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Regional 3D inversion modelling of gravity and magnetic data, Georgina Project, Northern Territory, Australia

Vale Exploration Pty Ltd

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1. Introduction

In March 2011, the Mira Geoscience Advanced Geophysical Interpretation Centre (AGIC) was commissioned by Vale Exploration Pty Ltd. to conduct regional scale modelling of gravity and magnetic data over the Georgina Project area, NT, Australia.

As indicated by Vale, the area is prospective for sedimentary phosphate mineralisation; the target being middle Cambrian carbonates deposited adjacent to or on top of basement topographic highs. The objective of the project is to maximise the use of gravity and magnetic data to model depth to geophysical basement (assumed to consist of either Lower Cambrian volcanics and/or pre Cambrian basement) through integrated interpretation and implementation of constrained inversion.

The steps taken during inversion and modelling are listed below and are discussed in further detail within the report:

1. Data compilation, assessment and preparation for modelling
2. Construction of starting model from supplied geologic data and magnetic depth to source estimation techniques.
3. Magnetic and gravity inversion of the model area

In this project, the VPmg 3D potential fields forward modelling and inversion software (Fullagar et al., 2000, 2004, 2007, 2008) was used. The VPmg software permits a wide variety of inversion styles and model options and is well suited to geologically constrained inversion.

VPmg permits imposition of a variety of constraints depending on the inversion style. In this project, available constraints for basement modelling and inversion included drillhole contact information (50 holes) and outcrop from geology maps.

Modelling assumed a simplified two layered model comprising a cover sequence overlying basement. The ‘basement’ unit comprises Precambrian Basement and overlying Cambrian Volcanics. The material overlying the basement is assumed to be magnetically inert.

The final basement model reproduced the gravity data to within 0.7 mGal RMS reduced from 14.5 mGal RMS for the starting model. The model fits the magnetic data to within 8.3 nT RMS reduced from 111.2 nT RMS for the starting model.

The final products are the magnetic susceptibility and density models which explicitly define basement contact within the project area. Key products have been generated from these models to assist interpretation including basement density, susceptibility and depth grids.

The final model has revealed regions of basement ridges coincident with increases in density. These could indicate the presence of middle Cambrian carbonates deposited adjacent to, or on top of basement topographic highs.

The purpose of this report is to document the methodology and results. It is assumed that the reader will have access to the accompanying digital inversion results, as listed in Appendix 1.

2. Data

The following data were provided for this project:

- *Airborne Magnetics data*
- *Gravity data*
- *Topography data*
- *Digital geological maps*
- *Drillhole information*

These data sets are briefly described below.

2.1. Airborne Magnetics Data

The provided airborne magnetic data was a consolidation of many magnetic surveys acquired from Geoscience Australia (GA) over the entire project area. The average sensor height for the surveys is 80m. Gridded merged aeromagnetic data was provided at a resolution of 90m (Figure 1).

Inducing magnetic field parameters of 50206nT, -49.41^{o} inclination and 4.8^{o} declination were adopted for modelling.

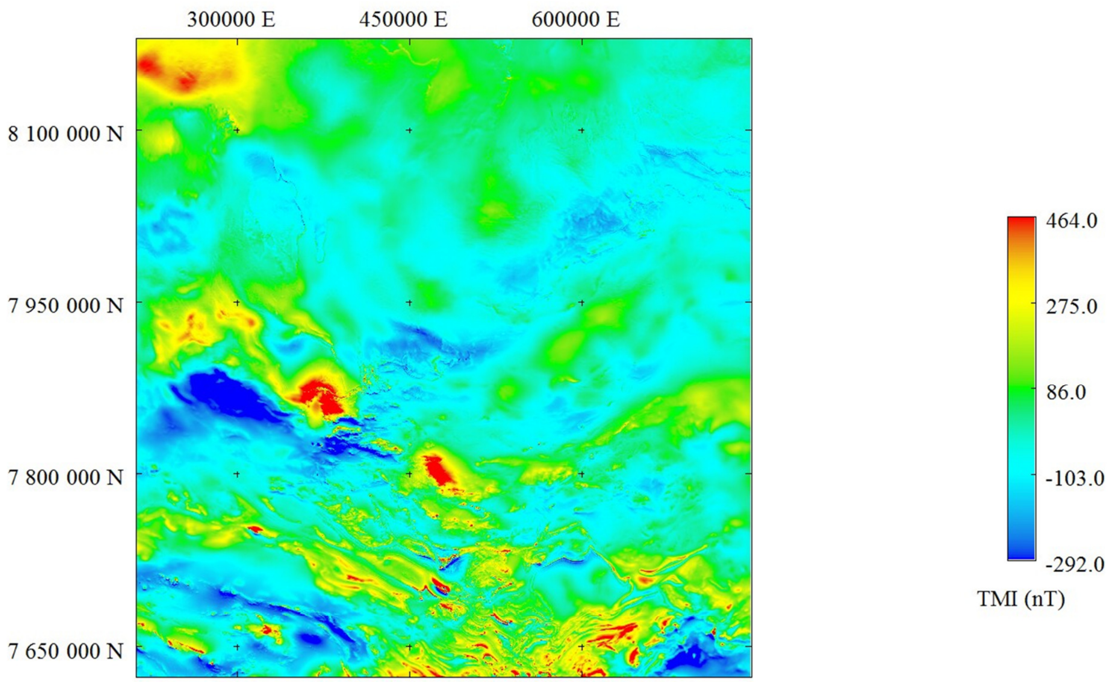

Figure 1: Image of supplied aeromagnetic total magnetic intensity (TMI) survey data over the project area.

2.2. Gravity data

Located gravity data were supplied over the entire project area (Figure 2). Station spacing ranges from >25m to <12500km, but is predominantly 500m.

This study focuses on a preliminary regional analysis and the provided gridded Bouguer gravity data (900m resolution) was assumed an appropriate representation of terrain corrected gravity data for modelling at this scale. In more detailed follow up studies, the actual gravity station locations of localised infill surveys and Vale proprietary ground gravity data would be used.

