Magnetotelluric Monitoring Of Geothermal Fluid Flow

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Monitoring fluid flow in enhanced geothermal systems (EGS) is vital to reservoir growth and production. Geothermal fluids are innately conductive due to high temperature and pressure and dissolved enhanced ion concentration. This can be exploited by geophysical measurements sensitive to subsurface conductivity changes at several hundreds of meters to a few kilometers depth, such as magnetotellurics (MT). It is proposed that fluid flow can be monitored by measuring subsurface conductivity as a function of space and time using the magnetotelluric method constrained by other geophysical and geological data. 3D MT forward modelling studies demonstrate the feasibility of the method. MT data will be collected in the near future across the EGS site at Paralana, South Australia.

Keywords: Magnetotellurics (MT), geothermal, monitoring, microseismic

Problem:

EGS reservoirs consist of low permeability/porosity rock volumes which need to be stimulated by forcing high pressure fluids into the hot rock layer in order to produce economically feasible amounts of heat. The process of stimulation induces fractures through which fluids can flow and absorb heat. Induced rock fractures can be remotely measured using microseismic methods. Rial et al. (2005) explore shear wave splitting as a viable method to measure microfracture growth. The method is based on the principle that shear waves travelling parallel and perpendicular to the principle fracture plane propagate at different velocities and that change in velocity is proportional to fracture density. However, shear wave splitting analysis cannot provide any information about fluid content nor connectivity of the fracture system. Therefore, another method is needed to complement the microseismic data.

Magnetotellurics passively measures the earth's response to changes in the earth's magnetic field and is sensitive to material properties, primarily the electrical conductivity of rocks and fluids in the subsurface. Hot fluids under pressure with high ion concentrations have enhanced conductivity characteristics, which can be measured with MT. Furthermore, multiple MT surveys over the same grid at different time intervals could produce a time lapse of subsurface fluid movement, effectively monitoring geothermal reservoir fluid flow. Spichak and Manzella (2008) claim that MT is the most effective electromagnetic method for defining conductive reservoirs.

The main goal of this project is to show that magnetotellurics is a viable method for characterising and monitoring enhanced geothermal systems. First, a forward model will be created using existing geological information of the test site. Then, before fractures are induced to produce a reservoir, a grid of MT stations will be set up at the test site such that a 3D resistivity image can be produced from the data. A few MT stations will be deployed permanently during the fracturing process from which conductivity will be measured as a function of time. After fracturing, another survey will be collected with plans to collect more surveys at intervals on the order of months. These surveys will provide spatial subsurface conductivity images as a function of time.

Hypothesis:

Geothermal fluids have enhanced conductivities due to high temperatures and pressures and high dissolved ion concentration. The dissolved ions will be a mixture of initial concentrations of salts as well as ions dissolved into the fluid picked up from lithology. Ussher et al. (2000) demonstrate that there are two conduction mechanisms in clay-rich sediments; firstly, conduction via pore water and secondly, through the double layer of cations. Temperature is the measurement of how fast particles are moving, which means at higher temperatures charges can move faster and easier under the influence of an external electromagnetic field, increasing the conductivity. When these fluids enter the fractured system, conductivity may increase by an order of magnitude or more, which will cause a change in the MT response. MT measurements crossing an area of a fractured system with two perpendicular lines will allow the delineation of the vertical and horizontal extent of the fluid-filled fractured rock. Other material properties of the fluids could also be estimated from the MT response such as temperature, porosity, permeability and salinity (Spichak and Manzella, 2008).

Another interesting phenomenon that might be explored in these surveys is seismoelectric effects due to fracturing. Seismoelectrics is based on the theory that seismic events cause charges to move which creates currents. More precisely, the double layers between pore electrolytic fluids and pore wall geometries emit an electric signal when displaced by seismic activity (Pride and Haartsen,

