004). Guillen et al. (2004) use these solutions to obtain a 3D geologic map. Euler solutions were used to make an initial model to geophysical modeling. Despite the facts mentioned before, the values of susceptibility in the forward modeling were given by the core of drillholes.

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Manuscript received by the Editor 31 August 2014; revised manuscript received 25 December 2014; published online 8 June 2015. This paper appears in *Interpretation*, Vol. 3, No. 3 (August 2015); p. T131–T143, 14 FIGS., 2 TABLES.
http://dx.doi.org/10.1190/INT-2014-0192.1.

At Carajas Province, magnetite-rich copper mineralization is associated with magnetic remanence, and in this case, we use the direction of magnetization obtained based on Dannemiller and Li (2006). The method used searches for the maximum crosscorrelation between the magnetic total gradient and vertical derivative over a range of field inclinations and declinations. The major difficulty is that the method requires the gradients to be calculated on a reduced-to-pole (RTP) image. This transformation is almost impossible to do accurately at this latitude (low inclination and high declination). A modified procedure using a more stable RTP transformation was used (Li, 2008).

For geomagnetic surveys near the equator, the RTP value tends to become numerically unstable particularly in the presence of noise. The problem usually presents as declination parallel striping in the transformed image. This instability can be partially compensated by using a pseudofield inclination, i.e., when computing the amplitude component of the RTP transform while still preserving the phase.

As a last phase of interpretation, we performed a 3D magnetic amplitude inversion using the AMP3D algorithm (Shearer, 2005). The amplitude transformation is based on RTP and is instable in low magnetic latitudes (Shearer, 2005). Leão Santos et al. (2015) demonstrate that the amplitude transformation can reach acceptable results even when started from an unconstrained model. In this area, we started the inversion constrained from the distribution of MS obtained from the forward modeling. We compared the final results with the forward modeling, and the susceptibility values were compared with the data measured in the drillholes cores.

To confirm the inversion and forward modeling results, a borehole magnetic (BHMAG) survey was performed in two different drillholes. The present survey confirmed the obtained model, the possible source geometry, and planned future works.

In this paper, we use the airborne magnetic data acquired using a sensor installed on a helicopter. The survey was carried out in 2012, and the area was covered by 25 flight lines with direction N25°E, with 200 m of spacing and one measurement approximately every 3 m. The survey has a total of 67 km of magnetic profiles.

Qualitative interpretation and geologic settings

As said before, the Leite target was established due to a total field anomaly from an airborne survey with 140 nT of amplitude, elongated in the northwest–southeast direction The shape of the total field anomaly, total gradient (analytic signal), and the results of the drillholes suggest that the source of the anomaly is dipping to the northeast with a high angle (>60°).

The target is composed by a blue low magnetic area and a red high magnetic area in the south part (Figure 1). In the image of the vertical derivative, it is clear that the two magnetic features form the target (Figure 2).

In CMP magnetic latitude, we expect that the induced magnetic anomaly shows a low magnetic response. The presence of remanence in the Leite target is expected because almost all of the big copper deposits at CMP have strong magnetic anomaly with remanence. A copper mineralization event with magnetite, dated in 2.5 Ga (Moreto et al., 2015), is associated with magnetic remanence in the deposits. Another mineralization event occurred in 1.8 Ga (Moreto et al., 2015), without magnetite.

The Águas Claras Formation is the principal geologic lithotype in Leite target, composed by sandstones and pelites locally metamorphosed in fault zones, with some intrusive gabbros and magnetite breccias. Trendall et al. (1998) date sandstones with zircon from syndepositional volcanic rocks in 2681 ± 5 Ma (SHRIMP U/Pb zircon), and Dias et al. (1996) date gabbro dikes that cut the sedimentary package in 2645 ± 12 Ma (U/Pb zircon).

The geomorphology of the target is a valley in the central portion surrounded by a plateau. The main fault zone is coincident with the valley; these faults have predominant east–west/northwest directions with ductile/brittle deformation that locally metamorphose the host rocks. This main fault zone is crossed by late secondary faults with the direction north–south/ northeast. These secondary faults structurally controlled the mafic dikes.

The drillhole data indicated subvertical layers dipping 75° to the north–northeast. This main fault zone is coincident with the magnetic anomaly and with the mineralization intercepted by the drillholes. Thus, we can interpret that this geologic fault served as conduit for percolation of the hydrothermal fluids responsible by the Cu/Au mineralization.

Geologic mapping at the target defined five different lithotypes (Figure 3): sandstones, pelites, basic volcanic rocks, and gabbros/diabase.

The mineralization of Leite target is composed by two tabulates and parallel bodies with a northwest direction (Figure 3). The south body has 940 m of extension, whereas the north body has 230 m of extension.

The geologic data show that the orebody is dipping 70° to north–northeast, open in depth and along the strike. The style of mineralization with a paragenesis of copper-gold associated with iron oxide indicates the iron-oxide-copper-gold (IOCG) deposit model. The good correlation of the anomaly with mineralization corroborates this type of model.

The litothype hosting the copper sulfide (mainly chalcopirite) mineralization was defined as a hydrothermal alteration zone with massive magnetite (Figure 4). Due to the high hydrothermal alteration (high fluid/rock ratio), it is impossible to identify the original rock. The other lithotypes intercepted by the drillholes show hydrothermal alteration, however, without magnetite and copper sulfides (Figure 4).

Due to the geologic characteristics of the Leite target, we can generate prospective targets to Proterozoic IOCG deposits at region from magnetic data sets; i.e., we can find the copper mineralization indirectly by mapping and drilling of magnetic anomalies.

Methods

After the acquisition, we process the magnetic data to obtain the total field magnetic anomaly (Figure 1) and the vertical derivative (Figure 2). To obtain the amplitude of magnetic anomaly (Figure 5), we applied the algorithm developed by Shearer (2005). In most of the cases, this transformation is unstable on low magnetic latitudes due to the RTP transformation. However, Leão Santos et al. (2015) show a successful case of application of the same algorithm in CMP. We understand that applicability of this technique is restricted in this scenario and should be evaluated. We perform a qualitative analysis with the comparison between the total magnetic gradient and the amplitude of magnetic field. The total magnetic gradient g is given by (Shearer, 2005)

$$g = \|\nabla M\| = \sqrt{(\partial M/\partial x)^2 + (\partial M/\partial y)^2 + (\partial M/\partial z)^2}, \tag{1}$$

where M is a given component of the anomalous field such as the total field anomaly or the vertical anomaly. The amplitude of magnetic anomaly B can be defined as follows:

$$B = \sqrt{Bx^2 + By^2 + Bz^2}, \tag{2}$$

where Bx, By, and Bz are the three components of the magnetic field in a 3D Cartesian coordinate system.

