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Flagship stimulation experiment in the deep underground laboratory, risk study

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SCCER SoE

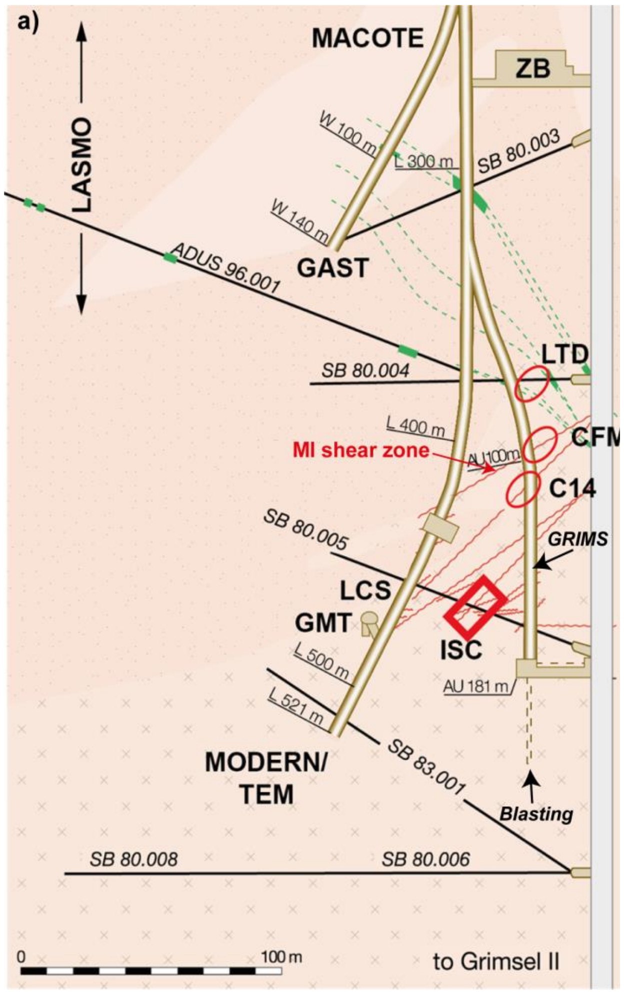
R&D Roadmap for deep geothermal energy

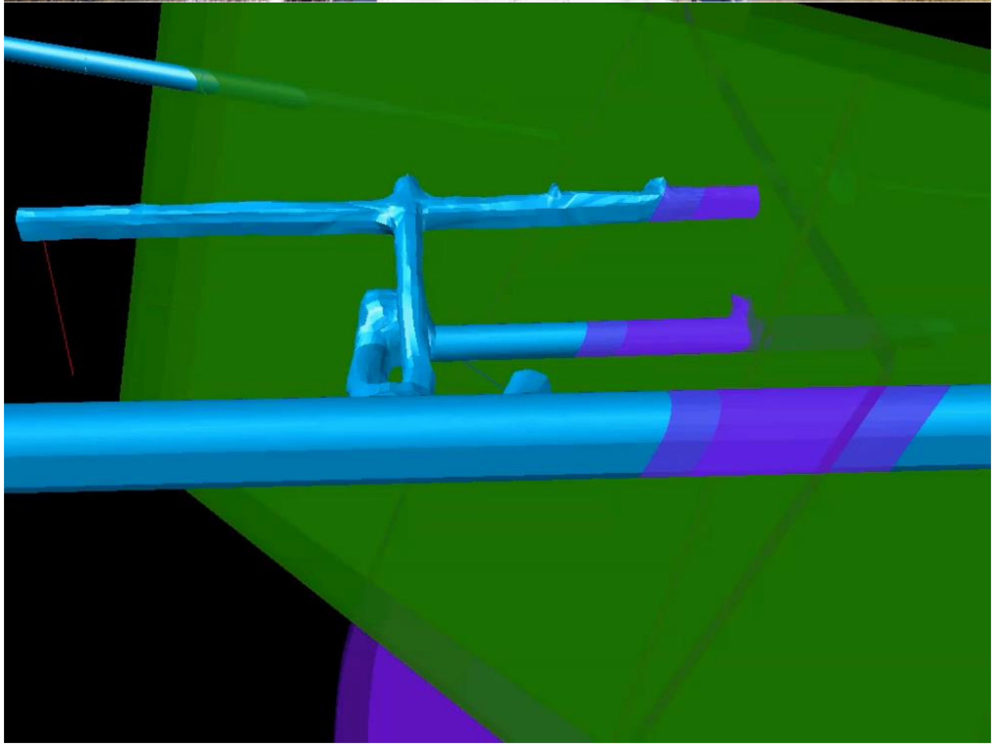
To enable the **large-scale exploitation of deep geothermal energy** for electricity generation in Switzerland, solutions must be found for two fundamental and coupled problems:

(1) How do we **create an efficient heat exchanger** in the hot underground that can produce energy for decades while
(2) at the same time keeping the nuisance and risk posed by **induced earthquakes to acceptable levels**?

→ Advance the capability to quantitatively model the stimulation and reservoir operation
→ **Advance process understanding and validation in underground lab experiments**
→ Develop petrothermal P&D project

ISC experiment at the Grimsel Test Site





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Procedure and time-line

Aug. 2015 – Nov. 2016 → Dec. 2016 – Mar. 2017 → Apr. 2017 – end 2017 →

Pre-Stimulationsphase

Seismic network
- regional scale
- tunnel scale

Stress measurements

Drilling

Characterization
- geophysical borehole logs
- hydraulic & thermal Tests
- geophysical charac. (GPR, active seismics)
- tracer Tests (dye tracer and nanotracer)

Monitoring boreholes
- strain and tilt
- pore pressure
- temperature
- micro-seismics

Stimulationsphase

Stimulation
- stimulation of existing shear zone
- hydraulic Fracturing in massive rock
- shut-in phases

Monitoring
- pressure und flow rates in active borehole
- pressure in passive borehole
- micro-seismicity in tunnels and boreholes
- pressure and temperature in boreholes
- tilt at the tunnel surface

Post-Stimulationsphase

Characterization
- geophysical boreholes log (OPTV, electrical resistivity, spectral gamma etc.)
- hydraulic test in boreholes and between boreholes (storativity and transmissivity changes)
- tracer Tests (dye tracer und nanotracer)
- active seismic tests and GPR between boreholes and tunnels

