Monitoring EGS Reservoirs Using Magnetotellurics

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A novel time-lapse magnetotellurics (MT) method is proposed to monitor and estimate areal extent of enhanced geothermal systems (EGS). Being directly sensitive to subsurface electrical conductivity, MT has the capability to measure fluids at depth which are both thermally and electrically conductive. MT measurements before, during and after fluid injection are compared to estimate the lateral extent of the induced reservoir at Paralana, South Australia. 3D forward modelling shows the residual MT response between a system with and without conductive fluids to be small, of the order of a few degrees in MT phase. It is crucial to obtain accurate and precise MT responses throughout the surveys in order to produce a reliable model of the changing subsurface. Presented are MT responses before fluid injection and after the first fluid injection. Furthermore, time series measurement of the electric and magnetic fields during the fracturing process may allow studies of EM disturbances generated by the seismic waves, also known as the seismoelectric effect, which can provide information about pore fluid inclusion.

Keywords: Magnetotelluric, EGS, Monitoring

Introduction

EGS has the potential to supplement energy production as the world slowly and resistantly shifts towards renewable energy. One important constraint of EGS is monitoring where the fluids go once injected into the hot lithology. Traditionally, reservoirs are monitored with micro seismometer arrays, which measure seismic events generated by fractures (Phillips et al., 2002). Tomography can be applied to estimate location of the fracture (House, 1987), and shear-wave splitting can be used to estimate size and orientation of the fracture (Elkibbi and Rial, 2005). Unfortunately, these measurements do not provide information about fluid inclusion.

Magnetotellurics (MT)

MT is a passive volumetric measurement that exploits Faraday's law of magnetic induction by measuring orthogonal components of the Earth's natural magnetic field and its subsequent electrical response. MT is a diffusive method, which means source energy spreads as a function of time and resolution is proportional to source period, as defined by the skin depth equation. It is sensitive to variations in electrical conductivity of the subsurface, which makes it a prime technique to monitor changes as electrically conductive fluids are introduced. The fluids are assumed to be conductive due to thermal and dissolved ion enhancement and will provide a large contrast with resistive host rocks (Spichak and Manzella, 2009).

Test site: Paralana, South Australia

The test site is in the northern part of South Australia, about 600km due north of Adelaide, near the edge of the Flinders Ranges and Paralana hot springs. Here, the thermal activity is generated by an innately large density of radiogenic elements, where residual heat is a by-product of millions years of decay (Brugger, 2005). The 1590Ma crystalline lithology of the uplifted Flinder Ranges has an estimated heat flow on the order of 60mW/m2 in (Neumann, 2000), compared to a typical basement rock heat flow of about 10mW/m2. To the East of the Flinders Ranges, the hot crystalline rocks are unconformably overlaid by about 4500m of Adelaidian sediments, which acts as a lithologic blanket keeping heat from escaping. As a result the heat flow is estimated to be 112mW/m2, making the area a prime location for EGS.

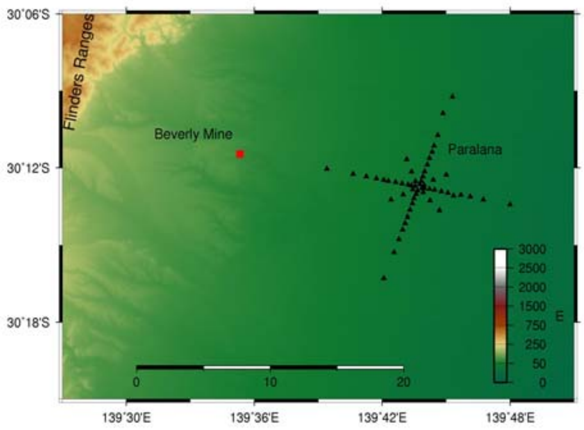

Figure 1: Survey design centred on Paralana 2 drill hole, overlying elevation (m). Two orthogonal lines parallel to assumed principle stress directions provide dense 2D estimation with 22 stations per line. Spacing varies from 200m near the centre to 1.5km near the extremities. Two off diagonal lines with variable spacing of 250m, 500m, 1km provide dimensionality constraints with 6 stations each. One survey encompasses a total of 58 stations, 56 plus two remote reference stations.

