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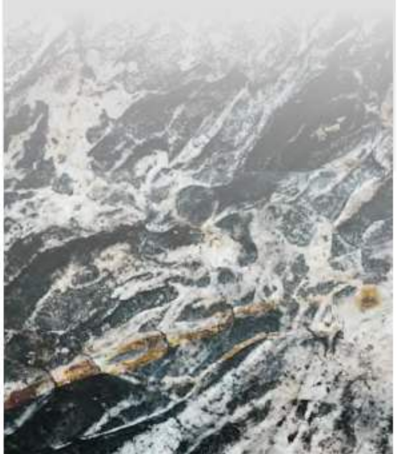

Introduction to the Special Issue: Deep Underground Laboratories (DUL)

Xiaodong Ma, Department of Earth Sciences, ETH Zürich
Special Issue Editor

An inherent limitation of studying the in situ geomechanical processes is due to accessibility constraints. Laboratory attempts to replicate realistic stress and temperature conditions tend to compromise on the issue of scale. To alleviate this problem, experiments in the Deep Underground Laboratories (DUL) have been considered as the stepping stone from ex situ to in situ full scale characterization. Recently, this concept has been particularly popular in the context of Enhanced Geothermal Systems (EGS) and anthropogenic seismicity. Using existing underground infrastructures -- for example, mines and tunnels -- rock masses at greater depths can be accessed, and sophisticated characterization, instrumentation and experimentation can be materialized.

The ongoing DUL work carried out at the Sanford Underground Research Facility (SURF), formerly the Homestake Gold Mine, is known to many ARMA members. Echoing such initiative in North America, underground laboratory efforts have in fact gained no less attention globally. In this Special Issue, we introduce some of the ongoing DUL activities in Europe, which might not be so well-known for North American and/or international readers. A total of 11 articles have been collected, which represent different geologic settings, lithologies and many aspects of the very inter-disciplinary DUL research.

In the order of appearance (and practically the DUL depth), the Special Issue consists of the articles listed with page numbers. The STIMTEC and Äspö experiments were conducted at the depth of 130m (by Renner et al.) and 410m (by Zang et al.), respectively. The depth of the Grimsel experiment (described by Gischig, Krietsch, et al.) is comparable to the latter, reaching approximately 500m. Notably, efforts of running up the scale and going deeper are continued by the transition from the Grimsel to the Bedretto experiments, both led by ETH Zürich. The second half of the articles highlights the newly-established Bedretto Lab (exceeding 1000m depth) in the Swiss Alps, covering its recent progress from multiple disciplinary perspectives.

We appreciate the contributions of the following authors to this Special Issue. Please note that a second Special Issue on the topic of Underground Labs is forthcoming, with a focus on the North American experience.

STIMTEC – A mine-scale hydraulic stimulation experiment of anisotropic metamorphic rock with evaluation by mine-back drilling

*Submitted by Renner, J. and the STIMTEC team**
STIMTEC team: B. Adero, F. Becker, F. Blümle, C. M. Boese, Y. Cheng, G. Dresen, T. Fischer, T. Frühwirt, C. Janssen, V. A. Jimenez Martinez, G. Klee, H. Konietzky, G. Kwiatek, K. Plenkers, S. Rehde, J. Starke, C. Wolin, T. Wonik

The STIMTEC experiment is a joint effort of interdisciplinary teams at German Research Centre for Geosciences (Potsdam), Leibniz Institute for Applied Geophysics, (Hannover), Ruhr-Universität (Bochum), Technical University (Freiberg), and Geomecon GmbH, (Berlin), and GmuG GmbH and Solepxerts GmbH as contractors. It focuses on the link between the seismic fingerprints and the alterations of the network of hydraulic conduits associated with hydraulic stimulations to provide diagnostic criteria for their success.

The integrated approach comprises extensive injection operations including periodic pumping tests, real-time monitoring of acoustic emission (AE) and microseismic events, active ultrasonic transmission measurements, validation (mine-back) drilling into stimulated volumes, laboratory experiments on samples, 3-D numerical stress modelling, and geomechanical simulation. The STIMTEC project targets a volume of about 60 by 30 by 30 meters of strongly foliated metamorphic gneiss in the Reiche Zeche underground laboratory in Freiberg, Germany. The investigation volume is crosscut by multiple small-scale open and healed fractures and three major, steeply-dipping, northeast-southwest trending shear zones at ca. 130 m below surface (Figure 1). The foliation is sub-horizontal causing elastic wave anisotropy best described by vertical transverse isotropy.

The mine-scale hydraulic stimulation experiment with ten stimulated intervals along the 63 m long injection borehole was conducted in July 2018 (see Table 1 for an overview of project activities). Hydraulic injectivity and interference testing was performed before and after the stimulation and in particular exploiting the three mine-back validation boreholes. The validation stage also comprised further stress measurements and re-stimulation of four intervals. The field measurements were concluded in December 2019.

The total injected volume per interval was 15 to 25 liters during the combined frac and refrac stages and up to 500 liters during the subsequent step-rate tests and periodic-pumping (with periods of 60 to 800 seconds), amounting to about 10 m3 of injected fluid volume in total. More than 11,000 high frequency AE events with source sizes on the cm-to-dm scale accompanied the stimulation at the three shallowest injection intervals, while less than 10 AE events were observed for each of the three intermediate-depth stimulation intervals. No AE activity was recorded for the deepest stimulation intervals, where the rock is highly fractured. Moderate seismic AE activity was associated with the stress measurements and subsequent hydraulic testing in the vertical validation borehole.

The evaluation of the experiments performed after the mine-back drilling is ongoing. Some of the central questions that can be addressed with the recently collected data are: To what extent are the apparent seismic inactivity and stress variability related to anisotropy and heterogeneity of the gneiss' physical properties? Do the seismic active zones exhibit enhanced hydraulic properties? How far do hydraulic modifications reach from the injection borehole? How do the hydraulic properties of the stimulated intervals compare to those of the natural damage zones?

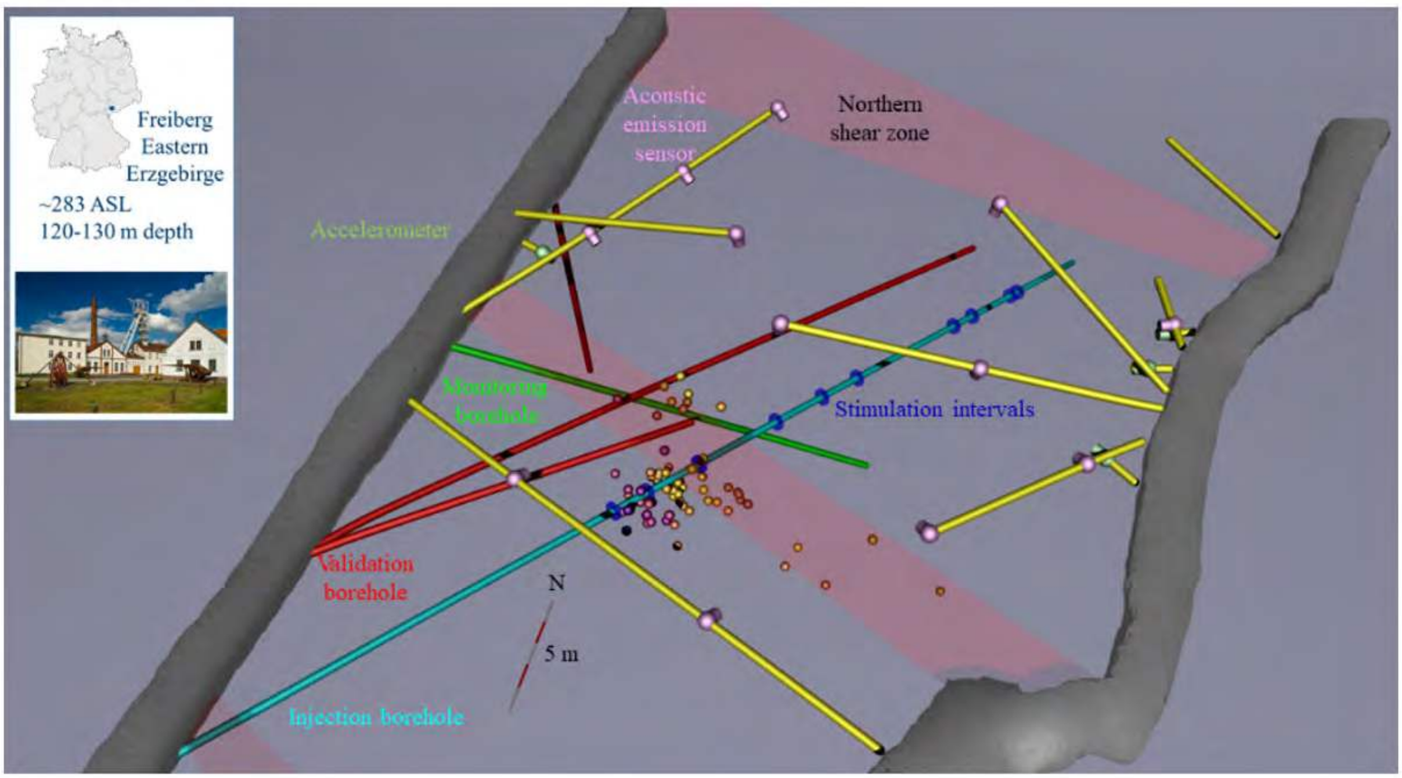

Figure 1: Borehole layout (color coding for boreholes: light blue – injection borehole, yellow: boreholes for sensors of seismic array, green: hydraulic monitoring borehole, red: mine-back validation boreholes) at the STIMTEC site in Reiche Zeche with damage zones (transparent red) as identified through mapping in the tunnels (grey), borehole logs, and retrieved cores. Acoustic emission events during the frac and refrac stages of the three shallowest stimulation intervals (dark blue rings around injection borehole) are shown as coloured spheres. The majority of the 11000 AE events observed for these intervals occurred during the periodic pumping after the frac-cycles. The seismic clouds extend about 5 m radially around the injection borehole. Inset shows location of the Reiche Zeche research mine in Freiberg, Germany.

Table 1: Overview of the measurements obtained during the STIMTEC field campaigns that are currently being analysed.

Dataset/ measurement (Unit)	Acoustic TV/Sonic log (length in m)		Impression packer (no. of intervals)	Pressure (no. of gauges)
Time relative to	before stimulation	after	after stimulation	during stimulation
Injection BH	60	60/49	10	continuous (5)
Hydraulic monitoring BH	25	-	-	continuous (2)
Vertical validation BH	-	15	3	-
Horizontal validation BH	-	64	-	-
Cable BH	-	-	-	-

Dataset/ measurement (Unit)	Ultrasonic transmission (points along well)		Hydraulic testing (no. of intervals)		Acoustic emission (events located)
Time relative to	before stimulation	after	before/after drilling of validation BH	after	during stimulation
Injection BH	30 x 2 orient.	67	6/9	7	11000
Hydraulic monitoring BH	-	26	-	-	-
Vertical validation BH	19	19	2	5	140
Horizontal validation BH	-	70	-	-	-
Cable BH	-	26	-	-	-

The 2015 Geothermal Fatigue Hydraulic Fracturing Experiment Performed at Äspö Hard Rock Laboratory, Sweden

Submitted by Zang, A. and Stephansson, O., GFZ German Research Center for Geosciences, (Potsdam, Germany) and the Äspö Project Group.