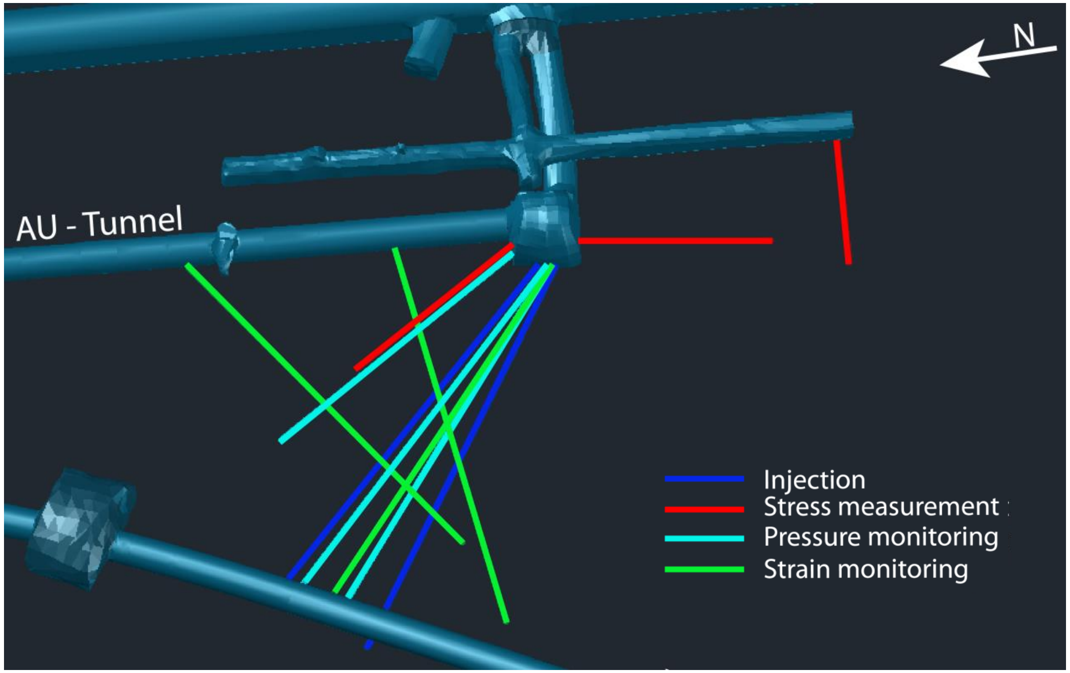
Preparation of circulation phase
- boreholes
- completion of boreholes with temperature sensors
- Installation multi-packer system

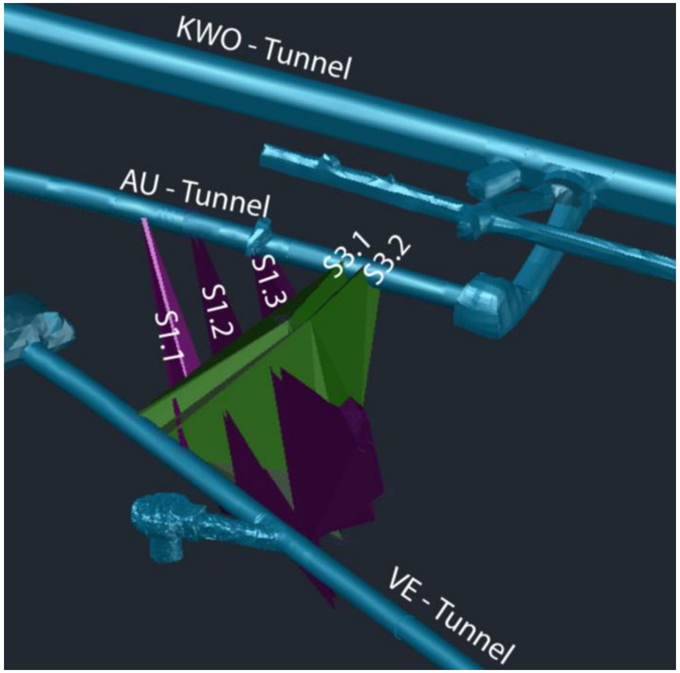
Circulationsphase

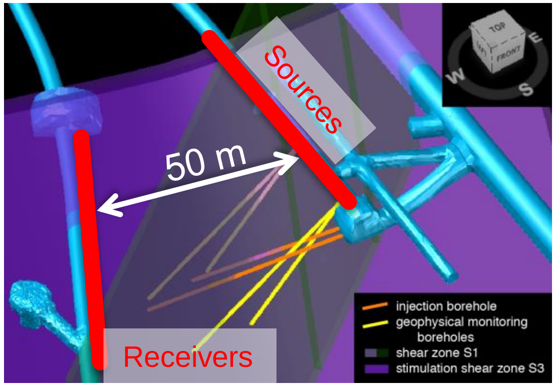
Circulation
- cold water injections
- warm water injections

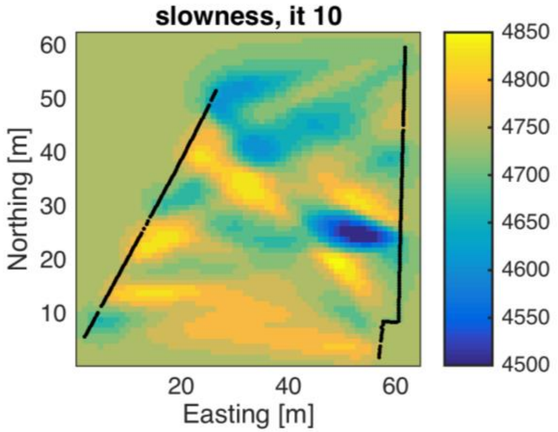
Monitoring
- induced micro-seismicity
- thermal break-trough
- thermo-elastic strains and tilt
- pore pressure changes
- temperature in reservoir

