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PRE-STIMULATION COUPLED THM MODELING RELATED TO THE NORTHWEST GEYSERS EGS DEMONSTRATION PROJECT

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ABSTRACT

The Northwest Geyser EGS Demonstration Project aims at creating an Enhanced Geothermal System (EGS) by directly and systematically injecting cool water at relatively low pressure into a known High Temperature (400°C) Zone (HTZ) located under the conventional (240°C) steam reservoir. In this paper we present the results of coupled thermal, hydraulic, and mechanical (THM) modeling made as part of a pre-stimulation project phase. We present modeling of a one year injection campaign for stimulating the reservoir and we compare the predicted extent of the stimulation zone with micro-earthquake (MEQ) monitoring data over the first several months of injection. The results show that, with a calibration of the geomechanical model against historic injection and MEQ data at a nearby well, we were able to make a reasonable prediction of the extent of the stimulation zone, given that the MEQ events are the results of shear activation of pre-existing fractures. Our modeling indicates that the MEQ and shear activation of pre-existing fractures are triggered by the combined effects of injection-induced cooling contraction and small pressure changes in a rock mass that is near-critically stressed for shear failure.

INTRODUCTION

The Geysers geothermal field in California is the site of the largest geothermal electricity generating operation in the world and has been in commercial production since 1960. In a portion of the northwestern part of The Geysers, exploratory drilling in the early 1980's discovered a relatively shallow High Temperature (about 280 to 400°C) Zone (HTZ) in low permeability rock below the Normal Temperature (240°C) steam Reservoir (NTR). The HTZ was originally called the high temperature reservoir (HTR) when it was first described (Walters et al., 1991). A number of steam production wells were drilled, but later abandoned because of problems caused by high concentrations of non-condensable gases (NCG) and highly corrosive hydrogen chloride gas in the steam. As a result, the northwest Geysers, containing a significant portion of the recoverable geothermal energy in The Geysers system, is currently underutilized. In the ongoing Northwest Geysers EGS Demonstration Project (funded by the US Department of Energy's Geothermal Technologies Program and Calpine Corporation), the objective is to develop and demonstrate the technology required to extract energy from this type of low-permeability HTZ that typically underlies any high-temperature geothermal system (Garcia et al., 2012). This project involves opening of some of the abandoned exploration wells and injecting water deep into the HTZ, with the objective to lower the NCG, stimulate fractures, and thereby provide a sustainable amount of usable quality steam for production.

The EGS demonstration project is organized into three phases: Phase I (Pre-Stimulation), Phase II (Stimulation), and Phase III (Monitoring). As a part of the pre-stimulation phase, two of the abandoned exploration wells, Prati 32 (P-32) and Prati State 31 (PS-31) have been reopened, deepened and recompleted as an injection/production pair (Figure 1). The deepened wells partially penetrate the HTZ over a depth ranging from about 3 to 3.5 km at a lateral distance of about 0.5 km from each other. More precisely, the PS-31 was deepened to a measured depth of 3058 m (10,034 ft), corresponding to a vertical depth of 2929 m (9611 ft TVD) below the ground surface, whereas P-32 was deepened to a measured depth of 3396 m (11,143 ft), corresponding to a vertical depth of 3326 m (10912 ft TVD), with the temperature reaching an astonishing 400°C at the base of the well. Apart from the field work associated with the deepening and readiness of the wells, the pre-stimulation project phase also involved site characterization and development of a stimulation plan. The subsequent stimulation phase formally begun on October 6, 2011, with the start of the injection into P-32, using highly treated waste water delivered by the Santa Rosa Geysers Recharge Pipeline (Garcia et al., 2012).

