Degradation of the Mechanical Properties Imaged by Seismic Tomography during an EGS Creation at The Geysers (California) and Geomechanical Modeling

Pierre Jeanne¹, Jonny Rutqvist¹, Lawrence Hutchings¹, Ankit Singh¹, Patrick F. Dobson¹, Mark Walters², Craig Hartline², Julio Garcia²

¹ Lawrence Berkeley National Laboratory, Earth Sciences Division, Berkeley, CA, 94720, USA.

² Calpine Corporation, 10350 Socrates Mine Road, Middletown, CA, 95461, USA

Abstract

Using coupled thermal-hydro-mechanical (THM) modeling, we evaluated new seismic tomography results associated with stimulation injection at an EGS demonstration project at the northwest Geysers geothermal steam field, California. We studied high resolution seismic tomography images built from data recorded during three time periods: a period of two months prior to injection and during two consecutive one month periods after injection started in October 2011. Our analysis shows that seismic velocity decreases in areas of most intense induced microseismicity and this is also correlated with the spatial distribution of calculated steam pressure changes. A detailed analysis showed that shear wave velocity decreases with pressure in areas where pressure is sufficiently high to cause shear reactivation of pre-existing fractures. The analysis also indicates that cooling in a liquid zone around the injection well contributes to reduced shear wave velocity. A trend of reducing compressional wave velocity with fluid pressure was also found, but at pressures much above the pressure required for shear reactivation. We attribute the reduction in shear wave velocity to softening in the rock mass shear modulus associated with shear dislocations and associated changes in fracture surface properties. Also, as the rock mass become more fractured and more deformable this favors

reservoir expansion caused by the pressure increase, and so the fracture porosity increases leading to a decrease in bulk density, a decrease in Young modulus and finally a decrease in V_p .

Keywords:

Enhance Geothermal System; microseismic events; geomechanical simulation; seismic tomography; V_p/V_s

1. Introduction

Enhanced Geothermal Systems (EGS) have the potential to extract geothermal energy under circumstances and in locations where conventional production is not economically feasible (Tester et al., 2006). Generally, EGS would be applied to extract geothermal energy at sites where the reservoir rock is hot (has sufficient heat content) but has insufficient permeability for economic production. The successful application of EGS technology could allow large, untapped resources to be utilized, greatly increasing geothermal electrical production worldwide. Reservoir permeability is increased by utilizing water injection to reactivate fractures or possibly create new fractures.

The US Department of Energy's Geothermal Technologies Program and Geysers Power Company (Calpine) funded The Northwest Geysers EGS Demonstration Project. The project goal was to create an EGS by directly and systematically injecting cool water at relatively low pressure into a known High Temperature (300-400°C) reservoir (HTR) located under the normal

1 temperature (240°C) Reservoir (NTR) (Garcia et al., 2012; Rutqvist et al., 2013). Water was
2 injected at a relatively low rate and bottom-hole pressure was kept less than the estimated
3 minimum principal compressive stress at injection depth. The aim was to avoid the propagation
4 of a single hydraulic fracture and to create a more pervasive stimulation zone by dilating a
5 network of pre-existing fractures through shear reactivation. One of the scientific challenges was
6 to develop a robust seismic array capable of monitoring the EGS creation and development. To
7 do that, large scale hydrogeological and geomechanical field data were acquired before and
8 during injection by monitoring microseismicity, reservoir pressure and surface deformations.

9 The microseismic activity was recorded by the current LBNL (Lawrence Berkeley National
10 Laboratory) seismic monitoring network, which currently consists of 31 three-component
11 digitally-telemetered seismic stations located within The Geysers production boundaries.
12 Recorded seismic events were transmitted to LBNL servers, processed in “real-time” and
13 integrated into the Northern California Seismic Network (NCSN) system. These microseismic
14 data were used to characterize the geological structural setting of the EGS area (Jeanne et al.,
15 2014a). The well head pressure evolution was monitored in several wells surrounding the EGS
16 injection well, and the ground surface deformations were measured by TerraSAR-X satellites
17 (Vasco et al., 2013). These data were used to develop and to calibrate a 3D hydro-geomechanical
18 model of the EGS area (Jeanne et al., 2014b). Finally, the comparison between the observed
19 temporal and spatial distribution of microseismic activity and the calculated shear activation of
20 pre-existing fractures using 3D hydro-geomechanical model simulations, were used to estimate
21 the local *in situ* stress field (Jeanne et al., 2014c).

22 In addition to the current LBNL seismic monitoring network installed at The Geysers, LBNL
23 also installed a total of 15 temporary three-component seismic stations inside a “focused array”

around the EGS area to collect specialized data during the start-up of the stimulation (from one month before to two month after the beginning of the injection in October 2011) (Fig.1). The aim was to test an approach where changes in reservoir properties are determined rapidly, with high resolution and cheaply, and results could be rapidly used to select the best location to drill a production well. To this end, LBNL developed an inexpensive, automated microseismic data collection and processing system and computational capability necessary to record and process large numbers of microseismic recordings and obtain tomographic images at lower costs and in shorter time frame than was previously possible (Hutchings et al., 2011). The aim of this paper is to understand the relationship between the evolution of the reservoir properties and the tomography results during the first months of the stimulation.