Boreholes and characterization



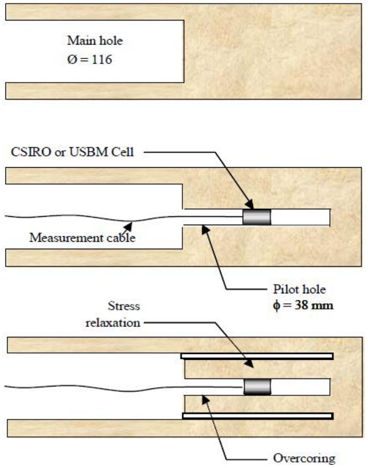


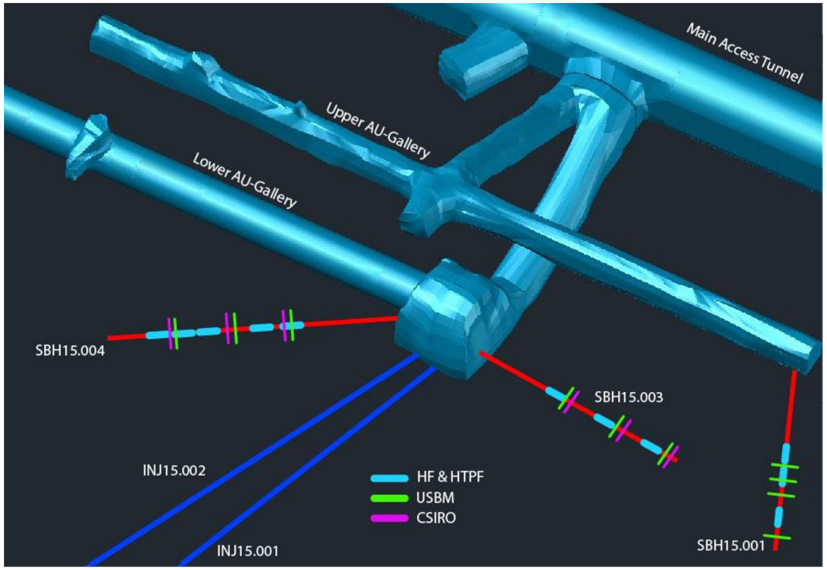


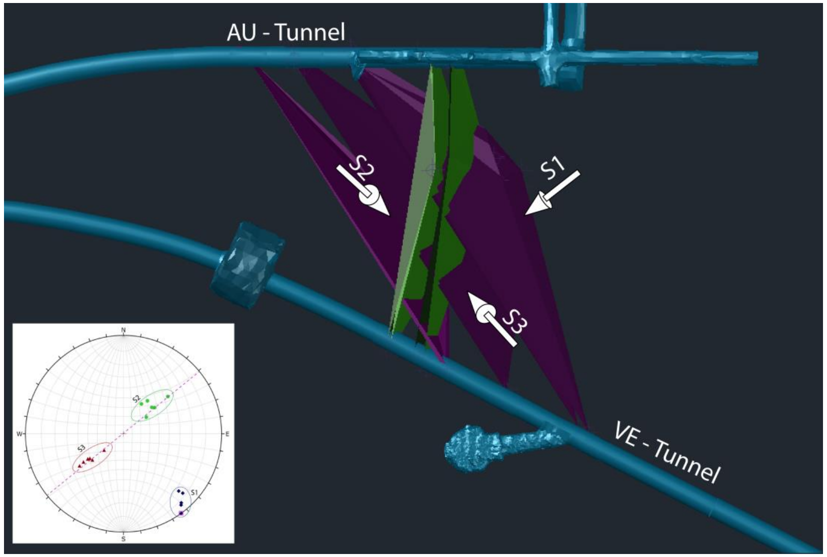


Stress measurements

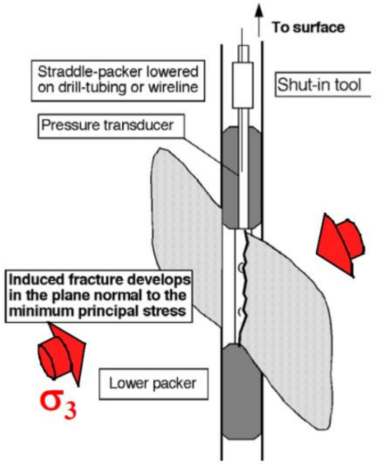
Overcoring



