SCCER-SoE Research Project Agreement with NAGRA – Project Description

1 Background

Geothermal Systems have the potential to provide long-term and (virtually) CO_2-emission-free contributions to the world's energy inventory. In order to extract geothermal energy from the subsurface, a heat extraction (or working) fluid needs to be able to flow through permeable pathways or porous media to advectively transport the underground heat to a production well as heat conduction through low-permeability formations occurs at rates that are too slow for economical use. As a result, various types of stimulation techniques for permeability enhancement have been proposed, and in some cases implemented, to create an efficient subsurface heat exchanger.

Hydraulic stimulation is one such technique that may be applied in low-permeability, naturally fractured reservoirs creating an artificial reservoir that exhibits enhanced formation permeability, which is thus typically referred to as an Enhanced Geothermal System (EGS). During EGS development, a fluid is injected into the formation to increase the pore-fluid pressure which propagates (diffuses) from the injection location to the surrounding formation, affecting the mechanical behaviour of the formation. This increase in pore-fluid pressure reduces the effective stress field and can initiate hydraulic fractures (i.e. hydro-fracturing) and/or reactivate existing natural, or previously hydro-fractured) fractures to shear (hydro-shearing). It has been shown that self-propping due to shear-induced dilation along natural and hydraulic fractures can contribute significantly to, in some cases, irreversible permeability increases, needed to develop a sustainable heat exchanger. However, hydro-fracturing and hydro-shearing induce (micro) seismicity in the stimulated volume as well as in the surrounding formation, which adversely influences public acceptance of hydro-fracturing/shearing in general, including EGS development.

2 Goals of the Deep Underground Geothermal Laboratory (DUG-Lab)

The primary goal of the DUG-Lab activities is to improve our understanding of geomechanical processes underpinning permeability creation during hydraulic stimulation and related induced seismicity as well as to evaluate the efficiency of the generated underground heat exchanger. Through process understanding, we aim to develop methods for:

- enabling large-volume fluid injections at high pressures to create an efficient, sustainable heat exchanger in hot reservoirs at depths > 3km,
- maximizing our ability to assess and model induced seismic hazard and risk

We approach the development of these methods by starting with well-controlled small-scale experiments and increasing both the scale and overburden in a series of demonstration field experiments. The design of each progressively larger, and therefore less controlled, experiment will build on the results of the previous smaller experiments and will be complemented by laboratory experiments. The scales of the experiments will range from the centimeter (laboratory) to the kilometer scale. Such demonstration experiments are a key element for increasing public acceptance of massive reservoir stimulations essential for the creation of efficient and sustainable heat exchangers at large depths in Switzerland.

3 Aims and objectives of the Insitu Stimulation & Circulation Project ISC

The experiment is a first multi-disciplinary demonstration experiment that covers an extensive list of scientific key questions related to EGS. The expected outcomes are:

- High-resolution pre- and post-stimulation permeability and fracture connectivity of a geologically simple set of interacting brittle shear zones.

- Real-time monitoring of 3D fault displacement, permeability changes, pore pressure propagation, and its relations to the transition between aseismic and seismic slip during hydraulic stimulation.
- The influence of the natural fracture network on the fluid pressure propagation during hydraulic stimulation at high spatial resolution.
- Fluid and heat transport properties of the rock volume, including detailed insights into the pathways, contact areas and accessible porosities and (fracture) permeabilities, controlling short and long term heat transport in the pre-existing and stimulated fractures (and within the surrounding low-permeability rock matrix).
- The stimulation efficiency of the fracture matrix system.
- Physical constraints to spatio-temporal induced seismicity characteristics relevant for seismic hazard and risk estimation, such as the relative size distribution, the stress drop of earthquakes, the relevance of static and dynamic stress transfer as fault reactivation mechanisms and the decay rate of activity.
- Application and development of novel computational tools merging earthquake source physical and reservoir geomechanical modelling techniques to reproduce inferred physical processes underlying seismicity characteristics and aseismic slip.
- Test and further develop currently existing real time seismic monitoring systems towards a "traffic light" system indicating seismic risks.
- Development of novel imaging techniques so that multi-offset single-hole and cross-hole radar and seismic data can be processed into 3D images of the volume around the boreholes.
- Joint inversion and imaging of collocated radar and seismic measurements to improve imaging reliability and resolution, and to investigate petrophysical relationships between elastic and electromagnetic rock properties.

The combination of a dense network of seismic monitoring devices, displacement, pore pressure, temperature and stress change measurements will provide novel reference 3D data set at exceptional high spatial resolution that will yield detailed insight into geomechanical processes associated with induced earthquakes and permeability creation.

