# The Flinders Conductivity Anomal(ies) revisited using AusLAMP Magnetotelluric Data

**Kate Robertson***
*The University of Adelaide*
*North Terrace, Adelaide*
*Kate.robertson@adelaide.edu.au*

**Stephan Thiel**
*Geological Survey of SA*
*101 Grenfell St, Adelaide*
*Stephan.thiel@sa.gov.au*

**Graham Heinson**
*The University of Adelaide*
*North Terrace, Adelaide*
*Graham.Heinson@adelaide.edu.au*

**presenting author asterisked*

## SUMMARY

We use 74 stations from the long period eventual-Australia-wide AusLAMP (Australian Lithospheric Architecture Magnetotelluric Project) dataset to image the electrical resistivity beneath the Neoproterozoic Ikara-Flinders Ranges and adjacent Paleo-Mesoproterozoic Curnamona Province. Results from 3D inversions using ModEM software show a relatively resistive Ikara-Flinders Ranges, with two parallel arcuate conductors at 20 to 80 km depth in the Nackara Arc. There is a good correlation of diamondiferous kimberlites occurring over conductors, which we interpret as evidence for these conductors to be residing on large lithospheric structures that have been conduits for partial melt and volatile movement in the Jurassic period. The Curnamona Province is remarkably conductive for a region that is thought to have a cratonic core, with Delamerian reworking only at its edges. We see an enriched crust that covers most of the province at depths of 10-40 km. The presence of the conductor at lower crustal depths suggests that conductive sediments cannot entirely explain the conductor. We suggest that fluids associated with subduction have pervasively modified the crust in the past, resulting in an enrichment of carbon and sulphides, enhancing conductivity. Additionally, we conclude that the notion of a single continuous arcuate Flinders Conductivity Anomaly is unlikely and that the anomalous response observed is instead a result of the combined response of three separate anomalies; the Curnamona Province Conductor and the two Nackara Arc Conductors.
**Key words:** magnetotellurics, electrical resistivity, lithosphere, AusLAMP.

## INTRODUCTION

The Flinders Conductivity Anomaly (FCA) is a well-known, but little understood anomalous electrical resistivity region that runs through the Curnamona Province and Ikara-Flinders Ranges. Since it was first observed in 1972, interpretations of the shape, location and nature of the anomaly has changed with each new dataset collected.

The FCA was first observed from a magnetometer array study by Gough et al. (1972) who observed a north-south conductor, which they interpreted as a conductive step in the upper mantle. They also defined a possible east-west conductor, to the north of the Ikara-Flinders Ranges. In 1974, Gough et al., stated, 'it is immediately evident that a complicated conductivity structure is present in southern Australia.' Since then, a multitude of surveys with varying interpretations have proven just that- the conductivity structure is complicated. Gough et al. (1974)'s interpretation put the conductor in the lower crust or upper mantle with a possible cause being related to high mantle temperatures under a postulated plate boundary. Lilley & Tammemagi (1972) suggest two interpretations for the conductor; buried rift sediments of the Callanna Beds, or an alternate mantle cause- a shear zone associated with the continental tectonics of Australia. A magnetotelluric (MT) transverse of nine stations by Tammemagi & Lilley (1973) interpreted the FCA as a NW-SE trending line running north of the Ikara-Flinders Ranges, with a resistivity as low as 0.1 Ωm and a minimum thickness of 10 km, with an uppermost surface no deeper than 10 km. Their interpretation related the conductor to the accretion of eastern Phanerozoic Australia on to the stable western Archean-Proterozoic Australia, with the possibility of saline sediments being present in weakened zones. By 1985, a possible southward extension of the FCA was identified with new GDS sites through the Central Flinders Ranges Zone (Chamalaun, 1985). The data revealed an anomaly with a depth estimated to not exceed 30 km, and the author favoured the crustal interpretation of Tammemagi & Lilley (1973), however he did state that, 'the overall conductivity structure may prove to be complex in a vertical plane allowing both shallow and deep seated contributions.' Chamalaun's 1986 paper refines their estimation of the depth of the anomaly to less than 10 km, but notes that for an upper crustal anomaly, it does cross several tectonic units, following the western edge of the Arrowie Basin in the north, entering the Callanna Beds further south, following the trend of the Houghton Anticline. Interpretations from the first MT transect across the Ikara-Flinders Ranges by Wang et al. (1995) revealed two conductive region, extending at some places to depths of 20 km, which were again interpreted as saline fluid-filled sediments. More recently, Milligan et al. (2012) performed a 3D inversion of two MT transects with average site spacing of about 15 km- a north-south transect through the Curnamona Province, and an east-west transect crossing the Ikara-Flinders Ranges and running along the southern edge of the Curnamona Province to the state border. A lower crust to shallow upper mantle (~30-60 km depth) conductor beneath most of the north-south transect was imaged, with the conductor extending to the upper crust in the north, just to the north of Lake Frome. Milligan et al. (2012) agree with the conductive sediment interpretation in the northern half, but suggest that thin coating of graphite may enhance the conductivity in the southerly part of the FCA.

