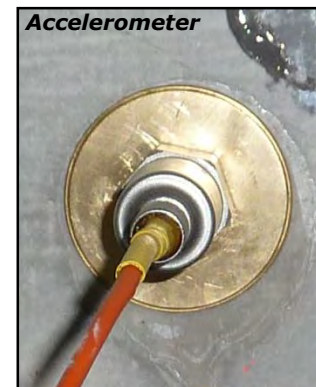
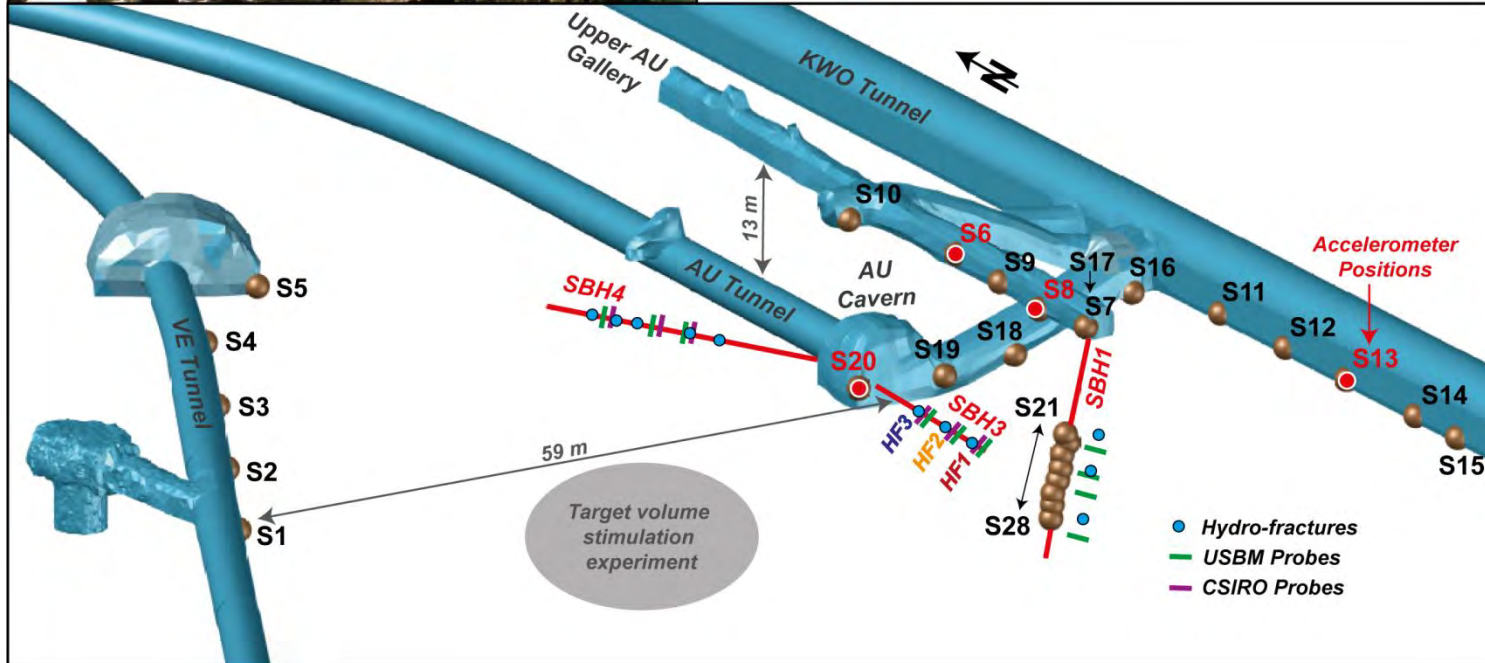
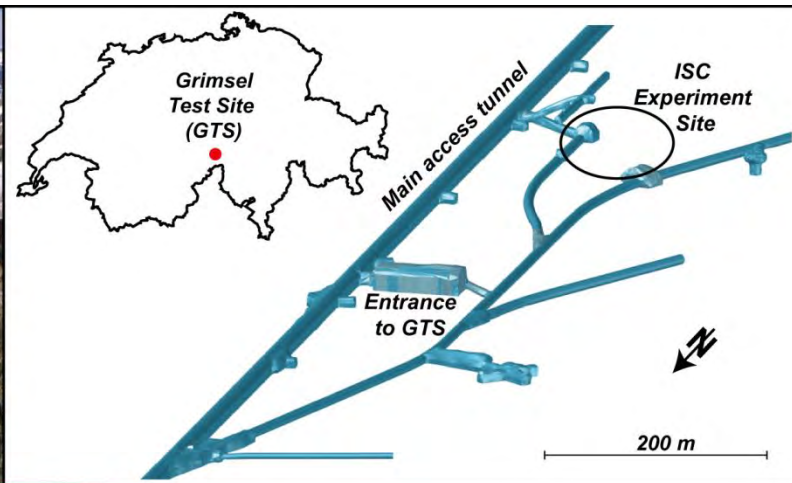




Induced micro-seismicity observed during meter-scale hydraulic-fracturing

V. Gischig, J. Doetsch, L. Villiger, H. Krietsch, H. Maurer, F. Amann, K. F. Evans, M. Jalali, A. Obermann, M. Nejati, B. Valley, S. Wiemer, D. Giardini

