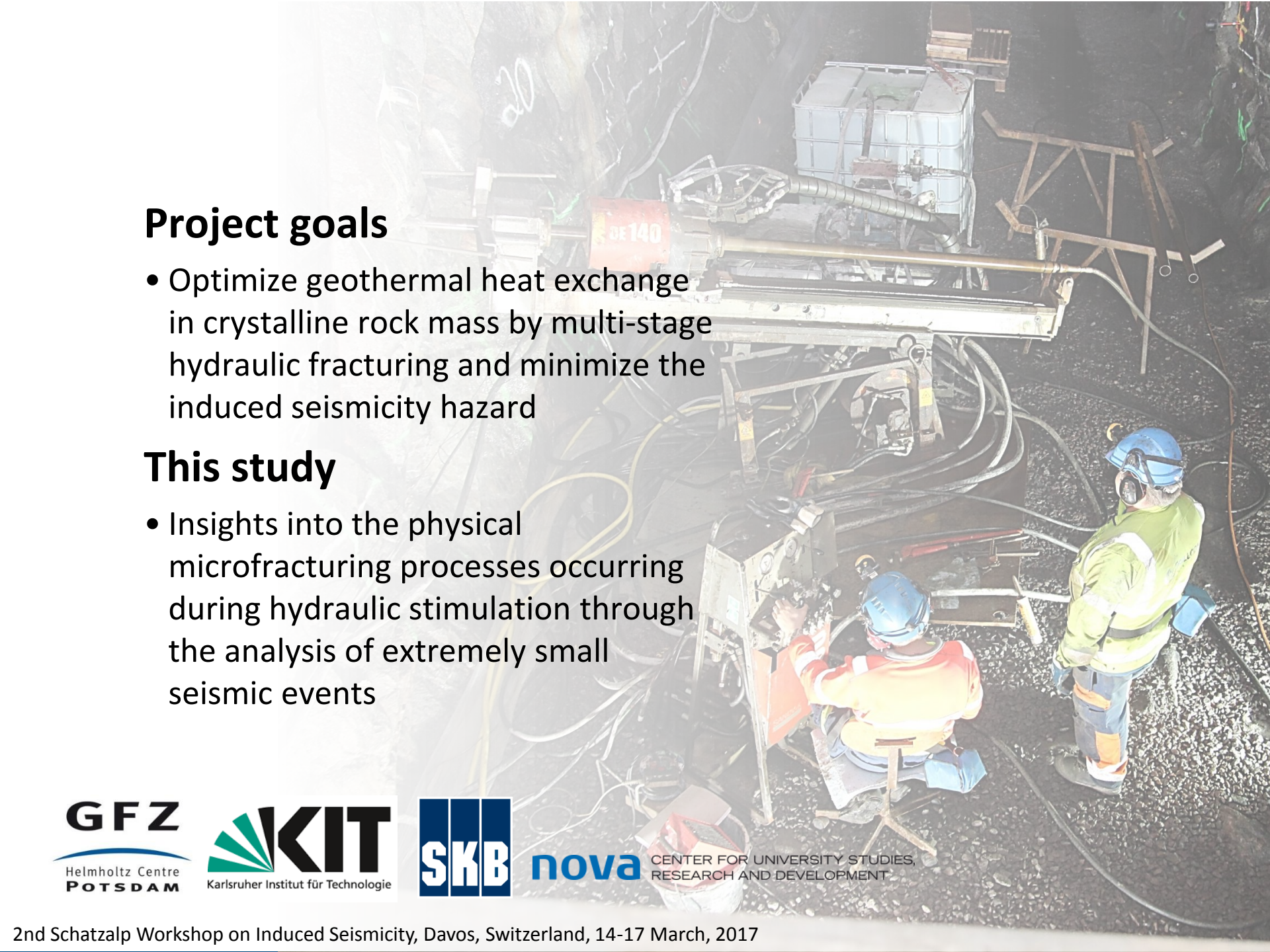
Insights into subdecimeter fracturing processes during the hydraulic fracture experiment in Äspö hard rock laboratory, Sweden

G. Kwiatek[1], P. Martínez-Garzón[1], K. Plenkers[2], M. Leonhardt[1], A. Zang[1], G. Dresen[1,3], M. Bohnhoff[1,4]

1. Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences
2. GMuG Gesellschaft für Materialprüfung und Geophysik mbH
3. University of Potsdam, Potsdam, Germany
4. Free University Berlin, Berlin, Germany



Project goals

- Optimize geothermal heat exchange in crystalline rock mass by multi-stage hydraulic fracturing and minimize the induced seismicity hazard

This study

- Insights into the physical microfracturing processes occurring during hydraulic stimulation through the analysis of extremely small seismic events

