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Keynote: Fatigue Hydraulic Fracturing

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Abstract

In this article, the concept of Fatigue Hydraulic Fracturing (FHF) is described, and its geothermal application is discussed. The basic idea behind fatigue fracturing is to vary the effective stress magnitudes at the fracture tip to optimize fracture initiation and growth. The optimization process can include lowering seismic radiated energy and/or generating fracture networks with various geometry and permeability. Historically, we start referring to results from mechanical laboratory core testing, discrete element simulation of fluid-induced seismicity, and application of cyclic water-fracs at the enhanced geothermal system site Groß-Schönebeck, Germany. Then, an in situ experiment at Äspö Hard Rock Laboratory is summarized to bridge the gap between laboratory core testing and wellbore-size hydraulic fracture treatments in hard rock. Three different fluid injection schemes (continuous, progressive and pulse injection) are tested underground in naturally fractured, crystalline rock mass in terms of associated induced seismicity and permeability performance. Under controlled conditions, hydraulic fractures are extended to about 20–40 m^2 in size from a 28 m long, horizontal borehole drilled from a tunnel at 410 m depth. The facture process is mapped by an extensive array of acoustic emission and micro-seismic monitoring instruments. Results from three water-injection tests in Ävrö granodiorite indicate that the fracture breakdown pressure in tendency becomes lower and the number of fluid-induced seismic events becomes less when continuous, conventional fluid injection is replaced by progressive fluid-injection with several phases of depressurization simulating the fatigue treatment. One reason for this may be that in the dynamic, fatigue treatment a larger fracture process zone is generated compared to the size of the fluid pressurized zone developing during the injection phases into crystalline rock. We see mine-scale tests with hybrid sensor arrays of importance to identify and understand the actual hydraulic fracture mechanisms in hard rock. In addition, the mesoscale data obtained underground allow downscaling to laboratory core results, and upscaling to borehole reservoir stimulation results.

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Keywords: Fatigue process; hard rock; hydraulic fracturing; stress measurements

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1. Introduction

Hydraulic fracture growth through naturally fractured rock is an area of interest and current research for petroleum, mining and geothermal applications. In particular in the development of enhanced geothermal systems (EGS), hydraulic fracturing is used to form fracture networks connecting injection and production well for heat exchange purposes. However, hydraulic fracturing imposes environmental risks, one of which is induced seismicity associated with the permeability enhancement process [1–3]. Of particular interest are, therefore, methods that limit the number and magnitude of seismic events while the required fracture permeability is obtained. In this context, the fatigue hydraulic fracturing (FHF) concept and the multi-stage hydraulic stimulation concept have been proposed. The key point in fatigue hydraulic fracturing is the frequent lowering of the injection pressure to allow stress relaxation at the fracture tip [4]. Reducing the maximum injection pressure by alternative injection schemes will affect the damage zone surrounding the fracture and also the radiation pattern of seismic events associated with fracture growth [5]. For multi-stage stimulation, instead of massive stimulation, injection rate and pressure are controlled, and the reservoir is formed stage by stage [6, 7].

The multi-stage stimulation method has been successfully applied at reservoir scale in commercial shale gas development [8] while the fatigue hydraulic fracturing method using alternative fluid-injection schemes is still at the concept proof stage and its validation in the field has been achieved only for a limited number of tests underground [5]. A general understanding of fatigue failure is that damage accumulates in rocks during cyclic loading, consequently leading to strength decrease. However, the mechanism of rock fatigue failure has not yet been fully understood. More important, the fatigue cycling process during mechanical loading [9] can be very different from fatigue hydraulic fracturing where a high-pressurized fluid is operated at the fracture tip [4].

