Integrating gravity, seismic, AEM and MT data to investigate crustal architecture and cover thickness: modelling new geophysical data from the Southern Thomson region

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SUMMARY

New geophysical data, including gravity, airborne electromagnetic (AEM), and both audio frequency and broadband magnetotelluric (AMT, BBMT) were collected along a series of traverses in the southern Thomson Orogen region of north-western New South Wales and southwestern Queensland in 2014 as part of the Southern Thomson Project. Comparing and integrating these data over the same spatial extents aimed to provide a better understanding of the crustal architecture of this region, and help estimate cover thicknesses above basement rocks. When comparing all available datasets, AEM cannot be reliably used when cover thickness is > ~150 m because of limitations in Depth of Investigation (DOI), and BBMT tends to overestimate cover thickness where it is less than 50 m. AMT likely provides the best resolution for estimating cover thicknesses of 0-1000 m on this regional scale. Forward modelling of the gravity data along selected traverses tested the interpreted crustal architecture and cover thicknesses inferred from available seismic images and the new AEM and MT conductivity models. The variable cover thicknesses interpreted from this combined approach produces a closer match with the observed gravity response when compared to a uniform, average cover thickness. The most accurate crustal-scale forward model is a thickened crust north of the Olepoloko Fault (the proposed southern boundary of the southern Thomson), split into simplified lower, middle and upper layers with basement lithologies immediately beneath cover based on the most recent basement interpretation map. Resistive bodies shown in the MT models were included in the gravity modelling, producing a good match between the observed and calculated gravity responses. These results demonstrate the utility in using a combination of different geophysical techniques to understand crustal architecture and estimations of basement depths in regions of Australia with little surface outcrop and thick cover sequences.

Key words: Thomson; gravity; MT; AEM; UNCOVER

INTRODUCTION

Scope

The UNCOVER Initiative (Australian Academy of Science, 2012) recognises that near-surface mineral resources are becoming increasingly difficult to discover due to the often substantial thickness of near-surface highly-weathered bedrock and sedimentary basin material covering ~80% of the Australian landmass (Roach *et al.,* 2016). There are four themes of the UNCOVER initiative:

1. Characterising Australia's cover
2. Investigating Australia's lithospheric architecture
3. Resolving the 4D geodynamic and metallogenic evolution of Australia
4. Characterising and detecting distal footprints of mineralisation

The Southern Thomson Orogen has been identified as one of the primary focus areas for the UNCOVER Initiative at Geoscience Australia (GA). The geology of this region in northern New South Wales (NSW) and Southern Queensland is poorly understood. Basement geology is poorly exposed and there are generally many tens to a few hundred metres of overlying unconsolidated or indurated Cenozoic and Mesozoic cover largely consisting of Eromanga Basin rocks.

The Southern Thomson Project is a joint venture between Geoscience Australia (GA), the Geological Survey of New South Wales (GSNSW) and the Geological Survey of Queensland (GSQ). The Project aims to collect new geophysical, geological, geochemical and geochronological data to promote mineral exploration in the region by reducing exploration risk. The data collation will lead to the identification of sites where new stratigraphic drilling will provide answers to scientific problems regarding the assembly of the Tasmanides, the age of the Thomson Orogen compared to the adjoining Lachlan Orogen and the potential mineral systems that may occur within the southern Thomson Orogen.

Geological Background

The southern Thomson Orogen in Queensland and northwestern New South Wales has remained an enigma in regards to its large-scale crustal architecture, due to the lack of available basement outcrops coupled with thick overlying cover sequences. Much of the interpretation of the geology has come from interpretation of aeromagnetic and gravity images of Northern NSW and southern Queensland and limited geological information from oil wells and water bores. This imagery shows that there is an east-west trending gravity ridge in northern NSW (the 'east-west zone'; see figure 2 in Glen *et al.,* 2013) that possesses a distinct geophysical character from the north-northwest trends in rocks commonly observed further south in the Lachlan Orogen. This east-west zone is thought to represent the southern margin of a different terrane, the southern portion of the Thomson Orogen.

Based on this model, various authors (e.g. Fergusson and Henderson, 2013; Glen *et al.*, 2013) identified differences between these two regions prior to the mid-Silurian (~430 Ma), when they were proposed to have had different histories. Evidence for this includes igneous rocks with different crystallisation ages and affinities between the two regions, and seismic reflection data suggesting different crustal thicknesses with markedly different structures and layering to the north and south of the Olepoloko Fault (the proposed boundary between the two orogens). It is generally agreed that after the mid-Silurian these two regions have a shared history.

