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3D MAGNETOTELLURIC CHARACTERIZATION OF THE COSO GEOTHERMAL FIELD

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ABSTRACT

Knowledge of the subsurface electrical resistivity/conductivity can contribute to a better understanding of complex hydrothermal systems, typified by Coso geothermal field, through mapping the geometry (bounds and controlling structures) over existing production.

Three-dimensional magnetotelluric (MT) inversion is now an emerging technology for characterizing the resistivity structures of complex geothermal systems. The method appears to hold great promise, but histories exploiting truly 3D inversion that demonstrate the advantages that can be gained by acquiring and analyzing MT data in three dimensions are still few in number. This project will address said issue, by applying 3D MT forward modeling and inversion to a MT data set acquired over the Coso geothermal field. The goal of the project is to provide the capability to image large geothermal reservoirs in a single self-consistent model. Initial analysis of the Coso MT data has been carried out using 2D MT imaging technology to construct an initial 3D resistivity model from a series of 2D resistivity images obtained using the inline electric field measurements (Z_{xy} impedance elements) along different measurement transects. This model will be subsequently refined through a 3D inversion process. The initial 3D resisitivity model clearly shows the controlling geological structures possibly influencing well production at Coso. The field data however, also show clear three dimensionality below 1 Hz, demonstrating the limitations of 2D resistivity imaging. The 3D MT predicted data arising from this starting model show good correspondence in dominant components of the impedance tensor (Z_{xy} and Z_{yx}) above 1Hz. Below 1 Hz there is significant differences between the field data and the 2D model data.

INTRODUCTION

A critical component in understanding the hydrothermal properties of complex geothermal reservoirs, typical of the Coso geothermal field, is technology to provide images of subsurface structures, which control geothermal fluid flow. Electrical resistivity/conductivity is a primary physical property of the Earth strongly influenced by hydrothermal processes present in geothermal reservoirs. If mapped, resistivity can be used to infer untapped fracture systems and regions of increased permeability and fluid content, as well as conductive alteration of minerals (clays, etc.) due to induced fracturing arising from hydraulic simulation of the reservoir. Magnetotellurics (MT) has a long history in geothermal exploration. With the recent advent of distributed computing, 3D MT modeling and inversion has emerged as a promising technique to model and image geothermal reservoirs in a single self consistent manner at presumably optimal accuracy and resolution. This will be demonstrated on MT data acquired over the eastern portion of the Coso geothermal field (Figure 1). It is an opportunity to test whether three-dimensional imaging/inversion, can avoid artifacts inherent in 2D inversion of 3D data. Demonstrating this in the geothermal context will push geophysical characterization of geothermal systems beyond the current state and may provide a new quantitative tool for geothermal well location.
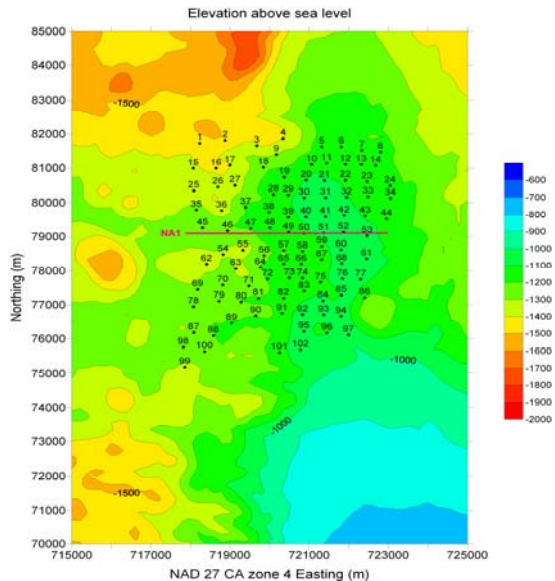
Figure 1. Coso MT Site and elevation map in meters. NA1 is contiguous bipole profile, Navy Array 1.