Monitoring changes in seismic velocity (i.e. compressional-wave velocity, V_P and shear-wave velocity, V_S) by seismic tomography is a powerful tool to detect and understand changes in reservoir properties. Indeed, according to Hooke's law, as given by Lamé, strain field (s_{ij}) resulting from a generalized stress can be separated into a volume change with amplitude λ and a shape change with amplitude μ according to

$$s_{ij} = \lambda \varepsilon_{ii} \delta_{ij} + 2\mu \varepsilon_{ij}, \quad (1)$$

where λ is the Lamé parameter, the ratio formed by stress and the strain orthogonal to it, ε is strain, δ is the delta function, and μ is the shear modulus, the ratio of shear stress to shear strain. The parameters λ and μ are used in the solution of the wave equation of V_P and V_S :

$$V_P = \sqrt{\frac{\lambda + 2\mu}{\rho}}, \quad (2)$$

$$V_s = \sqrt{\frac{\mu}{\rho}}, \quad (3)$$

,where ρ is bulk density of the material. Seismologists have also worked on the V_p/V_s ratio to propose relationships to estimated elasto-dynamic parameters, such as the dynamic Young modulus, “E” (Darracott and Orr, 1976).

$$E = V_s^2 \times \rho \times \frac{3\left(\frac{V_p}{V_s}\right)^2 - 4}{\left(\frac{V_p}{V_s}\right)^2 - 1}, \quad (4)$$

The effect of the pore pressure on V_p and V_s was studied (Wyllie, etc., 1958; King, 1966; Christensen and Wang, 1985; Prasad and Manghnani, 1997), showing that the increase of the internal pore pressure of the rocks will decrease both V_p and V_s . These pressure dependence results from the opening of cracks and fractures, which elastically soften (i.e. loss of the rock’s compressive strength) by the rock mineral frame. Therefore, imaging of EGS creation and development by seismic tomography were performed at several sites such the Newberry EGS site (Matzel et al., 2014) and at Soultz-sous-forêts (Charlty et al., 2006). Charlty et al. (2006) found a relationship between an increase in injection rate and seismic velocity changes. The correlation suggested that the velocity changes because of increases in the reservoir pore pressure and/or porosity. To explain this relation Charlty et al. (2006) suggested that the overpressure created by hydrofracturing opened fractures and microcracks through which the liquid water could migrate. These two combined effects can result in reduction of V_p .

In this paper, we evaluate new seismic tomography results associated with stimulation injection at the northwest Geysers EGS demonstration project using coupled thermal-hydro-mechanical (THM) modeling. As The Geysers is a vapor-dominated geothermal system, the seismic velocity

may be affected by both changes in fluid saturation and mechanical degradation associated with the stimulation of the fractured rock mass. In this paper we argue that with a matrix porosity of less than 1%, the effects of liquid saturation on the bulk density are negligible and hence also negligible on the seismic velocity. We focus on linking velocity changes to mechanical changes associated with shear reactivation fractures. In the paper we first present seismic tomography images built from data recorded during three time periods: A period of one month prior to injection denoted t_{0d} (from: September 06 through October 05, 2011), and during two consecutive one month periods after injection. The two consecutive periods after injection are denoted t_{30d} (from October 06 to November 06, 2011) and t_{60d} (from November 06 to December 05, 2011). The instrumentation and data processing are not presented here, but are fully described in Hutchings et al. (2014). Hutchings used the software SimulPS (Thurber, 1984), which was modified to perform double difference tomography for earthquake location, P- and S-wave velocity structure (Hutchings, personnel communication, Lawrence Berkeley National Laboratory, 2014; manuscript in preparation). Hutchings investigated resolution and found the diagonal of the resolution matrix to be 0.3 to 0.8 in the vicinity of the wells where most of the seismicity occurred. Then, the seismic tomography images are compared with a THM model of the EGS site developed in a previous study (Jeanne et al., 2014, c). Specifically, we investigate the link between seismic velocity variations and calculated shear failure (corresponding to shear reactivation of fractures), as well as changes in pressure, temperature, and microseismicity activity. Finally, we discuss how changes in these parameters may impact rock mechanical and petrophysical rock properties.

2. The Northwest Geysers area

1 The Northwest Geysers EGS Demonstration Project, is located in the northwest part of
2 the Geysers geothermal field, where a relatively shallow high temperature reservoir (HTR) with
3 temperatures up to 400°C was identified extending downward from 2.6 km below the surface.
4 The HTR underlies a normal temperature reservoir (NTR) between 1.6 and 2.6 km below the
5 surface, where temperatures are ~240°C (Garcia et al., 2012). The rocks are composed of
6 metagraywacke in the NTR and of contact metamorphosed biotite hornfelsic metagraywacke
7 (“hornfels”) in the HTR. These two geothermal reservoirs are bounded above by very low
8 permeability formations (“graywacke caprock”) and below by granitic intrusions (“felsite”)
9 encountered at a depth of approximately 4.0 km. The reservoir rock at The Geysers is highly
10 fractured, with extensive hydrothermal alteration and re-crystallization. Lockner et al. (1982)
11 suggested that fracturing has weakened the rock to such an extent that only a frictional sliding
12 load can be supported by the rock, and shear stress in the region is probably near the rock-mass
13 frictional strengths. Therefore very small perturbations of the stress field could induce seismicity.

14 In the EGS area, two previously abandoned exploratory wells Prati 32 (P32) and Prati
15 State 31 (PS31) were re-opened as an injection/production pair for the EGS Demonstration
16 Project (Garcia et al., 2012). One of the re-opened wells (P32) was deepened to penetrate a thick
17 portion of the HTR, and was dedicated as an injection well. Four other wells: PS31, Prati 38
18 (P38), Prati 25 (P25) (of which P25 was re-opened as a steam production well part way through
19 the injection period) and Wildhorse State 71 (WHS 71) were used to monitor fluid pressure
20 variations inside the reservoir during the initial injection in P32 (Fig.2a), which began on
21 October 6, 2011. Two other injections wells are located around the EGS area: Prati 9 (P9) and
22 Wildhorse State 34 (WHS 34) (Fig.3g). Injection started in 2007 in P9 and in May 2011 in WHS
23 34.

The hydraulic and mechanical behavior of the studied EGS reservoir is controlled by a network of intersecting shear zone family (S1 – S8) trending N130 acts as a drain and favors fluid pressure diffusion. The other family trending N050 (Sa – Sc) has a lower permeability and can potentially act as an impermeable boundary, such as is the case for shear zone Sc (Fig. 2a). One of the main consequences is that the EGS area is partially isolated from the rest of the Northwest Geysers geothermal field.

