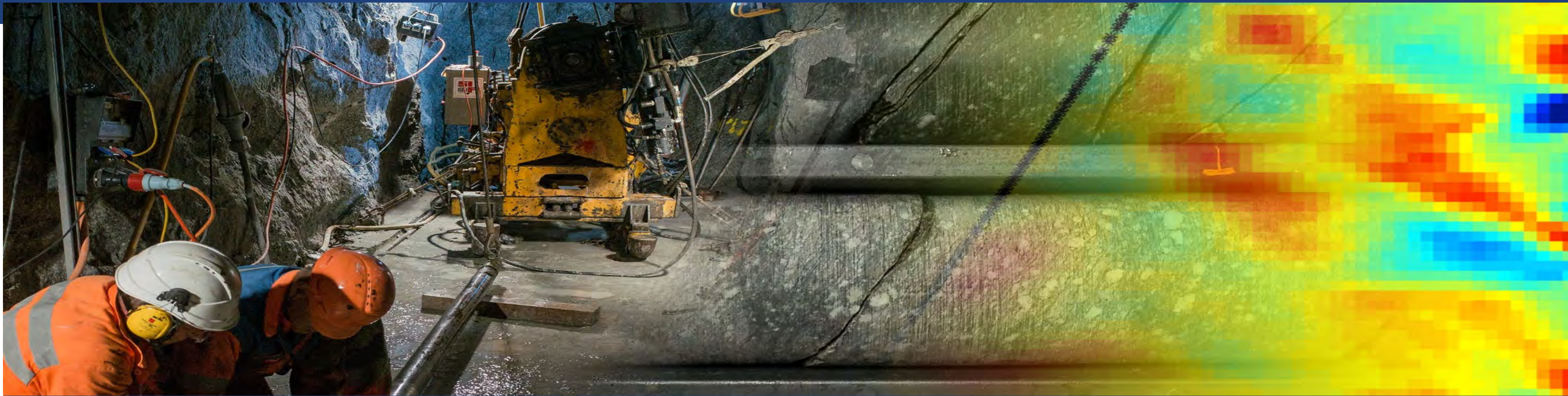
ETH zürich



Influence of reservoir geology on seismic response during decameter scale hydraulic stimulations in crystalline rock at Grimsel

SCCER-SoE annual conference, 04.09.2019

L. Villiger, V. Gischig, J. Doetsch, H. Krietsch, N. Duthler, M. Jalali, B. Valley, F. Amann & S. Wiemer

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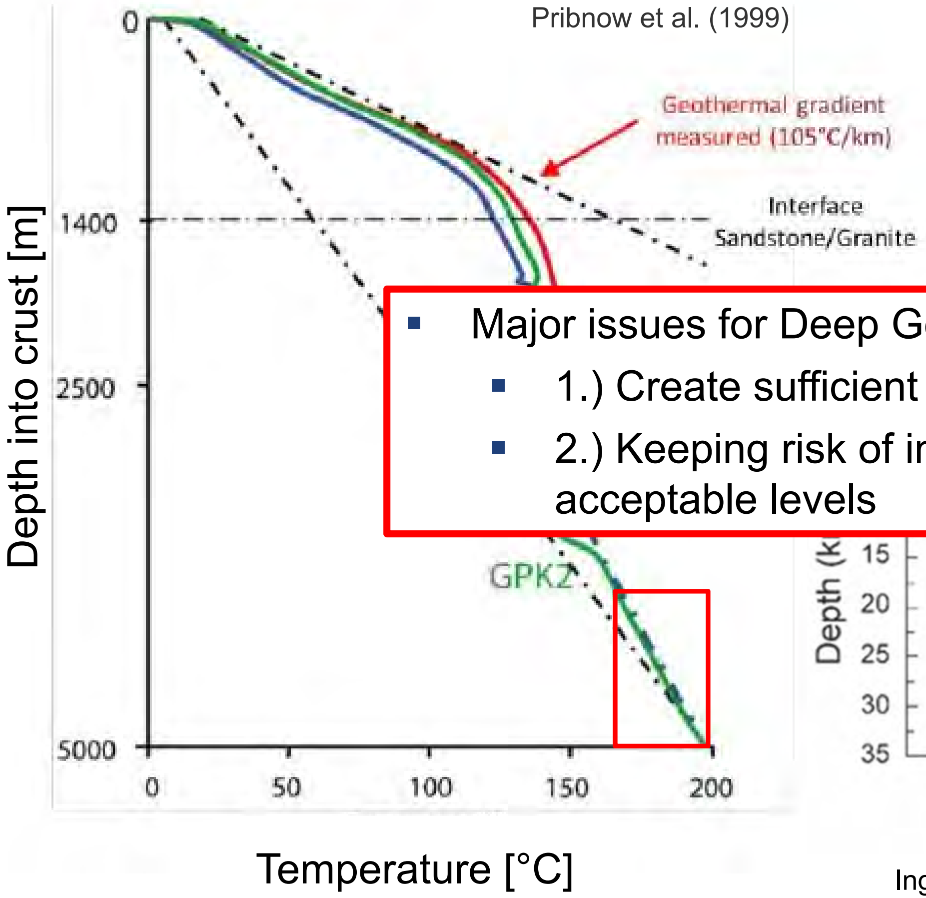
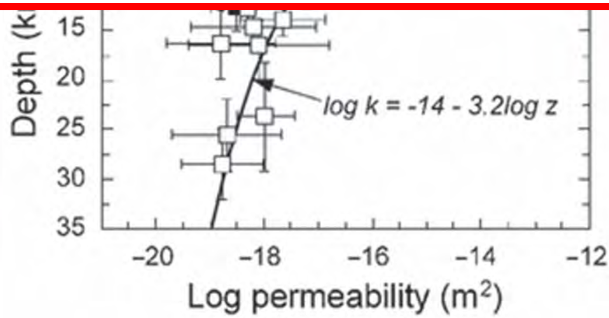
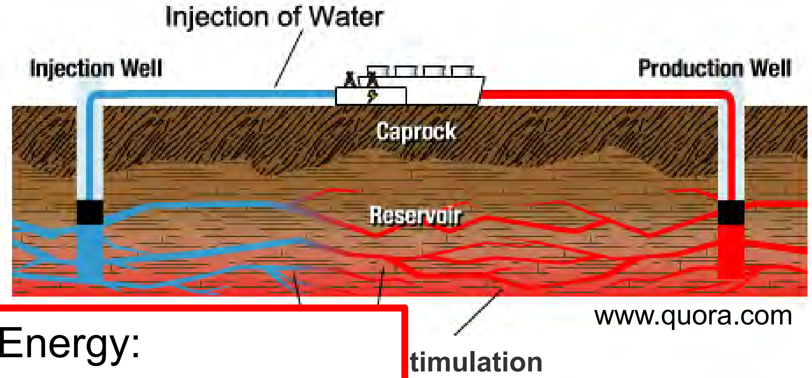
Harvesting deep geothermal energy

- Major issues for Deep Geothermal Energy:
  - 1.) Create sufficient heat exchanger
  - 2.) Keeping risk of induced earthquakes at acceptable levels





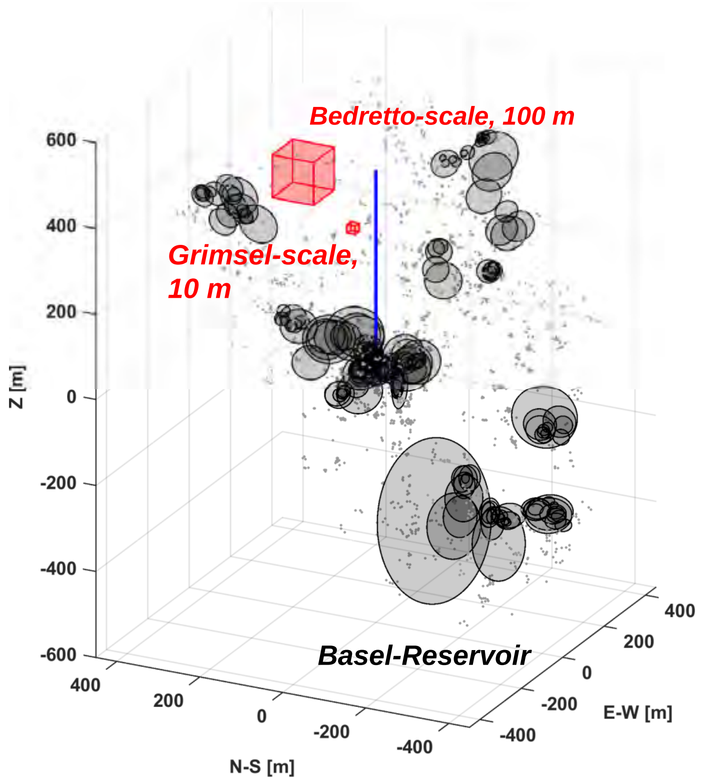
Ingebritsen, 1999

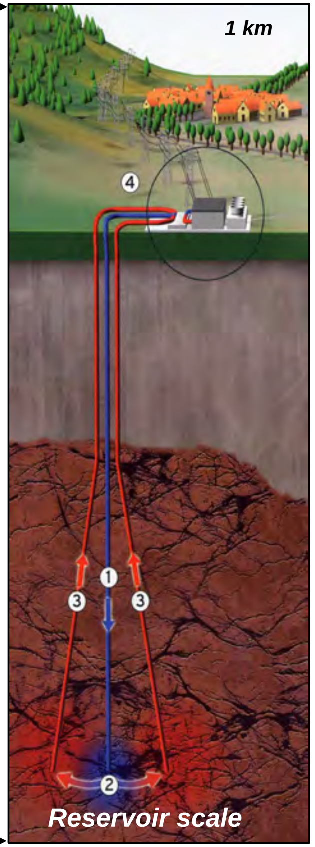


www.quora.com

Debris of collapsed wall after the Pohang 5.5 mag. eq. in 2017 (source: www.eenews.net)

Why do we need in-situ experiments?





