Crustal fluid pathways imaged using magnetotellurics - implications for the South Australian heat flow anomaly

Paul Soeffky
University of Adelaide
The University of Adelaide
SA, 5005, Aus
paul.soeffky@adelaide.edu.au

Jared Peacock
USGS
345 Middlefield Rd
Menlo Park, CA, USA 94025
jpeacock@usgs.gov

Stephan Thiel
University of Adelaide
The University of Adelaide
SA, 5005, Aus
Stephan.thiel@adelaide.edu.au

Lars Krieger
University of Adelaide
The University of Adelaide
SA, 5005, Aus
lars.krieger@adelaide.edu.au

SUMMARY

The global demand for clean energy alternatives is constantly increasing, creating significant interest for more sustainable energy resources such as uranium and geothermal. Australia is host to over 25% of the world's known uranium resources as well as having significant geothermal potential.

The Mount Painter Domain, in the Northern Flinders Ranges in South Australia, is in a region of anomalously high heat flow generated by radiogenic decay of uranium and thorium rich granites. Two distinct uranium deposits have formed from dissolved uranium carried from the ranges by fluids, being deposited where reduction in sediment pH causes uranium precipitation.

In May 2012 a magnetotelluric profile was collected, extending from the Northern Flinders Ranges to the Lake Frome embayment to help constrain existing resistivity models. Precipitation of uranium at the Beverley Mine site is anomalous as no surface water flow is present, suggesting the presence of subsurface processes. A conductive pathway extending to the surface at Beverley is linked to a 50 Ω m conductive body at the brittle-ductile boundary of the mid-crust, directly under the Paralana geothermal prospect.

Key words: magnetotellurics, fluids, uranium exploration, electromagnetic induction, graphite

INTRODUCTION

The north-eastern Flinders Ranges play host to uranium rich granites which have a significant effect on the local geological environment. Heat production due to the radiogenic decay of the basement rock has resulted in the presence of a significant geothermal potential at Paralana, as part of the South Australian heat Flow Anomaly (SAHFA) as defined by Neumann et al. (2000).

Anomalous heat flow measurements of up to 126 mW/m^2 have been recorded close to Paralana in the Mount Painter Domain (MPD) (Neumann et al. 2000; Brugger et al. 2005). The regional geothermal gradient for Paralana of 50 – 70 ° C km^{-1} (Cull & Conley 1983) is significantly higher than the global average value for intraplate sites (Fridleifsson et al. 2008).

The same uranium rich basement rocks of Paralana are present in the Flinders Ranges, where the MPD has been uplifted. Erosion of the ranges has resulted in dissolved uranium being deposited in palaeochannels on the plains below (Heathgate Resources 1998; Märten 2006). Uranium deposition favours a reducing environment as it is most mobile in its oxide form. It has been suggested that Beverley and Four Mile Creek uranium deposits could be linked to faults containing mobile reducing fluids.

Although the individual uranium deposits are too small to be directly detected using magnetotellurics (MT), graphite mineralisation can be used as a deposit identifier. Faults containing graphite enable uranium deposition through reduction, reducing uranium ions from soluble U^{6+} to insoluble U^{4+} ions (Tuncer 2007). Graphite has a significantly lower resistivity than non-metalliferous rock, making it easily identifiable and usable as a marker unit for uranium deposits when undertaking an MT survey (Duba & Shankland 1982; Simpson & Bahr 2005; Farquharson & Craven 2009).

In this study, an MT survey has been collected over the Paralana EGS, encompassing the Beverly and Four Mile Creek uranium deposits to collect resistivity information. Broadband MT sensors were used for near surface resolution, while long period sensors were used to give resolution to a much greater depth. The wide range in depth and resolutions offered by MT prescribes it as the preferred geophysical technique for linking deep crustal features with the surface. A 2D inversion model has been created over the profile, providing evidence as to how the observed deep conductors interact with the surface throughout the region.

METHOD AND RESULTS

An MT survey was conducted along a 42 km east-west transect across Paralana and Beverley in the northern Flinders Ranges. The survey consisted of 35 broadband stations at 1km intervals and 15 long-period sites, 3 km apart. The first station started recording on day 120 at 0300 UTC, 2012, and the final station stopped recording on day 128 at 0300 UTC, 2012. Broadband stations recorded 4-components (B*x*, B*y*, E*x*, E*y*) using AuScope instruments, while Bartington's fluxgate instruments were used at the long-period sites to record 5-components (B*x*, B*y*, Bz, Ex, E*y*).

