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Long-term evolution of fracture permeability in slate as potential target reservoirs for EGS

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MEET Project WP5, Task 5.1: Characterization of the four Variscan Reservoir types:

(6) Long-term sustainability of fractured rock system based on laboratory experiments (GFZ)

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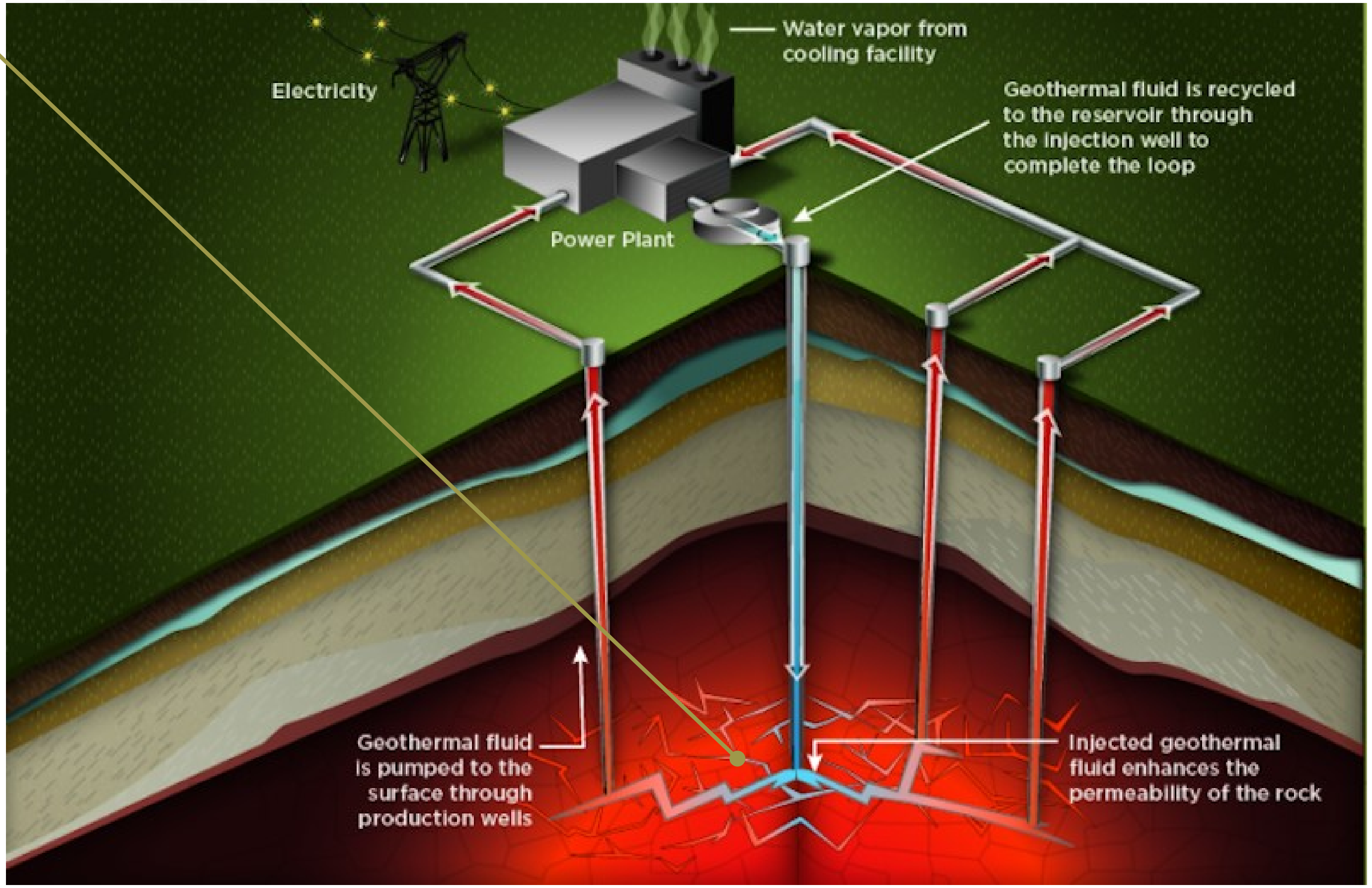
The success of an EGS

Properties:
- Geological properties (e.g., faults, stress field, rock types)
- Thermophysical rock properties (e.g., thermal conductivity, heat capacity)
- Hydraulic properties (e.g., fracture permeability)
- Fluid properties (e.g., density, viscosity, ions)

Indicators that guarantee the success of an EGS project:

reservoir aspects
- Temperature (depends on area and depth)
- Flow rate (can be controlled and enhanced!)



EGS diagram (source: DOE, Geothermal Technologies Program)

