The Impacts of Mechanical Stress Transfers Caused by Hydromechanical and Thermal Processes on Fault Stability during Hydraulic Stimulation in a Deep Geothermal Reservoir

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Abstract

We performed a series of 3D thermo-hydro-mechanical (THM) simulations to study the influences of hydromechanical and thermal processes on the development of an enhanced geothermal system, strongly influenced by a network of short fault zones. The model we developed was calibrated by comparing the simulated THM responses to field observations, including ground-surface deformations, well pressure, and microseismic activity. Of particular importance was the comparison between the observed temporal and spatial distribution of microseismic activity, and the calculated shear reactivation of preexisting fractures inferred from simulated elasto-plastic mechanical responses in the short fault zone. Using this approach, we could identify when fault zones were reactivated (as manifested in the field by a surge of local microseismic activity within the fault zone), and we could back-calculate the *in situ* stress field as being close to the stress conditions required for shear reactivation. Our results show that the main mechanisms of inducing seismicity are related to injection-induced pressure increase and cooling. During injection, the reservoir expansion caused by the pressure increase led to mechanical stress transfer through the reservoir, which prevented or delayed the reactivation of preexisting fractures. After injection stopped, there was an inversion of the mechanical stress transfers that favored shear reactivation, which may explain why microseismic activity occurred after the cessation of the injection.

1. Introduction

Economic geothermal energy production requires a fractured rock mass that has sufficiently high permeability, fracture density, and fractured surface area to act as an efficient heat exchanger. If the permeability is too low, the fracture network may be stimulated to enhance its permeability, a method being employed in enhanced geothermal systems (EGS) [1]. One strategy for creating an EGS is to increase permeability by shear reactivation of existing fractures in high temperature rocks through water injection at a low rate. However, this process may be accompanied by an increase in microseismic activity. It is important to understand the mechanisms that induce such microseismicity, because such knowledge can help to improve reservoir development and management [2].

It is widely accepted that microseismicity in geothermal systems results from stress perturbations caused by hydromechanical and thermal processes. During hydromechanical stimulation, the overpressure causes a reduction of effective stresses along preexisting fractures that may reactivate in shear [3] and [4]. Moreover, the injection of cold water in a hot reservoir induces thermal stresses [5] that can significantly affect the *in situ* stress state [6].

The thermoelastic effects within geothermal systems have been a central topic of some previous studies. Most of these studies have been focused on the perturbations generated within a single fracture or adjacent to a fracture surface [7],[8] [9] and [10]. The thermoelastic effects on the rock within and surrounding a fracture zone have also been analyzed by De Simone et al (2013) [11]. They performed 2D coupled thermo-hydro-mechanical (THM) and hydro-mechanical (HM) simulations and their results show that thermal effects induce a significant temperature-induced thermal stress perturbation in the surrounding intact rock. Inside the fracture, the results of THM and HM simulations were similar and depict a more stable condition. These studies were focused on the area where the temperature drop occurred. To our best knowledge, the propagation of such thermoelastic effects inside a fracture or fault network, and the shear activation associated with such thermoelastic effects, have not been investigated.

In this paper, we present three-dimensional THM and HM numerical simulations to study the mechanisms of induced seismicity within a geothermal reservoir, and specifically the role of mechanical stress transfer caused by hydro- and thermo-mechanical stress perturbations due to the injection of cold water. Modeling assumptions are based on the results of previous modeling of the Northwest Geysers EGS Demonstration Project in California [4], [12] and [13]. At The

Geysers, we first used the data collected during a one-year injection program to calibrate the hydraulic and mechanical properties of the reservoir and the *in situ* stress tensor. To estimate the impact of the thermal effects, we compared the results of the THM simulations to those of the HM simulations; then, we conducted a sensitivity analysis on the initial stress conditions. Specifically, we investigated the link between the direction of the maximum horizontal stress, the propagation of mechanical stress transfer within the reservoir, and the reactivation of fractures along fault zones.

2. Construction of the Numerical Model

2.1 Numerical analysis method

We use the coupled THM simulator TOUGHFLAC, which is described in [14] and [15], and previously applied to study fault reactivation related to multiphase fluid flow and crustal deformations [16], [17], [18] and [19]. The TOUGH-FLAC numerical simulator has the required capabilities for modeling of nonisothermal, multiphase flow processes coupled with stress changes in a steam-dominated geothermal reservoir. TOUGH-FLAC links the TOUGH2 (finite volume) multiphase flow and heat transport simulator [20], and the FLAC3D (finite-difference) geomechanical code [21].

