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Geophysical imaging and characterization of the DUG Lab at the Grimsel Test Site

Joseph Doetsch (ETH Zurich, joseph.doetsch@erdw.ethz.ch), Valentin Gischig, Hansruedi Maurer

1. Introduction

The experiments in the Deep Underground Geothermal Laboratory (DUG Lab) 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. Geological information is available from mapping of the tunnels, borehole cores and optical televiewer images of the borehole walls, but 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 first results of the geophysical campaign to characterize the rock volume of the DUG.

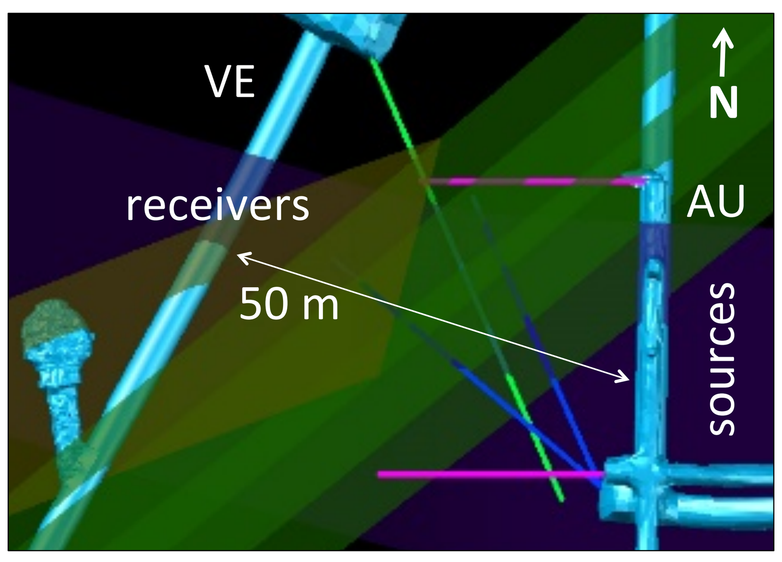
2. Methods

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 show very promising first results for imaging shear zone geometry away from the tunnels (see accompanying poster).

Here, we present data from cross-borehole and cross-tunnel seismic and GPR tomography. GPR traveltimes are sensitive to the water content und thus (under fully saturated conditions) to the porosity of the formation. Seismic traveltimes are sensitive to the elastic moduli of the rock and can detect variations of those. Imaged variations in porosity and seismic velocity can reveal different lithologies and their boundaries within the rock volume.

3. Data acquisition

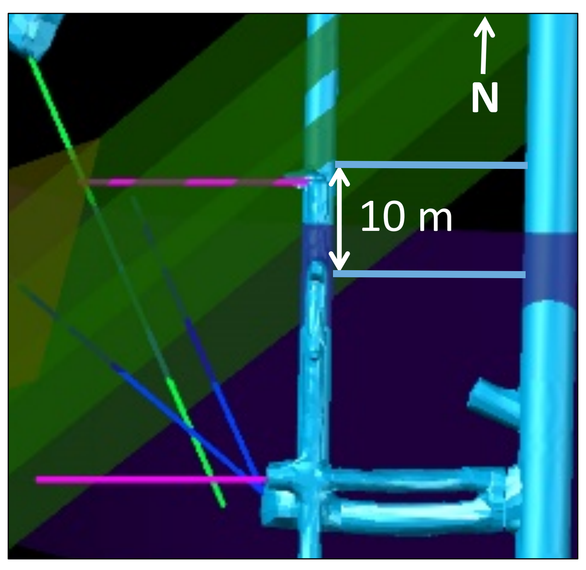
Tunnel – Tunnel tests and tomography

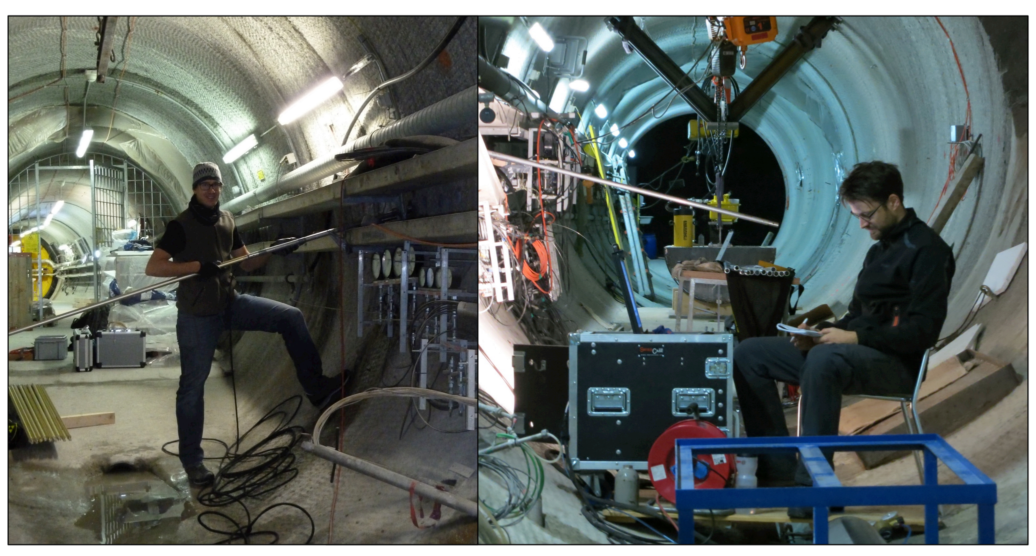


Tomography between AU and VE tunnels

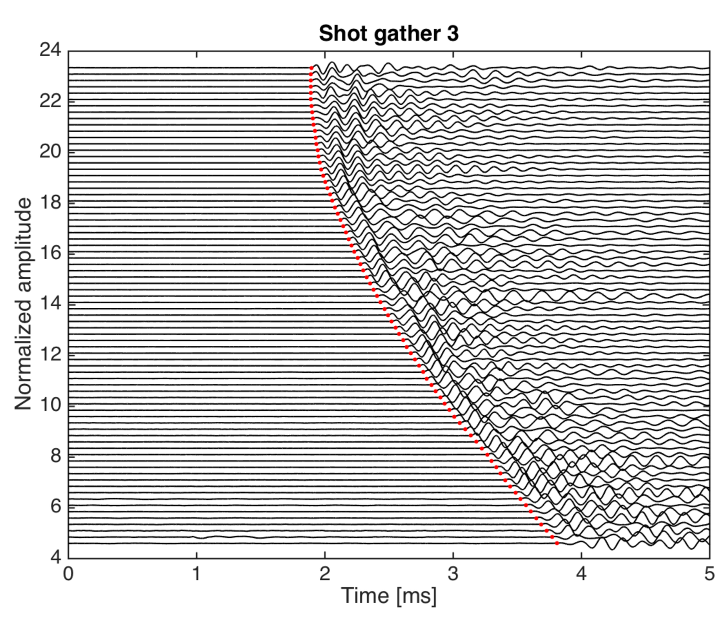
Geophones on the tunnel floor and the tunnel walls

