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Hydraulic stimulation and fluid circulation experiments in underground laboratories: Stepping up the scale towards engineered geothermal systems

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ABSTRACT

The history of reservoir stimulation to extract geothermal energy from low permeability rock (i.e. so-called *petrothermal* or *engineered geothermal systems, EGS*) highlights the difficulty of creating fluid pathways between boreholes, while keeping induced seismicity at an acceptable level. The worldwide research community sees great value in addressing many of the unresolved problems in down-scaled *in-situ* hydraulic stimulation experiments. Here, we present the rationale, concepts and initial results of stimulation experiments in two underground laboratories in the crystalline rocks of the Swiss Alps. A first experiment series at the 10 m scale was completed in 2017 at the *Grimsel Test Site, GTS*. Observations of permeability enhancement and induced seismicity show great variability between stimulation experiments in a small rock mass body. Monitoring data give detailed insights into the complexity of fault stimulation induced by highly heterogeneous pressure propagation, the formation of new fractures and stress redistribution. Future experiments at the *Bedretto Underground Laboratory for Geoenergies, BULG*, are planned to be at the 100 m scale, closer to conditions of actual EGS projects, and a step closer towards combining fundamental process-oriented research with testing techniques proposed by industry partners. Thus, effective and safe hydraulic stimulation approaches can be developed and tested, which should ultimately lead to an improved acceptance of EGS.

1. Introduction

A world-wide desire for nuclear-free and CO_2-free energy has raised interest in deep geothermal energy as an alternative energy source that can provide base load energy free from seasonal fluctuations. In Switzerland, phasing-out nuclear power and CO_2-intensive energy production is one of the goals of the governmental Energy Strategy 2050 that has become part of the federal legislation by popular vote in 2017. In response to this strategy, the Swiss Competence Centres for Energy Research (SCCER) have been initiated as a nation-wide research network that carries out innovative and sustainable research supporting the shift to efficient and renewable energies sources. Advancing technologies to exploit deep geothermal energy is a key goal

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of this initiative. Geothermal energy production has so far been successful predominantly in locations with favourable geological conditions (e.g. volcanic fields or hydrothermally active areas, sedimentary basins with deep seated permeable rock formations). So-called *Enhanced* or *Engineered Geothermal Systems* (EGS) (also referred to as *Hot-Dry Rock* or *petrothermal systems*[1]) are seen as one alternative way, among others, to exploit the Earth's heat independent of such conditions.

1.1. Enhanced geothermal systems

During the development of EGS, rock formations are hydraulically stimulated through hydraulic shearing (HS) of pre-existing faults and/or by hydraulic fracturing (HF) of intact rock. Hydraulic stimulation is done in an effort to increase permeability by several orders of magnitude to enable advective heat transfer from hot, but practically impermeable rock. In its natural state, such rock volumes allow only very limited fluid circulation through low-permeability faults and fractures, so that it is too low to enable cost-effective geothermal energy extraction.

Broad technological acceptance of EGS has so far been hampered by the often unpredictable outcomes of hydraulic stimulation operations related to insufficient knowledge about underground conditions. The recent push for this technology — in response to a societal change towards CO_2-emission and nuclear-free power generation – has yielded promising results in well explored areas (e.g. Soultz-sous-Fôret[2]; Rittershofen,[3] Insheim[4]), but also produced many examples facing difficulties (e.g. Newberry, USA[5]) that even led to the abandonment of some projects (Basel EGS project,[6]). Societal acceptance is compromised because of felt earthquakes produced by hydraulic stimulation that led to scepticism towards deep geothermal energy (e.g. the M_W3.2 earthquake associated with the Basel EGS project in 2006). More recently a M_w5.5 earthquake occurred close to a geothermal project site in Pohang (South Korea), which has been found to be associated with an inadequate risk management strategy during the reservoir stimulation operations.[7,8] Not only earthquakes, but also technical problems with wellbore integrity (e.g. Newberry, USA[4]), gas inflow that had to be suppressed to avoid borehole blow-out (e.g. the hydrothermal project at St. Gallen[9,10]) or too low production flow rates (St. Gallen; Bad Urach[11]) recently led to costly project delays or even halts. Additionally, the achieved power production at successful projects has so far hardly reached economically profitable levels; the capacity of the power plant at Soultz-sous-Fôret reaches 1.7 MWe,[12] the one in Insheim 4.8 MWe.[4] The Swiss Energy Strategy 2050 foresees roughly 4.4 TWh of electricity per year produced via geothermal energy by 2050, which corresponds to >100 times the capacity at Insheim, or 20 power plant with 25 MWe capacity. Nevertheless, estimates of the potential of geothermal energy[13] illustrate that scientific engineering and financial efforts towards developing EGS are worthwhile.

Evidently, engineering the complex Earth's crust at depths of several kilometres with only a few boreholes must hold surprises as not only recent cases show. Indeed, the nearly 45-year-old history of the EGS is one of unexpected and often undesired outcomes.[14] Nonetheless, sufficient wellbore productivities for power generation have been achieved: for instance, in Soultz-sous-Forêts,[2] Rittershofen[3] and Insheim[4] in the Upper Rhine Graben — examples that hold promise that the concept works in principle. Accepting that many other projects were terminated without producing electricity, they nevertheless led to an enormous gain in process understanding. Although the problem of induced seismicity has been intensively discussed in the literature,[11,15] it is not the only process that deserves attention. Evans[14] summarizes lessons learnt from a range of past EGS projects focusing mostly on hydromechanical aspects. The pioneering project to demonstrate the EGS concept began at Fenton Hill, Los Alamos in 1974.[1] Here, the many attempts that were made to connect two boreholes by means of hydraulic stimulation, documented in detail by[1], highlighted the difficulty of establishing a connected reservoir. The primary stimulation mechanism, originally thought to be *hydrofracturing* (i.e. formation and opening of new fractures), turned out to be dominated by slip-reactivation along the pre-existing fractures (i.e. *hydroshearing*) that were also the most hydraulically active.[1,16] Similar observations were subsequently made at Rosemanowes (1978–1991); the relative orientations of the natural fractures, the principal stresses, and the seismicity cloud produced by hydraulic stimulation indicated that shearing of natural fractures occurred in response to increased fracture fluid pressure. Although the stimulation injections greatly increased permeability, the cross-well flow resistance remained too high to produce commercial flow rates. These and other examples highlight a widespread problem of EGS projects: permeability in the near-field around the borehole can be adequately enhanced, but not necessarily in the far-field. While seismicity indicates that shearing can be induced at a considerable distance from the well, it remains to be understood how far hydrofractures that initiate at the injection well can propagate into the rock mass and create new flow paths.[14] This requires an improved understanding of the fluid pressure distribution during stimulation within low-permeability formations. McClure and Horne (2014)[17] analysed a number of cases and hypothesized that, what is often interpreted as pure hydroshearing mechanisms may actually be a mixed-mode mechanism with hydrofractures propagating as splay fractures from reactivated fractures.

1.2. Towards scaled experiments

The *in-situ* experiments at Le Mayet in France (1985), where stimulations were conducted in granite at 800 m depth,[18] and Fjällbacka in Sweden (1989), where two boreholes were linked through stimulation at 480 m depth,[19] are noteworthy in that these sites were dedicated to research on the seismo-hydromechanical response to stimulation and circulation in well-characterized rock. They were a consequence of mostly unsuccessful attempts to establish an EGS in the 1970s and 1980s that showed that there is a need to gain a more fundamental understanding of stimulation processes. Nowadays, we have arrived at a similar situation: the world-wide endeavours towards geothermal energy production, exploitation of gas or oil from shale reservoirs, waste water injection, as well as research on CO_2 storage highlight a need to understand the rock mass response to fluid injection, particularly with regard to problems of induced seismicity. Exploitation of these underground resources would benefit from an improved process understanding, the ability to control hydromechanical engineering processes at depths, but also from exploring innovative approaches to extract heat (e.g. CO_2 as working fluid[20–23]), novel drilling techniques,[24,25] and new stimulation approaches providing more control on the reservoir development process (e.g. zonal isolation).[26]

The major problems in this applied research field are *scalability*, *accessibility* and *controllability*. Research on the seismic, thermo-hydromechanical and chemical rock mass responses during fluid injections and circulations currently relies largely on either observations from full-scale projects or decimetre-scale laboratory experiments — spatial scales separated by at least three orders in magnitude. At the full reservoir scale, observations are usually indirect and sparse as the actual processes occur kilometres below the surface. Reservoir boundary conditions, geometry, structure and properties remain uncertain and operators have limited control on the processes themselves. At the same time, it remains unclear how well-controlled and well-understood laboratory experiments[27] can be transferred to the full scale. This research gap can only be filled with in-situ experiments performed at intermediate scales, ideally with good access to the experimental volume to facilitate rock mass characterization and experimental control, as well as showing sufficient similarity to the full-scale target rock mass conditions at several kilometres depth.

Several recent *in-situ* experimental programs have a focus on EGS related questions: In the USA, a 10 m-scale hydrofracturing experiment in the Sanford Underground Research Facility (SURF) in South Dakota was performed in 2015–2016 at 1500 m depth.[28] It is part of the FORGE initiative (Frontier Observatory for research in geothermal energy) of the Department of Energy (DoE) aimed at paving the way towards EGS by supporting cutting-edge research, drilling technologies and stimulation and circulation techniques. A follow-up stimulation project at the site, known as EGSCollab,[29] was performed in 2018. Hydrofracturing experiments were also conducted in the Aspö underground research facility in 2015[30–32] under the lead of the German Research Centre for Geosciences (GFZ), Potsdam, and at the Northparkes mine in Australia[33,34] under the lead of CSIRO. Hydraulic stimulation experiments with simultaneous recording of fault dislocation at the injection interval were performed for instance at the LSBB (laboratoire souterrain à bas bruit de Rustrel) in France.[35]

In Switzerland, extensive experimental work at the decametre scale has been performed at the Grimsel Test Site (GTS) between 2015 and 2017 (Fig. 1). New experiments on the hundred-metre-scale are currently being planned at a novel facility called the Bedretto Underground Laboratory for Geoenergies (BULG). These endeavours follow the strategy outlined in the Roadmap for Deep Geothermal Energy,[36] which was developed to guide research and development for the Swiss Competence Centre for Energy Research–Supply of Electricity (SCCER-SoE), and which recognizes scaled experiments as a key pillar for geothermal energy research. Additionally, these *in-situ* experiments are complemented and supported by laboratory-based experiments at the decimetre-scale using novel purpose-built facilities, e.g. the LabQuake facility[37] or the rotary shear apparatus, HighSTEPS.[38]

The experiments in Grimsel and Bedretto are the topic of this article. In Fig. 2, they are compared in terms of scale to the Basel EGS project as defined by the distribution of relocated seismic events.[40,41] Ten metre- and hundred metre-scale experiments will provide detailed insights into the processes active in a target rock mass undergoing stimulation, even though some upscaling issues may remain.