GFZ Helmholtz Centre Potsdam

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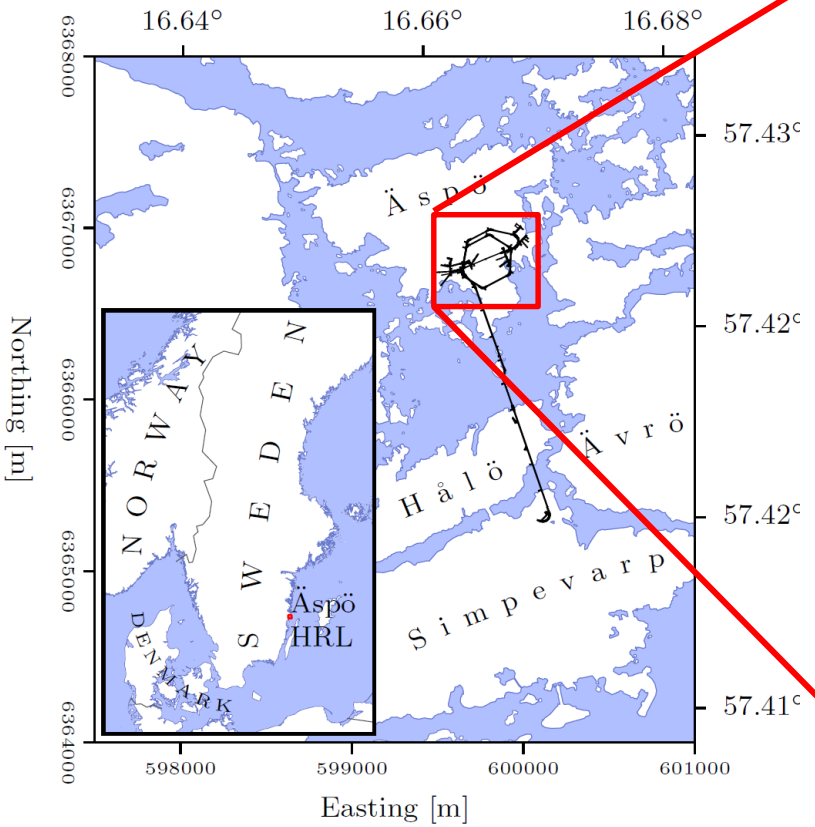
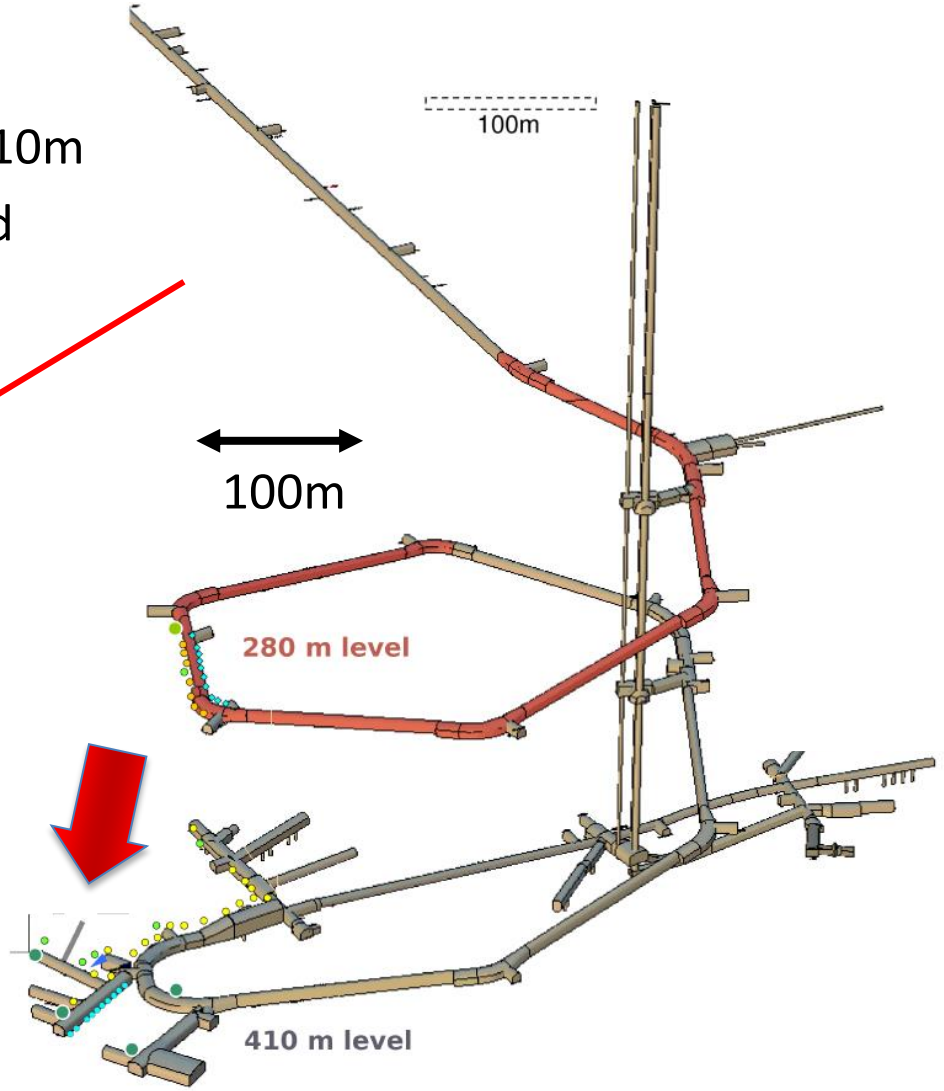
Äspö Hard Rock Laboratory

- Underground test site at a depth of 410m
- Rocks: Ävrö Granodiorite, fine-grained diorite-gabbro, granite

