Geological and geophysical integrated interpretation and modelling techniques

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SUMMARY

Exploration is becoming harder, at depth or under cover and decisions need to be made in model rather than data space; supported by multiple data sets. Geophysics plays an ever increasing role and integration of information from various geophysical data sets in tight collaboration with geological control is required to maximise the return from the individual data sets.

In terms of integrating geological and geophysical data, the essential goal is to interpret the available geophysical data in terms of geological domains. The process requires a common sense approach to interpretation that is flexible, adaptive and objective driven. It is not an exact formula or procedure; particularly when multiple geophysical surveys are involved. Understanding the relationships between geology, geophysical responses and rock properties is the key to develop a geological basis for your integrated interpretation. Following this, rapid 3D geological modelling and geologically based forward modelling and inversion are essential for model validation and quantitative integration of data. An integrated interpretation is not necessarily the simplest approach, but does provide answers to geoscientific questions that are stronger than individual elements interpreted on their own.

This paper presents a review of the mechanics involved in integrated interpretation and demonstrates the results with selected case study examples.

Key words: Integrated interpretation, forward modelling, geologically constrained inversion.

INTRODUCTION

The modern mineral exploration context is increasingly one of targeting at depth or under cover. This requires moving beyond traditional interpretation of data and its map representation towards interpretation of 3D models. In mineral exploration, the fundamental purpose of a model is to convert data, concepts and interpretation into an actionable construct.

Unequivocally, the concept of integrated interpretation is focussed on minimising ambiguity and providing answers to geoscientific questions that are stronger than individual elements interpreted on their own. The application of multi-disciplinary data integration directly in terms of exploration targeting has grown awareness in the industry (Joly et al, 2015 McGaughey 2006, Mitchinson et al, 2014, Chalke & McGaughey, 2015). But integrated interpretation also has a place during the development of the geological models (Jessel et al, 2014, Lindsay et al, 2013, Spampinato et al, 2015) that are a part of the multi-disciplinary targeting process (if not the common framework that links various data types). In terms of integrating geological and geophysical data, the essential goal is to interpret the available geophysical data in terms of geological domains.

Historically, 3D geological models have predominantly been utilised in a mining environment where interpretation is facilitated by large volumes of information obtained through dense drilling and pit/underground mapping. Models were typically built solely on the basis of direct geological observation. On the other hand, away from the mine site and its abundance of direct observation, 3D earth models have been based primarily on geophysical inversion. Often, these scenarios are addressed with unconstrained inversion to provide a first pass, smooth distribution of rock properties (Li and Oldenburg, 1996). Seldom is this model interpreted in terms of geological domains that can be attributed with rock property data and validated against the geophysical surveys.

The aim of this review is to reinforce the importance of integrated geological and geophysical interpretation and the mechanics involved, particularly in cases with limited sub-surface control. The aim is to highlight the geological information that can be drawn from geophysical survey data.

METHODOLOGY

It is important to recognise that the specific methodology for integrated interpretation of geological and geophysical data varies according to the geological objective and the data that is available. In a data rich environment, integrated interpretation of geological and geophysical data considers construction of a geological model from geological constraints, attribution of the model with petrophysical data, then validation and reconciliation of a model through forward modelling and inversion. This is essentially a model validation, but does still reveal new information and advance the understanding of the relationship between geology and rock properties.

In other cases, where subsurface control is limited, a geologically based model can be developed through 3D investigative modelling of geophysical data and other data sets. In these circumstances, the adopted geological framework may be largely conceptual. Rather than relying on an unconstrained inversion, the interpretation is dedicated to developing a geological prediction that remains true to all the other available data sets. Interpretation comprises not just one inversion, but many, to understand the relationship between geology, geophysical datasets and rock properties.

In either case, there are several key considerations to successfully approach an integrated geological and geophysical modelling exercise.

1) Interpret your data – assess the geophysical signatures and their relationship with geology and rock properties.
2) Develop a starting model and establish a geological framework for modelling.
3) Implement quantitative modelling and inversion to test conceptual ideas to incorporate into the model.
4) Model validation and update using geophysical inversion techniques in close collaboration with 3D geological modelling.

