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Joint opening or hydroshearing? Analyzing a fracture zone stimulation at Fenton Hill

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ABSTRACT

In this study, we analyze a deep hydraulic stimulation of a fracture zone that was conducted as part of the classical Fenton Hill Hot Dry Rock Program in the 1970s. At the time, it was suggested that a pre-existing fracture or multiple fractures within the fracture zone were jacked open by injection-induced increase in pressure. In this study, we analyze the same stimulation experiment, but investigate the possibility of an alternative mechanism of shear reactivation of pre-existing fractures. We conduct modeling that accounts for both jacking (or elastic-fracture opening) and shear-slip dilation and demonstrate that injection-induced shear reactivation (or hydroshearing) could have occurred simultaneously with seismic events of magnitudes lower than what can be felt by humans. In fact, simulations considering shear reactivation seem to better match observed fluid recovery after multiple injection cycles. Shear reactivation and shear dilation results in locked-open fractures, especially near the injection well that provides permeability of higher flow recovery. We then investigate the sensitivity of the proposed model by varying some of the critical parameters such as maximum aperture, dilation angle, as well as fracture density. Interestingly, none of the simulated cases resulted in a large event that could have been felt by humans, but did result in a cumulative seismic magnitude of less than 1 for each given stimulation step. These results suggest that a permanent irreversible permeability increase of several orders of magnitude can be obtained by hydroshearing in a "seismically" safe manner.

1. Introduction

A critical question to answer for the development of future, innovative, and viable forms of natural deep underground geothermal resources is: Can we avoid human-felt, induced seismicity and still effectively exploit a geothermal reservoir? The next-generation georesources exploitation will require an answer to this question, since induced seismicity currently poses a great challenge to the geoenergy community in terms of monitoring, discriminating, and managing induced seismicity as highlighted in a recent review paper by Grigoli et al. (2017).

The exploitation of deep subsurface georesources frequently requires injection (or withdrawal) of large amount of fluids, affecting the state of stress and pressure at depth and potentially causing fault reactivation. A typical example is geothermal energy production from a hot dry rock (HDR) reservoir: while on the one hand the geothermal energy is considered as the most promising, clean, and almost inexhaustible form of geoenergy, on the other, the risk posed by associated induced seismicity may still be too high.

Among the other factors influencing the feasibility of an Enhanced Geothermal System (EGS), understanding how the permeability changes with or without induced seismic events (or aseismic slow slip events) still represents a great scientific and economic challenge. The possibility of enhancing the permeability at EGS was demonstrated as far back as the early 1980s by creating the world's first HDR reservoirs at Fenton Hill (Brown et al., 2012). The Fenton Hill experiments demonstrated that fluid circulation can be effectively intensified by stimulating preexisting fractures and fracture zones, opening the path for future commercially viable energy production. The concept of "hydroshearing" involving injection-induced shear activation of preexisting fractures is considered as a promising technique for effectively enhancing reservoir permeability (Cladouhos et al., 2009, 2016). It has been known since the early 1980s that injection-induced hydroshearing of natural joints preferably occurs on fractures optimally oriented for shearing within the local stress field (Pine and Batchelor, 1984). Hydroshearing involves shear reactivation of joints because of a reduction of effective stress and frictional strength and could occur at a fluid pressure much lower than the pressure required to jack open a

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preexisting fracture or to create a new one (hydrofracturing).

The concept of hydroshearing is being applied worldwide for simulation of EGS reservoirs (*e.g.* Tester et al., 2006; Ziagos et al., 2013; Cladouhos et al., 2016) because it is a process which could enhance the permeability of natural fractures in a permanent manner through self-propping even after the stimulation period. However, shear reactivation of fractures can lead to seismicity, which can compromise the success of the project due to public concerns. While on one hand, the seismic activity may represent an indicator of a successful creation of the HDR reservoir, on the other, if the fracture stimulation crosses a large fault or fracture zone, the risk of inducing human-felt seismic events increases. Indeed, induced seismicity has been the cause of halting EGS projects at several locations around the world such as Basel, Switzerland (Häring et al., 2008) or more recently Pohang, South Korea (Kim et al., 2018; Grigoli et al., 2018).

Investigating the relationship among hydroshearing, earthquakes and permeability can potentially help to understand under what conditions fluid-induced seismicity can safely be used as a tool for enhancing reservoir permeability (*i.e.* by avoiding “felt” events). Several studies in recent years have focused on understanding the relationship between fluid flow, geomechanics, and induced seismicity. Laboratory and *in-situ* experiments have been successful in demonstrating the dependency of hydromechanical properties on the injection (*e.g.* Samuelson and Spiers, 2012; Pluymakers et al., 2014; Guglielmi et al., 2015; Scuderi and Collettini, 2016; Ye and Ghassemi, 2018); while numerical and observational studies have focused on understanding the triggering and propagation of induced seismicity (Goertz-Allmann et al., 2011; Bachmann et al., 2012; Gischig, 2015; Dempsey and Suckale, 2016; Dempsey et al., 2016; Catalli et al., 2016; Azad et al., 2017; Zbinden et al., 2017).