We simulate the rock mass as an equivalent continuum with implicit representation of fractures, whereas fault zones are explicitly represented as 15 m wide zones with different hydraulic and mechanical properties. The rock mass behaves as an elastic material, whereas faults are governed by an elastoplastic constitutive law. Fault zones are envisioned to include an intensively fractured damage zone, under the assumption that fractures of any orientation could exist (Fig.1). Such an assumption is supported by studies of fault-plane analysis of seismicity at The Geysers by [22] which indicate that seismic sources occur from almost randomly oriented fracture planes [23]. Under this assumption, the isotropic Mohr–Coulomb criterion can be used to describe maximum and minimum compressive effective stresses. Shear reactivation will occur when the 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 [24] showed that the limiting ratio of maximum principal effective compressive stress, $\sigma'_1 = \sigma_1 - \alpha P_f$ (where P_f is the fluid pressure

and α is Biot's coefficient (here, $\alpha=1$) [25]), and the minimum principal effective compressive stress at depth, $\sigma'_3 = \sigma_3 - \alpha P_f$, is given by:

$$\frac{\sigma_1}{\sigma_3} \leq q = [(1 + \mu^2) + \mu]^2 \quad (1)$$

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 tectonic fault zones and maximum shear stress [26] and [27]. The isotropic Mohr-Coulomb model do not consider a fault-frictional weakening and hardening law, so we cannot simulate the seismic cycle made of (1) a seismic phase including a fast rupture associated with seismicity and a large drop of fault friction, and (2) an interseismic phase where aseismic deformation (creep processes) is followed by healing processes [28]. So, with this the current approach, it is not possible to quantify seismic versus aseismic slip during the failure. However, when the failure starts we consider that detectable seismicity is induced.

2.2. Model geometry

A 3D numerical model was developed to represent the study area of the Northwest Geysers EGS Demonstration Project. The geometric configuration of shear zone network and the wells in this area are shown in Fig. 2. The numerical model extends vertically from 0 to 6500 m in depth and 20×12 km horizontally (Fig. 2). This model consists of four layers: a graywacke-dominated caprock, a normal temperature (240°C) reservoir (NTR), underlain by a high temperature zone (HTZ) (with measured values up to 400°C) in the hornfelsic biotite metagraywacke ("hornfels"), and finally, a granitic intrusive ("felsite") layer [29] (Fig. 2a). The shear zone network is composed of three northeast-striking (N050) shear zones and eight northwest striking (N140) shear zones spaced from 150 to 200 m apart (Fig.2b). The small difference between the shear zone orientation observed in the field (N130) and in the model (N140) is a result of geometrical model simplifications. Our mesh is made of bricks and we can only make a 90 degree angle between the two shear zone families N050 and N130. This shear zone network belongs to the Riedel system and form within the regional strike-slip fault zone system of the North Coast Ranges (Fig. 3a and 3b). The term *shear zone* is generally used to include discontinuous faults of limited extent, transtensional faults, shear zones, and Riedel shears. In this paper, we use the term *fault zones* to describe these shears zones.

The simulated wells each consist of two sections (Fig. 3f). For the cased portions 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 well bores, the simulated wells are curved to have the same trajectory as that of the wells in the field (Fig. 3e). 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 into the deep portions of the wells at 90°C in the model.

2.3. 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 [4]. As in [4] 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 value than the measured 400 °C was used because it is the upper temperature limit of the TOUGH module used.) At The Geysers, the steam pressure within the hydraulically confined NTR has gradually decreased with steam production since the 1960s, and is today a few megapascals (≈ 2 MPa); thus, the initial reservoir pressure in the model simulations uses this value as a starting point ($=1.9$ MPa). Null displacement was imposed on the bottom and side boundaries, whereas the top boundary is free to move. Open flow boundaries were imposed on all model boundaries (i.e., constant pressure and temperature).

2.4. Hydraulic and mechanical properties

The hydromechanical properties for the NTR and the caprock are equivalent to those used in [4] and are parameter values originally derived from standard reservoir models of The Geysers geothermal field. On the other hand, the hydraulic properties of the HTZ, the felsite and the fault zones were estimated during a sensitivity analysis by using the EOS3 module of TOUGH2 [20]. The hydromechanical properties are given in Table 1. Permeability and porosity were estimated by matching the monitored well-head pressure variations in three wells around the injection well: PS31, P38, and P25 (Fig. 4). These field data are the same as those used and presented in [12], but they have been extended to cover a longer period (600 days instead of 300

days of monitoring). The estimated hydromechanical properties using the extended data set are very close to those derived by [12]. Slight differences in the estimated hydraulic properties were found, because here the simulated pressure variations are calculated at the surface, whereas in the previous studies the simulated pressure variations were calculated downhole, at about 3 km depth.

In this study, the permeability and porosity values assigned to a number of the rock types and faults in the model were lowered relative to [12] to reproduce the observed well-head pressure variations. Estimated host rock permeability in the HTZ is $1 \times 10^{-16} \text{ m}^2$. The N140 fault zones have estimated permeability values ranging between $2.65 \times 10^{-13} \text{ m}^2$ and $6 \times 10^{-16} \text{ m}^2$ (Table 2). The lowest estimated permeability value was obtained for fault zones F7 and F8 ($6 \times 10^{-16} \text{ m}^2$) and the highest estimated permeability values were obtained for F1 to F6 ($k = 3.0 \times 10^{-15}$ to $2.65 \times 10^{-13} \text{ m}^2$). The permeability values estimated for the N050 fault zones (Fig. 2c) “Fa” and “Fb” was $5 \times 10^{-15} \text{ m}^2$. For fault zone Fc, the permeability was equal to 10^{-20} m^2 . This very low permeability is necessary to match the slight pressure response in P38 to injection in P32. Moreover some of the N140 trending fault zones needed to cut Fc without being affected by the permeability decrease in this area [12]. The estimated porosities were low in the host rock (2%) and the N050 fault zones (1%), and higher (3%) along the N140 fault zones.