We have collected 76 long period MT sites covering the Ikara-Flinders Ranges and Curnamona Province (Figure 1). We have processed the data and performed 3D inversions, resulting in a three-dimensional model of the electrical resistivity, 500 x 400 km in dimension, to a depth of ~200 km. The new addition of our array provides an excellent opportunity to help determine the nature of the FCA.

## METHOD AND RESULTS

In November 2013, we collected 29 long-period (~1 to 17 000 s) MT sites using AuScope instruments covering the entire Ikara-Flinders Ranges, commencing the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP). AusLAMP is a collaborative project between Geoscience Australia, various universities and state geological surveys, that aims to cover all of Australia with long period MT sites at 0.5 degree intervals (~55 km spacing). An additional 47 stations were collected in June, 2015 to expand the dataset northward, and eastward into western New South Wales. The resulting dataset encompasses the entire Ikara-Flinders Ranges and Curnamona Province. The data were processed using the robust remote processing algorithm BIRRP (Chave & Thomson, 2004) and sites were referenced to neighbouring sites that were recording simultaneously, to improve signal-to-noise ratio and responses at short periods (Gamble et al., 1979). The data were processed to a period range of 1 to 17 000 s. In MT data, longer periods correspond to greater depths, dictated by the skindepth equation which relates the skin depth $\delta(T)$ (in m) to period T by $\delta(T) \sim 500\sqrt{\rho_a T}$, where $\rho_a$ is the equivalent average resistivity of a uniform half-space.

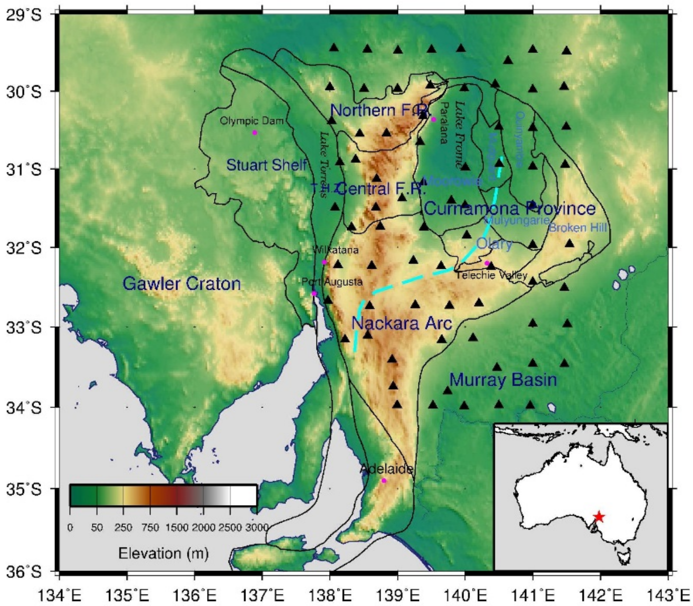


**Figure x: 10 km and 30 km depth slices with induction arrows at a period of 1000 s overlain. 1000s roughly corresponds to lower crust/shallow upper mantle depths. Red regions are conductive, blue are resistive. Induction arrows point in direction of increasing conductivity. Black lines are tectonic zone boundaries as in Figure 1.**

