# Task 1.3

## Task Title

Pilot and demonstration projects for reservoir creation

## Research Partners

Swiss Federal Institute of Technology in Zurich (ETHZ), Geo-Energie Suisse AG, SwissGeoPower, Prof. Rudolf von Rohr (ETHZ)

## Current Projects (presented on the following pages)



## Task Objectives

- Experiments in a deep underground laboratory: In order to better understand the physical processes associated with geothermal reservoir creation appropriate experiments will be devised in the "Deep Underground Geothermal (DUG)" laboratory near Grimsel Pass (Grimsel Test Site). The first comprehensive experiment is called "Insitu Stimulation and Circulation (ISC)". The primary goal 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.
- Geo-Energie Suisse AG received the approval for its deep geothermal energy project in Haute-Sorne (Canton of Jura). Drilling will start in late 2017 and the stimulation phase to create a deep reservoir is expected in 2018. Following its roadmap, the SCCER-SoE will be closely associated to the Haute-Sorne project and will support it with simulations, modelling expertise, stress analyses, and methodologies validated in the deep underground lab at the Grimsel Test Site.
- Revisit the roadmap for CO2 geological sequestration in 2015 and design a first Swiss pilot project for geological sequestration of CO2.

## Interaction Between the Partners – Synthesis

- The core team of the ISC experiment is composed by six senior researchers from different disciplines, sitting together in the same room and supported by a group of professors and PhD students from different institutes.

## Highlights 2016

- Activities within the experiment “in-situ stimulation and circulation” at Grimsel test site are running ahead of schedule. The first holes are drilled and the first small stimulation experiment has been performed. The activities are on schedule leading to the stimulation at the end of 2016 or early 2017; this will be the largest and best-monitored fault stimulation experiment carried out worldwide to date. In particular, the GEG Group has carried out the world’s first DNA Nanotracer tests in the subsurface at Widen, CH, and at the Grimsel Deep Underground Geothermal (DUG) Laboratory to help characterise the hydraulic properties of the faults in the underground lab. This was done in collaboration with the DUG Lab Team.
- Activities have been started to define a common pilot and demonstration experiment for the carbon sequestration in the underground.
- The GEG group is developing a next-generation numerical simulator for Thermal (T), Hydraulic (H), Rcok Mechanical (M) and Chemical Reaction (C) simulations, i.e., a THMC Simulator, to simulate the reactive flow and transport of fluids, solutes, and heat through the (fractured( subsurface.
- The GEG Group has developed, and is further developing a chemical reaction simulator, called Reaktoro (see: reaktoro.org) which can be used stand-alone or as part of the above THMC simulator (as the C-component).
- The GEG Group has started a research collaboration with Prof. Rudolf von Rohr in D-MAVT at ETH Zurich to research and develop revolutionary deep drilling methods, such as Thermal Spallation Drilling.
- The GEG Group has started a Magnetotelluric (MT) investigation of the northern Swiss heat flow anomaly in the Kenton Aargau to investigate if geothermal power (i.e., electricity production) is feasible in this region. This work, as all of the above highlighted projects, is ongoing.
- The GEG Group has run several simulations of CO2-Plume Geothermal (CPG) Systems, and published these results. CPG Systems use CO2, which they sequester, as subsurface heat extraction fluid for power generation. Thus, the system results in a CO2-sequestering geothermal power plant. CPG Systems are estimated to be about twice as efficient as traditional water-based geothermal power plants. As a result,the GEG Group investigates if these systems could be an alternative to Enhanced Geothermal Systems in Switzerland, as much lower-temperature resources, the only kind of resources available in Switzerland, than in high-enthalpy systems.
- The GEG Group is in contact with the St. Galler Stadtwerke to investigate the possibility of using the ~4km deep geothermal borehole there after all for geothermal power production using some aspects of the above-mentioned CPG technology.

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# Permeability Enhancement in Crystalline Rock as a Result of Hydraulic Fracturing and Hydraulic Jacking

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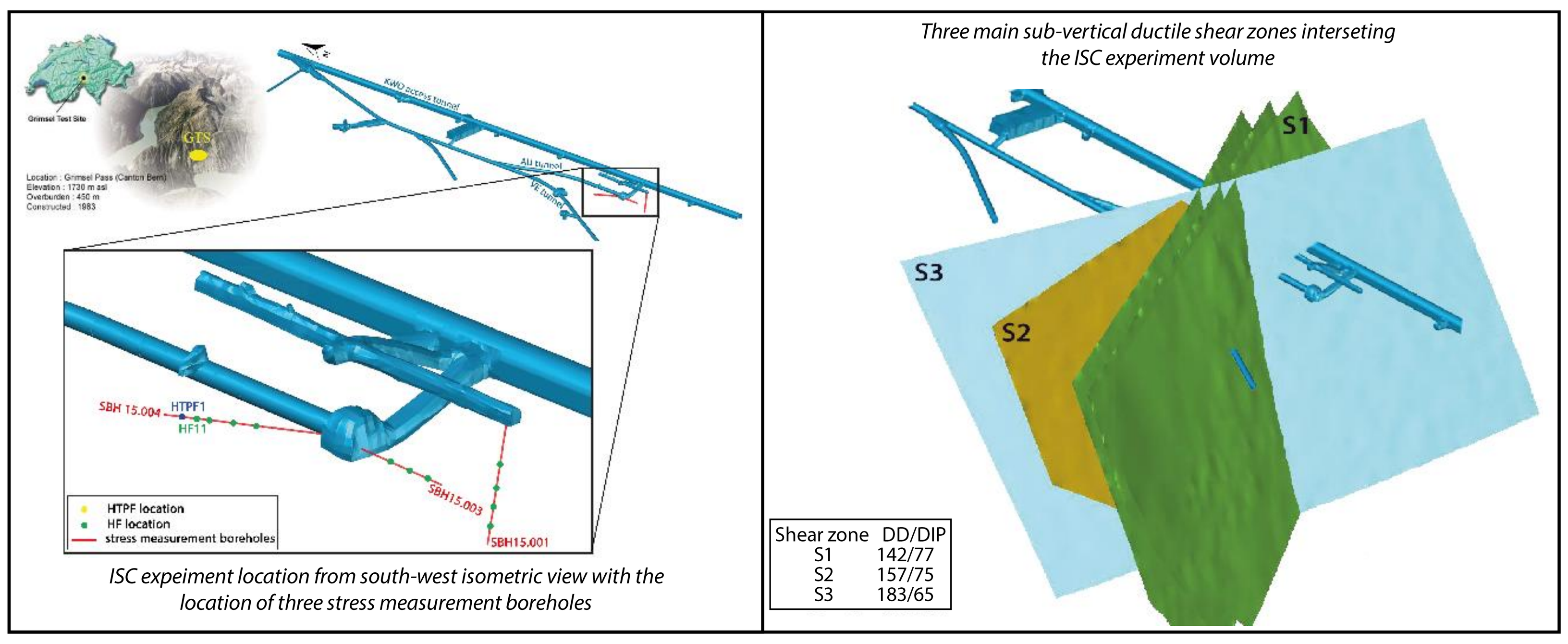
*ETH Zürich*

