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Three-dimensional seismic image of a geothermal reservoir: The Geysers, California

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Abstract. Three-dimensional seismic travel-time tomography of The Geysers geothermal area, in the coast ranges of northern California, shows a strong (–9%) anomaly in V_P/V_S, the ratio of the compressional and shear wave speeds, that is not evident in V_P alone and corresponds closely to the most intensively exploited part of the geothermal reservoir. This anomaly probably indicates low pore pressure and relatively dry conditions, caused partly by boiling of pore water as steam is extracted. Steam pressure decreases over the last decade have probably caused seismologically measurable changes in wave speeds. Tomographic measurement of V_P/V_S is a promising technique both for identifying geothermal resources and for monitoring them during exploitation.

Introduction

The Geysers is the world's largest producer of geothermal electricity. Large-scale steam production and electricity generation began about 1970, accelerated in the early 1980s, and peaked in 1987 at about 3.5×10^3 kg s^{-1} and 2000 MW. Since the late 1980s production has decreased by about 10%/yr [*Barker et al.*, 1992] because of a drop in steam pressure as pore water has boiled away. This unanticipated decline emphasizes the need for methods of measuring conditions within geothermal reservoirs. Here we use local-earthquake travel-time tomography to obtain three-dimensional images of seismic-wave speeds at The Geysers, and find that the ratio of the wave speeds, V_P/V_S, is relatively insensitive to lithology but quite sensitive to the compressibility of the pore fluid, and thus its state of saturation.

The Geysers reservoir (Figure 1) occupies metamorphosed marine sedimentary and igneous rocks of the Franciscan Complex and the upper portion of a "felsite" batholith [*Thompson*, 1992]. It underlies an area of about 75 km^2 and extends from near the surface to at least 3 km below sea level. The heat source is unknown, but surface gravity and teleseismic travel-time anomalies near Mt. Hannah are consistent with a body of partial melt at mid-crustal depths [*Iyer et el.*, 1981]. The reservoir temperature is about 240°C and the pre-production pressure was about 3.5 MPa (35 bars) [*Barker et al.*, 1992]. Temperatures up to 350°C and anomalous isotope ratios in the northwestern part of the field may indicate a young, perhaps partly molten and degassing, pluton there [*Walters et al.*, 1992].

The geothermal area is very active seismically, generating about 140 earthquakes per month with $M_L > 1.2$. Although pre-production earthquake rates are uncertain [*Ludwin and Bufe*, 1980], it is clear that most of the current seismicity is induced, by both steam extraction and liquid injection [*Stark*, 1990]. The most active zone is within the reservoir, and activity has increased and spread laterally along with exploitation.

Data

We use these microearthquakes to study the structure of the geothermal reservoir, applying tomographic inversion techniques to 4032 *P*- and 944 *S*-wave arrival times from 185 earthquakes recorded on dense local seismometer networks to derive three-dimensional models of the compressional-wave speed V_P and the compressional : shear wave-speed ratio V_P/V_S. The study volume is 20 × 20 km in surface area and ranges in depth from -1 km to 6 km. The data were recorded in April 1991 by 32 stations of the permanent seismometer networks of the UNOCAL Corporation and the U. S. Geological Survey (USGS) and by 15 portable PASSCAL instruments (Figure 1). Arrival times were measured from digitized seismograms using an interactive graphical computer program, and are accurate to about 0.01 s for *P* waves and 0.02 s for *S* waves. All *S*-wave measurements are from horizontal-component seismograms. All the earthquakes in the geothermal area are shallower than about 4 km (Figure 2).

Inversion Method

The arrival times were inverted using the computer program *SIMULPS12* [*Evans et al.*, 1994], which solves simultaneously for earthquake locations and crustal structure (V_P and optionally V_P/V_S) by the iterative damped-least-squares method. At each iteration step, ray paths and earthquake locations are fully updated. The program *VELEST* [*Kissling et al.*, 1994] provided a one-dimensional V_P model used as the starting point for the inversion. The initial estimate of 1.74 for the ratio V_P/V_S is the median of 126 values obtained from Wadati diagrams for events with five or more S–P time measurements. We derived three-dimensional