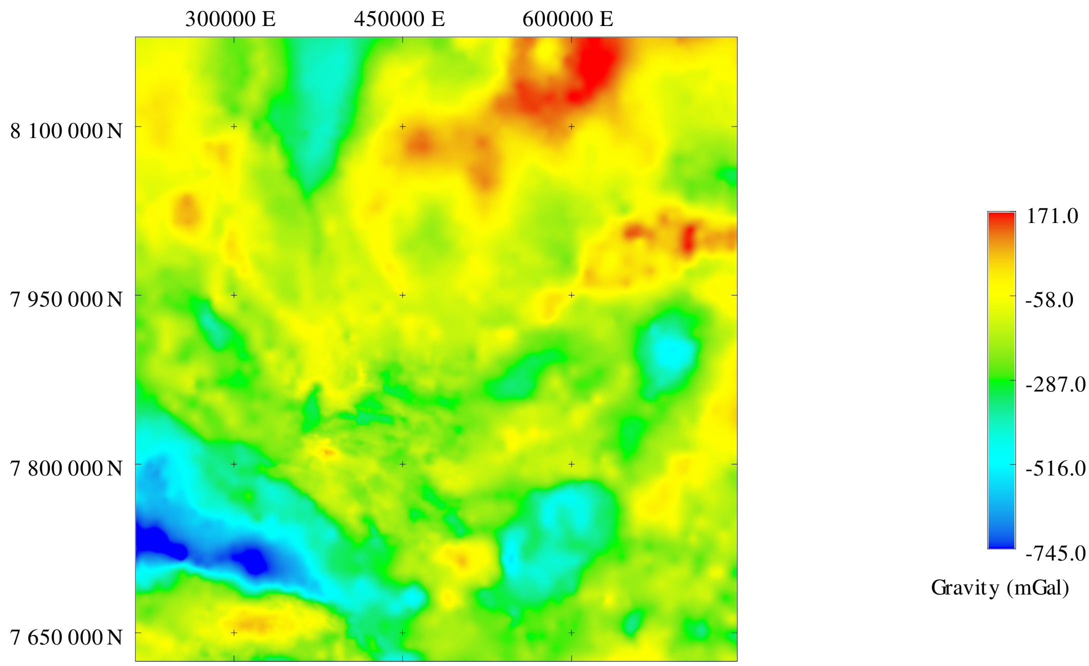

Figure 2: Image of supplied gridded Bouguer gravity survey data over the project area.

2.3. Topography Data

The DEM derived from the SRTM data at 90m resolution is used for modelling. Figure 4 illustrates the DEM, Vale tenements and the defined area of interest for modelling.

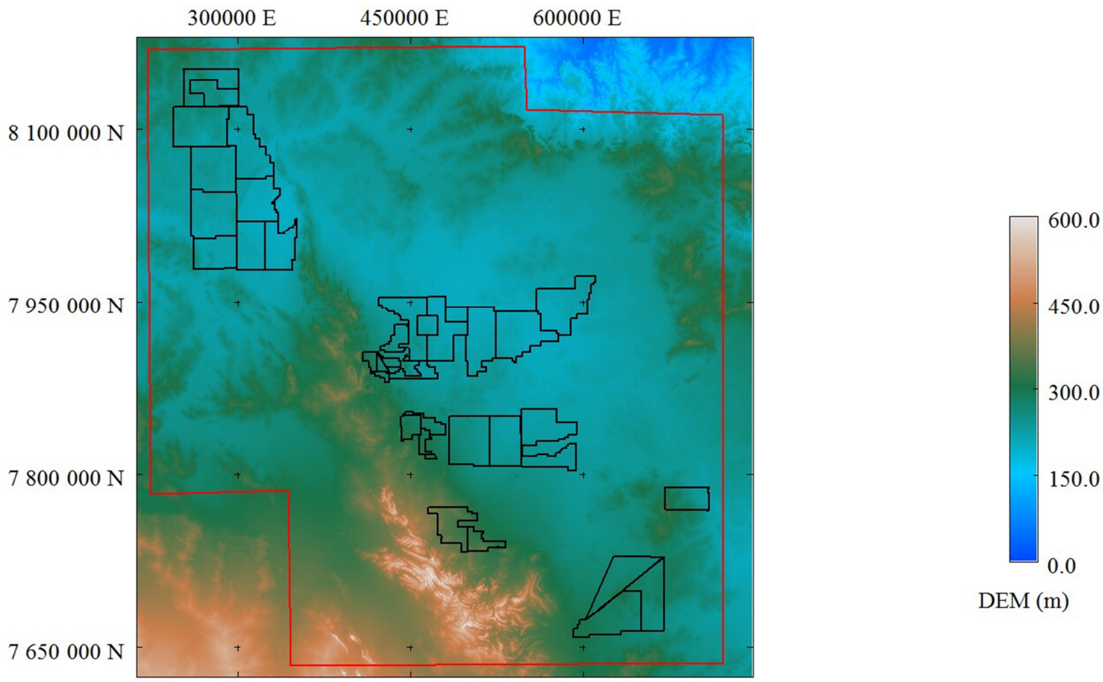

Figure 3: Topography of the project area with supplied area of interest (AOI) displayed as red polyline and Vale tenements displayed as black polylines.

2.1. Drill hole data

Collar locations for 50 vertical wells were provided (see Figure 4 for drill hole locations). Drillhole geology logs were imported defining four significant geological domains; Cover, Georgina Basin, Cambrian Volcanics, and Basement.

The markers for the tops of these geological units are available of 30 of the wells in the project area. Contacts for the Cambrian Volcanics units are in 27 of the holes, and nine drillholes reached basement.

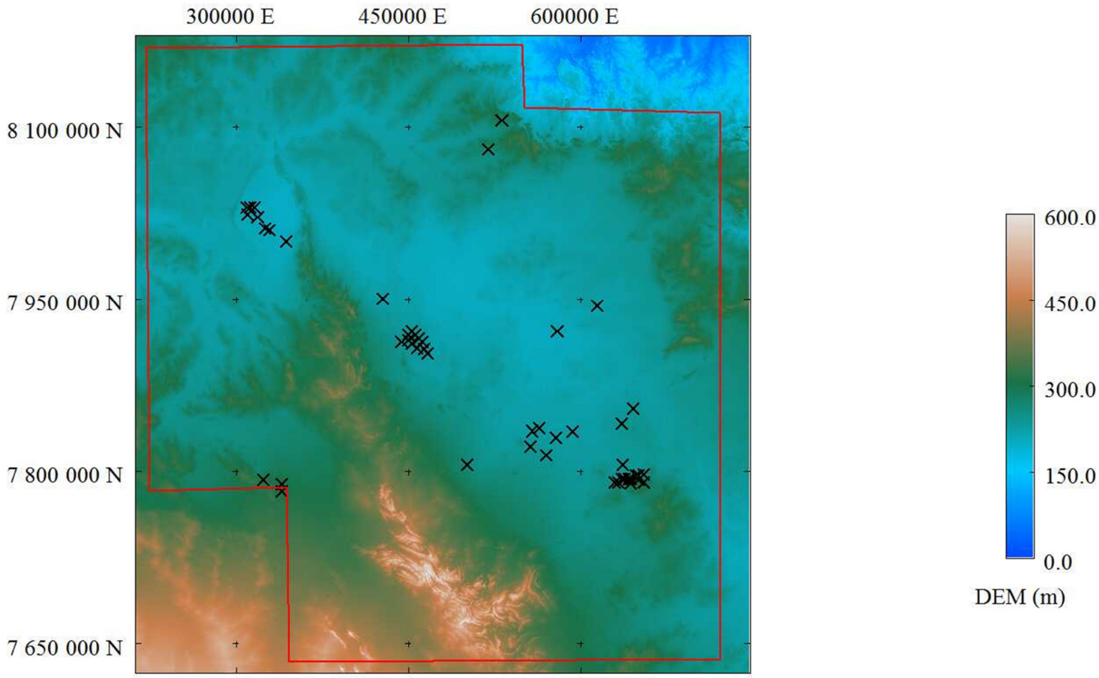

Figure 4: Topography of the project area with supplied drill hole collar locations displayed as black crosses. The red polygon depicts the area of interest for modelling.

