ELECTRICAL RESISTIVITY MAPS OF THE AUSTRALIAN LOWER CRUST

Graham Heinson*
Department of Earth Sciences
University of Adelaide
Adelaide SA 5005
Graham.Heinson@adelaide.edu.au

Stephan Thiel
Geological Survey of South Australia
101 Grenfell Street
Adelaide SA 5001
Stephan.Thiel@sa.gov.au

Kate Robertson
Geological Survey of South Australia
101 Grenfell Street
Adelaide SA 5001
Kate.Robertson2@sa.gov.au

Paul Soeffky
Department of Earth Sciences
University of Adelaide
Adelaide SA 5005
Paul.Soeffky@adelaide.edu.au

Yohannes Didana
Department of Earth Sciences
University of Adelaide
Adelaide SA 5005
Yohannes.Didana@adelaide.edu.au

SUMMARY

Crustal silicate rocks at sub-solidus temperatures normally have high electrical resistivities. However, although upper crust is typically $> 10^3$ Ω.m, it is not unusual for lower crust to be $< 10^2$ Ω.m, and in places $< 10^0$ Ω.m. That lower crust (below 10-15 km) can be as electrically conducting as seawater is remarkable, and indicates a substantial and highly-connected mineral, melt or aqueous phase. To date, temporal and spatial mechanisms to give rise to the low resistivity are speculative and poorly constrained by observation and laboratory measurement.

We present new maps of the Australian crust resistivity inferred from the regional EM responses. The project addresses the question as to whether the low resistivity is primary in the formation of the crust, or overprint due to melt and fluid migration from a deeper thermal source. A secondary question is how regions of low resistivity from an interconnected phase can be preserved through time-scales of billions of years. Observations are drawn from: the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP); 2D MT transects; and legacy MT and geomagnetic depth sounding (GDS) data.

Our research demonstrates a strong spatial correlation of crustal resistivity with tectonic domains in Australia. Lowest resistivities are often imaged just below the rheological boundary between upper and lower crust at ~10-15 km. Below, low resistivity appears as a broad zone, tens or hundreds of kilometres wide, and tens of kilometres thick; above the boundary, regions of low-resistivity appear as narrower pathways. Such maps are correlated with long-wavelength Bouguer gravity data, suggesting a common origin that changes both density and resistivity.

Key words: Magnetotellurics, AusLAMP, lower crust

INTRODUCTION

Long-period EM data in the bandwidth of $10^0 - 10^4$ s have skin-depths ranging from a few kilometres to several hundred kilometres. Thus, arrays of observations spaced over distances-scales of tens to hundreds of kilometres can be used to map the deep electrical properties of the crust and upper mantle. Ideally arrays are synchronous and have similar quality and bandwidth, but it is also possible to meld surveys that have been conducted over many decades to provide a wider aperture of sites. The current AusLAMP program (Robertson et al., 2016) is providing a framework for complete continental coverage with a uniform grid of approximately 3000 sites with spacing of 55 km.

With hundreds of sites of AusLAMP and other legacy data available across Australia, it is now possible to produce maps of regional scale resistivity properties. In this paper, we demonstrate how different data sets can be used to map large tectonic provinces and how they add significant value to the interpretation of smaller-scale surveys by providing a regional context. The most significant resistivity changes in the Australian continent appear to be in the lower continental crust, and provide insight into past thermal and fluid processes that have a strong link with mineral systems.

METHOD AND RESULTS

Long-period MT and GDS measurements have been made over five decades by various groups in Australia. Before the mid-1980s data were typically recorded on paper or photographic film, and thus original time series are not available. Moreover, most data were three-component time-series magnetics rather than being magnetic and electric fields for MT responses, so only GDS responses were computed. Over the last few years, some effort has been put into recovering legacy GDS and sometimes MT responses from paper or digital records to provide a larger database. In many cases, only a few periodicities are presented in papers (eg Parkinson et al., 1998 for Tasmania), but these too provide useful constraint.

The GDS responses are typically much easier to recover and more robust. This is because they are a simpler transfer function involving four components at each frequency rather than the eight components of the full MT impedance tensor, and are thus easier to recover from published materials. Additionally, GDS responses tend to be simpler to interpret as the vertical anomalous magnetic field is the integrated response of all anomalous currents in the region approximately described by the skin-depth, and thus are not as affected by near-surface distortion and static-shift issues.

