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Cyclic hydraulic stimulation design to develop Enhanced Geothermal Systems (EGS)

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ABSTRACT

Enhanced Geothermal Systems (EGS) are required to extract economic amounts of heat from low permeable geothermal reservoirs. We present hydraulic stimulation scenarios applying various cyclic water injection designs. The general aim is to reduce the risks of unwanted seismic events beyond a certain threshold depending on the vulnerability and exposure of people, buildings and infrastructure.

The presented case studies include hydraulic stimulation designs from experiments at different scales of investigation from laboratory scale to field scale applications. Cyclic hydraulic fracturing tests on cubic granite samples were conducted in the laboratory using a true tri-axial test equipment combined with acoustic emission (AE) monitoring. A new advanced protocol of progressively increased cyclic injection and a pulsed injection design for hydraulic fracturing experiments were applied at the Hard Rock Laboratory in Äspö, Sweden. On field scale, a cyclic stimulation treatment was carried out in granodiorites at the EGS site in Pohang, Republic of Korea in well PX-1.

1. INTRODUCTION

The general aim of hydraulic stimulation designs in context with geothermal application is to develop an advanced injection strategy to develop a suitable process zone at depth to extract heat for electricity provision or use heat directly for district heating or other purposes. The challenge is to optimize and control the fracture development and simultaneously mitigate the risks of unwanted seismic events beyond a certain threshold (Majer et al. 2007). We tested several injection strategies on different scale of investigation from laboratory experiments, experiments in underground research laboratories and field experiments to address this challenge. The results can be applied to better understand the fracturing processes and accompanied seismic events to redesign schedules for field experiments to reduce the seismic risks.

2. RESULTS

Experiments on different scale of investigation were carried out to test diverse injection strategies. Laboratory experiments were performed in a true tri-axial high pressure test equipment on Korean Pocheon granites combined with CT scans and acoustic emissions (AE) monitoring (Zhuang et al. 2018). The experiments on intermediate (meso) scale were carried out at Äspö Hard Rock Laboratory (HRL) in fine grained diorite-gabbro, Ävrö granodiorite and fine grained granites (Zang et al. 2017). This underground research laboratory is located near the city of Oskarshamn, Sweden. The field application was performed in the granodiorites at the Pohang EGS site in the well PX-1 (Hofmann et al. 2019).

2.1 Laboratory Experiments on Pocheon granites

Laboratory experiments were performed on cubic samples of Pocheon granites with a side length of 100 mm, including a 5 mm diameter borehole with a depth of 70 mm for the injection of water. Previous experiments on this rock type showed the reduction of breakdown pressure by ca. 20% for a cyclic injection strategy compared to conventional injection with constant rates (Zhuang et al., 2017). Concurrently measured induced seismicity (the maximum AE amplitude) could be reduced for cyclic injection by around 20% compared to the conventional experiment. A study by Patel et al. (2017) on Tennessee sandstones under triaxial stress conditions showed similar results. They observed a reduction of breakdown pressure by 16% for dry specimens but no effect for saturated sandstones.

A new series of experiments were carried out to test the influence of pulsed injection on the injectivity performance (permeability enhancement) and the related acoustic emissions (Figure 1). Stepwise pulse pressurization (SPP) showed the best permeability enhancement among the different injection schemes. Cyclic progressive injection (CP) showed the lowest induced seismicity while improvement in injectivity is not as pronounced as for the stepwise pulse pressurization (Zhuang et al., 2018).