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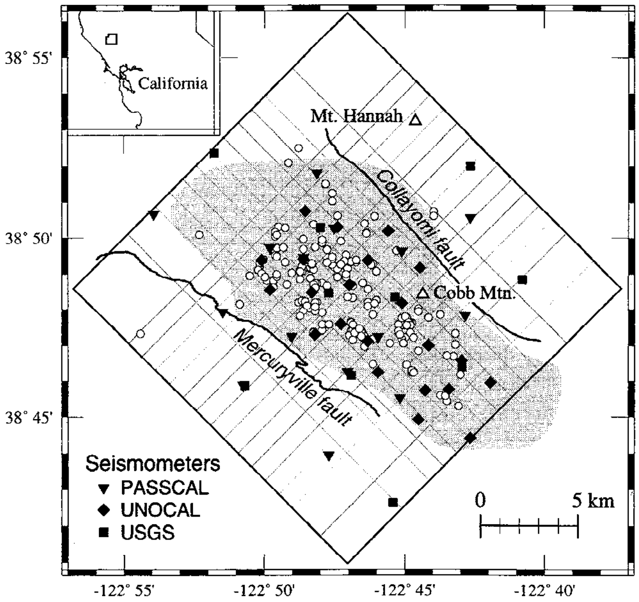

Figure 1. Map of The Geysers geothermal area, showing seismometer locations. Gray shading: geothermal field (*e.g. Thompson*, 1992). Large square: surface projection of the volume studied, with grid lines in gray. Crosses: epicenters of earthquakes used.

models in a series of "graded" inversions, in which a relatively coarse initial grid (63 nodes, 10-km horizontal spacing) is made progressively finer during successive inversions. The final grid has 1232 nodes with 1-km spacing. The final model gives a 70% reduction in variance, with RMS residuals of 0.022 s for P waves and 0.048 s for S waves. To assess the resolution of the results, we evaluate at each node a *spread* function, which measures the distance over which wave speeds are averaged [*Foulger et al.*, 1995]. In the main, the region shallower than 3 km is best resolved (Figures 3 & 4).

Results

The compressional-wave speed V_P varies horizontally by ±8.6% (RMS deviation) in the well resolved region above 3 km (Figure 3). The V_P model agrees broadly with those obtained in an early tomographic study of the coast ranges based on sparse USGS network data [*Eberhart-Phillips*, 1986] and a recent higher-resolution study of the central and northwest Geysers based on data from the UNOCAL network [*Zucca et al.*, 1993]. The regions of low V_P at Cobb Mtn. and northeast of the Collayomi fault are attributable to rocks of the Great Valley sequence and the Clear Lake volcanics [*Hearn et al.*, 1981]. V_P is systematically about 10% lower in the northwestern than in the central part of the reservoir at all well resolved depths. This anomaly is too large to be the effect of high temperature on the elasticity of minerals (about 3% for a 100°C change) and most of it must reflect variations in lithology or in the compressibility of the pore fluid.

Compared with V_P, variations in the wave-speed ratio V_P/V_S (Figure 4) are weaker ($< \pm 3\%$ RMS deviation) and have a simpler distribution. By far the strongest V_P/V_S anomaly (about –9%) coincides closely with the most intensively exploited part of the reservoir at depths of –1 to 2 km. At sea level this anomaly consists of two separate parts, as does the reservoir. The anomaly does not extend as far to either the northwest or the southeast as the reservoir. In the southeast, this discrepancy may be an artifact of limited resolution, but in the northwest the difference is real. A high-V_P/V_S "halo" surrounds the reservoir at depths down to 1 km, but this may be an artifact of limited resolution and high values may actually extend to greater distances.

Discussion

Table 1 gives theoretical estimates of the V_P/V_S anomalies that would be caused by differences in pore-fluid phase, temperature, and pore pressure, for rocks with porosities of zero and 0.02, the approximate value in the reservoir. For zero porosity, the V_P/V_S ratio equals that of the rock matrix, and the effects of pressure and temperature are much too small to contribute significantly to the observed anomaly. At finite porosities, the compressibility of the pore fluid strongly affects V_P/V_S. The largest effect is caused by the contrast between liquid and vapor, although the dependence of the vapor's compressibility on temperature and pressure is also significant.

The V_P/V_S anomaly is probably caused mostly by vapor domination. The reservoir was vapor-rich in its natural state, whereas the surrounding rocks are not, so the reservoir probably had a large V_P/V_S anomaly before exploitation began. This conclusion is supported by the results of a one-dimensional seismic study of the production area in 1984 [*O'Connell*, 1986], which found low V_P/V_S values at depths from 0 to 2 km. The magnitude of the anomaly in 1991 (–9%) could be explained entirely by the difference between water vapor in the reservoir and liquid water in the surrounding rocks, on the basis of the sensitivities in Table 1.

