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Laboratory simulation of binary and triple well EGS in large granite blocks using AE events for drilling guidance

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ABSTRACT

Multiple-well Enhanced Geothermal Systems (EGS) can enable economic recovery of energy from underutilized hot dry rock (HDR) reservoirs. Hydraulic fracturing is a promising stimulation method for improving fluid flow and heat extraction in EGS. Laboratory simulations of EGS with hydraulic fracture stimulation have recently been completed in two large 300 × 300 × 300 mm^3 granite block specimens to better understand this complex process of geothermal energy recovery. The first experiment implemented a binary well layout with an injector and producer. The second experiment used a triplet well layout with one injector and two producers. Selection of production well trajectory so as to intersect the hydraulic fractures was guided by acoustic emission (AE) events collected during stimulation. Both model reservoirs were subjected to heating and true-triaxial stress confinement throughout a series of drilling, stimulation, and flow and heat circulation tests. Stimulated thermal reservoir flow was characterized by a series of constant pressure, constant flow rate, stepped constant pressure and stepped constant flow rate injection tests. Tested blocks were cross-sectioned to characterize final locations and 3D geometries of the induced fractures. Insights and lessons learned from these experiments are presented with focus on application to field-scale EGS.

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1. Introduction

Enhanced Geothermal Systems (EGS) have the potential to enable economic recovery of energy from underutilized hot dry rock (HDR) reservoirs or increase production from conventional geothermal reservoirs (Tester et al., 2006). The basis of EGS involves drilling an array of injection and production wells into a target hot-rock reservoir and stimulating the reservoir to improve in situ permeability. This allows for sustained injection and circulation of fluid through the reservoir for commercial extraction of heat energy, a process also referred to as geothermal heat-mining. Hydraulic fracturing offers a means for stimulation where fluids are injected with sufficient rate and pressure to create new fractures. EGS is intended for implementation in deep high-temperature rocks which have complex geologic structures and contain significant thermal energy. However, experience with hydraulic fracturing in abundant crystalline HDRs, such as granites and diorites, is limited in comparison with sedimentary applications common to the oil and gas industry.

Research to advance EGS and hydraulic fracturing technology has included modeling efforts, laboratory experiments and field scale tests (GTO, 2014; Tester et al., 2006; Valkó and Economides, 1995). One topic that remains uncertain through the existing research is a strong understanding of how hydraulic fractures propagate through complex crystalline rocks, how actual prominent fracture locations relate to acoustic emission (AE) source locations, and how fluid flows through hydraulically stimulated fractures between wells (Warpinski and Teufel, 1987). Laboratory experiments can offer insight on these questions as a benefit of physical data collected in controlled conditions using measurement and monitoring capabilities beyond what is possible at the field scale. Relevant laboratory experiments have included hydraulic fracturing studies (Abass et al., 1996; Behrmann and Elbel, 1991; de Pater et al., 1994; Haimson and Zhao, 1991; Hallam and Last, 1991; Ishida et al., 2004; Warpinski et al., 1982) and fracture conductivity tests (API RP61, 1989). These studies, to the best knowledge of the authors, mostly neglect thermal effects, use ideal or sedimentary rock specimens, do not incorporate multi-borehole systems and coarsely inspect the final fracture geometry. A comprehensive study which includes these experiment parameters and meticulously investigates created fracture geometry, through cross-sections paired with AE, is expected to offer beneficial

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insights building on previous studies. The results from such as study are expected to improve understanding of the difficulties with applying EGS to crystalline HDR and the respective causes of these difficulties. This understanding can be applied to the field-scale where similar measurements are not possible but similar fracturing and fluid flow behavior can be assumed or inferred.

Comprehensive laboratory experiments were recently conducted in an effort to improve understanding of multiple-well EGS reservoirs in crystalline HDR. Two large $300 \times 300 \times 300\,mm^3$ granite blocks were subjected to HDR conditions and hydraulically fractured to create EGS models. A binary well configuration with one injector and one producer was implemented for the first experiment. The second experiment used a triplet configuration with an injector and two production wells. In both experiments, production well trajectories were selected so as to intersect the main hydraulic fracture wings using acoustic emission (AE) event source locations collected during stimulation. Both rock specimens were subjected to heating and true-triaxial stress confinement throughout drilling, stimulation and production operations. Simulation methods included conventional hydraulic fracturing, hydraulic re-fracturing and mechanical impulse stimulation. Treatment schedules for each test were tailored according to the observed response of the reservoir to successive injection and circulation treatments. Well injectivity and productivity was characterized by a series of repeated fluid injection tests. Creation of EGS reservoirs was successful in both experiments but the need for improvement to the stimulation process and well design was also apparent. Suggestions are presented for future EGS design following lessons learned from these experiments.