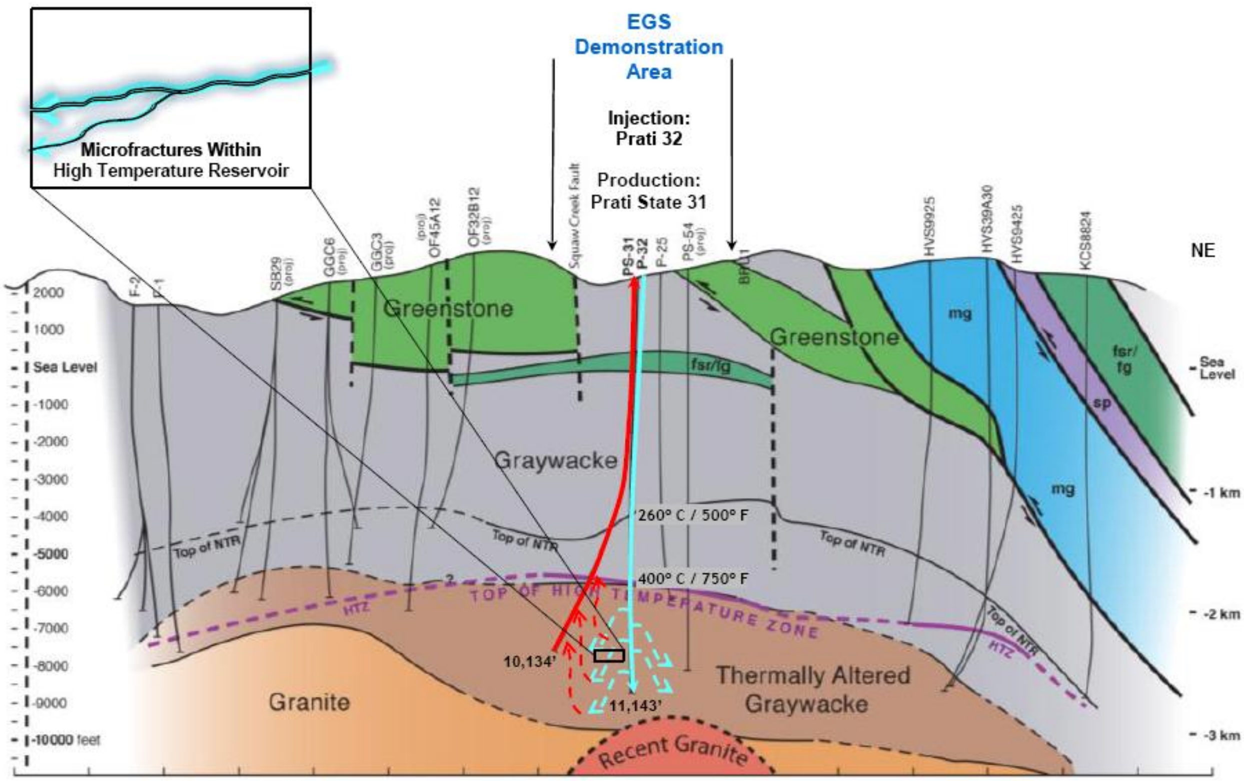


Figure 1: NE-SW geologic cross-section through the NW Geysers including the two wells P-32 and PS-31 that have been reopened for an injection/production pair within the HTZ (Garcia et al., 2012).

In the EGS demonstration project, coupled thermal, hydraulic, and mechanical (THM) modeling is integrated with field monitoring for planning, design and validation of the EGS. As part of this work, the coupled THM modeling is used to (1) gain insight into the underlying cause and mechanisms of MEQs and their potential role in enhancing permeability for the proposed EGS concept, and (2) to investigate injection strategies and effects upon the EGS system. The MEQ activity is monitored by an existing seismic array that was also used to collect background data prior to the injection program. In addition to real time MEQ monitoring and analysis, the field monitoring and data analysis also include (1) 3-D tomography and high-precision location source studies of MEQ, (2) satellite-based measurements of ground surface deformations, and (3) geochemical monitoring and analysis of injection and production fluids. Moreover, the demonstration wells are repeatedly logged with a Pressure-Temperature-Spinner (PTS) tool to evaluate changes in reservoir properties around the injection well (Garcia et al., 2012).

In this paper, we present coupled THM numerical modeling that was conducted as part of the pre-stimulation phase for guiding the stimulation plan. In particular, we present pre-stimulation model predictions of the extent of the stimulation zone and compare them to the observed extent inferred from MEQ monitoring data over the first several months of injection.