Figure 5 shows the calculated pressure and temperature distributions after 270 days of injection. The map views at 3550 m depth (Fig. 5a and 5b) show that the calculated fluid diffusion and temperature variations occurred mainly in the N140 direction, which represent the axis of highest permeability. At this depth, the injection well intersects fault zone F6, where the highest pressure and temperature variations are observed (Fig. 5c and 5d). After 270 days and along F6, the pressure increased by up to 5 MPa and the temperature decreased by 190°C relative to the initial rock temperature.

The mechanical properties were estimated by performing a sensitivity analysis using TOUGH-FLAC. The values of the Young’s modulus of the rock mass ($E = 28 \text{ GPa}$) and the fault zones ($E = 15 \text{ GPa}$) were back-calculated by fitting the calculated ground-surface deformations at three points with displacement time series from satellite measurements (Fig. 6, [12]). These three points are located at the surface near the injection well, P-32 (Fig.3c). The Young’s modulus of the rock mass is roughly a factor of 2 higher than that back-calculated in [12], because permeability and porosity were lowered in this study. The lower permeability and

porosity results in a higher pressure increase, which induced more poroelastic deformations of the reservoir leading to larger expansion and a higher uplift around the P32 injection well. To balance this increased vertical reservoir expansion and to achieve a good agreement with measured uplift, we had to increase the Young's modulus. The linear thermal expansion coefficient of the rock was set to $1 \times 10^{-5} \text{ }^{\circ}\text{C}^{-1}$, corresponding to values determined from core samples of the reservoir rock at high (250°C) temperature [5]. The thermal expansion does not significantly impact the surface uplift, but has a profound impact on the stress field around the injection well.

In our simulation, an initial *in situ* stress regime was imposed consistent with the dominant crustal transtensional stress regime at The Geysers [22, 30]. Studies of earthquake focal plane mechanisms in the Northwest Geysers indicate that the maximum principal horizontal stress (S_{Hmax}) is oriented N020E [31] and is approximately equal to lithostatic (or vertical) stress S_v [22] and [31]. Here, we made the hypothesis that $S_{Hmax} = 0.9S_v$.

To estimate the value of the least principal horizontal stress (S_{Hmin}) we performed a sensitivity analyses to match the calculated fault mechanical elasto-plastic response with the observed induced seismicity. In a previous work [13] a detailed study of the daily spatial appearance of seismic events after the beginning of the injection was conducted to understand the evolution of microseismicity distribution and to highlight the main fluid paths. In this way, [13] it was possible to identify several fault zones affecting the EGS area. In this study, we have estimated the evolution of the number of microseismic events per day occurring along six fault zones, F2 through F7 (Fig. 7). A strong increase of this daily number is considered to be the signature of the fault reactivation (see Table 2). The few isolated microseismic events occurring before injection at P-32 began can be interpreted as the movement of individual critically stressed fractures.

In our current model, we compared, for six faults, the number of days calculated and observed between the beginning of P-32 injection and their initial microseismic activity (Table 2). In the field, we considered that induced movement along a fault began when a surge in microseismicity occurred along the fault zone. In the model, we considered that the microseismicity is induced along the fault zones when shear failure starts for the first time. Note that microseismic activity along the fault zones can be associated with movement of small fractures intersecting the fault zone or being part of the fault zone architecture. Similarly, the

calculated shear failure using the isotropic Mohr-Coulomb model could be associated with shear failure along fractures of any orientation (Fig.1). The THM behavior of each fault zone was monitored by control points located where the highest pressure changes occurred within each 15 meter-wide fault zone (Fig. 5). We did not attempt to make an exact match between calculated and observed fault-zone movement, but rather tried to obtain a reasonable agreement in the general response of the fault-zone network.

THM behavior of the fault zones is very sensitive to the S_{Hmin} / S_v ratio. A slight variation of this ratio from 0.339 to 0.043 can delay the reactivation for almost 3 months (127 days). The best fit between the calculated fault mechanical elasto-plastic response and the observed induced seismicity was obtained with $S_{Hmin} = 0.341S_v$ (Table 2). 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 cause a fracture to move. These initial stress conditions are consistent with previous studies, where the concept of a critically stressed rock mass at The Geysers has been successfully applied [4] and [32], and dates back to rock mechanics studies conducted in the early 1980s [33].

3. Base-Case Modeling Results

We first present some base-case modeling results for the calibrated model, focusing on timing and propagation of the shear activation of fractures and deformations in the fault system. Again, our conceptual model of the fault zones are 15 m wide fractured rock zones that are likely more intensively fractured than the surrounding host rock. We use an isotropic Mohr-Coulomb model, meaning that shear failure could take place in individual fractures within the fracture zone, and that those fractures are not necessarily oriented along the strike of the fracture zones (Fig.1). Large-scale shear failure in the fracture zones would likely result in softening and enhanced inelastic deformations, which to a large extent might be aseismic.