Other studies have been focused on the dependency of permeability on stress and pressure conditions in rock fractures and fractured rocks. The works by Barton and others in the 1980s were groundbreaking in developing empirical models for relating stress to permeability through systematic laboratory investigations (Barton and Choubey, 1977; Bandis et al., 1983; Barton et al., 1985; Makurat et al., 1990). This works provided models for relating changes in effective normal stress and shear displacements to changes in hydraulic conducting aperture for rock fractures. Rutqvist and Stephansson (2003) argued that determining the relationships between stress and permeability in fractured rock may be best conducted *in-situ* due to issues related to unrepresentative sampling and sampling disturbances when trying to upscale laboratory data. Rutqvist (2015) presents cases of *in-situ* determination of stress-*vs*-permeability relationships suggesting the scale dependency of this relationship. However, there are still major uncertainties in the quantification of shearing on permeability for various rock types, including crystalline rock and shale. Rinaldi et al. (2014) compared three different models of permeability changes in the context of fault reactivation during CO_2 storage operation. Their results demonstrated a poor correlation between the magnitude of the induced seismic events and the amount of possible CO_2 leakage toward shallow depth. While the observed permeability changes were orders of magnitude, at the large scale of storage reservoir, the same modeling approach may not be appropriate for EGS. Indeed, their model was developed to intentionally trigger “felt” seismic events, which is to say, of a seismic magnitude larger than those commonly monitored during hydroshearing stimulation.

Recently, experimental results by Ye and Ghassemi (2018) provided indications that the hydroshearing involves both processes of shear slip and fracture propagation, and both contribute to enhance the system permeability, although they did not quantify such relationships. A recent review by McClure and Horne, (2014) investigate on the possible stimulation mechanisms at EGS, and while several models have been proposed recently in literature for hydroshearing and fracture opening (Rinaldi et al., 2015a; Norbeck et al., 2018; Salimzadeh et al., 2018; Xiao et al., 2018), the comparison with data is often qualitative with poor sensitivity analysis on the model parameters. In this study, we propose a relation between hydroshearing and permeability increase. In order to have a realistic formulation, we analyze a deep hydraulic stimulation of a fracture zone which was conducted in the Fenton Hill Hot Dry Rock Program. At the time, it was suggested that a pre-existing fracture or multiple fractures within a fracture zone were jacked open by injection-induced pressure increase. In this study, we analyze the same stimulation experiment, but investigate the possibility of an alternative mechanism of shear reactivation of pre-existing fractures. We conduct modeling that accounts for simultaneous jacking (or elastic fracture opening) and shear-slip dilation and demonstrate that injection-induced shear reactivation (or hydroshearing) could have occurred, aseismically or with magnitudes below the detection threshold at the time of experiment. We then investigate the sensitivity of the proposed model by varying some of the critical parameters such as maximum aperture, dilation angle, as well as fracture density. Finally, we conclude with a discussion including the possibility of enhancing permeability and fluid circulation at an EGS without causing large (felt) seismic events.

2. Fenton Hill observations

The Fenton Hill HDR project is known to be the world’s first full-scale EGS project. The overall goal of the concept studied at Fenton Hill was to create a human-made reservoir at 200 °C and circulate water through the use of two deep boreholes (Brown et al., 2012). The project was in operation for more than 20 years, including two different phases, and provided an exceptional amount of data and knowledge. Phase I focused on creating a reservoir and establishing a hydraulic connection between the two wells, constituting the concept of EGS designated at Fenton Hill. One of the main findings of the Phase I HDR reservoir creation was that the hydraulic stimulation in the granitic basement appeared to be related to re-opening pre-existing and sealed fractures with very complex geometries and orientations, rather than creating new fractures. The subsequent Phase II of the Fenton Hill project focused on creating a deeper HDR reservoir at about 4000 m depth, compared to the 3000 m reached during Phase I (Brown et al., 2012).

In order to understand the effect of joint opening and shear reactivation on permeability, we study a series of pressure-stimulation tests that were carried out during stage 2 drilling of the GT-2 well for the Phase I HDR reservoir creation of Fenton Hill. Starting in September 1974, several pressurization tests were performed in Zone 7, a 62-m open-hole interval (1981–2043 m depth) at the bottom of the borehole below a steel-and-cement liner. Pressure data were collected during an initial injection test, denoted as Test 1, when fluid was injected at a rate of 8 l/s for one minute. Fig. 1 illustrates how the pressure reached a leveling off value of 17.2 MPa within the first minute, and it did not show the breakdown pressure typical of hydraulic fracturing, indicating that one or several pre-existing joints had been opened. After one

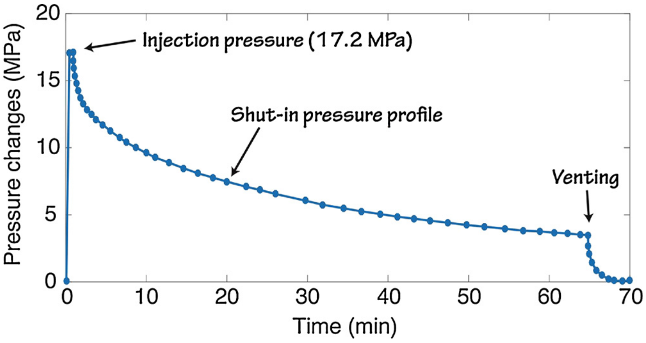

Fig. 1. Wellhead pressure recorded during stimulation of Zone 7 of well GT-2 at Fenton Hill after injection of about 105 gal of fluid (0.4 m^3). Modified after Blair et al. (1976) and Brown et al. (2012).