Conversely, other authors have suggested that the Southern Thomson Orogen is in fact an extension of the Lachlan Orogen that persists at least 500 km further north into Queensland (e.g. Murray, 1986; Burton, 2010). The evidence cited for this includes a similarity in magnetic and gravity data to the north and south of the Olepoloko Fault and the east-west zone, and a similarity in other ages between rocks in the Lachlan Orogen and further north into central Queensland.

This work aimed to further understand the nature of the crust in the southern Thomson region across the Thomson-Lachlan orogen boundary, as well as help constrain the large-scale variations in cover thickness/depth to basement via integration of new gravity, airborne electromagnetic (AEM) and magnetotelluric (MT) data as well as available seismic and drill hole data.

METHODS

The new geophysical datasets (gravity, AEM and MT) were collected along two primary traverses during an acquisition campaign in 2014 (Figure 1). The two traverses were:

- Line 3: a ‘western’ line running north from Tilpa (NSW) to the Queensland border at Hungerford and continuing north to Eulo (also known as the Thomson North-South AEM Traverse of Roach, 2015);
- Line 1: an ‘eastern’ line starting east of Byrock (NSW) that runs north to Brewarrina, NW to the Queensland border at Barringun, then continues north-west towards Thargomindah (also known as the Thomson East-West AEM Traverse; Roach, 2015).

Additional shorter traverses were also acquired, as depicted in Figure 1.

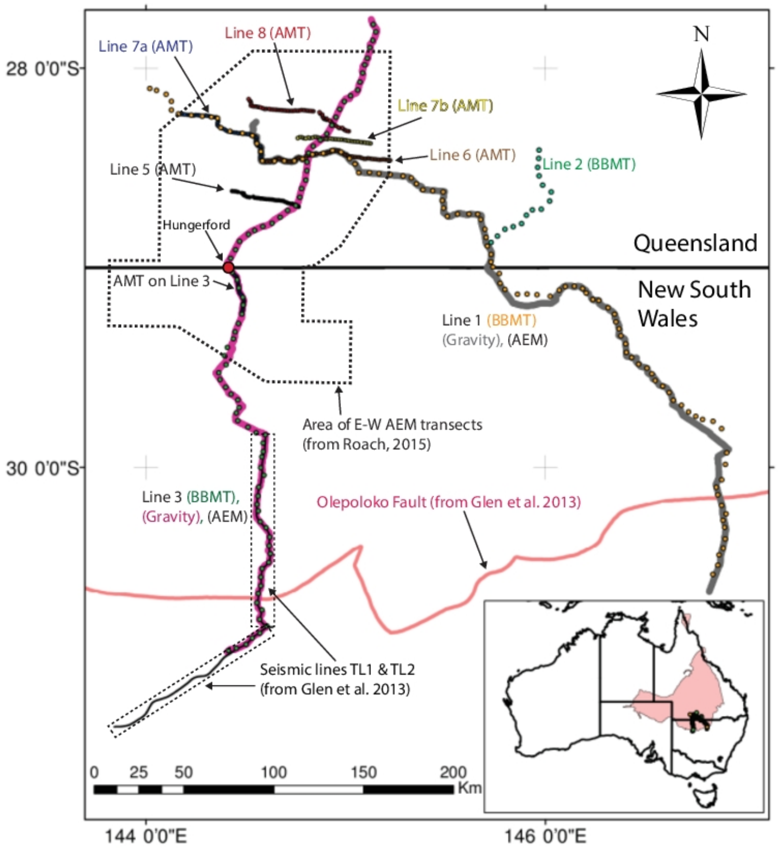

Figure 1: Gravity, AEM and MT datasets collected in 2014 for the Southern Thomson Project. The BBMT collected along Lines 1 and 3 mostly coincides with gravity data collected along these lines. Variations in station locations are due to land access issues. The thick red line denotes the location of Olepoloko Fault, suggested by Glen *et al.*, (2013) to be the boundary between the Lachlan and Thomson orogens. The inset figure shows the extent of the Thomson Orogen.

