Estimating Cover Thickness in the Southern Thomson Orogen – A Comparison of Applied Geophysics Estimates with Borehole Results

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SUMMARY

Potential sites for up to sixteen stratigraphic boreholes were selected to intersect the basement geology throughout the southern Thomson Orogen as part of the Southern Thomson Project. At each of these sites high resolution estimates of cover thickness were derived by applying refraction seismic, Audio-MagnetoTelluric, Targeted Magnetic Inversion and passive seismic geophysical techniques. Estimating cover thickness in this way reduced the technical risk associated with drilling and allows for the various geophysical techniques to be compared at each site.

A comparison of the estimates derived from the applied geophysical techniques with the actual cover thicknesses determined from borehole geological and geophysical logs, together with an analysis of the uncertainties for each method, has highlighted the effectiveness of each geophysical technique. These new data and interpretations contribute to an Explorers' Toolkit of techniques to help reduce the technical risk to the mineral exploration industry in searching for new mineral deposits in covered terrains in general, and in particular in the underexplored terrain of the southern Thomson Orogen.

The various geophysical estimates highlight that the basement-cover interface throughout the southern Thomson Orogen can be recognised by its seismic velocity, electrical conductivity and magnetic susceptibility contrasts. However, the cover thickness estimates determined by the geophysical techniques shown here provide non-coincident estimates in some cases and, as such, it is important to take into account their unique limitations and uncertainties. When comparing results from the GSQ Eulo 1 and GSQ Eulo 2 boreholes it is clear that the refraction technique produced the most accurate estimates due to a strong contrast between the velocity structure of the Eromanga Basin sediments and the basement geology throughout the study area.

Key words: UNCOVER, refraction seismic, Audio-MagnetoTellurics, Targeted Magnetic Inversion, passive seismic

INTRODUCTION

The geology of the southern Thomson Orogen in northern New South Wales and southern Queensland (Figure 1) is poorly understood. The rocks are rarely exposed (see outcrop extent in Figure 1) and there are generally tens to hundreds of metres of overlying unconsolidated, indurated and well-consolidated cover, largely consisting of Eromanga Basin sedimentary rocks, and some Lake Eyre Basin sedimentary rocks. These cover rocks are a significant impediment to mineral discovery and their presence emphasises the need to collect precompetitive data to gain an improved understanding of the geological character and mineral potential of the under-cover geology.

The Southern Thomson Project is a collaborative project between Geoscience Australia (GA), the Geological Survey of New South Wales (GSNSW) and the Geological Survey of Queensland (GSQ) that aims to collect new precompetitive data in the southern Thomson Orogen. The project is designed to collect new geophysical, geological, geochemical and geochronological data to improve geological understanding, promote mineral exploration (by reducing technical exploration risk), and inform future land and water resource management decision making.

Potential sites for up to sixteen stratigraphic boreholes (Figure 2), designed to intersect the basement geology, were selected using potential-field data, solid geology interpretation, airborne electromagnetic data and local water-bore information. Following site selection, high resolution estimates of cover thickness (i.e. the thickness of regolith and/or sedimentary rocks overlying crystalline or metamorphic basement) were derived by applying refraction seismic, passive seismic, Audio-MagnetoTelluric (AMT) and Targeted

Magnetic Inversion (TMI) geophysical techniques (Figure 3). These cover thickness estimates allowed for more accurate budgeting and reduced the technical risk associated with drilling at each of the proposed drilling sites.

Many of the proposed sites have since been drilled, and stratigraphic boreholes intersect the basement geology providing a unique opportunity to compare the estimates derived using the pre-drilling geophysical methods with the actual cover thickness determined within the borehole.