Background and experiment site



Challenges of induced seismicity analysis on a meter to decameter scale

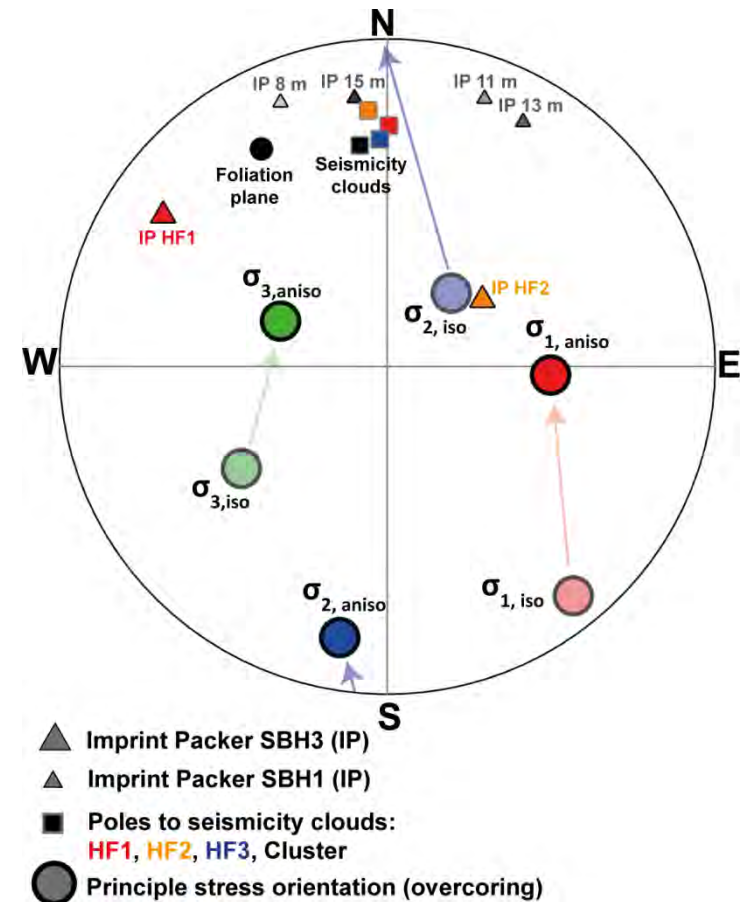
- **General:** Application of seismological tools from crustal earthquake analysis to the 1 m – 10 m scale.
- **At Grimsel:** HF-induced fracture orientations (from seismicity) do not fit with expectations from other stress measurements (i.e. overcoring).

Presented today:

Detailed analysis of HF-induced seismicity from October 2015.

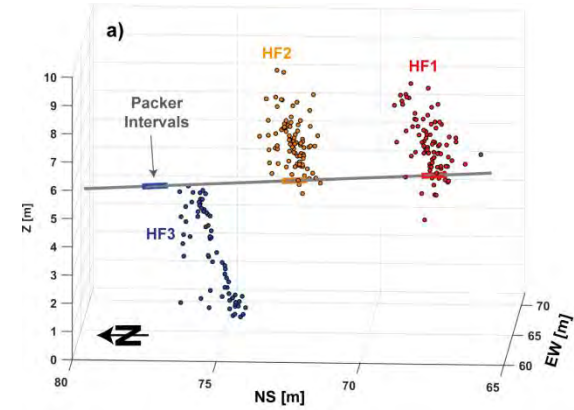
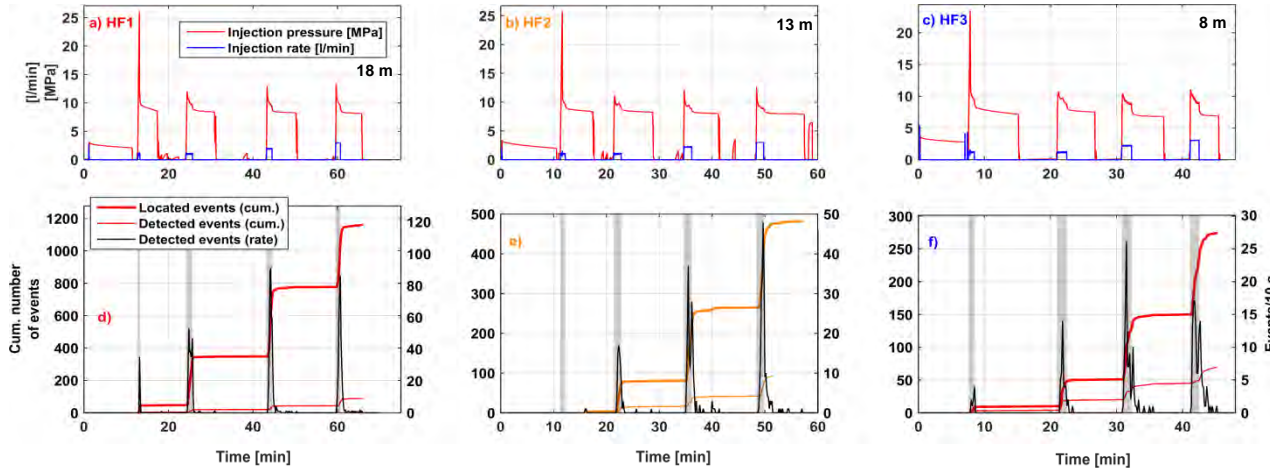
Preliminary results from stimulation experiment in February 2017.

Poster: Villiger et al., today P1-18

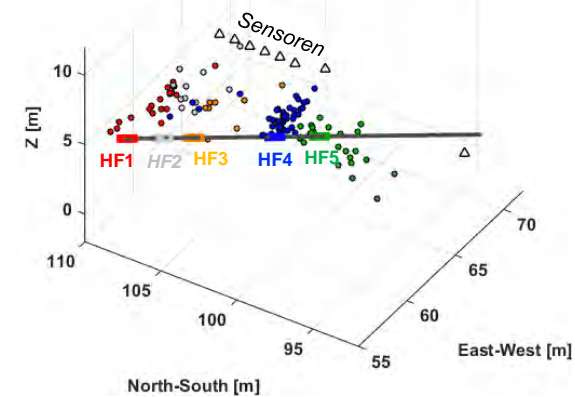
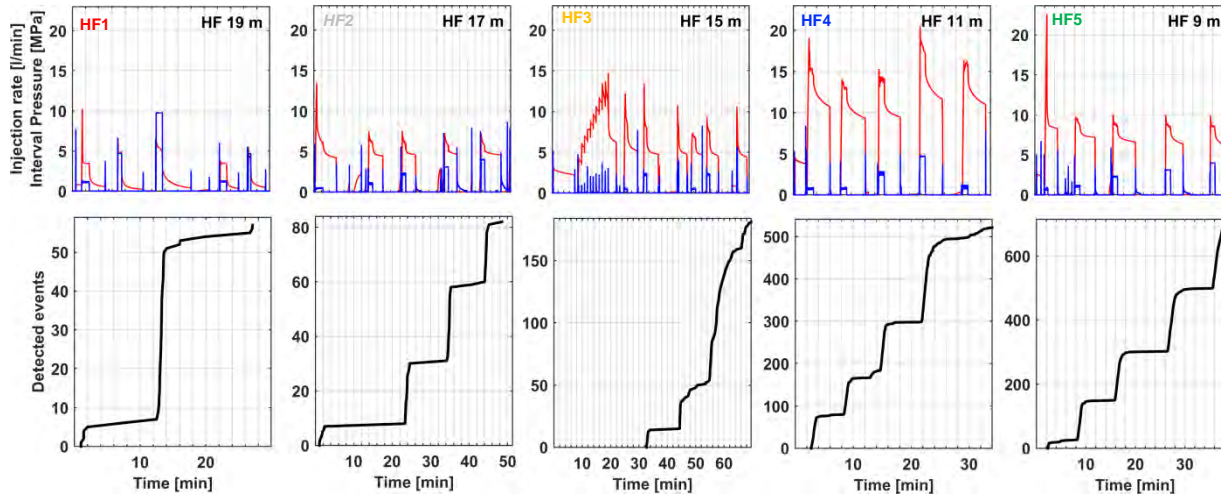


