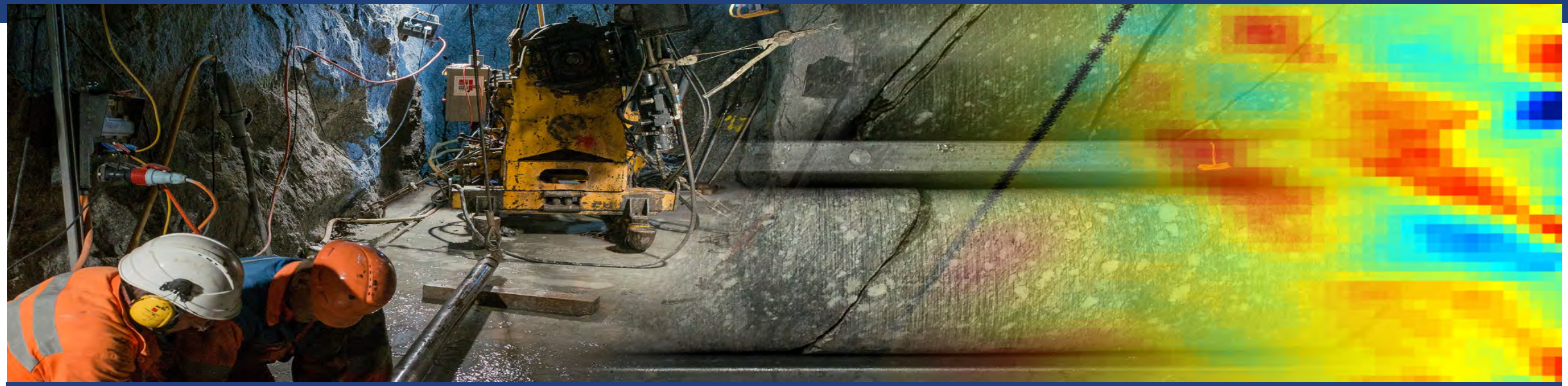
ETH zürich



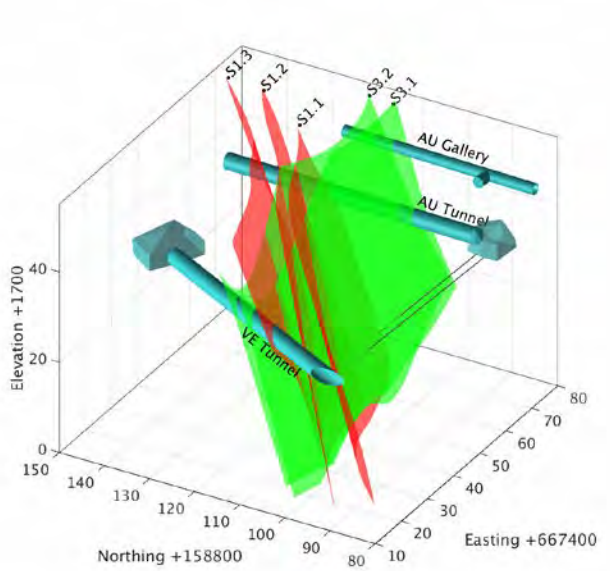
Complex interplay between hydraulic shearing and hydraulic fracturing during in-situ stimulations

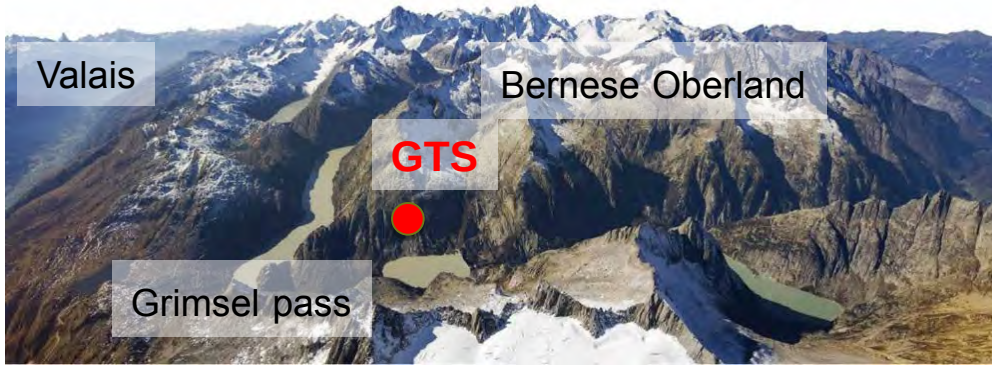
Hannes Krietsch and the DUG-Lab team:

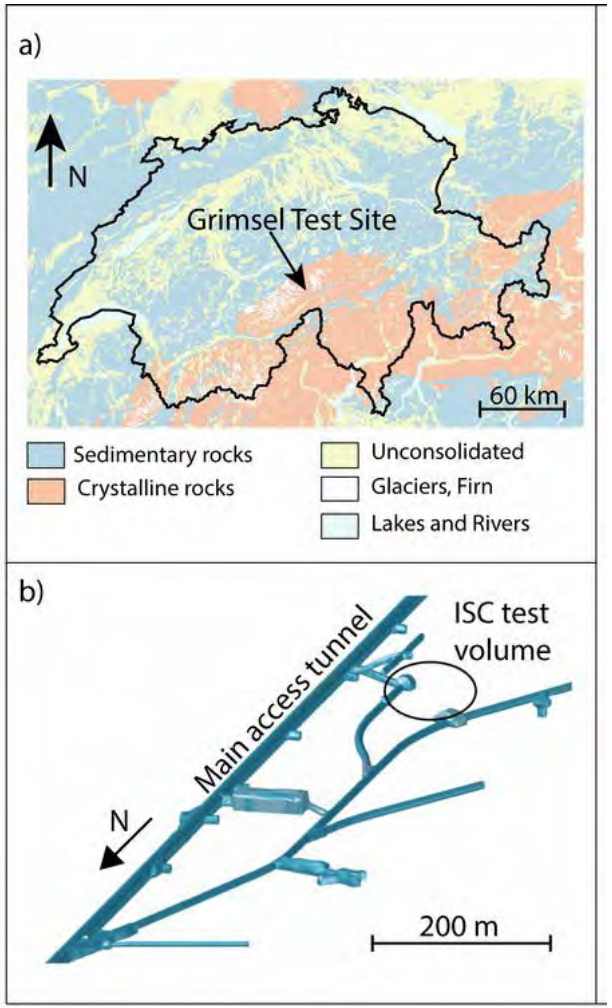
Prof. Florian Amann, Dr. Joseph Doetsch, Dr. Valentin Gischig, Dr. Reza Jalali, Prof. Benoît Valley, Dr. Keith Evans, Hannes Krietsch, Bernard Brixel, Linus Villiger, Peter-Lasse Giertzuch, Nathan Dutler, Anniina Kittilä, Dr. Maria Klepikova, Dr. Claudio Madonna, Dr. Clement Roques, Prof. Stefan Wiemer, Prof. Martin Saar, Prof. Simon Loew, Prof. Thomas Driesner, Prof. Hansruedi Maurer, Prof. Domenico Giardini

Grimsel Test Site / Test volume

- Operated by NAGRA
- Within crystalline rocks of Aar Massive
- Approx. 480 m below surface
- Test volume size: 20 x 20 x 20 m
- 5 major shear zones (3 ductile & 2 brittle-ductile)

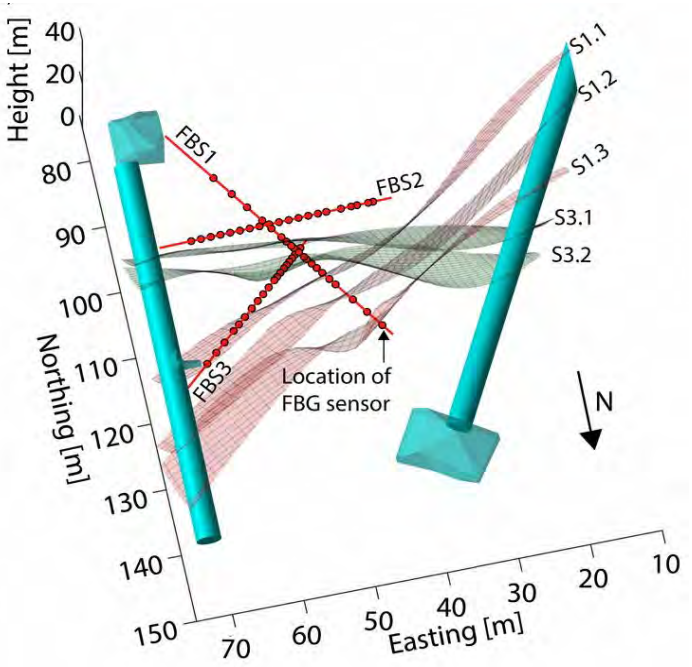




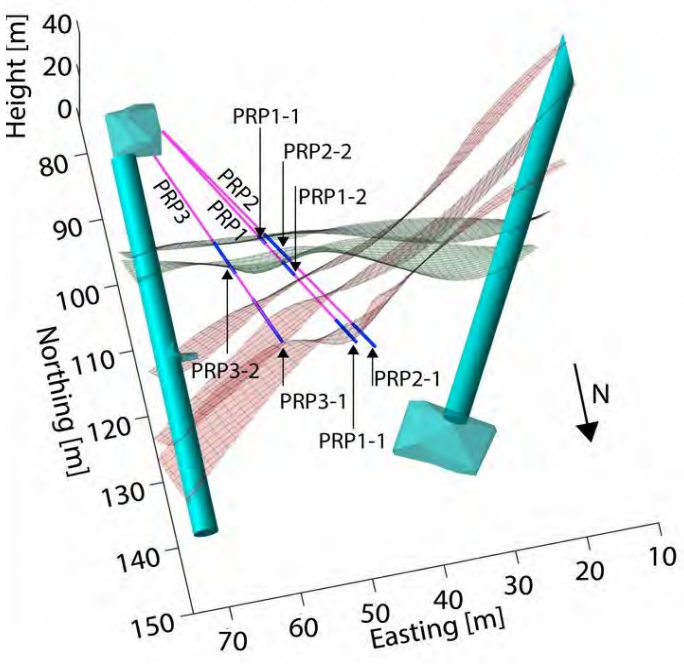


Monitoring systems

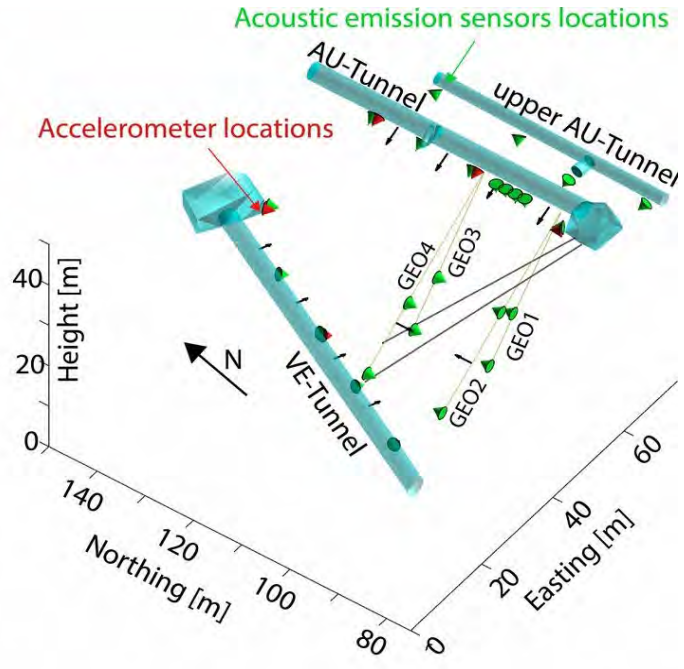
- Deformation monitoring:
  - 60 Fiber-Bragg Grating (FBG) strain sensors equally distributed in 3 boreholes
  - 2 loops of Distributed Brillouin Strain (DBS) sensing covering 6 boreholes.
  - 3 Tiltmeters