GEOPHYSICAL ACQUISITION, PROCESSING AND MODELLING

Refraction seismic data were acquired at all 16 sites using a system with 48 single-component geophones, deployed in a linear array, with a propelled weight drop as the primary-wave (P-wave) energy source. At 14 of the sites clear basement refractors were observed in the data. This allowed for unambiguous 'picks' of the basement velocities to be made. Due to a loss of signal, caused by seismic attenuation at far offsets, a clear basement refractor was not observed at Barrygowan 1 and no basement refractors were observed at Nantilla 1. Three distinct refractors are generally observed in the data (Goodwin *et al.* in prep.):

- Those with velocities ranging from 0.4 km/s to 1.5 km/s are interpreted as regolith or weathered Eromanga Basin sedimentary rocks,
- those ranging from 1.8 km/s to 2.4 km/s are interpreted as unweathered Eromanga Basin sedimentary rocks,
- and those ranging from 3.9 km/s to 5.7 km/s are interpreted as metamorphic/igneous basement.

Using the above velocity structure a two-dimensional velocity model of the subsurface geology is generated using the time-term inversion method (Scheidegger and Willmore 1957; Willmore and Bancroft 1960), this allows the thickness of each layer to be estimated. Cover thickness estimates using refraction data vary widely from site to site, with the shallowest estimate being GSQ Eulo 2 (49 m to 55 m) and the deepest GSQ Eulo 1 (295 m to 317 m). As the time-term inversion produces a two-dimensional image of the subsurface geology, the values reported by the seismic refraction method indicate the variations for the depth of the subsurface basement topography across the section (i.e. they are not error margins).

Audio-MagnetoTelluric (AMT) data were collected at 10 sites by simultaneously deploying four porous pot electrodes (Ex and Ey) and three magnetic induction coils (Hx, Hy and Hz) to collect a single station sounding. For each site, a one-dimensional inversion model was produced using Occam's inversion approach (Constable *et al.* 1987). The resultant Occam inversion models display contrasting resistivity layers which identify vertically the electrical conductivity discontinuities in the subsurface geology. In general, the models show a near-surface conductive layer with resistivity values $\leq 10\ \Omega\cdot m$ overlying layers with continuously increasing resistivities with depth (up to $10^2\ \Omega\cdot m$ to $10^3\ \Omega\cdot m$). Those layers which were $>10\ \Omega\cdot m$ were generally interpreted as metamorphic/igneous basement rocks and were observed to occur at depths of ~100 m to ~300 m across the survey sites, except at GSQ Eulo 2 (38 m ±10 %) and Barrygowan 1 (480 m ±10 %). Unlike the seismic refraction data, these ranges represent uncertainties in the estimates, rather than variations in basement topography.

Targeted Magnetic Inversion (TMI) was applied to freely available, good quality, regional airborne magnetic survey data (Goodwin *et al.* in prep). Fifty-three depth to magnetic source estimates were generated with confidence ratings, using a dipping tabular source body to model targeted magnetic anomalies in the vicinity of the proposed borehole sites. A combined depth estimate was generated using a distance and confidence weighted average from multiple depth estimates at all but two proposed borehole sites. Only one TMI depth estimate was available at GSQ Eulo 1, while no depth estimates were generated at Eulo 1. These combined depth estimates provide cover thickness estimates at the sites using the assumption that the depth to magnetic source estimates are likely sourced from, or near, the top of basement.

Passive seismic data were collected at 14 sites using a three-component broadband seismometer and applying the Horizontal-to-Vertical Spectral Ratio (HVSR) method (Chandler and Lively, 2014; Smith *et al.*, 2013). Shear-wave velocity profiles relating to the subsurface geology were then modelled using Geoscience Australia's Reversible-Jump Multiple Chain Monte Carlo (GARJMCMC) algorithm (Brodie, 2015; Brodie and Reid, 2013) on the National Computational Infrastructure. This method is still in development and results will be released as they are made available.

COMPARISON WITH BOREHOLE STRATIGRAPHY

A borehole provides a means by which the geophysical estimates of cover thickness can be validated. The results from two boreholes, GSQ Eulo 1 and GSQ Eulo 2, are discussed here. Borehole stratigraphy results from other sites are forthcoming and will be included in this comparison as their completion reports become available.

