Task 1.2

Title

Reservoir stimulation and engineering

Projects (presented on the following pages)

Evaporitically-triggered thermo-haline circulation and its influence on geothermal anomalies near unconformities
Julian Mindel

High-resolution temporo-ensemble PIV to resolve pore-scale flow in fractured porous media
Mehrdad Ahkami, Thomas Roesgen, Martin O. Saar, Xiang-Zhao Kong

Fracture process zone in anisotropic rock
Nathan Dutler, Morteza Nejati, Benoît Valley, Florian Amann

On the variability of the seismic response during multiple decameter-scale hydraulic stimulations at the Grimsel Test Site
Linus Villiger, Valentin Gischig, Joseph Doetsch, Hannes Krietsch, Nathan Dutler, Mohammedreza Jalali, Benoît Valley, Florian Amann, Stefan Wiemer

Does a cyclic fracturing process agree with a fluid driven fracture solution?
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Investigation on Hydraulic Fracturing of Granite
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Advances in laboratory investigation of fluid-driven fractures
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Building a geological model for analysis and numerical modelling of hydraulic stimulation experiments
Hannes Krietsch, J. Doetsch, V. Gischig, M.R. Jalali, N. Dutler, F. Amann and S. Loew
Abstract / Background

We hypothesize that downward flow of cooler basin brines may displace and mobilize stagnant, hotter, chemically stratified, and often fracture-hosted brines in sediment-covered basements. Previous conceptual studies postulated fingering as a major hydraulic mechanism allowing for mutually up- and downward flows of brines from the two reservoirs. We assume this is a potential key factor in establishing geochemical anomalies as well as the formation of basin-hosted ore deposits.

We have thus created the prototype of a hydrothermal simulation tool in which faults and fractures can be explicitly represented within a porous matrix. To understand how the geometry of the fractures affects thermo-haline transport, we performed a series of simulations utilizing an accurate equation of state. We designed synthetic geometries to study the propagation of salinity fronts using a simulator based on the CSM++ library (Paluszny et al., 2007), honoring the governing equations for compressible porous media flow and saline transport (Geiger et al., 2006; Weis et al., 2014).

This work is a further step towards modeling thermo-haline convection within realistic representations of discrete networks of thin fractures, a scenario typically observed in basement rocks of deep geothermal systems and at basement/sediment interfaces and related deposits (U, Pb, Zn, and others).

Conceptual Model

The sequence of events remains debatable in some aspects and could be site-specific. In general, we assume that the heavier and oxidizing/acidic new brine originating from the evaporating sea invades the more permeable basin rock and establishes flow.

Conclusions & Outlook

We established slightly more-complex-than proof of concept simulations in a bid to understand the onset of geothermal anomalies in particular circumstances/scenarios. Results show promise by pointing out probable locations with the help of markers, which help track pre-selected conditions. They also serve to highlight the importance of initial conditions, sedimentary ‘obstacle’ permeability, and the numerous possible scenarios that would need to be simulated, carrying out a sensitivity analysis, all of which is still needed prior to drafting any strong conclusions.

Results

We set up two separate fluid-tracking tracers: one for the evaporitic brine and the other aimed at the basement brine. With the help of the tracers, as well as temperature conditions, we set up two markers (shown in teal for Marker 1 and orange for Marker 2 in Figures 3 and 4) so that we may approximate and observe the level of mixing.

References

High-resolution temporo-ensemble PIV to resolve pore-scale flow in fractured porous media

Mehrdad Ahkami, Thomas Roesgen, Martin O. Saar, Xiang-Zhao Kong

Motivation
Fractures are conduits that can enable fast advective transfer of (fluid, solute, reactant, particle, etc.) mass and energy. Such fast transfer can significantly affect pore-scale physico-chemical processes which in turn can affect macroscopic mass and energy transport characteristics. Therefore, it is crucial to determine pore-scale transport properties and then upscale these properties to larger scales. However, only a limited number of experimental studies with sufficient spatial resolution over large Representative Elementary Volumes have been conducted to characterize fluid flow and transport features in fractured porous media.