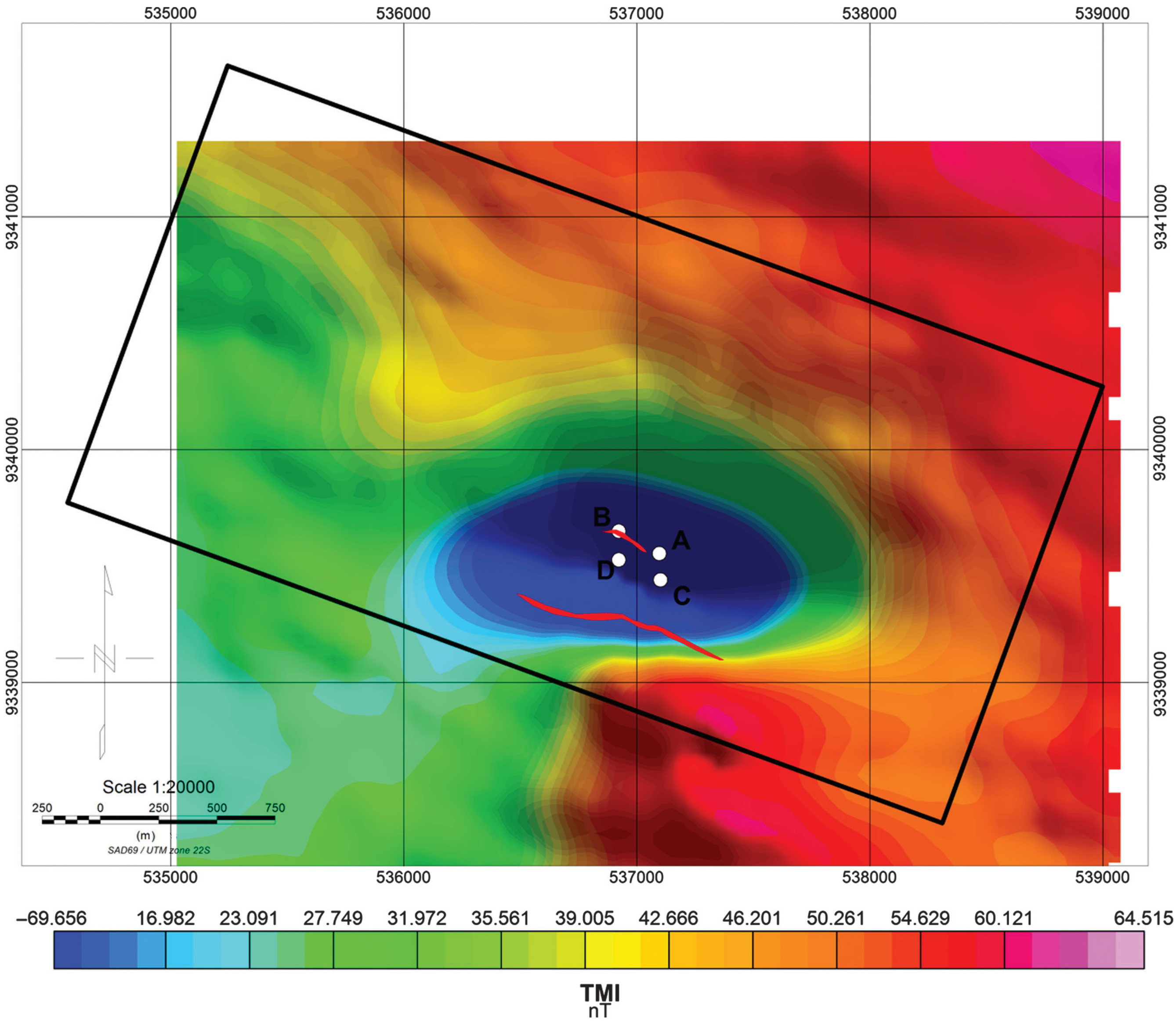


Figure 1. Heliborne total field magnetic anomaly over the Leite target. The direction of the inducing field was $I = -5.6°$ and $D = -18.5°$. The polygon indicates the area where the geologic mapping was done. Drills A, B, C, and D are indicated in the figure.

These two transformations should be similar in a qualitative analysis. Besides, we do not show any striping in the declination direction. When these two requirements are not achieved, the use of amplitude is refused.

To determine the geometry and the depth of the magnetic source, we perform SED (using Oasis Montaj® software) in the total field magnetic anomaly (Thompson, 1982). From the data obtained in the drillholes, we can assume that the magnetic layer has dips with a high angle (>70°) to north/northeast. The layer has 10 m of thickness and at least 900 m of extension in the east–west direction. Due to these geologic characteristic, the source can be assumed as a dike, and for the Euler deconvolution, we use structural index 1. Spurious solutions (above the topography) or those outside the Leite target were eliminated to focus on the solutions over the total field magnetic anomaly. Table 1 shows the parameters used for SED.

From the Euler solutions, we constructed an initial body with constant value of susceptibility. This value is the same found in the core analysis 0.5 SI. Although we have the susceptibility values on drillhole cores, we did not carried out the remanence measurements. Instead, we estimated the remanence from the total magnetic field using the methodology applied for Dannemiller and Li (2006). This methodology is based on crosscorrelation between the vertical gradient of the magnetic anomaly RTP and the total gradient of the same field.

As we know, RTP is unstable at low magnetic latitudes because of this reason, we decided to use RTP