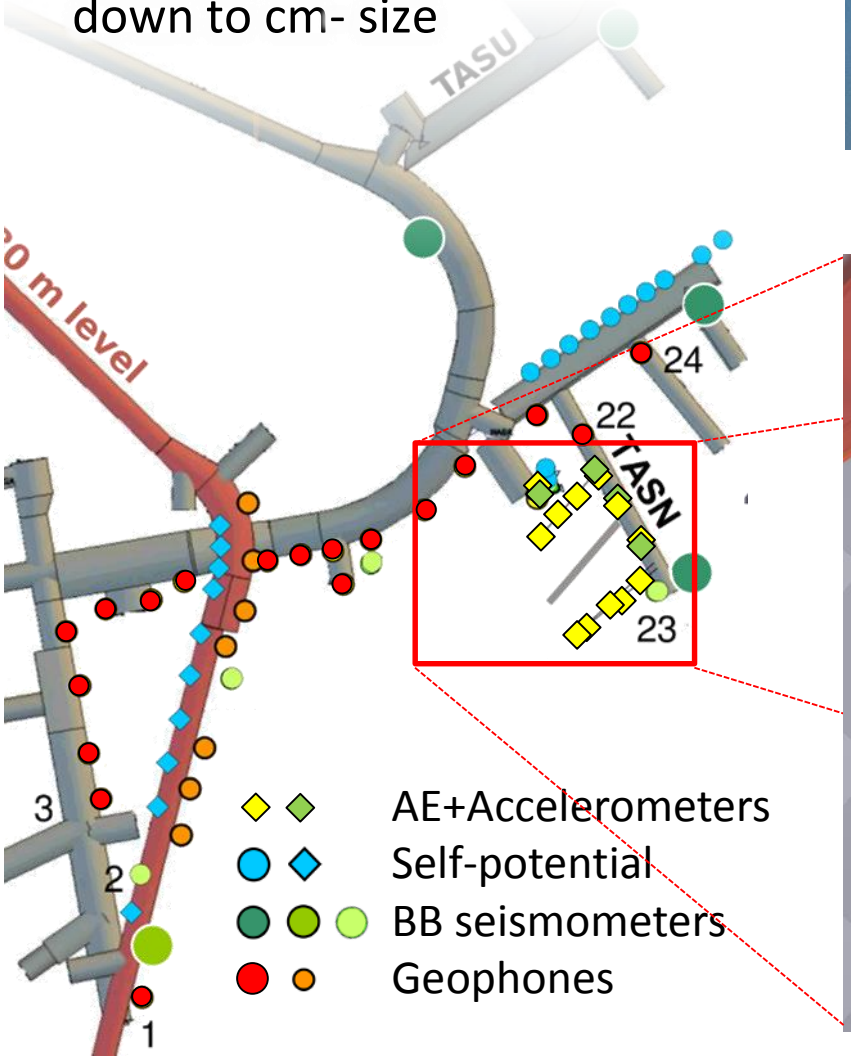


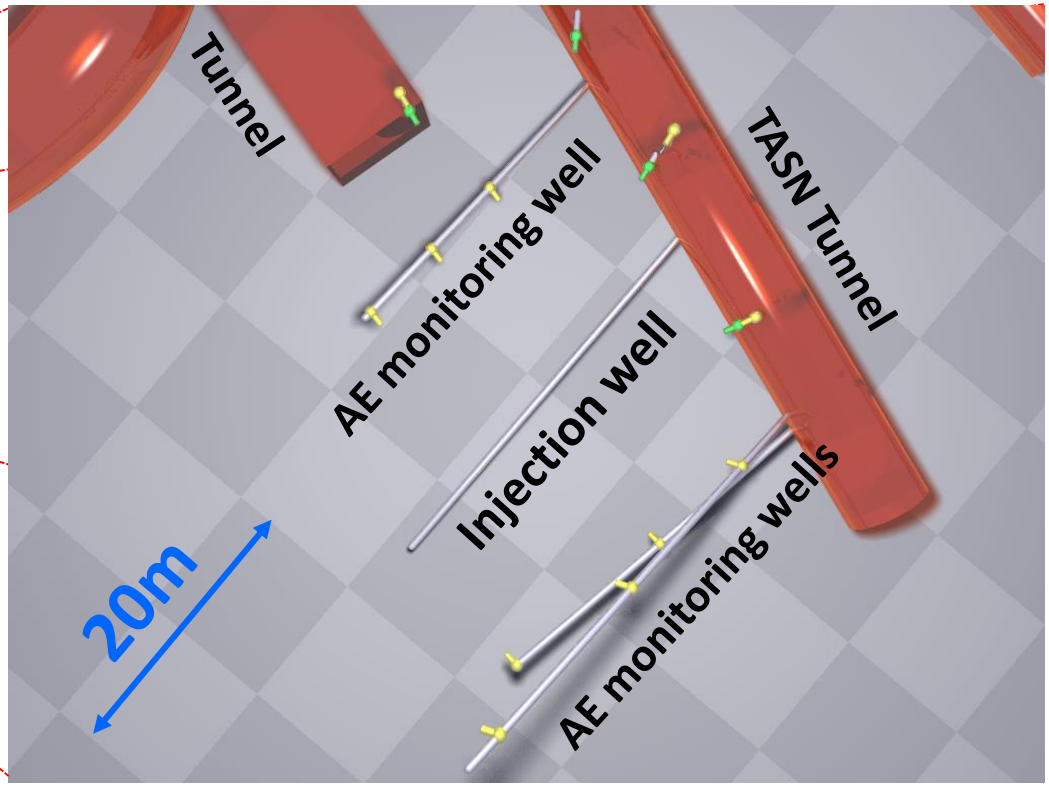


Modified after: Zang et al., GJI, 2017

Monitoring microfractures

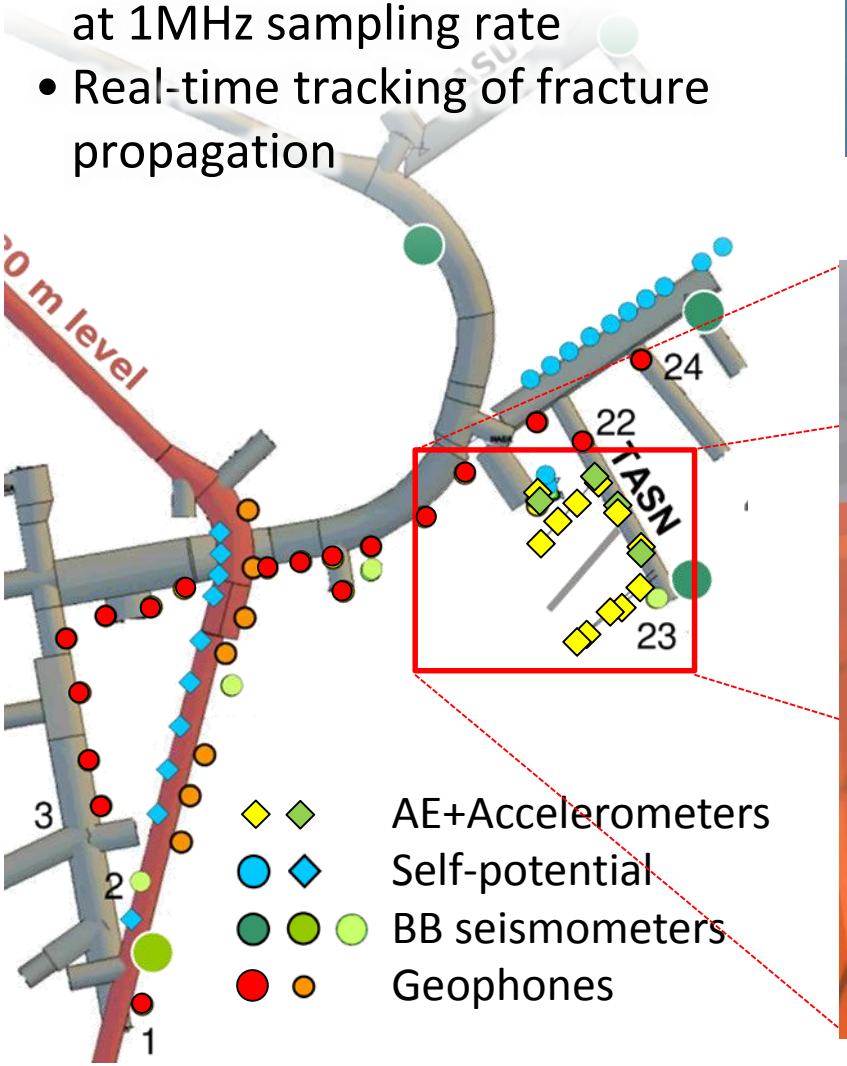
- Seismic monitoring using different networks
- Monitoring of fractures from km- down to cm- size

