Magnetotelluric survey of the Central Australian Craton, with a focus on the structural history of the Warumpi and Musgrave Provinces and the Arunta Complex.

Thesis submitted in accordance with the requirements of the University of Adelaide for an Honours Degree in Geophysics

Alan Geoffrey Oertel

November 2013

THE UNIVERSITY of ADELAIDE

MAGNETOTELLURIC STUDY OF CENTRAL AUSTRALIA

ABSTRACT

In spite of the continent of Australia being the oldest and most tectonically stable on Earth, its structural history is still the subject of much conjecture. The final closure of the South Australian Craton with the North Australian Craton at roughly 1080 million years ago deformed much of Central Australia into the lithospheric arrangement observed today. Structural constraints have been developed in the last 30 years on the history of the Musgrave Province, Amadeus Basin, Warumpi Province and Arunta Complex in the southern part of the Northern Territory. In this study the resistivity structure of these four provinces was assessed through the use of a long-period magnetotelluric survey along the Stuart Highway from the South Australia-Northern Territory border to 90 kilometres north of Alice Springs. A key focus was to determine whether the structural arrangement, identified in a magnetotelluric survey conducted 100 kilometres to the east of this profile in 2006, is laterally consistent between the four provinces. In the Stuart Highway profile model the major structures present exhibit a different arrangement, particularly in the northern part of the profile, resulting in the conclusion that the mechanism for the lithospheric closure of the region was a more complex nature than was previously thought.

KEYWORDS:

MAGNETOTELLURIC, WARUMPI, MUSGRAVE, ARUNTA, RESISTIVITY, STRUCTURE

TABLE OF CONTENTS

Magnetotelluric Study of Central Australia 1
Abstract 1
Keywords: Magnetotelluric, Warumpi, Musgrave, Arunta, Resistivity, Structure 1
List of Figures 3
Introduction 4
Methods 7
Physical Method 7
Magnetotelluric Theory 9
The Magnetotelluric Method 9
The Phase Tensor 9
Induction Arrows 10
Inversion and Forward Modelling 10
Observations and Results 11
Static shift 14
Appraisal of Model Robustness 19
Interpretation of structure 21
Discussion 22
Difficulties in modelling 22
Correlation of model with surface geology 22
Comparison of model with Selway et al. 2006 24
Regional phase tensors 26
Interpretation 28
Future work 29
Conclusions 30
Acknowledgments 31
References 31

LIST OF FIGURES

Figure 1: Geological map of the Northern Territory with the Stuart Highway and Selway et al. (2009) survey locations indicated. The Stuart Highway survey includes the Musgrave Province, Amadeus Basin, Warumpi Province and southern edge of the Arunta Complex……………………………………………6

Figure 2: Topographic maps of survey region with phase tensor ellipses and induction arrows for periods of 50 seconds and 500s overlain………………………………………………………………………..11

Figure 3: Model responses of apparent resistivity and phase characteristic of the Musgrave Province, Amadeus Basin, Warumpi Province and Arunta complex within the profile ....……………………13

Figure 4: Apparent resistivity and phase responses of survey site 2 showing clear static shift…………..14

Figure 5: Apparent resistivity and phase responses of survey site 22 showing clear static shift…………15

Figure 6: Occam inversion model of profile……………………………………………………………16

Figure 7: Occam inversion model of profile for TM-only mode………………………………………….17

Figure 8: Contrast-enhanced Occam inversion model of profile………………………………………….18

Figure 9: Occam inversion model with misaligned rotation of data showing potential 3-D effects below the Amadeus Basin………………………………………………………………………………………..19

Figure 10: Comparison of models with and without sites 22 and 23, testing robustness of shallow conductive features in the Arunta Complex…………………………………………………………….21

Figure 11: Resistivity model from Selway et al (2009) for parallel profile 100 kilometres to the west….25

Figure 12: Topographic map of greater region with phase tensor ellipses and induction arrows incorporated from Selway et al. (2009) and Selway et al. (2011)…..27

INTRODUCTION

The centre of Australia developed under tectonically active conditions, ending with the final closure of the Musgrave Orogeny which has been dated to 1080 Ma; however the tectonic regime and timing are not yet fully constrained. Surface geochronology including Morrissey et al. (2011), seismic surveys such as in Korsch and Kennard (1991) and Wright et al. (1993), and other sources, constrain the major structures. Magnetotelluric (MT) methods will be effective in further adding to the known history. Current evidence suggests a south-dipping subduction regime at around 1100 Ma, and this requires further evidence from sources, including MT, to support or refute the hypothesis by constraining lithospheric geometries. A key factor which requires constraining is the subsurface resistivity distribution. This is affected by whether a subduction-related metamorphic fabric dating to 1130 Ma in the Warumpi Province is corollary to a subduction closure, as this fabric may serve as a defining characteristic in the shallow resistivity structure of the region.

Over the last two decades the understanding of the age and mechanism of the Central Australian crust and lithosphere assembly has progressed and been redeveloped many times. A seismic modelling study by Wright et al. (1993) revealed no major lithospheric-scale structure between the Arunta Complex and the Warumpi Province of the North Australian Craton. This lead to the conclusion that they were the same crustal block, however this was refuted in the Selway et al. (2006) magnetotelluric survey and resistivity modelling. The new survey identified a lithospheric scale sub-vertical structure between the Warumpi Province and the Arunta Complex. This change in understanding is likely due to the sub-vertical nature of the structure to at least 40km depth being unable to produce a seismic reflecting surface. Further magnetotelluric study interpreted that below 40km depth the structure changes to a south-dipping orientation to at least 150km depth (Selway et al., 2009).

Isotope geochronology suggested that the Musgrave Province was reworked in a Grenvillian-Musgrave Orogeny reflecting the slow suturing of the North Australian Craton (NAC) with the South Australian Craton (SAC) between 1300 Ma and 1100 Ma (Wade et al., 2006). This is supported by the 1080 Ma dyke swarm identified as spanning both the Arunta Complex and the Musgrave Province. These observations lead to the conclusion that Central Australia region must have existed in its current configuration by no later than 1080 Ma.

Low-angle foliation structures defined by a garnet-staurolite fabric were found to have formed at 1130 Ma (Morrissey et al., 2009). This indicates that a Grenvillian-aged deformation was the cause of the garnet-staurolite fabric and subsequent andesite growth. This fabric is widespread across the entire Warumpi Province, but is not seen anywhere within the Arunta Complex, which indicates that the collision of the Arunta and Warumpi blocks was no earlier than 1130 Ma.

The Central Australian region is now thought to have been constructed in its current configuration during the Musgrave-Grenvillian Orogeny from 1200-1100 Ma. South-dipping subduction of the Arunta Complex beneath the Warumpi Province may have resulted in the garnet-staurolite metamorphic fabric, which has led to the more resistive bulk composition of the Warumpi Province (Close et al., 2003). Further magnetotelluric modelling of the region to confirm whether the major south-dipping structure is laterally extensive is needed to support or refute this hypothesis.

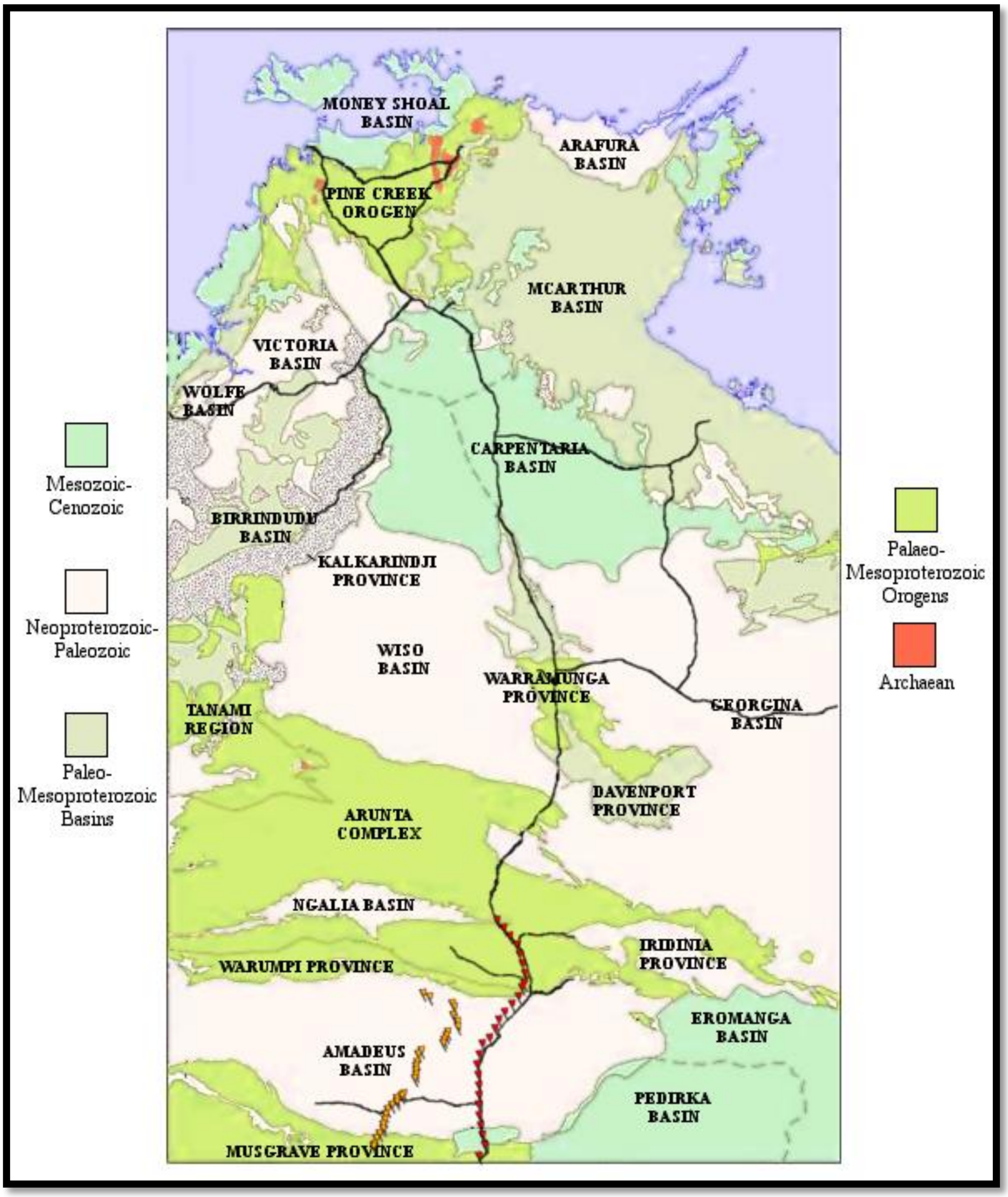

Figure 1: Geological Map of the Northern Territory with major roads also shown. The major lithological units of the Northern Territory have been identified, with some smaller ones omitted in the northern part of the territory. Units have been grouped by era of formation. Of interest to this survey are the Musgrave Province, Amadeus Basin, Warumpi Province and Arunta Complex. The locations of sites from the magnetotelluric survey are shown as red flags, while those from the survey in Selway et al. (2009) are indicated with yellow flags. It should be noted that the geological boundaries shown are surface interpretation and will be different at depth, and that in places these boundaries may be assumed where there is shallow cover and not entirely accurate. Adapted from Geoscience Australia geological map series.