2. EGS simulation methodology

Details on the test materials, equipment and procedures used for this study are provided in this section. Fluid flow data collected during experiments were synthesized to representative values following the methods described in this section to enable direct comparison of results.

2.1. Rock specimen characteristics

Granite specimens were obtained from the Liesveld Quarry in Lyons, Colorado. The specimens were extracted from an outcrop using water jet cutting and trimmed to $300 \times 300 \times 300\,mm^3$ cubes by diamond wire sawing. This specimen preparation process minimized mechanical damage. Supplemental element tests were performed to characterize the rock properties following relevant ASTM standards with the exact procedures detailed in Frash (2012). The respective results are shown in Table 1. The granite specimens typically exhibited low-porosity and low-permeability so matrix leak-off during fluid injection was expected to be negligible. Pre-stimulation well injectivity tests were performed for improved evaluation of stimulation effects.

Table 1
Granite material properties.

Property	Value
Uniaxial compression strength (MPa)	152 ± 19
Poisson's ratio	0.32
Elastic modulus (GPa)	56.9
Density (g/cm^3)	2.63 ± 0.03
Indirect tensile strength (MPa)	7.5 ± 1.8
Thermal conductivity (W/m^2)	3.14 ± 0.05
Volumetric specific heat capacity ($kJ/m^3\,K$)	2063 ± 92
Porosity	0.008 ± 0.001
Permeability (μD)	≤ 1.16
Shear wave velocity (km/s)	2.62
Compression wave velocity (km/s)	4.45

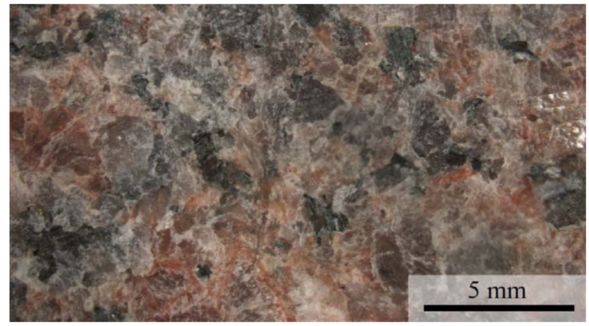

Fig. 1. Photomicrograph showing typical grain heterogeneity in the granite.

The dominant minerals in the granite were quartz and feldspar with minor biotite and muscovite. The grains of the granite were heterogeneous in size and distribution as is common for natural rocks. Typical grain sizes ranged from less than 0.0005 mm up to 15 mm in length, measured by photomicrographs and calipers. Large grains contained striations and composite structures making precise definition of grain size difficult. This difficulty is common in heterogeneous rocks and remains a topic of active research in regard to characterizing materials for modeling. Fig. 1 shows a typical photomicrograph of the granite's heterogeneous grains. This heterogeneity was preferred for these EGS experiments because real rock has a potential for producing more complex results than idealized materials. Complex results can in-turn offer insight for field-scale EGS where heterogeneity and discontinuities are a fact of nature.

2.2. True-triaxial equipment

A true-triaxial apparatus was used to apply heating and confining stresses to the cubical rock specimens. Stresses were applied by an assembly of flat jacks and platens as shown in Fig. 2. Heating was applied by external electrical elements with constant temperature control. Passive platens enabled drilling of multiple wells at orientations ranging from vertical through horizontal. The maximum confinement stress provided by the apparatus was 13 MPa and the maximum proof temperature was 100 °C. Data monitoring systems included pressure transducers, thermocouples, strain gages, and six Acoustic Emission (AE) sensors. Capability for pore pressure application and control at the boundary of the specimen was not incorporated into this equipment because HDR conditions were intended. Additional details on the equipment and instrumentation can be found in Frash (2012), and Frash et al. (2013b).

2.3. Injection fluids and equipment

Fluids injected for stimulation and flow testing included Valvoline® DuraBlend® SAE 80W90 gear oil and tap water. Estimated properties for these liquids at selected temperatures are shown in Table 2 (ASTM D341, 2009; Valvoline, 2012; White, 2009). Gear oil was used for hydraulic fracturing and water was used for most injection flow testing. Oil was chosen for its high viscosity relative to water. Previous studies suggest higher viscosity fluids are beneficial for laboratory hydraulic fracturing with respect to scaling laws (de Pater et al., 1994) and creation of less tortuous fracture pathways (Ishida et al., 2004). It was assumed that more ideal planar bi-wing hydraulic fracture geometries would result with increased fluid conductivity between the injection and production wells during EGS fluid flow testing. Water was used