With consideration for these guidelines, it is imperative to recognise that the exact process for completing an integrated interpretation is not defined from the outset of the project. The relationships learnt from the data and the investigative modelling that are completed shape the methodology that is deployed. The process is not entirely software driven, but requires basic interpretation and deductive reasoning, supported by advanced software such as rapid geologically-based forward modelling and inversion.

Establishing the key geological domains that need to be modelled to explain the geophysical data sets and meet the geological objectives is an important stage of the integrated interpretation. This "geological framework" is not always clearly defined at the start of the project. Often the 3D modelling (and therefore meeting the model objectives) is hindered by attempting to incorporate too much detail into the geological model that the geophysical survey is simply not responding to. Quantitative forward modelling plays a significant role in identifying the key domains to incorporate into the geological framework. Areas with constraints (mapping or drilling) provide focus areas for establishing how the geophysical responses are responding to known geological domains. In the absence of subsurface constraints, it can be conceptual.

Forward modelling and inversion are used extensively during modelling to quantitatively integrate geological and geophysical data. An important shift in technology is the ease and speed of completing a forward model of a geologically-based model. This provides a direct means for testing and validating geological hypotheses. Furthermore, inversion options (adjustment of properties and/or geological boundaries) provide feedback mechanisms for updating the geological model (either directly or indirectly). Inversion algorithms (e.g. VPmg, VPem1D, VPem3D) that operate directly on geological models are a driver for integrated interpretation (e.g. Pears et al, 2001, Fullagar et al, 2010, Fullagar et al, 2013). VPmg (Fullagar et al, 2007, 2008) is the potential fields modelling software that was used to develop the two case study models included in this paper, and when presented with a geologically-based model, facilitates inversion to adjust model geometry or model properties (either homogeneously or heterogeneously).

If a geological framework is carefully selected and suitably tested and adjusted using forward modelling and inversion techniques, a geological model will be achieved that is consistent with the measured geophysical responses. The robustness of the geological domains are validated by assigning a homogeneous physical property to each domain, forward modelling and observing a good correlation between the predicted and measured data. A final stage of inversion to solve for local property variations within the domains highlights anomalies that may be associated with potential targets or areas of geological complexity that require further investigation.

CASE STUDY #1 - MUTOOROO

This case study uses data from the regionally extensive magnetite-bearing sedimentary strata within Minotaur's Mutooroo project area in South Australia. In this case, the originally nominated modelling objective is to produce a magnetic susceptibility that can be equated to magnetite percentage in the host rock.

Conventional unconstrained inversion of magnetic data produces diffuse representations of magnetic susceptibility that are difficult to directly equate to magnetite percentage, and prompted for a geologically-based approach to modelling. The adopted methodology is therefore to a) define the geometry of the primary magnetic domains, then 2) invert for local magnetic susceptibility variations within those domains.

Given the area is undercover, and, at the date of modelling has 7 drill holes (all in a fairly localised area) for control, this case study is an example of developing a geologically-based 3D interpretation through modelling of aeromagnetic data.

The aeromagnetic survey was flown EW with 50m line spacing and a flight height of 25m. Cover, base of weathering was defined from Euler deconvolution depth to source techniques, using the drillhole data to calibrate the parameters for depth computation.

Modelling of discrete magnetic domains was based on interpreting the subcropping signatures of these domains from the 1VD RTP, then assessing forward modelled responses for 3D bodies extended down from the interpreted subcrop for a suite of model geometries. The dipole nature of the magnetic responses makes them ideal for inferring an optimal dip for the magnetic signatures associated with the various magnetic domains across the area. Figure 1 for example (upper right) illustrates an example where a suite of models were generated with a range of dips. The dip that had a computed response that best matched the measured data was incorporated into the full 3D model. Using this approach, various portions of the magnetic anomalies across the area were investigated separately and the geometry from the individual break out investigations was combined into a final 3D model. VPmg inversion techniques were used to optimise the homogeneous susceptibility assigned to each domain and locally refine the geometry of modelled domains (in particular, depth of weathering).