In this study the magnetotelluric long-period method of resistivity imaging will be used to determine the nature of resistivity structures on a north-south profile through the Musgrave Province, Amadeus Basin, Warumpi Province and Arunta Complex of the Central Australian region. By comparing models of data acquired along the Stuart Highway in June 2013 with models from previous magnetotelluric studies a more detailed model of the structural history of the Warumpi Province, the Musgrave Region and the Arunta Complex will be developed. The profiles used for comparison in this study were Selway et al. (2009) which is roughly parallel to the Stuart Highway ~100 km to the east, and Selway et al. (2011) extending along the profile line to the south through the Gawler Craton. It is intended that this will support or refute the south-dipping subduction model, constrain the age and spatial relationships of these provinces, and provide insight into the tectonic setting which led to the formation of the region.

METHODS

Physical Method

Fourteen long-period magnetotelluric data-loggers were placed at twenty eight sites spaced 15 kilometres apart along the Stuart Highway, with the southernmost being located near the South Australia-Northern Territory border and the northernmost being 90 kilometres northeast of Alice Springs. Each site recorded six days of variations in electric and magnetic field. In addition to the twenty eight long-period sites, twenty broadband sites were also deployed with one kilometre spacing to the north of Alice Springs. This targeted the eastern Warumpi Province and the southern Arunta Complex, across the Central Australian Suture. Five broadband instruments were used and each site recorded for between twenty and forty hours.

The long period sites employed Bartington sensors sampling at 10 Hertz while the broadband units sampled at 1000 Hertz. This gives an expected frequency range of 0.004 to 800 seconds for the broadband and 10 to 20000 seconds for the long period instruments. All 48 sites employed a three electrode system; a ground electrode, one electrode to the north or south, and one electrode to the east or west. Electrode separation of the dipoles averaged 45 metres.

MT impedances and error margins were calculated using BIRRP code as described in Chave and Thomson (2004). Remote referencing with data from the Alice Springs Magnetic Observatory was used to remove the majority of random noise. Impedances in the frequency domain were used to generate phase tensor plots (Caldwell et al, 2004).

A discrete Fast Fourier transform reduces the data to complex coefficients in the frequency domain. Once the data for a given site was stacked, dimensionality was examined through use of the phase tensor approach (Caldwell et al, 2004), which was used to determine dimensionality of the data. The iterative Occam algorithm from deGroot Hedlin and Constable (1990) used the apparent resistivity and phase of all sites to generate inversion models, and these models were used to generate pseudo-data through forward modelling. Comparison of the pseudo-data with the original data was used to determine the accuracy in the model, and the best model was obtained through iterative inversion with varying parameters such as apparent half-space resistivity. Repeated modelling with sites individually removed was used to test features of the model which were close to individual stations, and thus quality control the interpretation by confirming that features were real. Model parameters were adjusted to optimise the fit to the data while still maintaining good smoothness and RMS misfit in the apparent resistivity. Topographic images of the region were corroborated with previous magnetotelluric surveys and known geological features in the surface and upper crust to further constrain the geological feasibility of the interpretation.

Magnetotelluric Theory

THE MAGNETOTELLURIC METHOD

The magnetotelluric method is a passive electromagnetic method involving the orthogonal measurement of the electric and magnetic fields on the surface of the earth as defined in Simpson and Bahr (2005). It is a passive method insofar as it utilises naturally occurring variations in the geomagnetic field as the power source for measurement. The source of the geomagnetic field is the magneto-hydrodynamic process of the earth's outer core (McPherron, 2005); however external influences cause transient variations in the field which can be detected. The primary source of these variations is the interaction of solar winds with the ionosphere, with lightning strikes also producing small-amplitude variations in the field (Wait, 1954). These transient signals are of particular interest for the MT method due to their effects in producing secondary magnetic fields and eddy currents in the lithosphere due to the limited timeframe of discrete events producing the strongest eddy currents for the highest resolution detection (Simpson and Bahr, 2005).

THE PHASE TENSOR

The phase tensor introduced by Caldwell et al. (2004) is the ratio of the real and imaginary parts of the impedance tensor. The phase tensor method, unlike previous methods, does not require presumptions of dimensionality, and indeed is still applicable in the case of complex heterogeneous 3-D structures. The phase tensor is usually depicted graphically as an ellipse with the minor and major axes proportional to the values of $\boldsymbol{\varphi}_{\mathbf{min}}$ and $\boldsymbol{\varphi}_{\mathbf{max}}$ respectively. The skew angle β is also represented in the phase tensor ellipse as the deviation of the major axis from the axis of symmetry. This angle β is useful in identifying potential 3-D effects which cause disruptions or false features in a 2-D modelling process.

INDUCTION ARROWS

Induction arrows, described as quadrature Parkinson arrows in Lilley (1982), are used to depict geomagnetic induction as detected during magnetotelluric studies. They serve as a graphical representation of the variation in magnetic induction with depth, which is strongly correlated to changes in conductivity. As such, induction arrows will tend to point towards conductive features such as shear zones and sedimentary basins.

An individual induction arrow is for a specific period in the magnetotelluric time series, and as such is indicative of the signal at a single distance from the survey site. The longer the period, the greater the distance from the site, be it vertically or laterally.

INVERSION AND FORWARD MODELLING

Iterative inversion modelling is the process by which a predefined number of constant resistivity blocks have artificial resistivity values repeatedly generated. These artificial values then have pseudo-responses calculated and comparison of the pseudo-data with the responses of survey data is used to constrain the next generation of forwards models, with the goal of creating a smooth and feasible model which fits well to the survey data. In the Occam inversion code from deGroot and Hedlin (1990) the Lagrange multiplier $\boldsymbol{\lambda}$ is introduced. The $\boldsymbol{\lambda}$ value controls whether more weight is given in a forward model to minimising the norm of the model or the norm of the misfit of the model. In the final model figures produced, the norm of the model is denoted by the roughness, while the misfit is shown as the RMS of the model.

