PROCEEDINGS, 50th Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, February 10-12, 2025
SGP-TR-229

Summary of Results from Monitoring The Geysers with Continuous Passive Seismic and Repeat Magnetotelluric Measurements (2021-2023)

Jared R. Peacock[1], David L. Alumbaugh[2], Roland Gritto[3], Evan Um[2], Craig Ulrich[2], Michael A. Mitchell[4] Craig Hartline[5]

[1]U.S. Geological Survey, P.O. Box 158, Moffett Field, CA 94035, USA

[2]Lawrence Berkeley National Lab, 1 Cyclotron Road Mail Stop 74-316C Berkeley, CA 94720, USA

[3]EMR Solutions and Technology, 2020 Cedar Street, Berkeley, CA 94709, USA

[4]Voluneteer, U.S. Geological Survey, P.O. Box 158, Moffett Field, CA 94035, USA

[5]Calpine Corporation, 10350 Socrates Mine Rd, Middletown, CA 95461, USA

jpeacock@usgs.gov

Keywords: The Geysers, passive seismic, magnetotellurics, monitoring, 4D

ABSTRACT

Understanding temporal variations in a geothermal field can support operators in decision making that pertains to optimizing production and mitigating hazards. Between 2021 and 2023, The Geysers geothermal field in northern California was monitored with an array of continuous passive seismic sensors and annual repeat magnetotelluric (MT) measurements. Each of these data sets were analyzed and modelled separately to understand the data, sensitivity, and any observable changes. Then, the data were inverted jointly using a cross-gradient method to further constrain temporal changes in geophysical properties within the geothermal field. Multiple permutations of annual datasets were used as inputs to the joint inversion. Results demonstrate seismic data constrain smooth inversion of the MT data, and the MT data provide supplementary information about the location of temporal fluid changes. Estimating relative changes in steam saturation for various time intervals of the joint models shows compartmentalized changes in the field, and good spatial correlation with the location of injection wells. These results demonstrate that collecting both passive seismic and MT measurements then modeling them jointly provide complementary information and a relatively inexpensive method for monitoring temporal changes in an active geothermal field that provides results to support operators.

1. INTRODUCTION

The Geysers geothermal field in northern California is currently the world's largest energy producing steam field, and has been producing geothermal energy for over 60 years, resulting in significant changes in the steam reservoir (Barker et al. 1992). Production declined in the 1980s due to pressure loss from steam extraction without replenishment (Stark et al., 2005). Therefore, reinjection projects using treated wastewater from nearby municipalities were developed to increase steam production, including the 1997 Southeast Geysers Effluent Pipeline (Brauner & Carlson, 2002) and the 2003 Santa Rosa Geysers Recharge Project (SRGRP) (Stark et al., 2005). Over time production has stabilized though dynamics of the vapor-dominated field have become more complex. In an additional effort to increase production of geothermal power, Calpine Corporation created an enhanced geothermal system (EGS) demonstration project in The Northwest Geysers. The EGS stimulates a deep (>3 km), high temperature reservoir (400 °C) using treated wastewater from the SRGRP (Garcia et al., 2016).

Seismic methods are mainly sensitive to bulk rock properties but can also provide information about pore fluid content (e.g. Gritto et al., 2022). Estimations of the Vp/Vs ratio provide information on the phase of pore space fluid, where higher values suggest liquid phases and lower values suggest gaseous phases (e.g. Gritto et al., 2014). Electrical resistivity is directly sensitive to pore fluid content, and can change by orders of magnitude, where higher values suggest gaseous phases and lower values suggest liquid phases (e.g. Peacock et al., 2020). Combining seismic methods with electrical resistivity measurements should be complimentary where models of each image similar structures associated with pore fluids, specifically a steam reservoir. Therefore, using a cross-gradient joint inversion method that optimizes for similar structures between multiple methods should be valid (Um et al. 2014).

To help understand temporal subsurface variations in The Geysers steam field, the California Energy Commission funded a multi-year project led by Lawerence Berkeley National Lab to monitor The Geysers geothermal field using continuous passive seismic measurements (Gritto et al., 2022) coupled with annual MT surveys between 2021 and 2023 (Peacock et al., 2022, 2023, 2024). The result is a set of joint inversions of electrical resistivity and seismic velocity at three different time periods using a cross-gradient method (Um et al., 2023). Presented here is a brief summary of the joint inversion results.