- Pressure monitoring:
  - 8 open pressure intervals in 4 grouted boreholes
  - 1 pressure interval in the passive injection borehole (observation borehole)

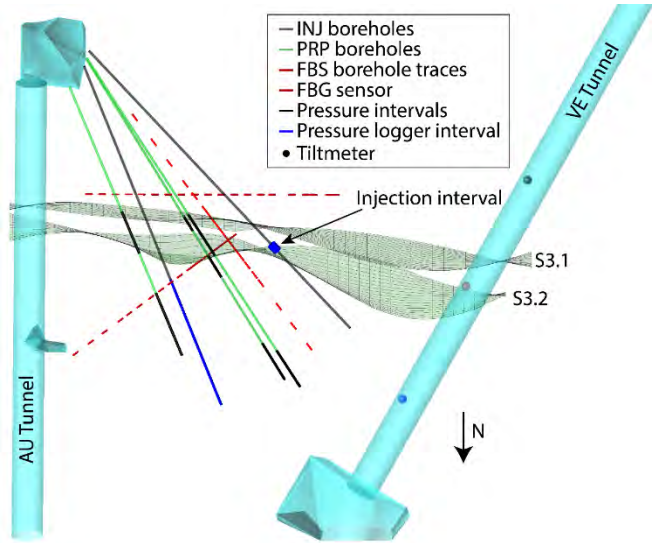


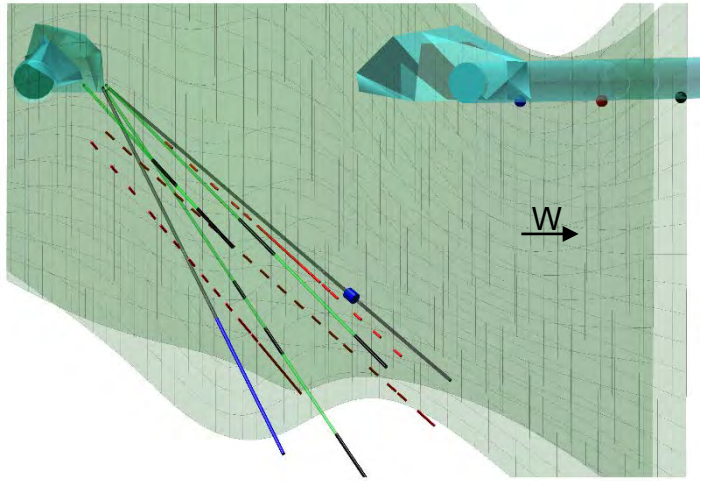
- Seismic monitoring:
  - 26 Acoustic emission sensors distributed along tunnel walls and within boreholes
  - 5 Accelerometers

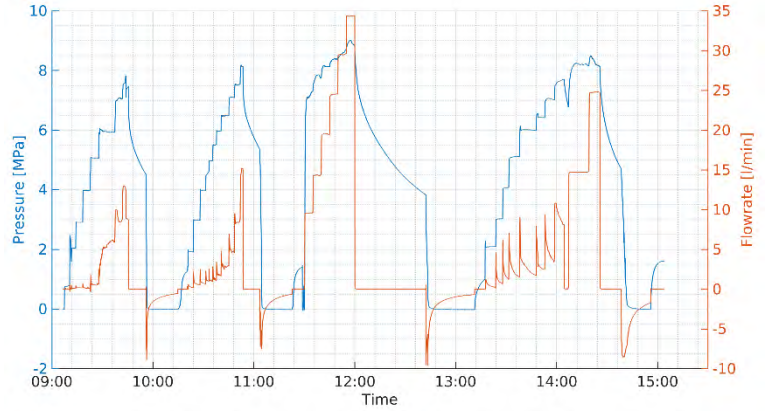


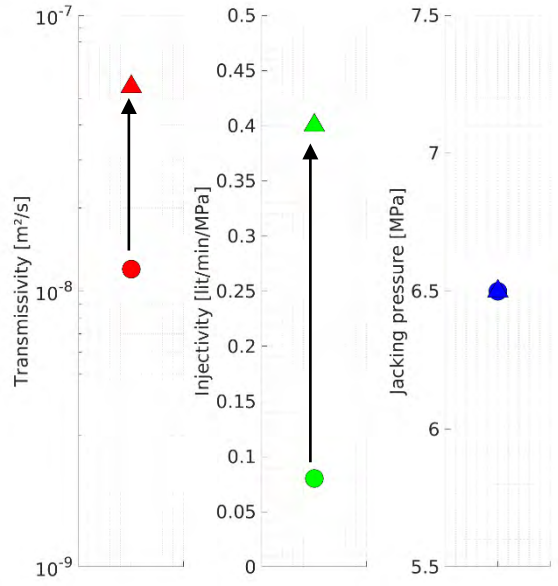
Hydraulic stimulation test «HS5»

- Injection location:
  - INJ1 – 31.2 m – 32.2 m
- Targeted shear zone:
  - S3.2
  - 1 macroscopic brittle fracture
- Injected Volume:
  - ~1 m^3
- EGS-relation:
  - Transmissivity and injectivity was increased in injection interval.



