Bedretto Underground Laboratory for
Geosciences and Geoenergies

Seismicity and Fracture Dynamics during Hydraulic Injection Experiments in the BedrettoLab

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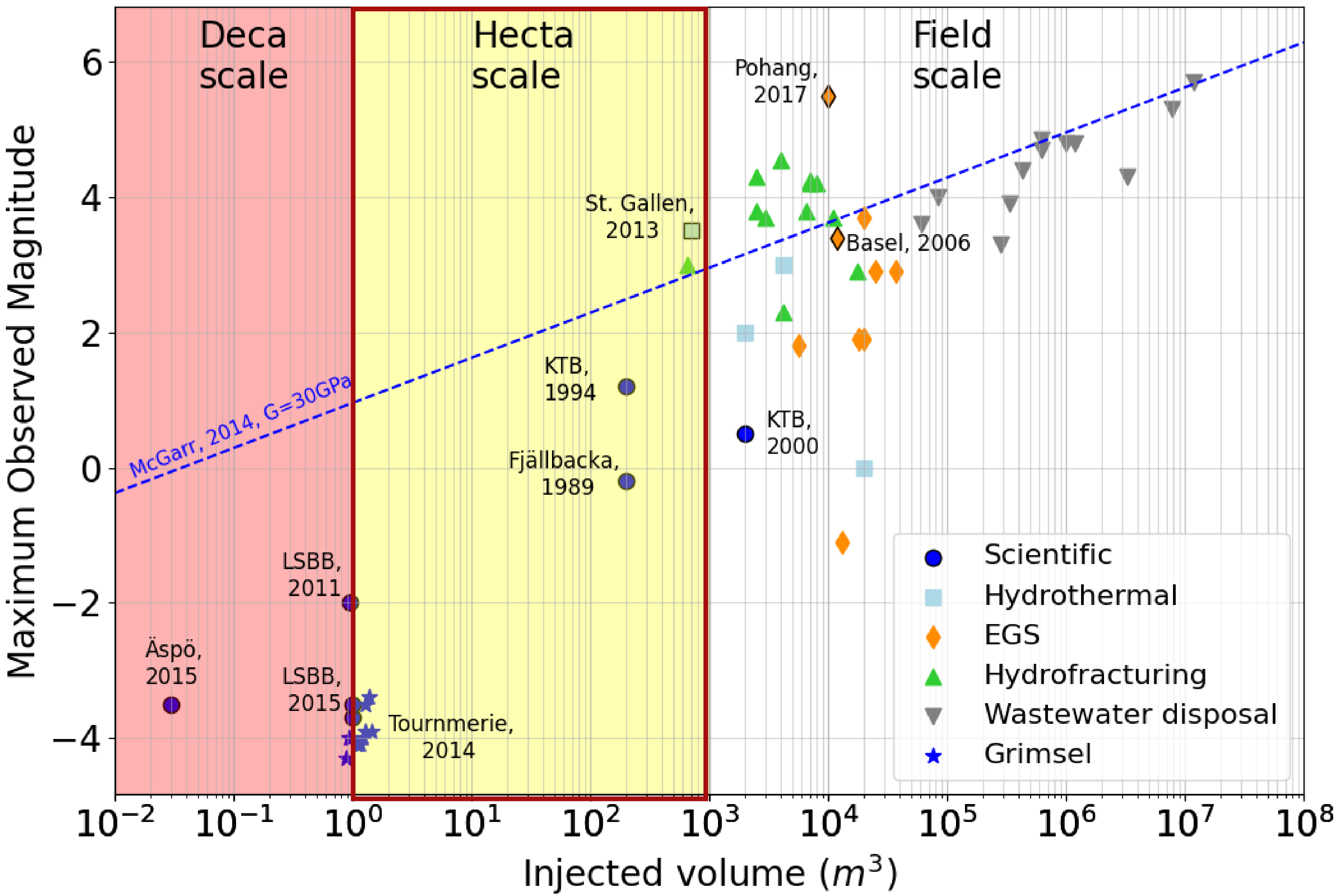
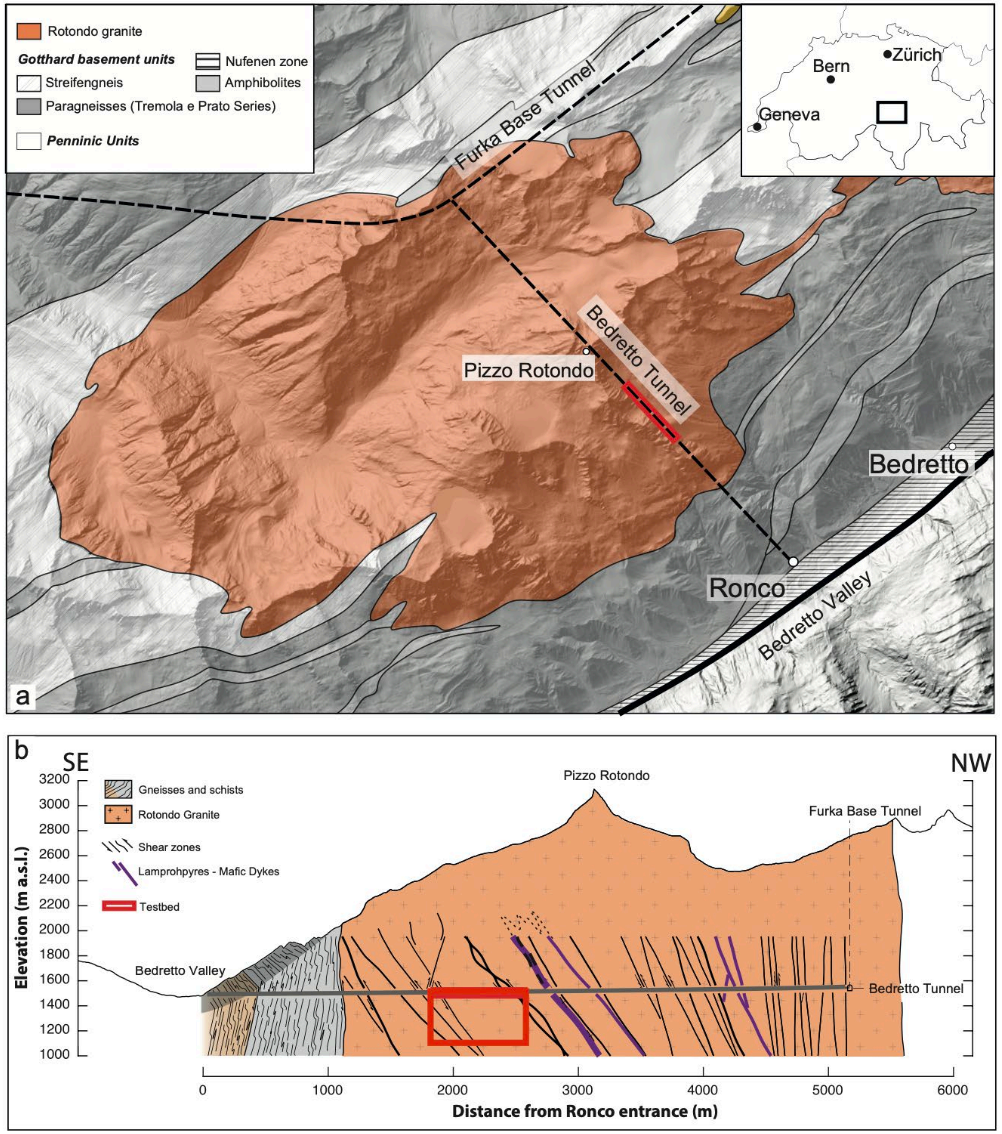
Motivation

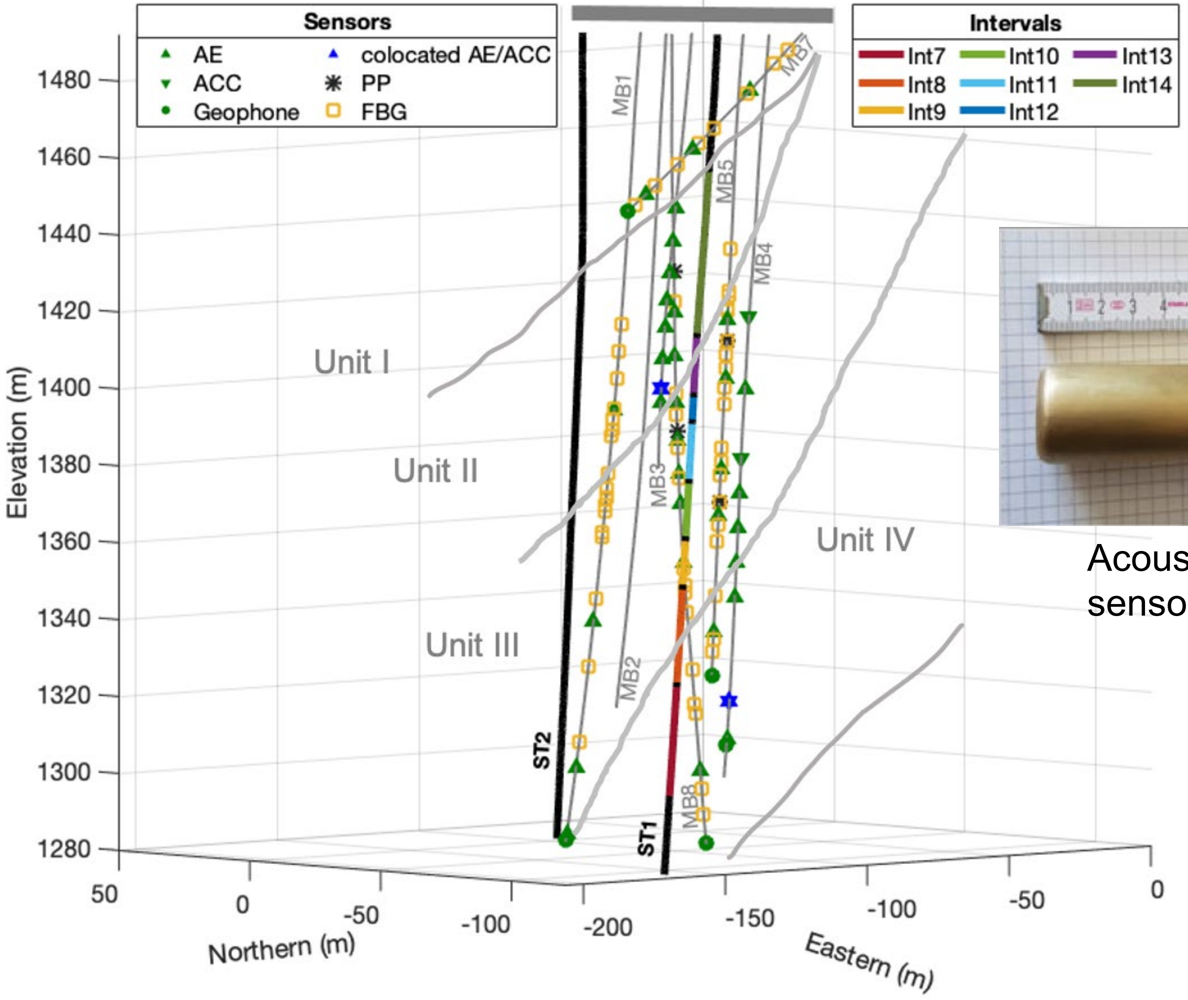


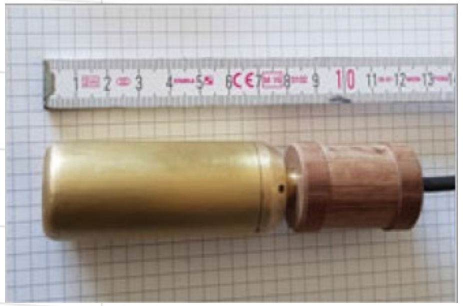
Deca scale
Hecta scale
Field scale
Maximum Observed Magnitude
Injected volume (m^3)
McGarr, 2014, G=30GPa
Pohang, 2017
St. Gallen, 2013
Basel, 2006
KTB, 1994
KTB, 2000
Fjällbacka, 1989
LSBB, 2011
Äspö, 2015
LSBB, 2015
Tournmerie, 2014
Scientific
Hydrothermal
EGS
Hydrofracturing
Wastewater disposal
Grimsel