## 1. Introduction

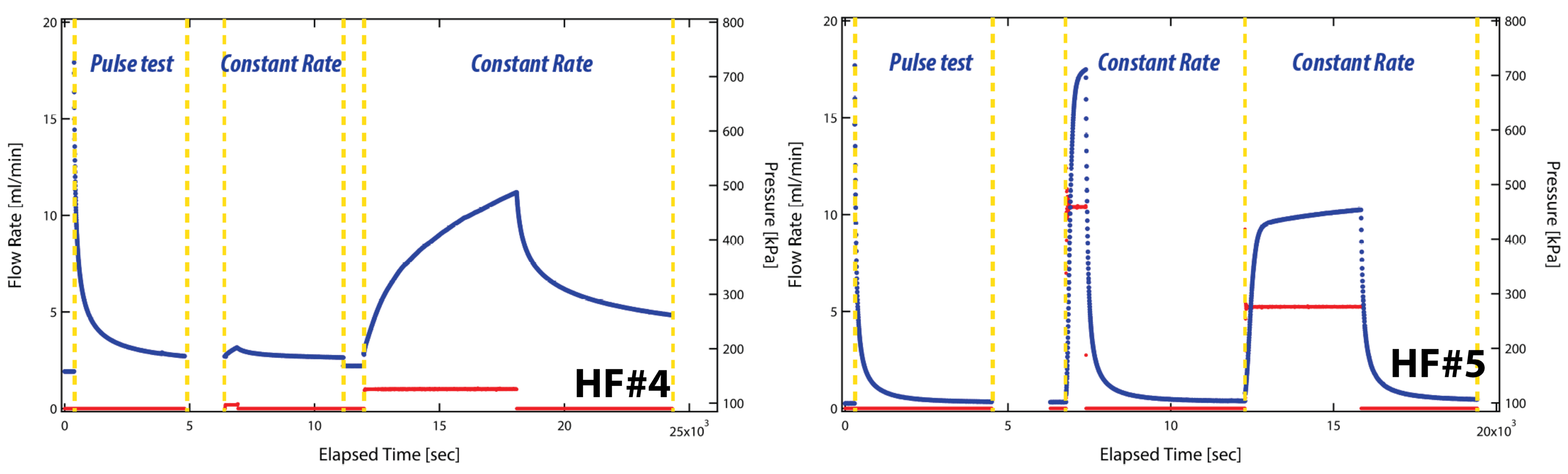
In-situ Stimulation and Circulation (ISC) experiment is executed in the southern part of the Grimsel Test Site (GTS) between the AU and VE tunnels in a low fracture density volume of Grimsel Granodiorite (GrGr). There exists three main sub-vertical ductile shear zones (i.e. S1, S2 and S3) as well as a brittle fracture zone which is confined with S3 shear zones in the considered volume.




As a part of stress measurement campaign during the pre-stimulation phase of the ISC experiment, a series of hydraulic fracturing (HF) and hydraulic tests in pre-existing fractures (HTPF) or hydraulic jacking were conducted in three stress measurement boreholes.

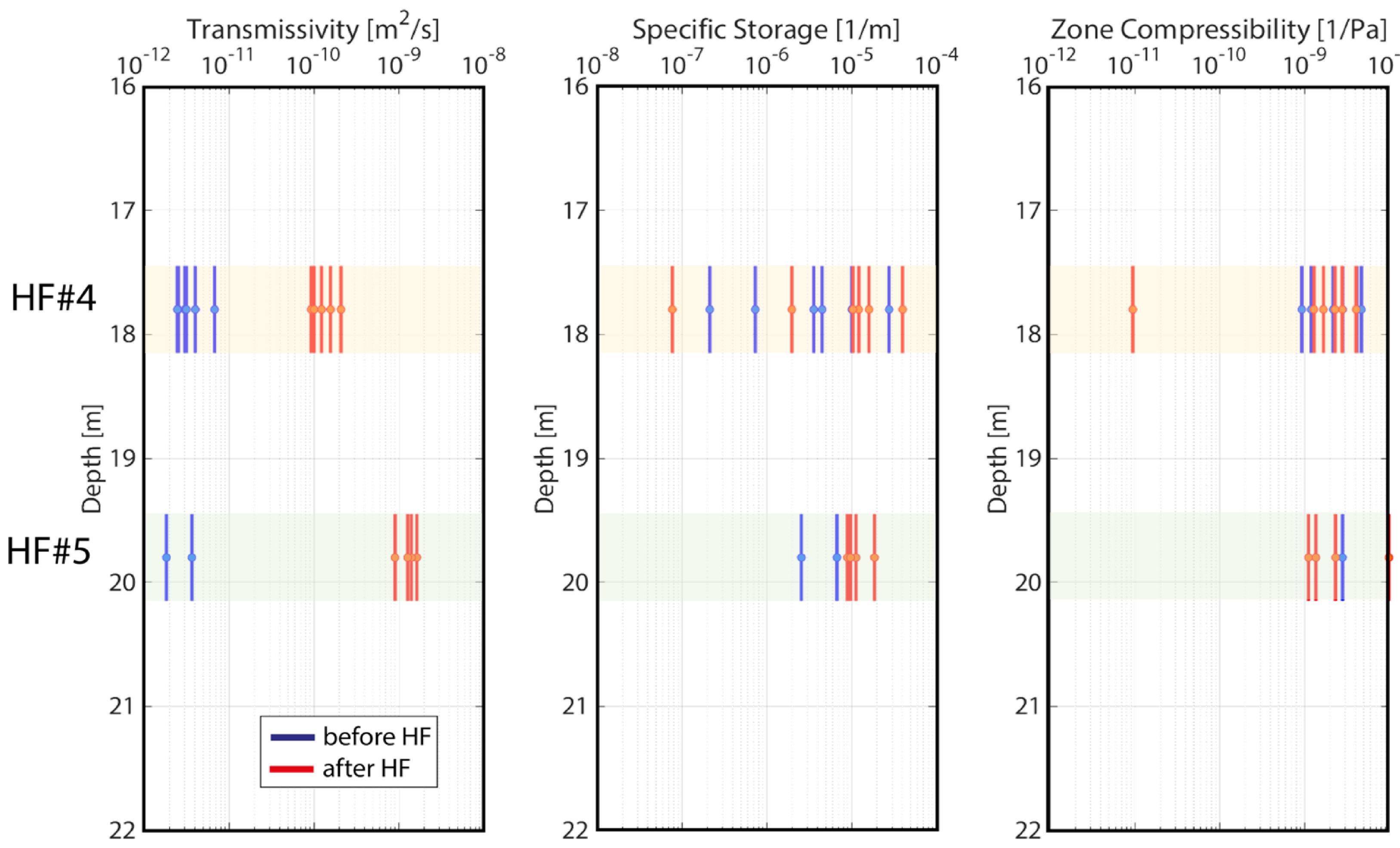
## 2. Hydraulic Characterization

In order to characterize the permeability enhancement as a result of hydraulic stimulation, a series of low-pressure (< 10 bars) hydraulic tests were conducted in SBH15004 borehole using a downhole triple packer system. These tests contain pulse and constant rate injection tests before and after the HF and HTPF tests. During each test, a specific amount of water was injected in the selected intervals. The pressure response as well as the injected volume were recorded over a chosen time and the collected data is then used for a curve matching (i.e. analytical solution) or inverse modelling (i.e. numerical solution) in order to estimate the hydraulic properties of the packed interval such as transmissivity, storativity and zone compressibility.




*Pressure response for HF#4 (interval 17.45-18.15 m) and HF#5 (interval 19.45-20.15m) of SBH15004 after HF and HTPF tests.*

