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Magnetotelluric Characterization of the Habanero Geothermal EGS Project: Initial Results on Fluid Injection Monitoring

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ABSTRACT

Magnetotelluric (MT) data was collected across the Habanero enhanced geothermal system (EGS) project site in the Cooper Basin , South Australia in view of delineating the crustal conductivity structure of the geothermal area and to monitor fluid injection of Habanero 4 geothermal borehole. Two MT surveys have been carried out. The first pre-injection MT survey consists of two perpendicular profiles, each about 20 km long. 2D inversion of MT data of the two profiles shows three main resistivity structures to a depth of 10 km: 2 km thick good conducting (< 10 Ωm) surface layer is underlain by relatively high resistivity(10 Ωm < □ < 100 Ωm) followed by high resistivity(> 100 Ωm). The low resistivity surface layer shows areas with poorly consolidated sands, siltstones and clay stones. Below the conductive layer, a relatively high resistivity zone that can be correlated to consolidated sandstones, siltstones and shale. The high resistivity structure is associated with basement granitic formation. The second MT survey was conducted during fluid injection of Habanero 4 well in November 2012 which lasted for two weeks. Initial results from MT residual phase tensor analysis of the fluid injection at depth of about 4 km show fractures opening in N/NE direction. This result is in good agreement with seismic cloud observed in the Habanero area during fluid injection. The thick sedimentary cover (> 2 km) which has a screening effect to the EM field makes it difficult to measure a significant change in the stimulated reservoir in the granite at a depth of about 4 km. In addition, the noise in the MT data is the main source of uncertainty in determining the direction of the fracture opened during fluid injection.

1. INTRODUCTION

The aims of this project are to study the relationship between the directions of electrical current flow in the crust and regional stresses, as well as to determine if electrical resistivity of upper crustal rocks can be used to determine temperature, porosity and permeability.

The Habanero EGS project is located in Copper Basin about 800 km from Adelaide in North Eastern South Australia. The approximate geographical location of the MT studied area as a whole is 140.66° E and 140.85° E longitude and 27.89° S and 27.72°S latitude presented in Figure 1.

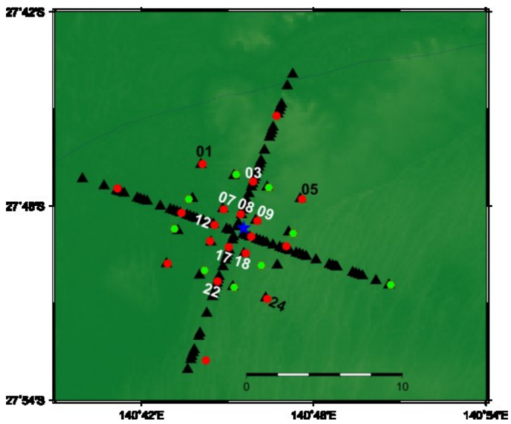

Figure 1: Station layout of MT measurement of the two MT surveys. Black triangles denote MT stations from Quantec survey recorded before stimulation. The red circles and blue hexagons denote broadband MT stations and E-field stations from second survey during fluid injection at Habanero 4, respectively. Blue star is Habanero 4 EGS well. Site names shown are the sites used in the pseudo-section plot on Figure 5 during fluid injection.

In November 2012, Habanero 4 was stimulated by injecting 34.2 Million liters of fresh water at a maximum pumping rate of 53 kg/s for over 14 days (McMahon and Basich, 2013(a, b)). During the extended stimulation and subsequent pressure decline, more than 24,000 seismic events were detected with a maximum event magnitude (ML) of 3.0 (Figure 2). Hypocenter locations indicate that seismicity occurred on the same sub-horizontal layer structure identified in previous stimulations (McMahon and Basich, 2013(a, b)). A single fracture zone was stimulated with a vertical extension of 100 – 150 meters and about 5 meter width during previous stimulations (Baisch, 2006, McMahon and Basich, 2013(a, b), Hogarth, 2013). Glikson and Uysal (2010) reported presence of parallel closely spaced (microns to tens of microns) planar features in quartz grains from the basement granitoids samples of Cooper Basin drill holes, which is interpreted as impact fracturing of target rocks.