Overview BedrettoLab – Mesoscale site



Boreholes and Sensor Network





Acoustic emission sensors

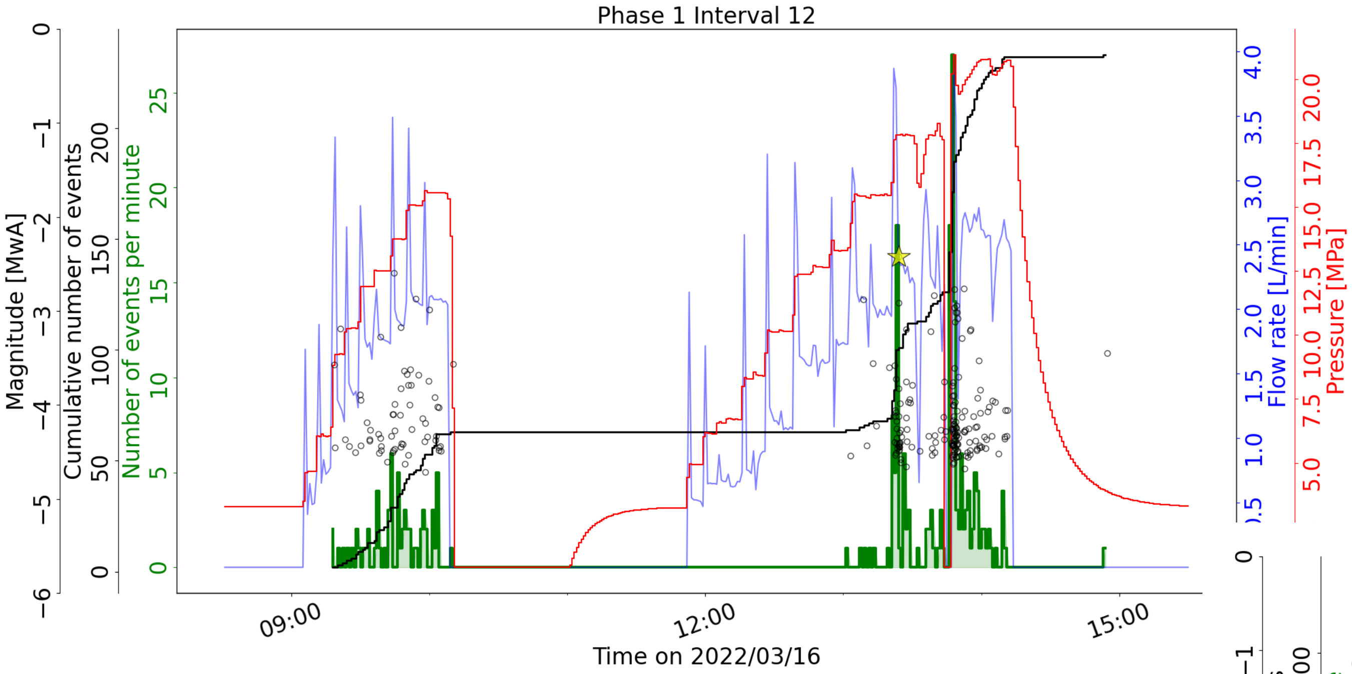
Multi-parameter monitoring system:
Seismic (AE, ACC, geophone); Hydromechanical (DTS, DSS, DAS, FBG, pore pressure sensor)

Stimulation borehole (ST1):
MultiPacker System dividing borehole into 14 Intervals

→ Controlled meso-scale experiments in realistic stress conditions monitored by multi-parameter network

Plenkers, et al (2023). *Multi-disciplinary monitoring networks for mesoscale underground experiments: Advances in the Bedretto Reservoir Project,* Sensors.

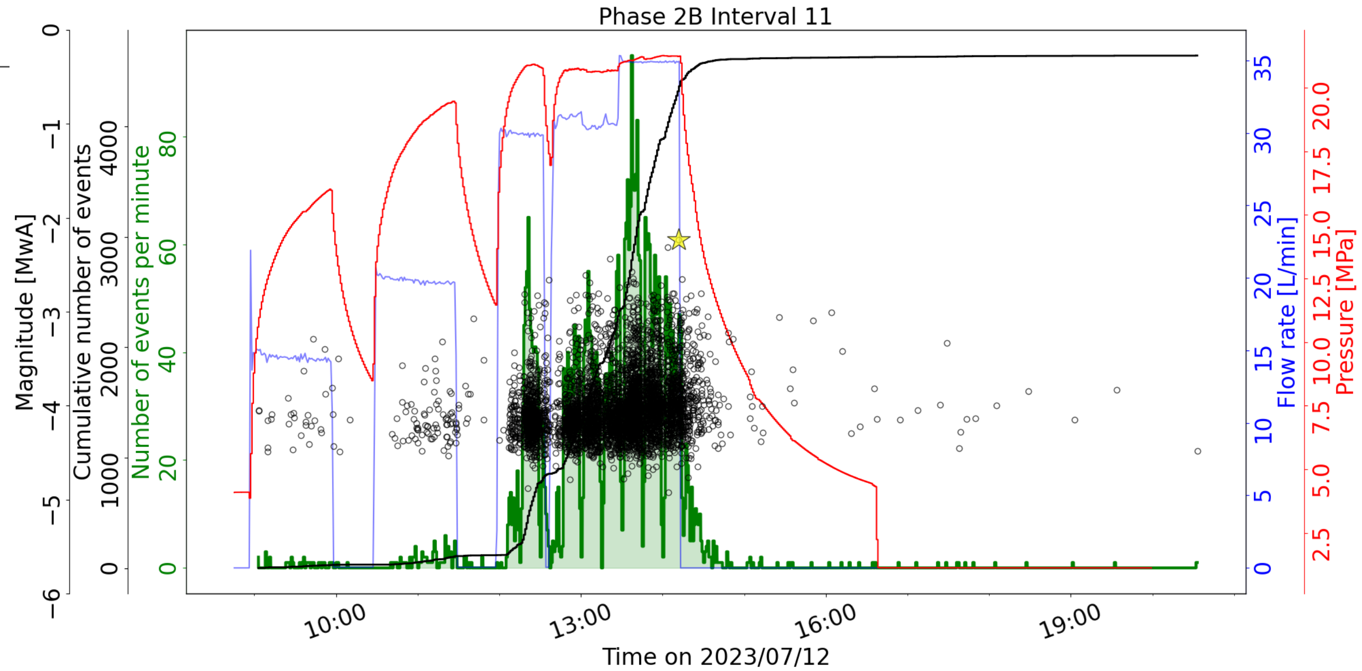
Hydraulic stimulations



17 injection experiments performed in 2021 to 2023 divided in Phase 1 and Phase 2

Phase 1: Characterize hydromechanical properties

Phase 2: Investigate rock behavior in terms of reservoir engineering with longer injection durations



Seismic catalogue creation with python-based open source software Dugseis: Rosskopf et al. (2024) *A Python package for real-time and post-processing of picoseismicity*, Journal of Open Source Software

Creation of picoseismic catalogs and the challenges

<u>Real-time</u>

→ Quick catalog needed for hazard assessment

<u>Post-processing</u>

→ Complete catalog essential for detailed seismic analysis

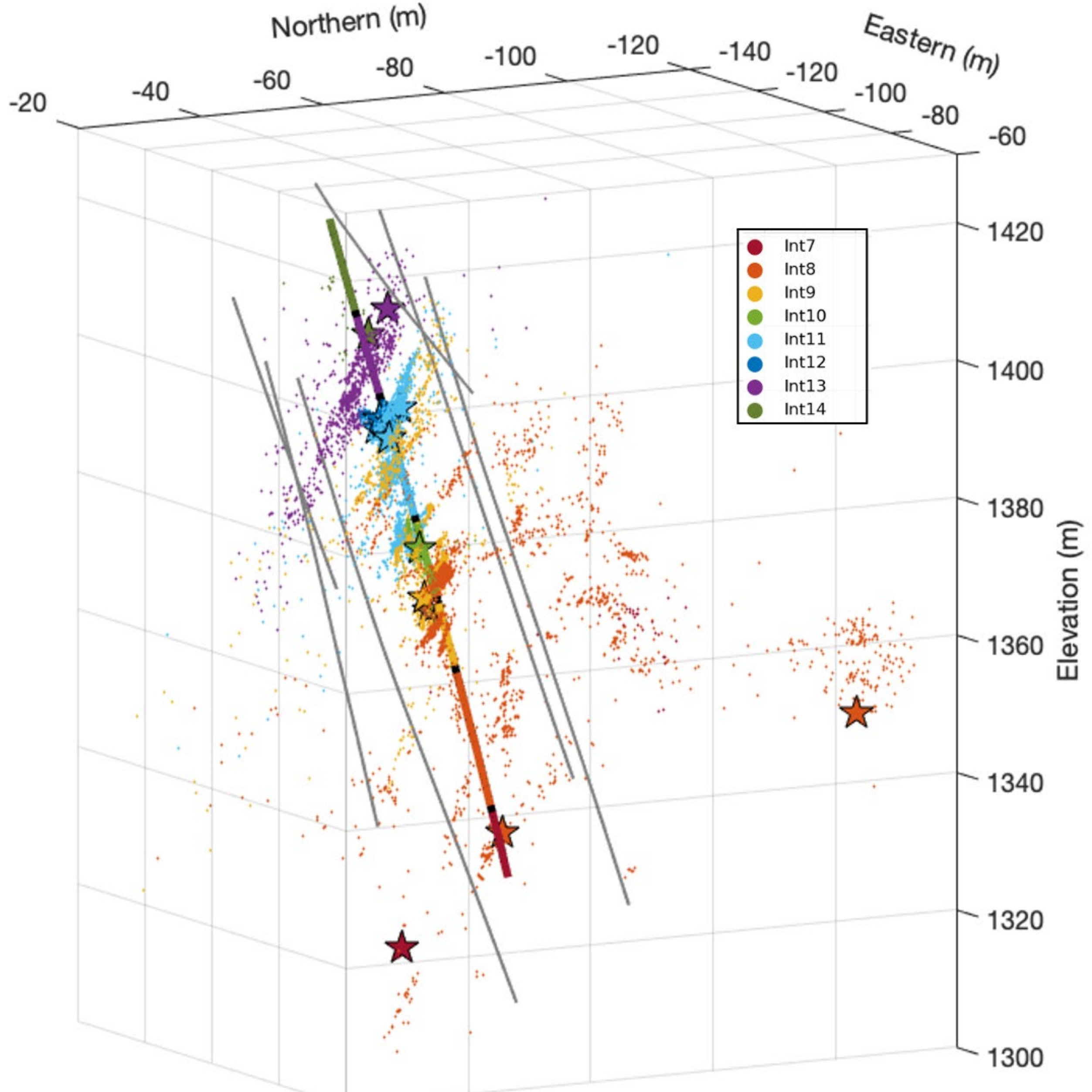
<u>Meso-scale experiments</u>

→ High sampling rates (kHz-MHz) to detect events with magnitudes <-5
→ High event rates (several per second)
→ Short event times
→ No typical 3 component seismometer
→ 3D coverage