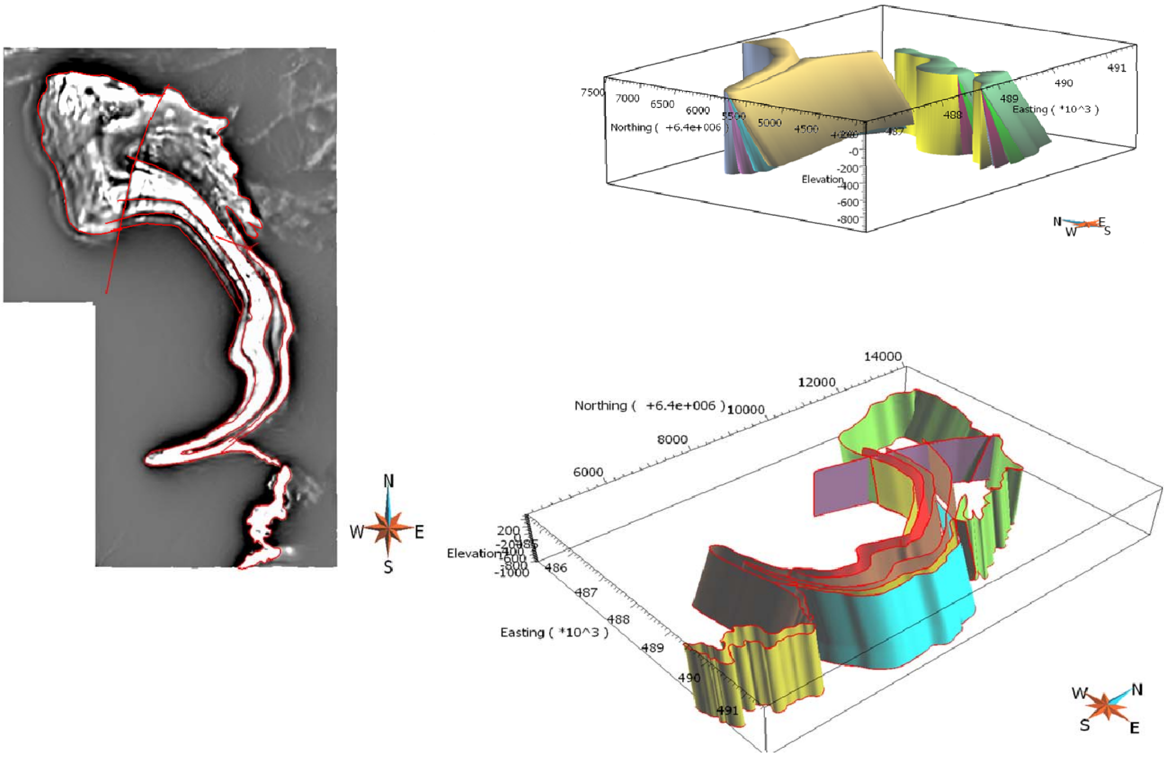

Figure 1: Illustrates the mechanics of interpreting the 3D magnetic domains; (left) interpreting sub-crop representation of domains, (top right) investigative modelling assessing various dips of domains used to compute magnetic responses for comparison with measured data and (bottom right) the collective wireframes from the investigative modelling used to construct a 3D geological model for the entire area for geologically constrained inversion.

The final 3D magnetic domains of the model (beneath cover) are illustrated in Figure 2, each domains is coloured by magnetic susceptibility. The computed response of the final 3D geological model, with homogeneous susceptibility assigned is shown in Figure 2. The correlation between the computed response and the measured data validates the derived geological model.

