Predicting the Spatial Extent of Injection-Induced Zones of Enhanced Permeability at the Northwest Geysers EGS Demonstration Project

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ABSTRACT: We present the results of coupled thermal, hydraulic, and mechanical (THM) modeling of a proposed stimulation injection associated with an Enhanced Geothermal System (EGS) demonstration project at the northwest part of The Geysers geothermal field, California. The project aims at creating an EGS by directly and systematically injecting cool water at relatively low pressure into a known High Temperature (about 280 to 350°C) Zone (HTZ) located under the conventional (240°C) steam reservoir at depths below 3 km. Accurate micro-earthquake monitoring from the start of the injection will be used as a tool for tracking the development of the EGS. We first analyzed historic injection and micro-earthquake data from an injection well (Aidlin 11), located about 3 miles to the west of the new EGS demonstration area. Thereafter, we used the same modeling approach to predict the likely extent of the zone of enhanced permeability for a proposed initial injection in two wells (Prati State 31 and Prati 32) at the new EGS demonstration area. Our modeling indicates that the proposed injection scheme will provide additional steam production in the area by creating a zone of permeability enhancement extending about 0.5 km from each injection well which will connect to the overlying conventional steam reservoir.

1. INTRODUCTION

The Geysers is the site of the largest geothermal electricity generating operation in the world and has been in commercial production since 1960. It is a vapor dominated geothermal reservoir system, which is hydraulically confined by low permeability rock units. As a result of the high steam withdrawal rates, the reservoir pressure declined until the mid 1990s, when increasing water injection rates resulted in a stabilization of the steam reservoir pressure. If The Geysers were produced without simultaneously injecting water, reservoir pressures and flow rates from production wells would decline fairly rapidly to uneconomical levels.

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 350°C) Zone (HTZ) in low permeability rock below the Normal Temperature (240°C) steam Reservoir (NTR). 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 result, the Northwest Geysers, which contains 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 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.

One of the motivations for the project is the ample evidence that a large EGS was inadvertently created in the late 1970's below the oldest production area in the central part of The Geysers when injected water reached the HTZ several kilometers below the deepest wells [1]. Micro-earthquake (MEQ) and geochemical monitoring of this EGS area indicated on-going reactivation of fractures in the HTZ, and a temporal correlation of sustained steam production and lower NCG concentration since injection of wastewater from the Santa Rosa Geysers Recharge Project began in 2003. If a similar type of EGS can be created and successfully demonstrated at the Northwest Geysers, then large untapped resources can be utilized with the potential to increase the production of geothermal energy at The Geysers.

The Northwest Geysers EGS Demonstration Project is currently in a pre-stimulation phase to develop a site geological model and plan for the initial injection and monitoring. Fig. 1 shows a NW-SE geologic cross section through the area. The plan is to inject cool water in two wells (Prati State 31 and Prati 32) that partially penetrate the HTZ at a depth of about 3 km and at a lateral distance of about 0.5 km from each other (Fig. 1). The microseismic activity will be monitored by an existing seismic array that will also be used to collect background data prior to the first moment of injection. Closely monitoring the spatial and temporal evolution of the microseismic activity serves as an effective method of remotely sensing the development of the enhanced fracture volume, and may provide a future constraint on the conceptual model.

Coupled thermal, fluid flow, and geomechanical modeling integrated with field monitoring will be used for planning, design, and validation of the effects of the injection on the system (Fig. 2). The modeling will be supported and corroborated by field monitoring and data analysis. Specifically, the coupled fluid flow and geomechanical modeling will be used to (1) gain insight into the underlying 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.

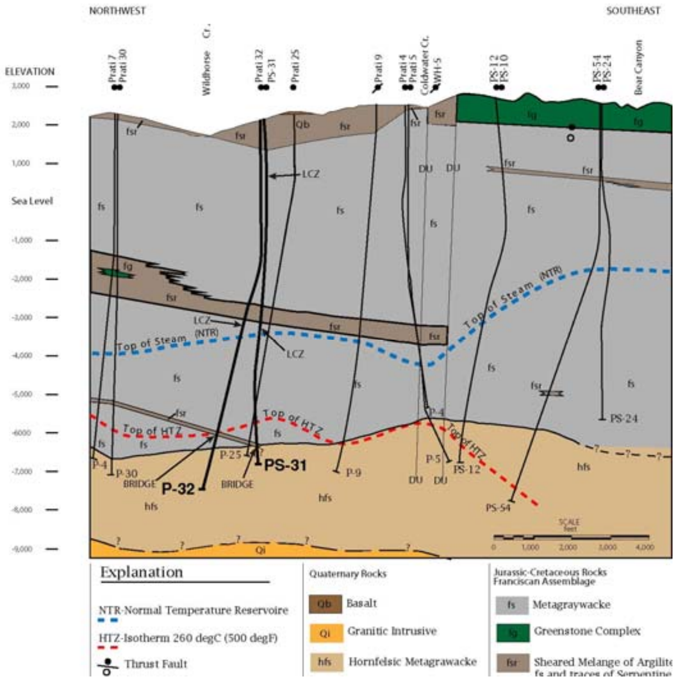


Fig. 1. NW-SE geologic cross-section through the NW Geysers including the two wells P-32 and PS-31 that will be reopened for injection directly into the HTZ.