Assessment and workflow for our experiments described in: Rosskopf et al. *Accuracy of picoseismic catalogs in hectometer-scale in-situ experiments*, in review SRL

Seismic event locations

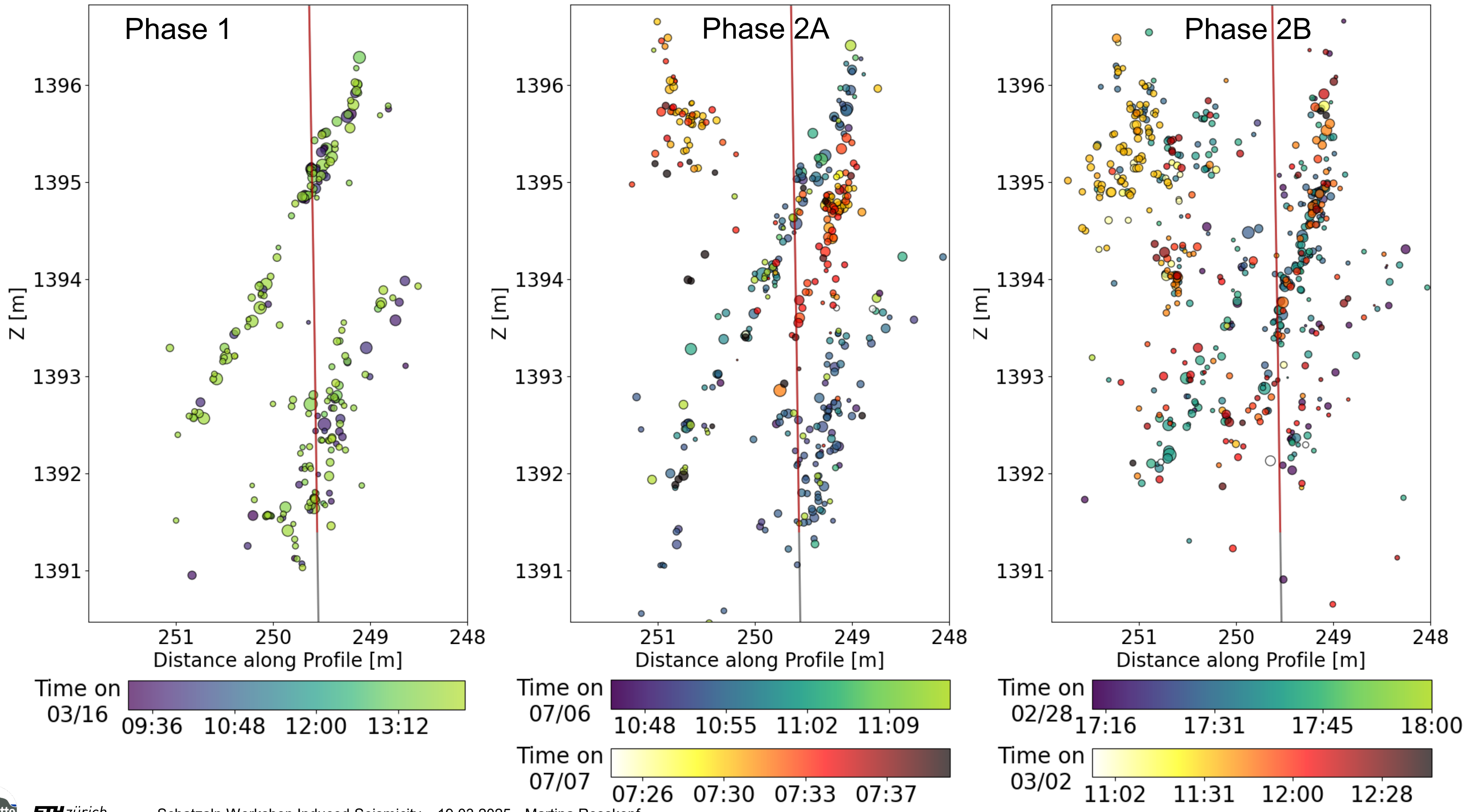
- Seismicity aligns with the pre-known fractures
- Reactivation of faults with NE-SW striking direction
- Several structures can be reactivated within one stimulation
- Spatial extension between 7 and 130 m



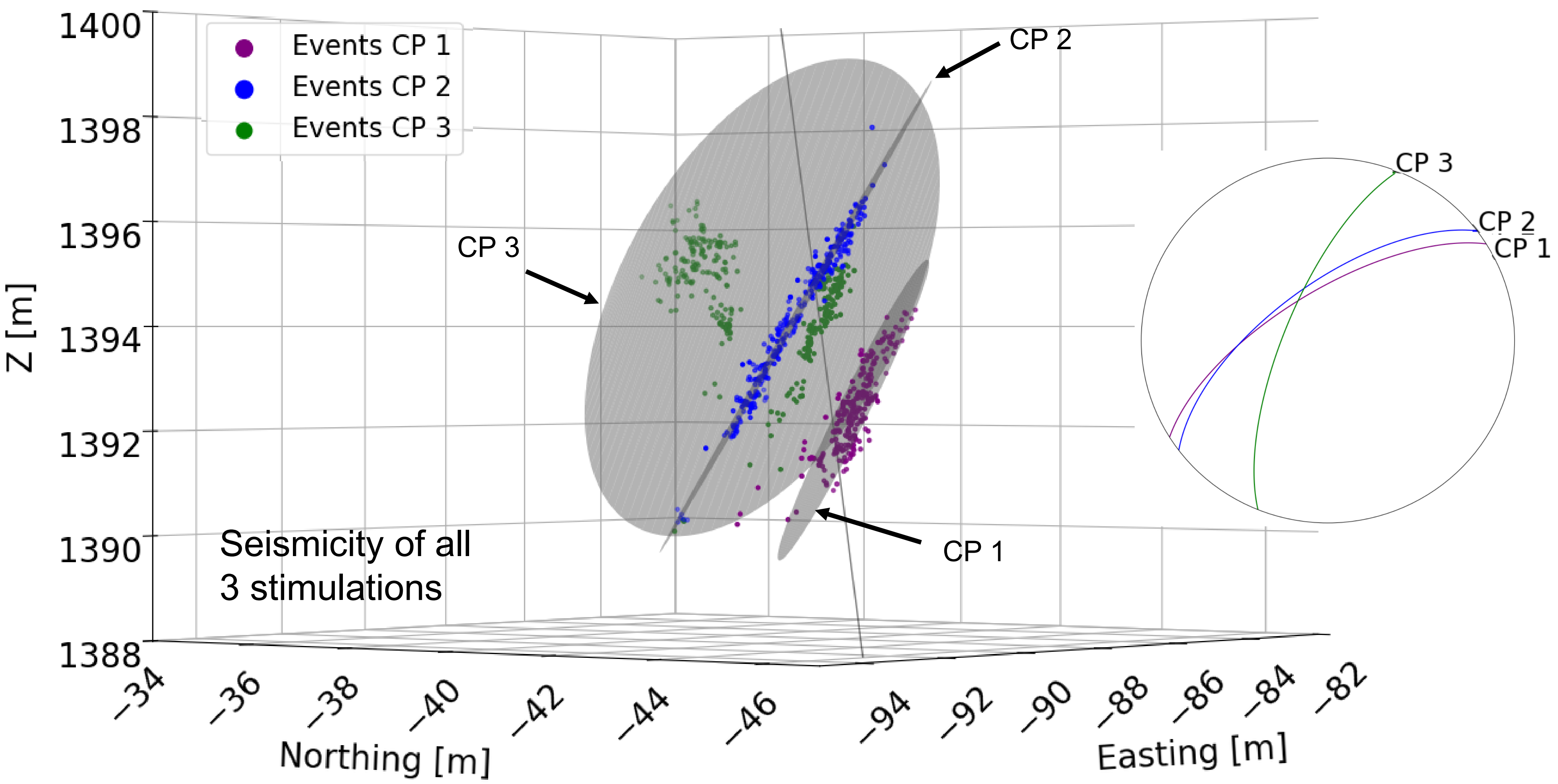
Obermann, Rosskopf et al. (2024) Picoseismic response of hectometer – scale fracture systems to stimulation with cm-scale resolution under the Swiss Alps, in the Bedretto Underground laboratory

Seismicity of interval 12 stimulations

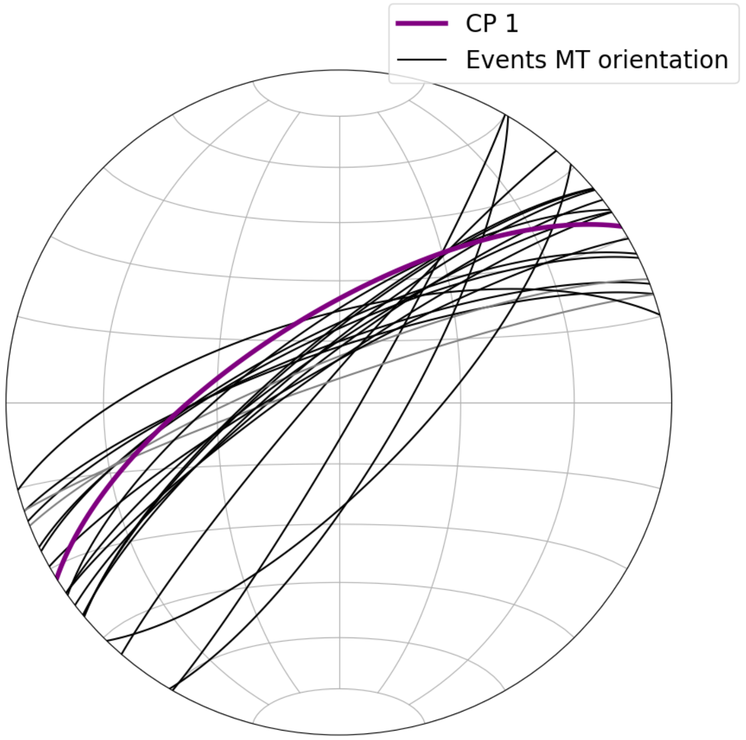
Rosskopf et al. *Seismicity Migration, Cluster Interaction, and Focal Mechanisms During Hydraulic Stimulation in the BedrettoLab*, to be submitted