Production probably has increased the magnitude of the anomaly and changed its spatial variation, both by boiling away interstitial liquid and by decreasing steam pressure. Between 1968 and 1988, borehole pressures decreased by as much as 2.0 MPa in places, and they vary spatially by more than 1.0 MPa [*Barker et al.*, 1992], which could cause V_P/V_S variations of 6.6% or more. The two largest pressure minima coincide with the two V_P/V_S minima found at depths of 0 and 1 km from tomography.

High temperatures in the northwest Geysers can not explain high V_P/V_S there, because the temperature effect is smallest at high temperature and low pressure, so that the lower sensitivities from Table 1 apply.

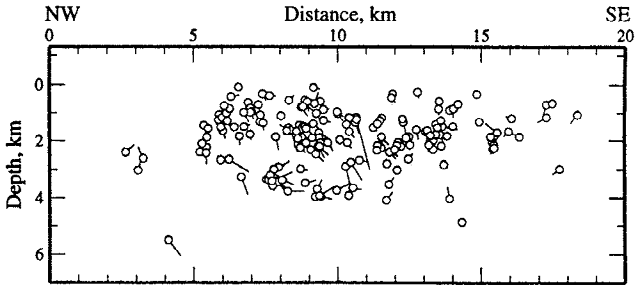

Figure 2. Northwest-southeast cross-section showing locations of earthquakes used. Lines connect locations determined using three-dimensional crustal model (circles) and one-dimensional starting model. Earthquakes are virtually absent below 4 km in the geothermal field.

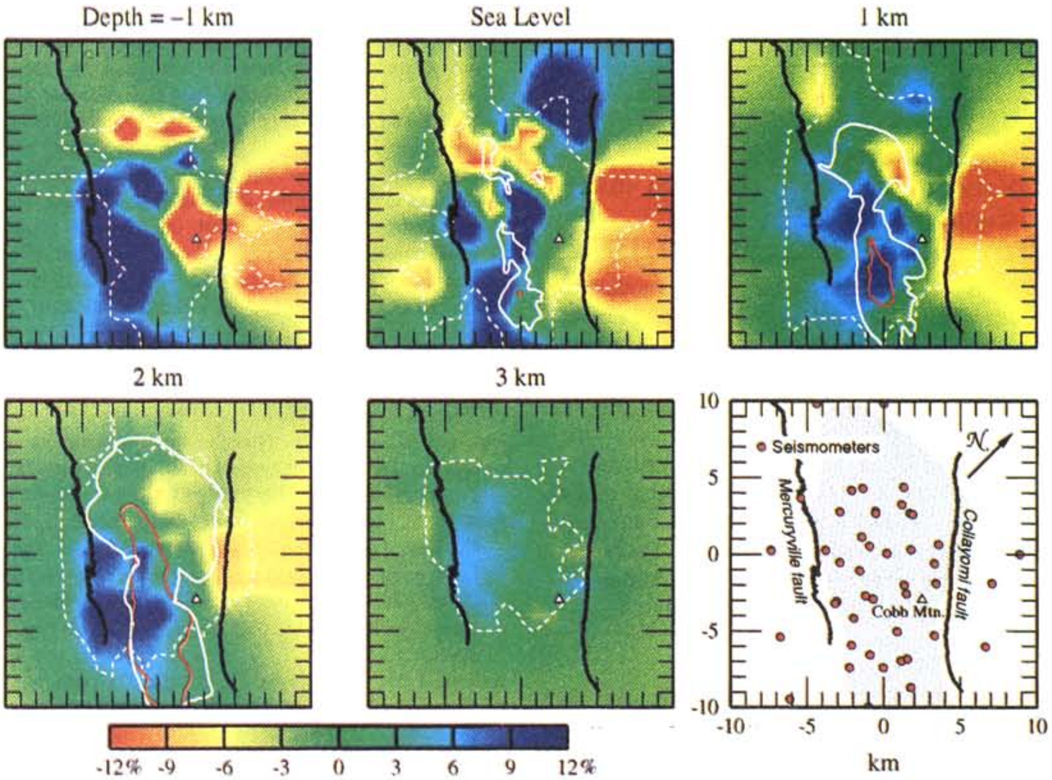

Figure 3. Maps showing variation of compressional-wave speed V_P from mean values at different depths (values to the left of maps). Areas within dashed white lines are well resolved (*spread* < 4 km). Solid white lines: boundary of steam reservoir. Red lines: boundary of felsite batholith. Gray shading (bottom right): surface projection of steam-production zone. V_P is low in the high-temperature northwest Geysers.

