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Magnetotelluric Monitoring of The Geysers Steam Field, Northern California: Phase 2

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ABSTRACT

An original magnetotelluric (MT) survey collected in 2017 included 42 MT stations mainly in the northwestern part of The Geysers geothermal field in northern California. These data were modeled in 3D and imaged the electrically conductive cover, the electrically resistive steam field, and the electrically resistive Geysers plutonic complex (Peacock et al., 2020; Peacock et al. 2020a). Success of the original survey initiated collaboration between the U.S. Geological Survey and Lawrence Berkeley National Labs to monitor the steam field with MT and passive seismic data to create a joint 4D model over the course of three years. This project, funded by the California Energy Commission, began in 2020. Two repeated MT surveys were collected at The Geysers, one in April 2021 (Peacock et al., 2022) and the second in April 2022 that extend further south adding 13 stations to the original 2017 survey. Reported here are observations comparing the 2017 data with the 2022 data. Preliminary results indicate the steam field changed variably across the steam field, similar to changes observed between the 2017 and 2021 data.

1. INTRODUCTION

The Geysers in northern California is the world's largest geothermal energy producing steam field. The field has been producing geothermal energy for over 60 years, resulting in significant changes in the steam reservoir. In the mid-1980s, production declined due to pressure loss from not replenishing extracted steam (Stark et al., 2005). To mitigate steam depletion, reinjection projects using treated wastewater from nearby municipalities were developed, including the 1997 Southeast Geysers Effluent Pipeline (Brauner & Carlson, 2002), and the 2003 Santa Rosa Geysers Recharge Project (SRGRP) (Stark et al., 2005). This has stabilized production and added more complexity to the dynamics of the vapor-dominated field. Expansion of the field includes the Enhanced Geothermal System (EGS) Demonstration Project in the northwest portion of The Geysers. The EGS stimulates a deep (>3km), high temperature reservoir with measured temperatures up to 400 °C using treated wastewater from SRGRP (Garcia, et al., 2016).

In 2017, a modern 3D magneotelluric (MT) survey was collected at The Geysers. These data (Peacock et al., 2020a) were used to develop a 3D electrical resistivity model detailed in Peacock et al. (2020). One key finding from this study was that quality MT data could be collected in what would appear to be a noisy environment that includes large powerlines, injection pipes, steam pipes, power stations, and pumps. Another key finding was that steam saturation could be estimated from electrical resistivity using a modified Archie's equation (Glover, 2010). Both these findings support previous studies (e.g. Peacock et al,, 2012) that suggest repeat MT measurements can assist in characterizing time-dependent variations within the steam field.

To help understand time-dependent subsurface variations, the California Energy Commission has funded a three-year project led by Lawerence Berkeley National Labs to monitor The Geysers geothermal field using constant passive seismic measurements coupled with yearly MT campaigns. The different data sets will be inverted seperately to provide 3D volumes of resistivity and seismic velocity at three different points in time. Then both data sets will be inverted joinlty to provide better structural control on time-dependent subsurface variations. Phase 1 of repeated MT measurements are summarized in Peacock et al. (2022). This study describes the initial results from the Phase 2 MT data collection at The Geysers.

2. MAGNETOTELLURIC DATA

In April 2022, 50 of the 55 MT sites collected in 2021 were repeated (Figure 1). Some locations had to be adjusted due to infrastructure development and some stations were not repeated due to permitting, road conditions, and poor data quality. When possible, data were collected in 2022 with the same data loggers, magnetic sensors, and electrodes as employed in 2021. Each station included two horizontal orthogonal ANT-4 magnetic induction coils and two orthogonal electrical dipoles with a nominal length of 50 m, dependent on vegetation and topography. Electric potentials were measured with Ag-AgCl Stelth 1 Borin electrodes buried in a saturated canvas bag of bentonite clay to reduce contact resistance, which ranged between ~1-7 kOhm. The setup was oriented with respect to geomagnetic north using a Brunton compass. All four components were connected to a 5-channel 32-bit ZEN data logger developed by Zonge International. The data were recorded on a repeating schedule of 5 hours and 50 minutes sampling at 256 samples/second, and 10-minutes sampling at 4,096 samples/second. The schedules were set such that all recording instruments recorded the sampling rates synchronously to allow for remote reference processing. Data will be made public upon completion of the project in 2024.