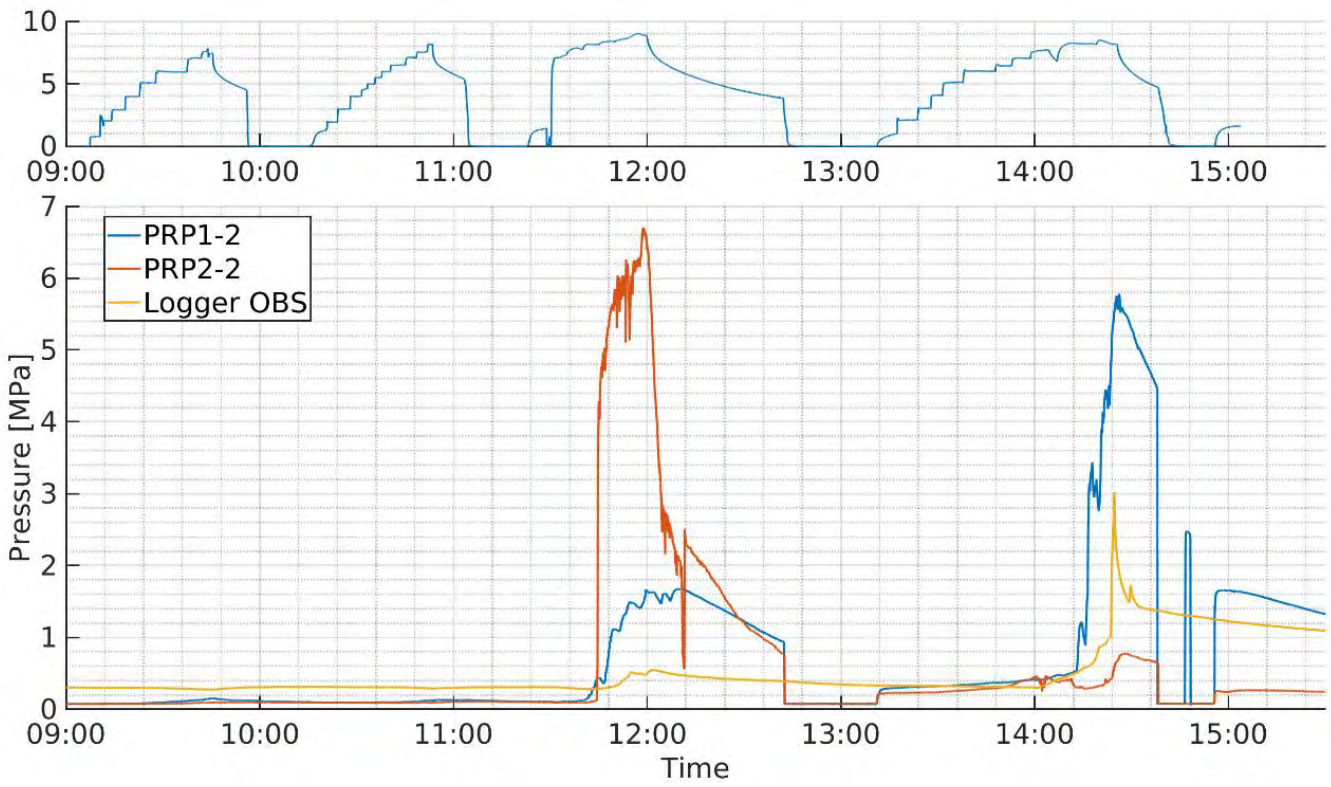






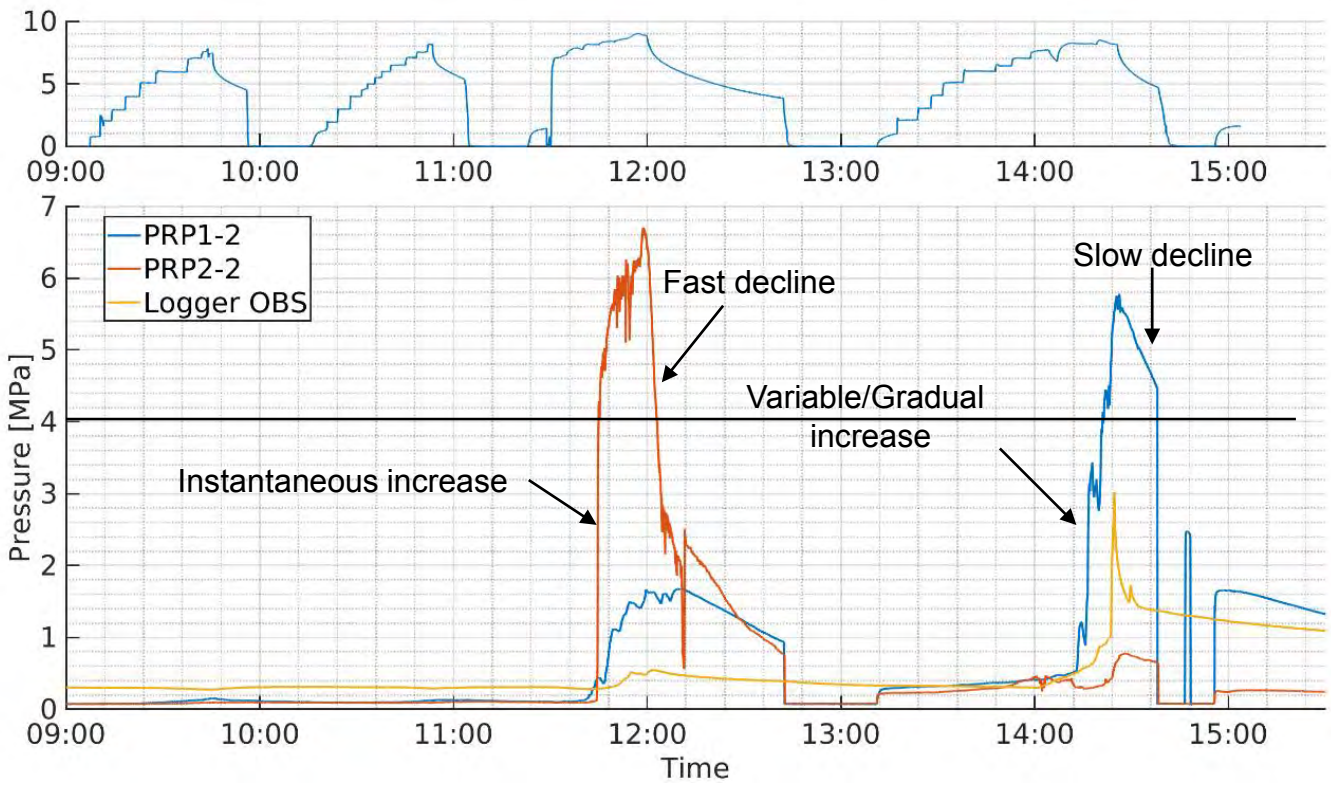
Pressure data

- 3 Intervals indicate minor pressure pertubations during cycle 1 and 2.
- Cycle 3:
  - PRP1-2: 1.7 MPa
  - PRP2-2: 6.7 MPa
  - Logger OBS: 0.2 MPa
- Cycle 4:
  - PRP1-2: 5.8 MPa
  - PRP2-2: 0.8 MPa
  - Logger OBS: 2.7 MPa



Pressure data

- 3 Intervals indicate minor pressure pertubations during cycle 1 and 2.
- Cycle 3:
  - PRP1-2: 1.7 MPa
  - PRP2-2: 6.7 MPa -> 21s to 4 MPa
  - Logger OBS: 0.2 MPa
- Cycle 4:
  - PRP1-2: 5.8 MPa -> 8min14s to 4 MPa
  - PRP2-2: 0.8 MPa
  - Logger OBS: 2.7 MPa



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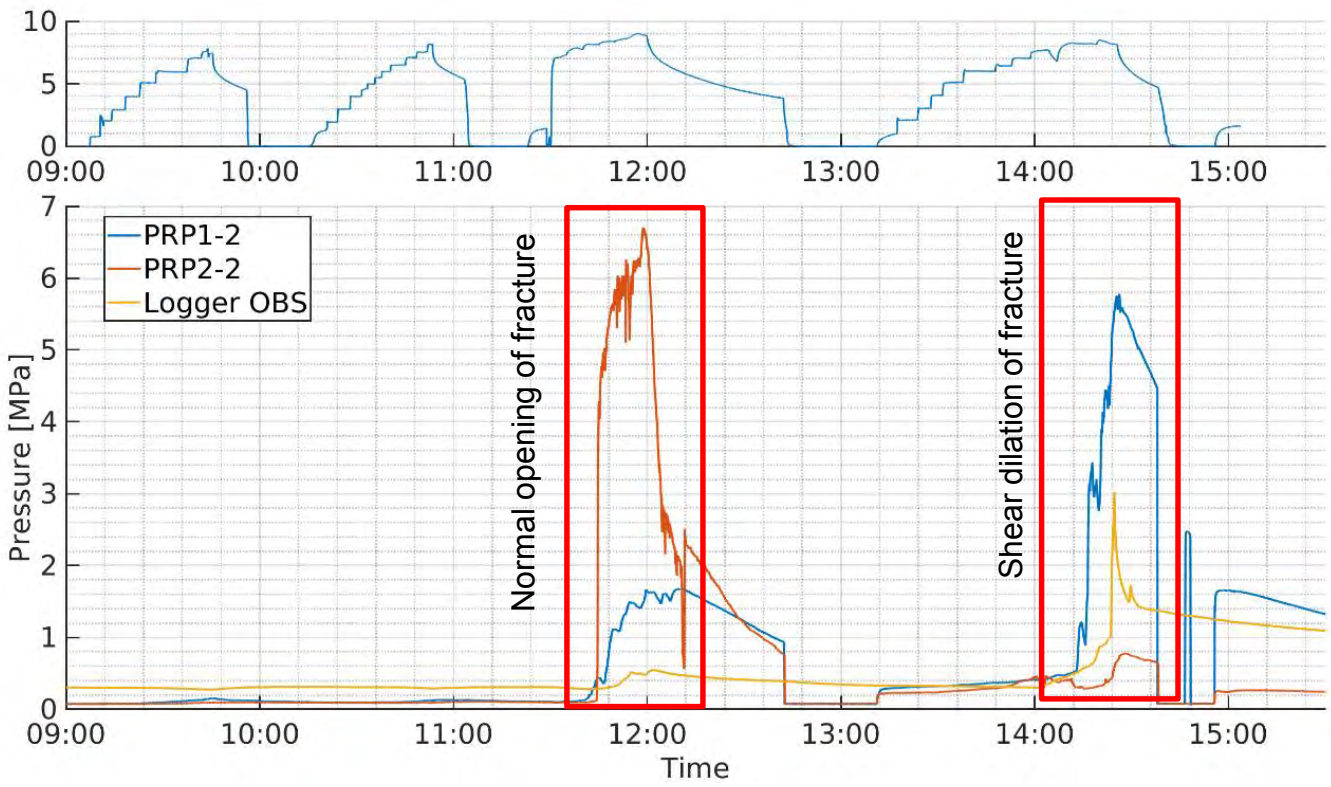
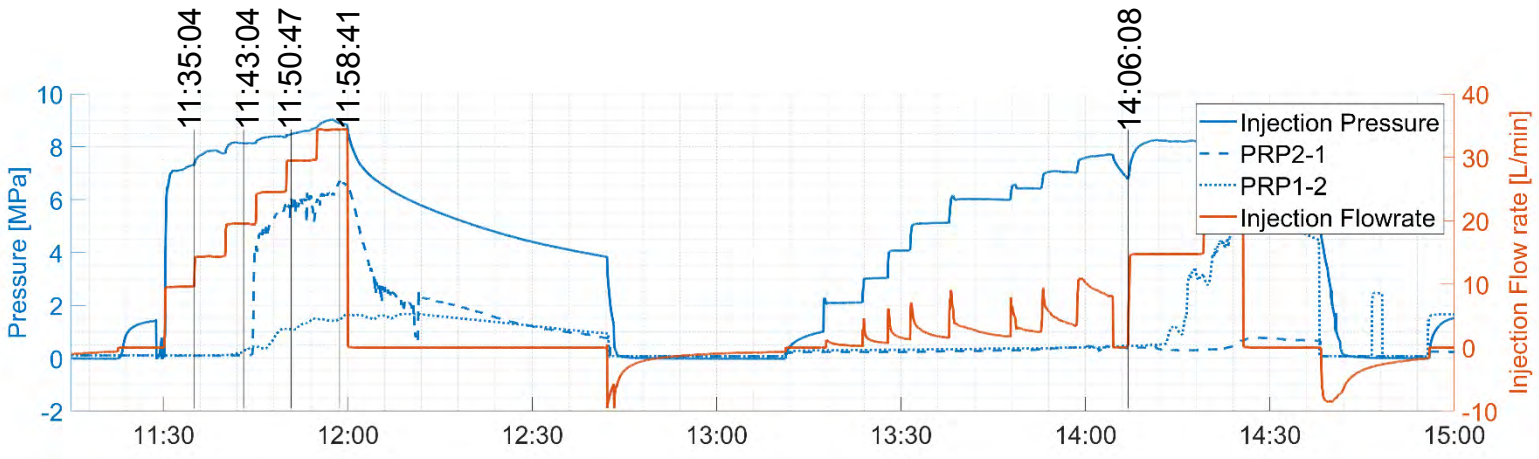
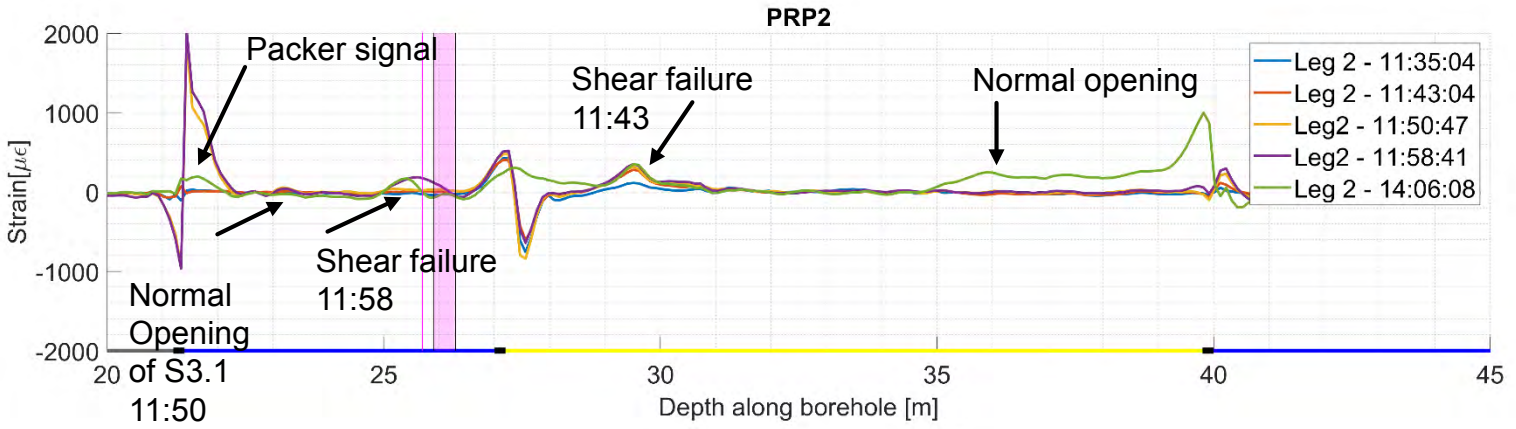
  - Logger OBS: 2.7 MPa