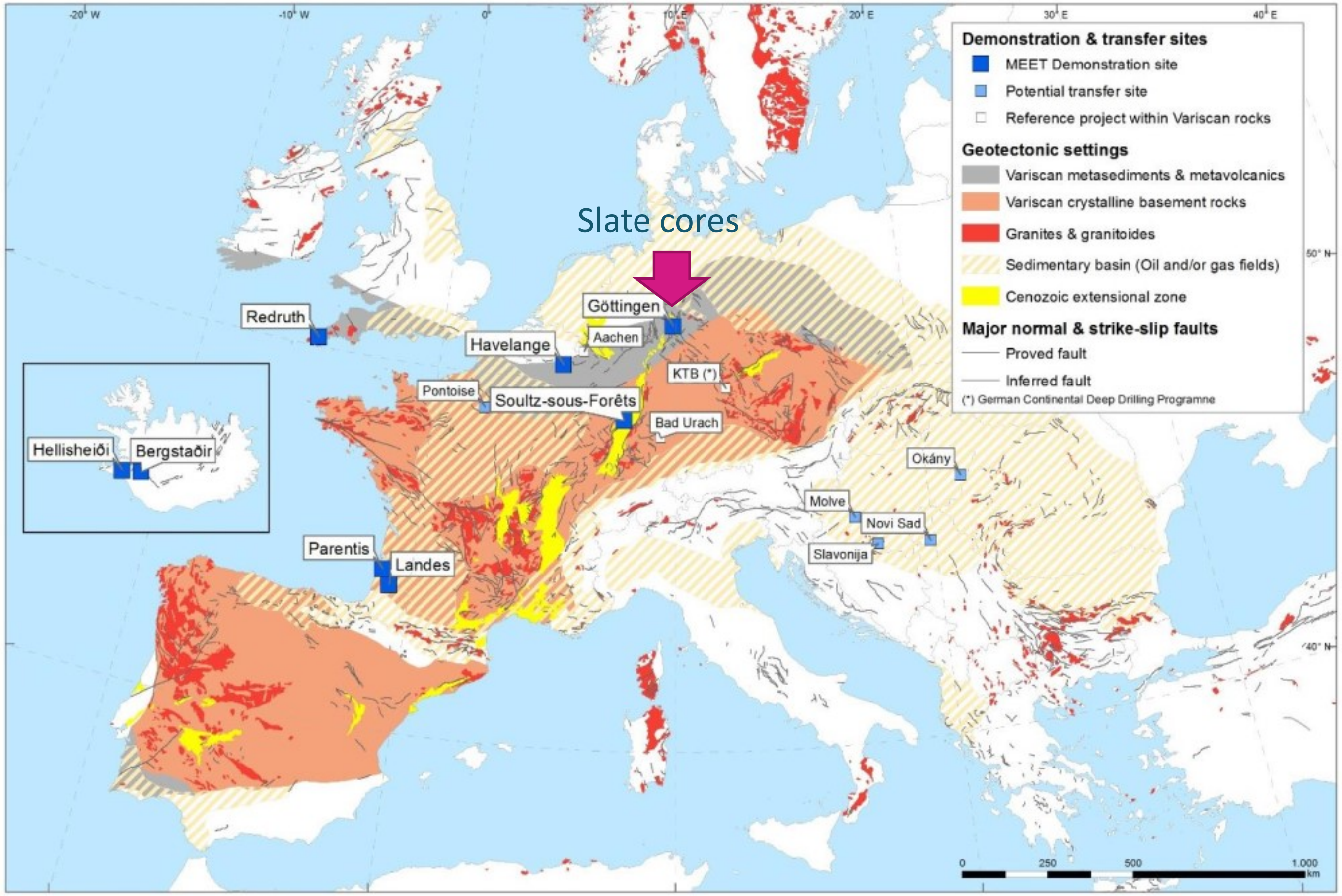
Geographical diversification for EGS

Granitic/crystalline rocks

Sedimentary rocks

➔ **Metamorphic rocks*** (this study)

Enlarge potential areas for installation of new capacities.
High/medium temperatures can be found in various contexts and their production can be enhanced by EGS.



Sources of geological datasets:
Asch, K. (2005): IGME 5000: 1 : 5 Million International Geological Map of Europe and Adjacent Areas. BGR (Hannover).
U.S. Geological Survey World Petroleum Assessment 2000: U.S. Geological Survey Digital Data Series DDS60: http://greenwood.cr. usgs.gov/energy/WorldEnergy/DDS-60

International Geological Map of Europe and Adjacent Areas. BGR (hannover)

Scientific / engineering problems

An abundant heat source (energy)

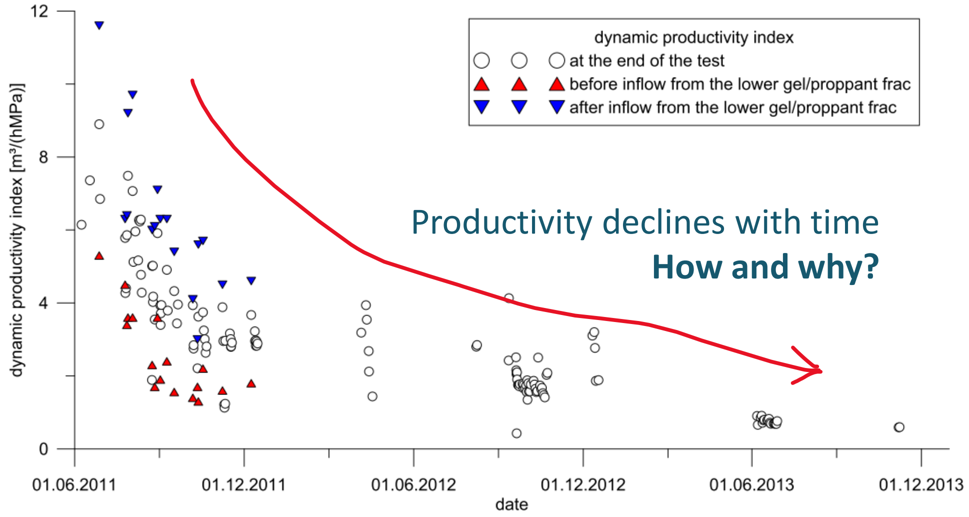
Fluid circulations (media for heat extraction)

Permeable pathways (fracture networks within target reservoirs)

Sustainability!! (the success of the project and investment)

- **Fracture closure***
- Scaling
- Corrosion

Deep Geothermal Reservoir Groß Schönebeck



Blöcher et al. 2016 (Geothermics)

Main task: demonstrate long-term fracture sustainability of fractured rocks based on laboratory experiments.