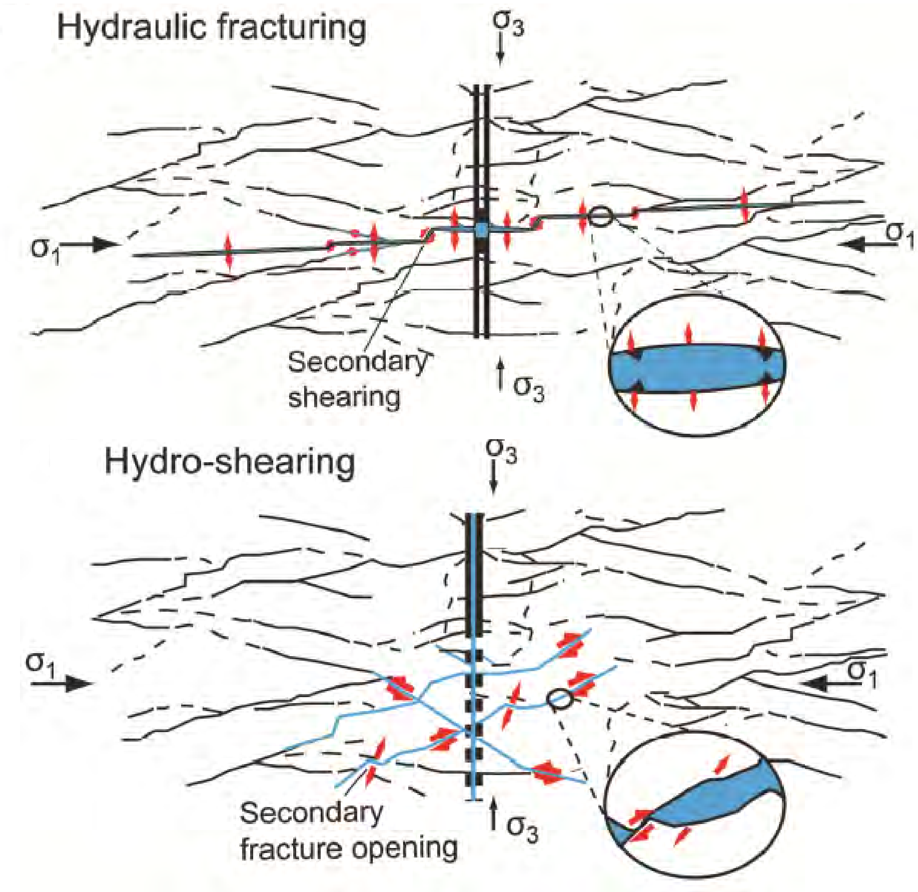
Scaling questionable

++ accessibility, controllability
-- lag realistic boundary conditions

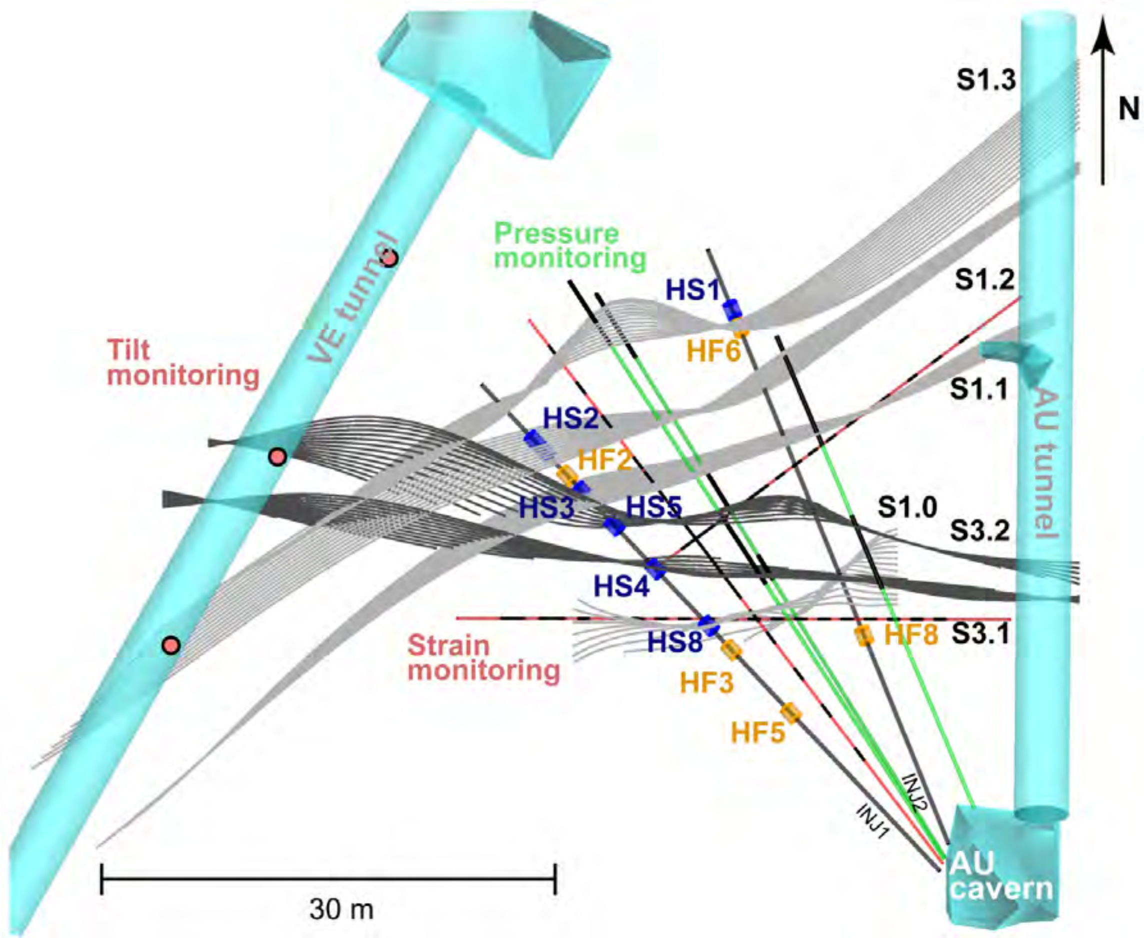
In-situ scale:
+ accessibility, controllability
- more realistic boundary conditions
  + geological, stress field complexity
  - temperature and stress level different

-- accessibility, controllability
++ realistic

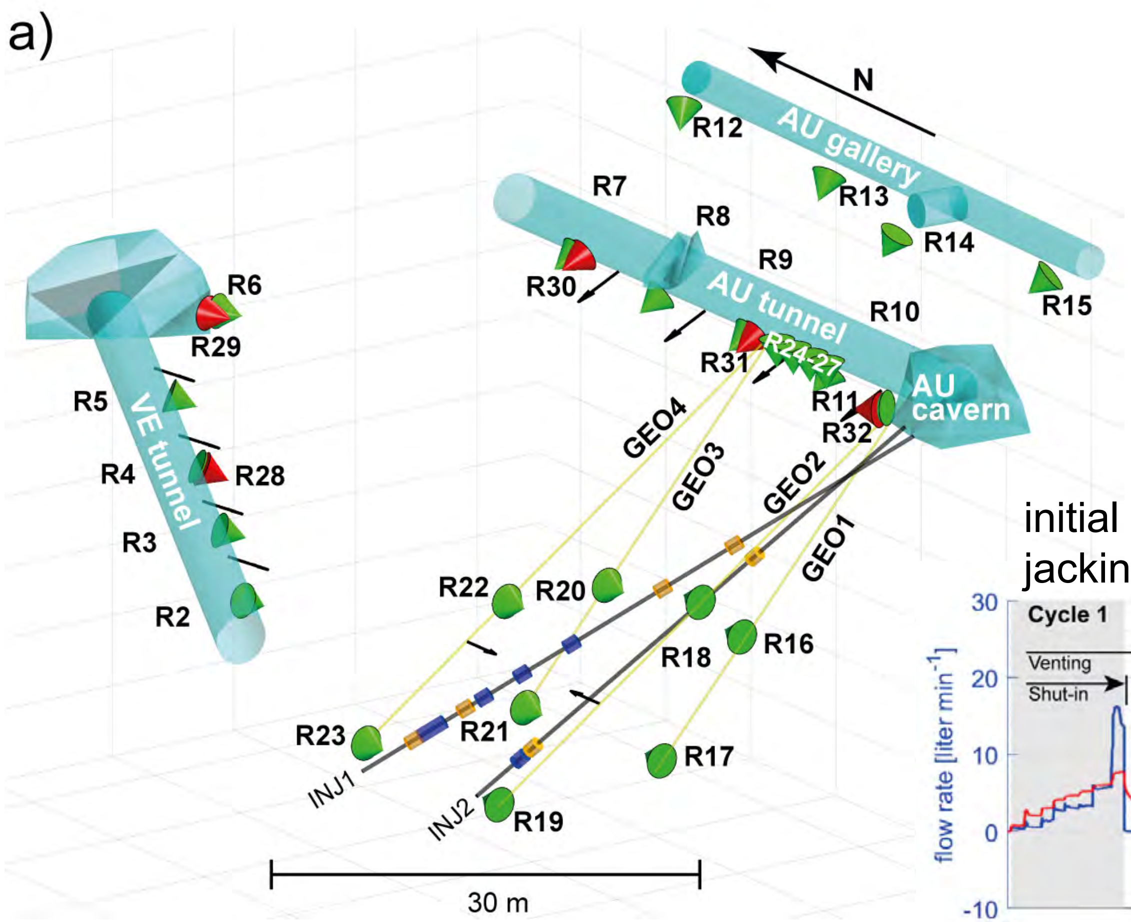
The hydraulic stimulation experiments at Grimsel