Petratherm and joint venture partners Beach Energy Ltd and Truenergy Geothermal Pty Ltd lease a 500km2 tenement where Paralana 2 has been drilled to a depth of 4012m and cased to 3725m. The bottom hole temperature has been estimated at 190 C and fluids were encountered at a depth of 3860m. Note the proposed EGS will not be located in the basement rock, but in the sediment package directly above, which has a dominant horizontal stress field. It is proposed that inducing permeability and porosity in this sediment package via mechanical fracturing will be achieved more easily than in the crystalline basement without losing much in reservoir temperature. The proposed reservoir size will be about 1km in the east-west direction and about 2km in the north-south direction and about 400m thick at around 3600m depth. Perforation of the well casing is proposed to commence in August, 2010, followed by two separate fracturing periods occurring in September, 2010 and January, 2011.

Procedure

A preliminary survey was collected to compare any changes in other surveys collected during and after the two fracturing periods. For all surveys, the basic layout, centred on Paralana 2, contains an orthogonal pair of NNE-SSW and WNW-ESE lines employing 22 stations each, Figure 1. The lines have variable spacing of ~200m near the centre increasing to 1.5km near the extremities to get maximal coverage at depths of investigation. Two off diagonal lines containing 6 stations each, again centred on Paralana 2, with variable spacing of 250m, 500m, 1km, aid in estimating 3-dimensionality. Each survey will employ 56 stations in total plus 2 remote reference stations 60km and 80km south of Paralana. The survey design is based on forward modelling and logistics. The goal is to estimate reservoir extent as a function of time by measuring changes in the MT responses.

Survey 1: Base survey

A base survey was collected in March, 2010 with AuScope instruments run by the University of Adelaide. The sampling rate was 500Hz, with 50m dipole lengths, measuring horizontal magnetic fields Bx and By, along with horizontal electric fields Ex and Ey, where the x component measuring the field relative to magnetic north and y measuring the field relative to magnetic east. The vertical magnetic component Bz was measured for 6 stations. Stainless steel stakes were used as dipoles for 51 sites, the other 5 sites employed Cu-CuSO4 pots. Induction coils were used as magnetometers. The average data collection time was 22 hours. MT responses were calculated using BIRRP (Chave, 2004) and an in house interface written in Python. It was found that 30 sites were not precise enough due to an unknown source of noise resembling a non-periodic charge-recharge pattern in the electric channels, Figure 2. The noise does not appear to correlate between stations and does not appear to have any location objectivity. Different filtering techniques were employed with little effect on transfer function accuracy. Therefore, those 30 sites have been redone using Cu-CuSO4 electrodes, which seem to produce more stable and reliable electric field measurements. Most data have low coherency and larger error bars around 1-10 seconds, Figure 5 which is a well known dead band. Also, the apparent resistivity and phase polarizations suggest a dominant 1D geoelectric structure to a period of a few seconds, then a multidimensional structure after periods of a few seconds. The site is near a large working uranium mine, Beverly in Figure 1, which produces 50Hz (and harmonics) EM signal. This signal is observed in the time-frequency spectrogram, and in estimated apparent resistivities and phases below periods of .1 seconds, where the estimations are less smooth.

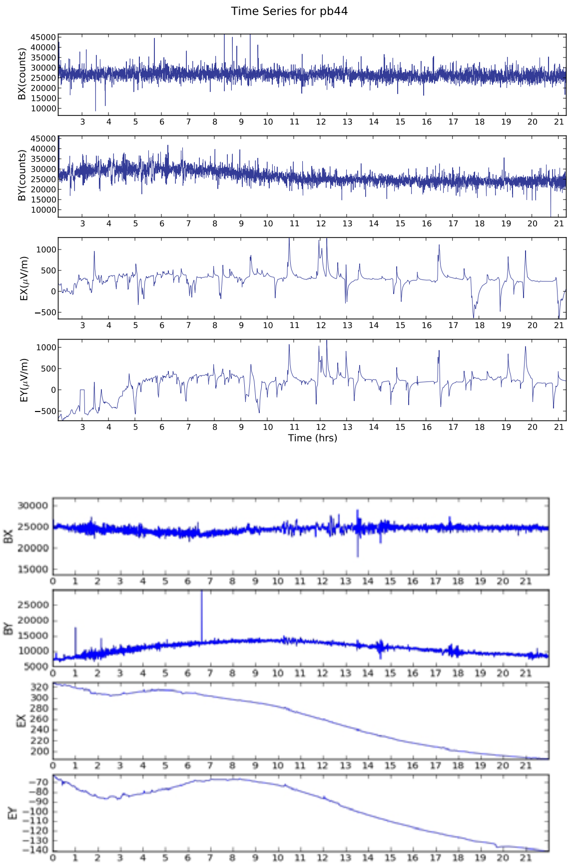

Figure 2: Plots of time series data for two stations plotting, Bx (counts), By (counts), Ex (mV/m), and Ey (mV/m). Bottom axis is time in hours. Top: station pb44, 5km west of Paralana 2, showing a sporadic charge-recharge pattern in the electric channels giving irregular estimates of the MT response. Bottom: station pb 24, 500m east of Paralana 2, showing smooth response in electric channels giving smooth estimates of the MT response.