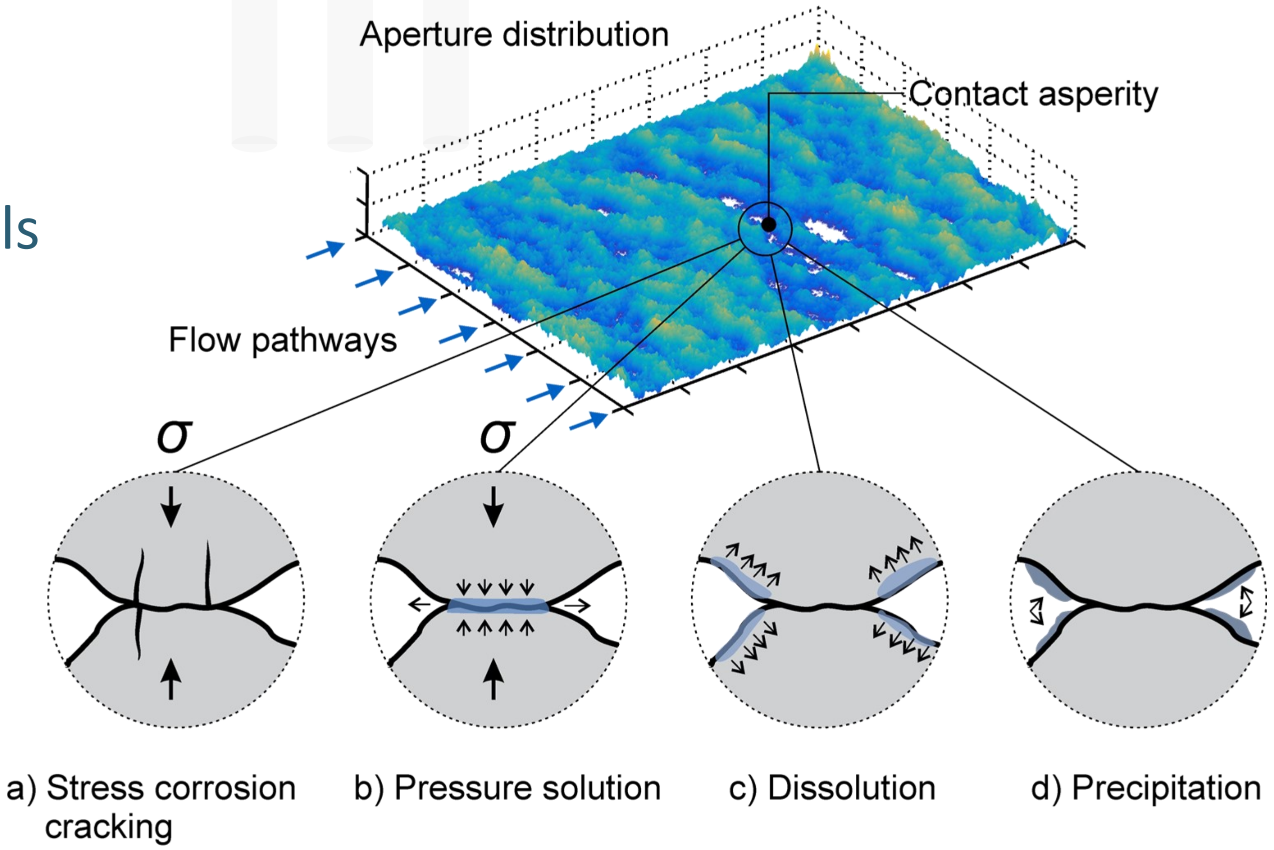
laboratory time scale (weeks & months) vs. in-situ time scale (years & decades)

Better understanding

Potential mechanisms

Fracture sustainability mediated by fluid-rock interactions

- Stress corrosion
- Pressure solution
- Dissolution at free walls
- Mineral precipitation



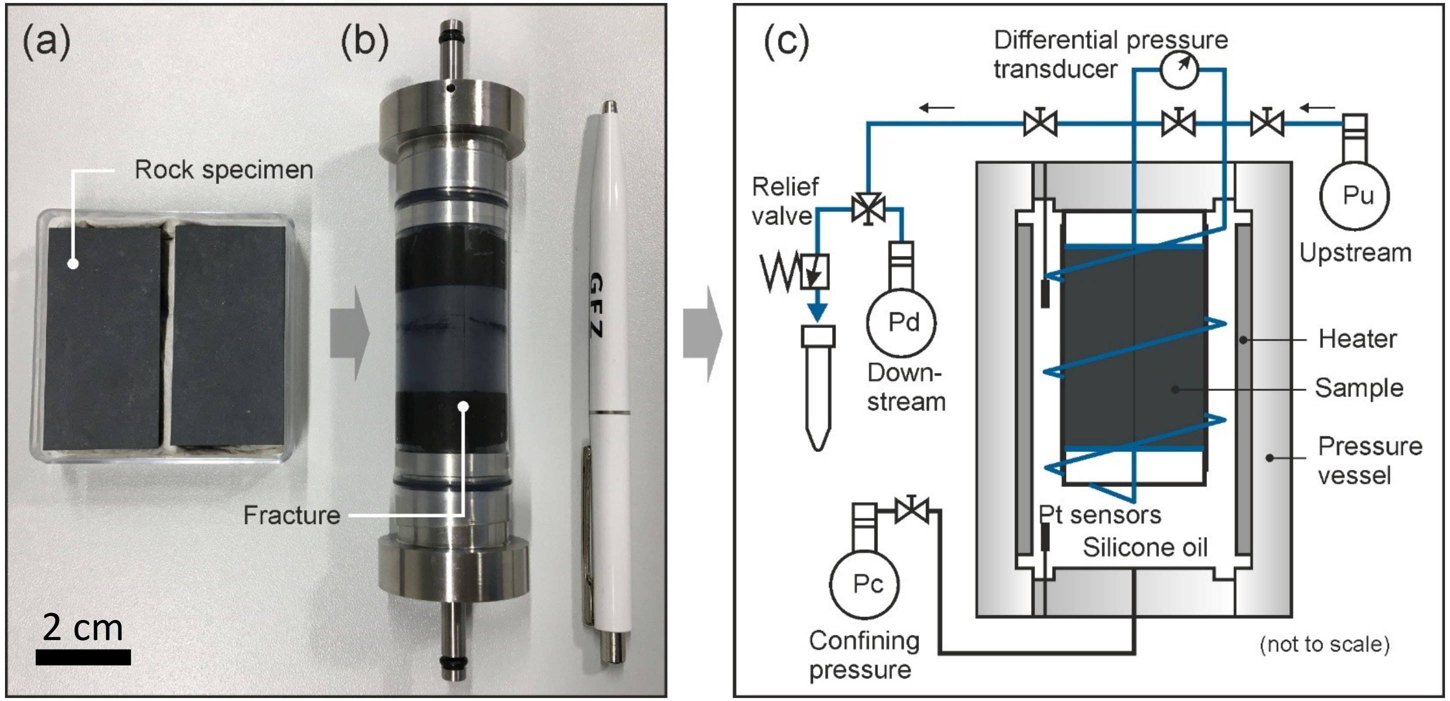
Experimental Procedures

Saw-cut slate fractures

Flow-through experiments were conducted to investigate the effects of ***flow***, ***temperature***, and ***time-dependent fluid-rock interactions*** on fracture permeability.