The recording instruments were time synchronised using GPS, to enable more reliable data correlation and remote referencing. Dipoles for all sites were approximately 50m in

length and consisted of non-polarising porous *Cu – CuSO$_4$* pot electrodes orientated towards geographic north and east, magnetic coils were orientated parallel to the electrode dipoles. Broadband stations sampled at 500 Hz and recorded for two days before being moved to a new location. Long-period stations recorded for three days sampling at 10 Hz, before also being moved to a new location.

A site 60 km south-west of the profile line was chosen as the broadband remote reference location, which operated continuously throughout the survey. The long period stations were remote referenced using magnetic observatory data collected in Alice Springs.

Processing was achieved using a robust bounded influence remote referencing method: BIRRP (Bounded Influence, Remote Reference Processing) described in Chave & Thompson (2004). The Occam inversion code developed by Constable et al. (1987) and outlined in deGroot Hedlin & Constable (1990) was used to produce a 2D inversion model containing both the TE and TM modes over the survey line. Error bars and smoothing parameters were used to control the model by adjusting the data fit tolerance of cells near the data points to achieve a model that was both geologically feasible and fit the data.

The resistivity and phase error bars were set to 10% and 5% respectively and the data was rotated 2.9° east to geoelectric strike with a uniform base resistivity of 100 Ω m set across the model. The resulting model had a final root mean square (rms) of 2.22 and a smoothness of 290. Sensitivity analysis was performed on the model to determine if the model features are robust or if any are artefacts. The model features were found to be consistent with no significant artefact features.

A 50 Ω m conductivity anomaly was detected under the Paralana borehole, with limbs extending to the surface at Paralana and Beverley. A large 20 Ω m conductive body was observed at approximately 20 to 30 km depth, with a thickness of 10 km (Figure 1).

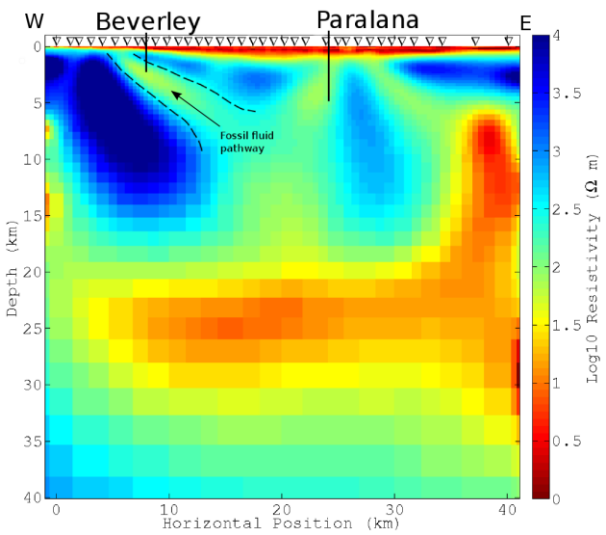

Figure 1. The 2D model of the survey line showing the 10km thick conductive unit at 20 - 30km depth with conductive limbs extending to the surface.

Graphite has been proposed as a source of high conductivity in the crust (Duba & Shankland 1982; Glover 1996; Glover & Ádám 2008; Yang 2011). Formation of highly conductive graphite films has been found to occur in the presence of CO/CO$_2$ fluid during fracturing (Roberts et al. 1999; Glover & Ádám 2008). Laboratory results by Nover et al. (2005) have shown graphite crystals can form at temperatures and pressures simulating continental crustal conditions. During these trials, formations of graphite lead to an increase in conductivity of the host rock of up to three orders on magnitude (Nover et al. 2005; Glover & Ádám 2008). These results are consistent with the modelled conductive anomaly under Paralana, suggesting that it is a large graphite-rich body formed during the uplift of the MPD during the formation of the Flinders Ranges.

The conductive limbs extending from the graphite body to the surface are associated with major faults in the region. The conductive limb rising under Beverley is likely the Poontana Fault, an off shoot of the Wooltana fault, which Beverley lies adjacent to (Heathgate Resources 1998; Märten 2006). The higher conductivity observed along the faults is consistent with the presence of CO/CO$_2$ fluids traversing the fault during formation. The presence of reducing fluids in the fault is supportive of the deposition of uranium at the Beverley site and the formation of graphite films promoting high conductivity (Skirrow et al. 2009; Farquarson & Craven 2009).