2.2. Digital geological maps

The geological maps and surfaces indicating outcropping basement and Cambrian volcanic units are imported into Gocad and located in 3D space. Outcrop from the various provided geology maps captured different amounts of detail. The representation of basement outcrop and Cambrian volcanics contained in the ArcView shape files “Basement.shp” and “Cambrian_Volcanics.shp” are shown in Figure 5. From information provided by Vale, both the basement and Cambrian volcanics are known to contain magnetic sources, and both were used to constrain the geometry of model basement for inversion

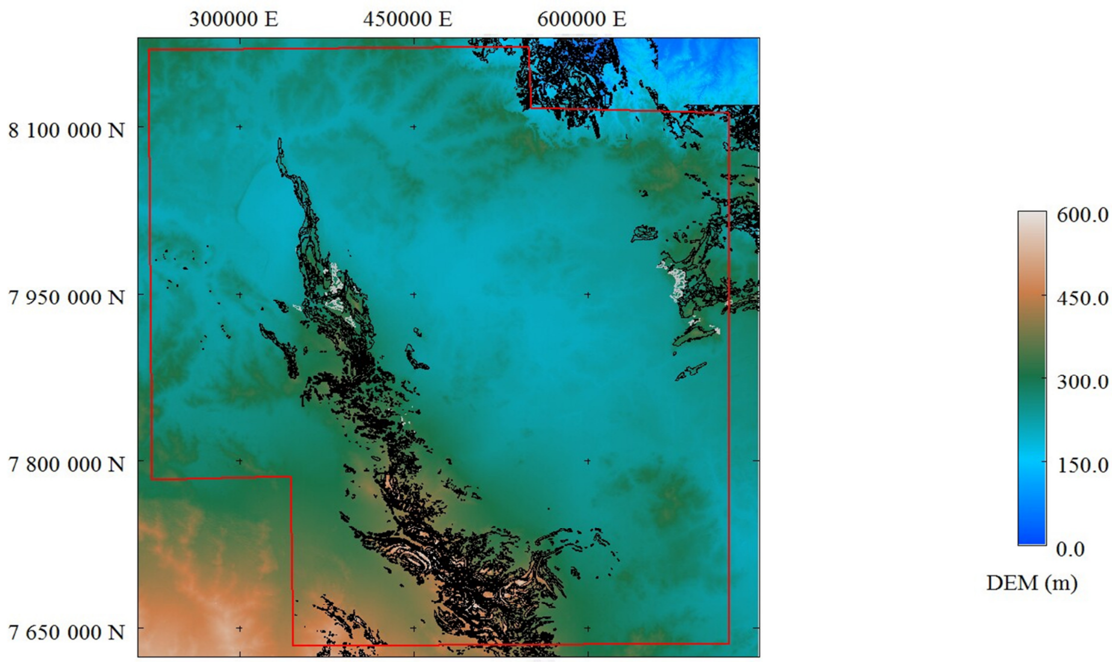

Figure 5: Topography with supplied outlines of outcrops of basement (black) and Cambrian volcanics (grey). The red polygon depicts the area of interest for modelling.

3. Methodology

The objective of this project to produce a regional basement model for the project area using potential fields inversion techniques that is consistent with the available constraints (drilling and outcrop).

Modelling assumed a two layered model comprising a cover sequence overlying basement. The basement unit comprises the Precambrian Basement and overlying Cambrian Volcanics. The cover unit was assumed magnetically inert comprising consolidated sediments and potentially carbonates. Given that cover represents a lower density or susceptibility than basement, the premise for this basement style of inversion is that increased gravity or magnetic response is associated with shallower basement.

The VPmg program (Fullagar et al., 2000, 2004, 2007, 2008) was used in this project for potential field modelling and inversion. The VPmg model parameterization lends itself to a variety of inversion options; in particular, it allows adjustment of model geometry (e.g. depth to basement) as well as density or susceptibility properties and is well suited to constrained inversion (see Appendix 2 for additional software details). A key feature of VPmg for this project was its ability to adjust depth to basement through inversion subject to geological constraints (e.g. outcrop and drill hole constraints).

Compilation of all relevant data into a 3D GIS package expedites integrated interpretation. The Gocad Mining Suite served as data repository, and platform for running the inversions (including data preparation, starting model construction, imposition of constraints, and assessment of results).

In overview, there were 4 key phases for this project:

1. Data compilation and assessment
2. Initial 3D basement starting model construction (including implementation of aeromagnetic depth to source algorithms)
3. Gravity and magnetics forward modeling and inversion
4. Interpretation and reporting.

The data compilation has been described in Section 2 and the remaining components of work are described in the following sections.

3.1. VPmg starting model construction

In a VPmg model, the Earth is divided into tightly packed vertical prisms (elongated cells). The tops of the prisms are coincident with the topography and geological boundaries (e.g. the basement) subdivide the vertical prisms (e.g. see Figure 6).

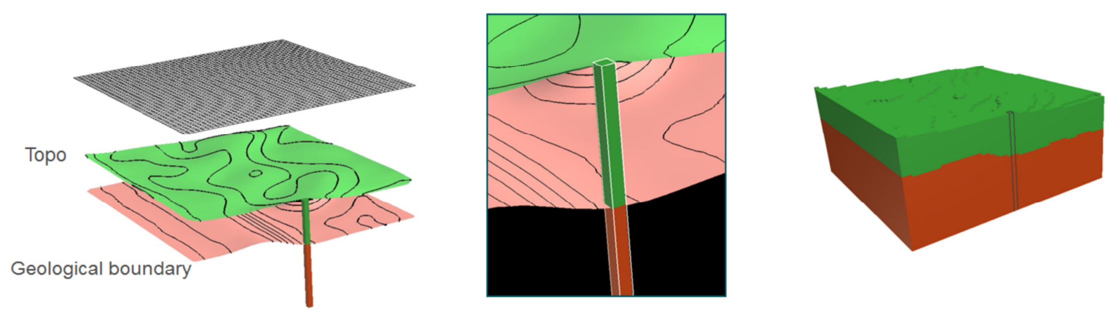

Figure 6: Schematic illustration of the VPmg basement model parameterisation; in horizontal section the model is divided into a regular array of tightly packed vertical prisms (left), each single prism is divided into 'cells' by geological boundaries (centre), the collection of prisms defines a solid 3D geological model (right).

To create a basement starting model for VPmg requires construction of a topography and basement surface in 3D. The basement starting model surface was created from drill hole markers and outcrop data. The starting model basement surface was set to topography within the provided regions of basement and Cambrian Volcanics outcrop. Given limited spatial coverage of drill hole constraints, the construction of the starting model relied upon depth to magnetic source estimated from Euler deconvolution of aeromagnetic data.

The starting model surfaces were construction in Gocad Mining Suite and exported to VPmg model file format at 4km x 4km resolution. The VPmg starting model encompasses an area of 516km x 548 km.

The starting model assumed a basement density of 2.7 g/cc, cover density of 2.4 g/cc, basement magnetic susceptibility of 0.02 SI, and a cover magnetic susceptibility of 0 SI.

3.1. Euler Deconvolution – aeromagnetic depth to source estimation

The Euler Deconvolution method (e.g. Reid et al, 1990) was implemented as an approach for estimating depth to source. This method computes the location of a magnetic source from a 2D window of data extracted from a TMI grid (for a specified source type or structural index, e.g. pipe, dyke, contact, etc.). The 2D window moves across the entire grid until the entire area is processed. Many depth estimates are produced by this approach and solutions are typically selected based on clustering, numerical confidence (returned from the algorithm), as well as where the solution was positioned with respect to the extracted window of data.