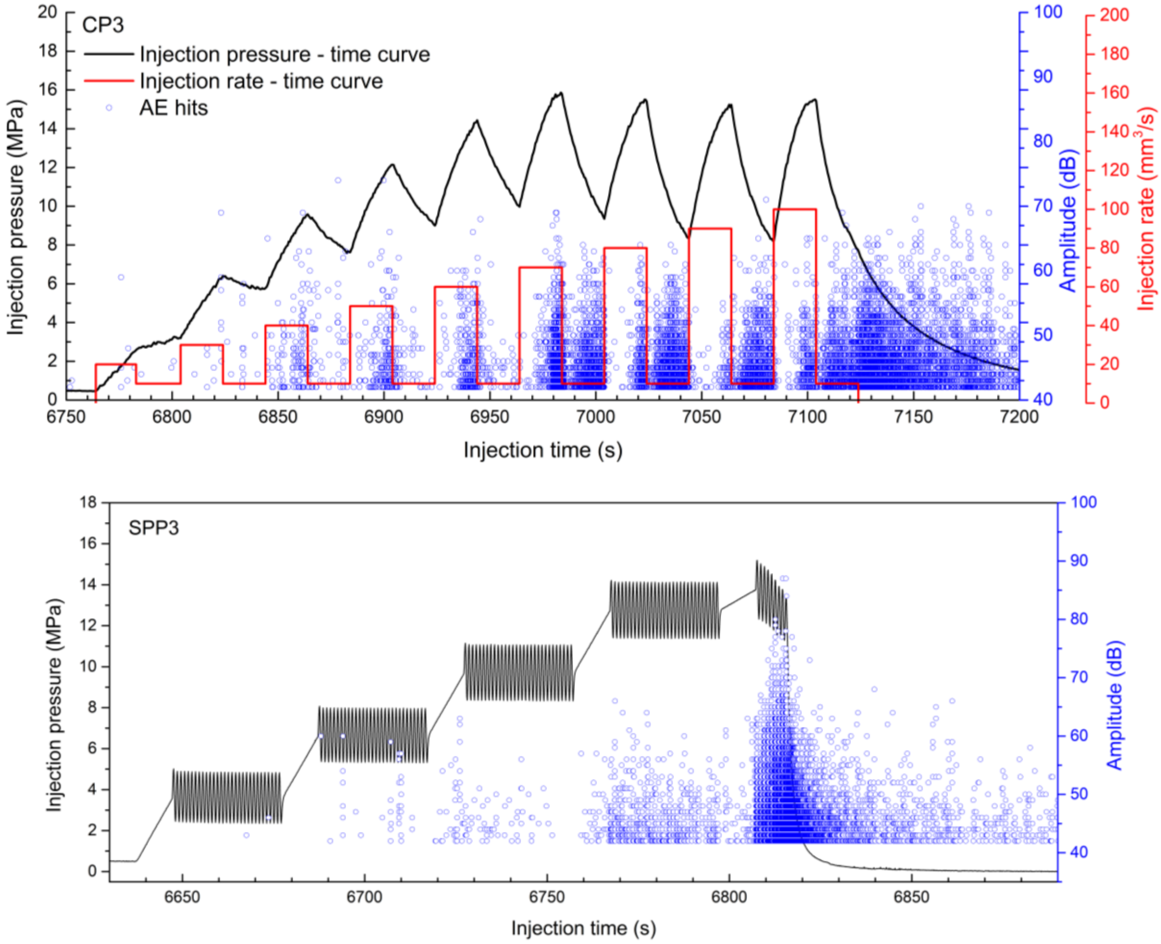

Figure 1: top: cyclic progressive injection (CP); bottom: stepwise pulse pressurization (SPP). Displayed are the injection pressures, flow rate (top figure) and related amplitudes of acoustic emissions versus time (from Zhuang et al., 2018)

2.2 Experiments at Äspö Hard Rock Laboratory

A series of hydraulic fracturing experiments were performed in the Hard Rock Laboratory in Äspö, which is located in the south of Sweden approximately 35 km north of the city of Oskarshamn. The experimental setup and the injection schedules are described in detail in Zang et al. (2017). Three different hydraulic injection protocols were performed (see Figures 2 and 3). First, conventional testing with constant flow rate was carried out. For the second design, the flow rate was progressively increased. For the third procedure, an additional pressure pulse was added on top of the progressively increasing constant pressure intervals (Figure 3).

Similar to the results of the laboratory experiments on Pocheon granites, the formation breakdown pressure (FBP) of the cyclic design schedule with progressively increasing flow rate (FBP = 9.2 MPa) is approximately between 30% and 16% lower than the formation breakdown pressures for the conventional hydrofracs (FBP = 13.1 MPa and 10.9 MPa, respectively), which were performed in the same rock type (Zimmermann et al., 2019).

Permeability development for the conventional hydrofracs is accompanied with an increase of acoustic events (Figure 2a). The highest increase of permeability is attributed to the refracs with the largest number of events. In contrast to this observation, the fracturing test with progressively increasing flow rate showed no acoustic events. Only during the last refracs a few events were measured (Figure 2b). A similar result is obtained for the pulsed fracturing experiment (Figure 3): no seismicity could be observed during testing, but a pressure reduction during the third cycle indicated the fracture breakdown (see arrow in Figure 3).