Modeling hydraulic fracture growth and associated induced seismicity is a highly nonlinear and complex process [10]. Based on laboratory tri-axial indenter tests results Yoon et al. [11] developed and calibrated a hydro-mechanically coupled modeling tool which is able to study the application of fatigue hydraulic fracturing for dynamic cyclic and pulse fluid injection schemes. During cyclic injection the fluid pressure in the discrete element simulation runs is found to be lower compared to constant injection rates as operated in conventional hydraulic fracturing. This is true for both, intact and naturally fractured crystalline reservoirs [11], and fractured reservoirs with multiple stimulated wells [12]. The interaction of hydraulic fractures with natural fractures in hard rock is investigated in a separate contribution in this volume [13].

There are different scales involved in hydraulic treatment of rock mass. Hydraulic fracture operations in hydrocarbon [14], shale gas [15] and geothermal exploitation [16] involves rock volumes up to several hundreds of meters. Hydraulic fractures at mine scale normally extend over few tens of meters only [17, 18].

At reservoir scale, a cyclic hydraulic stimulation treatment was performed in 2007 at the geothermal research well GtGrSk4/05 near Groß Schönebeck [19]. The aim of this stimulation treatment was the enhancement of productivity of the reservoir targets as a prerequisite for geothermal power generation of the Rotliegend Formation as an Enhanced Geothermal System (EGS). The stimulation treatment was carried out in the volcanic rocks (andesites) of the Lower Rotliegend, where permeability is mainly fracture dominated. During a cyclic stimulation treatment, the propagation of fractures and the final extension can be influenced by the flow rate and the duration of each cycle. This opens the possibility to regulate the growth of the fracture in height and length and leads to optimal connections to the reservoir rocks. Horizontal fracture growth is mainly achieved during the high flow rates whereas the low flow rates lead to a consolidation of fracture width (aperture). In addition, during the high flow rates of up to 9m³/min (150 l/s) low concentrations of quartz sand (20/40 mesh size) were added to support a sustainable fracture width. Transport of the sand in the fracture and the well was realized solely by the high flow velocity of the injected water. In total, 13,170 m³ of fluids and 24.4 tons of quartz sand were injected into the volcanic rocks. Maximum well head pressure achieved 586 bars at maximum flow rate. The total duration of the treatment was 6389 minutes (Fig. 1). Analysis of the micro-seismic events registered by the deep monitoring station in the adjacent well EGrSk3/90 in 3800 m depth revealed a very low seismicity during and after stimulation (80 events during the six days), with moment magnitudes (Mw) ranging from -1.8 to -1.0. The geophone recorded induced seismic events towards the end of the stimulation phases with the highest flow rates [20].

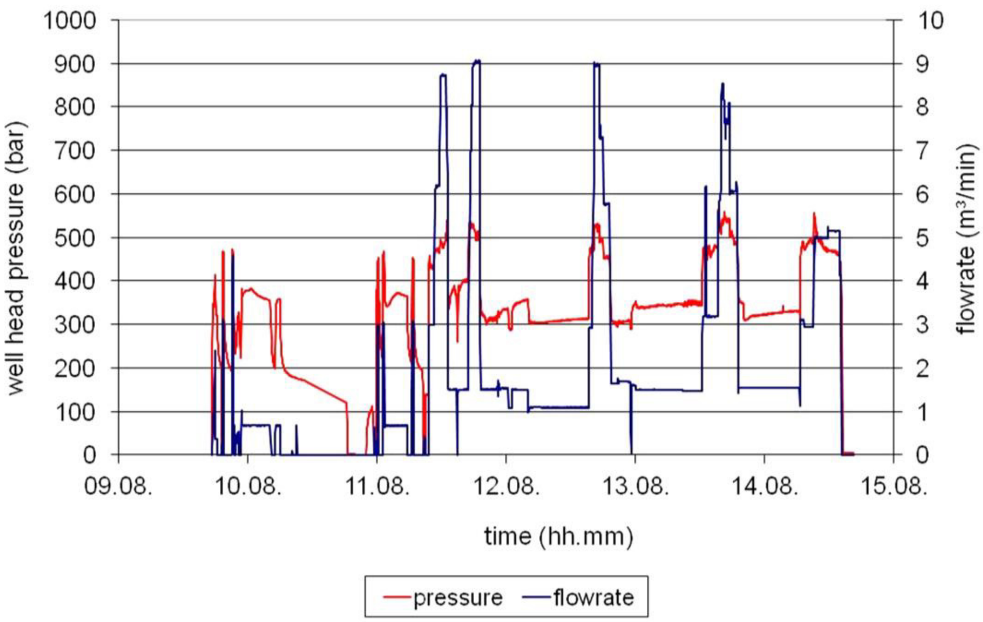

Fig. 1. Schedule of the cyclic hydraulic stimulation treatment in the volcanic rocks at the geothermal research site in Groß Schönebeck (modified after [19]).

