Applied geophysics for cover thickness mapping in the southern Thomson Orogen

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ABSTRACT
Potentially mineralised Paleozoic basement rocks in the southern Thomson Orogen region of southern Queensland and northern New South Wales are covered by varying thicknesses of Mesozoic to Cenozoic sediments. To assess cover thickness and methods for estimating depth to basement, we collected new airborne electromagnetic (AEM), seismic refraction, seismic reflection and audio-frequency magnetotelluric data and combined these with new depth to magnetic basement models from airborne magnetic line data and ground gravity data along selected transects. The results of these investigations over two borehole sites, GSQL Eulo 1 and GSQL Eulo 2, show that cover thickness can be reliably assessed to within the confidence limits of the various techniques, but that caveats exist regarding the application of each of the disciplines. A comprehensive analysis of the data has been done, and the results demonstrate that portable seismic systems, designed for geotechnical site investigations, are capable of imaging basement below 300 m of unlithified Eromanga Basin cover as refraction and reflection data. The results of all methods provide much information about the nature of the basement–cover interface and basement at borehole sites in the southern Thomson Orogen, in that the basement is usually weathered, the interface has paleotopography, and it can be recognised by its density, natural gamma, magnetic susceptibility and electrical conductivity contrasts.

Introduction
It is now widely acknowledged that Australia has a ‘cover’ problem, in that the easy-to-find mineral resources have mostly been found, and that future discoveries need to be made under the cover of regolith and sedimentary basins (Australian Academy of Science, 2012). When commencing exploration in these covered terrains, two of the first questions asked are ‘Where are the prospective rocks?’, and ‘How thick is the cover?’. The first question may be answered by geological mapping of sparse outcrop, regolith-landform mapping to recognise weathered bedrock materials, synthesis of regional borehole data, potential fields (gravity and magnetic) data interpretation of covered solid geology and new regional geophysical data acquisition. What data are needed to answer the second question, that relating to cover thickness? It is this second question that is the focus of this paper.

An understanding of cover thickness is important for a host of applications. Hydrogeologists need to know cover thickness in order to map hydrostratigraphic units for ground-water resource assessment. Geophysicists need to know cover thickness to produce better potential fields geophysical models. Mineral explorers, most importantly for this project, need to know cover thickness in order to assess the feasibility of accessing rocks that are of potential economic interest. A borehole is the culmination of all of the data collection and synthesis, and represents a large investment for a mineral exploration company in a single, one dimensional line of truth in the Earth. The aim of this work is to lessen the risk associated with such an investment.

A third question that is not often asked explicitly, but is implicit in the discussion above, is ‘Which basement are we looking for?’ One explorer’s basement is another’s cover, and in Australia local basement and cover may be represented by Archean under Proterozoic, Paleozoic under Mesozoic or Paleogene under Neogene, depending on the commodity sought.
Here we use and assess applied geophysical techniques and data synthesis to estimate cover thickness (also known as Depth To Basement—DTB) within the southern Thomson Orogen region of southern Queensland and northern New South Wales (NSW) (Figure 1). This region has the benefit of comparatively thin cover associated with the Eulo Ridge basement high (Figure 2). Additionally, DTB estimates in this region can be validated by two stratigraphic boreholes (GSQ Eulo1 and 2) drilled as part of a broader study to test solid geology syntheses (Doublier, Purdy, Hegarty, Nicoll, & Zwingmann, 2018; Purdy, Hegarty & Doublier, 2018; Purdy, Hegarty, Doublier, & Simpson, 2014). These new data and interpretations contribute to an explorers’ toolkit of techniques to help reduce the risk to the exploration industry in searching for new mineral deposits in covered terrains in general, and in particular the underexplored terrain of the southern Thomson Orogen.

Southern Thomson Orogen study area

Cover in the southern Thomson Orogen for our work is defined as Cenozoic sedimentary rocks of the Lake Eyre Basin, Mesozoic sedimentary rocks of the Eromanga Basin, and Paleozoic sedimentary rocks of the Darling Basin. Basement comprises Paleozoic rocks, including of Cambro-Ordovician, Silurian and Lower Devonian rocks that may have been mineralised during regional metamorphic events, including the Benambran and Tabberabberan orogenies. Basement could also include younger, potentially mineralised, Paleozoic (Middle Devonian to Permian) and Mesozoic (Triassic, Jurassic and Cretaceous) igneous rocks.

Basement rocks in the study area have the potential to host orogenic gold mineral systems (Brown, Vickery, & Greenfield, 2006; Skirrow, Armistead, & Main, 2015), Cobarstyle syn-orogenic Cu–Pb–Zn–Au mineral systems (Skirrow et al., 2013, 2015), intrusion-related Mo–W and Au–base metal systems (Armistead et al., 2017; Rothery, 2013) and intrusion-related Sn–W skarns (Plimer, 1984), described more fully in Armistead et al. (2017). There may also be potential for Macquarie Arc-style Cu–Au porphyry mineralisation. Younger igneous rocks also have potential for intrusion-related epithermal–mesothermal mineralisation, porphyries and skarn mineralisation, as seen in eastern Australia and detailed by Denaro, Ramsden, and Brown (2007) and Draper (1998).

Our work centres on the Eulo Ridge (Figure 2), an uplifted portion of Paleozoic basement that influences groundwater flow systems within the Great Artesian Basin (GAB) (Smerdon, Ransley, Radke, & Kellett, 2012). The Eulo Ridge separates the deeper, hydrocarbon-bearing Cooper Basin in the west from the Surat Basin in the east. The Eulo Ridge was first recognised as the Eulo Shelf by Whitehouse (1954) and was renamed by Senior (1971) after further investigation using regional water-bore data and geological mapping. This area was chosen because, although outcrop is less than 1% of the surface area, cover thickness estimates from regional borehole data indicate that Paleozoic rocks are close to the surface. Indeed, granites outcrop at Hungerford, Currawinya, Granite Springs and Eulo (Figure 2).

Existing cover thickness models

Prior to developing borehole target locations, we conducted a review of available cover thickness models for Cenozoic, Mesozoic and younger Paleozoic cover (Middle Devonian and younger) in the region.

The earliest models come from hand-drawn compilations by Senior (1971), based on the earlier work of Whitehouse (1954), who modelled the Eulo Ridge using waterbore log data. These proved to be informative, in that they provide an overall sense of the shape of the Eulo Ridge, but could not be relied upon for accurate information at high resolution except near the boreholes on which they were based. Similarly, the OZ SEEBASE Phanerozoic dataset (FrogTech, 2014) gave context to the Eulo Ridge as part of a basement high separating adjacent hydrocarbon-producing basins, but proved to be inadequate for characterising areas of shallow basement.

Both the GSNSW (Dick, Hegarty, & Vega Faundez, 2010) and the GSQ (Simpson & Cant, 2013) produced cover thickness models for the region derived from available
waterbore, petroleum and mineral borehole data and, in the case of the GSQ, depth to magnetic basement estimates. These models have some overlap along the NSW–Queensland border; how-ever, the two are not entirely complementary because the authors chose different stratigraphic units as their ‘basement’: the Lower Devonian in Queensland; and, the Upper Devonian in NSW. Both models are informative in that they refresh the hand-drawn model of Senior (1971) by adding new borehole data and new interpretation, and give an overview of the broad shape of the under-cover Eulo Ridge and the on-lapping relationship between the Eromanga Basin and the Lachlan Orogen to the south.