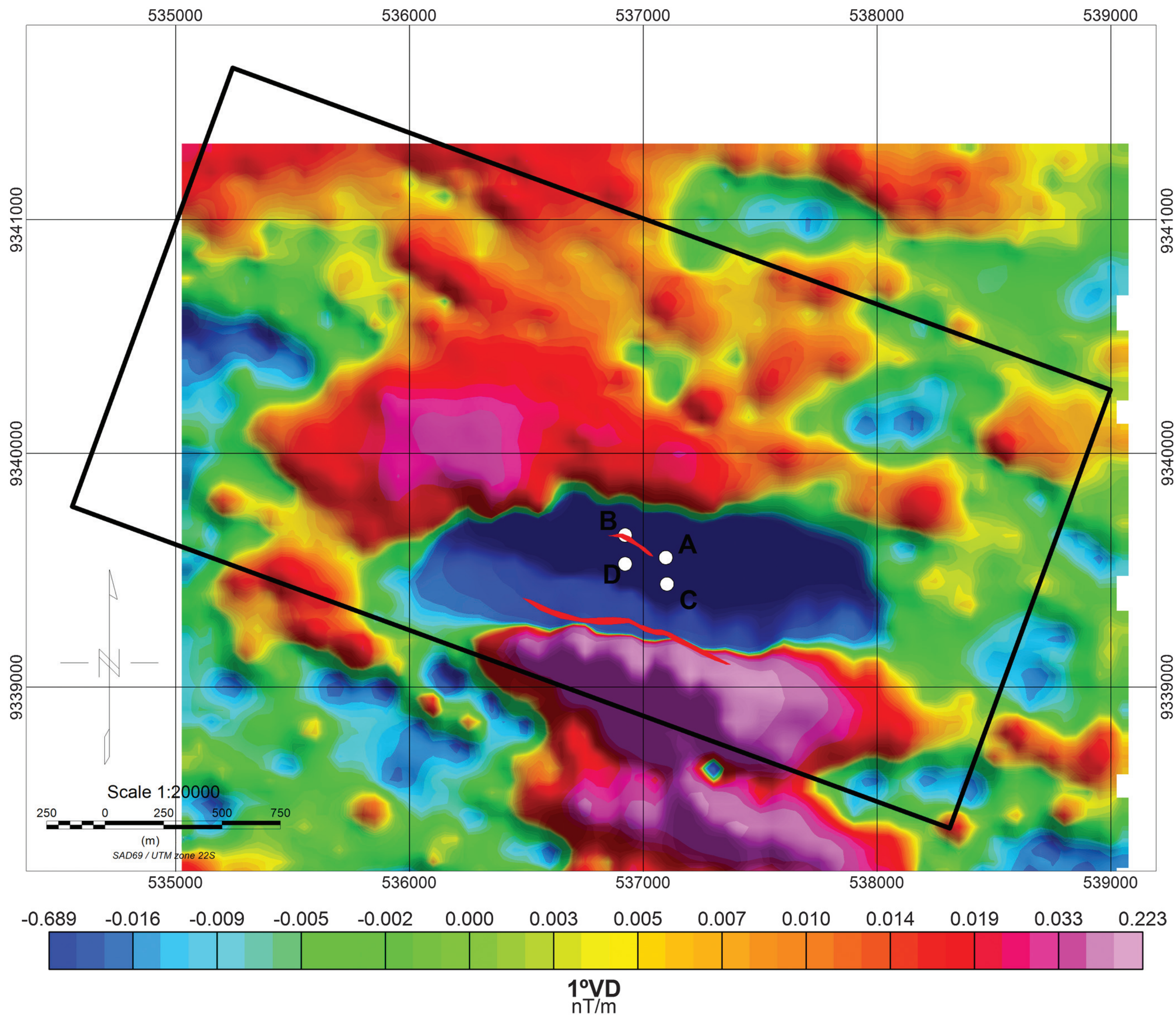


Figure 2. First vertical derivative (1°VD) from total magnetic field over the Leite. The polygon indicates the area where the geologic mapping was done. Drills A, B, C, and D are indicated in the figure.

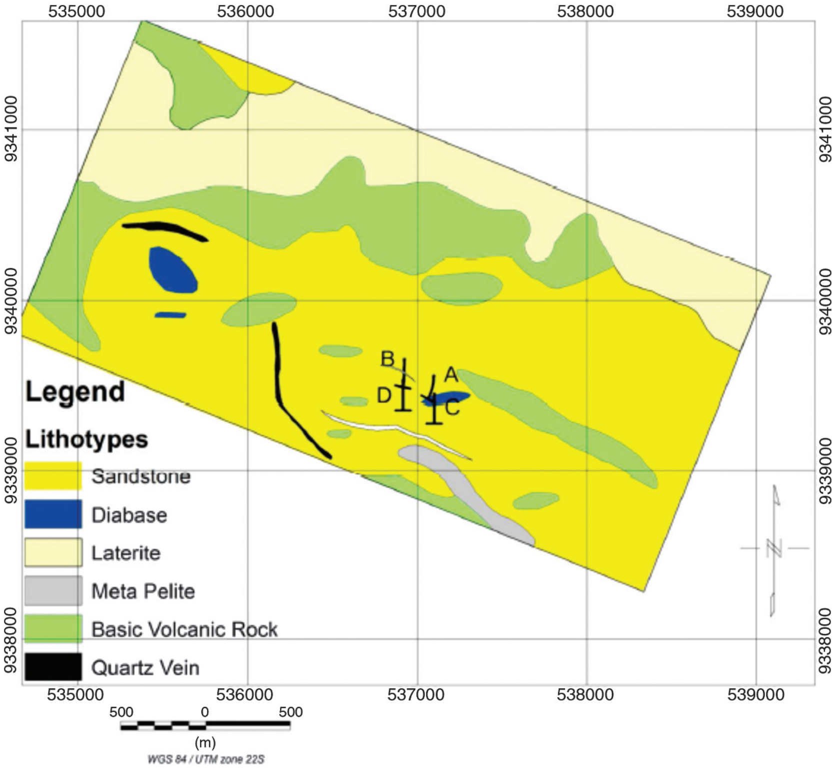


Figure 3. Leite target lithologic map.

to low latitudes (RTP-L) (Li, 2008). The RTP-L is affected by remanence magnetism and could not work properly. As occurred with amplitude after the application of the filter, we compared the transformation with the analytic signal (total gradient) and the analytic signal of vertical integration (Paine et al., 2001). The anomalies of these transformations must be similar, if not, we rejected the RTP-L transformation. Table 2 shows the values of remanent and total magnetization estimated for the Leite target; these values were used in the geophysical modeling. The direction of magnetization is similar to IOCG copper deposits such as the Alemão and Sequeirinho IOCG deposits.

For the modeling, we constrained fixed values of susceptibility, vertical extension, dip, and the value of direction of magnetization. We tried to fit the model to the observed data changing only the shape of the body until it reached an acceptable residual. The final result is a rigid body with homogeneous values of susceptibility. Because the model has a

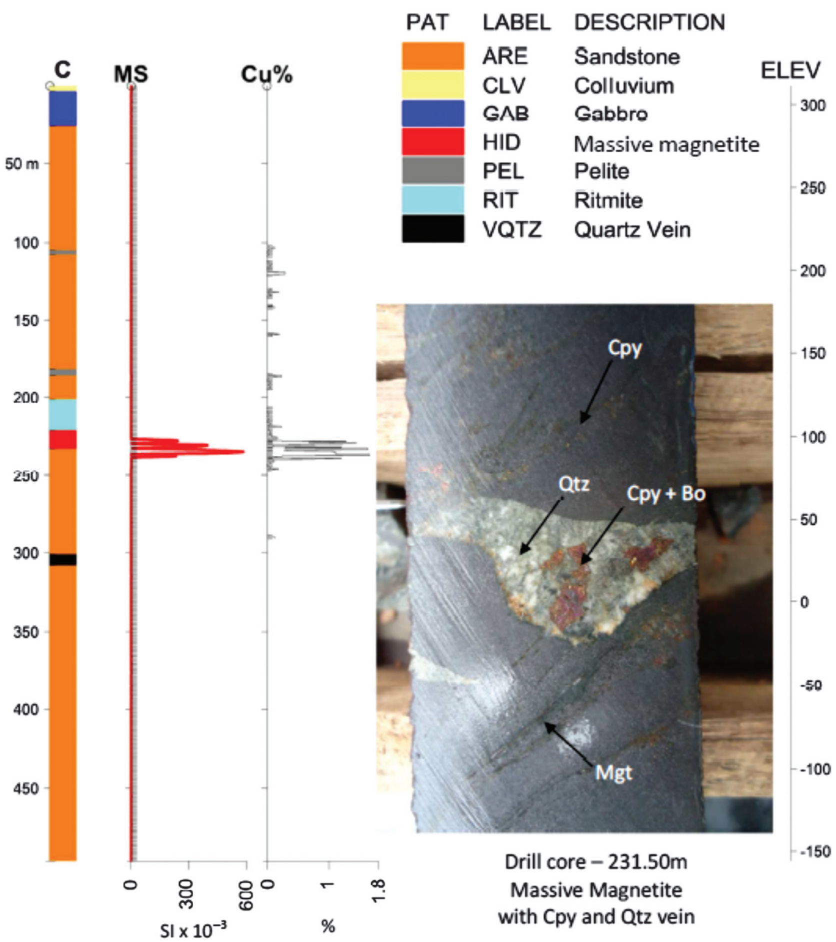


Figure 4. Borehole C strip log and the intercepted lithotypes. The red profile is the MS in SI $\times 10^{-3}$ units, and the black profile is the copper grade in percentage (Cu%). The picture shows the drill core at 231.50-m depth with magnetite hydrothermal alteration zone, chalcopyrite mineralization, and quartz vein. Legend: Mgt, magnetite; Qtz, quartz; Cpy, chalcopyrite; and Bo, bornite.

high susceptibility, the self-demagnetization was computed during the modeling.