In the following, we summarize a field test operated 2015 in Äspö Hard Rock Laboratory, Sweden to bridge the gap between reservoir-scale rock mass response after cyclic fracturing applied in EGS stimulation [19] and laboratory cyclic fluid injection experiments with X-Ray CT fracture pattern analysis [21]. The work described aims at understanding the mechanisms operating at the fracture tip when different high-pressure fluid-injection schemes are applied to hard rock. Second, the identified crack-tip mechanisms can be applied to design the permeability enhancement process by lowering the induced seismicity events associated with fracture nucleation and growth. Third, we are discussing optimum reservoir stimulation strategies and their technical realization applying the concept of fatigue hydraulic fracturing.

2. In situ Experiment

Validating the FHF concept requires three steps: (1) determination of the fracture breakdown pressure (FBP), (2) detection and comparison of fluid-induced seismicity events, and (3) information on the permeability enhancement process. In the following, we compare the conventional hydraulic fracturing injection scheme with alternative fluid injection schemes simulating the FHF treatment in the field under controlled conditions. Äspö HRL has been selected as test site because geology, hydraulics and rock mechanics are well known from a large number of tests, including hydraulic fracturing stress measurements [22] and integrated stress determination [23]. The stress conditions from [22] are assumed to be valid, i.e. if the borehole is drilled in the direction of minimum horizontal stress, such stress conditions would favor the propagation of radial and parallel fractures (Fig. 2). This is because once open, hydraulic fractures start to grow and orient themselves rapidly in the plane containing the maximum and intermediate principal stress.

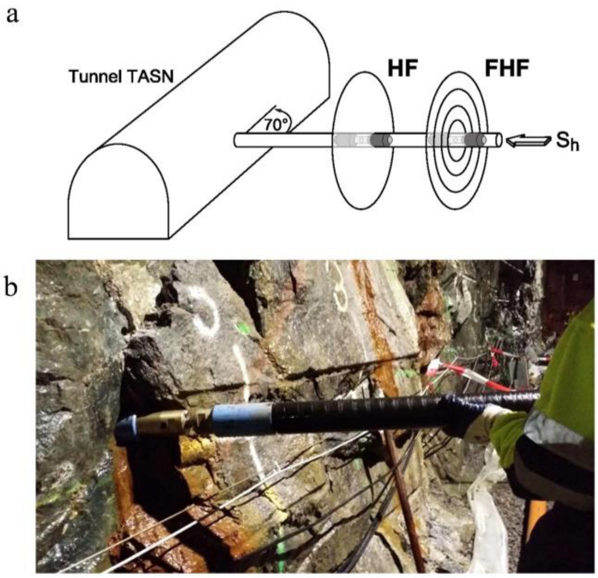

Fig. 2. (a) Two different fluid-injection schemes and their impact on induced seismicity evolution are compared in naturally fractured granitic rock mass at Äspö HRL. At depth level 410 m, conventional (HF) and fatigue hydraulic fracturing (FHF) are performed in a sub-horizontal borehole (diameter 4 inch) drilled from an experimental tunnel to total length of 28 m. (b) Fractures are designed by different water-injection schemes using a modified straddle packer system. The fracture process is mapped by acoustic emission and micro-seismic sensors.