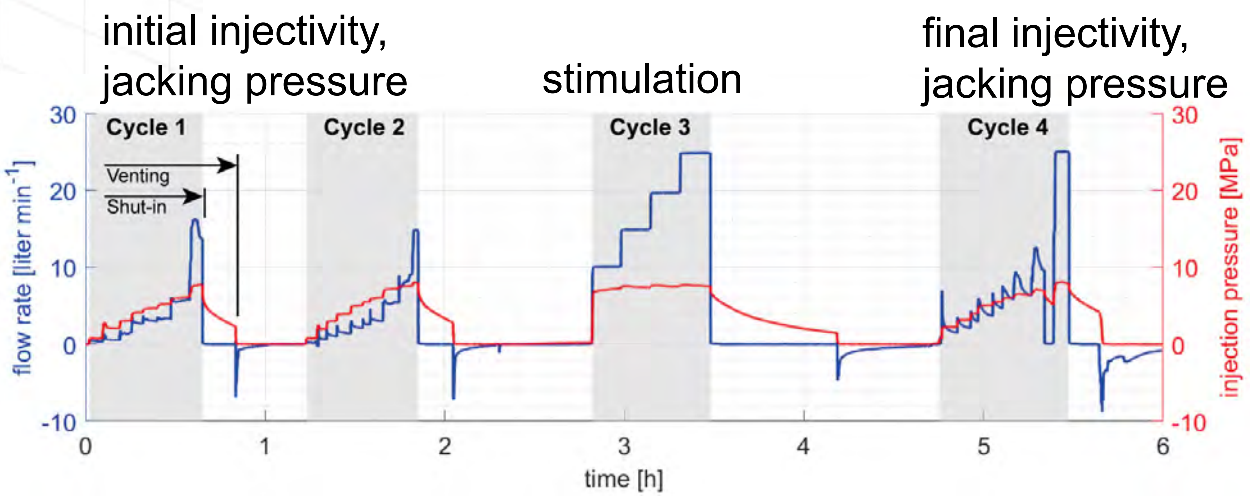
Gischig and Preisig, 2015



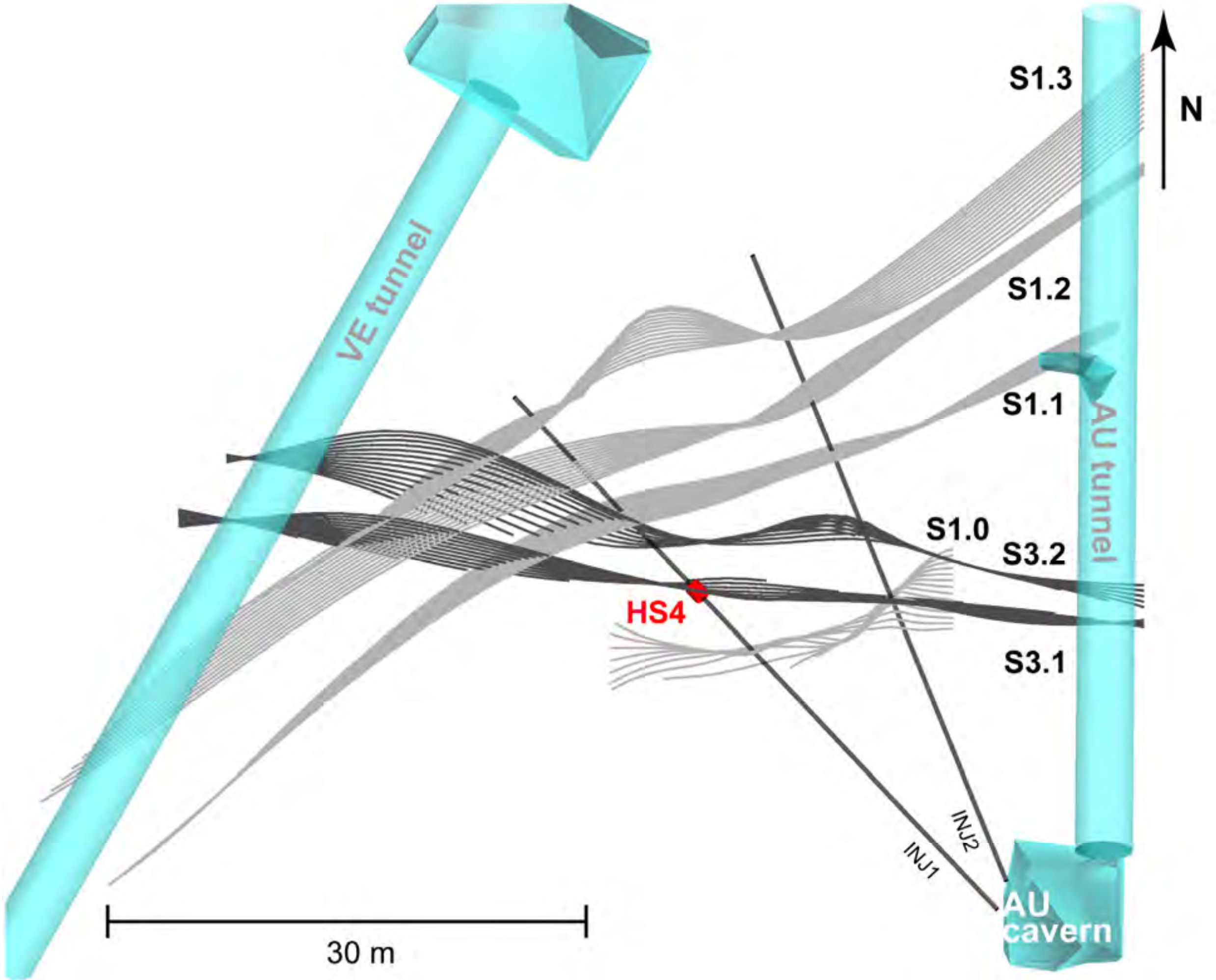
The seismic monitoring network

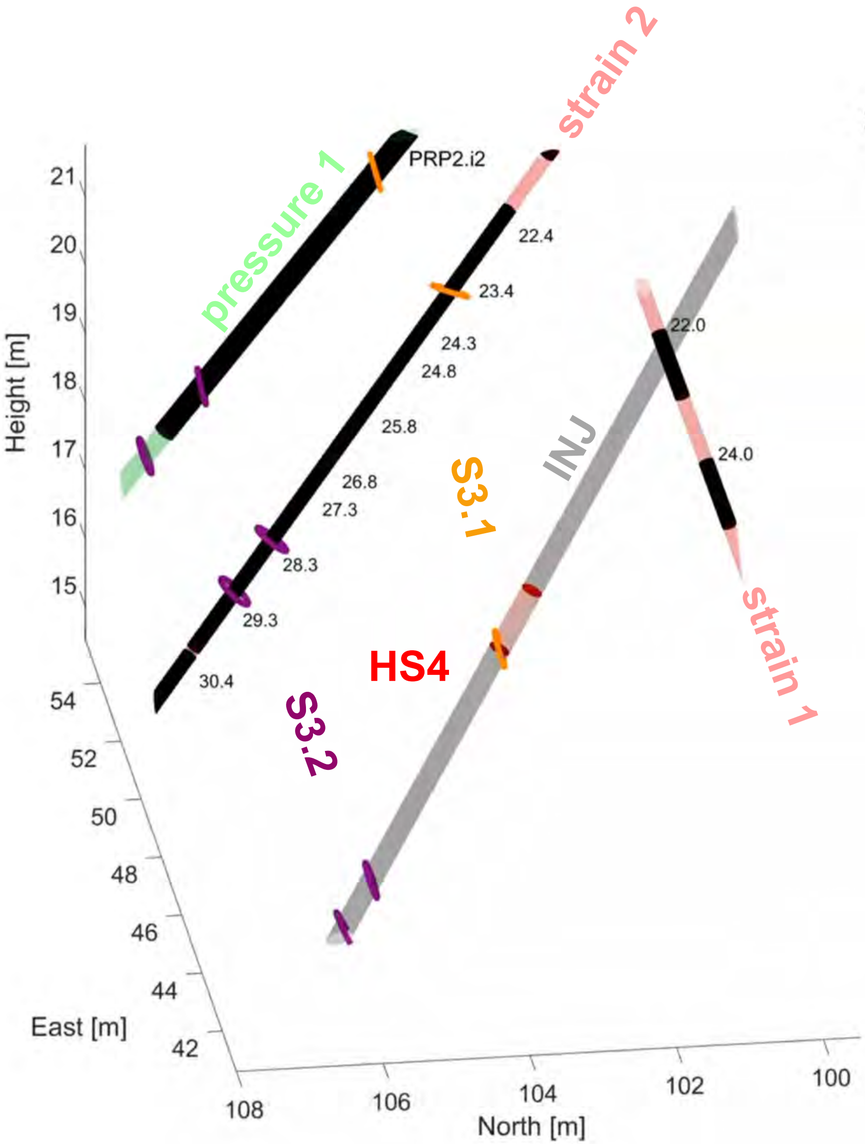


- 26 uncalibrated acoustic emission sensor (green cones)
  - 8 installed in boreholes surrounding the injection intervals
- 5 calibrated accelerometer on a tunnel level (red cones)

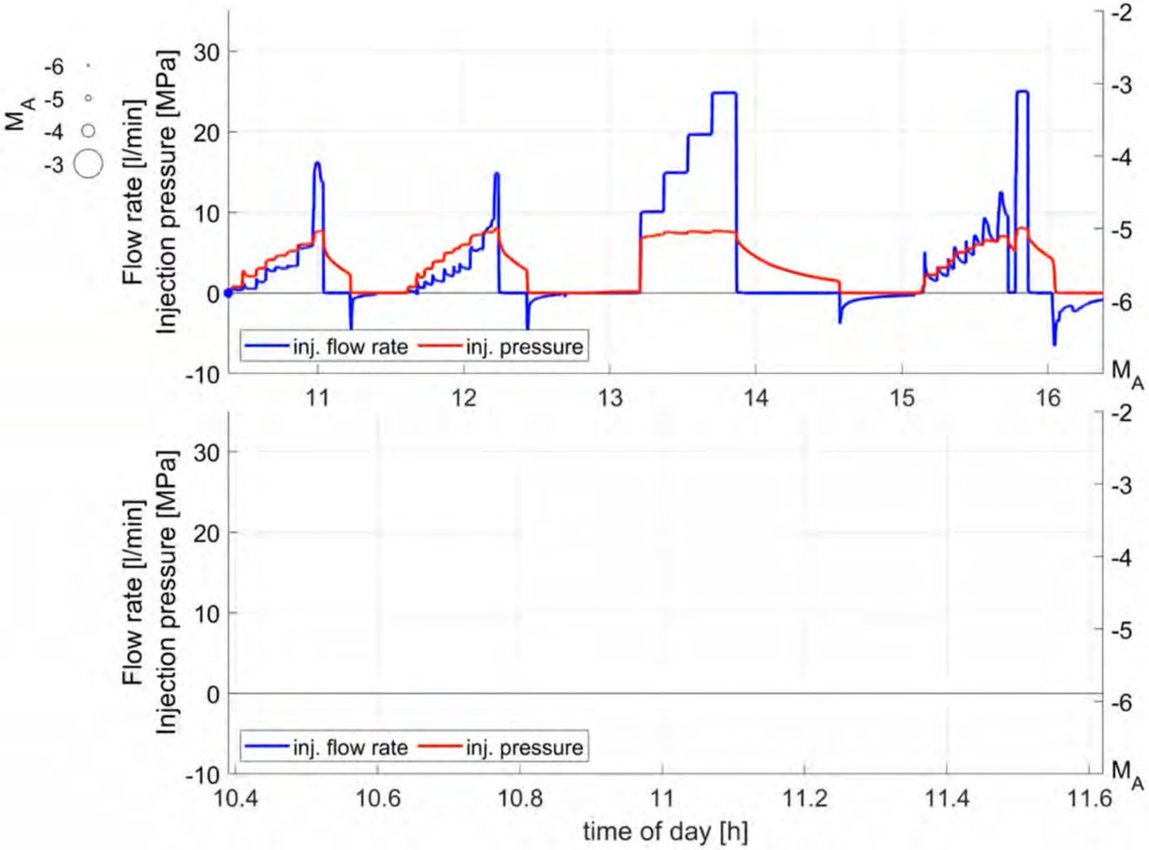


Experiment HS4 in shear zone S3.1

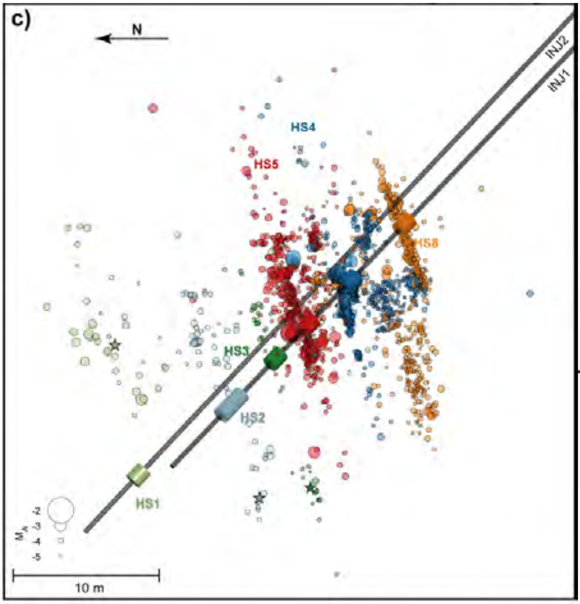




pressure 1
strain 2
PRP2.i2
22.4
23.4
24.3
24.8
25.8
26.8
27.3
28.3
29.3
30.4
22.0
24.0
INJ
S3.1
HS4
S3.2
strain 1
Height [m]
East [m]
North [m]
M_A



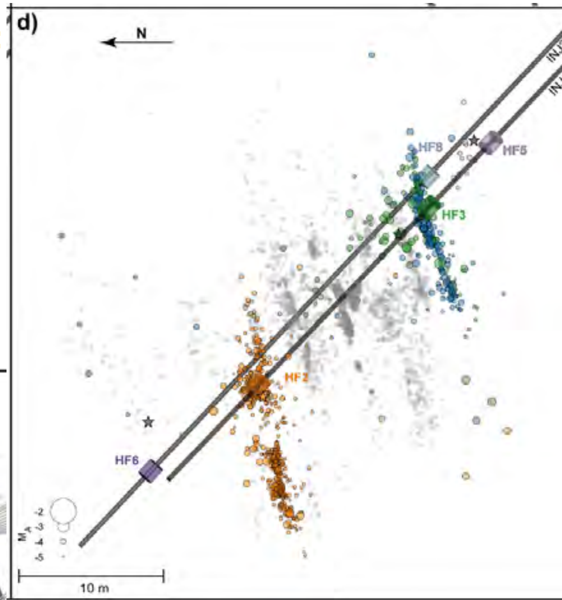
Flow rate [l/min]
Injection pressure [MPa]
inj. flow rate
inj. pressure
M_A
time of day [h]