GSQ Eulo 1

GSQ Eulo 1 penetrated 299 m of regolith and fresh Eromanga Basin sedimentary rocks (consisting of the Winton, Wallumbilla and Cadna-owie formations) before reaching the basement of Nebine Metamorphics (Figure 4; Roach *et al.*, 2017a). The basement section of the hole consists of ~35 m of weathered greenschist facies rocks, with the weathering transition into fresh rock occurring at ~334 m true vertical depth. From this depth, Nebine Metamorphics basement rocks consist of quartz-muscovite-biotite-chlorite schist that is partially albitised.

The refraction seismic time-term inversion defines three distinct layers at the GSQ Eulo 1 site. These included a weathering zone (P-wave velocity of 1.1 km/s) with the base lying between 24 m and 39 m depth, underlain by Eromanga Basin sedimentary rocks (P-wave velocity of 1.9 km/s) with the base lying between 295 m and 317 m (Figure 3), followed by a basement geology layer with a P-wave velocity of 4.2 km/s, open at depth. These estimates match well with the borehole stratigraphic log (Figure 4). The stratigraphic log indicates a weathered zone at ~42 m depth and the beginning of basement at 299 m. Although the basement is weathered within its top ~35 m (i.e. from 299 m to 334 m), the top of this zone still forms a distinct velocity contrast with the overlying Eromanga Basin sediments.

The Occam inversion modelling of AMT data at the GSQ Eulo 1 site suggests a low resistivity cover sequence (≤5 Ω·m) overlying a higher resistivity (1000 Ω·m) basement at 272 m ±10% (Figure 3). As the propagation of an electromagnetic field through the Earth is a diffusive process (acting to "smear out" sharp boundaries or thin layers; Constable *et al.* 1987) and the responses obtained are volumetric averages of measured Earth conductivities, an error margin of ±10% is applied to the cover thickness estimate. With this in mind, the technique is able to predict the cover thickness within this range (245 m to 299 m). The AMT method, however, could not distinguish the boundary between the surface weathered zone and the underlying fresh sedimentary rock of the Eromanga Basin due to the small conductivity contrast between the two layers.

As the GSQ Eulo 1 site was situated over a magnetically bland area, the TMI method was not ideal at this particular location. A magnetic anomaly was sourced ~5 km from the proposed borehole target and a depth estimate of 313 m with an error margin of 195 m to 431 m was obtained (Figure 3). The fact that this technique compares well will the actual cover thickness determined from the borehole may suggest that the basement topography between the site and the magnetic source anomaly is relatively flat. Also, magnetic susceptibility data from drill core and chips confirms that magnetic minerals are not abundant in the surface lag or through the Eromanga Basin sequence (Roach *et al.* 2017a) making it reasonable to assume that magnetic anomalies are being derived from the basement geology.

GSQ Eulo 2

GSQ Eulo 2 penetrated ~51 m of regolith and fresh Eromanga Basin sedimentary rocks (Winton and Wallumbilla formations) before reaching basement of intermediate volcaniclastic rocks of the Waihora Volcanics (Figure 4; Roach *et al.*, 2017b). The interface with the basement occurs at ~51 m, consisting of quartzose and lithic gravel covering a polymict volcaniclastic conglomerate of the Waihora Volcanics. The volcanic rocks continue to depth as a dense layered ignimbrite.

At GSQ Eulo 2 the time-term inversion modelling of refraction seismic data produced a three-layer model that compares well with the observed borehole stratigraphy. The time-term inversion shows an upper regolith layer between 5 m and 7 m thick (0.4 km/s velocity), underlain by Eromanga Basin sediments at 49 m to 55 m depth (1.9 km/s; Figure 3), before reaching basement with a P-wave velocity of 5.3 km/s. The modelled seismic velocity in the basement is slightly higher at GSQ Eulo 2 than at GSQ Eulo 1, reflecting the well-lithified, denser nature of the volcanic basement rocks.

