Fracture delineation and monitoring of geothermal and coal seam gas areas using magnetotellurics

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SUMMARY

New ways of energy production through the use of coal seam gas plays and geothermal hot dry rock and hot sedimentary aquifer systems pose challenges in identifying and monitoring fluid in the subsurface. We propose the use of the magnetotelluric (MT) method to image static and dynamic fluid distributions in the subsurface exhausting the contrast in electrical conductivity between resistive host rock and conductive fluid-filled, porous rock. Base line MT measurements provide reference transfer functions and inverse models to characterise the electrical conductivity distribute on which is linked with bore hole and other geophysical data to obtain knowledge about fluid distribution at depth. The reference models are used to accurately forward model fluid injection or extraction temporally and spatially. This work shows results from fluid injections at a hot dry rock system at Paralana, South Australia, and its applicability to other geothermal and coal seam gas systems.

Key words: magnetotellurics, geothermal, coal seam gas, modelling

INTRODUCTION

The detection and monitoring of fluids plays an increasing role in geothermal and coal seam gas (CSG) plays. Within Australia, the two major geothermal types are the hot dry rock (HDR) systems and the hot sedimentary aquifers (HSA). Both fulfil the minimum requirement of elevated temperatures for direct use or electricity generation. In coal seam gas plays fluid pumping and possible reinjection requires careful monitoring of water tables. Overall, the knowledge of the fluid extent spatially and temporally poses an important challenge.

The depths of interest range from a few hundred metres (CSG) to depths of up to 5km (HDR). While boreholes allow the in-situ detection of fluid in the subsurface, the lack of spatial coverage requires interpolation between boreholes. Particularly, geothermal areas usually only have one borehole which is the injector without additional monitoring boreholes at similar depths. It is therefore necessary to develop adequate geophysical tools to monitor fluid extent of already existing reservoirs in hot sedimentary aquifers and hydraulically injection fluid in hot dry rock and coal seam gas systems.

Seismic micro earthquake arrays are employed to image rock displacements during hydraulic fracturing (House, 1987; Phillips et al., 2002). It is assumed that the fluid front of the hydraulic injection correlates with the location of seismic events. While it is a plausible assumption it is not directly sensitive to the fluid reservoir itself.

Electromagnetic (EM) methods are directly sensitive to the bulk electrical conductivity (or its inverse resistivity) of the subsurface. In sedimentary basins, in which most of the Australian geothermal and coal seam gas plays are situated, the electrical conductivity is mostly controlled by fluids as a function of temperature, pressure, salinity and connectivity (Archie, 1942; Nesbitt, 1993; Nover, 2005). The depths required for monitoring fluids in geothermal and CSG areas require the use of the MT method. While near-surface EM methods, such as TEM, provide high resolution, their limited depth of penetration renders them not suitable for the majority of monitoring exercises.

Forward modelling is a crucial step in assessing the feasibility of monitoring and delineation of fractures. The main parameters are the thickness of a conductive overburden (if existing), the spatial extent of the fluid reservoir, as well as the resistivity contrast with the surrounding host rock.

Initial results of a monitoring experiment around a fluid injection well at Paralana, South Australia, shows promising results. Forward modelling, constrained by base MT data prior to the injection, suggests that changes are very small and just above error threshold. The findings are confirmed throughout the injection and occur in the modelled frequency range. The experiment showed that detailed forward modelling and good base line data are vital in successfully monitoring fluid reservoirs.

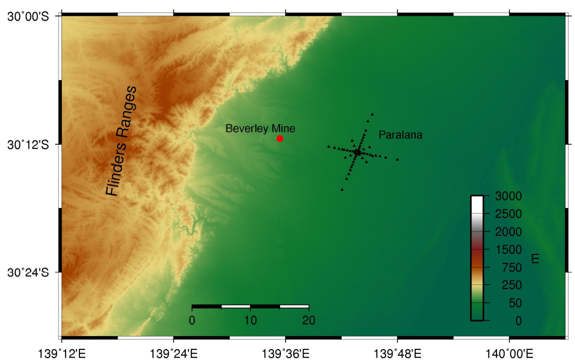

Figure 1: Example of survey design with two main perpendicular MT profiles centred on the borehole, Paralana South Australia. Site spacing increases from 250 metres near the borehole to 1.5 km near the margins and totals 22 stations on each line. Forward modelling indicates

that larger site spacing is sufficient, but redundancy is sought to reduce influence of noise.