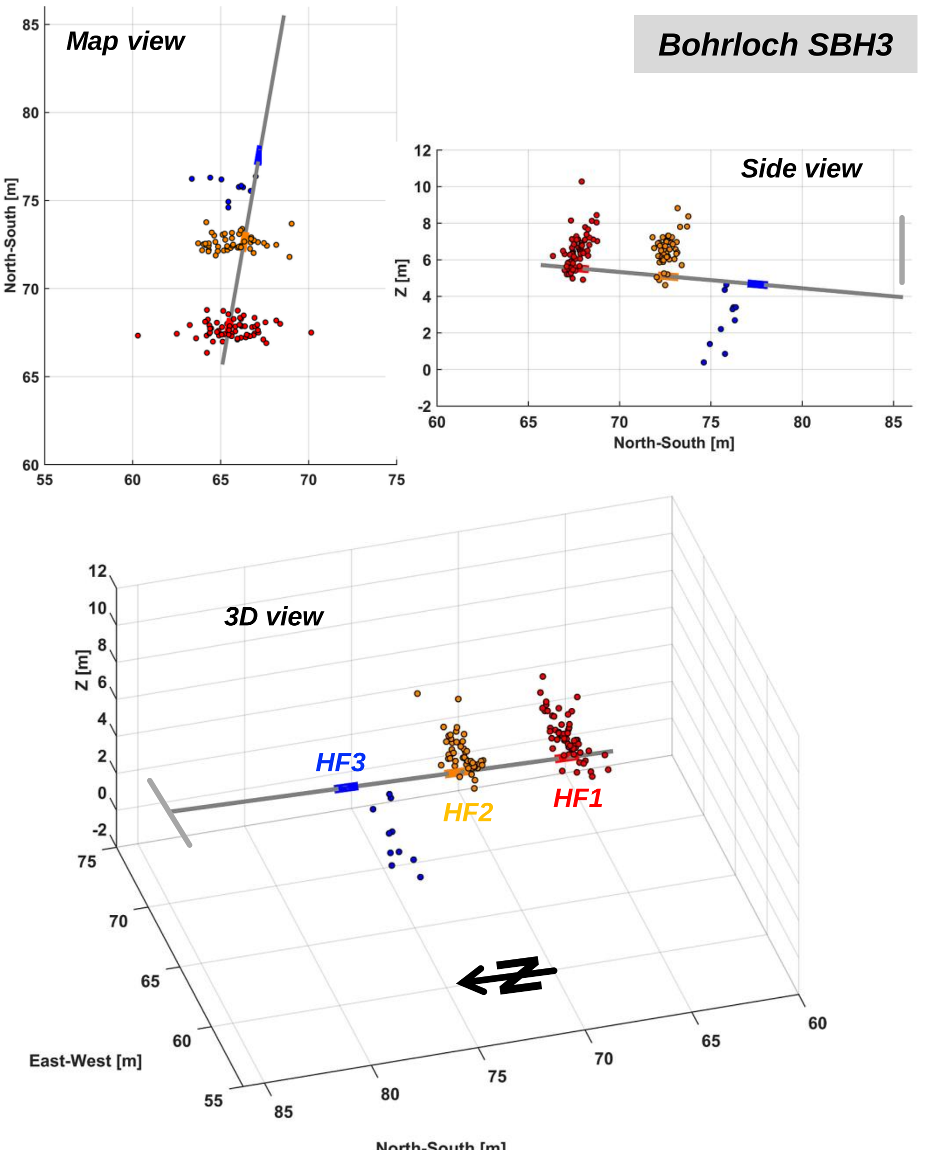


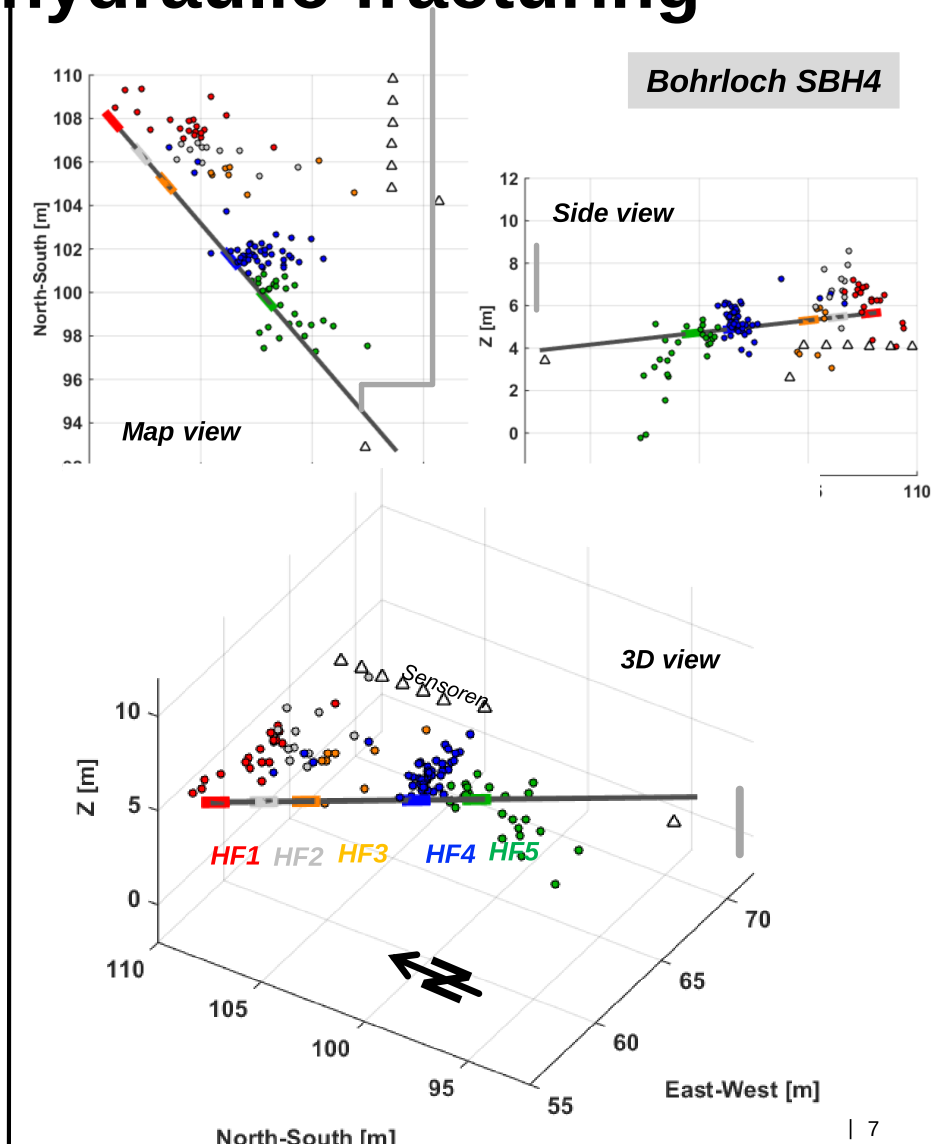


Hydraulic fracturing

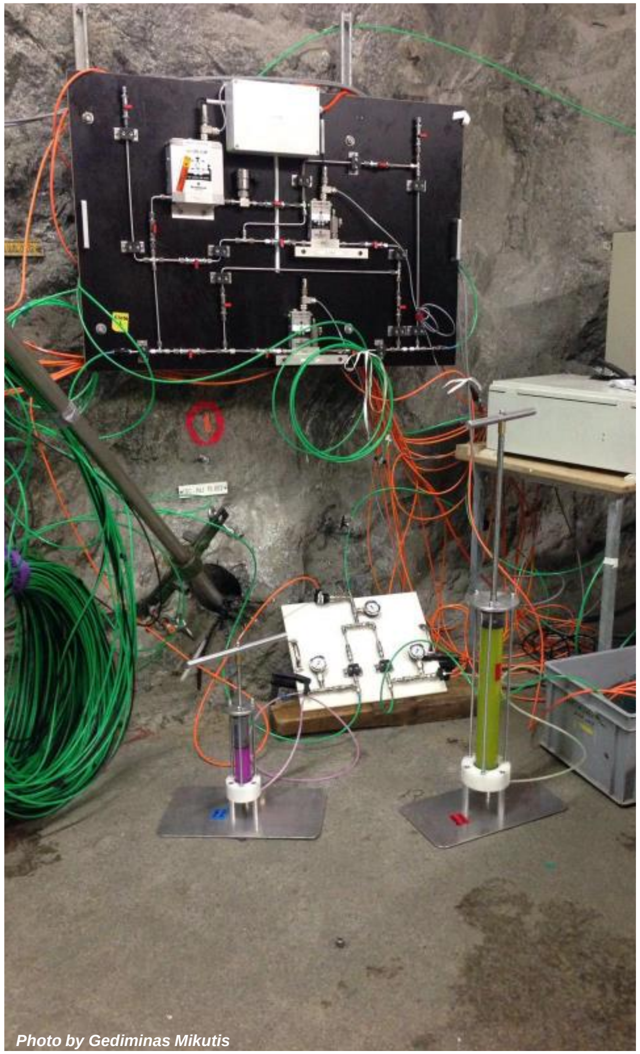


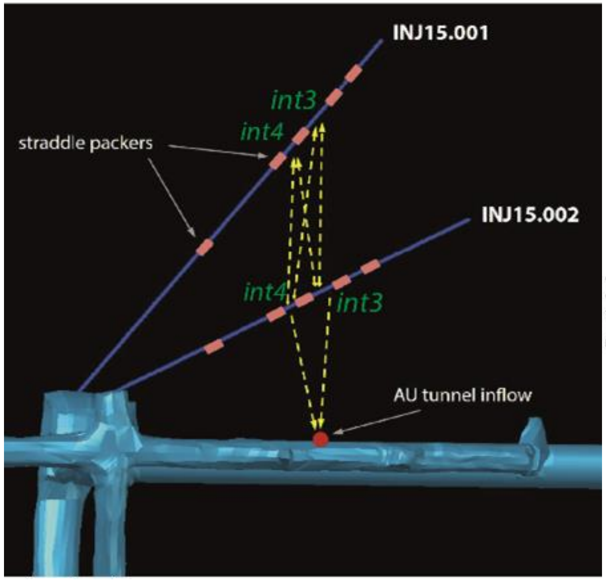
Micro-seismicity during hydraulic fracturing