MODELING APPROACH

The coupled THM analysis was conducted with TOUGH-FLAC (Rutqvist et al., 2002; Rutqvist 2011), a simulator based on linking the geothermal reservoir simulator TOUGH2 (Pruess et al., 2011) with the geomechanical code FLAC3D (Itasca, 2009). The simulator has the required capabilities for modeling of coupled geomechanical responses under complex multiphase flow and thermal responses within the steam-dominated geothermal system at The Geysers. The application of this simulator to the Northwest Geysers EGS Demonstration Project follows the approach used in a previous Geysers study by Rutqvist and Oldenburg (2007; 2008). The simulation involves modeling The Geysers' reservoir using a continuum approach, in which fractures are represented implicitly using equivalent hydraulic and mechanical properties.

One of the main features of our geomechanical modeling approach is the analysis of injection-induced stress changes and the potential for shear activations of fractures in a rock mass that is critically stressed for shear failure (Figure 2). The concept of a critically stressed rock mass at The Geysers dates back to early 1980s rock-mechanical studies indicating that the reservoir rock has undergone extensive hydrothermal alteration and re-crystallization, and that it is highly fractured (Lockner et al., 1982). Based on laboratory studies, Lockner et al. (1982) suggested that hydrothermal alteration and fracturing has weakened the reservoir rock at The Geysers to such an extent that models of the geothermal field should assume that only a frictional sliding load can be supported by the rock, and that shear stress in the region is probably near the rock-mass frictional strength. Therefore very small perturbations of the stress field could induce seismicity.

We evaluate the potential for shear slip under the conservative assumption that fractures of any orientation could exist anywhere (Figure 2a). Such an assumption is supported by studies of fault plane analysis of seismicity at The Geysers by Oppenheimer (1986), which indicated that seismic sources occur from almost randomly oriented fracture planes. One key parameter in estimating the likelihood of shear activation along a fracture is the coefficient of static friction, μ, entering the Coulomb shear failure criterion. Cohesionless faults are usually assumed to have a friction coefficient of 0.6 to 0.85 and a frictional coefficient of $\mu = 0.6$ is a lower-limit value observed in fractured rock masses associated with shear-enhanced permeability (Barton et al., 1995). Thus, using $\mu = 0.6$ in the Coulomb criterion would most likely give a conservative estimate for triggering seismicity. For $\mu = 0.6$, the Coulomb criterion for the onset of shear failure can be written in the following form:

$$\sigma'_{1c} = 3\sigma'_3 \qquad (1)$$

where σ_{1c} is the critical maximum principal compressive stress for the onset of shear failure. Thus, shear activation would be induced at a point of the rock mass whenever the maximum principal compressive effective stress is three times higher than the minimum principal compressive stress.

Based on the concept of a critically stressed rock mass, the initial stress will be in a state of incipient shear failure (Figure 2b, c and d). By studying how the stress state deviates from this near-critical stress state we determine the likelihood of triggering seismicity depending on whether the changes in the stress state tend to move the system into a state of failure or away from failure. The likelihood of shear reactivation would increase if the change in maximum principal compressive effective stress is more than three times the change in minimum principal effective stress (i.e., $\Delta\sigma'_1 \geq 3\times\Delta\sigma'_3$). Conversely, the likelihood of shear reactivation would decrease if the change in maximum principal compressive effective stress is less than three times the change in minimum principal effective stress (i.e., if $\Delta\sigma'_1 < 3\times\Delta\sigma'_3$).

Considering that the initial stress might not be exactly at the state of critical stress, we may quantify how much the $\Delta\sigma'_1$ has to exceed $3\times\Delta\sigma'_3$ to trigger shear reactivation. We therefore define a stress-to-strength change as $\Delta\sigma'_{1m} = \Delta\sigma'_1 - 3\times\Delta\sigma'_3$, and a critical stress-to-strength change $\Delta\sigma'_{1mc}$ when shear activation would be induced. Thus, the criterion for inducing shear activation would be $\Delta\sigma'_{1m} \geq \Delta\sigma'_{1mc}$. In this study, we quantified $\Delta\sigma'_{1mc}$ by model calibration against historic injection and MEQ data from the Aidlin 11 well, located in the northwest Geysers, a few km from the EGS demonstration area (Rutqvist et al., 2010).