2. JOINT INVERSION

The passive seismic array collected data continuously over the project time span from 2021 to 2023 (Gritto et al., 2022), whereas MT data were collected annually (Peacock et al., 2022, 2023, 2024) due to limited instrumentation (Figure 1). The joint inversion process proceeded in three steps. 1) Develop 3D seismic tomography models using data from at least one month before and after the MT surveys. 2) Develop 3D electrical resistivity models from the MT data for each year collected. 3) Use the final models from each method at a given time period as starting models for the cross-gradient method. The cross-gradient method enhances correlated structures and suppresses uncorrelated structures, which results in a model that highlights areas where both methods are sensitive to similar physical properties like relative steam content. The end result is a 3D tomography model constrained by the resistivity model, and a 3D electrical resistivity model constrained by seismic tomography. The models for each time period can then be compared to each other to estimate relative changes in the steam field (Figure 2).

The target for this project is the steam field. Calpine Corporation provided well data that defines the top of the steam field and the top of the thermally conductive heat source: the Geysers Plutonic Complex (also known as the Felsite) (Craig Hartline, Calpine Corporation, written communication, 2021). These two layers can be used to extract the volume of interest within the steam field from the geophysical models. A three-step approach was also utilized to get an estimate of relative steam changes over time. 1) Estimate the percent difference between joint inversion results as 100 * (time 2 – time 1) / time 1. 2) Extract the volume defined between the top of steam and top of the Geysers Plutonic Complex. 3) Depth integrate the volume to get a lateral relative change in steam saturation over time. The relative differences between all permutations of the yearly models were calculated for each permutation for each year 2021, 2022, and 2023 (Figure 2 shows the comparison between 2023 and 2021).

An observation made based on estimating relative temporal change estimates from joint inversions (Figure 2) include that changes in relative steam saturation are compartmentalized within the steam field and correlate with the locations of injection wells and fracture dominated permeability variations within the reservoir. Areas with increased relative steam saturation (red areas in Figure 2) are focused on the western part of the field and are either confined by bounding faults or controlled by fault intersections. Blue areas in Figure 2 represent areas of decreased steam saturation, increased aqueous fluids, or increased salinity of pore fluids and are in the eastern and northeastern parts of the steam field. The steam field is dominated by northeast and northwest trending faults. The northern part of the steam field is dominated by northeast trending faults, whereas the central part of the steam field appears to be dominated by northwest trending faults, and the southern part of the steam field shows evidence of a combination of these orientations.