3.1 Timing and propagation of the rupture

In this section, we study the impact of THM coupling on the microseismicity of pre-existing fractures along fault zones, and compare the results to an HM simulation. We only present results obtained at three control points located on three fault zones: F8, where no significant temperature change is observed; F4, where temperature change occurred after 74 days of injection; and F6, where temperature change occurred after a few hours of injection. The

points for monitoring the calculated evolution in F6 and F8 are both located at 3550 m depth, and horizontally 1 m and 340 m respectively from the bottom of the injection well (Fig. 5d) The monitoring point in F4 is located at 2800 m depth and horizontally 100 m from the injection zone (Fig. 5d).

In the model simulation, microseismic activity along F8 begins after 157 days of injection (Fig. 8a). The pressure increase in this fault (Fig. 8b) leads to a decrease in both the maximum and minimum principal effective stresses (σ'_1 and σ'_3), and the σ'_1/σ'_3 ratio reach the failure criterion ($\sigma'_1 = 3.12\sigma'_3$) after 157 days. From that moment, the shear reactivation keeps propagating along the fracture zone, and shear stress is relieved by a decrease in σ'_1 (Fig. 8c). The pressure increase also causes reservoir expansion, creating poroelastic compressive stress that is transferred inside the reservoir. Such compressive stress results in an increase in both σ_1 and σ_3 , which has the effect of decreasing the σ_1/σ_3 ratio, which in turn will tend to delay rupture (Fig. 8d). On the other hand, after the end of the injection (at $t=320$ d), the reservoir stops expanding and starts to contract, leading to an inversion of these hydromechanical effects. The σ_1/σ_3 ratio increases, and despite the pressure decrease, σ'_1 remains equal to $3.12\sigma'_3$ (on the failure line), and the rock keeps yielding microseismic events for an additional three months after shut-in (up to $t=410$ d).

Microseismicity along F4 begins 24 days after the start of injection at P-32 (Fig. 8e); microseismicity is caused by the pressure increase within the 15 meter-wide fault zone (Fig. 7f), leading to a decrease in both σ'_1 and σ'_3 . The temperature starts to decrease when liquid water reaches this point after 74 days of injection (Fig. 8f), from 285°C at $t = 74$ d to 260°C at $t = 108$ d. The cooling causes a contraction of the reservoir, which has a strong impact on the stress state. At $t = 108$ days, σ_1 and σ_3 have decreased by 7.5 MPa and 2.2 MPa, respectively. These thermomechanical effects are stronger in the σ_1 direction than in the σ_3 direction, so the σ_1/σ_3 ratio decreases (Fig. 8h). After 108 days of injection, the decrease in the σ_1/σ_3 ratio is so significant that σ'_1 becomes lower than $3.12\sigma'_3$ and the microseismicity stops (Fig. 8e). From $t=144$ d, the rate of decrease in σ_3 exceeds that of σ_1 , and the σ_1/σ_3 ratio starts to increase. F4 evolves again toward a critical state, and at $t=282$ d, F4 once more becomes microseismically active. The stress is released, σ_1 decreases, and the σ_1/σ_3 ratio increases more slowly (Fig. 8h). At the end of injection at P-32, the pressure decreases, the σ_1/σ_3 ratio stays constant, and the microseismicity stops.

Microseismicity along F6 begins a few hours after the beginning of injection at P-32 (Fig. 8i). Both the stress released during the rupture and the thermomechanical effects cause a strong decrease in σ_1 . The σ_1/σ_3 ratio decreases from 2.9 to 2.3 during the first 150 days. Then, the ratio stabilizes around 2.3 until the end of injection. This stabilization occurs because, as observed in F4, after some time the thermomechanical effects have a stronger influence on σ_3 than on σ_1 . Despite the decrease in the σ_1/σ_3 ratio, during the entire injection period, σ'_1 remains close to $3.12\sigma'_3$ and the microseismicity progresses (Fig. 8i). At the end of injection, both the pressure drop and the decrease in the σ_1/σ_3 ratio terminate the microseismicity. After 320 days of injection, the temperature drops from 370°C to 160°C and the pressure increases to 7.8 MPa (Fig. 8j).

