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A Magnetotelluric survey of the North Perth Basin: A technical case study

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SUMMARY

Original motivation of this study was to understand important structures with a proven geothermal signature associated with high temperatures in the shallower basin and high flow rates in the aquifers. Anomalous temperatures are recorded around the Beagle Ridge and significant flow rates observed near the Urella Fault, factors important to unconventional geothermal prospects. The focus of this study was therefore a detailed geophysical investigation of several Geothermal Exploration Permits (GEPs) in the North Perth Basin.

Two Magnetotelluric (MT) surveys are conducted over target areas in the North Perth Basin and adjoining tectonic domains to provide information about the electrical conductivity regime of the basin and western margin of the Yilgarn Craton. Existing geophysical data in this part of the basin are sparse and electrical data for the basin in general is limited to shallow Time Domain Electromagnetic (TDEM) data targeting superficial aquifers.

High-resolution MT data, acquired between 2011 and 2013, provide information on mid-deep crustal rocks. In addition, new gravity data and joint interpretation of these data sets are undertaken to improve the geological model of the North Perth Basin and test some existing hypotheses.

We present a best practice case study and workflow for data acquisition and filtering, robust dimensionality analysis and removal of distortion effects from impedance tensor estimates. 1D and 2D inversions are found to be largely sufficient for the majority of these data while 3D modelling provides an additional tool to verify results. Finally, modelling of gravity data and integrated interpretation ensures robust geological models for the area are consistent with all data available.

We conclude with several inferences about the geology in this area. 1) Electromagnetic (EM) and gravity data does not seem to support significant crustal thinning beneath the basin. 2) The Dandaragan Trough appears deeper than generally modelled and 3) extremely high conductivities persist to depth in the basin.

Key words: Magnetotellurics, Gravity, North Perth Basin

INTRODUCTION

The Perth Basin is a rift basin, dominated by north striking sub-basins, troughs and ridges, bounded by major normal faults (Song & Cawood, 2000). Covering approximately 45 000 km^2 onshore and 55 000 km^2 offshore it is located to the west of the Yilgarn Craton, and formed during Permo-Cretaceous rifting between Australia and Greater India (Song et. al. 2001). It is an established petroleum province, with operating fields both on and offshore, hosts large mineral sand deposits and is the source of most of Western Australia's ground water resources (Mory & Iasky, 1996, Song et. al., 2001).

The Perth Basin is considered prospective for geothermal resources. A thick sedimentary succession provides deep, highly porous aquifers, targets for Hot Sedimentary Aquifer (HSA) plays while regions of basement uplift, such as the Beagle Ridge, are thought to host radiogenic granites, potential targets for Hot Dry Rock (HDR) plays. Low porosity successions provide thermal insulation, trapping heat while proximity to major population centres provides a market. In 2009, Geothermal Exploration Permits (GEPs) were released for geothermal exploration and were acquired by several companies to explore for both HSA and HDR systems.

Chopra & Holgate (2005) present a nationwide analysis of temperature data within the Australian crust, extrapolating drillhole data to map temperature at depth, providing an invaluable tool for geothermal exploration. Heat anomalies in the Perth Basin are identified in several areas, particularly the Beagle Ridge. Increased heat production and thermal conductivity is measured in rocks of the Pinjarra Orogen, which form the Beagle Ridge and basement to the basin identifying the Beagle Ridge as a potential target (Hot Dry Rocks Ltd., 2008).

As a fundamentally different resource, improved understanding of not only the geology but also the geophysical characteristics pertinent to geothermal resources, are essential. Considerable geological and geophysical data exist for the Perth Basin. Gravity, Magnetics, Seismic, Borehole logging and some EM data are available, however distribution is varied with areas of the basin having almost no information.

Electrical resistivity methods are sensitive to both heat and fluid content (Archie, 1942, Llera et. al., 1990, Telford, 1990, Zisser et. al., 2010). Conductivity of fluid phases, including aqueous solutions and melts, tend to be orders of magnitude greater than that of the host rock. Even small volumes of interconnected pore space can greatly alter the electrical resistivity of a rock volume. Porosity and permeability play a crucial role in geothermal application, dominating energy recovery rates. Clay alteration halos, often associated with geothermal reservoirs, also significantly increase conductivity and in volcanic geothermal systems are mapped to identify potential reservoirs.