To estimate the MT transfer functions, the robust remote reference bounded-influence processing code BIRRP was used (Chave and Thomson, 2004). Multiple local remote references were used to remove incoherent noise between the stations, which is critically important in a noisy environment like The Geysers. Outliers are downweighted in a robust way through regression and coherency sorting. Each station takes between 15-30 minutes to process depending on input data and program settings. The same processing parameters were used for each repeated station to remove bias caused by algorithm parameters. The estimated transfer functions range from 1000 Hz to 0.0001 Hz, which is sensitive to 50m to 50 km.

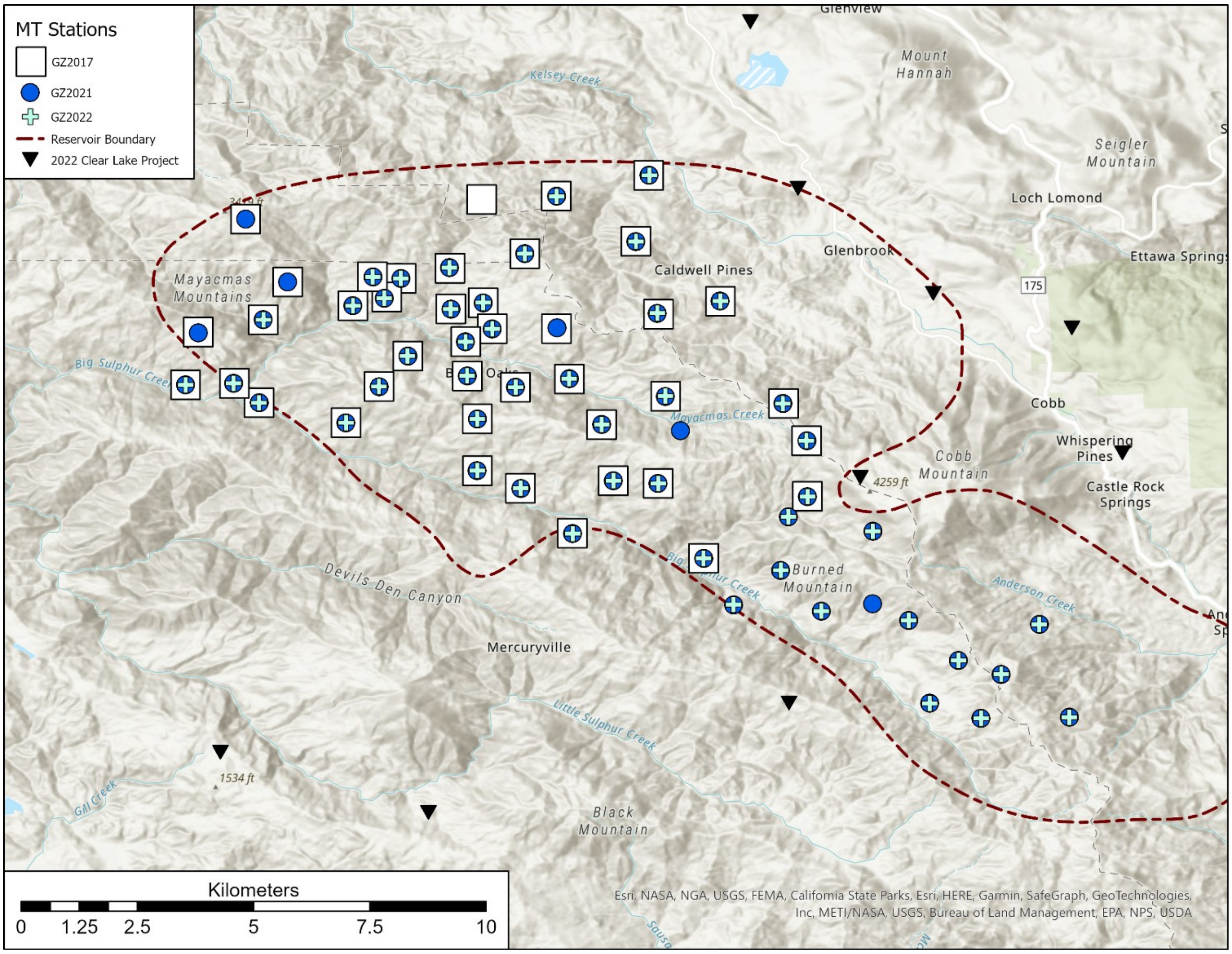

Figure 1: Map of MT stations collected to monitor The Geysers geothermal field. White squares: MT stations collected in 2017; blue circles: Phase 1 MT stations collected in 2021; cyan crosses: Phase 2 MT stations collected in 2022; black triangles: regional MT stations. Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