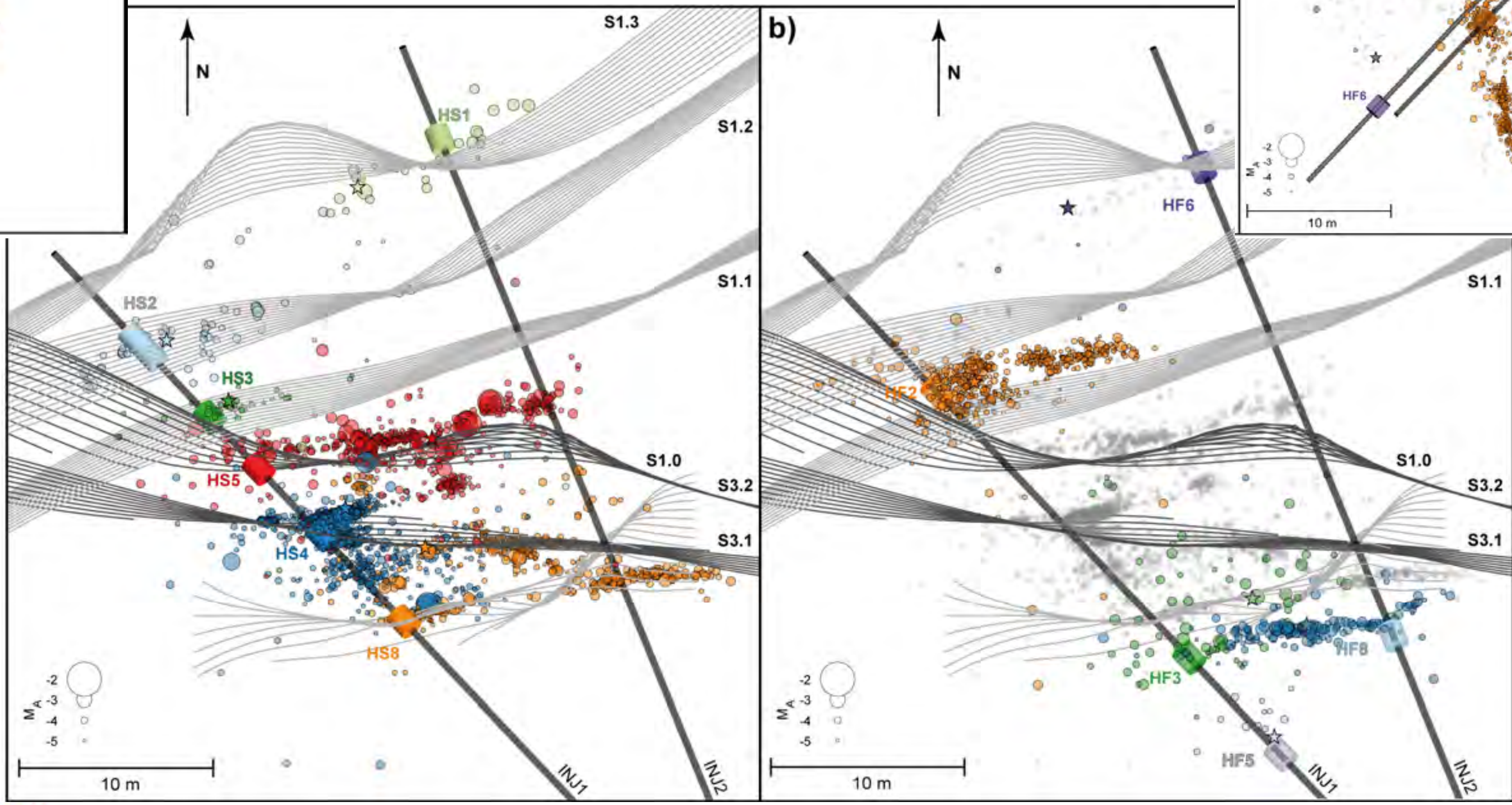
Side view

Hydro-shearing experiments:
- seismicity generally constrained to shear zones
- more seismic events in higher transmissive S3 shear zones
- evenly distributed seismicity S1 stimulations
- more clustery character of S3 stimulations

Hydrofracturing experiments:
- seismicity preferentially propagates downwards
- fracture orientation at wellbore according to stress field
- later interaction with geological structures



Side view



Top view

Locations:
5139

Magnitude range:
M_A - 6 to -2.5

Distance range:
2 – 50 m

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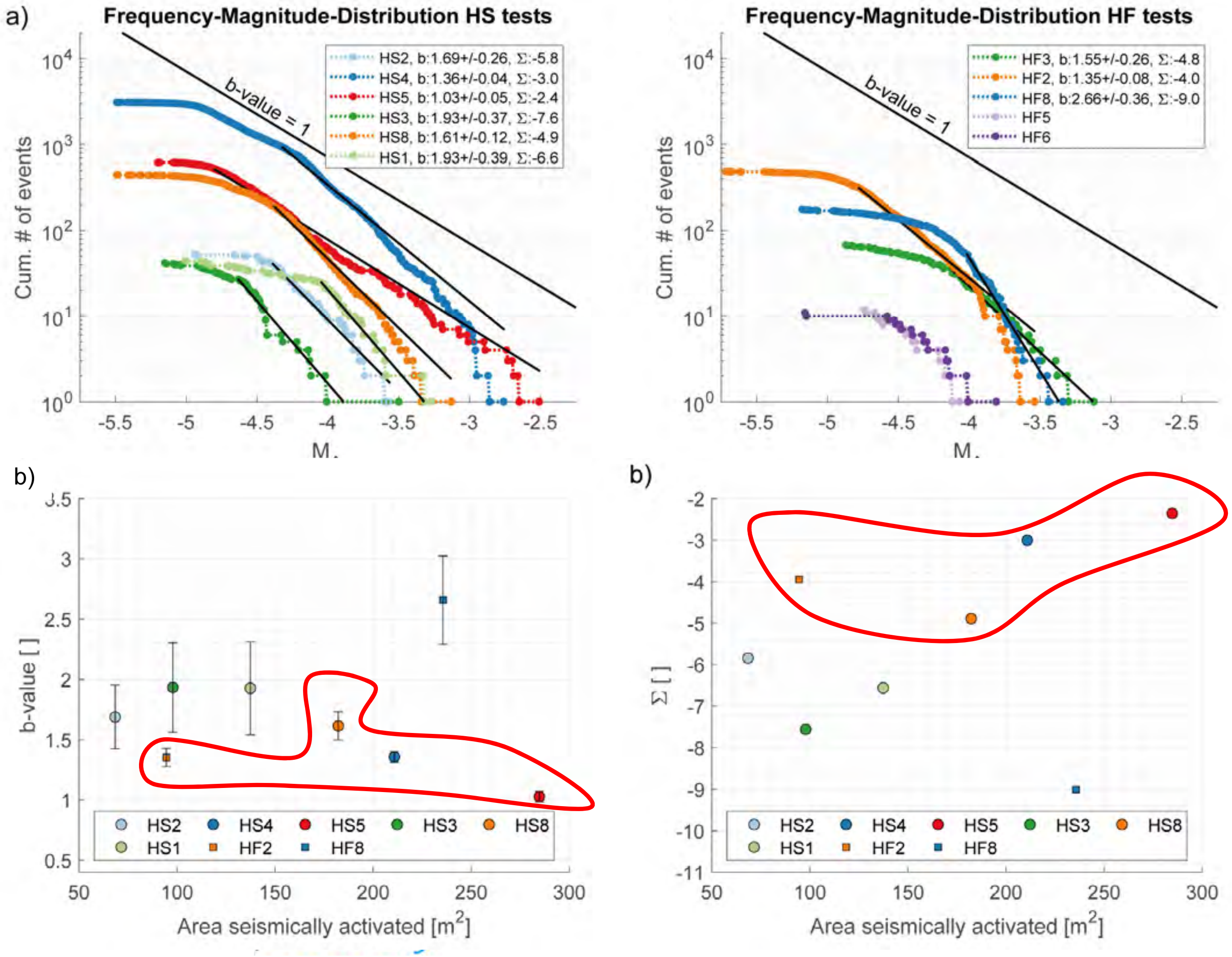
Seismic event statistics



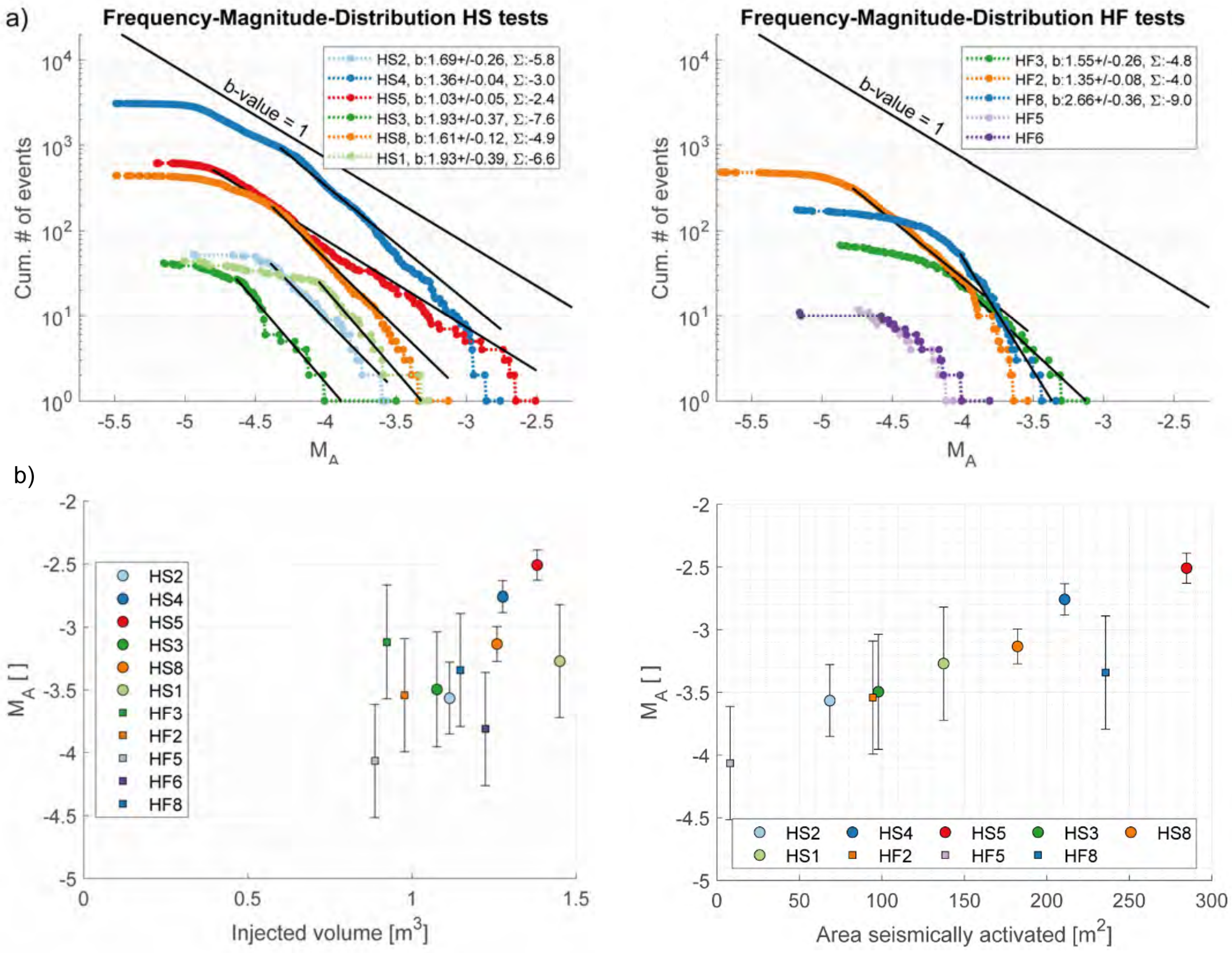
- **Highly variable seismic response** (i.e., the variability in b-values, and seismogenic indexes) over the experiments
  - b-value: ratio of large to small induced magnitudes
  - Seismogenic index (injected volume normalized a-value): productivity, seismoteconic state of a reservoir location

