Magnetic Vector Inversion, a simple approach to the challenge of varying direction of rock magnetization

Ian N. MacLeod
Geosoft Inc.
Suite 810, 207 Queens Quay West,
Toronto, ON, Canada
Ian.MacLeod@Geosoft.com

Robert G. Ellis
Geosoft Inc.
Suite 810, 207 Queens Quay West,
Toronto, ON, Canada
Robert.Ellis@Geosoft.com

SUMMARY

Modelling of local magnetic field anomalies, and in particular 3D voxel-based modelling, is now a primary tool in exploration targeting. The majority of current voxel-based magnetic inversions assume anomalous magnetization in the direction of the inducing earth's field as described by Li and Oldenberg (1993). However, as noted in numerous studies and the practical experience of many modellers, the direction of rock magnetization, particularly in strongly magnetized rocks, is often in a direction different from the primary geomagnetic field. This may be due to any combination of remanent magnetization, demagnetization, anisotropy of magnetic minerals or perhaps even other phenomena not yet understood.

Ellis *et al* (2012) developed the Magnetic Vector Inversion (MVI) method to directly model the vector of magnetization based only on anomalous TMI data. The method allows the modelling optimization process the freedom to orient the direction of magnetization to best fit the observed data. Notably, the MVI method does not concern itself with the reason for varying magnetization direction, which is left to the interpreter to ponder together with other information that may be at hand.

In this case-study work we demonstrate the application of MVI to particularly challenging and well known magnetic anomalies in both Brazil and Australia.

Key words: inversion, remanent magnetization, magnetic vector inversion, MVI

INTRODUCTION

Modern conventional magnetic surveys used in exploration measure the intensity of the total magnetic field (TMI). After subtracting the intensity of the modelled International Geomagnetic Reference Field (IGRF), interpreters work with a "residual" map that represents locally significant variations in the magnetic properties of the rock. While it is well understood that this anomalous field is the result of varying intensity and direction of magnetization within rock, the conventional approach to modelling the distribution of magnetic properties assume that the direction of all magnetization is aligned with the earth's field as a consequence of induced magnetization alone. Susceptibility, which is a measure of how "susceptible" a material is to being magnetized by an inducing field, has emerged as the primary rock property used in applied magnetic field interpretation. We call this *conventional susceptibility*.

Numerous studies have shown the weaknesses of attempting to model only conventional susceptibility, which is indeed the subject of the forum in which this paper is presented. In our admittedly brief review, we find numerous approaches to this problem, including Helbig analysis (Helbig, 1963; Schmidt and Clark, 1998; Foss and McKenzie, 2011, Phillips, 2005), multiscale-edge (Haney and Li, 2002), cross-correlation (Dannemiller and Li, 2004), total gradient modelling (Shearer and Li, 2004), normalized source strength (NSS) (Beiki et al, 2012, Pilkington and Beiki, 2012, Clark, 2012 and 2013) and multi-stage inversion (Foss and McKenzie, 2011). These approaches attempt either to derive the so-called "remanent" vector direction and strength, which is then reintroduced into the modelling in some way, or the problem is posed in a way that is less sensitive or not sensitive to the direction of the magnetization vector.

In our approach we have returned to the most basic and simple understanding that rock has become magnetized, and that the magnetization has two important defining characteristics – the intensity of the magnetization, and the vector direction of magnetization. The technique of Magnetic Vector Inversion (MVI) (Ellis *et al*, 2012) introduces both the amplitude and the vector direction as separate unknowns in a Tikohonov minimum gradient regularization, which is similar in approach to Kubota and Uchiyama (2005), Lelièvre and Oldenburg (2009) and Pratt *et al* (2012). The MVI technique is distinguished from other approaches by it's the use of magnetic susceptibility as the scalar proxy for the magnetic character of the model. We call this *MVI susceptibility* to distinguish it from *conventional susceptibility*. As an easily and well-understood scalar property, MVI susceptibility can be used directly in interpretation. The MVI modelling process also provides a vector direction should that be beneficial to the interpretation at hand.

In this paper we present results from applying the MVI method to two well known magnetized rock formations – the remanently magnetized Black Hill Norite of South Australia, and the complexly magnetized Quadrilátero Ferrífero, Minas Gerais, Brazil.