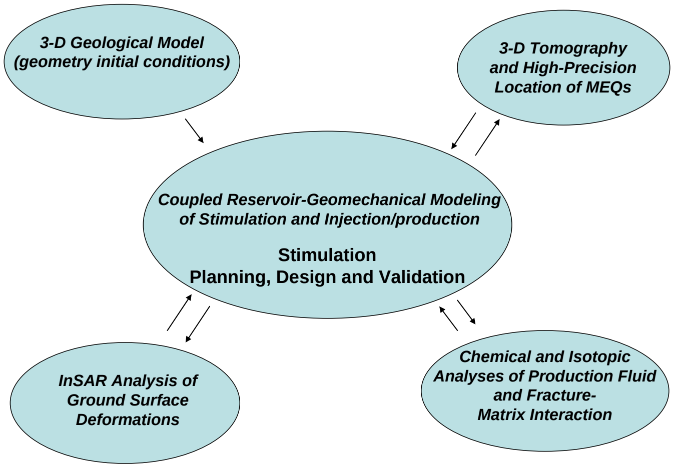


Fig. 2. Coupled THM modeling integrated with field monitoring associated with the Northwest Geysers EGS Demonstration Project.

The field monitoring and data analysis will focus on 3-D tomography and high-precision location source studies of MEQ, satellite based measurements of surface deformations, and geochemical monitoring analysis of injection and production fluids. These technologies are promising for monitoring and validation of the proposed EGS because they are expected to capture important changes in the geothermal reservoir away from an injection well, which includes changes in rock mass mechanical properties (as reflected by changes in sonic velocities) and exposure of new fracture surfaces (as reflected in changes in the chemical signature of the produced steam). In addition to these tools, Calpine will also repeatedly log the demonstration wells with its own Pressure-Temperature-Spinner (PTS) tool during pre-stimulation, stimulation and long-term monitoring phases.

In this paper, we present the initial coupled thermal-hydrological-mechanical (THM) numerical modeling of the proposed initial injection. We emphasize that the planned initial injection is not traditional hydraulic fracturing or fracture stimulation by fluid pressurization, but instead involves the injection of relatively cool water under low pressure directly into the hot fractured rock mass. The modeling aims at predicting the injection-induced spatial extent, or volume, of shear-enhanced fracture permeability and the associated zone of MEQ activity around the injection wells. We build upon a modeling approach developed by Rutqvist and Oldenburg [2, 3] to study how different aspects of injection contribute to the cause and mechanisms of seismicity at The Geysers. Here we extend this approach to quantitatively estimate the temporal and spatial extent of the MEQ zone around active injection wells.

In the paper, we first present the modeling approach and discuss the basic THM input parameters. We then present modeling of historic injection and MEQ activity at an existing injection well (Aidlin 11), located at the Northwest Geysers about 3 miles to the west of the new EGS demonstration area. The purpose of the Aidlin 11 modeling is to quantify a stress change criterion that defines the spatial extent of the zone of shear enhanced permeability and MEQ activity around an injection well at the Northwest Geysers. Finally, we present model simulation results of the proposed initial injection at the PS-31 and P-32 well pair for the new EGS demonstration area.

2. MODELING APPROACH

The coupled THM analysis was conducted with TOUGH-FLAC [4], a simulator based on linking the geothermal reservoir simulator TOUGH2 [5] with the geomechanical code FLAC^{3D} [6]. The simulator has the required capabilities for modeling of non-isothermal, multiphase flow processes coupled with stress changes induced by temperature and fluid pressure. The application of this simulator to the Northwest Geysers EGS Demonstration Project follows the approach used by Rutqvist and Oldenburg [2, 3].

One of the main features of our mechanical model is the analysis of stress path and the potential for shear reactivations of fractures in a rock mass that is critically stressed for shear failure (Fig. 3). The concept of a critically stressed rock mass at The Geysers arose from early rock-mechanical studies of Geysers samples that indicated that the rock has undergone extensive hydrothermal alteration and re-crystallization, and that it is highly fractured [7]. Lockner et al. [7] suggested that fracturing has weakened the rock 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 the authors maintained that shear stress in the region is probably near the rock-mass frictional strengths. Therefore very small perturbations of the stress field could induce seismicity. Based on the concept of a critically stressed rock mass, one of the main mechanisms we investigate at The Geysers is shear failure along existing fractures caused by small perturbations in the stress state.