Identical fracture samples:

SM1 → 90 °C
SM2 → 70 °C



Workflow for the long-term experiments conducted at GFZ. Fractured slate samples (a) are assembled (b) and tested at simulated reservoir conditions (c).

Experimental Tasks

Three main tasks:

1. Initial continuous flow tests (the influence of flow dynamics)
2. Cyclic temperature up to 70 °C or 90 °C (simulation of production and injection temperatures)
3. Intermittent flow-through tests for > one month (effects of chemical reactions)

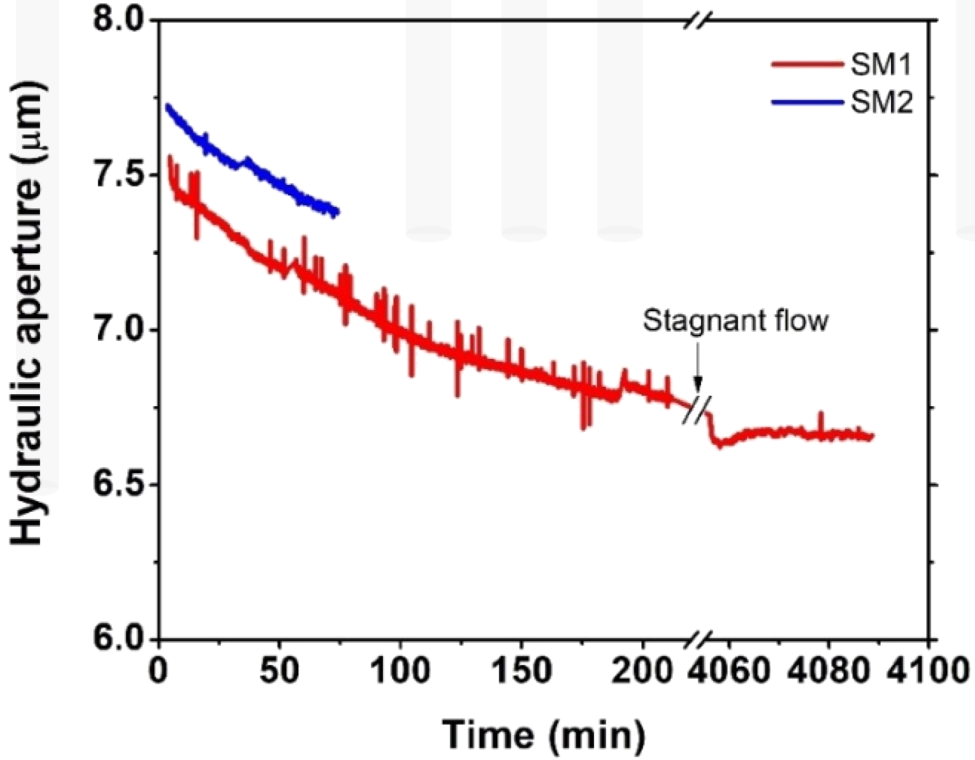
Flow-through measurements

- Pc: **10** MPa, Pp: **1** MPa
- Fluid type: **deionized water**
- Time interval of stopped flow: 6 days
- **Hydraulic aperture** is determined based on the “cubic law”.
- Effluent samples were measured with ICP-OES

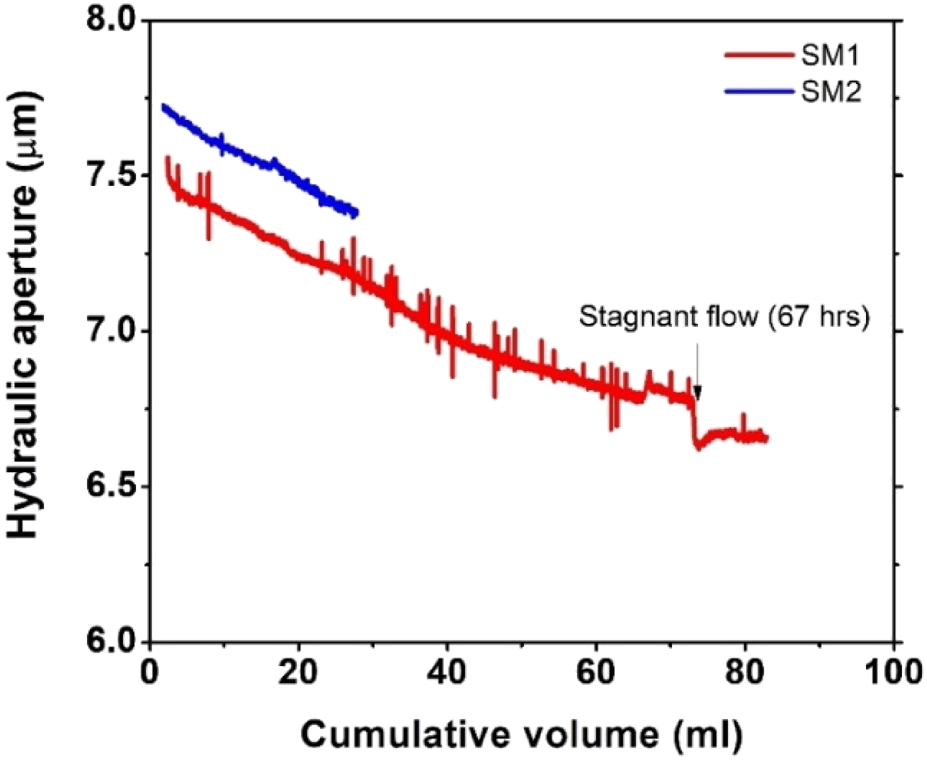
$$a_h = \sqrt[3]{\frac{12Q\mu L}{W \cdot \Delta P}}$$