Broadband magnetotelluric (BBMT) data were collected along the two main survey lines, whilst audio magnetotelluric (AMT) data (higher frequency with finer resolution and useful for imaging the top few km of the crust), was collected along a small part of Line 3 as well as short lines that crossed Lines 1 and 3 (Figure 1). Nominal station spacing was 25 m for AEM (Roach, 2015), 1 km for AMT, 5 km for BBMT (Wang *et al.*, 2016) and 333 m for gravity.

These datasets have been integrated with seismic reflection data, the basement geology interpretation map of Purdy *et al.*, (2014), and the Great Artesian Basin Water Resources Assessment (GABWRA; Ransley and Smerdon, 2012) depth to basement estimates, in order to inform the construction of forward models to be tested with gravity modelling.

The complete Bouger anomaly was calculated at the gravity stations by adding the terrain correction to the spherical cap Bouger anomaly. These datasets were imported into ModelVision ver. 14.00.05 to perform the forward modelling. ModelVision allows the construction of different shaped polygons of varying densities and for these to be forward modelled against the observed gravity anomaly data with different inputs for the background density and regional gravity variations to be included.

Forward models were constructed using the comparison and integration of the models from the different geophysical methods described above. After the generation of forward models, inversions were run, allowing the densities of rock units and the regional gravity field to vary. The ‘StatWatch’ function in ModelVision provides a quantification of the match between the calculated (modelled) and the observed gravity responses using two metrics – 1) RMS (root mean-squared) normalised by data dynamic range (lower values indicate a better match); and 2) correlation coefficient, where a value closer to unity indicates a better match.

RESULTS

Comparison of cover thickness/depth to basement from different geophysical techniques

Figure 2 shows a comparison of AEM and BBMT conductivity sections along Line 3 (Western Transect), and Figure 3 shows a comparison of AEM and AMT conductivity sections along the combined Lines 6 and 7a. Blue and purple colours denote highly resistive lithologies (e.g. felsic igneous bodies), whilst orange and red colours indicate highly conductive lithologies (e.g. Mesozoic and Cenozoic sedimentary basin cover). The lines overlain on the BBMT and AMT conductivity sections are the depth to basement (DTB - i.e. cover thickness) taken from the GABWRA dataset (black lines) and augmented with the AEM interpretation (white lines) of Roach (2015). Different interpreted basement lithologies as inferred from interpretation of aeromagnetic data (Purdy *et al.,* 2014) are also shown at the base of Figures 2 and 3.