4 Implementation of the ISC Project

In a first planning phase for the GTS fault slip experiment an experimental volume that contains a series of steeply inclined, interconnected faults (S1 fault zone, Figure 1) that interact with other faults (S2, S3) was identified. This experimental volume provides an ideal rock unit for a decameter scale stimulation experiment that contains faults of various fault architectures (i.e. single persistent fault planes, heterogeneous brittle to ductile fault zone) and allows addressing scientific key questions relevant for EGS.

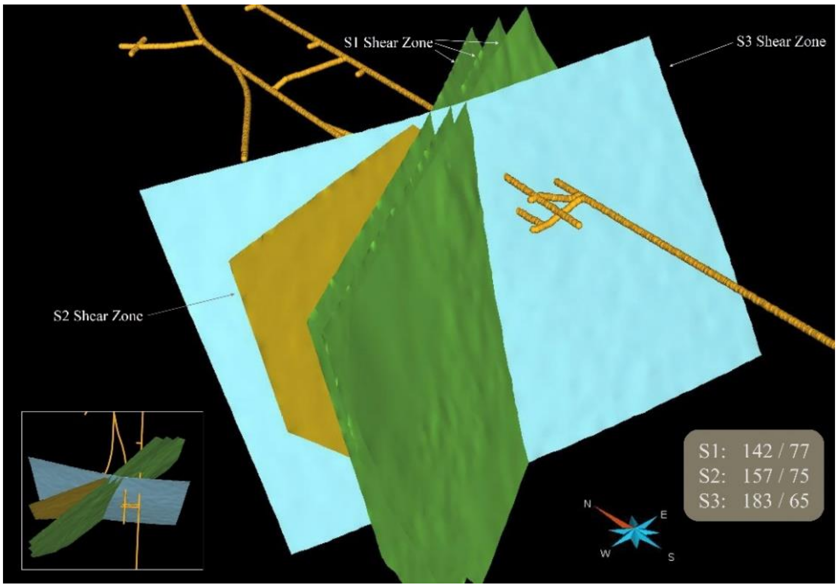

Figure 1. Geometry Fault zones S1, S2, and S3 as encountered at GTS within the experimental rock volume. The target rock unit is in the area where S1, S2, and S3 fault zones intersect.

Field activities associated with the planned stimulation experiment are subdivided into three major phases: A) a pre-stimulation, B) a stimulation, and C) a post-stimulation phase. The pre-stimulation phase is considered for 1) detailed characterization of the experimental volume, and 2) borehole drilling and installation of monitoring equipment that allows determination of the hydro-mechanical and seismic response during injection at an exceptionally high spatial resolution.

Rock mass characterization includes imaging with ground-penetration radar, and active seismics, tunnel mapping, logging of available and newly drilled boreholes in the vicinity of the experimental volume, hydraulic tests, and measurements of the in-situ stress tensor in both the near and far field of the faults. Stress characterization will be conducted from May to August 2015 and involves three boreholes which allow to perform overcoring, hydraulic fracturing and hydraulic testing of pre-existing fractures. For preliminary characterization activities existing tunnels and boreholes are currently utilized.

Existing tunnels and caverns at the GTS allow optimal access to the target rock unit and allow drilling of sub-vertical characterization and monitoring boreholes that penetrate the experimental volume and shear zones S1, S2, and S3 (Figure 2).

The monitoring system includes a dense array of three-component stress-meters, tiltmeters, high-resolution 3D-displacement sensors, multi-packer pressure, and flow rate sensors. A multi-scale passive seismic monitoring network will be in place during stimulation including 1) a surface network (base lengths of 1-5 km), 2) an underground laboratory scale network in the surrounding tunnels (max. 50 m base lengths), and 3) an injection scale network close to the experiment volume (10 m scale). Two inclined injection boreholes that will be drilled from an existing cavern (Figure 2) through the experimental rock volume are planned.

A straddled packer system that allows performing a pressure-step injection through a packer interval across a fault and contemporaneous monitoring of 3D displacements, velocities and fluid pressure will be utilized to trigger fault opening and eventually slip (Figure 3a and b). The initial hydro-mechanical elastic response will be characterized by a pressure pulse at the beginning of the stimulation protocol (Figure 3b), bevor the pressure is ramped up incrementally. Each pressure step will be either held constant for a pre-defined time or until a quasi-steady flow rate is achieved. The step-wise increase in pressure in these heterogeneous faults (average transmissivity of 10-9m2/s) will be continued until a shear dislocation across the shear zone is initiated (fault extension pressure; Figure 3d). When the fault extension pressure is reached (i.e., indicated by a significant change in the pressure-versus-flow rate; Figure 3d) the pressure will be slightly increased and maintained constant to characterize both failure and post-failure properties of the fault. This phase will be followed by a second pulse test to characterize the hydro-mechanical response of the activated fault and a step-wise pressure decrease. At low pressure a third pulse test will be utilized to estimate irreversible changes in the hydro-mechanical response. This procedure will be optimized during project execution and repeated for all relevant fault zones in the target rock volume.