The Great Artesian Basin Water Resource Assessment (GABWRA; Smerdon et al., 2012) is the most recent compilation of cover thickness data available in the area and adds new data to the previous compilations. The original waterbore data are available as part of the National Groundwater Information System database hosted by the Australian Bureau of Meteorology. The GABWRA generated hydrostratigraphic models describing the elevation of major aquifers within the GAB, and regards the top of the Paleozoic basement over the Eulo Ridge as the base of the Jurassic.

These cover thickness models are a reasonable starting-point for mineral explorers in the project-generation phase of exploration; however, they are unsuitable for advice when siting boreholes because of their coarse resolution, being based primarily on sparsely scattered boreholes. Geological logs derived from local boreholes are also problematic as they are commonly driller’s logs, with very poor geological descriptions, or have no descriptions at all. The paucity of accurate cover thickness data in the regions of interest for new stratigraphic drilling led us to acquire new geophysical data to provide more accurate cover thickness models and better...
inform the risk analysis underpinning the new stratigraphic drilling programme.

**New regional depth to basement modelling and mapping**

**Airborne electromagnetic cover thickness modelling**

Geoscience Australia completed regional airborne electromagnetic (AEM) surveys in the study area in 2014 (Roach, 2015) and in 2016 (Figure 2) to improve on previous borehole-derived cover thickness models. The AEM surveys, conducted using the helicopter-borne Geotech Ltd VTEMplus® AEM system, were designed to locate near-surface, electrically resistive Paleozoic basement under the generally electrically conductive cover of the Eromanga and Lake Eyre basins. This approach draws upon previous experience in regional AEM surveying for cover thickness mapping gained during the Onshore Energy Security Program (OESP; McKay, Bowen, Neumann, & Southgate, 2011). The OESP AEM survey data were used to successfully map basement-cover interfaceline in the Paterson (Roach, 2010), Pine Creek (Craig, 2011) and Frome (Roach, 2012; Roach, Jaireth, & Costelloe, 2014) regions of Australia, also summarised in Roach (2016) and Roach and McPherson (2016).

The 2014 Thomson AEM survey used regular east–west orientated flight lines with 5000 m line spacing to map the broad trend of the near-surface Eulo Ridge basement–cover interface at higher resolution than was possible using the borehole-derived cover thickness models described above. Two long AEM traverses were also acquired to complement ground-based regional gravity and magnetotelluric surveys extending south into the Lachlan Orogen, described by Folkes (2017) and below. The 2014 AEM survey also identified six basement ‘islands’, or small covered basement highs, each of which was only observable within a single flight line. In 2016, further AEM data were acquired primarily in NSW and also over some of the more strategically important basement highs in Queensland that were less well imaged in the 2014 AEM survey. Areas with basement highs were infilled between the earlier east–west flight lines resulting in flight lines at 2500 m line spacing, and also using north–south or obliquely orientated cross-lines to map specific basement highs, or join potential drilling sites. The 2016 AEM survey helped to spatially constrain the basement highs located in 2014, and mapped new shallow basement under cover of the Eromanga Basin in the Louth and Enngonia areas of NSW. Interpretation products were produced using the Geoscience Australia reversible-jump Markov chain Monte Carlo (GARJMC) inversion (Brodie, 2015; Brodie & Reid, 2013; Brodie & Sambridge, 2012), and a new algorithm in development, the Geoscience Australia sample-by-sample all-at-once algorithm, which is due to be released to the public in 2018 (Brodie & Ley-Cooper, 2018).

The AEM data were validated using existing surface geological mapping (Figure 3) and available borehole data, including stratigraphy, lithology, electrical conductivity or resistivity (Habermehl, 2001) data. These data were used to develop empirical rules describing the electrical conductivity textures of basement and cover rocks. These observations permitted mapping of the geoelectrical stratigraphy of the Eromanga Basin cover, and the basement–cover interface, to the limit of the Depth Of Investigation (DOI; Hutchinson, Roach, & Costelloe, 2010; Roach, 2015) of the AEM datasets. Uncertainties in depth to a specific geoelectrical horizon were assessed during the validation process using borehole stratigraphic data, and are estimated to be § 10 m where the AEM data unambiguously respond to a geoelectrical contrast above the DOI along flight lines.

The AEM data, together with available borehole data, were used to develop 3D surface models of the basement–cover interface (an example is shown in Figure 4), which were compared with previous models using difference grids (see Roach, 2015, 2018). As expected, data obtained at higher resolution displayed basement topography in greater detail and provided a more accurate cover thickness model along flight lines. Assessing cover thickness model uncertainty between flight lines is more problematic, given that these data require interpolation over a distance of 2500 m or 5000 m, using only sparse borehole data as a constraint. While along-line vertical uncertainty is estimated at $10 m in the smooth basement–cover interface model, it is estimated that between-line vertical uncertainties in the model may be as high as 100 m. This estimate is based on isolated basement highs being detected on single flight lines, and the potential that others remain undetected between flight lines. Nonetheless, this new, higher-resolution AEM-derived cover thickness model was then used in conjunction with the GABWRA cover thickness model to help assess the likely cover thickness in areas of interest for stratigraphic drilling operations. It also assisted planning of high-resolution ground geophysical data acquisition at potential drilling sites. Where possible, the proposed boreholes were sited on or near AEM flight lines to further improve cover thickness estimates, and also to help validate AEM data inversion results in the future using electrical conductivity borehole logging.

**Depth to magnetic source modelling**

Two depth to magnetic source (DTMS) methods were used to model cover thickness in the southern Thomson Oregon region. The AutoMag method (Pratt et al., 2005), an automated process that incorporates user input, was used to model DTMS across the broader southern Thomson Oregon region (Figure 5). The AutoMag method is an implementation of an improved Naudy-based technique (Naudy, 1971; Shi, 1991) that produces strike-corrected depth estimates to the top of dipping tabular bodies. The method also incorporates a filtering routine to eliminate low reliability depth estimates.

Targeted Magnetic Inversion Modelling (TMIM, previously referred to as TIM; Meixner et al., 2016) was used to generate...
2D inversions of dipping tabular bodies from individual magnetic anomalies, thereby delineating the depths to the top of the bodies, as close as possible to proposed drilling sites.

Both methods were performed on high quality regional airborne magnetic line-data acquired with flight-line spacings of 400 m or less, detailed in Table 1. Flight-line data are preferred over the derivative gridded data for two reasons. First, flight-line data are usually recorded with a radar altimeter channel so that the aircraft height above ground is known. The actual aircraft height may vary by tens of metres from the nominal flight height, leading to significant uncertainty in the depth estimates from gridded data. Second, the sample spacing along the lines (>7 m) is less than the cell size of the derivative grids (generally 80 m for a survey acquired at 400 m flight-line spacing). The closely spaced sampling along flight-line data ensures that the highest frequency anomalies from magnetic sources at the surface are adequately sampled, meaning that there is no loss of depth resolution that may occur for the same magnetic sources from the gridded data.

The results of the AutoMag method, generated using Encom ModelVision V14.0 software, are shown in Figure 5. No geological interpretation has been applied to the depth estimates. Although it is likely that the majority of the depth estimates are from magnetic sources at the top of the basement, depth estimates could also be sourced from deep within the basement, as well as from within the cover. To the east-southeast of Hungerford, for example, there are two depth estimates of over 500 m surrounded by estimates of less than 300 m. It is likely that these deeper estimates are sourced from deep within the basement and overestimate the cover thickness. Conversely, in the northwest of the project region on the WYANDRA 1:250 000 scale map-sheet, there are a small number of depth estimates of less than 100 m depth in a region with numerous deeper estimate solutions (>500 m). It is likely that these shallower estimates are from sources within the cover. The general trend is of shallow cover around Hungerford extending to the southeast to Louth and Byrock. This broad basement high is flanked by deeper solutions indicating thicker cover to the west of Hungerford as well as to the northeast around Cunnamulla.