A second base survey was collected in May, 2010 to redo the stations from the first survey that were not precise enough. The same parameters and locations were used, but Cu-$CuSO_4$ electrodes were used for all stations and no B_z signals were recorded due to instrument constraints. Unfortunately, at the same time this survey was being collected the Epic Pipleline, which runs parallel to the NNE-SSW line about 2km west of Paralana 2, was being tested for corrosion. To do this an electric 3 second square wave is sent down the pipeline every 12 seconds, Figure 3.

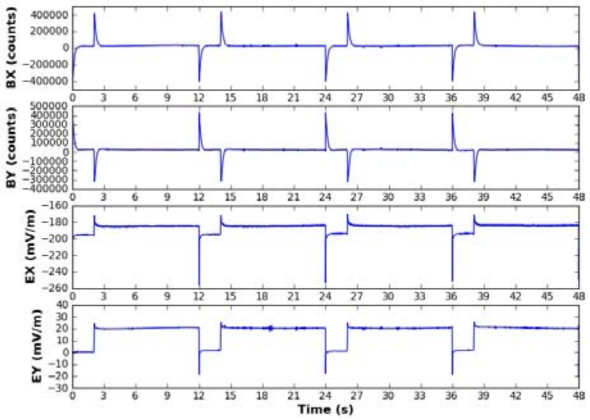

Figure3: Left: time series of Bx (counts), By (counts), Ex (mV/m), Ey(mV/m) for station pb37 from second survey, 200m near the pipeline. Notice the dominating 3 second square wave in the electric channels and the corresponding magnetic response.

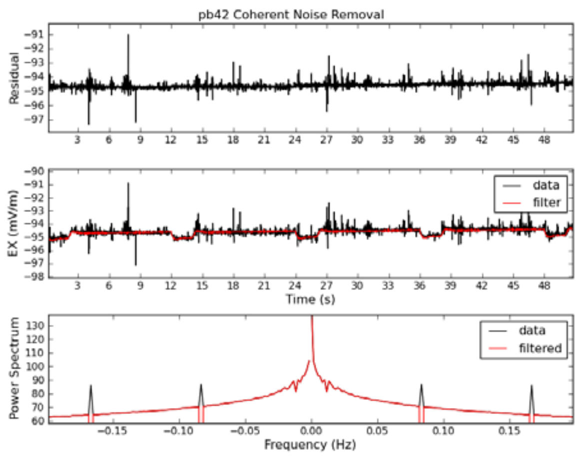

Figure 4: Plot demonstrating a method to remove periodic noise by subtracting the average wave form for a 12 second window from the data for pb42 E_x channel. Top: E_x (mV/m) with periodic noise removed plotted against time (s). Middle: filter in red compared to the raw data plotted against time(s). Bottom: Plot of the power spectrum of the raw data in black and the filtered data in red. Notice the large notches at 12 seconds and its harmonics are removed.