Many researchers hold the view that induced seismic hazard scales with the injected fluid volume. This hypothesis is examined in Fig. 3a which shows a plot of the largest induced earthquake magnitude versus injected volume for a diverse collection of fluid injection projects where both parameters have been reported. McGarr (2014)[42] proposed an upper threshold of the maximum seismic moment that can be released per injected volume, although the existence of a firm threshold is disputable as there remains a non-zero probability that earthquakes larger than this threshold can be induced.[43–45] The latter point of view is supported by recent observations of earthquakes larger than suggested by McGarr's upper limit (e.g.[43,46,47]). Importantly, Fig. 3a also shows that in many cases, large volumes of fluid can be injected whilst inducing maximum earthquake magnitudes that are far below McGarr's upper limit, implying that permeability creation operations can be conducted without excessive seismicity.

To better understand the physics behind these empirical findings, it is clearly of interest to explore rock mass responses to injection at experimental scales of 10–100 m (referring to the scale of seismicity clouds as proxy). These experiment scales roughly correspond to injection volumes on the order of 1–100 m^3; during the GTS experiments injection of about 1 m^3 produced 10 m diameter seismicity clouds (see below), in Fjallbäcka about 100 m^3 produced seismicity clouds with ∼100 m diameter, and at Basel 10,000 m^3 produced seismicity clouds with ∼1000 m diameter. Thus, by placing practical limits to injection volumes, smaller-scaled experiments are indisputably safer than full-scale operations in terms of seismic hazard. Only few experiments at the ten-metre-scale (1 m^3 injection volume) have been thoroughly described in the literature, and hardly any on the hundred-metre-scale (10–100 m^3 injection volume).

Typically, earthquakes induced at this scale have magnitudes much below M_w1.5. The physics of such earthquakes has been extensively studied in the context of mining-induced seismicity as the vast body of literature illustrates.[48–53] The source sizes of these earthquakes are on the orders of 10–100 m as can be derived from scaling laws that relate stress drop and seismic moment to source radius[54] (Fig. 3b). Nonetheless, source physical studies of injection-induced seismicity in this magnitude range are sparse.[55–57] This is illustrated in Fig. 3b, which Cocco et al.[58] produced to show the independence of stress drop from seismic moment over a broad range of magnitudes (scale-invariance of earthquake source processes). (Note that many of the aforementioned studies on mining-induced seismicity are missing). Furthermore, these studies rely on indirect observations based on seismic monitoring, while direct observations at the source (e.g. fault slip and dilation) have so far been rare. Earthquake source studies below the 10–100 m scale can potentially be explored with underground laboratory experiments studying injection-induced seismicity with complementary seismic and non-seismic (e.g. deformation, pressure) monitoring systems. However, the scale of an injection experiment may be at least an order of magnitude larger than the scale of the reactivated seismic sources. For instance, the experimental volumes at the GTS and at the Äspo underground laboratory may have been at a 10 m scale (injection volumes 1 m^3), the induced earthquakes did not reach beyond the metre-scale.[57,59] The experimental program planned for the BULG, complemented by laboratory experiments, will provide unique insights into earthquake source mechanics of injection induced events by allowing near-field observations of source processes of events with $Mw < 1.5$ (i.e. <10 m source radii).

2. Hydraulic stimulation experiments at the Grimsel Test Site

2.1. The Grimsel Test Site

The Grimsel Test Site (GTS) was established in the 1980s by Switzerland's Nagra (National Cooperative for the Disposal of Radioactive Waste) to conduct research related to nuclear waste storage (Fig. 4). It is located below ∼450 m of overburden in the crystalline rock of the Aar Massive consisting of granodiorites and granites of Variscan age (i.e. 300 Mio. Years[61]) overprinted by ductile and brittle deformation. The ductile deformation took place under lower greenschist facies conditions and established a pervasive foliation within the rock mass. As the Aar Massive consist of a tectonically uplifted pre-alpine basement, it is regarded as an analogue to the crystalline basement of the Swiss foreland despite some differences in tectonic history. The latter was the host rock of the Basel EGS and is likely to be a primary target for future EGS development. The low matrix permeability of low-porosity crystalline rocks such as the one at the GTS is likely to be similar to the rock mass permeability at the depth of most EGS reservoirs. The test site therefore has ideal conditions for a

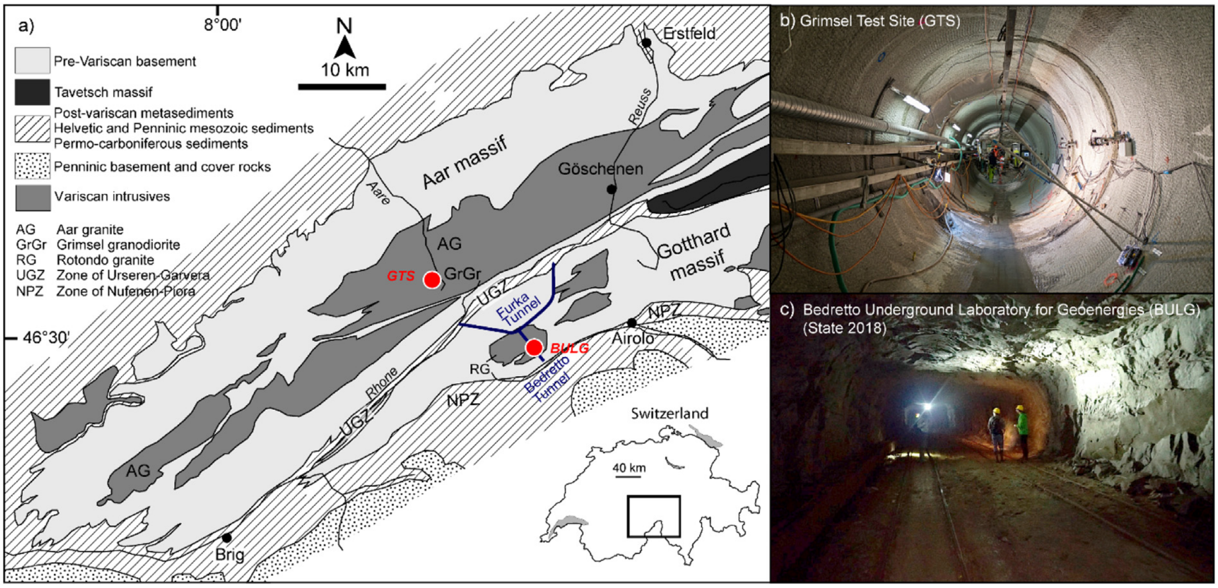

Fig. 1. (a) Geological map of the Aar and Gotthard massive hosting the Grimsel Test Site (GTS) and Bedretto Underground Laboratory for Geoenergies (BULG) (adapted from[39]), (b) Grimsel Test Site (GTS), AU tunnel, view towards ISC experimental cavern (AU cavern). (c) The experiment niche of the BULG (before established experiment infrastructure in 2018).

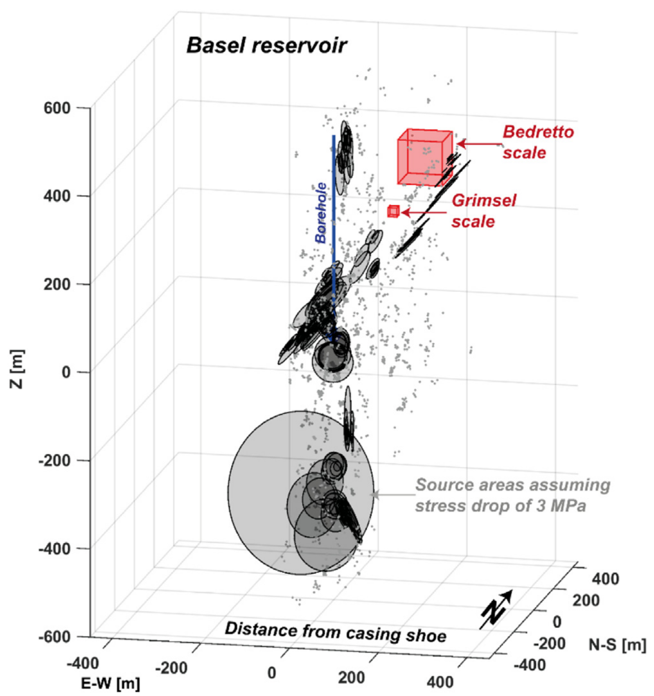

Fig. 2. Basel reservoir illuminated by >3000 seismic events that were induced during hydraulic stimulation with in December 2006, during which 11,570 m^3 of water was injected. Grey dots are relatively relocated earthquakes from the catalogue of Kraft et al. 2014.[41] Circles represent the inferred sources planes from earthquakes for which the focal plane was determined by Deichmann et al. (2014).[40] The source planes were estimated from earthquake moment magnitude assuming a stress drop of 3 MPa. 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.

decametre hydraulic stimulation experiment for several reasons: (1) the aforementioned similarity to basement rock of northern Switzerland, (2) well-characterized geology with accurately-constrained large-scale faults and fracture zones cutting through a rock mass with a low fracture density and permeability, (3) accessibility to the target rock volume from three tunnels at different sides and elevations, and finally (4) the pre-existing research infrastructure including power, water, internet, technical staff, and 30 years of research experience by Nagra, allowing fast project development and execution.

Our experimental rock volume is located between a V-shaped tunnel segment (between the AU and VE tunnels, Fig. 4). It contains three subparallel ductile shear zones (termed S1.1, S1.2 and S1.3 shear zone). These shear zones are intersected by two steeply dipping brittle–ductile shear zones (termed S3.1 and S3.2 shear zone) that are formed by deformation localization on biotite-rich metabasic dykes, separated by 2–3 m and bounding a heavily fractured zone (Fig. 4[62]). The local stress field, characterized during the first project phase, shows a maximum principal stress direction dipping 35° towards ESE, and a sub-horizontal NNE-SSW-striking minimum principal stress direction (see stereographic representation as inset in Fig. 4c).[63] As the intermediate and the minimum stresses are close in magnitude, an oblique strike-slip to thrust-faulting stress regime is conceivable. Evidently, the strong regional topography perturbs the GTS stress field. In addition, local stress perturbations are observed close to the S3 shear zones: The minimum principal stress magnitude systematically decreases from about 8–9 MPa at about 10 m south of the shear zone to <6.5 MPa closer to the shear zone. Additionally, the stress orientations rotate in the vicinity of the shear zone. The stress perturbation is possibly related to the larger compliance around and within the heavily fractured shear zone.