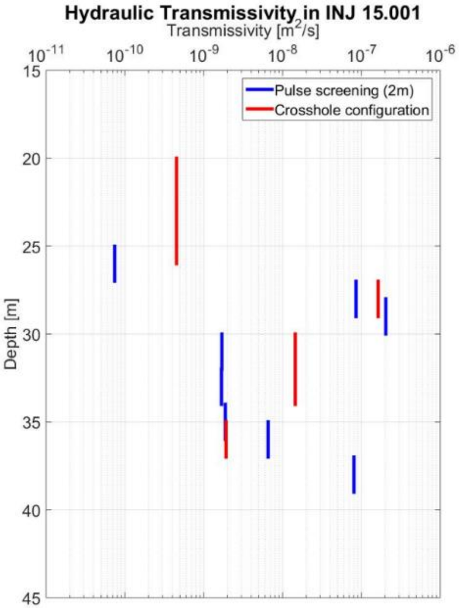


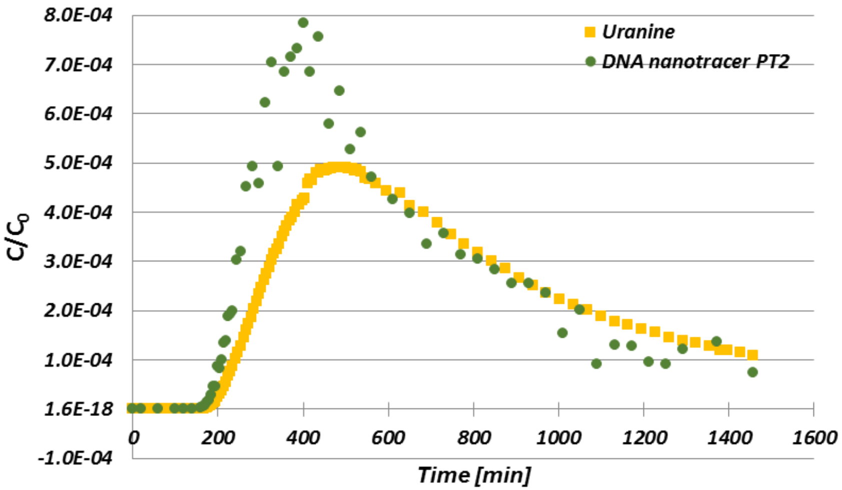


Hydraulic and Tracer Tests



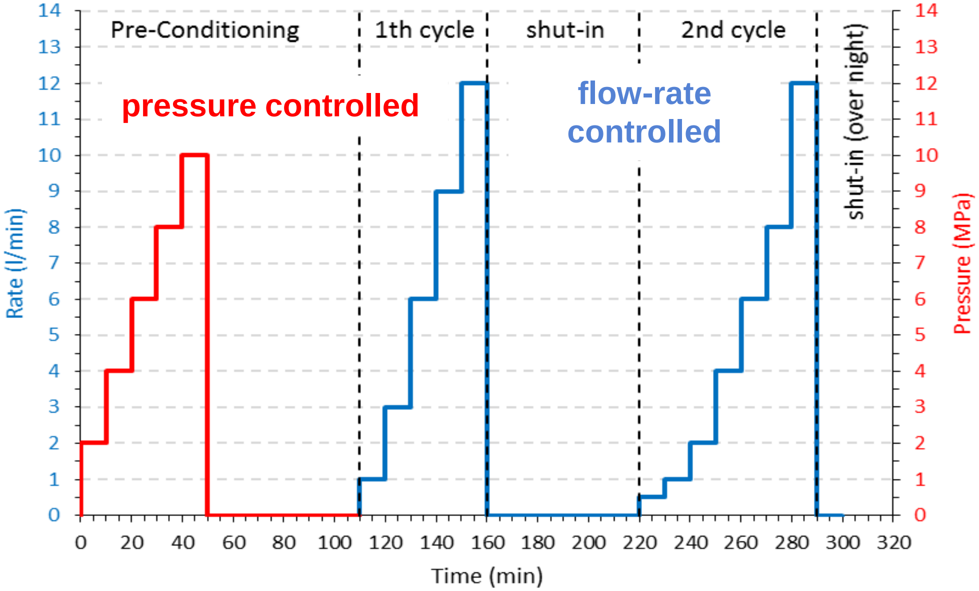




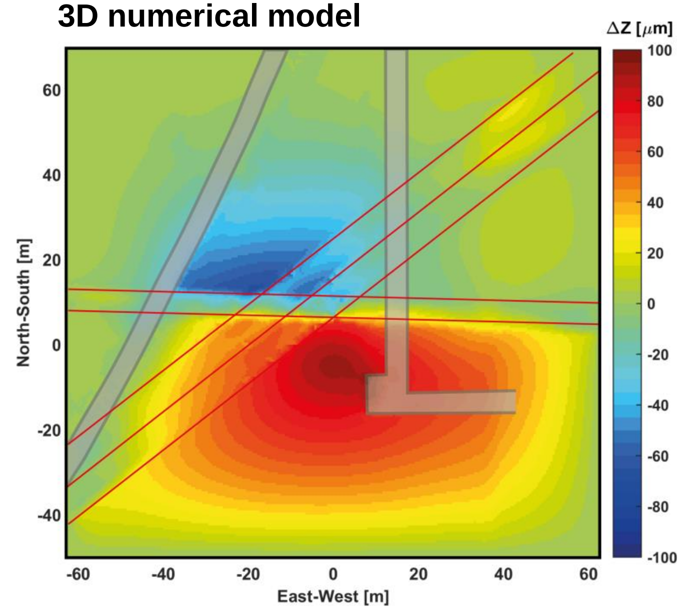


Stimulation phase

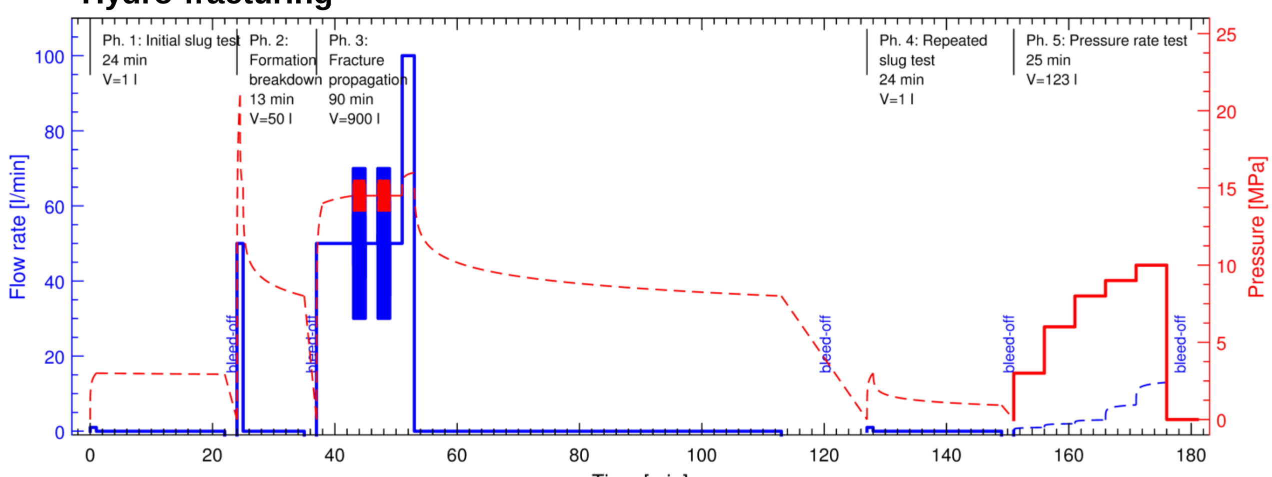
Hydro-shearing



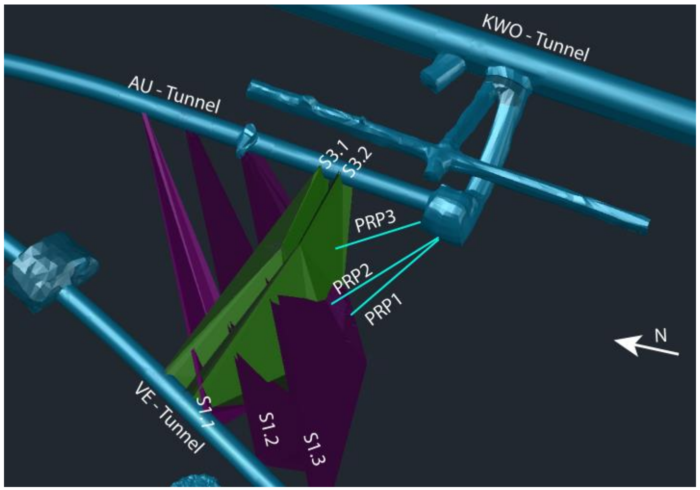
3D numerical model

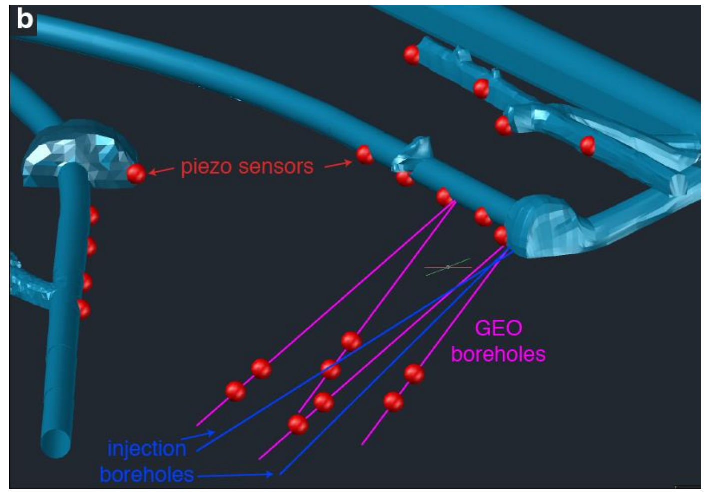


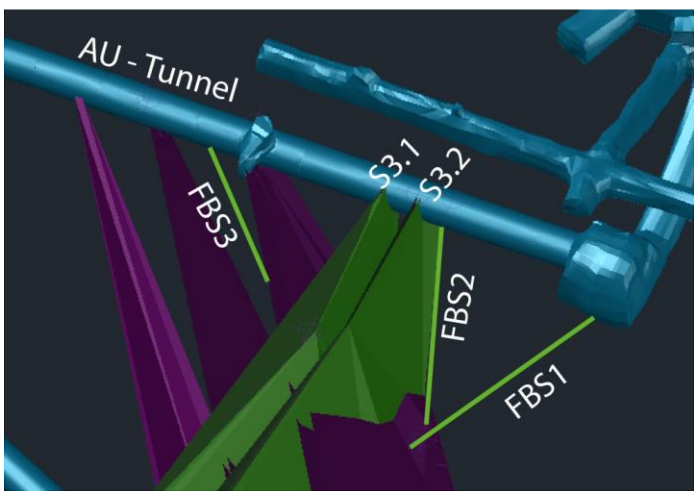
Hydro-fracturing



Monitoring during stimulation