In June 2015, a pioneering in situ experiment aiming at optimizing geothermal heat exchangers in granitic rock mass was performed at Äspö Hard Rock Laboratory, Sweden (Zang et al. 2017). The small-budget experiment compared to subsequent Swiss (Dutler et al. 2019) and US national projects (Kneafsey et al. 2018) of a similar target (Zang and Stephansson 2019) involved drilling a horizontal injection borehole subparallel to the minimum horizontal stress, and three inclined monitoring boreholes to map a rock volume of 30x30x30 cubic meter at 410 meter depth. Six hydraulic fractures 30 to 50 square meters in size were propagated from intact injection intervals into naturally fractured granite. Complementary sensors used were sensitive in a broad frequency range, i.e. acoustic emission (70 kHz), accelerometers (25 kHz), geophones (4.5 Hz), borehole geophones (28 Hz) and broadband (120 seconds) among others (electromagnetic).

The overarching goal of the project is to drive a set of parallel fractures at depth in multiple hydraulic stages from a horizontal borehole, and at the same time control induced seismicity and the permeability enhancement process by a innovative fluid-injection protocol (fatigue hydraulic test). Replacing conventional constant flow rate injection by progressive cyclic and pulse pressurization protocols (1) lowers the fracture breakdown pressure, (2) modifies the magnitude frequency distribution of seismic events, and (3) generates a more complex, multiple fracture network in hard rock.

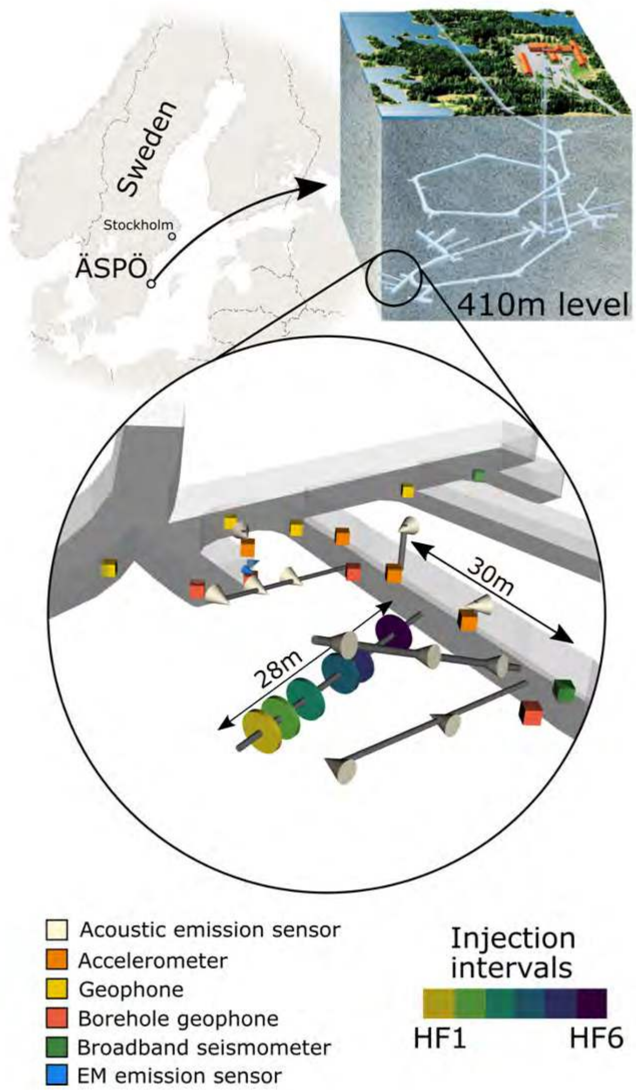

Figure 1. Location of Äspö Hard Rock Laboratory (HRL), Sweden and zoomed-in section of monitoring array of complementary sensors at 410 meter depth. Injection intervals are seen as color coded disks.

We conclude that whether a fracture is seismic or aseismic depends on the budget of the experiment performed. In the near-field (within 10 meters), no seismicity is observed from the hydraulic fracture growth when monitored with geophones, borehole geophones or accelerometers. The broadband sensor results could be used for tilt analysis of the tunnel floor while the hydraulic fractures are opening and closing. Analyzing triggered recordings of eleven high-frequency acoustic emission sensors identifies 197 induced events with moment magnitudes ranging from -4 to -3.5 (Kwiatek et al. 2018). Analyzing continuous recordings and applying full waveform detection (Lopez-Comino 2017) for classification and localization of very weak signals allows identifying 20,000 induced events from six hydraulic fractures (Niemz et al. 2020). Magnitude frequency distributions based on 2386 acoustic events indicate seismic b-values about two times as high as b values from tectonic earthquakes. Interestingly, the b -value of the cyclic injection (2.3) in tendency is higher compared to b-values determined from conventional injections (1.7 to 1.9), indicating a safer treatment (Niemz et al.).

The fracture breakdown pressure in two rock types (Ävrö granodiorite, fine-grained diorite gabbro) was lower (15%) in the variable-flow-rate test compared to the conventional breakdown. This also supports a safer treatment when applying cyclic hydraulic fracturing using smaller pumps. The treatment with progressive water injection plus a secondary pump acting as hydraulic hammer led to the best permeability performance. After the last re-fracturing stage of each experiment the fatigue permeability (25 mD) was five times the value obtained from constant flow rate injections (5 mD) as discussed in Zimmermann et al (2019).

The clustering of acoustic emissions obtained from full waveform analyses of the continuous recordings as well as impression packer results both point in the direction of a more complex, multi-fracture process as compared to conventional tests. In the cyclic test, fracture planes with varying strike and dip directions are inferred using expectation maximization clustering and are interpreted as a multiple fracture activation process (Niemz et al. 2020). On the other hand, results from the impression packer in the same test identify two fractures at the borehole wall propagated in two different directions (Zang et al. 2017) underpinning the multiple fracture growth in fatigue.

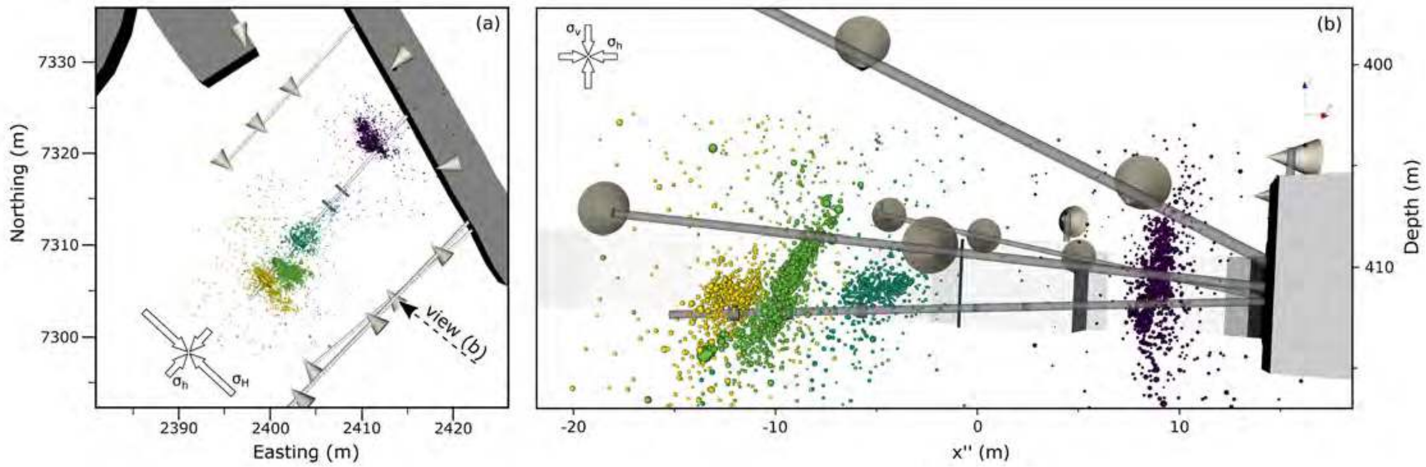

Figure 2. (above) Full waveform detected and located acoustic emission events from six hydraulic tests sections in a horizontal borehole drilled subparallel to the minimum horizontal stress (modified from Niemz et al. 2020).

We introduce the concept of fatigue hydraulic fracturing (Zang, Stephansson, Zimmermann 2017) which is the result of pressure cycles and depressurization phases, frequently allowing crack tip stresses to relax, as a possible explanation for the above mentioned observations. Massaging the fracture walls with a secondary pump (hydraulic hammer) allows movement of rock chips to the fracture tip in line with the Kiel process (Kiel 1977), and redistribution of stresses. This in turn makes the size of the fracture process zone larger in the fatigue as compared to the conventional treatment. In contrast to the Kiel process, our multiple pump and variable flow rate approach by cyclic/pulse hydraulic injection allows for an even more efficient rock fragmentation process. This is because in hydraulic fatigue a significant portion of the hydraulic energy is converted into rock damage and fracturing.

Our strategy for the future is to further refine the innovative fluid-injection protocol in laboratory testing, and then go back to Äspö HRL to test the most promising injection style underground. Future tests will be designed to find injection parameters that minimize the maximum seismic magnitude. Results from first generation injection tests on granite cores in conventional tri-axial testing lead to a reduction of fracture breakdown pressure by 10% after 10 injection cycles, and a reduction of fracture breakdown pressure by 20% after applying ca. 800 injection cycles (Zhuang et al. 2019). Post mortem X-Ray CT identifies a single through-going fracture in conventional testing, while asymmetric, multiple fracture growth is observed in cyclic hydraulic fracturing. The second generation of true-tri-axial injection tests on granite cubes (100 mm) under pressure-controlled conditions allows optimization of injection parameters (resting time, oscillation frequency, variable flow rates) with respect to acoustic emission amplitudes and energy, crack modes, X-ray CT fracture pattern and pumped-in hydraulic energy (Zhuang et al. 2020).

Our final goal is not only to compare radiated seismic and hydraulic energy from laboratory and mine testing, but also to provide fatigue hydraulic injection schemes which allow control of the energy partitioning in the fracture growth process (Zang et al. 2019). The hydraulic energy in small-scale underground tests was estimated to be 0.2 MJ, while hydraulic energies in the cyclic laboratory tests varied between 10 J and 10 kJ, increasing the number of cycles from one to 839. The findings reported appear to have potentially significant implications for managing the economic and physical risks posed to communities affected by fluid-injection-induced seismicity. The findings reported here can also be used to efficiently produce heat from granites or gas from shales with an environment friendly approach to reduce fracture breakdown pressure of high strength unconventional rocks by fatigue hydraulic fracturing.

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Running up the scale towards engineered geothermal systems with underground laboratory experiments

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The rock mass at depths viable for engineered geothermal systems (EGS) allows only limited fluid circulation through low-permeability faults and fractures, which makes cost-effective geothermal energy extraction impossible without reservoir engineering. Thus, faults and fractures have to be hydraulically stimulated to increase reservoirs permeability by several orders of magnitude to enable heat transfer from the hot rock to a circulating fluid. Although promising EGS project successes exist in well explored areas (e.g. Soultz-sous-Fôret; Rittershofen, Insheim), the breakthrough in hydraulic stimulation technology for EGS is still missing.