2.2. Experiment objectives

In a review on seismo-hydromechanical research, Amann et al.[64] identified the research questions that could be investigated in the ISC test volume. These encompass the hydromechanical response of fractures during stimulation, the pressure propagation away from the injection boreholes, rock mass deformation and stress interaction, the transition from aseismic to seismic slip and its relative importance, the interaction of hydrofractures with pre-existing structures, as well as the spatial

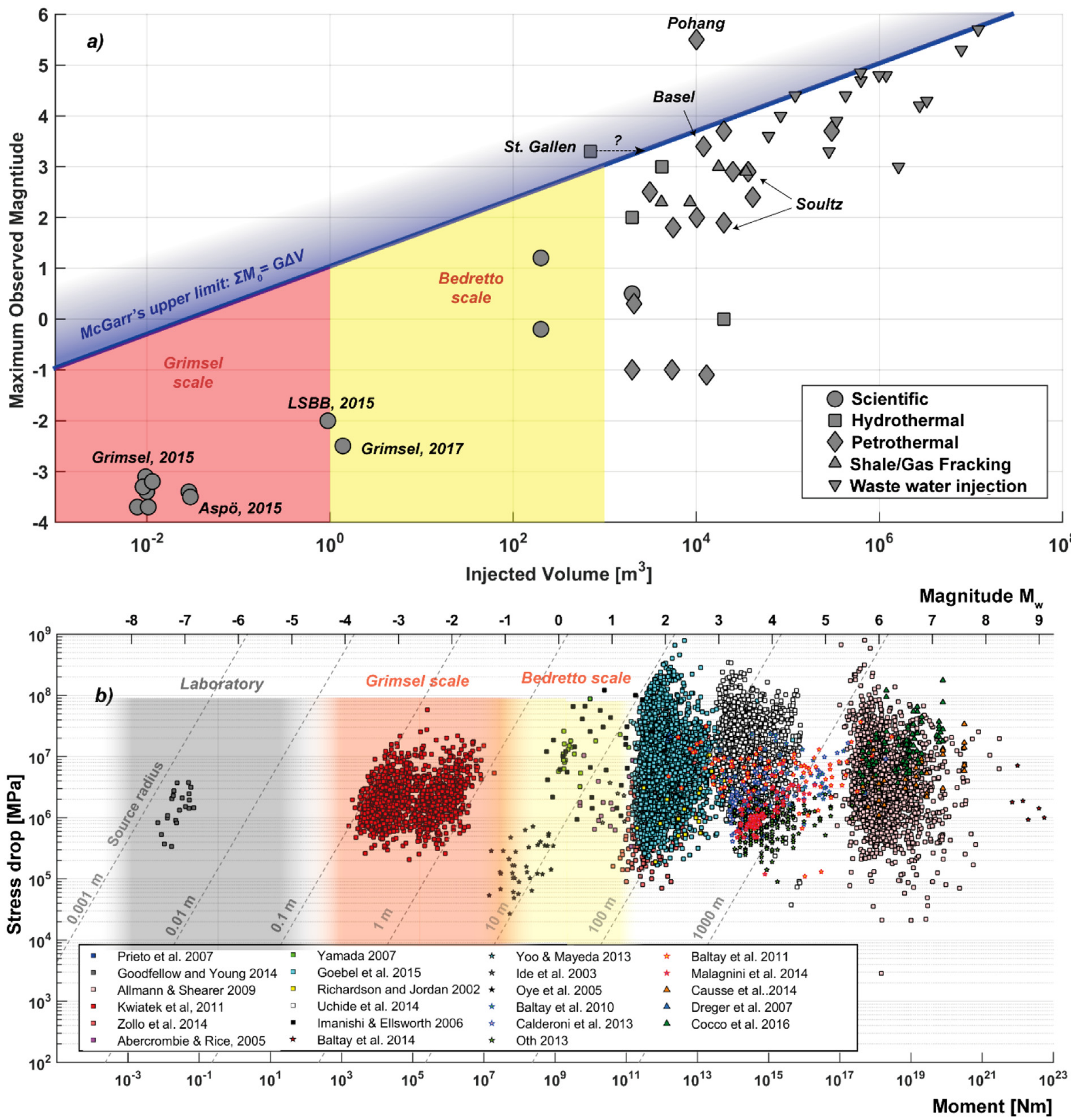

Fig. 3. (a) Largest earthquake magnitude versus injected volume for a diverse collection of fluid injection projects where both parameters have been reported.[11,42] The upper limit on earthquake magnitude proposed by McGarr (2014)[42] is shown. Events falling above the line (i.e. within and above the blue shading) support the notion that even larger earthquakes may occur, as argued for by various authors.[44,46] (b) Stress drop as a function of magnitude for a collection of natural and induced earthquake sources spanning a broad range of magnitudes, as originally presented by Cocco et al. (2016)[58] to illustrate scale-invariance of earthquake source processes. Grey lines indicate the source radii computed from stress drop and seismic moment. Squares represent stress drop estimates based on the model by Madariaga (1976),[54] stars are based on Brune's model,[60] and triangles are based on averaged finite source models. The collection illustrates that earthquake source studies for $M_W < 1.5$, i.e. of sources <10–100 m with radius, are sparse (although many existing studies at this scale in mines are missing in this case study collection). Experiments in rock laboratories (0.1 m-scale) and in underground laboratories (10–100 m scale) will help fill this gap.

and temporal variability of induced seismicity. The overall objective was to conduct fundamental research enhancing process understanding of hydraulic stimulations.

Both hydroshearing (HS)[65,66] and hydrofracturing (HF)[67] were investigated as distinct stimulation methods in two experiment sequences in February and May 2017, respectively. Six HS and HF experiments were conducted in two ∼45 m long boreholes (i.e. 12 experiments in total, Fig. 4b and d). We refrained from testing different injection protocols, as performing a statistically meaningful comparison of stimulation outcomes based on only six experiments is not reasonable. Instead, we applied standardized injection protocols (one each for HS and HF, see Figs. 6a and 7a) with the goal of isolating the effect of the rock mass conditions on the stimulation outcomes. Variability in various observations (e.g. permeability enhancement, seismicity, etc.) are thus related to local geological conditions and not to injection parameters.

2.3. Preparation phase

As part of the planning phase, a hazard analysis was conducted to evaluate the effect of the high pressure stimulations on long-term experiments running roughly 100 m away from the test volume (i.e. delicate radionuclide transport experiments that

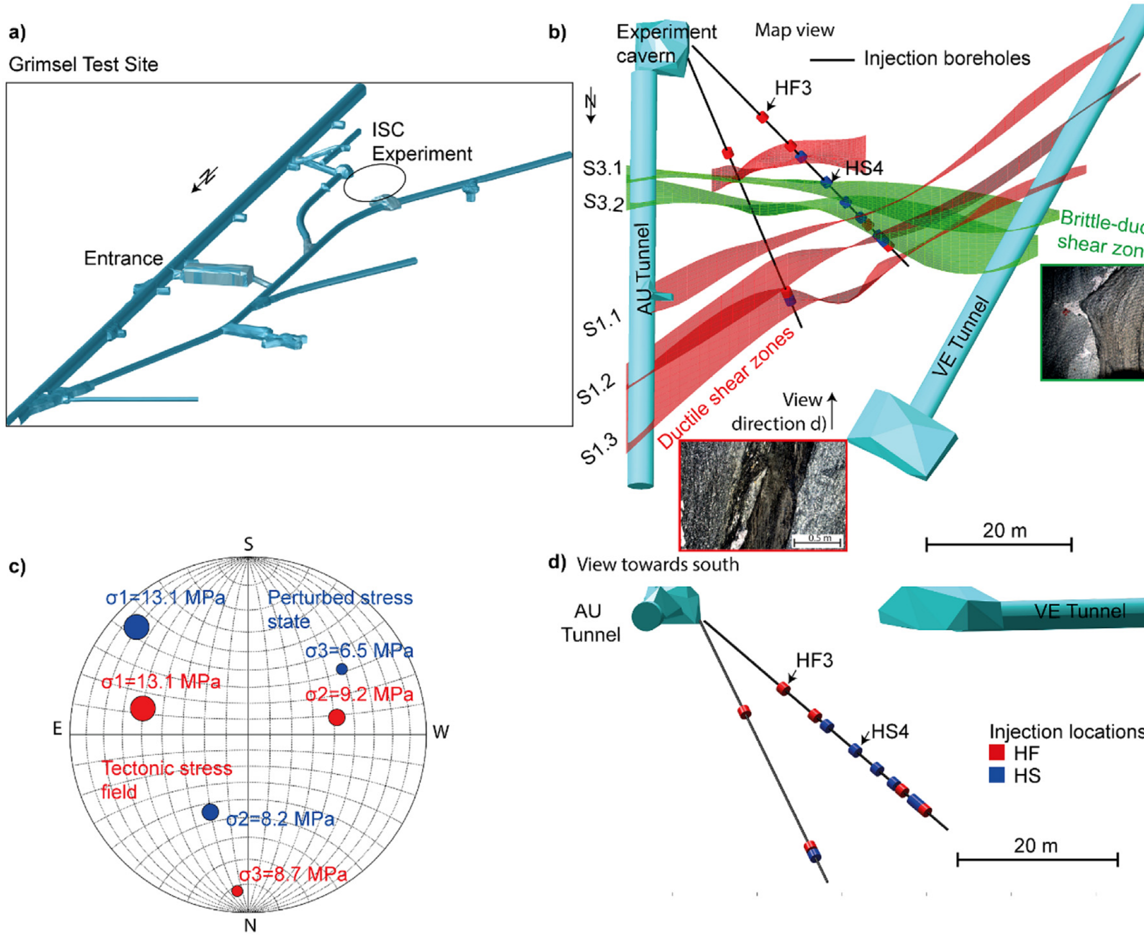

Fig. 4. (a) 3D view of the tunnel network of the GTS with the experiment site highlighted. (b) Experiment volume with the large-scale shear zones (green: brittle–ductile S3 shear zones, red: ductile S1 shear zones) as well as the two injection boreholes with the injection intervals of the hydroshearing (HS) and hydrofracturing (HF) experiments. Note that north is downwards for a better display of the shear zones. (c) Principal stress field components measured ca. 40 m south of the S3 shear zones (termed 'unperturbed or tectonic stress field' in red) and 0–10 m from the S3 shear zone (termed 'perturbed stress field' in blue). (d) Side view towards south of the tunnels, injection boreholes and injection intervals.

have been running for more than 10 years), as well as on the infrastructure of Nagra and the nearby hydropower company.[68] Potential effects of the stimulation on the nearby experiments may involve pressure diffusion through the fracture network or poro-elastic stress changes (both altering the pressure gradients within the radionuclide transport experiments) or ground shaking from induced earthquake disturbing these experiments or other infrastructure. The estimated level of all these potential disturbances were considered negligible or acceptable by stakeholders. Based on a probabilistic analysis that assumed a total injected volume of 1 m^3, the chance that induced earthquakes would create light damage to the experimental cavern was estimated to be <1:10,000. The maximum expected magnitude was estimated to be M_W −1.7. Estimates of the largest induced magnitude are M_w −2.5,[69] indicating that the induced seismic hazard may have been below the a priori estimates.

A thorough characterization program was performed between 2015 and 2016. This involved (1) constructing a high-definition geological model ([62], Fig. 4) based on borehole logging, mapping and geophysical imaging (seismic tomography and GPR reflection surveys).[70] (2) Characterizing the stress field and its spatial variability (Fig. 4) with stress relief methods and hydraulic fracturing.[63] (3) Hydrogeological testing including single-hole injection tests (pulse injections, constant rate injections, cycling injections), cross-hole injection tests without and with tracers (heat, solute, DNA).[71,72] The results of these investigations were essential for proper design of the experiments in terms of target intervals for HS and HF, specifications of pumps and packer systems as well as for monitoring systems. Monitoring included five boreholes for pressure monitoring in various intervals, deformation monitoring in three boreholes (60 high-resolution Fibre-Bragg-Grating, FBG, sensors and distributed strain sensing systems), three tiltmeters and a 32-channel seismic monitoring system for passive[69] and active[73,74] seismic observations (Fig. 5).