CONCLUSIONS

The high heat flow in the Mt. Painter Domain is caused by the radiogenic decay of the uranium and thorium rich basement granites. Uplift and faulting has resulted in surface expressions of the Mt. Painter granites in the north eastern tip of the Flinders Ranges. MT has been used to delineate graphite lined fossil fluid pathways linking deep sourced fluids with the uranium deposits targeted by Beverley and Four Mile Creek. The fossil fluid pathways are lined by graphite and the reducing fluids are responsible for the deposition of uranium.

ACKNOWLEDGMENTS

I would like to acknowledge Heathgate Resources, and in particular Jonathan Ross, for their help during this project and for allowing access to the Beverley mine site. The native landowners for conducting site clearances and allowing us on their land during the MT survey, and DMITRE for their support during the project.

REFERENCES

Brugger, J., Long, N., McPhail, D. & Plimer, I. (2005) An active amagmatic hydrothermal system: The paralana hot springs, northern flinders ranges, south australia, Chemical Geology 222(1-2): 35-64.

Chave, A. D. & Thompson, D. J. (2004). Bounded influence magnetotelluric response function enstimation, Geophysical journal international 157 (3): 988-1006.

Constable, S. C., Parker, R. L. & Constable, C. G. (1987). Occam's inversion: A practical algorithm for generating smooth models from electromagnetic data, Geophysics 52: 289-300.

Cull, J. & Conley, D. (1983). Geothermal gradients and heat flow in australian sedimentary basins., BMR Journal of Australian Geology and Geophysics 8: 329-337.

deGroot Heldin, C. & Constable, S. (1990). Occam's inversion to generate smooth, two-dimensional models from magnetotelluric data, Geophysics 55(12): 1613-1624.

Duba, A. & Shankland, T. (1982). Free carbon and electrical conductivity in the mantle., Geophysical Research letters 11: 1271-1274.

Farquharson, C. & Craven, J. (2009). Three-dimensional inversion of magnetotelluric data for mineral exploration: An example from the mcarthur river uranium deposit, saskatchewan, canada, Journal of Applied Geophysics pp. 450-458.

Fridleifsson, I., Bertani, R., Huenges, E., Lund, J., Ragnarsson, A. & Rybach, L. (2008). The possible role and contribution of geothermal energy to the migigation of climate change, IPCC Scoping Meeting on Renewable Energy Sources pp. 59-80.

Glover, P. W. J. (1996). Graphite and electrical conductivity in the lower continental crust, Physics and Chemisty of the Earth 21: 279-287.

Glover, P. W. J. & Ádám, A. (2008). Correlation between crustal high conductivity zones and seismic activity and the role of carbon during shear deformation, Journal of Geophysical Research 113: B12210-.

Heathgate Resources (1998). Beverlay uramin mine: Environmental inpact statement.

Märten, H. (2006). Environmental managment and optimization of in-situ-leaching at beverley, in B. J. Merkel & A. Hasche-Berger (eds), Uranium in the Environment, Springer Berlin Heidelberg, pp. 537-546. 10.1007/3-540-28367-6_54.

Neumann, N., Sandiford, M. & foden, J. (2000). Regional geochemistry and continental heat flow: implications for the origin of the south australian heat flow anomaly, Earth and Planetary Science letters 183: 107-120.

Nover, G., Stoll, J. B. & Von Der Gönna, J. (2005). Promotion of graphit formation by tectonic stress – a laboritory experiment, Geophysical Journal International 160(3): 1059-1067.

Simpson, F. & Bahr, K. (2005). Practical Magnetotellurics, Cambridge.

Skirrow, R., Jaireth, S., Huston, D., Bastrakov, E., Schofield, A., van der Wielan, S. & Barnicoat, A. (2009). Uranium mineral systems; Processes, exploration criteria and a new deposit framework, Geoscience Australia 20: 1-57.

Tuncer, V. (2007). Exploration for unconformity type uranium deposits with audio-magnetotelluric data: A case study from the McArthur river mine, Saskatchewan, Canada, PhD thesis, University of Alberta.

Yang, X. (2011). Origin of high electrical conductivity in the lower continental crust: A review, Surveys in Geophysics 32: 875-903.