A high-resolution borehole camera, scanning the entire borehole (diameter 102 mm), and the drill cores (diameter 86 mm) were used to select suitable test sections. In phase I of the experiment, a conventional fracture test with continuous increase of fluid pressure in the testing interval is carried out. For this, a continuous flow rate versus time is used until the fracture breakdown pressure FBP is reached (Fig. 2, HF). After the fracture is formed the flow in the injected part of the borehole is tested and determined (Lugeon test). In phase II, the hydraulic test is modified and a different water injection scheme is used (i.e. progressive) with frequent phases of depressurization before the FBP is reached allowing stress relaxation at the fracture tip (Fig. 2, FHF). After the flow test, an impression packer is used to map fracture orientation at the borehole wall. Phases I and II of the in situ experiment are repeated in different rock types, and are operated with fracturing equipment of two different companies (MeSy Solexperts Bochum, Germany and ISATech Prague, Czech Republic).

All phases of the hydraulic fracturing in situ experiment were monitored with acoustic emission (AE), micro-seismic borehole sensors and geophones, as well as electromagnetic sensors. In total, 39 sensors are operated in the near-field, close to the testing borehole (depth level 410 m), and 36 sensors were deployed in the far-field above (depth level 280 m) and below the test section (depth level 450 m). In the following, we report on data obtained from the AE monitoring system operated by the Gesellschaft für Materialprüfung und Geophysik (GMuG) mbH Bad Nauheim, Germany. This network monitored in the frequency range from 1 kHz to 100 kHz. The in situ AE system consists of eleven AE sensors and four accelerometers (Fig. 3a). AE sensors employed are uniaxial side view sensors for borehole installation. For this three inclined monitoring boreholes are drilled left and right of the hydraulic testing borehole F1. Additional sensors are installed in short boreholes in the tunnel roof (Fig. 3b).

Data was recorded using the measuring system GMuG AE system that is suitable both for continuous recording of data and recording in trigger mode with 1 MHz sampling frequency per channel. Below, we report on data registered with the in situ triggering system. Very sensitive trigger conditions were chosen in situ to maximize the sensitivity of the network. Once a trigger is detected, data is recorded on all synchronized channels. A ring buffer for pre-trigger recording is implemented. Picking of P- and S-wave onsets is based on a Hilbert transform and modified short term/long term average algorithm. Localization of AE events is based on gradient descent and a modified least square algorithm. For localized events the AE magnitude is estimated using the relative magnitude approach [24]. For more details on the in situ trigger data processing, see [5].

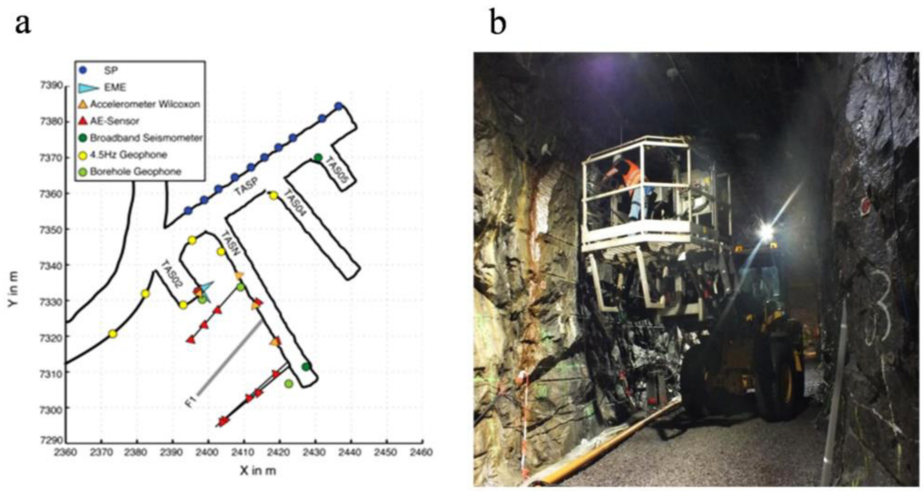

Fig. 3. (a) Near-field multi-sensor array design at depth level 410 m in Äspö HRL to monitor hydraulic fracture growth with different water-injection schemes. The hydraulic testing borehole F1 is drilled sub-horizontal, parallel to the minimum horizontal compressive stress. Three inclined monitoring boreholes on both sides of the testing borehole are equipped with AE sensors. (b) Additional sensors including accelerometers are installed in the tunnel roof; after [5].

