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Preliminary 4D Seismic Tomography Images for The Geysers, 2008-2014

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ABSTRACT

Time-dependent three-dimensional tomography of reservoir structure may provide an important tool for monitoring changes in operating geothermal reservoirs. The method may also be useful for oil and gas reservoirs, and for active volcanoes. Temporal changes in structure may be studied either using repeat, independent tomographic inversions or by inverting two epochs simultaneously for changes. We studied The Geysers geothermal field using MEQ data for the epoch 2008 - 2014. We obtained data from the Northern California Earthquake Data Centre (NCEDC) catalogue. The database comprises 1657 earthquakes, with 35,278 P-wave arrival-time measurements and 9,452 S-wave arrival-time measurements. We selected earthquakes for quality and chose events with at least ten P- and three S-wave arrival time measurements, station azimuthal gaps of less than 180°, and RMS arrival-time residuals smaller than 0.05 s. Production was stable during the period studied, whereas the injection rate increased in 2010 and decreased in 2014. We detected a strengthening negative Vp/Vs anomaly for the period studied in the NW Geysers and on the western and eastern boundaries of the field. Anomaly growth was slower than for the period 1991-1998, likely because large-scale water injections into the reservoir have arrested the fluid depletion that caused strong anomaly growth in the period 1991-1998. Future work will include a) hand-processing of selected datasets, and b) application of the powerful inversion program TOMO4D to subsets of the 2008-2014 data.

1. INTRODUCTION

The geology of The Geysers comprises mainly metamorphosed marine sedimentary and igneous rocks belonging to the Franciscan assemblage. The reservoir is bounded by the Collayomi fault zone to the northeast and the Mercuryville fault zone to the southwest (Figure 1). It is contained in fractured metagraywacke and an underlying felsite batholith. Felsite-hosted alteration and vein mineralization partially controlled by hydrothermal breccia increase permeability and fracture density within the steam reservoir (Gunasekera et al., 2003).

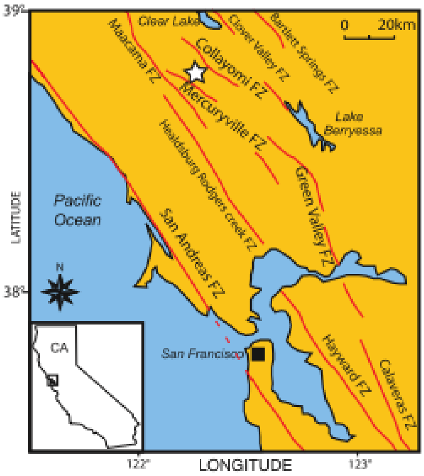

Figure 1: Geological setting of the region (from Jeanne et al., 2014). The Geysers geothermal area is shown by a star.

The geothermal reservoir is one of the largest in the world with approximately 1.6 GW of installed electric generating capacity and current production of about 850 MW. Operations commenced in the 1960s and have included the reinjection of condensates, rain and nearby creek water since the early 1970s to support steam pressure in the reservoir. These operations were supplemented in recent years by the injection of treated wastewater from nearby communities to sustain production. The South East Geysers

Effluent Project (SEGEP), a 46 km long pipeline from Lake County delivering 22 million l/day, was commissioned in 1998 to resupply the SE Geysers with water. A second 64 km long pipeline from Santa Rosa, the Santa Rosa Geysers Recharge Project (SGRP) delivering 41 million l/day, was commissioned in 2003 (Majer and Peterson, 2007).

The rate of steam production, water injection and induced seismicity from 1960 to the end of 2013 is presented in Figure 2. This figure shows that seismicity in the region correlates with the volume of injected water rather than steam production. Significant commercial development at The Geysers began in 1960 with a 12-MW electrical power plant. Production increased at a rate of 63 MW per year until 1981. Between 1981 and 1989 power generation increased by 150 MW per year to peak at an unsustainable 1800 MW in 1987, when steam was extracted at a rate of ~13x10^6 kg/h (Barker et al., 1992).