3. Seismic tomography

Figure 3 and 4 present the temporal evolution of the velocity structure (V_P and V_S) in a volume centered on the EGS area. Figures 3a to 3c and Figures 4a to 4c present vertical seismic profiles of the V_P and V_S distribution at t_{0d} , t_{30d} and t_{60d} , oriented northwest-southeast (along the direction of highest permeability axis). Figures 3d to 3i and Figures 4d to 4i shows horizontal seismic profiles at t_{0d} , t_{30d} and t_{60d} , and at two different depths (Fig. 3a) : Z2 = -1995 m below sea level (where the highest velocity drop was measured) and Z4 = -2565m below sea level (which corresponds to the bottom of the injection zone). The black points on Figures 3a and d represent the tomography grid where V_P and V_S values were established and used to build these maps of velocity structure by linear interpolation. On the horizontal cross section, wells located close to the EGS area were added. Wells in red were used to monitor pressure variations inside the reservoir, and wells in blue are the injection wells. The highest resolution is obtained in the EGS area, around P32 and PS31, and our study is focused on this zone. However, at a larger scale the seismic tomography show some general features, which are:

- The vertical cross sections show an increase in seismic velocity with depth. This is expected as a result of increased modulus associated with closing of micro-fractures and cracks due to the increased stress with depth. Therefore, low velocities are found

near the surface, and velocities increase with depth, where fewer thin cracks remain open as pressure increases (Tarif et al., 1988; Boitnott and Bonner, 1994). Once crack porosity is closed, velocity will no longer increase rapidly with depth.

- The horizontal and vertical cross sections with V_P contours (Fig. 3), shows to the southeast a low velocity area, which correspond to the northeast part of the main geothermal field.
- Around the injection wells, there is a decrease in seismic velocity. This is especially true for WHS34, where injection started in May 2011, i.e., only few months before the first tomography images, and for the well P32 where the injection associated with the EGS demonstration was performed.

4. Thermo-Hydro-Mechanical simulation

We use a THM model of the EGS area that is based on previous modeling studies at The Geysers (Rutqvist et al., 2013; Jeanne et al., 2014a, b, c). In particular, according to Jeanne et al., (2014a, b), the model contains a network of shear zones that have a significant impact on the spatial and temporal evolution of reservoir pressure, microseismicity, and ground surface deformations.

4.1. Numerical analysis method

We use the coupled THM simulator TOUGHFLAC, which is described in Rutqvist et al. (2002) and Rutqvist (2011). TOUGH-FLAC links the TOUGH2 (finite volume) multiphase flow and heat transport simulator (Preuss et al., 2011), and the FLAC3D (finite-difference) geomechanical code (Itasca, 2011) for coupled THM analysis under multiphase flow conditions. TOUGH-FLAC

1 has previously been applied to study fault reactivation related to multiphase fluid flow and
2 crustal deformations (Rutqvist et al., 2007; Cappa et al., 2009; Cappa and Rutqvist, 2011a,b),
3 and it has also been applied to model The Geysers geothermal field (Rutqvist and Oldenburge,
4 2008; Rutqvist et al., 2013; Jeanne et al., 2014a, b, c).

5 According to Jeanne et al. (2014a, b), the rock mass can be simulated as an equivalent
6 continuum with implicit representation of fractures, whereas fault zones are explicitly
7 represented as 15 m wide zones with different hydraulic and mechanical properties. The rock
8 mass behaves as an elastic material, whereas faults are governed by an elastoplastic constitutive
9 law. Fault zones are envisioned to include an intensively fractured damage zone, under the
10 assumption that fractures of any orientation could exist. Such an assumption is supported by a
11 study of fault-plane analysis of seismicity at The Geysers by Oppenheimer (1986), which
12 indicated that seismic sources occur from almost randomly oriented fracture planes. Under this
13 assumption, the isotropic Mohr–Coulomb criterion is used to model elastoplastic behavior of
14 fault zones and reactivation. According to Jeanne et al., 2014b, the shear zone reactivation in the
15 field is associated with an observed surge in microseismicity along the fault zone, whereas in the
16 model, the fault reactivation is simulated as a shear failure. Note that microseismic activity along
17 the faults zone can be associated with reactivation of small fractures intersecting the fault zone or
18 being part of the fault zone architecture. Similarly, the calculated shear failure using the isotropic
19 Mohr-Coulomb model could be associated with shear failure along fractures of any orientation.

20
21 According to the Mohr-Coulomb failure criterion, fault zone reactivation will occur when the
22 difference between the maximum principal compressive effective stress σ'_1 and minimum

compressive principal effective stress σ'_3 is sufficiently large. (We consider compressive stress a positive quantity). Jaeger and Cook (1979) showed that the limiting ratio of maximal principal effective compressive stress, $\sigma'_1 = \sigma_1 - \alpha P_f$ (P_f is the fluid pressure and α is the Biot's coefficient; see Biot (1941)), and the minimum principal effective compressive stress at depth, $\sigma'_3 = \sigma_3 - \alpha P_f$, is given by:

$$\frac{\sigma'_1}{\sigma'_3} \leq q = [(\mu^2 + 1)^{\frac{1}{2}} + \mu]^2, \quad (5)$$

where q is the limiting stress difference (slope of the σ'_1 versus σ'_3 line). For our study, μ was set to 0.6, which corresponds to a q value of 3.12. $\mu = 0.6$ is a lower-limit value frequently observed in studies of the correlation between active fault zones and maximum shear stress (Byerlee, 1978; Sibson and Rowland, 2003).