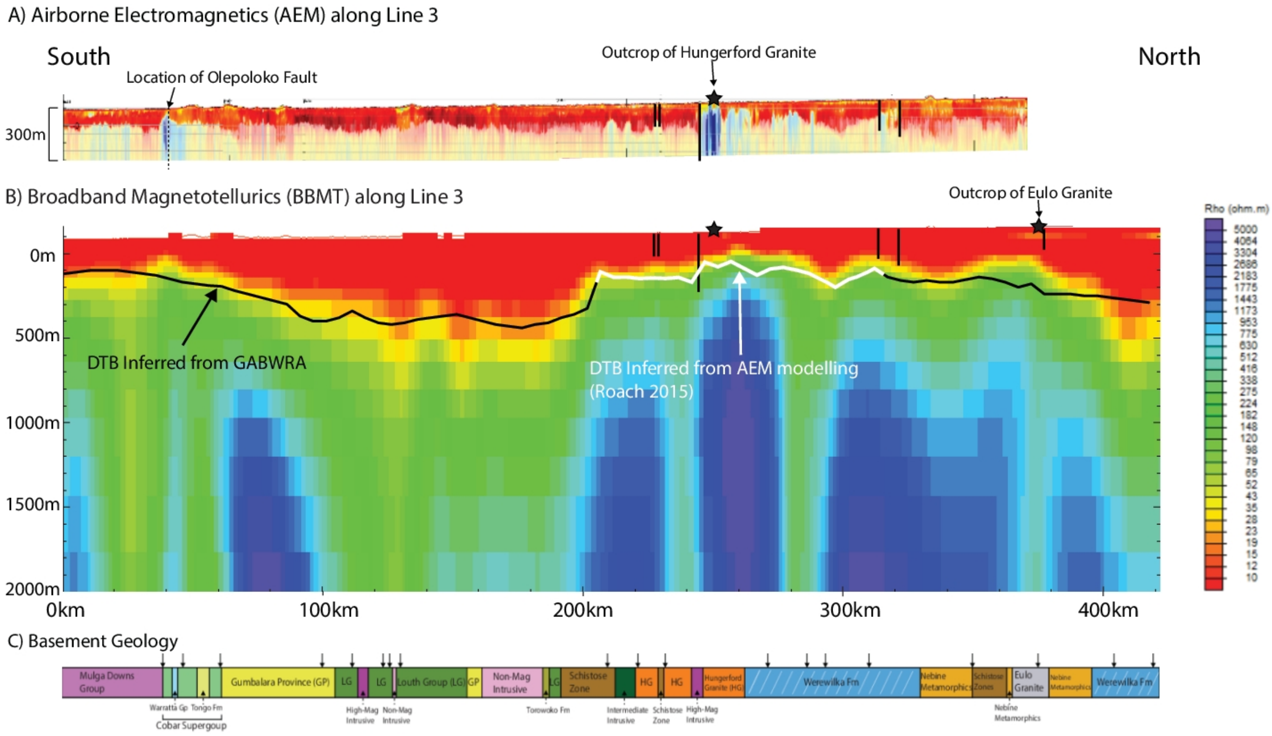

Figure 2: Comparison of A) AEM and B) BBMT conductivity sections along Line 3 (western transect). The black and white line at the base of the conductive region of the BBMT section refers to DTB estimates from the GABWRA model (Ransley and Smerdon, 2012) and the AEM interpretation of Roach (2015). Vertical black lines denote the maximum cover thickness estimation based on high-resolution ground geophysical surveys (Roach pers. comm. 2015). C) Interpretation of basement geology along Line 3 from Purdy *et al.*, (2014). Black arrows above the bottom strip denote the location of inferred faults.

Figure 2 shows there is generally a good agreement between the AEM and BBMT results regarding the relative variations and/or patterns of cover thickness. The cover thins where the dark blue/purple resistive bodies (presumably felsic intrusions) are close to the surface, or even outcrop directly (in the case of the Hungerford Granite). Cover thickness is estimated to be thicker (up to 600 m in the case of the BBMT conductivity section) in the area south of the Hungerford Granite outcrop(s) and north of the Olepoloko Fault. The DTB line from GABRA modelling and AEM interpretation matches well with the extent of the conductive cover from the BBMT modelling, both in absolute and relative depths between thin and thick areas of cover, although the wider station spacing of the BBMT data acquisition (~5 km) results in a coarse conductivity model derived from this method.

Figure 3 shows a comparison of the AMT conductivity section with the DTB estimates from the GABWRA dataset and AEM interpretation of Roach (2015) along lines 6 and 7a. The general patterns of cover thickness are similar between the datasets, most notably thinning of highly conductive cover towards the highly resistive body in the central part of the figure (presumably related to the outcrop of Granite Springs Granite - GSG), and thickening of cover to the margins of the section. The DTB inferred from AEM interpretation also shows a good correlation with the cover thickness estimated from the AMT conductivity section above the resistive GSG body. However, the DTB estimates from the GABWRA model are generally shallower than seen with the AMT conductivity section, and do not show any of the finer scale variations in cover thickness with the AMT method. A more detailed investigation into AMT for cover thickness assessments is given by Kemp *et al.,* (2016, this volume).