The Occam inversion modelling of the AMT data shows a contrast between a low resistivity cover sequence (1 Ω·m to 20 Ω·m) and a higher resistivity (~50 Ω·m to ~100 Ω·m) basement at 38 m ±10% (Goodwin *et al.* in prep.; Figure 3). This cover thickness estimate falls short of the actual cover thickness defined by the borehole stratigraphy even when considering the error margin (34 m to 42 m). This may be due to the dimensionality of the data, as determined by phase tensor analysis, which indicates that the geological structure at this site is most accurately modelled with a two- or three-dimension model, as opposed to a one-dimensional model (Goodwin *et al.* in prep).

Several magnetic anomalies in the surrounding area were used to inform the cover thickness estimate for the TMI method. These anomalies range from 359 m to ~3600 m away from the borehole (Goodwin *et al.* in prep.). The closest anomaly suggests a cover thickness of 83 m and the furthest a thickness of 376 m, with a combined weighted average of 214 m. This suggests that the basement topography is highly variable in this area. As with the GSQ Eulo 1 site, the anomalies used in this assessment are not located directly beneath the borehole and so it is not possible to make a direct comparison. However, the closest magnetic anomaly provides an estimate that is 32 m deeper than the actual cover thickness determined by the borehole, but sits within a large error range. Airborne electromagnetic imaging of the site revealed that the GSQ Eulo 2 borehole was drilled on the southwestern edge of a basement high approximately 900 m in diameter. The cover enclosing this basement high increases in thickness relatively rapidly on all sides to over 200 m, and may explain why TMI modelling gave mixed results at this site (Roach 2015; Crowe *et al.* in prep).

Other factors that should be considered when comparing the geophysical estimates with the borehole stratigraphy include the distance the technique was deployed from the actual borehole site, any assumptions made during the processing stage, and the ambiguity/non-uniqueness associated with geophysical inversion modelling. Further information on the acquisition, processing and modelling of the geophysical data can be found in Goodwin *et al.* (in prep).

CONCLUSIONS

Throughout the southern Thomson Orogen study area Eromanga Basin sedimentary rocks are the dominant form of cover. The comparison made here shows that ground geophysics and TMI produced varied results when applied to estimates of cover thickness in this scenario. Refraction seismic produced the most reliable results to inform on cover thickness. Using a 48-channel system and a propelled weight drop, this technique was able to provide useable refraction information in scenarios where Eromanga Basin cover was up to ~300 m thick. Audio-MagnetoTelluric data inversion showed that at both borehole sites the Eromanga Basin forms a conductive cover that can be distinguished from the resistive basement. The TMI analysis method produced reliable results; however the method suffers from the fact that the source anomalies required by the technique could not always be located near the actual borehole site.

The combined results provide much information about the nature of the basement-cover interface throughout the southern Thomson Orogen. In particular, that it is weathered, it has mappable topography and it can be recognised by its seismic velocity, electrical conductivity and magnetic susceptibility contrasts.

Borehole stratigraphy results from other sites are forthcoming and will be included in this comparison as their completion reports become available. Similarly, the GARJMCM method for inverting passive seismic data is still in development and will be compared with available borehole data when testing is completed.