2.4. The stimulation experiments: preliminary key observations

An exemplary hydroshearing experiment (termed HS4, see Fig. 4) is summarized in Fig. 6. It shows the four cycles of the standardized injection protocol.[65] The first two cycles were dedicated to recording pre-stimulation injectivity and jacking pressure, the third cycle is the main stimulation cycle, and a last cycle is dedicated to recording post-stimulation injectivity and jacking pressure. All cycles included shut-in and venting phases lasting 10–50 min. The injection location is shown in Fig. 4a and c. In this particular experiment, one of the two east–west striking steep brittle–ductile shear zones (S3.1) was stimulated. The fractures in the interval opened at ∼6 MPa as is evident during the first two pressure-controlled tests, during which the flow rate suddenly increases once injection pressure exceeds 6 MPa. Interestingly, the fluid pressure in the monitoring intervals containing the stimulated shear zone at about 7 m distance from the

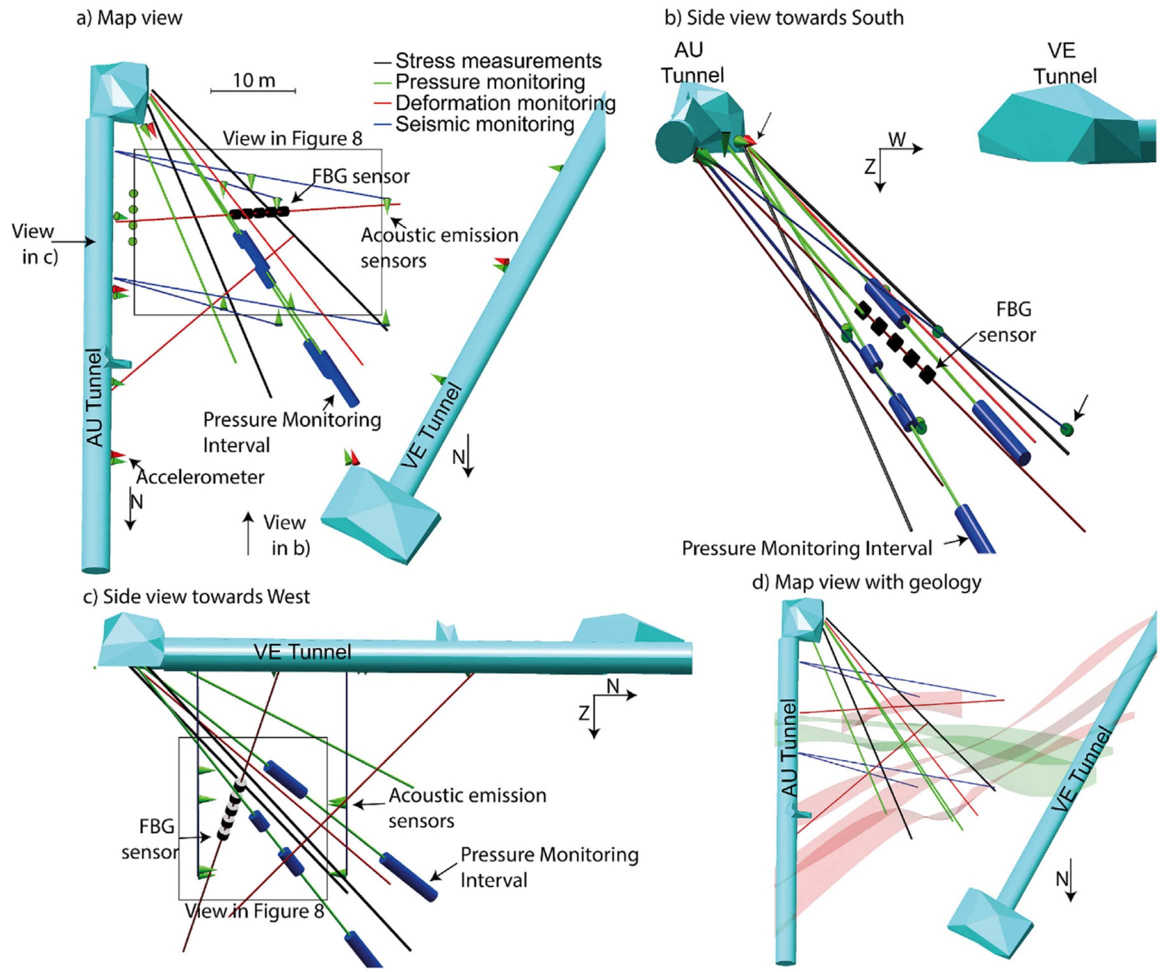

Fig. 5. Borehole layout and experiment tunnels from different perspectives: (a) Map view, (b) Side view towards South, (c) side view towards southwest, and (d) geological model in map view for reference. Note that only the pressure intervals and FBG strain sensors with data presented in this article are shown for simplicity.

injection interval reached maximum values of less than 0.6 MPa (i.e. <10% of the injection pressure). This was a common pattern across most experiments: pressure changes in the monitored intervals only reach a fraction of the injection pressure. Only during one injection experiment into the S3.2 shear zone (not shown here), pressure in the monitoring intervals across the shear zone reached values up to 6 MPa. It is somewhat unexpected that sharp pressure increases were only found in very few cases, because models of non-linear pressure diffusion that consider permeability increases from fracture dilation during stimulations predict steep pressure fronts, i.e. abrupt pressure increases at some distance from injection reaching pressures below, but on the order of magnitude of the injection pressure.[75–77] In contrast, linear diffusion models (considering constant permeability) predict smooth pressure changes much below the injection pressure at some distance from the injection point. In our case, injectivity and transmissivity increased by several orders of magnitude for most experiments (Fig. 8), yet pressure stayed mostly at a level of <1 MPa in the monitoring intervals few metres away from injection. We currently hypothesize that strongly channelized flow – as opposed to radial or spherically symmetric pressure propagation – may explain why such pressure fronts have not been detected by the monitoring intervals surrounding the injection borehole although they monitored the stimulated structures. Such behaviour is consistent with the stimulation models proposed by Evans et al.[78] and Rutledge et al.,[79] who proposed the creation of channels or jogs opening along the hydro-sheared fractures striking perpendicular to the shear direction. Hydromechanical modelling planned for future work will help investigating these hypotheses.

Complex rock deformation and fracturing processes are evident from the strain recording in Fig. 6c. The time series represents longitudinal strain recorded in a borehole parallel to the stimulated shear zone. During the main stimulation (cycle 3), strong extension of up to 400 μstrain (400 $\mu\varepsilon$) suddenly occurred at a sensor installed in intact rock (at 24 m depth along the borehole), which responded with strain amplitudes of less than 10 $\mu\varepsilon$ during the first two injection cycles. (Note that 1 $\mu\varepsilon$ = 1 μm relative displacement of the ends of our 1 m long sensors). A permanent extension of 150 μm remained at the end of the experiment. The relative displacements are interpreted as reflecting the opening of a new fracture that intersected the sensor interval (see sketch in Fig. 6). The adjacent sensor at 26 m also shows an abrupt opening occurring slightly earlier, which was then suppressed by the strong fracture opening at the sensor next to it (i.e. at 24 m). Furthermore, the other neighbouring sensor intervals at 22 and 28 m depth along the borehole show shortening in response to stress transfer. The observations highlight that the potentially hydroshearing-dominated stimulation process may be associated with propagation of new fractures. These strain time series illustrate the rich details recorded by the borehole strain sensors, which provides insight into the complex deformation occurring within the rock mass during stimulation, and is sensitive to both aseismic and seismic fracture dislocation fields.

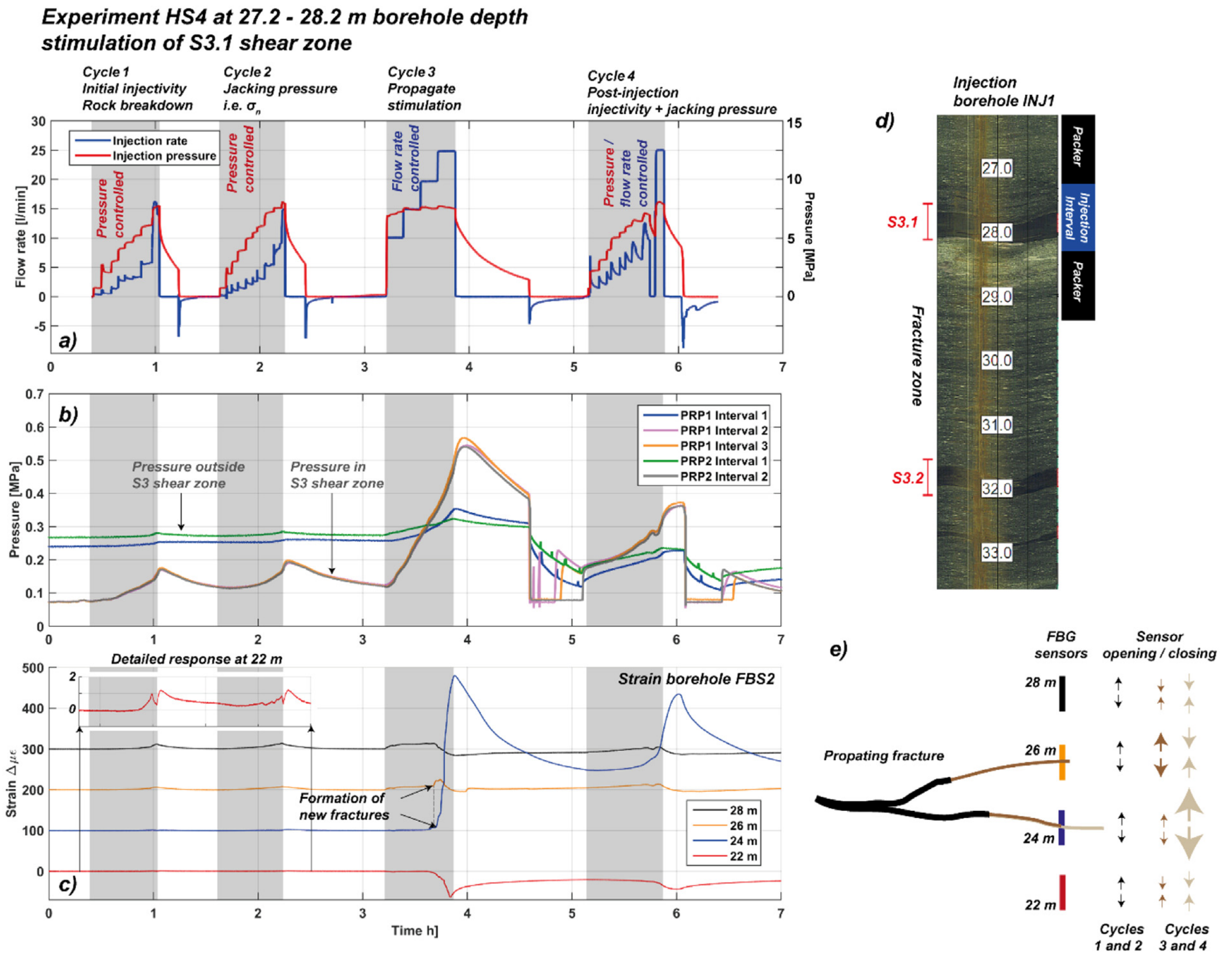

Fig. 6. (a) Injection rate and pressure during an HS experiment (referred to as HS4) during which a 1 m interval across the southern EW striking shear zone S3.1 at 28 m depths was stimulated (see OPTV image in d). The objectives of the four injection cycles are indicated. (b) Pressure during stimulation recorded in five pressure monitoring intervals in the boreholes PRP1 and PRP2 (Fig. 7). (c) Strain recorded at four depths in borehole FBS2. All sensors are installed across intact rock (i.e. no fractures detected in OPTV images). Negative strain indicates sensor shortening, positive strain extension. Note that 1 $\mu\varepsilon$ corresponds to 1 μm as the sensor base lengths are 1 m. (d) OPTV image showing the experiment interval at the target structure S3.1. (e) Sketch explaining the strong extensional strain signals in (c) being indicative of propagating fractures hitting the FBG sensors at 26 and 24 m depth during injection cycle 3.