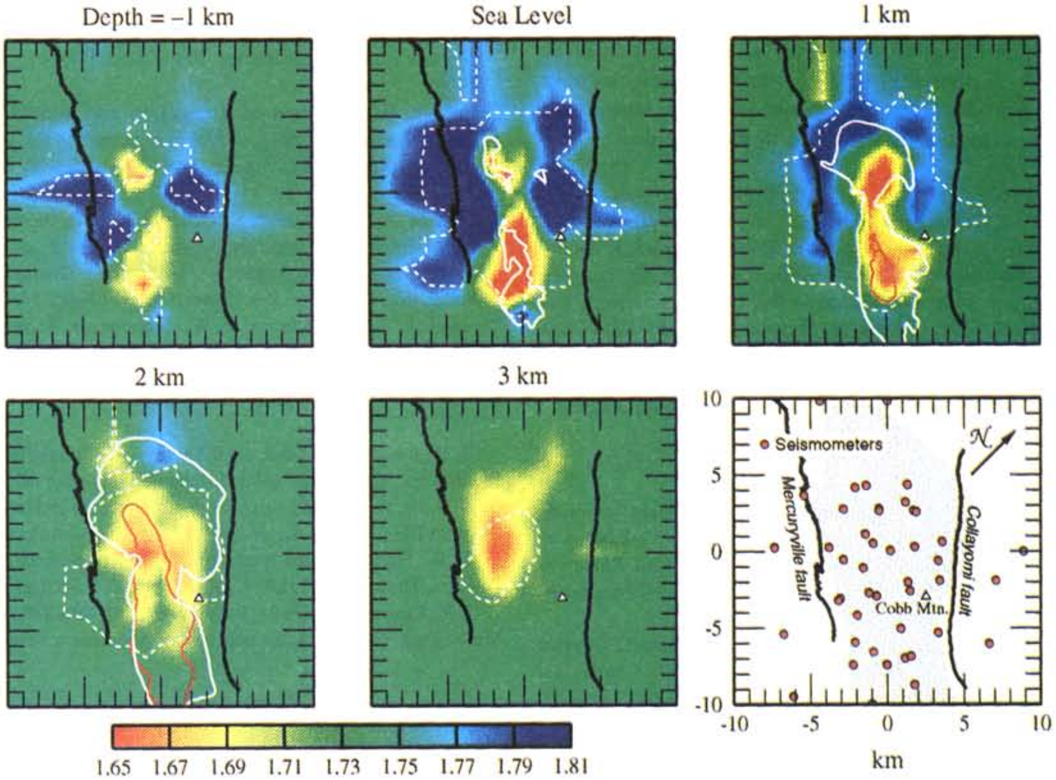

Figure 4. Same as Figure 3, for wave-speed ratio V_P/V_S. The value of V_P/V_S varies from 1.64 to 1.81 (average 1.74), corresponding to Poisson's ratios from 0.20 to 0.28.

Table 1. Theoretical V_P/V_S Anomalies

Cause	Porosity	
	0	0.02
Liquid -> Vapor	0	−14%
$\Delta T = +10°\mathrm{C}$ (Liquid)	−0.06%	−1.70%
$\Delta T = +10°\mathrm{C}$ (Vapor)	−0.06%	+0.10% to +0.68%
$\Delta P = -1$ MPa (Liquid)	+0.004%	−0.20%
$\Delta P = -1$ MPa (Vapor)	+0.004%	−6.6% to −10%

From $V_P/V_S = \left[K/\mu + 4/3\right]^{1/2}$ and the elastic moduli of water [*Keenan et al.*, 1969] and isotropic aggregates of rock-forming minerals [*Anderson and Liebermann*, 1969]. The macroscopic bulk modulus K is related to those of the fluid and the rock matrix, K_f and K_m, and the porosity ϕ by $1/K = \phi/K_f + (1-\phi)/K_m$. Both K_m and the macroscopic rigidity modulus μ are taken proportional to the corresponding moduli of quartz, and independent of the pore-fluid properties. Pressure changes in the matrix are assumed equal and opposite to those in the fluid. The ranges of values for the vapor phase correspond to conditions in the reservoir ($P = 2.0$ to 3.6 MPa; $T = 240$ to 350°C).

Although the pore fluid's properties affect the V_P/V_S ratio primarily by changing V_P, the anomaly is not clear in the V_P field alone (Figure 3). The reservoir must differ systematically from its surroundings in a way that increases both V_P and V_S and largely counters the effect of undersaturation. Lithologic variations associated with the "felsite" pluton and a metamorphic aureole above it [*Hulen and Nielson*, 1993], as well as hydrothermal alteration, may contribute to this effect.