Engineering the Earth's crust at depths of several kilometers leads inherently to unpredictable outcomes as the nearly 45-year-old history of the EGS shows [1]. As a consequence of unsuccessful EGS projects in the 1970s and 1980s, dedicated in-situ hydraulic stimulations experiments in well-characterized rock were performed at depth with the goal of advancing research on seismo-hydro-mechanical processes (e.g. Le Mayet, France, 1985, in 800 m depth, or Fjällbacka, Sweden, 1989, in 480 m). A widespread problem identified during past EGS projects -- in addition to induced seismicity -- is that the permeability in the near-field of the wellbore can well be enhanced, but not necessarily in the far-field by adequately connecting injection and production boreholes. Further understanding of the hydro-mechanically coupled processes within the reservoir rock mass -- the spatio-temporal fluid pressure evolution during stimulation, the propagation of hydrofractures into fractured rock or the static and poro-elastic deformation field associated with stimulation -- is required.

The major problems with all experimental work on hydraulic stimulation are accessibility, controllability and scalability. Research at the full reservoir scale has to deal with indirect and sparse observations on the reservoir boundary conditions, geometry, structure and properties and with the difficulty to control the processes many kilometers below the surface. Small-scale laboratory experiments can well be controlled and understood in detail, but it is unresolved how results may be generalized and transferred to the full scale. The recent world-wide interest in geothermal energy has the research community turning again to controlled in-situ experiments (e.g. Sanford URL [2], USA, hydrofracturing experiments in Aspö URL, Sweden [3], and stimulation experiments at LSBB).

The ongoing extensive experimental work in Switzerland tries to bridge this gaping experimental (nearly) blind spot of many orders of magnitude in scale by conducting experiments at the intermediate scale. These are done in underground laboratories with good access to the experimental volume and where the rock mass conditions are still sufficiently similar to the target rock mass at several kilometers depth. An extensive series of experiments at the ten-meter–scale have already been performed at the Grimsel Test Site (GTS) between 2015 and 2017 ([4][5][6]). Currently, experiments on the hundred-meter-scale are being planned and performed at a new underground research facility called the Bedretto Underground Laboratory for Geoenergies (BULG) ([7]).

In Figure 1a, both projects are compared in terms of scale to the Basel EGS project as defined by the distribution of relocated seismic events [7]. Ten meter- and hundred meter-scale experiments will provide detailed insights into the processes active in a target rock mass undergoing stimulation, even though some upscaling issues may remain. Hydraulic stimulation at these scales also requires smaller volumes of injected fluid volume, implying that these experiments may be advantageous over full-scale stimulation due to much smaller seismic hazard. Figure 1b shows the largest induced earthquake magnitude in dependence of injected volume for a diverse collection of injection operations. Also included is McGarr's [9] proposed upper threshold of the maximum seismic moment that can be released as a function of injected volume, although the existence of a firm threshold is disputable as earthquakes larger than this threshold can be induced [11] [12]). Yet, the Figure carries an important message: even with large volumes of fluid the induced maximum earthquake may be far below McGarr's upper limit. This implies that it may well be possible to enhance permeability without excessive seismicity. To better understand the physics behind these empirical findings, it is important to explore rock mass responses to injection at experimental scales of 10 – 100 m. These experiment scales roughly correspond to injection volumes on the order of 1 – 100 m3: during the experiments at the Grimsel Test Site injection of about 1 m3 produced ~10 m diameter seismicity clouds, in Fjallbäcka about 100 m3 produced seismicity clouds with ~100 m diameter, and at Basel 10,000 m3 produced seismicity clouds with ~1000 m diameter. Thus, by limiting injection volumes, smaller-scaled experiments are safer than full-scale operations in terms of seismic hazard. Figure 1b also shows that only few experiments at the ten-meter-scale (1 m3 injection volume) have been thoroughly described in the literature, and hardly any on the hundred-meter-scale (10 – 100 m3 injection volume). The observations at Grimsel and Bedretto will progressively fill this gap.

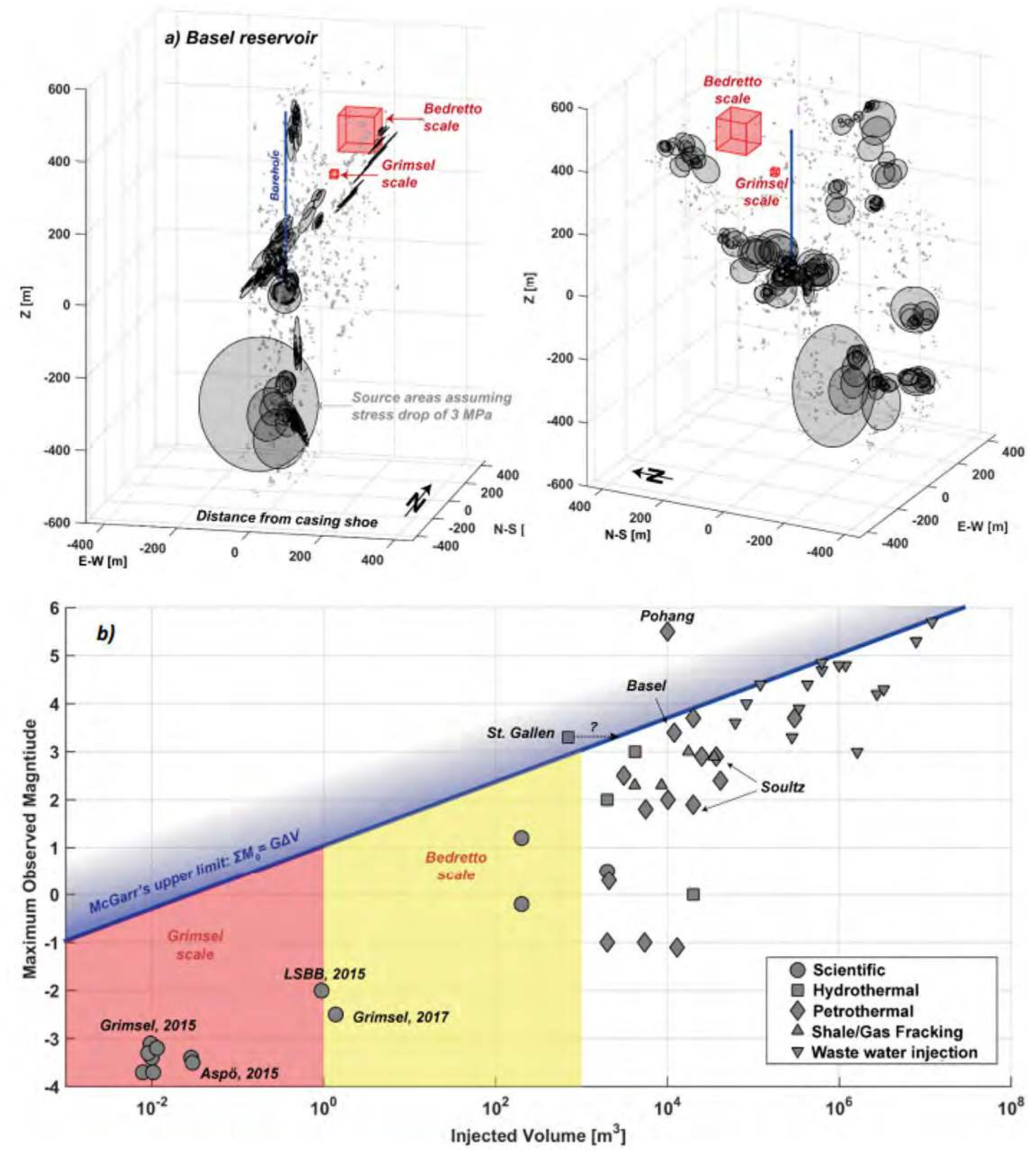

Figure 1: a) The Basel reservoir illuminated by >3000 seismic events that were induced during hydraulic stimulation in December 2006, during which 11,570 m3 of water was injected. Depth is referenced to casing shoe at 4600 m depth. Gray dots are relatively relocated earthquakes. Circles represent the inferred source planes from earthquakes for which the focal planes were determined [7]. For comparison, the scales of the GTS and BULG experiments are shown as 20 m and 100 m sized red boxes, respectively, to illustrate the relative portion of a full-scale reservoir that is investigated in the experiment series described in this article. b) Largest earthquake magnitude versus injected volume for different fluid injection projects ([9][10]). The upper limit on earthquake magnitude proposed by McGarr [9] is shown.

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How to prepare a decameter-scale crystalline rock volume for hydraulic stimulations? The Grimsel-ISC approach

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The In-Situ Stimulation and Circulation (ISC) project has been conducted between 2015 and 2018 in the crystalline rocks at the Grimsel Test Site, Switzerland (Amann et al., 2018). The target rock mass is located ~480 m below the surface at the southern end of the laboratory. As a first phase of the project, the decameter-scale test volume was characterized in detail and equipped with the monitoring system for the actual stimulation. This article provides a summary of this phase.

The geological mapping was based in the first step on tunnel mapping and subsequently on geophysical logging of 15 boreholes which were drilled in the framework of this project. Mapping the tunnel walls revealed two different shear zone types: a ductile shear zone that has been retrogradely deformed under brittle conditions and a brittle-ductile shear zone that contains fault gouge. A total of four ductile and two brittle-ductile shear zones were identified throughout the test volume. The interpolation between tunnel- and borehole-intersections of these shear zones was conducted based on 3rd order polynomial functions (Krietsch et al., 2018a). Additionally, the fracture densities were measured along the boreholes and transferred into volumetric estimates. The geological interpolations were validated by geophysical measurements, including ground penetrating radar (Doetsch et al., 2017) and seismic tomography (Doetsch et al., in prep). As no geological apriori knowledge was included in the geophysical analysis, their results provide an independent quality control of the 3D geological model. Based on the combination of geophysical prospecting and geological mapping, the rock mass foliation was identified, as well as a highly fractured zone in the eastern part of the test volume. The 3D geological model was later used as the basis for planning all subsequent experiments, design of the monitoring system and interpretation of seismo-hydro-mechanical observations during stimulation.

Simultaneously to the geological mapping, the in-situ stress field has been characterized by using hydraulic fracturing in combination with seismic monitoring (Gischig et al., 2018; Jalali et al., 2018a), and overcoring of CSIRO-HI cells and USBM probes. The stepwise integration of different measurement methods revealed the influence of the transversal isotropic rock mass elasticity on the overcoring inversion (Krietsch et al., 2018). To get all five independent elastic parameters for the inversion of the overcoring strain, a biaxial test simulator was developed. Rock stresses were measured in three boreholes, of which two were drilled at distance more than 40 m to the mapped shear zones, and one was approaching the shear zones and the highly fractured zone. Based on the measurement locations two complete principal stress tensors were compiled. The first one represents the ‘far-field’ stress field which is unperturbed of the shear zones within the test volume. For this tensor, no principal stress component is vertical and $\sigma 3$ is pointing sub-horizontally towards the north with a magnitude of 8.7 MPa. The second tensor describes the ‘near-field’ stress state, that is influenced by the shear zones within the test volume. Here, the principal stresses are slightly rotated, compared to the ‘far-field’ stresses and $\sigma 3$ magnitude drops to 6.5 MPa. Directly at the shear zones, $\sigma 3$ magnitude drops even below 3 MPa.

In addition to the geological, geophysical, and stress characterization, a detailed hydraulic screening has been conducted prior to stimulation (Brixel et al., under review; Jalali et al., 2018a; Jalali et al., 2018b). The characterization was split into two parts. The first one consisted of pulse test screening with a double packer system that was moved in all boreholes. Based on these measurements the mapped structures were characterized with respect to their near-wellbore transmissivity. Subsequently, transmissive structures were packed off with a customized packer system inside four boreholes, and two five-packer systems in two boreholes. Using this configuration, the cross-hole connectivity and transmissivity were measured throughout the test volume. Moreover, various tracer tests including dye, salt, heat and DNA nanotracers were implemented in this project to characterize the transport properties of the conductive fractures (e.g., Kittliä et al., 2019).

