
Paper 17

Advances in Geologically Constrained Modelling and Inversion Strategies to Drive Integrated Interpretation in Mineral Exploration

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ABSTRACT

Mineral exploration is becoming more difficult, with a developing focus on discovery under cover and at greater depth. In order to better understand a mineralization system, careful assessment and integrated interpretation of all available data is required to provide information about lithology, structure, and alteration. The need for integration is blurring the traditional roles of geological modelling and geophysical inversion. This paper presents an interactive approach for developing geological models from geophysical data in order to effectively integrate geological and geophysical data.

There is inherent ambiguity in all mineral exploration datasets. The impetus for integrated interpretation is to reduce ambiguity and maximize the benefit from various types of collected data. In terms of integrated geology and geophysics, the essential goal is to interpret the available geophysical data in terms of a 3D geological model populated with physical properties. The key to integrated interpretation is therefore to develop an understanding of the relationships between geology, geophysical responses, and rock properties. Those relationships can then be used to model 3D geological domains. Geologically-based forward modelling and inversion of geophysical data plays a vital role in quantifying these relationships, but it is important to emphasize that inversion is only one part of the interpretation process.

The availability of 3D inversion algorithms over the past several decades has given way to acceptance of inversion, particularly unconstrained inversion of geophysical data sets as a standard product. These inversion results are typically overlain on geological interpretations, sometimes revealing correlations amongst various geophysical and geological data but without truly integrating the data sets. The next generation of integrated interpretation involved constructing a geological model, attributing it with rock property data, then presenting it to inversion as a geological constraint. Although this approach facilitates a numerical integration of geological and geophysical data, the inversion results are not always sensible because of the ambiguity of the initial geological model which is the basis for the starting model for geophysical inversion. This approach still considers the geological modelling component of interpretation independently of geophysical interpretation. To truly integrate geological and geophysical data, 3D geophysical forward modelling and inversion needs to be at the core of the interpretation process, testing geological ideas from the outset, and used recursively to develop a 3D geological model that agrees with the geophysical data. This interactive interpretative process also facilitates the development of plausible 3D geological models from geophysical data in areas with limited geological information.

As software and technology evolve, the capability and efficiency of modelling and inversion tools is ever increasing. Inversion algorithms which provide lithology-based inversion options offer a flexible basis for integrating geology and geophysics, but effective use of these tools requires an interactive approach to forward modelling and inversion. The process of integrated interpretation therefore demands a shift in mindset when it comes to geophysical inversion. Rather than inverting a geophysical data set once, many forward modelling and inversion runs are required to test different geological hypotheses and to develop an understanding of the relationships between the geological, geophysical and petrophysical data. Integrating geological and geophysical data, particularly in cases with limited subsurface control, is interactive and requires a practical, adaptive, and objective-driven approach to interpretation. The culmination of this process is a 3D model which combines geological and other information to achieve the exploration goals.

The paper illustrates the interplay of geological modelling with geophysical forward modelling and inversion to achieve integrated interpretation in case studies from Mount Dore in Queensland and Cave Rocks in the Eastern Goldfields of Western Australia.
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INTRODUCTION

The modern mineral exploration context is increasingly one of targeting at depth or under cover. These new exploration settings require an increased contribution from geophysical methods, moving beyond traditional interpretation of data as maps or unconstrained inversions towards integrated interpretation of 3D models.

The concept of integrated interpretation is unequivocally focused on minimizing ambiguity and providing answers to geoscientific questions that are less uncertain than when individual elements interpreted individually. The application of integrated interpretation to exploration targeting has become increasingly common (McGaughey, 2006; Mitchinson et al., 2014; Chalke and McGaughey, 2015; Hope and Anderson, 2015; Joly et al., 2015). Integrated interpretation also has a place during the development of the geological models (Henson et al., 2010; Lindsay et al., 2013; Jessell et al., 2014, and Spampinato et al., 2015) that are a part of the exploration targeting process.

The main goal of integrating geological and geophysical data is to interpret the available geophysical data in terms of a geological model, in a manner that advances exploration. The geological model is the common link between different geophysical surveys. It is logical to identify which geological components the various geophysical data are responding to, and then to capitalize on this knowledge to develop a 3D geological model.

Historically, 3D geological models have predominantly been utilized in a mining environment where interpretation is supported by large volumes of information obtained through dense drilling and pit/underground mapping. Models have typically been built solely on the basis of direct geological observation. On the other hand, away from mine sites with their abundance of direct observation, 3D Earth models have been based primarily on unconstrained geophysical inversion (e.g. Li and Oldenburg, 1996), coupled with 2D interpretations such as lineament and domain analysis. Unconstrained inversion models provide a first pass, smooth distribution of rock properties, but are just a preliminary interpretation of geophysical data that can be used as a basis for interpreting geological domains.

Recently, there has been growing interest in developing 3D geological models from geophysical data, particularly in areas where subsurface constraints and outcrop are limited or even non-existent. Our approach is analogous to traditional 2D parametric modelling of potential field data profiles, and is not as ambitious as it first sounds. The process of adjusting the 2D geological domains to explain the geophysical survey data (either directly via inversion, or manually through geological modelling) can be extended to 3D. In this sense, geophysical modelling is an extension to geological modelling.

This style of interactive 3D interpretation involving multiple data sets requires an adaptive, iterative approach to modelling and inversion. The process is not entirely software driven, but requires the input of a human interpreter, supported by advanced software for rapid 3D geological modelling and geologically-based forward modelling and inversion. The key lies in establishing a good understanding of the relationships between geology, geophysics and rock properties. Sometimes this understanding is founded on *a priori* information, but otherwise must be developed through modelling and inversion exercises.

The aim of this paper is to present our approach to integrated interpretation and to outline the evolving role of 3D geophysical modelling and inversion, particularly in cases with limited subsurface control. We regard geological modelling and geophysical forward modelling and inversion as integral parts of the interpretation process. Rather than inversion being used once to produce a model for geological interpretation, development and testing of geological hypotheses may require repeated forward modelling and inversion.

Various themes will be discussed in regard to integrated interpretation of geological and geophysical data including exploratory data analysis, investigative modelling, establishment of a geological framework, constraining data, and the role of geophysical forward modelling and inversion in the process.

FORWARD MODELLING AND INVERSION

Forward modelling and inversion are used extensively to quantitatively integrate geological and geophysical data (Pears and Chalke, 2016; McGaughey et al., 2014). An important shift in technology is the ease and speed in which geological models can be constructed, and prepared for geophysical modelling. This provides a direct means for testing and validating geological hypotheses.

Forward Modelling

The importance of forward modelling needs to be emphasized. 3D forward modelling is playing an ever-increasing role in integrated interpretation, for establishing a geological framework, testing simple conceptual geological models, as well as in geologically constrained inversion. Although most commonly used for potential field data, the same mechanics of interpretation, and the same advantages of geologically-based forward modelling to test geological concepts, apply to all geophysical disciplines.

A quick forward modelling exercise allows immediate inspection of the calculated geophysical response of the geological model which can be compared directly to the measured data (e.g. Figure 1). Assessment of the misfit between the measured and calculated responses sets the foundations for determining shortcomings of the model, e.g., whether the starting model has some gross discrepancies, whether more interpretation and modelling is required, or which inversion option should be employed.

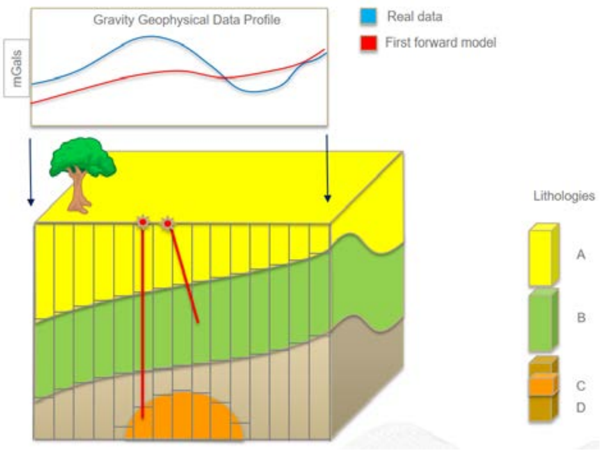

Figure 1: A synthetic example illustrating a starting model and its computed gravity response compared to 'measured' data. Each geological unit has homogeneous density.

Inversion Styles

The variety of inversion options available, such as lithologically constrained adjustment of properties and/or adjustment of geological boundaries, provide feedback mechanisms for updating the geological model either directly or indirectly. Inversion algorithms that operate directly on geological models (e.g. VPmg, VPem1D, VPem3D) are a driver for integrated interpretation (e.g. Pears et al., 2001; Fullagar and Pears, 2007; Fullagar et al., 2010; Fullagar et al., 2013).

Depending on the specific software, inversion options include adjustment of geological boundaries subject to geological constraints such as drill hole pierce points, or adjustment of physical rock properties within homogeneous or heterogeneous geological domains.

In the case of inversion algorithms that operate on a full 3D geological model, it is important to discuss the inversion styles that have been developed for litho-based modelling and inversion and are well suited to integrated interpretation.

Using the VPsuite software platform as an example, there are three key inversion styles to discuss;

- Homogeneous property inversion.
- Geometry inversion.
- Heterogeneous property

For a homogeneous unit inversion (Figure 2), the starting model is comprised of geological units with uniform properties. Inversion optimizes the assigned rock property of one or more units to improve the fit to the entire data set. Upper and lower property bounds for each unit can be imposed during inversion.