- **Dependency on geology!!!**

→ High seismic response (i.e., low b-value, high seismogenic index) for S3 stimulation experiments (HS4, HS5, HS8)

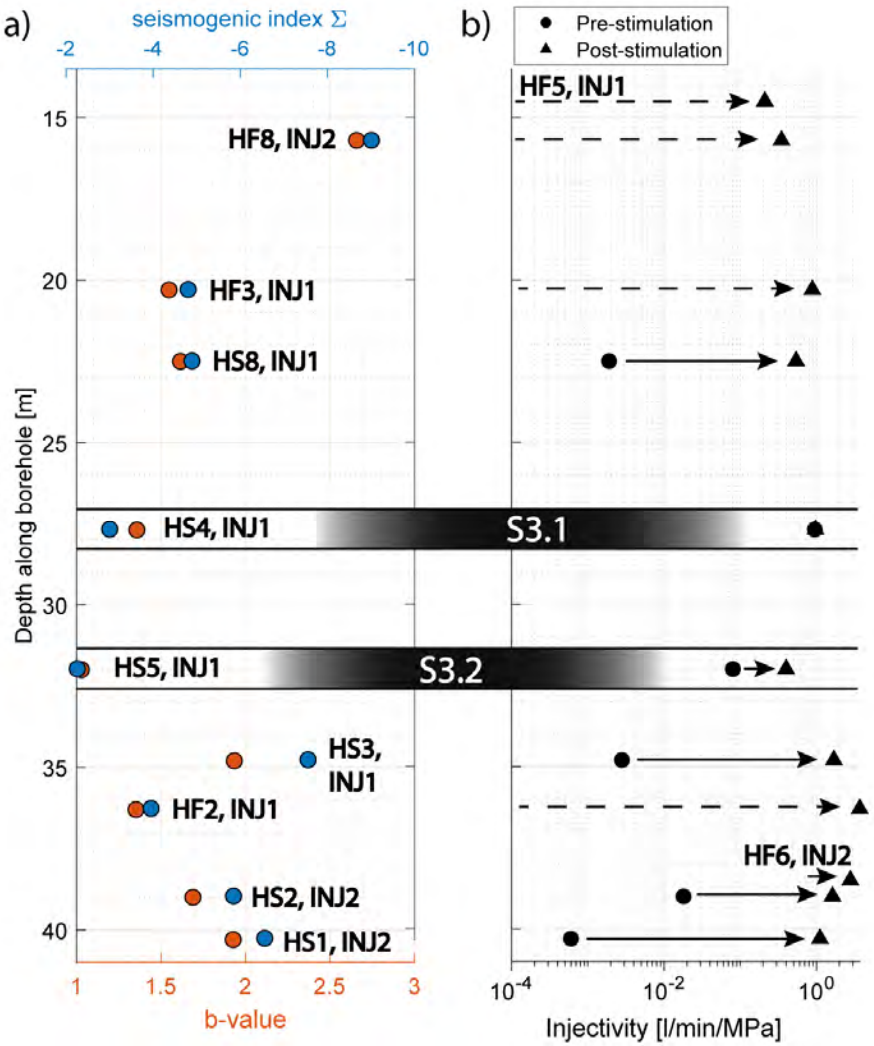
→ Also, high seismic response for experiment HF2

Seismic event statistics



- No correlation of induced maximum magnitude with injected volume
- Increasing trend of maximum induced magnitude with seismically activated area
- High variability in seismically activated area

Conclusion



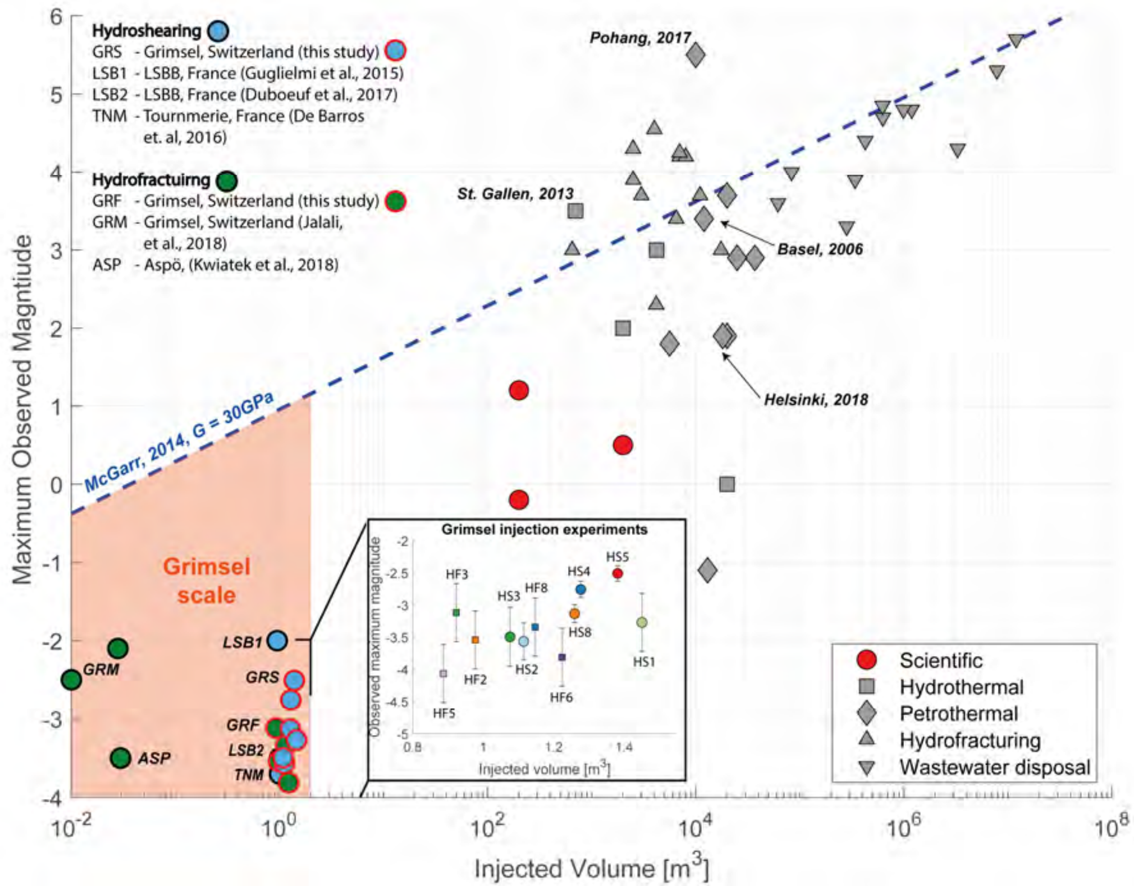
Despite similar injection protocols and injected volumes:

- Increased seismic response for S3 injection experiments in brittle–ductile, highly fractured shear zones, with high initial injectivity
- But no, or limited injectivity gain for S3 stimulations
- Final injectivities in same order of magnitude
- More planar seismicity clouds for S1 stimulation compared to S3 seismic clouds of clustery character

- Deformation to large extend aseismic (i.e., > 98%)

Implications for managing induced seismic risk at reservoir scale

- Anticipate variability
- Selective stimulation (zonal insulation, be able to skip and seal insulated zones, pre-stimulation)
- Update induced seismic hazard forecasting models (based on pre-stimulation)



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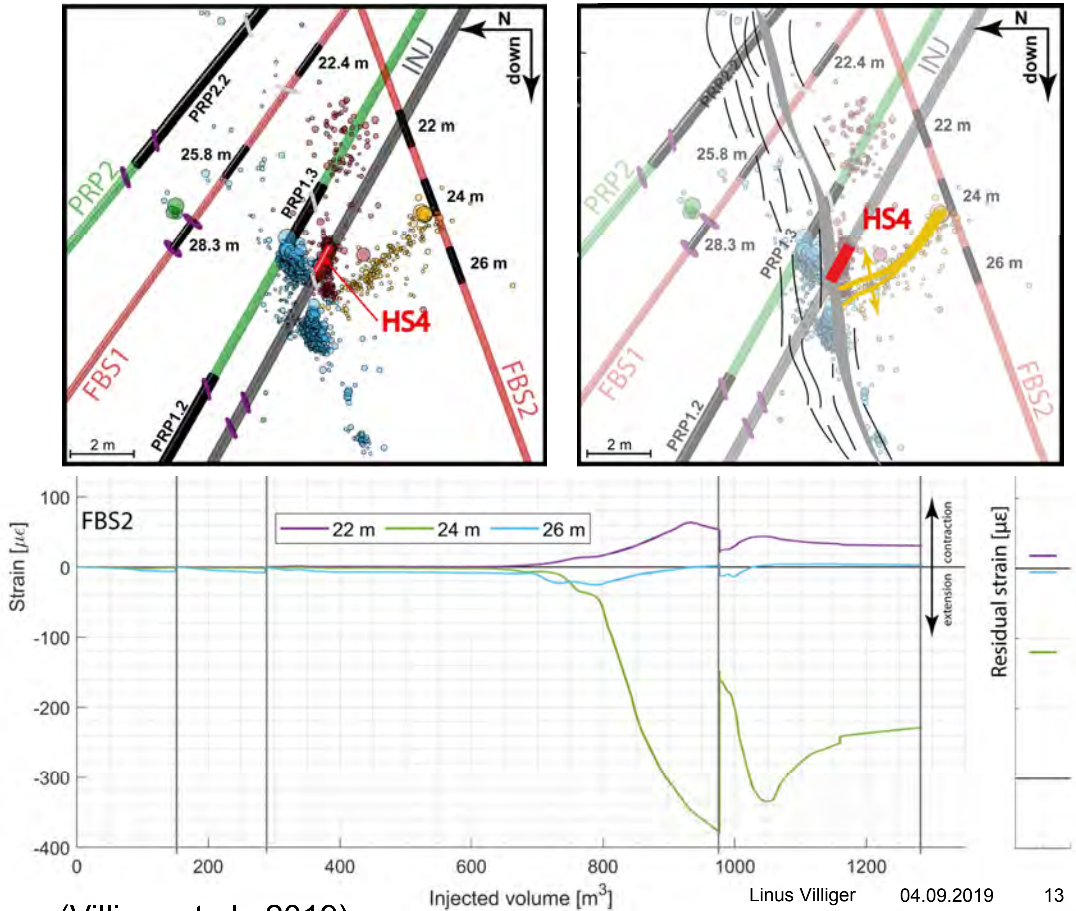
Outlook – Bring together seismo-hydro-mechanical observations

- Overviewing publications
  - Mechanical/hydrological
    HF: (Dutler et al., 2019)
    HS: (Krietsch et al., in prep.)
  - Seismicity
    all: (Villiger et al., in prep.)
  - Velocity variations
    (Doetsch et al., 2018), (Schopper et al., in prep.)
  - Pre-/post hydrological stimulation
    (Brixel et al., under review)

- Continuing work
  - …stimulation mechanism?
  - …deformation in combination with permeability change?
  - …modeling?
  - …

Example: Combining seismicity and strain observations



(Villiger et al., 2019)

Thank you for your attention!