METHOD

Ellis, de Wet and MacLeod (2012), describe the MVI method in mathematical detail together with its use in voxel-based 3D inversion software based on Tikohonov minimum gradient regularization. We refer readers of this case study to that paper for further detail.

All modelling and comparisons in the examples presented here were conducted using the Geosoft VOXI Earth Modelling system. Modelling of conventional susceptibility and MVI susceptibility was performed with equivalent data, mesh size and modelling parameters. The only difference between conventional and MVI modelling was to allow the magnetic vector direction to vary in the case of MVI susceptibility inversions. Other than topography, there were no constraints placed on the inversion other than minimum gradient regularization and standard depth weighting. In all cases, two passes of Iterative Reweighting Inversion Focus (Geosoft, 2012) were applied to enhance the focus of solutions. The Cartesian Cut-Cell method (Ellis and MacLeod, 2013) was used to deal with the air-ground interface imposed by topography. Further, the modelled responses fit the observed data within the error tolerances provided in all cases.

As computing performance imposes significant limitations on the problem of 3D inversion, both to the size of the problem and for the time required to perform inversions, Appendix A provides performance metrics for the modelling applied to create the examples presented in this paper. In all cases, only a single run of the inversion process was required, though this is considered exceptional by the authors (Ellis *et al*, 2013).

BLACK HILL NORITE

As described by Foss and McKenzie, 2011, the Black Hill Norite, located 80 km East of Adelaide in South Australia, is an Ordovician mafic (gabbroic) intrusion emplaced into Cambrian metasediments. Figure 1 shows the anomalous TMI over the complex, with four distinct magnetic source rocks as identified by Foss and McKenzie (2011). These strongly magnetic rocks have been the subject of numerous paleomagnetic studies, which are well summarized by Foss and McKenzie. Casual interpretation of the anomaly shapes in the TMI image of Figure 1 indicates significant distortion attributed to a vector of magnetization different from the inducing field. The analytic signal (AS) of the TMI is much less sensitive to the vector direction (Roest *et al*, 1992) and provides a good indication of the plan location of the more magnetic rocks.

Prior studies have confirmed strong remanent magnetization. Rajagopalan *et al* (1993) report remament mgnetization declination of 221º and inclination of +7.6º, with susceptibilities on the range 0.02-0.05 SI and a Koenigsberger ratio of 2.1. Pratt *et al* (2012), used inversion of a simple elliptic prism to model the MVI-equivalent magnetic vector and found the magnetization direction to be 234º with an inclination of +9º.

This entire dataset has been inverted to produce a 3D voxel susceptibility models using the Geosoft VOXI Earth Modelling system. Figure 2 shows the model results at a depth slice of 1000m for conventional susceptibility (left) and MVI susceptibility (right). For spatial reference, the models are shown with a contour of the analytic signal calculated from TMI upward continued to 1000m above the original survey elevation. We consider this contour to be a reasonable proxy for the outline of the more magnetic part of the intrusive complex.

The conventional susceptibility model shows prominent positive (red) and negative (blue) pairs. This clearly cannot represent the true rock property, either in shape, or by value, since a negative susceptibility is not physically reasonable. If only the positive susceptibility is considered, which is often the case in practice, this leads to a significant error in the location of magnetic rock. MVI susceptibility modelling gives the magnetic vector the freedom to rotate as part of the inversion, with the result that the scalar susceptibility that results from the MVI model (the MVI susceptibility) is consistent with the analytic signal and would appear more geologically reasonable.

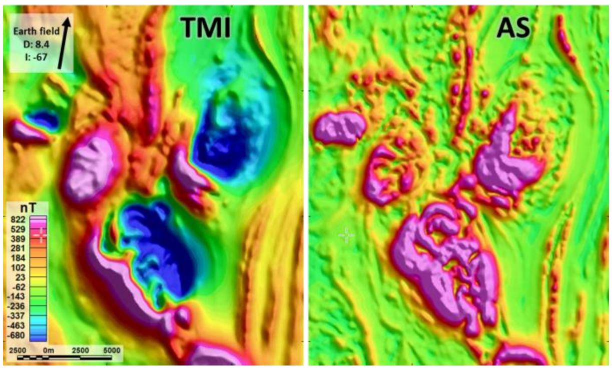

Figure 1. TMI and analytic signal (AS) of the area including the Black Hill Norite.