1. Continuous flow-through tests at room temperature

Hydraulic aperture vs. Time

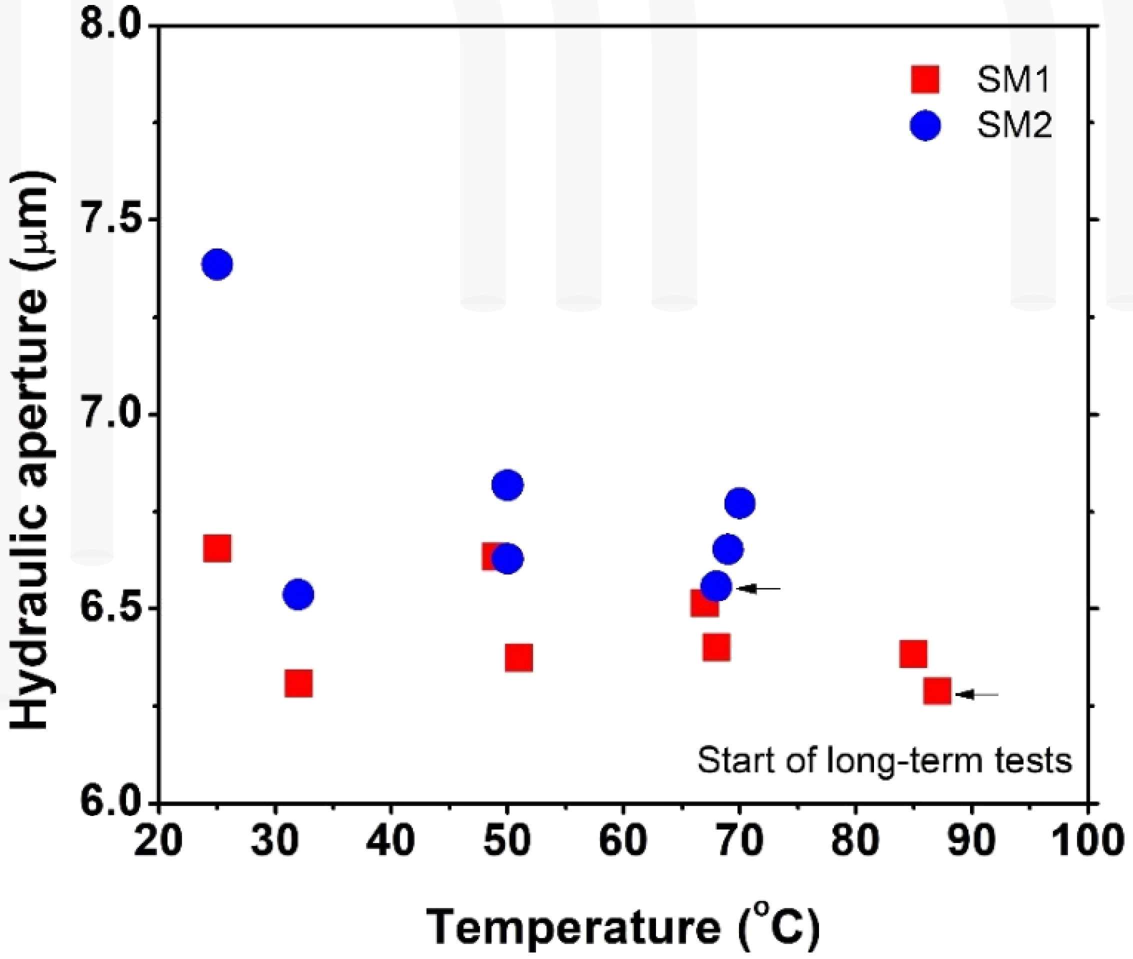


Hydraulic aperture vs. Cumulative volume



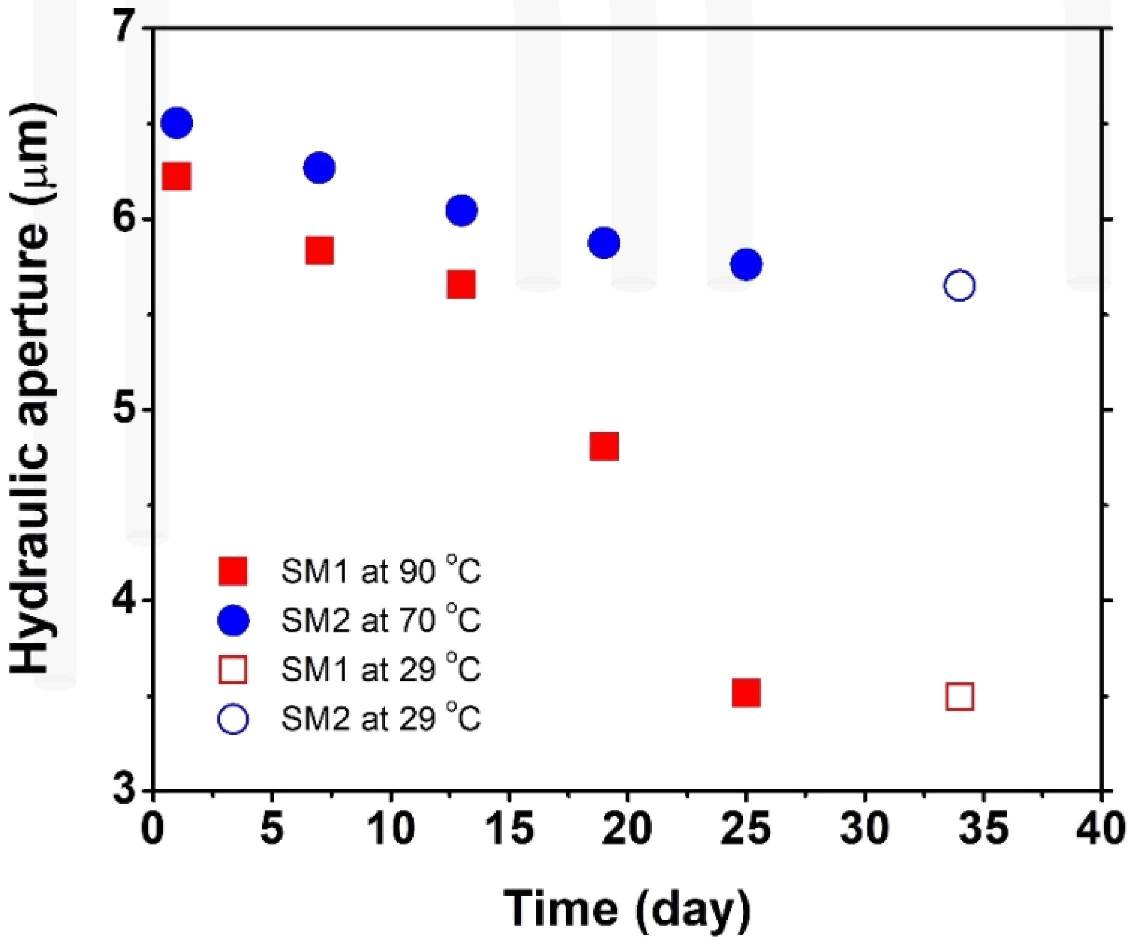
- Sample permeability first continuously decreases after pressurization, but progressively converges within about three days.

2. Cyclic temperature up to 70 °C or 90 °C



- Increasing temperature leads to an additional permeability decline that is irreversible.

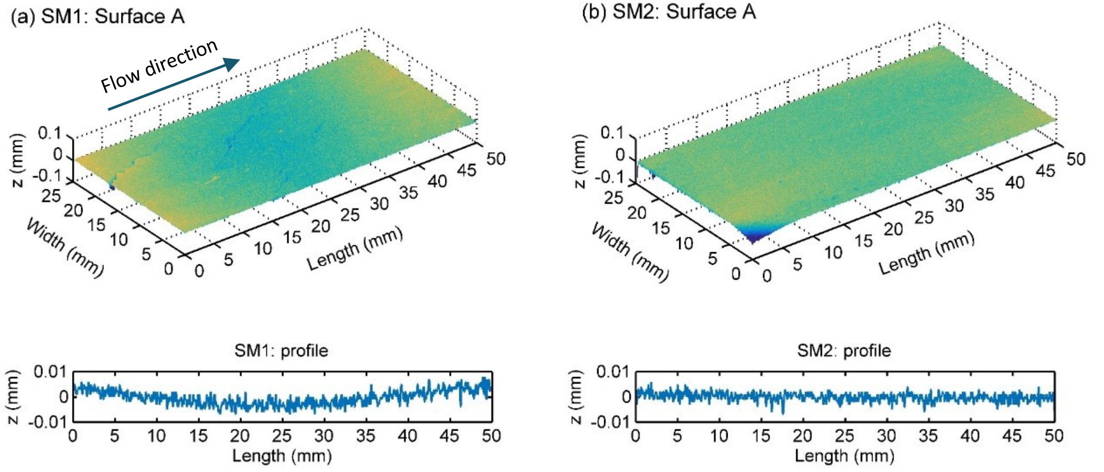