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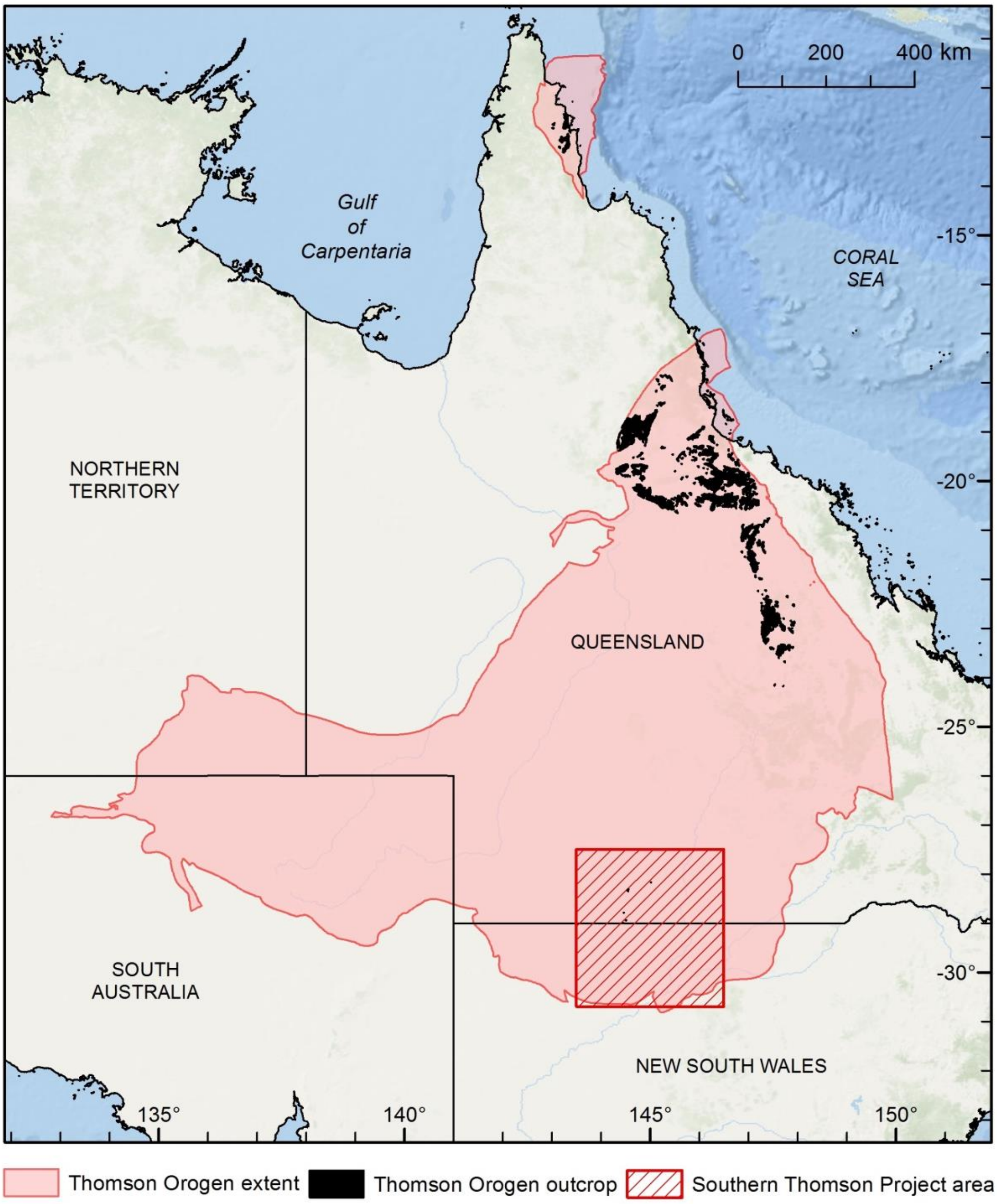

Figure 1: The inferred extent of the Thomson Orogen in north-eastern Australia, highlighting the location of the Southern Thomson Project study area. Surface outcrop (black) derived from Stewart *et al.* 2013.