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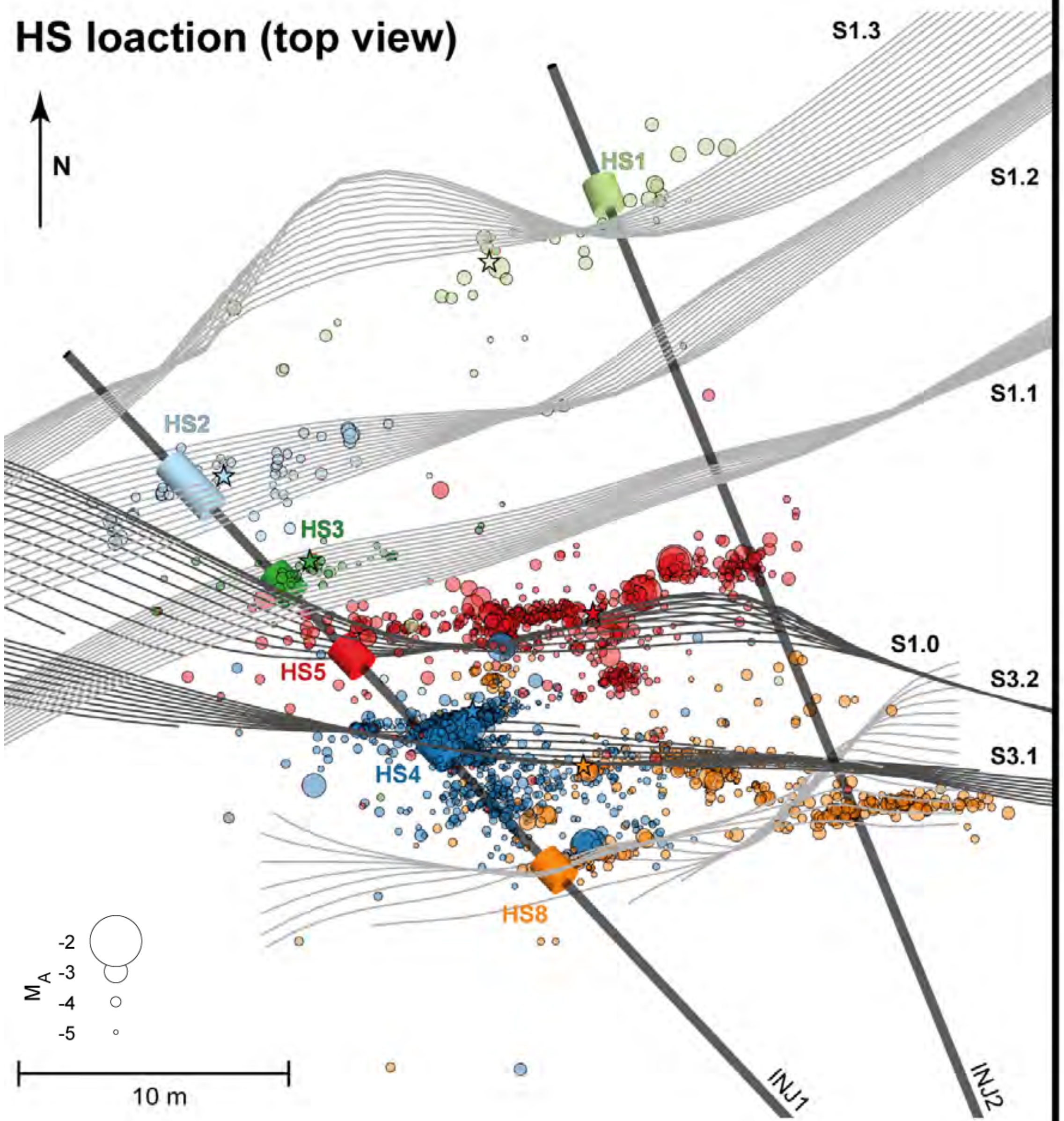
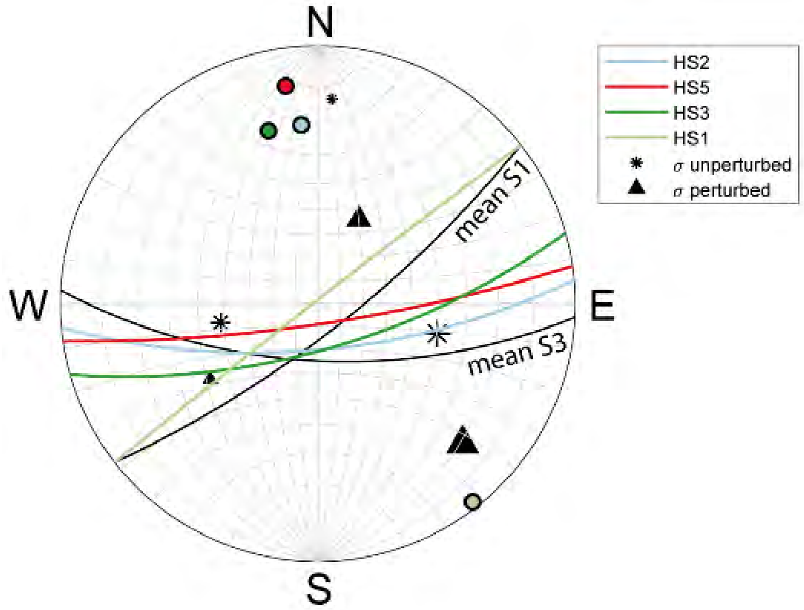
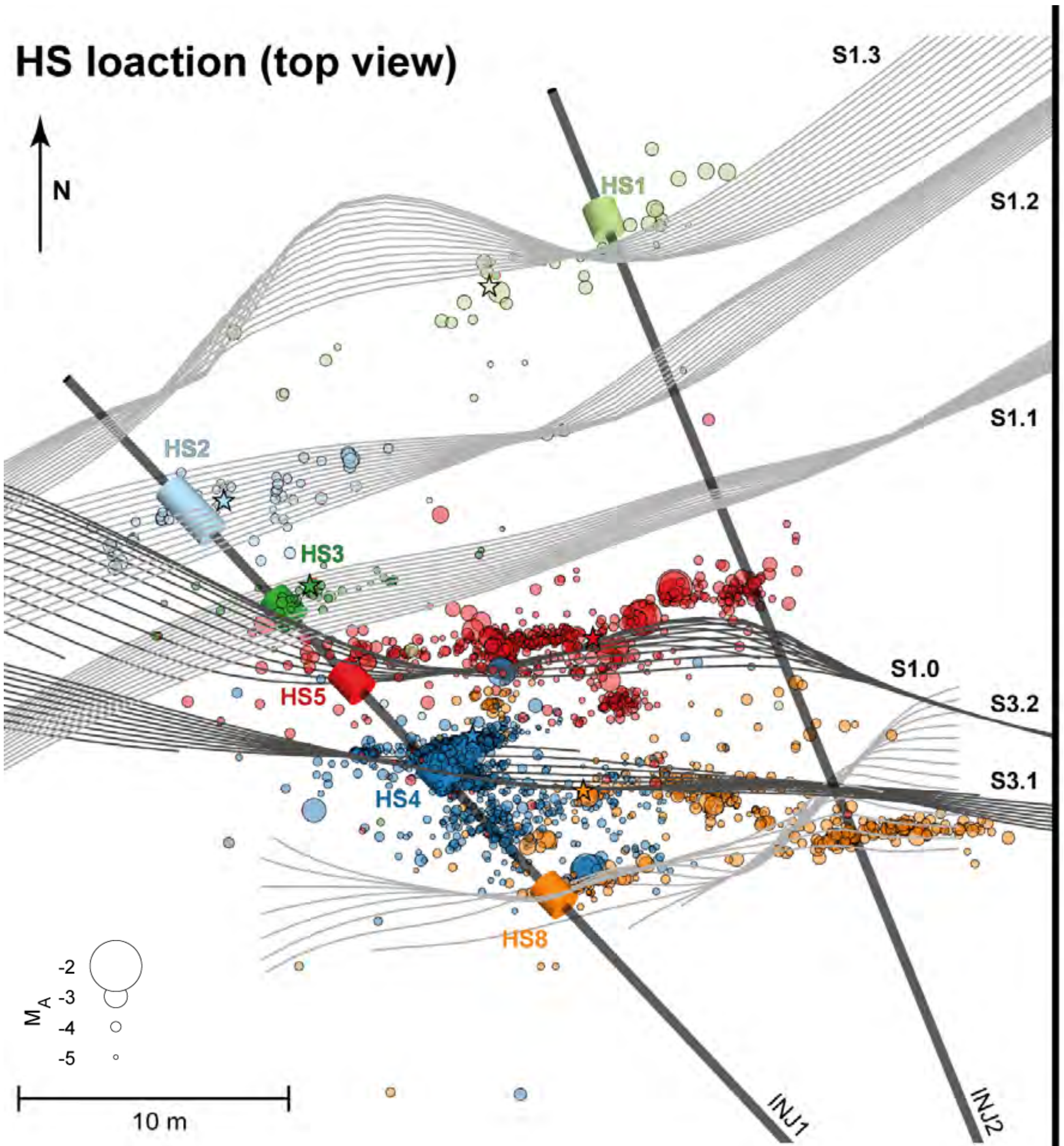
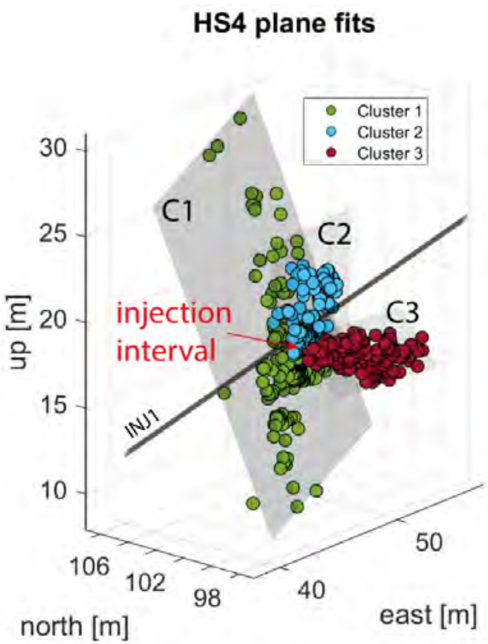
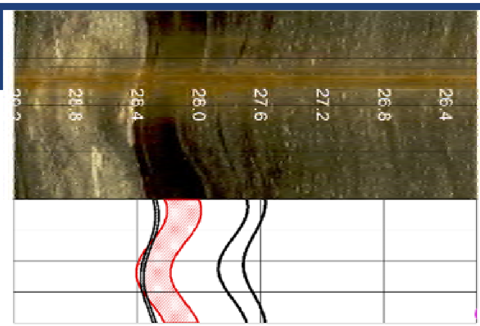