The model files were constructed using the graphical user interface, 3D Grid, for creating and visualising ModEM inputs and outputs (N. Meqbel pers. comms 2013). The mesh dimensions were 70 x 54 x 70 cells in the x, y and z directions respectively. Including padding, model dimensions were 1230 km in the x direction (north-south), 800 km in the y direction (east-west), and 1353 km deep. The dimensions of the survey area is 500 km in the x direction by 400 km in the y direction. Cell sizes are 10 x 10 km, and z layers begin with 50 m thickness, increasing by a factor of 1.125 each layer. Topography and bathymetry were included in the model. Layers were included beneath the ocean to account for sediments, with resistivity linearly increasing from 0.3 Ωm immediately beneath the ocean (which was fixed at 0.3 Ωm), to 30 Ωm at 8 km below sea level. Many inversions were run to investigate the effect of varying certain parameters such as the covariance, half-space starting resistivity, model dimensions, cell size, number of layers and the method of error calculation.

Our preferred model that we present in Figure 2 here inverted for the full impedance tensor and the tipper. It had a starting resistivity of 100 Ωm, a covariance of 0.3 in all directions, and error floors of 10% for the impedance tensor and 3% for the tipper error. A parameter in the ModEM inversion file that determines the minimum RMS decrease per iteration that can occur before the lambda value is decreased, has a default of 1e-2, and was reduced to 1e-3. This resulted in an inversion that took longer to run than other models and performed 228 iterations. Each iteration took about 2.5 hours, with total inversion time about 570 hours (~24 days) across 47 processors on an eRSA supercomputer. We inverted the full impedance tensor at 23 periods from 10 s to 16 000 s, and the tipper at 21 periods ranging from 10 s to 8000 s as the planar wave approximation fundamental to the magnetotelluric theory breaks down at these longer periods for the tipper. The model fit the data well, with a final RMS of 1.33.

Phase tensor ellipses for the measured data, and the modelled responses are shown in Figure 3. A phase tensor ellipse that is a circle indicates one-dimensional resistivity, while one that is elliptical in shape indicates the resistivity is two or three dimensional. The ellipses are shaded with the minimum phase angle, which gives an indication of how the resistivity changes with depth; angles greater than 45 degrees, or a shade of red in this case, show that the structure is becoming more conductive with depth. Conversely, angles less than 45 degrees, or ellipses shaded blue, are representative of increasing resistivity with depth. The phase tensor ellipses within the centre of the Curnamona Province at periods of 100, 500 and even 1000 s are red indicating there is a very conductive region within the Curnamona Province, as are the ellipses in the southern Nackara Arc. Blue ellipses in the north of the model and in the southeast represent the shallow conductive sediments of the Arrowie/Cooper Basins and the Murray Basin, respectively, overlying a more resistive basement. From the ellipses it is apparent that the eastern boundary of the Nackara Arc forms a significant electrical boundary, with the minimum phase lower, and the ellipses more circular, in the Murray Basin than the Nackara Arc. This boundary is also apparent in electrical resistivity models (Figure 2), with a large increase in resistivity moving from the Nackara Arc into the Murray Basin. This arcuate boundary is interpreted to be the transition from the Proterozoic Australia in the west to the Phanerozoic Australia in the east. Using ambient noise tomography, Rawlinson et al. (2014) show that the fast axis of anisotropy aligns in a curvilinear north-south direction with the western edge of the Murray Basin, roughly coinciding with the eastern limit of Precambrian basement.