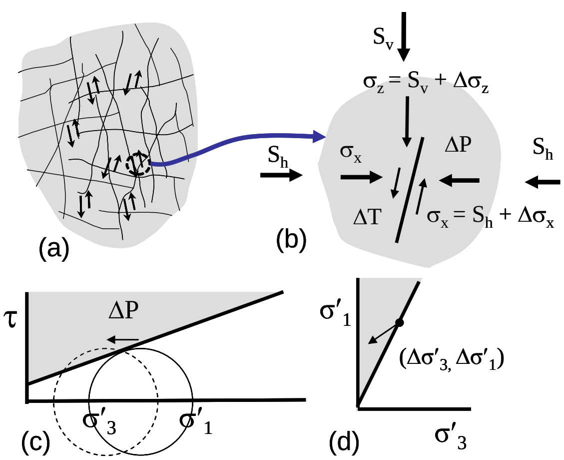


Figure 2: Illustration of the approach for failure analysis to evaluate the potential for induced seismicity at The Geysers: (a) Highly fractured rock with randomly oriented fractures, (b) changes in stress on one fracture plane, (c) movements of Mohr's circle as a result of increased fluid pressure within a fracture plane for a critically stressed fracture, and (d) corresponding stress path in the (σ'1, σ'3) plane.

PRE-STIMULATION MODEL OF THE EGS DEMONSTRATION AREA

In this initial model simulation to estimate the extent of the stimulation zone, we use a simplified, but yet representative geologic model of the field (Figure 3). For example, we extend geological layers horizontally to model boundaries and we assume perfectly vertical wells. This simplified model is sufficient for making a first order estimate of the temporal and spatial extent of the stimulation zone, corresponding to the zone of highest density of MEQ events. In the model the vertical wells are located at a horizontal distance of about 500 m N-S from each other and partially penetrate the hornfelsic graywacke ("hornfels") and the HTZ which extends downward into a granitic intrusion ("felsite").

The initial thermal and hydrological conditions (vertical distributions of temperature, pressure and liquid saturation) were established through a steady-state multiphase flow simulation. In this pre-stimulation modeling, the initial reservoir temperature in the NTR is about 240°C down to a depth of about 3.5 km and then gradually increases up to 370°C towards the bottom boundary at a depth of 6 km. Note that the temperature at depth in this pre-stimulation modeling is somewhat cooler then the very high temperature of 400°C that was encountered at the bottom of the P-32 well (the TOUGH module used is limited to temperatures below the critical point). A relatively low permeability of the HTZ below the NTR can be inferred from steep thermal gradients (~180°C/km) measured within the HTZ, which indicate a lack of heat convection and the dominance of conductive heat flow. At The Geysers, the steam pressure within the hydraulically confined NTR has gradually decreased with the steam production since the 1960s and is today a few megapascals; thus the initial reservoir pressure in our model simulations is a few megapascals.

Table 1 presents the input properties of the main geological units. The permeability values represent fracture permeability taken from Calpine's reservoir model and are several orders of magnitude higher than matrix permeability measured on core samples from the field. The elastic properties are equivalent to those used by Rutqvist and Oldenburg (2007; 2008), which are also effective large-scale rock mass properties, back-calculated from modeling calibration against observed depletion-induced subsidence of The Geysers field (Rutqvist and Oldenburg, 2007).

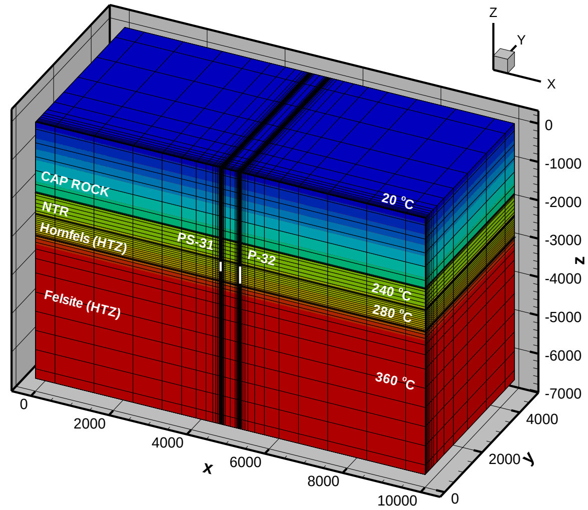


Figure 3: 3-D numerical grid for the pre-stimulation modeling of the Northwest Geysers EGS Demonstration Project with material layers and contours of initial temperature.