Methodology

Experimental setup: In this study, 3D-printing technology is employed to manufacture a transparent fractured porous medium to resemble dual-permeability and dual-porosity subsurface formations. Square pillars with a size of 800 μm are 3D-printed to construct fractured porous matrices inside the cell. Parallel to the main flow direction, the cell is divided into two halves: one half being a high-permeability matrix with 300 μm spacing between the pillars and the other half being a low-permeability matrix with 200 μm spacing between the pillars. Moreover, we embed one flow-through fracture and one dead-end fracture within each porous matrix. The permeabilities of two matrices are ~4.0 × 10⁻⁹ m² and ~7.5 × 10⁻⁹ m², respectively.

Due to an in-line illumination configuration, the seeding particles in the fluid cast shadows on a bright background. We then use Particle Shadow Velocimetry (PSV) method to optically resolve the fluid flow.

Temporo-ensemble PIV: Classical PIV method generally employs a relatively large interrogation window and can thus not resolve pore-scale micro-features of fluid flow. In this study, we introduce a new high-resolution PIV method that we term "temporo-ensemble PIV" that can reduce the size of the interrogation window down to ultimately one single pixel. Such a small interrogation window size enables substantially increased spatial resolutions of velocity vectors per unit area in 2D (or unit volume in 3D), allowing delineations of small, pore-scale flow features that are part of a much larger Field of View (FOV). We apply our new method to visualize a 2D fluid flow in a 3D-printed, fractured porous medium.

Results

Average Velocity magnitude, average longitudinal velocities, and average lateral velocities of low- and high-permeability matrices as well as embedded dead-end and flow-through fractures.

Conclusion

- The presented approach can resolve high-resolution 2D velocities in engineered porous media with various levels of heterogeneities.
- Compared to standard PIV methods, our approach preserves high spatial resolutions of velocity vectors, while enabling a large field of view.
- The resulting high-resolution velocity vectors delineate detailed 2D fluid flow structures in various regions of the 3D-printed fractured porous medium. This enables the analysis of various flow interactions, such as those between porous matrices, with different permeabilities and/or porosities, or between fractures and their surrounding porous matrices.
- Our work facilitates experimental investigations of pore-scale physico-chemical processes, with implications for various industrial and scientific fields such as the oil and gas industry, hydrogeology, geothemics, geochemistry.
Fracture process zone in anisotropic rock

1. Motivation

This experimental work aims at assessing the dependency of the fracture process zone (FPZ) on the angle between the fracture growth direction and the anisotropy (foliation) for the Grimsel Granodiorite. Samples were collected from cores of the In-situ Stimulation and Circulation project (Amann et al., 2018) and tested using a notched semi-circular bending (NSCB) method. The foliation consists essentially of aligned phyllosilicate minerals.

2. Methods

Three-point-bending tests on notched semi-circular specimens (Kuruppu et al., 2014) were performed. The deformation field of the specimens was monitored using Digital Image Correlation (DIC).

- 15 specimens are tested with 2 different configurations (0°, 90°)
- A quasi-static load was applied with controlled displacement rate of 0.1 mm/min
- Specimens are colored in white and afterwards fine sparkled with an air brush (Figure 2B)
- Stereo Digital Image Correlation (DIC) is used to get the strain field with a frequency of 4 Hz during the tests (Cam 1 + 2)

3. Localized FPZ at peak load

Figure 3: The contours of maximum principal strain showing the FPZ shape at peak load for the configurations φ = 0° and 90°. The average length to width ratio is L/W = 2.

The fracture process zone is larger in size when the crack grows along the foliation compared to the case it propagates normal to the foliation. The ratio of the FPZ size in two directions is L'/L = φ/90° ≈ 1.2. The fracture process zone is anisotropic in terms of size.

4. Width of the FPZ and critical strain

Figure 4: The calculation of the FPZ width based on localization of strain components (σxx,σyy,σxy) given in millistrain (mm/m) and the jump of displacement u for φ = 0° and 90% of pre-peak load. The width of the FPZ corresponds to the width of the shaded region and measures w = 5.8 mm for φ=0°. The width of the FPZ is picked using a criterion of averaging (ZOA) at 70% of pre-peak load. According to the displacement jump, the normal values of displacement imply movements to the left (Dutler et al., 2018).