SUMMARY OF COSO MT MEASUREMENTS

MT exploits naturally occurring, broadband electromagnetic wave fields over the Earth's surface as sources to image underground resistivity structure. The EM fields arise from regional and worldwide thunderstorm activity and from interaction of the solar wind with the Earth's magnetosphere. Due to the remote nature of these EM sources and the high index of refraction of the Earth relative to the air, the waves are assumed to be planar and to propagate vertically into the Earth. The waves are arbitrarily polarized over a 3D Earth, which necessitates a tensor formulation, in other words a vector measurement of the EM fields, to completely represent the subsurface geoelectric structure. A simplified view of a five-channel MT detector as deployed over the Coso geothermal field appears in Figure 2. Bipoles and coils measured the electric (E) and magnetic (H) fields at 102 detector sites (Figure 1). The EM time series were decomposed to frequency spectra via Fourier transformation and band averaging. Also acquired was a profile of 52 contiguous E-field bipole MT measurements across presumed strike in the northern east flank of the field (Figure 1). This collection mode fully samples possibly discontinuous responses across strike, to enhance resolution and reduce bias (Torres-Verdin and Bostick, 1992; Wannamaker, 1999).
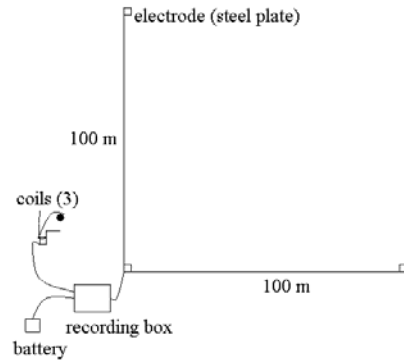

Figure 2. Simplified view of an MT station as deployed at the Coso geothermal field, after Wannamaker et al (2004).

The horizontal electromagnetic field spectra (E_x, $E_y H_x$, H_y) are interrelated by

$$\mathbf{E}=[\mathbf{Z}]\mathbf{H} \qquad (1)$$

where $\mathbf{Z}$ is a 2x2 tensor, obtained for at each MT recording station as a function of frequency. By manipulating the elements of the impedance tensor off diagonal components, apparent resistivity and impedance phase quantities can be readily obtained, which are more intuitive to inspect and interpret (Vozoff, 1991). A 1x2 tensor relation between H_z and $\mathbf{H}$ also is possible, but not considered here.

The 102 five-channel stations, including a contiguous measurement profile, were acquired utilizing 24-bit recording, narrow-band spectral scrubbing, and robust remote reference processing (Wannamaker et al., 2004). Substantial EM noise of a non plane-wave nature was nearly ubiquitous over the field, arising both from local power production activities and the nearby presence of a DC interstate power transmission system. This noise exhibited spatial correlations exceeding 100 km and required novel implementation of remote references over distances of 250-1000 km for its removal. In particular, efficacy of the Parkfield CA permanent MT observatory as a quiet remote reference was demonstrated. This site serves the western US for frequencies up to ~15 Hz (Wannamaker et al., 2004).

MAGNETOTELLURIC INVERSION

Our ultimate aim is to construct a 3D conductivity model of the Coso Geothermal system and use it to better understand the hydrothermal system. To accomplish this we will apply an inversion process, where the observed impedance data are fit in a least squares sense to model data. The model data are produced by solving Maxwell's equations for 3D conductivity variations and plane wave source excitation at a discrete set of frequencies. These frequencies correspond to those used to specify the impedance tensor in the field measurements. To stabilize the inversion process, additional constraints are added such as spatial smoothing of the conductivity model. Because the resources for 3D MT inversion and modeling are highly demanding, requiring significant computational resources and time (see Newman and Alumbaugh, 2000; Newman et al., 2003), it is logical to start to build the 3D conductivity model from 2D imaged sections of the reservoir. This starting model will be refined subsequently through the 3D inversion process.

2D DATA INTERPRETATION

The initial 2D inversion was performed on relatively sparse east-west profiles of 8-10 MT sites selected from the total survey data set of Figure 1, utilizing the 2D MT inversion algorithm of Rodi and Mackie (2001). The inversions were carried out using Z_{xy} impedance data and analyzed assuming the electric field is polarized perpendicular to a presumed N-S geological strike (y-axis); in actuality, polar diagrams show that geological strike varies with frequency and so is 3D, but at the lowest frequencies (<0.1 Hz), the polarization ellipses align in a north-northeast direction, which follows the trend of the Basin and Range fault-block geology. In spite of the obvious limitations in modeling and inverting the Coso data in 2D, it is a logical starting point for carrying out a full 3D analysis of the data. The transverse magnetic (TM) mode is used in the 2D inversion here because 3D modeling shows that it is usually more robust than the TE data to non-2D effects such as finite strike and static shifts (e.g., Wannamaker, 1999).