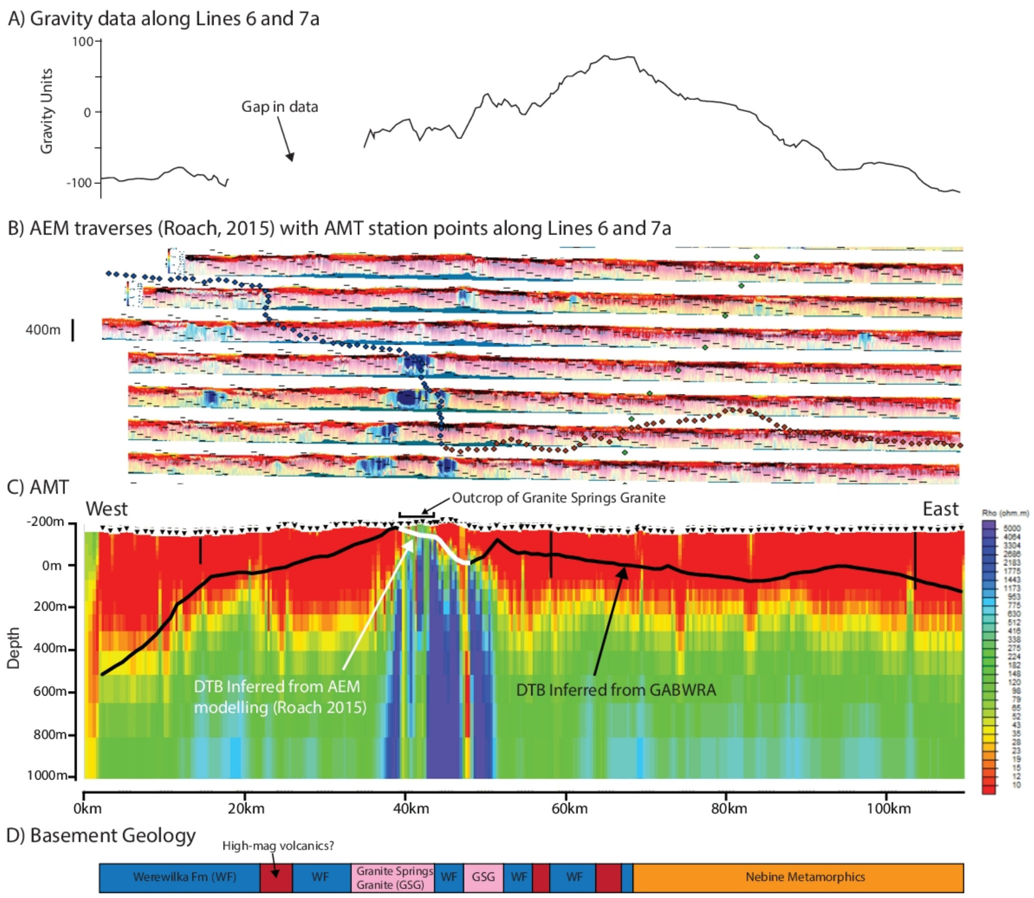

Figure 3: Comparison of A) Gravity data, B) AEM and C) AMT conductivity sections along Lines 6 and 7a. The black and white line at the base of the conductive region refers to DTB estimates as per figure 2. Vertical black lines denote the maximum cover thickness estimation based on high-resolution ground geophysical surveys (Roach pers. comm. 2015). D) Interpretation of basement geology along Lines 6 and 7 from Purdy *et al.*, (2014).

Forward Gravity Modelling

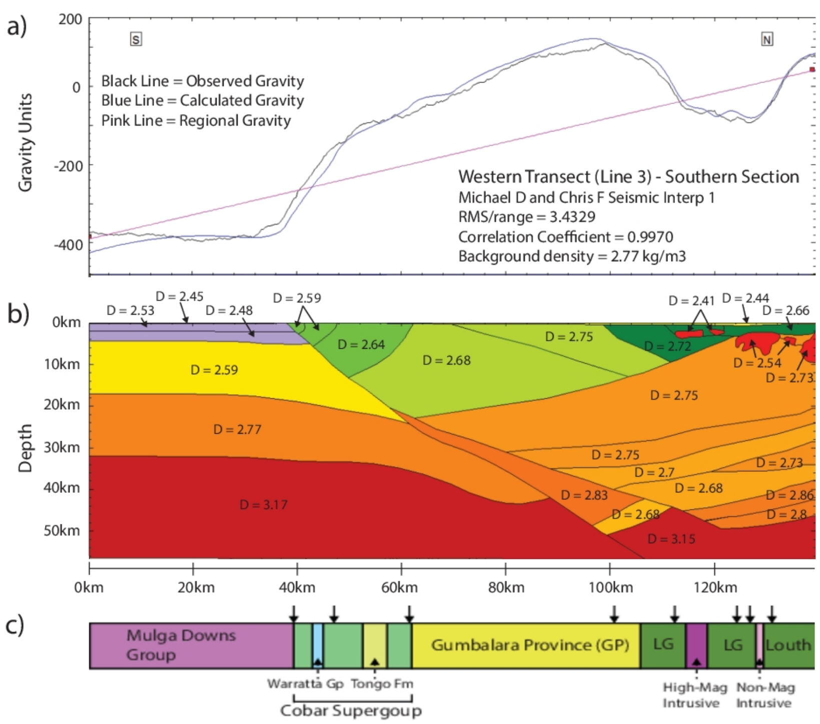

Figure 4: Gravity forward modelling along the southern section of Line 3; a) the results of forward gravity modelling; b) forward model based on seismic interpretation (densities for each unit are shown in g/cm^3); c) geological boundaries along Line 3 as interpreted by Purdy *et al.*, (2014).