Strain data – DBS Data – PRP2

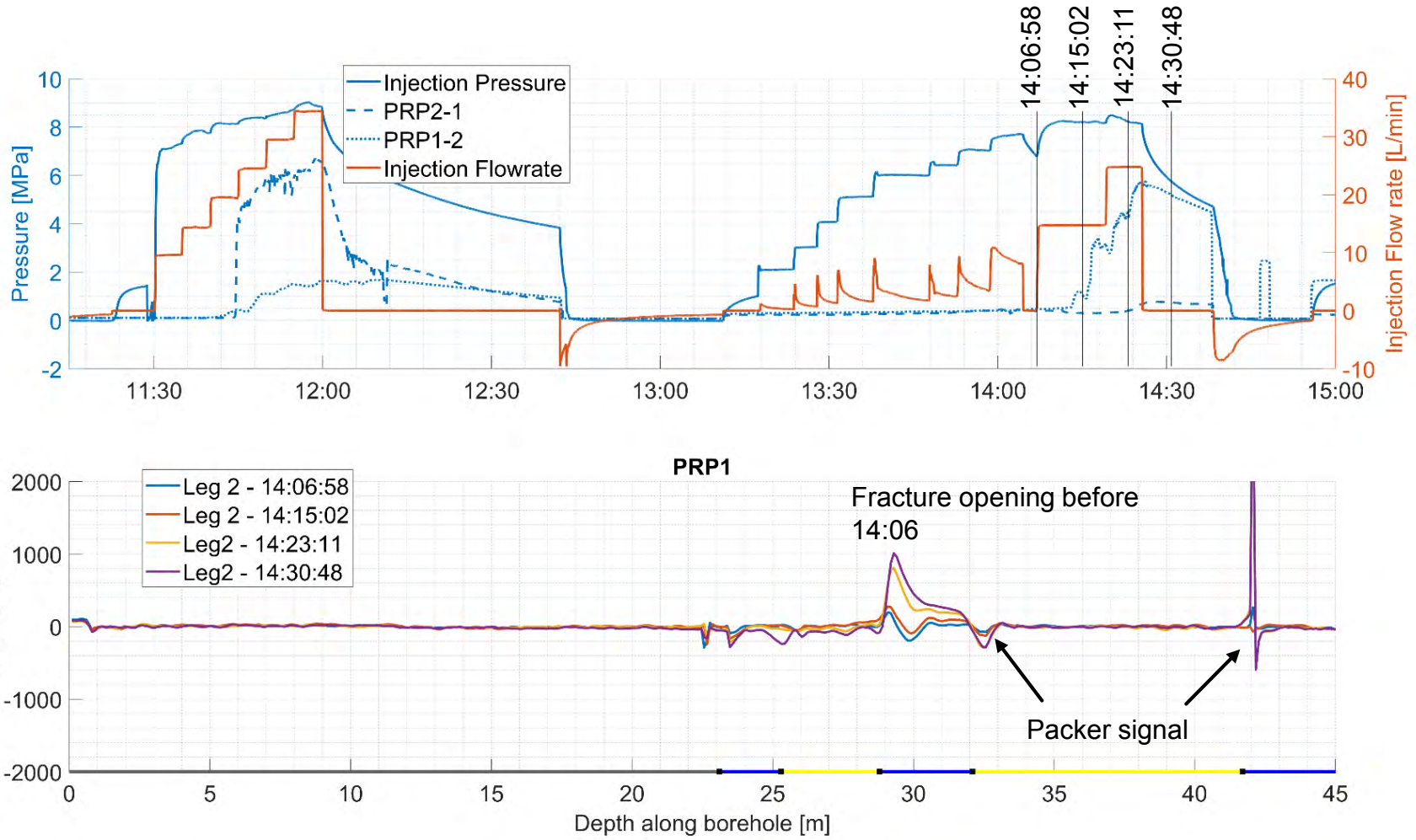
- Strong pressure increase in PRP2-1 might be not traced by DBS
  - Small facture opening
- S3.1 seemed to be jack opened by strong interval pressure.
  - Created shortcut between shear zones.
- Variable pressure increase after 11:50 might be due to shear dilation between 11:50 and 11:58.
  - Secondary deformation event at interval.





Strain data – DBS Data – PRP1

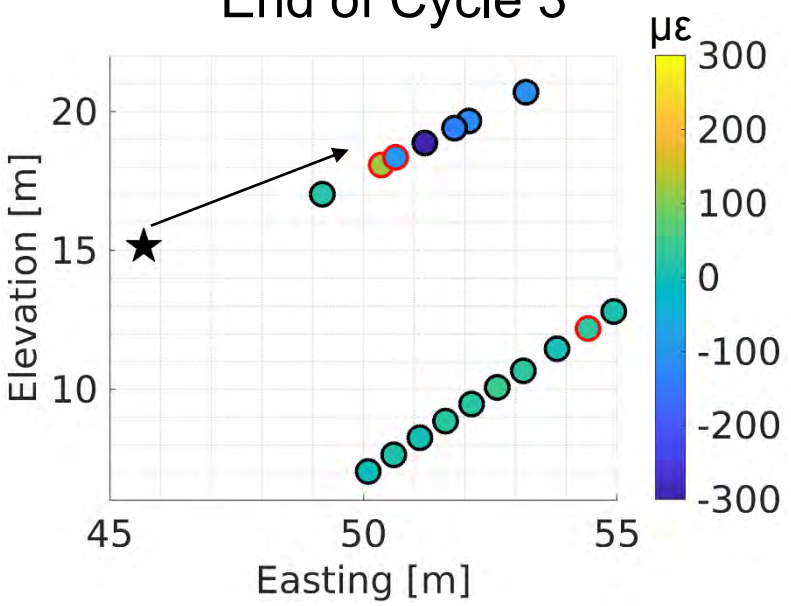
- Variable pressure increase might be due to fracture opening as indicated in DBS.
- Opening started in cycle 3.
- Deformation is a continuous process.
- Strong permanent strain after shut-in.



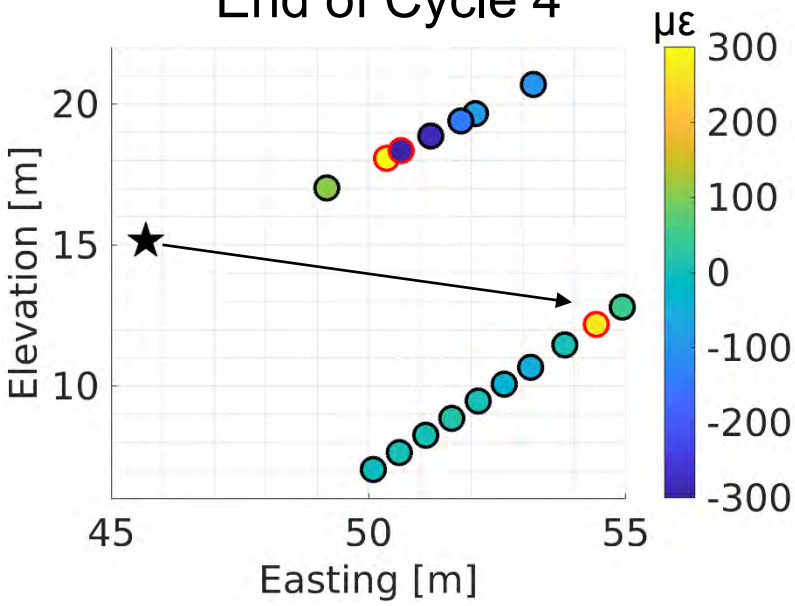
Strain data – FBG Data

- Cycle 3 indicates upwards propagation of deformation.
- Cycle 4 indicates dominant downwards component
- Strain signals show direction change of deformation field

