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Industrially induced changes in Earth structure at The Geysers geothermal area, California

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Abstract. Industrial exploitation is causing clearly-measurable changes in Earth structure at The Geysers geothermal area, California. Production at The Geysers peaked in the late 1980s at ~3.5 x 10^3 kg s^{-1} of steam and 1800 MW of electricity. It subsequently decreased by about 10% per year [*Barker et al.*, 1992] because of declining reservoir pressure. The steam reservoir coincides with a strong negative anomaly (~0.16, ~9%) in the compressional-to-shear seismic wave speed ratio v_P/v_S, consistent with the expected effects of low-pressure vapor-phase pore fluid [*Julian et al.*, 1996]. Between 1991 and 1994 this anomaly increased in amplitude by up to about 0.07 (~4%). This is consistent with the expected effects of continued pressure reduction and conversion of pore water to steam as a result of exploitation. These unique results show that v_P/v_S tomography can easily detect saturation changes caused by exploitation of reservoirs, and is a potentially valuable technique for monitoring environmental change. They also provide geophysical observational evidence that geothermal energy is not a renewable energy source.

Introduction

The Geysers geothermal reservoir occupies greywacke sandstones and a felsite batholith, and lies within the San Andreas shear zone [*Thompson*, 1992] (Figure 1). It's surface area is about 75 km^2 and it extends from about 0.3 km above sea level, down to at least 3 km below sea level Although the fluid emerging from wells at The Geysers is dry steam, the total amount of fluid extracted since 1960, when significant exploitation started, is too large to have been stored in the reservoir as vapor. It is thought that much of the reservoir fluid is stored as liquid water in the rock pores, which boils as steam is extracted [*Barker et al.*, 1992]. Since 1968, reservoir pressure has declined from ~3.5 MPa (ref. 1) to less than 2 MPa throughout an extensive volume, while the temperature has remained constant at about 240°C in the main reservoir [*Truesdell et al.*, 1992]. Steam production has declined by 10% yr^{-1} in recent years and power generation is now only about 65% of the installed capacity.

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Data and Tomographic Inversions

Steam extraction at The Geysers induces many small-magnitude earthquakes, widely distributed throughout the reservoir [*Eberhart-Phillips and Oppenheimer*, 1984; *Stark*, 1991]. These are monitored by a permanent seismic network operated by the UNOCAL Corporation, which comprises 22 stations, 7 of which have three-component sensors. We used compressional- (*P*) and shear-wave (*S*) arrival times from local earthquakes observed on this network to determine the three-dimensional distributions of *P*- and *S*-wave speeds (v_P and v_S) in and around the reservoir. The tomographic method used incorporates ray

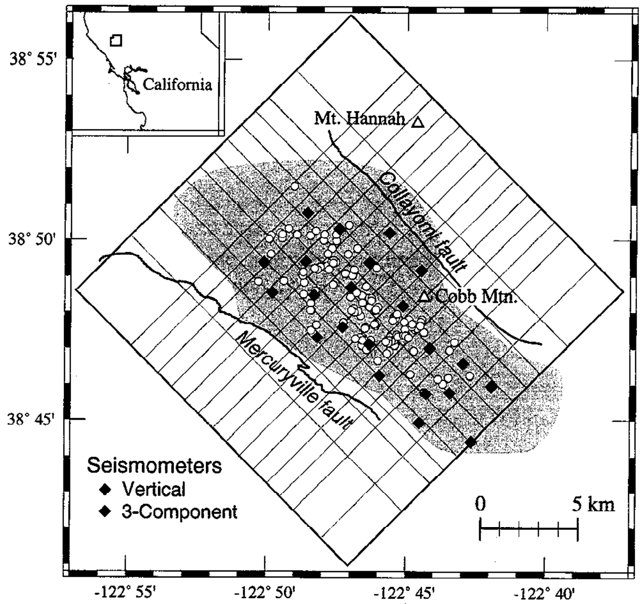

Figure 1. Map of The Geysers geothermal area. Gray zone: geothermal production are [*UNOCAL et al.*, 1991], diamonds: seismometers of the permanent UNOCAL network which were used in this study, circles: epicenters of earthquakes of the 1994 data set, large square: surface projection of the volume studied. Grid lines are shown in gray and intersect at nodes where seismic velocity is calculated. The grid extends from -1 to 4 km depth with 1-km node spacing, and has 1232 nodes. Heavy black lines: surface traces of the Collayomi and Mercuryville fault zones.