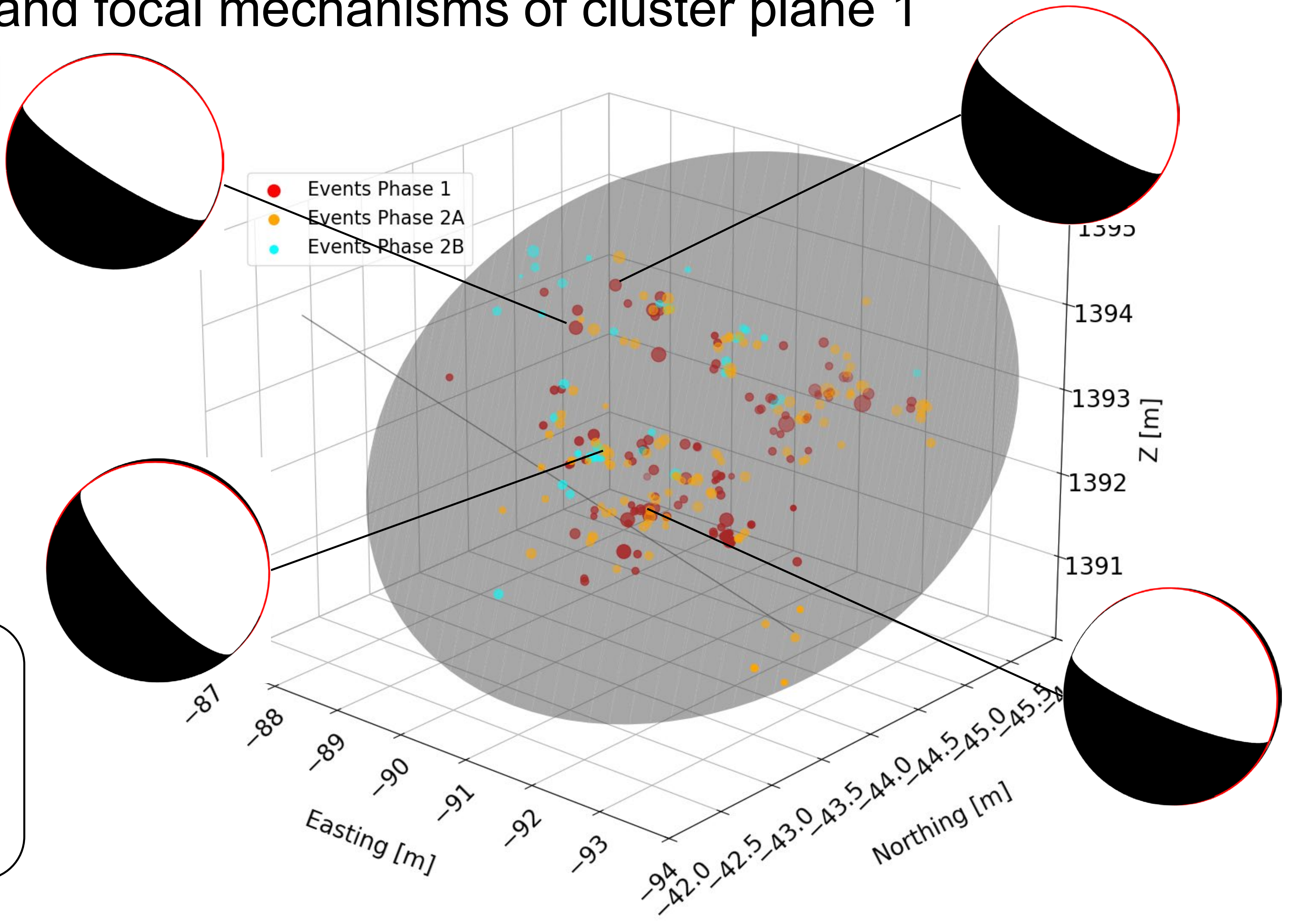


Seismicity described by three cluster planes (CP)



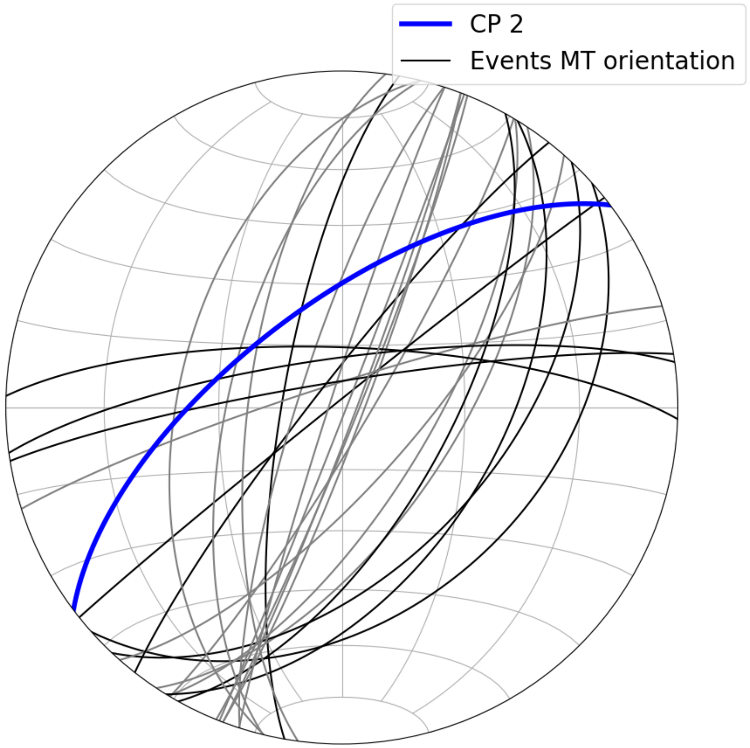
Seismicity migration and focal mechanisms of cluster plane 1



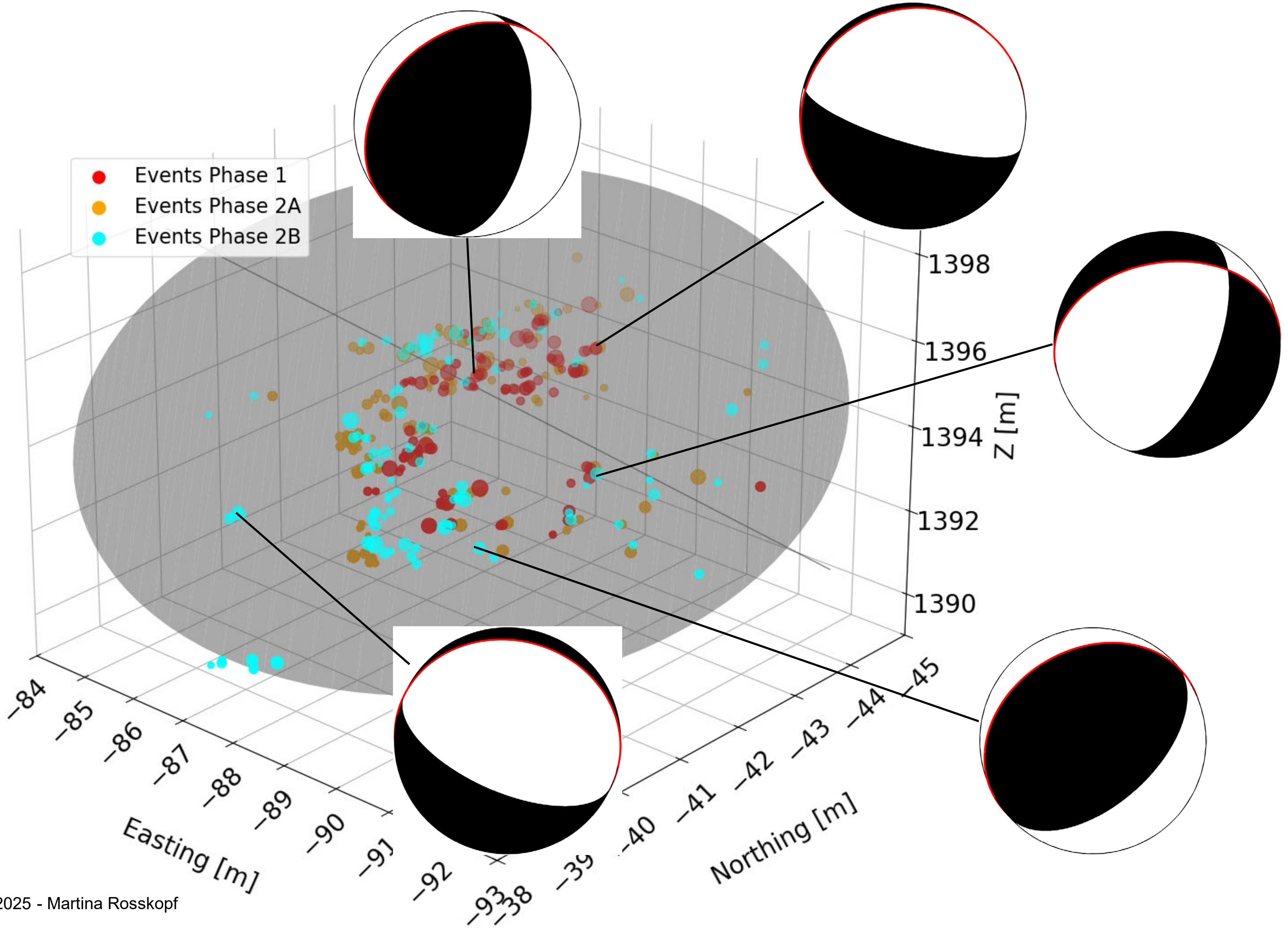


- Mostly active during phase 1 and 2A (beginning)
- Mixed mechanism between strike-slip and normal faulting aligned with the cluster plane

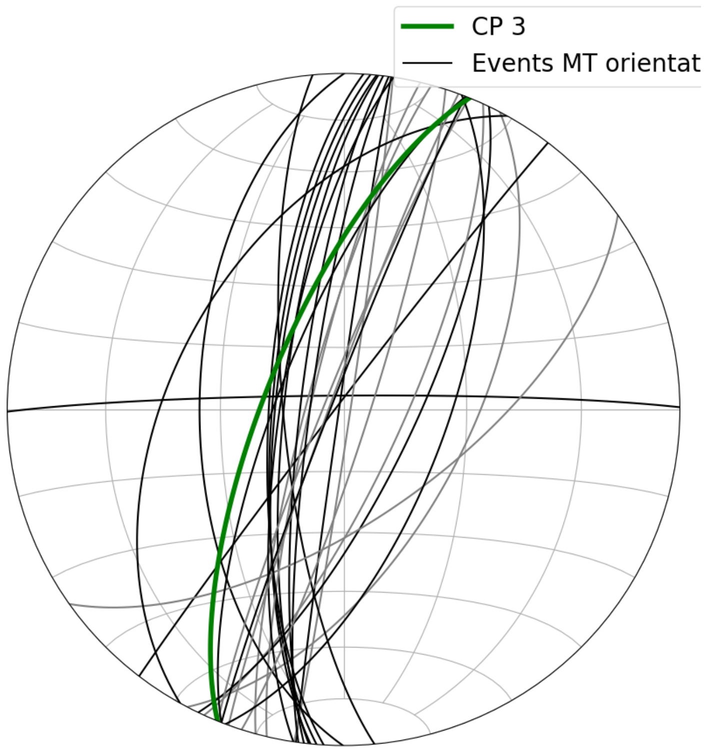
Seismicity migration and focal mechanism of cluster plane 2