The southern section of Line 3 was the only section that had an existing deep seismic reflection survey (Glen *et al.*, 2013), and therefore was the obvious choice for forward gravity modelling as the architecture is observed independently of the gravity data of the region. A new seismic interpretation of this section, coupled with the basement interpretation map of Purdy *et al.*, (2014), provided the basis for constructing a forward model (Figure 4). This forward model produced a gravity response that closely matches the observed gravity response, with the inversion process resulting in realistic densities for crustal units (Figure 4).

A number of forward models were generated with varying cover thicknesses (keeping all other variables constant). The model that produced the closest match with the observed gravity response was a variable cover thickness based on the highly conductive region of the BBMT conductivity section along Line 3 (Figure 5).

Finally, forward gravity modelling was performed along the whole of Lines 1 and 3. The BBMT conductivity sections were used to constrain the variable cover thicknesses and locations of major igneous intrusions (highly resistive areas in the models). The forward model that produced the closest match with the observed gravity response was a thickened crust north of the Olepoloko Fault with a simplified structure split into lower, middle and upper layers. These layers were overlain by lithologies taken from the basement interpretation map of Purdy *et al.*, (2014) and the overlying cover sediments with varying thicknesses according to the MT models.

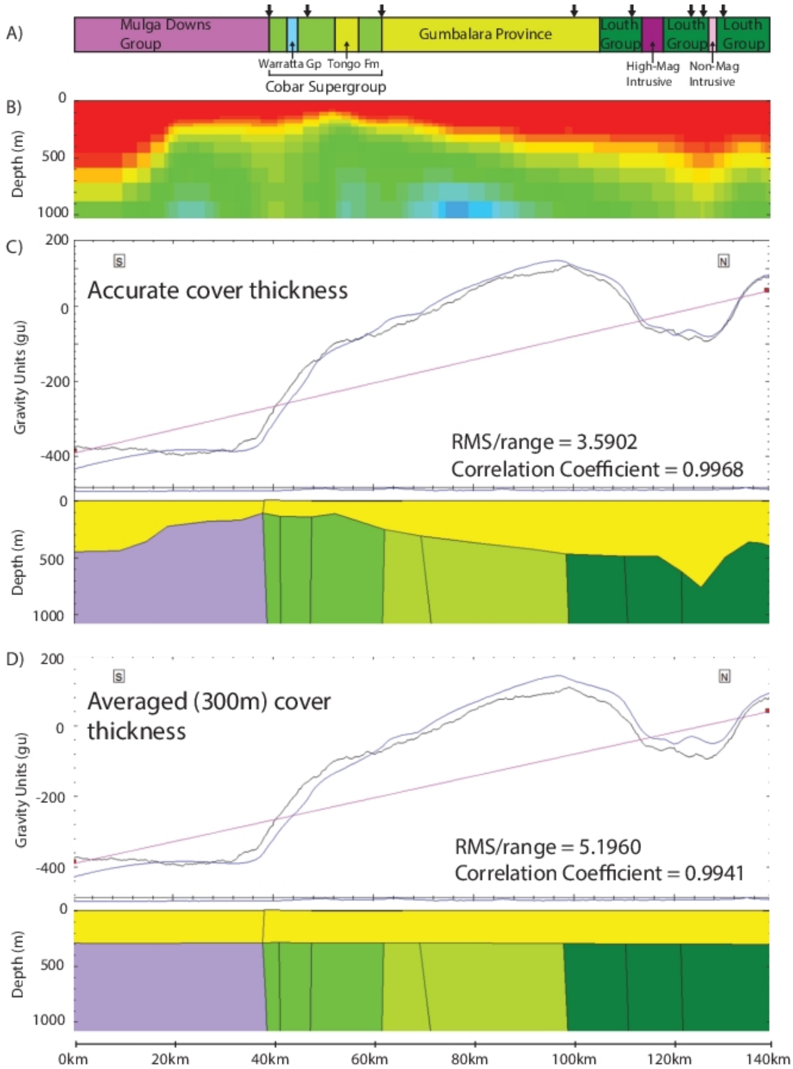

Figure 5: Comparison of the agreement between calculated and observed gravity data of two forward models with different cover thickness models.
A) Basement geology interpretation along Line 3 from Purdy *et al.*, (2014). Arrows above section are interpreted faults;
B) BBMT conductivity section showing interpreted cover thickness varying along the section;
C) Model 1, with varying cover thickness as per the BBMT method;
D) Model 2 with a uniform cover thickness (300 m). Both models have identical densities for all units (cover density = 2.45 kg/m^3). A varying cover thickness produces a better fit (a much lower RMS/Range and slightly higher correlation coefficient).

CONCLUSIONS

Cover thickness (or DTB) was investigated by comparing AEM, BBMT and AMT conductivity sections. All methods show great promise when estimating cover thickness with cover sediments and rocks identified by high electrical conductivities (usually orange-red colours on the modelled images produced) in this region. In particular, cover thickness variations interpreted using the MT methods agree with other datasets such as existing drill holes/water bores, the GABWRA dataset, and recent estimations based on high-resolution ground geophysical surveys. AMT provides the most suitable MT method for investigating cover thickness on this regional scale with a depth of investigation in excess of 1 km, while maintaining a high resolution that shows small-scale DTB variations. BBMT is more useful in imaging deeper parts of the crust at lower resolutions. The cover thickness estimations from MT models were examined with forward gravity modelling and show a better match between the observed and calculated (modelled) gravity responses than an averaged, uniform cover thickness across the study area.