An example of an HF experiment[67] (termed HF3) is shown in Fig. 7. The injection protocol differed slightly from the HS protocol; it involved an injection cycle to breakdown the intact rock, one or two injection cycles to propagate the HFs, and a last cycle to record post-HF injectivity and jacking pressure. Again, all cycles include shut-in and venting phases lasting 10–50 min. A 1-m-long intact rock interval 7 m above the HS4 injection in INJ1 (Fig. 4) was hydrofractured. The required pressure for breakdown of the interval was about 16 MPa (Fig. 6a). The fracture was propagated by injecting about 1000 l in two cycles (2a and 2b), between which the pump had to be switched to be able to reach flow rates of 90 l/min. During about 3 min of cycle 2a, the flow rate was oscillated between 10 and 30 l/min with periods of $\sim$15 s to explore how far pressure oscillations penetrate into the rock mass and whether they have an effect on seismicity. The injection pressure amplitude during oscillation was about $\pm$0.7 MPa.

While pressure changes were again below 1 MPa at most monitoring locations, a steep pressure front reaching interval 3 in borehole PRP1 (Fig. 7b) indicated that a propagating mode I fracture had intersected either the monitoring interval itself or a highly conductive fracture that connected to the interval. The pressure dropped twice during the continued injection, which may be related to periodic fracture growth. The pressure fluctuation continued after shut-in with two sharp peaks of even higher pressure before finally subsiding, suggesting that fracture growth continued after shut-in.

Similar to experiment HS4, a fracture appears to have intersected a strain sensor interval at 20 m borehole depth in FBS2, which was previously not fractured (Fig. 7c). The sensor interval extends by 850 μm during cycle 2b. Two adjacent sensors at 22 m and 24 m first close in response, but then reopen, possibly as pressurization in these intervals overcome the compression exerted by the nearby strong fracture opening. Recall that the sensor at 24 m detected a new fracture forming during HS4 (Fig. 5c). Note that the oscillating injection during cycle 2a is picked up well by the strain sensors; the amplitude is about $\pm$10 μm at the sensor at 20 m and about $\pm$1 μm at the sensors at 22 and 24 m.

High-quality seismicity catalogues have been collected for all experiments.[69] The borehole acoustic emission sensors located a few metres away from the injections have been key to detect up to 5000 events per experiment. During the experiment HS4 (Fig. 8a and b), about 3000 events could be located. Most seismicity occurred within a few clusters less than 2 m away from the injections. During cycle 3, seismic events show an excursion from these dense clusters, towards the strain monitoring borehole FBS2, where new fracture formation is evident from the strain sensors at 24 m depth (Fig. 6c). Thus, the seismicity appears to be associated with the formation of new fractures. In contrast,

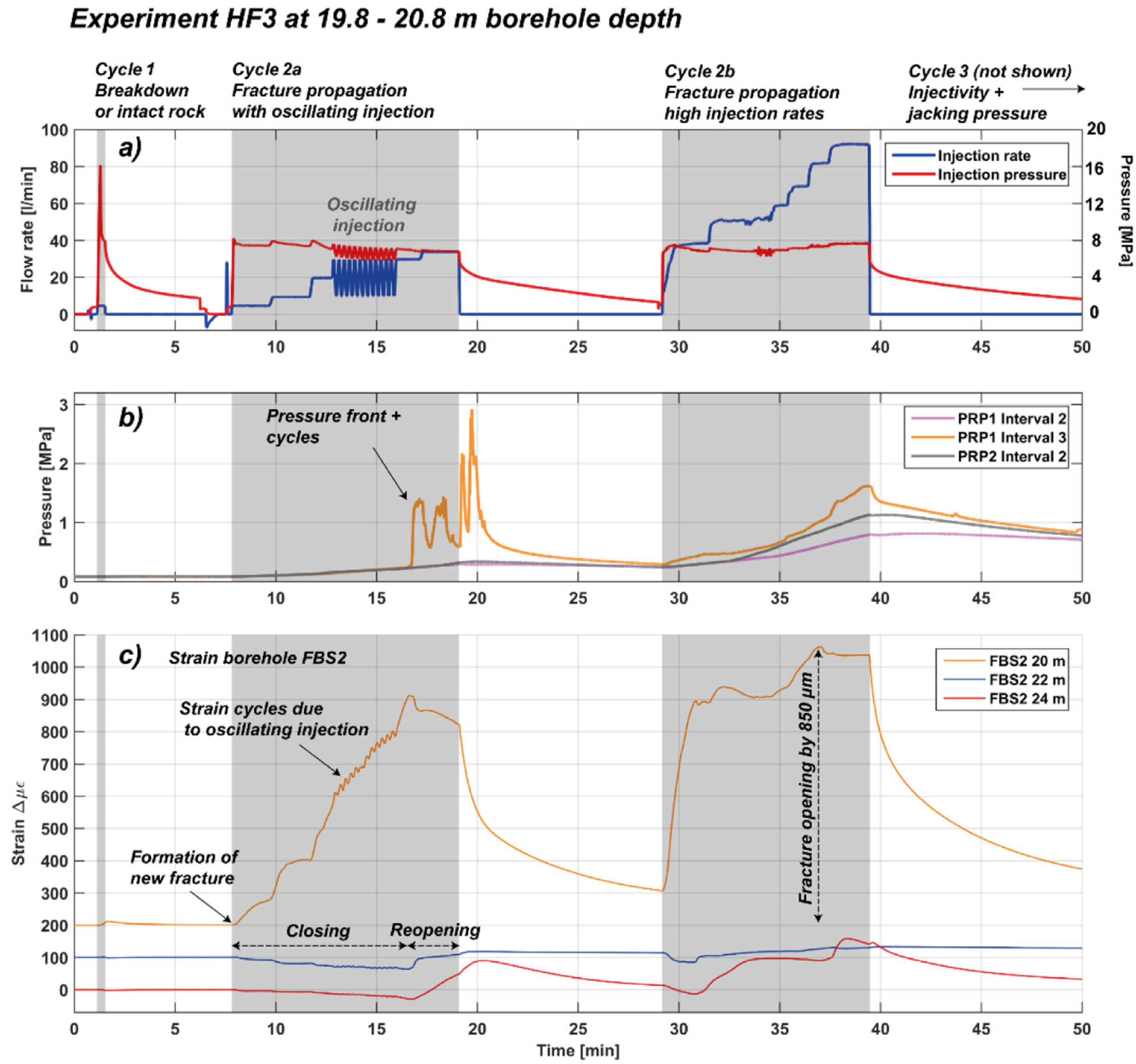

Fig. 7. Example of a HF experiment (HF3). (a) Injection rate and pressure during the HF experiment at an unfractured 1 m interval at 19.8 depth at along the injection borehole. Also indicated are the purposes of the injection cycles. Note that the last cycle 3, serving to measure injectivity and jacking pressure after HF is not shown to improve figure clarity. (b) Pressure during HF recorded in three pressure monitoring intervals in the boreholes PRP1 and PRP2 (see also Fig. 7). (c) Strain recorded at three depths in borehole FBS2. All strain sensors are installed across intact rock (i.e. no fractures detected in OPTV images). Negative strain indicates sensor shortening, positive strain extension (1 $\mu\varepsilon = 1$ μm for sensor base lengths of 1 m).

seismicity during the experiment HF3 (Fig. 8c and d) is sparse with only 70 events that could be located. Unlike during HS4, the fracture formation detected during HF3 (at 20 m depth in FBS2) is not clearly accompanied by seismicity. Generally, the seismicity clouds from all HS and HF experiments show strongly variable characteristics: neither the number of induced earthquakes, nor the spatial and temporal distributions show a simple systematic pattern (discussed in detail by Villiger et al.[52])

Across all experiments, the variability in stimulation outcomes is remarkable given the comparably small target rock volume[65]: the injectivities measured before (initial injectivity I_I) and after (final injectivity I_F) each experiment increased by more than two orders of magnitude for some experiments but very little for other experiments (Fig. 9a). Interestingly, the post-stimulation injectivity I_F of the test intervals measured after each experiment is comparable for all HS and HF experiments, although different geological structures and intact rock have been targeted. Apparently, the variability in injectivity increases, $\Delta I = I_F - I_I$, are related to the strong variability of initial injectivity I_I, while the final injectivity I_F reaches a value that may be characteristic for this rock volume and may be controlled by the most conductive shear zone (S3) in the experiment volume. The smallest injectivity increase ΔI was attained in the S3 shear zones where the initial injectivity I_I has already been high. Here, the largest seismic activity has been observed (Fig. 9b). In contrast, the S1 shear zones were characterized by low initial injectivity I_I, high injectivity increases ΔI and less seismic activity than in the S3 shear zones. The ductile shear zone set S1 seems to respond differently to fluid injection than the brittle–ductile S3 shear zones, possibly due to a different orientation in the stress field, differences in their fault architecture and both hydraulic and mechanical properties. Additionally, the variability in initial injectivity (and thus injectivity increase) and seismicity may both be a manifestation of the fracture density in the vicinity of the injections. Fig. 9e shows a tendency of higher fracture density close to intervals where high initial injectivity and high seismicity was observed. Note that the above discussion on injectivity (inferred from pressure-controlled injection steps