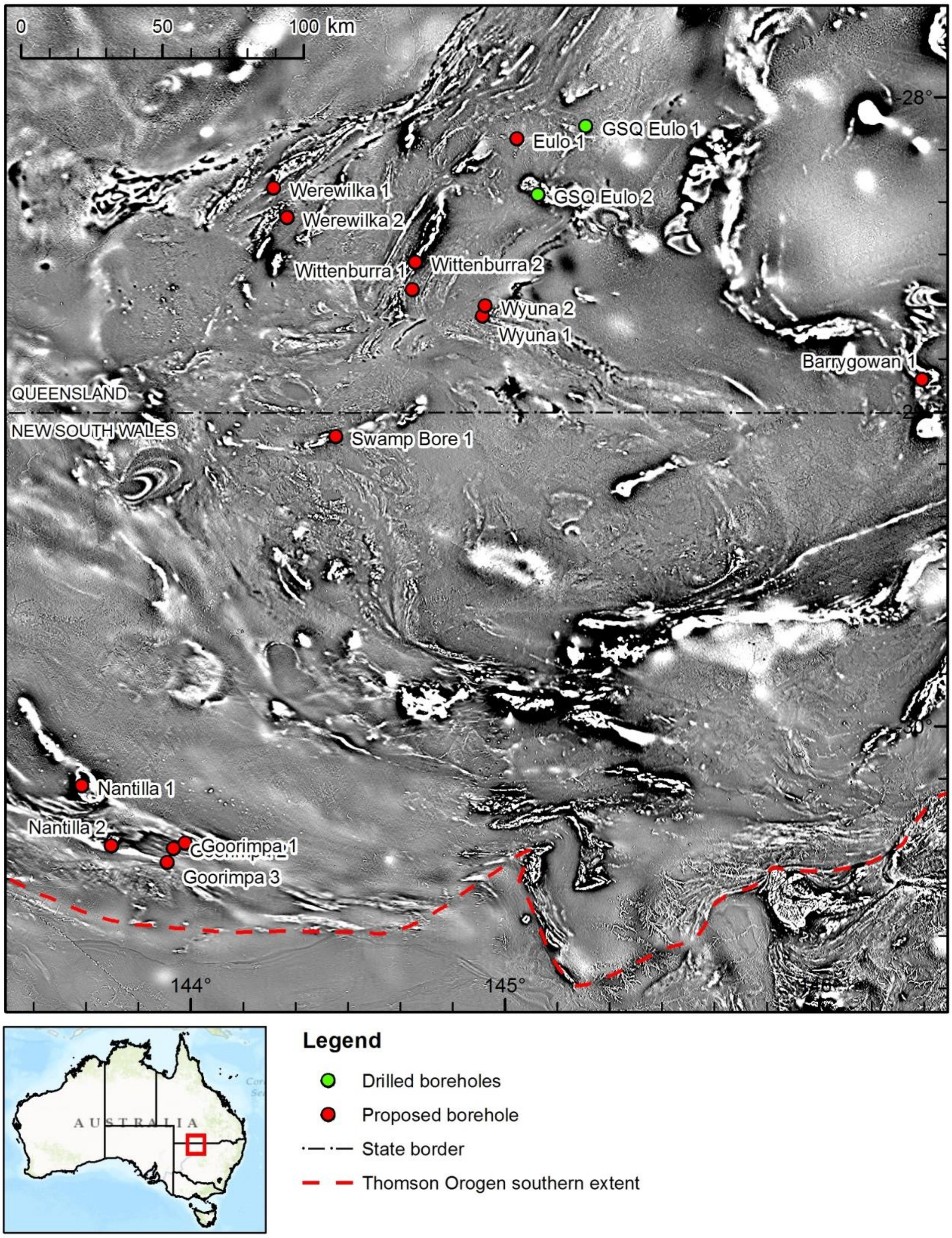

Figure 2: Total magnetic intensity image (Magnetic Anomaly Map of Australia version 6, 1st vertical derivative applied, greyscale colour stretch) highlighting the locations of proposed and drilled boreholes where pre-drilling geophysical data were acquired in the southern Thomson Orogen.