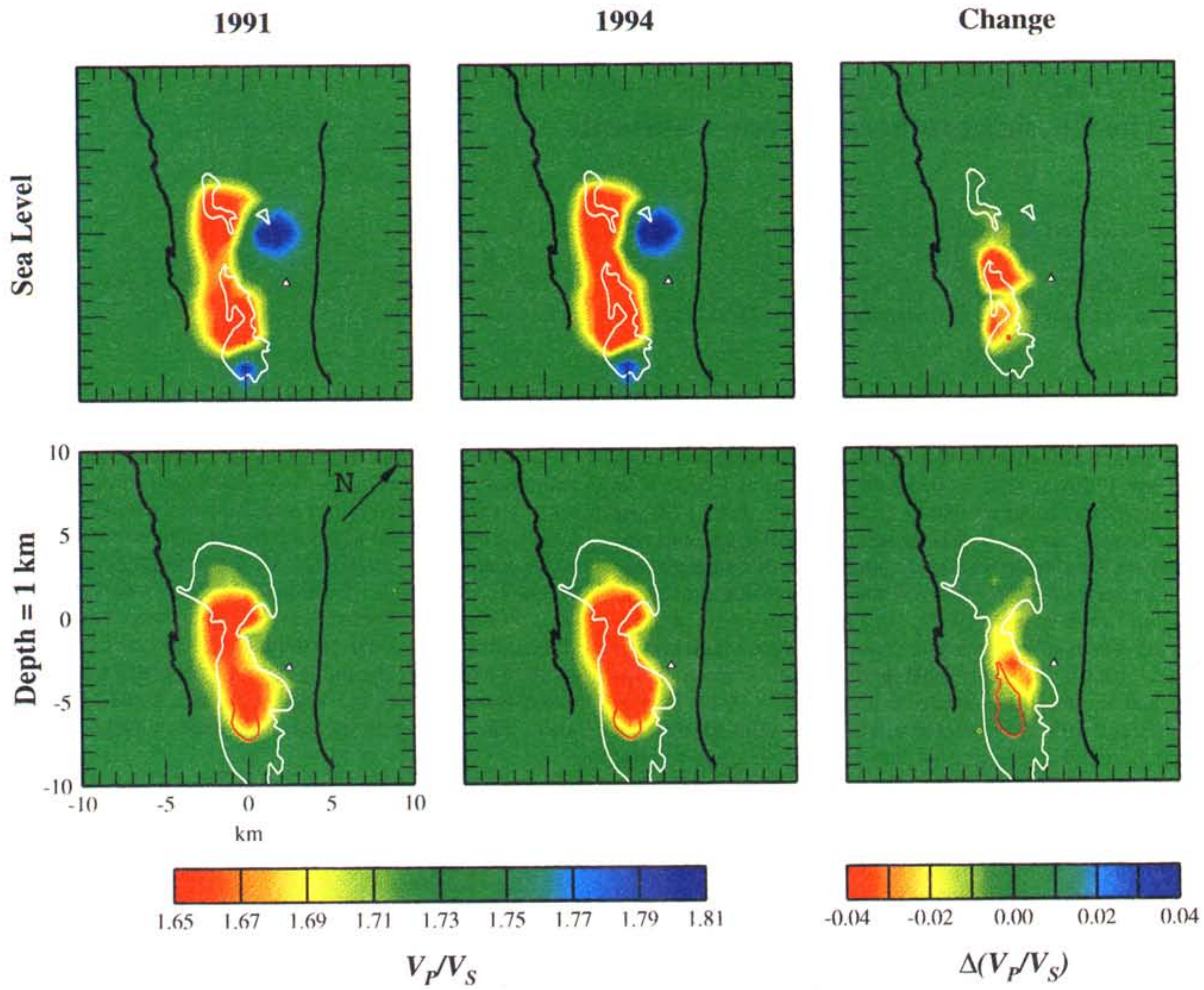

Figure 2. (a) Maps of wave-speed ratio v_P/v_S at two well-resolved depths for April 1991. Solid white line: boundary of the steam reservoir, black lines: surface traces of fault zones shown in Figure 1, (b) same as (a) except for December 1994, (c) same as (a) except showing change in v_P/v_S between 1991 and 1994.

bending and iteratively solves for earthquake locations and wave-speed structure, updating ray paths at each iteration step [*Thurber*, 1983; *Eberhart-Phillips*, 1986]. Separate inversions were performed using data from April 1991 and December 1994 and the results compared to reveal interim changes in the reservoir.