After the rock mass characterization phase the boreholes were equipped with monitoring systems for the actual stimulation procedure (Doetsch et al., 2018a). Three boreholes were dedicated for strain monitoring. For this purpose, a total of 60 Fiber Bragg Grating (FBG) sensors were equally distributed in these holes. Based on image logs the sensors were placed in a way that they span across intact rock, single or multiple fractures, or the main shear zones. In addition to these sensors, one optical fiber for Distributed Brillouin Sensing (DBS) (Krietsch et al., 2018b) and one for distributed temperature sensing (DTS) were installed in these boreholes. After all the sensors were set in place, these three boreholes were fully cemented. Another three boreholes were dedicated for pressure monitoring. Into these boreholes, the abovementioned customized packer system was placed. This packer system consists of two to three open pressure monitoring intervals which were sealed off by 20 cm long inflatable packers. To guarantee an enhanced stiffness of this system, and to prevent hydraulic short-cutting, resin was injected into the open sections which were not dedicated to pressure monitoring. Additionally, the uppermost part of the borehole was cemented (see Doetsch et al., 2018a). These boreholes were also equipped with DBS and DTS. Four additional boreholes were left open during stimulation, as they were used for seismic monitoring based on retrievable sensors. The sensors in these boreholes complete the seismic acquisition system that was installed along the two tunnels surrounding the test volume (Villiger et al., 2019). In addition to the sensors, active seismic sources were placed in the boreholes and hammers along the tunnel walls to enable active seismic surveying during stimulation (Doetsch et al., 2018b; Schopper et al., under review).

Due to the detailed hydraulic, geophysical, geological and stress characterization of the rock mass and the high-resolution monitoring setup, the ISC test volume provides unique insight into the seismo-hydro-mechanical rock mass responses during the stimulation experiments.

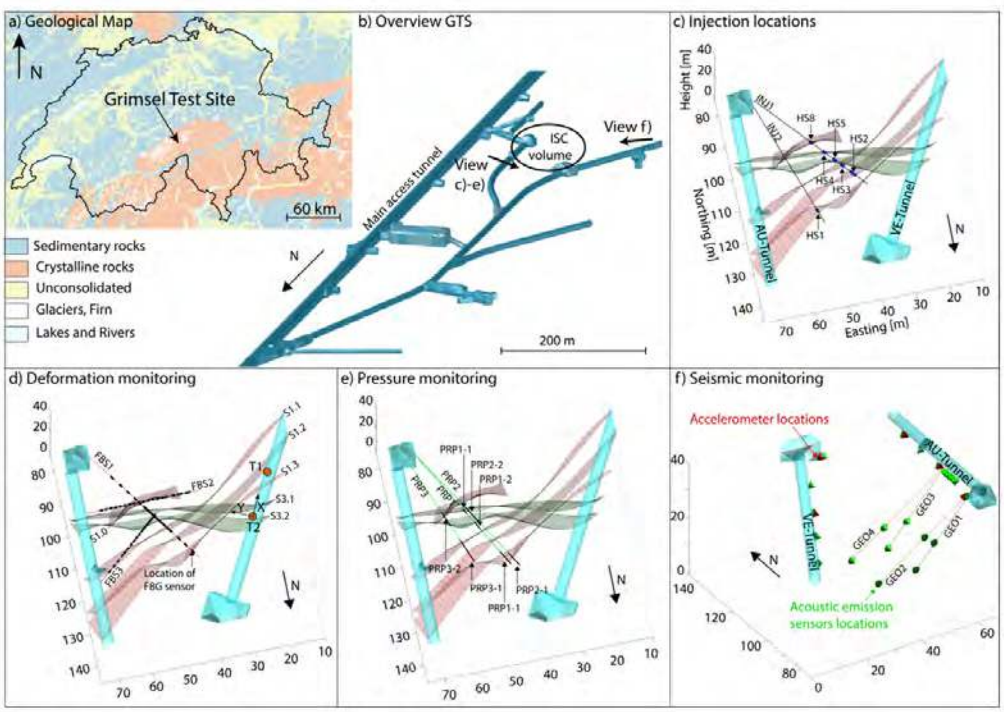

Figure 1. Visualization of the GTS location within Switzerland (a) and of the test volume within the GTS (b). Interpolation of important shear zones, as well as selected injection locations for future stimulation experiments are shown in c). Subfigures d), e) and f) visualize the setup for the deformation monitoring (d), pressure monitoring e) and seismic monitoring (f).

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Insight into seismo-hydro-mechanical rock mass responses from the Grimsel stimulation project

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Hydraulic stimulation treatments are known to have two endmember deformation types that can be initiated by high-pressure fluid injections into dedicated borehole intervals: 1) hydraulic fracturing (HF) and 2) hydraulic shearing (HS). Whereas the first one is based on tensile fracture initiation and propagation, the second one depends on effective normal stress reduction which eventually leads to shear failure of the target structure. Between February and May 2017, a total of six experiments were conducted at the decameter-scale on each of the endmember deformation types. These twelve experiments were carried out in the framework of the In-situ Stimulation and Circulation (ISC) project at the Grimsel Test Site, Switzerland (Amann et al., 2018). The test volume consisted of the crystalline rock of the Central Aar Massif. Prior to stimulation, the rock mass was characterized in detail with respect to its geology (Krietsch et al., 2018), in-situ stresses (Krietsch et al., 2019), hydrodynamics (e.g., Jalali et al., 2018) and geophysical properties (Doetsch et al., 2017b). Additionally, the rock mass was equipped with a borehole based seismo-hydro-mechanical monitoring system (Doetsch et al., 2017a).

During the stimulation phase, standardized injection protocols were used for all HF and HS experiments with the aim to establish experimental results that depend on the local geological conditions and not on the stimulation procedure. The total injection volume was limited to ~1 m3 during all experiments (Gischig et al., 2016). Only water was used for hydraulic shearing experiments, whereas a fluid with 30 times higher viscosity was used for 3 out of the 6 hydraulic fracturing tests.

During most of the HF experiments, the near-wellbore transmissivity was enhanced by 2-4 orders of magnitude, due to successful breakdown of the formation (Dutler et al., 2019). The final injectivity, jacking- and closure pressure are similar for fractures initiated within the same domain of the target rock mass. We argue that this is because of the interaction between induced and natural fractures, which leads to unexpected stepwise fracture growth and associated irregular pressure and flow responses in open monitoring intervals.

During HF experiments we controlled the injection volume and fluid viscosity, and either injection flow rate or pressure. The injection volume, rate and pressure are linked and can be expressed as normalized hydraulic powers presented at early and late time (see Figure 1), where the injection fluid reaches the fracture tip (1) or not (2). In our test volume flow paths depend on fracture density and the number of different oriented fracture systems. At early time, the normalized hydraulic power facilitates intact rock fracture initiation and propagation into the intact rock mass. With increasing viscous fluid volume hydraulic fractures propagate further into the rock mass with small leak-off into pre-existing fractures. The growth of hydraulic fractures is strongly influenced by natural fractures. The change from early (1) to late (2) time in Figure 1 was reached after 10 m (Dutler et al., 2019). The decrease in normalized hydraulic power and the increase in the involved volume result in an increase of local stress transfers, dead-end fractures and shearing induced failure. Despite the complexity of the local fracturing processes, the spatial distribution of microseismic events (Villiger et al., 2019) is predominantly controlled by the stress state. We observed rotations of the seismic cloud due to stress perturbation. A comparison of deformation and pressure monitoring data within the rock mass and the location of microseismic events suggests that the activation of seismic events lags slightly behind the propagation of the pressure front (Dutler et al., 2019).

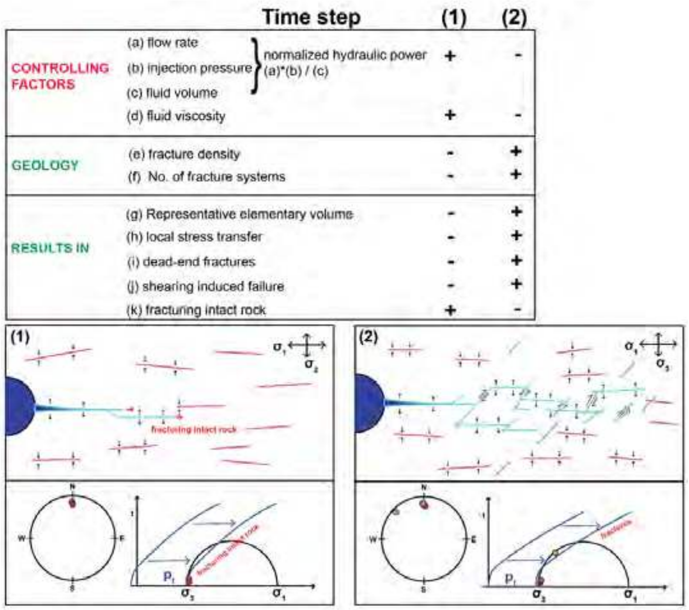


Figure 1: Schematic interpretation of the decameter-scale hydraulic fracturing experiments at early (1) and late (2) time (will be published in Dutler, n.d.).

Based on the pre- and post-stimulation hydraulic characterization it was observed that the shear stimulations were most effective in terms of injectivity enhancement, when initially low transmissive structures were targeted. The stimulation of these structures also induced fewer seismic events, compared to initially highly transmissive structures. Using acoustic televiewer logging, the maximum induced cumulative slip dislocation was estimated as being ~1 mm for each experiment. The maximum injectivity enhancement was in the range of three orders of magnitude (Krietsch, 2019). All injectivity and near-wellbore transmissivity values were at similar magnitude after stimulation, which is comparable to the highest initial value of each parameter.