3. Time-dependent intermittent flow



- Time-dependent permeability reduction is more pronounced at 90 °C in comparison to that at 70 °C, but both samples show a negligible decline with time at room temperature after cooling.

Topographies of the grinding fracture surfaces before and after the experiments

Before

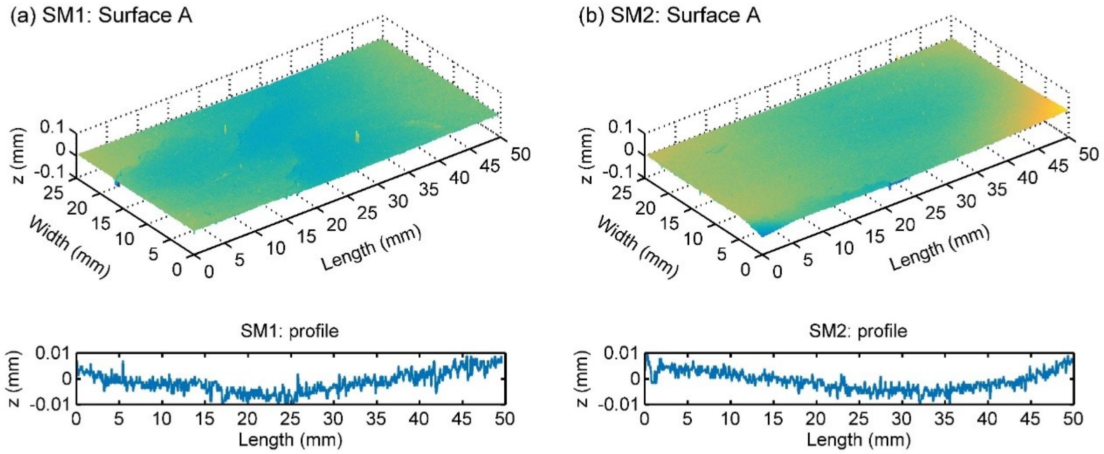


Sample	Max diff. (µm)	Average mean (µm)	Root-mean-square (µm)
SM1_SurfaceA	41	2.3	2.9
SM2_SurfaceA	70	1.4	2.1

Initial Hydraulic aperture a_h at room temperature (25 °C)