In this paper we describe the use of local-earthquake travel-time tomography to obtain three-dimensional images of seismic-wave speeds at The Geysers to study variations in the ratio of the wave speeds, Vp/Vs.

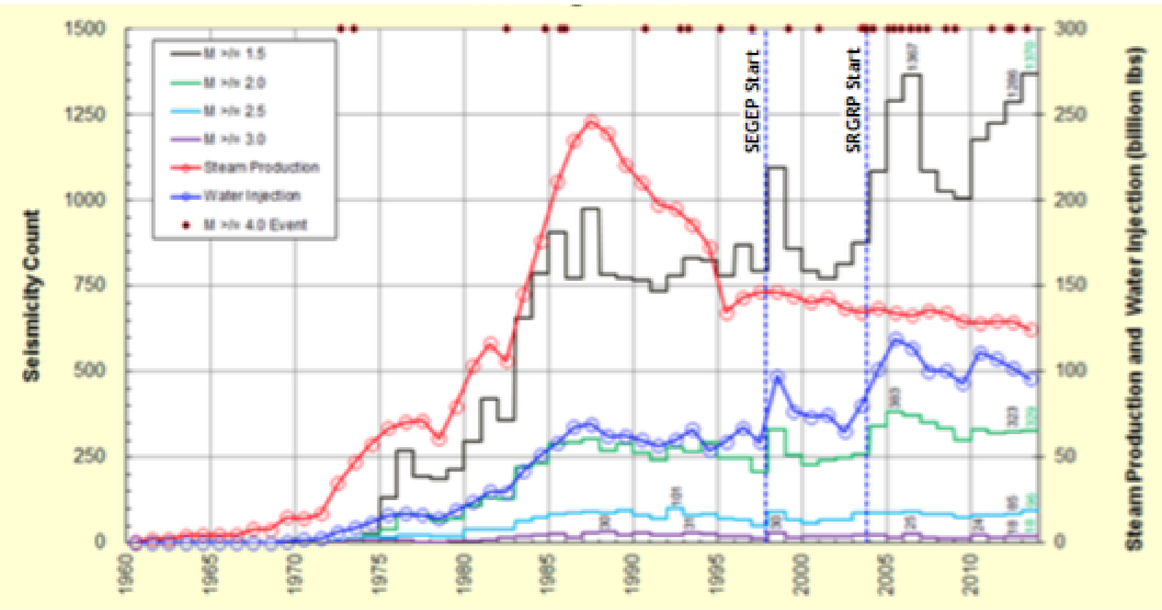

Figure 2: Yearly Steam Production from The Geysers, water injection and seismicity 1960-2013 (Calpine Corporation Report, 2014).

2. DATA AND METHOD

Seismic tomography is a technique for imaging three-dimensional Earth structure using a large set of observations (Evans et al., 1994). Most seismic tomography images infer the spatial distribution of seismic-wave speeds using seismic travel-time data. There have been many successful applications on local, regional and global scales. A range of techniques is available which use teleseismic phases, local earthquake P- and S-waves, surface waves, normal modes, and controlled sources. Global surface-wave tomographic inversions have provided insight into active tectonic regions, volcanoes, ridges and back arcs, while body-wave inversions have illuminated coarse mantle structure (Li and Tanimoto, 1993). Teleseismic tomography has successfully modelled undulations on the core-mantle boundary, mantle structure on global and regional scales, and the upper mantle and lithosphere (Morelli, 1993; Dueker et al., 1993). Oceanic crust subducting under continental crust has been imaged, e.g., in north America and Japan (Rasmussin and Humphreys, 1988; Benz et al., 1992; Harris et al., 1991; Hirahara, 1981). Teleseismic tomography has succeeded in defining low-velocity zones in the upper mantle or crust beneath volcanic centres which have been interpreted as magma chambers or zones of partial melt (e.g., The Geysers-Clear Lake area, Long Valley-Mono Lake, and Coso Hot Springs areas, California), and active volcanoes (e.g., Yellowstone, Wyoming, and in Hawaii).