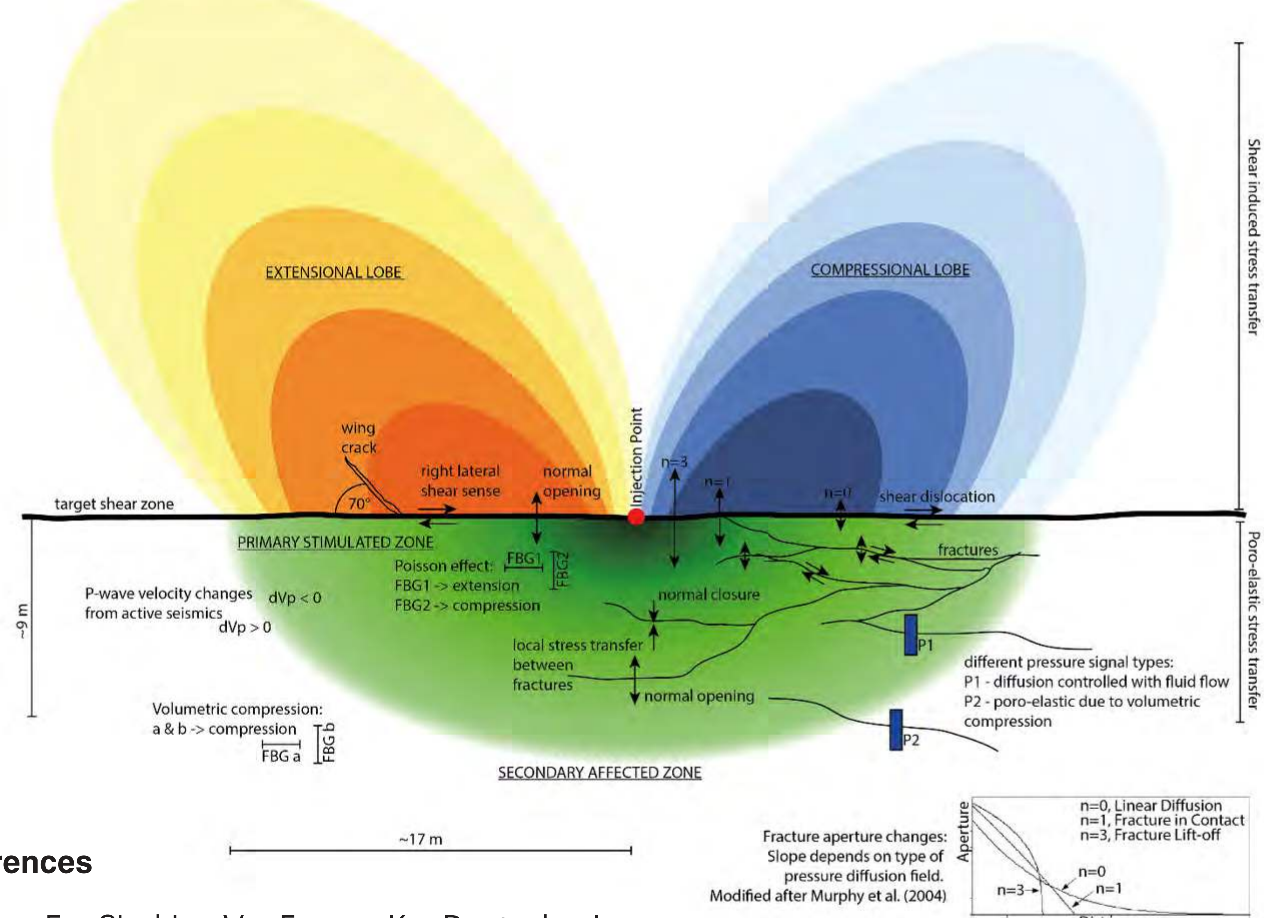
During the HS experiments, it was found that the pressure perturbations at the monitoring locations were usually less than 10% of the injection pressure. However, during a few experiments, pressure perturbations up to 80% of the injection pressure were observed at specific monitoring intervals. This indicates very channelized pressure propagation along the target structures. Additionally, it has been directly measured that these flow channels change during ongoing stimulation (Krietsch et al., under review). Based on the response of the monitored pressure signals to shut-in, we distinguished between hydraulically controlled (close to injection location) and mechanically induced (at greater distance to injection location) pressure response.

The mechanical signals similarly highlighted two different response types. Close to the injection locations, the deformations were rather complex, including normal opening and shear dislocation along fractures, stress transfer, wing crack formation and a rock mass scale Poisson effect. Further away from the injection location, the deformation monitoring system detected volumetric compression. The division into an inner (and thus primary) stimulated volume and an outer (and thus secondary) affected volume is consistent with observations from 3D active time-lapse seismic tomography surveys, conducted during ongoing stimulation (e.g., Doetsch et al., 2018). Taking advantage of the geological and stress characterization, it was possible to show that hydraulic fracturing and hydraulic shearing can occur simultaneously during ongoing stimulation within a target structure.

During HS and HF experiments, a high variability in seismic response (i.e., seismogenic indices, b-values, spatial and temporal evolution of seismicity) was observed, which was attributed to local geological heterogeneities. The seismic response for injections into the highly conductive brittle-ductile shear zones was most pronounced, while injectivity increase on these structures was only marginal. Seismic responses for HS and HF experiments were not clearly distinguishable, possibly because the induced HF's interact with the same pre-existing fracture network that is reactivated during HS experiments (Villiger et al., 2019).

Based on the overall observations from the hydraulic shearing experiments we argue that a superimposition of two fundamental deformation mechanisms takes place during fluid injection: a) static, shear induced stress transfer and b) dynamic poro-elastic stress transfer (Figure 2). These mechanisms explain the division of the affect volume into a primary and secondary volume, as well as the formation of wing cracks.

Figure 2. (below) Schematic interpretation of deformation mechanisms during decameter-scale hydraulic shearing experiments (Krietsch, 2019).



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Rock property measurements for Grimsel and Bedretto stimulation projects

Submitted by Nejati, M., and the Grimsel and Bedretto Lab teams; Department of Earth Sciences, ETH Zurich, Switzerland.

Introduction

Rock property measurement via laboratory experiments is an essential part of the rock characterization for any in-situ stimulation and circulation (ISC) project. For Grimsel project, rock characterization through laboratory tests was an important step that significantly helped the interpretation of the ISC experiments. In particular, it was found that the development of hydraulic fractures that are not normal to the direction of minimum stress can be explained by the rock anisotropy (Gischig et al., 2018, Krietsch, 2019). In addition, the nonlinearity of the rock explained how the pressurization of the rock volume leads to the slowness of the P-wave velocity (Doetsch et al., 2018). The characterization of the mechanical properties of Grimsel Granite was therefore assessed to be an essential part of the entire project. Learning from the past, a roadmap for the laboratory measurements is designed from the beginning of the Bedretto project. This short article presents some important rock properties of the Grimsel Granite, and describes the planning of the laboratory measurements for the Bedretto project.

Grimsel Granite

The laboratory measurements of the elastic and inelastic properties of Grimsel Granite indicated a strong anisotropy of these properties. The anisotropy of Grimsel Granite seems to be due to the foliation that happened during the rock formation process, which resulted in the creation of a set of micro-cracks that are predominantly aligned along the foliation. To analyze the elasticity of the Grimsel Granite, the transversely isotropic constitutive law, with five independent material constants, was employed (Dambly et al., 2019). Table 1 reports the Young's and shear moduli of the Grimsel Granite (in dry condition), measured statically using uniaxial compression test and dynamically using ultrasonic wave velocity, at zero-confinement. Here, E and E' are Young's moduli along and normal to the foliation, and also G and G' are shear moduli along and normal to the foliation. The results show (1) the significant anisotropy and (2) the significant difference between the dynamic and static moduli. Strength and fracture toughness of Grimsel Granite also exhibit anisotropy since the dominant orientation of micro-cracks provides a preferential path for the failure and fracture growth (Dutler at al., 2018). Table 2 shows the tensile strength, fracture toughness and the size of the fracture process zone in the Grimsel Granite. These results show that the fracture toughness and strength are both much higher in the direction of failure normal to the foliation compared to the one along the foliation.

Table 1: Comparison of the static and dynamic moduli under zero-confinement condition.

Value	E (GPa)	E' (GPa)	G (GPa)	G' (GPa)	E/E'	G/G'
Dynamic	40.8	19.9	17.0	11.1	2.1	1.5
Static	29.1	7.6	12.1	8.2	3.8	1.5
Ratio	1.4	2.6	1.4	1.4		

Table 2: Tensile strength σ_t, mode I fracture toughness K_{Ic}, and the length (L_{FPZ}) and the width (W_{FPZ}) of the fracture process zone along the foliation ($\phi = 0°$), and normal to it ($\phi = 90°$).

ϕ	σ_t (MPa)	K_{Ic} (MPa$\sqrt{m}$)	L_{FPZ} (mm)	W_{FPZ} (mm)
0°	5.6	0.7	10.8	5.4
90°	14.7	1.7	8.8	4.7
Ratio	2.6	2.4	0.8	0.9

The Grimsel Granite also exhibits strong non-linearity, with the moduli and Poisson's ratios increasing with an increase in stress. Figure 2 shows the variation of the tangent static elastic constants against the applied load (Nejati et al., 2019). In these plots, ν and ν' and are Poisson's ratios along and normal to the foliation.

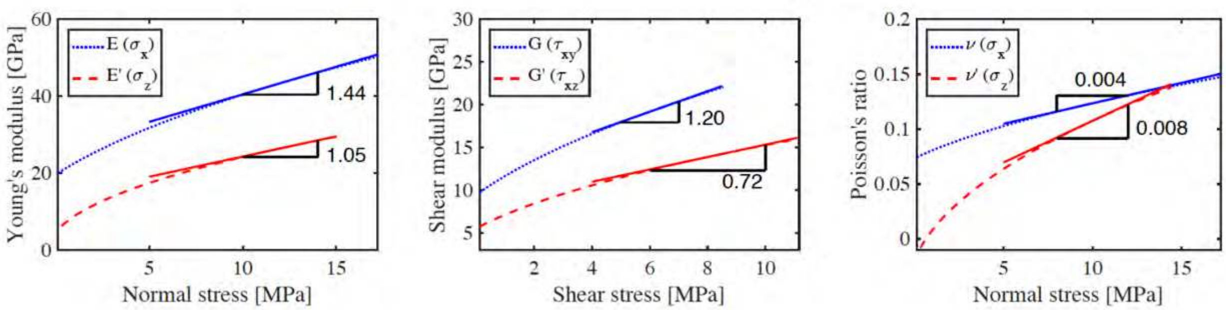

Figure 1: The variation of the tangent static Young's and shear moduli and the Poisson's ratios against of Grimsel Granite with normal or shear stresses.

Bedretto Granite

The newly built Bedretto Underground Laboratory for Geo-energies (BULG) is located within a granitic formation, with a rock type that seems to be more homogenous and isotropic compared to the Grimsel Granite. The drill of boreholes for stress measurement provided core material for the first laboratory tests on this rock. Only limited data is available for the rock properties of the Bedretto Granite, and we therefore planned to do a comprehensive laboratory measurement. Figure 2 presents a categorized list of rock properties, together with their influencing factors, all functions of the confinement. It is known that rock properties are dependent on the confinement, due to the fact that micro-cracking structure changes by stress (the closure and sliding of micro-cracks). What distinguishes the Bedretto ISC project from the previous ones is the large scale as well as the high in-situ stress. The dependence of the rock properties with in-situ stress and specimen size would be therefore important, and will be the main focus of the laboratory measurements.

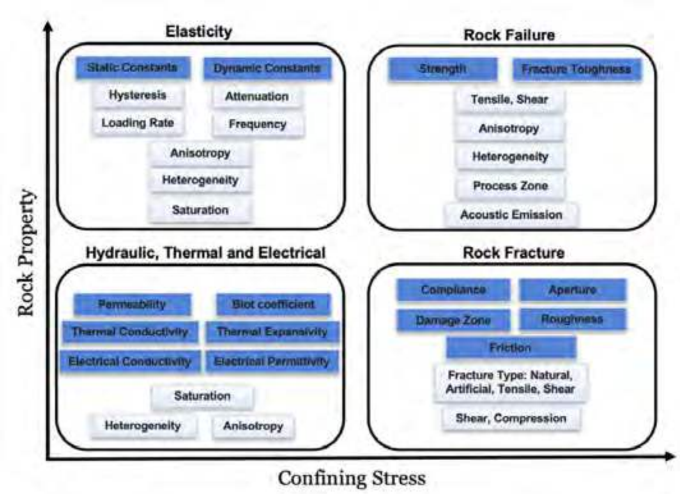

Figure 2: Different categories of rock properties are schematically shown along with their influencing factors as functions of the confinement. The main objective of the laboratory measurements in Bedretto project is the dependency of different rock properties on the confinement.

Conclusions

A good rock characterization through laboratory experiments is an important step towards having a more successful field experiment, as well as a clearer interpretation of the field results. The results of the Grimsel project, for example, showed that rock anisotropy is important, and shall be taken into account when interpreting the field results. For the Bedretto granite, which seems to be more homogenous and isotropic compared to Grimsel granite, we expect that the dependency of the rock properties on the confinement as well as scale to be a relevant research topic that should be explored.