Cross-borehole tomography





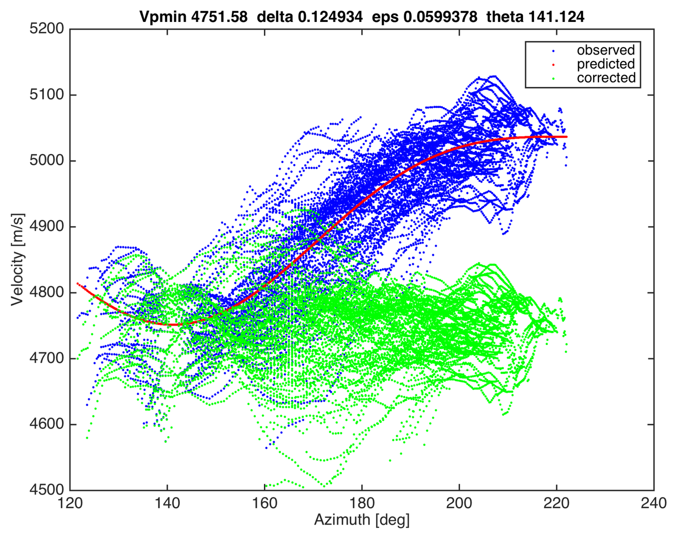
Tomography between FRI boreholes



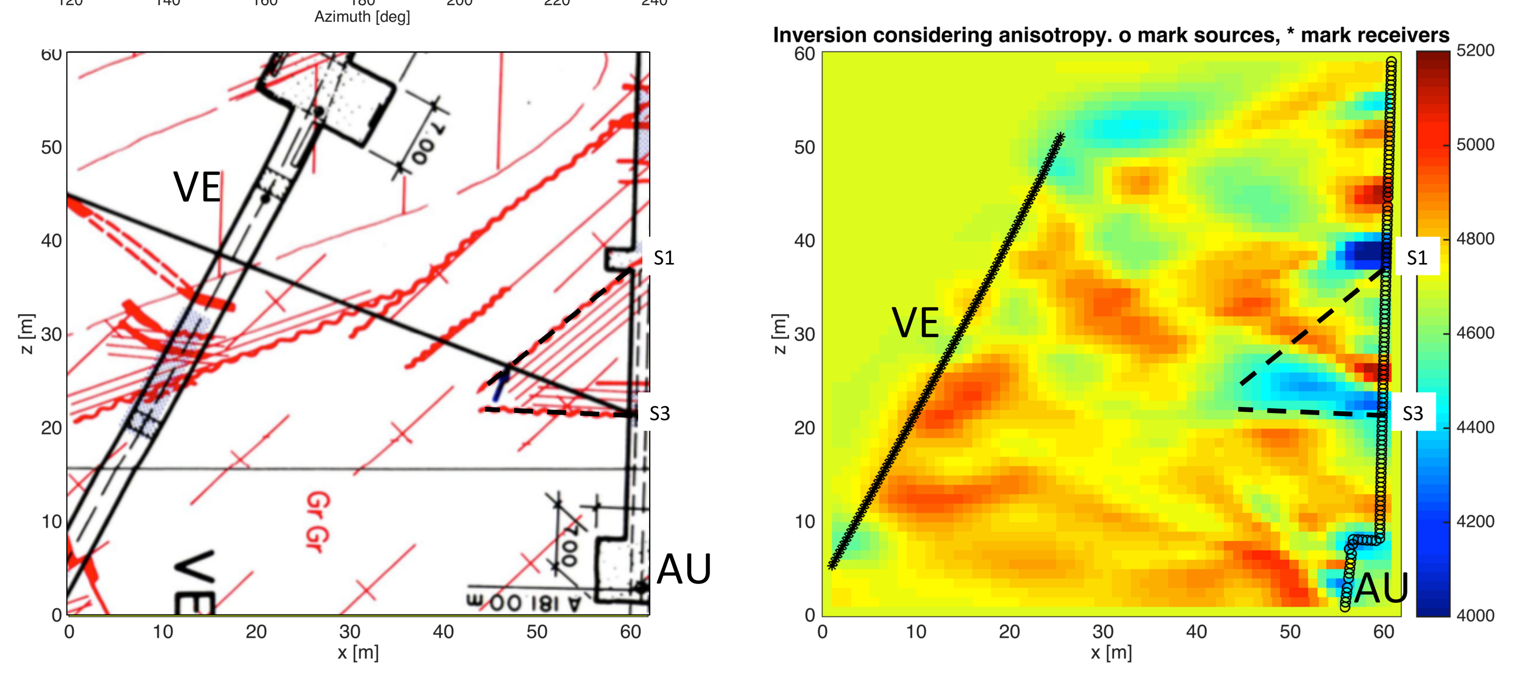
Sample shot gather with picked traveltimes

4. First results

Tunnel – Tunnel tomography: Seismic anisotropy

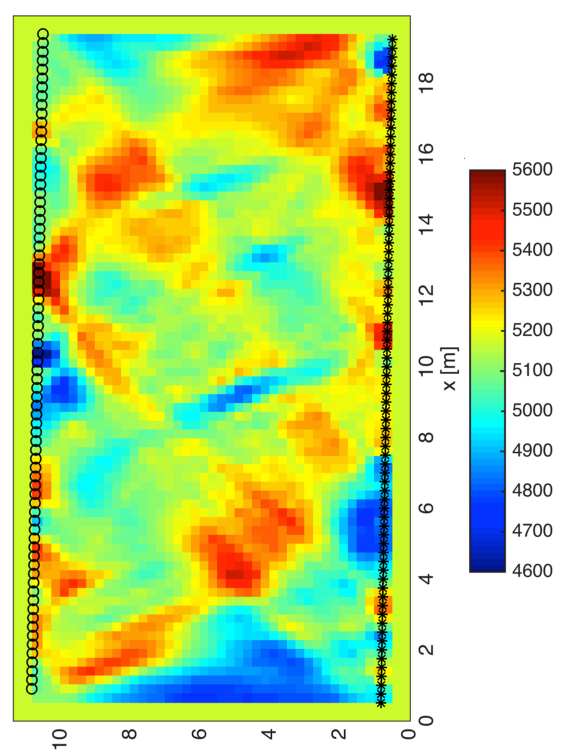


- *Blue dots: picked traveltimes. Anisotropy is apparent as the angle dependency of velocity.*
- *Assuming a constant anisotropy, there is a 6% difference in velocity and anisotropy is aligned with foliation and orientation of S1 shear zones*
- *Green dots: velocities with anisotropy effect removed.*

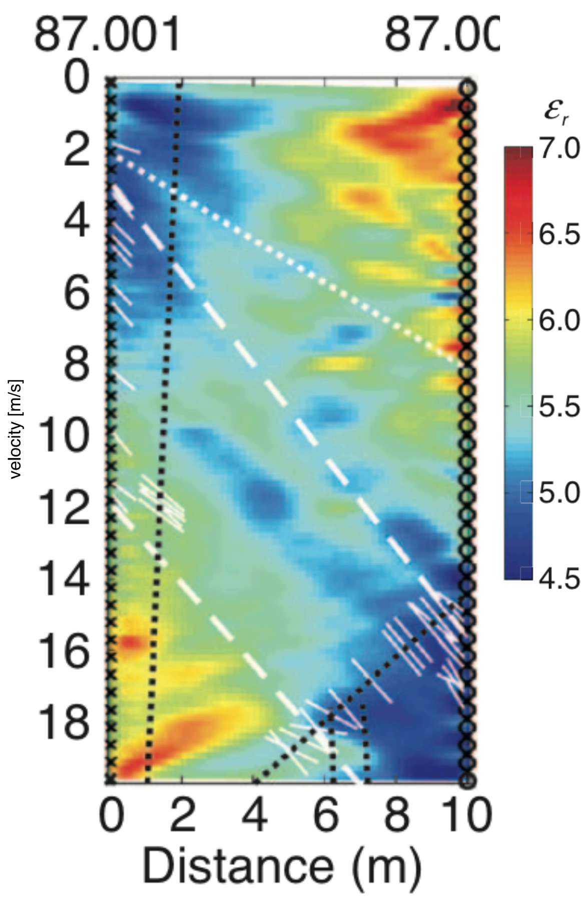


Traveltime inversion tomogram possibly reveals S1 and S3 shear zones at intersection with AU tunnel (geological map after Keusen et al., 1989)

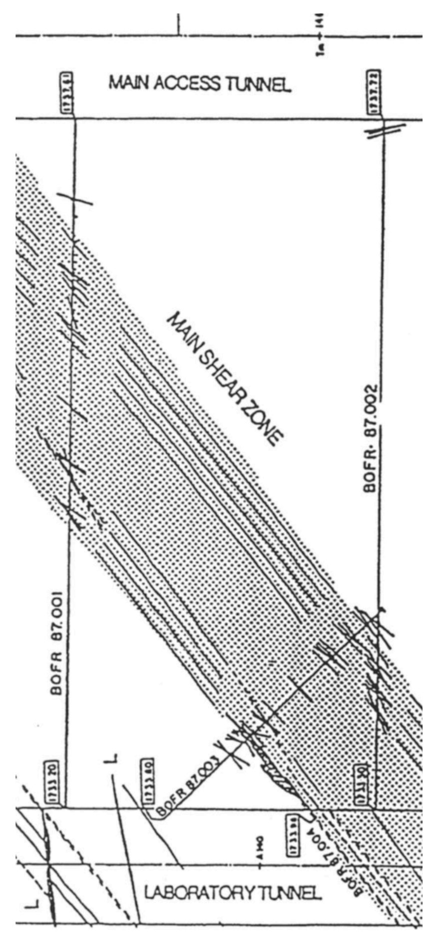
Cross-borehole tomography: GPR and seismics



Seismic velocity



GPR: relative permittivity (Ernst et al., 2007)



Geological model

Seismic and GPR traveltime inversions reveal structures that match with the geology extracted from tunnel mapping and from boreholes. In a next step, joint inversion will be applied to improve resolution and analyze petrophysical relationships.

5. Conclusions & Outlook

- Preliminary results are promising for resolving heterogeneity within the Grimsel rock mass
- Comparison between pre- and post injection aims at revealing the changes in the rock mass due to stimulation
- During circulation experiments, GPR tomography will aim at resolving flow paths of conductive tracer
- Fully anisotropic traveltime tomography will investigate variation in anisotropic parameters between shear zones and the main rock mass; anisotropic full-waveform inversion will be performed to resolve finer details

References

H. Keusen, J. Ganguin, P. Schuler, and M. Buletti. Grimsel test site: geology. Technical re- port, NAGRA, Baden (Switzerland), 1989, NTB 87-14.

J. R. Ernst. *2-D finite-difference time-domain full-waveform inversion of crosshole georadar data*. PhD thesis, ETH Zurich, Nr. 17105, 2007.