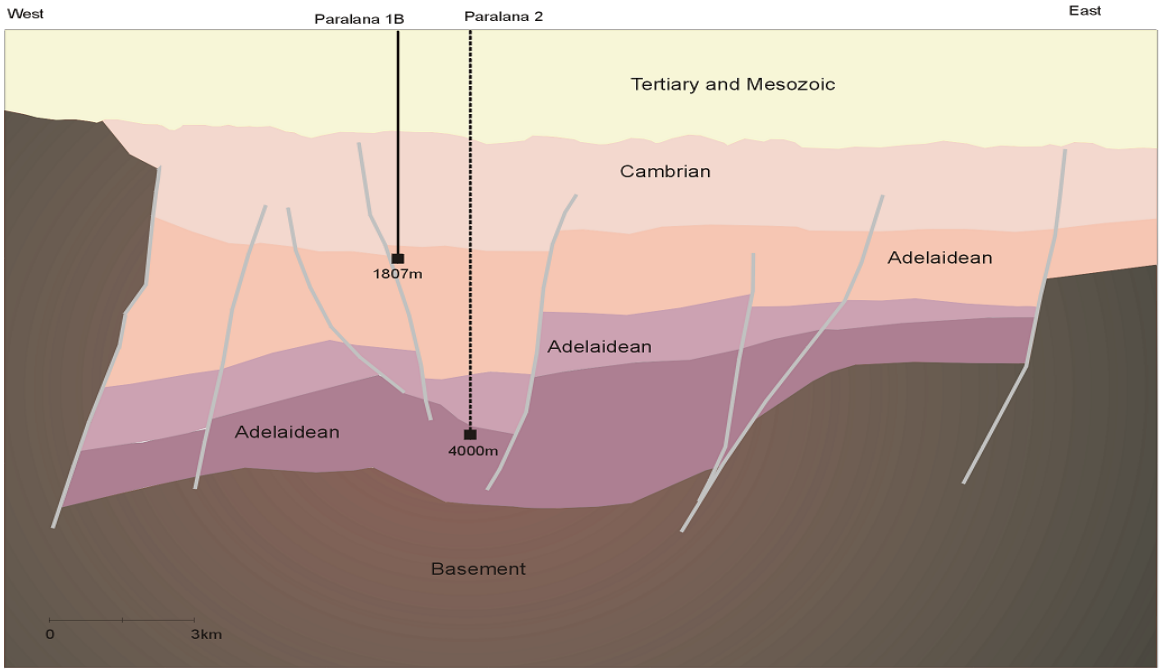

Illustration 1: Interpreted geological cross-section across the EGS site at Paralana.

1996). If the seismic, electric and/or magnetic fields are measured simultaneously, relationships between various material properties can be derived, such as resistivity and seismic velocity (Garambois and Dietrich, 2001, Haines et al., 2007).

The test site at Paralana, South Australia, has a conductive sedimentary layer near the surface with a few hundreds of meters thickness. The sedimentary layer overlies a more resistive basin. Two faults bound the proposed reservoir, which has a lateral extent of a few hundred meters at about 3-4km depth.

Procedure:

First, a geological model of the test site at Paralana will be produced using existing geological information such as regional structures along with well log data. This information will then be used to forward model the MT response of the existing geology before fracturing is induced. This will provide a control with which to compare changes in conductivity of the fractured layer. To simulate fluid injection, a conductive layer will be inserted in the Mt forward model at a depth of the proposed fracturing. A range of conductivity values will be used reflecting expected values calculated from Archie's Law using provided parameters (Archie, 1942). The conductive layer will then "flow" through the model by laterally expanding the conductive area of the forward model in incremented steps. At each step the MT response will be calculated. This will provide information about the type of MT responses predicted for the test site, which will give vital information about the measurement spacing and frequency ranges to be used.

Next, preliminary MT surveys will be collected at the test site in late November to early December 2009. The survey will include two perpendicular 2D lines and a small grid that covers the proposed reservoir. The MT data of the 2D lines will be inverted to obtain a 2D resistivity image of the subsurface underneath the drill site. This will provide constraints of the resistivity distribution in the east-west and the north-south direction. The additional MT sites outside the two 2D lines across will provide additional constraint.

Fracturing will then be induced into the reservoir in January 2010, which should take around one month to complete. A microseismic network will be in place during the fracturing process to monitor seismic events associated with the oping of the fractures. A few MT stations, covering a grid extending over the reservoir and powered by solar panels, will be deployed to collect data while fracturing is induced. This will provide time lapse data as well as detect possible seismoelectric effects when correlated with microseismic data. The data will be downloaded at intervals on the order of weeks and processed to produce 3D images of subsurface conductivity (Newman et al., 2008), from which the extent of the fluid-filled reservoir can be estimated if the resolution permits.

During and after fracturing, MT measurements will be repeated along the two 2D lines and compared to the MT data collected before the stimulation. Thus, this survey will provide information about the change of conductivity as a function of time, and will help to relate the outcomes with the extent of the fluid-filled reservoir.

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