This model was used as an initial model for the amplitude inversion. For the magnetic amplitude inversion, we used the algorithm presented by Shearer (2005) and Li et al. (2010).

We used the amplitude instead of the total magnetic field due to the problem of remanence. The amplitude has weak dependence on the direction of the total magnetization direction (Shearer, 2005).

We perform 13 inversions with different values of regularization parameters, from 10^{6} to 10^{-6} with 13 steps. The selected model was the inversion that matched the optimum regularization parameter (inflexion point) in the L-curve (Oldenburg and Li, 2005; Oldenburg and Pratt, 2007) and the biggest curvature. The final result is a smooth distribution of the recovered susceptibility, which was compared with the geologic data and drillholes results.

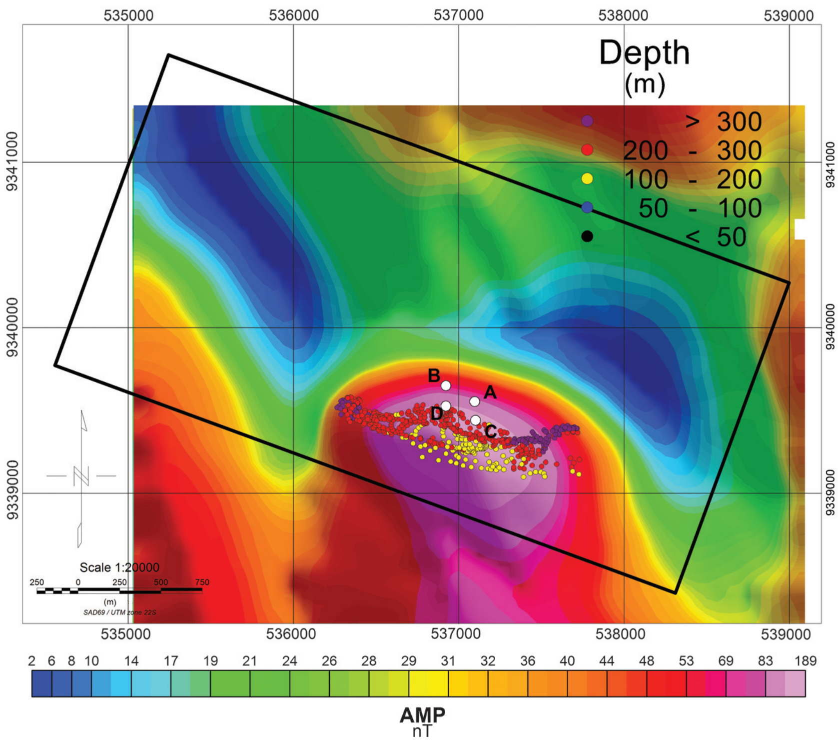


Figure 5. Standard Euler solutions over the magnetic amplitude classified by depth. The estimated solutions have a dip to the north–northeast. Almost all solutions are concentrated in the range of 200 to 300 m.

Table 1. Parameters used in the SED.

Parameters	Value
Structural index	1
Maximum % depth tolerance	10%
Windows	10
Maximum distance to accept	500 m

Table 2. Directions of the total magnetizations.

	Inclination	Declination	*Q*-Ration
Remanent magnetization	73°	160°	0.7096
Total magnetization	35.9°	339°	—

The last step was trying to identify any magnetic source that was not intercepted by drillholes or narrow bodies with no response in the magnetic survey, In this step, we performed a BHMAG survey in drillholes A and B. We used a reflex probe, which was designed to measure the drillhole deviation based on magnetic and gravimetric measurements. In our case, we were not interested in the dip or azimuth values of drillhole, but in the values of magnetic measurements done by the probe.

The probe has three fluxgate magnetometers and three accelerometers. The three fluxgate magnetometers, aligned in orthogonal directions, measured the earth magnetic field strength and dip. The magnetometers provided the horizontal component, the azimuth and the relative orientation to magnetic north (magnetic tool face). Three accelerometers aligned in orthogonal directions provide the vertical component, the dip, and the orientation to the high side of the hole. The accelerometer readings are also used to compensate for rotation of the instrument as it moves in the drillhole.

As a result of the survey, the probe provided the azimuth, dip, magnetic field strength, magnetic dip, gravity, gravity tool face, magnetic tool face, and temperature. The azimuth is measured with magnetometers. Based on data from the magnetometers, the direction of the instrument relative to the earth's magnetic field is calculated. Dip and roll angle (gravity tool face) are measured with accelerometers. Based on data from the accelerometers, the direction of the instrument relative to the earth's gravitational field is calculated. Based on data from the magnetometers and the accelerometers, the total magnetic field strength and the magnetic dip are also calculated. The accuracy of this tool is approximately ±50 nT. In the survey, we collected one point each 3 m along all holes.

The borehole survey profiles of the holes were used to identify any new susceptibility distribution and to validate the result of the inversion.

Results

The magnetic anomaly has 70 nT of amplitude, and the direction of inducing magnetic field in the region was $I = -5.6°$ and $D = -18.5°$. The anomaly shape in the target is not usual for this magnetic latitude; however, applying the methodology listed before, we found the direction of total magnetization and the remanence (Table 2).

In the first step used to determine the geometry and depth of the magnetic source (the magnetite hydrothermal alteration zone), we performed SED. The SED found 545 solutions with a depth average of 258 m. The SED 3D result over the magnetic amplitude image is shown in Figures 5 and 6

When plotted in 3D, we can observe that the surface formed by Euler solutions (Figures 6 and 7) has a dip less than the real layer. In the southern drillholes (C and D), the Euler surface intercepts the drillholes 75 m below the magnetic layer. In the northern drillholes (A and B), the Euler surface intercepts the drillholes 10 m above the massive magnetite. The Euler surface has 50° of dip to north–northeast; this value is 20° less than the real layer. Due to this reason, there is a dislocation to the north between the real body and the Euler solutions when we project them in the surface.

The SED solutions cannot estimate with precision the depth and the dip of the magnetic layer; however, the dip direction and the strike of the body were estimated correctly. The Euler surface was used as an initial model in geophysical modeling.

In the modeling, we assume that the total field magnetic anomaly had remanent magnetization (Table 2) and we restricted the vertical extension in 500 m.