We conducted a separate HM simulation for comparison to the full THM model simulation results. Here, we present results exclusively obtained at two control points located on the fault zones: a point within F8, where no temperature change was observed, and within F4, where a sharp temperature drop occurred after 74 days of injection. The control points in the HM simulations are the same as in the THM simulation. Away from the P-32 injection zone (F8), the injection-induced changes in σ_1 and σ_3 are smaller in the THM simulation than in the HM simulation (Fig. 9a and b). These stress changes are related to the reservoir expansion and transfer of compressive stress to farther distances. Reservoir expansion and stress changes are smaller in the THM simulation, as a result of the cooling contraction of the rock around the injection zone. As seen previously, such mechanical stress transfer tends to reduce the σ_1/σ_3 ratio and thereby tends to keep the local stress state away from failure. Consequently, the σ_1/σ_3 ratio decreases less (Fig. 9c), and the rupture occurs sooner in the THM simulation than in the HM simulation (Fig. 9d). This phenomenon of earlier reactivation when thermal effects are considered is observed for all the fault zones (Table 3). The calculated displacements are very small (<1 mm) (Fig. 9e). There is a competition between the compressive stress normal to the fault zone, caused by reservoir expansion, and the pressure increase inside the fault zone which tends to open it. At approximately 600 m from the injection (F8), the effect of the mechanical stress transfer is predominant, so before the rupture, there is a closure of the fault zone (up to 0.6 mm) and small shear displacements (up to 0.2 mm). When the rupture starts, some stress is released, the fault zone start to slightly open, and inelastic shear deformations occur (Fig. 9e). In our simulation no self-propping are considered, so no changes in permeability are associated

with the fault displacement. We noticed that the calculated inelastic shear displacements are more than 2 times larger after the injection (0.5 mm over 200 days) than during the injection (0.2 mm over 310 days). The difference between the THM and HM is very small (less than 1mm).

In the THM and HM simulations, the evolution of σ_1 and σ_3 closer to the injection zone (F4) are almost identical during the first 74 days of injection (Fig. 9f and g). The mechanical stress transfers, caused by the reservoir expansion, result in an increase in both σ_1 and σ_3 with a higher stress increase in σ_3 . The σ_1/σ_3 ratio decreases (Fig. 9h), but σ'_1 remains close to $3.12\sigma'_3$ and the rupture continues (Fig. 9i). During this period, displacements are characterized by a slight opening caused by a pressure increase inside the fault zone and by a small shear displacement (Fig. 9j). In the HM simulation, the state of stress evolves according to the pressure evolution, and the rupture stops when the injection rate is reduced (Fig. 9f). The fault opening also follows the pressure evolution, and shear displacements reaches a maximum of 1 mm after 60 days when the injection rate increases (Fig. 9j). In the THM simulation, the thermomechanical effects strongly influence the stress state, whereas the rupture is less dependent on the injection rate. The rupture stops earlier than in the HM simulation, and then restarts after seven months. The temperature drops during the period from 74 to 108 days (Fig. 8f), causing cooling shrinkage of the rock, leading to a closure of the fault zone (up to 8 mm). Both normal and shear displacements are strongly related to the stress evolution (Fig. 9j). Shear displacement reached a maximum of 8 mm at the end of the injection.

3.2. Displacements along the fault zones

Figure 10 presents vertical profiles of normal and horizontal shear displacements, and pressure and temperature distribution, along the F6 and F7 fault zones calculated during the THM and HM simulations at five different times (at 10, 50, 100, 200, and 270 days of injection). These vertical profiles contain the control points located within F6 and F7 shown in Fig. 5d. In the HM simulation, the pressure increase inside fault zone F6 causes a slight opening (normal expansion) and horizontal shear displacements both up to 3.1×10^{-3} m. The maximum displacements are reached at 3431 m depth (Fig. 10a and b), where the water is sucked into the fault (Fig. 10e and f) by the collapsing steam bubble (at the Geysers, a vacuum of about 1 bar occurs as water falls into the well bore and collapses the steam bubble in the well bore and reservoir, consequently, injected water is literally sucked into the reservoir). The normal

expansion of the fault is a direct result of the pressure increase over the simulated 15 m thick fault zone. Indeed, for a pressure increase up to 5 MPa, a Young's modulus of 15 GPa, and a thickness of 15 m, a few-millimeter expansion is expected. In the THM simulation, the vertical profiles of displacement along F6 are more complex. The injection of cold water causes a closing (normal compression) of the fault (up to -2.3×10^{-2} m) from 3431 m to 4180 m depth (Fig. 10c). A few centimeters normal compression is expected for a cooling exceeding 100°C , a thickness of 15 m, and a thermal expansion coefficient of $1 \times 10^{-5} \text{ }^\circ\text{C}^{-1}$. In this interval, the horizontal shear displacements are seven times higher than in the HM simulation (up to 2.3×10^{-2} m; Fig. 10d). The thermal-mechanical closing at the center results in a slight normal expansion (opening) of the fault F6 in its upper and lower parts, up to 8.5×10^{-3} and 2.8×10^{-3} m, respectively (Fig. 10c). These openings are very small (on the order of a few millimeters), but still higher or close to the maximum opening calculated in the HM simulation at the injection point. F7 is located at a relatively far distance from the injection well (<200 m), and there is no significant temperature change ($<1^\circ\text{C}$) within this fault zone. Still, for F7, the THM simulation shows a larger opening and shear displacement than in the HM simulation (Fig. 10g and h). The THM simulation shows larger displacement, because even at this far distance, deformations are affected by strain and stress transfer from cooling shrinkage around the injection well.