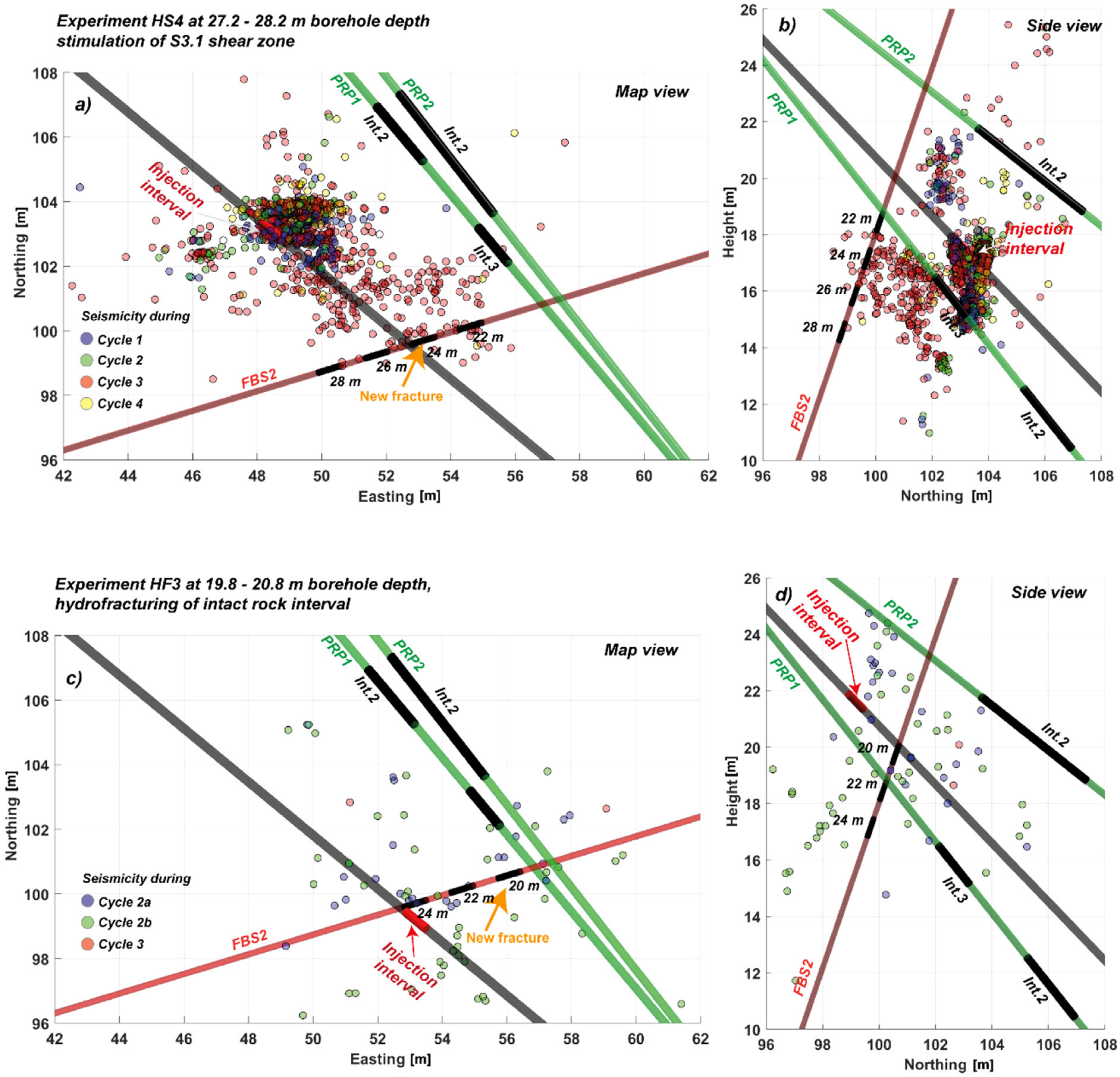

Fig. 8. (a) Map view of the seismicity cloud induced during the hydroshearing experiment HS4. Also included are the injection borehole and the monitoring boreholes for which data are shown in Fig. 6. (b) Side view of the seismicity cloud during HS4 looking towards east. (d) Map view of seismicity cloud during HF3. Injection and monitoring locations in Fig. 7 are shown. (d) Side view of the seismicity cloud.

lasting up to 10 min to reach flow rate equilibrium;[80,81]) regards near-wellbore hydraulic properties. Transmissivity would be a more representative metric for the entire stimulated rock volume. These values are discussed by Brixel et al.[71]

The GTS stimulation experiments include detailed rock mass, stress field and hydromechanical characterization, a total of 12 well-controlled and well-monitored stimulation experiments as well as a post-stimulation circulation experiment. It thus yields a dataset unprecedented in detail and comprehensiveness, which will be made available to the scientific community or the public in the near future ([70,82] http://sccer-soe.ch/en/publications/grimsel-isc-project/) to aid research and development in reservoir geomechanics.

Although the experimental data may eventually lead to a leap forward in process understanding of hydraulic stimulations, many EGS-relevant questions must remain unanswered, as various conditions at the GTS are different to the actual EGS-scale besides the experiment scale. The depth of only 450 m as well as the stress conditions do not correspond to the ones at typical EGS depths. The surrounding tunnels act as a drainage for the rock mass, which implies that pore pressure is depleted and atmospheric pressure boundary conditions affect the stimulation outcomes. Further, the experiment volume at the GTS has been exhaustively treated with stimulations. The limited space conditions do not allow for further investigation of hydraulic stimulation processes or testing of EGS-relevant technologies. Many of these limitations can be overcome with new experiments conducted in the BULG.

3. The Bedretto Underground Laboratory for Geoenergies (BULG) of ETH Zurich

3.1. The Bedretto test site

The Bedretto tunnel is a 5.2 km long access gallery to the Furka railway tunnel built for the construction of the Furka tunnel in the 1980s. The ETH research facility is located in a 100 m long cavern at distances between 2000 and 2100 m from the southern tunnel portal (Fig. 10) at an altitude of 1487 m a.s.l below an overburden

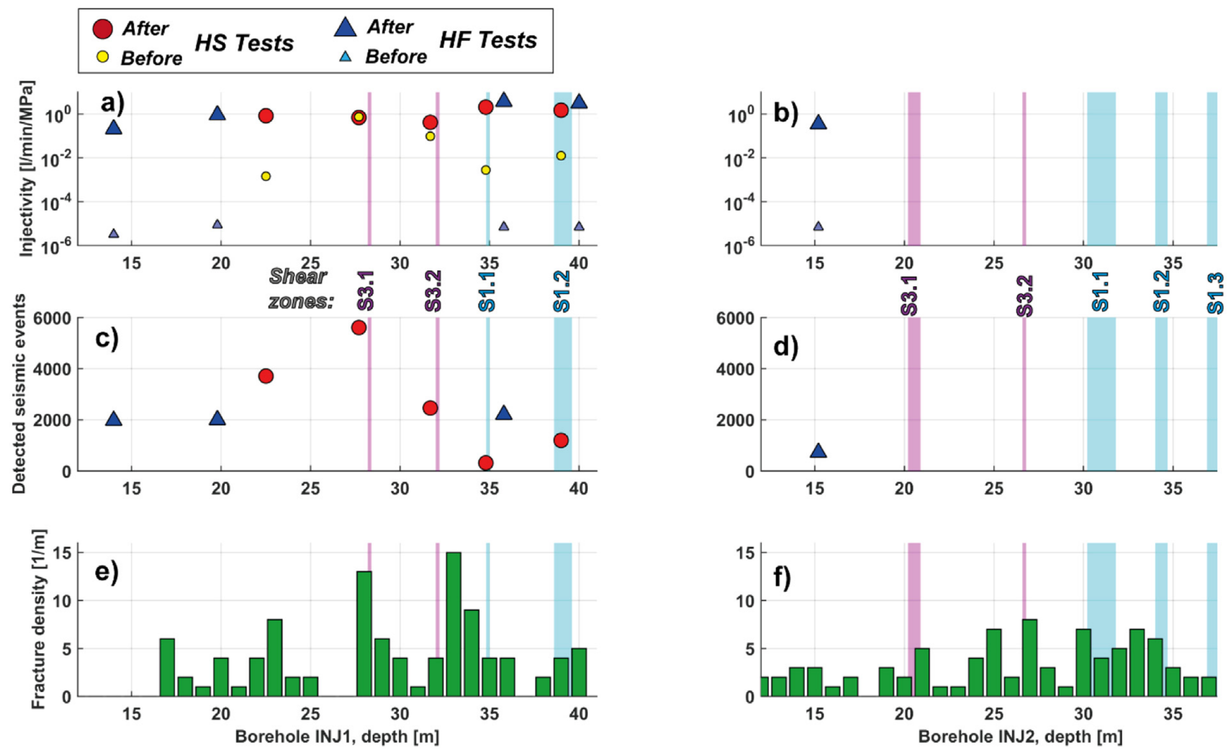

Fig. 9. (a) and (b) Injectivity recorded before and after the HS (circles) and HF (triangles) tests in borehole INJ1. Injectivity if the test intervals before each HS experiment and after each HS and HF experiment were derive from injection test with pressure-controlled steps. Injectivity values of the HF intervals before the HF experiments were roughly estimated from pulse test injections using the steady-state radial flow equation. (c) and (d) Number of detected seismic events during HS and HF tests. (e) and (f) fracture density per metre along the injection boreholes.

of about 1000 - 1200 m. Given the state of the unsupported tunnel left unused for decades, experimental work can only begin after essential infrastructure (power, ventilation, safety measures, communication, transport, etc.) has been built up. Construction was initiated in 2018, site characterization is currently (2019) ongoing, and experiments are expected to start in spring 2020.

Geologically, the BULG shares many similarities to the GTS, as it is located in a granitic intrusion – the Rotondo Granite – emplaced into pre-alpine crystalline basement rock around 300 Mio years ago (Fig. 1) that is now part of the tectonic unit called the Gotthard Massive. The Rotondo Granite is a largely homogeneous granite dissected by NE–SW-striking steep faults with well-developed cores of gouge and cataclasites.[39] Additionally, NS and EW striking and steeply dipping fracture zones occur frequently (Fig. 10). Sparse information from the World Stress Map[83] around the site indicates a regional maximum horizontal stress orientation subparallel to the tunnel in NW–SE direction. Observed stress induced rock failure at the tunnel walls (spalling)[84,85] indicates that the horizontal stress perpendicular to the tunnel is smaller than the overburden stress. Thus, normal faulting or strike slip faulting regime is conceivable, which consistent with the predominance of strike-slip faulting throughout the Swiss Alps and normal faulting in southern Switzerland.

3.2. Experiment objectives

Compared to the GTS experiments that focussed on fundamental research on hydraulic stimulation, the planned experiment series at the BULG are a step closer towards real EGS reservoirs in various aspects:

(1) The design scale in terms of the stimulated rock mass dimensions (100 m) and injected fluid volume (10–100 m^3) lies halfway towards the actual deep reservoir scale (1 km, 1000–10,000 m^3) and significantly above other recent injection experiments including the experiments at the GTS where about 1m^3 was injected (Fig. 2).
(2) With an overburden of over 1000 - 1200 m (Fig. 9), the experiment depth is closer to EGS-relevant depths than at the GTS (<450 m overburden).
(3) The stress regime (normal faulting to strike-slip) is the one predominantly found in the Swiss foreland basin, which is the prime target for future EGS development.
(4) Conditions (geology, infrastructure, etc.) at the GTS were ideal to address fundamental research questions related to seismo-hydromechanics.[64] In contrast, the experiments at the BULG will combine fundamental research together with testing of industry reservoir engineering concepts to be implemented at the EGS-scale.
(5) The circulation of water through the reservoir and the study of its heat exchanger capabilities were only a minor part of the GTS experiments and mainly consisted of extended heat tracer experiments lasting several days to weeks. At the BULG, it will become major focus as long-term circulation experiment will be conducted after a series of stimulation experiments.

Thus, the BULG experiments go beyond process-oriented research as they aim at responding to the pressing need to demonstrate, towards stakeholders and the public, that EGS technology can be safe and productive. The lifetime of the BULG is expected to go well beyond the currently planned experiments outlined below, as the BULG is established to become a new long-term research facility of ETH Zurich that welcomes external partners to conduct their own experimental research.