## 3. Hydraulic Tests Results

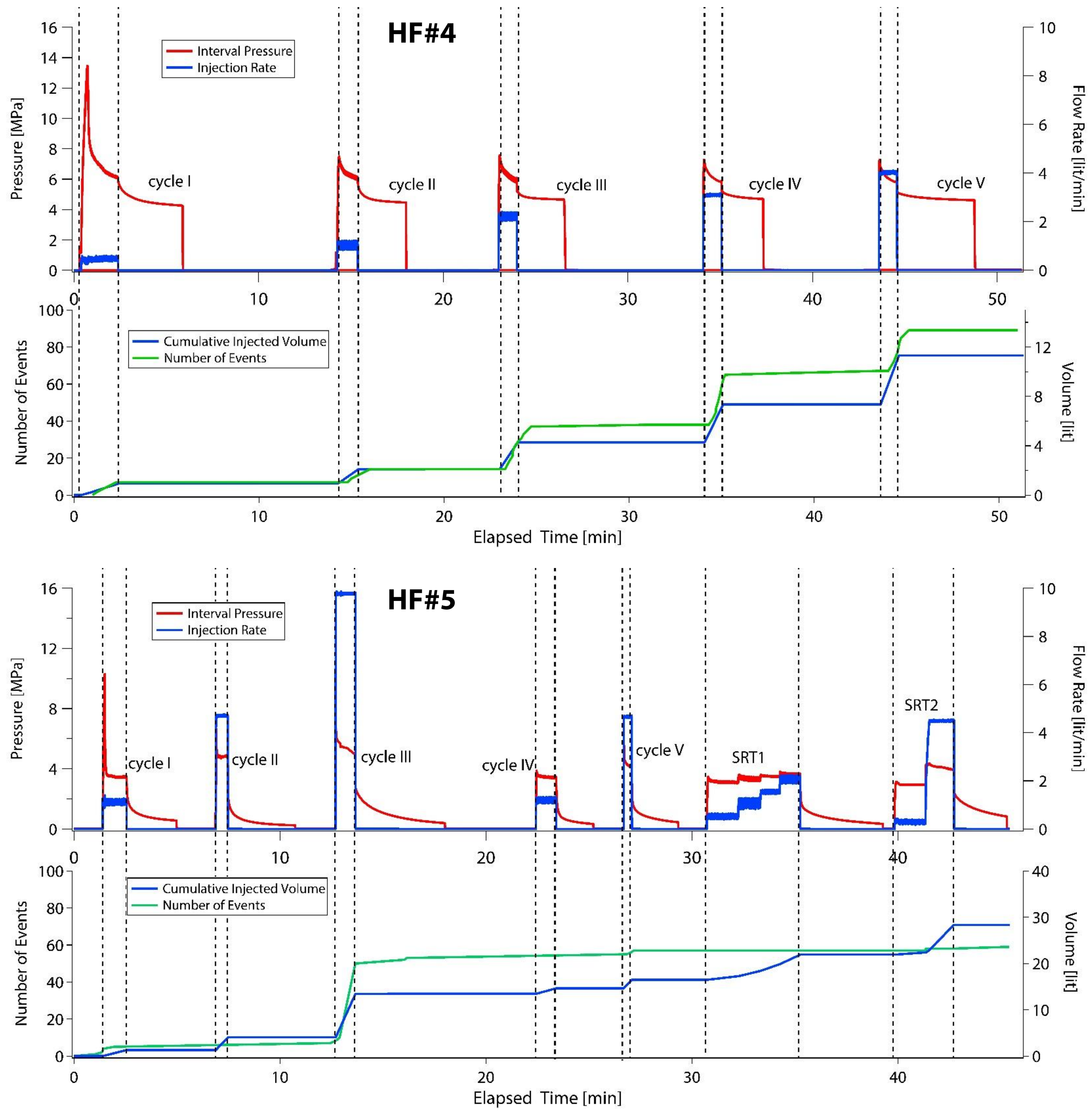



*Hydraulic properties of the selected intervals before and after stimulation*

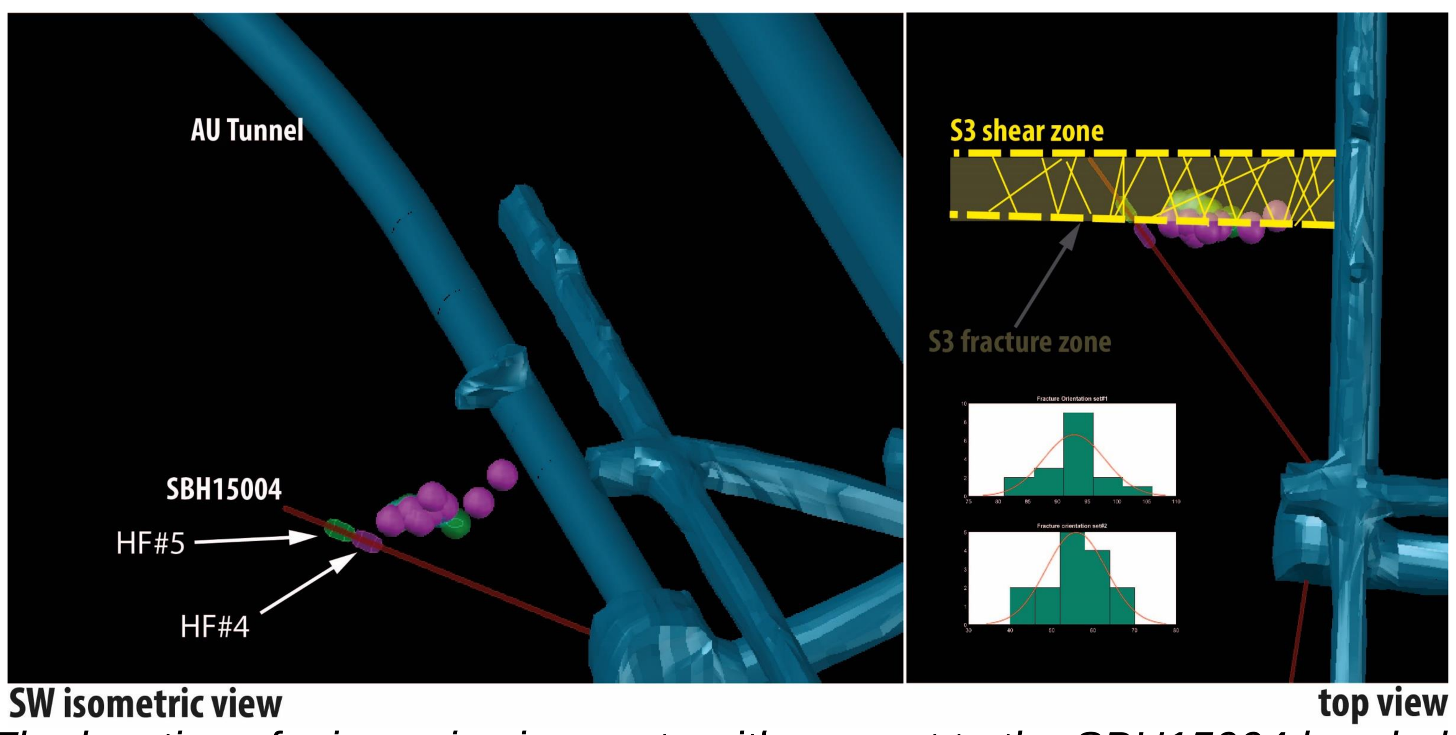
Hydraulic data obtained from both intervals are associated with a distinct permeability enhancement with difference in order of magnitudes. HF#4 in the interval without any distinguished fractures presents about two orders of magnitude permeability enhancement whereas this increment after HF#5 in the interval with the presence of S3 metabasic dyke is about three orders of magnitude. Due to uncertainty in estimation of specific storage, it is difficult to distinguish a clear trend before and after the hydraulic stimulation.

## 4. Discussion

The permeability increment during HF#5 can be explained as a result of hydro-shearing (mode II) of the S3 fracture zone as fluid injection was occurred in this area and there is a reasonable correlation between injection volume and seismicity (shearing) during the test.
For the case of HF#4 this permeability enhancement can be explained by intersection of the initial hydraulic fractures with some natural fractures and based on the seismicity cloud, it is clear that this fracture propagates toward the S3 fracture zone.




*Pressure, flowrate, cumulative injected volume and number of seismic events recorderded during HF#4 and HF#5 in SBH15004 borehole*




*The location of microseismic events with respect to the SBH15004 borehole and AU tunnel. Most of these events occurd in the S3 fracture zone.*

## Acknowledgements

This project is funded by the Swiss Competence Center for Energy Research –Supply of Electricity. We thank NAGRA for access to the Grimsel Test Site and the onsite support.

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# Hydrogeological characterization of a low-permeability crystalline reservoir before high-pressure stimulation


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## Motivation

Permeability enhancement lies at the heart of deep geothermal energy (DGE) technology and enhanced geothermal systems (EGS). Hence, a thorough understanding of pre-stimulation, baseline hydraulic and hydrogeological conditions across a target geothermal reservoir is critical in order to later interpret active and/or post-stimulation data and quantify the increase in permeability. Therefore, two of our main objectives are as follows:

- Provide high-resolution data for the development of a conceptual flow model for our experimental test volume under baseline conditions;
- Develop a set of hydraulic metrics/fingerprints to help detecting changes in hydraulic properties.

## Materials and Methods

To meet our objectives, extensive field measurements and hydraulic tests were completed throughout the year, including: monitoring formation pressures, automated tunnel inflow logging, and a series of packer tests (in single and cross-hole configuration). Presented in this contribution are preliminary interpretations and results on (i) hydraulic gradients and formation pressures; (ii) analytical estimates of transmissivity and (iii) pressure derivative analysis (PDA).

## Initial results

### Static formation pressures

Preliminary test results indicate that, under natural conditions, flow across our experimental reservoir rock volume is characterized by strong sub-vertical upward hydraulic gradients, increasing linearly with depth. Formation pressures along our two injection boreholes ranged from approx. 120 kPa to up to 300 Kpa under static conditions. See Fig. 3.

