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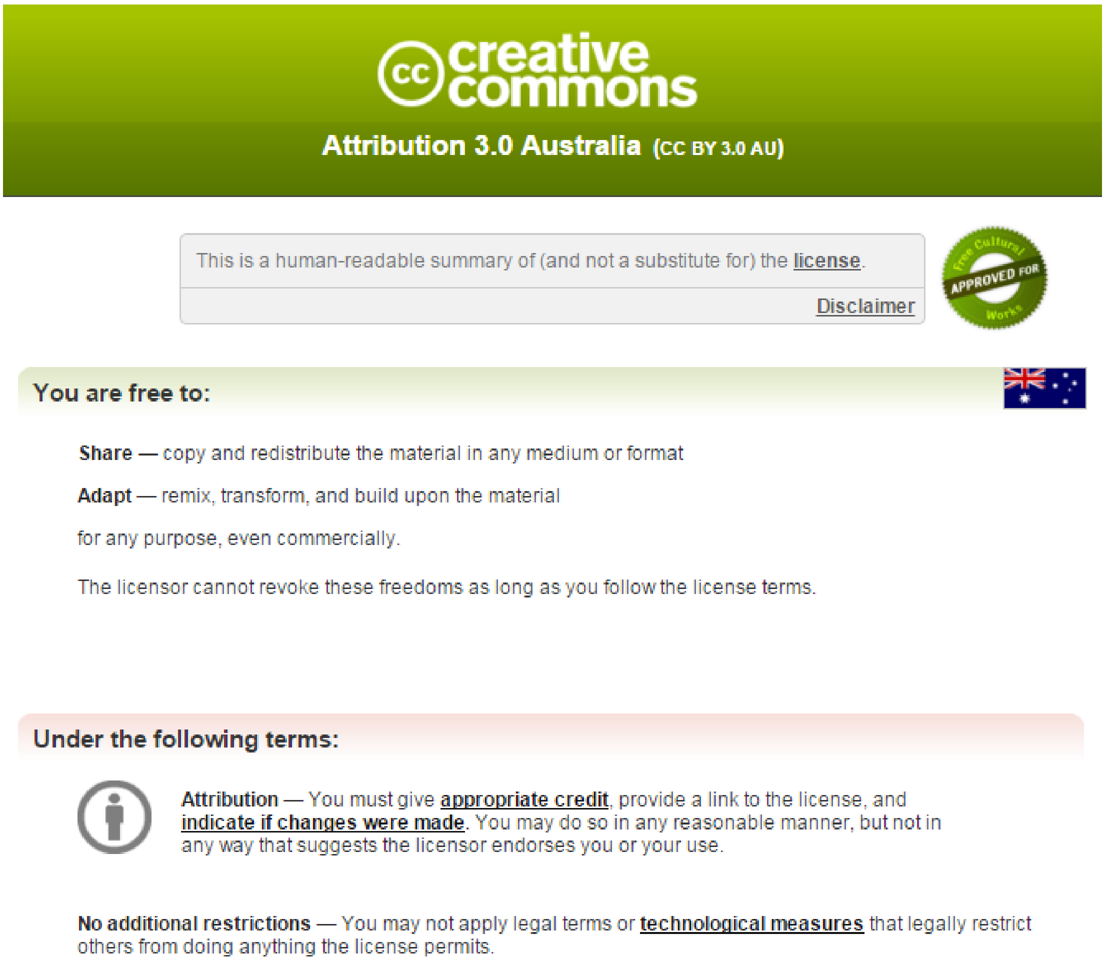

Electromagnetic monitoring of fluid injection – lessons learned

Thiel, S.[1],*, Peacock, J.R.[1], MacFarlane, J.[1], Heinson, G.[1]

[1] Center for 4D Electrical Earth Imaging, University of Adelaide, SA 5005

*Corresponding author: stephan.thiel@adelaide.edu.au

Abstract

Magnetotelluric data acquired over the Paralana project has provided valuable insight into the resistivity distribution across geothermal sedimentary basins. The time-lapse MT measurements during an EGS fluid injection trace the preferential fluid connection in a NNE direction aligned with the regional stress field. The results add information to existing micro-seismic measurements by providing the preferential fluid-filled fracture connection at depth. New results using 2D forward magnetotelluric anisotropy codes are able to reproduce the direction of enhanced fluid flow by fitting measured against modelled phase tensor residuals. Future surveys will need to address limited resolution issues between EM measurements from the surface compared to standard micro-seismic monitoring techniques.