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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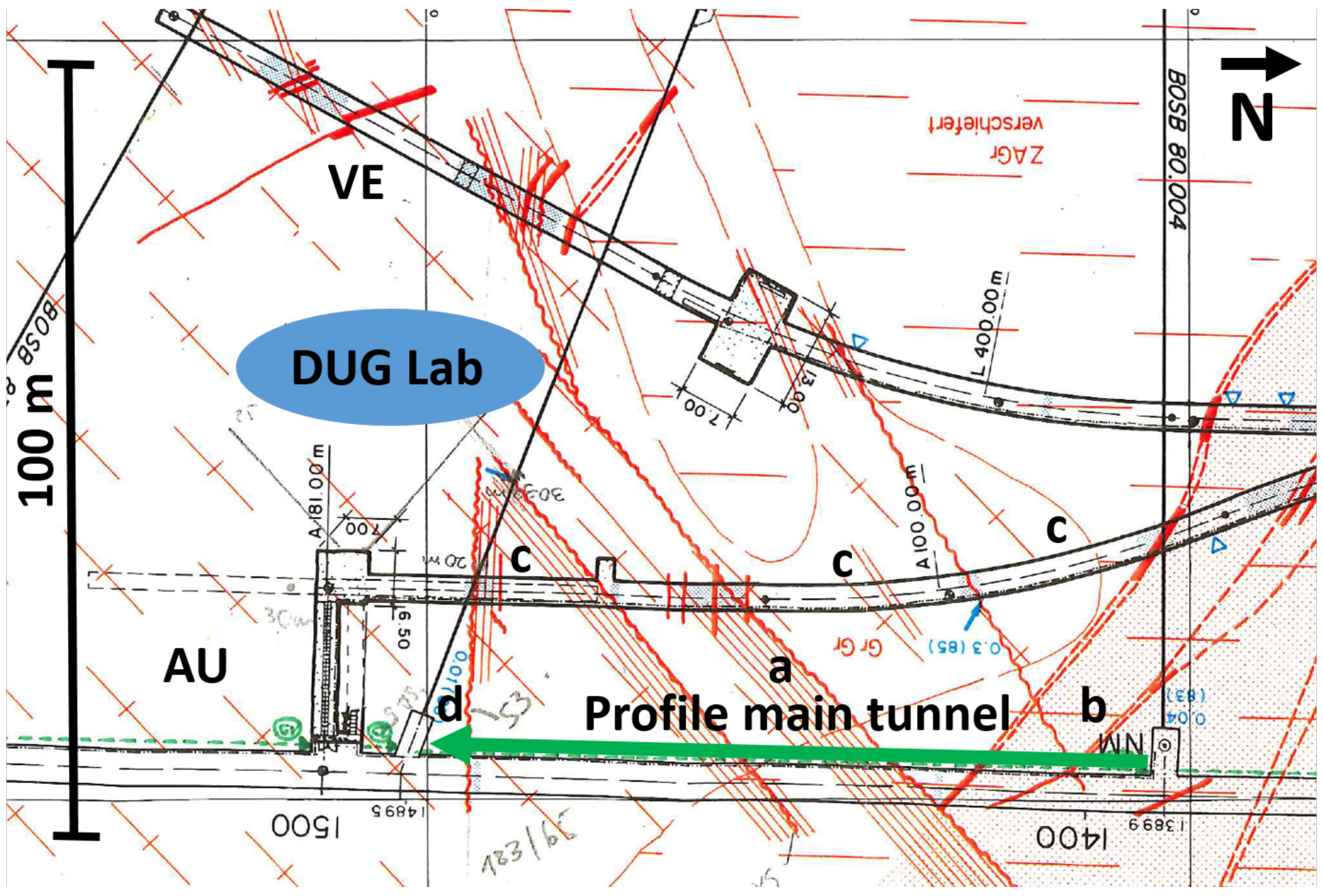
Georadar Imaging of Shear Zones at the Grimsel Test Site

Niko Laaksonlaita, Joseph Doetsch, Hansruedi Maurer

1. Introduction

We conducted Ground Penetrating Radar (GPR) reflection measurements in the Grimsel Test Site to determine the applicability of GPR in crystalline rock. In particular we imaged the area of the Deep Geothermal Underground (DUG) Lab and it's surroundings to characterize the structures within the rock. Variations in the porosity of the intact rock and shear zones imply heterogeneous water content throughout the rock. This leads to distinct reflections of the main shear zones. The GPR measurements serve as reconnaissance studies for the planned shearing experiments at the DUG Lab and allows us to use GPR as a long-period monitoring tool. The general goal is to gain advanced knowledge about efficient heat exchange in crystalline rock. The geological interpretation of the GPR images is done on the basis of geological information by Keusen et al. (1989). and the map seen below.



Section of the GTS (topview) illustrating the location of the DUG Lab (blue ellipse) and the GPR profiles shown to the upper right (green arrow: the start of the arrow matches wih x=0 in the profile)(modified from Nagra (1988))

2. Acquisition

The following antenna systems were used for reflection GPR measurements:

MALÅ GX HDR shielded antenna system:

- 80 MHz and 160 MHz

PulseEKKO shielded antenna system:

- 250 MHz, 500 MHz and 1000 MHz

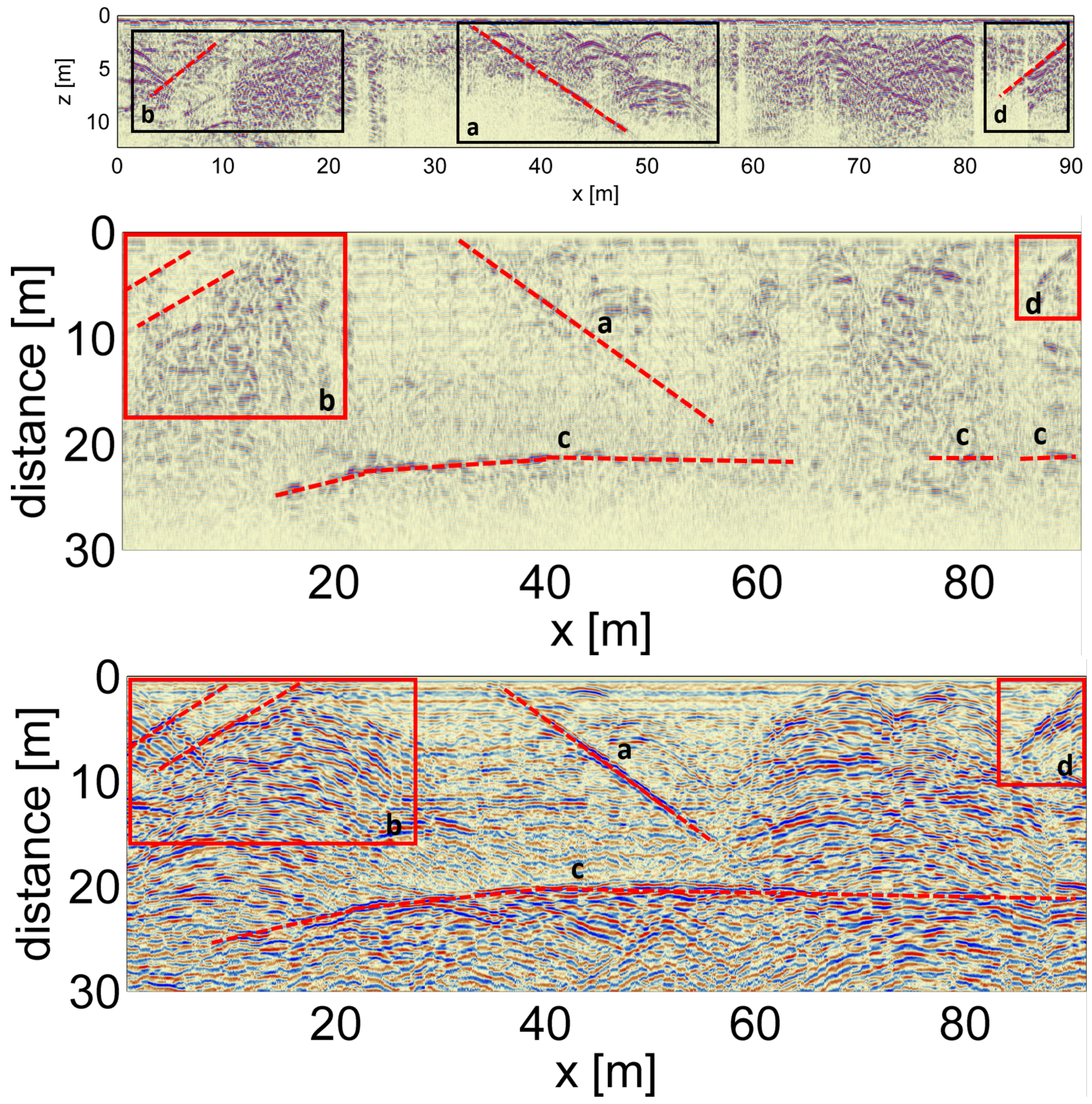
Performing GPR measurements with the PulseEKKO 250 MHz antenna (left) and the MALÅ GX HDR 80 MHz antenna (left)

References

Nagra, *Geologie des Felslabors Grimsel*, 1988.

H. Keusen, J. Ganguin, P. Schuler and M. Buletti. Grimsel test site: geology. Technical report, Nagra, Baden (Switzerland), 1989.

3. Results: Main tunnel profile with Shear Zone S1



From the top to the bottom: 250 MHz GPR profile, 160 MHz GPR profile and 80 MHz GPR profile from the west wall of the main access tunnel of the GTS (green arrow on the map to the left). Line a illustrates the shear zone S1, box b shows reflections that could arise from a lamprophyre zone, line c illustrates reflections from the GTS tunnel system and box d shows diffractions that arise from a borehole.