Table 1. Rock properties for modeling of the initial injection at the Northwest Geysers EGS Demonstration Project.

	Graywacke (NTR)	Hornfels (HTZ)	Felsite (HTZ)
Permeability (m^2)	5×10^{-14}	2×10^{-14}	1×10^{-15}
Porosity (-)	0.015	0.01	0.01
Thermal Cond. (W/(m°C))	3.2	3.2	3.2
Specific heat (J/(kg°C))	1000	1000	1000
Bulk Modulus (GPa)	3.3	3.3	3.3
Shear Modulus (GPa)	2	2	2
Thermal expansion coefficient (°C^{-1})	1×10^{-5}	1×10^{-5}	1×10^{-5}

As mentioned, we calibrated the critical stress-to-strength change $\Delta\sigma'_{1mc}$ by analyzing and modeling historic injection and MEQ data at the Aidlin 11 injection well, located about 5 km to the west of the new EGS demonstration area (Rutqvist et al., 2010). At Aidlin 11, the injection takes place at a depth of 3.5 km near the NTR/HTZ interface. A detailed MEQ analysis of Aidlin 11 injection was published in Majer and Peterson (2007), which is the data used in our model calibration. The actual model calibration, which is presented in detail in Rutqvist et al. (2010), showed that high MEQ density around the well corresponds to a zone with a stress-to-strength change of 1.5 MPa or higher. Hence, we estimated the critical stress-to-strength change to $\Delta\sigma'_{1mc}$ = 1.5 MPa.

MODEL PREDICTIONS OF STIMULATION EXTENT AT PS-31 AND P-32

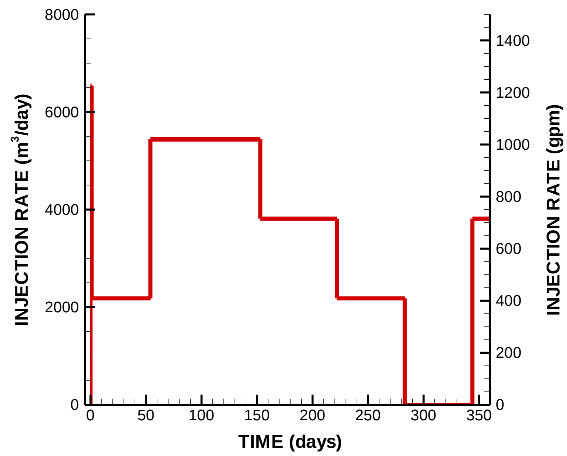
In the pre-stimulation modeling we estimated the expected injection-induced EGS volume (equivalent to the volume of relatively high density of MEQ events) for a number of injection scenarios. This was done using the same THM model with the same THM material parameters, as well as the back-calculated critical stress-to-strength change that will be used to predict the extent of the stimulation at the new EGS demonstration area.

Figure 4 presents modeling results of well pressure for the injection into P-32 following the injection scheme defined in the final stimulation plan. First there is an initial 24-hour period of relatively high-rate injection of 1200 gpm (gallons per minute) that is necessary to collapse the steam bubble in the well bore and nearby formation so that relatively lower sustained rates of liquid water injection are drawn into the fractured reservoir rock under vacuum. Thereafter, the injection consists of steps of increasing and decreasing rates. The simulated maximum bottom-hole pressure during these steps is less than 8 MPa in P-32 (Figure 4b). At this depth the least compressive stress magnitude may be bounded to be at least 24 MPa, using a conservative frictional strength limit of the rock mass. Thus, the predicted maximum bottom-hole pressure of 8 MPa is much less than the least principal compressive stress and therefore far below the fluid pressure that would be required for creating new hydraulic fractures. Thus, by injecting at a low pressure we avoid propagating a single hydraulic fracture, instead aiming at creating a more pervasive stimulation zone by dilating a network of pre-existing fractures though shear reactivation.