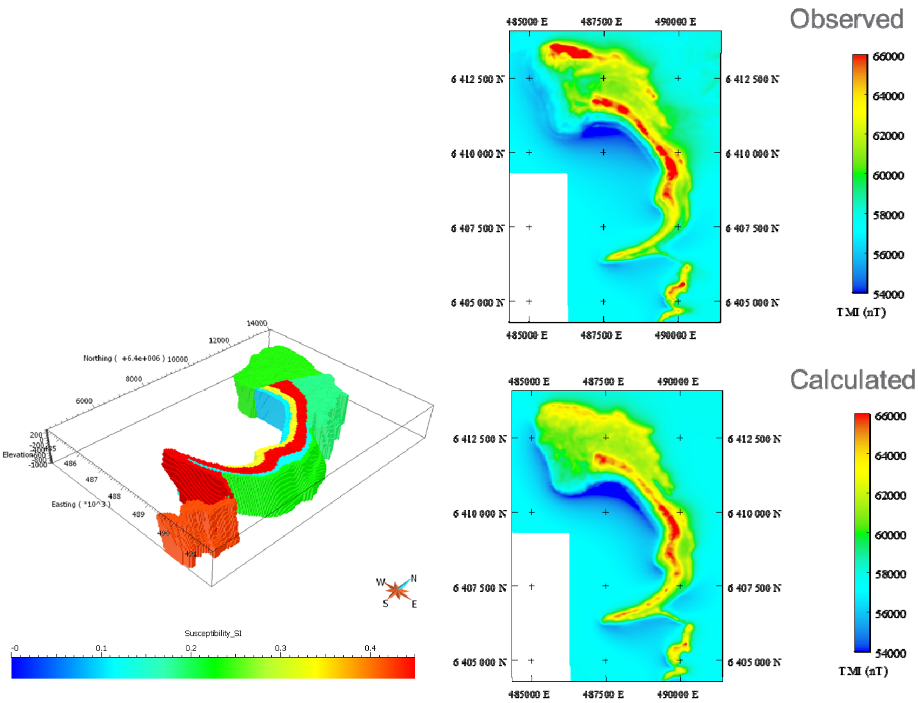

Figure 2: Illustrates the 3D magnetic domains coloured by magnetic susceptibility (left) in SI units and the measured and computed response of the final geological model attributed with homogeneous susceptibility.

A final stage of inversion to solve for local susceptibility variations within the modelled domains highlights areas of anomalous high and low susceptibility; the former defining targets (increased magnetite percentage) or areas of geological complexity that require further investigation. Figure 3 illustrates a horizontal section through the inverted model. The integrity of geological domains after inversion validates the developed geological framework and the final inversion highlights local variations within the domains.

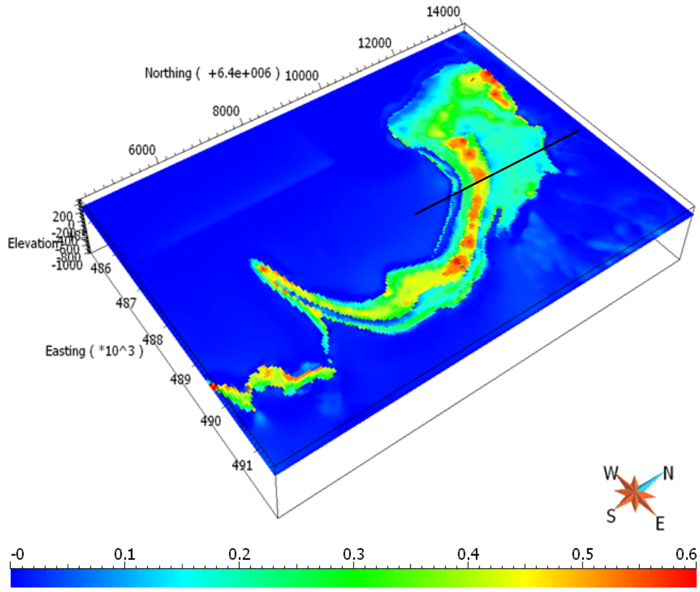

Figure 3: Illustrates the final inverted model with 3D magnetic susceptibility variations within the domains. The black profile marks the location of the EW section shown below in Figure 4.

An N-S section through the final inverted model and an unconstrained inversion for comparison is shown in Figure 4; the location of the section is illustrated in Figure 3. The geologically based model exhibits a more compact sub vertical domains of higher susceptibility than returned from the unconstrained inversion. The dipping strata is more geologically plausible than the diffuse susceptibility variations and thereby provides a higher confidence in the returned magnetic susceptibility for estimation of magnetite percentage.