Figures 1 shows AusLAMP and legacy GDS responses plotted as induction arrows (Parkinson, 1962) for a section of South-Australia and New South Wales, and Figure 2 is similarly for part of the Northern Territory and Queensland. Induction arrows are plotted on maps of Bouguer gravity data accessed through Geoscience Australia.

In the Parkinson convention, the sign of the transform between the anomalous vertical and horizontal magnetics fields are reversed for both in-phase (real) and out-of-phase (quadrature) components of the transfer functions. The real arrow (black arrow in both figures) in this convention point towards good conductors; the quadrature arrows (white arrows) are less intuitive to interpret, but should show continuous and smooth change across the arrays.

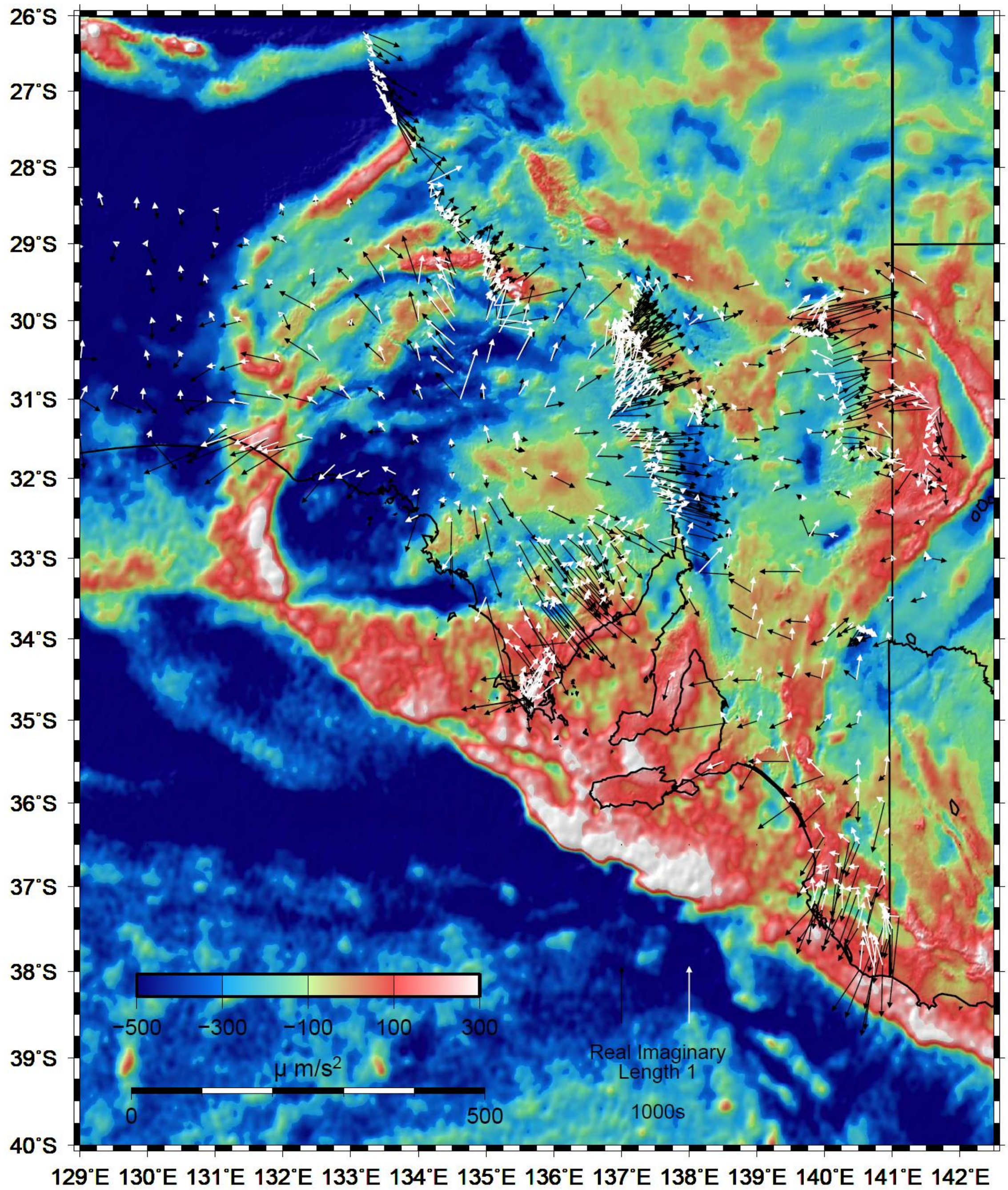

Figure 1: AusLAMP and legacy GDS responses plotted for a period of 1000 s for South Australia and western New South Wales. Induction arrows are plotted on Bouguer gravity data.