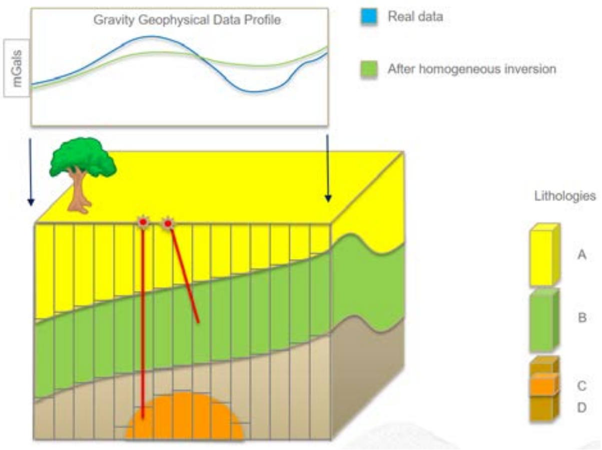

Figure 2: A synthetic gravity example illustrating the model and the 'measured' and calculated responses after homogeneous unit inversion. Only the density of the four domains has been adjusted to achieve the improvement in misfit.

Geometry inversion (Figure 3) adjusts the elevation of geological boundaries (Fullagar et al., 2008). Geological boundaries can be designated as free or fixed in their entirety or locally (e.g. where pierced by a drill hole). Boundaries may also be bounded above (e.g. by the end of drill hole).

Contrary to how the terminology has occasionally been perceived, geometry inversion itself does not manufacture an acceptable model geometry direct from a set of drill hole pierce point constraints and an outcrop map, but instead requires a geological starting model that can be adjusted during inversion. The geological boundaries in the starting model can either be interpreted or defined by geological observations.

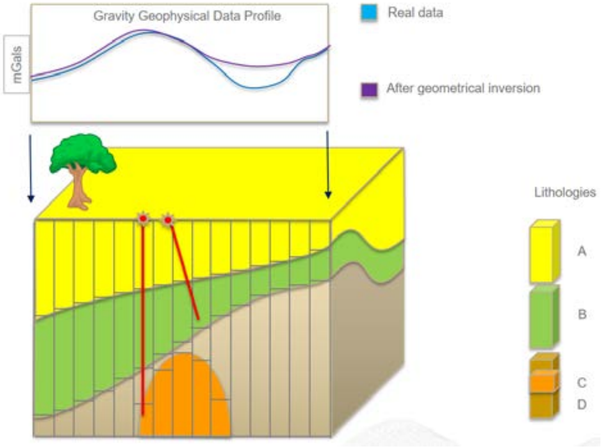

Figure 3: A synthetic gravity example showing the model and the 'measured' and calculated responses after geometry inversion. Each unit has homogeneous density. Note the interface between lithologies A and B was fixed during inversion, illustrating user control on the active interfaces.

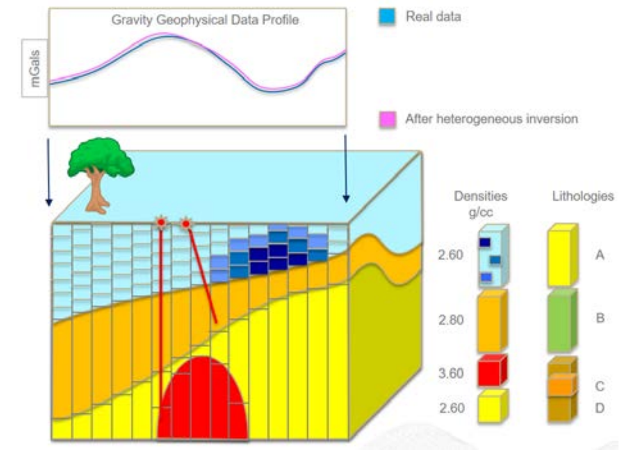

Figure 4: A synthetic gravity example illustrating the model and the ‘measured’ and calculated responses after a final phase of heterogeneous property inversion on the shallowest unit. The calculated response is providing an acceptable fit to the measured data. In this case, only the shallowest lithology was active during inversion.

Finally, heterogeneous unit inversion (Figure 4) introduces and adjusts density variations within one or more geological units, subject to upper and lower density bounds. Cells can be designated as fixed if their density has been defined by downhole logging or core measurements. Heterogeneous property inversion is a similar style of inversion to that offered by other algorithms (e.g. Li and Oldenburg, 1996; Ellis and Macleod, 2013).

METHODOLOGY

Mechanics of Modelling

The fundamental purpose of a mineral exploration model is to convert data, concepts, and interpretations into an actionable construct. Geology, and more importantly ‘anomalies’ within the assumed ‘geological framework’, are the cornerstone of the mineral exploration model. When integrating geological and geophysical data, the goal is to develop this 3D geological model in a manner consistent with the geophysical data sets. Identifying which geological domains to model and defining their geometry is an integral part of integrated interpretation.

A key milestone is to develop a 3D geological model that accounts for most of the observed data when each geological domain is attributed with a characteristic homogeneous rock property. This validates the overall geometry of the model that has been developed through geological and geophysical modelling. Homogeneous rock properties can be adjusted to optimize the data fit either empirically or using homogeneous property inversion.

Once this key stage is achieved, the model can be considered a ‘well-conditioned’ starting model for inversion. Unexplained geophysical response is attributed to detailed geology not incorporated in the developed geological model or possibly property variations within the assumed lithology that may be associated with potential targets.

The final stage of modelling is to reconcile the unexplained geophysical response in terms of localized property variations in the geological model. This is achieved by submitting the geological model, attributed with best estimate rock properties, to geophysical inversion to solve for rock property variations in the geological domains that will further reduce the misfit. Local property variations within the modelled domains highlight anomalies that may be associated with potential targets or areas of geological complexity. Sometimes, anomalous zones of material within an existing geological domain are re-interpreted or reclassified as different geological domains, or identified as potential targets.

Interpretation and Modelling Stages

In mature exploration projects and near-mine, where interpretation is supported by large volumes of information, it is possible to construct a geological model solely on the basis of direct observation. The model can be tested against geophysical data and updated manually by the interpreter or by geophysical inversions operating directly on the geological model. These scenarios require less investigative modelling.

In other cases, where subsurface control is limited, the amount of constraining data is not always sufficient to construct a suitable starting model and more investigative modelling is undertaken.

The exact process for completing an integrated interpretation of geological and geophysical data is not defined from the outset of a project. Variability exists because of differences in project aims, the available geophysical data sets, and the geological and petrophysical constraints. Accordingly, the process requires a commonsense approach to interpretation that is flexible, adaptive and objective driven. The relationships identified from the interpretation of the data and the investigative modelling shape the methodology employed.

First and foremost, it is important to define an exploration objective. Usually the exploration objective will have geological requirements. Thereafter, the key phases in our integrated geological and geophysical interpretation workflow are:

1) Data Compilation:
    - 3D visualization and cross-assessment of all data sets, existing interpretations and models
2) Preliminary interpretation:
    - Identification of geological and petrophysical constraints. Are there reliable existing interpretations that could serve as constraints?
    - Basic domain and lineament interpretation to identify key geological domains that need to be incorporated in the geological model to explain the geophysical data, by assessing geophysical signatures and their relationship with geology and rock properties.
    - Determination of whether the exploration objective is feasible—is there adequate rock property variation to

derive information about the geology to meet the exploration objectives?

3) Investigative geophysical modelling:
    - "Investigative modelling" is the term intended to describe modelling campaigns that serve to validate or to prompt revision of the shape, volume of position of geological domains or surfaces, e.g. base of cover, granite batholith geometry, dip optimisation.
    - Geological modelling, forward modelling and inversion are used to test geological concepts for subsequent incorporation into the model.
4) Geological Modelling:
    - Generation of geological model based on outcomes of investigate modelling.
5) Model validation:
    - Validation of the geological model through forward modelling, followed by updating of the geological model directly through geophysical inversion or based on interpretation of geophysical inversion.

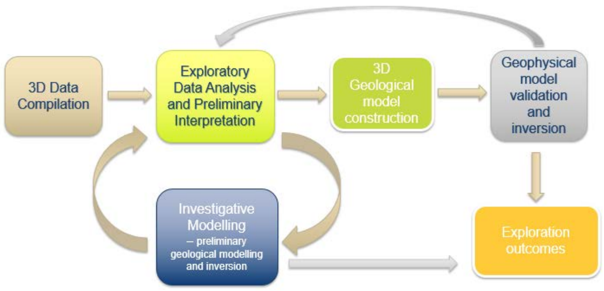

Figure 5: Flow chart of the integrated interpretation process.

By developing an understanding of how the geophysical responses relate to geology, geophysical modelling can assist geological model construction from the outset. Investigative modelling is used to refine the geometry and physical properties of geological domains before the full 3D model is constructed. This produces a better geological starting model for geologically constrained inversion.

This strategy outlined here diverges from the traditional approach to geologically constrained inversion which to a large degree performs geological modelling and geophysical modelling sequentially, and often (unfortunately) independently. In the traditional workflow, a detailed geological model is constructed and then submitted to inversion as a starting model or reference model. The problem is that geologically constrained inversion is not always capable of rectifying an incorrect geological interpretation or model in a geologically acceptable way.

For example, Figure 6 compares two geologically constrained magnetic susceptibility inversions using different starting model representations of a geological contact (separating high susceptibility on the left from lower susceptibility on the right). The starting model geometry (dip and position) of the contact in the lower panel was consistent with the magnetics data, while the starting model used for the upper panel was not. Starting susceptibilities were the same in both cases. The key point is that in the lower panel the susceptibility contrast across the contact is preserved after property inversion, validating the contact geometry of the starting model. In the upper panel, the poor starting model geometry results in a low-susceptibility zone developing in the unit on the left. The complexity in the upper panel is a sign that the contact may require re-interpretation (necessitating another 3D model construction), and detracts from other inverted susceptibility variations within each of the lithological domains.

Thus when the geological modelling was carried out in tight integration with geophysical modelling, by determining the dip and the position of the contact through investigative modelling at the outset, both the starting model and inverted model were improved.

In general, it is easier to identify potential targets or areas of interest when inversion is initiated with a well-conditioned geological starting model than when the inverted model has inadvertently overcompensated for a poor starting model.