High-quality *P*- and *S*-wave arrival times were hand picked from digital seismograms to an accuracy of ~0.01 s for *P* and ~0.02 s for *S* waves. We measured *S*-wave arrival times at three-component stations only, and chose the earliest *S* wave wherever there was evidence of *S*-wave birefringence caused by material anisotropy. Both inversions imaged a volume extending from -1 to 4 km in depth (Figure 1). The 1991 data set includes 163 earthquakes, 2268 *P*- and 226 *S*-wave arrival times and the 1994 data set 146 earthquakes, 2522 *P*- and 656 *S*-wave arrival times. A one-dimensional starting model was obtained from an initial inversion of the 1991 data and a starting v_P/v_S ratio of 1.74 was obtained from Wadati diagrams [*Julian et al.*, 1996]. A series of inversions was performed with progressively decreasing nodal spacing for the 1991 data [*Julian et al.*, 1996] and a 75% reduction in arrival-time variance was achieved. The final RMS arrival-time residuals are 0.021 s for *P* waves and 0.036 s for *S* waves. For the 1994 data set, the starting model used was the three-dimensional model obtained using the 1991 data and the reduction in arrival-time variance was 77%. The final RMS arrival-time residuals for the 1994 data are 0.019 s for *P* waves and 0.055 s for *S* waves. The spread function, derivative weight sum [*Julian et al.*, 1996] and node resolutions confirm that the reservoir volume is well-resolved in the depth range 0 to over 2 km below sea level for both inversions.

Results

First order spatial variations in v_P and v_S are similar and reflect variations in lithology [*Julian et al.*, 1996]. In the reservoir, however, v_P/v_S shows a clear, coherent negative anomaly of about 0.16 (9%), which is strongest in the most heavily depleted volumes, northwest and southeast of the center of the reservoir (Figures 2a and b). In these places, pressure had dropped from an initial 3.5

MPa to as little as 1.4 MPa by the late 1980s [*Barker et al.*, 1992]. The 1991 and 1994 results are similar except in the center of the reservoir, where the anomaly became stronger by about 0.07 (4%) in the intervening 3.7 years (Figures 2a and b, Figure 2c). This change arises mainly from lowering of v_P 1991-1994, which indicates an increase in the rock compressibility.

In order to ensure that different inversion procedures did not cause spurious differences in the results, the two inversions were kept as similar as possible. The same node configurations and seismic stations were used. Damping values were optimized for each inversion, but differed only slightly between the two inversions, and tests showed that this made no significant difference to the results. The damping used was relatively strong, to minimize statistically insignificant differences in the results. We also inverted the 1994 data starting with a one-dimensional starting model and compared the results with an inversion of 1991 data that included additional stations from the U.S. Geological Survey CALNET network, and 15 temporary 3-component stations that we deployed. That latter inversion involved 185 earthquakes, 4032 *P*- and 944 *S*-wave arrivals, and produced a very well constrained v_P/v_S field that correlated excellently with the production area [*Julian et al.*, 1996]. This comparison showed an even higher-amplitude and spatially more extensive increase in the v_P/v_S anomaly than that revealed by the conservative results that we present here.

Interpretation and Conclusions

Julian et al. (1996) interpreted the negative v_P/v_S anomaly as a zone of low pressure that was also relatively dry as a consequence of boiling of the original liquid pore fluid as steam was extracted. Such a correlation between v_P/v_S and pore-fluid properties is expected on the basis of theory and laboratory experiments on porous rocks. These show that v_P/v_S is sensitive to the compressibility of the pore fluid, through its effect on v_P, and is relatively insensitive to the properties of the rock matrix [*Ito et al.*, 1979]. The change of the v_P/v_S anomaly is thus most likely a result of both decreasing pressure and depletion of the remaining pore water remaining between 1991 and 1994. This conclusion is supported by the fact that the zone of maximum change in v_P/v_S was, in the late 1980s, the site of a local pressure maximum, and the region of most rapid pressure decline. A temperature increase of about 25°C in a water-saturated reservoir could, in theory, also cause the observed change in v_P/v_S. However, the reservoir temperature remained constant 1991-1994 and certainly no cooling to such a large degree occurred [*Mitchell Stark*, personal communication, 1994].

The seismically-detected v_P/v_S change implies that pressure and/or liquid saturation decreased in the center of The Geysers reservoir between 1991 and 1994, a prediction that is consistent with the sparse published information based on well data. These unique results show that seismic tomography can be used to monitor the depletion of geothermal reservoirs and perhaps reservoirs of other kinds where gas and liquid exchange takes place. Further tomographic studies at The Geysers, for which extensive proprietary data on production, injection, and reservoir conditions exist, would be valuable for calibrating such a method. Because the compressional-wave speed v_P changes most, it might be possible to detect *changes* in pore-fluid properties using repeated tomographic inversions and *P*-phase data alone, despite the fact that identifying even a strong reservoir anomaly like that at The Geysers from *P*-wave data alone is difficult or impossible because it is masked by much stronger anomalies associated with lithological variations [*Julian et al.*, 1996]. If so, then data from commonly-existing single-component seismometer networks may provide valuable information on the state of geothermal reservoirs and their response to exploitation.

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