4. Conclusions

- Three different types of reflections can be seen in the GPR images:
    - Reflections from known geological structures, boreholes and tunnels that can be correlated nicely.
    - Distinct reflections from unknown geological structures (vague interpretation).
    - Reflections, that can not be correlated with any geological structures, tunnels or boreholes.
- Consistency of the tunnel wall/floor has a major influence on data quality.
- Main shear zone S1 can be seen nicely in the GPR profiles.
- Reasonable penetration depth for the antennas:
    - 80 MHz: <40m
    - 160 MHz: <50m
    - 250 MHz: <15m
- Frequencies higher than 250 MHz have only a limited application spectrum at the GTS.

5. Outlook

- Analysis of all the GPR data
- Joint interpretation of the geophysical data with the geological data by Raphael Schneeberger (University of Berne)

Acknowledgements

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ETH zürich

This research was initiated as part of an ETHZ Bachelor Thesis. We thank Nagra for access to the Grimsel Test Site and technical support on site. The field work was funded by SCCER SoE.

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A Numerical Study on the Hydro-Mechanical Behavior of Conductive Fractures in the Deep Underground Rock Laboratory at the Grimsel Test Site

Mohammadreza Jalali

SCCER-SoE, ETH Zurich

Abstract

A decameter-scale in-situ hydraulic stimulation and circulation experiment (ISC) has been planned to be executed in the Deep Underground rock Laboratory (DUG Lab) at the Grimsel Test Site (GTS). The general objective of this experiment is the extension of our understanding about the pressure, temperature and stress changes on the rock mass behavior during the hydraulic stimulation for the EGS purposes. In this context, a coupled hydro-mechanical numerical model is implemented to represent the physical behavior of the existing conductive fractures on permeability enhancement, pressure propagation and stress changes in the stimulated area. The preliminary results of this simulation could provide an insight on the design and expected coupled response of the fractures and host rock during the hydraulic stimulation phase at GTS.

1. Introduction

The in-situ stimulation and circulation (ISC) experiment experiment area in this site is the DUG Lab in the southern part of the GTS (between AU and VE tunnels) in a low fracture density volume of the Grimsel granodiorite (GrGr). There exists three main sub-vertical fracture zones in the considered volume, i.e. S1, S2 and S3 which are intersecting in the middle of the DUG Lab (Figure 1).

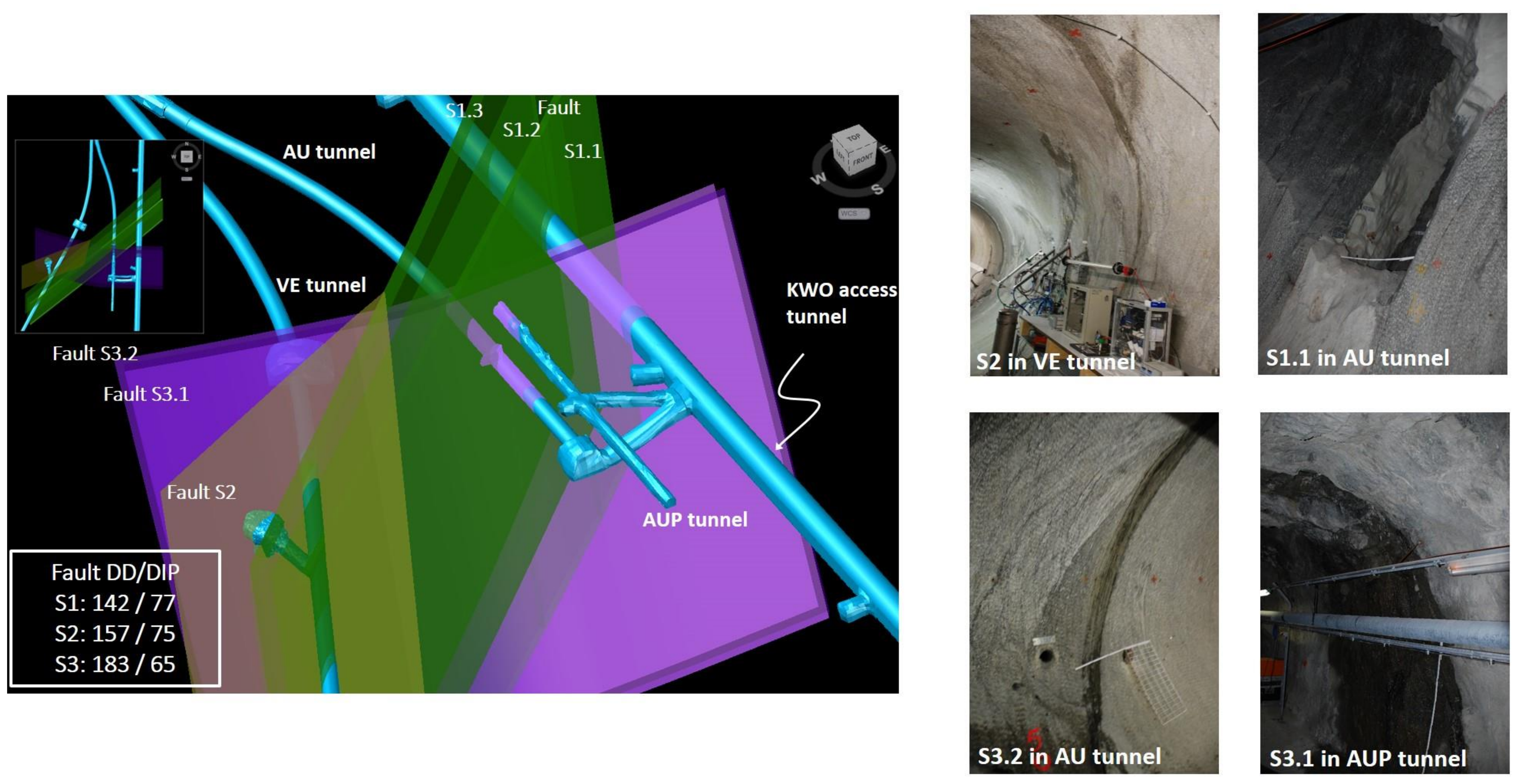


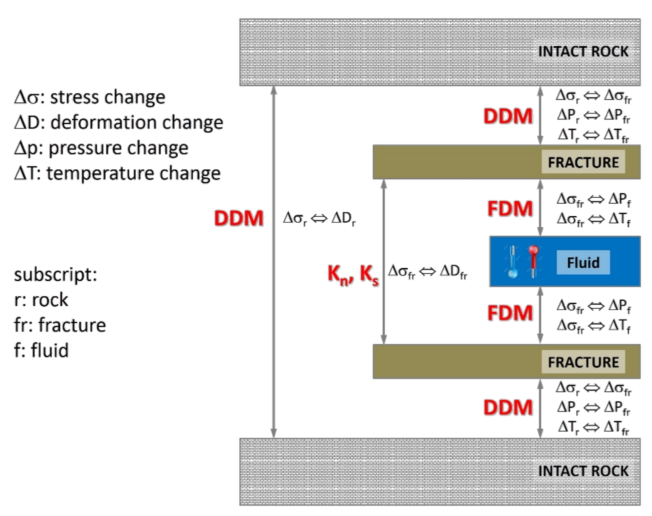
Figure 1. ISC experiment from south-west isometric view with three main intersecting sub-vertical fracture zones. Some intersection of these shear zones with the existing tunnels are shown on the right hand side.

2. Finite Difference – Displacement Discontinuity Method

Fracture fluid flow is modeled via the finite difference method (FDM) and the effect of pressure propagation on the fractures and surrounding rocks are estimated using an indirect boundary element, of which the displacement discontinuity method (DDM). The concept of this hybrid method is summarized in Figure 2.

Fracture Status	Contact Porosity*	Stress Condition	Fracture Pressure	Fracture Properties
closed fracture	$n_c = 0$	$\sigma_n' < 0$	$p = 0$	$K_n \to \infty$, $\psi = 0$
compliant fracture	$0 < n_c < 1$	$\sigma_n' < 0$ $\lvert\sigma_s\rvert < c + \lvert\sigma_n'\rvert \tan\phi$	$0 < p < \sigma_n$	$K_n = \partial\sigma_n/\partial u_n$**, $\psi = 0$
Mohr – Coulomb Criteria ($\lvert\sigma_s\rvert = c + \lvert\sigma_n'\rvert \tan\phi$)				
sliding fracture	$0 < n_c < 1$	$\sigma_n' < 0$ $\lvert\sigma_s\rvert > c + \lvert\sigma_n'\rvert \tan\phi$	$0 < p < \sigma_n$	$K_n = \partial\sigma_n/\partial u_n$** $K_s = 0$, $\psi \neq 0$
open fracture	$n_c = 1$	$\sigma_n' \geq 0$	$p \geq \sigma_n$	$K_n = \partial\sigma_n/\partial u_n$**, $\psi = 0$

*Contact porosity is defined as the ratio of non-contacting fracture area to nominal area.
**Fracture normal stiffness is updated based on the hyperbolic model.