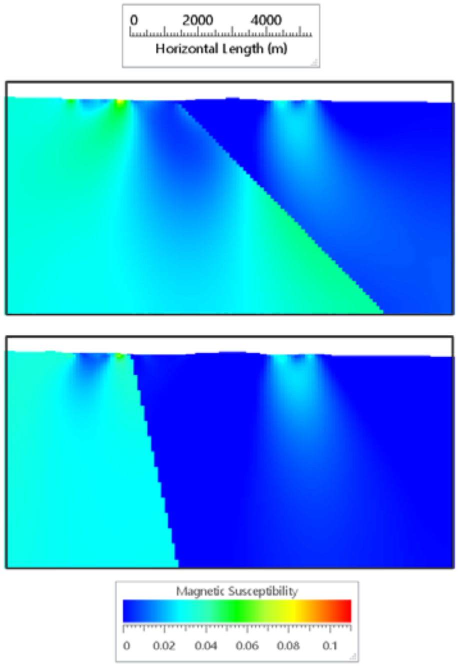

Figure 6: Geologically constrained magnetic inversion results for different starting models. Contact dip and position were based on geophysical investigative modelling (below), c.f. poorly-defined geometry (above).

Establishing a Geological Framework

What is a Geological Framework?

The 'geological framework' defines a set of geological domains that are required to explain the various geophysical responses. The geological framework adopted for modelling is typically a simplification of the true geology.

Geology is the common link between different geophysical surveys (Figure 7). It is logical to identify which geological components the various geophysical data are responding to and define a geological framework, which then becomes the basis for constructing a 3D geological model.

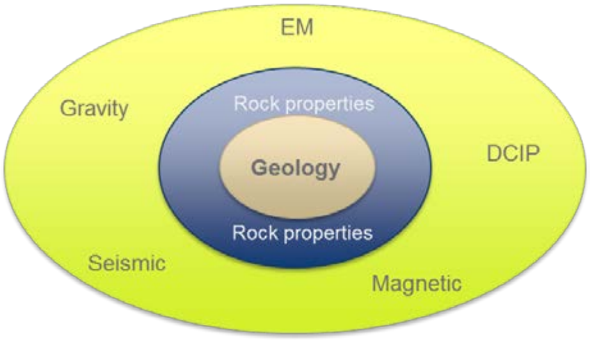

Figure 7: Conceptual diagram showing geology as the common link for all the geophysical surveys.

If the geological domains to model are carefully selected and different domains are tested using forward modelling and inversion techniques, the resulting full 3D geological model will be largely consistent with the measured geophysical responses.

Identifying a Suitable Geological Framework

Establishing a geological framework is the process of identifying the key geological units that are responsible for most the geophysical response.

The geological framework, and the level of detail to which domains need to be modelled, are not always clearly defined at the start of the project. Identifying the geological domains to model, and defining their geometry, requires interpretation and modelling. At the outset of an integrated interpretation, the following questions need to be considered:

- What is the exploration aim? What are the geological requirements to meet this goal?
- What is the geophysical data responding to?
- What geological and petrophysical constraints are available?

Setting exploration-focused, geologically-oriented goals often immediately identifies key geological domains that need to be modelled. For example, is the aim to model mineralization directly, or a prospective horizon, prospective host rock, or specific alteration type?

It is then important to understand whether there is a rock property contrast associated with those domains which will produce a geophysical response. If the geological domains that need to be modelled to meet the exploration aims do not have a geophysical signature in the available data sets, the feasibility of the goal needs to be questioned. For example, modelling cover thickness from gravity data is unlikely to be successful if there is only a weak density contrast between cover and basement.

Often, 3D geological modelling for inversion purposes is hindered by attempting to incorporate too much geological information. A rigorous review of available rock property data identifies the domains with strong rock property contrasts that need to be considered in the geological model for inversion. Conversely, rock property knowledge can flag opportunities for simplifying the required geological framework. A complex geological model with tens of rock types may yield a much simpler geological framework when attributed with density or magnetic susceptibility. For example, subtle density variations between sedimentary formations are not crucial for a first-pass depth-to-basement interpretation, for which a simpler two-layer model can be assumed.

This process of identifying the relationships between geology, geophysics and rock properties is often referred to as exploratory data analysis (EDA).

After identifying the geological domains directly relevant to the exploration objective and that the geophysical data is responding to, the next consideration is geological responses may complicate the interpretation. As examples, regional trends or varying cover thickness may mask the response from the features of interest. These additional geological elements need to be incorporated in the geological framework for geophysical modelling.

The Use of Constraining Data

The role of geological and petrophysical constraints in integrated interpretation varies from case to case. This is largely due to the amount, type and spatial distribution of constraining data available and the geological aims.

In mature exploration projects and near-mine, there is sufficient geological control to directly construct a geological model, and attribute that model with rock property values. This may be done either per domain, or through 3D property modelling such as kriging.

In some cases, it is common to have localized zones that are heavily constrained, but limited information away from the drilled area (e.g. Figure 8). The highly-constrained zone still provides a wealth of information to help establish the relationships between geology and geophysical signatures which can be extended to other parts of the model.

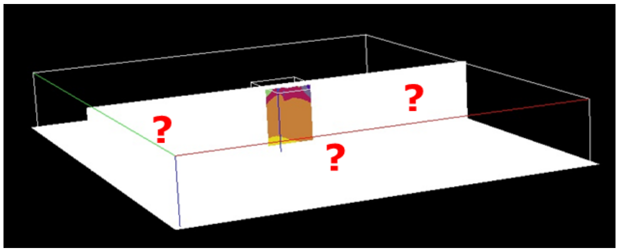

Figure 8: Schematic to illustrate a typical scenario where the area of interest is shown in white, but geological control exists only in a localized area (coloured). The control area provides constraints which can be used to leverage information from the geophysical data in the surrounding area.

In other cases, during the early stages of exploration, however, subsurface geological control can be sparse, and local rock property knowledge can almost be non-existent. Rock property knowledge is often restricted to general knowledge or similar studies.

After developing a starting model consistent with the constraining data, geological and petrophysical constraints can be imposed directly on the model during inversion. The ability for the inversion algorithms to impose geological constraints on a model (e.g. drill hole pierce points) or petrophysical constraints on model properties (upper and lower bounds, or down hole measurements) are well established (Fullagar and Pears, 2007; Fullagar et al., 2008).

Geological Constraints

Geologically-constrained inversion requires a geological starting model. Geological modelling can be conceptual, or based on actual observations, or somewhere in between. Actual observations usually include outcrop and drill hole geological logging. Other information such as seismic interpretations, conceptual cross-sections, interpretations from unconstrained inversions, and solid geology maps can also contribute to the construction of a geological model.

The complexity of the geological modelling varies depending on how advanced the interpretation is. For preliminary studies, the geological model may be a simple shaped body extrapolated from a single drill hole. For more advanced studies, it may be a full 3D structural and stratigraphic model. Either way, modelling platforms have evolved to the stage where these models can be produced more rapidly than ever before.

The geological model, attributed with rock property values, may become the starting model for homogeneous or heterogeneous property inversion, or for geometry inversion.

During geometry inversion, geological boundaries can be fixed where explicitly defined (e.g. by a drill hole pierce point, or by mapping). Inversion algorithms that permit assignment of drill hole pierce points generally requires a starting model constructed consistently with those constraints.

Petrophysical Constraints

Historically, rock property models were obtained via unconstrained inversion. This was largely a reflection of the lack of rock property data.

As downhole and core sample rock property data became more widely available, it began to be incorporated into starting models and constraints for inversion. Traditionally, the method for incorporating these constraints ranged from simply assigning and average value to the cells that host the measurement, to 3D interpolation (e.g. inverse distance, kriging) of rock property data.

In either case, geological domains did not always play a role in the property modelling. Rather, our attention has moved toward establishing the geological domains first, with homogeneous properties that match the rock property characteristic of each rock type. Once a homogeneous-unit geological model that explains the majority of the geophysical response has been established, the next step is to populate the geological domains using 3D property modelling (e.g. inverse distance or kriging), using each homogeneous property as a background value. Using this approach, it is usually possible to submit the updated model to heterogeneous property inversion and fit the geophysical data subject to the imposed rock property measurement constraints. The key is to initially establish the geological domains with homogeneous rock properties that match the characteristics of the rock property data.

It is worth noting that in many cases the lack of petrophysical data has been a serious impediment to integrated interpretation, but beyond that, the difference in scale between petrophysical and geophysical measurements is huge. Addressing the “support volume” issue is fairly straightforward in principle for density and (low) susceptibility, given adequate data coverage. However, the scale issue is often problematic for electrical properties.

The characteristic rock property contrast between geological domains also drives geometry inversion and the concept of deriving geological boundaries from geophysical data. Sometimes, the amount of rock property data or knowledge is limited and assumptions about rock property contrasts need to be corroborated by forward modelling and inversion. For example, how much would basement topography vary if a 0.1g/cc contrast was assumed between cover and basement?

Investigative Modelling

Investigative modelling is a term used to define any additional modelling and inversion exercises used to test a geological concept against the geophysical data. It may serve to locally define the shape of a particular geological domain, or it may be focused on a particular geological contact across the entire study area (e.g. base of cover). The discussion of investigative modelling as a separate activity serves to highlight the non-linear, adaptive work path often followed during an integrated interpretation.

The rationale for investigative forward modelling is that building a detailed geological model still requires time, but there are simplified model building options that allow components of the model to be directly tested against the geophysics and refined if necessary before the detailed geological model is constructed.