It is noteworthy that according to the values of tensile strength and Young’s moduli, a critical tensile strain of about 270 and 350 micro strains are obtained for the principal directions normal and parallel to the foliation.

5. The size of the FPZ

- In both configurations φ = 0° and φ = 90°, the average length to width ratio L/W = 2.
- The fracture process zone is larger in size when the crack grows along the foliation compared to the case it propagates normal to the foliation. The ratio of the FPZ size in two directions is L'/L = φ/90° ≈ 1.2. The fracture process zone is anisotropic in terms of size.
- The reason for a bigger FPZ along the foliation may be the preferred direction of micro-crack in such direction. Since the micro-cracks are oriented in the direction of crack growth, their activation and propagation can lead to a wider process zone.
- There is a negative correlation between the length and the width of the FPZ in both configurations. One can explain this trend by considering that the energy dissipated via micro-cracking is a material property, which is constant.

References

On the variability of the seismic response during multiple decameter-scale hydraulic stimulations at the Grimsel Test Site


Motivation

Predicting induced seismic activity or even occurring maximum magnitude events for hydraulic stimulation operations, e.g. used to increase transmissivity in reservoirs for deep geothermal systems (EGS), is an extremely challenging task. However, estimating at least induced large magnitude events is indispensable when it comes to the hazard assessment of possible new EGS sites. The main reason for the difficulty of the task is the limited knowledge of geological conditions as well as the in-situ stress state at depth. When it comes to hydraulic stimulation, one distinguishes between hydraulic fracturing (HF), where an induced fracture is propagated through the rock and hydraulic shearing (HS), where slip is induced on pre-existing fractures or faults. During stimulation, the two end-member mechanisms HF and HS occur in a complex interplay (see also talk by H.Krietsch on Friday, 11.45). The driving force, however, for HS on pre-existing structures are tectonic stresses, which hold a high potential for inducing large magnitude seismic events, if the fracture or fault is well oriented to the stress field.

In order to find strategies to mitigate large magnitude events and to better understand the seismo-hydro-mechanical coupled phenomena involved in hydraulic stimulation we performed six HS and five HF experiments in-situ at a decameter scale. In this contribution we focus on the six HS experiments. All experiments were performed in the framework of the In-situ Stimulation and Circulation (ISC) experiment at the Grimsel Test Site (GTS) (Amann et al., 2018).

Methods

The 6 hydraulic stimulation experiments were performed in a 20 x 20 x 20 m crystalline rock volume, in which the stress state and geology was exceptionally well characterized (Figure 1). The experiments targeted ducitic shear zones (referred to as S1) as well as brittle-ductile shear zones (S3). These S3 shear zones contain a highly fractured zone in the East. A standardized injection protocol was used for the six HS experiments. In total 1’000 litres of water was injected in every HS experiment. Aside of the high-resolution deformation- and pressure-monitoring networks, a highly sensitive acoustic emission monitoring network was installed (Figure 2).

Results

Table 1 shows an overview of the cumulative number of located events (orange bars) and transmissivity changes (blue bars) of the six HS experiments. The experiments are sorted according to the stimulated structure. Based on the far-field stress state, structures with S1 direction exhibit a larger slip tendency, compared to structures with S3 direction. Note also, that final transmissivities are in the same order of magnitude and generally controlled by S3 structures.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>In-Hydrofracture</th>
<th>Final transmissivity</th>
<th>FMD</th>
<th>HS5</th>
<th>HS4</th>
<th>HS3</th>
<th>HS2</th>
<th>HS1</th>
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<tr>
<td>b</td>
<td>afb</td>
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<tr>
<td>HS5</td>
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<td>-2.72</td>
<td>H5</td>
<td>1.35</td>
<td>2.81</td>
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<td>-4.93</td>
<td>H4</td>
<td>2.5</td>
<td>4.93</td>
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<tr>
<td>HS3</td>
<td>2.5</td>
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<td>H3</td>
<td>2.5</td>
<td>4.93</td>
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<tr>
<td>HS2</td>
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<td>-2.8</td>
<td>H2</td>
<td>2.5</td>
<td>4.93</td>
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<td>-2.8</td>
<td>H1</td>
<td>2.5</td>
<td>4.93</td>
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</table>