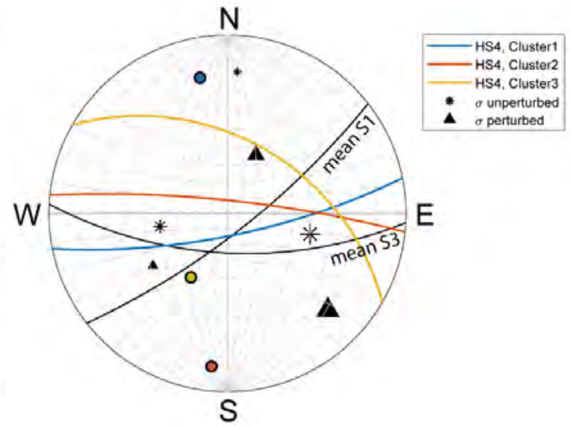


- Majority of HS seismicity clouds oriented in S3, EW direction
- Only seismic cloud of HS1 oriented in S1, NE-SW direction
- Orientation possibly dominated by geological features

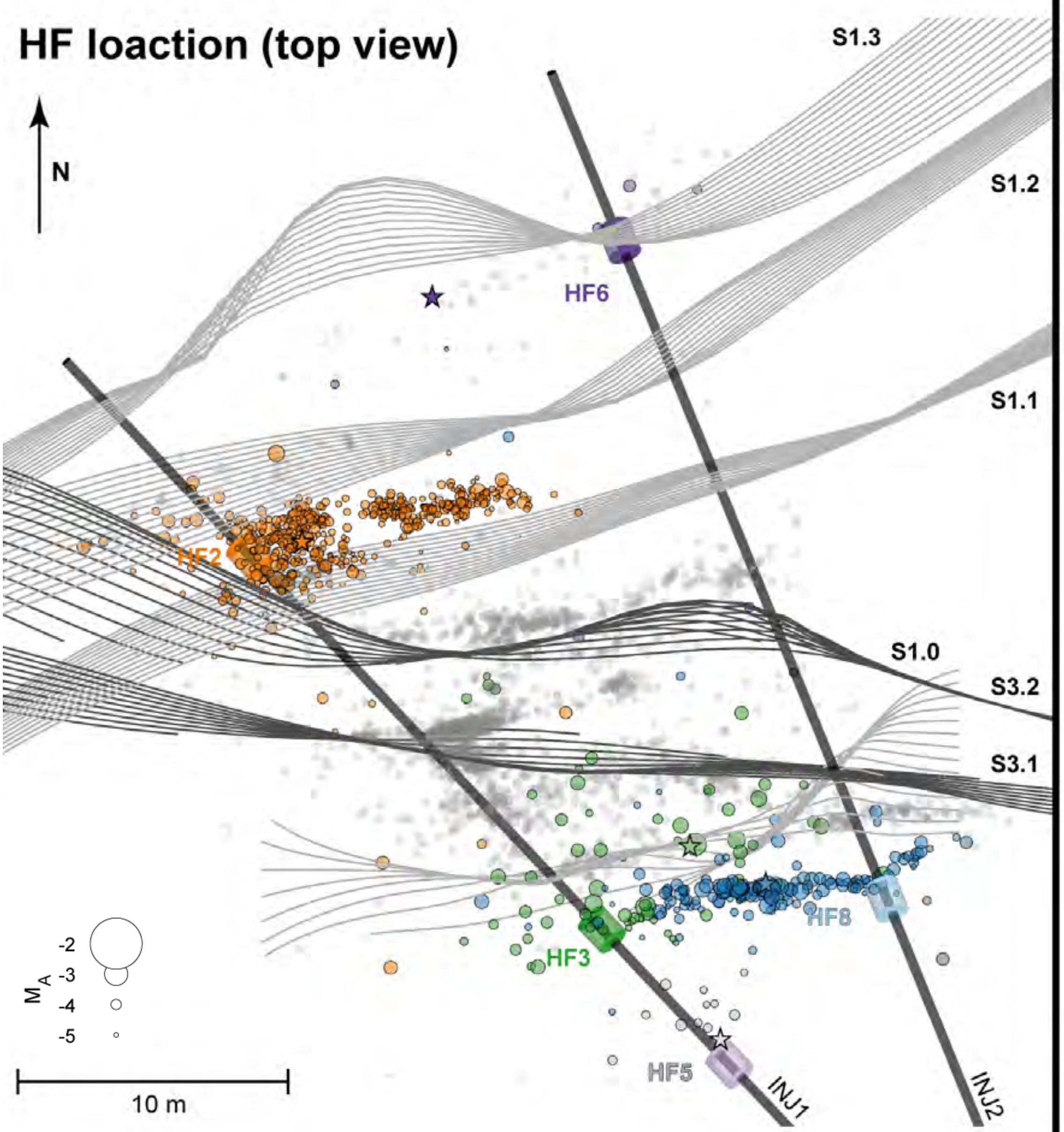


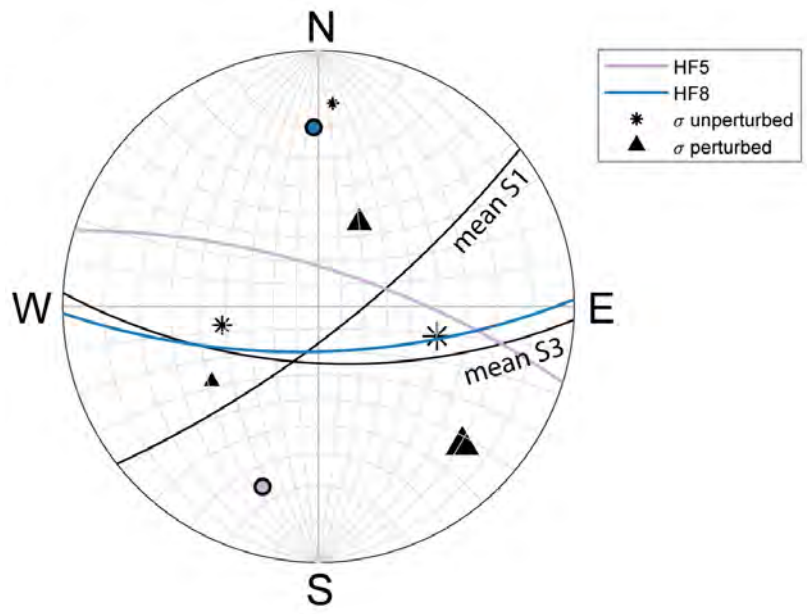




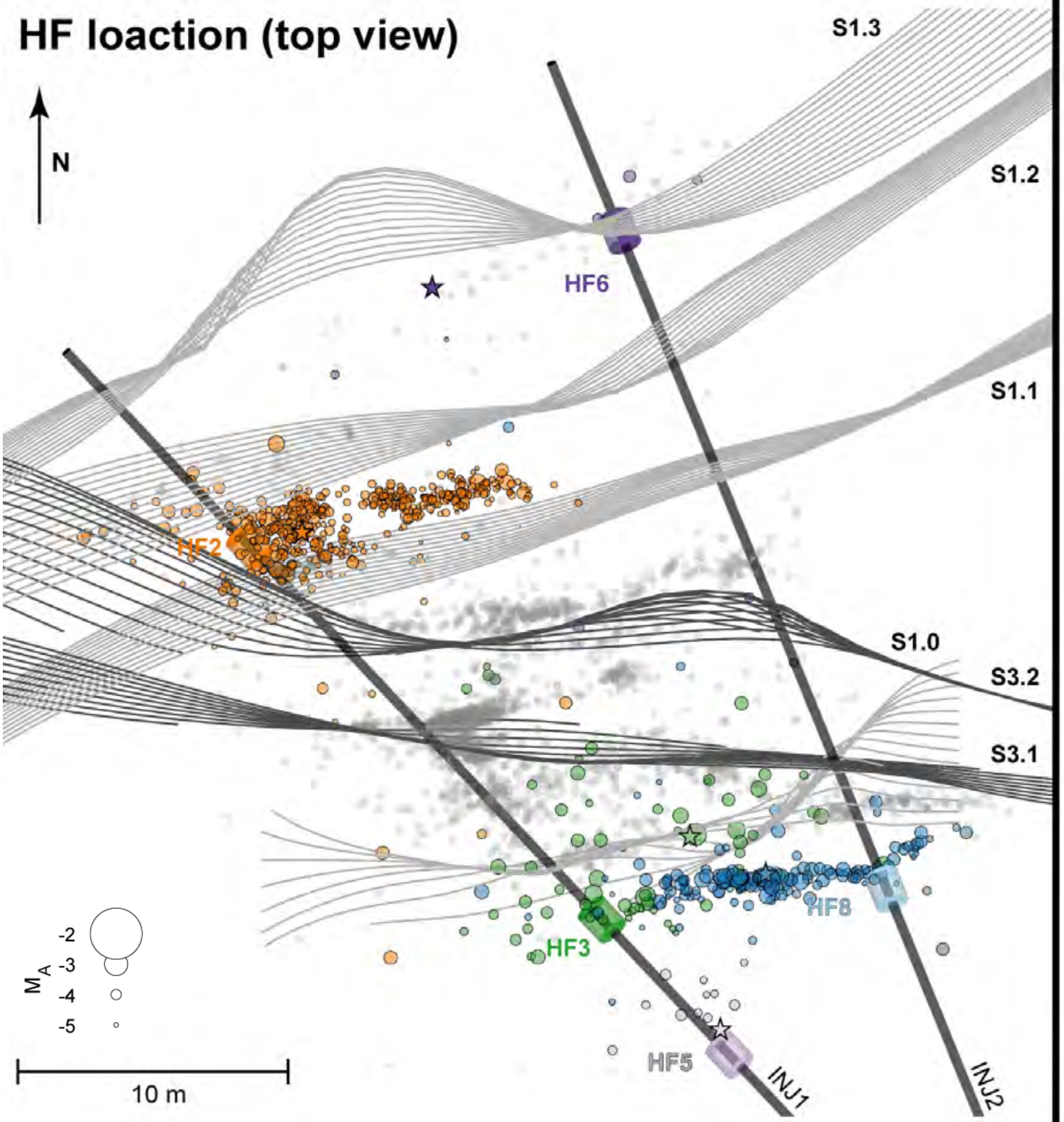


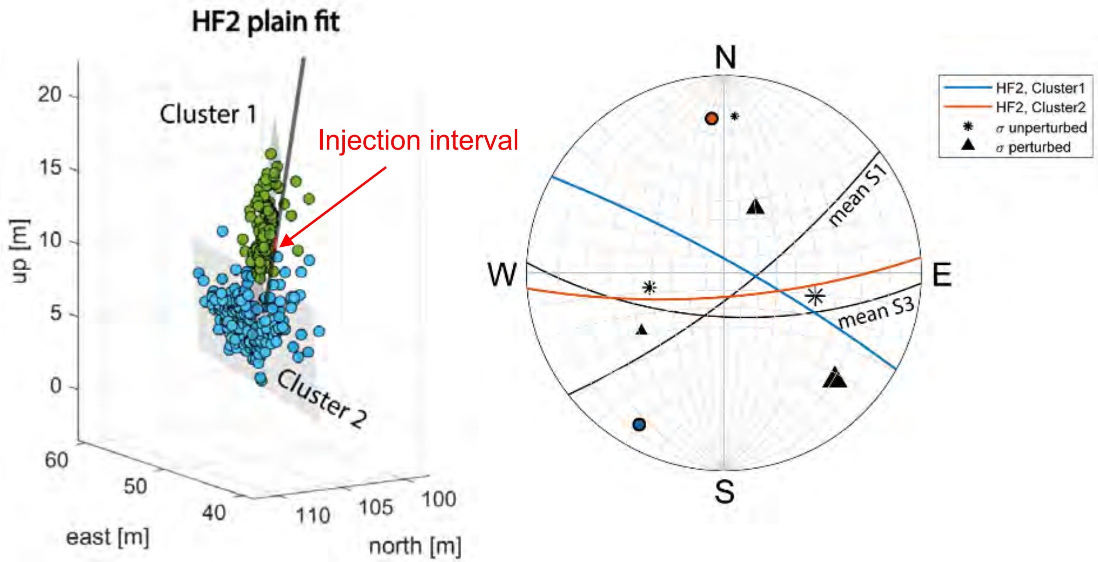
- Cluster 1: main stimulation in metabasic dyke region; Cluster 2: cluster from adjacent fractures; Cluster 3: newly induced fracture (orientation perpendicular to sigma 3 of perturbed stress state)
- HS4 stimulation confined in comparable small volume