The output of the method is dependent on the selected structural index and window size of data extracted from the grid. Accordingly, ambiguity exists and depth information from the Euler Deconvolution method remains subject to interpretation,

Initial Euler deconvolution depth to source estimation focussed on the areas where drilling data indicated top of volcanics and basement contacts to investigate optimum parameters. The entire model was divided into quarters so that Euler deconvolution could be performed on the whole dataset efficiently.

3.2. VPmg Forward modeling and inversions

Forward modelling is implemented initially to compute the gravity and magnetic response of the starting model. If the starting model does not produce a response that corresponds to the observed data, the model is updated via VPmg gravity and magnetic inversion (subject to geological constraints) to achieve a better fit to the measured data. In this project, the depth, density and magnetic susceptibility of the basement in the model have been adjusted through inversion (cover density and susceptibility remained constant).

For gravity modelling, the assumption was made that the cover was consolidated sediments (0.3g/cc less than the starting model basement density). With these starting model conditions, and the assumption of constant density cover, if carbonate reefs were present in the cover sequence, they would manifest in the model as anomalous zones of increased density or basement elevation highs.

During geometry inversion, depth to basement is constrained where intersected by drill hole pierce points (for Precambrian basement and Cambrian Volcanics), and regions of known outcropping basement are be fixed. By default, VPmg imposes a radius of influence to restrict changes to the model in the vicinity of drill holes constraints.

During property inversion, lateral basement density and susceptibility variations are permitted (i.e. each elongated prism or cell defining the basement unit could acquire its own density or susceptibility values). In this sense, a horizontal section through these prisms defines a map of density or susceptibility variations in the basement. Full 3D density and susceptibility inversion in selected model domains could be considered, but at this scale, provides no immediate benefit to the outcome of this project.

How to best integrate the two styles of inversion (geometry or property) in view of the available constraints is part of the interpretation process, often a variety of inversion options are explored to assess the non-uniqueness of the interpretation problem.

3.3. Data preparation for VPmg inversion

3.3.1. Gravity

An initial investigation was undertaken to assess the located gravity data, and the ability to use it directly for modelling. The first part of this assessment was a check on the positioning of the data relative to the SRTM. The difference in height from topography varied over the many gravity datasets; gravity stations ranged between 70m below and above topography.

Addressing these discrepancies rigorously would require assessing the data on a survey by survey basis and often making subjective decisions about the integrity of individual gravity stations or surveys. Reconciliation of these discrepancies would be a time consuming process. Given the regional nature of this first-pass interpretation and that GA have already prepared a gridded representation of Bouguer gravity response, this data was assumed an acceptable representation of terrain corrected data for this first-pass regional interpretation. If in the future, the focus is on sub areas at a higher resolution, the integrity of located gravity data in the sub-areas will be reconsidered.

Using the GA gravity, preparation of the gravity data for inversion simply involved:

- Resampling the gravity data to the 4km resolution of the model for inversion
- Positioning of the resampled magnetic data at 1m above topography.

3.3.2. Magnetics

Preparation of the aeromagnetics data for inversion involved:

- 2000m upward continuation of the GA TMI magnetic data,
- Resampling for the upward continued data to the 4km resolution of the model for inversion
- Positioning of the resampled magnetic data at 2080m above topography, i.e. the average flight height (80m) plus the upward continuation distance of 2000m.

The upward continuation distance of 2000m was chosen so that the simulated measurement altitude represents ~1/2 of the highest resolution model cell size above topography.

Magnetic field parameters used for inversion were inclination= -49.4°, declination=4.8° and amplitude 50206 nT.

4. Results

The results for the magnetic and gravity inversions are described in turn below. The outputs of VPmg inversion are magnetic susceptibility and density models that explicitly define the basement contact. The basement contact in this case is common to both models. The computed responses of the inverted models are illustrated in this section for comparison with the observed data.

While illustrations are included here to convey the modelling results, it is recommended that the reader specifically review the accompanying digital inversion deliverables (Appendix 1).

4.1. Starting Model

Construction of the starting model incorporating provided geological constraints and magnetic depth to source estimates was completed in Gocad Mining Suite. The first step involved computation of the depth to source estimates using Euler deconvolution. Assessment of the solutions revealed that the absolute depths of the solutions were generally over-estimated when compared to drill hole basement intersections.

This was accepted given that depth estimates are approximate and use gross generalisation across the entire area. Furthermore, the resolution of the input data (90m) was at the limit of being able to accurately resolve shallow sources. The relative variations in the depth to source results nonetheless exhibited plausible consistency with overall basin structure. Accordingly, the entire set of depths of the Euler solutions were calibrated using the drill hole data. A basement surface was then created from these points. The created surface was updated to fit through the drill hole constraints and outcrop to provide the starting model basement topography (Figure 7). The Euler deconvolution depth to source estimates used in starting model construction are included in the digital deliverables (Appendix 1).

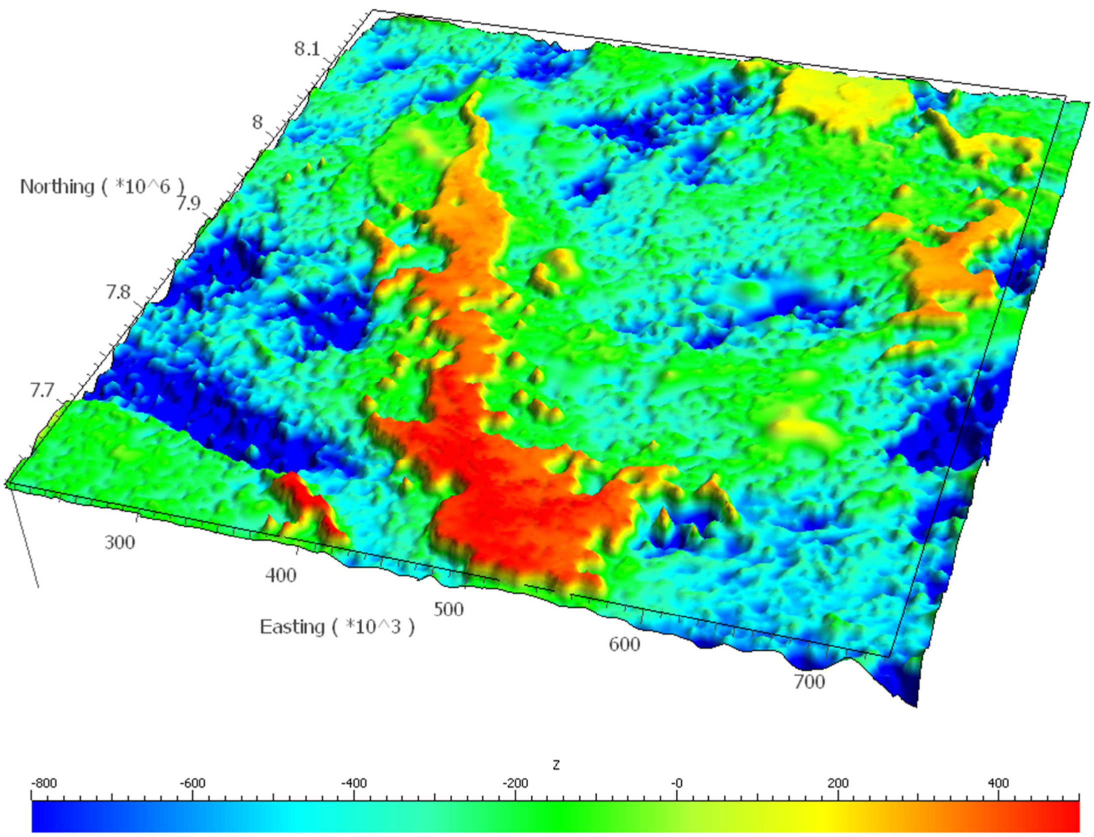

Figure 7: 3D perspective view of the starting model depth to basement (before export to VPmg format) coloured by elevation (15x vertical exaggeration).