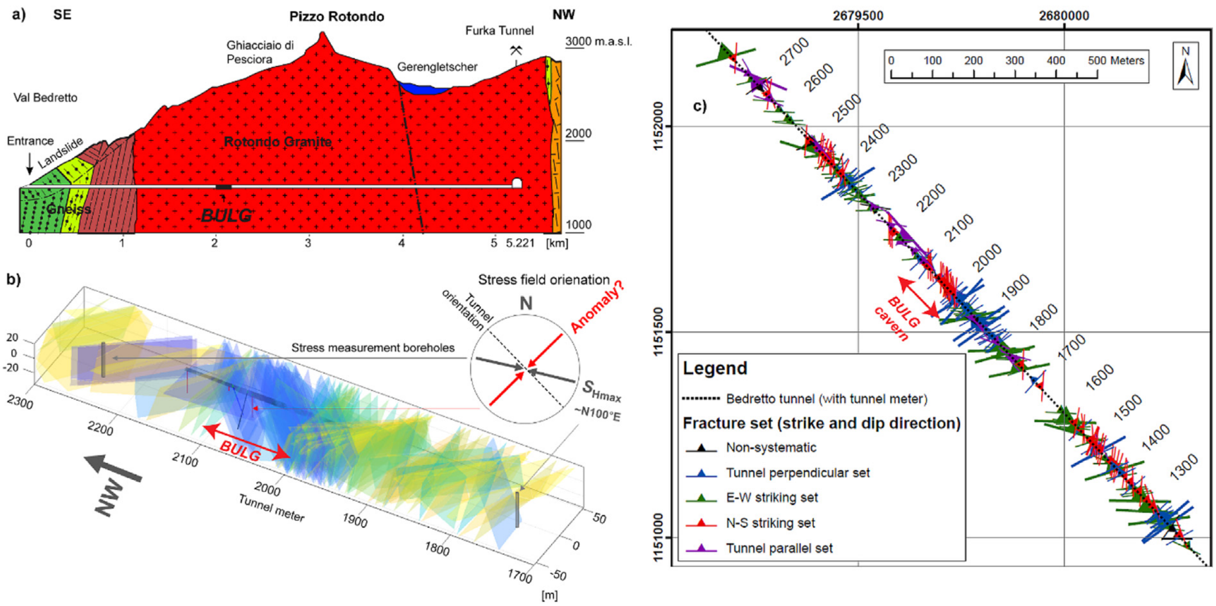

Fig. 10. (a) Geological cross section along Bedretto tunnel (adapted from Keller and Schneider[86]) (b) 3D view of the BULG experiment niche including the mapped faults and fracture zones, the stress measurements boreholes used for hydrofracturing and the inferred stress directions. (c) Map view of the faults and fracture sets mapped at the tunnel walls before and after the BULG cavern.

3.3. Rock mass characterization phase

In parallel to establishing the basic infrastructure at the BULG, comprehensive rock mass characterization is required to support the design of the planned experiments.

Local *stress characterization* is essential as the stress field largely defines the orientation of hydrofractures and hydrosheared faults – hence the entire experiment geometry – and cannot solely rely on the aforementioned regional information. In 2019, the local stress field has been characterized with small hydraulic fracturing tests in short (i.e. < 30 m long) vertical and inclined boreholes.[87] As the BULG is >1000 m below surface, we assume that topographic influences are minor, i.e. that one principal stress component is vertical and corresponds to the overburden stress S_V. Its magnitude is estimated to be ∼26.5 MPa. It was found that the maximum horizontal principal stress S_{Hmax} is oriented towards N100°E. However, strong stress rotations (from N100°E to N40°E) across the BULG towards is possible. The minimum principal stress S_{hmin} has a magnitude of 13–16 MPa. S_{Hmax} is about 0.8–1·S_V, which confirms that stresses are at the transition from normal faulting to strike slip.

The local preliminary *geological model* (Fig. 10) is being built from characterization boreholes in the BULG cavern, structural mapping of the tunnel aided with laser scanning, and from geophysical imaging. Various fault and fracture sets can be distinguished (Fig. 10c). NE–SW striking faults often exhibit a several metres wide fault architecture (including high fracture density zones and a fault core with fault gauge), and are hydraulically conductive with active inflow to the tunnel. Given the orientation of the maximum principle stress towards N100°E, faults with and EW to NE–SW orientation can well be activated in shear.

Hydraulic characterization will involve borehole temperature logging of borehole fluid that was replaced by warmer or cooler water than the rock mass temperature. This will help identifying hydraulically active fractures along the boreholes. Afterwards, pulse tests will be conducted on these structures, to quantify their initial near-wellbore transmissivity. To characterize the hydraulic network within the reservoir, constant rate injection tests will be carried out in several injection intervals, while pressure is monitored in multiple intervals distributed along the other boreholes. Finally, solute and heat tracer tests will quantify the hydraulic transport properties in the reservoir.

Borehole geophysical methods will be used to characterize the rock mass properties and existing or newly created fractures. These include time-lapse Ground Penetrating Radar (GPR) and Active Seismics (AS) in single- and cross-hole modes with a wide range of frequencies. Using time-lapse difference reflection imaging and tomography, the fracture evolution and permeability enhancement can be traced during different injection experiments. Such coupled hydrogeophysical experiments will make use of electrically conductive tracers for GPR and tracers with density contrasts for AS to infer fluid flow, transport and pathway creation. In the short boreholes used for stress measurements (Fig. 10b), Electrical Resistivity Tomography (ERT) surveys are coupled with GPR and AS to assess the potential of ERT for fracture detection. Emphasis is placed on coupling various geophysical data (with novel experimental and modelling approaches) to better condition fracture properties and assess their evolution during and after hydraulic stimulation.

Background seismicity is characterized using both broadband and strong motion stations inside the tunnel and at surface, as well as high-frequency accelerometers and in-situ AE sensors inside the boreholes. As a result, we are able to lower the recording completeness of natural seismic events locally and gain in-depth knowledge on the local seismotectonic setting. In addition, the background seismic monitoring aims at quantifying very small seismic events ($M < -3$) in the direct vicinity of the tunnel that give information on the long-term stress re-distribution from the excavation.

As Fig. 3 illustrates, the larger scale of the experiments compared to those at the GTS, requires a thorough *induced seismic hazard analysis*,[88] which is updated in later phases as the site-specific seismic behaviour becomes progressively more known. Together, the rock mass model, stress field and the hazard analysis place important constraints on the experimental design.

3.4. The BULG experiments

A key objective of the experiments planned at the BULG is to put novel concepts for hydraulic stimulation, fluid circulation and seismic hazard mitigation to the test by emulating these procedures on a scale smaller than the full EGS scale.

3.4.1. First experiment series

In a *first experiment sequence*, multi-stage stimulation, well completion techniques, injection strategies and fluid circulation concepts will be investigated. The world-wide success of multi-stage hydraulic fracturing in horizontal wells has led to the breakthrough of shale gas and oil exploitation.[89] This strategy may also be advantageous for future EGS projects in Switzerland[26] for several reasons: (1) A larger rock mass volume can be accessed with a horizontal well. (2) Stimulation of several parallel zones may lead to improved heat exchanger properties as an extended volume is accessed, while for a single stimulation only an oblate-shaped volume is exploited. (3) Although still controversial, multiple small stimulations may in total create less induced seismicity as a single stimulation with the same injection volume.

This first experiments series encompasses three projects that are currently being planned by SCCER-SoE and project partners:

(1) The project *VALTER (Validation of Technologies for Reservoir Engineering)*, funded by the Swiss Federal Office of Energy (SFOE), aims at demonstrating that a large rock volume can be stimulated to allow fluid circulation in significant quantities whilst keeping seismic risk under control. A high-resolution seismo-hydromechanical monitoring will be installed in boreholes and within the tunnel to address the questions: What is the link between the stimulation concept (injection protocol, HF or HS), on the one hand, and hydromechanical rock mass response, permeability creation and the induced seismicity, on the other hand?

(2) The project *DESTRESS* (*Demonstration of soft stimulation treatments of geothermal reservoirs*), a Horizon 2020 project funded by the EU (www.destress-h2020.eu), aims at optimizing stimulation treatments while minimizing environmental impacts such as seismic events or pollution of groundwater reservoirs. The DESTRESS project is divided into seven work packages. Five of them will deliver technologies for prototype demonstration and two will demonstrate innovative stimulation treatments. The DESTRESS work in the BULG investigates the effectiveness of cyclic hydraulic treatments and of multi-stage stimulations.

(3) The project *ZoDrEx (Zonal Isolation, Drilling and Exploitation of EGS Projects)*, funded by EU initiative Geothermica – Era Net (www.geothermica.eu/projects/zodrex), aims at demonstrating drilling, completion and production methods that will increase the technical and economical chances of success in geothermal energy applications. At the BULG, the project will focus on the performance of zonal isolation technologies and their potential importance during EGS stimulations as well as on the fluid driven percussion drilling method in highly deviated trajectory boreholes to enhance drilling efficiency in crystalline rock.

The three projects are additionally complemented by the project *OPASIN (OPtimized A/Seismic Injection*), led by the German Research Center of Geosciences, which focuses on the relative importance of seismic and aseismic deformation.

The project partners SCCER-SoE and the members of the DESTRESS, ZoDrEx and OPASIN consortia have decided to implement the parts of the three projects that concern the BULG in close collaboration and, wherever appropriate, take advantage of possible synergies in the implementation. These synergies include common instrumentation for monitoring and observation, shared access to boreholes in the rock volume under investigation, reduced mobilization and installation costs for external contractors, e.g. drilling-, completion- and instrumentation-companies. In the following, the conceptual experiment procedure encompassing these four experiments is outlined (Fig. 11):

3.4.2. Experiment implementation

In one or several 150–300 m long boreholes, open-hole stimulations (OHS) along an extended open-hole section (as done in many past EGS projects such as Basel or Soultz-sous-forêt) will be compared to multi-stage stimulations (MSS), i.e. sequential injections into isolated intervals every 10–30 m. Single-hole and cross-hole hydraulic tests performed before and after the OHS and again after the MSS will help to evaluate whether the MSS approach is superior to that of the OHS regarding the reservoir transmissivity and connectivity that can be achieved. To isolate and access many short intervals (zonal isolation), a casing with a sequence of packers will be installed. The isolated intervals will be accessed by sliding sleeves that can each be individually opened. Additionally, a range of other zonal isolation techniques will be tested in dedicated boreholes, such as perforations and notches in cemented borehole casings, or micro-boreholes drilled from a cemented casing. By stimulating and hydraulically testing all these intervals, the outcomes in terms of transmissivity and connectivity to other boreholes can then be compared for the different completion strategies. Additionally, stimulation-while-drilling will be evaluated as an alternative MSS method, and novel techniques for directional drilling will be tested.

There is an on-going discussion in the literature as to whether fluid injections strategies can be adjusted to give an optimum balance between seismic risk and permeability enhancement, such as by performing cyclic injections rather than step-rate injections.[30] In addition, shut-in strategies that might be effective in reducing post-injection seismicity have been discussed.[90] The ISC experiments at GTS have shown that local geological conditions can give rise to a large variability of stimulation outcomes, which may also be related to the scale of investigation. Thus, a robust comparison of stimulation strategies requires a statistically significant number of experiments. Approximately, some 30 or more stimulations are planned for this phase, which may be sufficient to identifying stimulation strategies that are more favourable regarding seismic hazard. Note that a significantly less hazardous injection would require at least an order of magnitude reduction of seismicity rates. Additionally, varying the spacing between stimulation intervals would allow the investigation of stress interactions between stimulations (i.e. stress shadowing), with particular regard to the question whether interactions between multiple parallel stimulations may adversely affect permeability enhancement and stimulation propagation.