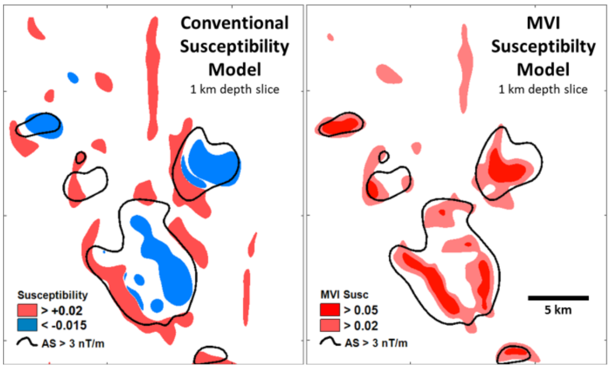

Figure 2. Comparison of conventional susceptibility with MVI susceptibility model at a plan depth slice of 1 km. An outline of the anomalously high analytic is shown as a black line for spatial reference.

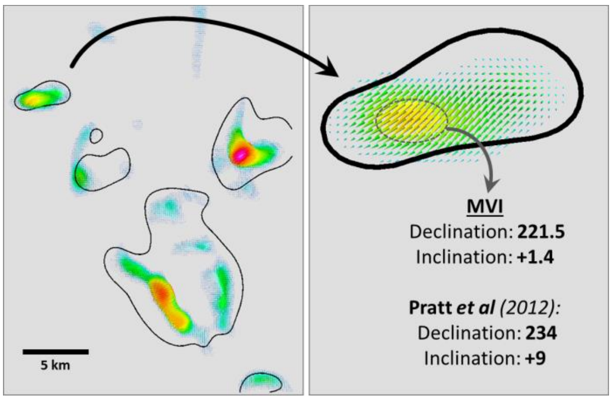

Figure 3. MVI model magnetization shown as vector cones coloured by susceptibility.

Figure 3 presents the MVI susceptibility model results as vector cones, which provide a visual indication of the modelled direction of magnetization. The cone size and colour are controlled by the scalar MVI susceptibility, with red having the greatest intensity. We have focused on the feature in the North-West corner of the larger model, which is anomaly "C" in the Foss and McKenzie (2011) study, and has been modelled using a similar approach by Pratt *et al* (2012).

Averaging the MVI-modelled direction of magnetization from the most magnetic part of the feature (241 cells with MVI susceptibility above 0.175 SI units) produces a declination of 221.5º and an inclination of +1.4º, which is reasonably consistent with results from other studies, which are summarized in Table 1.

Decl.	Incl.	Source
221.2	7.6	Remanence direction Rajagopalan *et al*, 1993
221.5	1.4	Magnetization direction (MVI) this study
234	9	Elliptic prism inversion Pratt *et al*, 2012
232	8	Staged inversion Foss and McKenzie, 2011
223	6	Helbig scan Foss and McKenzie, 2011
273	28	Helbig scan Phillips, 2005

Table 1. Direction of magnetization comparing this study with those reported by from Foss and McKenzie (2011) and Pratt *et al* (2012).

QUADRILÁTERO FERRÍFERO, BRAZIL

The Quadrilátero Ferrífero, (Iron Ore Quadrilateral) in the state of Minas Gerais, Brazil, is the host to perhaps the largest commercial iron deposits in the world. A coloured surficial geology map of the area is shown in Figure 4 (Baltazar *et al*, 2005), on which the axis of the primary magnetic iron formations are shown and used to provide spatial reference in all figures. Figure 5 shows the TMI anomaly map and the analytic signal, with the magnetic unit axis shown as a white dashed line.

The Quadrilátero Ferrífero is an interesting subject for the study of magnetic interpretation for a number of reasons:

- The strength of magnetization;
- The relatively low latitude of the geomagnetic field (inclination -29º, declination -21º);
- The fact that the magnetized formations include sections oriented perpendicular to and roughly parallel to the current geomagnetic field, each of which interact very differently with the inducing magnetic field.