A suite of investigative modelling techniques can be deployed. Often these are perceived as stand-alone modelling exercises, but are actually just a component of integrated interpretation. Examples of investigative modelling exercises include:

- Model/concept validation (forward modelling).
- Depth to basement modelling
- Profile modelling
- Regional modelling
- Intrusive/dyke modelling
- Modelling position and geometry of key lithological contacts
- Inversion

As such, an entire integrated interpretation project may involve tens to hundreds of forward modelling and inversion exercises to test different geological ideas that lead to the final result.

In cases where subsurface control is limited, investigative modelling can play a significant role in identifying the key domains to incorporate into the geological framework. Modelling of areas with outcrop or drill hole constraints can establish the geophysical responses from known geological domains. Simplified localized models can be generated to develop an understanding rock property contrasts in these geologically controlled zones using forward modelling.

Part of investigative modelling is validation of models. Models may be conceptual or may be based on constraints and interpretations such as cross-sections. Forward modelling and inversion also serves to test the robustness of other interpretations contributing to the geological model.

Investigative modelling often requires a tight interaction between geological and geophysical modelling. Geological modelling packages and their connectivity to geophysical inversion algorithms have advanced, making it easier for geological concepts to be rapidly converted to a 3D geophysical model. Geological concepts can be readily tested against the geophysical data and refined, before larger amounts of time are spent incorporating them into a fully detailed 3D geological model.

A key strategy when integrating data is to identify what the geophysical data sets are responding to, then utilize one data set to leverage information from another. A typical example of this is using airborne electromagnetics (AEM) to estimate cover thickness, then explicitly incorporating this cover thickness as a constraint for gravity modelling of basement domains. This leveraging process is an important aspect of integrated interpretation.

CASE STUDY – MT. DORE

The Mt. Dore project area is located in a prospective corridor within the Eastern Succession of the Mount Isa Inlier in central west Queensland, Australia. We illustrate our methodology on a sub-set of data from a much larger project completed by Mira Geoscience in collaboration with the Geological Survey of Queensland (Chalke et al., 2012; Geological Survey of Queensland, 2011). From the integration of petrophysics, mapping, seismic, gravity, magnetics and AEM, the key outcomes of this project were a 3D mineral potential model, and reclassification of the geological starting model based on inversion results. In this paper, our focus is on showcasing the modelling techniques for developing a geologically-based model through geophysical modelling and inversion, in an area where actual constraints are limited.

Key data sets contributing to this exercise are public-domain magnetics, gravity and AEM (Geotem) and geological mapping (Figure 9). The area of interest (red polygon) is ~ 13.5 km by 18.5 km.

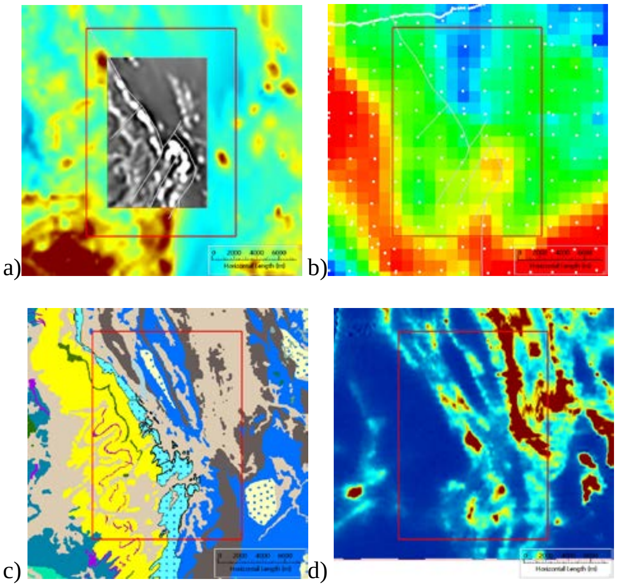

Figure 9: Overview of contributing data sets; a) extract from the public-domain reduced to pole (RTP) total magnetic intensity (TMI) grid of Australia (grey scale insert is the 1st vertical derivative of the RTP TMI); b) public-domain Bouguer gravity with observation points (~2 km spaced) superimposed; c) Geological Survey of Queensland regional geology, and d) Geotem vertical-component dB/dt data (899 µs delay time). The red polygon shows the area of interest for this exercise.

In this example, the goal is to define a simple geological framework that explains the key features of the geophysical data and provides a geological starting model for heterogeneous magnetic susceptibility inversion within those domains. In overview, the workflow for interpretation was as follows:

1. Data compilation:
2. Preliminary Interpretation:
    - Image enhancements.
    - Assess various inputs and identify key features in the data sets; AEM response and cover, key structures and lithological domains in cover.
3. Investigative geophysical modelling:
    - Model paleo-topography (cover thickness) from AEM data.
    - Model simple geological contacts.
    - Use simple contact model to isolate residual response associated with discrete features.
    - Model prominent discrete magnetic domains using isolated residual response.
4. Geological Modelling:
    - Combine modelling outcomes into single geological model.
5. Model validation and inversion:
    - Forward modelling.
    - Use model as a geological constraint for magnetic inversion to solve for magnetic susceptibility variation within geological domains.

Key milestones of this interpretation and mechanics of the modelling process are discussed below. This data set is also used to highlight the benefits of using a sensibly-constructed started model for inversion.

AEM Modelling

Correlations between mapped transported cover and increased AEM response were noted. Assuming a two-layer model of conductive cover (50 mS/m) over less conductive basement (2 mS/m), VPem1D geometry inversion (Fullagar et al., 2013) was employed to model paleo-topography from the AEM data. Conductivity estimates were based on conductivity depth imaging results and corroborated with forward modelling.

The cover thickness model derived from the AEM modelling is shown in Figure 10. Identification of the relationship between the AEM data and mapping prompted this first investigative modelling exercise to define base of cover. For all magnetic modelling, the base-of-cover topography was explicitly incorporated into the model, as a geological constraint. Magnetic susceptibility variations were not permitted in the cover.

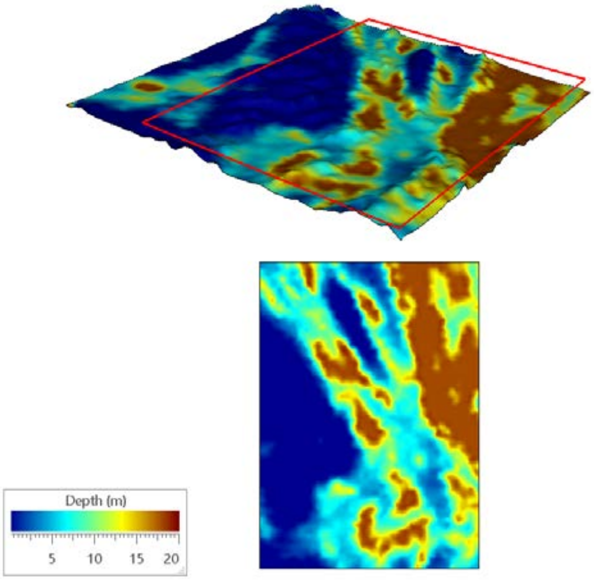

Figure 10: Perspective view (above) and map view representation for the area of interest (below) of cover thickness predicted from AEM inversion. The area of interest shown by the red polygon is ~ 13.5 km by 18.5 km.

Magnetic Interpretation and Modelling

After assessing the key features and structures in the magnetic data, attention was drawn to the apparent lithological change evident from the higher (and more variable) magnetic amplitudes in the west/southwest to the lower amplitude magnetic response towards the east/northeast (Figure 9a). The western domain is associated with Jaspilite and Mitakoodi domains (light blue and yellow respectively in Figure 9c), whereas the subdued magnetic signatures towards the east are associated with the younger Stavely-Lewellyn sediments (blue in Figure 9c).

Interpretation of structures and domains from the aeromagnetics provided the foundations for constructing a simple geological model comprising a high magnetic susceptibility domain towards the west and a low magnetic susceptibility domain towards the east (Figure 11). The change in lithology was corroborated by outcropping basement, and a change in gravity amplitude, but actual gravity modelling and inversion at this scale was not completed as part of this exercise largely due to limited data resolution (Figure 9b). Gravity modelling was completed as part of the original regional scale project (Chalke et al., 2012, Geological Survey of Queensland, 2011).

Magnetic forward modelling using VPmg facilitated estimation of the susceptibility of the two domains (0.032 SI in the east, and 0 SI in the west) and assessment of a range of dips for the contact. For simplicity, a uniform dip 80^{o} towards the east was assumed for the entire contact initially, but additional complexity could be introduced to the contact at a later stage.

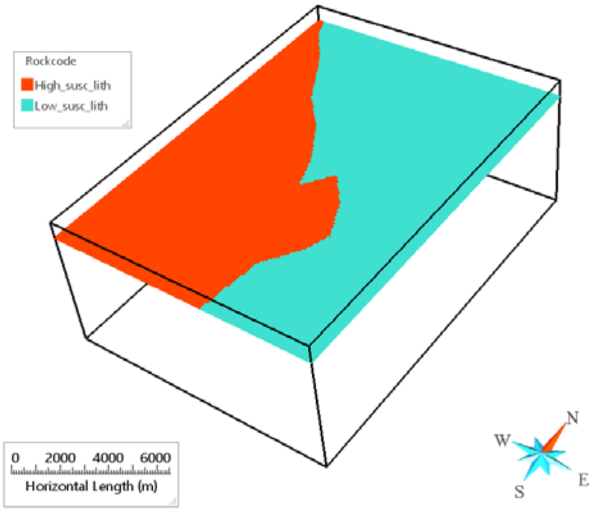

Figure 11: Perspective view of horizontal slice through the block model representation of the lithological change from higher susceptibility in the SW to lower susceptibility in the NE. The magnetically inert cover unit inferred from AEM modelling overlies these two domains.

The computed response of the simple model is compared to the measured data in Figure 12.