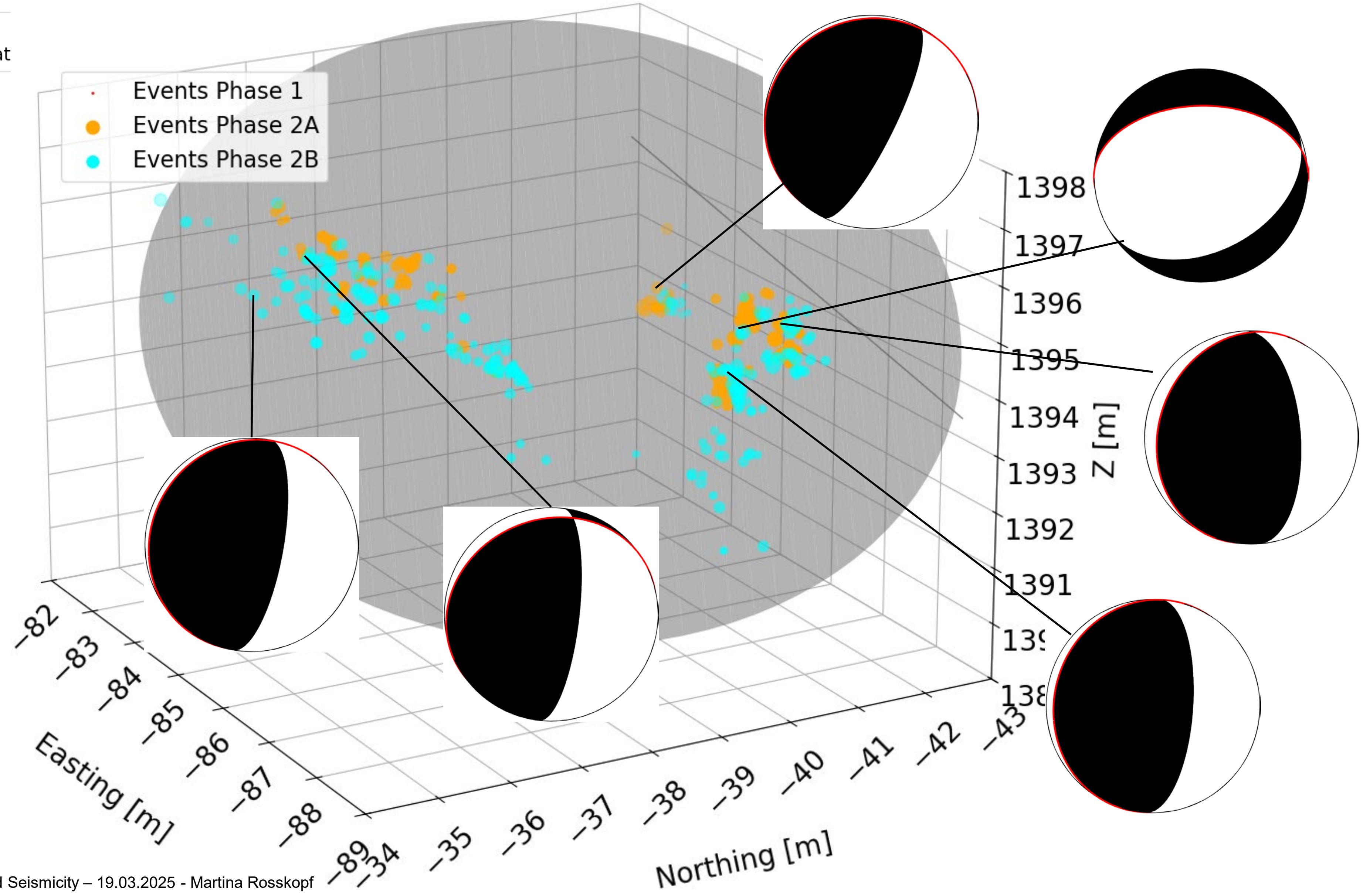
- Active through all phases with migration to NE and down in phase 2A/B
- Diffuse focal mechanism with no clear pattern



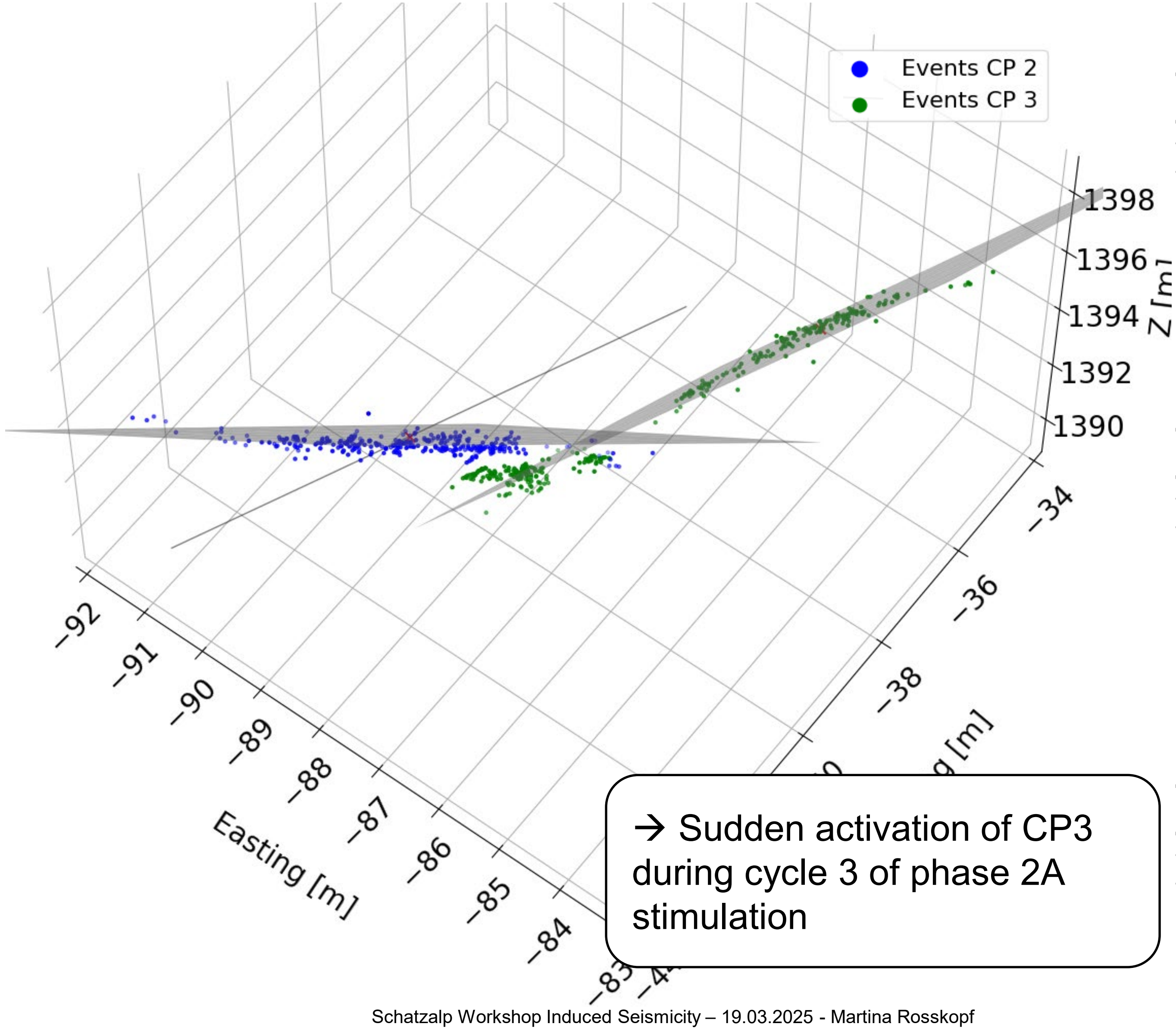
Seismicity migration and focal mechanism of cluster plane 3

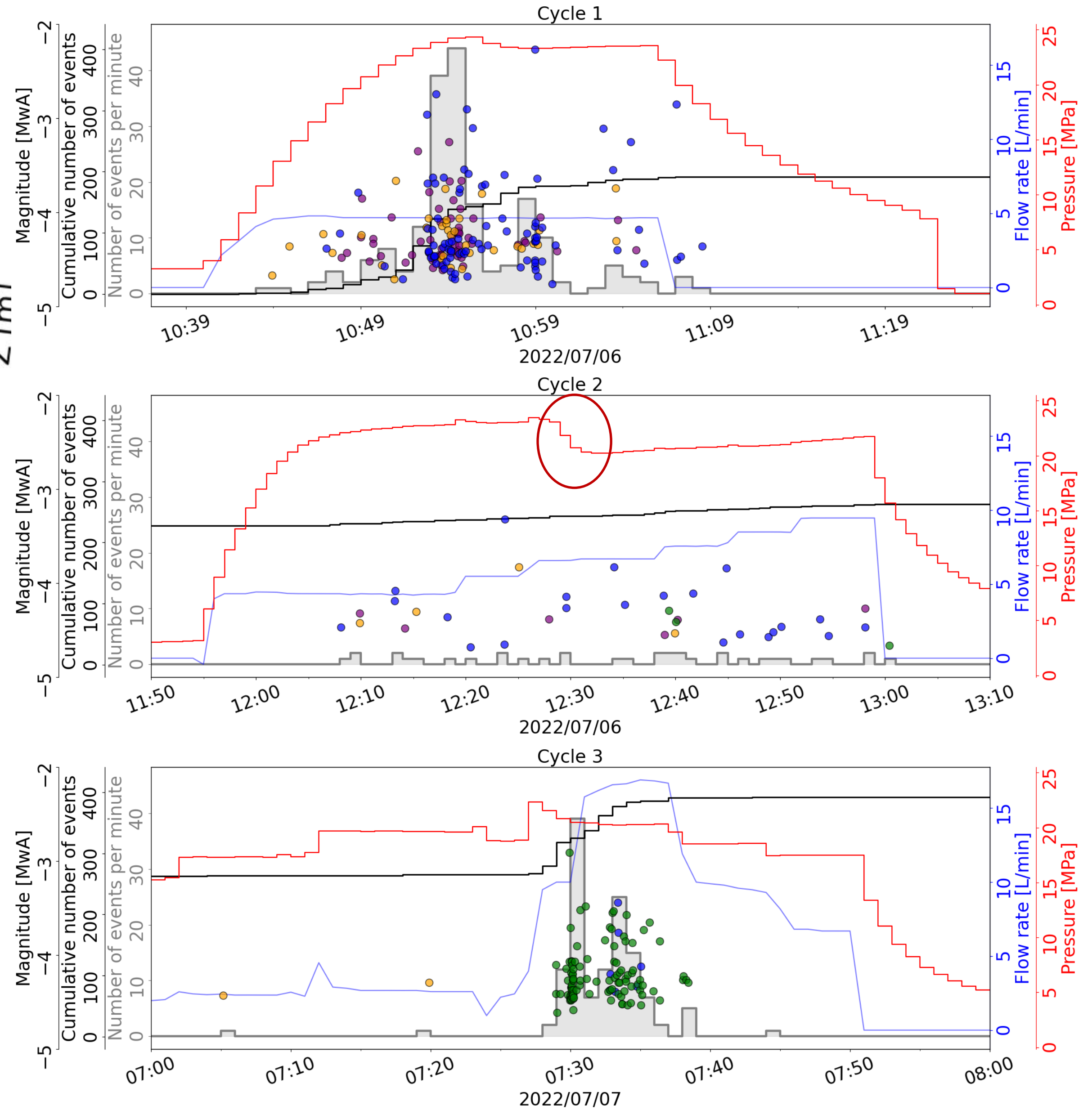


- Only activated during Phase 2A stimulation
- most event show strike-slip mechanism aligning with the cluster plane