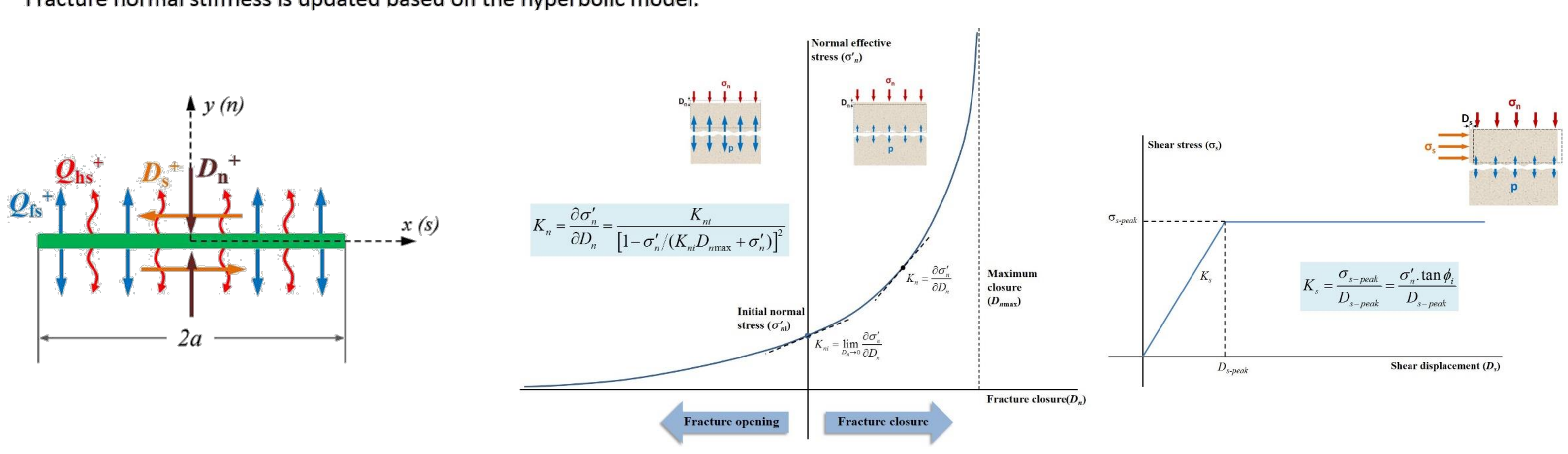


Figure 2. Theoretical concept of the FD-DDM hybrid model

3. Results

A horizontal cross-section plane at the level of the AU and VE tunnel is considered as the plane-strain cut of the stimulation area (Figure 3). Water is injected at the intersection of S1.1 and S3.1 fractures under a step-rate flow rate scenario. The evolution of injection pressure and flow rate for the case where the principal stresses are along x- and y-axes (β = 0) as well the shear failed area and permeability enhancement over time are shown in Figure 4.

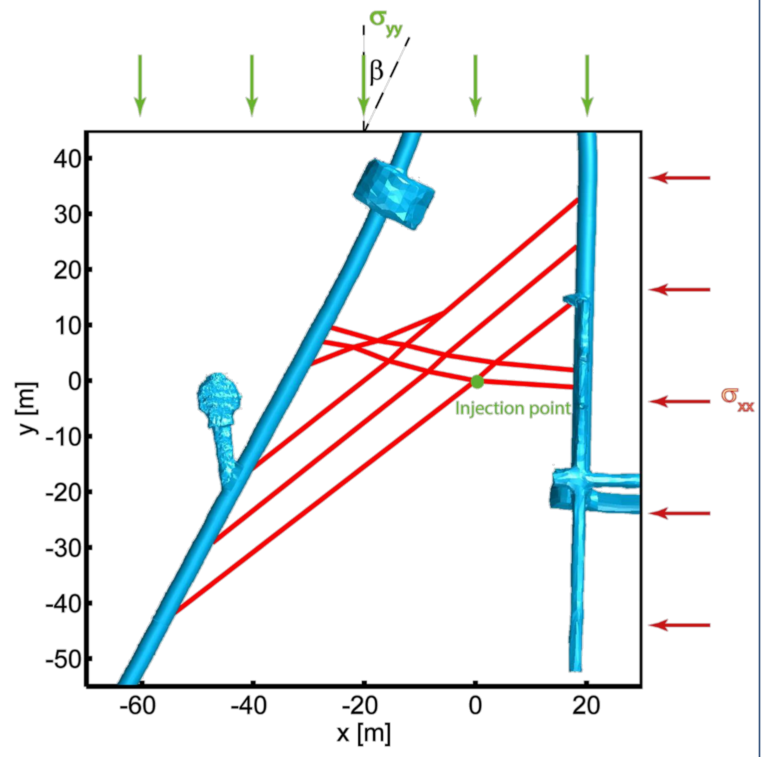


Figure 3. schematic representation of the horizontal cross-section between AU and VE tunnel

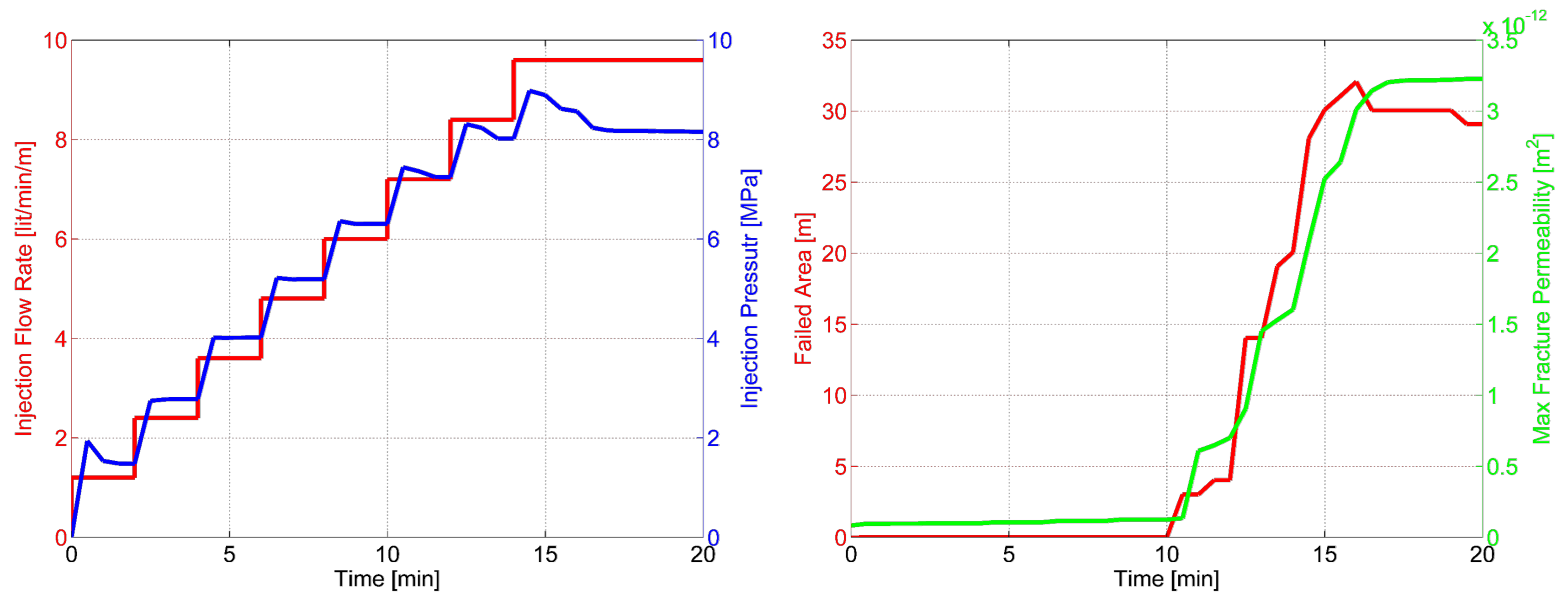


Figure 4. Injection flow rate (red solid line) and injection pressure (blue solid line) over 20 minutes of injection (left), Shear failed area (red) and permeability enhancement (green) over time as the consequence of water injection (right) .