OBSERVATIONS AND RESULTS

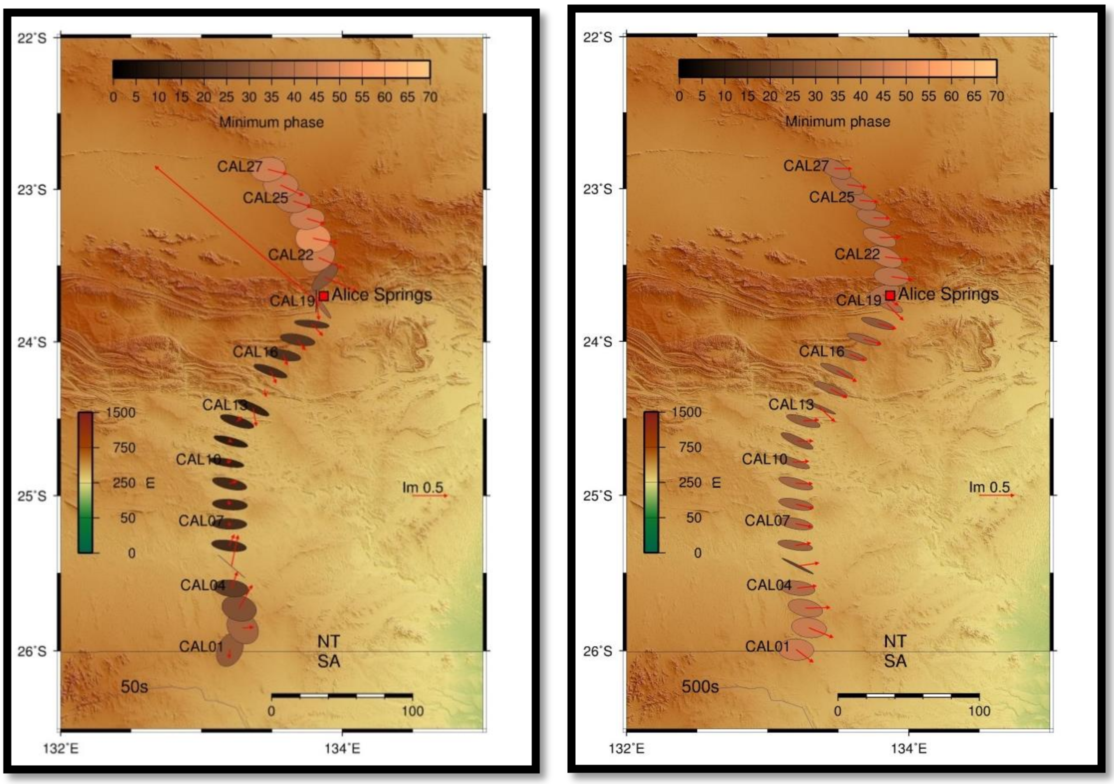

Figure 2: Topographic map of the Central Australian Region from 132° to 135° East and 22° to 25° South. Phase tensor ellipses and induction arrows of the 27 long-period magnetotelluric sites are overlain onto the topography. The phase tensor ellipses are for period of 50s and 500s, and indicate that the geoelectric strike of the region is approximately E-NE and the minimum phase varies much more than the ellipse orientation. This regional geoelectric strike is used to orient the impedance tensor information for modelling. The induction arrows are also for periods of 50s and 500s. These arrows tend to be directed towards conductive regions such as boundaries between provinces and shear zones, which is the case in the left image, yet in the right image of the figure the arrows are directed almost uniformly south-east. This indicates that there is likely a large conductive body east of the profile. This may be a large sedimentary basin or fault complex. There are variations in the south-east direction of induction arrows and these variations, which are more evident in the left image, indicate where some of the boundaries within the profile are. The induction arrow of site 12 points to the east, while site 13 points south-east, thus there is a strong likelihood of a conductive boundary between those sites. There is a trend in the left image for sites 3 to 6 to be directed north and sites 13 to 19 to be directed south, which is expected due to the presence of the sedimentary Amadeus Basin. The strong south-east trend of the induction arrows in the 500s period image obscures the identification of other conductive boundaries from being observed through induction arrows.

The induction arrows in Figure 2 with periods of 50s show variable direction, while those with periods of 500s show a clear trend towards the east and south-east. Induction arrows are used to identify the presence of boundaries in the electromagnetic resistivity structure, as they will tend to be directed towards conductive bodies such as shear zones (Lilley, 1982). In this case the very strong trend in direction of the 500s image indicates the likelihood that there is a large conductive structure to the east and south-east of the profile. The trend being much more evident in the longer period indicates that the conductive body is several hundred kilometres from the profile, as the 50s period will detect much more localised features. This conductive body may be a sedimentary basin, and to the south-east the Pedirka Basin is overlain by the Eromanga Basin as seen in Figure 1. These basins are potentially the source of this signal. Deviations in the direction of the induction arrows may still be used to identify potential conductive zones in the profile, as in Figure 2 between sites 12 and 13. In this case the induction arrows point more towards the adjacent site than other sites do, deviating from the overall easterly trend and indicating a second influence on arrow direction.

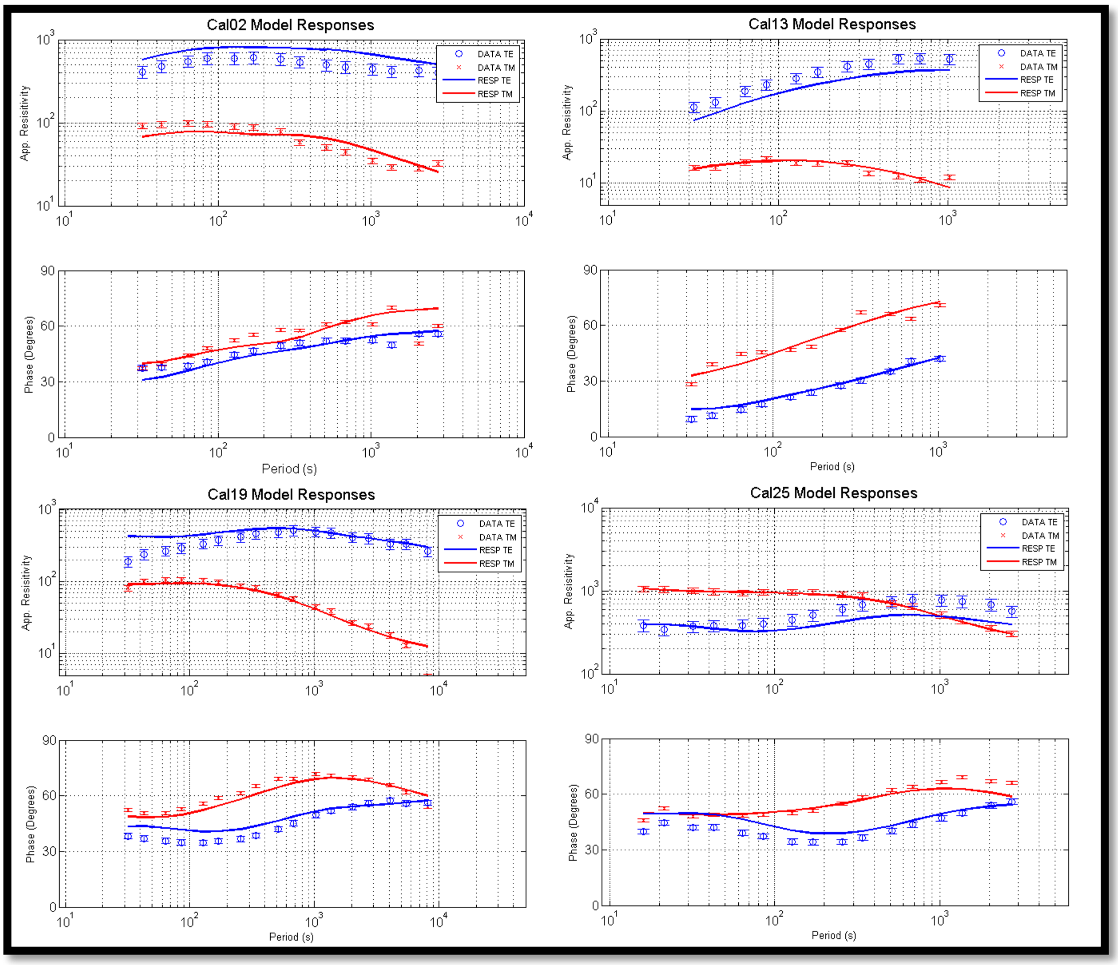

Figure 3: The apparent resistivity and phase curves of sites which are representative of the four major lateral zones of the profile. The more resistive at depth and southernmost zone is represented by site 2. The most laterally extensive zone comprising of sites 4 through to 18, and characterised by site 13, shows a clear conductive layer in the upper crust to a depth of <10 km, which is superseded by a resistive body of up to 80 km depth. The lower part of the model is then more conductive. Of particular interest in this part of the profile is the tendency for the phase of the TM mode to exceed 90° for longer periods. These periods show 3-D effects and are discarded before inversion modelling, however this may result in lack of resolution at depth. The third site depicted in this figure is site 21, which can be considered representative of sites 19 to 22. This set of sites shows a very distinct resistive structure to ~90 km depth, with the body being elongated to the north along the crust. The fourth and final zone is of sites 22 to 27 which is uniformly resistive at depth, but shows a series of shallow conductive bodies which are quite small and distinct compared with other structures in the profile. This zone is characterised by the apparent resistivity and phase curve profile of site 25.

The four geological regions included in the profile were the Musgrave Province, Amadeus Basin, Warumpi Province and Arunta Complex. These regions appear in the model as sets of similar resistivity responses which are characterised in Figure 3 by a site from each region of the profile. The Musgrave Province is the southernmost, and is characterised by Site 2. The Amadeus Basin is the most extensive at the surface, spanning sites 4 to 18, and characterised in Figure 3 by Site 13. Typical of this region, the phase of the transverse electric mode increases with depth, so longer periods have been masked from the data prior to modelling when the phase exceeds 90°.

Site 19 is indicative of the Warumpi Province showing high apparent resistivity decreasing in longer periods. Site 25 is characteristic of the Arunta Complex spanning sites 23 to 27, with typically high apparent resistivities at all periods. The Arunta Complex is the region of the survey which was most subject to the effects of static shift.

Static shift

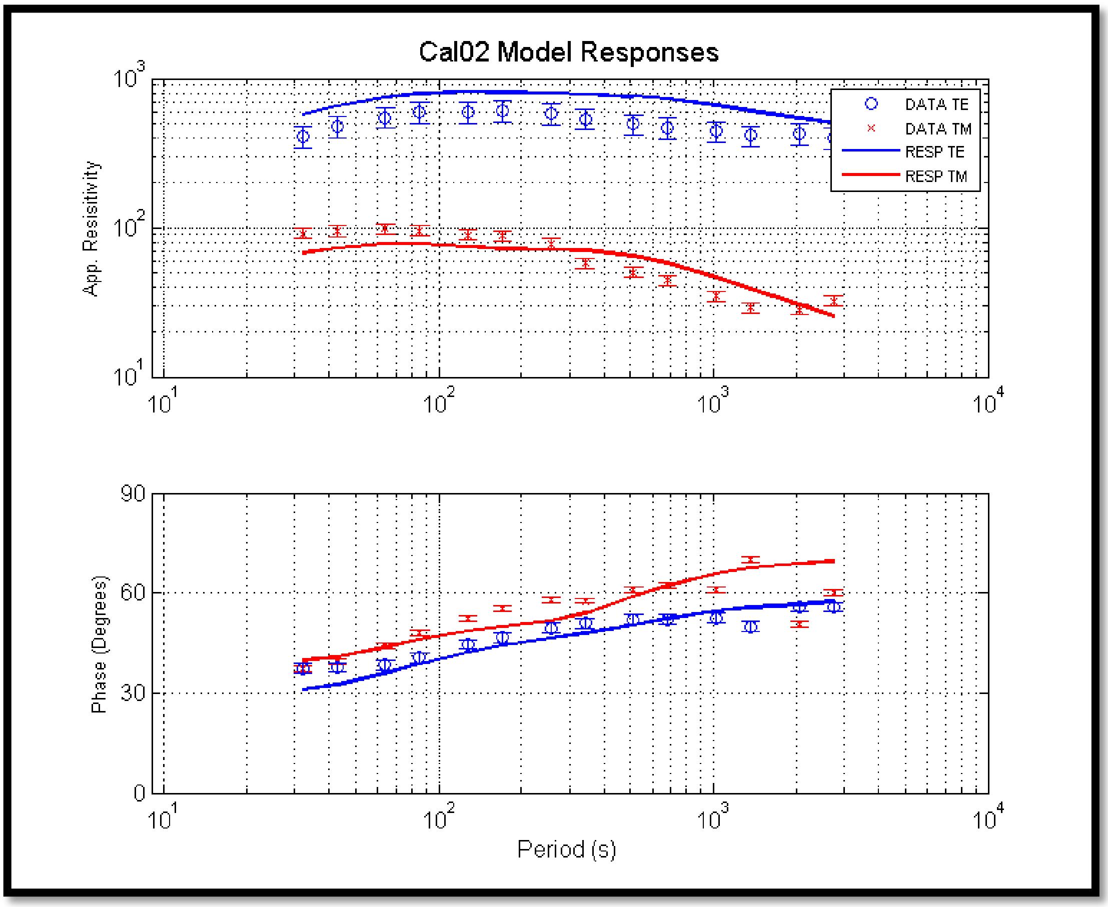

Figure 4: Apparent resistivity and phase curves of station CAL02. As with all sites included in the model, both the apparent resistivity and phase curves for the TM mode modelled a good fit of the model to the observed data. The phase of the TE mode is also a good fit to the data, yet the

apparent resistivity of the TE mode has higher modelled amplitude than the original data. This is due to static shift.