During injection another straddled packer device across the shear zones will be in place for capturing both pore pressure response and 3D displacements as the flow rate is increased. Several additional multi-packer systems, flow meters and fiber-optics displacement monitoring chains in sub-horizontal boreholes across the faults allow to 1) monitor strain and pore pressure propagation at a high spatial resolution within a set of brittle faults, and 2) to estimate both pressurized area and slip surface. Seismic events triggered during stimulation are captured in real time by the seismic monitoring network that is designed for great sensitivity (at least M > -4.0) and a location accuracy better than 10 cm. At least four stress-meters along with tiltmeters in boreholes penetrating the rock volume adjacent to the faults capture stress changes and deformations associated with induced shear dislocation.

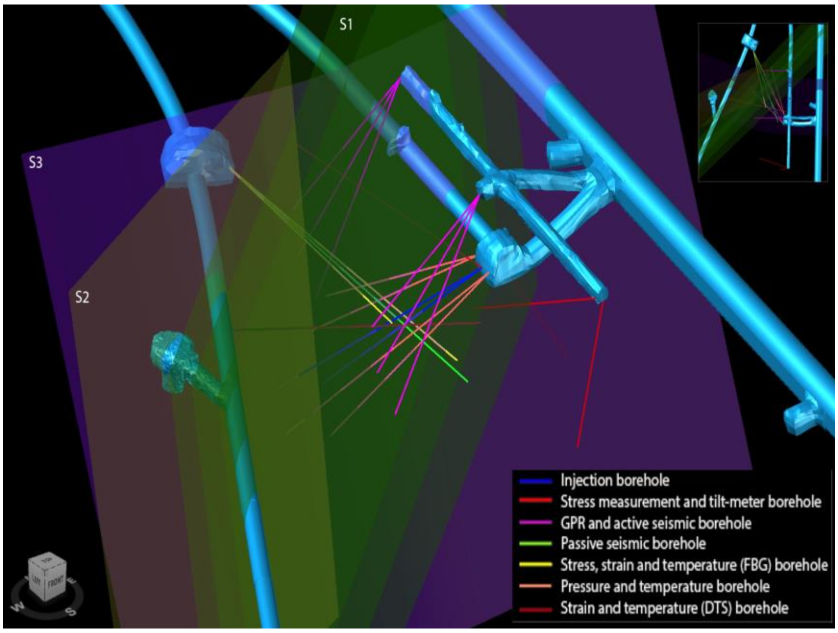

Figure 2. Current layout of the GTS stimulation experiment. Several boreholes are drilled and equipped with characterization tools and monitoring sensors from existing tunnels (blue) or a newly excavated tunnel (pink).The injection borehole (blue) penetrates both massive crystalline rock and the faults zones. The three main fault zones are shown (S1, S2, and S3).

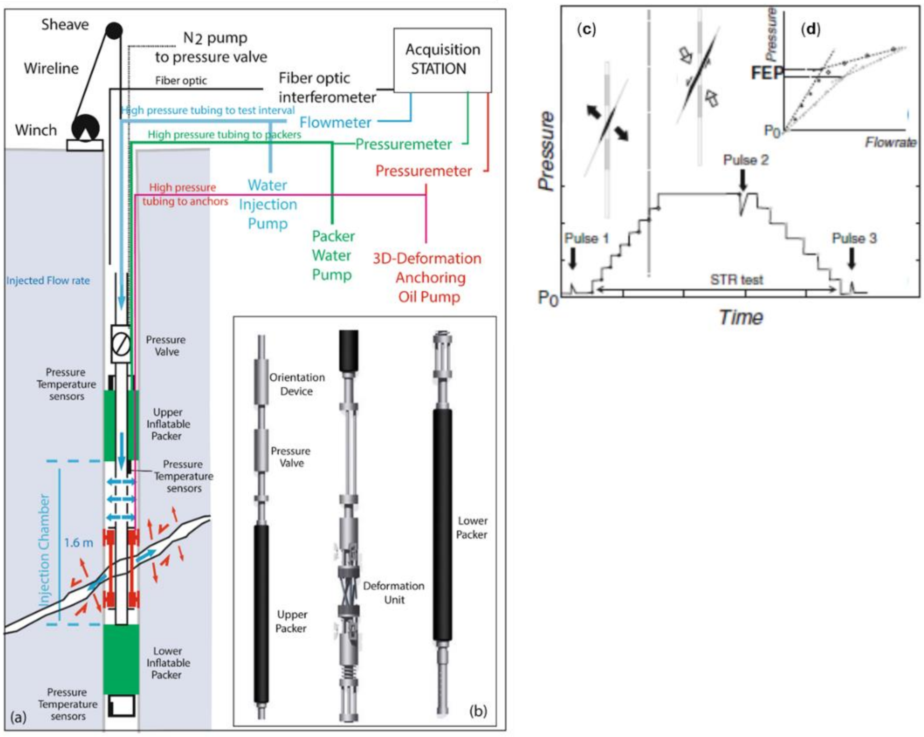

Figure 3. a) and b) Details of the straddled packer system for pressure step injections across the faults. Both, the injection chamber and deformation measurement base length will be adjusted for the experimental requirements. c) Injection protocol with a step wise increase in pressure and pulse test phases. d) Pressure-versus-flowrate curve which allows to determine the fracture extension pressure (FEP).