In Figure 3, frequency magnitude distributions (FMD’s) along with b- and afb-values (activation feedback parameter. Mignan et al., 2017) of all HS experiments are shown. The amplitude magnitudes M0 are presented from amplitudes recorded with the uncalibrated AE receiver (Figure 2) and adjusted to absolute magnitudes Mv estimated from AE receiver/accelerometer pairs installed on a tunnel level. Mv for all experiments was estimated at Mv = 2.8.

Discussion

A highly variable seismic response (number of seismic events, a- and b-values) is observed from six 1’000 l water injections into a small 8’000 m³ crystalline rock volume with variable geology following a standardized injection protocol. Furthermore, there is a tendency that an increased seismic response does not necessarily lead to a higher transmissivity increase. But, out of a far-field stress perspective: a higher slip tendency leads to a higher transmissivity increase.

Furthermore, we can observe that the maximum induced magnitude during the stimulation experiments at Grimsel (Figure 4) does not exceed McGarr’s (2014) formulation of the upper bound of the seismic moment of an induced seismic event which is proportional to the total volume of injected fluid.

These outcomes lead to the following questions we would like to tackle in future work:

- What is causing these high variabilities? Is the geology (e.g., increased crack density) the driver for an increased seismic response?
- What can we learn from this scale? Are these findings relevant to the field scale?
- What does this high variability tell us for the predictability of induced seismicity?
1. Motivation

Observation of two stick-split like behaviour in the pressure response interval PRP13 during the hydraulic fracturing experiment as part of the In-situ Stimulation and Circulation (ISC) project executed in the Grimsel Test Site.

Does a cyclic fracturing process agree with a fluid driven fracture solution?

Nathan Dutler*, Benoît Valley, Valentin Gischig, Linus Villiger, Hannes Krietsch, Joseph Doetsch, Reza Jalali & Florian Amann

2. Stick-split mechanism

1. Fluid filled tip building up pressure and increase aperture
2. Tensile failure occurs and pressure drops
3. Fracture closing due to pressure drop brings fluid to the tip
4. Fluid pressure builds up and aperture increase with fluid at the tip

The FBG sensor in FBS2 at 3.7 m indicates a change in behavior (flattening) at the time the seismic event a) occurs. Shortly afterwards, the interval PRP13 starts to react and at the same time the beforementioned FBG sensor show a slight decrease in tension and stabilizes again.

The new fracture was observed at a borehole depth of 20 m by the distributed strain system using optical fibers.

Event b) and c) occur on the other site of the propagating fracture compared to the events a), d) and e).

Highest increase in pressure is observed during shut-in phase without any located seismic event.

The located seismic events during the two episodic fracturing cycles indicate an asymmetric episodic fracturing.

3. Fluid driven fracture solution

The problem can be stated with the following governing equations:

- Elasticity equation
- Lubrication approximation of the non-linear Reynold’s equation
- Boundary conditions on both moving fronts:
  - Crack front: \( w(x_0, t) = 0 \), \( K(x_0, t) = K_{cr}, x_0 \in C_c(t) \)
  - Fluid front: \( p_f(x_0, t) = 0 \), \( \bar{V}(x_0) = \frac{2a}{(a + c)^2}, x_0 \in C_f(t) \)

A scaling analysis revealed that the propagation of a penny-shaped fracture in an impermeable medium is characterised by two time-scales and can be presented by a parametric space \( OMK \) with three vertices representing a small-time \( O \), intermediate-time \( M \) and large-time \( K \) self-similar solution (Bunger & Detournay, 2007).