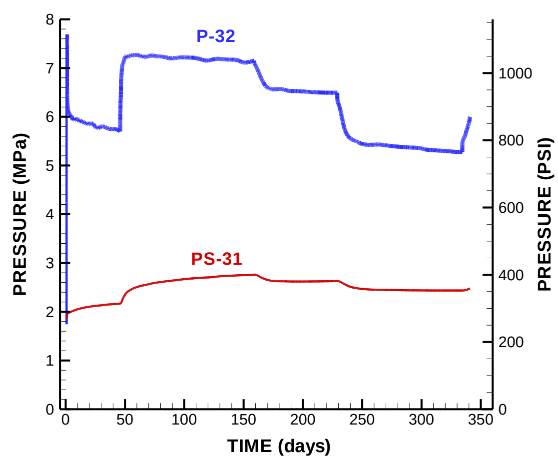
Figure 5 shows predicted changes in pressure and temperature after 3 months (90 days) of injection, while Figure 6 shows predicted changes in stress parameters and MEQ potential in the form of the calculated stress-to-strength change. At 90 days, the injection rate is the highest at about 1000 gpm. Despite the injection rate being the highest, the pressure increase around the injection well is only a few megapascals (Figure 5a). At the same time, substantial cooling is observed below the injection well, which coincides with a zone of liquid water from the injection (Figure 5b).

Figure 6c shows the MEQ potential in terms of stress-to-strength change ($\Delta\sigma'_{1m.}$) after 90 days of injection. Recall that the critical stress-to-strength change was estimated to $\Delta\sigma'_{1mc}$ = 1.5 MPa through back-analysis by modeling the nearby Aidlin 11 injection well. A $\Delta\sigma'_{1m}$ = 1.5 MPa or higher corresponds to the blue contour in Figure 6c, which is therefore the predicted extent of the stimulation zone.

In Figure 6c, the blue contour extends about 0.5 km from the P-32 injection well, barely reaching the PS-31 well. However, modeling of the continued injection beyond 90 days shows the zone of high MEQ density would continue to grow to encompass the PS-31 well before the end of the 1 year injection campaign.



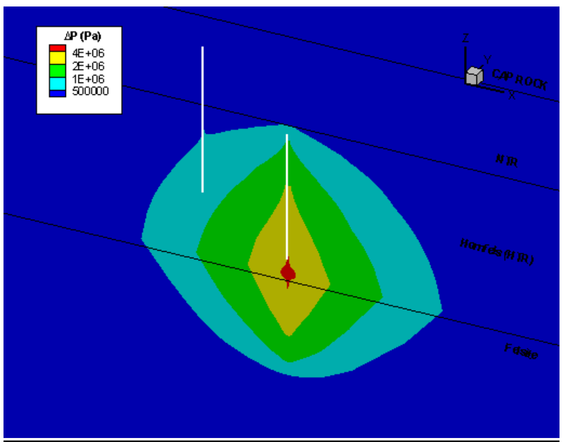
(a)



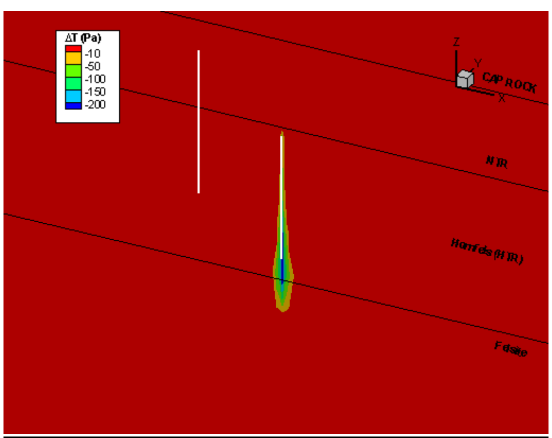
(b)

Figure 4: Injection rates (a) and calculated downhole pressure evolution (b) for the proposed injection schedule.

A closer examination at the simulation results in Figure 6 indicates that reduction in effective stress, with unloading of pre-existing fractures and associated loss of shear resistance would be the mechanism leading to shear reactivation. This is illustrated by the similarity in the shape of high potential MEQ zone in Figure 6c and the zone of reduced effective stress in Figure 6a. We also see that this reduction in effective stress correlates with the zone of a pressure increase of more than 1 MPa in Figure 5a. Moreover, from comparison of Figures 6b and 5b we observe that high shear stress is developed close to the zone of cooling around and below the injection well. This indicates that the injection-induced cooling is important for triggering seismicity close to the injection well and around the liquid water zone. Away from the well, on the other hand, injection-induced changes in the steam pressure appear to be the dominant cause for triggering shear reactivation.