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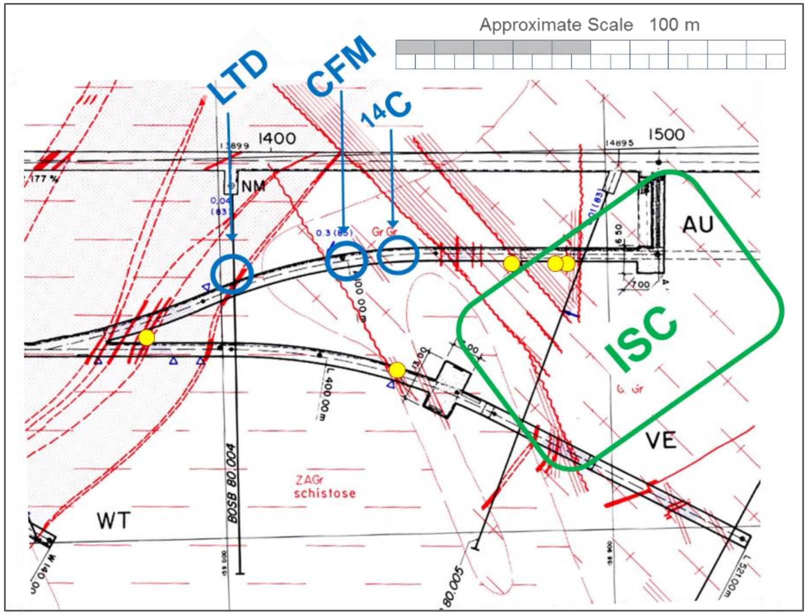
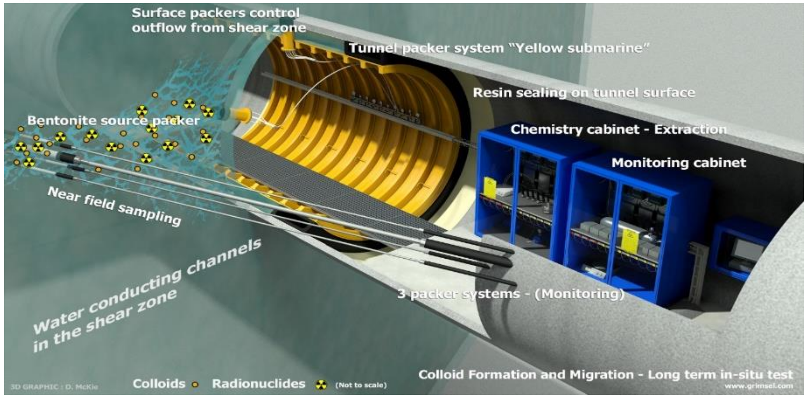
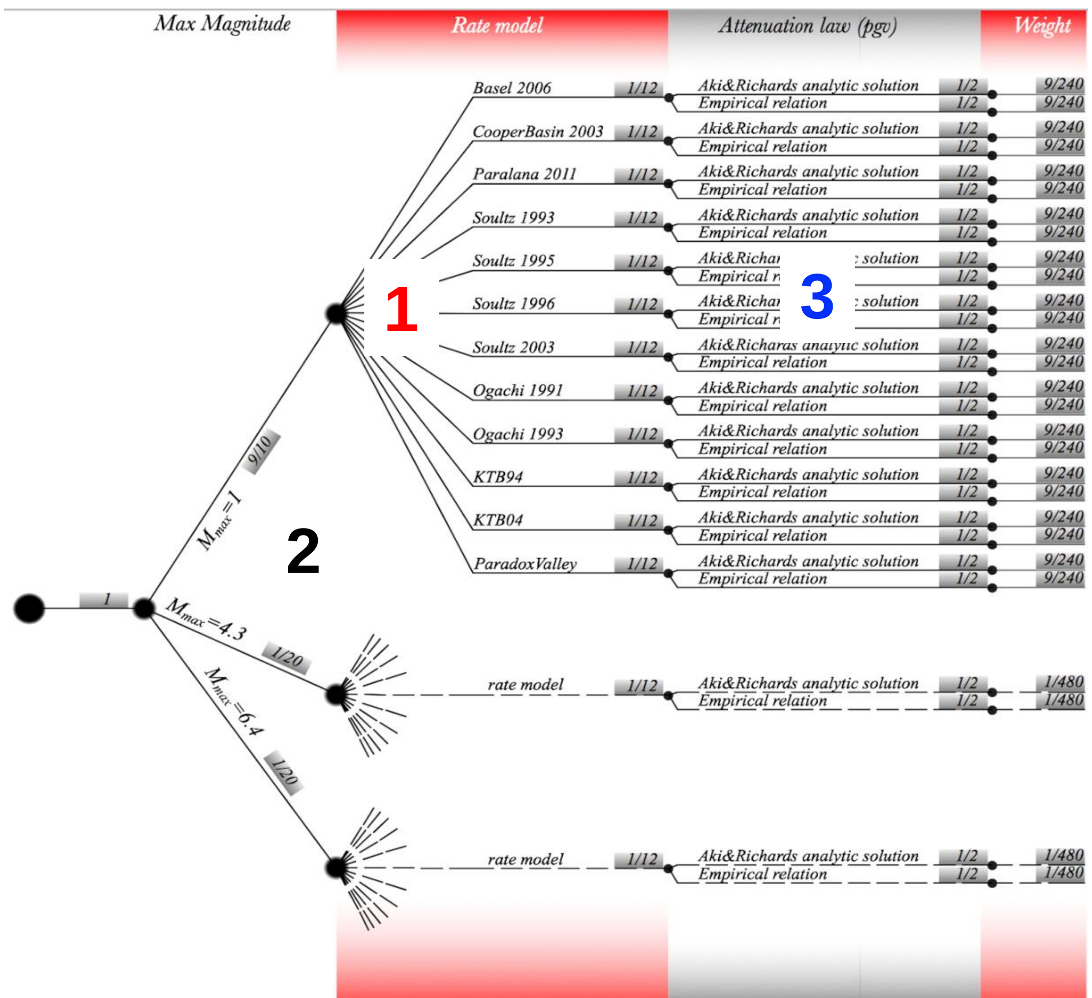
Risk assessment

- Considered
  - Perturbation near-by experiments
  - Seismic risk assessment
- Approach for seismic risk assessment
  - Experience from similar experiments and hydraulic fracturing tests (i.e., France M = -2.0; ISC estimated to be Mw ≈ -2.5)
  - Computed scenarios for ground motions (qualitative assessment)
  - **Probabilistic assessment of ground motion (down to an exceedance probability of 10^{-4})**