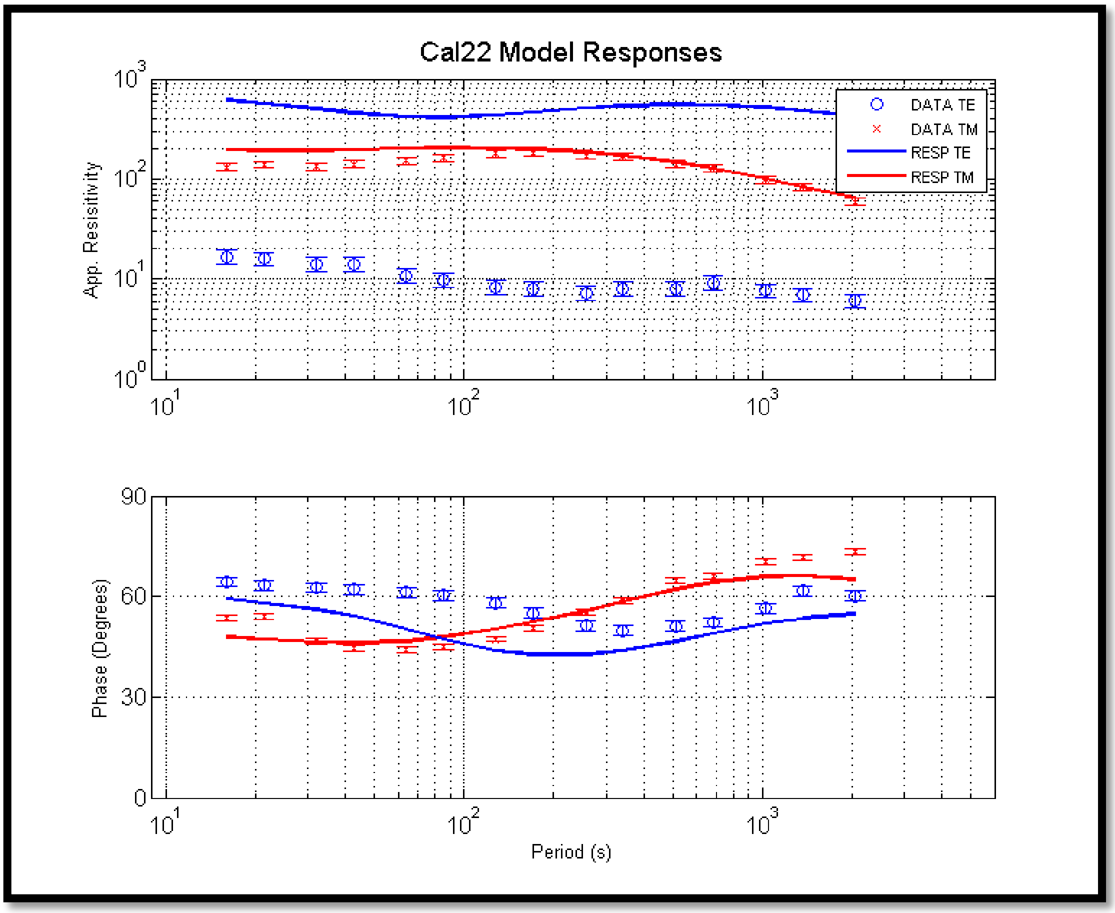

Figure 5: Apparent resistivity and phase curves of station CAL22. As seen in figure 4 of site 2 as well as all other modelled sites, the phase and apparent resistivity curves of the TM are a good fit of the model to the original data. As with the majority of sites, the TE mode phase curve is a good fit to the data. The modelled TE apparent resistivity curve shows a similar shape to the original data, however the amplitude is completely different, clearly indicating that static shift is affecting the data of the profile.

There is evidence of static shift in the apparent resistivity curves. Sites with phases which fit the model to the data well may still show discrepancies in the apparent resistivity curves. Figure 4 and Figure 5 are the apparent resistivity and phase curves of site 2 and site 22 respectively. Both of these figures show clear indications of static shifting in that while the phase curve of the model very closely matches that of the data, there is a distinct difference in the amplitude of the apparent resistivity in the TE mode. The transverse electric (TE) mode is more prone to show static shift than the transverse magnetic (TM) mode in the MT method (Spitzer, 2001), which supports this as being static shift rather than galvanic distortion (Groom and Bailey, 1989).

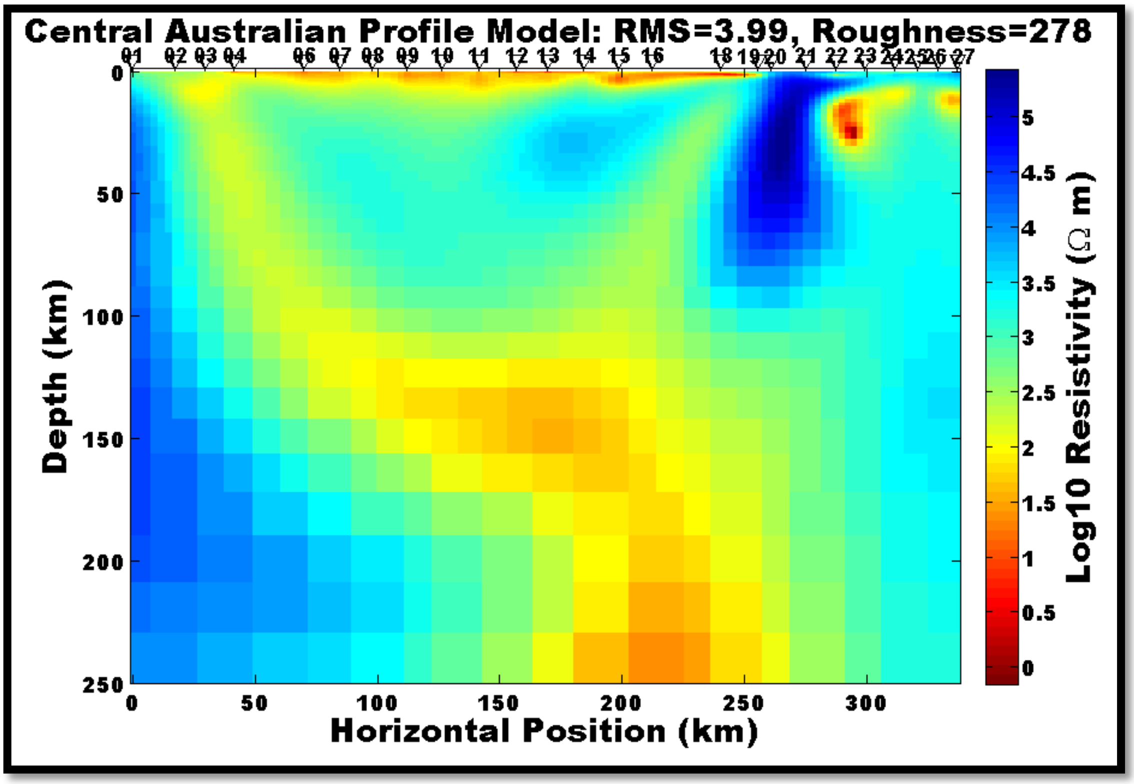

Figure 6: Two-dimensional Occam inversion model of the Central Australian survey line to a depth of 250km. The profile extends from -26.0° south latitude on the left to -22.7° south latitude on the right of the model. A distinct conductive layer is observable in the upper crust between site 4 and site 19. The thinner and thicker portions of this reflect the shape of the two most resistive portions of the overall resistive body below these sites to a depth of up to 100 km. This conductive layer underlain with a more resistive body is the region of the Amadeus Basin.
A more conductive structure dipping 60° down to the north from site 2 correlates on the surface with the boundary between the Musgrave Province and Amadeus Basin, and likely represents the deeper boundary between these lithospheric blocks. Similarly a conductive structure dipping 60° down to the south from site 19 correlates with the surface boundary between the Warumpi Province and the Arunta Complex, indicating it represents the lithospheric boundary between these units. This structure is present to at least 100 km depth, and is similar to the structure observed in the Selway et al. (2009) profile 130 km to the west of this profile. This is evidence that the structure is laterally extensive, though it was modelled in Selway et al. (2009) as continuing to 150 km depth.