Hydro-fractures Flow, pressure, event counts

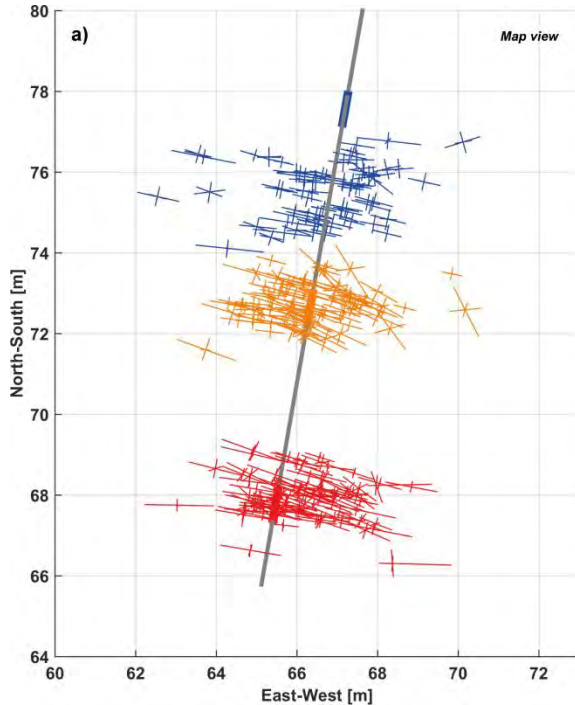
Borehole SBH3



Borehole SBH4



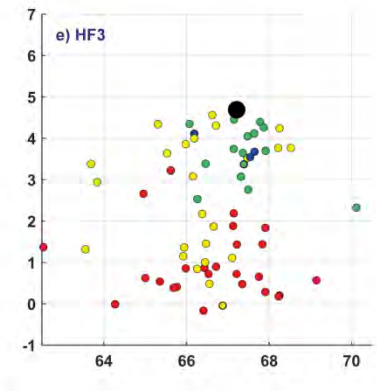
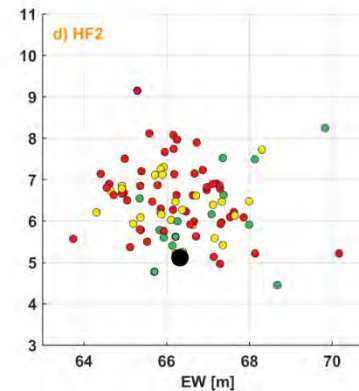
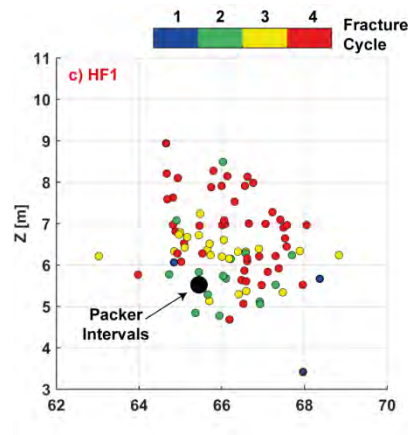
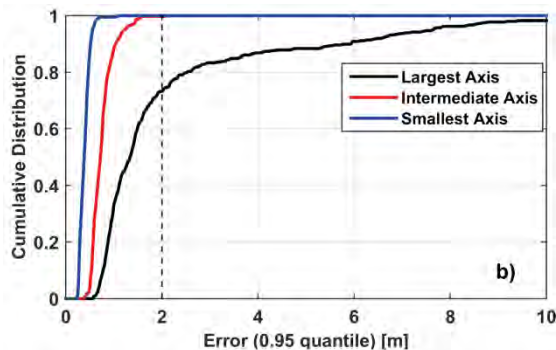
Error estimate and fracture propagation



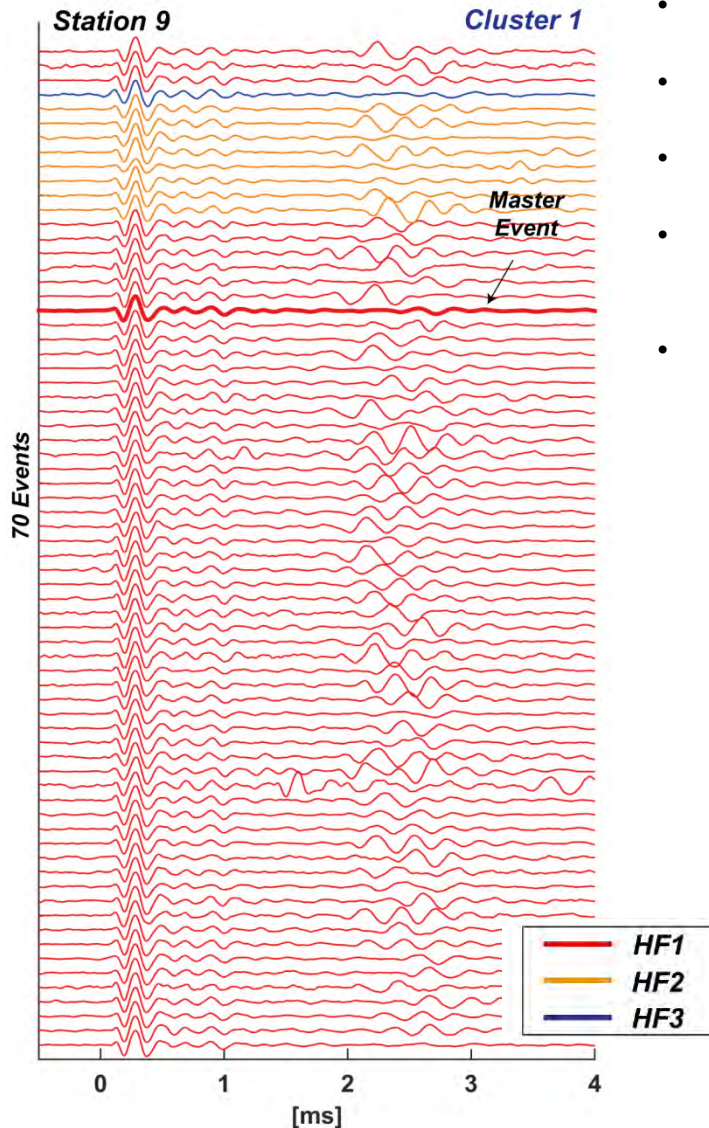
- Anisotropic homogeneous velocity model + station corrections
- Error $< \pm 1\text{m}$ for 75 % of all events
- Predominant EW-propagation
- Two fractures propagate upwards, one downwards
- Fractures have 3 – 5 m diameter

Question: does internal structures have different orientations?