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The Bedretto Underground Laboratory for Geoenergies (BULG) -- a multidisciplinary test-bed

Submitted by Hertrich, M. and the Bedretto Lab team; Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE) & Department of Earth Sciences, ETH Zürich.

To achieve the goals specified in the Swiss Energy Strategy 2050, it will be necessary to produce electricity of about 4.4 TWh/year from geothermal energy. Experiences from the past deep geothermal projects in Switzerland (Basel, St. Gallen) and worldwide (e.g., Pohang, South Korea), have shown that this is a non-trivial task and that the underlying physical processes are poorly understood. For that purpose, the Competence Center for Energy Research (SCCER-SOE) has established a Swiss national roadmap for advancing the state of the art on deep geothermal energy. Initial experiments in so-called Deep Underground Laboratories (DUGLabs) have already been performed in the Grimsel region. Successfully creating and operating an underground heat exchanger at depths of 3-5 km. will require a highly interdisciplinary approach that describes and models the complex interactions between geophysical, mechanical, hydrological, biological and chemical processes. DUGLabs play a critical role in advancing process understanding, model development, calibration and validation. For extending the very successful initial experiments at Grimsel to realistically sized geothermal reservoirs, ETH Zurich has established the unique Bedretto Underground Laboratory for Geoenergies (BULG) (http://www.bedrettolab.ethz.ch/home/).

The Bedretto tunnel has been identified as providing ideal conditions for underground in-situ experiments related to geoenergies and other geoscience disciplines. The tunnel of about 5km length provides ventilation to the railroad tunnel connecting the Gotthard area to the Valais. At about 2km from the entrance in Val Bedretto, a 6m wide and 100m long niche was excavated, providing the ideal conditions for an underground laboratory, with over 1000 m of overburden and in excellent granite rock (Figure 1). The tunnel has been retrofitted with a new access road, power supply, ventilation, IT infrastructure and an external laboratory.

Initially, the Bedretto Reservoir Project has begun as a joint effort of three major projects, namely the BFE funded project “Validating of technologies for reservoir engineering” (VALTER), the EU funded project “Soft stimulation treatments of geothermal reservoirs” (DESTRESS), and the EU funded project “Zonal isolation, drilling and exploitation of EGS projects” (ZoDrEx). Furthermore, the Geoforschungszentrum Potsdam is joining as an additional partner. Within these projects the partners aim at developing a model geothermal reservoir, simulating full-scale conditions as closely as possible. In a first comprehensive characterization phase, the teams conducted a detailed structural mapping of the tunnel and boreholes, dense stress measurements, hydraulic characterization and an extended geophysical campaign. Next, the reservoir will be equipped with a high-resolution monitoring system for seismicity, strain, pore-pressure and temperature. This will allow an unparalleled resolution to observe the processes of reservoir creation across the volume.

When the reservoir volume is completed two boreholes will be drilled into this volume and equipped with state-of-the-art multi-stage stimulation technology. By sequential stimulation a heat exchanger geometry will be created that will allow circulation across the newly engineered fracture network. After successful reservoir engineering and circulation is achieved, an extended program of reservoir management is planned to investigate and test innovative technologies to systematically exploit a geothermal reservoir and understand related processes of thermal and geo-mechanical interaction.

In parallel to the geothermal reservoir engineering, projects related to earthquake rupture processes are being funded and are currently kicked off. These fully-controlled experiments of fault stimulation and earthquake initiation at relevant depths and pressures in Bedretto will provide further understanding of earthquake physics and help in bridging scales from laboratory to actual earthquake scales.

These projects constitute only the initial phase of a long-term research endeavor. BULG is expected to establish itself as an international platform for geothermal and related research.

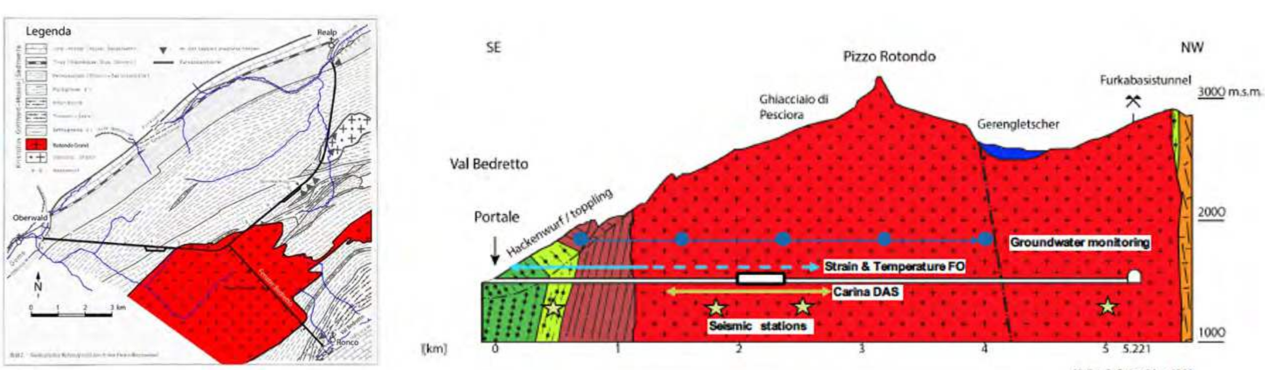

Figure 1: a) map view of the Bedretto-tunnel, intersecting the Rotondo Granite. b) Cross-section of the Rotondo-massif along the tunnel axis with the background monitoring systems schematically drawn.

In situ geomechanical characterization: stress measurements and fracture mapping

Submitted by Ma, X., Bröker, K. and the Bedretto Lab team;Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE) & Department of Earth Sciences, ETH Zürich

Introduction

The objectives for the geomechanical characterization at the Bedretto Lab originated from the following questions:

> *What are the in situ stress and pore pressure conditions and their variations?*
> *What are the orientations and the distributions of the pre-existing natural fractures?*
> *What are the slip tendencies of these pre-existing fractures under the prevailing in situ stress conditions, given elevated pore pressure during stimulation?*

The answers to these questions are critical to the design of the stimulation experiments and the interpretation of the subsequent observations. Our geomechanical characterization relies on the integration of all available information at the Bedretto Lab, from tunnel fracture mapping to dedicated in situ stress measurements. While our characterization is still ongoing, we briefly describe some of our efforts and preliminary observations.

Tunnel mapping and preliminary observations

Fractures have been mapped between approximately 1km before and beyond the Bedretto Lab. Those natural, brittle fractures that manifest themselves as sharp discontinuities that are potentially relevant for fluid flow were mapped (Figure 1). In general, the fractures are sub-vertical or steeply-dipping. We arbitrarily categorize them into four groups: East-West (E-W), North-South (N-S), tunnel-perpendicular, tunnel-parallel. A general observation is that the E-W and tunnel-perpendicular sets bear higher flow rate than the N-S set (tunnel-parallel sets were not sufficiently sampled), which is potentially related to the higher shear-normal stress ratio on these sets, informed by the maximum horizontal stress (SHmax) azimuth (detailed at length later).

Locally, there were no previous stress measurements conducted. The regional SHmax rotation pattern along the Swiss Alpine chain (Kastrup et al., 2004; Heidbach et al., 2016) suggests a NW-SE direction of SHmax near the Bedretto Lab, which would be sub-parallel to the Bedretto Tunnel. A thrust-faulting environment here is unlikely. Along the Bedretto tunnel, stress-induced spalling and kinking are often observed on the sidewalls at certain sections where natural fractures are absent. If these failure features are not predominantly associated with the tunnel excavation (e.g., blasting), they indicate that the horizontal stress component perpendicular to the tunnel is smaller than the vertical stress. Therefore, the local stress environment at the Bedretto Lab is unlikely to be thrust-faulting.

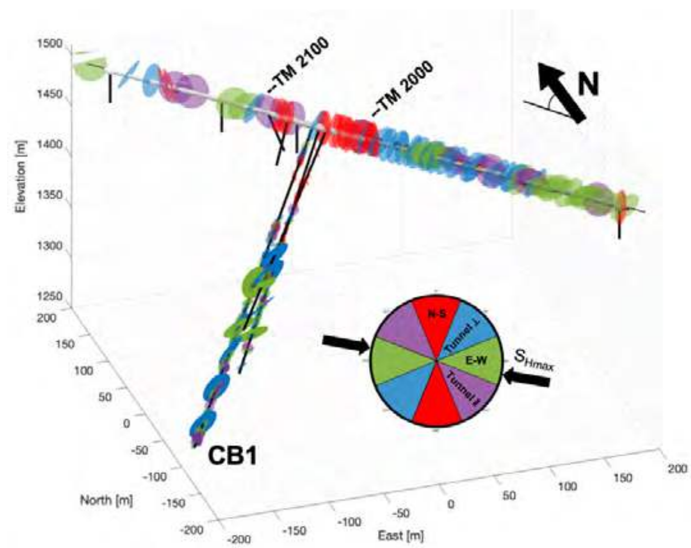

Figure 1. Configuration of the Bedretto Lab (TM2000-2100) with respect to the short and long characterization boreholes. The fractures mapped from the tunnel wall and the boreholes are colored according to their azimuths.

Mini-frac measurements in short boreholes

In situ stress measurements via the classic hydraulic fracturing technique (or mini-frac, c.f. Haimson and Cornet, 2003) have been conducted in several short boreholes around the Bedretto Lab rock volume (for details, see Ma et al., 2019). A total of six short boreholes (four 30m verticals and two 40m deviated) distributed along the tunnel were dedicated to this purpose

(Figure 1). Each borehole has been mini-frac'ed at multiple intervals >10m away from the tunnel floor. The two deviated boreholes along with a nearby vertical borehole were arranged so as to set up downhole microseismic monitoring of hydraulic fracture propagation in one of these three boreholes. We derived the minimum stress (minimum horizontal stress, Shmin, in this instance) magnitude from analyzing pressure transients of the mini-frac's (Broker, 2019). The optical/acoustic image logging conducted after the mini-frac's revealed the azimuth of the Shmin. The magnitude of SHmax was estimated based on the initial breakdown pressure and re-opening pressure, albeit with questionable assumptions (Haimson and Cornet, 2003). Notably, in selected mini-frac tests, we allowed the shut-in to continue for several hours and even overnight, which provided constraints on the in situ pore pressure. Although our data show uncertainties of both the stress magnitudes and orientations, the preliminary conclusion is:

SV ≈ 26.5 MPa
SHmax ≈ 0.8~1 * SV
Shmin ≈ 13~16 MPa
Pp = 3-6 MPa

The SHmax azimuth is approximately N100E, close to the NW-SE quadrant as expected. The vertical stress SV is estimated based on the Bedretto Lab overburden of ~1000 m granite (density of 2.7 g/cm3). This state of stress is consistent with the expected normal faulting and/or strike-slip environment in the region.

Ongoing characterization in long boreholes

In situ characterization of the Bedretto Lab continued as additional long boreholes were placed. Three deviated boreholes (length between 180-300m, azimuth N135W, dip between 40-50) were drilled off the west side of the tunnel wall (Figure 1). Extensive fractures/fault zones from these boreholes have been mapped from both the cores and image logs. These discontinuities are colored following the same designation as the tunnel mapped ones, showing a predominant trending of E-W and tunnel-perpendicular. Strong evidence indicates that these fracture sets are hydraulically connected to the tunnel. A few more mini-frac tests were conducted at shallow intervals of the 300m borehole (CB1). The derived Shmin and Pp estimates are shown in Figure 2 (left). The Shmin values generally follow a higher gradient than that of the short boreholes, though the pore pressure measured in the CB1 doesn't seem to be significantly different from the latter. We attribute such discrepancies to the near-tunnel perturbation and compartmentalized hydro-structures in the Bedretto rock mass.