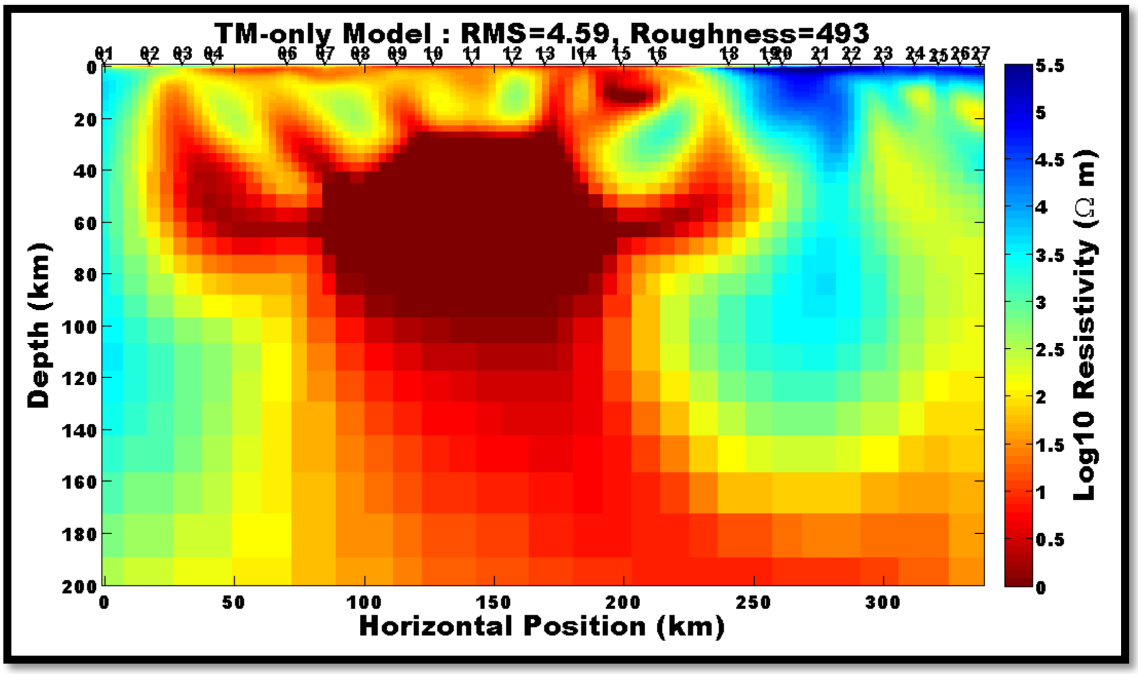

Figure 7: TM mode model of the Central Australian profile, with all TE mode values excluded from the modelling process. Several major features are apparent in the TM model of the profile. In particular, the large zone of apparent resistivity <10 Ωm which covers much of the profile at the near surface to 100 km depth beneath sites 2 to 19, and below 100 km depth beneath sites 9 to 16. The TM mode is much less sensitive to true apparent resistivities; however it provides strong guidelines for where boundaries between zones of different resistivities exist. The RMS on this model is relatively high as only an error of 5% was permitted between the raw data and modelled apparent resistivity, while the error floor of the phase was 2%.

The four major zones in the TM profile closely correlate to those in the model; however the apparent resistivities of those zones are significantly different. The resistive basement of the Amadeus Basin which extends on the surface from site 4 to site 18 and reaching up to 100 km depth in the combined TE and TM model shown in Figure 6 is very similar in location and shape to the broadly conductive zone in Figure 7. Similarly the highly resistive Warumpi Province in the northern part of the profile is still evident, with a lower modelled apparent resistivity. The consistency in the size and location of these zones is strong evidence of the model being accurate in these locations despite the apparent resistivity being different. The discrepancy in apparent resistivity is a product of using only half of the data. Resistivity signals in the TE orientation are absent so the overall resistivity modelled is much lower.

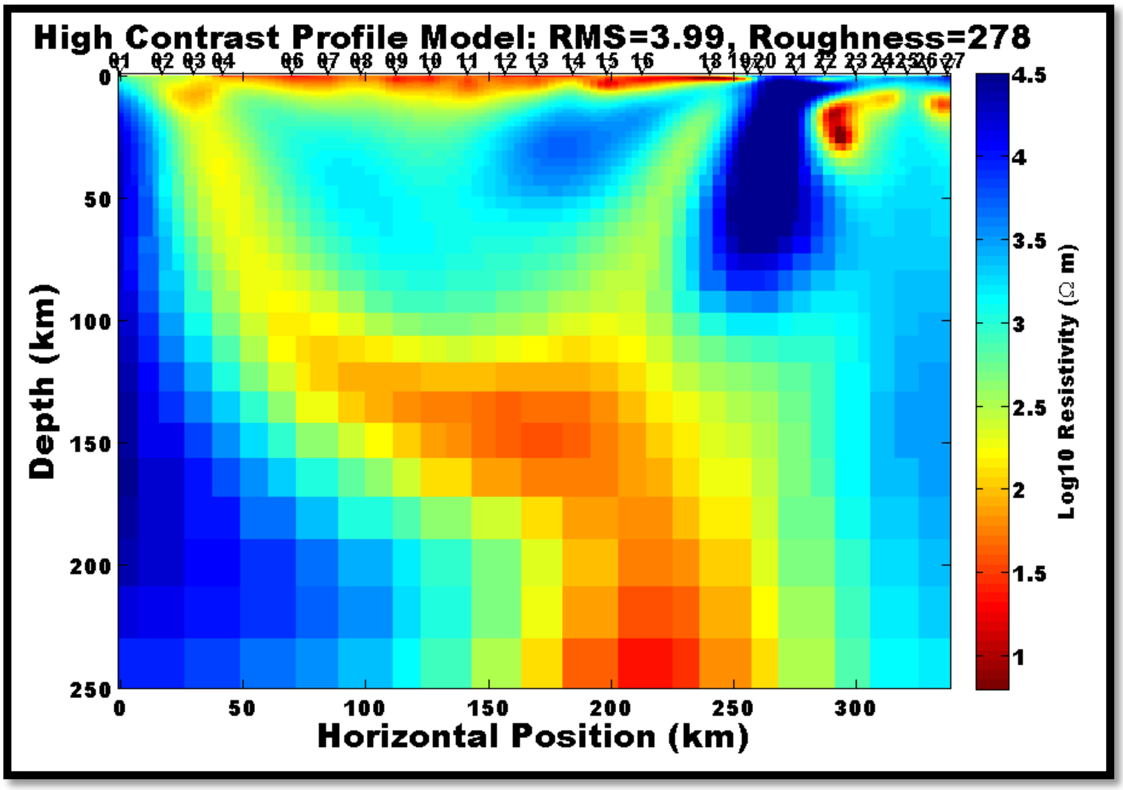

Figure 8: Contrast-enhanced model of the Central Australian profile. In this figure the colour scale of the resistivity has been enhanced with a narrower spectrum, enhancing the visibility of features such as conductive paths between zones of similar resistivity.

By altering the spectrum of the model to enhance the contrast, features with less sharp resistivity gradients are easier to distinguish. The small conductive body beneath sites 22 and 23 becomes more pronounced, as does the large resistive zone extending to roughly 90 km depth beneath sites 19 through 22. Another feature that is noticeably enhanced is the internal structure of the inverted hemisphere extending to 80 km depth at its deepest point and spanning from site 4 to site 19 at the surface. The internal structure of this feature appears to be two lobes of high resistivity starting from the near-surface at opposite ends of the body and extending towards the middle in the high-contrast figure.

Appraisal of Model Robustness

The robustness of the model was assessed through the use of additional altered models. The phases exceeding 90° in the TM mode of the central zone spanning sites 4 to 18 are susceptible to rotation of the data, and as such a 15 degree rotation counter-clockwise from the calculated geoelectric strike aligns a greater number of these phases to below 90°. While this orientation does not agree with the geoelectric strike model it was used as a tool to assess the potential presence of 3-D effects disrupting the 2-D modelling.

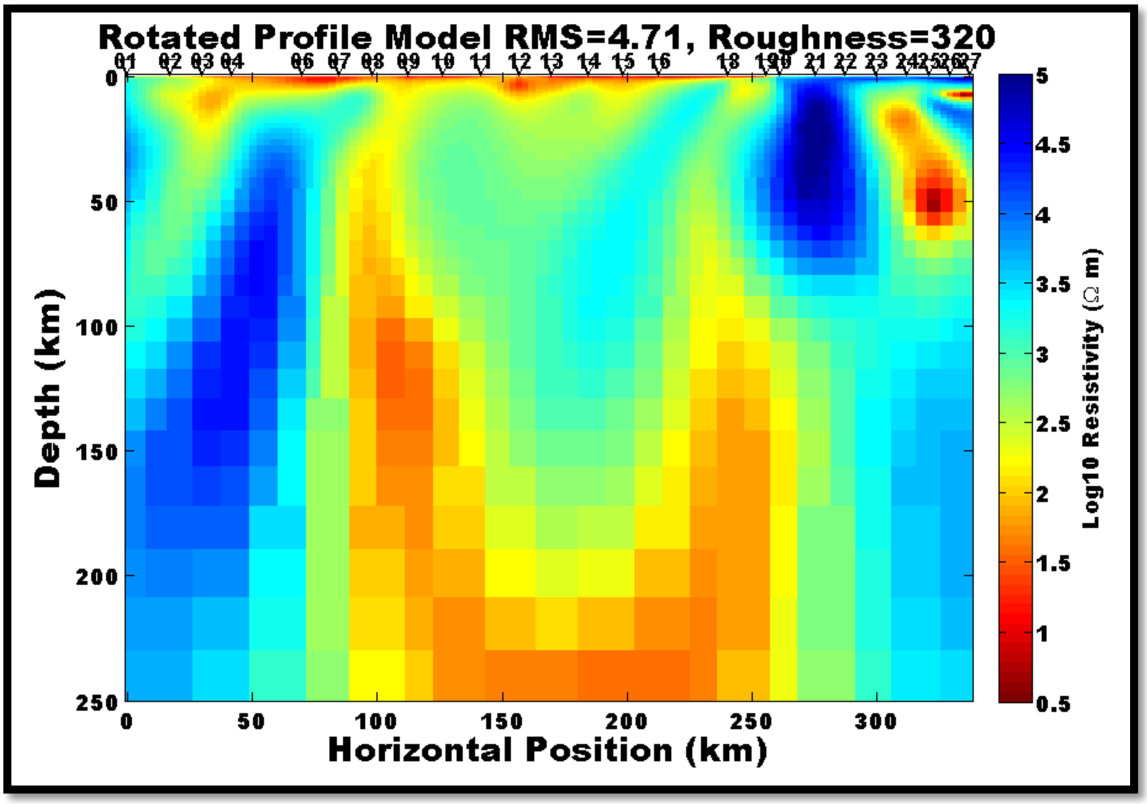

Figure 9: OCCAM model of the Central Australian profile using the same parameters as Figure 6. The apparent resistivity error floor is 16% for the TE mode and 8% for the TM mode, while the phase error floor is 5% for the TE mode and 3% for the TM mode. As with the model in Figure 6 this difference in the TE and TM mode error floors allows for the effects of static shift in the TE mode to be reduced in the model. The major difference between this model and Figure 6 is that the EDIs of the individual sites have been rotated 15° counter-clockwise prior to masking. This rotation is inconsistent with the calculated geoelectric strike of the region but allows more periods in the region from site 4 to site 18 to be included in the model, as without this rotation the phases of longer periods in this section are greater than 90°.