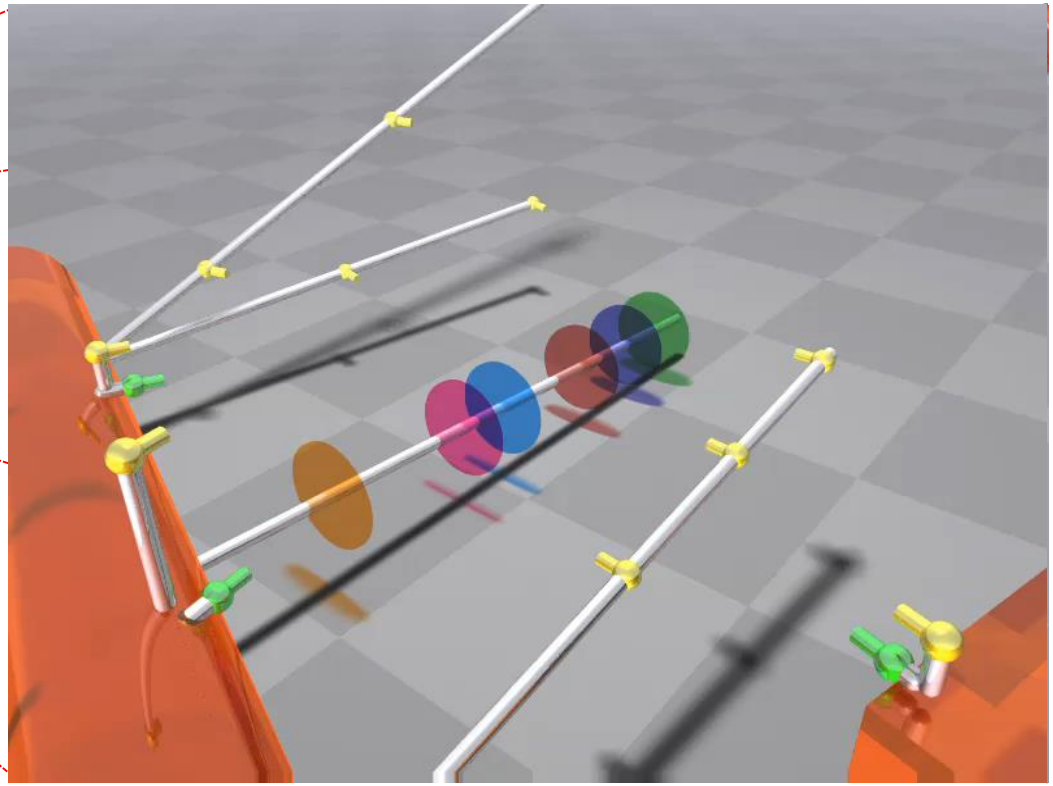




High frequency network

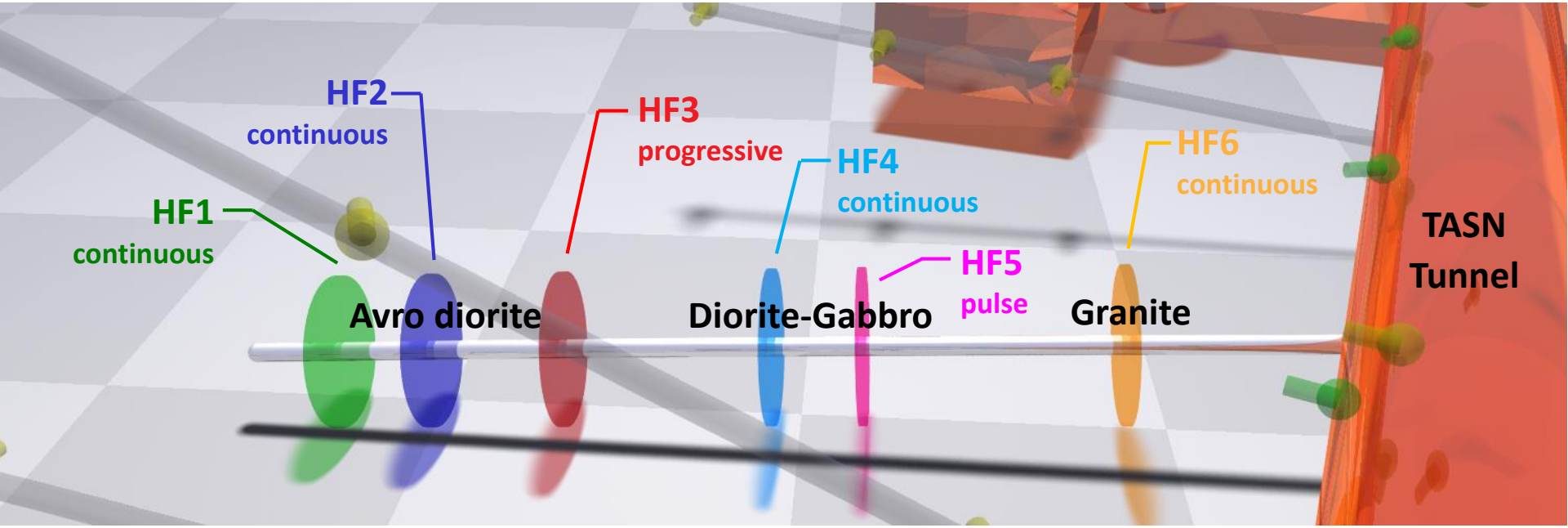
- 11 AE sensors (1-100kHz) and 4 accelerometers (<25kHz)
- Continuous/triggered acquisition at 1MHz sampling rate
- Real-time tracking of fracture propagation





Fluid injection

- 28m length borehole subparallel to S_h
- 6 stimulations in 3 rock formations
- 3 different injection schemes
- Up to 5 refracs in each stimulation
- Up to 30l injected at $Pinj^{max}$=13MPa



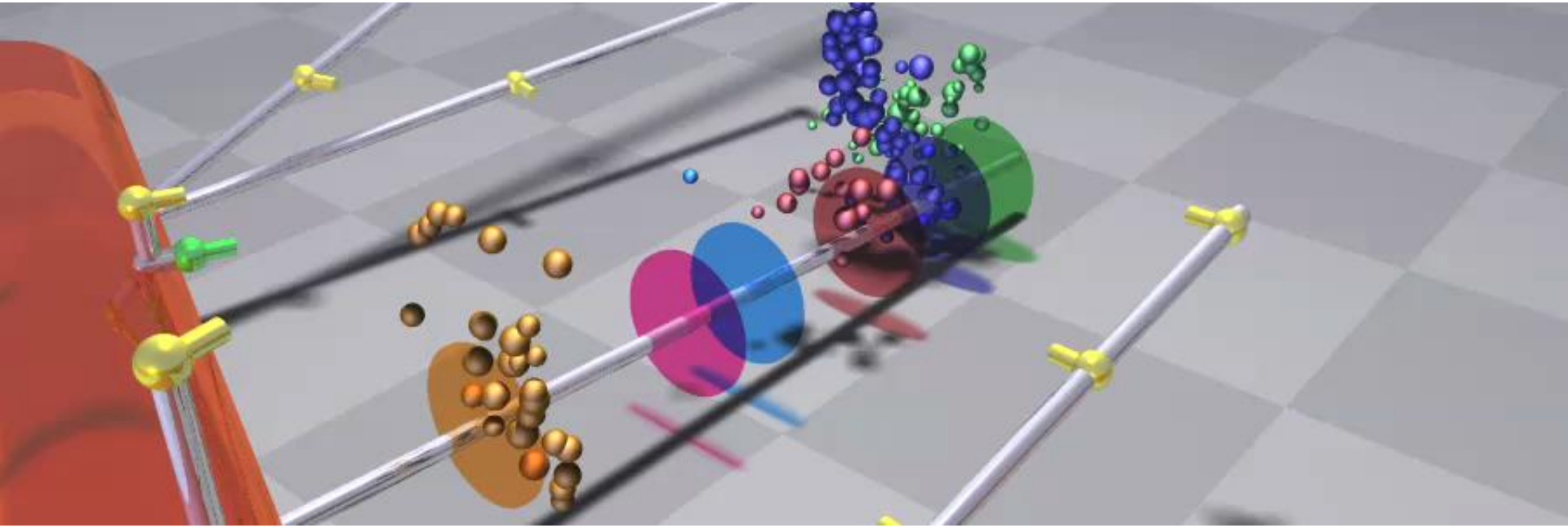
HF1 continuous, HF2 continuous, HF3 progressive — Avro granodiorite

HF4 continuous, HF5 pulse — Diorite-Gabbro

HF6 continuous — Granite

Microfracturing overview

- 200 AE events (M_W -4.2 to -3.5)
  - ⏩ see also *López-Comino et al.* (this workshop)
- Activity changes with injection type and refrac number
- Seismicity during stimulations and shortly after (P_{inj}>8MPa=S_3)
- Quasilinear (d=1.71) upward expansion