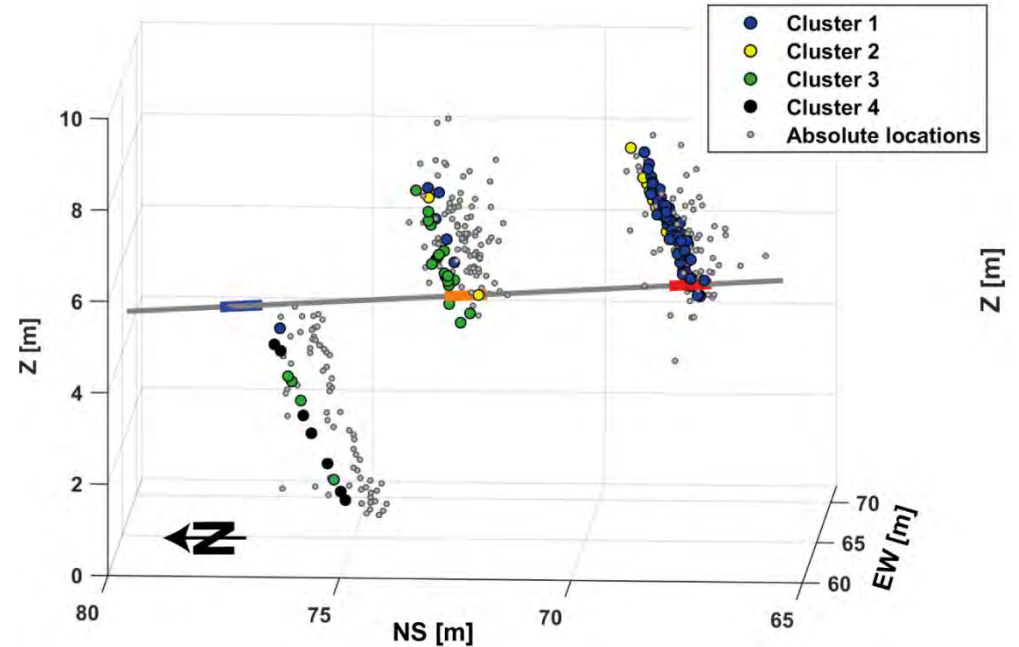
→ Cluster analysis



Cluster analysis + relative relocation

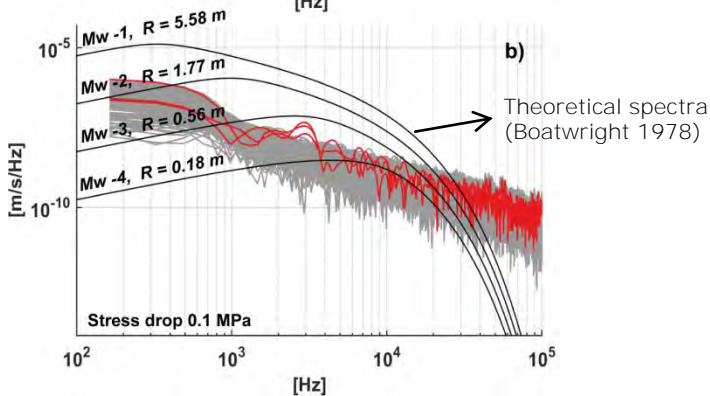
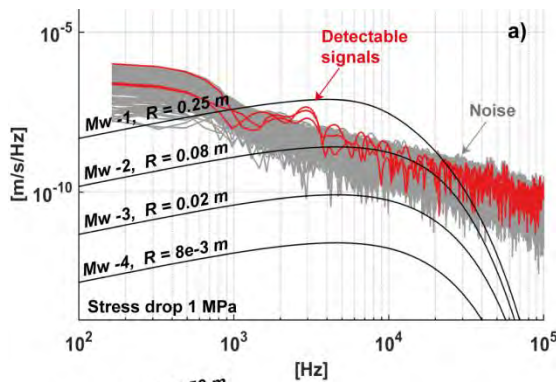
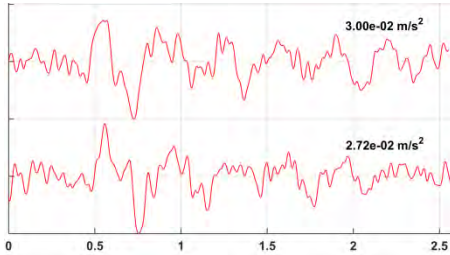


- Very high similarity of P-wave.
- S-waves more variable in arrival time and amplitude.
- Cluster include events from different fractures.
- Long axes of clusters have similar extend that clouds from absolute locations.
- EW orientation of fractures confirmed!
(Important for stress field characterization)



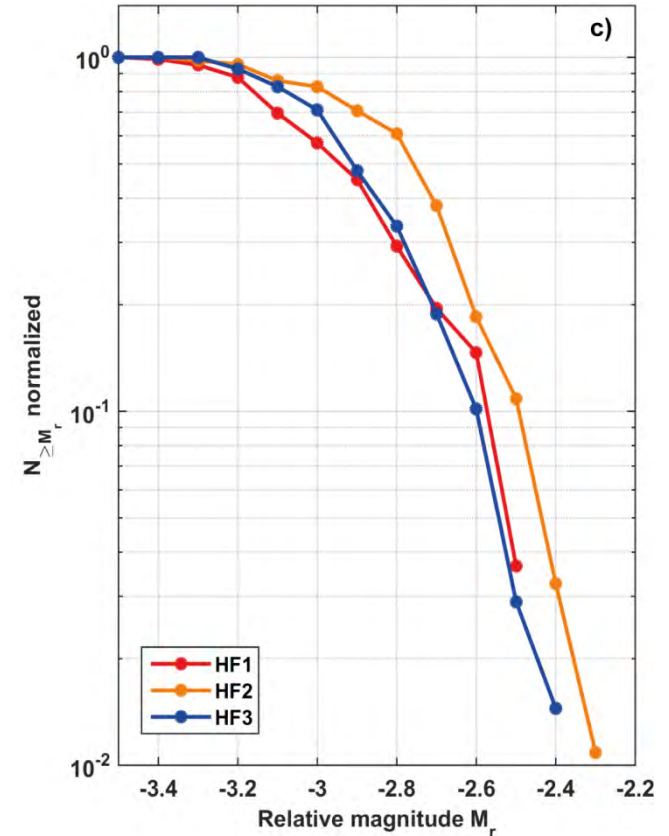
Magnitude calculation: challenging!