4.2. Model geometry

The 3D numerical model represents the study area associated with the Northwest Geysers EGS Demonstration Project. The numerical model extends vertically from 0 to 6500 m in depth and 20×12 km horizontally. This model consists of four layers: a graywacke-dominated caprock, a normal temperature (240°C) reservoir (NTR), underlain by a high temperature reservoir (HTR) (with measured values up to 400°C) in the hornfelsic biotite metagraywacke (“hornfels”), and finally, a granite intrusive (“felsite”) layer (Garcia et al., 2012) (Fig. 5a). Eleven shear zones are represented: eight trending N130 and three trending N050 (Fig. 2b and 5b).

The simulated wells are made of two parts (Fig.2d). For the cased part of the wells, from the surface to the top of the injection or production zone, wells are simulated as vertical, and no fluid

flow and no heat exchange are allowed with the surrounding rock. Below the cased part, the simulated wells are curved to have the same trajectory as that of the wells in the field. These parts correspond to the injection or production zones, where heat and flow communication are allowed with the reservoir. This configuration enables injection of water from the surface and permits estimation of the well-head pressure variations as in the field. Water was injected at 90°C in the simulations, which results in a downhole fluid injection temperature of 90°C at the bottom of an internal well liner.

4.3. Initial and boundary conditions

The initial thermal and hydrological conditions (vertical distributions of temperature, pressure, and liquid saturation) were established through steady-state, multiphase flow simulations (Rutqvist et al., 2013). As in Rutqvist et al. (2013) the initial reservoir temperature in the NTR is ~ 240 °C down to a depth of about 2.5 km, and then gradually increases up to 370 °C toward the bottom boundary at a depth of 6.5 km. (This lower temperature value of 370 °C is used instead of the actual temperature of 400 °C at about 3.5km in Prati 32 because it is the upper temperature limit of the TOUGH module used.) At The Geysers, the steam pressure within the hydraulically confined NTR gradually decreased with steam production since the 1960s, and is today a few megapascals; thus, the initial reservoir pressure in the model simulations related to the new EGS and injection is a few megapascals. Null displacement is imposed on the bottom and side boundaries, whereas the top boundary is free to move. Open flow boundaries are imposed on all model boundaries (i.e., constant pressure and temperature).

4.4. Hydraulic and mechanical properties and *in situ* stress field

1 The hydraulic properties for the NTR and the caprock are equivalent to those used in Rutqvist et
2 al. (2013) and are parameter values originally derived from standard reservoir models of The
3 Geysers geothermal field. On the other hand, the hydraulic properties of the HTR and the shear
4 zones were estimated during a sensitivity analysis by using multiphase fluid flow analysis with
5 TOUGH2 and the EOS3 fluid equation of state (Pruess et al., 2011). Permeability and porosity
6 were estimated in Jeanne et al. (2014c) by matching the monitored well-head pressure variations
7 in three wells around the injection well: PS31, P38, and P25 (Fig. 6). The mechanical properties
8 were estimated by a back-analysis using TOUGH-FLAC (Jeanne et al., 2014b). The values of the
9 Young's dynamic modulus of the rock mass ($E = 25$ GPa) and the fault zones ($E = 15$ GPa) were
10 back-calculated by fitting the calculated ground-surface deformations with displacement time
11 series from satellite measurement at points located just around the injection well (Fig. 7, Jeanne
12 et al., c).

13 The linear thermal expansion coefficient of the rock is set to $1 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$, corresponding to values
14 determined from core samples of the reservoir rock at high (250°C) temperature (Mossop and
15 Segall 1997). The thermal expansion does not significantly impact the surface uplift, but has a
16 profound impact on the stress field around the injection well. In the simulation, an initial *in situ*
17 stress regime was imposed consistent with the dominant crustal transtensional stress regime at
18 The Geysers (Oppenheimer, 1986; Stark, 2003). Studies of earthquake focal plane mechanisms
19 indicate that the maximum principal horizontal stress ($S_{H\max}$) is oriented N020E (Boyle et al.,
20 2013) and is approximately equal to lithostatic (or vertical) stress S_v (Boyle et al., 2013;
21 Oppenheimer, 1986). Here, we made the hypothesis that $S_{H\max} = 0.9 \times S_v$. To estimate the value
22 of the least principal horizontal stress ($S_{H\min}$) we performed sensitivity analyses to match the
23 fault mechanical elasto-plastic response with observed induced seismicity (Jeanne et al., 2014c).

The best fit was obtained with $S_{Hmin} = 0.341 \times S_v$. The ratio between S_v/S_{Hmin} is equal to 2.93, very close to the value of q (≈ 3.12 ; Eq. 1). This means that the rock mass is initially in a stress-state close to shear failure, and small perturbations of the stress field can reactivate a fracture. These initial stress conditions are consistent with previous studies, where the concept of a critically stressed rock mass at The Geysers was successfully applied (Rutqvist and Oldenburg, 2008; Rutqvist et al., 2013), and dates back to rock-mechanical studies conducted in the early 1980s (Lockner et al., 1982).

5. Comparison between seismic tomography and THM modeling

5.1. Extension of the EGS

To better characterize the EGS development, we have calculated and built several contour maps of V_P (Fig. 8a and b) and V_S (Fig. 8c and d) changes from t_{0d} to t_{60d} ($\Delta V_{P\ t60d}$ and $\Delta V_{S\ t60d}$). These results can be compared with maps showing the microseismic event density (Fig. 8e and 8f) as described below, and the pressure variations estimated from the THM modeling (Fig. 8g and 8h) at two different depths ($Z2 = -1995\text{m}$ and $Z4 = -2565\text{m}$ below sea level) after 60 days of injection at P32. To build the contour maps of the microseismic event density we have selected two 500 m thick horizontal slices centered on $Z2$ and $Z4$. Then, within the EGS area (black square in Fig. 8a), these slices were divided into bins with dimensions equal to 50×50 m. In each bin we have counted the number of seismic events occurring during the 60 days of injection evaluated in this study.

