Mapping cover-thickness to UNCOVER basement and deep Earth architecture and processes

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SUMMARY

Under the UNCOVER initiative it is generally accepted that construction of accurate cover-thickness maps is the most tractable and urgent means of facilitating resource exploration under cover. To meet this goal we have been undertaking benchmarking of various geophysical techniques, constructing a national database of Estimates of Geological and Geophysical Surfaces (EGGS) to store legacy estimates and developing machine learning algorithms to interpolate between these estimates. Benchmarking magnetic top estimates to ~700 drill sites across the Murray Basin highlights the importance of performing estimates using profile data as opposed to grids. Inversion of horizontal to vertical spectral ratio data, derived from single broadband seismometers, reveals surprisingly robust cover-thickness estimates. While these insights are directly relevant in supporting drilling programs they can also be used to constrain deep Earth architecture and processes. We show that inversion of basin subsidence data can be used to constrain lithospheric thickness and mapped chrono-stratigraphic surfaces can be used to test models of uplift of the Australian continent related to convective flow within the Earth's mantle.

Key words: cover-thickness, magnetics, passive seismic, lithosphere, mantle.

INTRODUCTION

Within the UNCOVER initiative it is generally accepted that accurate maps of cover-thickness are the most tractable and urgent means of facilitating resource exploration beneath cover. Here, we focus on Geoscience Australia's efforts to improve cover-thickness mapping over Australia and the use of this information to constrain deep Earth architecture and processes. Our work seeks to address three priorities which arose from the 2014 post UNCOVER summit technical workshop on cover-thickness:

1. Benchmarking geophysical methods against drill sites with constrained petro-physical properties over a range of cover types;
2. Development of a point data repository of legacy cover-thickness estimates derived from geological and geophysical investigations;
3. Production of predictive cover-thickness maps based on new and legacy data.

BENCHMARKING

We have focused benchmarking of geophysical methods over data rich regions of sedimentary cover using existing data sets supplemented by targeted geophysical data acquisition in conjunction with current Geoscience Australia and state government drilling programs. Here, we report results from regional benchmarking of depth to magnetic top estimates over the Murray Basin and targeted passive seismic experiments conducted over drill sites in the southern Murray Basin (Stavely, Victoria). Results of benchmarking other techniques such as refraction and reflection seismic experiments were reported by Meixner et al. (2015) and the results of airborne electromagnetic (AEM) estimates have been reported by Roach et al. (2015; and references therein).

Magnetic estimates

The Murray Basin an ideal natural laboratory to test the reliability of magnetic methods for cover-thickness estimation as the generally non-magnetic Cenozoic sediments of the basin (with the exception of magnetic strandlines, paleo-channels, maghemite rich near surface regolith and cultural anomalies) overly tilted magnetised pre-Cenozoic basement stratigraphy. We benchmarked four magnetic methods against a dataset of ~700 reliable drill holes compiled by Brown and Stephenson (1991) which penetrate through the <600 m thick Murray Basin. Two methods, extended Euler de-convolution and the "tilt method", rely on gridded data and the remaining two methods, AutoMag and Targeted Inversion Modelling (TIM), utilise full resolution flight-line data.

Generally, methods that rely on gridded magnetic data perform poorly. Magnetic depth estimates from the extended Euler deconvolution (Mushayandebvu et al., 2001) were generated utilising the three equations method of FitzGerald et al. (2004), which solves for source location (X, Y and Z) and structural index simultaneously. The resulting depth solutions were then clustered in order to cull poor solutions. Tilt-depth estimates were generated from a tilt-angle of the reduced-to-pole total magnetic intensity grid (Salem et al., 2007) assuming the magnetic sources have vertical contacts and no remanent magnetisation. The correlation between estimates and drilled depths for both methods is poor with correlation coefficients (R^2) between 0.03 and 0.04 (Figures 1a and 1b).

The poor performance of these estimates is in part due to the low fidelity of the starting gridded data set and associated simplifying assumptions but also the inability of interpreters to apply adequate geological filters (i.e.. implement geological rigor) to the hundreds of thousands of solutions rapidly produced by these methods in order to confidently isolate signal from the base of the Murray Basin.