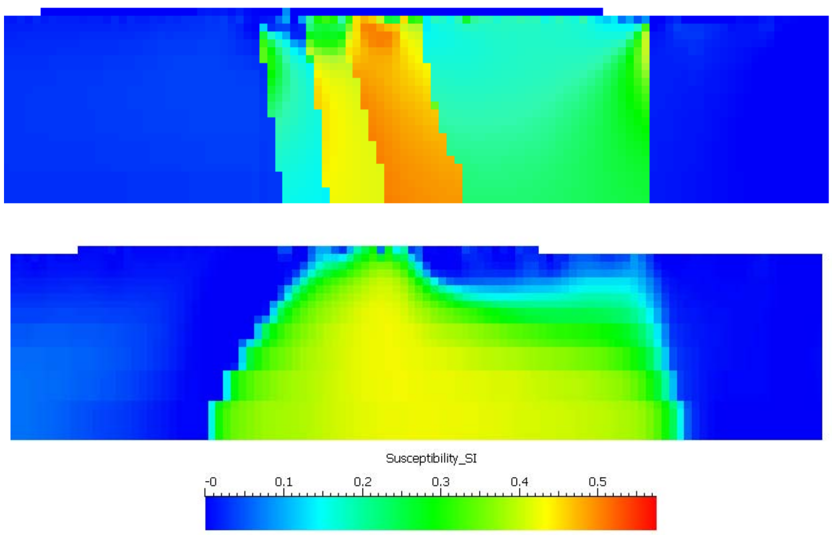

Figure 4: Illustrates an E-W section (see Figure 3) of the geologically-based model (top) and an unconstrained inversion (bottom). The geologically-based approach results in more compact domains avoiding diffuse subsurface magnetic susceptibility variations.

CASE STUDY #2 – REGIONAL BASEMENT MODELLING CHILE

The second case study is a regional scale, basement modelling exercise from northern Chile. The area of interest is largely covered by Atacama gravels overlying intermediate intrusive and volcanics. Exploration is for Cu-Au porphyry deposits; exploration in similar terranes has been published by Hope & Anderson, 2015. In this case study, the aim of the integrated interpretation is first to define depth of basement, then to utilise the modelled basement contact as a constraint for gravity and magnetic inversion to resolve density and magnetic susceptibility in the basement. All potential field forward modelling and inversion in this project uses the VPmg software. The quantitative basement modelling using potential field data follows a similar procedure to that described by Pears et al, 2001.

A compilation of the various inputs is illustrated in Figure 5.