4. Sensitivity to Initial Stress Condition

Sensitivity to initial stress condition was investigated. We performed five other simulations during which S_{Hmax} was rotated 30 degrees from N020 to N170. In this way, we analyzed the effects of S_{Hmax} orientation on the propagation of mechanical stress transfer through the reservoir, and on the reactivation of preexisting fault zones. To do this, we compared the distribution of the σ_1/σ_3 ratio (Fig. 11) with fault-zone stability during the injection (Table 3). Common to all simulations is a zone of reduced σ_1/σ_3 ratio around the injection well. The reduction in stress ratio in this zone mainly results from the failure that tends to release any shear stress and make the stress field more isotropic, and hence decreases the σ_1/σ_3 ratio.

Figure 11 represents this area for the six THM simulations at 270 days after the beginning of injection. Inside this area, two regions of interest can be distinguished. The first region of interest is located close to the injection well where the highest decrease in the σ_1/σ_3 ratio is observed. Common to all the simulations, this part is elongated in the direction parallel to

the faults where the fluid is injected. We can state that at the beginning of the injection, gravity flow is predominant. As σ_1 is vertical, σ_1 will be strongly influenced by the temperature drop. Then, after some time, the liquid-saturated zone starts to expand laterally in the fault zone, impacting the horizontal constraint. If σ_3 is parallel to the fault direction (S_{Hmax} oriented N050), the reduction in σ_3 will be higher than the reduction in σ_1 . The σ_1/σ_3 ratio will increase, favoring the rupture, as observed in Figure 8h. Conversely, if σ_3 is perpendicular to the fault, σ_1 and the σ_1/σ_3 ratio will continue to decrease. For example, after 270 days of injection, the lowest value of the σ_1/σ_3 ratio (equal to 1.99) is obtained when S_{Hmax} is parallel to the main fluid flow direction (N140), and the highest value ($\sigma_1/\sigma_3 = 2.34$) is obtained when S_{Hmax} is oriented perpendicular to the main fluid-flow direction (N050). These variations influence the stability of the preexisting fault zones where fluid is injected. Figure 12 shows the evolution of the σ'_1/σ'_3 ratio close to the injection point inside the fault F6 when S_{Hmax} is oriented N140 and N050. In these two simulations, F6 is reactivated during the first day of injection due to the pressure increase (Table 3), but depending on the orientation of S_{Hmax} , the rupture may terminate. The same phenomenon is visible along the faults where the temperature drop occurred, i.e., F4 (Fig. 12b) and F5.

The second region is located around the first one. The impact to the second region is caused by hydromechanical effects and is strongly influenced by the orientation of S_{Hmax} . Since the propagation of mechanical stress transfer is anisotropic, the part of the reservoir where the σ_1/σ_3 ratio decreased forms an elongated shape in the σ_3 direction. When σ_3 is parallel to a fault family, the decrease in the σ_1/σ_3 ratio affects only a few faults in this family, while other faults are unaffected and therefore can still be easily reactivated. Inversely, when σ_3 is perpendicular to a fault family, the decrease of the σ_1/σ_3 ratio affects more faults, which become less critically stressed and harder to reactivate. Close to the injection zone, when the N140 faults have the same orientation as σ_3 (S_{Hmax} oriented N050), they are less critically stressed and show delayed reactivation. Such is the case for the faults F4 and F5, which are reactivated after 54 and 26 days with S_{Hmax} oriented N050, against 34 and 1.5 days with S_{Hmax} oriented N140. Farther from the injection zone, N140 faults oriented in the σ_3 direction (F1, F2, F3, F7, and F8) are less influenced by the mechanical stress transfer and reactivate earlier. For example, F8 is reactivated after 67 days of injection with S_{Hmax} oriented N050, and F8 is not reactivated with S_{Hmax} oriented N140. In this case, the mechanical stress transfer reached the fault F8 and prevented the rupture. The exact same phenomenon occurred with the fault family oriented N050.

5. Discussion

5.1. Mechanisms of induced seismicity during the injection

Injection of cold water inside a hot reservoir results in a cooling shrinkage around the well and an overpressure inside the reservoir, reducing the effective stresses. Our simulations suggest that the mechanism of inducing microseismicity is related to injection-induced pressure, and the stress reduction caused by the thermal effect promotes additional displacements along the fault zone during the rupture, therefore increasing the likelihood of microseismic events. The maximum shear displacements in the reservoir are reached at the same depths where the cooling shrinkage occurs along the injection well. Therefore, since shear failure is considered to be the main mechanism for enhancing permeability in an EGS, we can assume that the vertical extension of the EGS into the reservoir will be affected by the vertical extension of the cooling shrinkage along the injection well.

5.2. Impact of the thermomechanical effect on the microseismicity

Thermomechanical processes affecting microseismicity are complex. They cause a cooling-stress reduction, which is higher in the direction of the water flow, e.g., along a permeable fault zone. In our simulations, there was first gravity flow of the injected water, the vertical stress (here σ_1) decreased as a result of cooling contraction, and the σ_1/σ_3 ratio decreased, which tended to delay shear reactivation of preexisting fractures within the fault zone. Then, the liquid zone started to expand laterally, which changed the horizontal stress more than the vertical stress. In general, if σ_3 is parallel to the flow direction, cooling-stress reduction is higher in σ_3 direction, so the σ_1/σ_3 ratio increases, and the fracture network becomes more critically stressed. Conversely if σ_3 is perpendicular to the flow direction, the σ_1/σ_3 ratio keeps decreasing and the fracture network becomes less critically stressed. We can assume that if σ_1 is horizontal (equal to S_{Hmax}) and σ_3 vertical, gravity flow will likely cause a reduction in the vertical stress (σ_1 will be less affected, so the reduction of σ_1/σ_3 ratio will be lower, and the fracture network will stay more critically stressed).