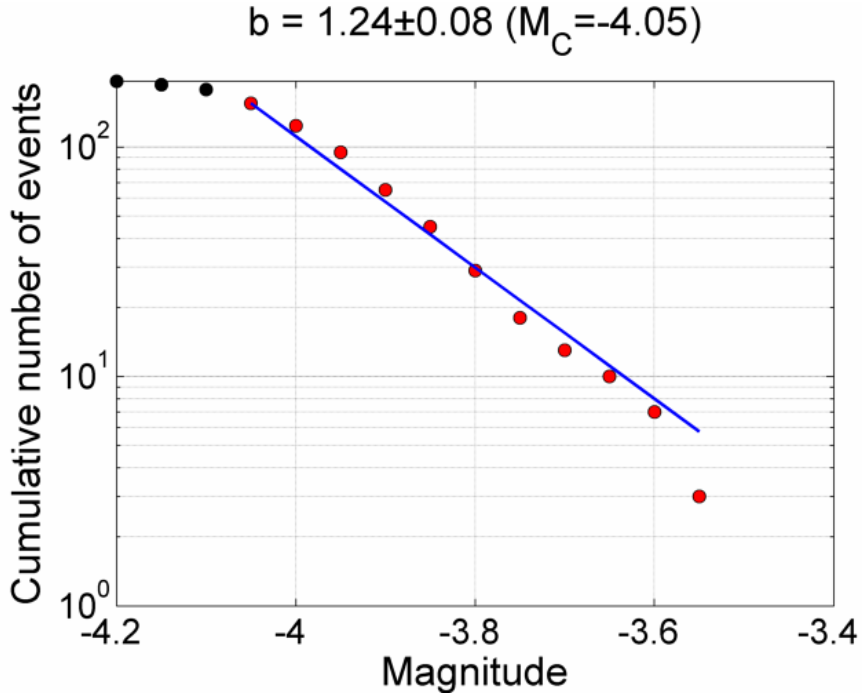


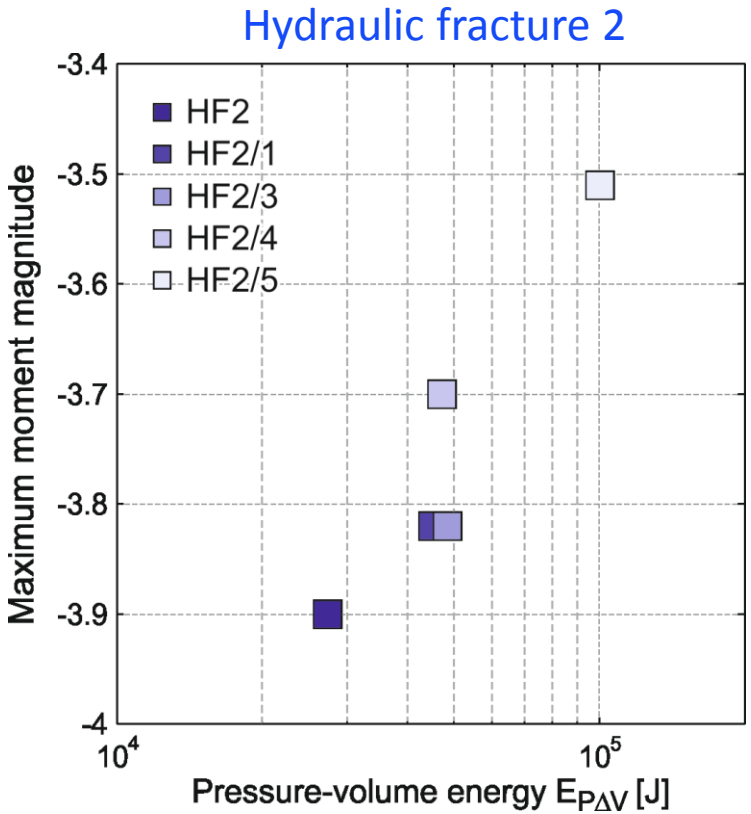
HF1	HF2	HF3	HF4	HF5	HF6
continuous	continuous	progressive	continuous	pulse	continuous
□ ■■■■■	■ ■□■■■	□ □□■■	□ ■□□	□ □□□	■ ■■■

▲ Seismic activity during fracs and refracs: □ No activity ■ Activity

General characteristics of all AE events

- Magnitude-frequency: *b*=1.24
- Correlation of maximum magnitude with injection energy ($P \times \Delta V$)