Comparing the 2022 transfer function estimations to that of? 2017 and 2021 demonstrates that measurements can be accurately repeated (Figure 2). Generally, the 2022 transfer functions have reduced errors and are smoother due to greater natural magnetic source field variations related to increased solar activity. However, a few 2022 stations are affected by introduced noise sources caused by infrastructure changes such as new wells and pumps.

Near-surface distortions such as changes in soil moisture can cause a static shift in the apparent resistivity of one or both modes of the apparent resistivity (xy and yx in Figure 2). To remove this effect for more accurate comparison between campaigns, the two lowest period decades of apparent resistivity for the 2021 and 2022 data are matched to that of the 2017 data for each mode. When comparing transfer functions between 2017, 2021, and 2022, the one common feature observed in nearly all processed results is an increase in apparent resistivity between 5-50 seconds and decrease in phase between 2-50 seconds (Figure 2). However, the magnitude of change in apparent resistivity is larger between 2017 and 2021 than between 2021 and 2022, suggesting temporal changes vary slowly. One important observation is that the changes in impedance phase predict changes in apparent resistivity which satisfies the dispersion relation of the MT transfer function (Fischer & Schnegg, 1980). Importantly, this implies that the observed changes in the MT transfer function are caused by temporal subsurface variations.

MT transfer functions can also be represented as the phase tensor (Caldwell et al., 2004), which is a distortion free, rank 2, frequency dependent tensor. Invariants of the phase tensor provide directional information and information about whether the subsurface is becoming more resistive or more conductive. The phase tensor is graphically visualized as an ellipse in Figure 2. Plotted in map view, ellipse shape provides information about the dimensionality of subsurface resistivity structures, where the long axis aligns and elongates in the preferred direction of electrical current flow. Comparing the phase tensors from the various surveys demonstrates that between 0.001-1 seconds ellipses are similar between the surveys, but then change shape and orientation after two seconds (Figure 2).