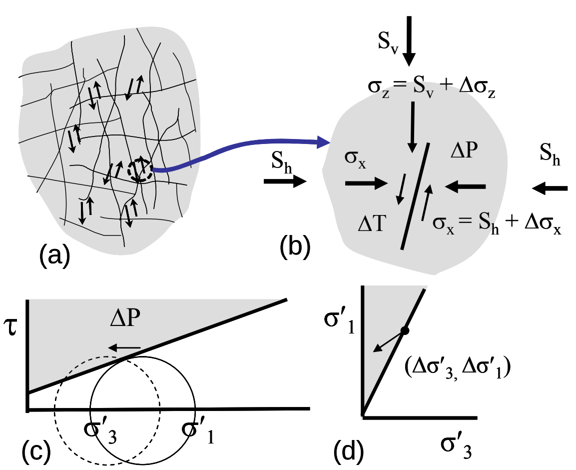


Fig. 3. Illustration of the approach for failure analysis to evaluate the potential for induced seismicity at The Geysers (a) Highly fractured rock with randomly oriented fractures, (b) Changes in stress on one fracture plane, (c) Movements of Mohr's circle as a result of increased fluid pressure within a fracture plane for a critically stressed fracture, and (d) corresponding stress path in the (σ'_1, σ'_3) plane.

We evaluate the potential for shear slip under the conservative assumption that fractures of any orientation could exist anywhere (Fig. 3a). Such assumptions were confirmed by studies of fault plane analysis of seismicity at The Geysers by Oppenheimer [8], which indicated that seismic sources occur from almost randomly oriented fracture planes. One key parameter in estimating the likelihood of shear reactivation 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 (e.g., [9]). Moreover, a frictional coefficient of $\mu = 0.6$ is a lower-limit value observed in fractured rock masses [9]. Thus, using $\mu = 0.6$ in the Coulomb criterion would most likely give a conservative estimate of likely seismicity. For $\mu = 0.6$, the Coulomb criterion for the onset of shear failure can be written in the following form:

$$\sigma'_{1c} = 3\sigma'_3 \tag{1}$$

where σ'_{1c} is the critical maximum principal stress for the onset of shear failure. Thus, shear reactivation of a fracture slip would be induced whenever the maximum principal effective stress is three times higher than the minimum principal stress.

Based on the concept of a critically stressed rock mass, the initial stress will be in a state of incipient failure (Fig. 3b, c and d). By studying how the stress state deviates from this near-critical stress state we may investigate whether the changes in the stress state tend to move the system into failure or away from the state of failure. We also may start at any initial state away from failure and consider if a change in the stress state increases or decreases the likelihood of shear 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., if $\Delta\sigma'_1 \geq 3\times\Delta\sigma'_3$). 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 point of critical stress, we may quantify how much the $\Delta\sigma'_1$ has to exceed $3\times\Delta\sigma'_3$ to induce additional shear reactivation. We therefore define a stress-to-strength change margin as $\Delta\sigma'_{1m} = \Delta\sigma'_1 - 3\times\Delta\sigma'_3$. How large $\Delta\sigma'_{1m}$ needs to be to induce shear reactivation during injection will be quantified by model calibration against historic injection and MEQ data.

3. THM INPUT PARAMETERS

The various coupled THM models of The Geysers developed in this study as well as those used in Rutqvist and Oldenburg [2, 3] consist of the normal temperature reservoir sandwiched between an impermeable cap and a relatively low-permeability high temperature zone. The equivalent fractured rock permeability in the reservoir is about $1{\bullet}10^{-14}$ m^2 (10 millidarcies) with about 1% porosity.

The initial thermal and hydrological conditions (vertical distributions of temperature, pressure and liquid saturation) for each model are typically established through steady-state multi-phase flow simulations. 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 350°C towards the bottom boundary at a depth of 6 km. The relatively low permeability of the HTZ below the NTR is inferred from the steep thermal gradient, which indicates lack of heat convection and dominant conductive heat flow. The steam pressure within the hydraulically confined NTR has gradually decreased with the steam production since the 1960s and is today a few megapascals.

The basic geomechanical properties used in this analysis are generally equivalent to those developed and used by Rutqvist and Oldenburg [2, 3]. This includes a rock-mass bulk modulus of 3 GPa, which approximately corresponds to values back-calculated by Mossop and Segall [10] based on strain analyses at The Geysers. The linear thermal expansion coefficient of the rock is set to 1×10^{-5} $°C^{-1}$, corresponding to values determined on core samples of the reservoir rock at high (250 °C) temperature [10]. Using these properties, Rutqvist and Oldenburg [2, 3] simulated the 44 years of production from the early 1960s in a reservoir-wide cross-section. The simulation of 44 years of steam-production and injection resulted in reservoir-wide pressure and temperature declines of a few MPa and a few degrees, respectively, as well as subsidence of about 0.5 to 1 meter. These numbers are in general agreement with field observations at the Geysers [11, 10].