The model comprises a mainly resistive Ikara-Flinders Ranges, with resistivity varying from 1000-5000 Ωm in the crust, reducing to about 1000-2000 Ωm by 60 km. At a depth of 1 km, the model is very resistive, with the exception of the Murray Basin in the southeast, and the Cooper Basin in the north, which are both very conductive (~10 Ωm). The Curnamona Province exhibits a complex resistivity structure, with a very resistive Broken Hill Domain on the eastern third of the province (~2000-10 000 Ωm). The eastern two-thirds of the province are host to a large conductor (~1-50 Ωm), spanning a depth of about 5-40 km. At 10 km, the conductor is elongated in the north-south direction, 250 km long by 100-150 km wide, residing almost entirely within the Quinyambie Domain of the Curnamona Province. The conductor dips steeply westward, and by 20 km the conductor almost covers the Mudguard and Moorowie Domains. By this depth, other conductors begin to appear, this time within the Nackara Arc. Two broken up conductors follow the arcuate axis of the Nackara Arc, 50 km in diameter and about 250 km along, fully connected by 30 km, extending down to at least 60-80 km, with resistivities of about 1-50 Ωm. At 30 km, the shape of the Curnamona Province conductor has altered, forming an upside-down T-shaped conductor, until it disappears almost entirely by about 40 km.

## DISCUSSION

It seems unlikely that the observed anomalous features in the GDS and MT surveys summarised in the introduction are all highlighting one single conductor. Within the Nackara Arc of the Ikara-Flinders Ranges, the 3D model delineates two roughly parallel, arcuate conductors that follow the curve of the arc (labelled the Western Nackara Arc Conductor-WNAC, and the Eastern Nackara Arc Conductor-ENAC). The main conductor of the ENAC spans depths of about 20 km to 60-70 km, and the WNAC from 20 km to 80 km. It is difficult to say whether these conductor extend further into the mantle with a lower conductivity, as resolution decreases significantly beneath large conductors, creating a downward smearing effect of conductors. Further north, an apparently separate conductor exists probably entirely within the crust of the Curnamona Province (Curnamona Conductor-CC). The CC starts at a depth of about 5 km in the North, although we cannot eliminate the possibility of a connection to the surface, and 20 km in the south of the Curnamona Province, extending to about 40 km depth throughout most of the CC.

Figure 2 shows induction arrows at a period of 1000 s over a 10 km and a 30 km depth slice, with the current best estimate of the Flinders Conductivity Anomaly indicated by the cyan dashed line. Within the northern half of the array, most induction arrows arrays point toward the Curnamona Conductor, which spans depths of about 10-35 km. Induction arrows in the northern half of the FCA point to the large conductive body in the Curnamona Province at depths of 10-30 km. Moving southward from the Curnamona Province into the Nackara Arc, the notion of a continuous conductor now seems unlikely. We observe a large conductor in the Nackara Arc spanning depths of about 30 km to 160 km, with the orientation of the conductor roughly matching the orientation of the expected FCA at depths of 30-50 km. Thus we can deduce that the 'FCA' can be split into three different conductors, the Curnamona Conductor at 10-30km and the Eastern and Western Nackara Arc Conductors at 30-80 km.

The enhanced conductivity of the Curnamona Province suggests that it may have been pervasively altered. However, the Broken Hill Domain remains resistive at all depths, despite it being a highly mineralised region. Resistivity, geochemistry and potential field data suggest that the transition from the majority of the Curnamona Province to the Broken Hill Domain is a significant lithospheric boundary (Williams & Betts, 2007; Rutherford et al., 2006). Geochemical data indicates that the Olary Domain may have been reworked from subduction-associated sediments and fluids which may have resulted in an enhanced conductivity signature, which has been retained for perhaps over 1.5 Ga, since the Olarian Orogeny (Rutherford et al., 2006).

The ENAC is within the locality of the Proterozoic-Phanerozoic transition, and is therefore likely to be a considerably weakened lithospheric zone. Diamondiferous kimberlites erupted in the Jurassic have been found within the conductive region encompassed by the Nackara Arc Conductors, indicating that in the past there has been major pathways ascending throughout the lithosphere. We suggest that mantle-sourced fluids or partial melt have moved through the lithosphere in the past, altering the subsurface and depositing conductive phases such as grain-boundary graphite films.