The TMIM DTMS estimates were produced using Encom ModelVision v14.0 software. The flight-line data were imported into the software and the magnetic profiles from individual flight lines were viewed in the vicinity of the proposed drill sites. Ideally the magnetic anomalies targeted for modelling in the profile data correspond to linear anomalies on the gridded images. Distinct, non-overlapping anomalies are preferred in order to simplify modelling. A regional field of polynomial order one was computed for each anomaly prior to inversion. A tabular body was generated manually in the software for each anomaly. Initial properties consisting of an X, Y and Z location of the mid-point of the top, horizontal face, as well as the thickness, depth extent, dip, strike length, strike azimuth and the magnetic susceptibility were set such that the modelled anomaly approximately matched the observed anomaly. The strike length and azimuth of the body were set manually from observation of the targeted anomaly on the magnetic grids and were not modified during the inversions. The Quick Inversion tool of the software iteratively adjusted the remaining body properties in order to optimise the fit between the observed and modelled magnetic line data. The inversions were halted when the root mean square (RMS) fit between the observed and the modelled data ceased to improve.
The DTMS results of the TMIM method are shown in Figure 6, while an example of an inversion run is shown in Figure 7. The anomalies targeted for inversion are assumed to be at the top of basement and are, therefore, an indication of the cover thickness. The GSQ Eulo 1 borehole is located in a magnetically bland region so it is not possible to produce a depth estimate at the borehole location. There is a linear east–west-trending anomaly directly to the south of the borehole that would be an ideal magnetic source to apply the TMIM method if the aeromagnetic survey flight-line direction were orientated north–south. Unfortunately, flight lines for the aeromagnetic survey covering this region are orientated east–west and it is not possible to model a body that strikes in the same direction as the flight lines. The next closest anomaly, approximately 5 km to the WSW of GSQ Eulo 1, is circular, meaning that
the likely magnetic source is not a tabular body. It is possible, however, to model a circular anomaly as a tabular body by restricting the strike length of the body to the same length as the width of the body. The confidence in the depth result (313 m) will, however, be lower for a circular body modelled in this way than for a linear magnetic anomaly, as it is possible that the magnetic source is from a circular pipe, a spherical body or the equidistant tabular body that was modelled to produce the depth result. The magnetic anomaly in close proximity to the GSQ Eulo 2 borehole is also circular and so the confidence of the depth estimate (83 m) is also less than if it were a linear...
anomaly. The depth estimates to the northeast and south-east of GSQ Eulo 2 are deeper, 376 m and 186 m, respectively, indicating that the cover thickness appears to be increasing to the east of the borehole.

The TMIM depth estimates in Figure 6 have an assigned confidence. The confidence is a subjective ranking of the depth estimates by the modeller that takes into account the following factors: how likely the geological body being modelled matches the tabular body being modelled (a close match increases the depth confidence); the RMS misfit between the observed and modelled anomaly (lower misfit, higher confidence); the sensitivity of the modelled anomaly to vertical perturbations of the modelled body (bodies with large depth extent have high sensitivity to vertical perturbations resulting in a higher confidence in the depth estimate); and, the simplicity of the anomaly being modelled (an isolated anomaly that has no interference with adjacent anomalies will result in a higher depth confidence). A more detailed analysis of modelling confidence is given in Meixner et al. (2016).

Regional electrical conductivity models for gravity modelling and validating cover thickness models

New geophysical data were collected to generate 2D geological models of the southern Thomson Orogen crustal architecture and the Thomson–Lachlan orogens boundary (Folkes, 2016, 2017). To this end, new AEM data were acquired along two traverses following road corridors (Figure 2) as part of the 2014 AEM data acquisition programme (Roach, 2015), to provide detailed cover thickness information. This acquisition was followed-up by coincident magnetotelluric data acquisition to provide cover thickness information in areas where the AEM signal could not penetrate thick conductive cover (greater than the depth of the DOI, on mean 166.9 m for the entire AEM survey area; Roach, 2015), in order to more accurately model the basement–cover interface. Magnetotelluric (MT) data were acquired at a nominal 5000 m station spacing (broadband MT—BBMT) or at a nominal 1000 m station spacing (Audio frequency MT—AMT) (Figure 8) along the AEM traverses and other shorter traverses designed to map basement features (Wang, Chopping, & Duan, 2017). Finally, new ground gravity data were acquired at a nominal 333 m station spacing where possible along all the traverses in order to model the crustal structure of the southern Thomson Orogen, and to test cover thickness estimations obtained from the MT data using forward gravity models.

Cover thicknesses of 0 to >500 m were initially estimated along the traverses through a combination of AEM and MT data interpretation and using existing borehole data. Most datasets yielded broadly similar results in terms of mapping relative cover thickness variations, although AEM data could not reliably be used where cover thickness exceeded the DOI, and BBMT tended to overestimate cover thickness where it is known to be less than 50 m (Folkes,

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**Table 1. Specifications for aeromagnetic survey data used for the TMIM analysis for DTMS estimation.**

| GADDS survey number | Survey name | Year Flown | Flight line spacing (m) | Nominal flight height (m) | Radar altimeter data availability | Line Direction | Sampling rate (Hz) |
|---------------------|-------------|------------|-------------------------|--------------------------|---------------------------------|---------------|------------------|
| P732                | NSW DMR, Discovery 2000, 1994–95, AREA B, Darling Basin | 1995 | 400 | 80 | Yes | North–south | 10 |
| P733                | NSW DMR, Discovery 2000, 1994–95, AREA C, Bourke | 1995 | 250 | 60 | Yes | East–west | 10 |
| P755                | NSW DMR, Discovery 2000, AREA R, Enngonia, NSW | 2001 | 400 | 80 | Yes | East–west | 10 |
| P1106               | Eromanga – Thomson Airborne Survey, NSW | 2005 | 250 | 60 | Yes | East–west and north–south | 10 |
| P1174               | Cooper Basin East, Qld | 2008 | 400 | 60 | Yes | North–south | 10 |
| P1248               | Thomson Orogen, Qld | 2011 | 400 | 80 | Yes | East–west | 20 |
Cover thickness estimates using MT methods (especially AMT) agreed with other datasets, including existing boreholes, GABWRA (Ransley & Smerdon, 2012) cover thickness results, and the targeted high-resolution ground geophysical surveys described in this paper. On this regional scale, AMT data provide the most suitable resolution for estimating cover thicknesses between 0 and 1000 m for use in gravity data modelling.

Figure 9 demonstrates the suitability of AMT data to interpret cover thickness over a line acquired immediately south of Hungerford (refer to Figure 8 for location).

In Figure 9a, the modelled AMT conductivity section along the combined lines 6 and 7a shows a pluton of the Granite Springs Granite approaching the surface. Cover thickness was inferred using the interface between conductive cover of the Eromanga Basin (<20 Vm) and more resistive basement (>20 Vm; Figure 9a). This is included in Figure 9b, together with observed and modelled gravity responses shown with the solid geology of Purdy et al. (2014). The match between modelled and observed gravity responses is assessed using two metrics: RMS normalised by dynamic range (a lower value indicates a better match); and, correlation coefficient (a value closer to 1 indicates a better match).

In Figure 9c, the gravity is modelled using a uniform cover thickness of 350 m. The model with a varying cover thickness based on the AMT data (Figure 9b) produces a gravity response with a closer match to the observed gravity data (lower RMS/range and higher correlation coefficient). This result shows cover thickness variations can produce discernible variations in gravity responses and need to be taken into account in gravity modelling. Furthermore, this supports the application of a combined approach in using AEM, MT and gravity models to assess cover thickness variations over a broad region.