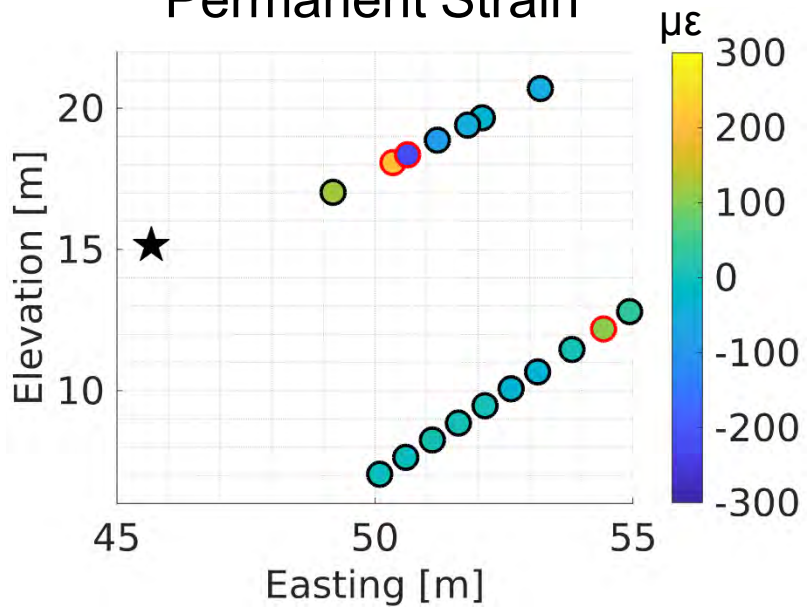
End of Cycle 3



End of Cycle 4



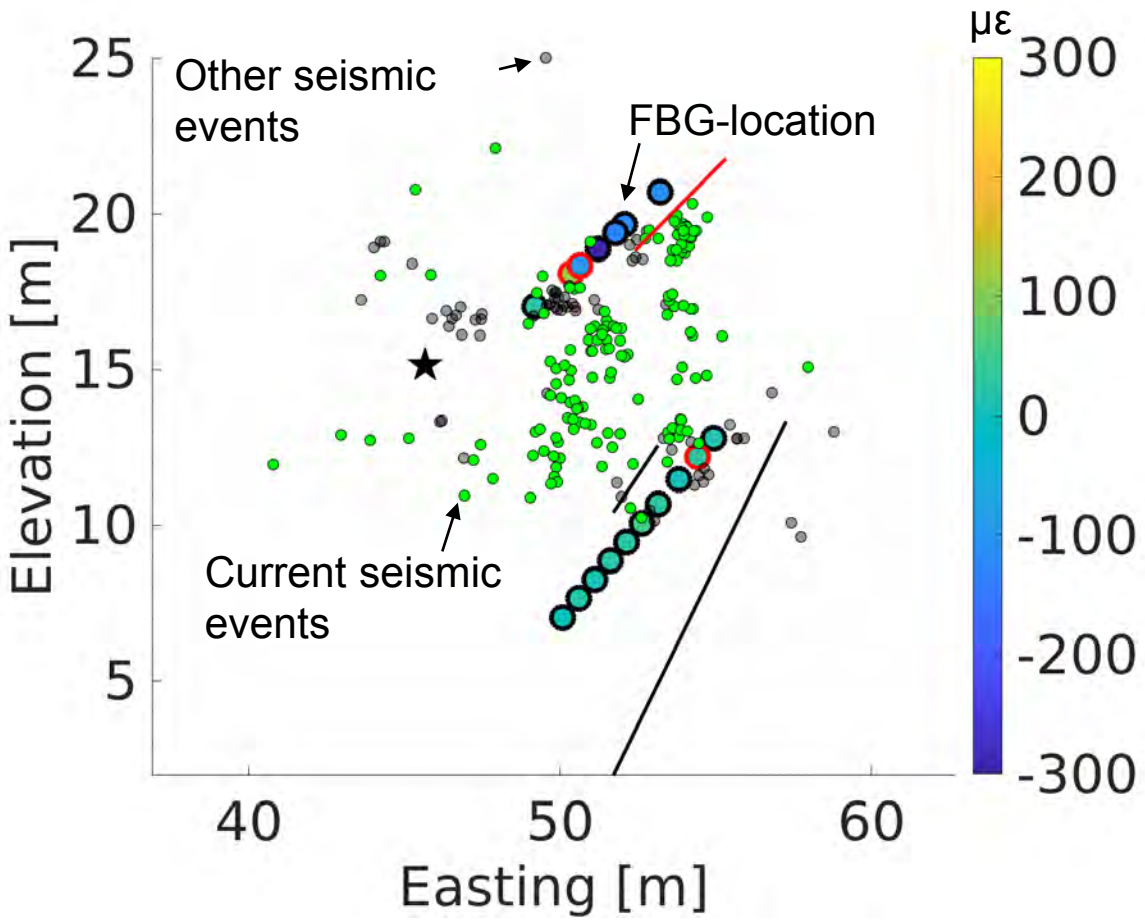
Permanent Strain



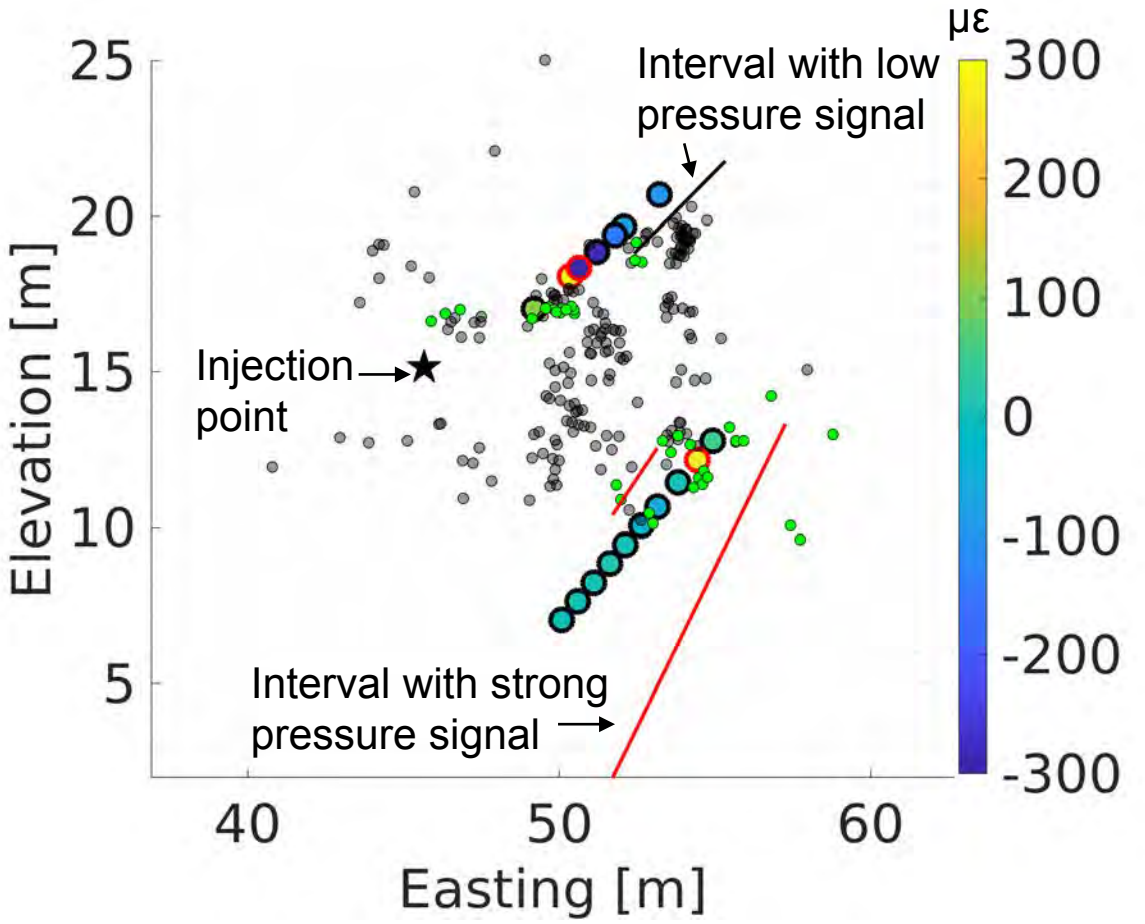
→ Arrows indicate propagation direction of deformationfield & «Red» marker edge color indicates FBGs inside S3.2 shear zones