4. MODEL CALIBRATION AT AIDLIN 11

We first analyzed and modeled historic injection and MEQ data at the Aidlin 11 injection well, located about 3 miles to the west of the new EGS demonstration area. The analysis of the Aidlin 11 data was conducted to study the cause and mechanisms of observed MEQs, and to constrain the stress criterion for the spatial extent of the MEQ zone around an injection well.

Injection in Aidlin 11 began in late 2004 at a relatively small rate (several hundred gallons per minute). The injection rate was held relatively steady until September 2005 when the injection rate sharply increased [12]. The injection takes place at a depth of 3.5 km near the interface between the normal and high temperature reservoirs. The observed MEQ evolution within a 6 km cube containing the Aidlin 11 injection well has been published by Majer and Peterson [12]. Fig. 4 shows an east-west cross section through the center of the cluster as well as the trace of the well. The seismicity during the first year of constant rate injection was concentrated near the bottom the well. Some of the sparse seismicity away from the injection well may be associated with production wells in the area.

We simulated the response to injection in Aidlin 11 using a three-dimensional model domain that is one-quarter of a 2 km by 2 km block in the horizontal plane and 5.5 km deep. The initial thermal and pressure gradients were calibrated in an initial steady-state simulation as described above. For the model calibration we study the injection and MEQ activities for the first year when injection took place at a relatively constant rate in Aidlin 11. In the modeling a constant average injection rate of 7.7 kg/s and injection temperature of 90°C were maintained for 1 year.

Figure 5 shows the calculated changes in pressure, liquid saturation, and temperature after 1 year of injection. In general, the temperature change is several tens of degrees, but is confined within the zone of liquid saturation migrating downwards from the bottom of the injection well. The pressure change is only a few MPa, but takes place far beyond the extent of the liquid water zone.

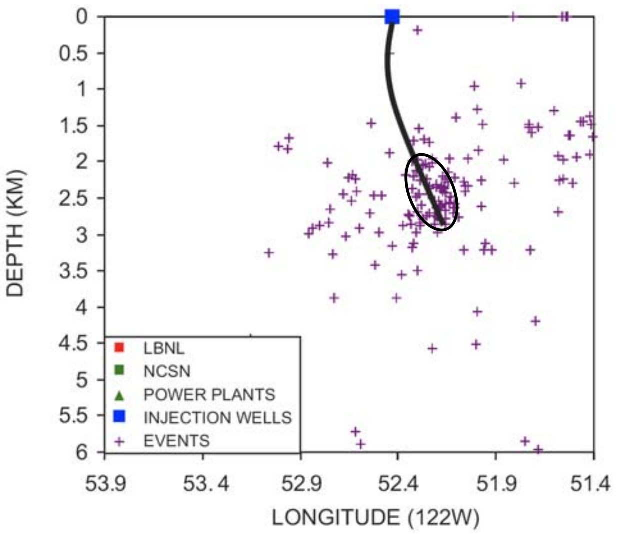


Fig. 4. E-W projection through a 6 km cube containing MEQ hypocenters of magnitude 0.8 or larger during 1 year of injection at Aidlin 11 (from Majer and Peterson [12]).

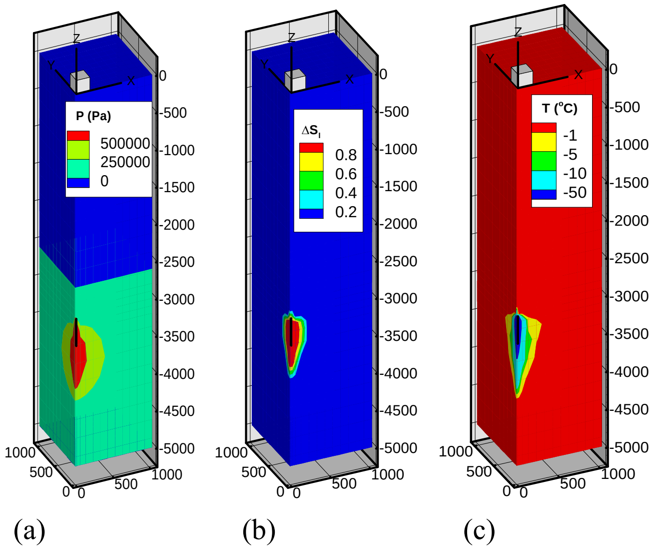


Fig. 5. Simulation results of after 1 year of water injection at Aidlin 11: Changes in (a) fluid pressure, (b) liquid saturation, (c) temperature after 1 year of injection.