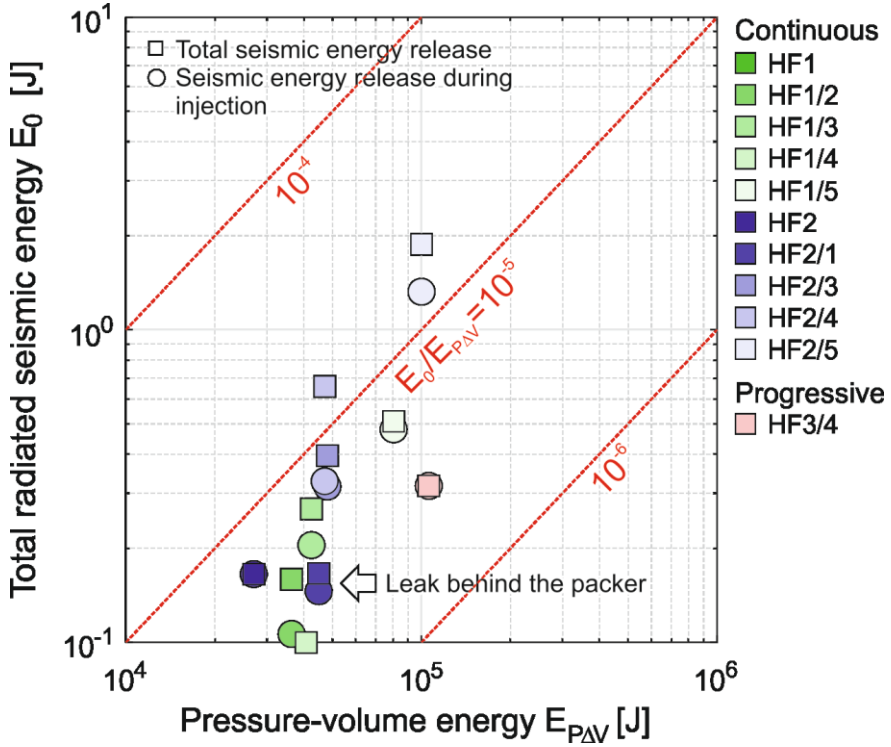


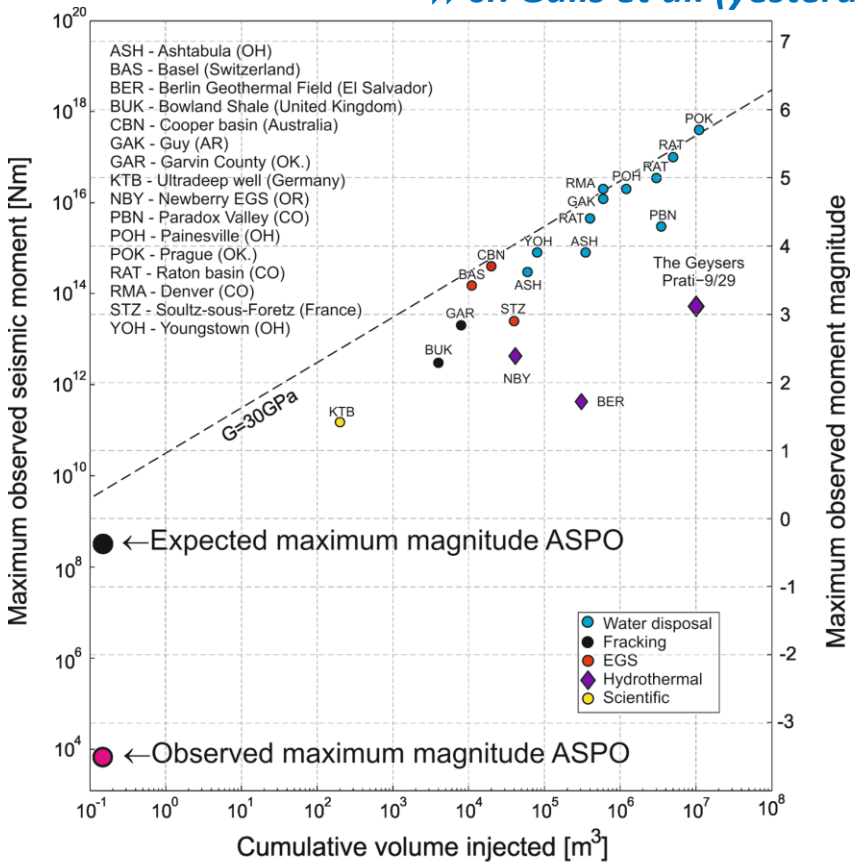


Low seismic energy release

- Low seismic efficiency of 10^{-5} (natural earthquakes: ~0.01)
- Continuous and progressive stimulations results in similar seismic efficiency
- Observed M_W^{max} low (-3.5) compared to McGarr's model (-0.21)