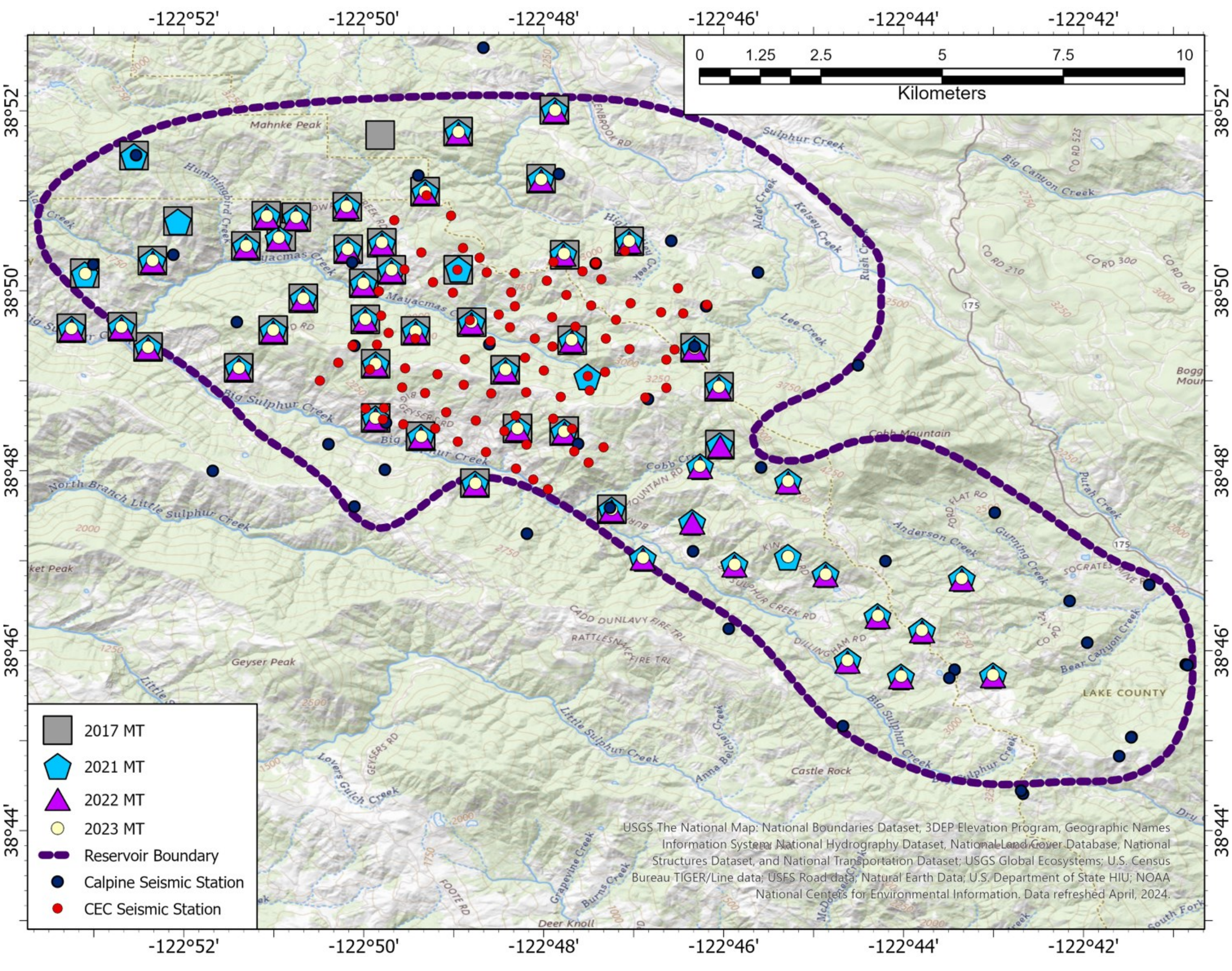

Figure 1: Map of passive seismic and MT stations deployed during the project at The Geysers. Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