Then, when the liquid zone starts to expand laterally, if σ_3 is parallel to the flow direction, the σ_1/σ_3 ratio will increase faster, leading to rupture. In a reverse faulting stress regime with σ_1 horizontal and σ_3 vertical, the gravity flow of cold water can lead to an increase in the σ_1/σ_3 ratio

and favor rupture. Finally, even if the thermomechanical effects are located close to the injection well, they influence the reactivation of the preexisting fault zone far away. Because the cooling shrinkage reduces the reservoir expansion and mechanical stress transfer, the likelihood of microseismicity decreases.

5.3. Role of mechanical stress transfer in EGS development

During injection, the hydromechanically (poroelastic) induced reservoir expansion generates mechanical stress transfer that plays an important role in fracture stability. In the model simulations, the stress variations caused by the reservoir expansion are higher in the σ_1 direction than in the σ_3 direction, because the stress field moved along the failure line ($3\sigma'_3$). The σ_1/σ_3 ratio decreases and the rock become less critically stressed, which makes it harder to reactivate the fracture network. However, during an EGS project, it is crucial to stimulate the fracture network as much as possible, to enhance reservoir permeability and make geothermal energy production economic.

Our sensitivity analysis shows the importance of considering the initial stress state and the main fluid flow direction in the design and development of an EGS. We also show that the most effective means of stimulating a fracture network composed of wide shear zones is obtained when the primary fluid-flow direction is perpendicular to the principal horizontal stress; in this case, the area subject to mechanical stress transfer (which restricts the stimulation) is also subject to overpressure, which favors shear reactivation. Major questions remain as to how to best locate a site to develop an EGS system. Screening criteria have to be proposed in the exploration process to increase the success rate of geothermal development projects. The relationship between S_{Hmax} and the faults mapped in the field can be one of these criteria.

Finally, it was observed at various geothermal sites: Soultz-sous-Fôret [34], Basel [35] and [36] and Cooper Basin [37], that microseismicity can continue after injection terminates. Indeed, in the post-injection period the vicinity of the injection well remains seismically quiet, whereas seismic activity solely occurs at the outer rim of the zone of previous seismicity. Baisch et al. [37] explained this distribution and evolution of the seismic activity are caused by (1) the Kaiser Effect, where the near well region experienced its peak hydraulic overpressures already during an early stage of the stimulation and therefore remained seismically quiet at later times, and by (2) the propagation of the pressure front away from the wellbore. Our results also suggest

that at the end of injection, the pressure decrease affects the local stress state, which can evolve with time. There can be an inversion of the mechanical stress transfer. Pressure depletion leads to reservoir contraction, with a greater decrease in σ_3 than σ_1 ; the σ_1/σ_3 ratio increases, favoring shear reactivation. This inversion of the mechanical stress transfer caused by hydromechanical effects can also be involved in the occurrence of seismic events after shut-in of the injection well.

6. Conclusion

We have performed a series of 3D thermo-hydro-mechanical simulations to study the influences of hydromechanical and thermal processes on the development of an EGS. Our main results are as follows.

The primary mechanism of induced seismicity at The Geysers is related to injection-induced pressure increase and temperature drop, sufficient to induce detectable microseismic events.

During injection, reservoir expansion, caused by the pressure increase, can lead to the propagation of mechanical stress transfer through the reservoir, which can prevent or delay rupture along preexisting fractures. This phenomenon is in competition with the pressure increase, which is the main mechanism of induced seismicity at The Geysers.

At the end of injection, there is an inversion of the mechanical stress transfer that favors shear reactivation.

Thermal processes lead to stress reduction, which may cause shear reactivation along the fracture network channeling the fluid flow (for example, inside the fault damage zone), depending on the fluid-flow direction and the initial state of stress.

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Figure captions

Figure 1: (a) Illustration of the highly fractured shear zone with randomly oriented fractures, and (b) movements of Mohr's circle as a result of increased fluid pressure within a fracture plane for a critically stressed fracture belonging to the shear zone.

Figure 2: Three dimensional numerical grid with (a) material layers showing the caprock (dark blue), the Normal Temperature Reservoir (NTR, green), the High Temperature Zone (HTZ, blue), the Felsite (red) and (b) fault zone network, only one member of each fault zone set is shown.

Figure 3: Geological setting with: (a) the location of the studied area (white star) in the San Andreas Fault zone system and (b) at The Geysers geothermal field. Comparison between the study area where the Northwest Geysers EGS Demonstration Project is performed and the geometric configuration of the 3D model. (c) Structural map with the well locations P25, PS31, P32 and P38 [12] the measured points monitored by satellite survey (three black stars), the northeast-striking (N050) shear zones Fa, Fb, and Fc, and the northwest-striking shear zones F1 to F8. (d) top view of the model geometry. Three dimensional view of the wells (e) in the field and (f) in the model.