The energy dissipation mechanism corresponds either to the viscous fluid flow (M-vertex) or to the creation of new surfaces (K-vertex). The new length scale for the fluid lag is:

\[
\ell = \frac{E}{K' \mu'} = 1.3 \quad \text{with} \quad E' = \frac{E}{1 + \epsilon}, \quad K' = \frac{2(1 + \mu)}{\mu} K_{cr}, \quad \mu' = 12 \mu
\]

using \( E = 30 \text{ GPa}, \nu = 0.25, K_{cr} = 0.8 \text{ MPa} \sqrt{m} \) and \( \mu = 1.2 \times 10^{-3} \text{ Pa s} \), \( V = 1 \text{ m/s} \)

Assuming the fracture radius is \( R = 4 \text{ m} \). This leads to a ratio \( \frac{\ell}{R} = 0.3 \) which corresponds to a viscosity-dominated case.

If \( K(x_0, t) < K_{cr} \) during episodic fracturing, the outer boundary does not move until the \( K(x_0, t) = K_{cr} \) is fulfilled. This has a direct influence on the propagation velocity, which decreases when it is averaged over time. We can conclude that the best approximation for the episodic fracturing is a viscosity-dominated case.

Further considerations:

- An asymmetric fracturing behavior, where \( K(x_0, t) = K_{cr} \) changes at the fracture boundary needs to be numerically modeled.
- Asymmetric fracturing is often observed, but what is the driving mechanism behind this effect?

References


Investigation on Hydraulic Fracturing of Granite
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Motivation and Goals
Enhanced Geothermal Systems (EGS) constitute a large renewable source for electricity production. Hydraulic fracturing permits to increase the permeability of the rock in a naturally fractured environment.

→ Hydraulic stimulation in deep rock to reactivate existing fractures by injecting pressurized water
→ Understand better the mechanisms of hydraulic fracturing for EGS: induce shear failure in Barre Granite

Methods
The interaction between hydraulic fractures and pre-existing, non-pressurized flaws is investigated experimentally. The experiments are performed on prismatic specimens of Barre Granite containing two pre-cut flaws under uniaxial or biaxial external load. Fluid is injected in the flaw until failure. Pressure and injected fluid volume are recorded. The crack development is captured with a high-speed camera and a high-resolution camera. Shearing is identified under different flaw geometries and loading conditions.

Analytical investigation on hydrofracturing and hydroshearing
The type of failure (i.e. shear or tensile) is defined by the location of the intersection of the critical Mohr circle with the failure envelope. The evolution of the stress state around a pressurized opening is observed while the external stress and the internal pressure increase. The tangential stress is determined by an analytical solution (Pollard and Fletcher, 2005) and the normal stress corresponds to the internal pressure.

From hydrofracturing to hydroshearing
Tensile failure is observed in the uniaxial experiments whereas shear failure is observed within the biaxial experiments: dilatancy, en echelon crack patterns and sliding. Hydroshearing occurs with a different test procedure corresponding to an increase of vertical stress and a constant internal pressure leading to the intersection of the Mohr circles with the linear part of the failure envelope (Fig. 4).

Conclusion
The experiments have shown that:
→ Visible cracks propagation and crack patterns are highly influenced by the large grains in Barre Granite
→ Micro-cracks develop in the form of white areas in the shear fracture process zone
→ Hydroshearing is observed under a combination of biaxial external stress and hydraulic pressure.

The identification of the conditions leading to either hydrofracturing or hydroshearing will allow to understand better the difference between both mechanisms and its effect on induced seismicity through acoustic emissions measurements

References

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Advances in laboratory investigation of fluid-driven fractures

Thomas Blum and Brice Lecampion
Geo-Energy Laboratory, EPFL

1. Introduction

Wide range of applications:

- oil and gas extraction
- geothermal energy recovery
- CO2 sequestration

Need for models to:

- efficiently fracture the targeted formation
- better understand the physics of fluid-driven fracturing
- get an estimate of fracture size and shape during growth

Scaled laboratory experiments:

- allow to validate theoretical predictions
- provide datasets under controlled conditions
- include physical limitations