For the forward modeling, we manually change the shape of the body and the value of susceptibility until it reaches a good fit. As a result of the geophysical modeling, a narrow dike body was obtained dipping 65° to N27°E. The body obtained by the modeling has 0.5 SI of MS, which is the same as the MS measurements on the drill cores. The effect of self-demagnetization was computed automatically by the modeling algorithm. The modeled data have a good fit with the measured data (Figure 8). The modeled body has a dip greater than the Euler solutions; however, this does not intercept the drillhole in the same place of the real magnetic layer. In the southern drillholes, the modeled body intercepts the drillhole in the same point of the Euler solutions; however, in the northern drillholes, the model is almost 50 m below the real layer (Figure 9).

As we expected, the Euler surface crossed the modeled body due to the different dip. We interpret that the difference between the real layer and the modeled body is due to the remanent magnetization. Although we calculate

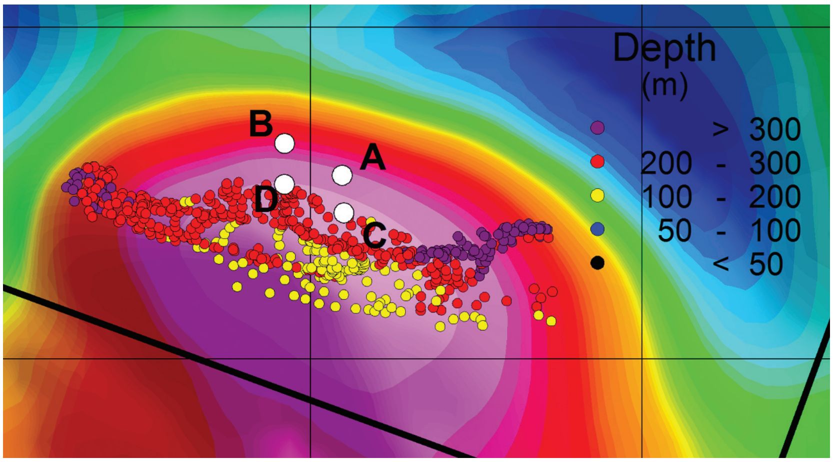


Figure 6. Magnification of Figure 5.

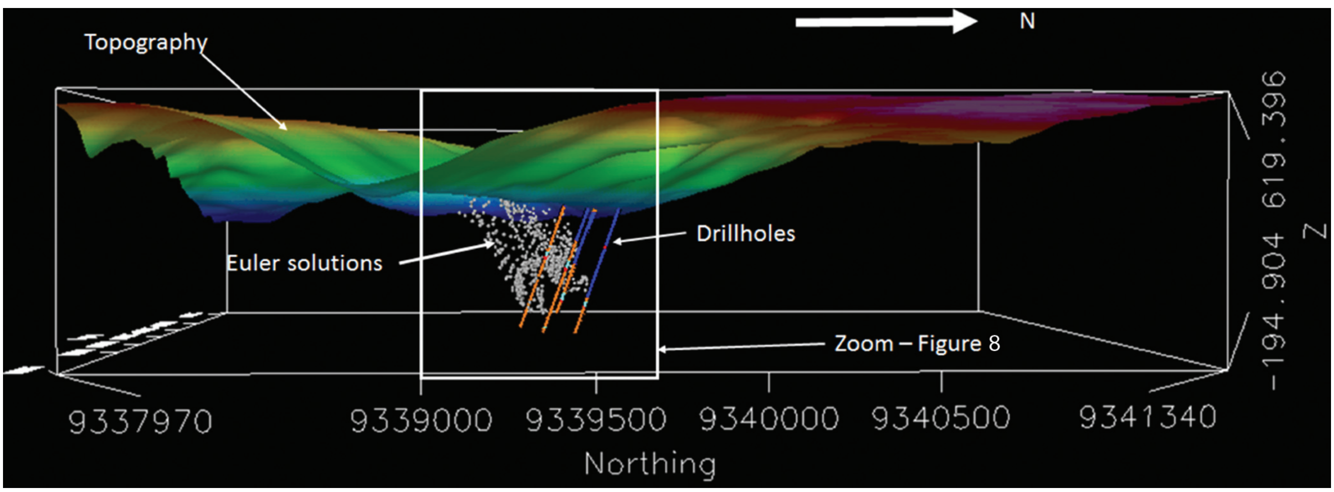
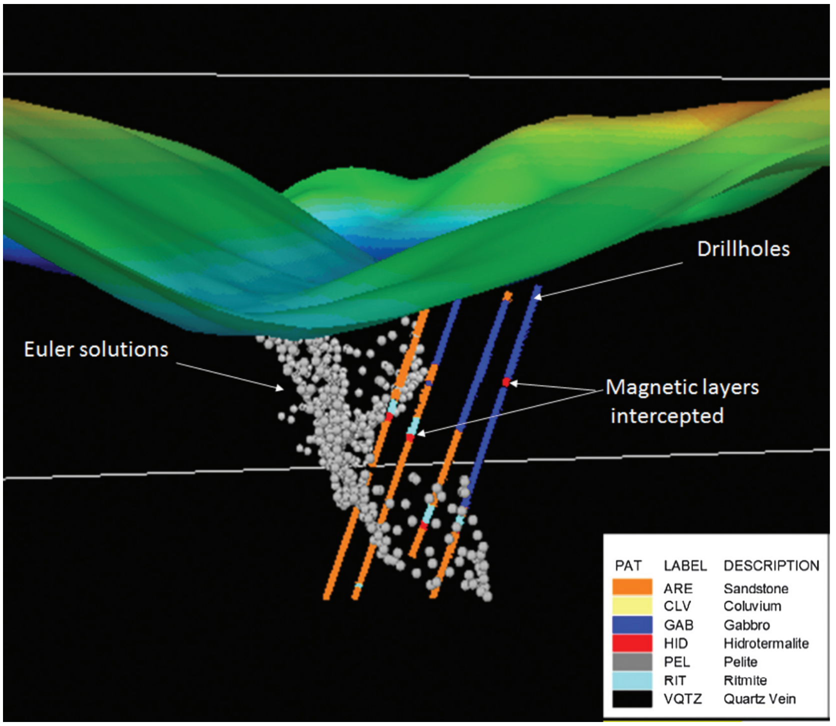


Figure 7. SED solutions in 3D view with the topography and the drillholes. The white square identifies the magnified area in Figure 8.

the direction of magnetization, we understand that in this latitude, the RPL-L is not reliable; the real direction of magnetization could be different from that we calculated. Probably, the remanence affects the dip and the vertical extension. One way to reach the true direction is by constraining the geologic layer and trying to perform a forward modeling adding a range of magnetic remanent inclination and declination. Another question is the value of MS. We used the value found with a susceptibility meter during the susceptibility log. However, it is necessarily a reliable remanence measurement in a paleomagnetic laboratory.

In the Greenfield exploration program, we consider both methods to be good approaches to better understand the magnetic source, despite the inaccuracy found in the depth of sources. At the advanced explo-

Figure 8. Magnification of Figure 7.