The injection phase is followed by hydraulic and geophysical characterization phase to analyse changes in the rock mass.

In a final stage of the experiment, a fluid circulation phase will be executed, which will address both the fluid and the heat transport properties of the stimulated volume. Both heat and conservative solute tracers and changing flow rates and volumes of the injected tracers will be used to provide detailed insights into the pathways, contact areas and accessible porosities controlling short- and long-term heat transport in the pre-existing and stimulated fractures. The stimulation efficiency of the fracture matrix system will be explored and quantified leading to improved protocols for subsequent larger scale experiments.

5 Schedule

The project execution has been started in 2015 with the installation of a seismic monitoring network outside the GTS. The first main stage of field implementation will start end of May 2015. Field investigations will continue until approximately the end of 2017 (Figure 4).

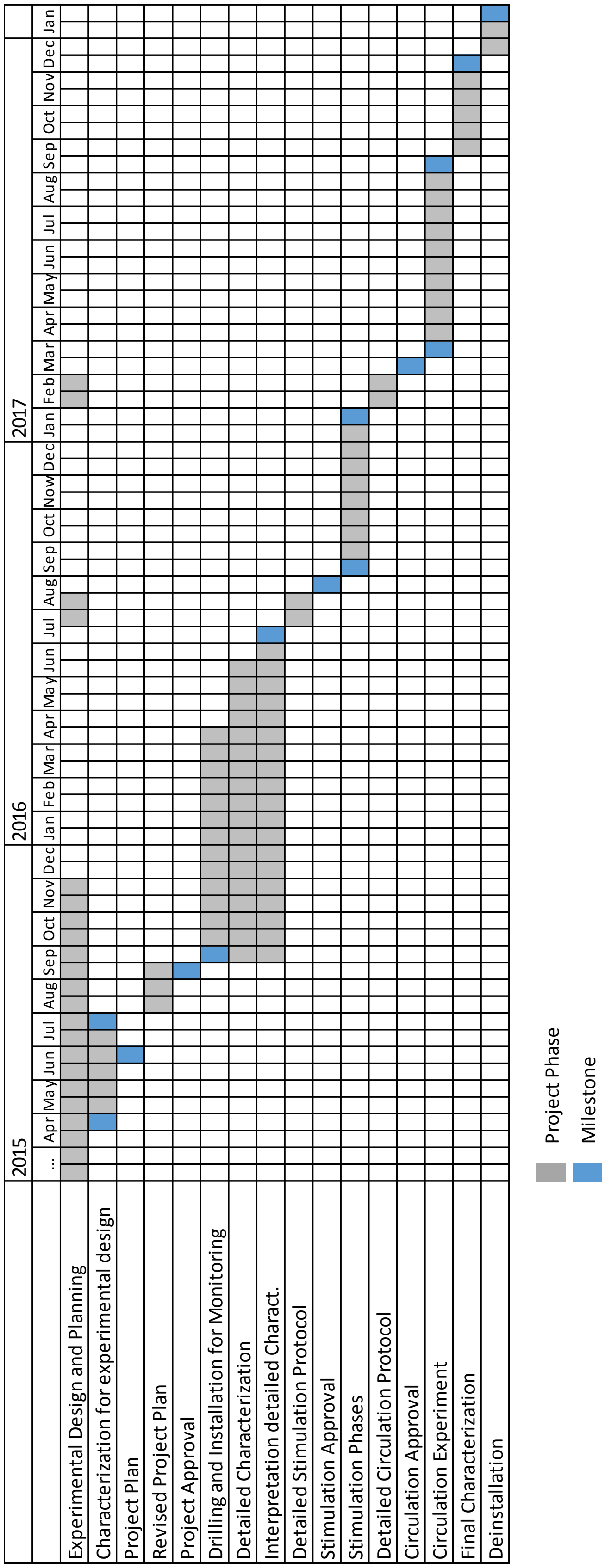

Figure 4. Current schedule and milestones of the Project. Milestones are either associated with the approval of a project sub-phase (e.g. characterization or experimental design) or major phase, an important step in the Project or a successful execution of a sub-phase or major phase. Each milestone requires an approval of the ETH steering committee and the project partner.