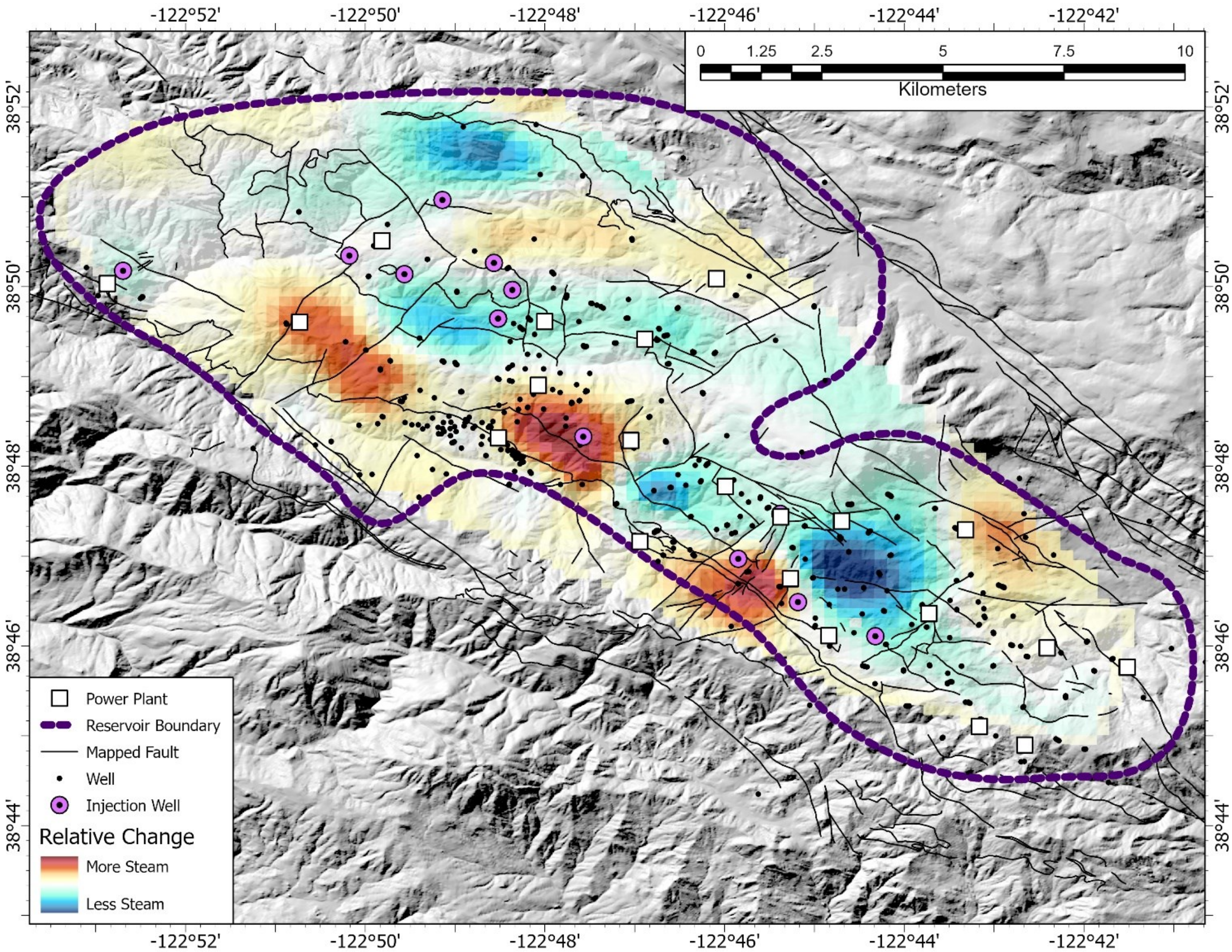

Figure 2: Relative steam change between 2021 and 2023 estimated by comparing annual joint inverse 3D models of passive seismic tomography and electrical resistivity models. Red areas represent increased steam over time, whereas blue areas suggest regions with decreases in steam or increases in aqueous fluids. The changes are compartmentalized within the field demonstrating fault-controlled permeability. Faults are from McLaughlin (1978) and Sadowski et al. (2016). Map image is the intellectual property of Esri and is used herein under license. Copyright © 2020 Esri and its licensors. All rights reserved.

3. SUMMARY

This project demonstrates the utility of collecting complimentary geophysical datasets to characterize and monitor a geothermal system. Passive seismic data are sensitive to pore fluid content and MT data are sensitive to the connectivity of pore fluids. Jointly inverting passive seismic and MT data using a cross-gradient method provides information about fluid saturation. Furthermore, comparing annual jointly inverted models yields estimates of temporal changes in fluid saturation. Preliminary results show that temporal changes in steam saturation at The Geysers geothermal field correlate well with injection wells and controlling faults. This information can support operators in decisions related to optimizing injections and production using existing wells, and in determining the strategic placement of future wells to meet growing energy demands.

This project used campaign style data collection for MT, which is relatively inexpensive and provides adequate information to estimate subsurface changes. However, if resolving temporal variations over shorter time periods are the target, future campaigns could include permanent monitoring MT stations collocated with passive seismic stations. This project showed that larger time spans produced larger changes, therefore future surveys could include estimations on the order of several years to identify long-term trends of subsurface changes.

Further developments and tuning of the joint inversion could produce better results, specifically tuning data weights to increase the strengths and reduce the weaknesses of each method. Moreover, other joint inversion methods could be used such as petrophysically guided joint inversions that could include other geophysical datasets like gravity and InSAR.

Collection of other hydrological data could help refine physical estimates of changes observed in the joint inversion of the steam field. For example, injection rates, porosity, permeability, and injection fluid chemistry could be used in conjunction with modeled seismic velocity and electrical resistivity to estimate bulk saturation.

ACKNOWLEDGEMENT

Thanks to Jacob Anderson, William Schermerhorn, and Heather Welch for comments to improve this abstract. This project was funded by the California Energy Commission (CEC) under contract EPC-19-019. MT data can be found at https://doi.org/10.5066/P94D21UL. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

REFERENCES

Barker, B. J., M. S. Gulati, M. A. Bryan, and K. L. Riedel (1992). Monograph on The Geysers geothermal field, Special Report No. 17, *Geothermal Resources Council*, 167.