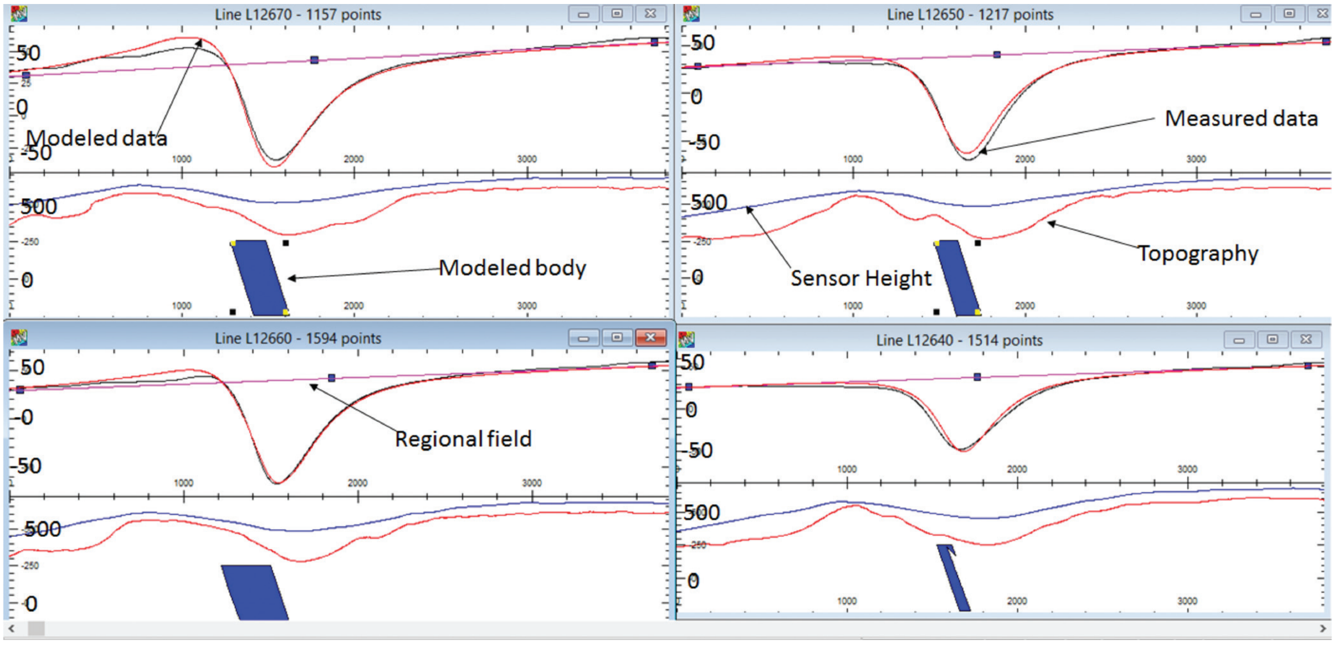


Figure 9. Forward modeling recovered a narrow body (brown) with a limited vertical extension.

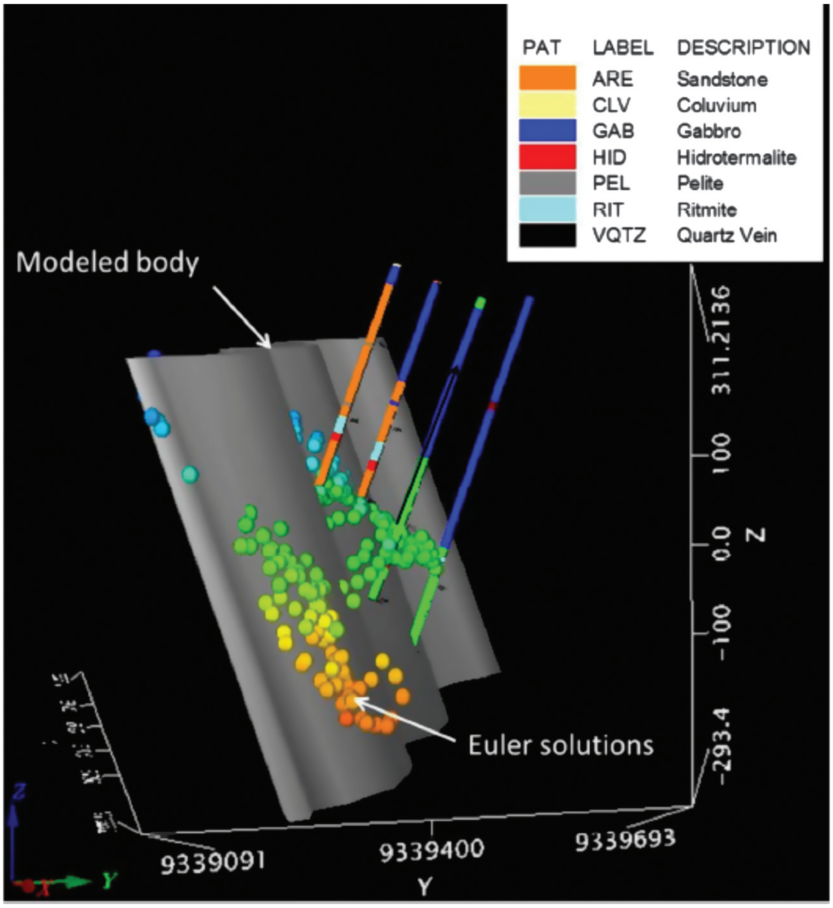


Figure 10. The body modeled (gray) with the Euler solutions (dots) and the drills.

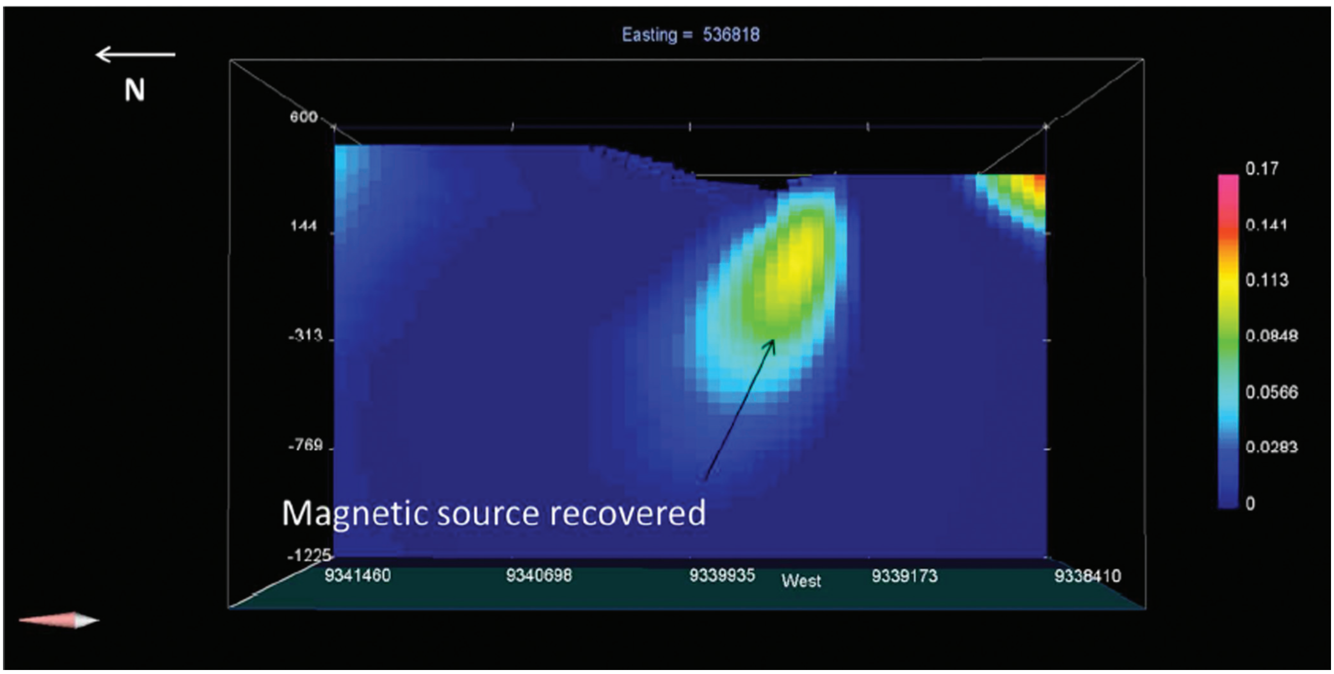


Figure 11. The forward-modeled body (gray) with the Euler solutions (dots) and the drillholes.