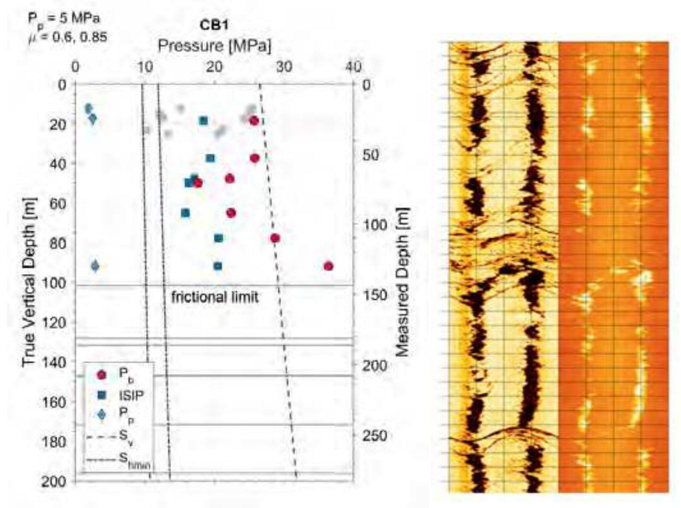

Figure 2. (left) Preliminary results of the mini-frac stress measurements conducted in the Bedretto Lab. ISIP - instantaneous shut-in pressure. Pb (circles) denotes the breakdown pressure. The colored symbols are derived from CB1 measurements. The gray symbols represent the measurements in the short borehole closest to the CB1. Figure 2(right) An ~6m long interval of borehole breakouts seen in the acoustic televiewer log at CB1 measured depth around 170m.

One prominent feature of the long boreholes is the appearance of breakouts, coinciding with the heavily-fractured intervals (Figure 2 (right)). It is unclear whether the decreased rock strength or the stress rotation induced the breakouts. The stress variation at this degree certainly warrants further investigation. The overall in situ geomechanical characterization is challenging. While we are cognizant of the in situ stress variations at multiple scales, our emphasis will be the evaluation of the Bedretto Lab rock volume against the desired characteristics of an EGS test bed.

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Hydrogeological Characterization: identification of hydraulic-backbone and connectivity

Submitted by Gholizadeh-Doonechaly, N. and the Bedretto Lab team; Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE) & Department of Earth Sciences, ETH Zürich

Overview

A hydrogeological model of the test volume is one of the fundamental components of the BULG project and will be developed from a combination of measurements carried out during the drilling operations, as well as during a special characterization phase following the drilling phase. The long boreholes will also be monitored using pressure sensors over the longer term after the hydraulic characterization phase.

Hydrological Characterization Campaign

- **During Drilling**

A set of short- and long-boreholes are being drilled at BULG for hydrological characterization purposes. From the onset, the major flowing zones within the boreholes are detected by monitoring the borehole outflow during the drilling. Using the precision flow meter at the surface base allows a continuous profile of flow rate versus depth. In combination with geophysical logging results in the same boreholes, the permeable fractures will be identified and selected for further testing. Also, pressure sensors installed on the wellhead have been used to record the pressure build up curves while the borehole is closed during the drilling breaks. Such a procedure gives us firsthand information regarding the flowing intervals within a borehole as well as an estimated transmissivity, with minimum perturbance of the hydraulic system.

Using such a technique, the flowing zones will be identified with a resolution of the length of a single drill-pipe (i.e. 3m). An example of the generated flow profile during drilling for a 300m borehole at BULG is presented in Figure 1. The results show that no major flow zone was observed until the borehole depth of ~150m, beyond which the cumulative flow rate increases linearly with depth. At the depth range of 270m-290m MD, a significant flowing zone is intersected by the CB1 borehole with a flow rate of 9 L/min, which is equivalent to half of the total flow from the whole CB1 borehole. As shown in the figure, the logged flow profile points to a strongly heterogeneous system over relatively short distance in the target reservoir volume.

- **After Drilling**

In order to improve the resolution of the location of the flowing zones (characterized based on the well outflow during drilling), a combination of heating cable and fiber optic distributed temperature sensing (FO-DTS) devices has been implemented in the boreholes to artificially induce temperature disturbances of ~20˚C above the formation temperature for a short time and then to measure the temperature decay (due to inflow from fractured intervals) until the stable temperature is reached. With such a technique, the major flowing zones are identified with a resolution of ~30cm and then are cross-checked with the information obtained during the drilling as well as the logging-phase. After identifying the major flow zones (permeable fractures) within the boreholes, the hydraulic characterization continued by a) pressure pulse testing of individual fracture zones to obtain the corresponding transmissivity, b) hydraulic tomography by cross hole well testing to reconstruct the spatial map of heterogeneity and directional properties of the system and c) tracer tests to identify the heat exchange area of the system. The already obtained hydraulic tomographic data shows a strongly connected volume in the target reservoir, although the heterogeneity as well as anisotropy prevails.

Figure 2 shows the recorded pressure profiles in three individual boreholes (CB1-3) during a drawdown and buildup tests in CB1 while all other intervals were closed. CB1 and CB3 are monitored using a single pressure sensor at the surface while CB2 is monitored over six packed intervals within the borehole (packer seat locations are selected based on the interpretation of the major flow zones identified, based in turn on the measured flow rate from the boreholes during drilling operation, as previously mentioned).

Results show that the pressure drawdown in CB1 influences the pressure of the two other boreholes -- in particular, all packed intervals in CB2 --- although, the travel time of the pressure signal varies between different intervals. Also the results show that the fastest response due to drawdown in CB1 was observed in uppermost section of CB2 (Interval 7 in Figure 2). Based on the interpreted geometry, the corresponding fractures observed in the intervals 7 (in borehole CB2) are expected to intersect CB1 borehole in the depth range of 270m-290m MD which is consistent with the measured largest borehole inflow during the drilling in CB1 borehole (Figure 1).

- **Longer Term**

In order to monitor the transient behavior of the target reservoir volume, the multi-packer system -- that is already installed in CB2 -- will remain in the borehole over the longer term in order to monitor the dynamic changes of the system attributes, such as hydraulic backbone, permeability, pressure boundaries, etc. (for example due to stimulation operations).

Outlook

The results from hydraulic characterization will primarily be used to identify a) the link between the in-situ stress condition and the fracture (zones) permeability as well as its dynamic evolution due to stimulation or other artificial perturbations, and b) dynamic changes in the flow backbone of the system due to stimulation.

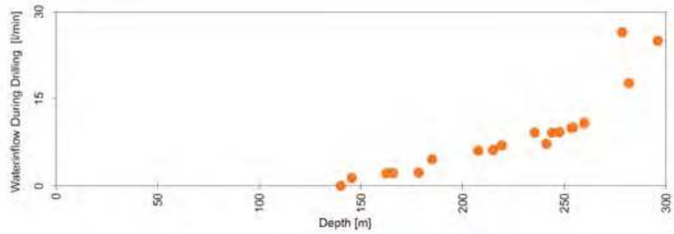

Figure 1. Borehole outflow measured during drilling in CB1 borehole at BULG (Gholizadeh Doonechaly et. al. 2019).

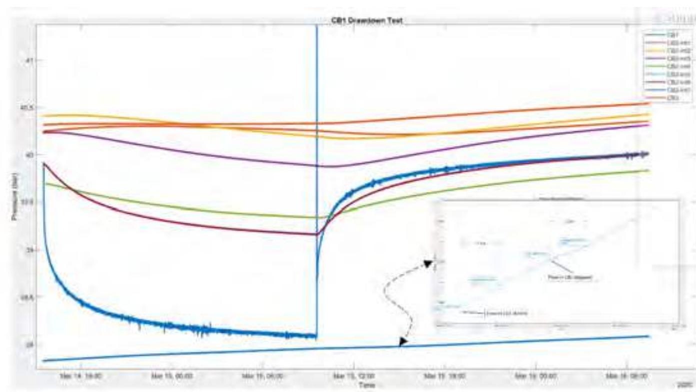

Figure 2. Cross-hole connections between boreholes CB1-3 during drawdown- followed by a buildup-in CB1. The interval indexes in CB2 correspond to the packed intervals with lowermost interval in the borehole represented by #1.

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Geophysical imaging of fractures from boreholes: combining data from different scales

Submitted by Shakas, A., Krietsch, H., and the Bedretto Lab Team; Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE) & Department of Earth Sciences, ETH Zürich.

Introduction

Crystalline rock masses are common reservoirs for engineered geothermal systems (EGS). They are typically characterized by an impermeable matrix and discrete fractures and faults. These discontinuities contribute to most of the fluid flow in the system and their characterization is therefore essential in understanding and predicting the potential of EGS. Geophysical tools offer a low-cost, non-destructive and multi-scale approach of characterizing fractures. We present a combination of borehole tools that have been used to map fractures that are assumed to be hydraulically important in the Bedretto Underground Laboratory for Geosciences (BULG), Switzerland.

As a rule of thumb, the further away from a borehole the less the resolution of a given method. For example, an acoustic borehole imager (ABI) offers very dense sampling and high-resolution fracture information but is limited to the borehole wall. On the contrary, Ground Penetrating Radar (GPR) is highly sensitive to the dielectric contrast between granite and water and can be used to remotely image fractures (Dorn et al.). Nevertheless, GPR reflection data suffer from borehole reflections that shadow what happens in the vicinity of a borehole. More importantly, GPR antennas are omni-directional, meaning that there is information on a structure's dip but not its azimuth. The combination of these datasets is rarely done in practice, and if so, often in an "interpretative" manner. Doing so in a more robust way requires statistical tools and forward modeling schemes. In the following article, we present a first step in combining ABI and GPR data in a simple framework that helps us constrain fracture geometrical properties of interest, namely fracture length and orientation.

Experimental setup

The results presented here were measured in a 300 m long borehole oriented at a dip of 45° from horizontal. The borehole is intersected by several fractures at depth, but the first 100 m are essentially intact. The setting is a granitic host matrix with many water-filled fractures that contribute to the backbone of the larger fracture network.

The ABI generates an acoustic wave which is reflected at the borehole wall and recorded by the probe again. Energy level and travel time of the reflected wave are indicative of open fractures intersecting the borehole. The principle works due to the acoustic contrast between the fracture opening and rock matrix. The reflections also provide information about the fracture's dip and azimuth, and in combination with an internal 3-axis magnetometer the fracture can be oriented in 3D with an accuracy of a few degrees. Despite this high accuracy, there is no information of how far this fracture propagates into the rock matrix and whether other fractures are present in the near vicinity of the borehole.