Integration of monitoring data

End of Cycle 3

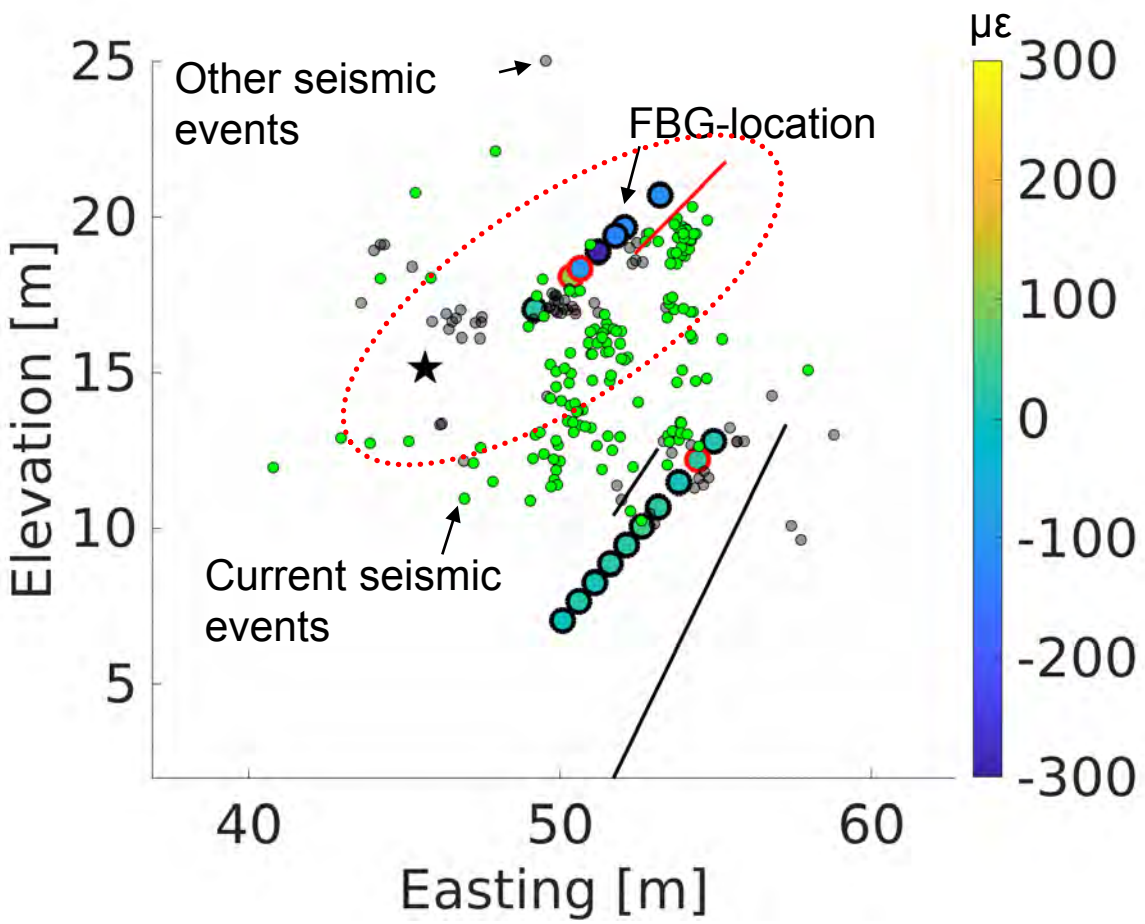


End of Cycle 4

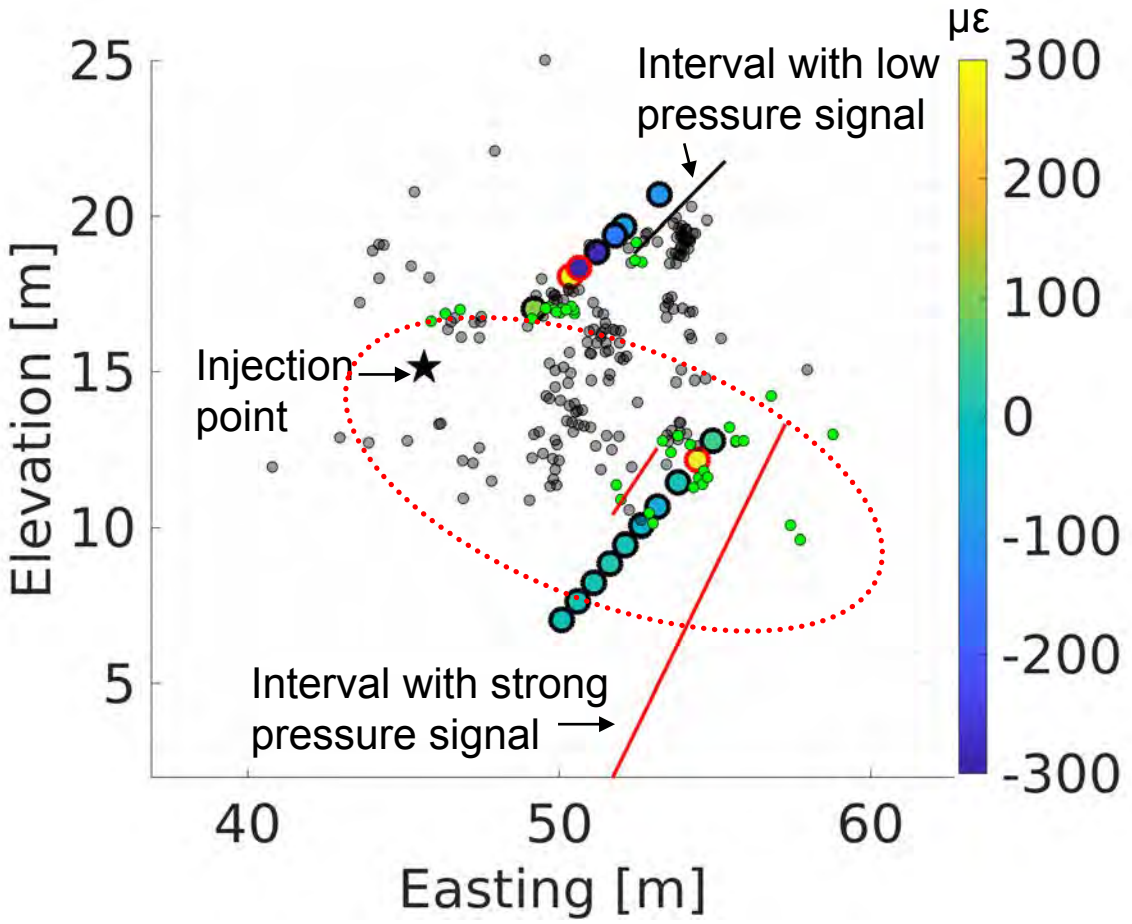


Integration of monitoring data

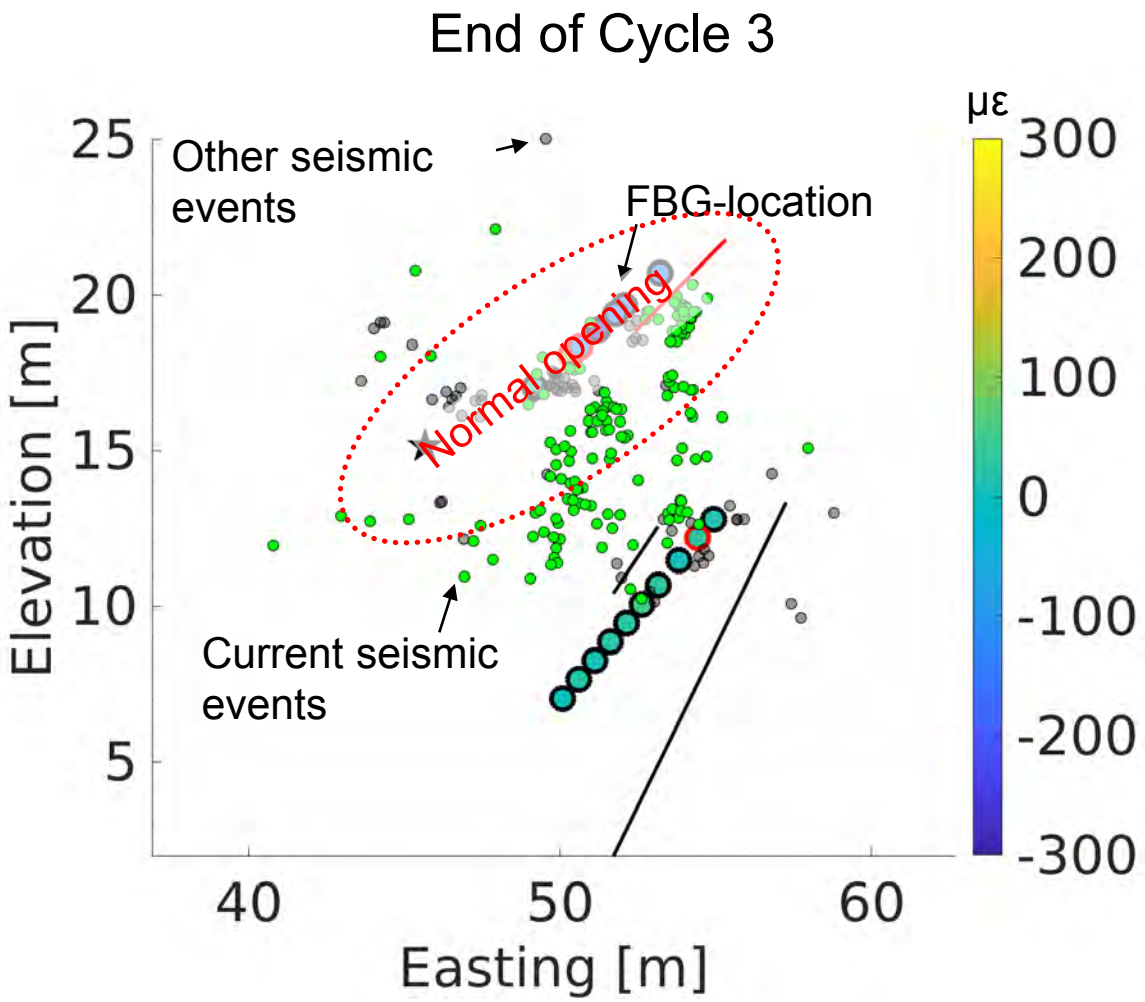
End of Cycle 3

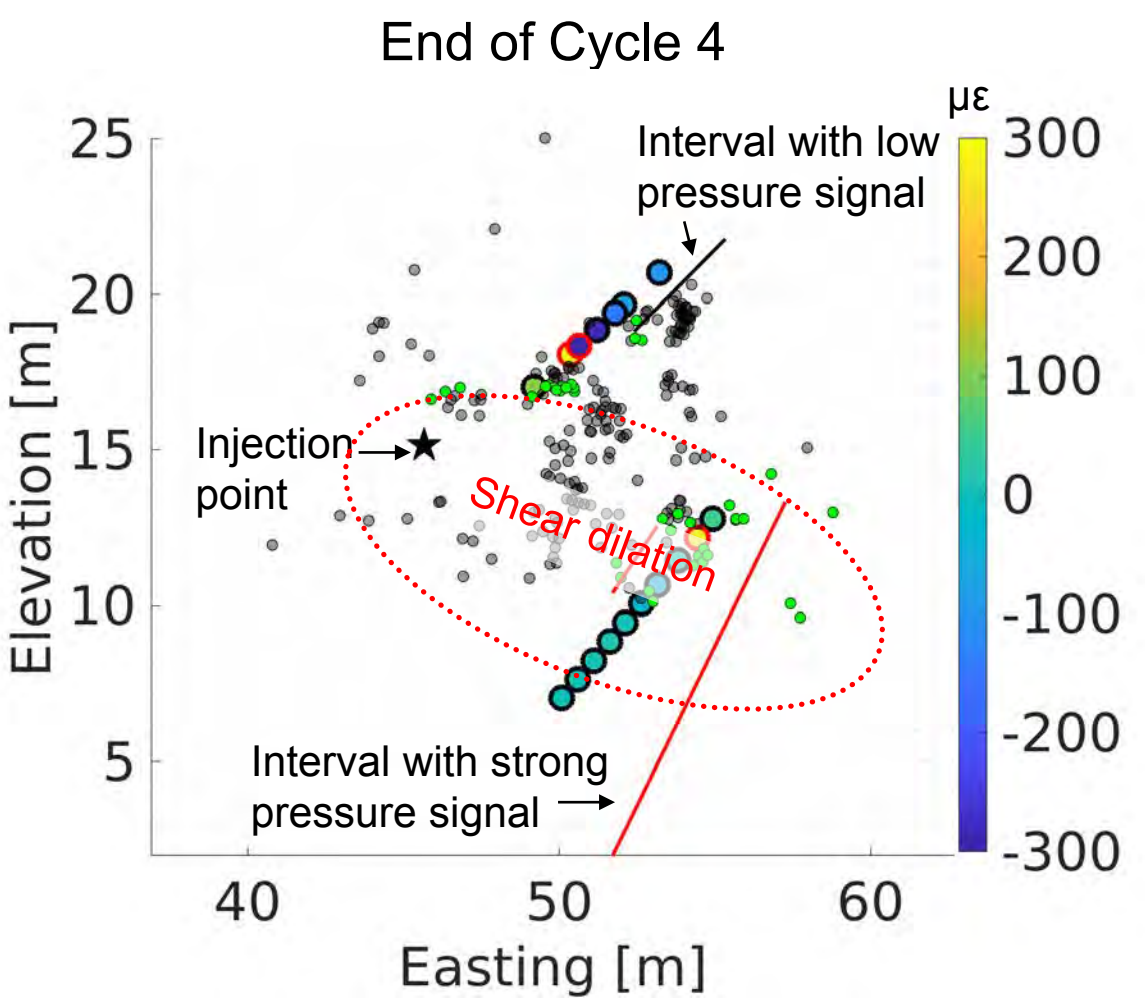


End of Cycle 4



Integration of monitoring data



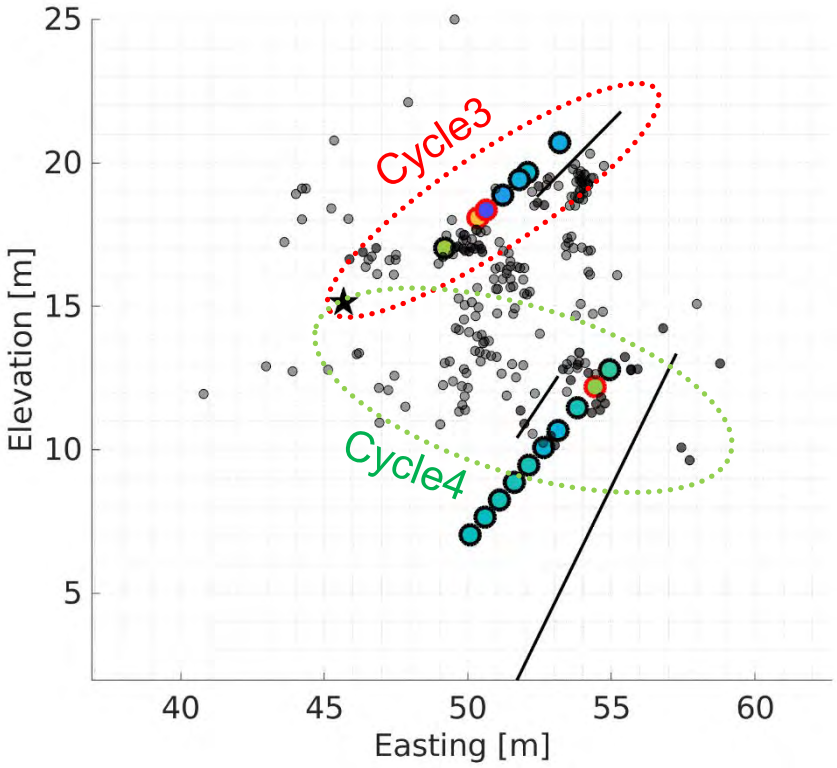


Conclusion & Outlook

- The pressure data seem to indicate channeling within the shear zone and different stimulation mechanism.
- Strain data indicate a change in deformation direction during stimulation and permanent strains over entire shear zone.