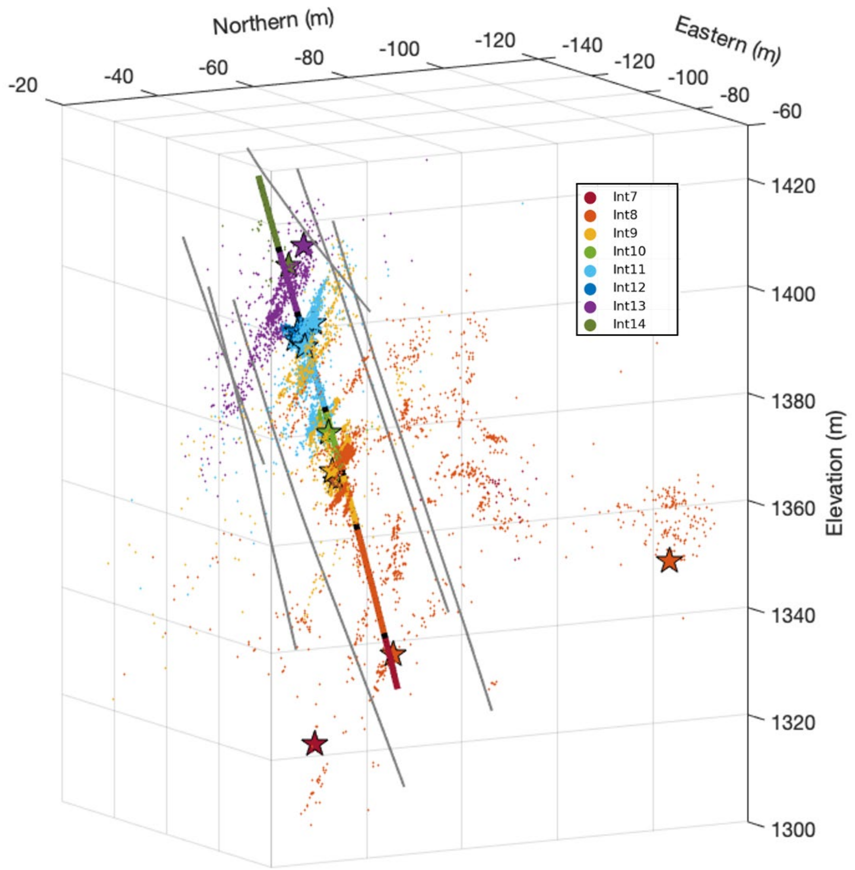
Activation of cluster plane 3 through connection of plane 2

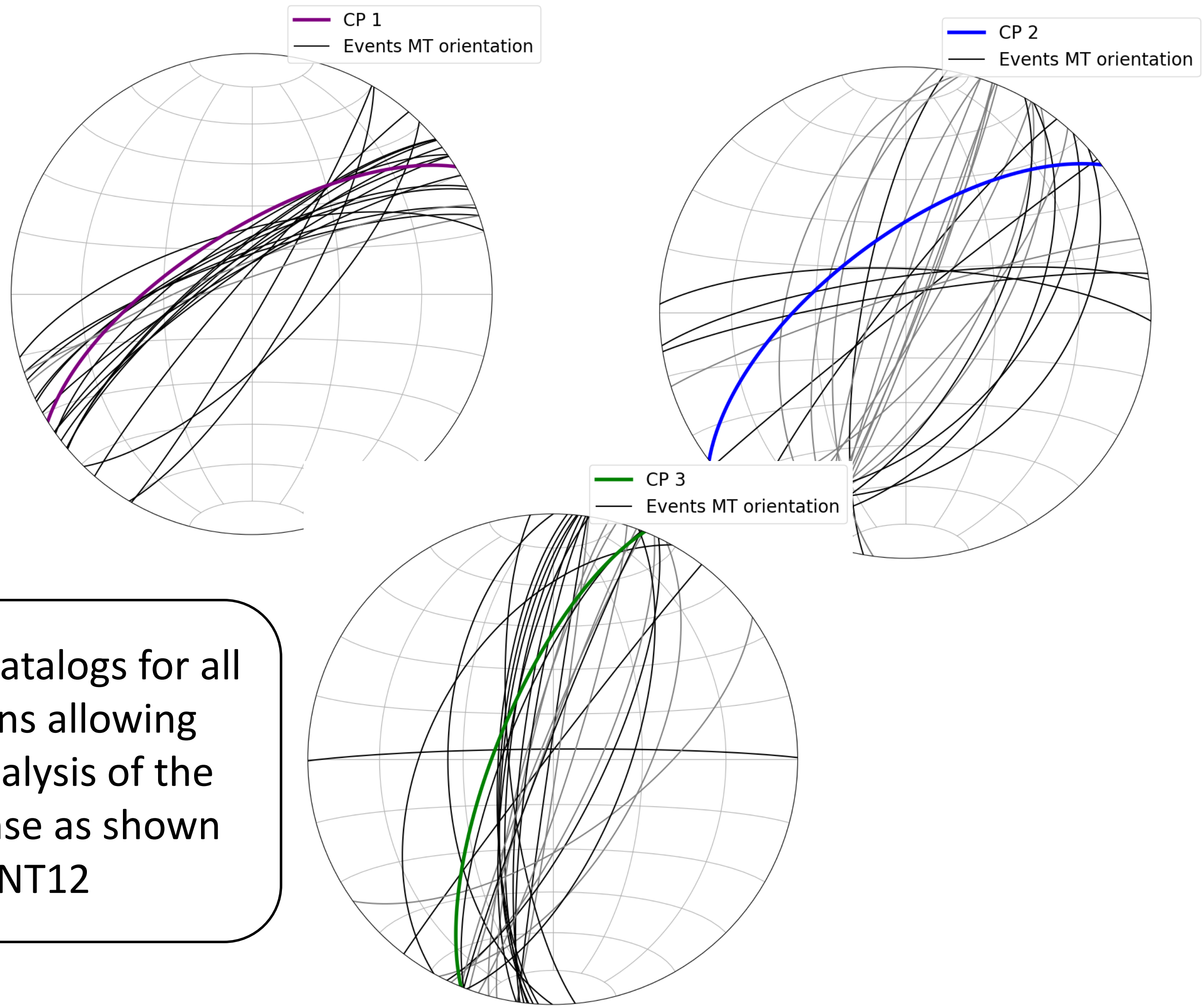




→ Sudden activation of CP3 during cycle 3 of phase 2A stimulation

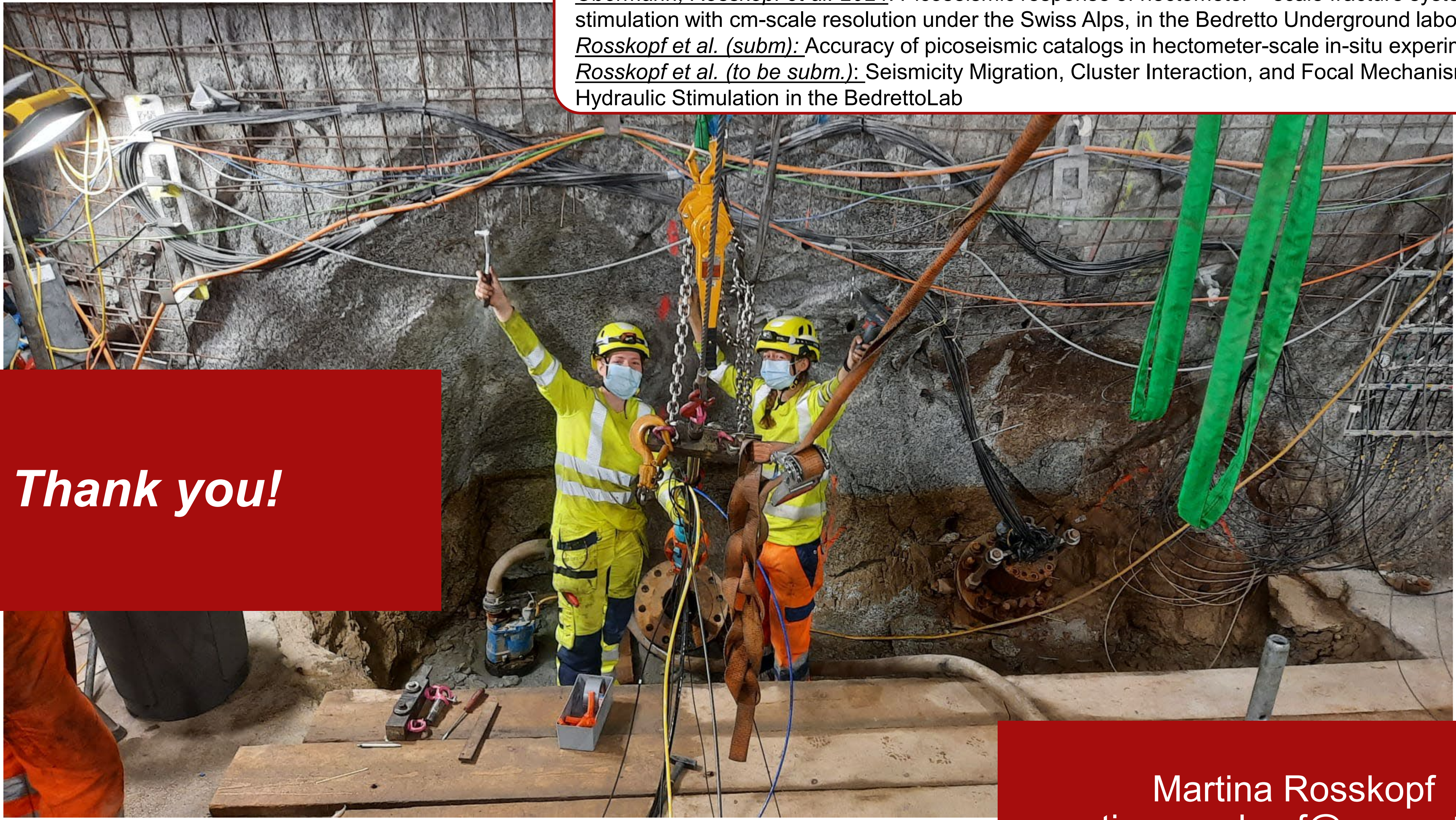
Summary and Outlook





HQ seismic catalogs for all stimulations allowing detailed analysis of the rock response as shown for INT12

Next steps:
- Interpret seismicity together with hydromechanical response for the whole fracture network



Rosskopf et al. 2024: DUGseis: A Python package for real-time and post-processing of picoseismicity
Obermann, Rosskopf et al. 2024: Picoseismic response of hectometer – scale fracture systems to stimulation with cm-scale resolution under the Swiss Alps, in the Bedretto Underground laboratory
Rosskopf et al. (subm): Accuracy of picoseismic catalogs in hectometer-scale in-situ experiments
Rosskopf et al. (to be subm.): Seismicity Migration, Cluster Interaction, and Focal Mechanisms During Hydraulic Stimulation in the BedrettoLab

Thank you!