Absolute magnitudes



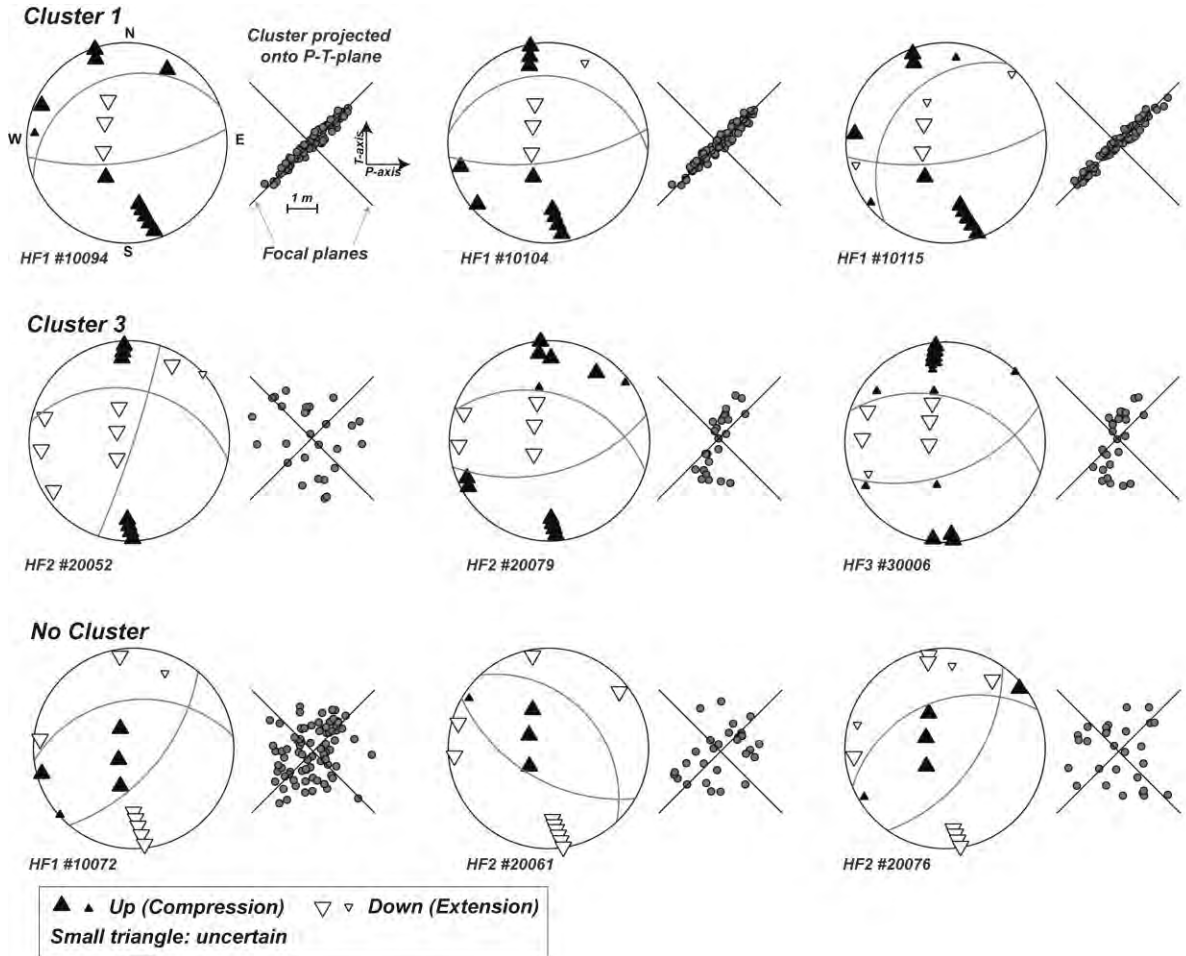
- Only three events detected on accelerometers
- M_w by spectral fitting not possible
- Maximum upper limit ranges from -3.5 to -1.5
- Source radii of these event few decameters
- Relative magnitudes cover only small range of less than one magnitude step
- Ongoing work

Relative magnitudes



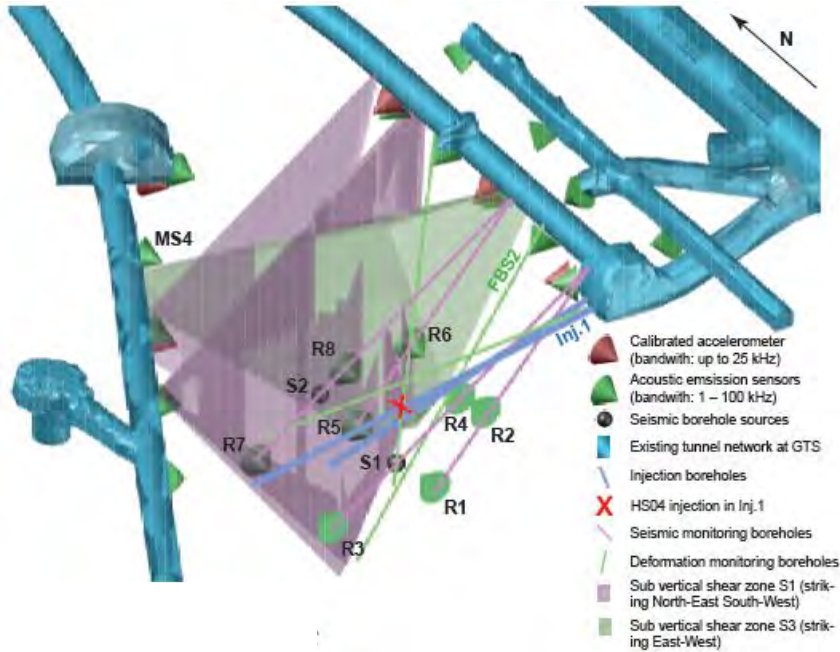
$$M_r = \log_{10} \left(\frac{1}{N} \sqrt{\sum_{i=1}^N \left(A_i \frac{r_i}{r_0} e^{\alpha(r_i - r_0)} \right)^2} \right)$$