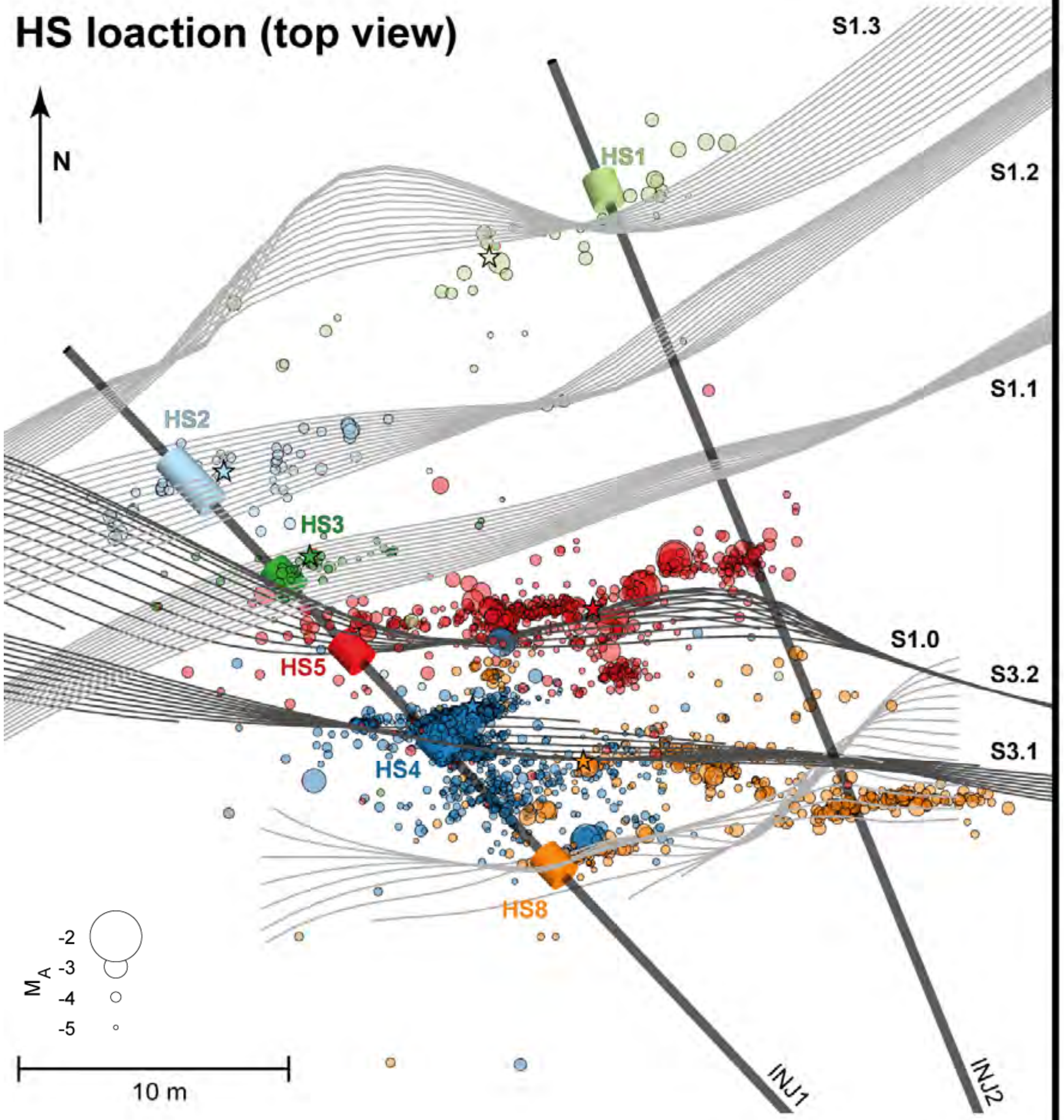


- HF5 seismicity cloud oriented ESE, possibly dominated by stress field (perturbed stress state)
- HF8 seismicity cloud oriented EW, dominated by stress field (unperturbed stress state), or geological features?

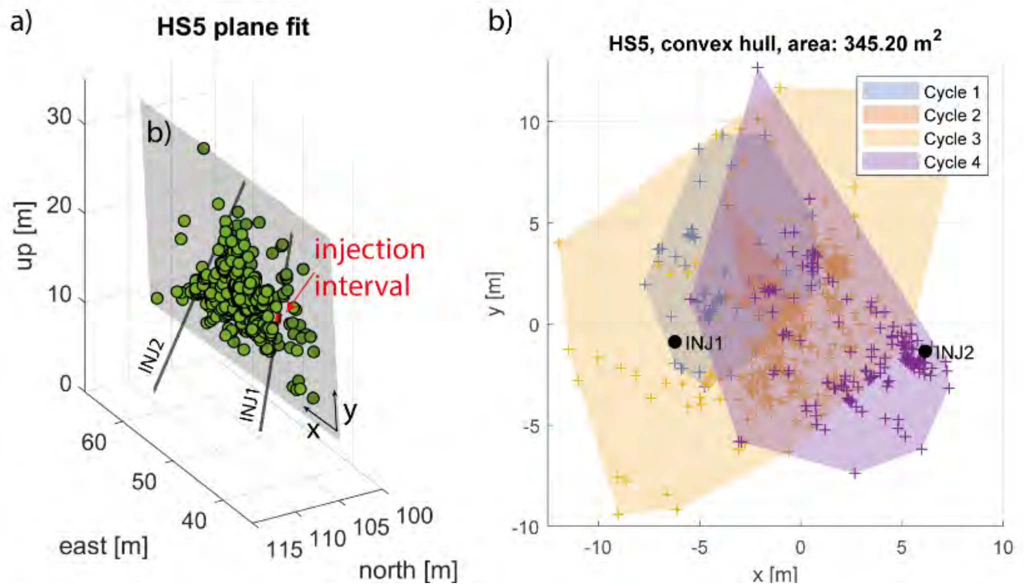




- HF2, cluster 1 orientation ESE, possibly stress field dominated
- HF2, cluster 2 orientation EW, geology or stress field dominated?



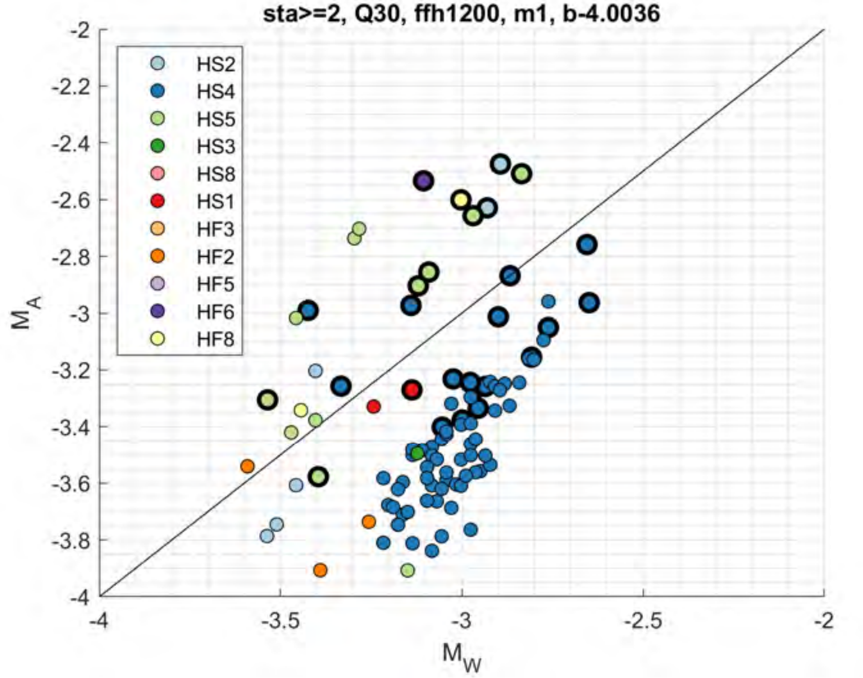
Seismic event propagation



- Seismicity propagating in various directions
- Repeated rupturing on seismically active patches
- Results in estimate of seismically activated area

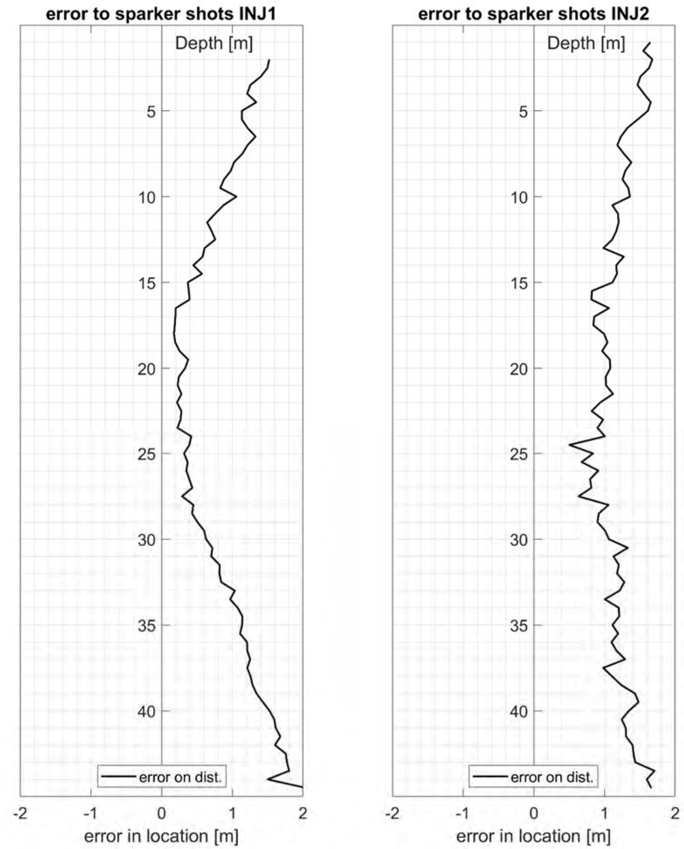
Lessons learned, suggestions

- Magnitude computation
  - Place piezosensors close (not too close) to injection and collocate them with accelerometers



- Seismicity from monitoring boreholes
  - Matlab .fig file

- Location
  - Anisotropic/heterogeneous velocity model useful



Additional material