Small-scale and extreme lateral heterogeneities characterise geothermal and volcanic areas. Teleseismic tomography uses low-frequency seismic waves and can therefore only resolve large-scale features. Techniques such as local earthquake tomography (LET) and active-source high-resolution tomography (NeHT) that increased resolution by using higher frequency data from local earthquakes and explosions are more suited to studying these areas. Active source NeHT tomography uses one or more rings of controlled sources to undershoot a central target volume beneath a receiver array. LET uses earthquakes within a model crustal volume to generate three-dimensional images of the velocity structure (Thurber, 1993; Eberhart-Phillips, 1993).

We use microearthquakes to study changes in the three-dimensional structure of The Geysers geothermal reservoir, applying tomographic inversion techniques to 35,278 P- and 9452 S-wave arrival times from 1657 earthquakes recorded on the local network. We derived models of the compressional-wave speed Vp and the compressional/shear wave-speed ratio Vp/Vs. Data recorded between 2008 and 2014 on the local network were obtained from the Northern California Earthquake Data Center (NCEDC) (Figure 3). Only the highest-quality earthquakes that they have a minimum 10 P-wave and 3 S-wave readings, an azimuthal GAP smaller than 180° and an RMS smaller than 0.05 s were selected.

The arrival times were inverted using two computer programs: SIMUL2000A (Evans et al., 1994) and TOMO4D (Julian and Foulger, 2010). Both programs solve simultaneously for earthquake locations and crustal structure using iterative damped-least-squares. The velocity structures are parameterized by values defined at the nodes of a three-dimensional grid, between which the Vp and Vp/Vs values are assumed to follow trilinear functions. We used nodes spaced at intervals of 1 km horizontally and vertically throughout most of the study volume.

Using SIMUL2000A, structural change is detected by inverting two epochs of data separately and differencing the resulting output models. This approach suffers from the disadvantage that variations in experimental setup, *e.g.*, earthquake locations, between the two epochs may be mapped into spurious structural change. TOMO4D was developed to avoid this problem by inverting both epochs of data simultaneously, minimising structural change. This approach results in only the changes in structure most strongly required by the data being imaged.

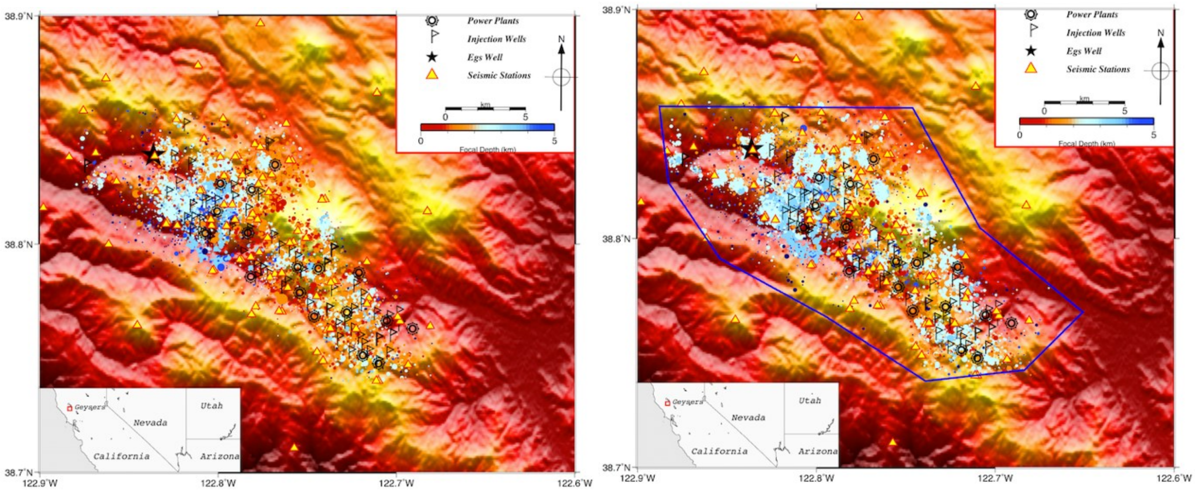

Figure 3: Seismicity at The Geysers for 2008 (left panel) and 2014 (right panel) recorded by the NCDCE.