MT is a favoured tool for deep crustal studies. As a passive technique, source signals are high amplitude with a broad frequency range, allowing conductivity anomalies to be imaged at greater depth than other EM techniques. Impedance tensors are frequency dependent providing a measure of depth control not available with potential field techniques. The combination of investigative depth and sensitivity to resistivity variations, key proxies for porosity, permeability and alteration, make MT an ideal tool for fluid delineation in the crust at depths significant in the context of the Perth Basin and geothermal resources.

It is essential to establish a workflow for acquisition, processing and modelling of MT data which adequately applies proper analysis and modelling techniques. Poor data analysis and modelling practises are common in many published MT case studies, leading to erroneous results and a lower consideration of MT data. We apply a range of modern techniques to analyse the MT impedance tensor. 1D and 2D modelling are conducted using robust modelling algorithms and appropriately decomposed impedance tensors.

The main aims of conducting MT surveys in the basin are to 1) map depth to basement, 2) investigate the conductivity regime of the basin, 3) to investigate the nature of major geological structures. Gravity, Magnetic, Seismic and Borehole data are also used to constrain MT models and aid in interpretation.

METHOD AND RESULTS

MT and TDEM soundings are acquired along two, east-west traverses of the North Perth Basin and western Yilgarn. The New Norcia (NN) traverse follows the 1992 BMR New Norcia geo-scientific traverse (Middleton et. al., 1993) and the Coorow-Greenhead (CGH) traverse follows pre-existing seismic lines from the Booragoon and Dandaragan East Flank reflection seismic surveys where possible, extending to the east onto the Yilgarn near the town of Marchagee.

19 MT and Time Domain Electromagnetic (TDEM) soundings are acquired along the NN traverse, with a maximum station spacing of 2-3km, and 90 MT, 36 AMT, 9 long period MT and 48 TDEM soundings are acquired along the CGH traverse. Nominal station spacing is 2km with extensive infill conducted across the Darling Fault Zone (DFZ) and Beagle Ridge, providing higher resolution across the fault and prospective geothermal environments.

The MT method is a passive electromagnetic method which measures temporal variations in the Earths naturally occurring electric (*E*) and magnetic fields (*H*). For each sounding, two horizontal components of the electric field, *Ex* and *Ey*, two horizontal components, *Hx* and *Hy* and, where possible, one vertical component, *Hz*, of the magnetic field are measured. Electric field components are measured using non-polarising electrodes while magnetic field components are measured with coil magnetometers, sensitive to frequencies from 10kHz up to 2000 s.

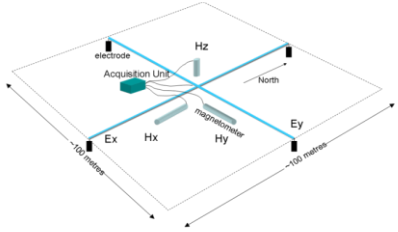

Figure 1: Standard MT deployment for Phoenix MT system

MT soundings were conducted over two nights, AMT soundings over 3 hours and long period MT over approximately 22 days. A combination of broadband Phoenix and AuScope systems were used to acquire MT time-series data. For long period deployments induction coils are replaced with fluxgate magnetometers providing sensitivity from 10s to over 10000 s. TDEM measurements were made using the Phoenix V8 system using a standard in-loop configuration and vertical component only, receiver coil located at the centre of the MT station.

WORKFLOW

Time series exhibit relatively low noise, with localised, 50 Hz power-line noise being the only consistent major contributor. Pre-processing is applied to eliminate 50 Hz and harmonic noise, which varies in severity from site to site.

MT data were processed using Chave & Thompson's Bounded Influence Remote Reference Processing (BIRRP) code, providing robust estimates of the MT response function from 10kHz down to 10k seconds (Chave & Thompson, 2003). Proprietary processing algorithms provided with Phoenix recorders have also used to process time-series recorded using Phoenix systems to compare with BIRRP results to verify processing codes. Comparison indicate better results are obtained at higher frequencies using Phoenix processing, however, at longer periods BIRRP produce more robust results characterised by smaller errors. Remote referencing is used as standard, to reduce local station noise and improve impedance tensor estimates.