Brauner, E., & Carlson, D. C. (2002). *Santa Rosa Geysers Recharge Project: GEO-98-001.* California Energy Commission. Office of Scientific and Technical Information (OSTI). https://doi.org/10.2172/897791.

Garcia, J., Hartline, C., Walters, M., Wright, M., Rutqvist, J., Dobson, P. F., & Jeanne, P. (2016). The Northwest Geysers EGS Demonstration Project, California. *Geothermics, 63*, 97–119. https://doi.org/10.1016/j.geothermics.2015.08.003.

Gritto, R. and S.P. Jarpe (2014). Temporal variations of Vp/Vs-ratio at The Geysers geothermal field, USA, *Geothermics,* http://dx.doi.org/10.1016/j.geothermics.2014.01.012.

Gritto, R., Jarpe, S. P., & Alumbaugh, D. L. (2022). New large-scale passive seismic monitoring at The Geysers geothermal reservoir, CA, USA. *Proceedings, 47th Workshop on Geothermal Reservoir Engineering*, Stanford University, Stanford, CA, 1-11.

McLaughlin, R.J. (1978). Preliminary geologic map and structural sections of the central Mayacmas Mountains and The Geysers steam field, Sonoma, Lake, and Mendocino counties, California.

Peacock, J. R., Alumbaugh, A., Mitchell, M. A., Hartline, C., (2022). Repeat magnetotelluric measurements to monitor The Geysers steam field in northern California, *47th Workshop on Geothermal Reservoir Engineering*, *SGP-TR-233,* Stanford, California.

Peacock, J. R., Alumbaugh, A., Mitchell, M. A., Hartline, C., (2023). Magnetotelluric monitoring of The Geysers geothermal field, northern California: Phase 2, *48th Workshop on Geothermal Reservoir Engineering*, *SGP-TR-233,* Stanford, California.

Peacock, J. R., Alumbaugh, A., Mitchell, M. A., Hartline, C., (2024). Summary of Annual Repeat Magnetotelluric Surveys of the Geysers Geothermal Field, *49th Workshop on Geothermal Reservoir Engineering*, *SGP-TR-233,* Stanford, California.

Peacock, J. R., Earney, T. E., & Schermerhorn, W. (2020a). Magnetotelluric and gravity data from the Northwest Geysers, California. *U.S. Geological Survey data release*. https://doi.org/10.5066/P94D21UL.

Peacock, J. R., Earney, T. E., Mangan, M. T., Schermerhorn, W. D., Glen, J. M., Walters, M., & Hartline, C. (2020). Geophysical characterization of the Northwest Geysers geothermal. *Journal of Volcanology and Geothermal Research, 399*, 106882. https://doi.org/10.1016/j.jvolgeores.2020.106882.

Sadowski, A. J., Forson, C. K, Walters, M. A., Hartline, C. S., (2016). Compilation surface geologic map for use in three-dimensional structural model building at The Geysers Geothermal Field, northern California. *41st Workshop on Geothermal reservoir Engineering, SGP-TR-209*, Stanford, California.

Stark, M. A., Box W. T., Jr., Beall, J. J., Goyal K. P., & Pingol, A. S. (2005) The Santa Rosa -- Geysers Recharge Project, Geysers Geothermal Field, California, USA, *Proceedings World Geothermal Congress*, Antalya, Turkey, 24-29 April 2005.

Um, E. S., Commer, M., & Newman, G. (2014). A strategy for coupled 3D imagin of large-scale seismic and electromagnetic data sets: application to subsalt imaging. *Geophysics, 79*, ID1-ID13. https:/doi.org/10.1190/geo2013-0053.1.

Um, E. S., Commer, M., Gritto, R., Peacock, J. R., Alumbaugh D. L., Jarpe, S. P., Hartline, C., (2023) Cooperative joint inversion of magnetotelluric and microseismic data for imaging The Geysers geothermal field, California, USA, *Geophysics*, 88, 5, WB45-WB54. https://doi.org/10.1190/geo2022-0521.1.