4.2. Forward modelling

Forward modelling was performed on the starting model to assess the gravity and magnetic response of the derived basement topography (assuming a homogeneous basement property). For gravity, the starting model was assigned with a basement density of 2.7g/cc, a cover density of 2.4g/cc and then its gravity response was computed. The observed and calculated gravity response before inversion is shown in Figure 8 (on the same colour stretch for comparison).

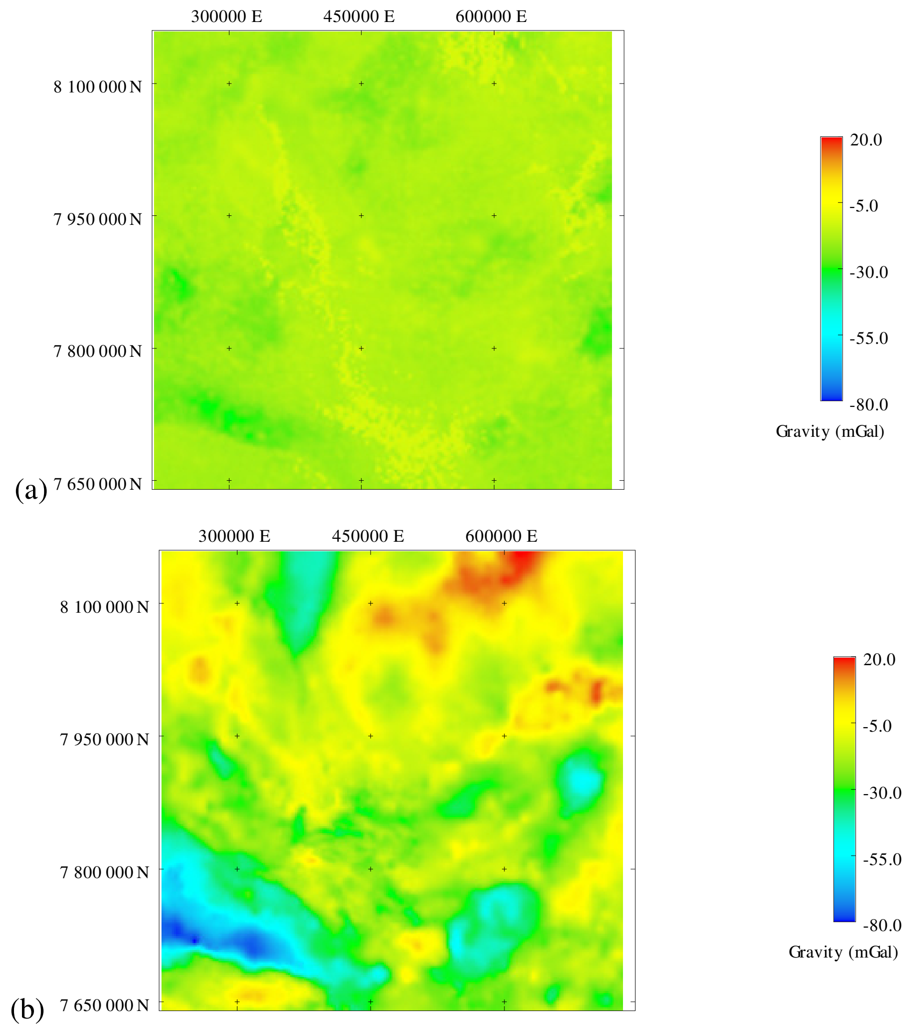

Figure 8 Image of the forward modelled starting model gravity response (a) and the observed data (b).

The calculated response is muted compared to the observed data implying that the majority of the gravity response is associated with basement domains of different density rather than the inferred basement topography. The RMS misfit between the observed and computed gravity for the starting model is 14.5 mGal.

For magnetics, the magnetic starting basement model was assigned a basement magnetic susceptibility of 0.02 SI and 0 SI for the cover and then its TMI response was computed (at the 2000m upward continued simulated observations). The observed and calculated TMI response before inversion is shown in Figure 9 (on the same colour stretch for comparison).

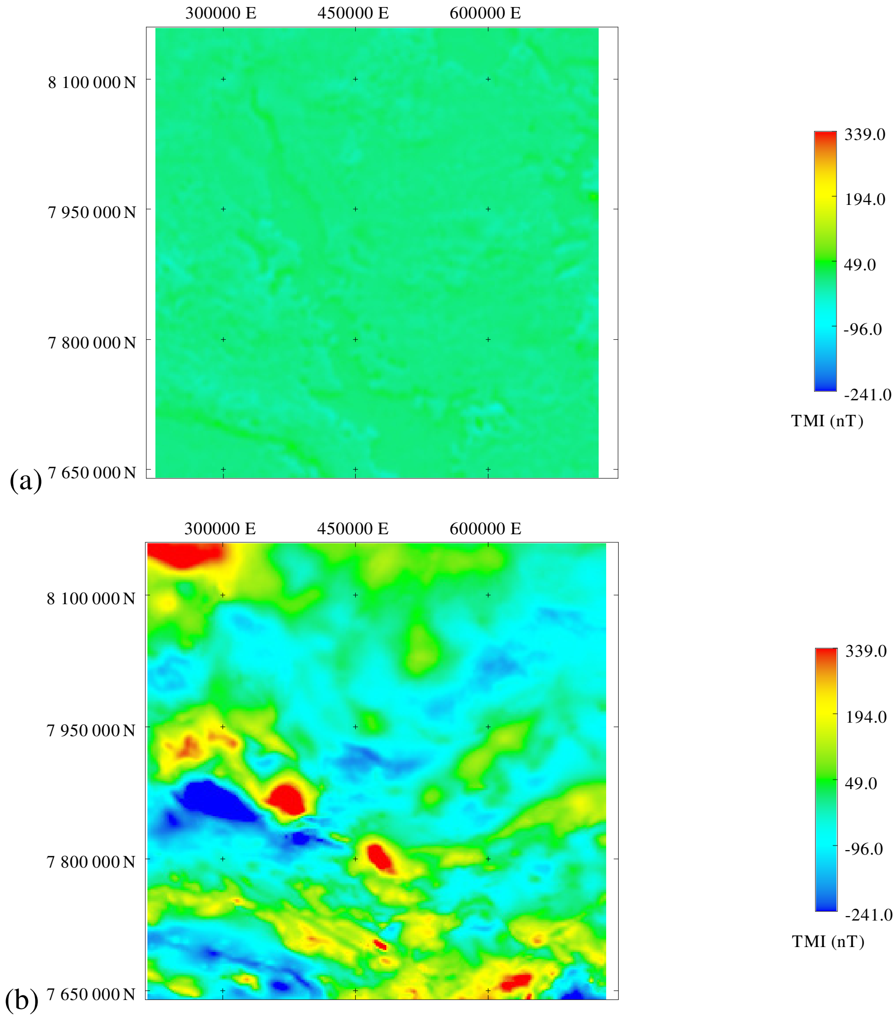

Figure 9: Image of the 2000m upward continued computed TMI response of the starting model (a) and the 2000m upward continued observed (b) data.