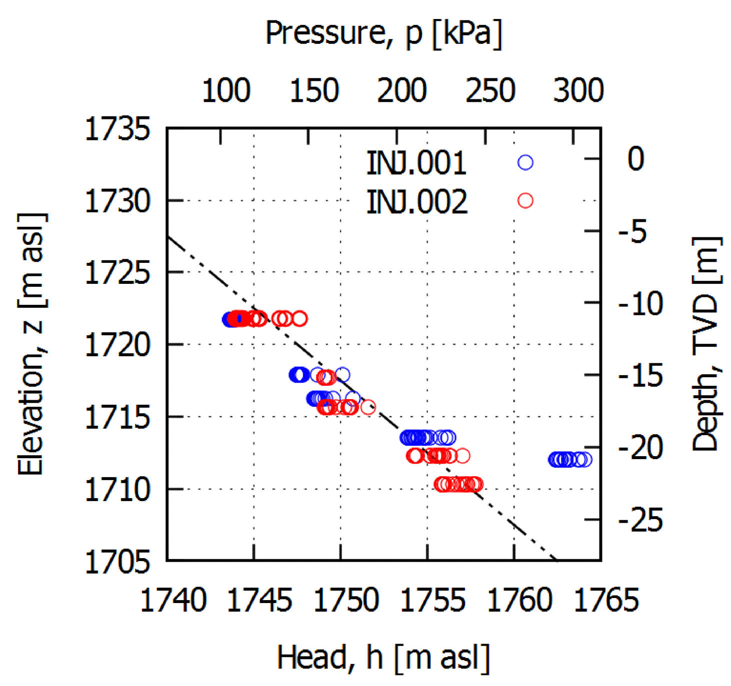


Fig. 3

### Transmissivity estimates

Transmissivity values obtained from pulse, slug and single-well packer tests exhibit a wide range of values, varying from approx. $10^{-11}$ $m^2/s$ (matrix-dominated zones) to $10^{-6}$ $m^2/s$ (fracture-matrix to fracture-dominated intervals). See Fig. 4.

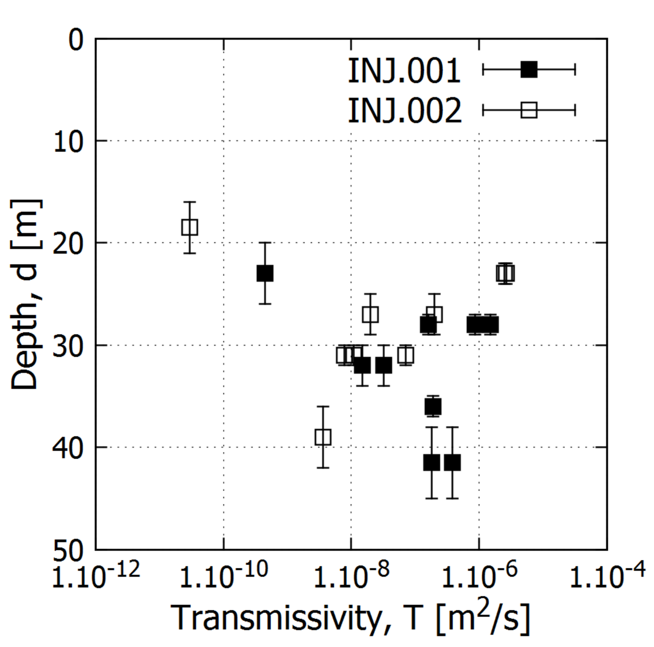


Fig. 4

### Flow regimes

Diagnostic plots completed for constant rate tests, where both the raw pressure buildup/fall-of and its derivative are shown revealed a variety of hydraulic responses/flow regimes, including (i) infinite-acting radial flow (IARF); (ii) linear to bilinear «fracture» flow; and (iii) possibly double-porosity. See Fig. 5.

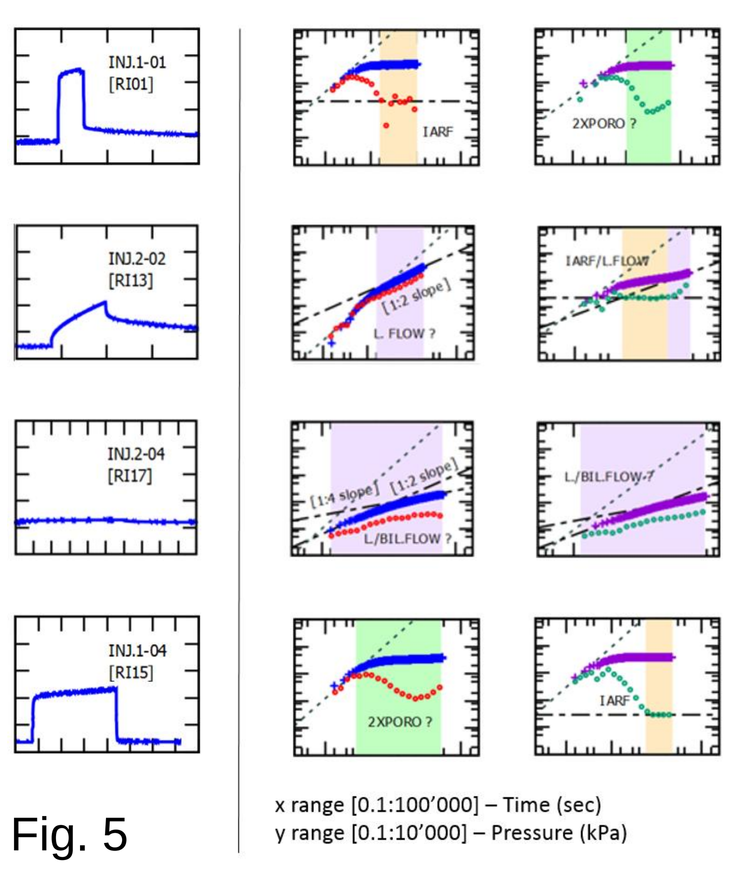


Fig. 5

## Grimsel Test Site (GTS)

- Up to 450 m
- Low-K cryst. rock
- Sub-vertical myloni. shear zones
- Geotherm. reservoir analog