- Seismicity visualizes shear displacement over entire shear zone with strong propagation towards lower east direction

- HS5 highlights an interplay of hydraulic fracturing (normal opening) and hydraulic shearing (shear dilation) within one shear zone.

- Constrain deformation mechanisms within the known fault plane based on models of dislocation fields.

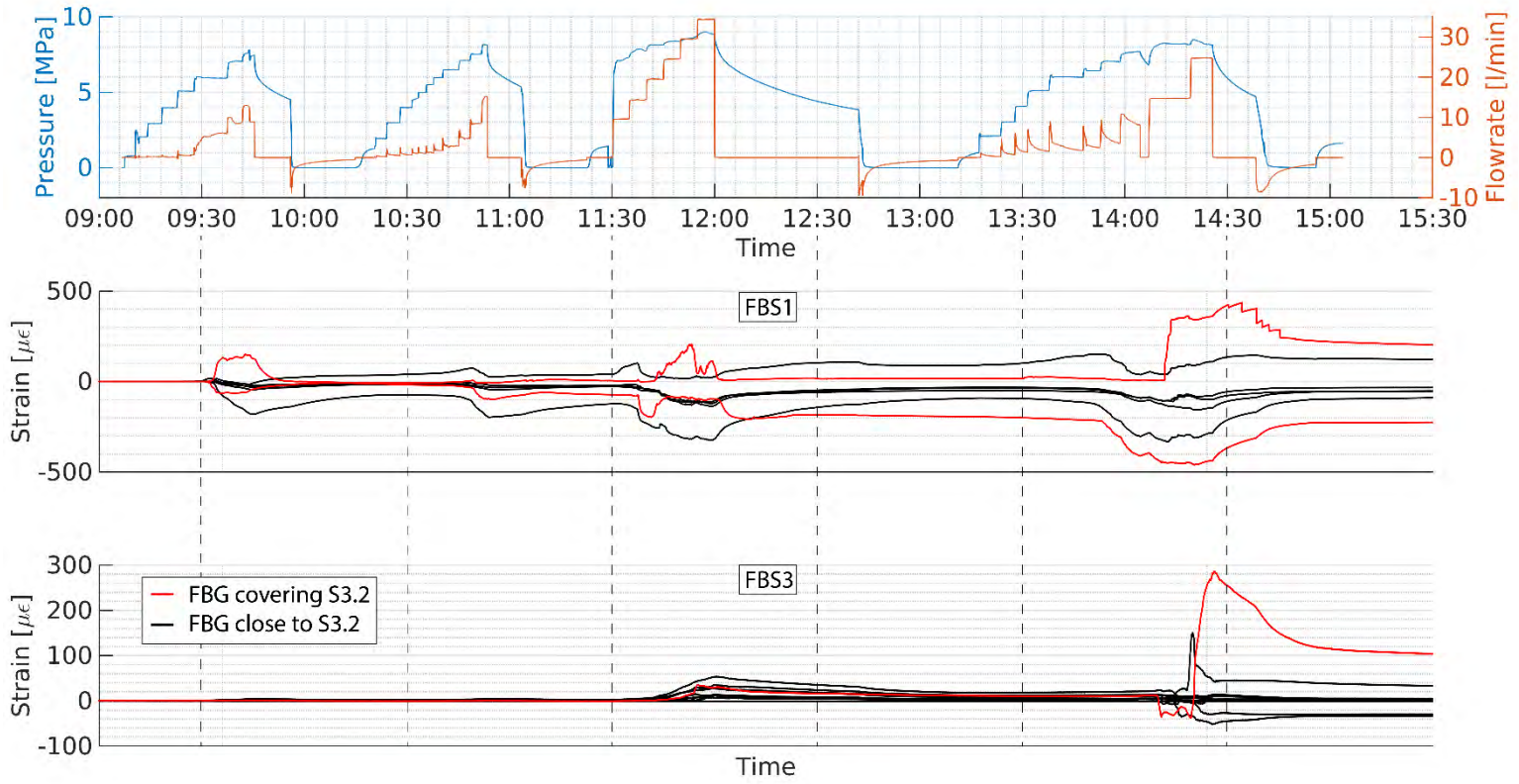


Thank you for your attention!

BACKUP

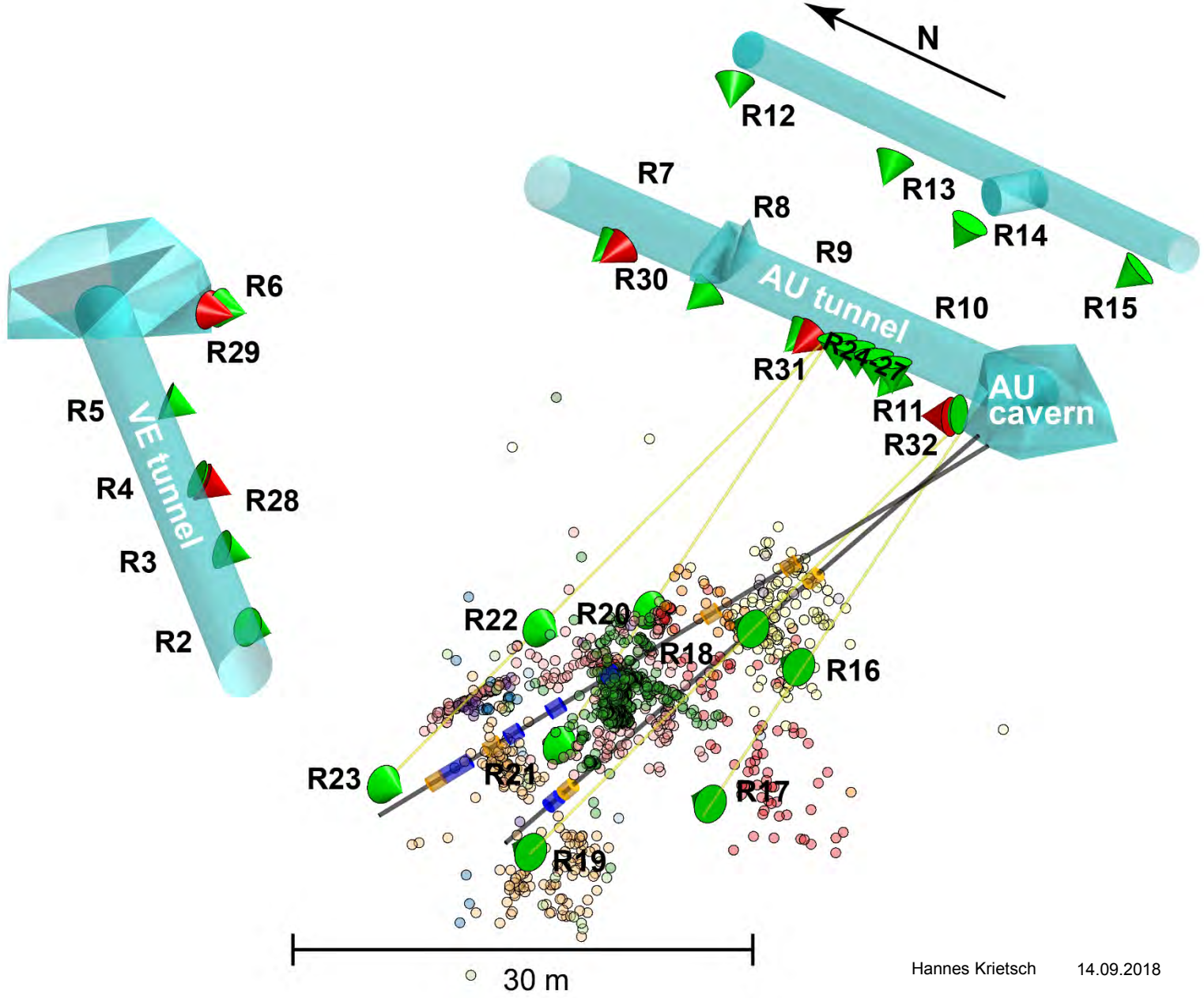
Strain data – FBG Data

- FBGs covering S3.2 indicate opening and strong permanent strains.
- FBGs surrounding S3.2 are partially closed.
- Sensors in FBS1 show strong compressional component.