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References

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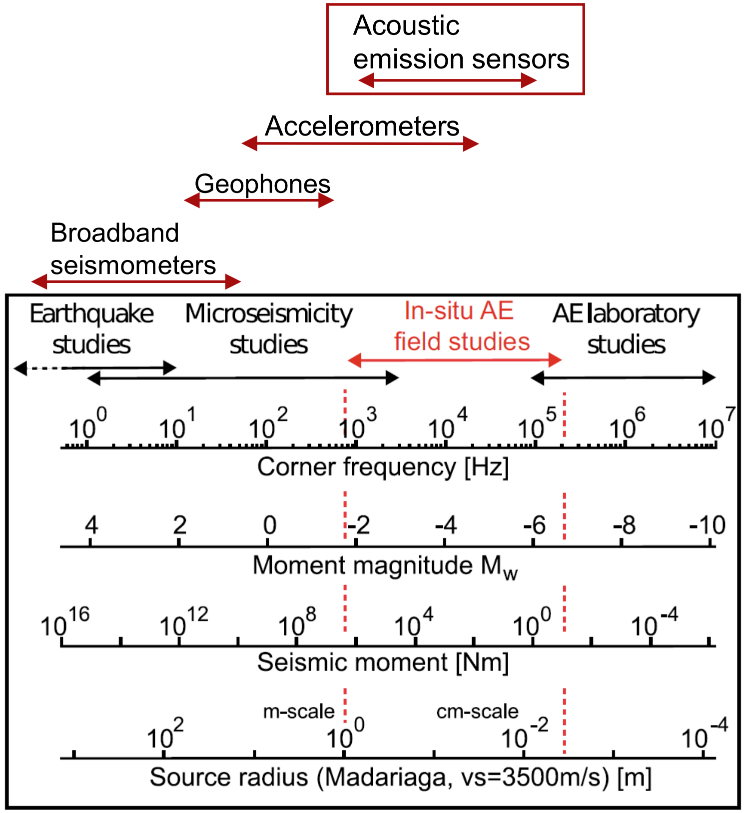
Rosskopf, M ., Durand, V., Villiger, L., Doetsch, J., Obermann, A., Krischer, L. (2024). DUGseis: A Python package for real-time and post-processing of picoseismicity. Journal for Open Source Software. Manuscript submitted for publication.

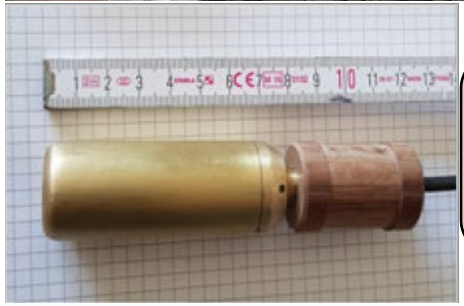
Seismic Network

Need to cover frequency range between 0.01 Hz to 50kHz to record seismicity down to Mw < -5

Installed sensors:
- Tunnel strong motion/broadband seismometers
- Downhole geophones
- High-frequency accelerometers
- Acoustic emission sensors



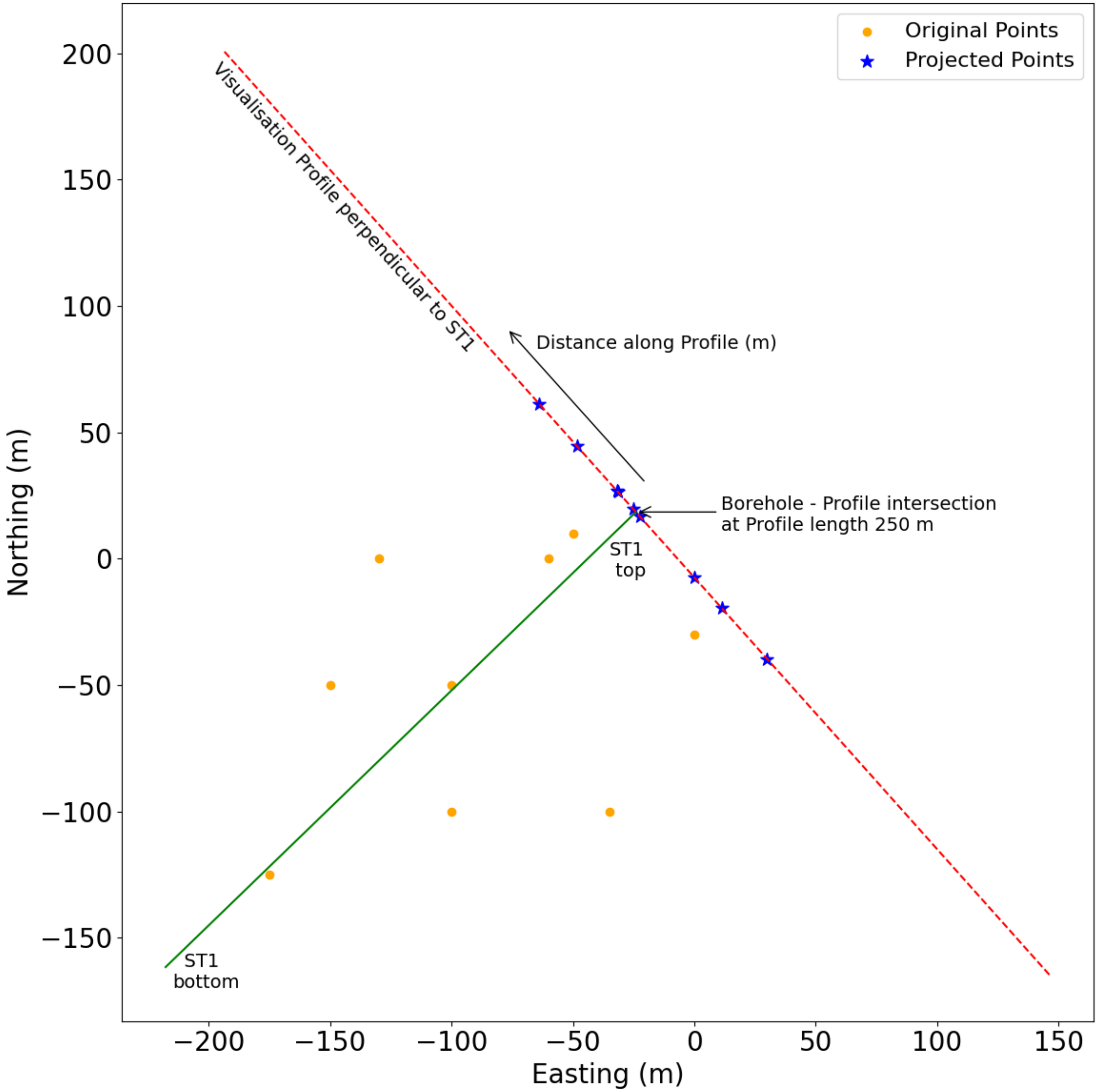
Plenkers et al. 2022; 2023



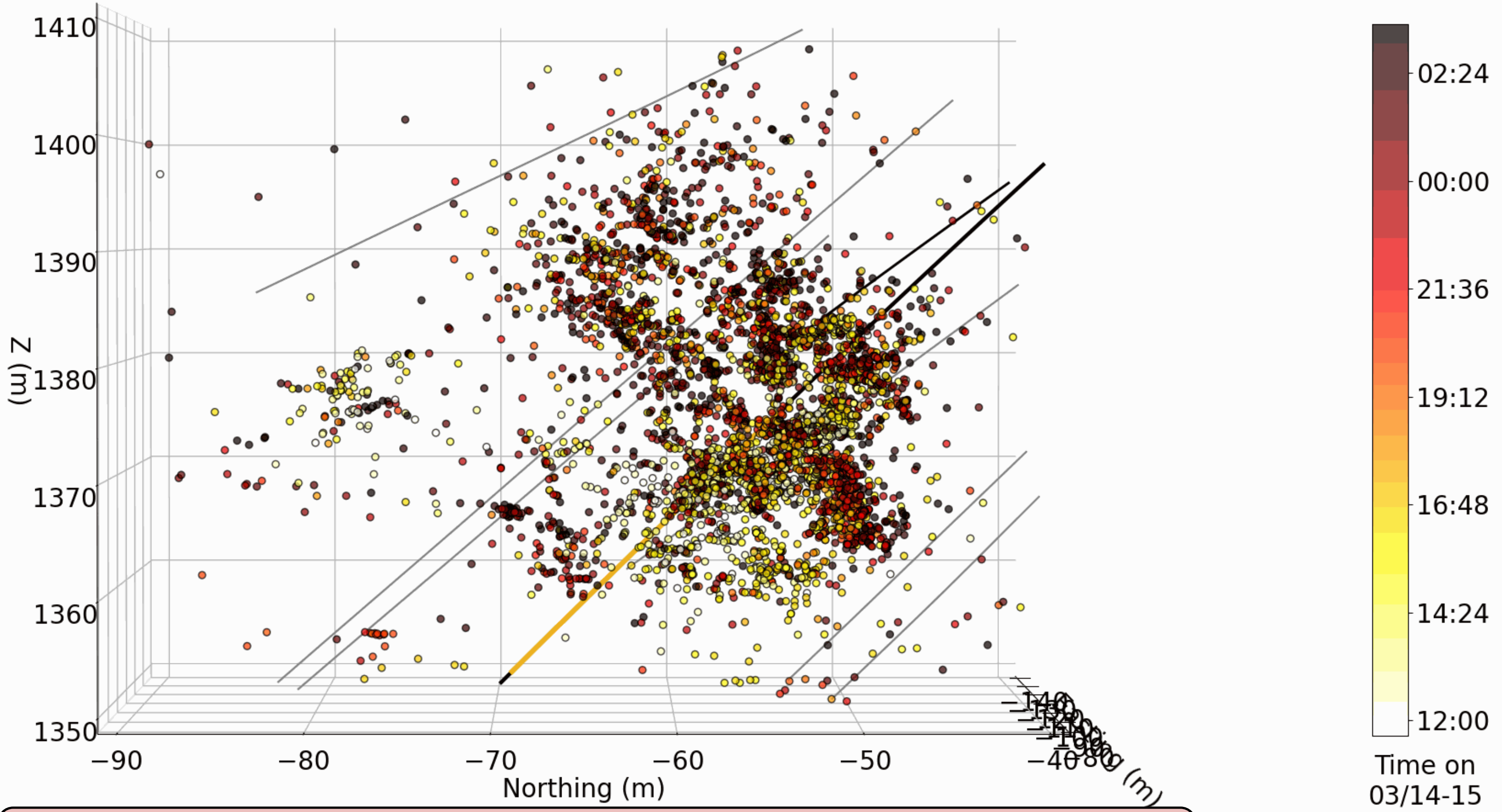
Calibration through colocated accelerometers