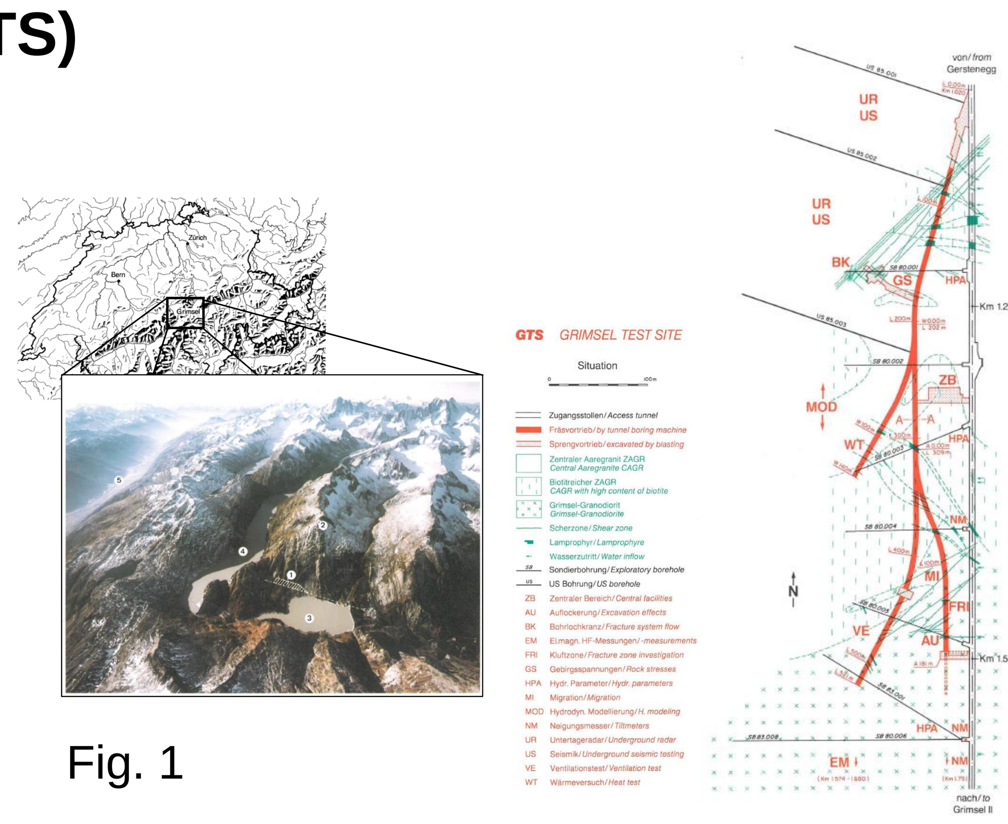

Fig. 1

## ISC laboratory

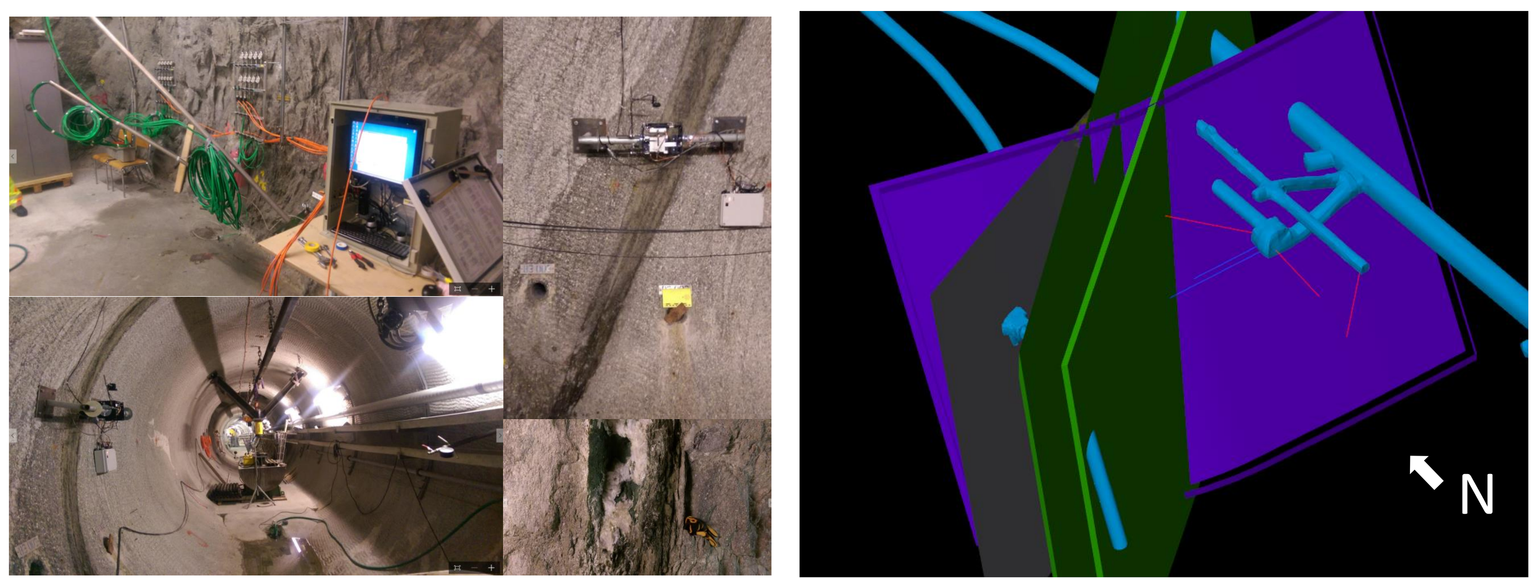


Fig. 2

## Discussion

- Under static conditions, flow across our experimental reservoir volume is oriented upwards towards local underground discharge areas (i.e. access tunnels and research galleries), taking place through a network of discrete fractured zones, exhibiting low-to-moderate transmissivity (~$10^{-8}$ to $10^{-6}$ $m^2/s$).
- The use of pressure derivative analysis (PDA) and diagnostic plots allowed us identifying various flow regimes, ranging from Infinite Acting Radial Flow (IARF) and double-porosity to linear and bilinear flow regimes, reflecting the heterogeneous nature of the local geological structures and their effect on local fluid flow patterns. Such a broad range of hydraulic responses and flow behaviour precludes the use of a single standard conceptual flow model, calling instead for an assessment of discrete fractured network (DFN) versus continuum modeling approaches.
- Additional field testing is on-going to further characterize monitoring boreholes and add to our catalog of hydraulic responses. Looking ahead, we plan to supplement analytical estimates of transmissivity through numerical modelling work aimed at evaluating how to best calibrate numerical flow simulations, together with the reconstruction of fractured networks, using parameters generally hard to estimate and/or typically overlooked (e.g. the flow dimension (Barker, 1988; Le Borgne et al., 2004) and two-point hydraulic connection data (Day-Lewis, 2000)).

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Day-Lewis, F. D., Hsieh, P. A., Gorelick, S. M. 2000: Identifying fracture-zone geometry using simulated annealing and hydraulic-connection data, Water Resources Research, 36, 1707-1721.

Le Borgne, T., Bour, O. de Dreuzy, J. R., Davy, P., Touchard, F. 2004 : Equivalent mean flow models for fractured aquifers : Insights from a pumping tests scaling interpretation, Water Resources Research, 40, W03512

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# Geophysical characterization of the ISC volume at the Grimsel Test Site

*Joseph Doetsch, Hannes Krietsch, Myriam Lajaunie, Valentin Gischig, Hansruedi Maurer, Florian Amann, Reza Jalali*

## 1. Introduction

The In-situ Stimulation and Circulation (ISC) experiment at the Grimsel Test Site (GTS) will hydraulically stimulate a rock volume that has not been used for previous experiments and has thus not been studied in detail. A detailed geological characterization campaign was carried out, including mapping of the tunnels, logging of borehole cores and optical televiewer imaging of the borehole walls. While highly accurate, this information can only be interpolated for regions between tunnels and boreholes. Geophysical imaging from tunnel walls and tomography between tunnels and boreholes has the potential to resolve variations in bulk properties such as porosity and can image fractures and shear zones and their intersections. Here, we present results of the geophysical characterization of the ISC volume.

## 2. Methods

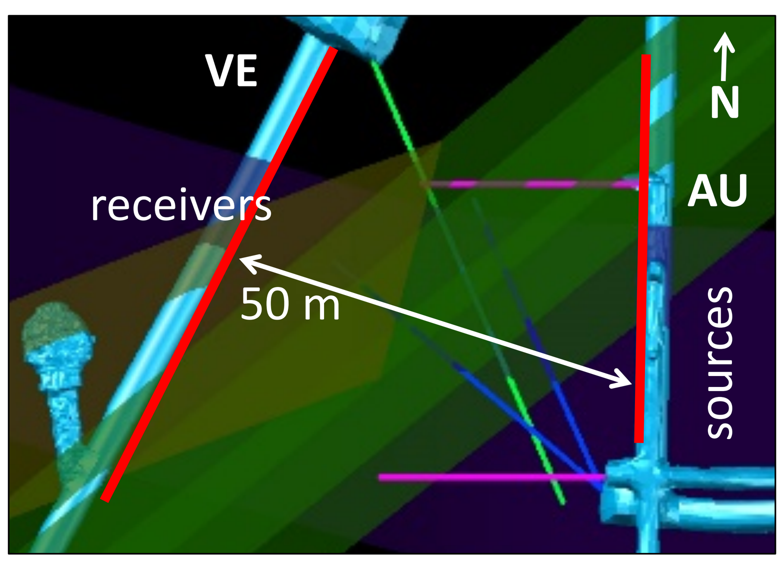
Wavefield methods such as seismic and ground penetrating radar (GPR) imaging and tomography are well-suited to characterize the rock volume around and between tunnels. GPR reflection surveys are sensitive to porosity and other rock properties so that the shear zones and metabasic intrusions can be clearly imaged. Due to the low resistivity of the Grimsel rock, the penetration depth of GPR is very good and structures can be imaged up to a distance of >30 m.

Seismic traveltimes are sensitive to the elastic moduli of the rock and can detect variations of those. At Grimsel, the elastic tensor is anisotropic so that the traveltime inversion needs to account for the angular dependence of the seismic wavespeed. The anisotropy is mostly due to the foliation of the rock, so that a tilted transverse anisotropy with a well-defined preferred direction can be assumed. We describe the anisotropy using the Thomsen parameters (Thomsen, 1986), where

- $vp_0$ is the velocity along the symmetry axis,
- $\varepsilon$ describes the strength,
- $\delta$ quantifies the anellipticity of the anisotropy and
- $\theta$ is the angle of the symmetry axis.