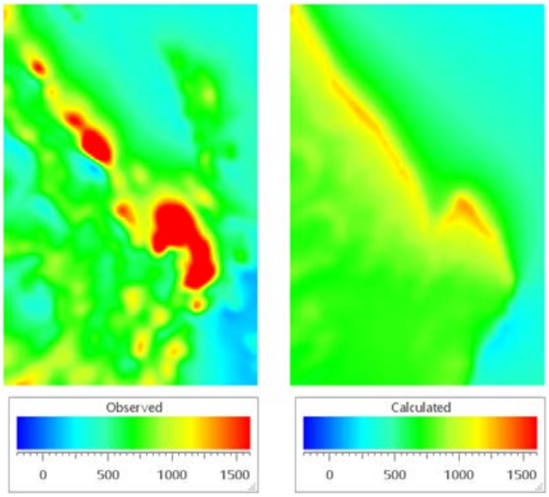

Figure 12: Measured TMI response (left) compared to the calculated TMI response of the simple lithological model.

Ignoring the magnetic response from local features, the similarity in the background magnetic amplitudes from west to east validates the modelling thus far.

It is interesting to note that the contact itself contributes to the amplitude of the prominent magnetic features that run along the contact. Conventionally, simple trend removal or filtering techniques may have been used to isolate the background response from the response of discrete bodies for modelling, but in doing so, the shorter wavelength response along the northeastern edge of the contact would not be removed.

Construction of this simple geological model provided a quantitative way to separate the magnetic signatures of discrete causative bodies from the background lithological response.

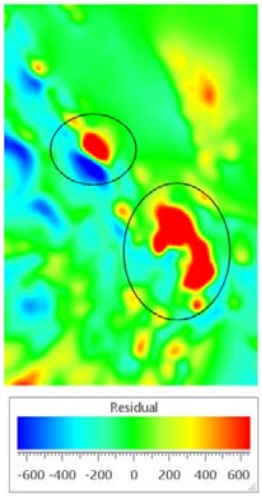

Figure 13: The residual magnetic response (observed minus calculated) for the simple lithological model. Two prominent magnetic features that are the focus of the next phase of magnetic modelling are highlighted (black ovals).

The residual response shown in Figure 13 illustrates the magnetic response after removing the effect of the modelled contact and draws attention to the prominent discrete magnetic features.

As part of the investigative modelling, 3D volumes (domains) of individual causative bodies can be defined on the basis of the discrete residual response anomalies. The principle of superposition implies that individually-modelled domains can then be combined or added back into the final model.

Developing shapes for the discrete causative bodies involved a combination of interpretation, forward modelling and inversion. First, an outline for the top of the body was interpreted from the first vertical derivative of the residual magnetic response RTP. The depth to the top of each body was estimated using Euler deconvolution (Reid et al., 1990) to be 100 m. The dip, dip direction, magnetic susceptibility and depth extent were evaluated empirically by generating a suite of models (Figure 14) with varying parameters and assessing the fit to the residual magnetic response.

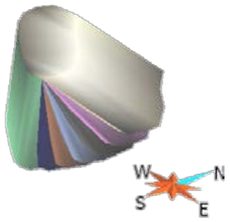

Figure 14: A suite of models with varying dip generated from the same subcrop.

Calculated responses of the various models can be compared to the measured data. Figure 15 illustrates the calculated responses of the southern body for a dip of 50° to the west, and a vertical dip (susceptibility = 0.2 SI, relative to host rock). Although the shift in anomaly shape and position is subtle when assessing the calculated response, the adverse effect of the vertical dip on the data misfit, is evident upon inspection of the residual response. The vertically-dipping body is over-estimating the magnetic response on the eastern side, and it is reasonable to infer that the 50° dip to the west is a better model.

After determining the optimal simple dipping body model, an improved fit can be achieved by presenting the simple dipping body model to geometry inversion. Geometry inversion adjusts the shape of the domain to provide a better fit to the measured data (Figure 16).

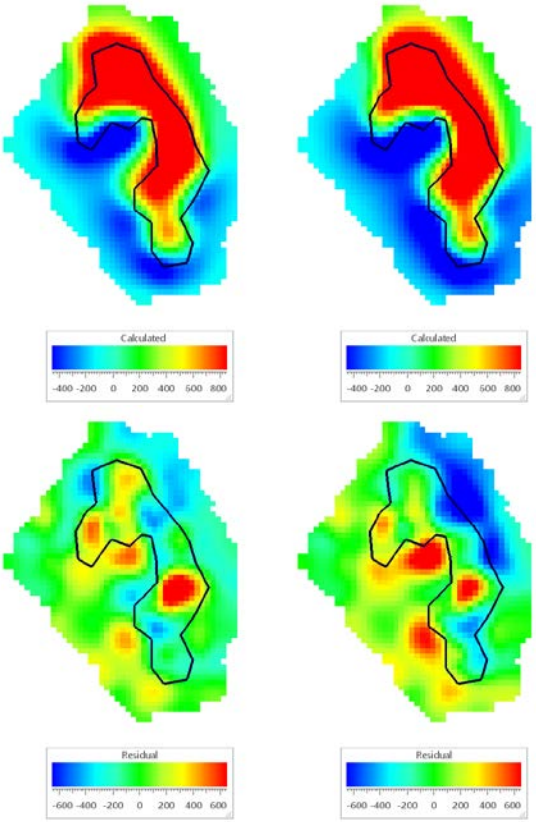

Figure 15: Calculated TMI (above) and corresponding misfit (below) for models with identical tops (traced in black) but different dips. Images on the left are for the more favourable 50^{o}W dip; vertical dip responses shown on the right

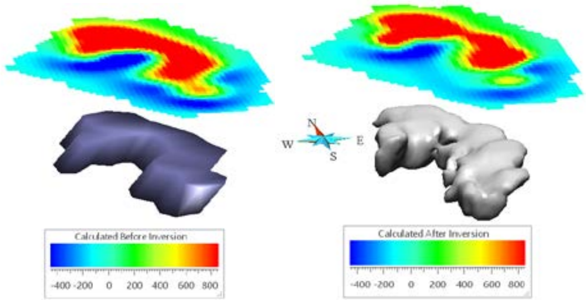

Figure 16: Starting model (constant 50^o dip to the west) with computed response above (left) and the updated shape of the magnetic domain with computed response above after geometry inversion (right).

The two most prominent magnetic anomalies on the western side of the contact were modelled in this fashion. Additional modelling of this style could be considered for other discrete domains, e.g. the broader anomaly on the east of the contact in Figure 13.

The two magnetic bodies were incorporated in a revised 3D geological model that represents the starting point for a 3D magnetic susceptibility inversion (Figure 17). The predicted base of cover surface defined the top of the magnetic domains as before.

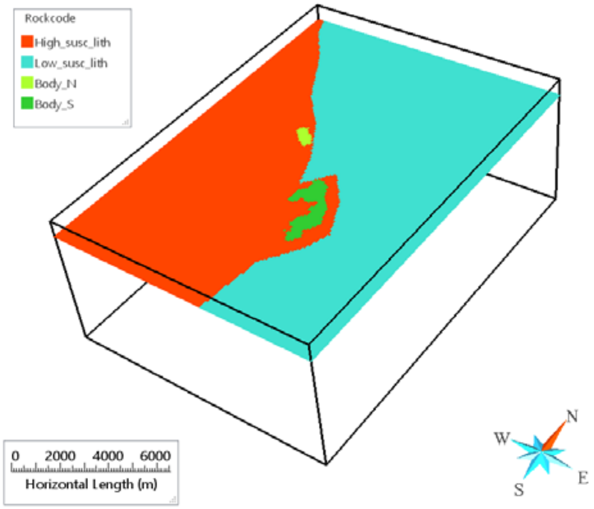

Figure 17: Perspective view of horizontal slice through the block model containing the change in background lithology (orange/blue) and the two discrete magnetic bodies (lime green/green).

In the Mt. Dore case, forward modelling (using susceptibility values of 0.032 SI west of the contact, 0 SI east of the contact and 0.232 SI for each of the north and south bodies, derived through the individual modelling exercises), produced a good correlation between the predicted and measured TMI data (Figure 18).

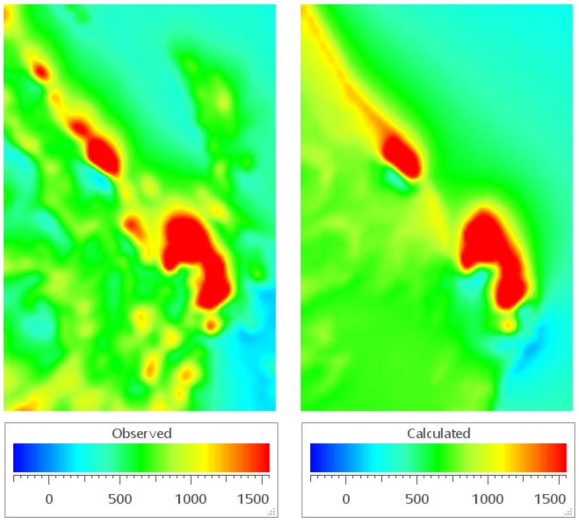

Figure 18: Measured TMI (nT) response (left) and calculated TMI response (right) of the simple lithological model incorporating the two discrete magnetic domains.

It is important to note that the above comparison is made before heterogeneous property inversion within the domains: the calculated response relates to four homogeneous domains, namely east lithology, west lithology and the two discrete magnetic bodies. The good correlation between the observed and measured data validates the modelling process thus far.

To reconcile unexplained magnetic response, an inversion was performed to solve for local property variations within each of the geological domains to reconcile unexplained magnetic response. Horizontal and vertical sections through the susceptibility model after heterogeneous inversion are presented in Figure 19. Review of the susceptibility variations in this model may prompt for minor adjustment of existing domains, inclusion of additional geological domains or be directly interpreted in terms of prospectivity.