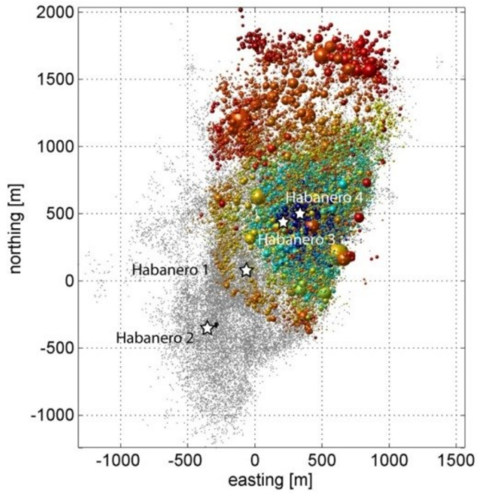

Figure 2: Hypocenter locations of the induced seismicity from the 2012 stimulation in Habanero 4. Each seismic event is displayed by a globe scaled to the event magnitude. Color encoding denotes occurrence time according to legend. Previous seismic activity (2003/05) is indicated by grey dotes.

2. MT DATA ACQUISTION AND PROCESSING

Two MT surveys were conducted at Habanero EGS project site in August 2012 by Quantec Ltd before fluid injection and in November 2012 by University of Adelaide during fluid injection, respectively. The first MT survey before fluid injection consisted of 119 MT sounding along two perpendicular profiles (Figure 1). The MT survey gave good results of impedance estimates for periods of 0.01 s to 1000 s. To remove galvanic distortion in the MT soundings, the method suggested by Bibby et al. (2005) was used. A typical resistivity and phase curve from pre-injection survey is shown on Figure 3 (a).

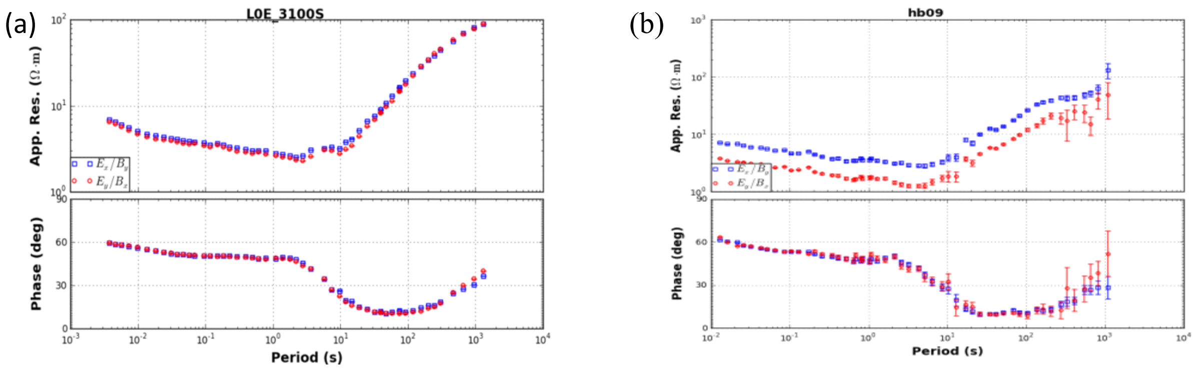

Figure 3: (a) Resistivity phase curve of site LOE_3100S from pre-injection survey. (b) Resistivity phase curve of site 09 during fluid injection. The split between the resistivity curves show static shift. Large error bars are observed at long periods. The blue squares and the red circles denote xy and yx components of resistivity and phases, respectively. The resistivity and phase curve show the 1D nature of the sounding.

The second MT survey was conducted concomitantly with fluid injection of Habanero 4 well by Geodynamics (Figure 1). Based on the findings of Peacock et al (2012), the survey has been expanded to include 19 broadband MT sites and 10 new E-field loggers. The grid is about 4 km along each side to obtain a better spatial resolution. The time series processing resulted in fairly good impedance estimates for periods of 0.01s to 200s (Figure 3(b)). Some MT sites were affected by cultural noises from fluid injection operation and gas pipeline generators.