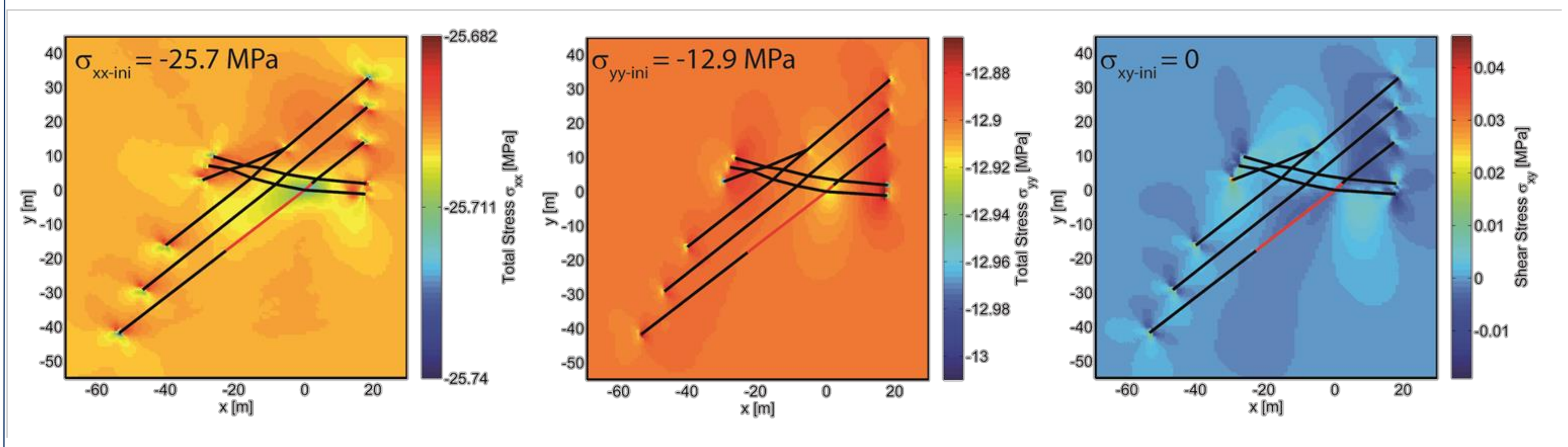


Figure 5. Total stress changes after 20 minutes of water injection as a result of pressure increment and fracture dislocation

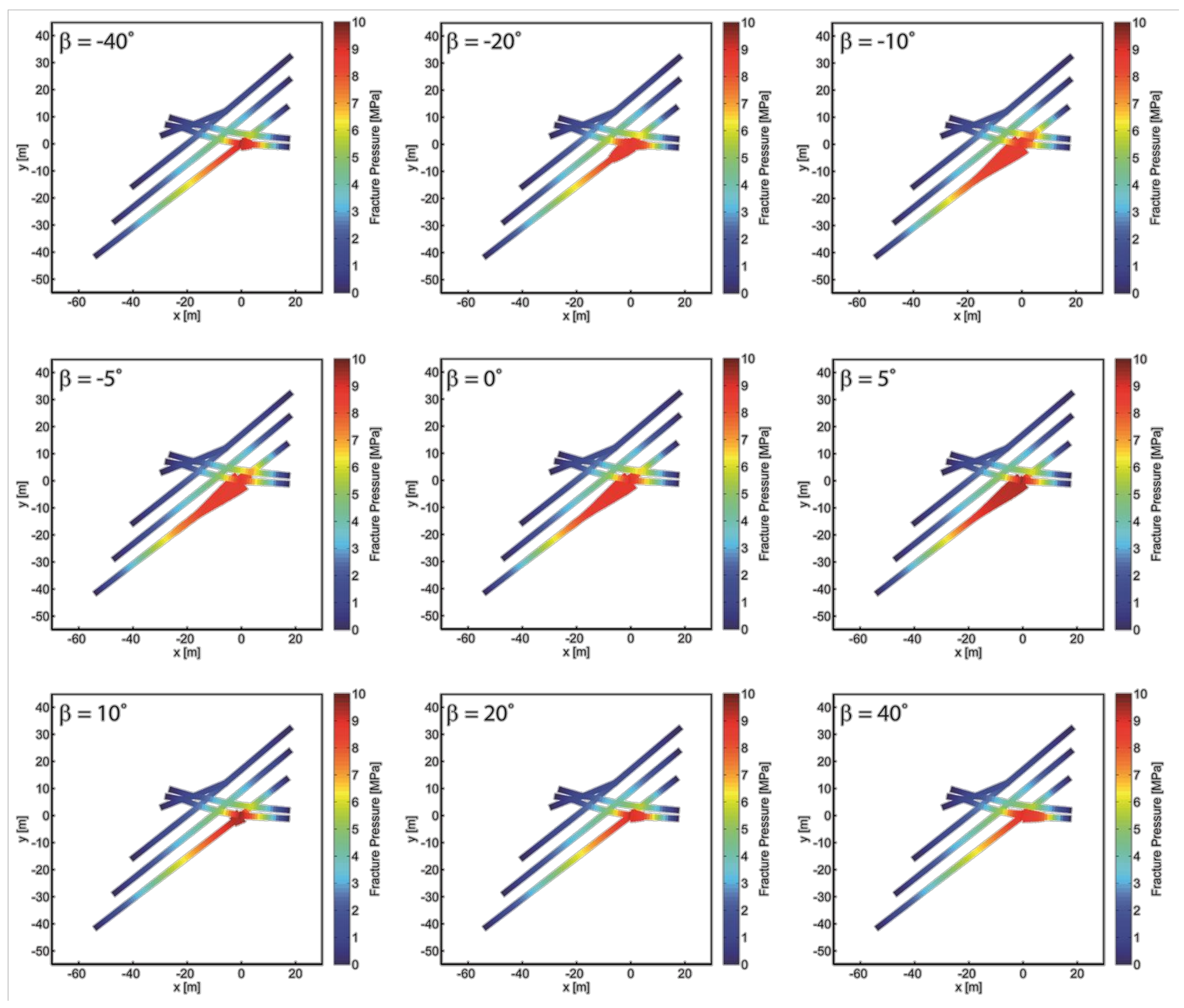


Figure 6. The effect of in-situ stress orientation (β) w.r.t y-axis on the fracture pressure propagation as well as fracture aperture

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Understanding of key physical and chemical processes during geologic CO_2 sequestration in saline aquifers

Xiang-Zhao Kong[1], Martin O. Saar[1]
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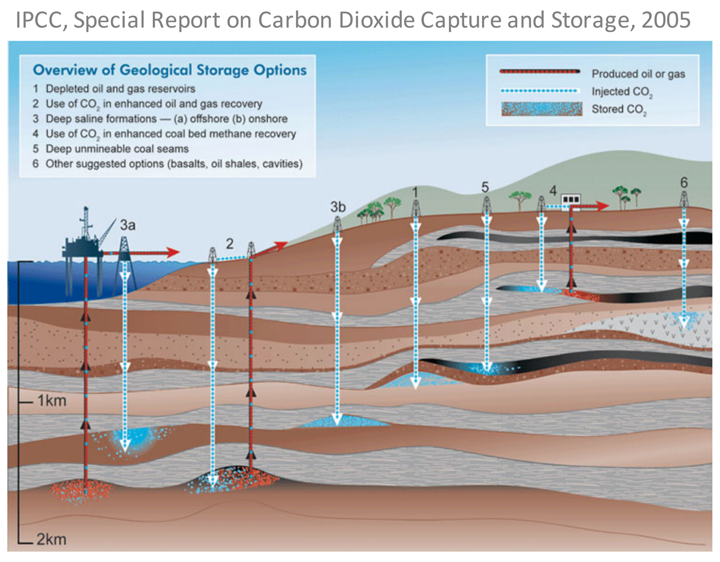
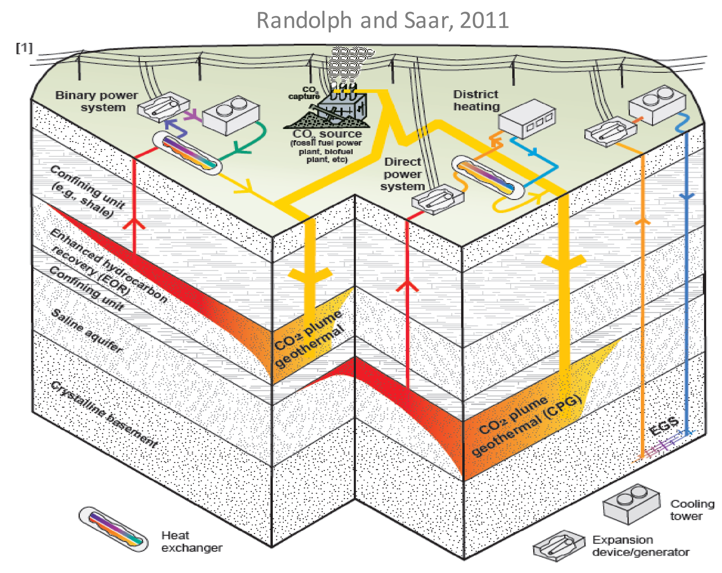
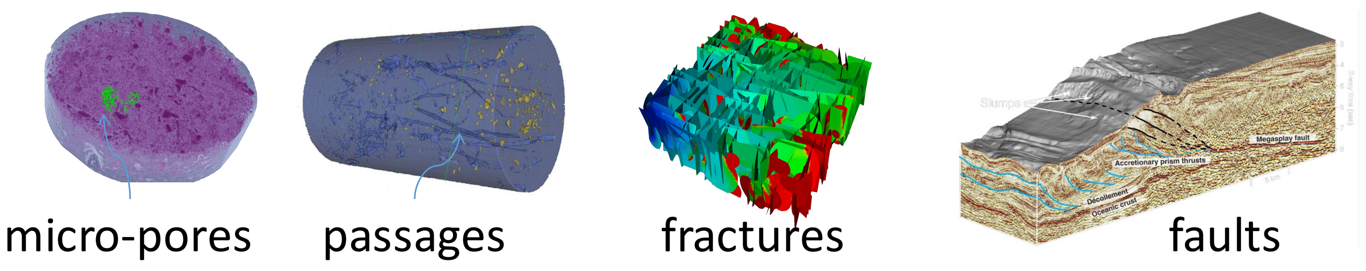