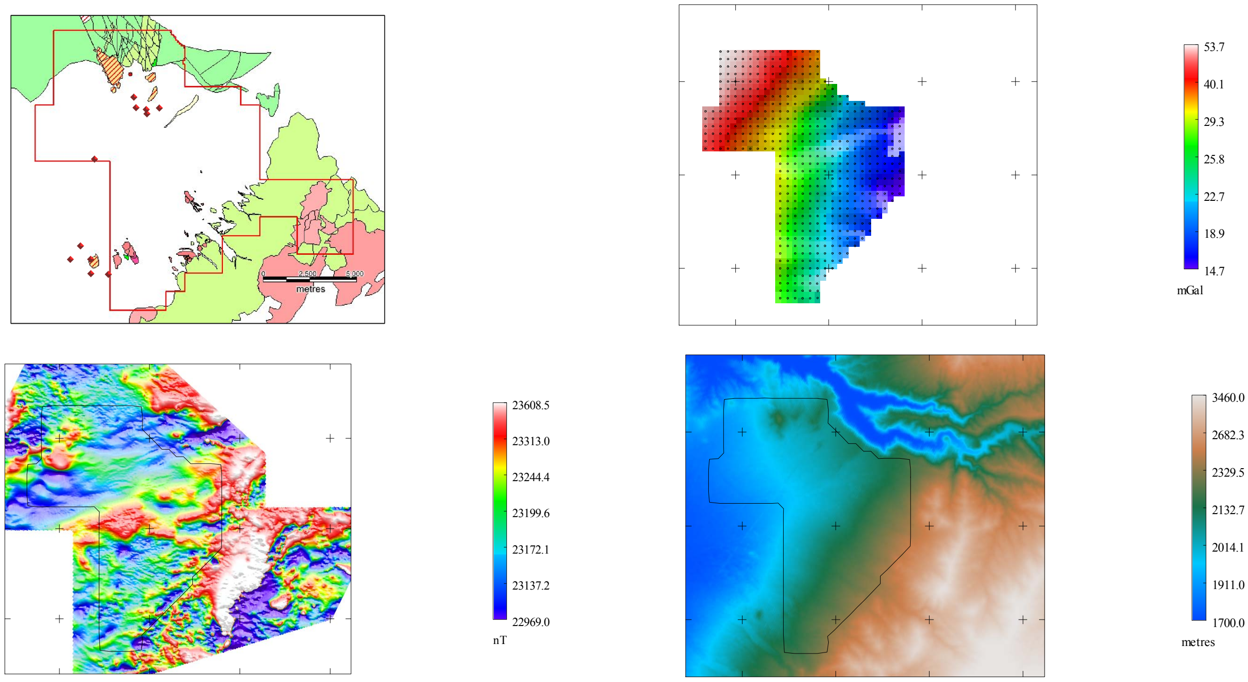

Figure 5: Illustrates the key inputs for the integrated interpretation; (top left) geology mapping showing outcrop and drill hole locations (red diamonds), (top right) gravity, (bottom left) magnetics (TMI), (bottom right) topography.

Regional gravity data was collected at 400m x 400m station spacing across the project area. The airborne magnetic data was from a survey flown with NNE orientated flight lines at 100 m spacing. The nominal sensor height for the magnetic survey is 30m.

There are 11 drill holes across the project area of which only 5 are in the area covered by gravity (see red diamonds in Figure 5). Based on drilling, expected basement depth is in the order of 100m to 200m. Summaries of the density and susceptibility information were provided, but were based on limited samples and general knowledge of rock types in the area. A density contrast of 0.6g/cc between cover and basement was assumed for modelling basement topography (e.g. ~2.1g/cc overlying 2.7g/cc basement).

The modelling procedure was as follows:

a) Compile all geological and geophysical data into a 3D modelling software environment and assess relationships between drill holes, mapping and geophysical signatures.
b) Address the prominent regional trend across the gravity data using 3D modelling techniques.
c) Construct a simple two layer starting model of cover overlying basement from outcrop and drill hole control.
d) Gravity forward modelling to assess the starting model response.
e) Drill hole constrained gravity geometry inversion to update the basement topography.
f) Validation of updated basement topography; preliminary heterogeneous density inversion in the domains and forward model basement topography against the magnetics data.
g) Gravity and magnetic inversion to solve for basement density and magnetic susceptibility variations using the final basement topography as a constraint.

In this case study, a basement topography model has been produced which is consistent with geology and potential field data. Using this as a geological constraint on inversion has produced a model depicting basement density and magnetic susceptibility variations.

Inverted basement densities and magnetic susceptibilities were assessed revealing discrete zones of low density (possibly associated with felsic intrusive) that were also enveloped by increased magnetic susceptibility (possibly associated with potassic alteration typical of porphyritic style mineralisation). Figure 6 illustrates the final basement topography and regions (volumes) queried from the geophysical derived models highlighting these zones of decreased density within the basement and the surrounding zones of increased magnetic susceptibility.