**Borehole site selection**

A number of potential borehole sites were identified, with a bias towards areas where cover thickness estimates had a high confidence, using input from the data synthesis and modelling described above. The sites described in this paper were selected in order to characterise two types of solid geology: (1) suspected metamorphic rocks potentially representative of a broader area of basement; and (2) younger intrusive igneous rocks. The following sections focus on the two borehole sites where ground geophysical investigations and boreholes were successfully completed in 2016: GSQ Eulo 1 (Roach et al., 2017a) and GSQ Eulo 2 (Roach et al., 2017b) (Figure 8, 10).

The GSQ Eulo 1 site (Roach et al., 2017a) was selected in order to characterise geophysically bland rocks interpreted to consist of greenschist facies Nebine Metamorphics (Purdy et al., 2013, 2014). Prior to detailed site investigations, cover at the site was interpreted to be up to ~300 m thick based on the cover thickness model of Simpson and Cant (2013); while the GABWRA model (Smerdon & Ransley, 2012) suggested that cover could be up to 350 m thick.

The GSQ Eulo 2 site (Roach et al., 2017b) was selected in order to intersect an interpreted relatively young igneous complex visible in magnetic data, with the aim of determining the geochemistry and isotopic age of the complex and, by inference, other such features in the region. Prior to detailed site investigations, cover at this site was estimated to be ~200 m thick based on the cover thickness model of Simpson and Cant (2013), in close agreement with the GABWRA model (Smerdon & Ransley, 2012) at ~193 m thick.

**Borehole site geophysics**

High-resolution pre-drilling data acquisition (Goodwin et al., 2017) was undertaken at each of the proposed drill sites using a variety of geophysical techniques including active and passive seismic, AMT and Electrical Resistivity Imaging (ERI). The ERI technique was attempted at several sites during the preliminary data acquisition in 2015, but failed owing to the extremely dry ground conditions caused by prolonged drought in the region resulting in poor electrical coupling. No further attempts were made to apply this technique.

The following sections present information and results from AEM and high-resolution ground geophysical investigations over (or proximal to) the two borehole sites. Summarised results of the borehole investigations are then presented for comparison. Further details of the pre-drilling data acquisition, processing and interpretation for both the borehole sites are found in Goodwin et al. (2017).
Airborne electromagnetics

Airborne electromagnetic data coverage did not extend over the GSQ Eulo 1 borehole site. This was due to initial depth estimates of >300 m of cover, meaning that there was a low likelihood of being able to image the basement because of the known electrically conductive cover of the Eromanga Basin and its effects on the DOI.

The GSQ Eulo 2 borehole site was overflown in 2014 (east–west-orientated lines at 5000 m spacing), and a small electrically resistive basement high was interpreted within the conductivity section on a single flight line. In 2016 the site was revisited, acquiring east–west-orientated lines infilling the previous data at 2500 m line spacing, and a north–south-orientated line across the top of the previously interpreted electrically resistive basement high (Figure 10). Surface geological mapping and local waterbore stratigraphy, where available, were used to interpret the conductivity sections of the AEM data. In Figure 11, near-horizontal electrical conductors and resistors are interpreted to represent the upper portions of the Eromanga Basin stratigraphy (the Winton Formation, and the Coreena and Doncaster members of the Wallumbilla Formation). These conductors and resistors appear to thin towards the top of the electrically resistive basement high, which is approximately 900 m in diameter. The thinning geoelectrical stratigraphy implies that deposition occurred onto the pre-existing basement paleotopography of the Eulo Ridge, and that the resistive

Figure 8. Location map of ground geophysical data traverses including 333 m gravity, 1000 m AMT and 5000 m BBMT data. Background image: 0.5 vertical derivative of the reduced to pole magnetic grid of Australia 2015 (Geoscience Australia).
basement high represents an island in the shallow Cretaceous sea. More information on the AEM data planning, acquisition, processing and interpretation is available in Roach (2015).

Seismic refraction

Seismic refraction data were collected from single spreads at the GSQ Eulo 1 and GSQ Eulo 2 borehole sites. At GSQ Eulo 1, the survey was centred near the proposed borehole along a fence line access road (Figure 12), while at GSQ Eulo 2, the survey was centred across the top of a claypan (Figure 13) as close as practicable to the proposed borehole site. Data were acquired using a 40 kg accelerated weight drop seismic source mounted on the rear of a 4WD vehicle, striking an aluminium impact plate. The receiver array used 48 £4.5 Hz geophones at 5 m station spacing and the source was operated at multiple offsets up to 1040 m from the centre of the spread, with up to 40 stacked shots at the far offsets to improve signal/noise.

After data processing, results at both sites were modelled to produce time-depth converted 3-layer mean velocity models (Figure 14). At GSQ Eulo 1 (Figure 14a), a three-layer P-wave velocity model shows mean seismic velocities of 1.1 km/s in what is interpreted to be the near-surface weathering zone within Eromanga Basin sediments, 1.9 km/s in unweathered Eromanga Basin sediments, and 4.2 km/s in basement. Basement at GSQ Eulo 1 is interpreted to lie between 295 and 317 m below surface, sloping to the northeast under the receiver spread, which was centred about 70 m from the actual borehole site. Basement at GSQ Eulo 2 is interpreted to lie between 49 and 55 m below surface under the receiver spread, which was centred about 380 m from the actual borehole site. More information regarding the seismic data acquisition, processing and interpretation for both the borehole sites are available in Goodwin et al. (2017).
Audio-frequency magnetotellurics

The magnetotelluric (MT) method measures the natural magnetic and electrical (telluric) fields of the Earth, and uses their relationship to characterise the electrical structure of the Earth. When applied using appropriate data inversion and interpretation, the method provides a means to investigate the resistivity structure of the subsurface from depths of a few tens of metres to hundreds of kilometres. The AMT method (Chave & Jones, 2012; Dobrin & Savit, 1988; Vozoff, 1991) provides higher-resolution information within the upper part of the Earth’s crust at depths typically <2 km, when compared with BBMT, by acquiring data at higher frequencies between 20 kHz and ~1 Hz.

Data were collected from a single cross-shaped array at both the GSQ Eulo 1 and GSQ Eulo 2 borehole sites (Figure 12, 13). The arrays were aligned to magnetic north and consisted of four porous pot electrodes spaced 50 m from a central electrode to measure two components of telluric data (Ex and Ey), and three magnetic coils arranged orthogonally to collect three components of magnetic data (Hx, Hy and Hz). Data were modelled using a 1D Occam’s inversion algorithm to generate smooth models from the sounding data (Constable, Parker, & Constable, 1987). For each dataset, the geometric mean of apparent resistivity r(xy) and r(yx) (which couple orthogonal electric and magnetic field components), along with the arithmetic mean of the two phases, were used to calculate an inversion model. Figure 15 shows inversion models and the derived resistivity and phase plots for the GSQ Eulo 1 and GSQ Eulo 2 sites. A 20-layer smooth model was used to explicitly fit the data. Because the actual resistivity structure commonly has fewer layers than that modelled, a more simple three-layered model (shown as a diagonally hachured model) is estimated from the 20-layer smooth starting model using the inversion software, as shown in Figure 15. More information regarding the array design, dimensionality, data inversion and error levels is available in Goodwin et al. (2017).