3. Results from In Situ Testing

Some results from three hydraulic in situ tests in Ävrö granodiorite are listed in Table 1. Experiment HF1 and HF2 are conventional hydraulic fracturing tests with continuous increase in injection pressure. In experiment HF3, the fatigue concept is simulated by progressive water-injection with four phases of depressurization before the FBP occurred. The FBP is determined from the initial fracturing cycle of the conventional HF. The reopening pressure FRP is determined from the first re-fracturing cycle of HF. The magnitude of the minimum horizontal stress, Sh is determined from the instantaneous shut-in pressure. The vertical stress is computed from the overlying rock density to be 10.9 MPa. In Table 1, the mid test interval in borehole F1, the injection style, the fracture breakdown pressure (FBP), the fracture reopening pressure (FRP) and the horizontal minimum stress (Sh) determined from instantaneous shut-in pressure (ISIP) is listed.

Table 1. Results from three in situ hydraulic fracturing experiments in Avrö granodiorite, after [5].

Experiment	Test interval	Injection style	FBP (MPa)	FRP (MPa)	Sh (MPa)
HF1	25.0	continuous	13.1	8.9	8.3
HF2	22.5	continuous	10.9	6.7	8.6
HF3	19.0	progressive	9.2	8.8	9.2

In situ triggered AE data were used to obtain information about the fracture growth, its location, orientation and extension in near real time. During the experiment all events that were located automatically during fracturing, shut-in or bleed-off were then manually reviewed and plotted on site. During post processing a seismic catalogue was created that is free of noise events. In total, this catalogue contains 196 relocated AE events which occurred during the fracturing time periods. More information on this data set is found in [5]. Below, some results from hydraulic testing in Ävrö granodiorite are summarized using this catalogue.

In Figure 4, results from one conventional (HF2) and one progressive, fatigue hydraulic fracturing test (HF3) next to each other in Ävrö granodiorite are compared. Hydraulic data are indicated on the left ordinate, i.e. injection pressure and flow rate. Cumulative AE amplitude from the in situ triggered and localized data is indicated on the right ordinate. Both data sets are shown versus experimental time on the abscissa.

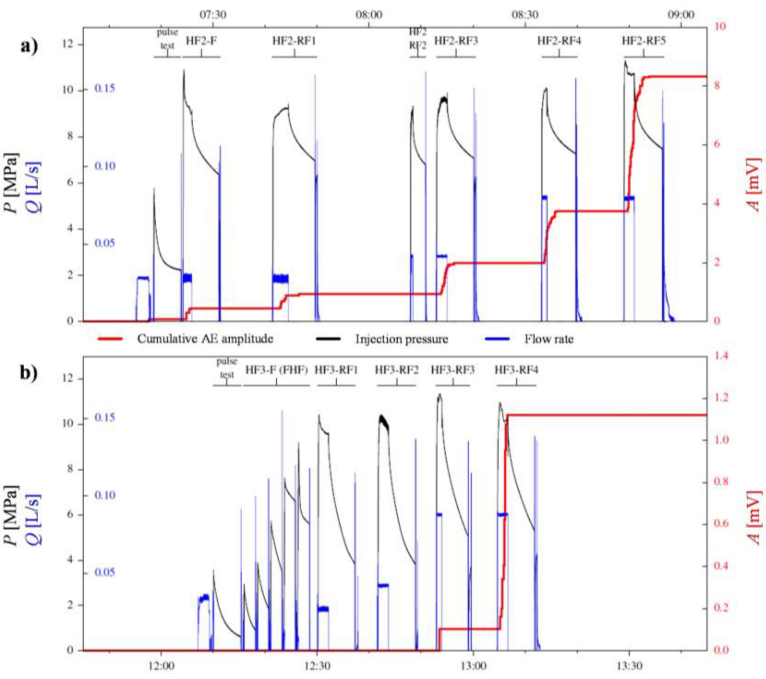

Fig. 4. Injection pressure and flow rate (left ordinate) and relative AE magnitude (right ordinate) for two in situ experiments with different fluid-injection schemes: (a) continuous water injection in conventional hydraulic fracturing (HF2), and (b) progressive water injection in five stages interrupted with four stages of depressurization simulating the fatigue treatment (HF3); after [5].