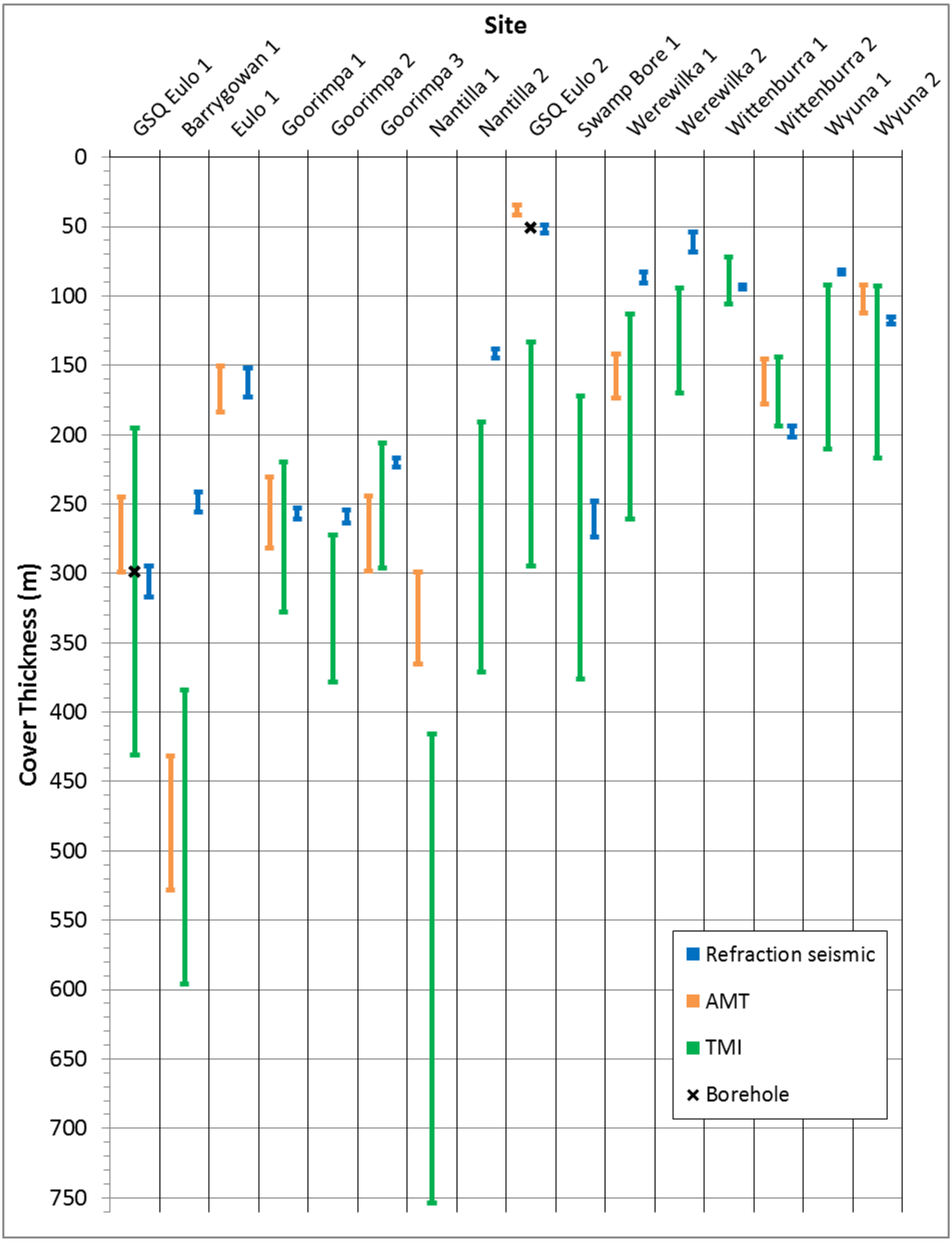

Figure 3: Comparison of cover thickness estimates for the refraction seismic, AMT and TMI techniques. The range of values for the refraction sesimic estimates at each site show basement topography variations across a transect, whereas AMT and TMI estimates are from a single point only and include an error margin.