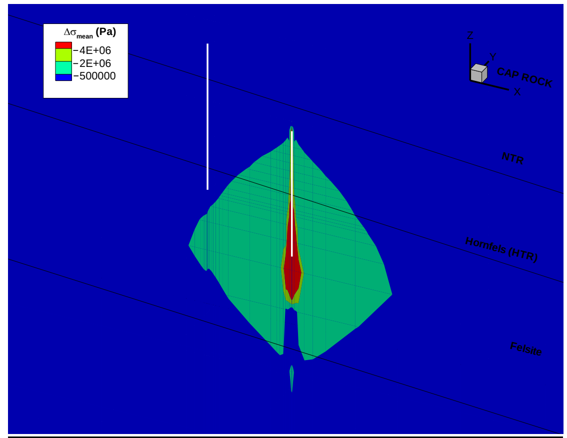


(a)

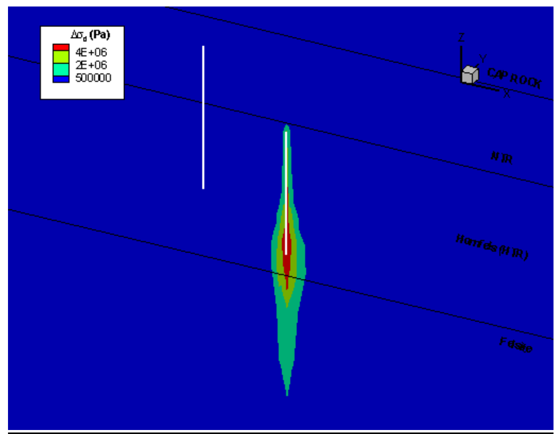


(b)

Figure 5: Calculated changes in (a) fluid pressure, and (b) temperature after 90 days of injection.



(a)



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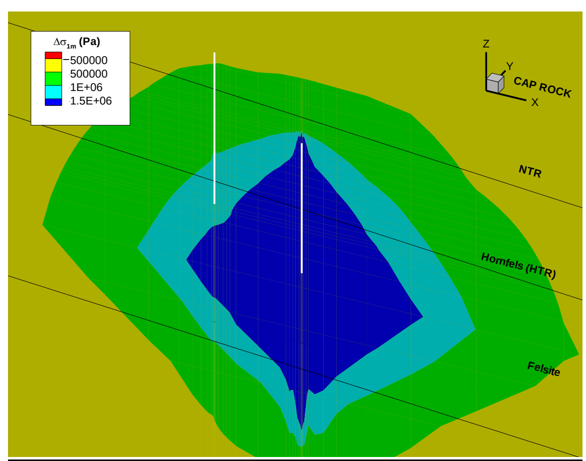

(c)

Figure 6: Calculated changes in (a) effective mean compressive stress, (b) shear stress, and (c) MEQ potential in terms of stress-to-strength margin.

COMPARISON TO MEQ DATA

We compare our predicted extent of the stimulation zone with MEQ data recorded by a dedicated seismic array deployed at The Geysers. The seismic array consists of 34 three-component short-period stations with a sampling frequency of 500 Hz (Majer and Peterson, 2007). In addition, a number of temporary stations have been located around the EGS demonstration area.

Figure 7 and 8 show comparison of the predicted extent of the stimulation zone and observed MEQ events around the P-32 injection well. Recall that the blue contour of the simulated MEQ potential represents the predicted zone of the highest likelihood of MEQ and therefore the expected zone of a high density MEQ activity that we can define as the simulation zone. In Figure 7 and 8 we observe a good qualitative agreement between the predicted and observed extent of the stimulation zone. In Figure 8, the stimulation zone of relatively high MEQ density barely reaches the PS-31 well after about 3 months, but expand more during the continued injection.

Figure 7 and 8 show MEQ data that include all recorded events during the first 3 months of injection. All these events plotted on a projection appear to form a cloud of MEQ events without showing any apparent geological structures around the injection well. However, a more detailed analysis of the MEQ time evolution shows that MEQ events appear to initially propagate along discrete major fractures, some of which are connected to the well at observed steam entries. Such major fractures, faults and more detailed 3D representation of the geology will be considered in future model simulations of the site.