Initial fracturing cycle and first refrac of HF2 test (Fig. 4a) indicate pressure values of 10.9 MPa and 6.7 MPa. After five cycles of fatigue testing (Fig. 4b), the FBP is determined to be 9.2 MPa. This value is 15% lower compared to the FBP value from conventional HF2. While AE events are observed during all re-fracturing phases (except refrac 2) of the conventional HF2 (Fig. 4a), in experiment HF3 with progressive water injection, AE events occur in the third and fourth re-fracturing stage only (Fig. 4b). No AE activity is observed during five progressive pressurization stages interrupted by four depressurization phases before the FBP occurred despite the steady increase of flow rate in the last three re-fracturing cycles. The in situ trigger level of the AE system and the procedure in AE localization technique were the same in all experiments, namely HF1-HF3.

In Figure 5, relocated AE events from three experiments HF1-HF3 are shown in map view and side view. For experiments HF1 and HF2 the AE events cluster and outline near vertical fracture planes. AE activity migrates with time away from the borehole in the direction of maximum and intermediate principal stress (perpendicular to the testing borehole F1). For the HF3 experiment, no clear fracture plane is outlined by AE hypocenter results, and no clear migration of AE hypocenters is visible. The maximum fracture extension from AE analysis is 5.3 m, 6.7 m and 2.3 m for HF1, HF2 and HF3, respectively [5]. The AE fracture outline was compared to impression packer results. While in conventional HF1 and HF2 single hydraulic fractures were confirmed from AE data and impression packer results, in the experiment HF3 simulating FHF two fracture planes were identified by borehole impression packer. Further analysis is needed to conclude on the nature of the FHF fracture pattern.

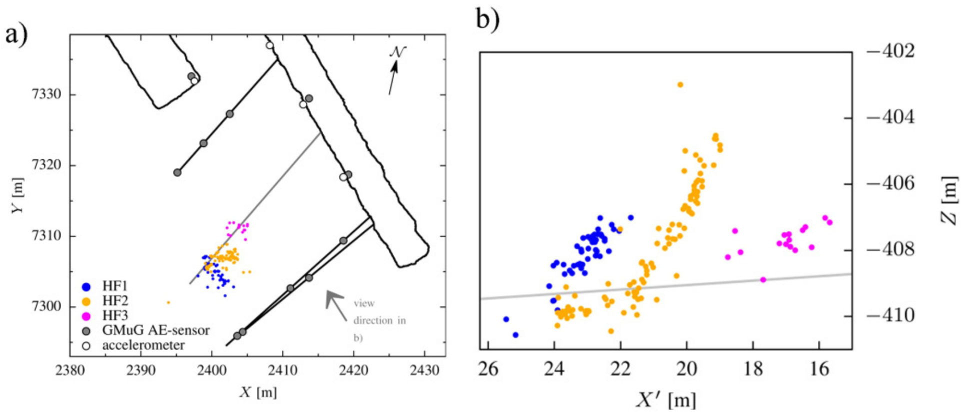

Fig. 5. Comparison of relocated acoustic emission events for three tests HF1-HF3 in Ävrö granodiorite (a) in map view, and (b) in side view. Solid black line outlines the tunnel at the experimental site. Thin black lines outline the long monitoring boreholes and solid grey line outlines the hydraulic testing borehole. Circles symbolize the sensors locations (grey – AE sensor, white – accelerometer); after [5].

