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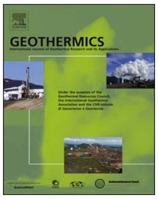

Influence of injection-induced cooling on deviatoric stress and shear reactivation of preexisting fractures in Enhanced Geothermal Systems

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ABSTRACT

Cold water injection into a hot, fractured, geothermal reservoir may trigger shear activation of pre-existing fractures that can help to enhance reservoir permeability, but may also result in unwanted seismicity. In this paper, we investigate through numerical modeling of a hypothetical geothermal reservoir how injection-induced cooling may influence the potential for shear activation, paying special attention to the evolution of deviatoric stress under various stress regimes. In each case, we consider either a reservoir with homogeneous hydraulic properties or the presence of a more permeable fracture zone intersecting the injection well. This fracture zone is either oriented in the maximum (S_{Hmax}) or minimum (S_{hmin}) horizontal stress direction. Our main finding is that depending on the configuration, injection-induced cooling stresses can favor or prevent shear reactivation of the preexisting fracture, and this effect can vary temporally and spatially.

1. Introduction

In the US, it is estimated that only 2% of the total geothermal energy stored between 3 and 10 km depth could be sufficient to provide the US primary energy for 2800 years (MIT, 2006). To exploit this huge geothermal resource the technology of extracting heat from an 'Enhanced Geothermal System' (EGS) is being developed. It consists of artificially enhancing or creating the permeability of the reservoir by hydraulic stimulation. Geothermal production is then carried out by cold water injected into the reservoir and hot water/steam recovery at production wells. This injection/extraction perturbs the in-situ stress state in the reservoir, potentially leading to the reactivation of preexisting fractures and/or possibly creating new fractures. These processes can be accompanied by microseismic events which could provide valuable information on the EGS development, but could also potentially result in felt seismic events that could be a nuisance to the local population. Therefore, it is important to understand the mechanisms that induce such microseismicity or seismic events because valuable information regarding the extent of a stimulation zone (Rutqvist et al., 2015), in situ stress field (Boyle and Zoback, 2013), fracture orientation (Verdon et al., 2011), fault zone location (Jeanne et al., 2014a), and on reservoir hydromechanical properties (Jeanne et al., 2014b) can be obtained by monitoring and analyzing these events.

It is well known that increased reservoir fluid pressure can bring faults closer to a state of failure and induce seismic events, whereas the role played by thermal effect on fracture stability is less well understood. The theory of thermoelasticity predicts that if the rock is subjected to both a temperature change and an applied stress state, then the resulting stress is the sum of the two (Jaeger et al., 2012, Eq. (1)).

$$
\begin{aligned}
\sigma_{xx} &= 2G\varepsilon_{xx} + \lambda(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) + 3\alpha K\Delta T \\
\sigma_{yy} &= 2G\varepsilon_{yy} + \lambda(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) + 3\alpha K\Delta T \\
\sigma_{zz} &= 2G\varepsilon_{zz} + \lambda(\varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}) + 3\alpha K\Delta T \\
\sigma_{xy} &= 2G\varepsilon_{xy},\ \sigma_{xz} = 2G\varepsilon_{xz},\ \sigma_{xz} = 2G\varepsilon_{yz}.
\end{aligned} \tag{1}
$$

with λ the Lame parameter, G the shear modulus, K the bulk modulus, ΔT the temperature variation, 3α the volumetric thermal expansion coefficient, ε the components of the strain tensor and σ the components of the stress tensor.

Eq. (1) shows that (i) thermally induced stresses are not caused by temperature changes *per se*, but rather by the combination of a change in temperature and a mechanical restraint that inhibits free expansion or contraction of the rock (Jaeger et al., 2012). This highlights the importance to consider a 3D thermal stress solution coupled to a 3D elastic stress analysis to study the fracture stability during geothermal operation. However, many studies about thermoelastic effect in geothermal systems consider either 1D (Elsworth, 1989; Nygren and Ghassemi, 2005) or 2D thermo-hydro-mechanical (THM) models (Kohl et al., 1995; de Simone et al., 2013; Izadi and Elsworth, 2013; Ghassemi and Tao, 2016) to investigate the influence of the thermo-poroelastic effects on a single fracture or a fracture zone. Some studies using a 3D

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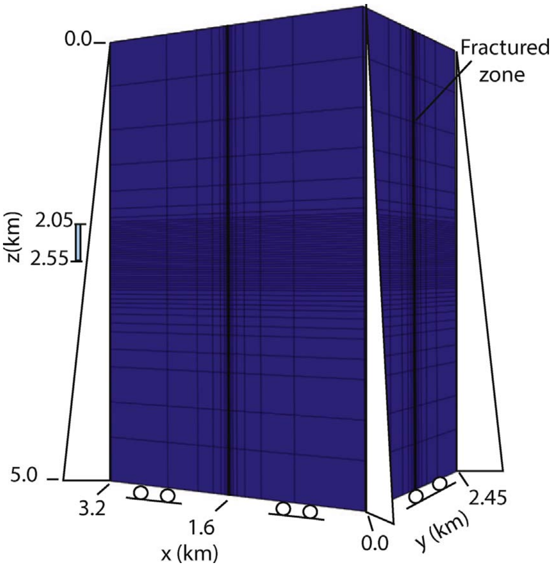

Fig. 1. Three dimensional numerical grids used to simulate a vertical injection well. The blue area along the z axis shows the position of the 500 m open section where injection occurs. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Hydraulic and mechanical properties.