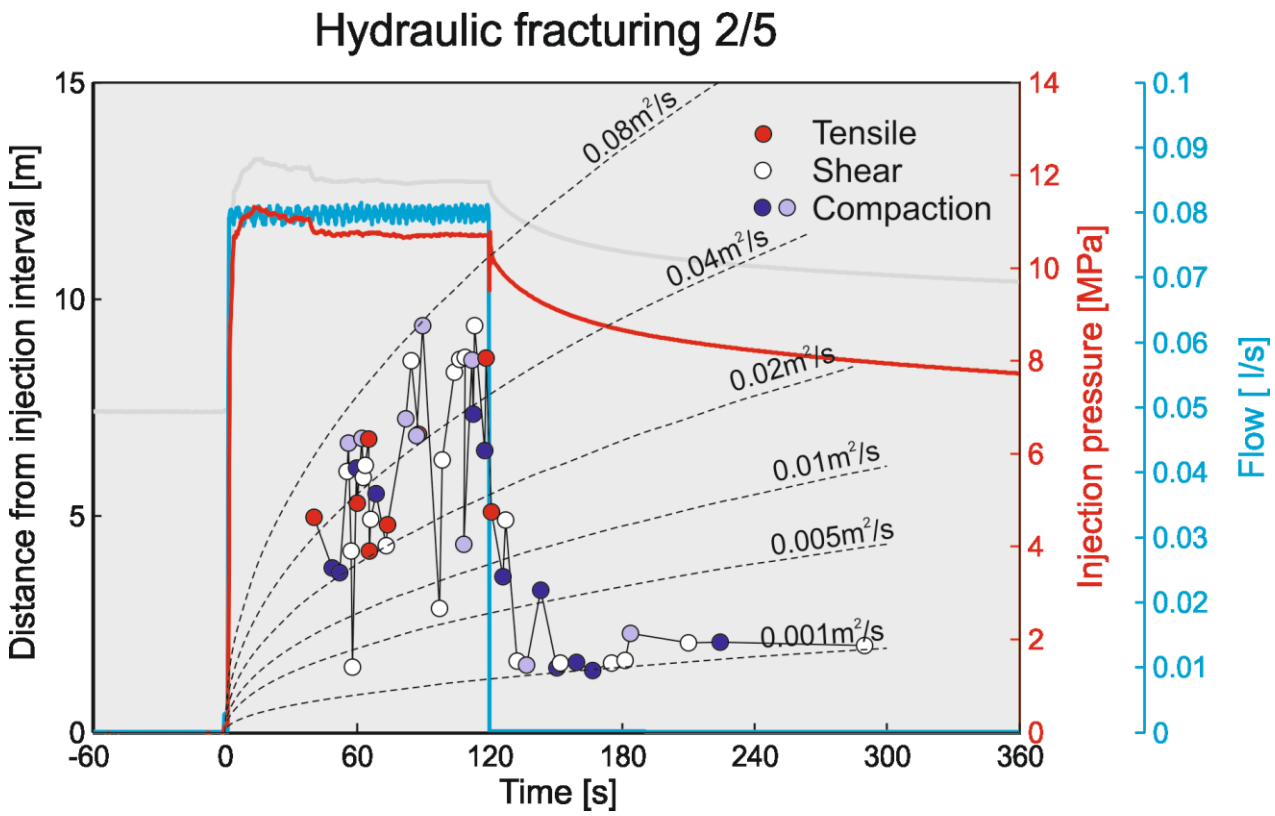
cf. *Galis et al. (yesterday)*

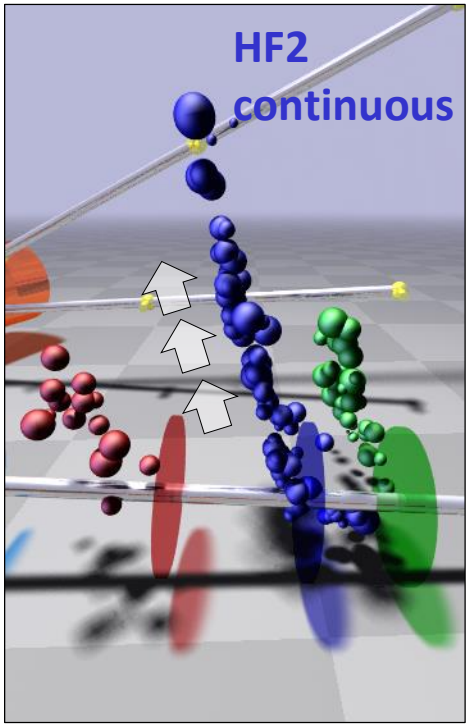




Spatio-temporal behavior

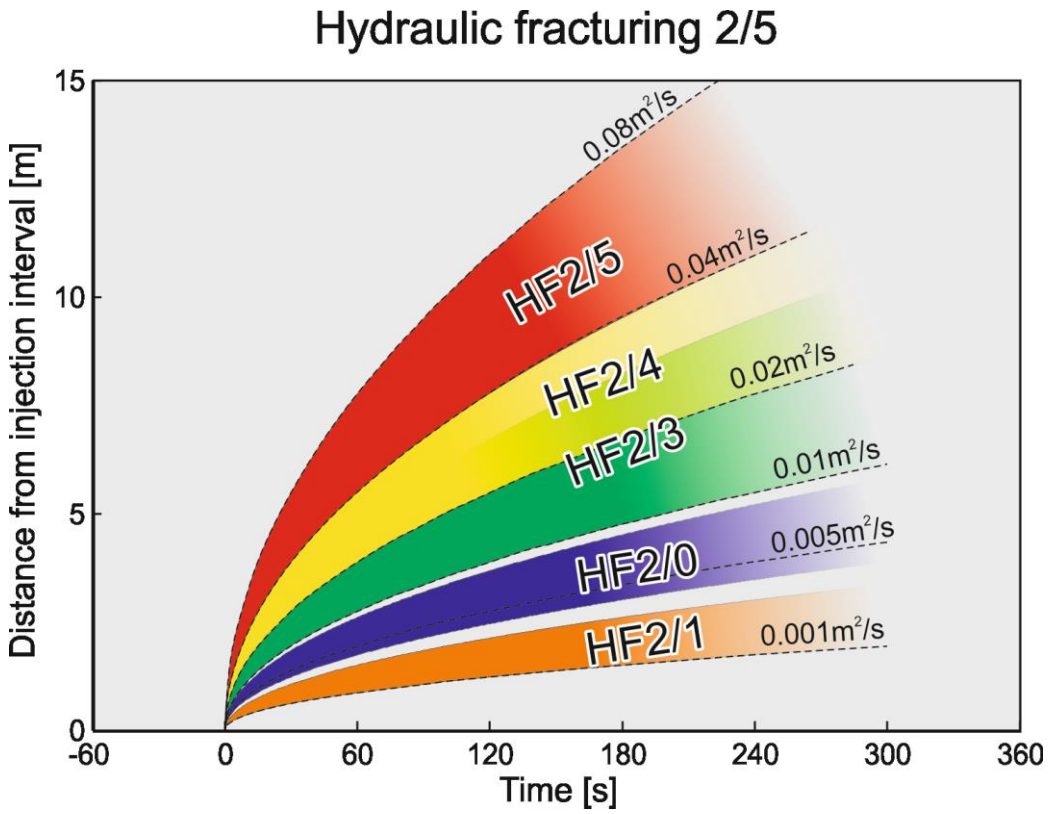
- Upward propagation of AEs during injection / retreat of AEs after shut-in
- Transition from shearing, crack opening, compaction (injection) to crack closing and shearing (after shut-in)

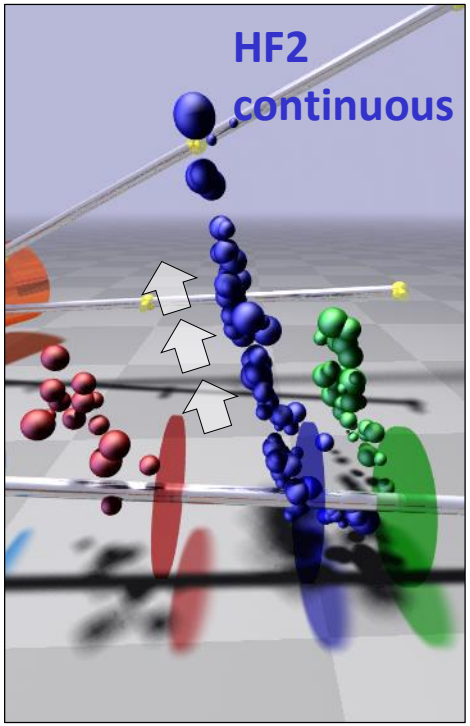




Apparent hydraulic diffusivity changes

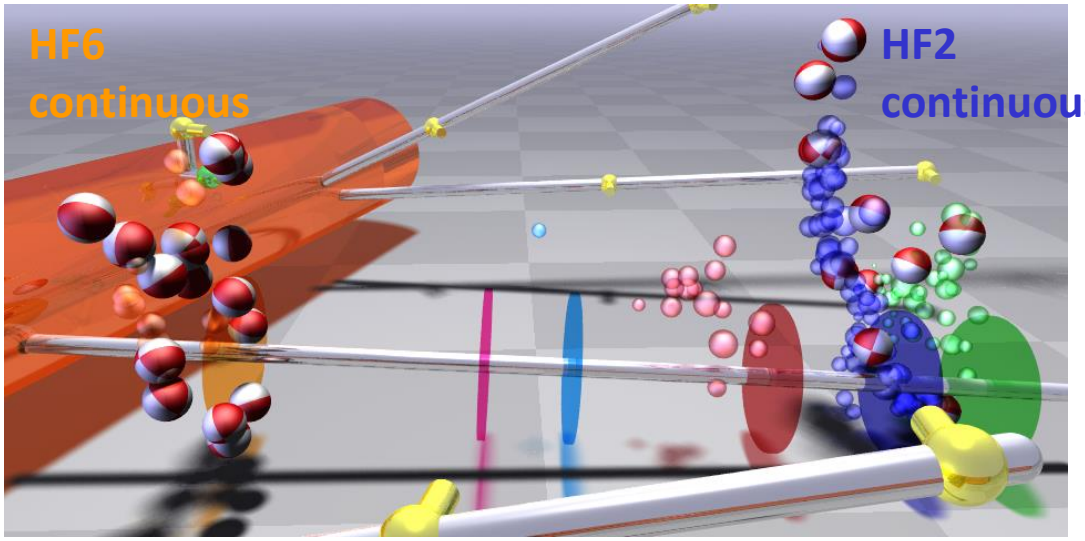
- Subsequent stimulations lead to faster propagating seismicity reaching larger distances ▸ increase of damage and permeability
- Increased apparent hydraulic diffusivity for HF2 from 0.005m²/s ▸ 0.08m²/s