As for the gravity data, the calculated TMI response is muted compared to the observed data also implying that the majority of the magnetic response is associated with basement domains of different magnetic susceptibility rather than basement topography. The RMS misfit between the observed and computed TMI for the starting model is 111.2 nT.

This exercise corroborates that inversion needs to permit density and magnetic susceptibility variations in the basement to reconcile the potential field survey data.

4.3. VPmg inversion results

In order to produce a model with an improved fit to the potential field survey data, VPmg geometry inversion adjusted the starting model basement topography (subject to drill hole constraints), while VPmg property inversion adjust the density or susceptibility variation beneath the basement.

An integrated approach was adopting using both gravity and magnetics data to converge to a common basement representation. Key quantities (basement depth, density and susceptibility) can be extracted from these models and represented as maps. Of particular importance to this project is the final depth to basement map illustrated in Figure 10.

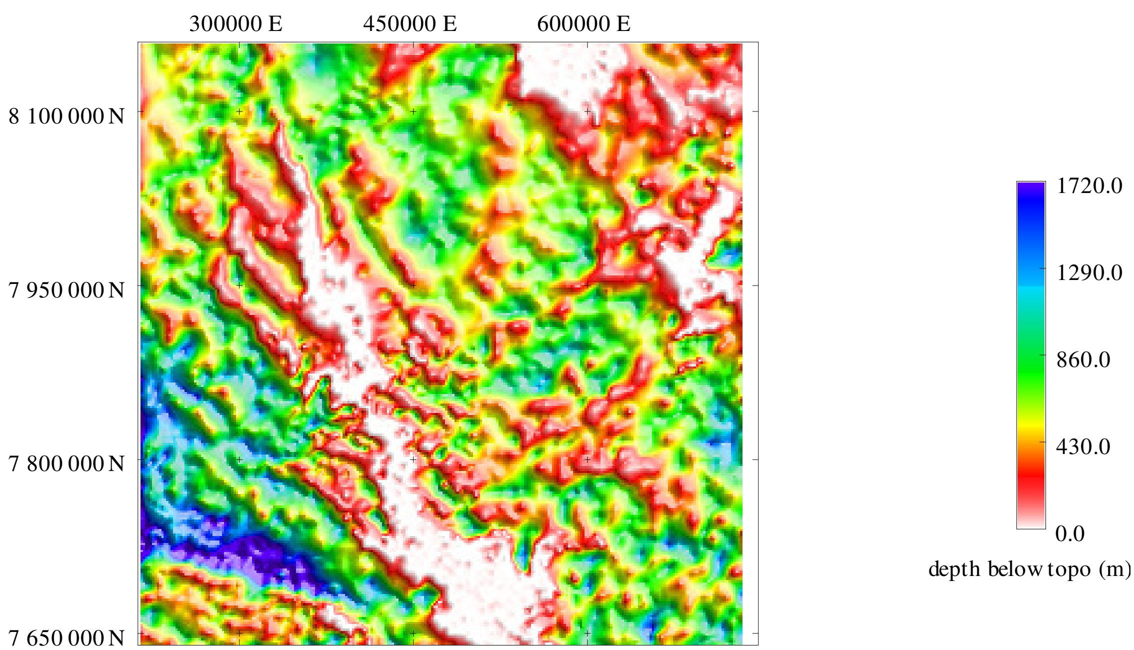

Figure 10: Sun-shaded depth of basement (from topography) after inversion.

The computed difference in elevation between the starting model basement representation and the inverted basement representation (Figure 11) explicitly defines where the potential field inversion has adjusted the basement to be shallower (positive change in depth). This represents areas where the starting model basement contact originally defined by aeromagnetic depth to source needs to be shallower (i.e. notionally in association with a density deficit). Such occurrences may be symptomatic of situations where denser carbonate reef may exist in the cover sequence.

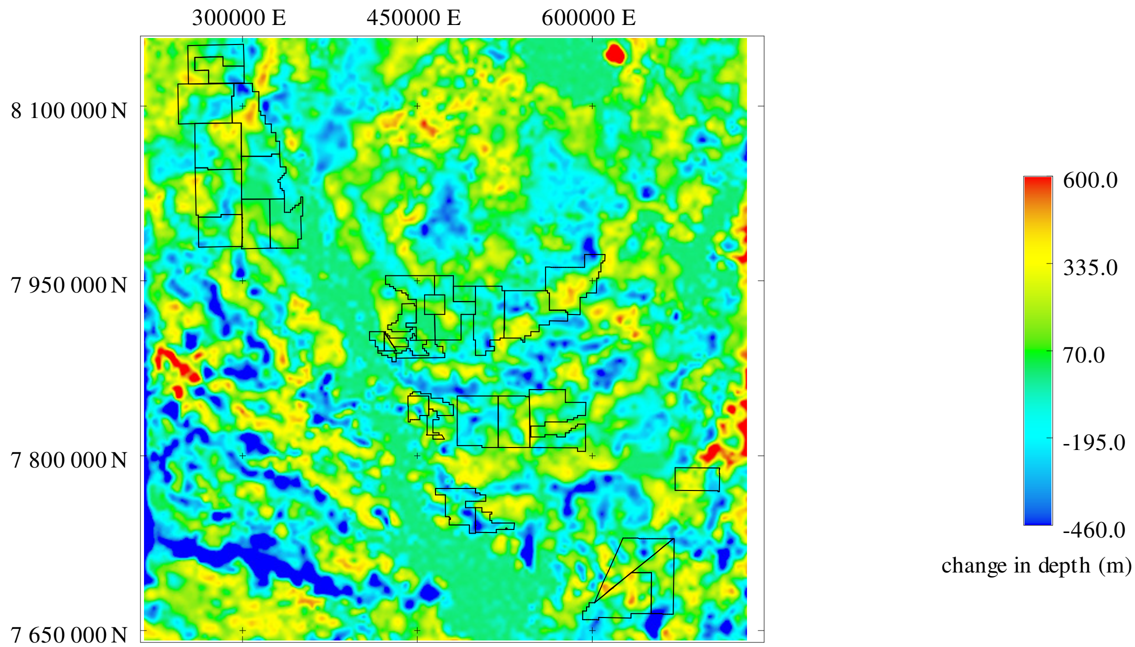

Figure 11: The change in depth of basement from the starting model to the final model with tenements superimposed. A positive change in depth implies that the basement is shallower than the starting model (and vice versa).

Grids of inverted geophysical basement density and susceptibility respectively are shown in Figures 12 and 13 below. Basement depth, change in depth, density and magnetic susceptibility are provided as geosoft grids for detailed assessment.

From the perspective of identifying or targeting middle Cambrian carbonate reefs in the cover sequence, the following criteria may be considered; 1) shallow basement, 2) decrease in basement elevation with respect to the starting model, and/or 3) density increases in the basement. The role of magnetic basement domains in identification of areas containing carbonate reefs remains subject to interpretation by Vale.