The TMI map clearly demonstrates the challenge of modelling rock properties when assuming magnetization only in the direction of the geomagnetic field. While the East-West feature in the Northwest part of the map has a strong negative anomaly, as would be expected at this latitude, the more Northerly-trending features on the East side of the map cannot be easily explained. In the experience of the authors, the magnetic patterns observed here are typical of Archean terrains in Brazil, with magnetic response from changes in topography interspersed with strong negatives and positives that can only be explained by introducing a rotated magnetization vector.

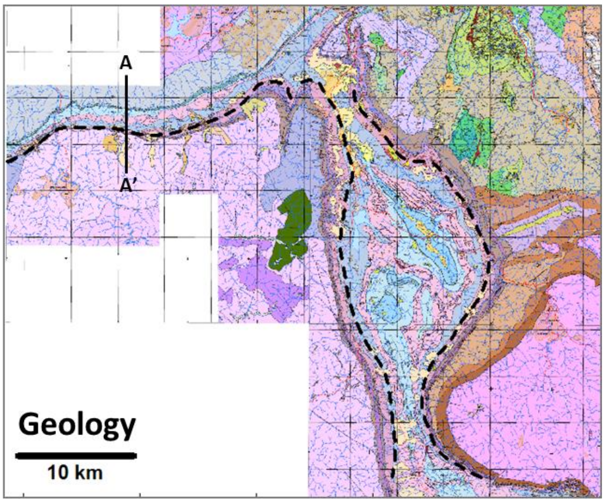

Figure 4, Geology map of the Quadrilátero Ferrífero. The dashed black lines mark the magnetic iron formation of interest. A-A' is the profile shown in Figure 7.

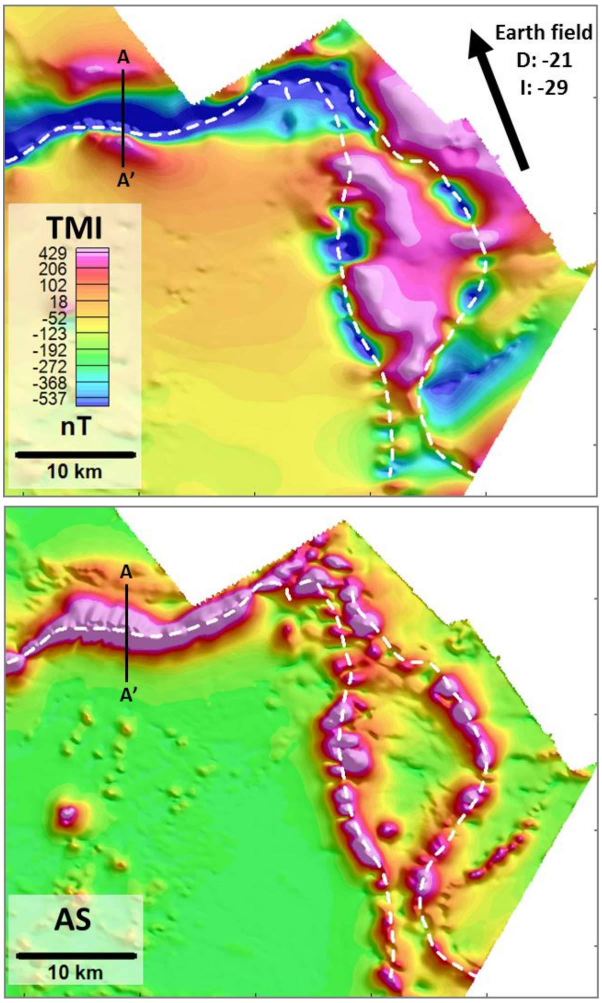

Figure 5. TMI and analytic signal showing the mapped magnetic iron formation in white for reference.

