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EDITORIAL

# Special Issue "Hydraulic Fracturing in Hard Rock"

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## 1 Introduction

According to our knowledge, hydraulic fracturing in hard, crystalline rock is not well understood as hydraulic fracturing in sedimentary rock for oil and gas. To support the development of geothermal energy, in particular, a thorough understanding of hydraulic fracturing in granitic target rock for generating heat exchangers at depth is needed. In shale gas fracturing, the mechanism of permeability enhancement in tight rock also needs further work to understand the impact of multiple fractures designed in horizontal wells by multiple fracturing stages. In general, creating fracture networks in tight rock at depth is a prerequisite for the development of gas from shale and heat from granite.

In this Special Issue, research papers are collected and organized to highlight the status quo of in situ monitoring hydraulic fracturing mechanism in hard rock. Results from cross-scale experiments include hydraulic testing on laboratory core samples, hydraulic in situ experiments conducted in underground research facilities, and data obtained from borehole monitoring of hydraulic fracture operations in the field. Numerical studies of the initiation and growth process of hydraulic fractures allow verification of the experimental results.

The purpose of this Special Issue is to improve our physical understanding of the hydraulic fracture nucleation, propagation and arrest process, in particular, for multi-stage, multiple fracture scenarios. Although moderate magnitude seismic events have been attributed to hydraulic fracturing operations, the acoustic and seismic response to fracturing of hard rock is expected as local micro-, or even pico-seismicity events. This exceptional low detection limit of weak events requires an advanced array monitoring approach with preferentially hybrid sensor geometries.

The challenge is to map the weak signals in the nucleation and propagation phase of the fractures, and cross-correlate high precision, re-localized source hypocenters with advanced fluid-injection protocols and the resulting permeability enhancement process in the tight formations. The cross-scale approach will allow us to understand the different phases of the fracture process by identifying source mechanisms from acoustic and seismic full waveform signatures and shed light on the complex mixed-mode (tensile, shear, tear) of a single hydraulic fracture, usually assumed to be a pure mode I tensile fracture event.

## 2 The Special Issue

The motivation behind the Special Issue is a suite of underground experiments designed to understand the processes in situ when a geothermal doublet (injection and production well) is in operation. Creating geothermal heat exchangers at depth in granitic rock is a non-trivial task. Some of the geothermal pilot projects were suspended because of the occurrence of larger magnitude fluid-injection-induced seismic events, in particular in the stimulation phase of granitic rock at target depth (Häring et al. 2008; Giardini 2009). Three key experiments performed in hard rock underground facilities tackling these problems are listed in Table 1. The first experiment to understand multi-stage hydraulic fracture growth in horizontal wells in granitic rock mass at 410 m depth was designed in Äspö HRL, Sweden (Zang et al. 2017).

Three contributions of this Special Issue are dealing with in-depth analysis of this experiment performed in June 2015. Zang et al. (2019) focus on the seismic footprint of six hydraulic fractures propagated in granitic rock mass from a horizontal borehole. In particular, advanced fluid-injection protocols are presented which have the potential to replace larger magnitude seismic events by a cloud of smaller magnitude seismic events with about the same energy content. The underlying hydraulic fatigue process postulated plays

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**Table 1** History of interest in underground experiments for geothermal research

| Year of experiment | Underground laboratory | Early reference | Budget relation |
|---|---|---|---|
| 2015 | Äspö Hard Rock Laboratory (HRL), Sweden | Zang et al. (2017) | ×1 |
| 2016 | Grimsel Test Site (GTS), Switzerland | Amann et al. (2018), Gischig et al. (2018) | ×10 |
| 2018 | Homestake Mine, Sanford Underground Facility, North Dakota (USA) | Kneafsey et al. (2018), Morris et al. (2018) | ×100 |

a key role in understanding the energy partition in this innovative technology. Zimmermann et al. (2019) evaluate in detail the permeability enhancement process of the six hydraulic fractures in the Äspö underground experiment. A combination of cyclic hydraulic injection and pulse injection produces the maximum permeability performance. For this, however, two independent pump systems are required. The technical note by Stephansson et al. (2019) describes the impact of the cyclic and pulse injection scheme re-analyzed on the core material drilled from the horizontal wells tested in Zang et al. (2019) underground experiments in Äspö HRL.