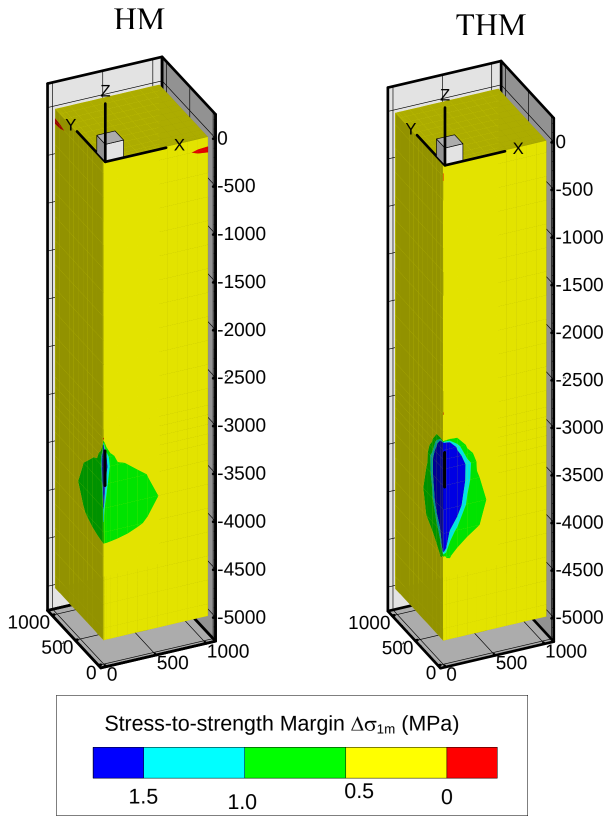


Fig. 6. Simulation results of MEQ potential estimated using stress-to-strength margin, $\Delta\sigma_{1m}$, for HM and THM couplings considered.

Figure 6 present the rock mass stress-to-strength change margin, $\Delta\sigma'_{1m}$. We present the results for considering THM coupling and only HM coupling. We can observe that when considering full THM coupling, $\Delta\sigma'_{1m}$ is higher and the zone of high $\Delta\sigma'_{1m}$ tends to spread farther downwards. The calculated results in Fig. 6 can be compared to the observed MEQ cloud (depicting events with $M \geq 0.8$) around the Aidlin 11 (Fig. 4). The extent of the MEQ cloud around Aidlin 11 roughly corresponds to the extent of the blue contour for the THM model. This blue contour corresponds to a zone with a stress-to-strength margin of 1.5 MPa or higher. This means that the maximum compressive effective stress has increased by 1.5 MPa relative to compressive strength.

A closer look at the simulation results indicates that the reduction in effective stress, with unloading of pre-existing fractures with associated loss of shear resistance would be the mechanism leading to shear reactivation. The injection-induced cooling is the most important cause for stress changes in the liquid zone near the well. Away from the well and the wet liquid zone, the pressure changes gives rise to stress changes that also could induce shear reactivation of pre-existing fractures.

5. MODEL PREDICTIONS AT PS-31 AND P-32

We analyzed the proposed initial injection at PS-31 and P-32 using the same modeling approach as was employed in modeling Aidlin 11. In this initial model simulation to estimate the extent of the shear-enhanced permeability zone around the injection wells, we use a simplified, but yet representative model of the field (Fig. 7). 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 zone of shear-enhanced permeability (corresponding to the extent of the MEQ zone). The 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")..

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}

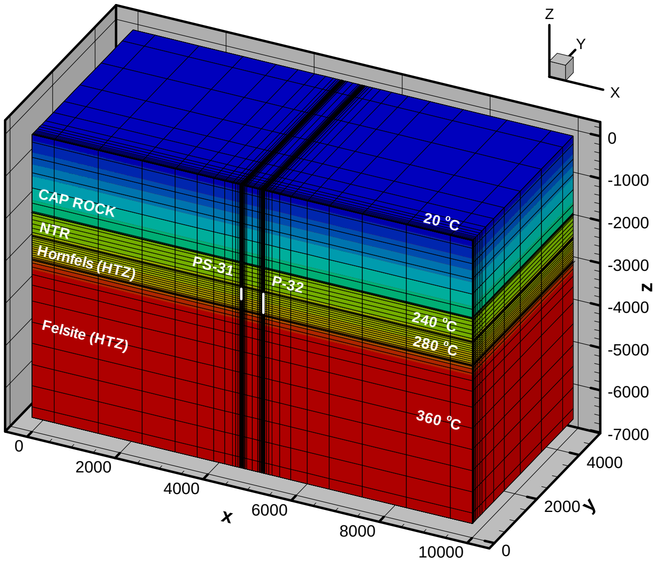
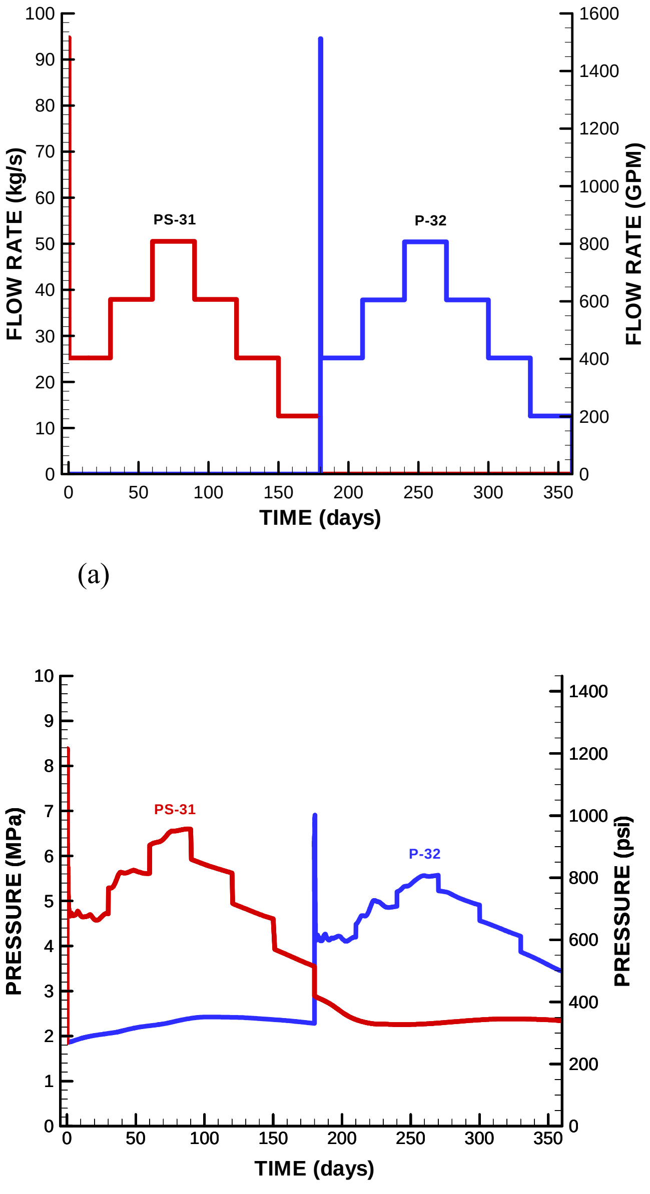