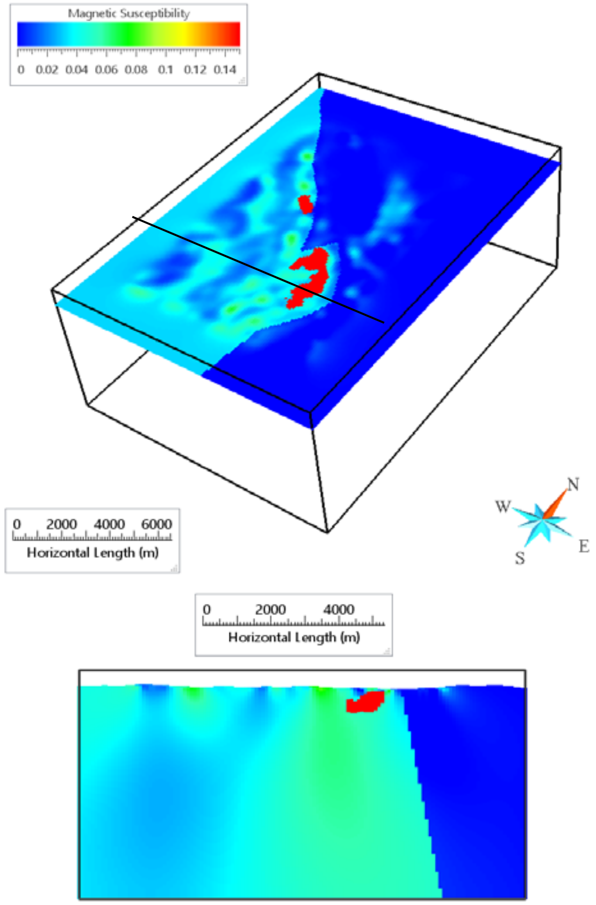

Figure 19: Perspective view of a horizontal slice (above) and EW section (position marked by black line) through the block model (below) after inverting for susceptibility variations within the geological domains. The discrete magnetic domains appear uniformly red, but this is due to the color stretch which was chosen to highlight variations in the host rock domains.

In general, this staged approach to developing a geological model and testing the individual elements against the geophysical data during the interpretation and modelling process serves to produce a model that is already largely consistent with the measured geophysical responses. Heterogeneous property inversion applied to this model reconciles residual response associated with local variations within each domain. Heterogeneous property inversion also serves to validate the starting geological framework when geological boundaries associated with the magnetic domains are preserved in the inverted model (Figure 19). This may be compared with blurred or smeared contact information as evident in Figure 6.

CASE STUDY - CAVE ROCKS

The Cave Rocks project area is located in the Eastern Goldfields of Western Australia, approximately 12.5 km west-northwest of Kambalda (Figure 20), and is prospective for both nickel and gold mineralization. The study area lies within a major north-northwest trending structural corridor, which probably represents a primary syn-extensional rift, into which greenstones were subsequently emplaced. The stratigraphy at Cave Rocks is separated from that at Kambalda, immediately to the east, by the Zuleika and Merougil Shear Zones.

The objective of the project was to produce an integrated 3D geological model based on existing geological mapping, very sparse exploration drilling, and airborne geophysical data. The prime objective was to target potential nickel mineralization. The main geophysical datasets available included fixed-wing Falcon airborne gravity gradiometry (AGG), TMI and VTEM helicopter time-domain electromagnetic (HTEM) data. The AGG and TMI surveys completely covered the area of interest, whereas the VTEM data was confined to the central part of the area, covering the main geological units considered to be prospective for nickel. The essential specifications of the various surveys are given in Table 1.

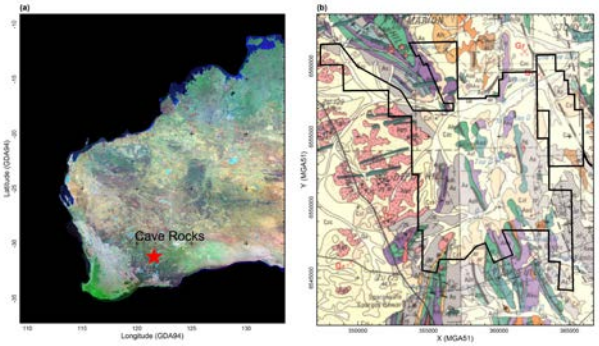

Figure 20: a) Regional location of the Cave Rocks study area; b) Regional geology (Geological Survey of Western Australia, 1988) showing the tenements of interest. The main geological units are unconsolidated cover/regolith (light yellow); ultramafics (purple), mafics (green), sediments (grey) and granodiorite (stippled red).

Airborne geophysical system	Year	Line spacing (m)	Tie Line spacing (m)	Line orientation (°)	Nominal sensor height (m)
FALCON AGG	2007	100	1000	090/270	80
Magnetics	2007	100	1000	090/270	80
VTEM	2009	200	-	070/250	30

Table 1: Cave Rocks airborne geophysical survey parameters.

Figures 21 and 22 show the tenements of interest in the study and the TMI and first vertical derivative, Falcon AGG Gdd (vertical gravity gradient) and VTEM dB_z/dt data.

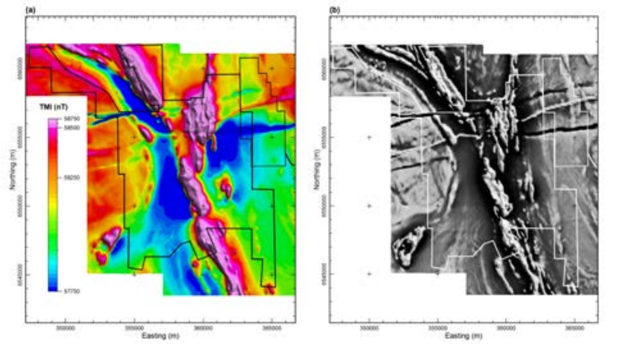

Figure 21: Cave Rocks TMI (left) and first vertical derivative of TMI (right), showing tenement outlines.

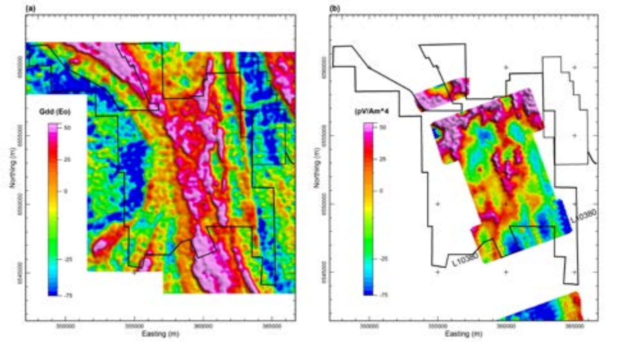

Figure 22: Cave Rocks Falcon AGG G_{DD} (left) and VTEM dB_z/dt Channel 30 (3.391 ms) (right), showing tenement outlines.

Geological information available at the beginning of the interpretation suggested that the major fold seen in the central northern part of the AGG and TMI data was an anticline, and that the prominent gravity and magnetic responses trending north-northwest-south-southeast in the AGG and TMI data corresponded to the axis of a regional anticline. Initial quantitative interpretation of the potential fields data was commenced subject to this assumption.

Model Construction

Construction of Cover Model

Interpretation of the VTEM data was undertaken concurrently with construction of the anticlinal potential fields model. The interpretation used both EMFlow conductivity-depth images (CDIs) and identification and analysis of anomalies due to discrete, steeply-dipping, bedrock conductors.

A cover thickness model was required in order to provide a constraint on the potential fields inversions. A geometry inversion for cover thickness was attempted using VPem1D, but was found to substantially overestimate the actual thickness at those locations where it was known. This was thought to be due to the lack of a consistent conductivity contrast between the cover and basement, heterogeneous conductivity within both cover and basement not associated with the base of cover, and because of widespread anomalies due to steeply-dipping bedrock conductors.

In general, conductors with dips greater than 30° are incorrectly imaged by 1D inversion or conductivity-depth imaging (CDI), and responses from steeply-dipping bedrock conductors generate artifacts in the inversion sections. Due to the lack of success with the geometry inversion, the base of the conductive cover was manually digitized from EMFlow conductivity-depth sections. This allowed a human interpreter to discriminate between the relatively flat-lying cover from conductivity artifacts produced by steeply-dipping bedrock conductors. A base of cover surface was constructed from the VTEM interpretation, limited outcrop and drilling (Figure 23).

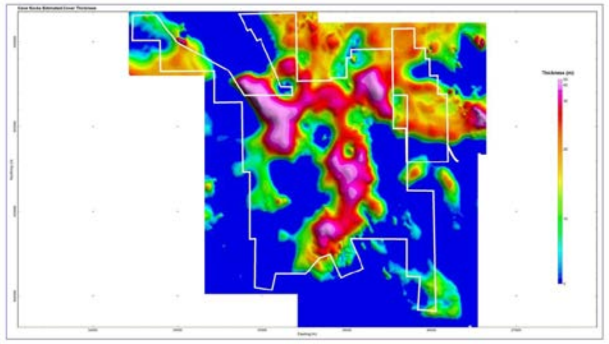

Figure 23: Cave Rocks cover thickness model derived from VTEM data, drilling and outcrop.

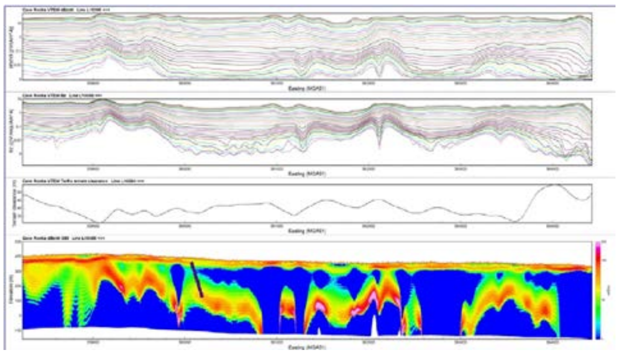

Figure 24: From top: VTEM dB_z/dt, B_z, transmitter terrain clearance and EMFlow CDI section for Line 10380 (Figure 22). The conductors on the southwest and northeastern end of the line dip to the northeast and southwest respectively. The single drill hole on this line intersected thin cover and ultramafics (purple).