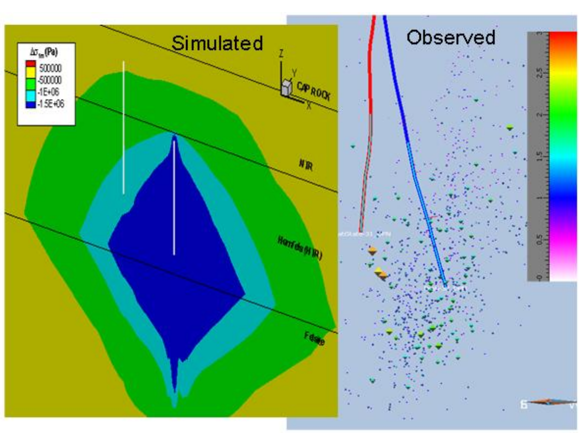

Figure 7: Comparison of simulated (predicted) MEQ potential (left) and observed locations of MEQ events (right) during the first 3 months of injection.

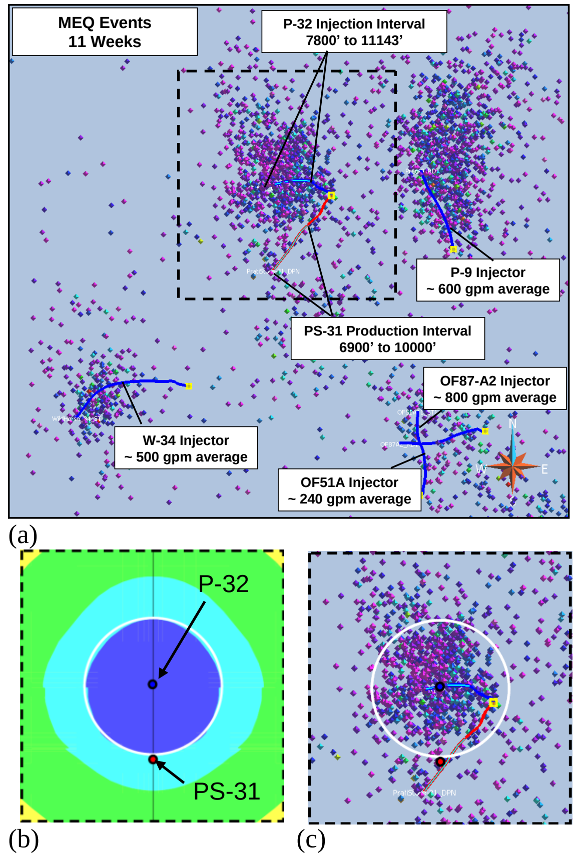

Figure 8: Comparison of predicted MEQ potential with observed locations of MEQ events within the first 3 months of injection. (a) Observed MEQ events around the EGS demonstration area during 75 days of injection. (b) Predicted MEQ potential in which the blue contour represents the expected extent of the stimulation zone. (c) Observed MEQ events around P-32 injection well.

CONCLUDING REMARKS

We have conducted coupled thermal, hydraulic, and mechanical (THM) modeling of deep water injection at the Northwest Geysers EGS Demonstration Project, California. The numerical modeling was conducted as part of a pre-stimulation project phase as a guide for planning the stimulation of the EGS. In particular, the pre-stimulation modeling aimed at predicting the injection-induced spatial extent, or volume, of shear-enhanced fracture permeability and the associated zone of MEQ activity around the wells. The results show that, with a calibration of the geomechanical model against historic injection and MEQ data at a nearby well, we were able to make a reasonable prediction of the extent of the stimulation zone, given that the MEQ events are the results of shear activation of pre-existing fractures. Our modeling indicates that the MEQ and shear activation of pre-existing fractures are caused by the combined effects of injection-induced cooling contraction and small pressure changes in a rock mass that is near-critically stressed for shear failure. A closer examination of the daily MEQ evolution suggests that MEQs initially propagate along discrete major fractures, some which are connected to the injection well at observed steam entries. Such effects are currently being studied in refined model analyses that include more detailed representation of geology and the local fracture system.

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