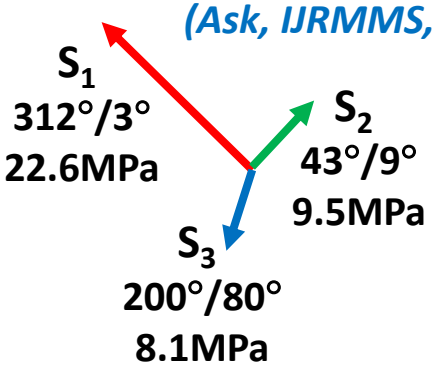


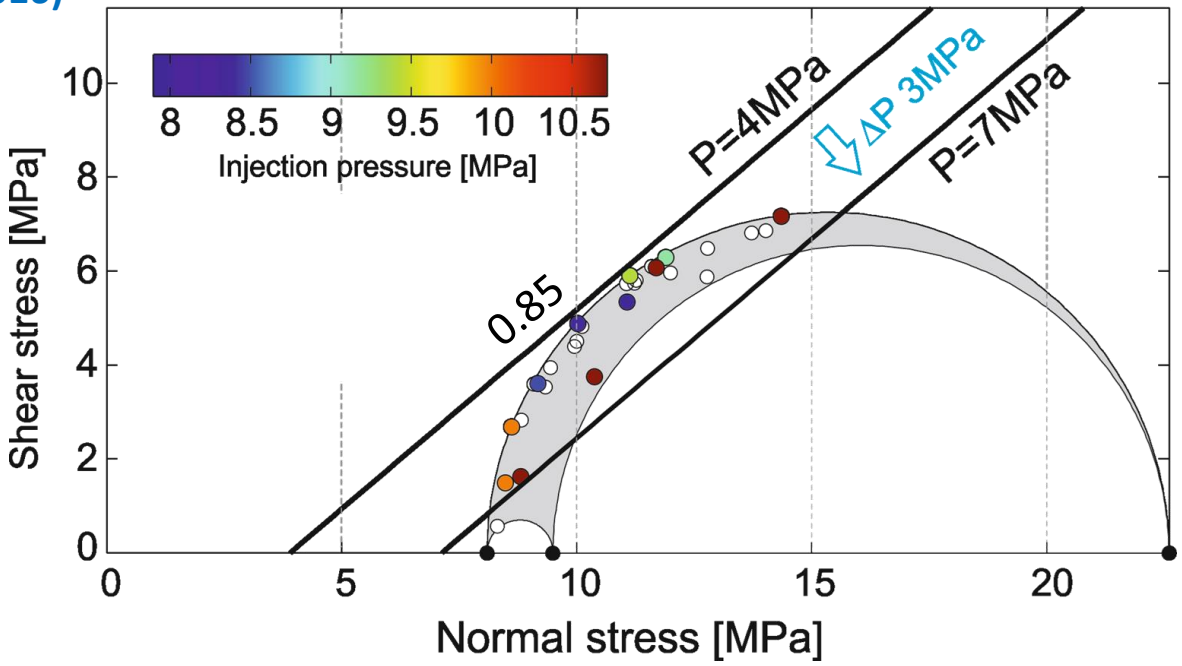
AE mechanisms and injection/pressure changes

- Limited focal mechanism data
  - **hybridMT software package**
    ***Kwiatek et al.* (SRL, 2016)**
- Complexity of faulting
- Fault planes mostly critically stressed
- EQs with less optimally oriented planes at higher injection pressures
  - ***Martínez-Garzón et al.* (JGR, 2016)**



Stress tensor from overcoring
(Ask, IJRMMS, 2006)



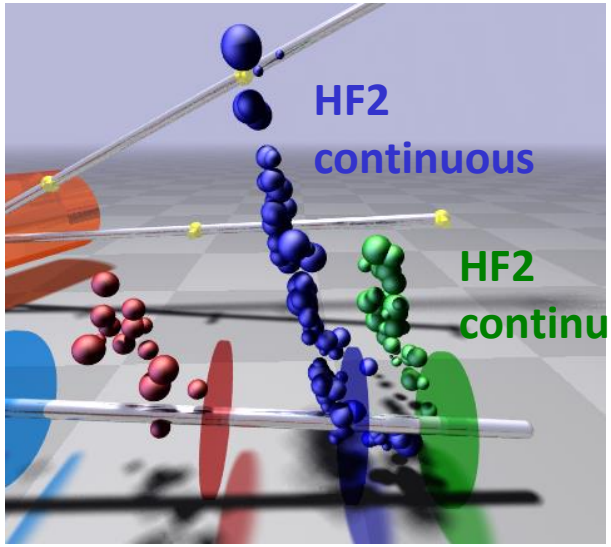


Stress tensor vs injection

- Using aggregated polarity data from similar refracs and stress inversion from P-wave polarities
- Post-injection AE data reproduce stress tensor orientation from overcoring
- Different stress tensor for injection period

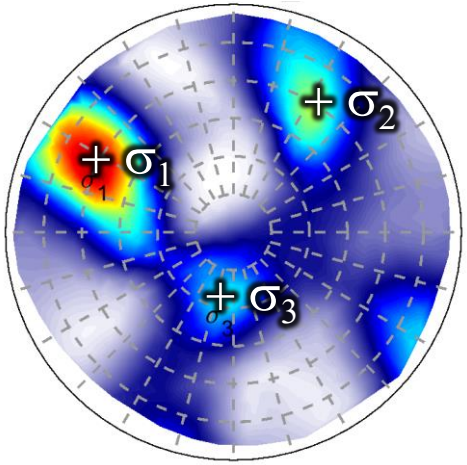
⏩ *Martínez-Garzón et al.* (GRL, 2013)

⏩ *Ziegler et al.* (this workshop)



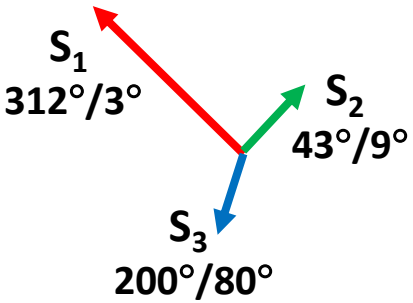
Post-injection

HF2/4+HF2/5



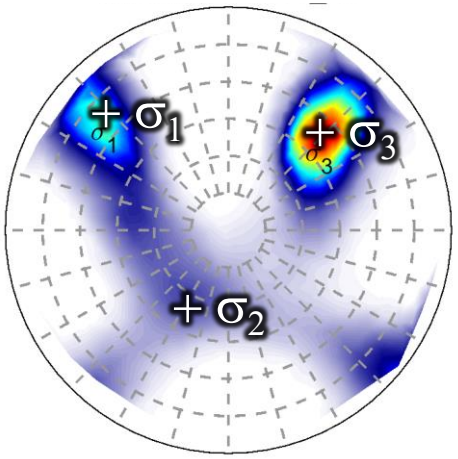
Overcoring

(Ask, IJRMMS, 2006)



Injection

HF1/3+HF1/5+HF2/4+HF2/5



Summary and conclusions

- Successful tracking of microfractures evolution of M_W-4.2 to -3.5 (cm-dm) size only observed with AE acqusition system.
- Seismic activity is observed during stimulations and shortly after with . The seismic energy release is extremely low with respect to the injected volume. No significant difference in seismic energy release between continuous and progressive injection.
- Correlation of injection operations with seismic moment release and maximum magnitude.
- Spatial and temporal evolution of AE activity signify increased rock damage and permeability enhancement.
- Shear-type mechanisms abundant. AE mechanisms respond to injection operations with fracture opening observed predominantly during stimulation and compaction occurring after shut-in.
- The fault planes are heterogeneous, but display favorable orientations with respect to the stress field. Less favorable oriented planes are observed at higher injection pressures.

Thank you for your attention!

Contact: kwiatek@gfz-potsdam.de

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