Qualitative Interpretation of Steeply-dipping Conductors

The VTEM vertical-component data contained numerous ‘M’-shaped anomalies characteristic of steeply-dipping plate-like targets. All such anomalies were picked from the VTEM data, along with an estimated dip and dip direction. This exercise revealed that, in general, dips on the southwestern side of the survey area were to the northeast and vice versa (e.g., Figure 24). Figure 25 shows a 3D view of the estimated conductor dips and confirms that this is the case in general. The background image in Figure 25 is the VTEM vertical-component response at a delay time of 3.4 msec. No bedrock anomalies have been picked in areas of thick conductive overburden. Figure 26 shows the VTEM anomalies superimposed on the interpreted bedrock geology. Many stratigraphic conductors are located on the contact between the sediments and mafic units.

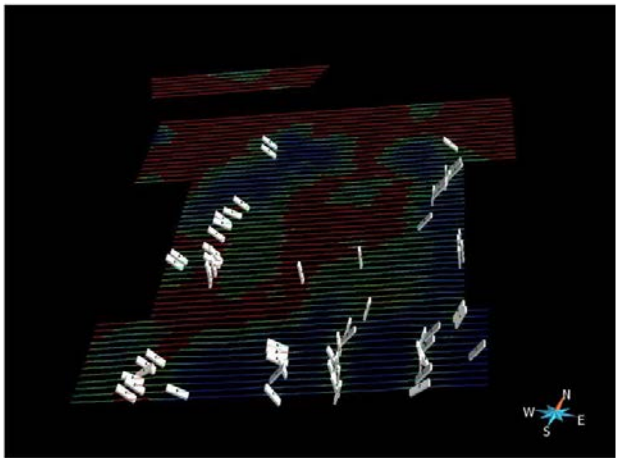

Figure 25: Perspective view showing conductor dips interpreted from the Cave Rocks VTEM data. In general, conductors on the southwestern side of the survey area dip to the northeast, and vice versa. The background image is the VTEM dB_z/dt response at 3.391 ms delay time.

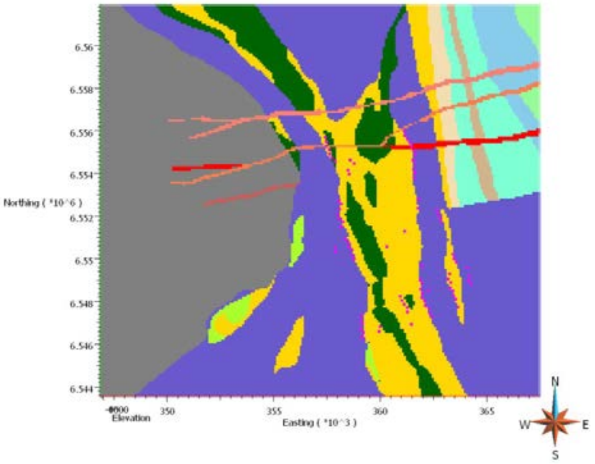

Figure 26: VTEM anomalies (pink squares) superimposed on interpreted bedrock geology. The main geological units are granodiorite (grey), sediments (purple), mafics (yellow) and ultramafics (dark green). Cross-cutting Proterozoic dolerite dykes are shown in pink and red.

Geological Modelling

The 3D geological model for Cave Rocks was constructed via interpretation and integration of different data sets, including the airborne geophysical data, government geological maps, previous geological interpretations and published petrophysical data. An initial review identified that sediments, ultramafics and mafic rocks appear to be distinguishable based on the airborne geophysical data, and that the published geology map is generally consistent with the magnetic, AGG and VTEM data.

The AGG data provided information on the eastern contact of the Depot granodiorite in the western part of the area; the contact between the sediments and main mafic/ultramafic package; discrimination of individual units within the sediments, and cover thickness.

Aeromagnetic data was used to discriminate the mafic and ultramafic packages and to interpret regional dykes. Typical susceptibilities for the mafic and ultramafic units are 0.007 SI and 0.05 SI respectively.

Figure 27 shows the interpretation line work derived from the AGG data. This should be interpreted as the geological contact locations at the base of cover (top of fresh rock). The line work derived from the potential fields data is supported in places by the VTEM data, which shows several stratigraphic conductors coincident with geological contacts (Figure 26).

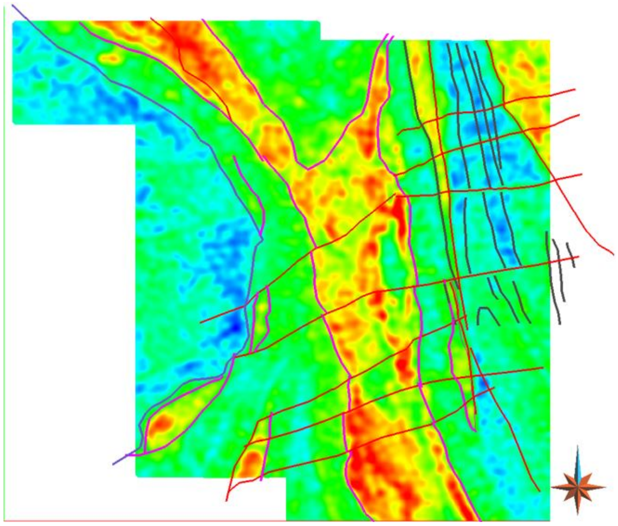

Figure 27: Interpretation line work based on Falcon AGG data and unconstrained inversion. The pink lines define the boundary between the mafic/ultramafic units and the adjacent sediments. The blue line defines the boundary between the Depot granodiorite in the west and the adjacent sedimentary, mafic and ultramafic rocks. The black lines differentiate separate sedimentary packages. The red lines are the faults interpreted and needed for 3D geological model construction.

The existing geological interpretations reviewed at the commencement of modelling indicated that the major structure in the area is a regional anticline plunging to the south. The initial model construction followed this guidance and also used the unconstrained inversions to provide dips on other contacts within the area e.g., the contact between the Depot granodiorite and the sediments.

During construction of the model it was noted that the unconstrained inversion results conflicted in places with the anticline model. Figure 28 shows a north-south section through the north-central part of the anticline model. The trace of the geological surface defining the contact between the sediments to the north and mafic/ultramafic units to the south is shown as a white line. This contact corresponds to the hinge of the postulated south-plunging anticline. The unconstrained inversion places zones of high density and susceptibility to the north of the contact, and is inconsistent with the anticline model.

Homogeneous-unit geologically-constrained inversion of both the Falcon and aeromagnetic data was conducted based on the anticline model. Both inversions show high misfit in the centre-north of the area of interest, where the major anticlinal structure is located (Figures 29a and b).

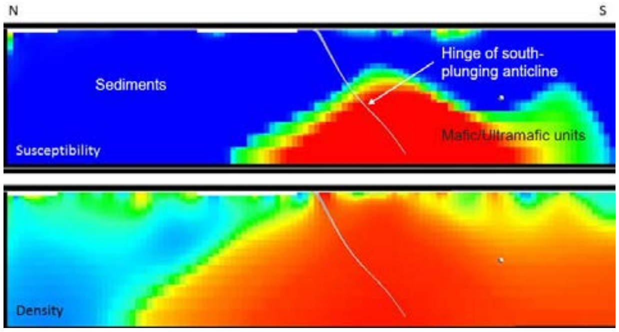

Figure 28: North-south cross-section through the unconstrained density and susceptibility inversion results for the anticline model, showing the conflict between the unconstrained inversion results and the assumed model.

Anticline or Syncline?

The poor fit to the potential fields data obtained by constrained inversion based on the anticline model prompted reconsideration of the geological model. The government regional geological map shows the major structure at Cave Rocks to be a syncline, whereas more recent company reports interpreted it as an anticline. The unconstrained and homogeneous-unit potential fields inversion results are also more consistent with syncline than an anticline (Figure 29). Magnetic forward modelling also favoured the synclinal model—the shape of the magnetic anomalies associated with the ultramafics (in particular, the low or negative part of the induced anomaly) was better explained with the synclinal model. Lastly, interpretation of the dips of the geological contacts based on the VTEM data also support a syncline model.

Further evidence to resolve the question could have come from soil and drill hole geochemical data, as the MgO content of the ultramafics is expected to be high at the basal contact, and to decrease upwards. However, geochemical coverage of unweathered ultramafics was insufficient to support either geological model.

Syncline Model

Based on all of these factors, it was decided that the likely regional structure is in fact a north plunging syncline. This has significant exploration implications as the basal contact of the ultramafic unit against either mafic units or sediments is opposite to that previously conceived. Accordingly, the geological model was reconstructed using the dips interpreted from the VTEM data and unconstrained potential fields inversions for initial construction. (Figure 30).

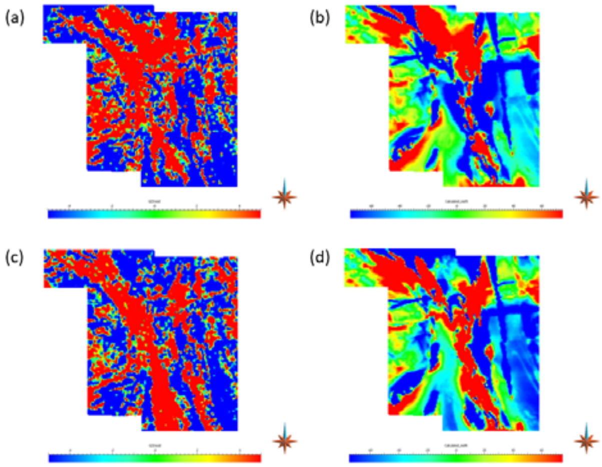

Figure 29: G_{DD} (left) and TMI (right) residuals following homogeneous unit geologically-constrained inversion based on the anticline model (a and b), and the syncline model (c and d).