After 2 months of injection, a significant low-velocity anomaly appeared around the injection zone, with the highest reduction in V_P and V_S reached at $Z2 = -1995$ m depth: -0.7 km.s^{-1} and -

0.9 km.s⁻¹, respectively. This low-velocity anomaly is elongated along the northwest-southeast direction (Fig. 8a to 8d), suggesting a strong influence of the more permeable shear zones trending N130. Similarly, at Z4 = -2565m, changes in V_P and V_S seem to be spreading also in the northeast-southwest direction indicating some impact of the N050 shear zones (Fig. 8b and 8d). The maps of the seismic density and the pressure distribution after 60 days of injection depict similar characteristics. Microseismic events seem to occur along the N130 and N050 shear zones (Fig. 8e), which have a significant impact on the pressure distribution around the P32 injection well (Fig. 8g). Moreover, it seems that the most seismically active area and the area of the highest pressure variations coincide with the zone of low seismic velocity.

Figure 9 presents vertical cross sections along shear zone S5 shown in Figure 2a (N130 direction) of $\Delta V_{P \text{ t60d}}$ and $\Delta V_{S \text{ t60d}}$ (Fig. 9a and b), the microseismic event density (Fig. 9c), and changes in pressure (Fig. 9d), temperature (Fig. 9e) and liquid saturation (Fig. 9f). Similar observations to those noted previously in Figure 8 can be made: a low-velocity anomaly appears around the injection zone where significant microseismic activity is recorded and where the estimated pressure increase is significant. Moreover, significant cooling occurs just around injection well and this is also the zone of the highest pressure increase and part of the zone of most significant seismic velocity reduction. From these observations it seems that near the injection well cooling and pressure changes may both contribute to induce shear reactivation and degradation of mechanical rock mass properties, whereas away from the injection well, injection-induced changes in steam pressure may be sufficient to cause shear activation and mechanical degradation.

5.2. Mechanisms responsible for the drop in seismic velocity

For a more detailed investigation of the mechanisms involved in the EGS creation and in the apparent degradation of the reservoir mechanical properties, we focus our analysis on a small part of the EGS. On the vertical cross sections presented in Figure 3a, b, c and Figure 4 a, b, c where the highest V_P and V_S variations were observed, we have selected six points at each depth from Z1 to Z4. For example, Figure 8a, which is view map of $\Delta V_{P\ t60}$ at Z1, show the location of the six points (i.e. black diamonds). This corresponds to a total of 24 points (Fig. 9a). For each points, we have calculated the changes in V_P and V_S from t_{0d} to t_{30d} ($\Delta V_{P\ t30d}$ and $\Delta V_{S\ t30d}$) and from t_{0d} to t_{60d} ($\Delta V_{P\ t60d}$ and $\Delta V_{S\ t60d}$). Then, in our THM model, we have selected 24 points located along shear zone S5, where the highest changes in pressure and temperature were calculated (black diamonds on Fig. 8g). These 24 points (Fig. 9d) are approximately located at the same depth as the 24 points selected on the seismic tomography (Fig. 9a). For each point, we calculated the variation in pressure (ΔP), temperature (ΔT) and effective stress ratio (σ'_1/σ'_3) after 30 and 60 days of injection.

Figure 10 presents changes in seismic velocity (ΔV_P and ΔV_S), and effective stress ratio (σ'_1/σ'_3) as a function of pressure variations (ΔP) at four different depths (Z1 to Z4) and at t_{30d} and t_{60d} . Generally, the pressure increase results in a decrease in both the maximum and minimum principal effective stresses (σ'_1 and σ'_3), leading to an increase in the σ'_1/σ'_3 ratio, which eventually reaches the failure criterion ($\sigma'_1 \approx 3.12 \times \sigma'_3$) (Fig. 10), signifying reactivation along pre-existing fractures. The pressure increase needed to reactivate the preexisting fractures increases with depth: from 0.7 to 1.4 MPa over the depth interval of -1710m to -2565m. One significant observation from Fig. 10 is a close correlation between calculated shear failure and decreases in S wave velocity. At locations where pressure is sufficiently high to exceed the

threshold for shear activation, there is a decrease in V_s which keeps decreasing with the increase in fluid pressure. Changes in V_p occurred from a higher fluid pressure and seem not be directly related to the reactivation of the preexisting fractures. We also note that in few places (at Z1 for $\Delta P = 1.2$ MPa; at Z2 for $\Delta P = 2.4$ MPa; at Z3 for $\Delta P > 2.9$ MPa; and at Z4 for $\Delta P = 1.7$ MPa) the σ'_1/σ'_3 ratio rebounds to lower values when the changes in fluid pressure increases to high values, e.g. 2 to 3 MPa. This reason for this rebound in stress ratio is described in Jeanne et al (2014c). In essence, the fluid injection rate and increased fluid pressure causes reservoir expansion that leads to the propagation of mechanical stress through the reservoir, which tends to decrease the σ_1/σ_3 ratio.

To characterize the impact of temperature variations (ΔT) on the changes in seismic velocity we have investigated the relationship between ΔP and ΔV_p (Fig.11a) and between ΔP and ΔV_s (Fig.11b) and how this relationship is affected by temperature variation. In Fig. 11, points where temperature changes occurred during the THM simulation are highlighted by red circles and labeled with the drop in temperature. Figure 11a shows a linear relationship between ΔP and ΔV_p from a threshold value close to 1.6 MPa. From the few data points where cooling occurred we cannot see a clear trend of the ΔT effect on the relation between ΔP and ΔV_p .