Fig. 7. Three dimensional numerical grid with material layers and contours of initial temperature.

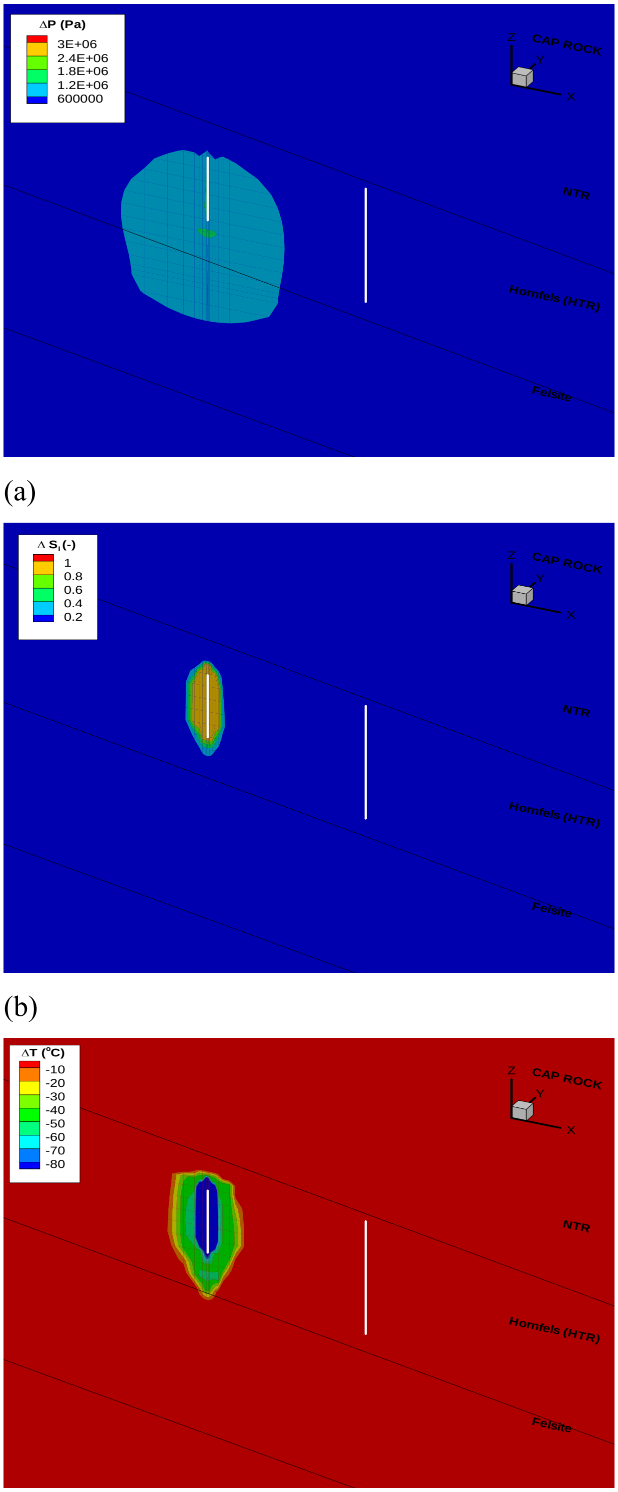
Table 1 presents the input properties of the main geological units. The permeability values represent fracture permeability taken from Calpine’s reservoir model and are several orders of magnitude higher than matrix permeability measured on core samples from the field. The elastic properties are equivalent to those used by Rutqvist and Oldenburg [2, 3], which are also effective large-scale rock mass properties, consistent with observed depletion-induced subsidence of The Geysers field.