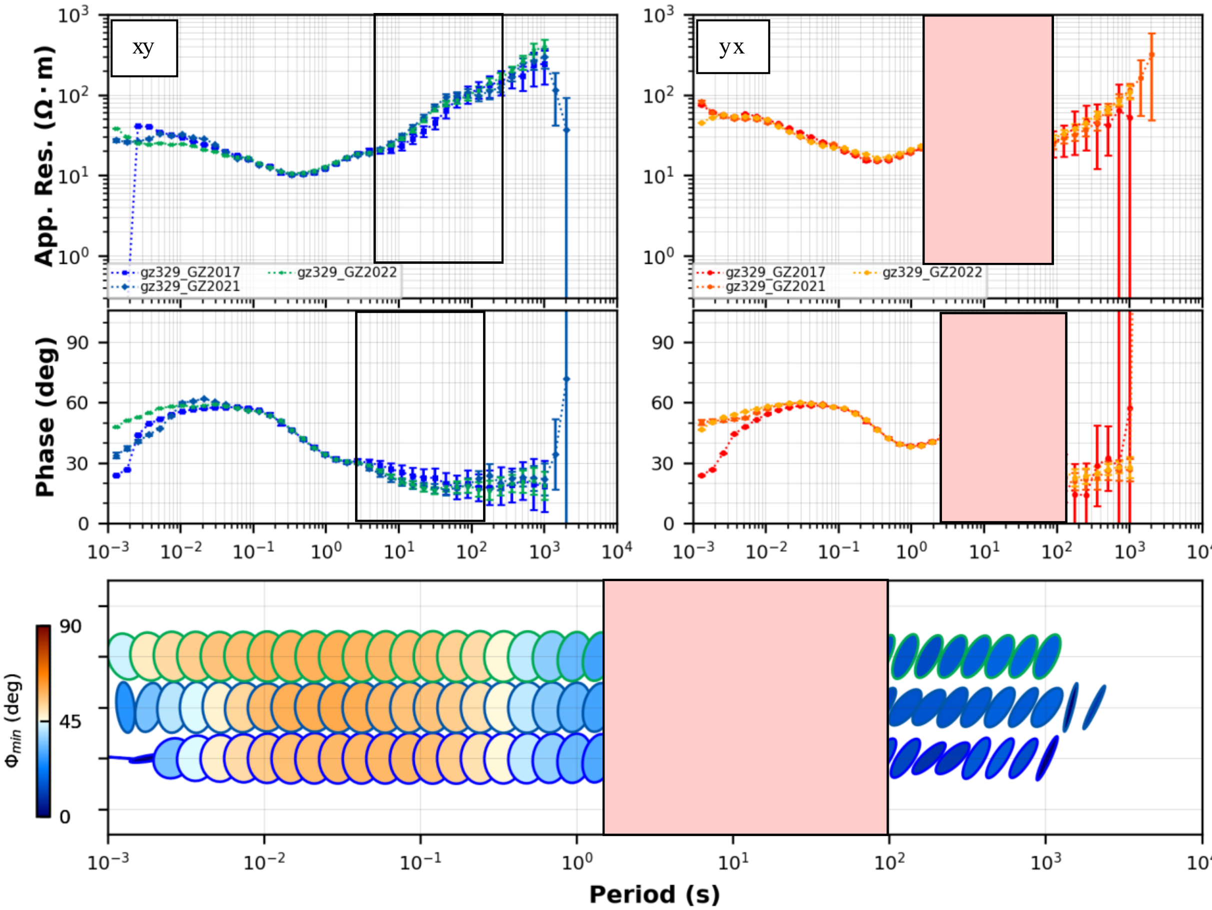

Figure 2: Example of an MT transfer function comparison between 2017, 2021, and 2022 at a single station. Top panels are the apparent resistivity, where the 2021 and 2022 data have been corrected for static shift relative to the 2017 data. Middle panels display impedance phase, and the bottom panel shows phase tensor representations of the impedance tensor where each year is shifted vertically for clarity. Both impedance phase and phase tensor representations are unaffected by near surface distortion. Left panels are components oriented with the electric fields to geographic north and magnetic fields to geographic east (xy). Right panels are components oriented with the electric fields to geographic east and magnetic fields to geographic north (yx). The transparent boxes highlight the increase in apparent resistivity starting at around 5 seconds and a dip in phase and change in phase tenor starting at around 2 seconds indicating causality (Fischer & Schnegg, 1980; Peacock et al., 2012). This suggests the subsurface is becoming more resistive between the 2017, 2021, and 2022 surveys, with a smaller change between 2021 and 2022.

A different way of comparing two data sets is to calculate the residual phase tensor (Peacock et al., 2012). The residual phase tensor is invariant to near surface distortions and provides directional information on how the subsurface changed between two MT transfer functions but does not indicate whether the subsurface is becoming more resistive or conductive. Graphically the residual phase tensor is represented as an ellipse similar to the general phase tensor (Figure 3). Ellipse elongation indicates a larger resistivity change in the long axis direction. Ellipse color represents the percent change between transfer functions but does not indicate if the change was more resistive or more conductive.

In general, between 2017 and 2021, a 5-20% change in the residual phase tensor is observed at periods longer than 10 seconds (Peacock et al., 2022), and between 2021 and 2022, observed changes in the residual phase tensor are on the order of 5-15%. In both comparisons the residual phase tensor indicates compartmentalized changes of subsurface resistivity variations within the steam field. In the northwest Geysers, near the EGS site, variations in subsurface resistivity structure have a southwest-northeast direction, whereas to the east, near Caldwell Pines, variations have a north-south direction (Figure 3). The orientation of these structures could be fault controlled.