The relationship between ΔP and ΔV_s is more complex. As seen previously in Figure 10, change in V_s occurs when pressure is sufficiently high to exceed the threshold for shear activation. This threshold value varies according to the state of stress and therefore according to the depth (from 0.7 to 1.4 MPa over the depth interval of -1710m to -2565m) (Fig.10). Because of this complexity, points on the Figure 11b plot, ΔP versus ΔV_s , are more scattered than in Figure 11a. However, the general trend in Figure 11b is that the greatest ΔV_s are obtained in the upper part of the injection zone (between -1710 to -1995m: red squares and green diamonds with ΔV_s between

-0.2 to -0.9 km/s) and the smallest ΔV_S is obtained deeper (between -2280 to -2565m: orange triangles and blue circles with ΔV_S between 0 to -0.2 km/s). ΔV_S seems also be influenced by ΔT ; the highest drop in V_S are obtained where the highest drop in estimated temperature occurred. As can be observed in Figure 9e, the highest temperature drop occurs just around the injection well and this cooling also coincides with the liquid zone formed adjacent to the injection well (Figure 9f).

6. Discussion and Conclusion

From Equations 3 and 4, we have calculated the dynamic shear modulus and Young modulus at t_{0d} , t_{30d} and t_{60d} (Fig.12). Figure 12 shows a progressive decrease of the elasto-dynamic mechanical properties around the injection zone, and a slight increase of the mechanical properties below the injection zone.

The increase in Young's dynamic modulus, E , below the P32 injection well (at $z = -3350\text{m}$) is very slight: from 63 to 69 GPa. It might be an artifact, because at this depth, the resolution is not good. We also note that, as expected, the Young's dynamic modulus calculated from seismic velocities is significantly higher than the static Young's modulus applied in the THM model to calculate shear failure and match the surface uplift shown in Fig. 7. Around the injection zone, as the rock mass is critically stressed, small variations in steam pressure trigger microseisms by shear reactivation along the preexisting fractures. This shearing could result in a modification of roughness and frictional characteristics of the joint walls. There is a progressive failure of intact segments (referred to as rock bridges) along the joints and mechanical abrasion of the joint walls due to shear displacement could result in a decrease of the rock mass shear modulus. One of the consequences is a decrease in V_S . This decrease in S wave velocity depends on the evolution of

1 σ'_1/σ'_3 and on the temperature variations. The injection of cold water results in thermal
2 contraction around the well where the highest reduction in shear modulus are observed.

3 With the reactivation of preexisting fractures, the rock mass can generally become progressively
4 more fractured and so more deformable facilitating reservoir expansion caused by the pressure
5 increase. This expansion causes a progressive increase in fracture porosity resulting in a decrease
6 in V_p , which can explain the linear relationship between ΔV_p and ΔP obtained in our analysis.

7 8 **Acknowledgments**

9 This work was conducted with funding provided by the Assistant Secretary for Energy
10 Efficiency and Renewable Energy, Geothermal Technologies Program, of the U.S. Department
11 under the U.S. Department of Energy Contract No. DE-AC02-05CH11231. Calpine Corporation
12 provided funding to the EGS Demonstration Project under a separate DOE contract.

13 **Reference**

- 14 Biot, M. A. (1941), General theory of three-dimensional consolidation, J. Appl. Phys., 12, 155–
15 164, doi:10.1063/1.1712886.
- 16 Boitnott, G. N. and B. P. Bonner, Characterization of rock for constraining reservoir scale
17 tomography at the Geysers geothermal field, in press, Proceedings of the Stanford Workshop
18 on Geothermal Reservoir Engineering, 1994.
- 19 Boyle, K., Zoback, M., 2013. Stress and fracture orientation in the northwest Geysers geothermal
20 field. Proceedings of the 38th workshop on geothermal reservoir engineering, Stanford
21 University, Stanford, California, February 11-13, 2013.

- 1 Byerlee, J. D. (1978), Friction of rocks, *Pure Appl. Geophys.*, 116, 615– 626,
2 doi:10.1007/BF00876528.
- 3 Cappa, F. (2009), Modelling fluid transfer and slip in a fault zone when integrating
4 heterogeneous hydromechanical characteristics in its internal structure, *Geophys. J. Int.*, 178,
5 1357–1362, doi:10.1111/j.1365-246X.2009.04291.x.
- 6 Cappa, F. & Rutqvist, J., 2011a. Impact of CO₂ geological sequestration on the nucleation of
7 earthquakes. *Geophys. Res. Lett.*, **38**, L17313, doi:10.1029/2011GL048487.
- 8 Cappa, F. & Rutqvist, J., 2011b. Modeling of coupled deformation and permeability evolution
9 during fault reactivation induced by deep underground injection of CO₂, *Int. J. Greenhouse*
10 *Gas Contl.*, **5**, 336–346, doi:10.1016/j.ijggc.2010.08.005.
- 11 Charlty, J., Cuenot, N., Dorbath, C., Dorbath, L., 2006. Tomographic study of the seismic
12 velocity at the Soultz-sous-Forets EGS/HDR site. *Geothermics* 35, 532–543.
- 13 Christensen N. and Wang HF., 1985. The influence of pore pressure and confining pressure on
14 dynamic elastic properties of Berea Sandstone. *Geophysics*, 50: 207–213.
- 15 Darracott, B.W.& Orr, C.M. 1976. Geophysics and rock engineering. Symp. on Exploration for
16 Rock Engineering. Johannesburg 1976. I: 159-164. Cape Town/Rotterdam: Balkema.
- 17 Garcia, J., Walters, M., Beall, J., Hartline, C., Pingol, A., Pistone, S., Wright, M., 2012.
18 Overview of the Northwest Geysers EGS demonstration project. *Proceedings*, 37th
19 Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California,
20 Jan. 30-Feb. 1, 2012.
- 21 Hutchings, L., Bonner, B., Singh, A., Jarpe, S., Philson, H., Boyle, K., 2014 Lawrence Berkeley
22 National Laboratory, Berkeley, California 94720. Submitted Journal Geophysical Research.