Figure 4: (a) Evolution of the measured and simulated in P32. 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 number of days after P25 was completed and before the well was placed into production.

Figure 5: Map view and vertical cross section oriented N050 of changes in (a & c) pressure and (b & d) temperature at 3556 m depth after 270 days, with the location of the control points (black points) and the fault zones on figure 5a.

Figure 6: Comparison between the evolution of the calculated vertical displacement (solid black line) with the surface displacement (blue squares) time-series measured by satellite in three points (see Fig. 3c).

Figure 7: Evolution of the number of microseismic event by day along the short fault zones (a) F2, (b) F3, (c) F4, (d) F5, (e) F6 and (f) F7 and the relationship of the water injection rates (gpm) of P-32. See Figure 3c for the mapped location of each fault zone and its spatial relationship to the injection well, P-32.

Figure 8: Calculated evolution change in effective principal stress path (a, e and i), fluid pressure and temperature (b, f and j), σ_1 and σ_3 (c, g and k), and the ratios σ_1/σ_3 and σ'_1/σ'_3 at three control points located within the fault zone F8 (at $z = 3550$ m and 1 m from injection well), F4 (at $z = 2800$ m and 100 m from injection well) and F6 (at $z = 3550$ m and 340 m from injection well).

Figure 9: Comparison between THM and HM simulation for the fault F8 and F4: (a and f) evolution of σ_1 , (b and g) evolution of σ_3 , (c and h) evolution of the σ_1/σ_3 ratio, (d and i) evolution of the σ'_1/σ'_3 ratio, and (e and j) evolution of the shear and normal displacement (negative normal displacement is closure). The dotted line represents the end of injection.

Figure 10: Comparison between the vertical profile of the calculated normal and horizontal shear displacements along the fault F6 (a to d) and F7 (e to h).

Figure 11: Distribution of the σ_1/σ_3 ratio for S_{Hmax} equal to (a) N020, (b) N050, (c) N080, (d) N110, (e) N140 and (f) N170.

Figure 12: Influence of S_{Hmax} orientation relative to the fault zone orientation on the rupture (represented by the σ'_1/σ'_3 ratio) and the stress state (represented by the σ_1/σ_3 ratio) evolutions inside two faults: (a) F6 and (b) F4.

Table Headings

Table 1: Materiel properties used during the simulations.

Table 2: Sensitivity analyses on the S_{Hmin} / S_v ratio. Numbers of days between the beginning of the injection and the reactivation of the fault zone. The dashed line means that the fault zone was not reactivated during the 320 days of injection.

Table 3: Numbers of days between the beginning of the injection and the reactivation of the fault zone. The dashed line means that the fault zone was not reactivated during the 320 days of injection.

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Table1

	F1	F2	F3	F4	F5	F6	F7	F8	Fa	Fb	Fc	HTR	FELSITE
Young (GPA)	15	15	15	15	15	15	15	15	15	15	15	28	28
Poison (-)	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Thermal conductivity (W/m°C)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
Th expansion (°C ⁻¹)	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05	1.0E-05
Specific heat (J/kg°C)	880	880	880	880	880	880	880	880	880	880	880	880	880
Friction angle (°)	31	31	31	31	31	31	31	31	31	31	31		
Cohesion (Mpa)	0	0	0	0	0	0	0	0	0	0	0		
Dilation angle (°)	0	0	0	0	0	0	0	0	0	0	0		
Tension (Mpa)	0	0	0	0	0	0	0	0	0	0	0		
Permeability (m/s)	1.0E-14	2.0E-15	3.0E-15	8.0E-14	2.7E-13	1.0E-14	6.0E-16	6.0E-16	5.0E-15	5.0E-15	1.0E-20	1.0E-16	1.0E-16
Porosity (%)	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	1.0	1.0	1.0	2.0	2.0

Table2

<i>σ_1/σ_3</i>	F2	F3	F4	F5	F6	F7
in the field	56	32	24	5	2	56
0.339	37	1	20	7	<1	11
0.34	55	7	22	11	<1	37
0.341	57	27	24	23	<1	55
0.342	62	55	31	61	<1	57
0.343	77	56	39	130	<1	60

Table3

	Faults N140								Faults N050	
	F1	F2	F3	F4	F5	F6	F7	F8	Fa	Fc
in the field		56	32	24	5	2	56			
N020 HM	100	60	28	35	26	<1	56	203	1	-----
N020 THM	87	57	27	24	23	<1	55	157	1	-----
N050	64	37	6	54	26	<1	6.64	67	0.76	-----
N080	76	56	6	37	8.12	<1	7.34	66	0.95	65
N110	152	86	29	34	1.46	<1	27	214	10	24.82
N140	-----	141	55	34	1.36	<1	110	-----	11	27
N170	-----	-----	59	34	1.5	<1	125	-----	5	67