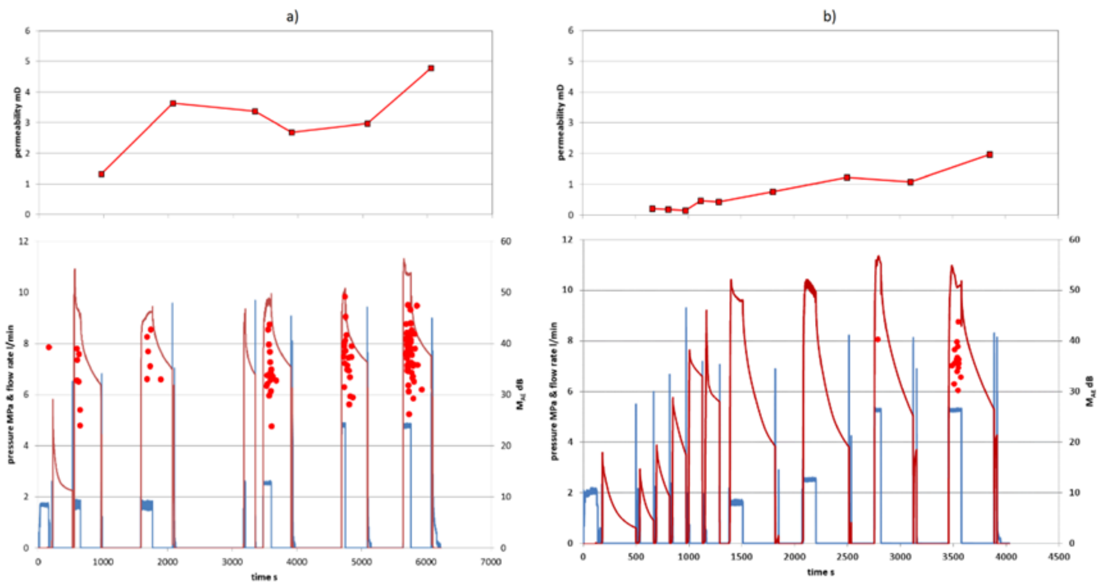

Figure 2: Permeability development of hydraulic fracturing tests at the Äspö HRL. a) conventional hydraulic fracturing experiment with main frac and subsequent refracs. b) progressively increasing flow rate design with subsequent refracs (Zimmermann et al., 2019; Zang et al., 2019).

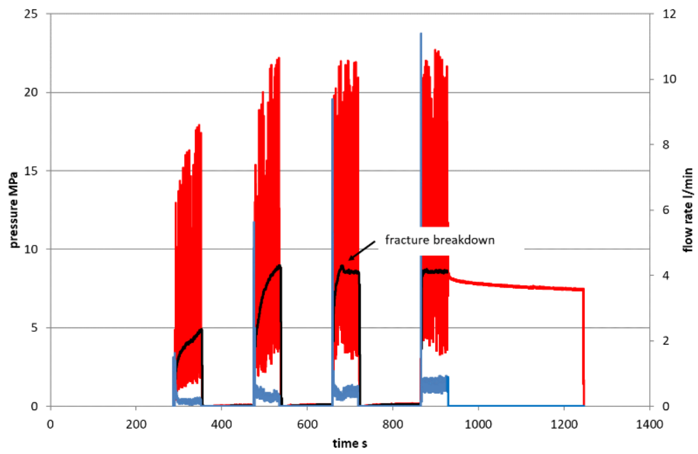

Figure 3: Pulsed hydraulic fracturing experiment in the Äspö HRL. Displayed are the flow rate and the interval pressure of the main frac with four increasing flow rate stages and pulses on top. The formation breakdown pressure (FBP) is attributed to the pressure reduction during the third cycle and is indicated by an arrow (modified from Zimmermann et al., 2019).

2.3 Field scale experiment in the well PX-1 at Pohang EGS site

In the framework of the European funded DESTRESS project a cyclic soft stimulation (CSS) experiment was performed at the Pohang geothermal site, where an advanced injection protocol and an adjusted traffic light system was applied to mitigate the seismic risks (Hofmann et al., 2018, 2019).