	faulted reservoir		no fault
	reservoir	fault zone	reservoir
Young's modulus (GPA)	28	15	28
coefficient's Poison (−)	0.25	0.25	0.25
Biot coefficient (−)	1	1	1
Thermal conductivity (W/m°C)	3.2	3.2	3.2
Thermal expansion (°C $^{-1}$)	1.E-05	1.E-05	1.E-05
Specific heat (J/kg°C)	880	880	880
Permeability (m^2)	1.0E-15	1.0E-13	1.0E-13
Porosity (%)	5.0	15.0	15.0

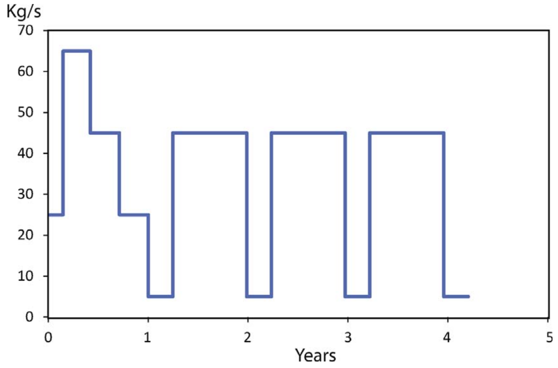

Fig. 3. Simulated injection rate.

THM model were performed but with a 1D approach to model the temperature field and the thermal stress in the rock mass (Mossop, 2001; Kohl et al., 1995; Willis-Richards et al., 1996; Megel et al., 2005), and as reported by Ghassemi et al. (2003), a 1D heat transport model can underestimate the heat transfer from the rock to the fluid, and a 1D treatment of the elasticity problem does not predict the correct distribution of thermal stresses.

It is commonly believed that the temperature contrast between the injected cool water and the geothermal reservoir contributes to enhance the potential for induced seismicity. Thermal contraction of the rocks can reduce normal stresses and increase shear stresses on a fault promoting fault reactivation and induced seismicity (Ghassemi et al., 2007; Orlic et al., 2013). Thermal effects can also cause the rotation of the stress tensor below the cooling area promoting the observed long-term deepening of the microseismicity below active injection wells at The Geysers (California, US) as discussed by Jeanne et al. (2015a). The coupling between pore pressure and temperature also has a major role. The thermal contraction causes the fracture to open increasing the effective normal stress by reducing the pore pressure (Ghassemi and Tao, 2016). However, a recent study performed in support of the Northwest Geysers EGS Demonstration Project(Jeanne et al., 2015b) suggests that thermal processes prevent shear reactivation and lead to the appearance of an aseismic domain just around the injection well. Jeanne et al. (2015b) explained this phenomenon by the fact that gravity-flow injected liquid into the host steam reservoir resulted in a preferential vertically extensive cooling zone that caused higher reduction in the vertical stress (S_V) than in the horizontal stresses. In the case of a normal stress regime this results in a decrease in deviatoric stress preventing shear reactivation of pre-existing fractures.

The motivation of this paper is to investigate the role of thermal processes on induced seismicity and to try to understand why thermo-mechanical effects can either favor or prevent shear reactivation of preexisting fractures. Here we investigate how the initial stress regime and the permeability tensor influences the induced-thermal stress variation and impact the induced seismicity. First we present the methodology, the numerical simulation used and our results.

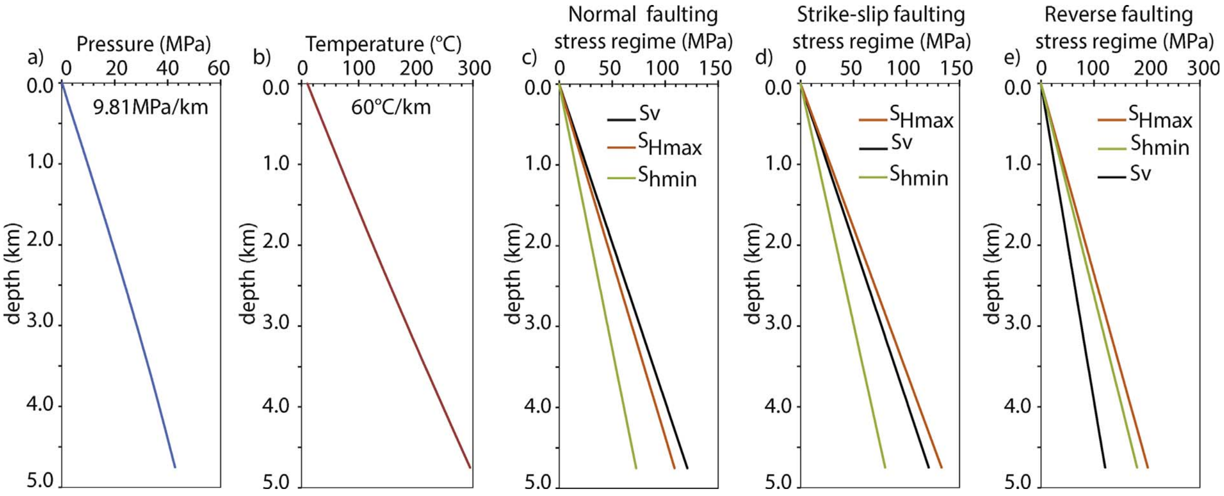

Fig. 2. (a) Hydraulic, (b) temperature and stress gradients used to simulate the (c) normal, (d) strike-slip and (e) reverse faulting regimes.