The number of events used is 9845 for 2008 and 15,312 for 2014. The magnitudes of the events ranged from M 0 to M 4.5. Julian et al. (1996) and Ross (1996) obtained a tomographic model for the Geysers using a composite data set recorded in April 1991 on the UNOCAL and NCSN networks, and a temporary 15-station network deployed by the USGS. We used a starting model from Ross (1996) with 1.0 km nodal spacing in the reservoir region.

3. RESULTS

Figure 4 shows the changes in structure between the years 2008 and 2014 imaged using both SIMUL2000A (left panels) and TOMO4D (right panels). Both programs find that Vp/Vs reduced in the central and southern part of The Geysers. The changes are relatively strong and the results agree fairly well between the two programs.

Gunasekera et al. (2003) showed that the low-Vp/Vs anomaly that characterises The Geysers geothermal reservoir grew steadily in the period 1991-1998. This was a period of particularly strong reservoir depletion since it pre-dated the present large-scale reinjection that is now mitigating net fluid loss. The longer (6-year) period of the 2008-2014 epoch is expected to exhibit structural change of the order of a 2-year epoch during 1991-1998. This expectation is largely bourn out by our results. The results do suggest, however, that the part of the reservoir that is depleting most strongly has moved and is now centered on the NW Geysers and on the western and eastern edges of the field (Figure 5).

4. CONCLUSIONS

We applied time dependent tomography to The Geysers Geothermal Field. Repeat local earthquake tomography can potentially reveal changes in the seismic structure of The Geysers caused by exploitation of the reservoir. Factors that influence Vp/Vs include fluid saturation, fluid pressure, and hydration of minerals. Increased saturation raises Vp/Vs while decreased saturation (replacement of water with steam) depresses it. Relatively high Vp/Vs may indicate water-saturated parts of the reservoir, whereas low Vp/Vs regions may indicate steam zones.

Such work was successfully achieved by Gunasekera et al. (2003) for the period 1991-1998. They used earthquake arrival-time data that had been carefully measured by hand and extensively examined for outliers. In this study we extend this work through the period 2008-2014 using data taken from the NCDCE catalog. We used two different tomographic inversion techniques, by applying the programs SIMUL2000A and TOMO4D.

For the 6-year interval we studied, we detected anomaly growth of the same kind as reported by Gunasekera et al. (2003) for 2-year periods. This likely reflects the reduced rate of reservoir depletion achieved by recent large-scale water injections into the reservoir. Furthermore, different regions of the reservoir showed strengthening Vp/Vs anomalies, namely the NW Geysers and regions on the western and eastern margins of the field. This suggests that the region of strongest depletion has migrated to different parts of the field as a result of the current injections in the main part of the field.

This paper is a preliminary report on the results to date. Future work will include a) hand-processing of selected datasets to improve the quality of the arrival-time measurements, and b) further application of TOMO4D to sub-epochs in the 2008-2014 period.