Focal mechanisms

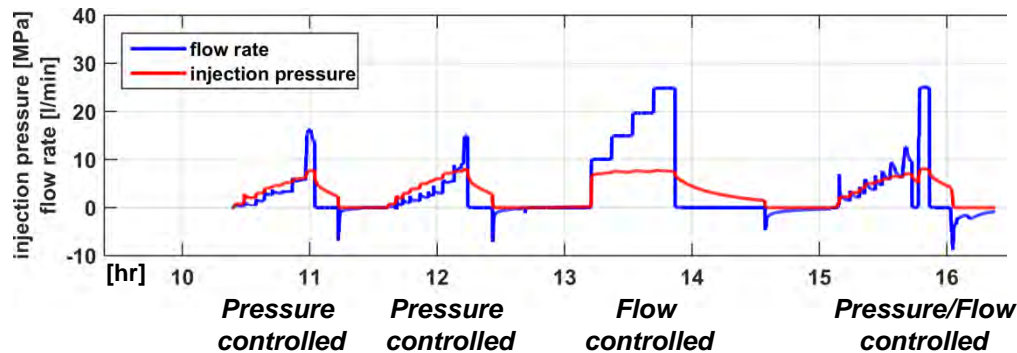


- Few events have sufficient number of clear P-wave polarity.
- For some of the events one focal plane coincides with the cluster plane.
- Mix of normal and thrust faulting, while stress field is thrust faulting.
- Possible non-double-couple component?

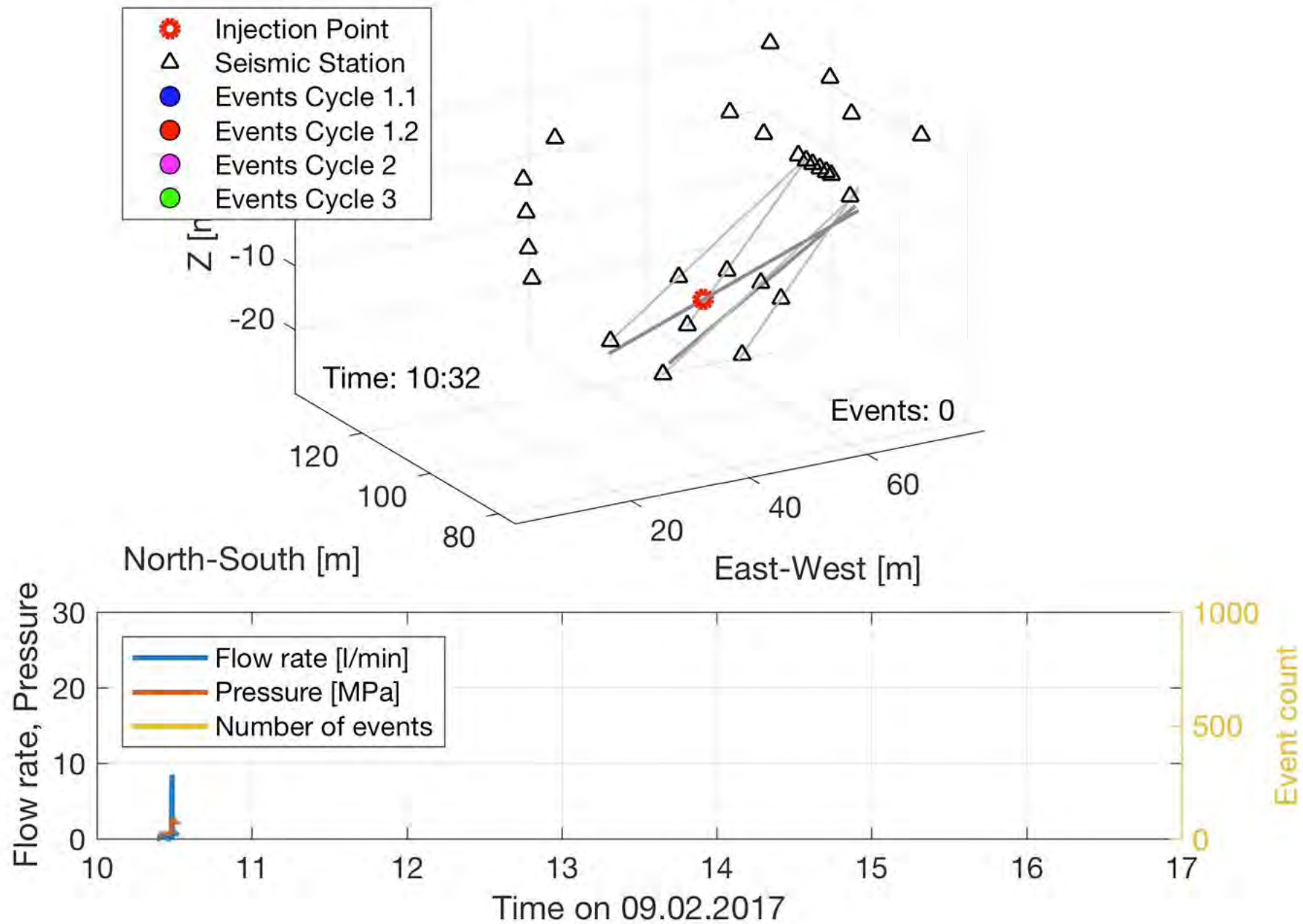
In-situ hydraulic stimulation experiment



- Stimulation of pre-existing structures
- 6 stimulation experiments (1 per day)
- Mixture of pressure and flow controlled cycles
- Multicomponent monitoring system:
 - 32 seismic sensors
 - 3 tiltmeters
 - 60 strain sensors (FBG)
 - 150 m distributed strain sensing cable
 - 13 pressure monitoring intervals
 - Active seismic surveys during injection