A reinterpretation of the seismic images along the southern section of Line 3 (western traverse) was used as a basis for the forward gravity modelling of this region with the results producing a very close match between the observed and modelled gravity responses. A subsequent gravity inversion produced densities of lithospheric units that were reasonable given the known (and inferred) rock properties in this region.

Various simplified cross sections depicting different lithospheric architectures were constructed and examined via the forward gravity modelling for the whole of Lines 1 and 3. The models producing the best match of observed and calculated gravity responses coupled with the most reasonable densities for crustal and upper mantle units contained a simplified, thickened crust (~45 km) north of the Olepoloko Fault. The highly resistive bodies (interpreted as felsic igneous intrusions) observed in the MT conductivity sections were also included in the gravity modelling and produced gravity responses that have a good match with the observed values and yield reasonable densities (for average felsic intrusions) after an inversion was run. The inversion process did produce unrealistic densities (much higher or lower densities than typically expected for these rock types) for some of the units found immediately beneath the cover based on the basement interpretation map of Purdy *et al*., (2014), so this should be investigated further in any future geophysical modelling.

The forward gravity models produced provide a good initial evaluation of the crustal architecture and variations in cover thickness in the southern Thomson region. More accurate and realistic gravity models will be generated through an iterative process as more data are acquired through pre-drilling geophysics and analyses of the subsequent drill core material (e.g. geochronology, geochemistry, and petrophysics).

There are numerous advantages to conducting different geophysical surveys along the same transects or in the same regions. Firstly, different geophysical methods (e.g. electrical, seismic, gravity, magnetics) are measuring different physical properties of the crust and may reveal different features. This allows a more complete understanding of crustal architecture than if only one method is available or is relied upon too heavily. Secondly, when used in combination, these different geophysical methods may validate each other if the modelled outputs are similar, or alternatively if they show something different, this demands the question of why these differences exist.

The biggest problem for gravity modelling highlighted with this study is the lack of available data on the correct stratigraphic order of crustal units, their rock properties (i.e. density), their structural relationships and much of the crustal architecture of the region north of the Olepoloko Fault (the proposed southern Thomson Orogen). As such, much of the gravity modelling in this report has used highly simplistic and generalised models to represent the crust. The next stage of the Southern Thomson Project, should help to refine these datasets and improve the inputs into any future gravity (and/or other geophysical) modelling. Targeted pre-drilling geophysics, the drilling program itself and subsequent geochronology and geochemistry investigations will allow better inputs into any future large-scale modelling of this nature.

ACKNOWLEDGMENTS

Ian Roach, Michael Doublier, and Richard Chopping are thanked for their reviews of this abstract. This paper is published with the permission of the CEO of Geoscience Australia.

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