ration program (Brownfield), we understand that these methods will not add any considerable information.

The last method to determine the geometry of Leite target was the amplitude of the anomalous magnetic field inversion in 3D. The L-curve has an inflexion point in the regularization parameter value of 0.1; the inversion using this value was chosen as the final model.

In contrast to the first two techniques, constrained inversion recovered a smooth magnetic source with a wide shape, dipping to the northeast and with susceptibility values between 0 and 0.17 SI (Figure 10).

To correlate the results of the inversion, we used two geophysical/geologic sections AC and BD (Figures 11 and 12, respectively). The massive magnetite hydrothermal alteration zone is in the central axis of the inversion susceptibility model. However, the recovered values of susceptibility contrast are low, approximately 0.1 SI, if compared to the MS measured on drillhole cores. These values could be explained due to the self-demagnetization effect. When the magnetic amplitude inversion is performed in a target with high values of susceptibility, we cannot recover the real value of susceptibility (Krahenbuhl and Li, 2007). Krahenbuhl and Li (2007) show that in a high-susceptibility environment, the amplitude inversion cannot recover the entire model and the full vertical extension.

In Figures 11 and 12, it is possible to observe that the dip of the modeled magnetic layer is 62°, different from the real value. Besides, in Figure 12, it is possible to observe that the vertical extension of the source was not recovered in the same points. This situation is explained by Krahenbuhl and Li (2007).

We compared the three depth and dip estimation results (Figure 13), and as we expect, the modeled and inverted bodies are coincident, unlike the surface formed by the Euler solutions. This surface is dislocated from the two bodies and is crossing due to the lower dip.

Finally, after the modeling of the Leite target source (Figure 14), we perform a BHMAG survey in two drillholes to validate the models and to investigate if any source remained without being intercepted by drillholes. The results of this survey show the strong magnetic response of the mineralization; in some points, the massive magnetite zone has almost 25,000 nT of amplitude.

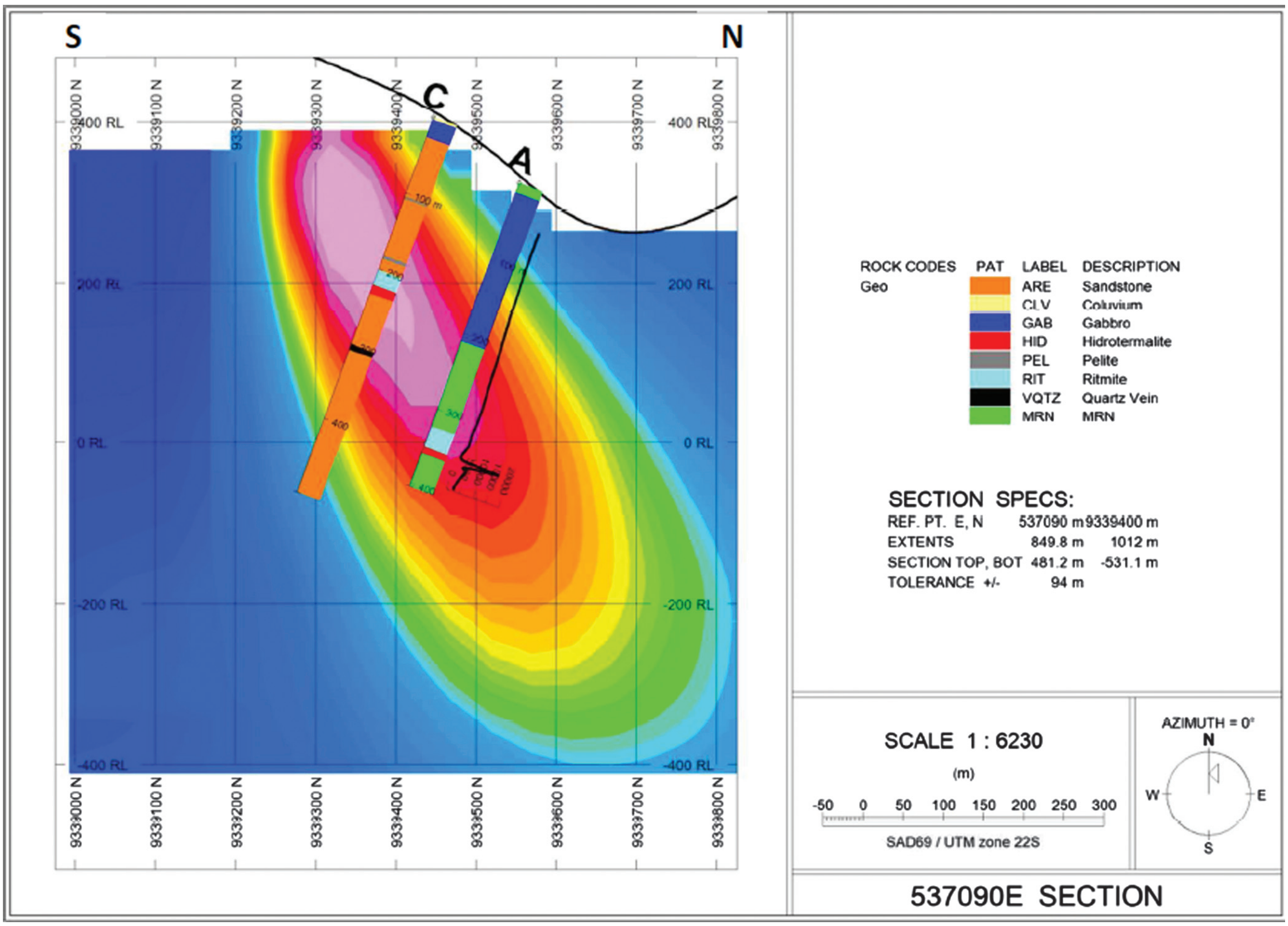


Figure 12. Section BD (north–south) with boreholes B and D, intercepted lithotypes, and the 3D inversion model slice. The magnetic source is the magnetite hydrothermal alteration zone. The black profile is the BHMAG.