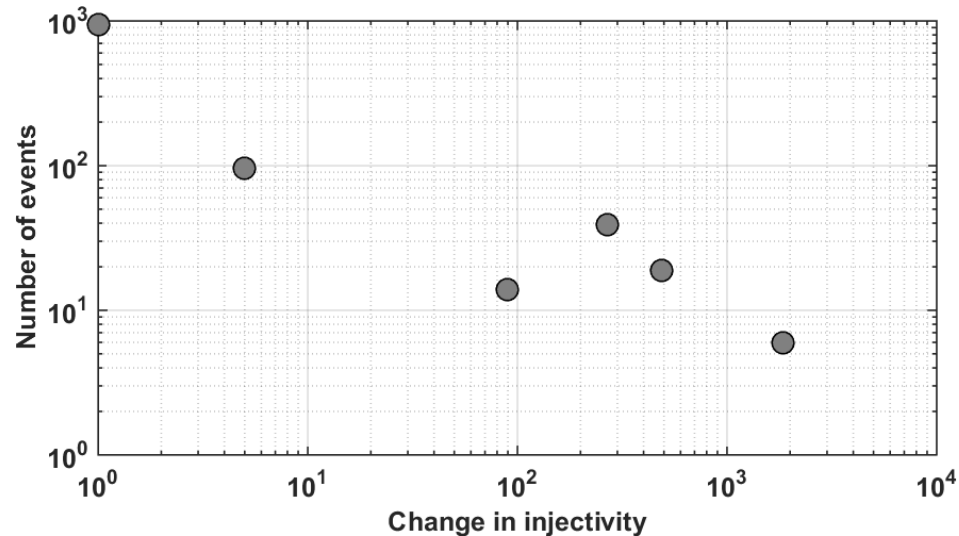


HS 4, Injection at 27.7 m in INJ1

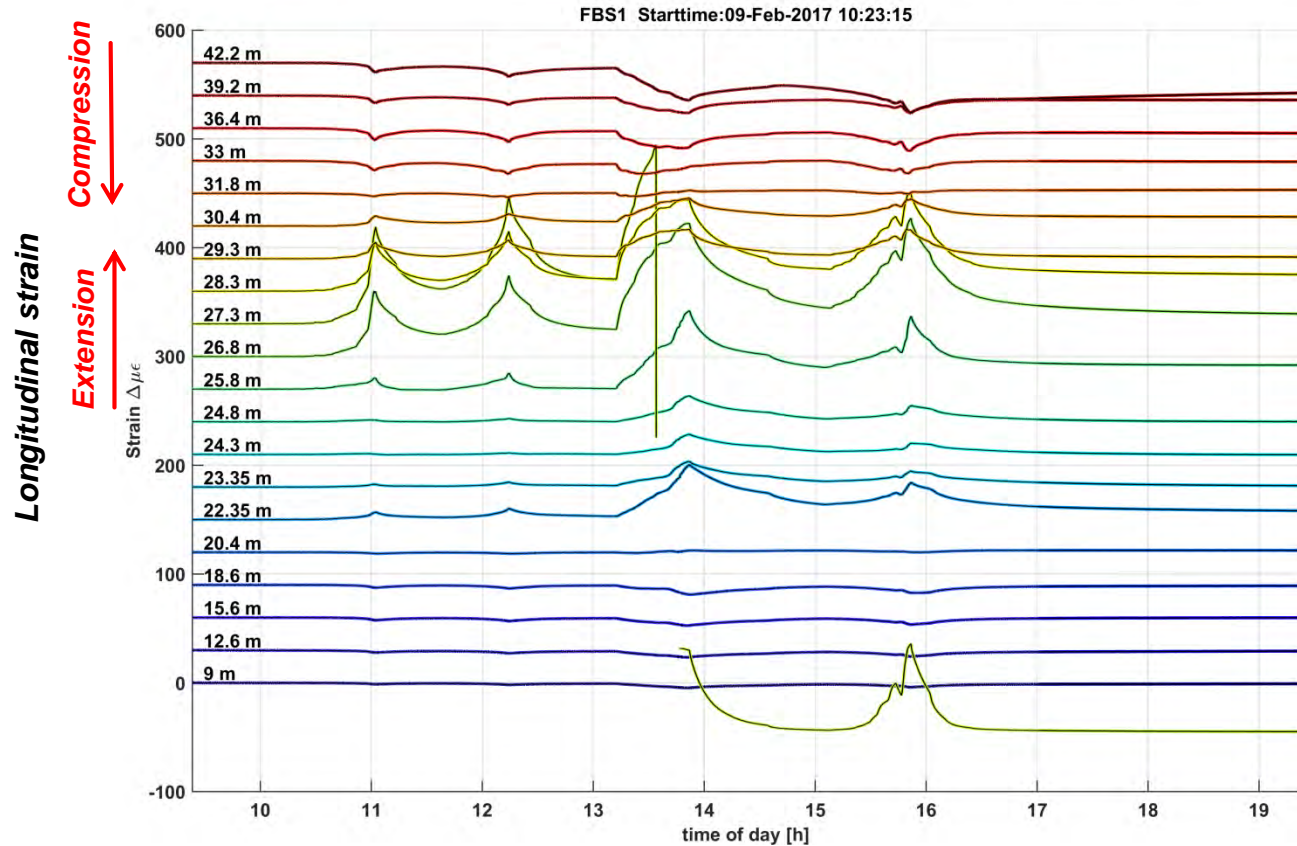
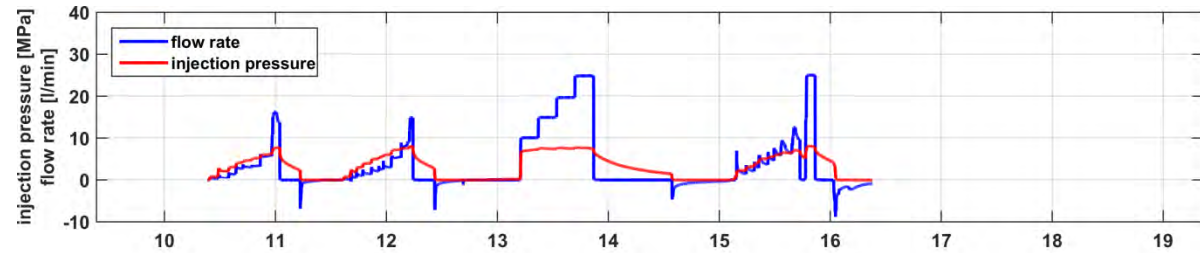
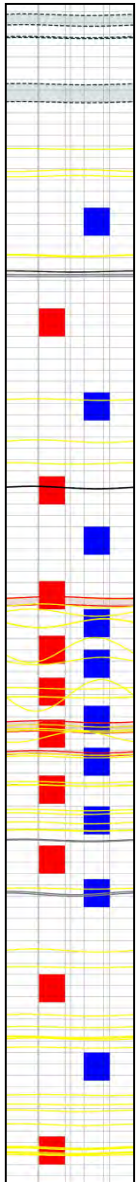