Temporal variations in V_P/V_S, caused by decreases in both liquid saturation and pressure, probably are large enough to measure seismologically. If, as expected, the compressional-wave speed V_P is changing most rapidly, then analysis of P-phase data from existing single-component seismometer networks can provide valuable information on the state of the geothermal reservoir and its response to exploitation.

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References

Anderson, O. L., and R. C. Liebermann, Elastic constants of oxide compounds used to estimate the properties of the Earth's interior, in *The Application of Modern Physics to the Earth and Planetary Interiors,* edited by S. K. Runcorn, pp. 425-448, Wiley–Interscience, London, 1969.

Barker, B. J., M. S. Gulati, M. A. Bryan, K. L. Riedel, Geysers reservoir performance, in *Monograph on The Geysers Geothermal Field*, C. Stone, Ed., *Geotherm. Res. Council Special Rept., 17*, 167-177, 1992.

Eberhart-Phillips, D., Three-dimensional velocity structure in the northern California coast ranges from inversion of local earthquake arrival times, *Bull. Seismol. Soc. Am., 76*, 1025-1052, 1986.

Evans, J. R., D. Eberhart-Phillips, and C. H. Thurber, User's manual for SIMULPS12 for imaging v_p and v_p/v_s, a derivative of the Thurber tomographic inversion SIMUL3 for local earthquakes and explosions, *U. S. Geol. Surv. Open-File Rept., 94-431*, 142 pp., 1994.

Foulger, G. R., A. D. Miller, B. R. Julian, J. R. Evans, Three-dimensional v_p and v_p/v_s structure of the Hengill triple junction and geothermal area, Iceland, and the repeatability of tomographic inversion, *Geophys. Res. Lett.*, *22*, 1309-1312, 1995.

Hearn, B. C. Jr., J. M. Donnelly-Nolan, F. E. Goff, The Clear Lake volcanics: Tectonic setting and magma sources, in *Research in The Geysers-Clear Lake Geothermal Area, Northern California* , R. J. McLaughlin and J. M. Donnelly-Nolan, Eds., *U. S. Geol. Surv. Prof. Pap., 1141*, 25-45 , 1981.

Hulen, J. B., and D. L. Nielson, Interim report on geology of The Geysers felsite, northwestern California, *Geotherm. Res. Council Trans.*, *17*, 249-258, 1993.

Iyer, H. M., D. H. Oppenheimer, T. Hitchcock, J. N. Roloff, J. M. Coakley, Large teleseismic P-wave delays in The Geysers-Clear Lake geothermal area, in *Research in The Geysers-Clear Lake Geothermal Area, Northern California*, R. J. McLaughlin and J. M. Donnelly-Nolan, Eds., *U. S. Geol. Surv. Prof. Pap., 1141*, 97-116 , 1981.

Keenan, J. H., F. G. Keyes, P. G. Hill, J. G. Moore, *Steam Tables - Thermodynamic Properties of Water including Vapor, Liquid, and Solid Phases*, 162 pp., (John Wiley & Sons, New York, 1969.

Kissling, E., W. L. Ellsworth, D. Eberhart-Phillips, U. Kradolfer, Initial reference models in local earthquake tomography, *J. Geophys. Res.*, *99*, 19635-19646, 1994.

Ludwin, R. S., and C. G. Bufe, Continued seismic monitoring of The Geysers, California, geothermal area, *U. S. Geol. Surv. Open-File Rept., 80-1060*, 50 pp., 1980.

O'Connell, D. R., Seismic velocity structure and microearthquake properties at The Geysers, California geothermal area, Ph. D. thesis, Univ. of Calif., Berkeley, 1986.

Stark, M. A., Microearthquakes – a tool to track injected water in The Geysers reservoir, *Geotherm. Res. Council Trans.*, *14*, 1697-1704, 1990.

Thompson, R. C., Structural stratigraphy and intrusive rocks at The Geysers geothermal field, in *Monograph on The Geysers Geothermal Field* , C. Stone, Ed. *Geotherm. Res. Council Special Rept.*, *17*, 59-63, 1992.

Walters, M. A., J. R. Haizlip, J. N. Sternfeld, A. F. Drenick, J. Combs, A vapor-dominated high-temperature reservoir at The Geysers, California, in *Monograph on The Geysers Geothermal Field* , C. Stone, Ed., *Geotherm. Res. Council Special Rept., 17*, 77-87, 1992.

Zucca, J. J., L. J. Hutchings, P. W. Kasameyer, Seismic velocity and attenuation structure of the Geysers geothermal field, CA, *Geothermics*, 23, 111-126, 1993.

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