Introduction

EGS systems are an alternative to conventional hydrothermal systems as seen in New Zealand and Iceland for energy production. Creating fluid reservoirs at depths has been established at Habanero and Paralana, South Australia to create a volume of hot fluids for extraction. Prior knowledge of the extent and direction of fluid connection at depth is still a matter of research and relation to regional stresses and pre-existing faults are suggested. Conventional industry standard monitoring techniques of fluid injection involve microseismic monitoring (Wohlenberg and Keppler, 1987), sensitive to fracture opening events as a result of the fluid injection pressure.

Recent results from electromagnetic monitoring of a fluid injection at Paralana (Figure 1) indicate that a volume of 3.1 million litres of injected fluids at 3.6 km depth are sufficient to detect changes above measurement error in MT response at the surface (Peacock et al., 2012). The response changes calculated from successive 24 h blocks of frequency domain MT responses are spatially and temporally coherent and coincide with the injection schedule. Inversions of the MT responses relate the changes in the frequency domain to depth and estimates result in a conductive block at around 2.8 km depth, a few hundred metres shallower than the injected fluid. The discrepancy is due to the uncertainties in the inverse process and its non-uniqueness about the data. While the depth estimation is still matter of ongoing research, the use of invariant phase tensor representation of the measured impedance tensor Z (E=ZB) allows for a rigorous estimation of the directional dependence of the time-lapse measurements in view of the temporal changes. Peacock et al. (2012) show that time-lapse MT measurements result in preferred NNE orientation of current change of measurements taken a few days after fluid pumping began. The preferred orientation seems consistent from measurements weeks after the injection (Peacock et al., 2012a) and is aligned with the regional stress field.

Microseismic monitoring of the Paralana fluid injection appears to support the findings with seismic events aligned preferably in the NNE direction. The faults appear to be only a few hundred metres apart questioning the accuracy of surface MT measurements to individually resolve these faults. We propose that MT is still sensitive to these features without having the resolution to individually map the faults. The expected effect is similar to assuming electrical anisotropy of the fluid injection volume.