The stimulation experiment was carried out from 7 August until 14 August 2017; a total of 1,756 m³ of surface water was injected into Pohang well PX-1 at flow rates between 1 and 10 l/s, with a maximum wellhead pressure of 22.8 MPa, according to a site-specific cyclic soft stimulation schedule and traffic light system (Hofmann et al., 2018; Figure 4). A total of 52 induced micro-earthquakes were detected in real-time during and after the injection (Hofmann et al., 2019). After the Mw=1.4 event the flow rate was reduced to the minimum possible flow rate according to the applied traffic light system. During this low flow rate stage, the largest event with Mw=1.8 (revised later to Mw=1.9) was observed and injection was terminated and the well was opened for pressure release and flow back. During flow back a total of 1,771 m³ of water was produced from the well over roughly one month, while no larger-magnitude seismic event was observed. The dataset collected during this injection exhibits pressure-dependent injectivity increase with fracture opening between 15 and 17 MPa wellhead pressure. A transmissivity increase during the injection stages was calculated by harmonic pulse testing (Salina Borello et al., 2019), but no significant permanent transmissivity increase was observed due to the limited volume of the treatment.

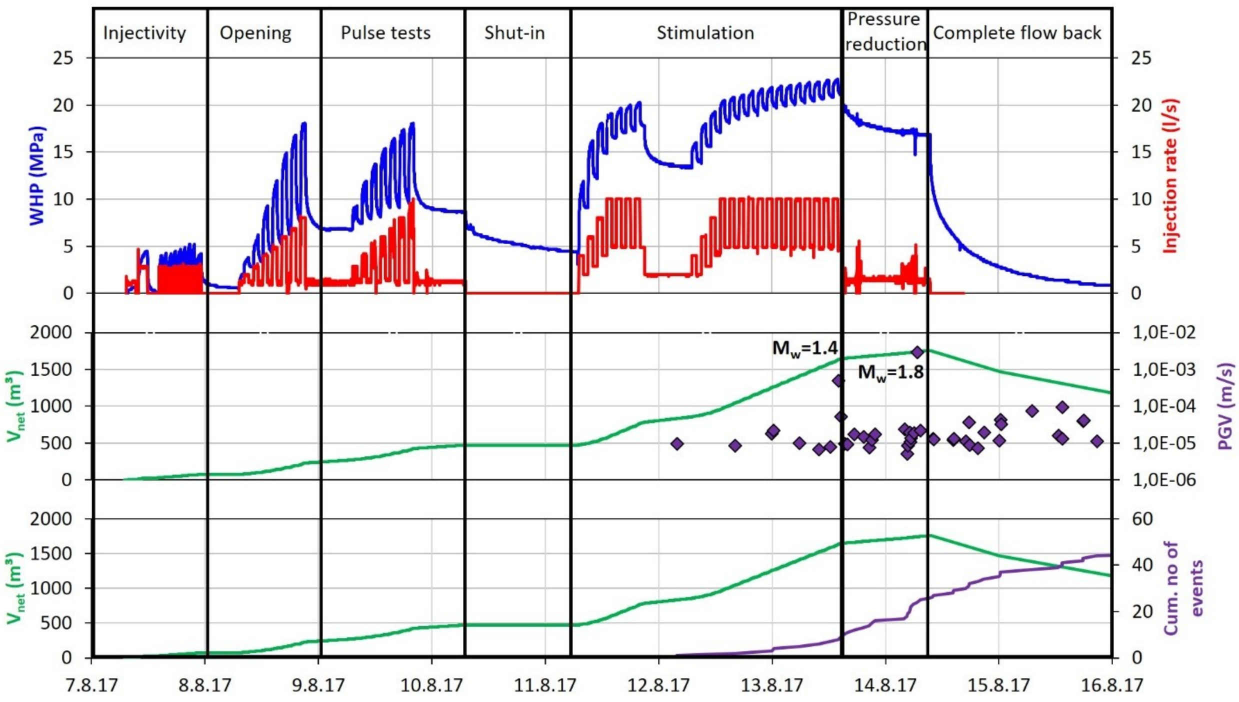

Figure 4: Field experiment in granites at the Pohang EGS site from August 2017 to test the cyclic soft stimulation (CSS) design (Hofmann et al., 2018; Hofmann et al., 2019).

3. CONCLUSION

The risk of unwanted high seismic events during and after hydraulic stimulation treatments is a major concern in geothermal site developments and can lead to the suspension of projects due to the loss of acceptance of the authorities and the general public. To address this problem, experiments at smaller scales within mines or in laboratories under safe conditions without the risk of any harm or damage to the environment offer the opportunity to perform a large number of hydraulic stimulation tests to verify different injection scenarios to mitigate the seismic risks. Thereafter, the results help to better understand the fracturing process and the accompanied origin of seismicity to redesign the injection schedule for field experiments accordingly.

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