Cover thickness at each site was estimated as the depth at which the calculated resistivity value exceeds 10 Vm (0.1 S/m conductivity), which is the estimate of the maximum resistivity of the central Eromanga sedimentary sequences (Spence & Finlayson, 1983). At GSQ Eulo 1, cover thickness was estimated at 272 ± 30 m, and at GSQ Eulo 2, cover thickness was estimated at 38 ± 30 m. The centres of the acquisition arrays were located ~480 m and ~420 m from the borehole locations at GSQ Eulo 1 and GSQ Eulo 2, respectively.

Validation of data modelling: borehole results

A borehole represents a single line of truth along which all other models and interpretations can be validated. The results of the investigations described above were used to help site the GSQ Eulo 1 and GSQ Eulo 2 boreholes (see Figure 2), although the operational requirements of the drilling contractor determined the ultimate borehole location. The results of the boreholes are used here to assess the relative success of the cover thickness investigations using both the geological and geophysical data acquired from the boreholes.

Lithological logs and geophysical wireline logs were compiled for both boreholes during the drilling process. These were used, together with stratigraphic interpretations from nearby waterbores, to interpret the stratigraphy of the Eromanga Basin sedimentary sequence in each borehole.

GSQ Eulo 1 stratigraphy and rock properties

The GSQ Eulo 1 borehole penetrated 299 m of regolith and fresh Eromanga Basin sedimentary rocks before reaching the basement of Nebine Metamorphics (Roach et al., 2017a). The graphic log of GSQ Eulo 1 (Figure 16a) shows silicified weathered siltstone and fine sandstone of the Winton Formation, which is affected by surface weathering to ~42 m, but is fresh below this to ~48 m. Below this, the Wallumbilla Formation continues to ~234 m, consisting of dark bluish grey carbonaceous mudstone with lignite bands, harder layers of shale and some thin (~1 m) siltstone and fine sandstone layers. During the borehole
operations artesian groundwater flows were encountered in the Winton and Wallumbilla formations associated with the gravel and sandstone bands. Below this the borehole encountered the Wyandra Sandstone Member of the Cadna-owie Formation, which is a moderately productive aquifer yielding groundwater of \( \text{C}^{2+} 500 \text{ ppm total dissolve solids (TDS)} \) at \( \text{C}^{2+} 60 \text{ m}^3/\text{day} \). Finally, the borehole encountered the basal Cadna-owie Formation, which has at its base a \( \sim 2 \text{ m}-\text{thick gravel layer consisting of rounded quartzose and lithic granules and pebbles above the basement. The basement section of the hole consists of \( \sim 39 \text{ m of paleoweathered greenschist rocks, with the base of the paleoweathering front occurring at } \sim 334 \text{ m true vertical depth. From this depth, Nebine Metamorphics basement rocks consist of fresh quartz–muscovite–biotite–chlorite schist that is partially albited. Mineralogical layering is reflective of compositional layering in a turbidite sequence (Roach et al., 2017a).}

Wireline logging of GSQ Eulo 1 (Figure 16a) reveals a subdued natural gamma signature in the Eromanga Basin cover sequence, with the characteristic ‘ski-jump’ of increasing natural gamma signal towards the base of the Cadna-owie Formation, as seen in other gamma logs from the region—refer to the compilation by Habermehl (2001). Natural gamma is elevated in the basement, at up to 10 times the intensity of the overlying Eromanga Basin. The paleoweathered basement is noticeably less radioactive than fresh basement rocks, and total counts increase towards the base of the paleoweathering profile. Induction (electrical) conductivity logging occurred in stages as uncased portions of the borehole were made available. The central portion of the borehole including the basement–cover interface was not logged using this method owing to the urgent need to insert casing to stem groundwater flow from the Wyandra Sandstone Member. However, those data that were collected show a variable but elevated electrical conductivity in the Eromanga Basin cover, while conductivity values approaching \( 0 \text{mS/m} \) are indicative of a highly electrically resistive basement. Electrical conductivities measured in the Eromanga Basin cover sequence are similar to those modelled from AEM data flown further to the west of the borehole (Roach, 2015).

Magnetic susceptibility data (Figure 16a) were collected using hand-held equipment at 1 m intervals from drill chips in the cover sequence, and at 0.5 m intervals in the basement diamond drill core. Magnetic susceptibility is generally subdued in the cover sequence, apart from the upper few metres, where maghemite is common in the surface lag. Below 165 m true vertical depth, many of the chip samples recovered were found to be contaminated by steel particles created during borehole casing welding and cutting operations, particularly in portions of the borehole immediately below where casing had been recently inserted. Accordingly, elevated magnetic susceptibility values in the lower portion of the Eromanga Basin cover sequence are not regarded as being reliable. The diamond drill core is not contaminated in any way by introduced magnetic particles and shows a subdued magnetic susceptibility in the paleoweathering profile, increasing below the paleoweathering front.

Saturated bulk density values of the basement drill core (see Roach et al., 2017a) show two populations—one above and one below the paleoweathering front. In the weathered
zone of the basement, densities range from 2.44 to 2.59 g/cc (mean 2.49 g/cc), and below the weathering front densities range from 2.67 to 2.79 g/cc (mean 2.73 g/cc). These results lie within the expected range of values for schists (2.39 to 2.9 g/cc) and chloritic slates (2.75 to 2.98 g/cc) (Telford, Geldart, Sheriff, & Keys, 1976), and are similar to schists from Victoria (range 2.47 to 2.87 g/cc, mean 2.65 g/cc) (Skladzien, 2007). The paleoweathering front is detectable as a correlation between a slight drop in electrical conductivity from ~245 to ~240 mS/m, and an increase in magnetic susceptibility to values >0.4 SI £10 in Figure 16a.

**GSQ Eulo 2 stratigraphy and rock properties**

The GSQ Eulo 2 borehole penetrated 51 m of regolith and fresh Eromanga Basin sedimentary rocks before reaching basement of intermediate volcaniclastic rocks of the Waihora Volcanics (Figure 16b; Roach et al., 2017b). Surface weathering in the Winton Formation occurs to ~14 m. Small gravel bands occur within the Winton Formation containing quartzose and lithic granules, also with abundant gypsum flakes. Below the base of surface weathering, the Winton Formation is a blue siltstone with lignite bands and transitions into the Wallumbilla Formation at ~28 m, which here is a dark blue to light grey siltstone with a carbonaceous layer at ~28 m and a quartzose sandstone layer at ~40 m. The interface with the basement occurs at 51 m, consisting of quartzose and lithic gravel covering a polymict volcaniclastic conglomerate of the Waihora Volcanics. Below this, there is a sharp boundary to strongly welded dacitic ignimbrite that is altered along pyritised vein selvages, and is heavily pyrite-veined in places. During the borehole operations, artesian groundwater flows were encountered in the Winton and Wallumbilla formations associated with the gravel and sandstone bands. Another aquifer was encountered at the basement–cover interface, yielding groundwater with ~500 ppm TDS increasing from 56 to 96 m³/day flow rate as the hole was deepened; this is interpreted to be a fractured rock aquifer connected to the Wyandra Sandstone Member of the Cadnaowie Formation.

Wireline logging of GSQ Eulo 2 (Figure 16b) shows a subdued natural gamma signature in the Eromanga Basin cover sequence, with values increasing into the basement volcaniclastic rocks. An increase in natural gamma from the basement–cover interface at ~51 m to elevated values at ~60 m depth may imply that a thin paleoweathering profile exists within this depth range. Certainly, there was difficulty in diamond drilling the first few metres of the volcaniclastic conglomerate because of ‘chattering’ owing to the drill bit rolling on loose, rounded pebbles. The natural gamma signal varies with mineralogy in response to compositional variation and alteration in the borehole.