## CONCLUSIONS

Overall, the Ikara-Flinders Ranges are quite resistive (1000-5000 Ωm), however the magnetotelluric data imaged a very conductive crust within the Curnamona Province, which we interpret to be the result of conductive sediments and refertilisation from subduction associated fluids and sediments. Despite induction arrows from electromagnetic studies over the last 45 years suggesting that there exists a single continuous conductor of length ~400 km, we observe two distinctly separate conductors occurring in the Nackara Arc. The Eastern Nackara Arc conductor is a significant lithospheric structure, situated at the approximate location of the transition from Proterozoic to Phanerozoic lithosphere. The conductors coincide with diamondiferous kimberlites erupted in the Jurassic, indicating that this region may once have formed a lithospheric-scale pathway. We suggest that a conductive phase, perhaps grain-boundary graphite films, may have been deposited during the ascent of the partial melt or fluids, enhancing the conductivity, a signature still retained in the lithosphere today.

**ACKNOWLEDGMENTS**

We would like to thank AuScope for use of the instruments, and Goran Boren for looking after the instruments. Thanks to the many field personnel and to Geoscience Australia for logistical assistance. Thank you to Peter Milligan for introducing KR to the Flinders Conductivity Anomaly early in her PhD. Thanks to Andy Love for assistance with contacting landholders, and to the landholders and traditional owners themselves for granting permission to their lands. Thanks to Wolfgang Preiss and Anthony Reid for helpful discussions. All figures were produced using GMT, and 3D inversions were performed on eResearchSA supercomputers.