Shown in Figures 3 and 4 are 2D fits to Coso data (apparent resistivity and phase) along the profile containing MT station locations 45 through 53. Fits to the apparent resistivity data (red curves) agree closely with the field observations over the entire frequency band. The phase data, however, are not fit as well, especially below 0.1 Hz, most likely indicating a three-dimensional characteristic of the data.

The resulting 2D resistivity image along this profile as well as those from other profiles are presented in Figure 5. Perhaps the most conspicuous feature of our ensemble of 2D inversion sections is a moderate resistivity zone dipping steeply west from the Coso east flank area. This zone terminates abruptly both to the south and the north. Several of the more productive wells on the east flank dip toward this structure suggesting some correlation with higher permeability and fluid content.

Wannamaker (2004) first identified this conspicuous feature using 2D TM mode analysis of the dense array line NA1 in Figure 1. The inversion model of this line (Figure 6) provides more detail than individual sections of Figure 5 due to the contiguous sampling over 52 bipoles, 100 m in length.

The array line inversion also shows the west dipping lower resistivity zone seen in the stitched sections of Figure 5. Producing well 34-RD2 grazes this zone along its east boundary. Shallow low resistivity material in the model represents thin alluvium and clay alteration over the east flank, plus deeper alluvium of Coso Wash toward the east part of the model section. Wannamaker (2004) also concluded that it was necessary to consider a 3D interpretational framework to fully explain the data.
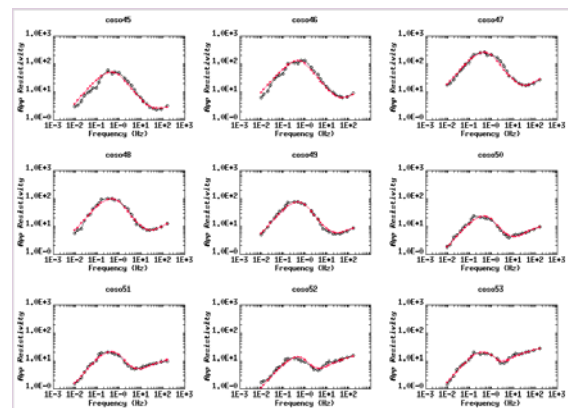

Figure 3. 2D TM fits to the Z_{xy} Coso data (apparent resistivity), where open circles represent the field data and red curves the model responses.
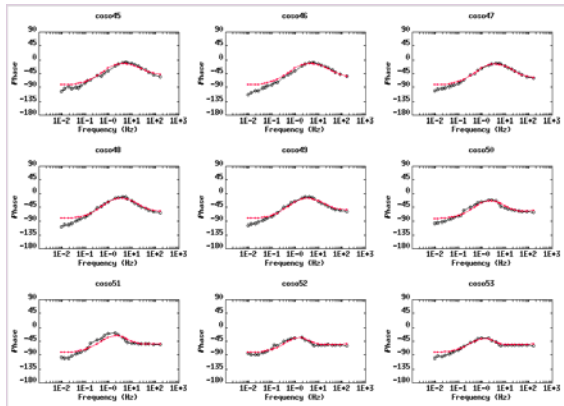
Figure 4. 2D TM fits to the Z_{xy} Coso data (impedance phase), where open circles represent field data and red curves are model responses.

INITIAL 3D MODEL OF THE COSO FIELD

In order to simulate the 3D MT fields from the resisitivity model shown in Figure 5, we spatially interpolated the resistivity between the transects onto a finite difference grid with 120 nodes along each coordinate direction. This interpolated 3D resisitivity model will serve as the starting model, which will be used to launch the full 3D inversion analysis of the data. The simulated fields (Z_{xy} and Z_{yx} apparent resistivity and phase) for this starting model are shown in Figures 7 and 8 and are compared with the corresponding field observations for sites 45 through 53.

For frequencies above 1 Hz, the 3D fields generally show good correspondence with the field data for both polarizations, even though there are some grid-induced statics arising from the interpolation process that affect primarily the predicted Z_{yx} apparent resistivity at a few sites. Significant differences, however, arise at all sites between the model and field curves in both apparent resisitivy and phase at lower frequencies. When the field data were analyzed using 2D assumptions, such discrepancies appeared confined to the phase.