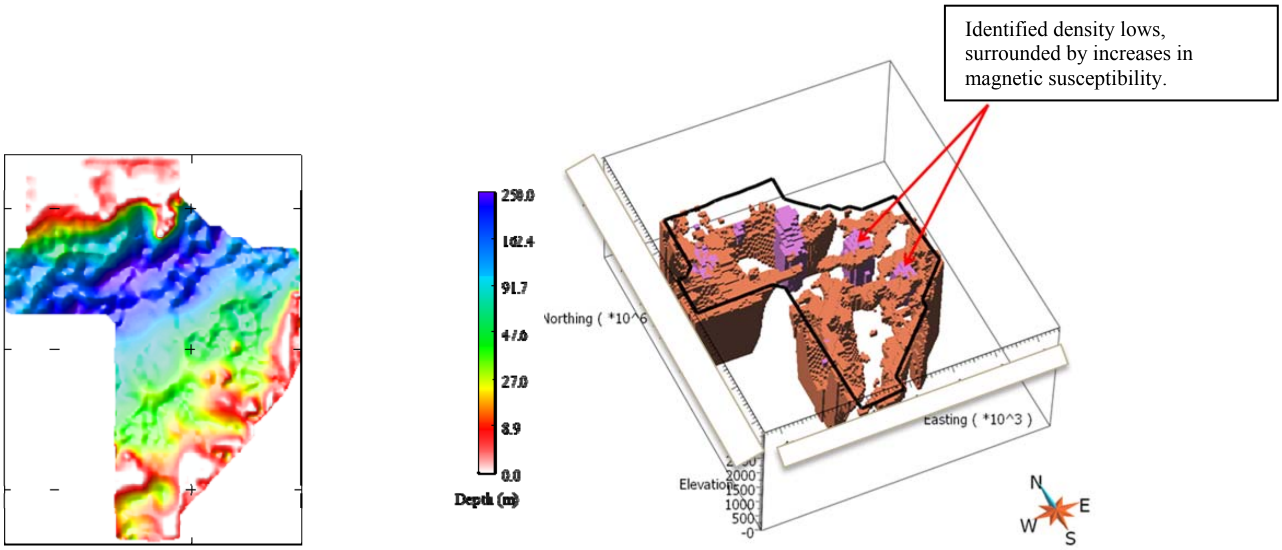

Figure 6: Illustrates a map generated for the gravity survey extents of the final depth to basement topography incorporated in the constraining model (left). On the right, is a perspective view of domains queried from the inverted density and magnetic susceptibility models; density lows pink, magnetic highs brown. Evidence of possible alteration patterns around the identified density lows (red arrows).

During the course of the interpretation, potential field modelling revealed that gravity was responding more strongly to the basement topography than magnetics and accordingly the derived basement model was largely dependent on quantitative modelling of the gravity. During modelling however, correlations were noted between the inferred basement topography and the magnetics ENE corridors (Figure 3). By forwarding modelling the basement topography, inferred from gravity modelling, against the magnetics data it shows that this is not the case. This concept of leveraging information from one data set and quantitatively testing against another is the cornerstone of integrated interpretation.

Subsequent drilling has validated basement depth, strengthening confidence in the modelled basement geometry and heterogeneous properties. Specifically, it was reported by First Quantum Minerals that:

"*drilled depths have all been within ~10% error of total depth and we have yet to hit any surprises including holes with gravel from 30m-200m*".

Drilling results associated with mineralisation outcomes are not reported in this publication.

CONCLUSIONS

The fundamental aim of integrated interpretation of geological and geophysical data is to develop a geological model that is consistent with conceptual understanding, and quantitatively consistent (validated) with all available data. It provides an answer to geoscientific questions that is more robust than if each of the individual elements were interpreted on their own.

It is important to recognise that the exact methodology for completing an integrated interpretation is not defined from the outset of the project. Rather, it requires a common sense approach to interpretation that is flexible, adaptive and objective driven. The relationships learnt from the various available data, and the investigative modelling that is completed, shape the methodology that is deployed. It is most important to recognise that geological modelling should not be considered separate to geophysical interpretation, rather geophysical interpretation should be considered an extension to geological modelling.

Software innovations still play a vital role for integrated interpretation. Though, rather than integration of geological and geophysical data being a black box algorithm, it is efficient geological modelling and model validation tools (forward modelling and inversion algorithms) which are the keys for testing geological hypothesis and quantitatively integrating geological and geophysical data. In terms of developing an integrated interpretation, the concept of "geophysical inversion" needs to adapt from a single pass exercise to recursively using forward modelling and inversion algorithms multiple times to test geological hypotheses and validate models as the interpretation evolves.