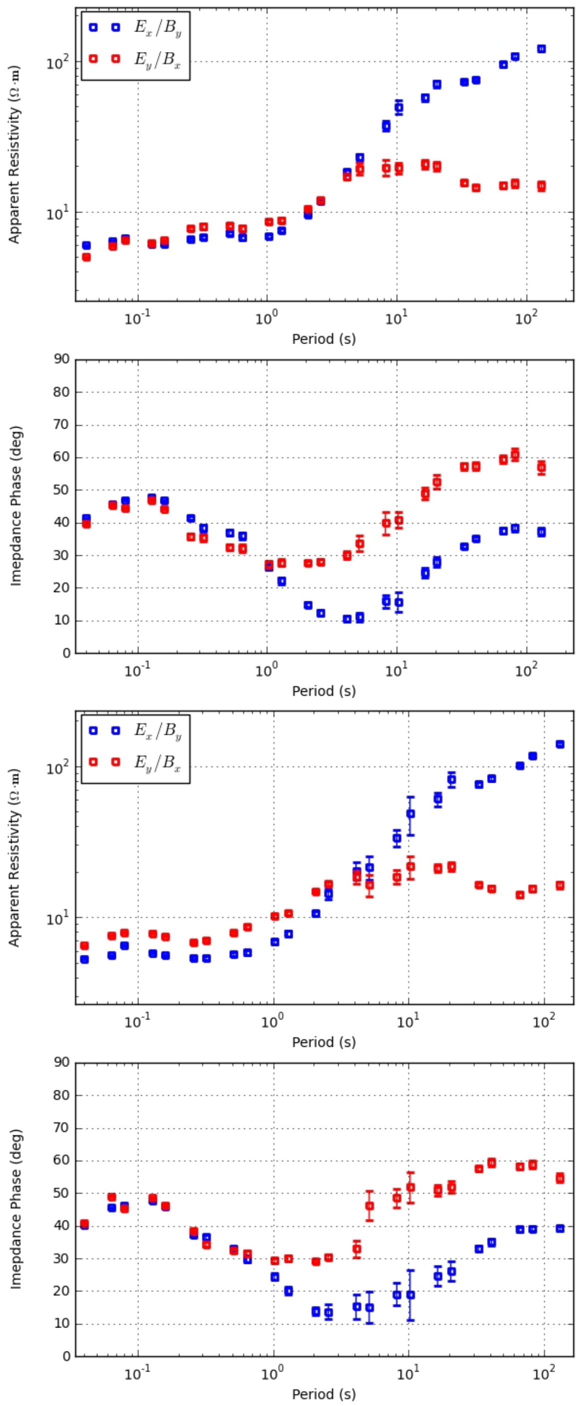

Figure 5: MT responses of two orthogonal modes Ex/By and Ey/Bx. Top are log-log plots of apparent resistivity versus period. Bottom plots are phase in degrees versus log period. Top: pb24 from first base survey displaying a relative smooth MT response with minimal error bars. Bottom: pb42 from second survey with periodic noise removed. Again notice the plots display relative smooth MT responses with minimal error bars, but still have a coherent biased in periods of 1-10 sec. Notice in all plots the error bars are larger around 10 seconds which is where a change in the MT response is expected to occur when fluids are injected. This is also the known dead band where there is naturally low signal power.

Because this signal is distinctly periodic and regular, simple time series analysis can remove this from the data. By taking an average of a 12 second window the average wave form can be calculated. That wave form is convolved with a series of delta functions every 12 seconds. A linear trend calculated from the data is added to the filter time series to fit the data better. The filter is then subtracted from the raw data, Figure 4. This method works fine for stations at least 1 km away from the Epic Pipeline, but breaks down closer due to the large amplitudes of the periodic signal. Along with this method, remote referencing is used to constrain the transfer functions, Figure 5. Unfortunately, with the periodic noise remove some of the signal is also removed which ads to larger error bars around 3-12 seconds. It was decided to redo the inner 30 stations to get the best estimate of the MT response as possible and reduce error bars. This survey will be collected at the end of August, 2010 in conjunction with the perforation test.

Analysis

The MT responses commonly suffer from near-surface galvanic heterogeneities that distort the calculated impedance tensor Z. Given the existence of a subset with 1D characteristics in the data it is possible to fully calculate the distortion-free regional impedance tensor (Bibby et al., 2005). In the current case, the presence of the 1D resistivity distribution of the sediment strata allows a reliable estimate of the regional impedance tensor. Knowledge of the distortion-free regional impedance tensor ensures a more accurate estimation of the subsurface resistivity. The regional impedance tensor is inverted in a 2D sense to obtain the resistivity distribution underneath the profiles (Rodi and Mackie, 2001). This has been applied to

Conclusions

A novel method of monitoring enhanced geothermal systems using the magnetotelluric method has been proposed because MT is sensitive to the bulk electrical conductivity of the subsurface and therefore directly to the high conductivity of the injected fluids. The EGS system at Paralana will be induced in the sediment package above the hot basement rocks. The relatively high conductivity of the sedimentary basin near the surface requires high quality MT responses to ensure detection of small changes in the MT responses before and after the injection of fluids. Keep in mind the base survey to which all changes are going to be compared to needs to be precise and accurate. Therefore it is important to collect the best data possible even if it means repeating surveys. Learning is about making mistakes, therefore the more you make the more you learn.

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