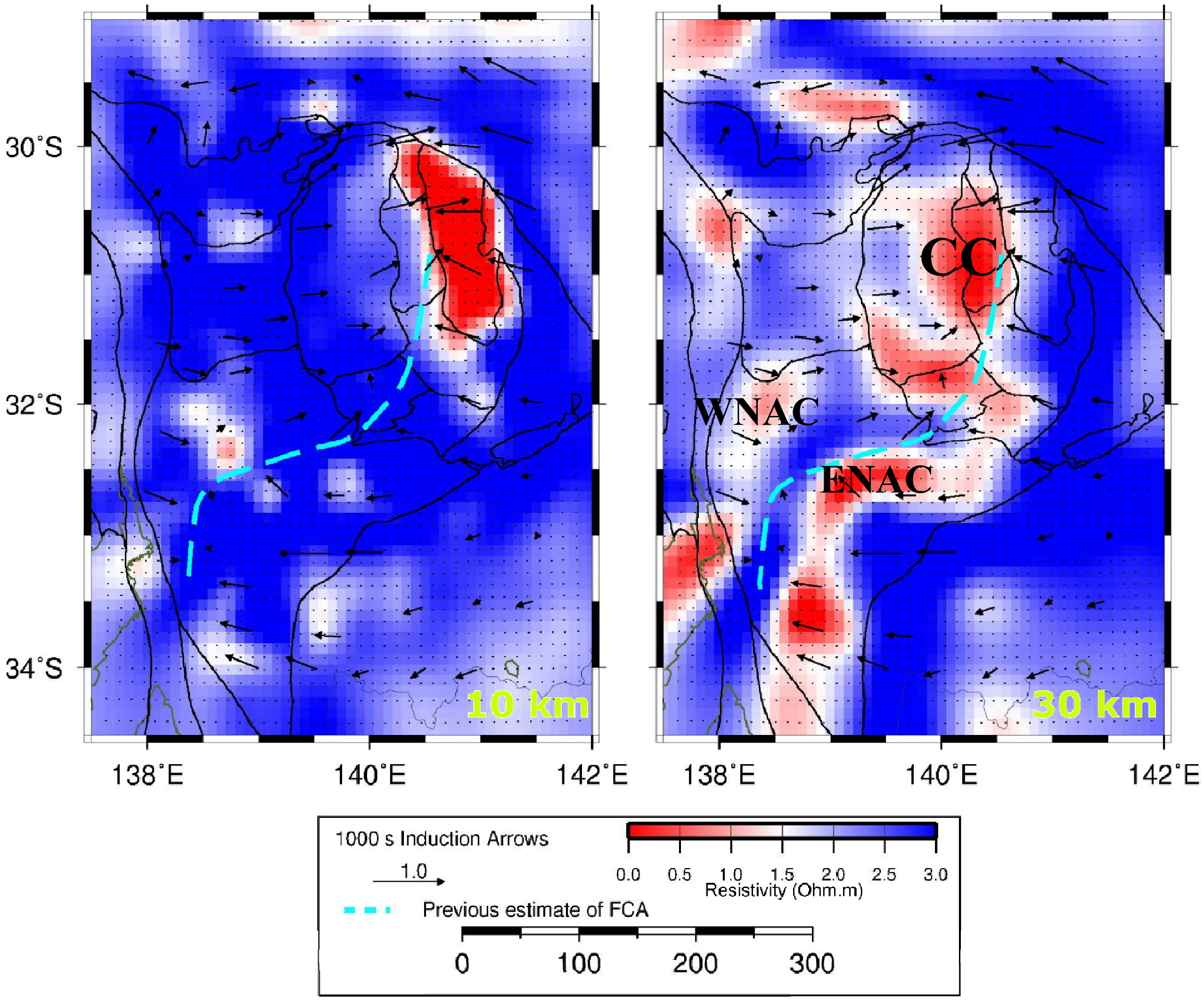


**Figure 2: 10 km and 30 km depth slices with induction arrows at a period of 1000 s overlain. One arrows is shown for each station, and arrows point in direction of increasing conductivity. A period of 1000 s roughly corresponds to lower crust/shallow upper mantle depths. Red regions are conductive, blue are resistive. Black boundaries are the tectonic zones as labelled in Figure 1. CC= Curnamona Conductor, ENAC=Eastern Nackara Arc Conductor, WNAC=Western Nackara Arc Conductor**

