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Experimental investigation of fracture aperture and permeability change within Enhanced Geothermal Systems

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ABSTRACT

A method was developed for experimentally observing the evolution of fracture aperture/permeability within a granite-based Enhanced Geothermal System (EGS) in an attempt to better understand the reduction of fracture permeability due to chemical and mechanical processes. Specimens of granite were subjected to flow-through column-like experiments to characterize the evolution of fracture aperture/permeability in a near-field setting for 20 and 40 days. Near-field experimental conditions approached in-situ shallow EGS conditions: granite rock, tensile fracture, 120 °C temperature, and 25–35 MPa effective stress. Following each 20–40 day experiment, permeability, fracture aperture, and mass of minerals dissolved were computed using pore-pressure observations, effluent chemistry, and non-concurrent X-ray computed tomography (CT) scan imaging. Results showed an increased upstream pore pressure, which could indicate a decline in permeability due to a combination of the dissolution of fracture propping asperities and mechanical creep. Effluent solution composition was in agreement with the dissolution of silicates (most notably feldspars) which points to a geochemically driven decrease in aperture due to mineral dissolution rather than mechanical effects. In comparison, the pore pressure measurements corresponded to a greater aperture change than the effluent chemistry (0.127 vs 0.101 μm, respectively). This discrepancy may be attributed to the contribution of other physical processes to fracture aperture change, including mechanical creep. Similarly, the CT scan showed a decreased fracture aperture, but the low resolution and non-concurrent scans influenced higher aperture closure estimates in comparison to the effluent chemistry and pore pressure measurements. However, the CT-scan confirmed the scale-dependency of the chemical and mechanical processes. Fundamentally, the study demonstrated a method for ensuring near-field conditions and observing the chemical and physical processes associated with fracture permeability decline.

1. Introduction

As fossil fuels become more difficult to obtain and renewable energy sources become more accessible, geothermal energy presents a versatile, abundant, and environmentally friendly source of power (Report, 2006). Among the various geothermal alternatives, Enhanced Geothermal Systems (EGS) are one of the more geographically and geologically versatile options. The system accesses thermal energy stored deep within the Earth's crust (3–5 km) by flowing fluid through a fracture network between an injection well and a production well 10–800 m apart and at ≈3 km depth (Report, 2006). In order to effectively heat the injected fluid during its travel between wells, a pressurized stimulation is required to open up existing fractures in the *dry* hot rock matrix. Once both wells are connected by fractures, "cold" water (80–100 °C) is pumped into the injection well and through the fractured rock matrix. Upon contact with the rock, the cold water is heated to 150–250 °C and pumped from the production well. The hot fluid is obtained at the surface to generate steam and electrical power via a binary or flash-steam power cycle. Additionally, the hot fluid may be used directly for industrial applications. EGS can be applied almost anywhere in the world where high crustal heat flow exists (western region of North America, western Europe, eastern Africa, etc.) According to Report (2006), EGS has the potential to contribute up to 20 large cities worth (100,000 MWe) of baseload power to the United States electric grid by year 2050. Furthermore the land requirements for EGS sites are less than a nuclear power plant and less than one quarter of a solar field. However, the uncertainty associated with production decline (flow rate and water temperature) has largely

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deterred the commercial industry from investing in EGS (Report, 2006).

The success and longevity of EGS depends strongly on the permeability of its underground fracture network. If the permeability decreases, so does the flow rate, production temperature, and the associated electricity generation. Several processes affect the permeability of the system, including thermal, hydrological, mechanical, and chemical processes (THMC – Ghassemi (2012)). Among these processes, chemically mediated mineral dissolution and stress-mediated mechanical creep (stress corrosion) both may contribute to the evolution of fracture permeability (Yasuhara, 2004; Yasuhara and Elsworth, 2008; Yasuhara et al., 2011). Additionally, thermal and pressure imbalances may also result in mineral dissolution and precipitation (Xu et al., 2001; Ghassemi and Suresh Kumar, 2007; Ghassemi, 2012). Further, available studies on fractured rocks (Moore et al., 1994; Durham et al., 2001; Polak, 2003; Yasuhara et al., 2006) suggest fracture transport is more sensitive to thermal, hydrological, mechanical, and chemical processes compared to porous medium flows. Some processes may increase permeability such as dilatant shear, free-face dissolution, and thermal cracking (Taron and Elsworth, 2009) but other processes are believed to decrease permeability such as the dissolution of fracture propping asperities in combination with fracture sealing due to pressure solution (Yasuhara, 2004) (Fig. 1).