An almost complete log of induction conductivity is available for GSQ Eulo 2 (Figure 16b), particularly across the basement–cover interface. Differences between the medium and deep induction channels signify differing amounts of drilling fluid penetration into the sidewall of the borehole, and are interpreted to be associated with gravel bands in the Eromanga Basin sequence and void spaces in the volcaniclastic conglomerate layer. Overall, induction conductivity logging showed elevated electrical conductivity in the Winton and Wallumbilla formations, affected by surface weathering and gravel bands, and an electrically resistive basement showing small variations between the medium and deep induction channels. These latter variations may relate to fluid penetration in void space in the volcaniclastic conglomerate.
Magnetic susceptibility measurements in the Eromanga Basin cover (Figure 16b) reflect the overall subdued magnetic susceptibility characteristic of these rocks. In the basement rocks, magnetic susceptibility is far more variable, reflecting compositional layering and variation in mineralogy, including the presence or absence of hematite and magnetite, and accessory minerals such as pyrite, pyrrhotite and ilmenite.

Saturated density of the drill core (see Roach et al., 2017b) ranges from 2.59 g/cc to 2.69 g/cc (mean 2.67 g/cc), within the range for ‘dactite’ (Telford et al., 1976), and similar to values reported for the Lachlan Orogen by Skladzien (2007) and Wyatt, Yeates, Tucker, and Vetter (1984). The presence of a thin paleoweathering profile in the volcanioclastic conglomerate can be interpreted through the correlation of increasing natural gamma and magnetic susceptibility, and decreasing electrical conductivity, with the weathering front occurring at 60 m depth.

Assessing the tools for the explorers’ toolbox

The objective of the pre-drilling geophysical data acquisition was to determine the cover thickness more accurately than possible from the predictions using regional models. This supported the aim of reducing drilling risk by allowing more accurate budgeting, and better informing the drilling contractor about likely hazards that could be encountered along the way (e.g. likely depths to artesian aquifers), and of course the depth at which basement rocks could be expected. More widely, the tools used and knowledge gained from them may be extended to any drilling operations where targets exist under cover.

Cover thickness estimates and complications

The cover thickness estimates modelled using the various pre-drill geophysical techniques provide, within error, accurate measures of the final drilled cover thickness values (Table 2; Figure 17), despite the centres of some of the arrays (AMT in particular) being up to 480 m from the final borehole sites. The more accurate cover thickness estimates derived from the pre-drill geophysics, together with local waterbore stratigraphic summaries, also allowed us to estimate which of the major artesian aquifers were likely to occur, and at what depth, to within ~10 m in the two completed boreholes. This gave the drilling contractor more information to make decisions on the drilling rate of penetration, particularly in terms of when to exercise caution, use weighted drilling mud and insert casing. This was problematic at GSQ Eulo 1, where the predicted presence of the Hooray Sandstone (a major aquifer in the GAB) resulted in the drilling contractor being instructed to drill cautiously. Instead of encountering the aquifer, basement was encountered, and as a result valuable production time was lost. Conversely, the non-interaction with an artesian aquifer, and the preparedness to do so had it been intersected, may well have resulted in a net efficiency and avoided potential technical and safety issues. In the Eulo Ridge area, the Hooray Sandstone laps onto the paleotopographic surface of the Eulo Ridge, and around basement highs. It is difficult to predict where the aquifer occurs, and commonly its presence is misinterpreted within waterbores. Waterbore records indicate that the local waterbores are commonly terminated in the Hooray Sandstone. Instead, the aquifer being tapped near the GSQ Eulo 1 borehole is actually the Wyandra Sandstone Member of the Cadnaowie Formation, as is also the case near the GSQ Eulo 2 borehole (Roach et al., 2017a, 2017b).

Previous cover thickness models depicted the Eulo Ridge as a gently undulating, predictable paleotopographic surface, cut by some normal faults on the western side where it slopes away into the Cooper Basin (Senior & Habermehl, 1980; Senior, Mond, & Harrison, 1978). At GSQ Eulo 1, the Eulo Ridge is modelled to have a gently east-sloping paleotopographic surface both in the borehole-derived cover thickness models and in the seismic reflection model. However, new higher-resolution data (i.e. AEM data) over the larger Eulo Ridge show that the paleotopography of the Eulo Ridge is far more variable and has a higher local relief than previously interpreted in the borehole-derived cover thickness models mentioned above. The borehole-derived cover thickness models fail to map any of the small basement highs that are imaged in the AEM data; in many instances these are <1 km diameter. The GSQ Eulo 2 borehole was located on the western edge of one of these basement highs, which appears to be roughly circular and about 900 m in diameter when mapped by AEM crosslines (Figure 11). Pre-drilling geophysical data acquisition at this site took place on a claypan that marks the surface expression of this basement high. The paleotopographic surface of this basement high is also relatively flat-lying, meaning that the pre-drill geophysics cover thickness results are similar to the actual result from the borehole. The two new boreholes also illustrate that paleoweathering profiles are present within the basement rocks, further complicating any cover thickness estimates that may be possible using the geophysical techniques employed. Below, we consider these potential complications for each of the geophysical methods employed and discuss how lithology and measured rock properties may affect the results.

Rock properties constraints on pre-drilling geophysics results

Borehole wireline and drill core rock properties measurements are useful for interpreting the results of the pre-drilling geophysical data acquisition. In situ and laboratory-based measurements in the borehole and on the drill chips and core, and an adequate literature review of boreholes in the local region, help guide the interpretation of results.
We obtained in situ natural gamma, induction conductivity and (where possible) magnetic susceptibility data from the boreholes, magnetic susceptibility data from the drill chips, and magnetic susceptibility and density data from the drill core, shown in Figures 16, 17, and available from Roach et al. (2017a, 2017b). It was not possible to obtain in situ gamma density (gamma-gamma) data from the boreholes owing to operational restrictions. These petrophysical data are used to validate the pre-drilling geophysical observations and guide interpretation of these data, and are discussed below.

**Airborne electromagnetics**

Airborne electromagnetic systems are sensitive to changes in the bulk electrical conductivity of the Earth, which is controlled by factors including pore fluid electrical conductivity, pore fluid saturation, porosity and permeability (tortuosity), and the electrical conductivity (including cation-exchange capacity) of solid matter (Rhoades, Raats, & Prather, 1976). Typical AEM systems respond well to saltwater and clays, which have high ion exchange capacity, but poorly to electrically resistive rocks (typically basement rocks). However, the systems can commonly differentiate between different basement rocks provided the signal can penetrate conductive cover. Accurate knowledge of waterborne electrical conductivities (or if no other data are available, electrical resistivity, because the two parameters can be measured differently) and magnetic susceptibility can aid the processing geophysicist and geological interpreter in developing more accurate constrained geophysical inversion models, and gauge the extent of conductive cover. This knowledge can also identify the presence of conductive basement, which can be a good mineral exploration target owing to the presence of chemically reactive mineralogy (e.g. black shales, with clays and carbon or graphite) or even massive sulfides (except sphalerite, which is non-conductive; Palacky, 1981).

Present-day weathering profiles, and covered paleoweathering profiles, can affect AEM signal penetration by the presence of clays and saline water. In much of arid Australia extant weathering profiles can also contain abundant maghemite, which is blamed for superparamagnetism (SPM) affecting AEM signal penetration, creating false positive anomalies (Macnae, 2016). Recent work on the Induced Polarisation (IP) effect in AEM data indicates that residual IP effects can also produce false positive anomalies from clays, which are chargeable owing to their high ion-exchange capacity (Viezzoli, Kaminski, Ebner, & Menghini, 2016). Thus, good prior knowledge of groundwater chemistry, and regolith or fresh rock petrography and mineralogy, is necessary for data interpretation and to predict the effects of both SPM and IP in arid, iron-rich, saline landscape settings.