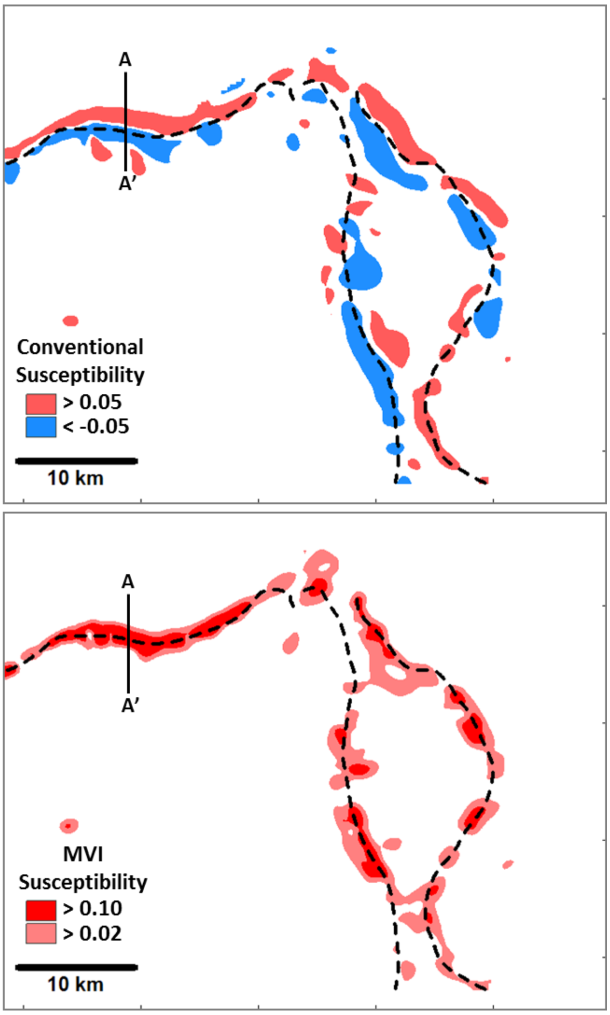

Figure 6. Comparison of conventional susceptibility model (top) with MVI model (bottom). Magnetic iron formation is traced for reference.

Magnetic anisotropy plays a significant role in the iron formations of the Quadrilátero Ferrífero, where the dominant rock magnetization is the consequence of induced magnetization, but the vector of magnetization in rock is rotated to align with the bedding of the iron formation (Rosière et al, 1998). We also note that the analytic signal does a very good job in identifying the surface location of the most magnetic rocks, particularly at such low magnetic latitudes (MacLeod *et al*, 1992).

We have again used the Geosoft VOXI Earth Modelling system to invert the TMI anomaly data for both conventional susceptibility, which constrains the magnetization vector to the direction of the earth's field, and using MVI susceptibility. Figure 6 shows a comparison of the susceptibility from two results at a plan elevation slice of 900m, which is just beneath the lowest topographic elevation of the area. As with the Black Hill example, the conventional susceptibility model again requires significant negative susceptibilities to fit the data together with a now predictable displacement of the positive susceptibility parts of the model. Notable is that even the East-West striking feature to the Northwest requires a strong negative susceptibility component. This is somewhat surprising given that our initial casual interpretation was that this anomaly appeared more "normal" for this latitude. The scalar MVI susceptibility more accurately follows the expected axis of magnetic rock and is also consistent with a simple interpretation of the analytic signal.

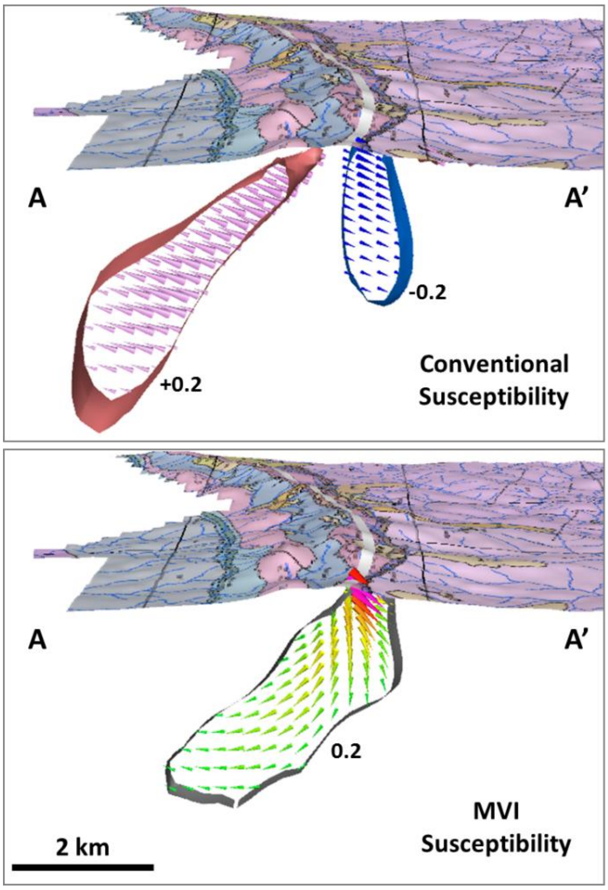

Figure 7. 3D perspective view of the susceptibility and MVI models looking East across section A-A'. The magnetization vector is shown as cones in both cases together with the isosurfaces as indicated.