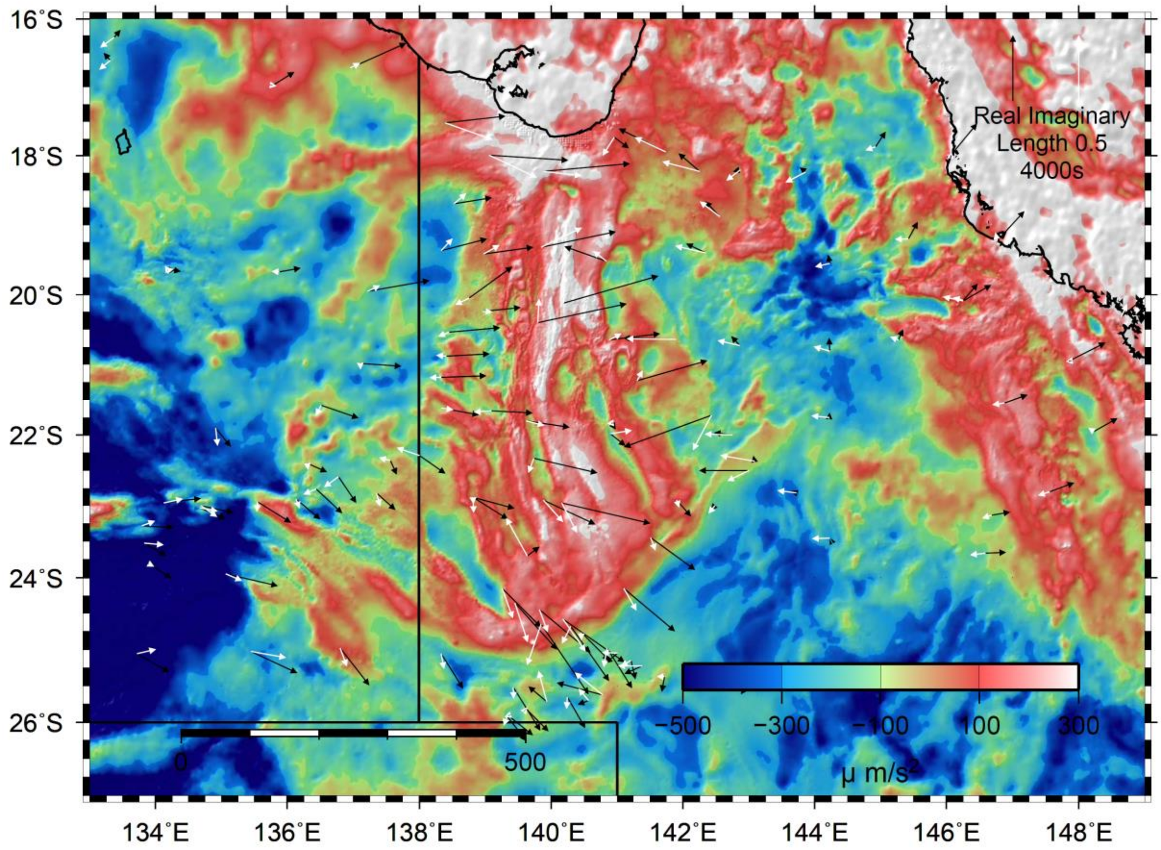

Figure 2: Legacy GDS responses plotted for a period of 4000 s for the Northern Territory (left) and western Queensland (right). Induction arrows are plotted on Bouguer gravity data.

The signal periodicity window is centred at 1000 s for the South-Australia and New South Wales map, and 4000 s for the Northern Territory-Queensland data. For a period of 1000 s, in crust of resistivity 100 Ω.m, the skin-depth is about 150 km and for 4000 s it is about 300 km. Thus, the induction arrows in both plots effectively sample the entire lithosphere.

Arrows are largest adjacent the most significant changes in lateral electrical properties. The largest near-surface contrast is at coastlines where conductive seawater is next to resistive continental crust. In Figures 1 and 2 sites immediately next to the coast demonstrate this response known as the coast effect. However, there are more significant long-wavelength trends through the continent and there is a remarkable correlation with the regional gravity structures indicating a potential causal relationship.