The case studies illustrate two successful examples of where integrated interpretation has been deployed to advance the exploration model. In the Mutooroo case, specifically modelling magnetic domains, and then solving for local susceptibility variations within those domains provided a more robust, geologically-based representation of magnetic susceptibility than just considering an unconstrained inversion.

The basement modelling case study from north Chile, illustrated an exercise that progressed from depth to basement modelling to recognition of potential targets. The integrity of the basement model has since been corroborated by drilling.

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REFERENCES

Chalke and McGaughey, 2015, Realising the benefit of integrated interpretation in minimising 3D model uncertainty. Conference abstracts: Saying goodbye to a 2D Earth conference abstracts 2015. Government of Western Australia, DMP Bookshop.

Fullagar, P.K., and Pears, G.A., 2007, Towards geologically realistic inversion: Proceedings of Exploration '07, Fifth Decennial International Conference on Mineral Exploration,Toronto.

Fullagar, P.K., Pears, G.A., and McMonnies, B., 2008, Constrained inversion of geological surfaces - pushing the boundaries: The Leading Edge, 27, 98-105.

Fullagar, P.K., Pears, G.A., and Reid, J.E., 2013, Hybrid 1D/3D geologically constrained inversion of airborne TEM data: Extended Abstract, ASEG 23rd International Geophysical Conference and Exhibition, August, Melbourne, Australia.

Fullagar, P.K., Vrbancich, J., and Pears, G.A., 2010, Geologically-constrained 1D TEM inversion: Extended Abstract, ASEG Conference, Sydney.

Hope, M., and Anderson, S., 2105, 'Geophysical Response of the Atlántida Cu-Au Porphyry Deposit, Chile – An Undercover Discovery in an Old District', Extended Abstract, ASEG 24th International Geophysical Conference and Exhibition, February, Perth, Australia.

Joly, A., Porwal, A., McCuaig, T.C., Chudasama, B., Dentith, M.C., Aitken, A.R.A. 2015, 'Mineral systems approach applied to GIS-based 2D-prospectivity modelling of geological regions: Insights from Western Australia', Ore Geology Reviews, 71, pp. 673-702.

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

McGaughey, J., 2006, The Common Earth Model: A Revolution in Mineral Exploration Data Integration: in GIS Applications in the Earth Sciences, Geological Association of Canada Special Publication #44, J.R. Harris (ed.), 567-576.

Mitchinson, D., Phillips, N., Perron, G., Williston, C,, McMonnies, B., and Gilmore, K., 2014, District scale targeting over the Chisel and Lalor properties using multi-disciplinary criteria and weights of evidence methods: in Exploration for Deep VMS Ore Bodies – the Hudbay Lalor Case Study, Manitoba Geological Survey Symposium, November 22nd, Winnipeg.

Jessell, M.W., Ailleres, L., de Kemp, E.A., Lindsay, M., Wellmann, F., Hillier, M., Laurent, G., Carmichael, T.L., Martin, R.J., 2014, Next generation three-dimensional geologic modeling and inversion, Society of Economic Geologists. Special Publications Series [P], vol 18, Society of Economic Geologists, Inc, Littleton United States, pp. 261-272.

Lindsay, M., Perrouty, S., Jessell, M.W., Ailleres, L., 2013, Making the link between geological and geophysical uncertainty: geodiversity in the Ashanti Greenstone Belt, Geophysical Journal International [P], vol 195, issue 2, Oxford University Press, Oxford UK, pp. 903-922.

Pears, G., Fullagar, P., and Andrews, P., 2001, 3D Gravity Modelling and Interpretation for the 1:250,000 Boulia Map Sheet, Queensland: Extended Abstract, ASEG 15th Geophysical Conference and Exhibition, August, Brisbane.

Spampinato, G.P.T., Ailleres, L., Betts, P.G., Armit, R.J., 2015, Crustal architecture of the Thomson Orogen in Queensland inferred from potential field forward modelling, Australian Journal of Earth Sciences [P], vol 62, issue 5, Taylor & Francis, Abingdon Oxon UK, pp. 581-603.