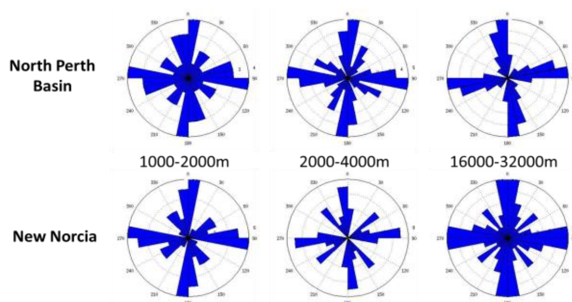

Figure 2: Geo-electric strike directions calculated for both the NN and CGH transects, demonstrate a general NNW strike direction.

Dimensionality of the MT response function is characterised using several methods. Impedance tensor rotational invariants are used to summarise dimensionality across the data set using the WALDIM method (Marti et. al., 2009). Caldwell, (2004) Phase Tensors and McNeice & Jones, (2001) Strike Analyses, Figure 2, were used to determine the dominant geo-electric strike strike for major tectonic elements are summarised in Table 1.

Strike	*Geological Feature*
355-360°	Yilgarn Craton
020-040°	Pinjarra Orogen - long periods over the basin
335-010°	Basin Sediments

Table 1: Geo-electric strike for major geological features in the study area, determined from a combination of WALDIM, Phase Tensor and Strike Analysis.

Distortion effects, caused by inhomogeneities at scales smaller than the resolving power of the experiment, are also known to be particularly problematic to MT results. McNeice & Jones (2001) show that distortion effects can be described by the distortion tensor, C, which has several determinable elements, Twist, Shear and Anisotropy, and an indeterminable element, g, which is also called the static-shift (McNeice & Jones, 2001).

The McNeice and Jones tensor decomposition method allows the determinable parts of the distortion tensor to be estimated using either single or multiple sites. Distortion and dimensionality effects are then removed, providing distortion free, correctly rotated impedance tensors for 1D and 2D modelling.

DISCUSSION

Pronounced differences in electrical characteristics of major elements of the Yilgarn Craton allow these to be delineated. A contrast in resistivity of 1-2 orders of magnitude, correlates with the Yandanooka Cape-Riche lineament, the eastern boundary of the South West Gneissic Terrane (SWGT) and the Lake Grace Terrane, see Figure 3. An easterly dipping resistivity contact correlates with shear zones inferred from seismic interpretation (Middleton et. al., 1993). Previous investigations identify a 40 mGal gravity anomaly associated with the SWGT across this lineament, as well as decreased seismic velocity (Everingham, 1966, Dentith, 1994).

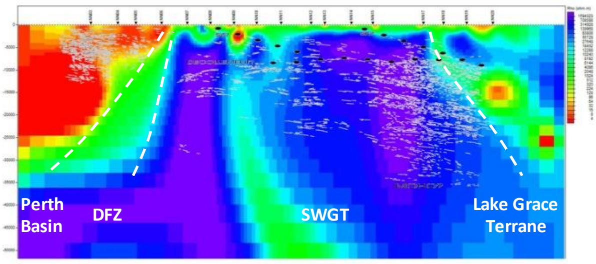

Figure 3: NN transect 2D inversion illustrating major tectonic elements.

While the resistivity regime of the SWGT largely homogenous, a narrow, eastward dipping conducting anomaly is observed in upper 2km that correlates with a second shear zone identified from seismic data, characterising the contact between the Chittering and Jimperding metamorphic belts (Middleton et. al., 1993).

We find correlation between the geometry of conductive rocks overlying the Yilgarn and a zone of lower density required to fit observed gravity data (Long, 1996). However, there is little evidence in EM results of the delamination and stratification of the Yilgarn at depth (Dentith et. al., 1994).

A deep seated conductivity anomaly is identified associated with the DFZ. While fault zone conductors have been identified on large tectonic fault zone, these usually exhibit seismic character, with conductivity anomalies in the upper 10-20km only. As a seismically quiescent feature, identification of such a deep conductivity anomaly warrants further investigation of the fault architecture and plausible scenarios for generating these anomalies.

Current best models for depth to basement are still poorly constrained for this part of the basin but a maximum basement depth of 10km is interpreted (Mory & Iasky, 1996, Aitken, 2010). Depth to basement models rely primarily on gravity data, locally constrained by seismic interpretations. Gravity data are more regular distributed though are inherently non-unique. Many gravity measurements are old, ~50 years with poor elevation precision and large (~12km) station spacing. Seismic data have limited distribution and seldom image basement in the basin. We treat these data as unreliable and where possible use 2D modelling of more recent gravity data to interpret basement depth.