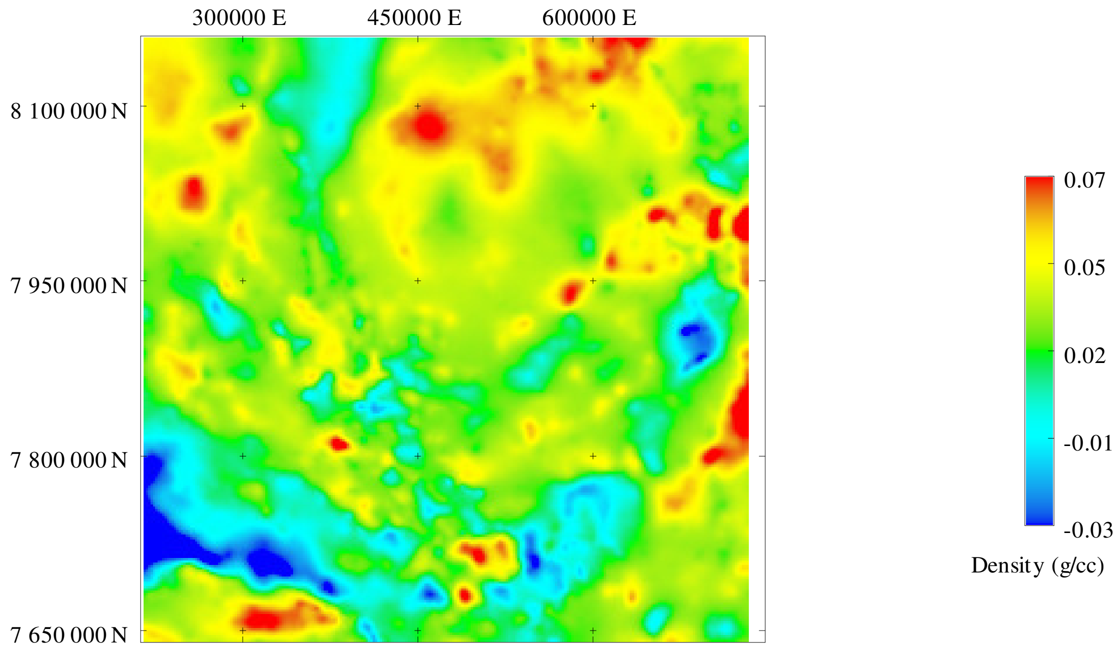

Figure 12: Inverted basement density (w.r.t 2.67g/cc).

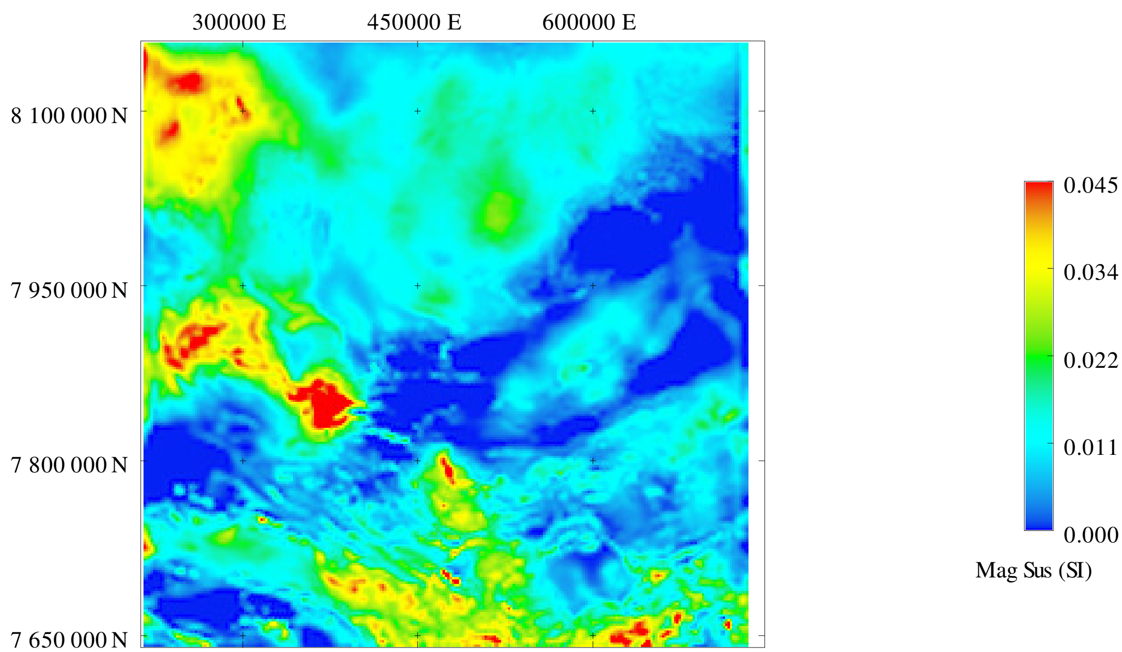

Figure 13: Inverted basement magnetic susceptibility (SI).

In terms of final data fit, Figure 14 illustrates the gravity response computed from the inverted model which has a good fit with the observed data. This final model achieved a 0.7mGal RMS data misfit with the observed gravity data.

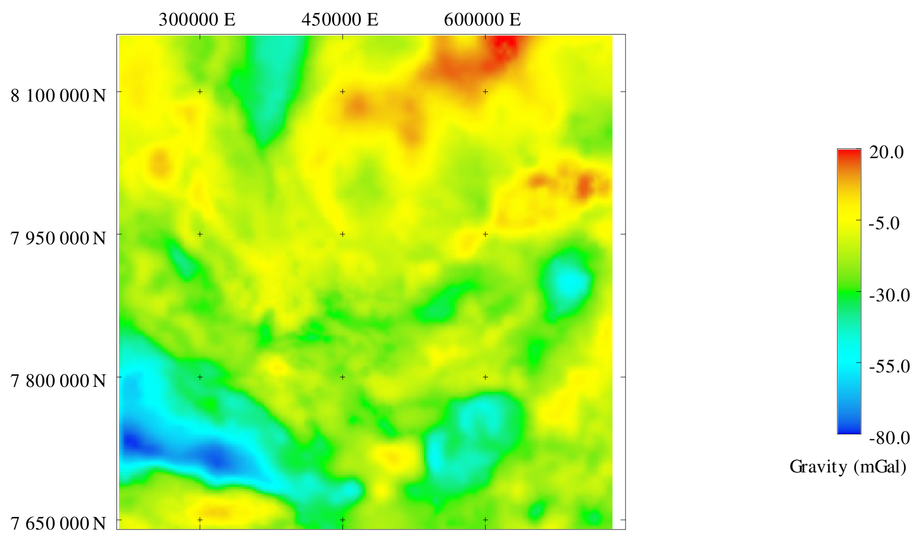

Figure 14: Calculated gravity after inversion, for comparison with the observed data (Figure 8 a)

Figure 15 illustrates the TMI response computed from the inverted model. The final basement model reproduced the magnetic data to within 8.3 nT RMS.