Airborne electromagnetic data inversion, like some of the other methods described in this paper (i.e. AMT, magnetic and passive seismic) also suffers from non-uniqueness, in that without prior knowledge of some of the petrophysical constraints of the geological system, data inversions may produce an almost limitless range of results from one dataset. Rock properties data gained from borehole wireline logging in the two boreholes confirm the broad knowledge that the Eromanga Basin sequence is generally electrically conductive, and the basement is generally electrically resistive in the local area. These data have been used to validate the inversion algorithms used to process the raw AEM data and produce the interpretation products such as the conductivity sections shown in Figure 11. Magnetic susceptibility data from drill core and chips confirm that magnetic minerals are not abundant in the surface lag and within the Eromanga Basin sequence, ruling out the possibility of superparamagnetic effects on AEM data within the vicinity of the GSQ Eulo 2 borehole. IP effects cannot be ruled out within the AEM dataset owing to the clay-rich nature of the Eromanga Basin sequence, but were not assessed for this study. Overall, the AEM data
over the GSQ Eulo 2 site produced reliable cover thickness estimates that were very close to the actual borehole result for a combination of reasons including the presence of relatively thin electrically conductive cover, a very electrically resistive basement, a relatively sharp boundary between cover and basement, the presence of brackish rather than saline groundwater, and relatively simple flat-lying stratigraphy over the basement that could be easily modelled.

**Depth to magnetic surface**

Both the AutoMag and TMIM methods use a dipping tabular body as the modelled magnetic source. Owing to the inherent ambiguity of potential field data, a model that fits the observed data is only one of an infinite number of possible models, and thus the method suffers from non-uniqueness. Confidence in a depth estimate is dependent on how well the model, the dipping tabular
Spikes in the GSQ Eulo 1 magnetic susceptibility data in the Eromanga Basin sequence are almost certainly owing to steel particle contamination in the drilling chips.
borehole location (Figure 6). Paleotopographic relief can result for GSQ Eulo 2 is only about 100 m away from the borehole location, whereas the anomaly that produced the results for the GSQ Eulo 1 site is 6 km to the WSW of the those results. Thus, the anomaly that produced the DTMS able magnetic anomalies that can be modelled to produce DTMS results are highly dependent on the locations of suit-

The stratigraphy at each borehole site can be interpreted from surface geological mapping and local borehole stratigraphy. At GSQ Eulo 1 the borehole is sited in weathered Winton Formation with a silica-indurated cap of porcellanite forming small mesas. Interpretations from the stratigraphy of nearby waterbores show that the borehole progresses through unweathered Winton Formation, Wallumbilla Formation, Wyandra Sandstone Member, Cadna-owie Formation and possibly Hooray Sandstone overlying metamorphic basement rocks. At GSQ Eulo 2, the local stratigraphy consists of weathered Winton Formation and the borehole progresses through unweathered Winton Formation and Wallumbilla Formation overlying igneous basement rocks.

Modelled mean interval velocities in the weathered zone are typical for weathered sedimentary rock (GSQ Eulo 1) and unconsolidated sediment (GSQ Eulo 2). Modelled mean P- wave velocities for the Eromanga Basin are slightly slower than those reported from the Eromanga Basin.
elsewhere, averaging about 2.2 km/s (Finlayson & Collins, 1987; Lock & Collins, 1983). More accurate P-wave velocity data come from petroleum well check-shots in the region including the Brewarrina No. 1, Hutton No. 1 and Mirintu No. 1 wells. In Brewarrina No. 1, a mean P-wave velocity of 1.88 km/s is reported in the basal Winton Formation (Carty & Moffitt, 2001). In Hutton No. 1, mean P-wave velocities of between ~2.1 and ~2.2 km/s are reported in compacted Wallumbilla Formation (Dirstein, Walton, & Kjellgren, 2008). Mean P-wave velocities of ~2.0 km/s are reported for the Cadna-owie Formation in Mirintu No. 1 (Offshore Oil, 1984). Lavering (1992) reported on changes in the velocity function (see Telford et al., 1976) of the Wallumbilla Formation, noting that the unit was ‘undercompressed’ in some areas and may have an inverse velocity–depth gradient. Given this, and that (a) the two borehole sites occur near the crest of the Eulo Ridge and (b) Eromanga Basin sedimentary rocks were not highly compressed, the modelled mean interval velocity of 1.9 km/s for what is interpreted to be undercompacted Eromanga Basin sediments at the GSQ Eulo 1 and GSQ Eulo 2 sites is considered reasonable. Basement P-wave velocities of 4.2 km/s and 5.3 km/s are typical of values reported for metamorphic rocks and igneous rocks, respectively (Greenhalgh & Whitely, 1977; Telford et al., 1976).

A simple test of the veracity of the seismic refraction models comes from Gardner’s relation \( r \approx \frac{a}{b} \), where \( a \approx 0.31 \), \( b \approx 0.25 \), and \( V_p \) is metres per second, where seismic P-wave velocity is used empirically to derive density (Gardner, Gardner, & Gregory, 1974). Seismic refraction data from both sites were processed as three-layer models (Figure 14) defining the upper weathered zone on Eromanga Basin sedimentary rocks, then unweathered Eromanga Basin rocks, and basement. Measured saturated density data from the two boreholes, and estimates of bulk density ranges of the Eromanga Basin sequence and soils, can be compared with seismic velocities modelled from the data at the two borehole sites to test the validity of the modelling (Table 3). In general, Gardner’s relation holds well for sedimentary rocks in the Eromanga Basin, which comprise the bulk thickness of the modelled seismic refraction profiles in Figure 14. The density of the weathered zone at the top of the Eromanga Basin sequence derived using Gardner’s relation also fits within the range of saturated bulk densities expected for well consolidated lithic soils and unconsolidated clay soils (Mckenzie, Jacquer, Isbell, & Brown, 2004). At GSQ Eulo 1, the seismic refraction spread was laid out over a lithosol at the top of a silcrete rise, and at GSQ Eulo 2, the spread was laid out over a claypan, helping to explain the difference in saturated bulk density derived at both sites. At GSQ Eulo 1 the modelled seismic velocity in the basement is 4.2 km/s, yielding a density using Gardner’s relation of 2.49 g/cc; this is identical to the mean measured density in the paleoweathering profile in the borehole (2.49 g/cc; Roach et al., 2017a), suggesting that the modelled refractor represents the top of the weathered basement, rather than the unweathered basement beneath. At GSQ Eulo 2 the modelled seismic velocity in the basement is slightly higher than at GSQ Eulo 1, reflecting the well-lithified, denser nature of the volcanic basement rocks, and thus the density derived using Gardner’s relation is slightly higher (2.64 g/cc), but is also reflective of the actual mean value (2.7 g/cc; Roach et al., 2017b). All of these correlations are made with the assumption that the modelled seismic velocities are the mean velocity.

**Seismic reflection data processing**

Seismic refraction data from the GSQ Eulo 1 site were reprocessed using seismic reflection processing techniques in a proof-of-concept exercise to demonstrate that basement reflectors could be extracted from refraction data if a basement refractor was not visible in the data after processing. This could occur where basement is buried too deeply for the far offset shots to produce refracted first break arrivals. Based on our own experiments using the accelerated weight drop seismic source, we demonstrated that for shot offsets exceeding ~1200 m, refracted arrivals could not be detected above the background noise in the receiver array, theoretically corresponding to basement buried >~400 m depth. Further experimentation led to the conclusion that the seismic refraction technique had difficulty imaging bedrock where the cover thickness exceeded ~300 m owing to the excessive distance between the geophone spread and the far offset source shots required. We demonstrated that the seismic source could not provide sufficient signal over the ambient noise to allow definitive recognition of refraction first arrivals at offset distances greater than ~1 km, despite stacking multiple shots and burying the geophones to minimise wind noise.