Basin sediments exhibit extremely low resistivity, in some cases less than 3 Ω.m. Mapping basement topography over the Beagle Ridge and shallower parts of the basin is easy, as basement rocks have resistivities over 4 orders of magnitude greater than those encountered in sediments. Unexpected high conductivities in the basin, coupled with thick sediments, lead to a significant reduction in depth of penetration of broadband MT (BBMT) soundings. We rely on long period MT soundings to increase the depth of penetration to supplement broadband data. EM results indicate a depth to basement of about 12km. We test this hypothesis using gravity modelling and find we can fit a basement at 12km with limited alteration to assumed density values for the deeper basin sediments.

Previous gravity modelling implies a fundamental change in crustal thickness across the DFZ is required to fit gravity data, from 27km to 45km (Middleton et. al., 1993). EM models are more reliable in areas of shallow basement, such as the Beagle Ridge and Cadda Terrace. Highly resistive basement blocks are observed to depth in these areas, Figure 4. Conductivity structure beneath the Dandaragan Trough is less reliable however, broadly supports limited crustal thinning to the west of the DFZ as no conductivity change, indicative of the Moho, is observed.

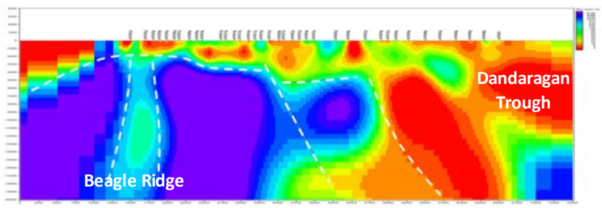

Figure 4: Resistive anomaly associated with uplifted basement blocks is observed to continue to depth.

While these findings are inconclusive, we note similar observations from the Moho Geometry Gravity Inversion Experiment (MoGGIE) models as well as seismic receiver functions calculations (Revets, *pers. comms.*, 2011). Remodelling of gravity data we find gravity response can be well fit by either model, again with limited alteration to assumed densities of basin sediments.

Published models for extension during the cretaceous follow a classic narrow rift model, as defined by Buck, (1991), Figure

5(a). Considering the lack of appreciable crustal thinning and the DFZ becoming listric at depth, we propose core complex mode of extension is a more accurate model for extension which formed the Perth Basin, Figure 2(b).

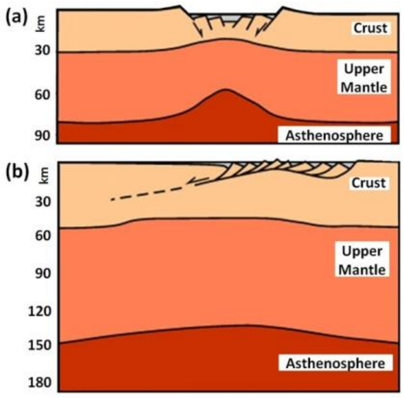

Figure 5: Models for crustal extension (after Buck, 1991) illustrating the classic model for rift systems (a) and the model which better fits our observations (b)

Deep Conductivity

Accurately imaging resistors below conductors is difficult using electric techniques as electrical energy is attenuated by the conductor, effectively reducing the depth which can be imaged. Basin environments are characterised by highly conductivity sediments due to highly conductive fluids filling pore space.

Initial analysis of BBMT data, located over the Dandaragan Trough, indicate apparent reistivities decrease with depth, from 10-100s of Ω.m., to <3 Ω.m. at the longest periods. Induction logs, from proximal petroleum wells, measure similarly low resistivities (5-70 Ω.m.) for shallow sediments. We might expect, due to compaction of pore space and subsequent closing of permeability pathways, to see an increase in resistivity with depth.

Ongoing work aims to 1) correlate resistivity profiles between MT and downhole measurements and 2) map permeability and estimate porosity for the North Perth Basin.

CONCLUSIONS

MT models allow us to provide a new estimate of maximum depth of basement in this area which can be shown to be consistent with other geophysical data sets. EM results indicate high resistivity anomalies, associated with basement rocks, persist to depth suggesting a crustal thickness of approximately 33 km.

We identify a deep seated conductive anomaly associated with the DFZ, implying a more complex internal structure. Fundamental differences in electric character between the Yilgarn and the Pinjarra Orogen support pronounced change in lithology across the DFZ. Finally ongoing research into mapping porosity and permeability in the basin will provide a useful tool for Geothermal Exploration in the Perth Basin.

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