  - **Define mitigation actions**





Probabilistic assessment – logic tree



1) Rate Model (Shapiro 2010) → seismogenic index Σ and b

$$\log_{10}(N_{M \geq Mi}) = \log_{10}(Q(t)) + \Sigma - bMi$$

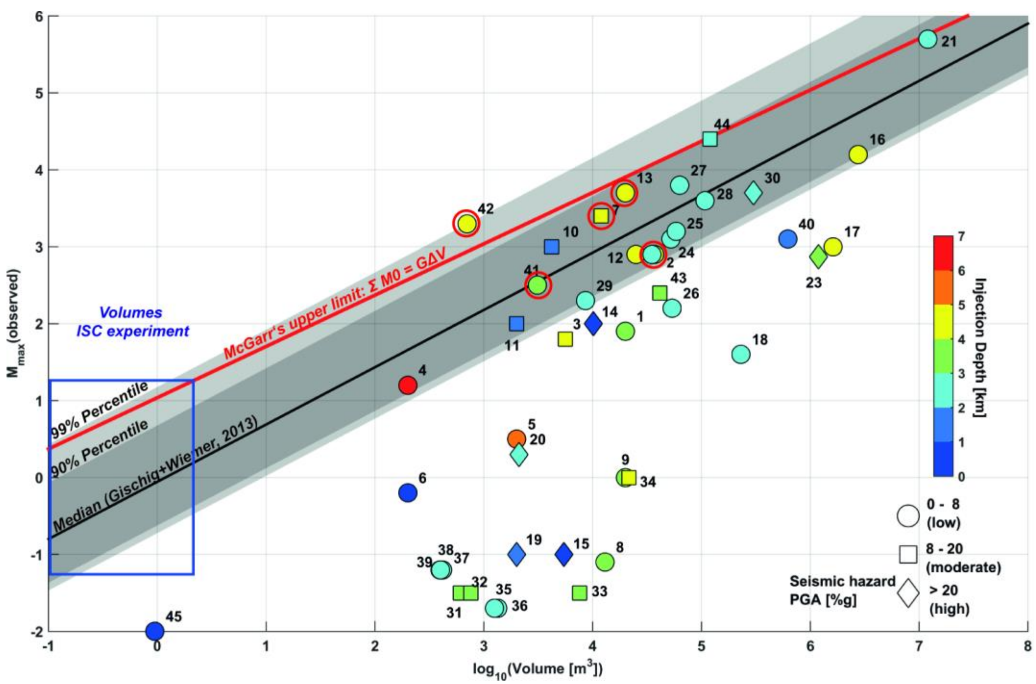
Q = 1m3
Σ and b: calibrated against various data sets

2) Different assumptions for M_{max} made for the rate model (i.e. M_{max} 6.4, 4.3, 1.0); Weighing: Mmax = 1.0 = 90%

3) Ground motion prediction equation (analytical and observation based)