In the GTS experiments, the circulation phase was relatively short, lasting only a few weeks, due to the proximity of tunnels and their interconnection to permeable fractures which prevented the establishment of a true dipole between the injection and production boreholes.[71] Once a permeable reservoir has been developed at the BULG, it will be subject to long-term circulation experiments to investigate in detail its hydraulic conductivity and connectivity, heat exchange properties, as well as any fluid–rock interactions that might occur. Different circulation methods will also be explored: for instance, production under backpressure to keep fractures more hydraulically conductive.

3.4.3. Monitoring concepts

The described experiments will be accompanied by detailed monitoring of seismicity, strain, fluid pressure and temperature in boreholes sub-parallel to the stimulated boreholes. Thus, not only the advantages of different stimulation, completion and drilling techniques can be compared, but also a scientific-quality dataset of rock mass responses will be generated, further enhancing process understanding. Monitoring in BULG is divided into the general monitoring (i.e. of the entire BULG and not experiment-specific) and monitoring of individual experiments.

General monitoring includes distributed fibre-optic strain and temperature measurements along the entire Bedretto tunnel,

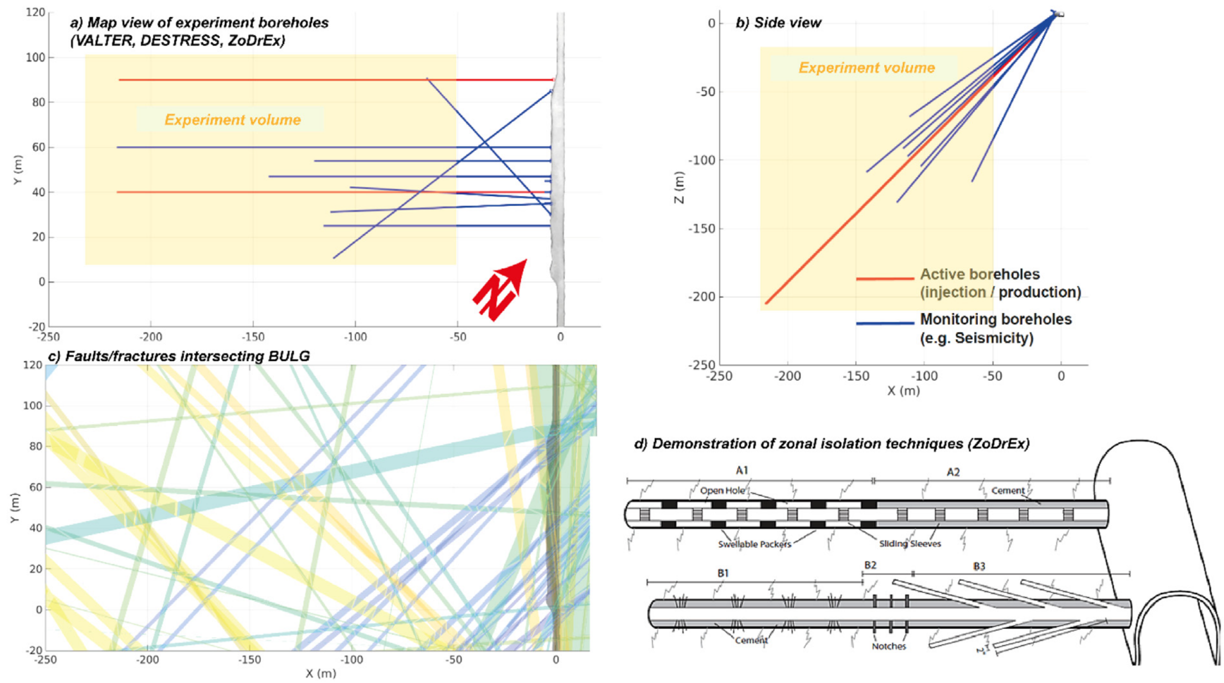

Fig. 11. (a) and (b) Experimental setup for the first experiment series at the BULG combining the projects VALTER, DESTRESS, ZoDrEx and OPASIN in one experiment. (c) The fracture and faults extrapolated from the tunnel are shown in map view for comparison. (d) Sketch of different zonal isolation techniques.

groundwater and radon monitoring inside the tunnel, and enhanced monitoring of nearby seismicity (natural and induced with $M_W > 0$, see aforementioned background seismicity) using a local network of both surface and in-tunnel seismic stations (frequencies below 100 Hz). The monitoring system is maintained during all future experiments. It serves both a scientific purpose and to meet obligations regarding health, safety and the environment.

Experiment-specific monitoring for the first set of experiments planned in spring 2020 include a comprehensive monitoring system installed in at least six dedicated boreholes (similar to the GTS experiments). The monitoring system aims to capture mechanical, hydraulic and seismic responses during stimulation and circulation. All monitoring boreholes will be sealed by grouting after the installation of sensors.

During the ISC stimulation experiment, monitoring the complex hydromechanical fault zone response close to the injection was feasible. In contrast, monitoring of poro-elastic effects will operate on a larger scale and focuses on far-field responses at the BULG . Krietsch et al.[65] have shown that the zone of complex hydromechanical responses (including pressure-induced reversible and irreversible fracture opening and shear dislocation) close to the injection point is surrounded by a zone of transient poroelastic volumetric compression during high-pressure fluid injections. The hydro-mechanical monitoring at BULG aims to capture the temporal evolution of the transition zone between these different poro-elastic zones. Further, the induced permanent deformations in the 'far-field' will help constrain the deformation field within the stimulated zones. Thus, monitoring will include a variety of sensors are installed such as FBG strain sensors, pressure and tilt sensors.

Seismicity will be monitored over a magnitude range of at least six orders of magnitudes from events with magnitudes below −5 (source radii on mm scale) to microseismic events above magnitude 0 (source radii on m scale). To achieve the recording of this large variety of seismic signals (dominant frequencies from 1 Hz to 100 kHz are expected) different sensors are implemented, i.e. geophones, piezoelectric accelerometers as well as in-situ acoustic emission (piezoelectric) sensors. The passive seismic monitoring system is complemented using ultrasonic sources for active seismic surveys.

Unlike the 10 m scale experiments in underground laboratories like the GTS experiment that are conducted close to the tunnel infrastructure, the first experiment series targets rock volumes that are not disturbed by the tunnel in terms of stress of ambient pore pressure. Monitoring under these conditions and the installation of equipment in long boreholes poses a significant challenge that requires designing novel sensor strings, rod systems and completion techniques.

3.4.4. Future experiments

A *second experiment series* following the aforementioned experiments will focus on earthquake source processes of both induced and natural earthquakes. Understanding the physical processes of earthquake rupture has been most elusive to date as research is hindered by the inherent physical complexity and the lack of accurate observations in close proximity (Fig. 3b[58]). The BULG is an ideal facility to explore induced earthquake processes at close distance and under relatively well controlled and monitored conditions. Thus, its objective – to establish an *in-situ* laboratory for fault mechanics – reaches ultimately beyond the context of EGS development, as it addresses questions of earthquake physics that have been the subject of seismological research for decades (Fig. 3b). To directly observe slip nucleation and propagation behaviour, several experiments will be performed adjacent to each other along a single extended target fault. The key element of the experiments is that rupture processes are studied under variable *stress conditions that are artificially imposed* so that the role of stress heterogeneities on rupture initiation, growth and arrest can be explored. Variable stress conditions along the fault may be induced for instance by (1) natural or imposed hydraulic head gradients around the BULG tunnel e.g. due to drainage by the tunnel, (2) artificial cooling of the rock around the fault, (3) slip along the adjacent fault segment or along nearby faults (induced by stimulation). The main experiment consists of injection-induced fault slip experiments along portions of the target fault that have experienced different preloading conditions to study fault mechanics (e.g. slip onset, velocity and decay, rupture propagation, off-fault processes, etc.) under varied conditions. For comparability between each experiment, a dense multi-component monitoring system, with comparable geometry around the experiment, is essential. Observations of rupture mechanical processes can be linked to the frictional experiments with high slip rates performed with the HighSTEP facility giving insight into rupture mechanics at a smaller scale. The experimental work is conducted with international partner institutions (INGV Rome, RWTH Aachen, among others).

4. Summary

Past experiences in hydraulic reservoir stimulation for heat extraction from Enhanced Geothermal Systems (EGS) have shown that outcomes are often nearly unpredictable and the underlying processes remain too uncertain. A change in approach is needed that yields a major improvement in process understanding, as well as in the technologies required to develop deep underground heat exchangers for EGS development. In two underground laboratories in crystalline massifs in the Swiss Alps experimental efforts are aimed at making progress in these regards: At the Grimsel Test Site, a series of stimulation experiments, conducted in 2015–2017, produced a wealth of detailed observations, providing insights into the stimulation processes at a 10 m scale. The complexity of hydromechanics underlying fracture opening, dislocation, propagation and interaction was resolved on the 1–10 m scale. The variability in the seismic and hydromechanical response at this scale is remarkable and is likely related to fault architecture and orientation. However, despite achieved process understanding, the experiments are still limited in their significance for full-scale EGS. The scale is two orders of magnitude too small; the depth is an order of magnitude too shallow; the stress field, in-situ pore pressure (drained by the surrounding tunnel network) and hydraulic boundary conditions (i.e. atmospheric pressure in tunnels) are dissimilar to realistic EGS reservoir conditions. These limitations can partly be overcome in the newly established Bedretto Underground Laboratory for Geoenergies. Here, the scale of planned experiments is closer to reservoir scale, rock mass conditions are closer to target reservoir depths, and the research foci are on exploring the feasibility of novel engineering approaches for reservoir creation planned for future EGS projects. At the same time, detailed monitoring will further deepen our understanding of involved processes. The experiments should help clarify whether hydraulic stimulation procedures can be devised to engineer heat exchangers within rock masses with acceptable levels of induced seismicity.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.[82]

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Corrigendum to "Hydraulic stimulation and fluid circulation experiments in underground laboratories: Stepping up the scale towards engineered geothermal systems" by Gischig et al. https://doi.org/10.1016/j.gete.2019.100175

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In section 1.2 of the above mentioned article, the hydraulic fracturing tests performed in 2015 in the Äspö Hard Rock Laboratory (Sweden) are listed as one of the scaled in-situ experiments with focus on geothermal related questions. In citing this experiment, however, a misleading reference is given. The reference (31) by Lopez-Comino et al. (2017) is about hydraulic fracturing tests at the Wysin site in Poland, and has nothing to do with the geothermal in situ tests in granites at Äspö HRL. By accident, we have been mixed up this reference with a reference of the same author using data from the hydraulic tests in Äspö HRL, Sweden.

Correct reference
Lopez Comino, J. A., Cesca, S., Heimann, S., Grigoli, F., Milkereit, C., Dahm, T., Zang, A. (2017): Characterization of Hydraulic Fractures Growth During the Äspö Hard Rock Laboratory Experiment (Sweden). - Rock Mechanics and Rock Engineering, 50, 11, 2985-3001. https://doi.org/10.1007/s00603-017-1285-0

Incorrect (misleading) reference
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