- SM1: 7.48 µm
- SM2: 7.72 µm

After



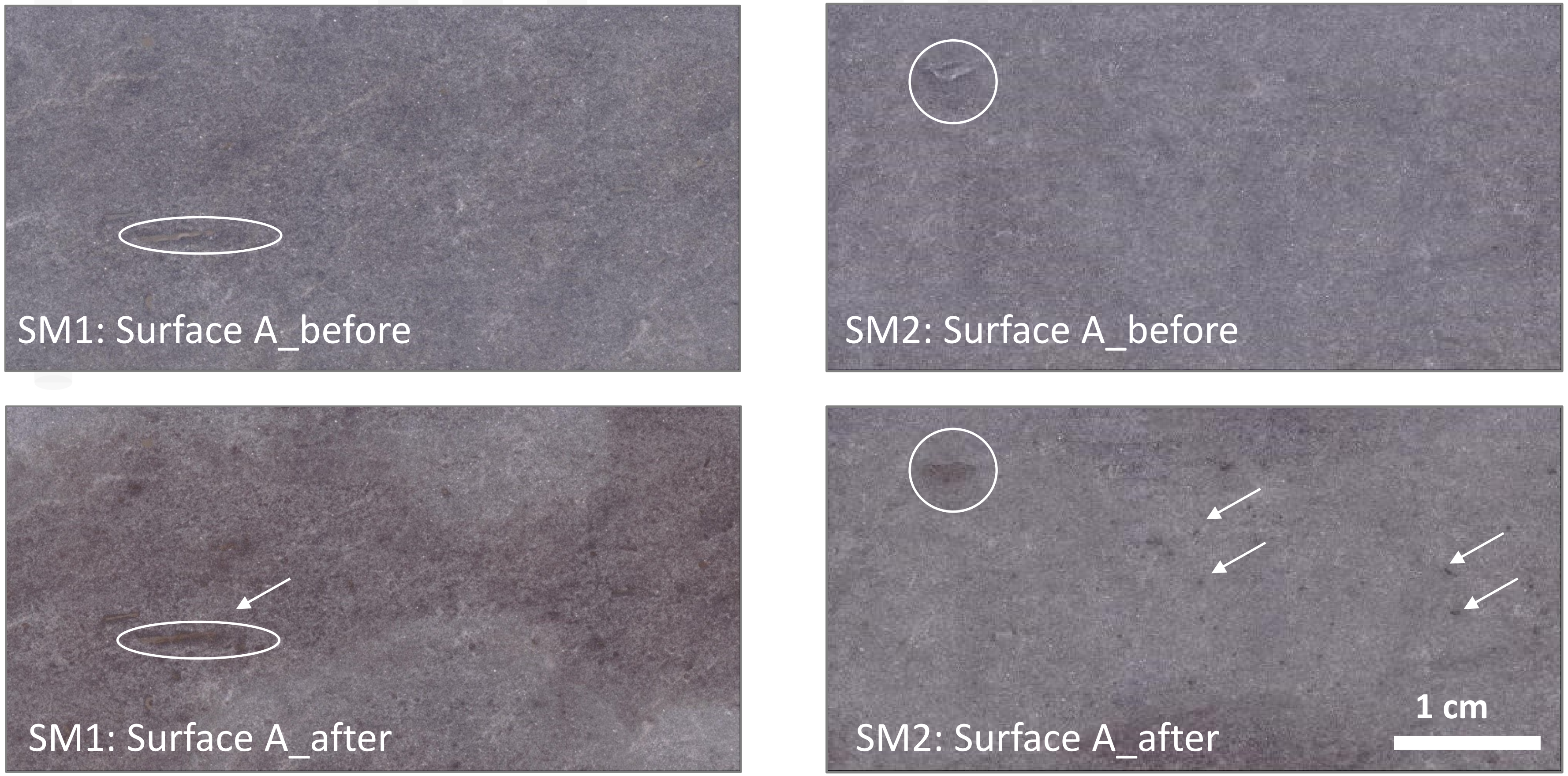
Sample	Max diff. (µm)	Average mean (µm)	Root-mean-square (µm)
SM1_SurfaceA	45	3.5	4.3
SM2_SurfaceA	35.1	3.5	4.5

Final Hydraulic aperture a_h at room temperature (29 °C)