Methods, which rely on flight line data performed significantly better than grid based algorithms. The AutoMag method (Pratt et al., 2005) is an implementation of an improved Naudy-based technique (Shi, 1991; Naudy, 1971). This method produces strike corrected depth estimates to the top of dipping tabular bodies while eliminating low reliability estimates. Once a geological filter is used to identify those estimates sourced from anomalies directly beneath the basin the correlation co-efficient increases from 0.17 to 0.4 (Figure 1d). The TIM produces depths to the top of a 3D body (generally a dipping tabular body) following a parametric inversion that minimises the misfit between the observed and calculated anomaly. Inversions were performed utilising the Quick Inversion tool within ModelVision. Individual anomalies inferred to be sourced from the top of basement beneath the Murray Basin sediments with little to no interference from adjacent anomalies were targeted. This method produced the least amount of scatter (Figure 1c), with the largest R^2 value of 0.53, indicating a higher correlation with drill-hole depths. Significantly, the slope of the line of best fit is best aligned with the ideal one-to-one magnetic to drill-hole depth slope compared to the other methods where the line of best fit tends to overestimate in regions of thin cover and underestimate thicker cover.

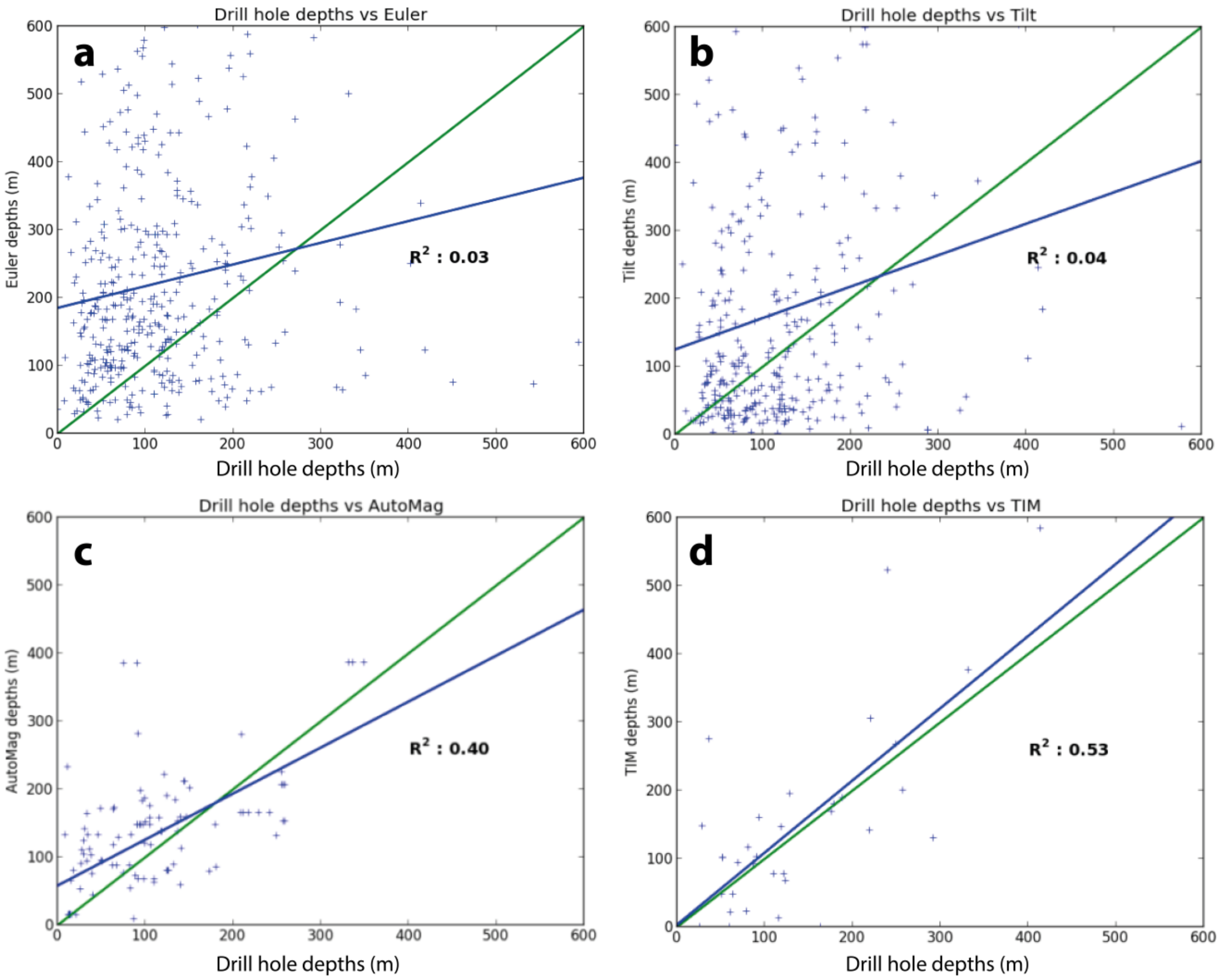

Figure 1. Scatter plots of magnetic depth estimates versus drill-hole depths to the base of the Murray Basin with 2,000m of the estimate. Green line = ideal one-to-one magnetic depth to drill-hole slope, blue line = line of best fit, R^2 = correlation coefficient. a. Clustered Euler depth estimates. b. Tilt depth estimates. c. AutoMag depth estimates post geological filter. d. Targeted Inversion Modelling (TIM) depth estimates.