The second series of underground experiments with geothermal focus was designed at Grimsel Underground Test Site in the Swiss Alps (Table 1, Amann et al. 2018). Compared to the Äspö experiment (ca. 250,000 Euros) the budget of this project was about a factor of 10 larger. In Gischig et al. (2018), acoustic emission events from four hydraulic fractures are discussed with respect to hydraulic parameters of the stimulation and circulation tests and the in situ stress field. Krietsch et al. (2019) evaluate the in situ stress field in Grimsel granodiorite and Central Aar granite by analyzing results from overcoring and hydraulic fracturing stress measurements. Overcoring stress inversions benefit from using both anisotropic rock properties in the inversion algorithm and relocated hypocenters of acoustic emissions.

The most sophisticated (and expensive) program to investigate coupled processes of fracturing and flow in Enhanced Geothermal Systems (EGS) at mine scale is the ambitious US Collab Project currently performed at Sanford Underground Research Facility (SURF), South Dakota (Table 1, Kneafsey et al. 2018). One mile below surface, key questions such as (1) how to stimulate fractures efficiently in various hard rock and stress conditions, (2) how to isolate zones for controlling fast fluid pathways and early thermal breakthrough, and (3) how to secure long-term EGS reservoir sustainability are addressed. In Morris et al. (2018), the experimental design for hydro-fracturing and fluid flow is expanded resulting in the first testbed of the EGS Collab project. Horizontal boreholes are placed in phyllite of the Precambrian Poorman Formation at SURF, located at the former Homestake Gold Mine in Lead, SD. Compared to the Grimsel experiments, the budget of this US project is increased again by about a factor of 10 (Table 1). This documents the effort and needs to control and "mine" geothermal heat.

As far as this issue, in Ishida et al. (2019), a small-scale hydraulic fracturing experiment in Mitsunami Underground Research Laboratory in Central Japan is described. At 500-m level, a vertical borehole is drilled from the gallery, and fluid-injection induced acoustic emissions are located by 16 sensors in four monitoring boreholes in the near-field of the test (ca. 1 m away from the injection borehole). The experimental results suggest that the increase of the flow rate by a factor of three is an efficient way to create new tensile fractures in granitic rock, in particular, during re-fracturing stages.

Farkas et al. (2019) report on hydraulic fracturing tests performed in boreholes located in central Hungary to determine the in-situ stress for a geological site investigation. At depth of about 540 m, the observed pressure versus time curves in mica schist with low dip angle foliation show atypical pressure versus time results. Based on a series of discrete element computations, a viscous blocking effect by the mud is postulated. Viscous blocking prevents leak-off from the opened fracture in anisotropic rock that can explain the increased fracture reopening pressure in subsequent pressurization cycles.

At laboratory scale, Zhuang et al. (2019) investigate the effect of water infiltration, injection rate and anisotropy on the hydraulic fracturing behavior of granite from Korea. Hydraulic fracturing tests are conducted on Pocheon granite cylinders with various injection rates, and are compared with sleeve fracturing tests. A threshold injection rate is found to fracture the granite specimen under given stress conditions. When the injection rate is below the threshold, the specimen reaches full saturation without fracturing. Injection pressure develops non-linear with time in the injection experiments while it develops linear with time in the sleeve tests.

Valliappan et al. (2019) present a two-dimensional numerical model for simulating hydraulic fracturing in anisotropic media. The model is based on the extended finite element method. The impact on fracture propagation due to anisotropies induced by Young's modulus, permeability and overburden pressure is studied. Different regimes are identified controlling the direction of fracture propagation by the degree of material anisotropy rather than the stress anisotropy.

Tang et al. (2019) use the numerical tool TOUGH-FEMM to model three-dimensional fluid-driven propagation of multiple fractures. Rock deformations associated with fracture propagation are modeled using the finite element-mesh-free method (FEMM). The fluid flow in fractures and porous rock is modeled through TOUGH2 which is a code for the analysis of multiphase and multi-component fluid flow. Fluid-driven fracture growth is simulated at laboratory scale, and multiple interacting fractures are simulated at decameter and 100 m scale.

Finally, it is to be mentioned that two papers dealing with the topic of this Special Issue were published earlier in the RMRE Journal. In Lopez Comino et al. (2017), full-waveforms of the Äspö hydraulic fracturing experiments are analyzed. Li et al. (2018) did a thorough analysis of hydraulic fracturing analysis of shale blocks in the laboratory by simultaneously monitoring acoustic emission events and hydraulic parameters during nucleation and propagation stages of the hydro-fractures.

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