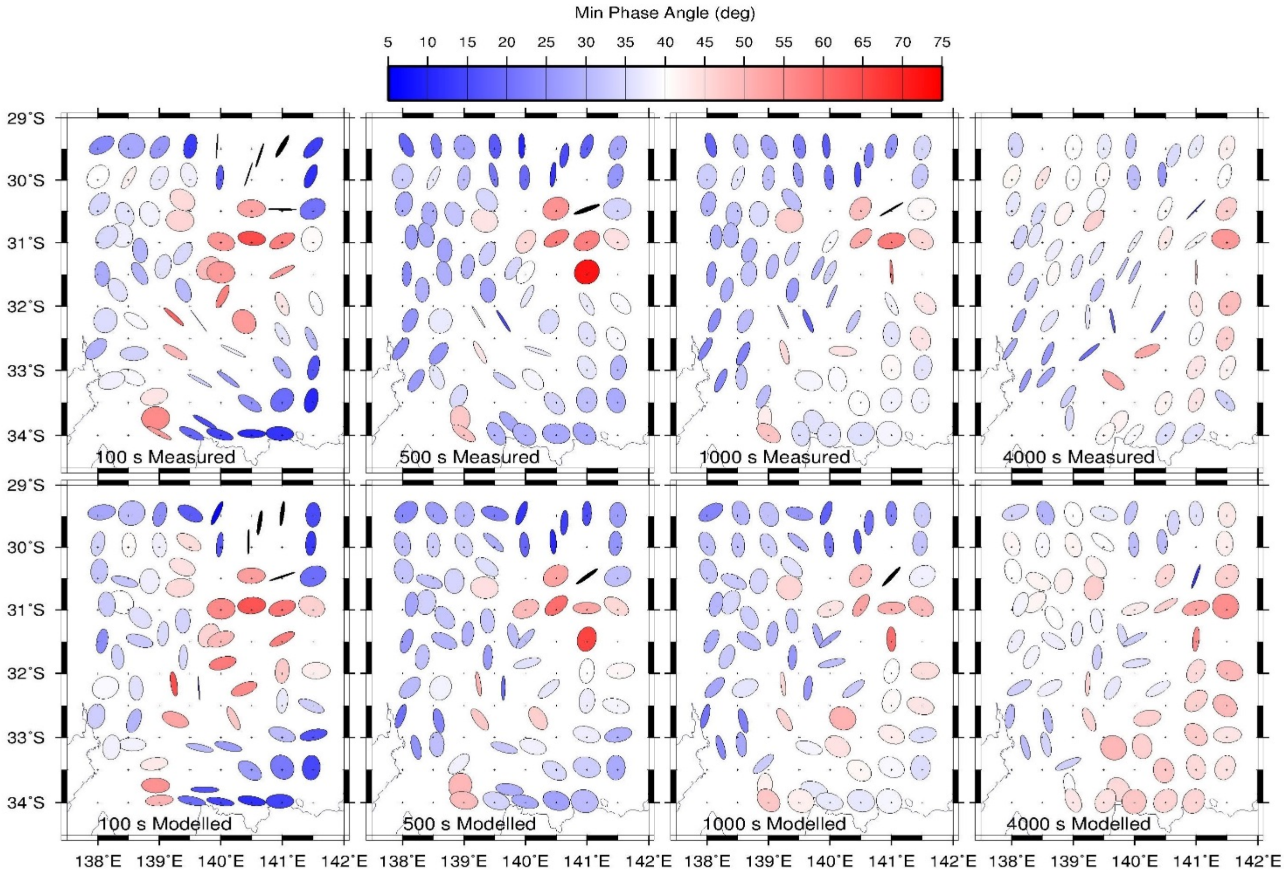


**Figure 3: The top row show phase tensor ellipses for the actual data for periods of 100 s, 500 s, 1000 s and 4000 s. The bottom row show the phase tensor ellipses of the modelled data. Red ellipses indicating conductivity increasing with depth, blue indicates conductivity decreases with depth.**

## REFERENCES

Chamalaun, F.H., 1985, Geomagnetic deep sounding experiment in the central Flinders ranges of South Australia: Physics of the Earth and Planetary Interiors, 37(23), 174-182.

Chamalaun, F.H., 1986, Electrical conductivity structures and anomalies: extension of the Flinders Ranges anomaly: Exploration Geophysics, 17, 31.

Chave, A.D. and Thomson, D.J., 2004, Bounded influence magnetotelluric response function estimation: Geophysical Journal International, 157(3), 988-1006.

Egbert, G.D.and Kelbert, A., 2012, Computational recipes for electromagnetic inverse problems: Geophysical Journal International, 189(1), 251-267.

Gamble, T.D., Goubau, W. M. and Clarke, J., 1979, Error analysis for remote reference magnetotellurics: Geophysics, 44 (5), 959-968.

Gough, D.I., McElhinny, M.W. and Lilley, F.E.M., 1974, A magnetometer array study in southern Australia: Geophysical Journal of the Royal Astronomical Society, 36(2), 345-362.

Gough, D.I., Lilley, F.E.M. and McElhinny, M.W., 1972, A Polarization-sensitive Magnetic Variation Anomaly in South Australia: Nature Physical Science, 239. 88-91.

Lilley, F.E.M. and Tammemagi, H.Y., 1972, Magnetotelluric and geomagnetic depth sounding methods compared: Nature Physical Science, 240, 184-187.

Milligan, P.R., Dhu, T., Duan, J. and Thiel, S., 2012, New magnetotelluric data across enigmatic conductivity anomalies that span Australia north-south: 21st Electromagnetic Induction Workshop, Darwin.

Rutherford, L., Barovich, K., Hand, M. and Foden, J., 2006, Continental ca 1.7- 1.69 Ga Fe-rich metatholeiites in the Curnamona Province, Australia: a record of melting of a heterogeneous, subduction-modified lithospheric mantle: Australian Journal of Earth Sciences, 53(3), 501-519.

Tammemagi, H.Y. and Lilley, F.E.M., 1973, A Magnetotelluric Traverse in Southern Australia: Geophysical Journal of the Royal Astronomical Society, 31(4), 433-445.

Wang, L.J. and Chamalaun, F.H., 1995, A magnetotelluric transverse across the Adelaide Geosyncline: Exploration Geophysics, 26, 539-546.

Williams, H.A. and P. G. Betts, P.G., 2007, Imaging links between lithospheric architecture and surface geology in the Proterozoic Curnamona Province, Australia: Journal of Geophysical Research: Solid Earth, 112.