## 3. Data acquisition

**GPR**
Mapping of tunnel walls and floor using shielded GPR antennas with a center frequency of 160 MHz.




*Geometry for seismic and GPR surveys: Seismic sources and receivers were located along the same tunnel walls as the GPR profiles (red lines).*

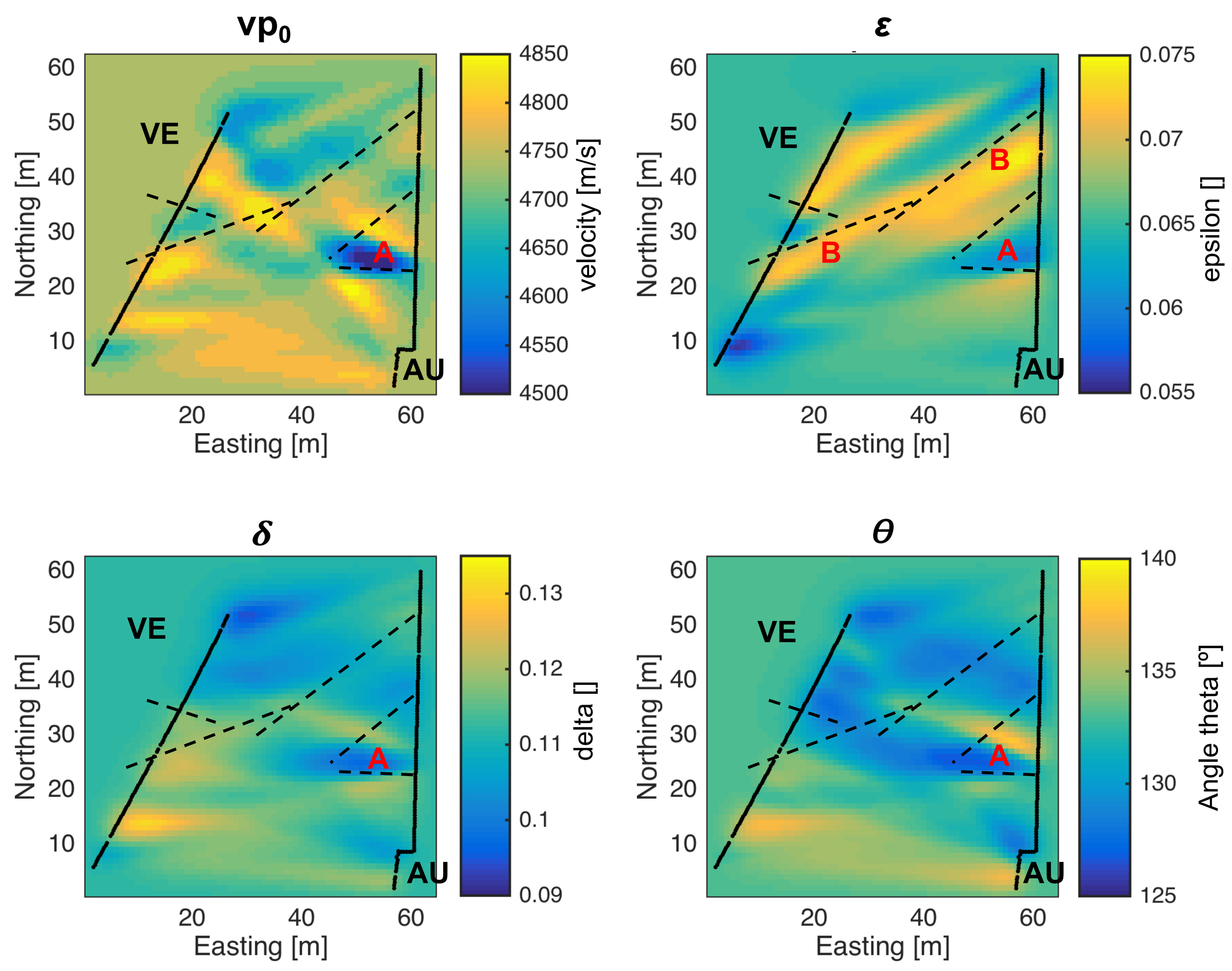
*GPR antenna and acquisition unit*

***Seismic tunnel – tunnel tomography***

*Source:*
*Hammer and chisel*
*Receiver:*
*100 Hz geophones*

## 4. Results anisotropic seismic traveltime tomography

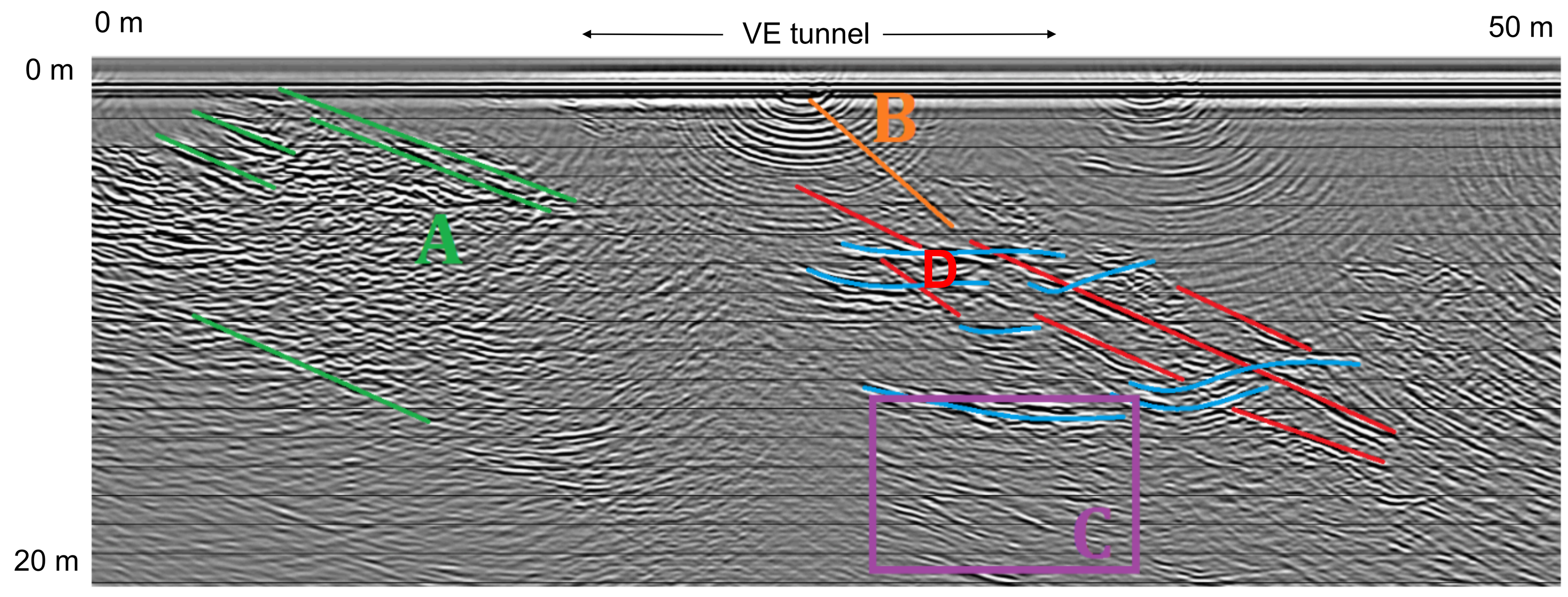
The anisotropic traveltime inversion reveals different geological information in the different parameters. The velocity $vp_0$ identifies a low velocity zone (**A**) that is known to be associated with a zone of high fracture density. It is visible in all parameters and terminates about 15 m away from the tunnel. The anisotropy strength $\varepsilon$ clearly identifies the shear zones (**B**, marked with dashed lines).




*Thomsen parameters resulting from anisotropic traveltime inversion*

## 5. GPR results

The GPR results allow to follow the shear zones through the ISC volume and especially help to understand the intersections of the different shear zones. Near the VE tunnel, the GPR data (see below) shows a dextral offset in the S1 shear zones (red lines) that is associated with the S3 shearing (**D**). This observation fits the relative age of S1 and S3 (i.e. S1 is older than S3).