Phase tensor residuals give information about geo-electric strike transformation during fluid injection and help to infer direction of change in current flow (Heise et al., 2007, Peacock et al, 2013, Booker, 2014). The residual phase tensor is calculated as a percent change and given by:

$$\Delta\Phi_{12} = I - (\Phi_2^{-1}\Phi_1) \qquad (1)$$

where Φ_2,Φ_1, I, Φ^(-1) are phase tensor post-injection, phase tensor pre-injection, identity matrix of rank two and the inverse, respectively.

3. RESULTS

2D MT cross section LOE (Figure 1 and Figure 4) consists of a total of 48 MT station with a total distance of about 20 km. 2D inversion of MT data of profile LOE shows three main resistivity structures to a depth of 10 km: 2 km thick good conducting (< 10

Ωm) surface layer is underlain by relatively high resistivity (10 Ωm < ρ < 100 Ωm) followed by high resistivity (> 100 Ωm). The low resistivity surface layer shows areas with poorly consolidated sands, siltstones and clay stones. Below the conductive layer, a relatively high resistivity zone that can be correlated to consolidated sandstones, siltstones and shale. The high resistivity structure is associated with basement granitic formation. The isotropic smooth inversion model shows the topology of the basement granite at depth of about 4 km. The 2D MT resistivity model doesn't clearly show the presence of individual fractures in the granitic reservoir as MT is not sensitive to small geologic structures at depth of 4 km.

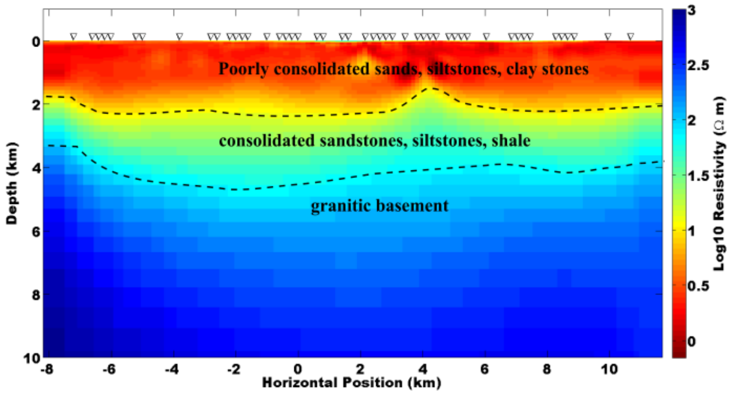

Figure 4: 2D resistivity model of profile LOE from survey one showing the three main resistivity structures at Habanero EGS field.

The residual phase tensor pseudo-section plot of the MT data taken pre and post fluid injection (shown as red circles on profile LOE on Figure 1) gave a direction of maximum change in geo-electric strike in N/NE direction as shown on Figure 5. Plots of residual phase tensor map for different periods in Figure 6. The inferred change in the phase tensor residual ellipse occurs at period of about 10 s and later which is equivalent to the targeted fracture at depth of 4 km during the injection. The calculated residual phase tensor changes effect is also observed at periods greater than 10 s. The soundings closer to Habanero 4 well reveal greater changes in residual phase tensor compared to soundings far way.

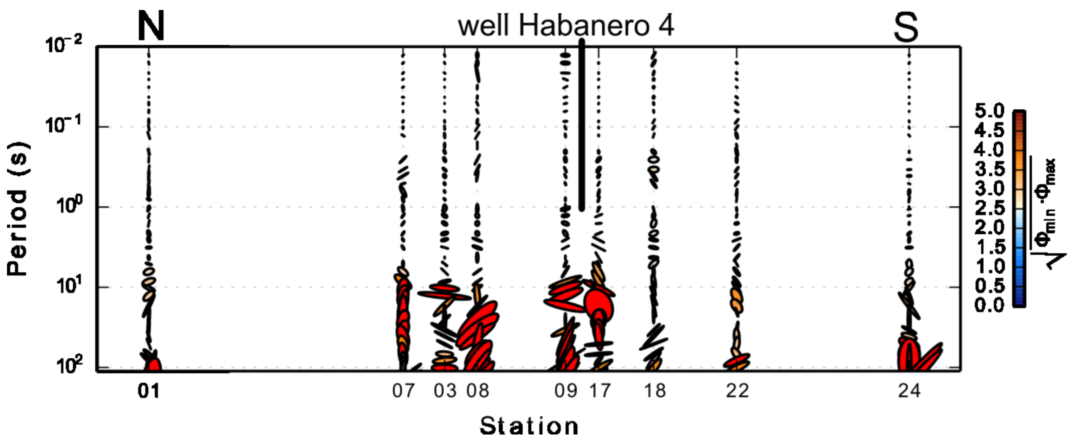

Figure 5: Residual phase tensor pseudo-section plot of pre and post injection of Habanero 4 along profile LOE in Figure 1 showing changes in direction of maximum current flow because of the fluid injection close to the well Habanero 4. The possible changes in residual phase tensor are observed after period of 10 s. The ellipses are colored by the geometric mean of maximum and minimum phases.