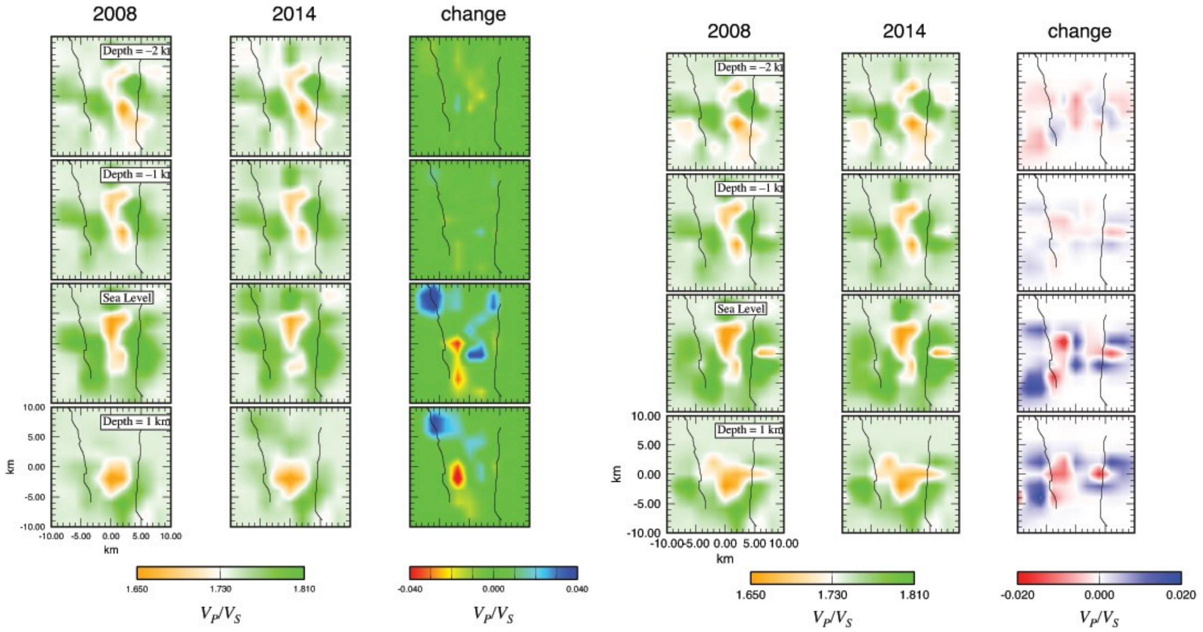

Figure 4. Anomalies in Vp/Vs at depths of -2 km, -1 km, sea level and 1.0 km below sea level for 2008 and 2014, along with the change between epochs. Leftmost three columns: results obtained using SIMUL2000A; rightmost three columns: results obtained using TOMO4D.

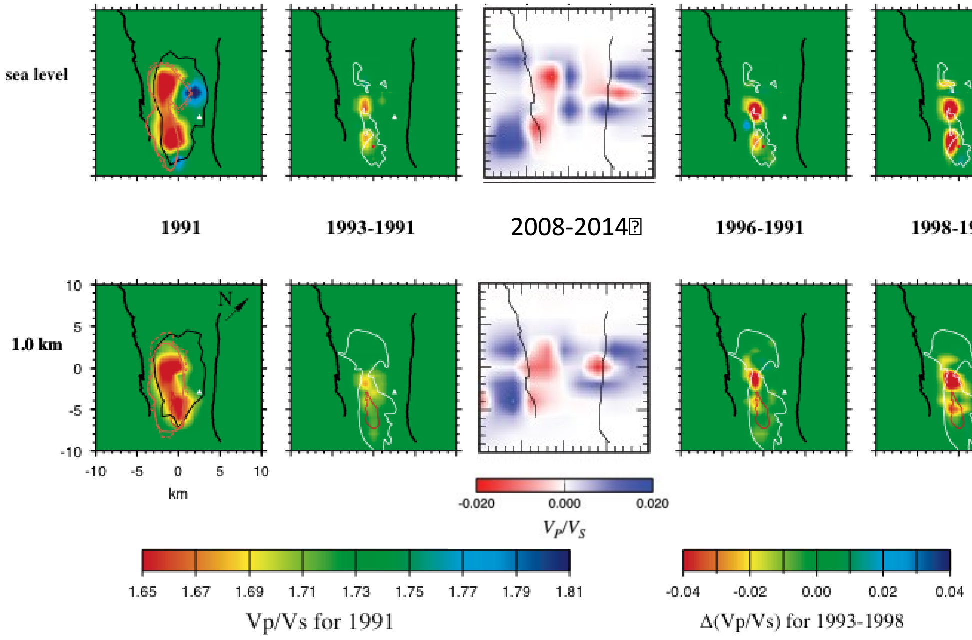

Figure 5. Comparison of results of 2008-2014 inversion using TOMO4D with selected results from Gunasekera et al. (2003), which were obtained using SIMUL2000A. The reservoir depletion for 2008-2014 is comparable to that for 1993-1991. This largely agrees with the strength of anomaly changes during these two periods. During the period 2008-2014, depletion occurred mostly in the NW Geysers, and on the western and eastern reservoir edges, rather than in the center of the field as was found for 1991-1998.

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