## 6. Conclusions

- Anisotropic traveltime inversion reveals important geological details with the different Thomsen parameters showing complementary information.
- Using reflection GPR, it is possible to follow the shear zones throughout the volume and detect features (e.g., offsets) that cannot be proven using tunnel and borehole mapping alone.
- Combining geological mapping and geophysics can considerably improve the geological model, even for rock volumes that are as well characterized as the Grimsel Test Site (Keusen et al., 1989).
- Only the careful joint interpretation of geophysical and geological evidence can reveal details such as the dextral shearing of the S1 shear zone.

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# Flow path characterization using DNA-based smart tracers in the Grimsel Deep Underground Geothermal Laboratory (DUG-Lab)

GEL
Geothermal Energy & Geofluids

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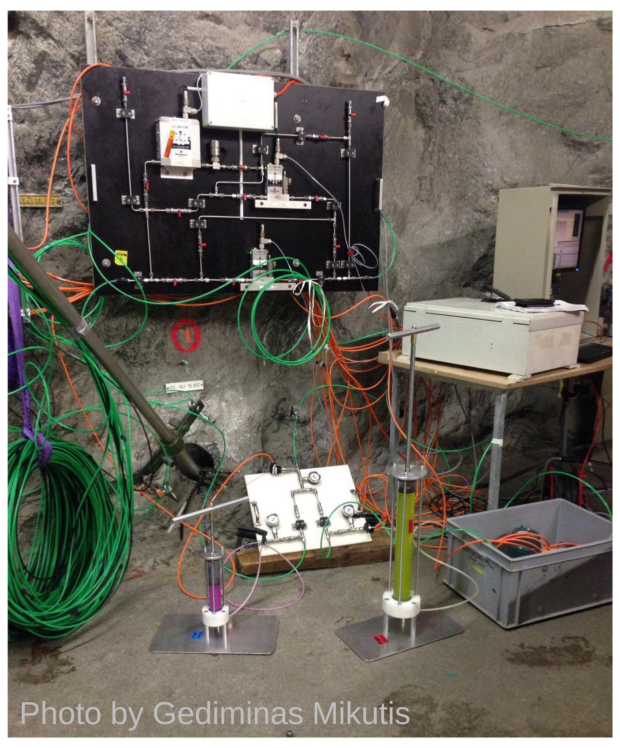
## 1. Introduction

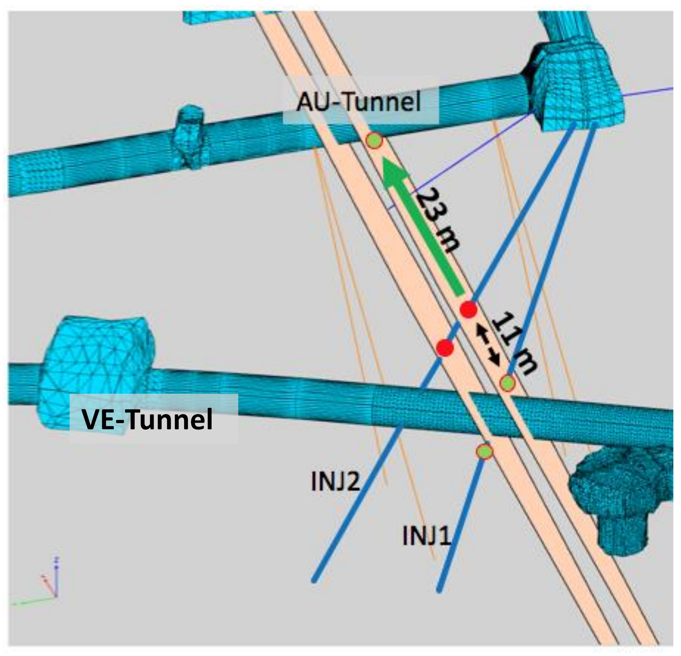
The Deep Underground Geothermal Laboratory (DUG-Lab) at Grimsel allows controlled and densely monitored experiments to be conducted on a decameter-scale to study permeability enhancement and changes in pore-space connectivity within a fracture zone as a result of hydraulic stimulation. This experiment will improve our understanding of how to enhance reservoir permeability in so-called enhanced or engineered geothermal systems (EGS).
In this project, a combination of field work and modelling is used to characterize connected flow paths both before and after the rock mass stimulation to evaluate the changes that have taken place in fluid transport properties in the fracture-dominated reservoir. Tracer tests, using novel DNA nanotracers in concert with conventional solute dye tracers, are conducted to characterize the flow paths within the rock mass test volume in the DUG-Lab.

## 2. Tracer tests

Tracer tests are a well-established method to obtain transport parameters and information on the geometry and swept volume of flow paths. The tracer mixture of a solute and DNA nanotracer was chosen to characterize the flow paths and evaluate the novel DNA nanotracers concurrently.




*Tracer mixtures ready to be injected. Both syringes have 10 ppm of a dye, sulforhodamine B on the left and uranine on the right, with 400 ppm of differently encoded DNA nanotracer.*




*Boreholes INJ2 and INJ1 (blue) (Obs: The VE-Tunnel is further away that it appears) intersect the fracture zones (flesh-color) studied in the pre-stimulation tracer test. Multi-packer systems isolated intervals (red circles for injection and green circles for sampling) within the fracture zone. The tracer mixtures were injected as a pulse to a steady-state injection flow in INJ2.*

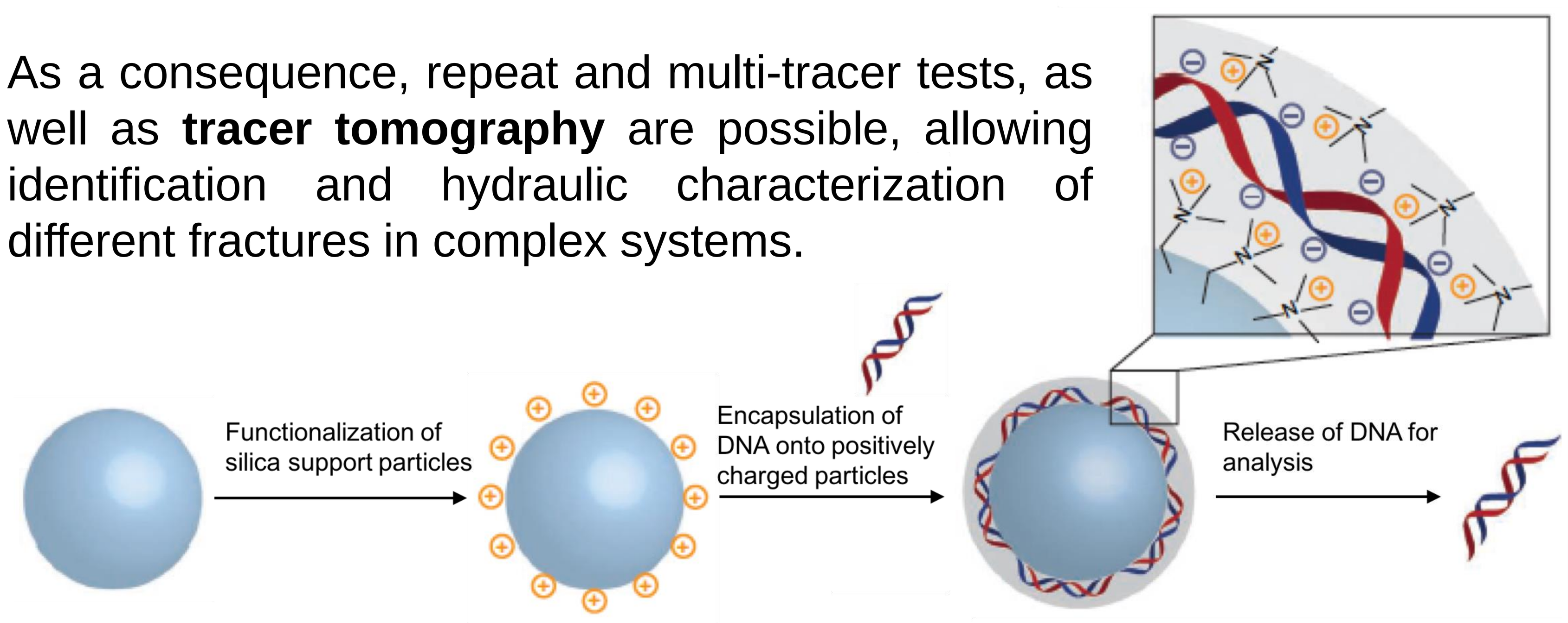
## 3. DNA nanotracers

(Paunescu et al. 2013a,b)