Method and results

The MT method records naturally occurring magnetic and electric field at the surface of the earth (Cagniard, 1953). The primary magnetic field induces secondary electric fields in the earth, which through Ohm's Law cause large scale eddy currents. The depths of the induced electric field is proportional to the frequency (or its inverse period) of the magnetic field, a relationship also known as skin-depth relationship. Since the MT method is sensitive to a volumetric half-space, the resolution decreases with increasing skin-depth, i.e. longer periods sense deeper but with less resolution.

The method was applied to the hot dry rock system at Paralana, South Australia. Radiogenic granite is covered by dense sediment packages of up to 5km thickness to the east of the Northern Flinders Ranges and provides a heat source for the overlying sediments. Petratherm Ltd has drilled a borehole to 4012m with casing down to 3725m with projected bottom borehole temperatures of 190C. The measured heat flow was measured at 112μW/m^2.

56 MT stations were deployed along two main profiles (Figure 1) in the NS and EW direction with increasing site spacing away from the borehole. Prior to the deployment, 3D forward modelling (Mackie et al., 1993) indicated the optimal site spacing for a fluid fracture reservoir at depths between 3.5 and 4 km. Between March 2010 and April 2011, three base line surveys were deployed to minimise influence of noise sources from gas pipelines and mining activity. These surveys act as reference data to measurements taken during the injection test in July 2011. Figure 2 illustrates the 2D inverse model obtained from the NS line using smooth Occam inversion approach (deGroot Hedlin and Constable, 1990). The area is characterised by an approximately 500 m thick conductive overburden and reaches resistivities of several hundred Ωm at 4 km depth.

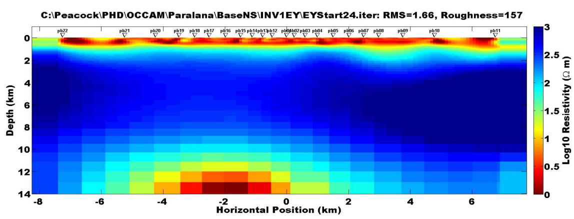

Figure 2: 2d inverse OCCAM model of the NS profile. The sedimentary basin shows low resistivities (5 Ωm) to depths of around 500m and increases to several hundred Ωm at depths of 4 km.

The MT data of the base surveys was used to compare to MT transfer functions collected during injection. Initial results indicate a response change for stations to the east and north of the borehole, but less so to the west and south. Figure 3 shows the temporal change in responses for a station approximately 300 m away from the borehole. A day after pumping the resistivity begins to decrease in the period range of around 1-10 s as predicted by forward modelling.

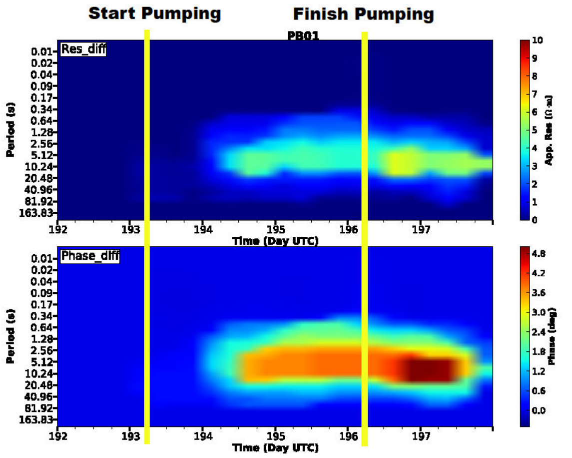

Figure 3: Temporal changes of apparent resistivity (top) and phase (bottom) throughout the fluid injection for a station 300m away from the borehole. MT transfer functions are computed every 6 hours and median filtered. The onset of transfer function changes is offset by about a day.

CONCLUSIONS

The results show that deep fluid injection in geothermal areas can be monitored using the MT method. The response changes are small as predicted by 3D forward modelling but are nevertheless visible. The change correlates with the onset of pumping and also spatially with results from micro-earthquake measurements. The findings are encouraging for the Australian geothermal sector, as most hot dry rock systems are at similar depths as Paralana. Moreover, hot sediment aquifer and coal seam gas systems are usually situated at depths shallower than hot dry rock. In general, a higher resolution of the injected fluid into the subsurface may be achievable for those areas.

Forward modelling shows that certain boundary conditions have to be fulfilled for successful monitoring. For each area the conductive overburden, amount of injected fluid, resistivity contrast between injected fluid and host rock / formation fluid, and depth of reservoir have a significant influence on the measurement sensitivity to the fluid reservoir. For each new geothermal area these parameters have to be carefully assessed and constrained by borehole and base line EM data, ranging from near-surface EM methods, such as time-domain EM to deep penetrating MT.

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