Some experiment characteristics

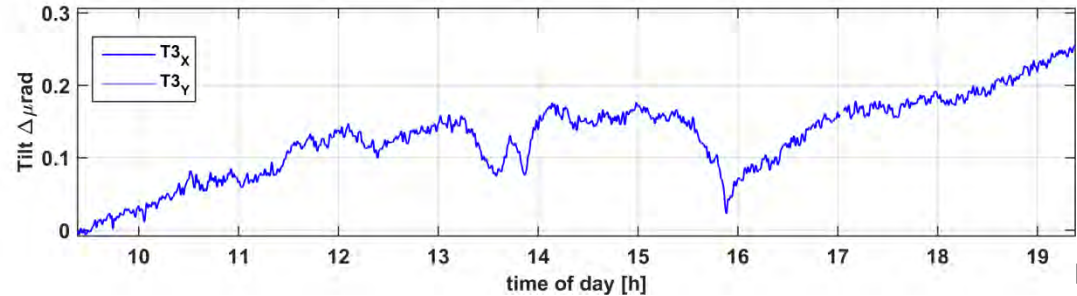
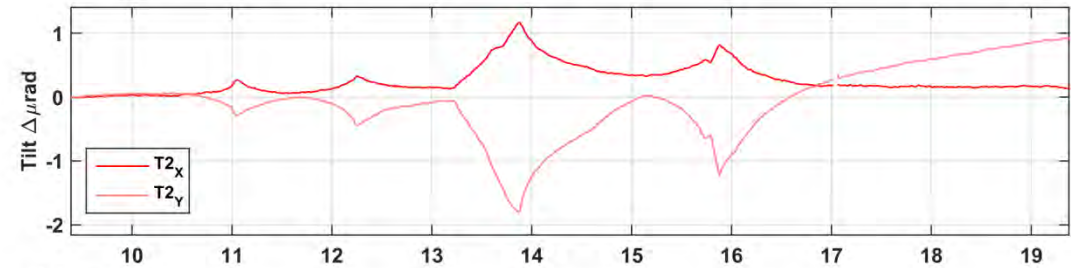
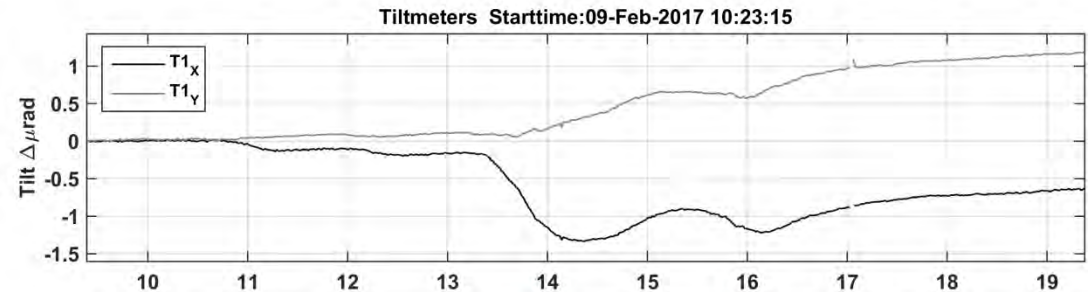
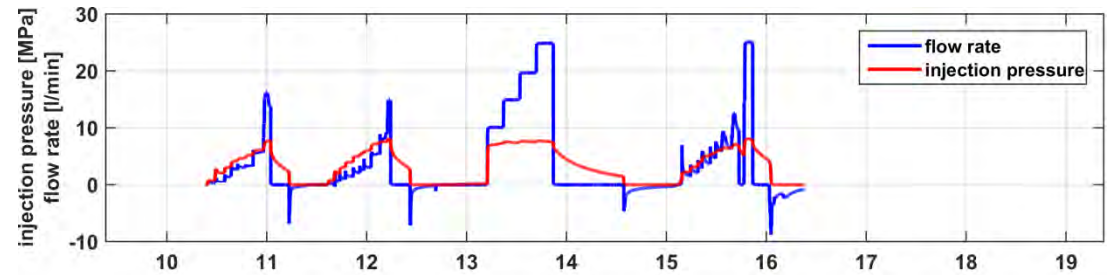
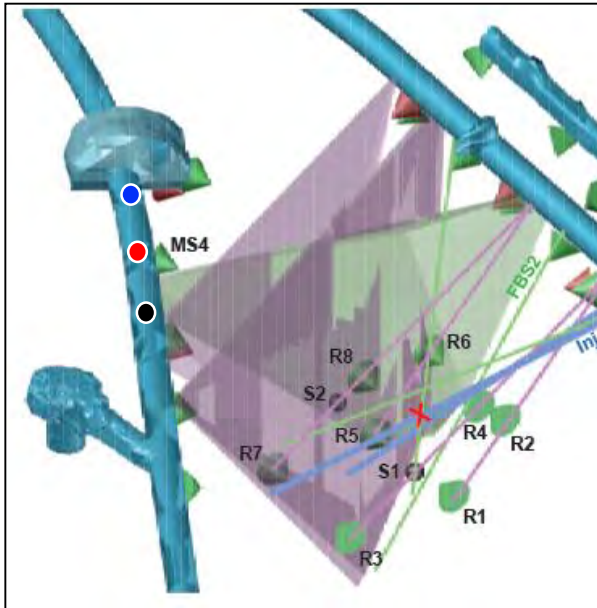
Test Date	Test ID	Injection borehole	Volume [l]	Interval [m]	Initial Injectivity [(l/min)/MPa]	Final Injectivity [(l/min)/MPa]	Change in injectivity	Detected events
08.02.2017	HS2	Inj1	797	38.0 - 40.0	0.018	1.6	89	14
09.02.2017	HS4	Inj1	1253	27.2 - 28.2	0.9	0.9	1	936
10.02.2017	HS5	Inj1	1211	31.5 - 32.5	0.086	0.4	5	96
13.02.2017	HS3	Inj1	831	34.3 - 35.3	0.0035	1.7	486	19
14.02.2017	HS8	Inj1	1258	22.0 - 23.0	0.002	0.54	270	39
15.02.2017	HS1	Inj2	982	39.8 - 40.8	0.0006	1.11	1850	6



Additional observations: fibre-optics sensors



Additional observations: Tilt meters



Conclusions

→ For more infos / data / discussions, please visit the poster of **Villiger et al., today, P1-18**

- Micro-seismic monitoring can resolve centimeter to meter scale fracturing processes.
- Strong variability in seismicity and hydro-mechanical response in a small rock volume.
- Our induced seismicity data set is complemented with many other observations.
- More data, more analysis, more conclusions next time we meet!!!