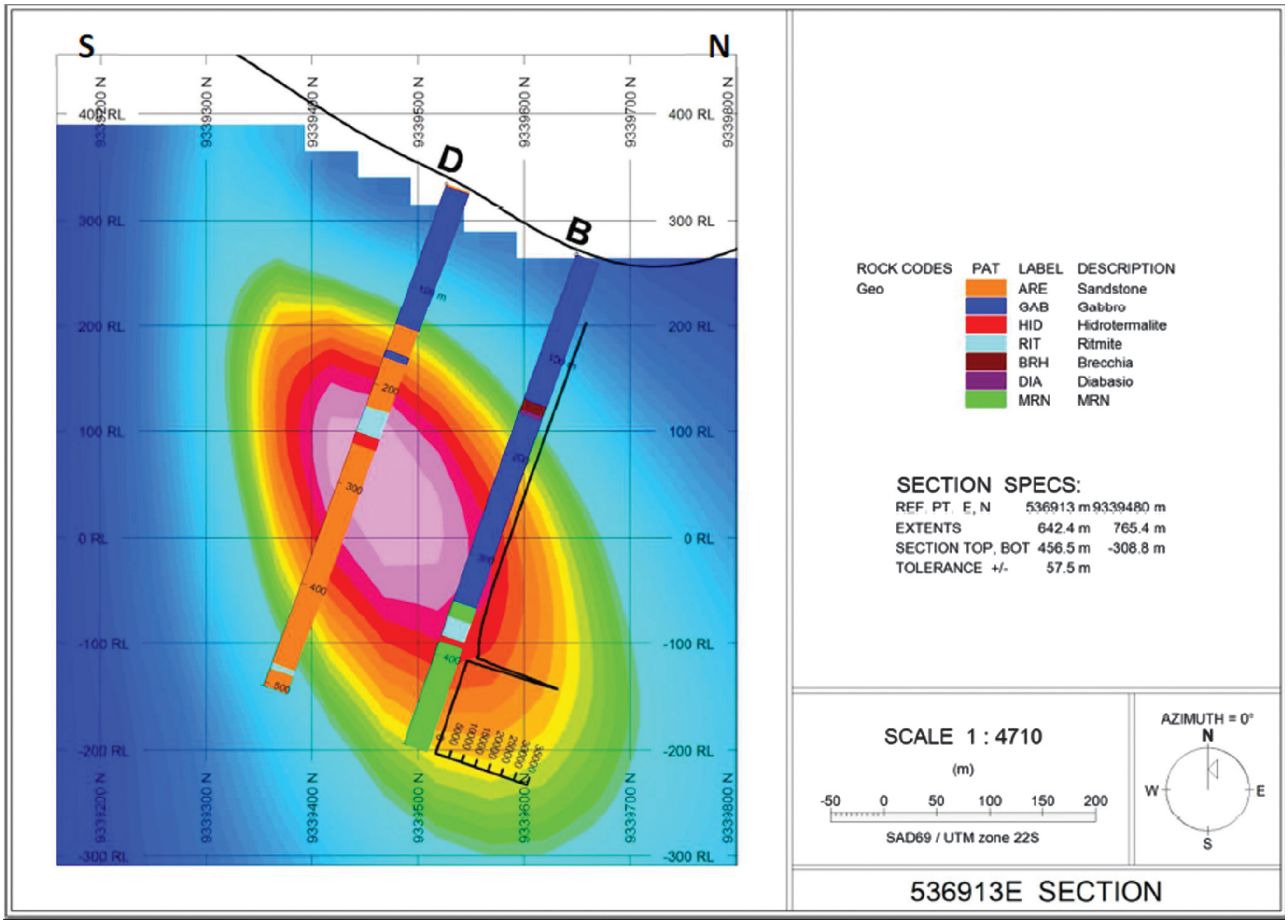


Figure 13. Section AC (north–south) with boreholes A and C, the intercepted lithotypes, and the 3D inversion model slice. The magnetic source is the magnetite hydrothermal alteration zone. The black profile is the BHMAG.

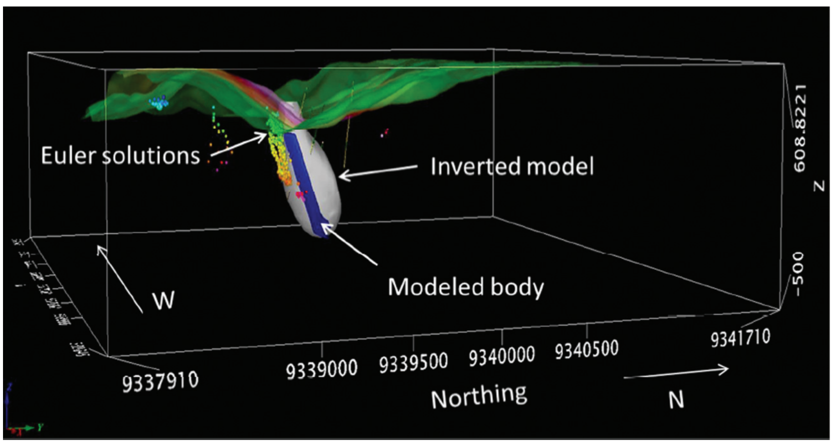


Figure 14. Leite target 3D view with the Euler solutions (colored dots), forward-modeled body (blue polygon) and the inverted model (gray body). The blue modeled body was obtained by modeling the total field magnetic anomaly, and the inverted body was derived by the amplitude inversion.

Conclusion

The three techniques used in this paper showed limitations to obtain the geometry and depth of the magnetic source. The exact value of the dip was a problem in the three techniques applied. The vertical extension was another problem that we could not determine with precision.

However, all the techniques gave correct results in relation to the strike and dip direction. The worst result was by Euler deconvolution; the surface formed by the solutions is dipping 50° to the north–northeast, almost 25° of difference between the real source and the surface. The Leite target layers and structures have a strong dip (>70°). The magnetic modeling showed a dip of 65°, 5° less than real. This result is more acceptable than the Euler deconvolution result. The amplitude inversion showed three problems: dip, vertical extension, and the susceptibility value. The dip recovered by this technique was 62°; in some points, we can observe that the source was not totally recovered and the value of the recovered MS is lower that the values found in the core.

Although the magnetic anomaly of the Leite target is isolated and inside of a nonmagnetic environment, we expect that the results of this work have an inaccuracy when compared with the real data. This imprecision observed in the data we assigned to two sources: The first one is the high susceptibility. In an environment with high susceptibility, the ability to get the vertical extension could be affected. The other factor is the low latitude; in this latitude, it is very hard to get a reliable reduction to the pole. This problem directly affected the calculation of the remanence.

In this paper, we have demonstrated that these three methods will be useful to give support to a Greenfield drilling exploration program. In the Brownfield projects, we think that these techniques will not bring any relevant information.

Acknowledgments

The authors would like to thank Vale S.A., Department of Exploration and Mineral Projects, for permission to publish this work and for providing magnetic data, the Vale S.A., Department of Planning and Development of Ferrous, for providing the magnetic amplitude code from the Gravity and Magnetics Research Consortium with the Colorado School of Mines, and Vale S.A. and the PKC Project for providing the geologic data used in this study.

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Biographies and photographs of the authors are not available.