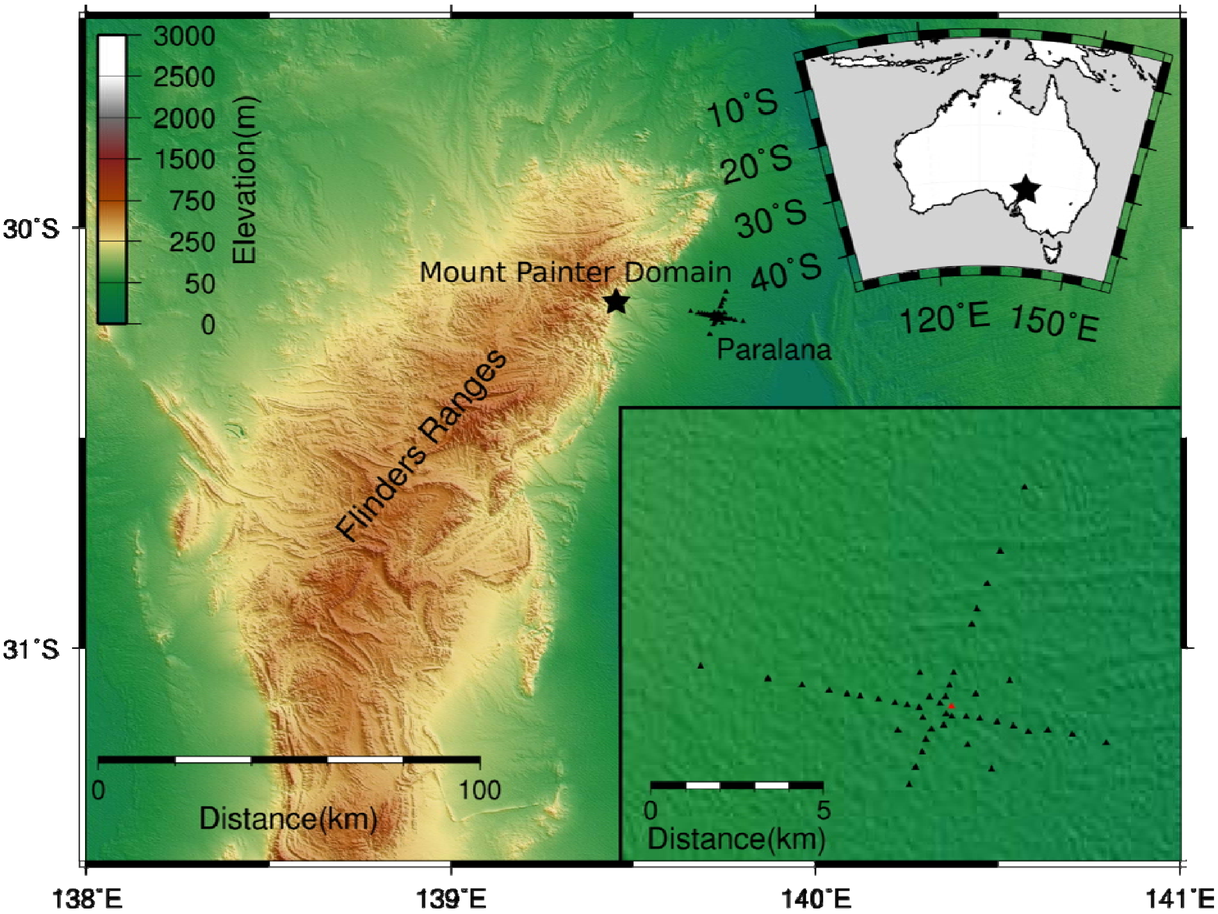

Figure 11: *Survey layout of the Paralana MT survey across the fluid injection site of the Paralana EGS system. The EW line is chosen for 2D anisotropic forward modelling of the injection volume at 3.6 km depth.*

Anisotropy modelling

In order to reproduce an electrical anisotropy response due to fluid injection the 2D forward anisotropy code by Pek & Verner (1997) was employed to simulate electromagnetic fields as a response to a fluid injection scenario at 3.6 km depth. The 2D model domain extending in the EW direction across the Paralana injection site is populated with isotropic (equal in all measurement directions) resistivity changing with depth (1D) following 2D inversion results of the observed MT data across the injection site Paralana 2. The top layer extends to 900 m with resistivity of 10 ohm.m, underlain by the basement and compacted sediments with an isotropic resistivity of 500 ohm.m. The anisotropic fluid injection volume is situated at a depth of 3.6 km with dimensions of 1km wide and 600 m high. The resistivities are equal for the resistivity in the x-direction (north) and z-direction (vertical) but are more resistive in the y-direction. Usual values assigned to the x-, and z- direction vary between 0.01 ohm.m and 100 ohm.m while maintaining a 500 ohm.m resistivity in the y-direction, equal to the background resistivity. In addition to changing the principal resistivities, the strike and dip angle of the resistivity structure is altered to match the observed responses. The best fit between modelled and observed responses is achieved by using an anisotropy strike angle of N10°E parallel to the regional stress field (Figure 2).