Seismic monitoring

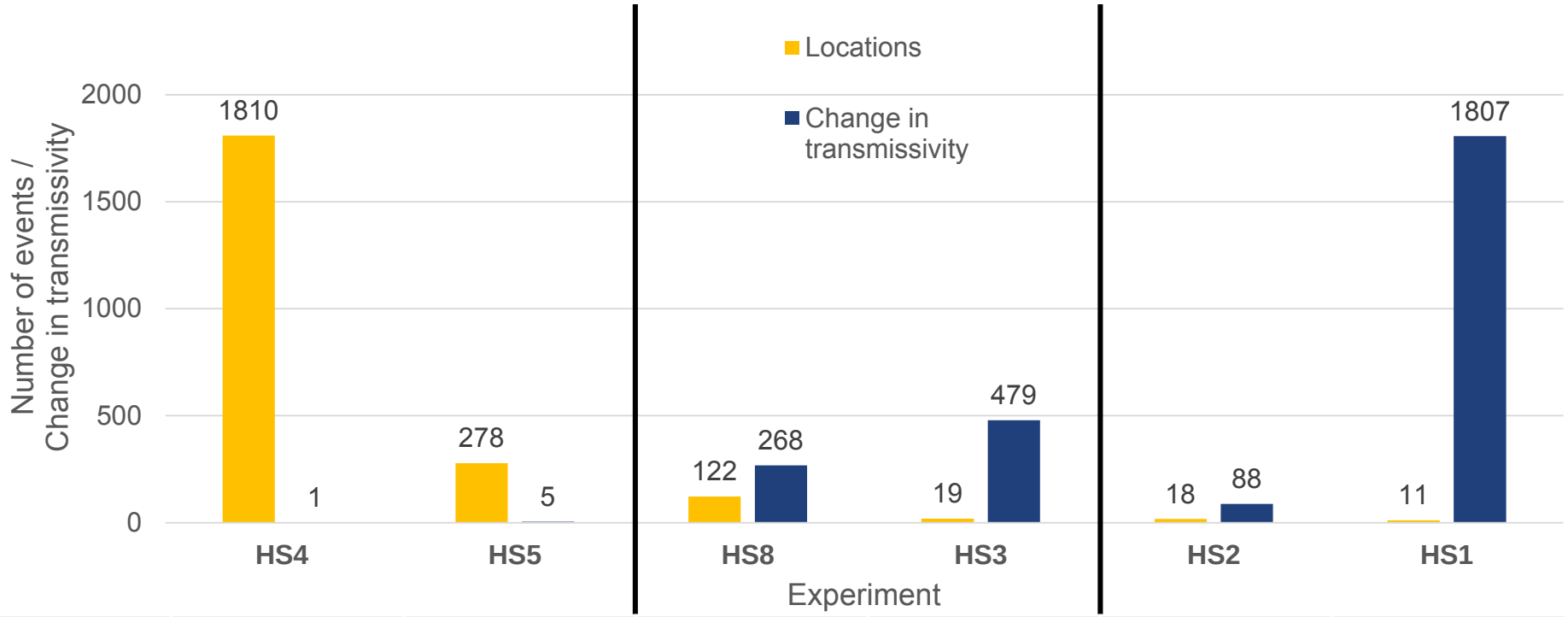
- Seismic network consists of:
  - 26 highly sensitive AE receiver, 8 of them in boreholes
  - 5 accelerometer (1D)
- Detected events:
  - 20’824
- Manually picked, located events:
  - 2’605
- Absolute location procedure:
  - Joint Hypocenter Determination (JHD)
  - Velocity model: homogeneous, anisotropic
- Accuracy of location: ~ 0.5 m



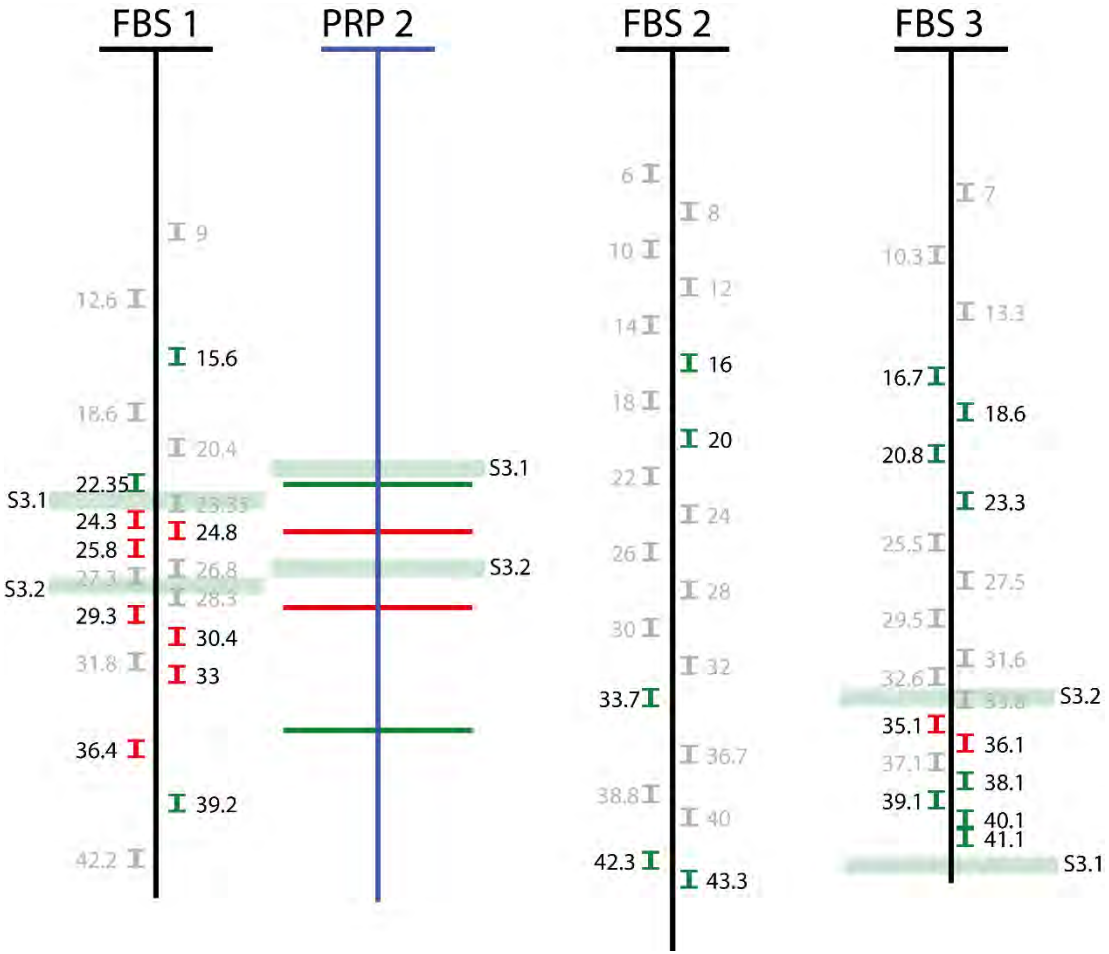
HS experiments: Seismicity vs. change in transmissivity

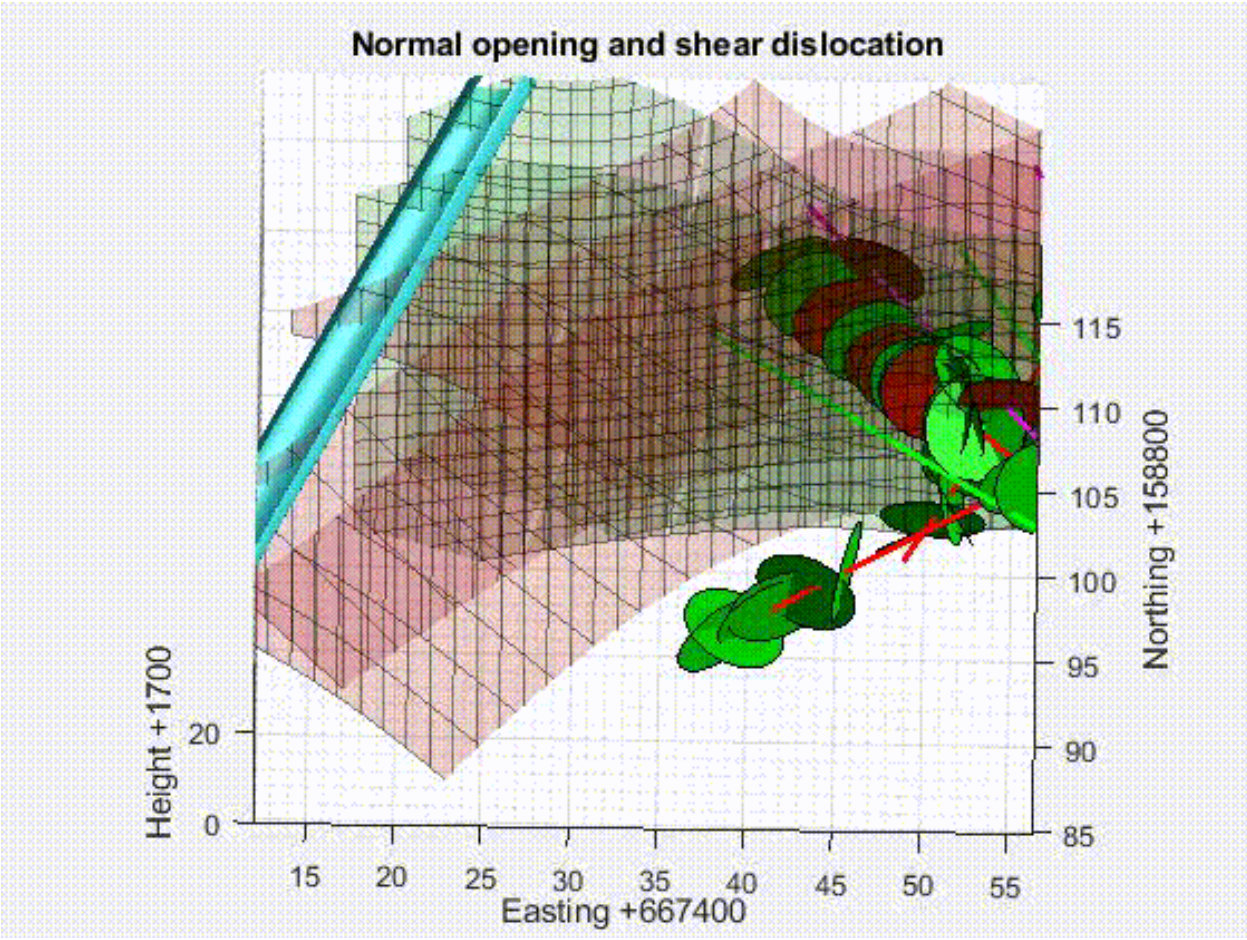
Slip tendency

Structure	Shear zone S3		Shear zone S3 and S1		Shear zone S1	
Initial transmissivity [m2/s]:	1.2e-7	1.2e-8	2.8e-10	4.8e-10	2.5e-9	8.3e-11
Final transmissivity [m2/s]:	1.2e-7	5.5e-8	7.5e-8	2.3e-7	2.2e-7	1.5e-7



Static analysis of deformation





- Normal opening- > green && Shear failure -> red