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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 zones. 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 [3,4]. 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 [7–10]. The thermoelastic effects on the rock within and surrounding a fracture zone have also been analyzed by De Simone et al. [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

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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 thermomechanical 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 [4,12,13]. 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 TOUGH-FLAC, which is described in [14,15], and previously applied to study fault reactivation related to multiphase fluid flow and crustal deformations [16–19]. 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 stresses at failure. 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 [26,27]. 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.

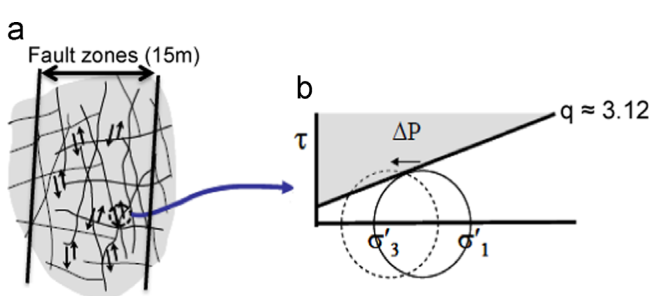

Fig. 1. (a) Illustration of the highly fractured shear zone with randomly oriented fractures, and (b) movements of Mohr's circle as a result of increased fluid pressure within a fracture plane for a critically stressed fracture belonging to the shear zone.

2.2. Model geometry

A 3D numerical model was developed to represent the study area of the Northwest Geysers EGS Demonstration Project. 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 geometric configuration of shear zone network and the wells in this area are shown in Fig. 3. 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 forms within the regional strike-slip fault zone system of the North Coast Ranges (Fig. 3a and b). 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 shear 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