(a)

(b)

Fig. 8. Injection rates (a) and calculated downhole pressure evolution (b) for the proposed injection schedule.

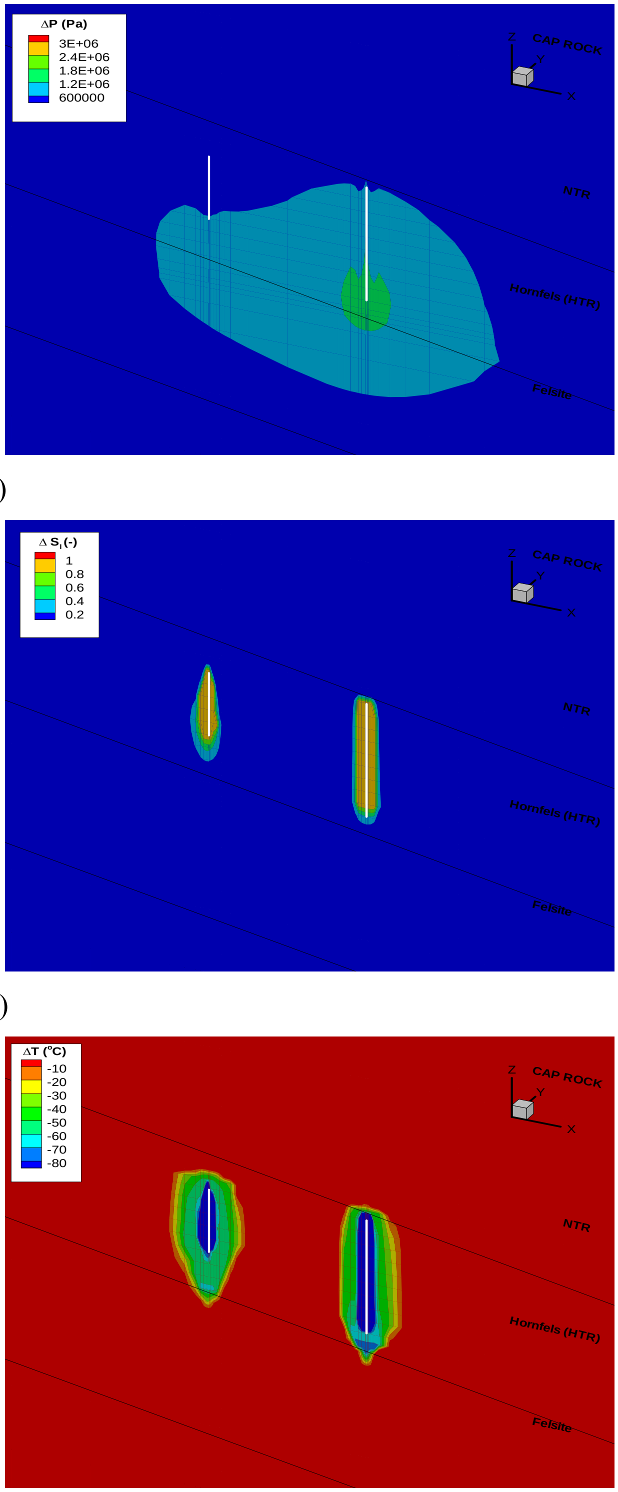


(a)

(b)

(c)

Fig. 9. Simulation results of PS-31 and P-32 at 6 months: Changes in (a) fluid pressure, (b) liquid saturation, and (c) temperature.