The effects of coupled THMC processes on fracture permeability in EGS reservoirs have been separately investigated through numerical, analytical, and semi-analytical studies (Kohl et al., 1995; Ghassemi and Zhang, 2004, 2006; Yasuhara and Elsworth, 2006, 2008; Izadi and Elsworth, 2013). These studies demonstrate the individual influences of THMC processes on fracture aperture and permeability. For example, studies have shown that heat extraction from rock results in thermal contraction (Ghassemi et al., 2008; Koh et al., 2011), which increases aperture width/permeability on the long term and encourages the development of internal stresses (Ghassemi et al., 2005). On the other hand, poroelastic effects resulting from fluid injection typically lead to a temporarily increased fracture aperture followed by leak off and aperture reduction on the long term (Xiong et al., 2013). Other numerical simulations have coupled thermoporoelastic effects to show that thermoelastic effects dominate poroelastic effects over the course of a reservoir's lifespan (Ghassemi et al., 2008; Ghassemi and Zhou, 2011). Some studies have investigated the contribution of chemical processes to fracture aperture and permeability (Eslworth and Yasuhara, 2010; Chaudhuri et al., 2012). Xu et al. (2001) numerically demonstrated the reduction of permeability at the production well due to dissolution caused by higher temperature and silica content of the rock compared to the circulated fluid. Other studies have developed models that predict fracture aperture evolution with respect to mechanically and chemically induced dissolution within novaculite fractures (Yasuhara et al., 2006; Yasuhara and Elsworth, 2008). These numerical studies collectively show that THMC processes play important individual and combined roles during permeability evolution within EGS. Very limited experimental research has been performed to investigate the combined effects of these processes on fracture permeability in EGS reservoirs.

The majority of experimental studies that simulated fully coupled THMC processes did so on specimens that did not represent the granite rock type of basement EGS (Durham et al., 2001; Polak, 2003; Polak et al., 2004; Singurindy and Berkowitz, 2005; Yasuhara et al., 2006). Some experimental studies have focused on the permeability of intact and fractured granite at various temperatures and pressures. Low temperature and high pressure experiments performed by Kranz et al. (1979), Brace (1980), and Barnabe (1986) investigated permeability hysteresis and the contribution of fracture surface roughness to permeability, but did not consider mineral dissolution. Other investigations have incorporated geochemistry into their experimental methods and post processing techniques. Savage et al. (1992) employed novel working fluid compositions (stream water and synthetic EGS analogs) but the study was constrained by fairly low temperatures (60–100 °C). The study concluded that rock dissolution is a heterogenous process: the effluent gained certain elements and lost others depending on local equilibrium dynamics. Another important conclusion was that the most reactive minerals (in order of decreasing reactivity) were calcite, feldspar, biotite and quartz, which is predicted by thermodynamics (Goldich reaction series). Morrow et al. (2001) also investigated granite permeability under hydrothermal conditions. Although the study focused on fault sealing mechanisms, it included the flow of deionized water through crushed/intact granite specimens at EGS temperatures and pressures. Scanning electron microscope imaging and inductively coupled plasma (ICP) analyses of the effluents were used to determine the existence and magnitude of dissolution and precipitation reactions. Finally, Yasuhara et al. (2011) used low pressure (5–10 MPa confining) experiments run on an artificially fractured granite specimen to develop a chemical–mechanical process based model to predict aperture change. Yasuhara et al. (2011) postulated that aperture change was likely due to a combination of mechanical crushing and chemical dissolution of contacting asperities. The study presented here experimentally investigated the effect of chemical and mechanical processes on fracture permeability at EGS conditions.

The objective of this study was to develop and modify an experimental methodology that analyzes fracture permeability with respect to coupled THMC processes by prioritizing in-situ EGS conditions. The investigation used the ability to model an in-situ EGS fracture to test the hypothesis that fracture surface asperities initially prop the fracture open and dissolve upon introduction to deionized water resulting in decreased fracture permeability (Fig. 1). Specifically, the experimental research presented here is defined by the extreme characteristics associated with a granite based EGS: high effective stress, high temperature, and low pressure gradient. These characteristics combined with attention to rock–water interactions demonstrate an investigation of coupled THMC processes within an intact rock-column. In order to link the THMC processes to fracture aperture and permeability evolution, the study presented here tracked the evolution of upstream pressure for the duration of the experiment. Additionally, influent and effluent water samples were analyzed for elemental concentrations to determine the mass of minerals dissolved. Lastly, this study acquired and processed pre- and post-experimental CT scans to investigate the modification of fracture asperities and the reduced fracture aperture.

2. Materials and methods

2.1. Granite selection and characterization

A specimen of Barre Granite (Rock of Ages quarry, Barre, Vermont) was selected and considered EGS representative due to its similarity in mineral composition to granites of existing EGS such as Soultz-sous-Forêts (France) (Ledésert et al., 2012) or Rosemanowes (UK) (Savage et al., 1992). The foliation (Akesson et al., 2003) of the Barre Granite was used to identify the plane of greatest weakness. This plane is associated with the greatest number of discontinuities (Fitz Osbourne, 1935; Nasseri et al., 2010) and accommodated the recreation of an in-situ fracture.

This study used microscopic and image analysis methods to determine the existence and direction of foliation within the granite block. The microscopic investigation was carried out on three 30 μm thin sections – one orthogonal to each axis of the block (Fig. 2). These thin sections were analyzed under a petrographic