1 Micro-earthquake Analysis for Reservoir Properties at an Injection Test at The Geysers,
2 California Geothermal Field.

3 Hutchings, L., Bonner, B., Singh, A., Jarpe, S., Singh, A. Micro-earthquake Analysis for
4 Reservoir Properties at the Prati-32 Injection Test, The Geysers, California. Proceeding,
5 Geothermal Resources Council, August, 2014.

6 Hutchings, Lawrence, Steve Jarpe, Katie Boyle, Gisela Viegas, and Ernest Majer (2011)
7 Inexpensive, Automated Micro-Earthquake Data Collection and Processing System for
8 Rapid, High-Resolution Reservoir Analysis. Geothermal Res. Council, Transactions, 2011
9 Annual Meeting, San Diego, CA.

10 Itasca (2009) FLAC3D, fast Lagrangian analysis of continua in 3 dimensions, version 4.0.
11 Minneapolis, Minnesota, Itasca Consulting Group

12 Jaeger, J. C., and N. G. W. Cook (1979), Fundamentals of Rock Mechanics, 3rd ed., 590 pp.,
13 CRC Press, Boca Raton, Fla.

14 Jeanne, P., Rutqvist, J., Hartline, C., Garcia, J., Dobson, P.F., Walters, M., 2014a. Reservoir
15 structure and properties from geomechanical modeling and microseismicity analyses
16 associated with an Enhanced Geothermal System at The Geysers, California. Geothermics.

17 Jeanne, P., Rutqvist, J., Vasco, D., Garcia, J., Dobson, P.F., Walters, M., Hartline, C., Borgia, A.,
18 2014b. A 3D Hydrogeological and Geomechanical Model of an Enhanced Geothermal
19 System at The Geysers, California. Geothermics, 51 (2014) 240–252.

20 Jeanne, P., Rutqvist, J., Dobson, P.F., Garcia, J., Walters, M., Hartline, C., The Impacts of
21 Mechanical Stress Transfers Caused by Hydromechanical and Thermal Processes on Fault
22 Stability During Hydraulic Stimulation in a Deep Geothermal Reservoir. Int. J rock mech
23 Min Sci, 72 (2014) 149-163.

- 1 King, M. S., 1966, Wave velocities in rocks as a function of overburden pressure and pore fluid
2 saturants: *Geophysics*, 31, 56-73.
- 3 Lockner DA, Summer R, Moore D, Byerlee JD (1982) Laboratory measurements of reservoir
4 rock from the Geysers Geothermal Field, California. *Int J Rock Mech Min Sci* 19:65–80.
- 5 Matzel, E., Templeton, D., Petersson, A., Goebel, M., 2014. Imaging the Newberry EGS Site
6 using Seismic Interferometry. PROCEEDINGS, Thirty-Ninth Workshop on Geothermal
7 Reservoir Engineering Stanford University, Stanford, California, February 24-26, 2014 SGP-
8 TR-202
- 9 Mossop, A., and Segall, P., 1997. Subsidence at The Geysers geothermal field, N. California
10 from a comparison of GPS and leveling surveys. *Geophys. Res. Lett.*, 24, 1839-1842.
- 11 Oppenheimer, D.C. 1986. Extensional tectonics at the Geysers Geothermal Area, California, J.
12 *Geophys. Res.*, 91, 11463–11476.
- 13 Prasad, M., and Manghnani, M. H., 1997, Effects of pore and differential pressure on
14 compressional wave velocity and quality factor in Berea and Michigan sandstones:
15 *Geophysics*, 62, 1163-1176.
- 16 Pruess, K, Oldenburg, Moridis, G. 2011. TOUGH2 User's Guide, Version 2.1, LBNL-
17 43134(revised), Lawrence Berkeley National Laboratory, Berkeley, California.
- 18 Rutqvist, J., Wu, Y-S., Tsang, C-F., Bodvarsson, G., 2002. A modeling approach for analysis of
19 coupled multiphase fluid flow, heat transfer, and deformation in fractured porous rock, *Int. J.*
20 *Rock Mech. Min. Sci.*, 39:429-442.
- 21 Rutqvist, J., J. Birkholzer, F. Cappa, and C.-F. Tsang, 2007. Estimating maximum sustainable
22 injection pressure during geological sequestration of CO₂ using coupled fluid flow and

1 geomechanical fault-slip analysis, *Energy Convers. Manage.*, 48, 1798 – 1807,
2 doi:10.1016/j.enconman.2007.01.021.

3 Rutqvist, J., 2011. Status of the TOUGH-FLAC simulator and recent applications related to
4 coupled fluid flow and crustal deformations. *Comput. & Geosci.* 37: 739-750.

5 Rutqvist, J., Dobson, P.F., Garcia, J., Hartline, C., Jeanne, P., Oldenburg, C.M., Vasco, D.W,
6 Walters, M., 2013. The Northwest Geysers EGS demonstration project, California: Pre-
7 stimulation modeling and interpretation of the stimulation. Mathematical Geosciences, DOI
8 10.1007/s11004-013-9493-y.

9 Rutqvist, J., Oldenburg, C.M. 2008. Analysis of injection-induced micro-earthquakes in a
10 geothermal steam reservoir, Geysers Geothermal Field, California. Proceedings of the 42th
11 U.S. Rock Mechanics Symposium, San Francisco, California, USA, June 29- July 2, 2008:
12 American Rock Mechanics Association, Paper No. 151.

13 Sibson, R. H., and J. V. Rowland (2003), Stress, fluid pressure and structural permeability in
14 seismogenic crust, North Island, New Zealand, *Geophys. J. Int.*, 154, 584–594,
15 doi:10.1046/j.1365-246X.2003.01965.x.

16 Stark, M.A., 2003. Seismic evidence for a long-lived enhanced geothermal system (EGS) in the
17 Northern Geysers Reservoir, *Geothermal Resour. Counc. Transactions*, 27, 727-731.