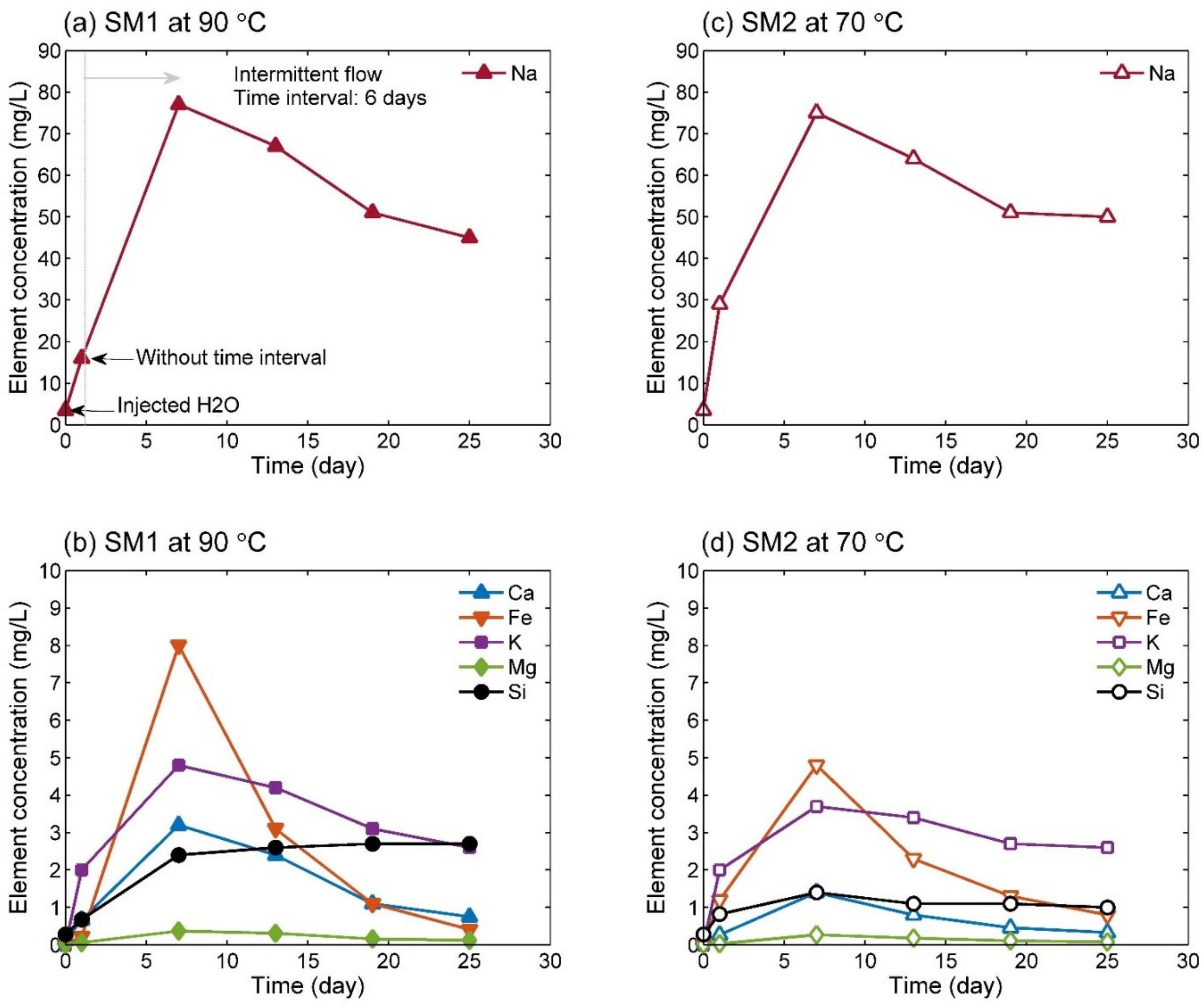
- SM1: 3.49 µm (up to 90 °C) -53%
- SM2: 5.65 µm (up to 70 °C) -27%

Images of fracture surfaces

- For SEM analyses



Fluid chemistry analyses



GFZ geochemistry lab

Minerals	Content (%)	Composition	Ions
Quartz	22.70	SiO2	Si
Calcite	8.34	CaCO3	Ca
Dolomite	16.44	CaMg(CO3)2	Ca, Mg
Muscovite	12.81	KAl2[]AlSi3O10(OH)2	K, Al, Si
Illite	16.43	K0.65Al2[]Al0.65Si3.35O10(OH)2	K, Al, Si
Chlorite (group)	17.10	(Mg,Fe++)5Al(Si3Al)O10(OH)8	Mg, Fe, Al, Si
Feldspar (group)	5.72	(Na,K)AlSi3O8	Na, K, Al, Si

Data from Göttingen team

Potential mechanisms

- Mineral dissolution/precipitation (at free walls)
- Pressure solution (at contact asperities)
- Cation exchanges (clay minerals)

    - Divalent ions → monovalent ions

Fluid inclusions

Fluid inclusion type	Composition	Host	CH_4 mol%	CO_2 mol%	N_2 mol%	Total salinity wt.% NaCl-eq.	NaCl (wt%)	$CaCl_2$ (wt%)	H_2O (wt%)	Homogenization teperature (°C)
primary	H_2O-NaCl	Qtz				0			100	148 (L) - 372 (V)
	CH_4 ±N_2	Qtz	97.9 - 100*	0 - 2.1*	---	---	---	---	---	-92 (L) to -83 (V)
primary	H_2O-$CaCl_2$-NaCl	Qtz				19 - 32	2 - 8	14 - 25	72 - 82	98 (L) - 243 (L)
	CH_4 ±N_2	Qtz	98.3 - 100*	0 - 1.7*	(10)**	---	---	---	---	-86 (L) to -80 (L)
primary	H_2O ±NaCl	Qtz				1 - 4			96 - 99	105 - 260 (L)
primary	H_2O ±NaCl	Qtz				2 - 3			97 - 98	---
	CH_4 ±N_2	Qtz				---	---	---	---	-83 (L) to -99 (L)
primary	H_2O-$CaCl_2$-NaCl	Calcite				12 - 30	7 - 18	5 - 12	77 - 87	103 (L) - 262 (L)
primary	H_2O ±NaCl	Qtz				0 - 5			94 - 100	139 (L) - 262 (L)
primary	CH_4 ±N_2	Qtz				1 - 5			95 - 99	137 (L) - 362 (L)
primary	H_2O ±NaCl	Qtz				1 - 4			96 - 99	150 (L) - 242 (L)
primary	H_2O ±NaCl	Qtz				2 - 4			96 - 98	142 (L) - 178 (L)

Data from Göttingen team

In-situ fluid inclusions within slates are mainly composed of water with low salinity: NaCl and CaCl2.

In contrast to the deionized water used in this study, natural brines may lead to different fracture closure behaviour due to fluid chemistry.

Conclusions

- Fluid-rock interactions cause partial fracture closure, which is irreversible.
- Temperature increase could accelerate fluid-rock interactions, which are negative to fracture aperture sustainability.
- Natural brine circulation may cause different fracture deformation behaviours due to various ions, which needs to be investigated.

What learnt from the preliminary results

- Isn't slate suitable for an EGS?
  - The current experiments only show the results of fractures in several microns, larger fractures (e.g., natural tensile fractures, high roughness fractures) may exhibit different behaviours.
  - Natural brine contains different ions that may reach chemical equilibrium, and thus fluid-rock interactions could be decelerated.
  - Needs more investigations.

Next step:

- Flow-through experiments with prepared brines (e.g., NaCl solutions)
- Continuous strain measurements during flow-through experiments

Thank you very much for your attention

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