In this respect GPR provides complementary information. By generating an electromagnetic wave that propagates into the rock and is reflected by rock-water interfaces, GPR remotely maps the presence of water-filled fractures. Nevertheless, the dipole antennas used in most

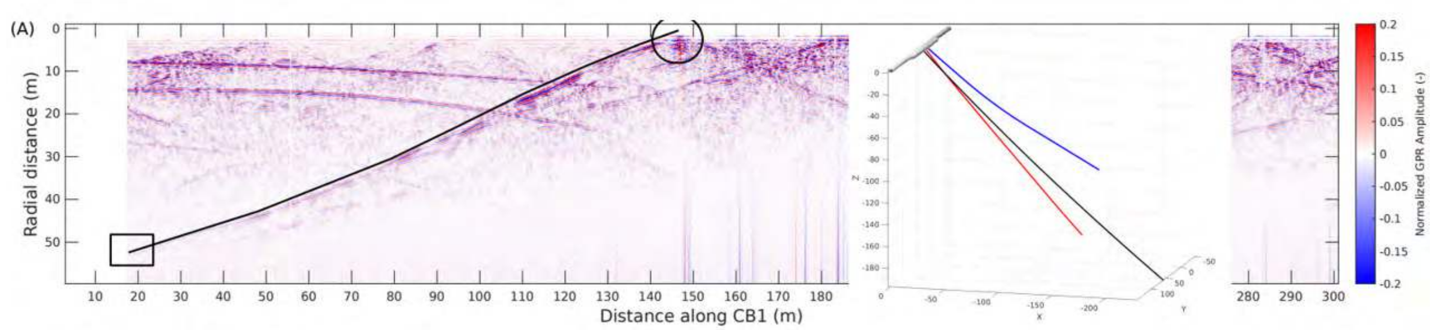

Figure 1. GPR reflections from borehole CB1.

GPR borehole systems create an omni-directional spherical wave and therefore provide limited information about fracture azimuth – but reveal fracture dip and length in good precision (Olsson et al.) as seen in Figure 1.

The two other boreholes can be seen as long parabolic reflectors starting from the left side (which roughly represents the tunnel wall). The analysis here focuses on one long fracture that is seen to cross all boreholes. The fracture extends to the left and intersects the tunnel wall (rectangle). The fracture also intersects the borehole somewhere between 140 m and 150 m length. The 3D insert in the figure shows the orientation of the three boreholes, CB1 (black), CB2 (red) and CB3 (blue) as well as the tunnel axis (gray).

Combining datasets

The GPR image in Figure 1 provides clear information about the fracture length (~200m) and dip (~75° from borehole axis). This fracture is also probably highly permeable, since it provides clear and strong reflections due to its water content. Moreover, GPR reflections are known to carry invaluable information about the aperture heterogeneity of fractures (Shakas and Linde) and are especially sensitive to fractures oriented in the survey direction (Tsoflias and Hoch). Here, we focus the discussion on one main fracture that is prominently seen in the GPR dataset, marked on the reflection data in Figure 1 by a solid segmented line. This line follows the trajectory of the fracture as seen in the GPR reflections using a constant velocity model. However, no information about the fracture's absolute orientation can be deduced from this dataset and is therefore difficult to say whether it actually intersects the other boreholes and the tunnel wall. To assess the GPR information using high-resolution ABI data, we have identified 5 potential fractures in the region of interest where the fracture crosses the borehole. These fractures were chosen based on their dip in a way that they correspond well to the GPR computed angle. The ABI data gives both the dip and azimuth in good precision, but does not reveal whether the fracture propagates away from the borehole. The combined results are shown in Figure 2.

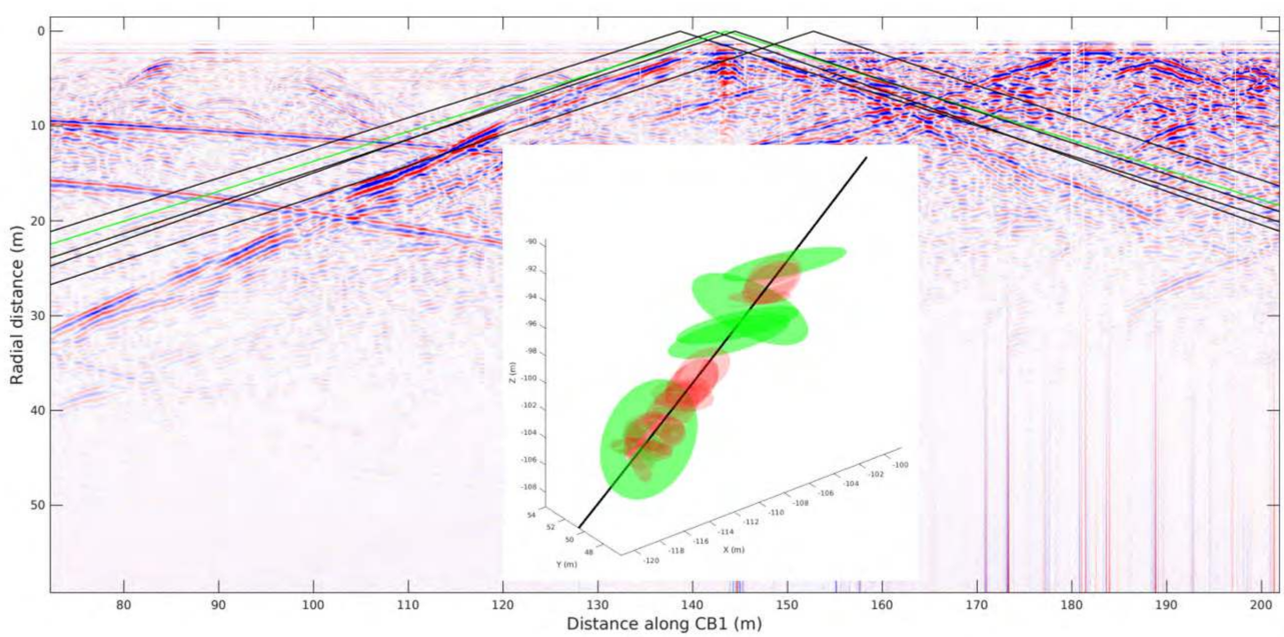

Figure 2. A zoom in on the reflection of interest from Figure 1, where the long fractures intersects borehole CB1. The fractures that likely cause this reflection, as identified from the ABI logs, are plotted as lines on top of the GPR data. The most likely fracture is highlighted by the green color (identified as the most permeable). The 3D insert in the figure shows the extrapolated fracture planes along the borehole in this region, uniquely picked from the ABI log. Fracture planes in red do not fulfill the dip criteria set by the GPR reflections, in contrast to the fracture planes in green.

Conclusions

By combining geophysical borehole data of various resolutions, we can create a more comprehensive geological map of the subsurface – in this case fractures in a potential EGS. Combining datasets is difficult and often done in an interpretive way. In the case above, we have two methods that work on different physical principles (acoustic vs. electromagnetic waves) but it is still possible to create a link between the two. Additionally, hydraulic tests have revealed a high inflow (0.8 l/min) region at a borehole length of 143 m. Hydraulic data are the ultimate confirmation in this case, because an EGS relies on hydraulic properties (permeability, hydraulic conductivity). We are working on building robust statistical frameworks in which these datasets can be combined with the final goal of creating a comprehensive geological model, used for creation, monitoring and prediction of the EGS.

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New challenges in monitoring hectometer scale experiment

Submitted by Plenkers, K. and the Bedretto Lab team; Swiss Competence Center for Energy Research – Supply of Electricity (SCCER-SoE) & Department of Earth Sciences, ETH Zürich

In-situ experiments in underground research laboratories advance research as they allow accessibility to the earth crust, controllability and scalability. So far the different experiments conducted gave rich data and valuable insights for hydraulic stimulation on the 10m-scale. As the next step ETH Zurich is aiming for hydraulic stimulations on the 100m-scale in the Bedretto Underground Laboratory for Geoenergies (BULG). One important aspect in this project is experiment conditions that are more comparable to the conditions of full-scale experiments, i.e. higher stresses due to more overburden and more realistic pore pressure conditions due to much longer distances to access tunnels and the free surface. Moreover, due to larger volumes of injected fluids that can trigger larger seismic events, a distance of > 100m from the stimulation to the infrastructure tunnel is mandatory for risk control.

For monitoring, it follows that several aspects have to be taken into account: a) monitoring equipment must be installed in up to 300m long monitoring boreholes with a limited borehole diameter; b) all instruments must be suitable for pressure conditions up to 10 MPa (maximum expected hydrostatic pressure); and c) all instruments must be watertight. Finally, monitoring boreholes within the reservoir must be carefully sealed, because any shortcut of fluid migration must be prevented, which means that the instrumentation must be suitable for environments with PH<13. This article highlights monitoring decisions and solutions developed in BULG.

In the BULG stimulation experiment the seismo-hydro-geomechanical processes during stimulation and circulation are studied, i.e. the rock response to the operation in terms of induced seismicity, (poroelastic) deformation and permeability increase. For this reason, the most important observables apart from pumping parameters are particle motion (seismic waves), strain, absolute pore pressure and temperature. Compared to decameter experiments, the resolution aimed for in the monitoring is reduced in order to monitor a much larger rock volume.

Pore pressure changes influence the local stress field and for this reason the release of seismic energy. The slow opening of pathways results in volumetric deformation in an aseismic manner. To capture the aseismic deformation in the BULG reservoir experiment we use a twofold approach. On the one hand, side Fibre-Bragg Grating Sensors are installed for high resolution and continuous monitoring of strain at selected intervals. Due to the limited size of these sensors of 1m, this measurement is a point measurement. In order to reduce the effect in case that cables are cut during the installation, two FBG chains with alternating sensor placement are installed in a loop configuration. Second, one single mode and one multimode fiber optic cable is installed, which allows measurement of temperature and strain (rate) continuously along the fiber, using the distributed temperature sensing, distributed acoustic sensing or distributed strain sensing method.

Monitoring induced seismicity in underground experiments allows monitoring the rock response away from monitoring boreholes and gives valuable information on damage, fracture growth and critical stressed structures. Microseismic events with magnitudes larger M=0 are possible in the Bedretto stimulation experiment, which corresponds to rupture areas of several meters. At the same time very small seismic events with magnitudes as small as M=-6 (source size on cm-scale) delineate, for example, planes of future macroscopic damage, fluid migration and stress re-distribution.

In Bedretto we aim at recording seismic events over seven magnitudes from M= -5 to M = 2 in the frequency range 1 Hz to 100,000 Hz, which is possible with using different seismic sensors only. We therefore implement triaxial geophones (able to record microseismic events from close distances), high-frequency triaxial piezoelectric accelerometers (able to record events down to M-4) and in-situ Acoustic Emission sensors (highest sensitivity in the kHz frequency range) into the network. A challenge for these sensors is the pressure regime of the experiment in combination with the small borehole diameter, which is why all seismic sensors were re-designed to fit-for-purpose by the manufacturers. Seismic data will be recorded with up to 200 kHz sampling frequency in continuous recording, which results in an expected data stream of 4.4 TB per day.

All sensors together will be placed in multi-sensor monitoring boreholes and sealed using a pre-engineered cement grout. The placement in one borehole is beneficial as it reduces the number of boreholes within the stimulated volume. At the moment eight monitoring boreholes with up to 300m length are planned. In order to accomplish this in all-in-one installation and in order to reduce the risk that the sensor chain gets stuck during the installation, a rod system was developed that consists of one centralized tube (cementation line), rotatable centralizers and fixed cables clamps. The latter ensures not only the proper fixation of cables, but organizes the cable outline in such a way that each cable is separated to order allow the cement to reach all interspaces. In order to reduce the number of cables in the boreholes, eleven coaxial cables were gathered in one multi-cable with internal sealing. Boreholes will be cemented in overpressure in order to support the cementation of all clearings and to reduce the risk of leakage along cables. Because casing increases the risk for leakage through the annulus along the pipes and reduces the sensitivity of sensors, no casing is used.

Last but not least, the in-borehole installation will be complemented by sensors installed in the tunnel that include seismic strong motion stations, tiltmeters and gas- and fluid sampling.

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