The arrangement of apparent units and structures in Figure 9 is consistent with Figure 6 on page 15, particularly in the upper 100 km. The comparison of these models serves to test the robustness of several features in the resistivity profile. The very highly resistive (>10^5 Ωm) Warumpi Province is present from the near-surface to a depth of ~90 km beneath sites 18 to 22 in the rotated model, as is the south-dipping conductive structure on the southern boundary of province. This conductive boundary structure appears distorted in the rotated model.

A noticeable difference between the correctly and incorrectly rotated models is the depth of the zone of low (<300 Ωm) resistivity in the lower central region of the profile. In the model aligned with the assessed geoelectric strike this feature is present at a minimum depth of 80 km. However in the model rotated the additional 15° this feature has been drastically lowered in its centre, such that beneath sites 12 to 17 it is not present above 200 km depth. This discrepancy is potentially a result of 3-D effects in the region. This is further evidenced by the longer phases being above 90° in this part of the model and being excluded as previously discussed, although the presence of a very highly conductive region with a resistivity of less than 10 Ωm at the near surface leaves this in doubt. The highly conductive region will tend to reduce the resolution and distort the model beneath it (Simpson and Bahr, 2005).

A further test of robustness was suitable for the small zones of anomalously low resistivity in the northernmost region of the profile. The size and amplitude of these anomalies leads to the possibility that they are errors in the data of individual sites. In order to test whether the response of the anomalous zone of <100 Ωm resistivity beneath site 22 represented a true feature inversion models were created for modified data sets; removing each of sites 22 and 23 in discrete models.

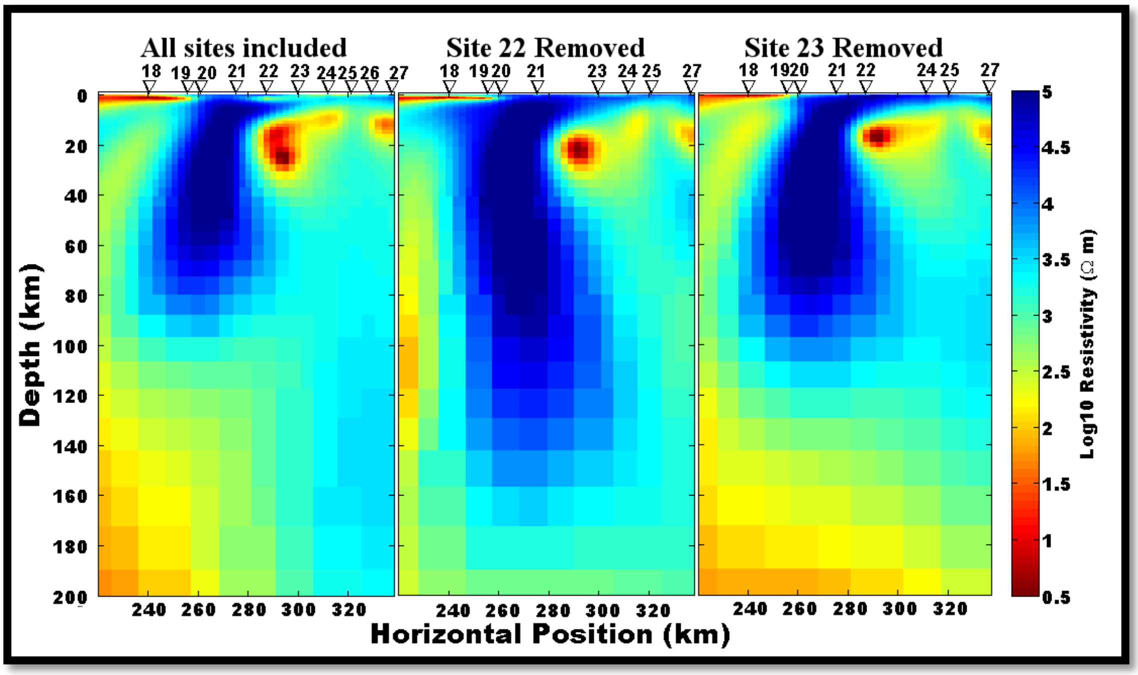

Figure 10: Comparison of sites 18-27 for models with all sites included (A), site 22 removed (B) and site 23 removed (C). The positions of some boundaries move slightly, and apparent resistivities vary minor amounts, however all of the major features remain consistent. The anomalous zone of very low resistivity beneath site 22 is consistent in amplitude and position across all three models.

The consistency across the three models compared in figure 10 shows clearly that the anomalous zones beneath the northern sections of the profile are highly robust. This demonstrates that while the region has amplitude changes in the order of 10^4 in the apparent resistivity across a relatively small distance of less than 10 km, the model has a low error margin in these zones, and is consistent with real features.

Interpretation of structure

This profile describes a complex arrangement of several major lithospheric blocks and structural features. The surface correlations of the four major zones of the profile are that sites 1-3 are within the Musgrave Province, sites 4-18 lie within the Amadeus Basin, sites 19-22 are across the Warumpi Province and sites 23-27 are within the southern part of the Arunta Complex. The structures between, and arrangement of, these major zones indicates a multi-staged tectonic history, and correlation with other sources of information is needed to determine the timing and regime of the regions tectonic closure.

DISCUSSION

Difficulties in modelling

The profile surveyed shows certain features indicating the presence of potential 3-D effects. The induction arrow tendency to be directed south-east as shown in Figure 2 is non-ideal for 2-D magnetotelluric inversion. If a major conductive body is oriented with varying depth close to the profile, it may distort the apparent resistivities of features within the profile, or even generate false features at longer periods. Of similar concern is the skew of sites within the profile. Skew analysis of each site revealed a number of periods in multiple sites where the skew β in the phase tensor exceeded $\pm 5°$, which indicates a strong likelihood of 3-D structural features. Such effects may alter the profile and cause incorrect apparent resistivity, that lead to the necessity of masking groups of periods which displayed high skew angles.

Another difficulty previously mentioned was the presence of phase angles greater than 90° for several longer periods in roughly half of the sites. These periods were masked as phase angles greater than 90° cannot be interpreted correctly by 2-D modelling, and as such this likely lead to a loss of resolution at depth in the central part of the profile.

Correlation of model with surface geology

The southernmost region of the modelled profile, which spans the first three stations, correlates in geographic location to the northern side of the Musgrave Province (Cawood and Korsch, 2004). This region of the Central Australian Profile is characterised by high resistivity quite uniformly to depths in excess of 200 km. The Musgrave Province is a crystalline basement dating to the mesoproterozoic characterised by layered volcanic and sedimentary rocks. These were later intruded at ~1200 Ma in the early part of the Musgrave Orogeny (Betts et al., 2002), and by the mafic-ultramafic dyke swarm known as the Giles complex at ~1070 Ma near the time of the final closure of the region.

The Amadeus Basin is characterised by a succession of shallow marine and non-marine sediments (Korsch and Kennard, 1991). It is typical of sedimentary basins to contain fluids unless significant heating and pressure have occurred to remove the fluids native to the process of deposition (Betts et al., 2002). Sandstone and calcrete are both resistive, while fluids in a rock body will increase conductivity proportional to both porosity and permeability (Simpson and Bahr, 2005). In the case of the Amadeus Basin region these fluids are still present in the upper 10 km which has not undergone the pressures and temperatures of significant burial. This results in a highly conductive upper layer, while below this threshold the resistivity increases rapidly with depth. This type of resistivity profile is seen in the Central Australian profile model as the structure spanning sites 4 to 18 from the surface, reaching a depth of 80 km in the centre. The conductive band is of uniform thickness across the zone, which is typical of sedimentary basins, with basement rocks being more dense and thus generally having lower conductivity.

The highly resistive structure which spans sites 19 to 22 to the north of the Amadeus Basin in the Central Australian profile model is the Warumpi Province. The Warumpi Province of the Central Australian Craton is host to complex metamorphic fabrics which include highly resistive garnet-staurolite fabrics as outlined in Morrissey et al.

(2005). The model shows that the Warumpi Province extends to a depth of 90 km with approximately uniform width to that depth. It has been said that the high resistivity of the Warumpi Province is due to metamorphic fabrics generated in the Musgrave Orogeny, however these fabrics would not be present to a depth of 90 km, and so this assumption is inconsistent. This leads to the conclusion that the bulk composition of the Warumpi Province is the real source of the high resistivity. The Warumpi Province experienced complex deformation ending with the Teapot Event at 1140 Ma (Scrimgeour, 2003) and the Musgrave Orogeny closure at 1080 Ma and has remained largely undeformed since then despite being subjected to the Alice Springs Orogeny thermal activity from 450 Ma to 300 Ma.