Thus, as an experiment, the seismic refraction data (i.e. acquisition with varying source locations including far offsets) were processed using seismic reflection techniques (Figure 18). Seismic reflection data processing uses stacking to improve the signal-to-noise ratio allowing a weight drop source to be used for imaging depths of >300 m. Velocity inversions (slow layers under faster layers) do not affect reflection processing and are not hidden layers in the reflection data, and hence will not cause bedrock time–depth conversion errors. Processing seismic refraction data as seismic reflection data can provide depths for layers to verify the refraction results and identify if any slow hidden layers exist. The resulting seismic reflection profile in Figure 18 illustrates that the acoustic impedance contrast of the bedrock–cover interface slopes gently to the northeast between 280 m and 320 m depth. The basement–cover interface reflector was stacked within a limited velocity range, outside which the reflector is incoherent. The stacking velocity range used defines a depth error range of about 10%. These results confirm the seismic refraction modelling results, and also demonstrate that the basement–cover interface contains some
micro-topography in the order of 100 m wavelength. Processing refraction data as reflection data is a useful value add for the refraction data. Reflection processing is relevant where cover thicknesses are estimated to be too deep for a small-scale refraction acquisition system such as the one used here, which would be generally unable to image a basement refractor at cover thicknesses >300 m. The seismic refraction and reflection data produced reliable results despite the centre of the arrays being located some distance from the actual borehole sites (Table 2).

Audio-frequency magnetotellurics

There are several limitations and sources of uncertainty in applying the AMT method for the purposes of cover thickness estimation. First, the propagation of the electromagnetic fields through the Earth is a diffusive process, and responses obtained are volumetric means of the measured Earth conductivities (Constable et al., 1987). Thus, the magnetotelluric response cannot resolve the transition from conductive to resistive structure precisely and a vertical error margin of ~30 m is suggested for AMT data (Constable et al., 1987). Second, assumptions associated with the 1D inversion technique lead to uncertainty in model results. For a site affected by 2D/3D structure, a 1D assumption may not satisfy the true physical process and 2D/3D models are required, which involves data acquisition along a traverse or grid, whereas only a single sounding was acquired at both sites in this study. Another uncertainty source is from data error owing to the intrinsic uncertainty in an instrument and the inevitable noise in the field, as well as deployment skills of the field crew. Every effort was made to avoid cultural noise, and to accurately install the sensors in the study area. Finally, the non-uniqueness of inversion models (Constable, Orange, & Key, 2015), and the experimental nature of the inversion codes, raises uncertainty in terms of the depth to basement estimates. The Occam 1D inversion code produces step-like smooth models from a set of parameters, and prior knowledge is needed to identify the major discontinuities in the resistivity structure of the Earth, e.g. an approximation of the resistivity value at which the geological structure transition occurs. Owing to these limitations, it is recommended that other geophysical techniques be considered as complementary methods for determining estimates of cover thickness.

Magnetotelluric data inversion and interpretation thus benefit from the acquisition of the same rock properties data as AEM, given that both methods are sensing the same rock property—electrical conductivity (and also magnetic susceptibility, for MT data), but at different scales. Borehole wireline data confirm the broad results of the AMT data inversion, in that both boreholes have an electrically conductive cover in the Eromanga Basin sequence, and electrically resistive basement. Similarly to the AEM data, the GARUMCMC inversion algorithm can be used to produce conductivity models from single soundings of the Earth (Figure 15) to cross-check other codes. Again, a priori knowledge of electrical conductivity and magnetic susceptibility in the local region helps constrain and interpret AMT data. Borehole wireline electrical conductivity, electrical resistivity and magnetic susceptibility data also help validate the inversion results. The AMT method produced reliable results for similar reasons to the AEM results, in that the borehole sites possess electrically conductive cover over electrically resistive basement, with a relatively sharp boundary between the two, and flat-lying stratigraphy in the Eromanga Basin cover that could be easily modelled. Similarly, borehole magnetic susceptibility data show that the Eromanga sequence is by and large relatively weakly susceptible, and that much stronger magnetic sources exist within the basement at both borehole sites.

Conclusions

The success of mineral exploration ventures in moving away from areas of outcrop towards areas of cover depends on skills, knowledge and technology to map covered, potentially mineralised basement terrains and reduce exploration risk. The applied geophysical methods discussed here are demonstrated to reduce exploration risk by providing more accurate estimates of cover thickness at a reasonable cost, and are only a few of those available in the array of tools in the modern explorers’ toolkit. These methods can be applied relatively quickly, easily and inexpensively to produce reliable cover thickness estimates, and provide more surety when planning and budgeting drilling campaigns through cover. These methods have been tried and verified by Geoscience Australia in the Stavely region of Victoria (Meixner et al., 2016), and are now demonstrated to be useful in the southern Thomson
Orogen, where the presence of artesian groundwater can greatly increase drilling risk and costs.

The success of the individual geophysical methods depends on a combination of operator skill and knowledge, a priori information about the petrophysical properties of local rocks and regolith materials, and sometimes (but not necessarily) supercomputer time for data inversion. During the data compilation and literature review phase, we demonstrated that some of the fundamental rock properties of unweathered cover materials in the GAB (i.e. density and magnetic susceptibility) do not vary significantly over many tens of kilometres, thus data from boreholes over the region may be used to make assumptions regarding local conditions. Regolith materials and groundwater-saturated rocks, however, show significant rock properties variation, and need to be studied before assumptions can be made. Proxies for rock properties information can be used in the local area to help constrain inversions and interpretations. Additional information is available from literature review, surface geological and regolith mapping, waterbore logs, previous mineral exploration boreholes and potential field data.

The results shown here (Figure 17) demonstrate that AEM and ground geophysics, and to a lesser extent DTMS modelling (which was shown to more of a regional cover thickness mapping tool), can produce reliable results when applied to the well-recognised exploration problem of determining cover thickness. The results also demonstrate that a portable 48-channel seismic system, designed more for geotechnical site investigations, is capable of imaging basement below 300 m of unlithified Eromanga Basin cover as refraction and reflection data. The combined results from the geological and geophysical investigations provide much information about the nature of the basement–cover interface and basement at these two sites. Specifically, the basement is usually weathered, the basement–cover interface has paleotopography and it can be recognised by its density, natural gamma, magnetic susceptibility and electrical conductivity contrasts.

Figure 17. Comparison of cover thickness estimates and uncertainty margins from all the methods listed in Table 2 and borehole intersections for the (a) GSQ Eulo 1 and (b) GSQ Eulo 2 boreholes. Borehole data are from Roach et al. (2017a, 2017b).
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Disclosure statement

No potential conflict of interest was reported by the authors.

Data sources

Geophysical datasets used in this paper are available for free download from Geoscience Australia. Airborne electromagnetic data are available from http://www.ga.gov.au/about/projects/resources/continental-geophysics/airborne-electromagnetics. Magnetic and gravity data are available from the Geophysical Archive and Delivery System (GADDS) http://www.geoscience.gov.au/gadds. Magnetotelluric data are available from http://www.ga.gov.au/scientific-topics/minerals/unlocking-resource-potential/southern-thomson. Rock properties data for both boreholes are available through the Geoscience Australia Rock Properties Explorer at http://www.ga.gov.au/explorer-web/rock-properties.html. Waterbore data are available from the Bureau of Meteorology http://www.bom.gov.au/water/groundwater/ngis/.

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