For the South Australian and New South Wales map, the induction arrows point out of the centre of the Archaean Gawler Craton towards the Proterozoic belts around its margin, and are generally orthogonal to the gravity trends. Across the Stuart Shelf and Flinders Ranges, there is a pervasive eastward trend of arrows until the Barrier Ranges in western New South Wales, where the induction arrows are more to the west. Induction arrows in the Northern Territory and western Queensland are aligned mostly east and south-east to the eastern margin of the Mount Isa block. Here arrows are again reversed in orientation to point more to the west. In both figures, a confluence of induction real arrows indicates a concentration of anomalous electrical current between them.

We argue that these induction arrow maps are essentially a proxy for the lower crust conduction. This argument is based on the premise that most significant resistivity heterogeneities are focused in the lower crust, reflecting past thermal and fluid events that have a clear link with the emplacement of mineral systems. Below, we outline the logic in the argument.

NEAR SURFACE

In the context of long-period GDS, the near surface can adequately be defined of order 5 km. For the ocean, seawater depths approach 5 km in the abyssal regions, and give rise to the coast-effect (Parkinson, 1962). For seawater of resistivity of 0.3 Ω.m, the electrical conductance (depth-integrated conductivity) of 5 km ocean is about 16,000 S.

On land, sedimentary cover varies from 0 to about 10 km for the deepest basins. The electrical properties of sedimentary systems are largely determined by the porosity, which decreases exponentially with depth, but with a folding distance of about 10 km (Gleeson et al., 2015). However, saline pore fluids also decrease in resistivity with increasing temperature, which counteracts the porosity decrease and thus the effective resistivity is about 10 Ω.m for most of the basin depths. Some stratigraphy will naturally be considerably more conductive due to surface-charge effects in clays to about 1 Ω.m, but overall the total electric conductance of basins is typically less than 1000 S except for the deepest basin that may approach 2000 S. Thus, the influence of sedimentary basins is less than that of the oceans, and moreover tends to lead to gradual change in GDS response as basins thicken slowly in most places. An example is shown by the small induction arrows across the Officer Basin at the western side of South Australia.

BRITTLE UPPER CRUST

Magnetotelluric models of 2D transects typically show the brittle upper crust to a depth of about 10-15 km to be uniformly resistive > 10^3 Ω.m when sampled by observational sites that are a few kilometres apart (Thiel and Heinson, 2010; Robertson et al., 2015; 2017). Crystalline rocks at low-temperatures are highly resistive and conduction will mainly be in secondary porosity associated with fractures and faults. With coarse lateral sampling, such fine-scale conduction is not apparent in the GDS responses.

DUCTILE LOWER CRUST

The lower crust has long been noted as being electrically heterogeneous, varying from 10^0 to 10^3 Ω.m (Selway, 2014; Robertson et al., 2015; 2016; Thiel et al., 2016). The lowest resistivities of ~1 Ω.m are often imaged in relatively narrow zones at the rheological boundary between the brittle and ductile crust at about 10-15 km depth. At greater depths > 25 km, the lower crust conductive regions tend to be broader and a little more resistive, typically in the range 10-100 Ω.m (Robertson et al., 2016). Overall, the electrical conductance of the lower crust from 10 km to the Moho can be 10,000 S or more, making it of comparable conductance to the deep ocean.

UPPER MANTLE AND ASTHENOSPHERE

Continental upper mantle in the top 100 km is expected to be mostly electrically resistive (Selway, 2014). As continental upper mantle is largely comprised of olivine at temperatures below 1000℃, laboratory measurements suggest resistivities will be of order 10^3 Ω.m or more. Exceptions may be due to electrical conduction in hydrated minerals (Selway, 2014; Thiel and Heinson, 2013) or some other mechanism that may enhance conduction to as low as 1 Ω.m in places. However, as the mantle fertility state is likely to be over distance –scales of hundreds of kilometres, variations in upper mantle resistivity cannot explain the heterogeneous induction arrow response.

CONCLUSIONS

Merging of recent and legacy MT and GDS responses yields a continental-scale view of changes of electrical resistivity. Although ocean bathymetry and sedimentary basins can account for some of the regional response, the continental crust displays a remarkable degree of heterogeneity in electrical properties. We argue that the bulk of the heterogeneity is evident in the lower crust, based on more localised interpretations from smaller transects and grids.

Knowledge of regional-scale lower crust electrical properties is important for two reasons. Firstly, regional correlation with Bouguer gravity and local correlation with known mineral systems suggests that a map of lower crust resistivity may provide a useful first-order proxy of regional-scale mineral-system prospectivity. Secondly, 3D regional deep crustal resistivity is important in modelling and interpreting small-grids and transects of MT, as inductive effects may be significant hundreds of kilometres away from actual surveys.

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