3. CONCLUSION

The preliminary 2D inversion of MT data showed thickness of the sedimentary formation over the granitic basement. The residual phase tensor analysis showed the period at which the maximum change in the direction of current flow occurred during the fluid injection. The preliminary result indicated possible fracture orientation of N/NE direction because of the fluid injection at Habanero 4 well. This result is in good agreement with seismic cloud observed in the Habanero area during fluid injection.

The thick sedimentary cover (> 2 km) which has a screening effect to the EM field makes it difficult to measure a significant change in the stimulated reservoir in the granitic basement at depth of about 4 km. In addition, the noise in the MT data during injection is the main source of uncertainty in determining the direction of the fracture opened during fluid injection.

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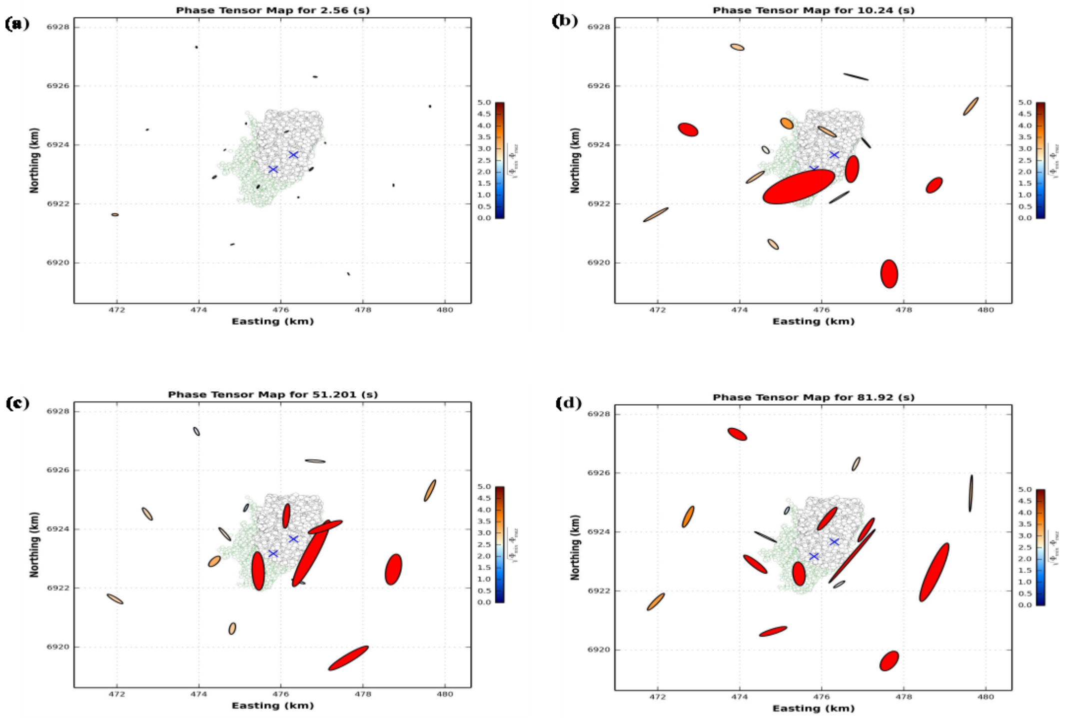

Figure 6: Maps of phase tensor residuals between pre and post stimulation measurements (a) at period of 2.56 s (b) 10.24 s (c) 51.201 s (d) 81.92 s. The green and black blobs at the background represent the seismic cloud from microseismic data collected during previous and 2012 injections, respectively. The x symbols are Habanero 1 (injector) and Habanero 4 (producer) wells. See Figure 2 for locations.

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