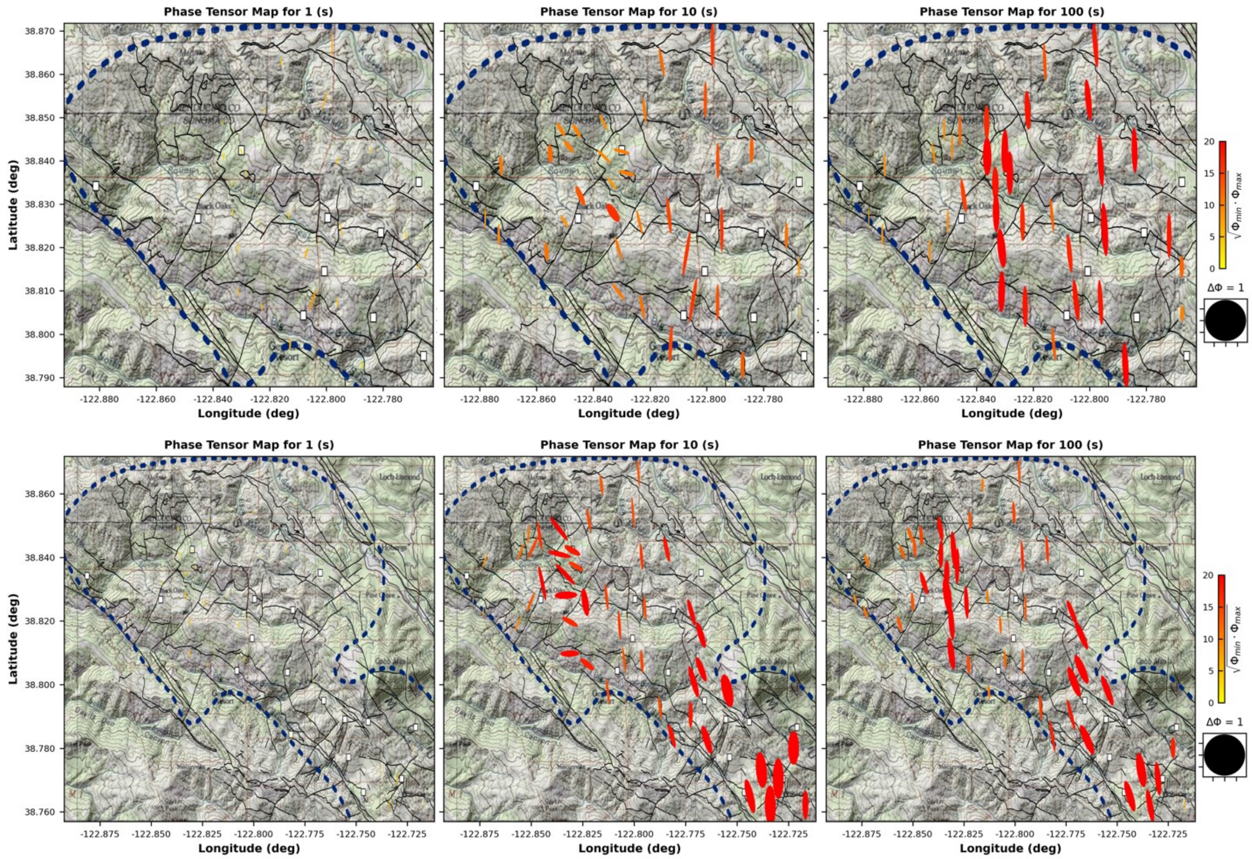

Figure 3: Residual phase tensor ellipses for 3 different periods: 1 (left), 10 (middle), and 100 (right) seconds. White squares: power stations, blue dashed line: steam reservoir outline; black circle: unit change in all directions. Top row: comparison between 2017 and 2022 MT transfer functions. Bottom row: comparison between 2021 and 2022 MT transfer functions, note the extension to the southern part of the steam field with stations that were not collected in 2017. At 1 second minimal changes are observed. At 10 seconds compartmentalized changes are observed with more north-south changes in the east and more east-west changes in the west. Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

3. FUTURE RESEARCH

The 2022 MT data needs to be inverted to image subsurface resistivity and compared to 2017 and 2021 3D resistivity models to identify changes between surveys. Sensitivity tests are needed obtain a robust model. This includes changing inversion parameters, using different starting models and prior models, allowing only various parts of the model to change, and a limited forward modeling study where various parts of the model are changed, and synthetic results computed to determine the sensitivity of different parts of the model to the data. The final robust model will then be used as input to a joint inversion with the passive seismic data (Gritto et al. 2022) linked to MT results using the workflow described in Um et al. (2014). The final MT field campaign is planned for March 2023, with the processing workflow described here repeated to image 4-D subsurface variations over The Geysers steam field.

Note: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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