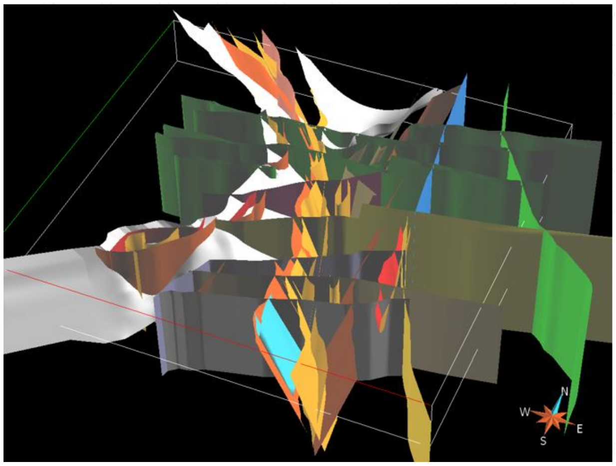

Figure 30: Geological surfaces used in creation of the syncline block model.

Geologically-Constrained Potential Fields Inversion

The base of cover was that derived from the outcrop, drilling and VTEM interpretation (Figure 23). The regolith was assigned a magnetic susceptibility of zero and a density contrast of -0.5 g/cc, corresponding to a density of 2.17 g/cc. Regolith thickness was held constant during all constrained potential fields inversions, but the final inversions allowed the regolith physical properties to be heterogeneous.

Magnetics Inversion

The key steps in the magnetic inversion were construction of geological starting model (Figure 30), optimization of the magnetic susceptibility of the geological domains via homogeneous-unit inversion, and inversion for heterogeneous susceptibility within the domains.

Significant effort was expended on obtaining a geologically-plausible representation of the dykes, in order to minimize their influence on the inversion results for the surrounding lithologies. The magnetic polarity of some dykes was clearly reversed, and these needed to be explicitly incorporated into the geological model in order to allow incorporation of remanence effects. A Koenigsberger Ratio (Q) of 2 was empirically determined for the reversely-magnetized dykes, assuming a vertical remanence direction. These remanence settings produced a forward-modelled magnetic response that corresponded with the shape of the magnetic anomaly associated with the dykes.

The final magnetic model obtained following heterogeneous-unit inversion is shown in Figure 31. Zones of high and moderate susceptibility within the main north-northwest–south-southeast trending belt represent ultramafics and mafics respectively.

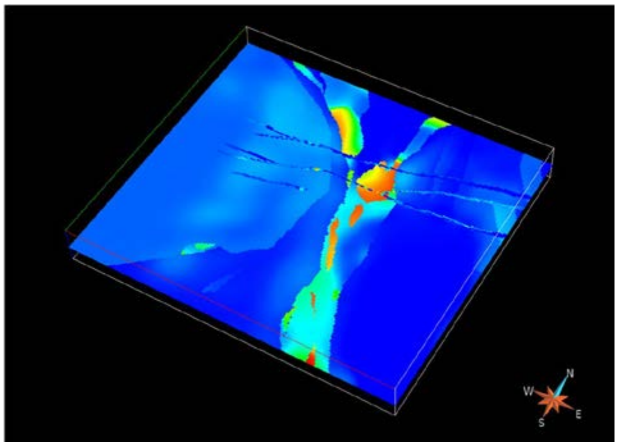

Figure 31: Horizontal section through final heterogeneous geologically-constrained magnetic susceptibility model.

Airborne Gravity Gradiometry Inversion

As for magnetics, the first stage of AGG (G_{DD}-component) modelling optimized the density of each geological domain, assumed homogeneous. The homogeneous-unit model which gives the best fit to the data becomes the starting point for heterogeneous inversion. The resulting final model includes localized density variations which may be zones that require revision or which could be potential targets.

The final step in gravity gradient modelling was to compute the G_{NE} and G_{UV} component responses of the density model derived from the G_{DD} data. The G_{DD} model was found to provide an acceptable fit to the measured G_{UV} and G_{NE} components.

The final gravity gradient model following heterogeneous-unit inversion is shown in Figure 32.

Application to Exploration Targeting

Trench and Williams (1994) identified the following geophysically-detectable characteristics of nickel ore environments at Kambalda:

- Thickening of the basal ultramafic flow units
- Lack of interleaved sedimentary units between the mafic rocks and overlying ultramafics, and between successive ultramafic flows
- ‘Ore troughs’ in the footwall mafic rocks

It is important to note that the scale of structure which defines the localized ore troughs would not be detectable at the scale of the geological model (which covers an area of ~20 km × 20 km) and potential fields models (50 m × 50 m model cells). However, the common Earth model provides other inputs for targeting of nickel sulphide mineralization, including proximity to the basal contact of the ultramafic, increased thickness of the ultramafic units, differentiation of ultramafic units based on density and susceptibility (i.e. talc-carbonate vs serpentinized), breaks in stratigraphic conductors close to the basal contact of the ultramafic, and identification of local electromagnetic anomalies near the basal contact.

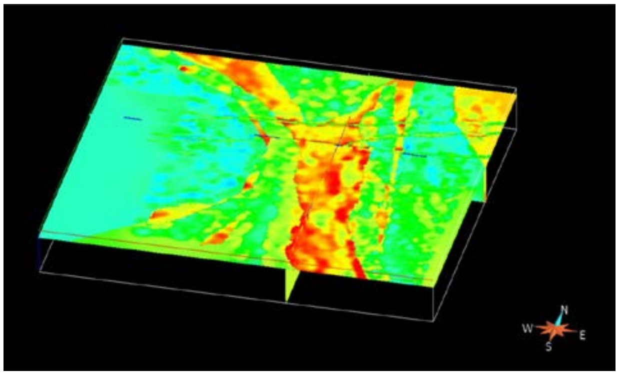

Figure 32: Horizontal (and vertical) sections through the final heterogeneous geologically-constrained density model after AGG inversion.

Following analysis of the geophysical responses and the published geology map, it was decided that the main regional structure at Cave Rocks is a north-plunging syncline. The structure had previously been interpreted as a south-plunging anticline.

The syncline model is supported by the gravity gradient and magnetic inversion results, conductor dips interpreted from the VTEM data, and government regional-scale geological mapping (1988). In addition, none of the existing company drill holes within the area of interest, drilled assuming an anticlinal structure, were considered to have intersected the basal contact of the ultramafic.

The interpreted syncline at Cave Rocks has significant exploration implications as the basal contact of the ultramafic against either mafic units or sediments is opposite to that previously conceived, i.e. on the external rather than interior margins of the main ultramafic-mafic belt.

CONCLUSIONS

The fundamental aim of integrated interpretation of geological and geophysical data is to develop a geological model that is qualitatively consistent with conceptual understanding, and quantitatively consistent with all available data. The integrated interpretation minimizes ambiguity and provides answers to geoscientific questions that are more robust than if each of the individual data sets were interpreted on their own.

The exact methodology for completing an integrated interpretation is not defined from the outset of the project. Rather, it requires a commonsense approach to interpretation that is flexible, adaptive and objective driven. The relationships inferred from the various available data sets, and the investigative modelling that is completed on data subsets, shape the methodology that is employed. It is most important to recognize that geological modelling should not be considered separate to geophysical interpretation, but that geophysical interpretation should be considered an extension to geological modelling. Rather than having one preconceived geological model that is used as a constraint in a geologically constrained inversion, forward modelling and inversion are an integral part of development of the 3D geological model.

Even where subsurface control is limited, 3D geological models can be developed by adopting a pragmatic integrated approach to 3D interpretation of geophysical data sets. If multiple data sets exist, one data set may be used to leverage additional information from another (e.g. infer cover thickness from AEM and use it to constrain gravity).

This involved, reactive, approach to interpretation serves to impart a greater understanding of the model space, and of the limits imposed on the model space by the constraints and data. The process of modelling and making deductive decisions about the interpretation based on the modelling outcomes reduces ambiguity by eliminating results that are not geologically plausible.

Rapid 3D geological modelling and geologically-based forward modelling and inversion are essential for testing geological models or hypotheses, and for driving updates to the geological models. Testing 3D geological hypotheses at the outset of a project through forward modelling and inversion can save hours if not days of wasted modelling time.

Identifying the geological domains to model, and defining their geometry requires interpretation and modelling. At the stage of running the final geologically constrained heterogeneous inversion, the culmination of many forward modelling and inversion exercises should have resulted in a starting model that matches the geophysical responses fairly well. This model is then considered well-conditioned as a starting model for inversion. If not, further refinement to the geological framework and model geometry should be considered.

Software innovations still play a vital role for integrated interpretation. Efficient geological modelling and model validation tools are the keys for testing geological hypotheses and quantitatively integrating geological and geophysical data. In terms of developing an integrated interpretation, “geophysical inversion” needs to evolve from a single pass exercise to a recursive process involving multiple forward modelling and inversion runs to test geological hypotheses and validate models as the interpretation develops.

In addition to geological constraints, rock property measurements are vital to an interpretation, but effective use of them requires having sufficient measurements to characterize the geological domains of the model. Initial modelling still commences with homogeneous domains that conform to the bulk rock property characteristics. Once a suitable homogeneous-unit model has been created, populating the model domains with local physical property variations from laboratory measurements or downhole logging produces a model that likely fits the data to similar accuracy. This can then be submitted to geologically-based property inversion, constrained where the local rock property measurements exist to further improve the misfit in data.

The case studies illustrate the benefits of integrated interpretation by producing value-added geological outcomes collaborated from different data sources, and illustrating the evolution of a 3D model through investigative interpretation.

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