CONCLUSIONS AND PLANNED WORK

An initial 3D resisitivity model of the Coso geothermal field has been constructed. The model shows geological structure that may correlate with a zone of higher permeability and fluid content, as evidenced by the well locations at the field. Predicted Z_{xy} and Z_{yx}, apparent resisitivity and phase data from the model show good correspondence to the field data above 1 Hz. Below 1 Hz, however, significant differences are evident.
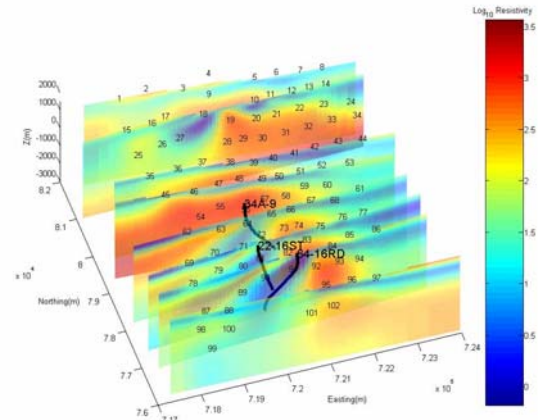

Figure 5. Resistivity model of the Coso geothermal site compiled from multiple 2D transects. Wells 64-16RD, 22-16ST and 34A-9 are also shown. The model view is from the southwest and includes site locations shown in Figure 1.

ACKNOWLEDGEMENTS

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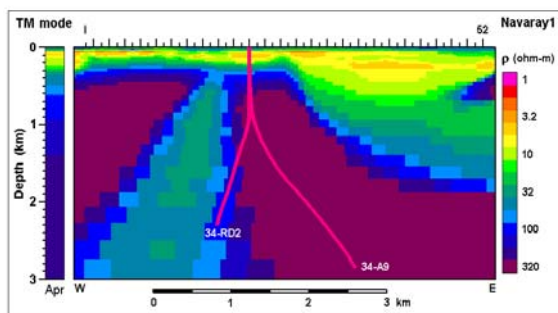
Figure 6. 2D inversion model using TM mode data of contiguous bipole profile NA1. Also plotted

are deep wells 34-RD2 and 34-A9 which project from about 500 m south of the profile. Inversion code used was developed by Wannamaker from the U. Utah finite element code and damps variations from an average 1D a-priori model (Apr). This plot adopts warm colors for low resistivity. View is toward the north.
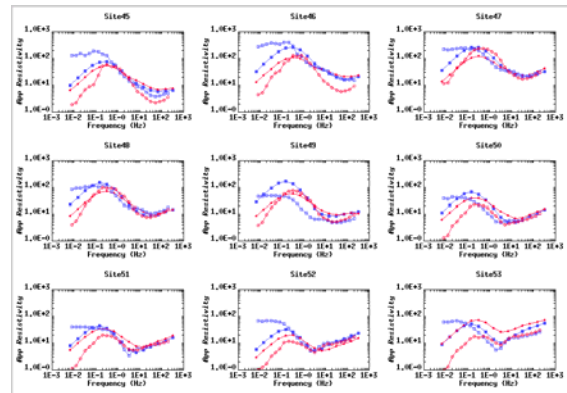

Figure 7. Plots of apparent resistivity for selected measurement sites, 45-53. The blue curves with solid and open squares denote predicted and observed Z_{xy} apparent resistivity. The red curves, solid and open circles, denote predicted and observed Z_{yx} apparent resistivity.
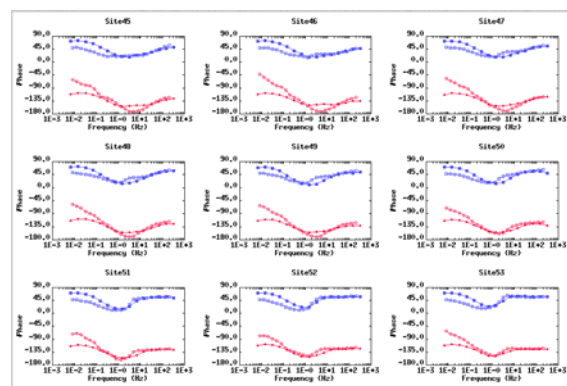

Figure 8. Plots of impedance phase for selected measurement sites, 45-53. The blue curves with solid and open squares denote predicted and observed Z_{xy} phase. The red curves, solid and open circles, denote predicted and observed Z_{yx} phase.