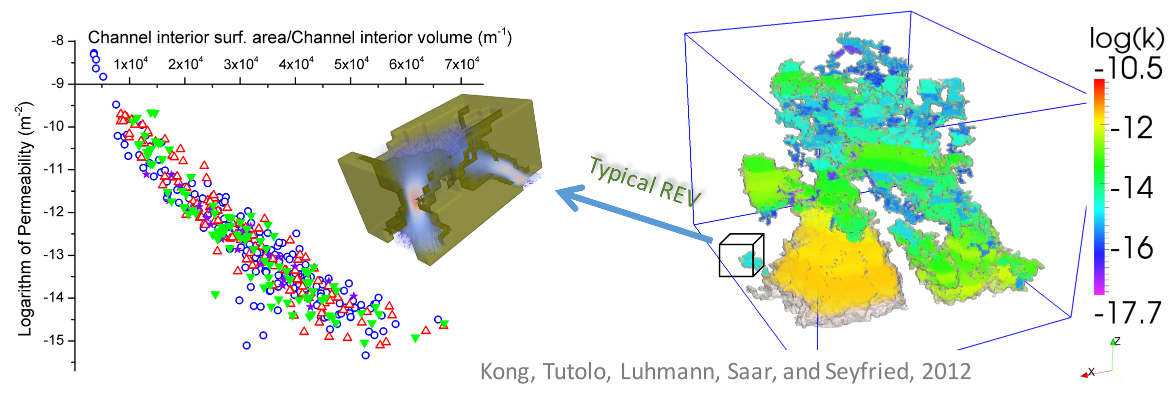
Geologic CO_2 sequestration involves injection of captured CO_2 into saline formations, oil and gas reservoirs, unmineable coal seams, organic-rich shales, basalt formations, and other geological reservoirs to mitigate global climate change what is caused by increasing atmospheric CO_2 concentration. Perceptively, geologic CO_2 sequestration can be combined with enhanced oil recovery, enhanced coal bed methane recovery, and enthalpy extraction in geothermal reservoirs (the far right figure) as a form of carbon capture, utilization, and storage (CCUS).

As CO_2 is injected into deep, saline aquifers, it will first displace some of the pre-existent formation fluid, but eventually dissolve it, lowering the pH and increasing the reactivity of the formation fluid which reacts with the host rocks. Optimally, CO_2 remains isolated from the atmosphere via a series of trapping mechanisms that start with structural and stratigraphic as well as capillary trapping, continue with solubility trapping, and eventually ends with mineral trapping. The primary concern is the uncertainty of the ultimate fate of the injected CO_2 and the related processes. To address this concern requires answers to the following key questions: (1) What are the key physical and chemical processes involved when CO_2 is injected? (2) What are the associated important hydrogeochemical parameters? (3) What controls the feedbacks between flow fields and chemical reactions?

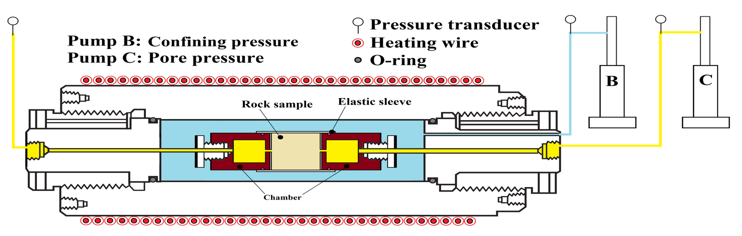
Geometry (pore size and its distribution)



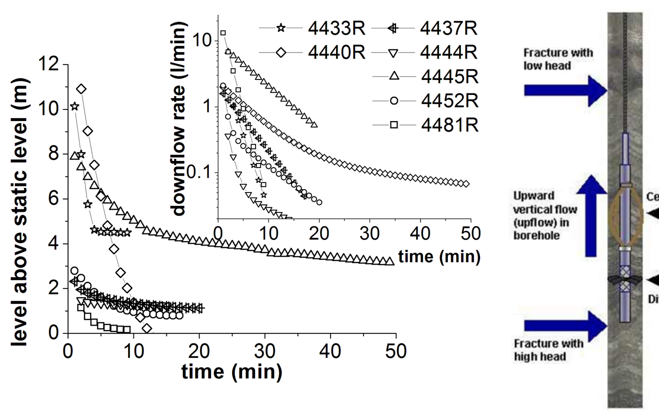
Once CO_2 is injected underground, multiple scales (from micro-pores, to passages, to near-field fractures, and to large-scale faults) of physical and chemical processes are involved. The permeability of a Representative Elementary Volume (REV) at each relevant scale will need to be evaluated using all kinds of methods.



Above: The lattice Boltzmann method can be applied to predict the permeability of an REV of the sample if its geometry is known, e.g., by X-ray CT.

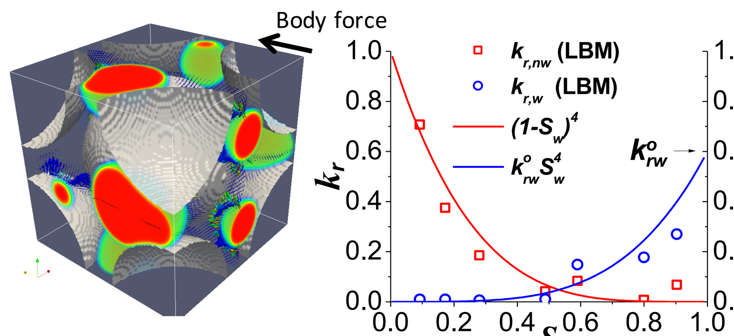


Permeameter-Pycnometer for simultaneous measurement of permeability and connected porosity at elevated T of up to 200 °C and P of up to 250 bar.

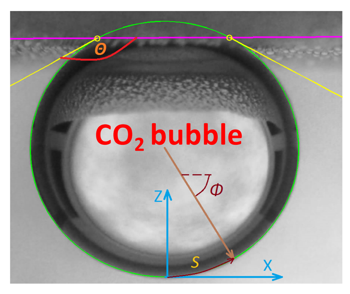


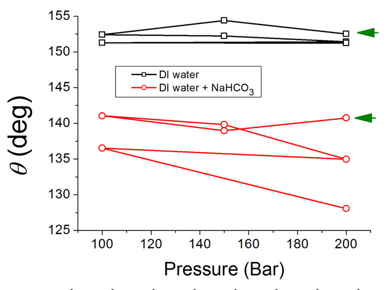
Permeability of a basin-scale REV can be obtained via boreholes.

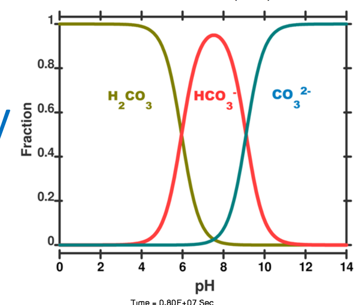
Flow/Heat/Solute Transport (drainage, imbibition, diffusion, convection)



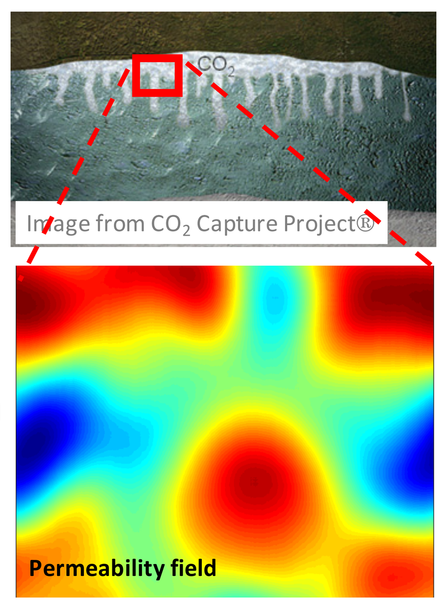
Above: Evaluation of relative permeability using pore-scale lattice Boltzmann method