Finally, Figure 7 shows a section across A-A', which compares conventional susceptibility and MVI susceptibility in profile. We have presented conventional susceptibility as vector cones to reinforce our appreciation that this approach constrains the magnetization direction to align with the geomagnetic field.

The geology map is draped onto the terrain surface for reference, and the expected axis of magnetic rock is indicated by the white band superimposed on the geology. The conventional susceptibility model (top) does not agree with the geology, while the MVI model (bottom) agrees very well. Extensive surface bedding dip measurements indicate that the formation dips between 65 and 80 degrees to the North in this area, which is also consistent with the MVI model. It is interesting to note how the MVI vector aligns with the dip of the model in this case, which is consistent with our expectation that magnetic anisotropy has rotated the induced magnetic vector to align with the formation bedding.

CONCLUSIONS

We have shown that the relatively straight-forward approach of inverting jointly for intensity and direction of magnetization will produce magnetic property models that agree with other more complex studies of the Black Hill Norite. This technique is also shown to be very effective at the Quadrilátero Ferrífero in Brazil, where the geomagnetic field is closer to horizontal and produces very typical and challenging anomaly patterns in the TMI. The ability of MVI to vary direction throughout the inversion area is particularly important. MVI modelling is consistent with extensive ground geological mapping in the Quadrilátero Ferrífero. In both examples, MVI susceptibility is aligned with the interpretation of the analytic signal anomaly calculated from the TMI anomaly, further strengthening our confidence in the MVI models.

And finally, working with MVI susceptibility as a scalar rock property improves the practical use of the model because susceptibility can be directly compared and constrained by known or more conventionally measured rock properties when available.

ACKNOWLEDGMENTS

Airborne TMI data of the Black Hills Norite was provided by the Department of Primary Industries and Regions, South Australia (PIRSA). Airborne TMI data of the Quadrilátero Ferrífero, Brazil was provided by the Companhia de Desenvolvimento Economico de Minas Gerais (CODEMIG). Cloud modelling services were provided by Geosoft VOXI Earth Modelling, and all data processing and figures were created using Geosoft Oasis montaj.

REFERENCES

Baltazar, O.F.; Baars F.J.; Lobato, L.M.; Reis, L.B.; Achtschin, A.B.; Berni, G.V.; Silveira, V.D. (2005). Mapa Geológico Brumadinho na Escala 1:50.000 com Nota Explicativa. In: Projeto Geologia do Quadrilátero Ferrífero - Integração e Correção Cartográfica em SIG com nota explicativa. Lobato *et al*. (2005) CODEMIG. Belo Horizonte

Beiki, M., Clark, D., Austin, J., and Foss, C. (2012), Estimating source location using normalized magnetic source strength calculated from magnetic gradient tensor data." Geophysics, 77(6), J23–J37.

Clark D. A. (2012) New methods for interpretation of magnetic vector and gradient tensor data I: eigenvector analysis and the normalised source strength, Exploration Geophysics , Vol. 43 No. 4 Pages 267 – 282

Clark D. A. (2013) New methods for interpretation of magnetic vector and gradient tensor data II: application to the Mount Leyshon anomaly, Queensland, Australia, Exploration Geophysics , Vol. 44 No. 2 Pages 114 - 127

Clark D. A., Schmidt P.W. (1993) Palaeomagnetism and magnetic anisotropy of proterozoic banded-iron formations and iron ores of the Hamersley Basin, Western Australia. Exploration Geophysics 24 , 223–226

Dannemiller, N., Li, Y. (2004), A new method for determination of magnetization direction, Geophysics, 71, L69-102