18 Tarif, P.A., R.H. Wilkens, and C.H. Cheng, 1988. “Laboratory Studies of the Acoustic Properties
19 of Samples From Salton Sea Scientific Drilling Project and Their Relation to Microstructure
20 and Field Measurements.” *J. Geophys. Res.* v. 93, No. B11, p. 13,057–13,067. Tester, J.W. et
21 al., 2006. The future of geothermal energy. Part 1—Summary and Part 2—Full report.
22 Massachusetts Institute of Technology, Cambridge, MA.

1 Tester, J.W. et al., 2006. The future of geothermal energy. Part 1—Summary and Part 2—Full
2 report. Massachusetts Institute of Technology, Cambridge, MA.

3
4 Vasco, D.W., Rutqvist, J., Ferretti, A., Rucci, A., Bellotti, F., Dobson, P., Oldenburg, C., Garcia,
5 J., Walters, M., Hartline, C., 2013. Monitoring deformation at The Geysers geothermal field,
6 California using C-band and X-band Interferometric Synthetic Aperture Radar. Geophysical
7 Research Letters doi: 10.1002/grl.50314.

8 Wyllie, M. R. J., Gregory, A. R., and Gardner, G. H. F., 1958. An experimental investigation of
9 factors affecting elastic wave velocities in porous media: Geophysics. v. 23. p. 459-493.

10
11
12
13
14 **Figure captions:**

15 **Figure 1:** The study area defined by the blue box and seismic instrument locations shown in
16 white are permanent LBNL network stations; yellow are temporary DOE monitoring sites; and,
17 red are supplementary seismic instruments installed by LBNL for the Prati-32 test. Only
18 instruments located within the study area were used for the tomography.

19 **Figure 2:** Comparison between the study area where the Northwest Geysers EGS Demonstration
20 Project is performed and the geometric configuration of the 3D model. (a) Structural map with
21 the well locations P25, PS31, P32 and P38 (Jeanne et al., submitted), and the measured points

monitored by satellite survey (three black stars), (b) plan view of the model geometry. Three dimensional view of the wells (c) in the field and (d) in the model.

Figure 3: Evolution of the P-wave seismic velocity around the EGS area. Vertical seismic profiles oriented NW-SW with the injection well P32, at (a) t_0 , (b) t_{30} and (c) t_{60} . Horizontal seismic profiles at t_0 , t_{30} and t_{60} at (d, e and f) -1995m and at (g, h and i) -2565m below sea level. On figure (a) and (d), the black points represent the tomography grid and the black arrows show where the vertical and horizontal cross sections were performed.

Figure 4: Evolution of the S-wave seismic velocity around the EGS area. Vertical seismic profiles oriented NW-SW with the injection well P32, at (a) t_0 , (b) t_{30} and (c) t_{60} . Horizontal seismic profiles at t_0 , t_{30} and t_{60} at (d, e and f) -1995m and at (g, h and i) -2565m below sea level. On figure (a) and (d), the black points represent the tomography grid and the black arrows show where the vertical and horizontal cross sections were performed.

Figure 5: Three dimensional numerical grid with (a) material layers and (b) fault zone network

Figure 6(a) Evolution of the injection rate and of the simulated well head pressure in P32 (Jeanne et al. submitted). Comparison between the pressure evolutions measured in situ in wells (b) PS31, (c) P38 and (d) P25 with the calculated pressure evolution. Note that the pressure monitoring for P25 was limited to the time before the well was placed into production.

Figure 7: Comparison between the evolution of the calculated vertical displacement with the surface displacement time-series measured by satellite in three points, at locations shown Fig. 2a (Jeanne et al., submitted).

Figure 8: Comparison, around the EGS area and after 60 days of injection, between : (a and b) View maps of $\Delta V_{P \ t60}$, (c and d) $\Delta V_{S \ t60}$ at -1995m and -2565m below sea level, of the

microseismic density (e) from -1745 to -2245 m and (f) from -2815 to -2315 m below sea level, and between changes in pressure at (g) -1995m and (h) -2565m below sea level. Diamonds on (a) and (g) show the points used to compare the seismic velocity and our model.

Figure 9: Vertical cross section oriented NW-SE of (a) $\Delta V_{P\ 160}$, (b) $\Delta V_{S\ 160}$, (c) the microseismic density, changes in (d) pressure, in (e) temperature and in (f) liquid saturation along the shear zone F5 after 60 days of injection. Location of the 24 points shown as squares, diamonds, triangles and circles used in figure 10 and 11 are presented on (a) and (d).

Figure 10 : Comparison between changes in V_P calculated at t_{30} and t_{60} with changes in the σ'_1/σ'_3 ratio estimated during the THM simulation at t_{30} and t_{60} at (a) Z1 = -1710 m, (c) Z2 = -1995 m, (e) Z3 = -2280m and (g) Z4 = -2565m shown in Figure 5. Comparison between changes in V_S calculated at t_{30} and t_{60} with changes in the σ'_1/σ'_3 ratio estimated during the THM simulation at t_{30} and t_{60} at (b) Z1 = -1710 m, (d) Z1 = -1995 m, (f) Z3 = -2280m and (h) Z4 = -2565m. Comparison are performed between 24 points belonging to the tomography grid present along the vertical cross section shown in Figure 9a and 9b with 24 points located in our geomechanical model along the shear zone S5 (Fig.2b).

Figure 11: Relationship between (a) ΔV_P and ΔP and between (b) (a) ΔV_S and ΔP . Describe the red circles and temperature here (as in the text) so that the figure stands alone.

Figure 12: Evolution at t_0 , t_{30} and t_{60} of the rock mass (a, c and e) shear modulus and (b, d and f) dynamic Young modulus.

ΔV_p (km/s)

ΔV_s (km/s)