To the north of the Warumpi Province, in the known surface geology from Mclaren et al (2009), is the Aileron Province of the Arunta Complex. This corresponds in the resistivity model with the northernmost region of the profile spanning from site 22 to site 27. The electromagnetic response of this zone is complex, with small regions of high conductivity in a larger block of higher resistivity, though still notably lower than that of the Warumpi Province to the south.

Comparison of model with Selway et al. 2006

The lithospheric blocks present in this profile are similarly configured, as with those present in Selway et al. (2006) and Selway et al. (2009), although the Stuart Highway profile extends to a greater depth and the surveys are separated by 130 km. One of the outcomes of this profile was to determine whether structures first interpreted in Selway et al. (2009) are laterally extensive across the Warumpi-Arunta boundary; however the structural composition interpreted in Selway et al. (2009) is notably different to what is evident in the Stuart Highway profile.

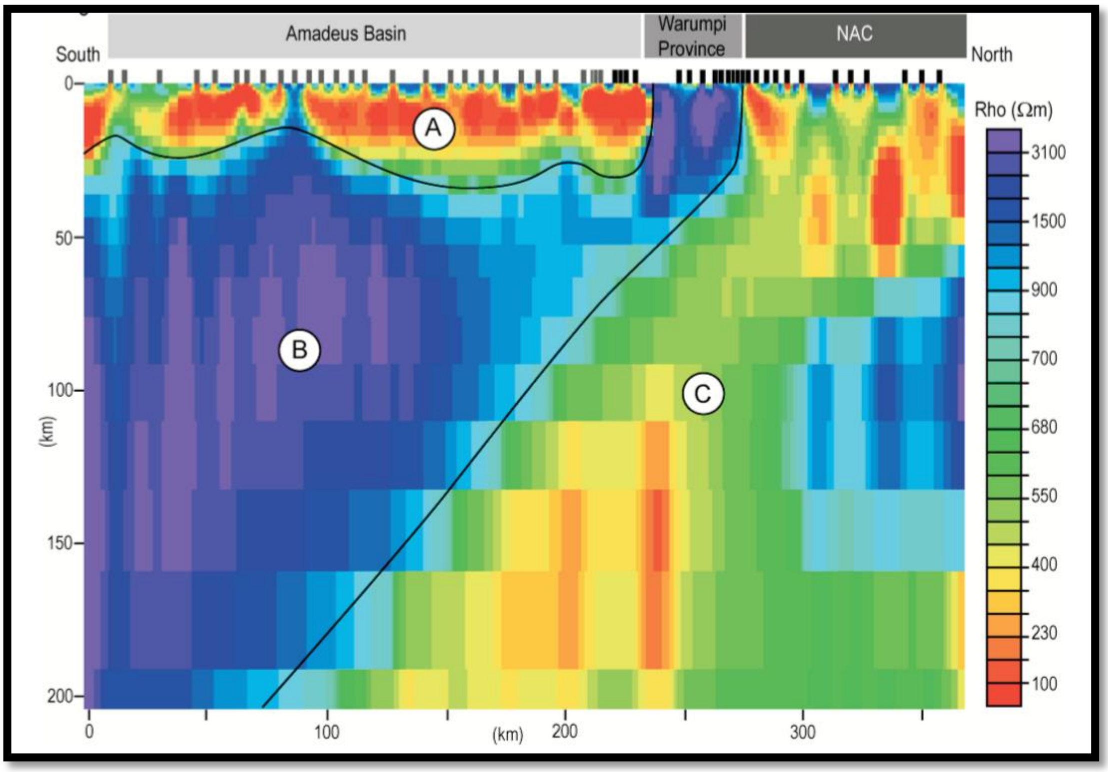

Figure 11: Long-period magnetotelluric model of the Amadeus Basin (A), Warumpi Province and Arunta Complex (C) with interpretations from Selway et al. (2009). Modified from Selway et al. (2009). The steeply south-dipping structure defined as the boundary between the Arunta Complex and Warumpi Province, the surface expressions of the regions (B) and (C), has been named the CAS and is of particular interest.

As can be seen by comparison between Figure 11 above and Figure 6 on page 15, the arrangement of blocks is similar, however the orientation of structural features appears to have several noticeable differences. The feature identified as the Central Australian Suture (CAS) in Selway et al. (2009), which defines the boundary between the Arunta Complex and Warumpi Province, is not present in the same orientation 130 km to the east. In the Selway profile, the CAS has been offset by the Redbank Thrust Belt (RTB) at the surface, which has altered the orientation of the CAS in the upper 40 km of the structure. In the eastern profile the RTB does not overprint the CAS in the crust, resulting in a more consistent south-dipping angle for the entire depth of the structure, as opposed to being near-vertical in the upper 40 km in the west. Another difference in this major structure is the depth it is present to in the model. Unlike in the western profile, the structure terminates at ~100 km depth at a conductive body. This difference is likely an issue of resolution as the western profile is modelled to a lesser depth, and in both cases the structure is below a conductive upper layer.

A key difference between the two profiles is the difference in resistivity of the Arunta Complex, the northernmost region of each profile. In Figure 11 the Arunta complex is seen to have a low resistivity of less than 500 Ωm while in the profile 130 km to the east of this shown in Figure 6 the bulk resistivity of the complex is greater than 3000 Ωm with small, discrete zones of less than 100 Ωm resistivity. This is potentially due to the multi-unit nature of the Arunta Complex, and the complex structural history of the wider region.

Regional phase tensors

By combining the dataset of this survey with that of the profiles of Selway et al. (2009) to the west, and Selway et al. (2011) which continues along the Stuart Highway through the Gawler Craton to the south, a larger-scale comparison of phase tensor ellipses and particularly induction arrows is possible.

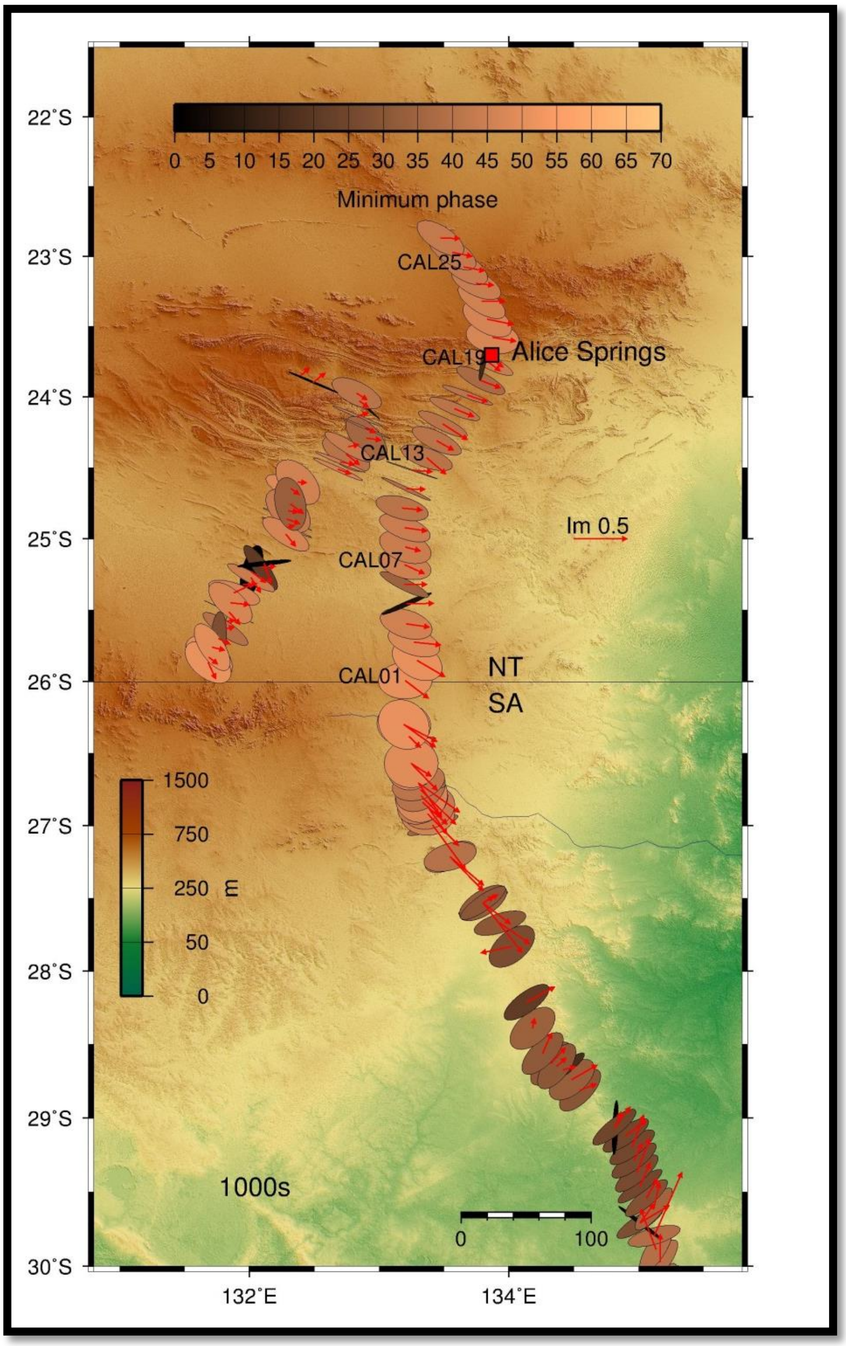

Figure 12: Topographic map of the Central Australian region from -21.5° south latitude to -30° south latitude, and from 130.8° east longitude to 135.8° east longitude. The map is overlaid with phase tensor ellipses and induction arrows with a period of 1000 s from the Stuart Highway magnetotelluric profile in the southern part of the Northern Territory, the magnetotelluric profile of Selway et al. (2009) to the east and the magnetotelluric profile of Selway et al. (2011) continuing south along the Stuart Highway through the Gawler Craton of South Australia. Of particular note is the strong regional trend for induction arrows to be directed to the east, being more south-easterly in the northern part of the region and more north-easterly in the southern part of the region.