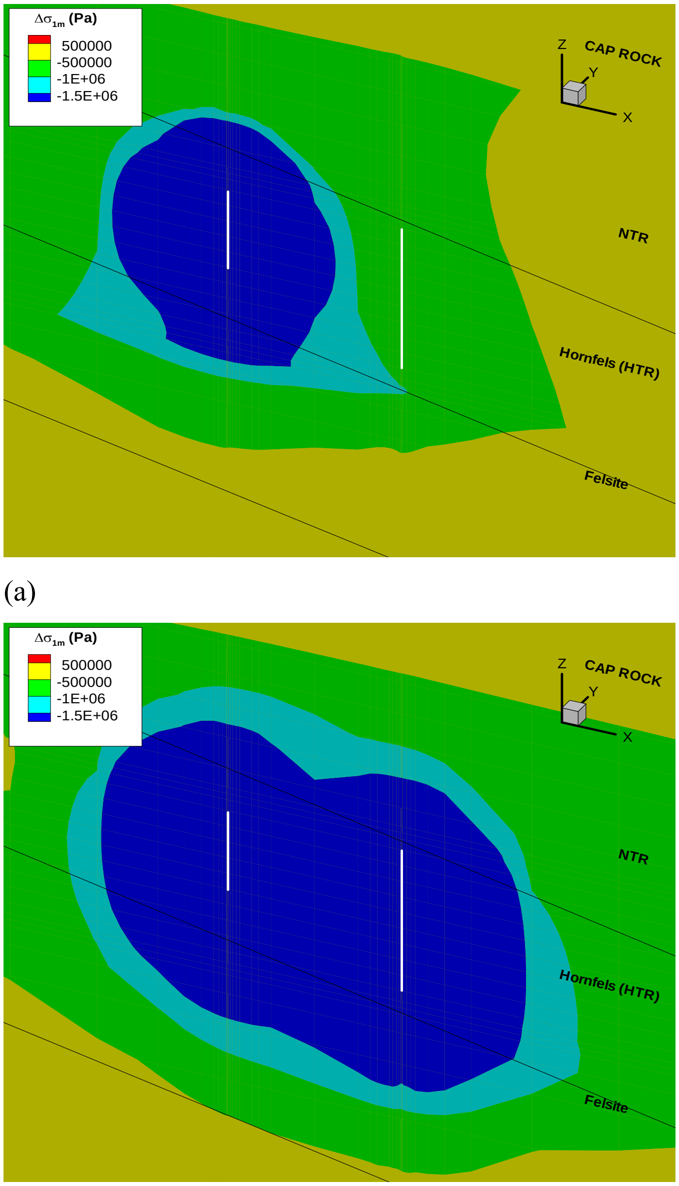


(a)

(b)

(c)

Fig. 10. Simulation results of PS-31 and P-32 after 12 months: Changes in (a) fluid pressure, (b) liquid saturation, and (c) temperature.



(a)

(b)

Figure 11. Simulated results of MEQ potential estimated using stress-to-strength margin, $\Delta\sigma_{1m}$, after (a) 6 months and (b) 12 months.

We simulated a 1-year proposed injection scheme that will be conducted using a carefully monitored series of steps that will increase and then lower injection flow-rates and down-hole pressures (Fig. 8). First there is an initial 8-hour period of relatively high-rate injection 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 scheme consists of 1-month-long steps of increasing and decreasing rates. The simulated maximum bottom-hole pressures during these steps are about 6.5 MPa in PS-31 and 5.5 MPa in P-32. At this depth the least compressive stress may be bounded to be at least 24 MPa using the frictional strength limit of the rock mass. Thus, the injection pressure is much less than the least principal stress and therefore far below the hydraulic fracturing pressure. The injection is done at a low pressure to avoid hydraulic fracturing, but aims at dilating pre-existing fractures by shear reactivation.

Figs. 9 and 10 show changes in pressure, liquid saturation, and temperature after 6 and 12 months, while Fig. 11 shows contours of the stress-to-strength change margin. The pressure increases and falls off rapidly along with the injection rate and spreads several km, but increases only up to a few MPa (Figs. 9a and 10a). A liquid zone forms around each injection well and some downward gravity flow can be observed (Figs. 9b and 10b). Substantial cooling is observed where liquid phase is present (Figs. 9c and 10c). A zone with high potential for shear reactivation and associated MEQ grows with the cooling and pressure increase at each injection well. In Fig. 11, the blue contour zone of high likelihood of reactivation of existing fracture extends about 0.5 km from each injection well. Moreover, this zone connects with the overlying NTR and can thereby provide additional steam production in the area.

6. CONCLUDING REMARKS

In this paper we presented the results of a coupled thermal, hydraulic, and mechanical (THM) modeling of a proposed stimulation injection associated with an Enhanced Geothermal System (EGS) demonstration project at the northwest part of The Geysers geothermal field, California. Our modeling of proposed initial injection at the well pair PS-31 and P-32 indicates that the injection into a High Temperature Zone (HTZ) is likely to stimulate a zone with reactivation of existing fractures and associated MEQ activity extending about 0.5 km from each injection well. The modeling indicates that the zone of shear reactivation and likely enhanced permeability in the HTZ is expected to connect to the overlying Normal Temperature Reservoir (NTR) and thereby provide additional steam production in the area. Moreover, our analysis shows that for the proposed injection scheme, the most important cause and mechanism for the shear reactivation is cooling and associated thermal-elastic cooling shrinkage of the rock around the injected fluid. The cooling shrinkage results in unloading and associated loss of shear strength in near-critically shear-stressed fractures, which are then reactivated. The model predictions presented in this paper will be compared with observed MEQ evolution once such data become available.

We are also working on a number of improvements of the model, including 1) use of exact three-dimensional model geometry based on a detailed geological model, 2) dual continuum model of the fractured rock, and 3) consideration of discrete fractures. These model improvements may be important when making a detailed comparison to the observed MEQ data once available.

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