4. Discussion

Results from the in situ field test indicate that the fracture breakdown pressure of rock (Ävrö granodiorite) in the fatigue test was lower compared to the conventional test (30 % lower HF1 versus HF3, 15% lower HF2 versus HF3). During five phases of progressive water injection with four phases of depressurization (HF3), no induced seismic events were observed. However, most of the fracturing stages of the conventional tests HF1 and HF2 were accompanied by in situ triggered and relocated AE events.

The in situ test results in granitic rock are in line with laboratory results on rock cores (diameter 100 mm, length 200 mm) and concrete blocks (one cubic meter in size) [25]. In their study, the authors found a fracture breakdown pressure 18% lower using cyclic instead of continuous water injection. The same tendency of lower fracture breakdown pressure using cyclic water injection was found when testing Pocheon granite cores from Korea (diameter 50 mm, length 100 mm) [21]. In their study, the conclusion was that hydraulic fracturing in the field can be conducted with smaller injection pressure (82% of conventional value) when it is subjected to fatigue cycles. In the laboratory the cycle number was varied from 2 to 150.

We see further upscaling of the fatigue hydraulic fracturing concept to the wellbore scale valuable. However, based on the findings from laboratory and mine-scale testing, a careful design of the fatigue hydraulic fracturing treatment at wellbore scale is needed. Appropriate numbers of operational injection parameters need to be assigned (e.g., number of cycles, injection duration, interval duration, rate increment per cycle, number of fracturing stages). Only in this way, the fracture optimization process can be guaranteed. The most ambitious task will be to design a test with minimum seismic radiated energy and maximum permeability performance.

Our present knowledge about fatigue hydraulic fracturing treatment indicates that reduction of breakdown pressure and seismicity can be obtained with the pump capacity and testing time that is normally applied in conventional testing for fracture extension operations, leak-off testing and hydraulic stress measurements. The new approach is to allow the stresses at the fracture tip to fully relax (frequently) and thereafter generate a new loading state that permits the fracture to seek and find the optimum and least energy consuming fracture extension at the new stress state at the fracture tip. Laboratory experiments on crystalline rock and results from the Äspö experiments have shown that the resting time after venting the pressure system has been enough to release the old and generate the new stress situation at the fracture tip to enhance the fracture propagation. If this also holds for fatigue hydraulic fracturing at wellbore scale needs to be tested in the field. If the procedure is functioning it is likely that existing industrial pump capacities can be applied and it is a matter of modifying the scheme of pumping to reach lower breakdown pressure and reduced induced seismicity.

5. Conclusion

Based on the analysis of three hydraulic fractures propagated at 410 m depth in Ävrö granodiorite and mapped with acoustic-emission monitoring, the following conclusions are drawn. (1) In the framework of the limited amount of tests performed, the formation breakdown pressure in fatigue treatment is lower compared to the conventional hydraulic fracturing. Also, the total number of acoustic events is lower in the progressive water-injection test with frequent phases of depressurization. (2) The in situ acoustic emission monitoring system recorded events in the frequency range above 1 kHz for three fractures in Ävrö granodiorite. Acoustic emission relocations outline the fracture location, orientation and expansion. The single fracture location and orientation is in good agreement with impression packer results for the two conventional tests. The double fracture observed in the progressive water injection test needs further interpretation. (3) To bridge the gap between hydraulic fracturing results on laboratory cores tested and borehole size stimulation tests in geothermal applications, hydraulic testing in underground research laboratories is seen valuable. The fracture monitoring system, however, has to be adapted to the frequency range expected. Different arrays with complementary sensors need to be in operation during in situ testing.

A more detailed picture of the hydraulic fracture growth process will follow when (a) double difference relocation methods are applied to the in situ triggered acoustic emission catalogue [26], or (b) the post-processing of the continuous waveform recordings of the experiment is completed [27]. This picture will include information on local fracture modes (tensile, shear), their evolution in space and time, as well as numbers of fracture apertures from hydraulic readings. Future goal is to evaluate the energy partition in hydraulic fracturing (hydraulic energy, seismic radiated energy, fracture surface energy and dissipation), and to minimize the seismic energy while the fracture energy (permeability) is maximized.

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