Passive seismic estimates

In shallow passive seismology it is generally accepted that the spatial autocorrelation (SPAC) method is more robust than the horizontal-over-vertical spectral ratio (HVSR) method at resolving the depth to surface-wave velocity (Vs) interfaces (e.g. Smith et al., 2013). Here we present results of a field test of these two methods over ten drill sites in western Victoria. The target interface is the base of Cenozoic unconsolidated to semi-consolidated clastic and/or carbonate sediments of the Murray Basin, which overlie

Paleozoic basement rocks. For the ten drill sites, depths of this interface intersected in drill holes are between ~27 m and ~300 m. Seismometers were deployed in a three-arm spiral array, with a radius of 250 m, consisting of 13 Trillium Compact 120 s broadband instruments. Data were acquired at each site for 7–21 hours. The Vs architecture beneath each site was determined through nonlinear inversion of HVSR and SPAC data using the neighbourhood algorithm, implemented in the geopsy modelling package (Wathelet, 2005). The HVSR technique yielded depth estimates of the target interface (Vs > 1000 m/s) generally within ±20% error. Successful estimates were even obtained at a site with an inverted velocity profile, where Quaternary basalts overlie Neogene sediments, which in turn overlie the target basement. Half of the SPAC estimates showed significantly higher errors than were obtained using HVSR. Joint inversion provided the most reliable estimates but was unstable at three sites. We attribute the surprising success of HVSR over SPAC to a low content of transient signals within the seismic record caused by low levels of anthropogenic noise at the benchmark sites. At a few sites SPAC waveform curves showed clear overtones suggesting that more reliable SPAC estimates may be obtained utilizing a multi-modal inversion. Nevertheless, our study indicates that reliable basin thickness estimates in the Australian conditions tested can be obtained utilizing HVSR data from a single seismometer, without a priori knowledge of the surface-wave velocity of the basin material, thereby negating the need to deploy cumbersome arrays.

NATIONAL REPOSITORY OF COVER-THICKNESS ESTIMATES

In order to provide reliable and transparent estimates of cover-thickness to underpin exploration under cover it is necessary to develop a container to store individual point estimates of cover-thickness from which maps of cover-thickness are constructed. With this aim in mind Geoscience Australia has begun to develop a national database to store Estimates of Geological and Geophysical Surfaces (EGGS). Here we store interpretations and uncertainty of the depth of stratigraphic horizons interpreted from bore-holes and geophysical datasets (such as magnetics, seismic profiles and airborne electromagnetic surveys). We store enough metadata to link the interpretation back to the datasets and processing stream used to derive them.

PREDICTIVE COVER-THICKNESS MAPS

The point dataset(s) stored in EGGS need to be combined in order to generate predictive surfaces away from data sites. Classically, simple interpolation schemes such as minimum curvature surfacing, delaunay triangulation and kriging have been used to achieve this goal. Recently we have been trialling the use of more advance machine learning algorithms that combine cover-thickness estimate with supplementary raster information in order to create more robust predictions of cover-thickness. This approach establishes predictive relationships between cover-thickness point estimates with a suite of covariate datasets that we know reflect, in part, properties of the cover (e.g. outcrops maps, surface terrain models for predicting shallow cover in valley floors and gravity lows associated with basin deposition centres). Model uncertainty is estimated through a bootstrapping approach. Using ~65k constraint points over the Murray Basin we have achieved cover-thickness models with an R^2 correlation co-efficient of between 0.7–0.8.

USING COVER-THICKNESS TO CONSTRAIN DEEP EARTH ARCHITECTURE AND PROCESSES

The stratigraphic information compiled in EGGS can be used to place powerful constraints on the architecture of the lithosphere and deep earth processes such as the temporal variation of lithospheric thickness and the uplift history of the Australian continent. For example, stratigraphic information from the Canning Basin can be used to constrain the subsidence of this basin through time which can then be inverted to determine the underlying lithospheric thickness assuming a simple kinematic rifting model (Crosby et al., 2010). Recently Czarnota et al. (2014) recognised the admittance between gravity and topography at wavelengths greater than 500 km across Australia (~50 mgal/km) implies Australia's topography is mostly supported by the pattern of convective circulation within the mantle. They went on to constrain the history of landscape uplift and hence the pattern of convective circulation since the Cretaceous using inversion of longitudinal river profiles for uplift rate. Their hypothesis can be tested using the datasets compiled within EGGS by calculating the solid sediment flux to onshore and offshore basins.

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