2. Laboratory setup

- cubic geologic specimen, 250 x 250 x 250 mm
- reaction frame: confining stresses of up to 25 MPa along each axis
- independently controlled pairs of flat-jacks to apply confining stresses
- high-pressure injection pump: flow rate from 1 µL to 90 mL/s
- notch at the bottom of the wellbore for localized initiation
- experiment duration on the order of minutes to a few hours

3. Acoustic monitoring

- 64 piezoelectric transducer arranged in 32 sources and 32 receivers
- mix of compression and shear in order to use both P- and S-waves
- sequential excitation of all 32 sources every few seconds for snapshots of the acoustic properties during the fracture propagation

Schematic of the transducer layout and different arrival modes.

- R - reflected signal: fluid content of the fracture
- T - transmitted signal: fracture thickness
- D - diffracted signal: position of the fracture tip.

Transmission coefficient through a planar fluid layer of thickness $h$:

$$T(\omega, h) = \frac{(1 - r^2_{ff}) \exp(i\alpha)}{(1 - r^2_{ff}) \exp(2i\alpha)}$$  \hspace{1cm} (1)

where $\omega$ the signal frequency; $r_{ff} = \frac{z_f}{z_c}$, $z_r = \frac{\rho_f c_f}{\rho_c c_s}$; $\rho_c, \rho_f$ are the densities of the solid and fracturing fluid, respectively; and $c_s, c_f$ the P-wave velocities of the solid and fracturing fluid, respectively.

4. Work progress

- Investigations of Carmen slate: highly bedded anisotropic material, relevant for fracture propagation normal to the bedding plane. Currently issues with notching and fracture initiation.
- Fractures in Carrara marble: propagation in fine-grained material, comparison between toughness- and viscosity-dominated regimes of propagation.

5. Injection in Carrara marble

- No vertical confining stress
- 2 MPa horizontal stresses
- Injection fluid: glycerol, $\eta = 0.6$ Pa.s, flow = 0.02 mL/min

Analysis of transmission measured with one pair of transducers, placed opposite from one another:

6. Conclusions

Extensive analysis of elastic wave data to follow soon for a diverse set of geologic specimens and experimental conditions.
Building a geological model for analysis and numerical modelling of hydraulic stimulation experiments

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Motivation

We build a geological model (Krietsch et al., 2018a) for the in-situ stimulation and circulation experiment (Amann et al., 2018). The model is used for:
- High resolution of geological visualization
- As a baseline for a DFN
- Hydraulic characterization
- Geophysical characterization
- Analysis and interpretation of experimental data
- Numerical modelling of the experiment

Geochemical mapping

The test volume is bound by two tunnels and intersected by 15 boreholes. The mapping included mapping of the tunnels using geodetic measurements and panorama images, pictures of the wet and dry cores, and acoustic and optical televiewer borehole logging. Fig. 1 shows a summary of the mapping approach including the interpolation between tunnels and boreholes.

Geological structures

A total of 5 shear zones (3 ductile and 2 brittle-ductile) were mapped. Various brittle fractures (partly open or biotite covered), a pervasive foliation, quartz bands and minor meta-basic dykes were mapped, too (Fig. 2).

Shear zone interpolation steps

- Mapping all shear zones along tunnels and boreholes
- Definition of shear zone sets
- Triangulation between coordinates of each set, neglecting local orientations.
- Third order polynomial interpolation including third order orientations (Fig. 3).

Technical validation using geophysical methods

Seismic tomography between two tunnels revealed a low velocity zone between two S3 shear zones that correlates with a mapped highly fractured zone (Fig. 4).

Summary/Outlook

The geological model represents a high resolution geological baseline visualization of the test volume. It can be used for the construction of a DFN/HydroDFN using e.g., Golder’s FracMan, and can be used for setting up a grid for numerical modelling of the stimulation experiment.

References:

Amann et al., 2018 – The seismo-hydro-mechanical behavior during deep geothermal reservoir stimulations: open questions tackled in a decameter-scale in-situ stimulation experiment Solid Earth, 9, 115-137
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