The strong trend in Figure 2 for longer periods to exhibit distinctly southeast pointing induction arrows is further supported by the orientations observed in the induction arrows of the additional profiles shown in Figure 12 above. The profile to the west has a strong trend of southeast arrows albeit with a smaller magnitude than those of the eastern profile, caused by the increase in distance from the source of the orientation. The southern profiles continue the trend in induction arrow orientation, although as the profile extends to the south the arrows show a more easterly to north-easterly orientation. This is strong evidence for a large conductive body several hundred kilometres to the east of the Stuart Highway, with indications being that it is on-line with or south of the SA-NT border.

Interpretation

Morrissey et al. (2011) established that the age of metamorphic fabrics within the Warumpi Province are dated to 1130 Ma. These fabrics are not present in the Arunta Complex, so it is a logical progression that these lithological blocks were not directly adjacent during the formation of these fabrics. This provides a constraint on the maximum age of the closure of the region. Deformation from the end of the Musgrave Orogeny, dating to 1080 Ma, is present in both the Arunta Complex to the north of the Warumpi Province, and the Musgrave Province to the south. This provides a constraint of the minimum age of closure for the region.

The identification of a suture for this closure was a key focus of this survey; however such a structure is not consistently strong between this profile and the Selway et al. (2009) profile to the west. This leads to the conclusion that the closure of this region was likely not uniform across the boundary. The variable strengths of the lithospheric blocks across the region during the closure lead to discrepancies in which areas were more compressed during closure. During a subduction setting, regions will have been extended and compressed by inter-plate stresses. There may also be an effect of a difference in resolution between Figure 6 and Figure 11, as the Selway et al. (2009) survey has narrower site spacing, particularly in the region of the CAS. The difference in the profile models suggests that the major region of extension and summary contraction forming the boundary between the NAC and SAC is not laterally consistent. In the Selway profile, the major structure in the resistivity profile is at the northern boundary of the Warumpi Province, while in the Stuart Highway profile the southern boundary of the Warumpi province is the site of the stronger boundary. Therefore the history of the overall region is more complex than a simplistic subduction.

Future work

The evidently complex structure of the region is in need of further study. As the structure previously identified as the Central Australian Suture is not laterally consistent the simple subduction model of the region closure, during the Musgrave Orogeny, is insufficient to describe the major boundaries between lithospheric regions. A multi-stage regime of extension and contraction must have occurred, however further study is needed to constrain the sequence and overprinting of these contraction events. In addition to this, constraining the location and effect of the conductive body evidenced by the induction arrows and phase tensor ellipses of the collaborative surveys of the region is a valuable next step in identifying the major structural components and history.

A comprehensive three-dimensional magnetotelluric survey of the region would be highly informative. It is noted, however, that this could be impractical with the topography through the Musgrave and Warumpi Provinces. 3D modelling of 2D data sets would be a beneficial step in obtaining further constraints on the regional structures.

CONCLUSIONS

It has been shown in this study that the structural closure of the Musgrave Province, Amadeus Basin, Warumpi Province and Arunta complex, which ended at 1080 Ma, was a tectonically complex event. Sequences of extension and contraction of the region in a subduction setting has resulted in highly varied resistivity responses both across and along the closure zone. Further study incorporating three-dimensional magnetotelluric modelling is needed to constrain the lateral extent of the structures and units expressed in the findings of this two-dimensional survey, and this is particularly the case for the Warumpi Province and Arunta Complex in the northern part of the profile. There is much more study to be undertaken before a full understanding of the complex region described in this paper can be reached.

ACKNOWLEDGMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor Dr Stephan Thiel for his continuous support of my Honours study, and for his patience, motivation, and immense knowledge. His foresight and guidance helped me immeasurably through the process of research and the writing of this thesis. I could not have asked for a better supervisor and mentor for my Honours study.

I would like to thank my secondary supervisors; Prof. Graham Heinson and Prof. Martin Hand, for their insightful comments and for encouraging me to think in new directions during the planning of my Honours project.

My sincere thanks also go to Kate Robertson, Sebastian Schnaidt, and Yohannes Didana, for joining me for the fieldwork aspect of my research, and particularly to Kate for always being available to assist me with technical issues which usually stemmed from operator error.

And finally my thanks go to Dr Katie Howard for enduring no end of grief; ensuring repeated reminders of due dates were sent and chasing up forgotten documents. I am sure that without her influence half of my Honours papers would never have been submitted.

REFERENCES

BAHR, K. 1988, Interpretation of the magnetotelluric impedance tensor: regional induction and local telluric distortion. *Journal of Geophysics* **62**, 9.

BAHR, K. 1991, Geological noise in magnetotelluric data: a classification of distortion types. *Physics of the Earth and Planetary Interiors* **66**, 15.

BETTS, P. G. GILES, D. LISTER, G. S. FRICK, L. R. 2002, Evolution of the Australian lithosphere. *Australian Journal of Earth Sciences* **49**, 35.

BETTS, P. G. GILES, D. 2006, The 1800-1100 Ma tectonic evolution of Australia. *Precambrian Research* **144**, 34.

CALDWELL, T. G. BIBBY, H. M. BROWN, C. 2004, The magnetotelluric phase tensor. *Geophysical Journal International* **158**, 13.

CAWOOD, P. A. KORSCH, R. J. 2008, Assembling Australia: Proterozoic building of a continent. *Precambrian Research* **166**, 1-38.

CLOSE, D. SCRIMGEOUR, I. EDGOOSE, C. 2003, Redefining the Warumpi Province. *Annual Geoscience Exploration Seminar 2003 Record of Abstracts*, 3.

DE GROOT HEDLIN, C. D. CONSTABLE, S. C. 1990, Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data. *Geophysics* **55**, 12.

GAMBLE, T. D. GOUBAU, W. M. CLARKE, J. 1979, Magnetotellurics with a remote magnetic reference. *Geophysics* **44**, 16.

GILES, D. BETTS, P. G. LISTER, G. S. 2004, 1.8-1.5 Ga links between the North and South Australian Cratons and the Early-Middle Proterozoic configuration of Australia. *Tectonophysics* **380**, 27-41.

GROOM, R. W. BAILEY, R. C. 1989, Decomposition of magnetotelluric impedance tensors in the presence of three-dimensional galvanic distortion. *Journal of Geophysical Research: Solid Earth* **94**, 13.

JONES, A. G. 1988, Static shift of magnetotelluric data and its removal in a sedimentary basin environment. *Geophysics* **53**, 12.

KORSCH, R. J. Kennard, J. M. 1991, Geological and geophysical studies in the Amadeus Basin, central Australia. *Department of Primary Inductries and Energy Bulletin* **236**, 19.

LILLEY, F. E. M. 1982, The Sign Convention for Quadrature Parkinson Arrows in Geomagnetic Induction Studies. *Review of Geophysics and Space Physics* **20**. 513-518.

MAIER, R. HEINSON, G. THEIL, S. SELWAY, K. GILL, R. SCROGGS, M. 2007, A 3D lithospheric electrical resistivity model of the Gawler Craton, Southern Australia. *Applied Earth Science* **116**, 13-21.

MCLAREN, S. SANDIFORD, M. DUNLAP, W. J. SCRIMGEOUR, I. CLOSE, D. EDGOOSE, C. 2009, Distribution of Palaeozoic reworking in the Western Arunta Region and northwestern Amadeus Basin from Ar40/Ar39 thermochronology: implications for the evolution of intracratonic basins. *Basin Research* **21**, 315-334.

MCPHERRON, R. 2005, Magnetic Pulsations: Their Sources and Relation to Solar Wind and Geomagnetic Activity. *Surveys in Geophysics*, **26**, 545-592

MORRISSEY, L. PAYNE, J. L. KELSEY, D. E. HAND, M. 2011, Grenvillian-aged reworking in the North Australian Craton, central Australia: Constraints from Geochronology and modelled phase equilibria. *Precambrian Research* **191**, 141-165.

SELWAY, K. M. HAND, M. PAYNE, J. L. HEINSON, G. S. REID, A. 2011, Magnetotelluric constraints on the tectonic setting of Grenville-aged orogenesis in central Australia. *Journal of the Geophysical Society, London* **168**, 14.

SELWAY, K. HAND, M. HEINSON, G. S. Payne, J. L. 2009, Magnetotelluric constraints on subduction polarity: Reversing reconstruction models for Proterozoic Australia. *Geology*, 799-802.

SELWAY, K. HEINSON, G. Hand, M. 2006, Electrical evidence of continental accretion: Steeply-dipping crustal-scale conductivity contrast. *Geophysical Research Letters* **33**, 4.

SIMPSON, F. BAHR, K. 2005, *Practical Magnetotellurics*. vol. 1. Cambridge University Press.

SPITZER, K. 2001, Magnetotelluric static shift and direct current sensitivity. *Geophysical Journal International* **144**, 11.

TELFORD, W. GELDART, L. SHERIFF, R. KEYS, D. 1976, *Applied Geophysics*. Cambridge University Press, New York.

WADE, B. P. BAROVICH, K. M. HAND, M. SCRIMGEOUR, I. R. CLOSE, D. F. 2006, Evidence for Early Mesoproterozoic Arc Magmatism in the Musgrave Block, Central Australia: Implications for Proterozoic Crustal Growth and Tectonic Reconstructions of Australia. *The Journal of Geology* **114**, 43-63.

WAIT, J. R. 1954, On the relation between telluric currents and the Earth's magnetic field. *Geophysics* **19**,9.

WRIGHT, C. GOLEBY, B. R. SHAW, R. D. COLLINS, C. D. N. KENNET, B. L. N. LAMBECK, K. 1993, Seismic structure and continuity of the Redbank Thrust Zone, central Australia. *BMR Journal of Australian Geophysics* **13**, 359-368.