Ellis, R. G. , de Wet, B., MacLeod, I. N. (2012), Inversion of magnetic data for remanent and induced sources. ASEG Extended Abstracts 2012 , 1–4

Ellis, R. G., Diorio, P., MacLeod, I. N. (2013), Auxiliary Information in Geophysical Inversion. Presented at the ASEG Inversion Forum, 2013

Ellis, R. G., MacLeod, I. N. (2013), Constrained voxel inversion using the Cartesian cut cell method, ASEG Extended Abstracts 2013

Foss, C. A., and McKenzie, K. B., (2011) Inversion of anomalies due to remanent magnetization: an example from the Black Hill Norite of South Australia: Australian Journal of Earth Sciences, 58, 391-405

Geosoft (2013), Sharpening using Iterative Reweighting Inversion, Oasis montaj Best Practice Guide, http://bit.ly/11NAzAn

Haney, M. and Li, Y. (2002) Total magnetization direction and dip from multiscale edges. SEG Technical Program Expanded Abstracts 2002: pp. 735-738

Helbig, K. (1963), Some integrals of magnetic anomalies and their relation to the parameters of the disturbing body, *Zeitschrift für Geophysik*, **29**, 83-96.

Kubota, R., and Uchiyama A. (2005), Three-dimensional magnetization vector inversion of a seamount, Earth Planets Space, 57, 691–699

Li, Y., Shearer, S., Haney, M., and Dannemiller, N. (2010), Comprehensive approaches to 3D inversion of magnetic data affected by remanent magnetization, GEOPHYSICS, 75(1), L1–L11.

MacLeod, I. N., Vierra, S., and Chaves, A. C. (1992), Analytic signal and reduction to the pole at low magnetic latitude, Proceedings of the third international congress of the Brazilian Society of Geophysics.

Phillips, J. D. (2005) Can we estimate total magnetization directions from aeromagnetic data using Helbig's integrals?, Earth Planets Science, 57, 681-689

Pilkington, M. and Beiki, M. (2012) Mitigating remanent magnetization effects in magnetic data using the normalized source strength. SEG Technical Program Expanded Abstracts 2012: pp. 1-4.

Pratt, D. A., McKenzie, K. B., White, A. S. (2012) The remote determination of magnetic remanence, ASEG Extended Abstracts 2012, 1-5.

S. Rajagopalan, P. Schmidt, D. Clark, Rock magnetism and geophysical interpretation of the Black Hill Norite, South Australia. Exploration Geophysics, Vol. 24 No. 2 Pages 209-212

Roest, W., Verhoef, J., and Pilkington, M. (1992). Magnetic interpretation using the 3-D analytic signal. Geophysics, 57, 116–125

Rosière, C.A., Quade, H., Siemes, H., Chemale Jr., 1998, Fabric, Texture and Anisotropy of Magnetic Susceptibility in High-Grade Iron Ores from the Quadrilátero Ferrifero, Minas Gerais, Brazil, Materials Science Forum,, Vil 273-275, 693-700

Schmidt, P.W. and Clark, D.A. (1998), The calculation of magnetic components and moments from TMI: A case study from the Tuckers igneous complex, Preview, 76, 128 (ASEG Conference Hobart, 1998)

Shearer, S. and Li, Y. (2004) 3D Inversion of magnetic total gradient data in the presence of remanent magnetization. SEG Technical Program Expanded Abstracts 2004: pp. 774-777.

APPENDIX A

The following are model parameters and computing resources applied using the Geosoft cloud-based VOXI Earth Modelling service.

Black Hill

Mesh points	285 x 290 x 38 (3,140,700 cells)
Smallest voxel cell	100, 100, 50m (x, y, z)
Data points	75,947
IRI focussing	2 passes

Conventional susceptibility

CPU time	52 minutes
Number of CPUs	64

MVI susceptibility

CPU time	164 minutes
Number of CPUs	64

Quadrilátero Ferrífero

Mesh points	233 x 185 x 33 (1,422,465 cells)
Smallest voxel cell	250, 250, 125m (x, y, z)
Data points	28,730
IRI focussing	2 passes

Conventional susceptibility

CPU time	38 minutes
Number of CPUs	32

MVI susceptibility

CPU time	93 minutes
Number of CPUs	32