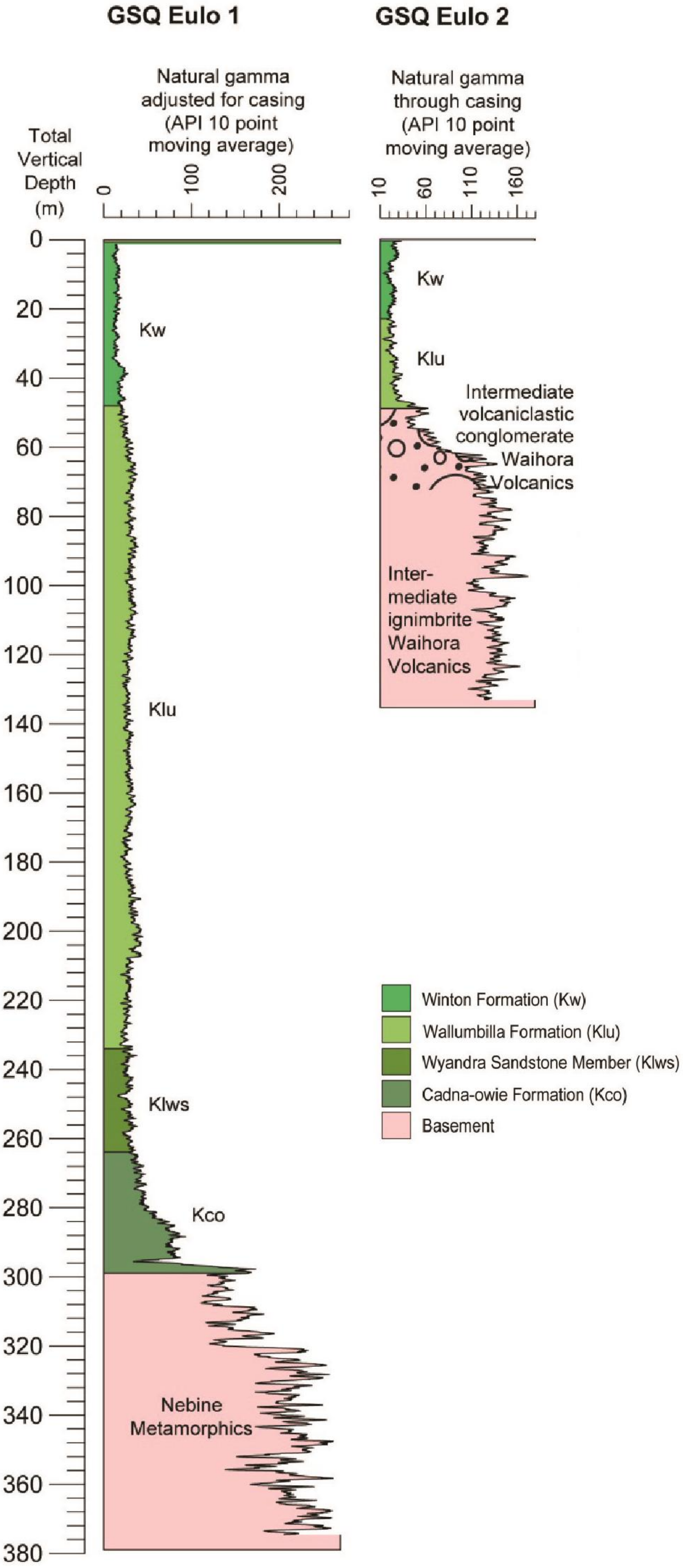

Figure 4: Graphic logs of the GSQ Eulo 1 and GSQ Eulo 2 boreholes. Borehole data are from Roach *et al.* 2017a and 2017b.