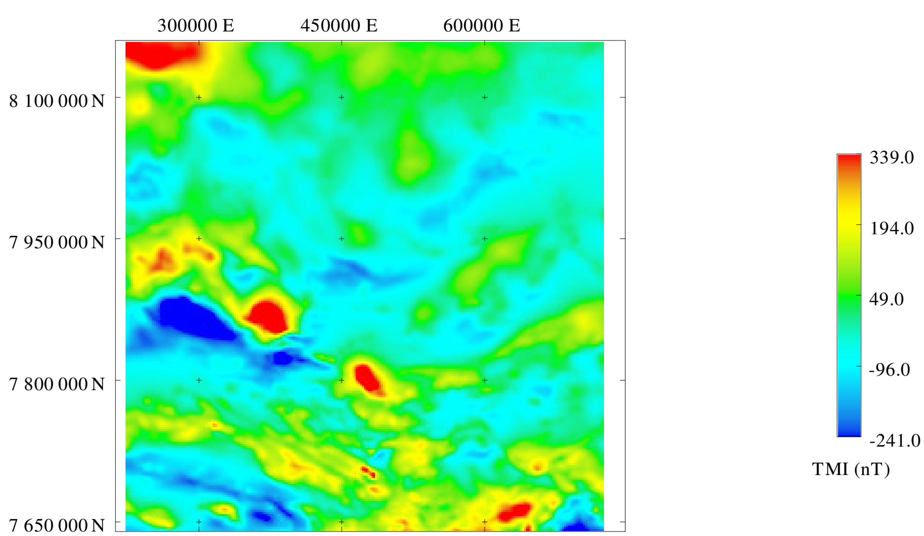

Figure 15: Calculated TMI after inversion, for comparison with the observed data (Figure 9a)

5. Conclusions

Potential field modelling using the VPmg software has been undertaken as part of this project to produce a regional-scale depth to geophysical basement model for the Georgina basin project area. The final model fits the gravity data to within 0.7mgal RMS and the magnetics data to within 8nT RMS.

Interpretation of potential field data is non-unique and this project has benefited from an integrated approach. In particular, the derived basement models for both gravity and magnetics share a common depth to basement interpretation consistent with the geological constraints (drill hole pierce points and outcrop).

Key products derived from the inverted 3D model include:

- A depth to basement map.
- Basement density map
- Basement susceptibility map

The final model has identified regions of basement highs or ridges coincident with increases in density. Since the cover unit was held fixed during inversion, these model features could by symptomatic of the presence of middle Cambrian carbonates deposited adjacent to, or on top of basement topographic highs and warrant further investigation. The role of basement magnetic susceptibility in targeting carbonate reefs remains subject to interpretation by Vale.

Additionally, as discussed with Vale during the course of this project, option exists for investigating different inversion scenarios, for example, inverting for cover density to directly identify carbonate reefs. To do this as unambiguously as possible requires additional control on basement depth and on the density of underlying basement domains. As an alternative line of investigation, gravity forward modelling could be implemented on conceptual models of carbonate reefs to directly assess their detectability.

While due care has been taken to generate models consistent with all available geological constraints it is important to recognise that even when a constrained approach is adopted, there are many models which could explain the project magnetic and gravity data. Accordingly, the inversion results should therefore be regarded as a first-pass interpretation and as a starting point for future refinement.

6. Recommendations

The first step is to review the derived results. The inverted model represents a regional geological hypothesis that needs to be assessed and validated in terms of other geological interpretations and drilling.

Scope exists for refining the regional interpretation by explicitly incorporating additional control on the basement as it becomes available, e.g. additional drill hole pierce points, seismic, incorporation of different basement rock types attributed with appropriate density or susceptibility values.

Ideally, as opposed to pursuing refinements to the model at a regional scale, the regional model should be used to identify areas of interest and move towards a more detailed study. Factors affecting the choice of sub areas of interest include:

- Prospectivity – identifying areas potentially indicative of carbonate reefs (e.g. coincident basement ridges and density highs).
- Availability of constraining data in particular areas (or a plan to collect constraining data in areas of interest).
- Existence of high resolution gravity data to support a more detailed interpretation.

After subareas of interest are established, the derived regional model still plays a role for future smaller scale interpretations. A 'local' model at higher resolution (perhaps incorporating a more complex geological model) can be incised into this regional model. Inversion can then be applied to the higher resolution model (subject to additional geological constraints) while explicitly accounting for the surrounding regional model density or susceptibility variations. The VPmg inversion software used for this project is able to explicitly combine regional and local modelling.

When considering a higher resolution study, a more complex model could be adopted incorporating additional geological domains, e.g. transported cover, carbonate reefs or different specific basement formations. This strategy will benefit from continued compilation of geological and physical rock property constraints for local lithologies.

References

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Reid et al., 1990, Magnetic Interpretation in three dimensions using Euler deconvolution. Geophysics, vol 55 No. 1, p80-91.

Appendix 1: List of deliverable files

All model files are returned in the GDA94 Zone53 co-ordinate system.

Geosoft Grids

- Geosoft grids for inverted basement density, magnetic susceptibility, depth and change in depth as represented in the report are included as .grd files.

XYZ file

- Depth to source estimates used in the construction of the starting model basement surface are provided as a .csv file

Appendix 2: VPmg Software

VPmg is a gravity, gravity gradient, magnetic, and magnetic gradient 3D modelling and inversion program developed by Fullagar Geophysics Pty Ltd (Fullagar et al, 2000; 2004; Fullagar & Pears, 2007; Fullagar et al, 2008).

In VPmg, the models are geological (categorical) insofar as each volume of the subsurface is assigned to a rock unit. The shape and property (density or susceptibility) of each unit can change during inversion, but its geological (or topological) identity is preserved. Geological contacts can be fixed (where pierced by a drill hole for example), bounded, or free to move during inversion. Bounds can be imposed on each unit's properties, and density or susceptibility measurements (on drill core samples or from downhole logs) are honoured during property inversion.

VPmg represents the sub-surface as a set of tightly-packed vertical rectangular prisms, which in plan view appear as a regular mesh or grid. Prism tops honour surface topography, and in its simplest form, internal contacts representing geological boundaries divide each prism into (usually elongated) cells. The vertical dimension of cells is arbitrary, implying that the vertical position of the geological boundaries is not "quantised" by vertical discretisation. The internal contacts represent geological boundaries that collectively define the shape of geological units. The geological units can either be homogeneous, i.e. uniform in density or susceptibility, or fully heterogeneous. When considering property inversion, a geological unit can be discretised in different ways. In the first instance, the property of each vertical prism segment of a geological unit can be allowed to vary independently, thereby introducing a lateral property variation within the unit. Full 3D property variation is achieved by introducing vertical sub-celling within the selected units.

VPmg offers considerable flexibility during interpretation. The model complexity ranges from conventional (uniform density) terrain models, to discrete bodies in a uniform background, to layered stratigraphy on basement, to complex 3D models. Regional effects can be handled by constructing a regional model, based on a relatively large rectangular mesh. The regional model is in turn embedded in a uniform half-space. A local model, comprised of smaller prisms, can be embedded in a regional model. The local model parameters can be adjusted by inversion until the gravity, gravity gradient, TMI, or magnetic gradient data within the local model area are satisfied.

VPmg offers a variety of inversion styles: homogeneous unit property, contact geometry, and heterogeneous property. During property inversion, model contacts (geometry) are fixed. During contact geometry inversion, geological boundaries are altered while physical properties remain fixed. The user is able to easily switch from one inversion style to another.

Gocad Mining Suite utilities developed by Mira Geoscience facilitate communication of model and data information to and from VPmg, and expedite assignment of drill hole constraints.