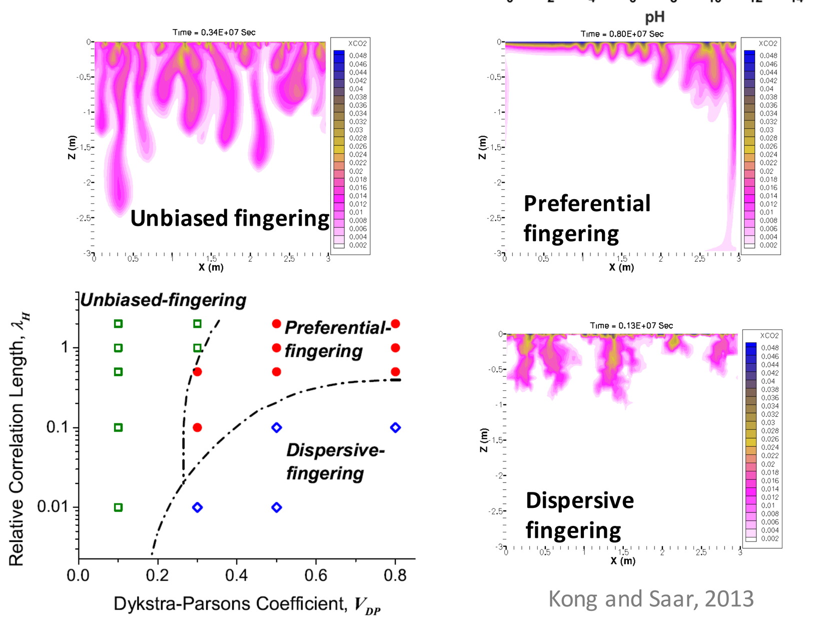




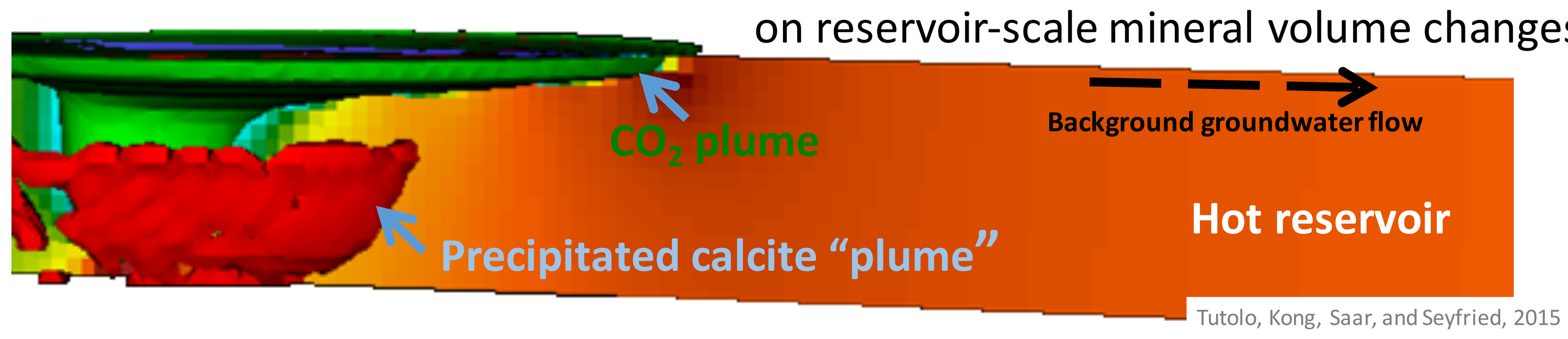
Surface tension and wettability of CO_2 may change with pressure and fluid composition



Right: Permeability heterogeneity also governs CO_2 dissolution patterns in brines saturated formations

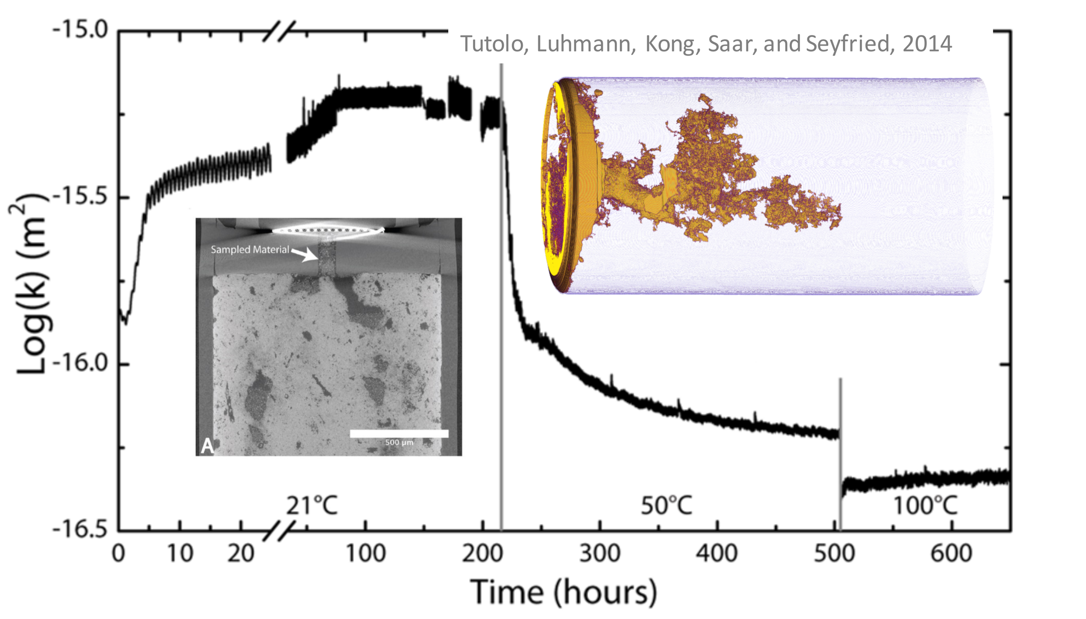


Below : High-performance computing is utilized to examine the coupled effects of cool CO_2 injection into hot reservoirs and their background hydraulic head gradients on reservoir-scale mineral volume changes



Chemical reaction (kinetics)

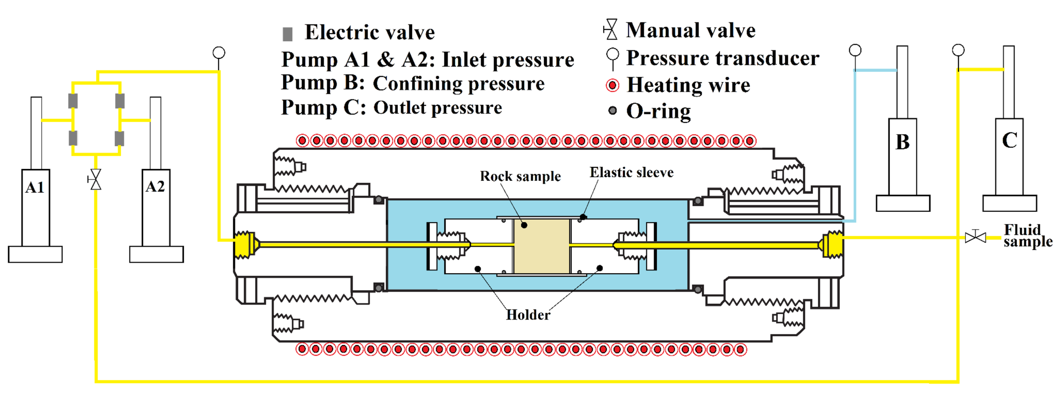
Reservoir properties (such as permeability and porosity) can be modified by geochemical reactions that occur when in-equilibrium fluids (due to heat and/or chemistry) are introduced into otherwise equilibrated geothermal reservoirs, for example during geothermal energy extraction from such reservoirs and subsequent reinjection of cooled fluid.



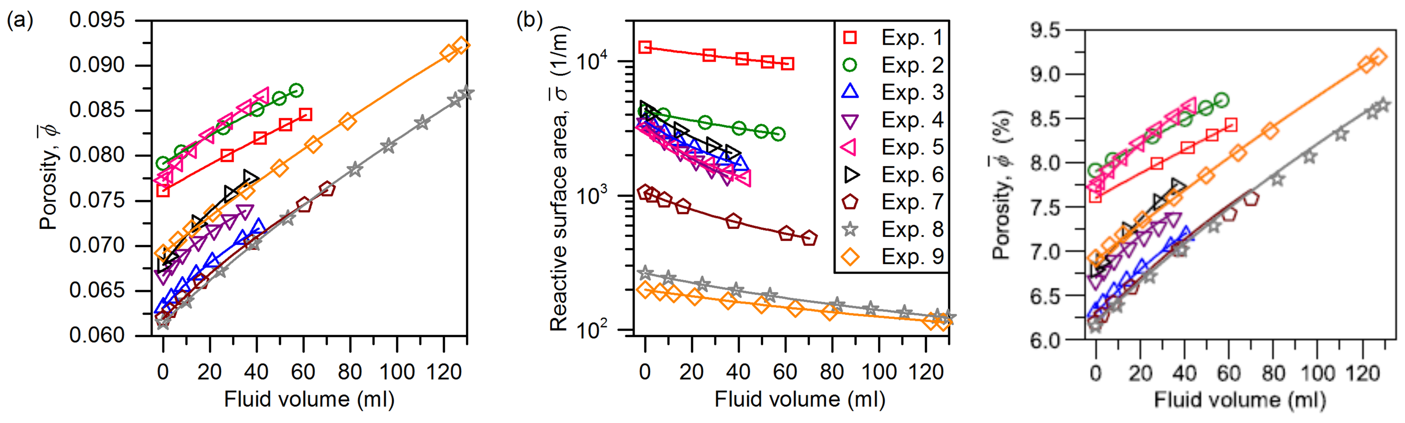
Above: Permeability (k) vs. time during a time series experiment on a dolomite rock core.

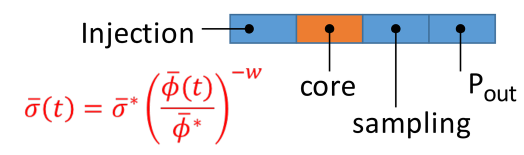
Understanding geochemical processes requires determination of mineral reactivity, including kinetic reaction rate and reactive surface area of minerals. However, mineral surface areas of natural rocks are generally poorly characterized.

Volume registration techniques, combining with 3D imagery, help determine interior structure changes during reactive flow-through experiments.



Left: Hydrothermal flow system designed for single-pass and recycling fluid-rock reaction experiments under formation conditions.





Middle: Porosity and reactive surface area vs. injected fluid volume. A 1D numerical experiment (Above) was set up to validate the fitting model of porosity and reactive surface area.