- Environmentally friendly, even edible
- Silica particles encapsulating short fragments of DNA
- Diameter approximately 150 nm

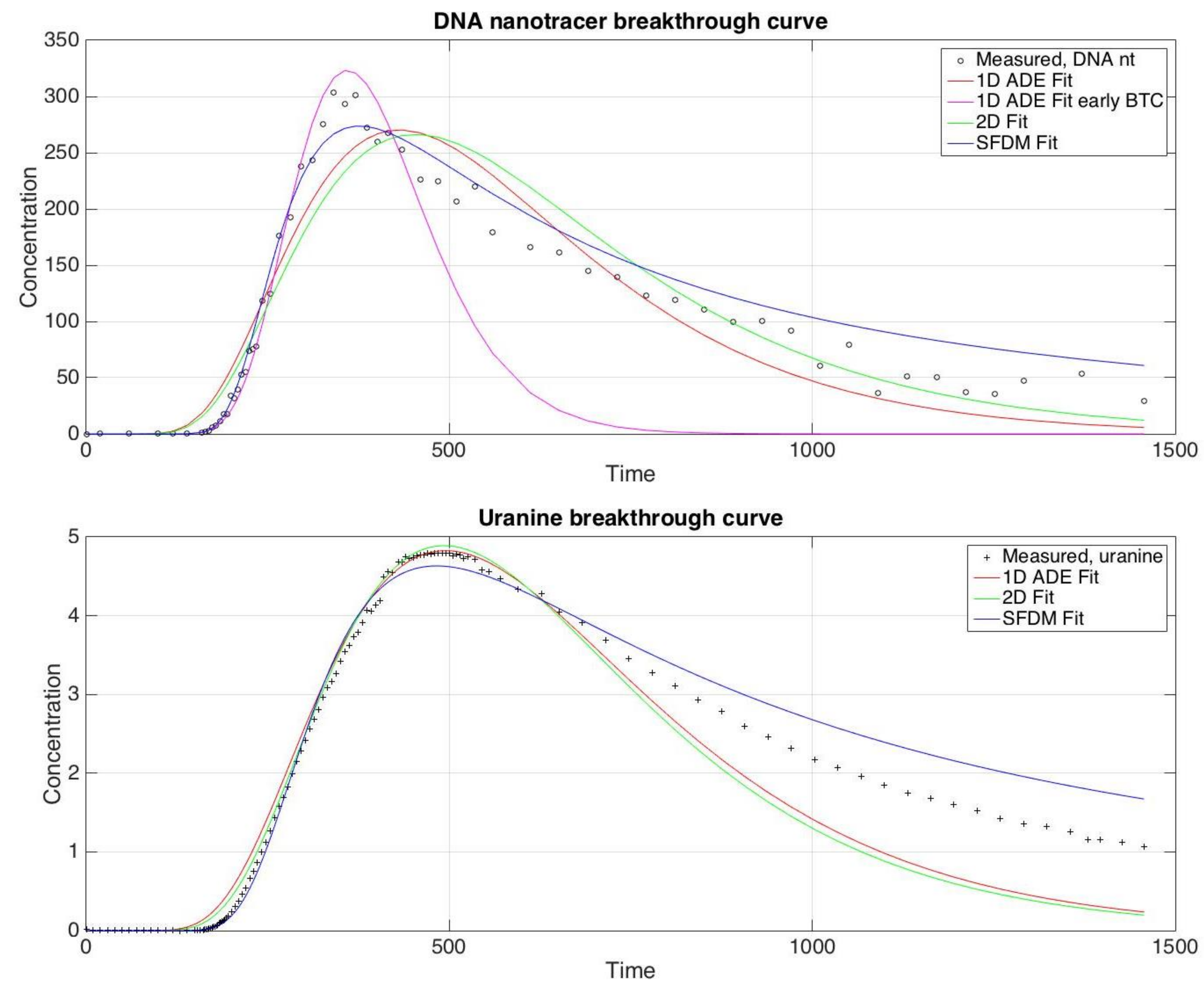
The encapsulated DNA can be produced with virtually **unlimited distinct signatures**. All DNA nanotracers exhibit the **same transport properties**, determined by the spherical silica particles. The detection and **unique identification** of each of the tracers is determined by their distinct DNA signatures.

As a consequence, repeat and multi-tracer tests, as well as **tracer tomography** are possible, allowing identification and hydraulic characterization of different fractures in complex systems.



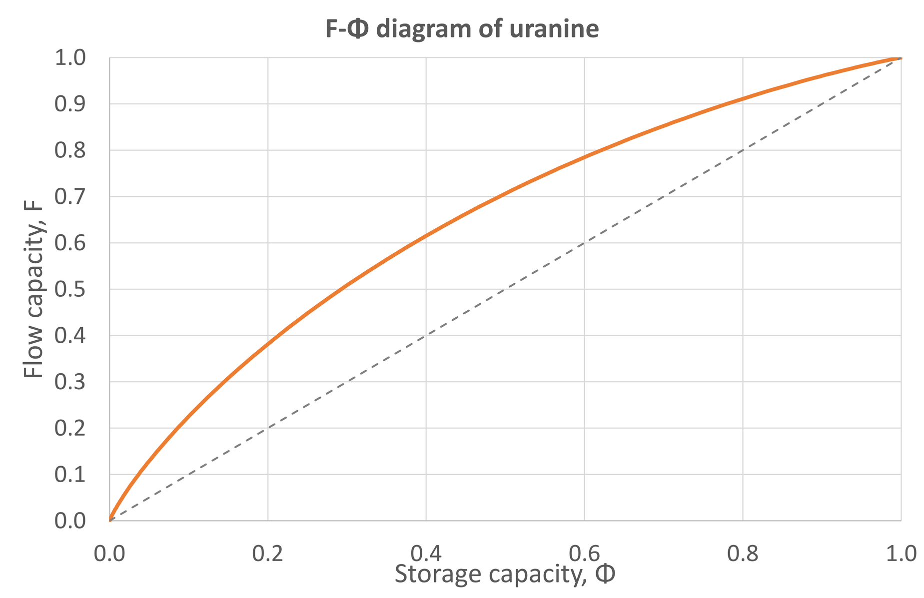

*Procedure of DNA nanotracer production. The DNA comprises 0.1 % weight of the particles.*

## 4. First results




*Examples of measured and fitted breakthrough curves of a DNA nanotracer (top) and a solute dye tracer uranine (bottom). In general, the single fracture dispersion model (SFDM) (Maloszewski and Zuber 1985, 1993) that takes matrix diffusion into account results in a better fit for both solute and DNA tracers than 1D or 2D advection-dispersion (ADE) solutions, which can capture only the advection dominated ( i.e. the early part) of the breakthrough curves. Further analysis will include separate solutions for DNA nanotracers with colloidal transport, and a more detailed investigation of the factors influencing the tailing of the breakthrough curves.*

- DNA nanotracers, described by particle transport, are transported preferentially in the main flow channel(s) due to size exclusion, but are prone to entrapment in irregularities of the fracture walls.
- Solutes exhibit faster molecular diffusion rates into stagnant (dead-end) flow paths and tend to access smaller pores and thus a larger overall volume of the reservoir.




*Moment analysis (Shook and Forsmann 2005) can be used to determine swept pore volume and flow/storage geometry (F-Φ diagram), where deviation from the diagonal is a measure of flow path heterogeneity, i.e., how the storage capacity is distributed within the flow paths.*

## 5. Discussion and outlook

- A comprehensive characterization of the flow paths in the rocks of the DUG-Lab appears possible by combining the novel DNA nanotracers with conventional solute dye tracers.
- It is hoped that the number of possible injection-observation pairs will increase after the hydraulic stimulation to enable the application of tracer tomography during the post-stimulation tracer experiment.
- By comparing the results from pre- and post-stimulation tracer tests we hope to be able to characterize the change in the flow path properties and overall permeability enhancement due to hydraulic stimulation.

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