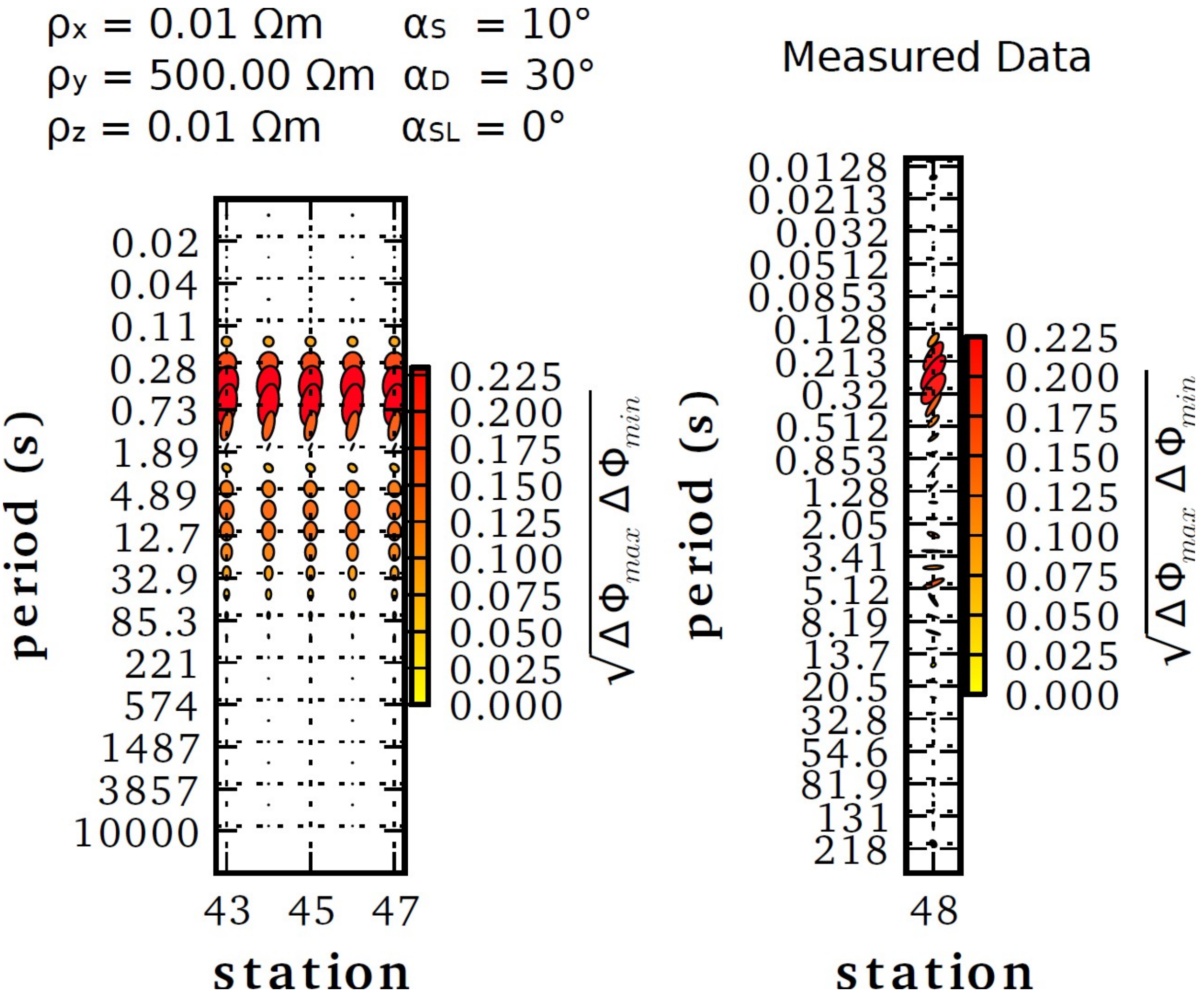

Figure 2: *Comparison of phase tensor residuals for anisotropy modelled (left) and observed (right) stations adjacent to the injection well. Responses are the difference between pre-injection and post-injection magnetotelluric responses. Orientations of the major axes denote direction of maximum connection of fluids and therefore electric currents as a result of fluid injection. An injection body with highest conductivity defined at a strike of N10°E and a 30° dip results in observed phase tensor residuals that match the observed responses.*

Conclusion

The estimation of extent from a fluid injection experiment remains an outstanding research question. Electromagnetic methods offer a useful complementary data set to microseismic monitoring. While microseismics images a high-resolution event cloud of fracture opening, magnetotelluric imaging is directly sensitive to the fluid volume and shows distinct directional dependence aligned with the regional stress field. Observed MT responses are ideally represented using anisotropy due to the lack of resolution of small fractures at depth, which however still produce a polarised MT response. MT anisotropic forward modelling is able to reproduce preferred fracture alignment and results compare well with observed MT responses at Paralana and with the measured microseismic cloud.

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