Estimates for M_{max} – 2 Methods

McGarr



Scaling law

$$M_0 = 16/7\,\Delta\tau \cdot r^3$$

Slipped area	*5 m*	*10 m*	*20 m*
Stress drop 0.1 MPa	-1.1	-0.5	0.1
Stress drop 1 MPa	-0.4	0.2	0.8
Stress drop 10 MPa	0.3	0.9	1.5

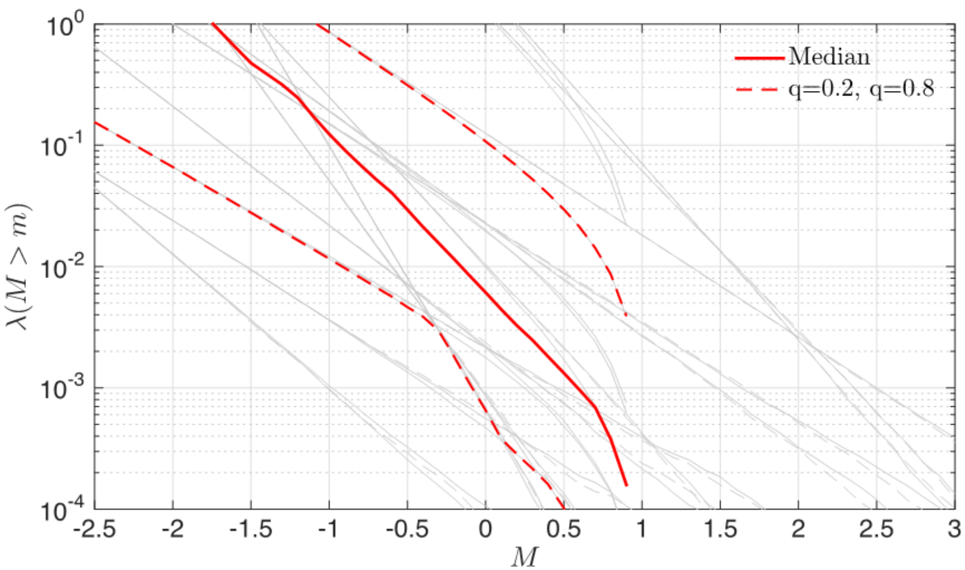
Both methods suggest a maximum magnitude of $M_{max} \approx 1.0$

Results – Rate Model

$$\log_{10}(N_{M\geq Mi}) = \log_{10}(Q(t)) + \Sigma - bMi$$

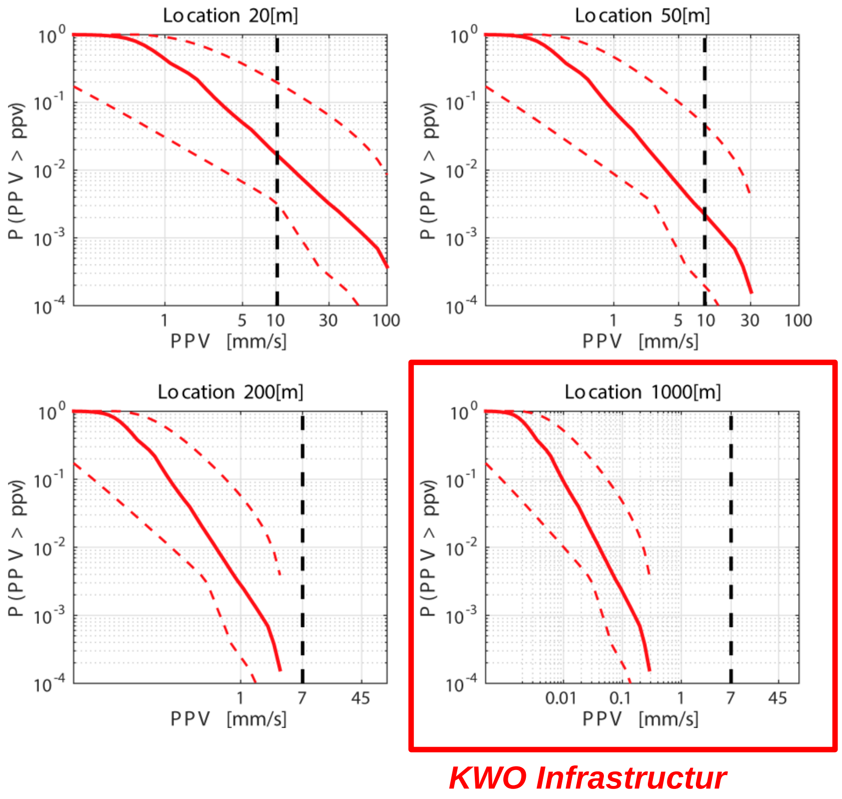
- $\log_{10}(N_{M\geq Mi})$: Number of quakes with a magnitude larger M_i
- $\log_{10}(Q(t))$: Rate of quakes scale with the injected volume Q(t)
- Σ: Site specific parameter: seismogenic index
- bMi: Relation between the number of large quakes to small quakes

Fallstudie	*b*	*Σ*	*Referenzen*
Basel, 2006	1.45	0.3	Kiraly et al., 2014
Cooper Basin, 2013	0.84	-0.9	Kiraly et al., 2014
Paralana, 2011	1.32	0.1	J. Albaric, pers.comm.
St. Gallen, all	1.0	0.4	Kiraly et al., 2014
Soultz-sous-forêt, 2003	0.82	-1.7	Kiraly et al., 2014
Soultz-sous-forêt, 1996	1.77	-3.1	Dinske et al., 2011
Soultz-sous-forêt, 1995	2.18	-3.2	Dinske et al., 2011
Soultz-sous-forêt, 1993	1.38	-2.0	Dinske et al., 2011
Ogachi, 1991	0.74	-2.7	Dinske et al., 2011
Ogachi, 1993	0.81	-3.2	Dinske et al., 2011
KTB, 1994	0.93	-1.8	Dinske et al., 2011
KTB, 2004	1.1	-4.2	Dinske et al., 2011
Paradox Valley,	0.98	-2.6	Dinske et al., 2011



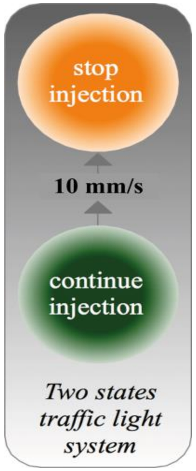
- Maximum possible magnitude ca. **M1.2**
- Maximum expected magnitude ca. **M-1.7**
- The likelihood for a **M0.5** is **1/1'000**.

Results – Ground motion prediction



- The probability to exceed a ground motion of 10 mm/s in > 100m distance is 1:10'000
- The probability for damage in the GTS and KWO tunnels (PPV > 100 mm/s) is < 1:5'000
- The experiment will be interrupted or newly evaluated when the ground motion exceed 10mm/s. The probability is 1:100

→ Maximum 1m³ water per injection
→ Two-states traffic light system



Thank you for your attention