Plenkers et al. 2022

Visualization of the profile perpendicular to ST1

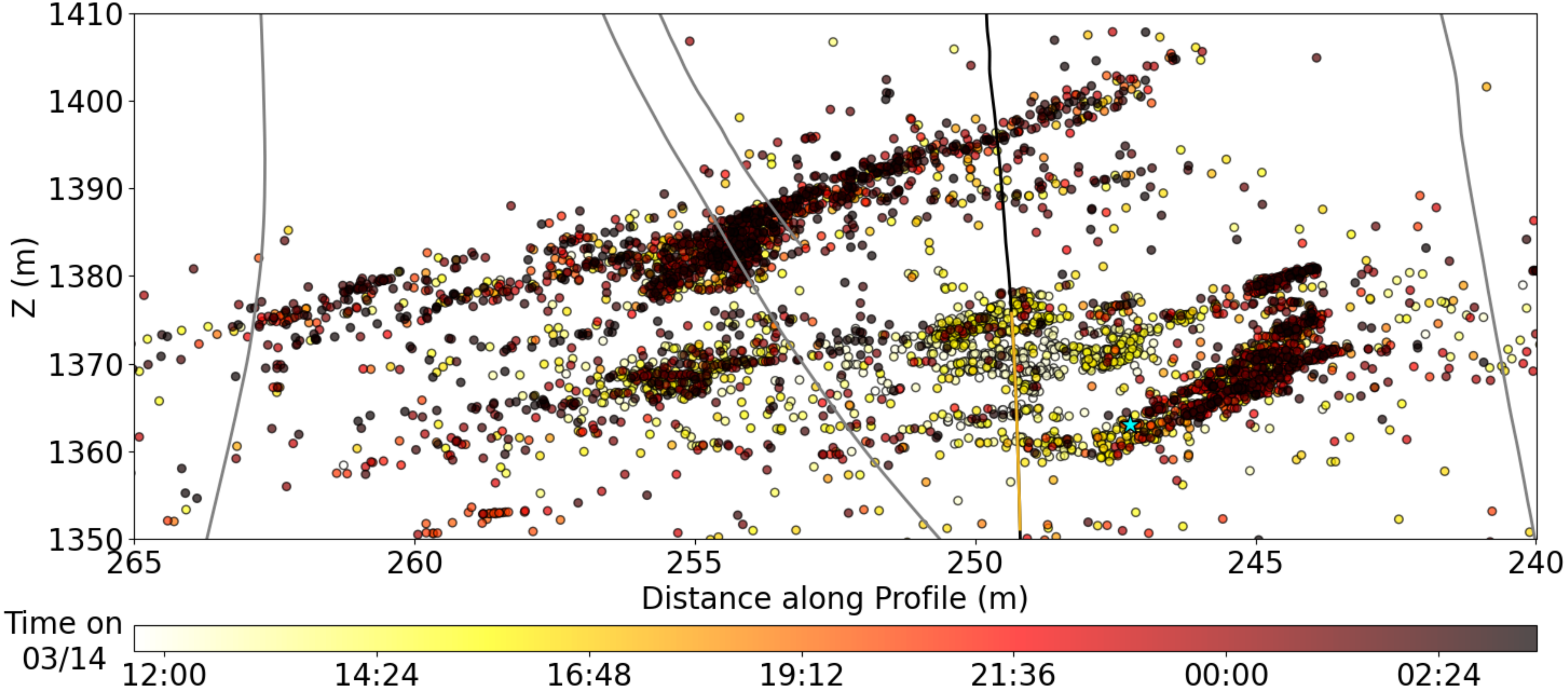


Zoom into seismicity of interval 9 + 10 phase 2



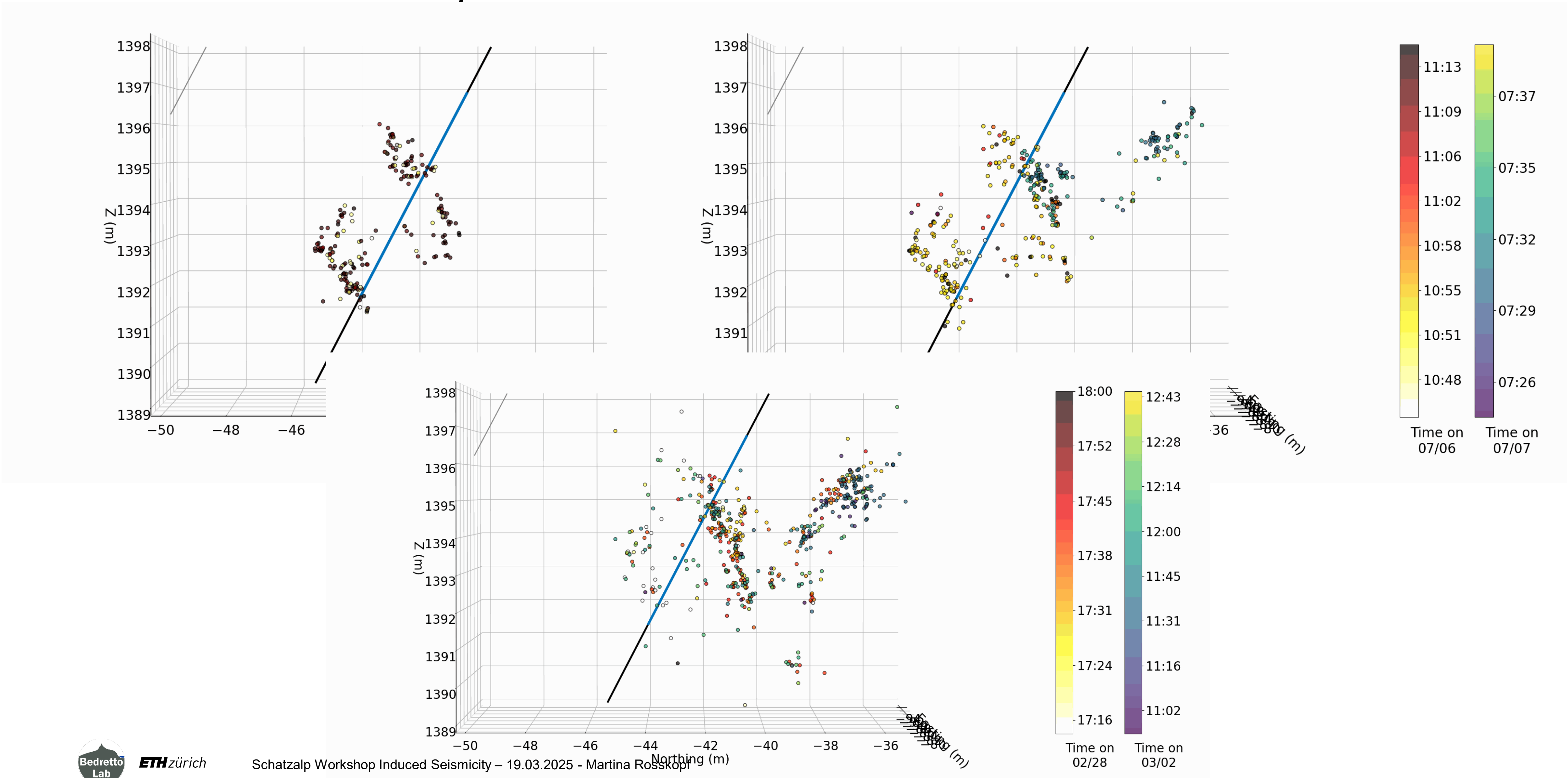
Spatio-temporal evolution of the seismicity along different fractures

Zoom into seismicity of interval 9 + 10 phase 2

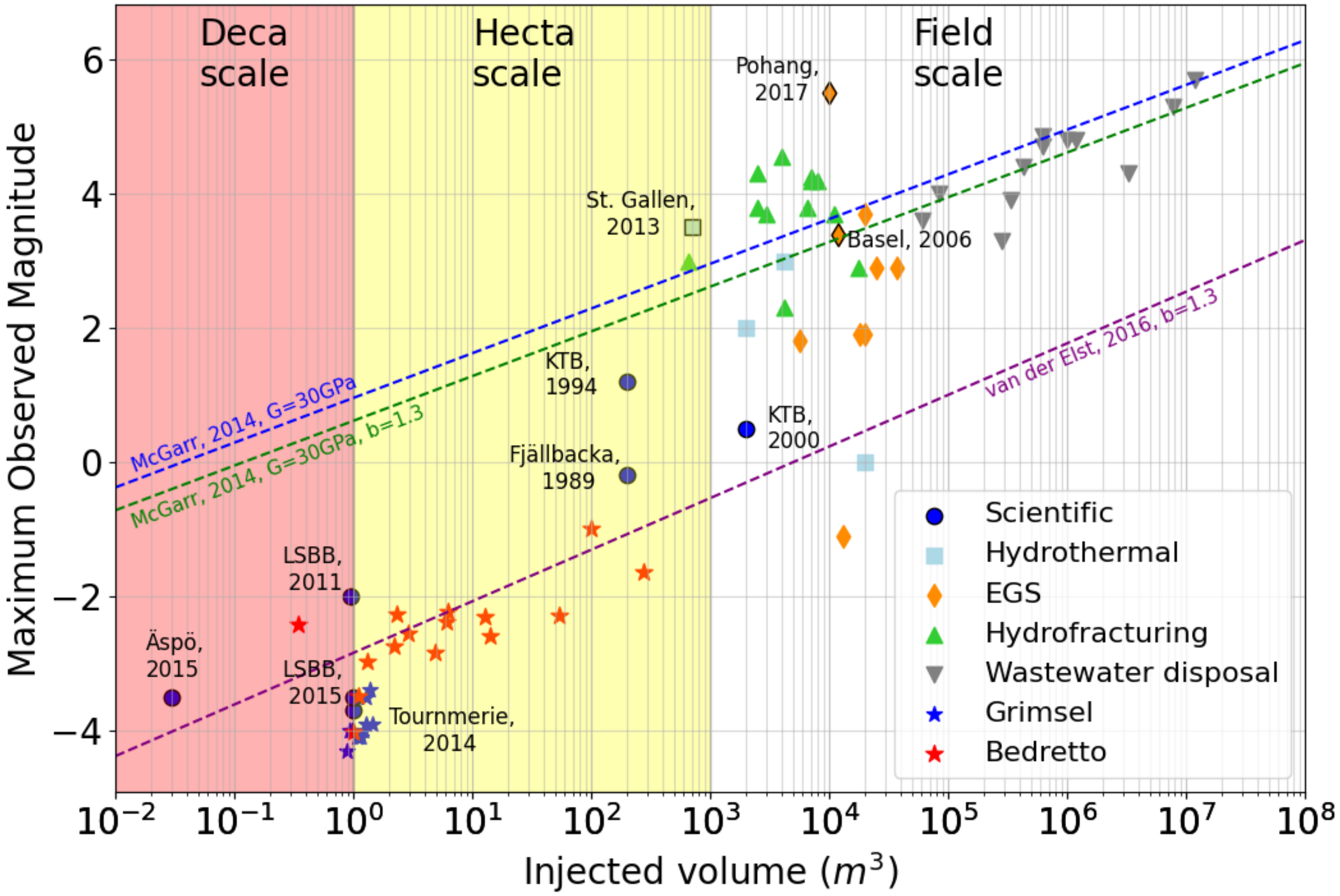


Spatio-temporal evolution of the seismicity along different fractures

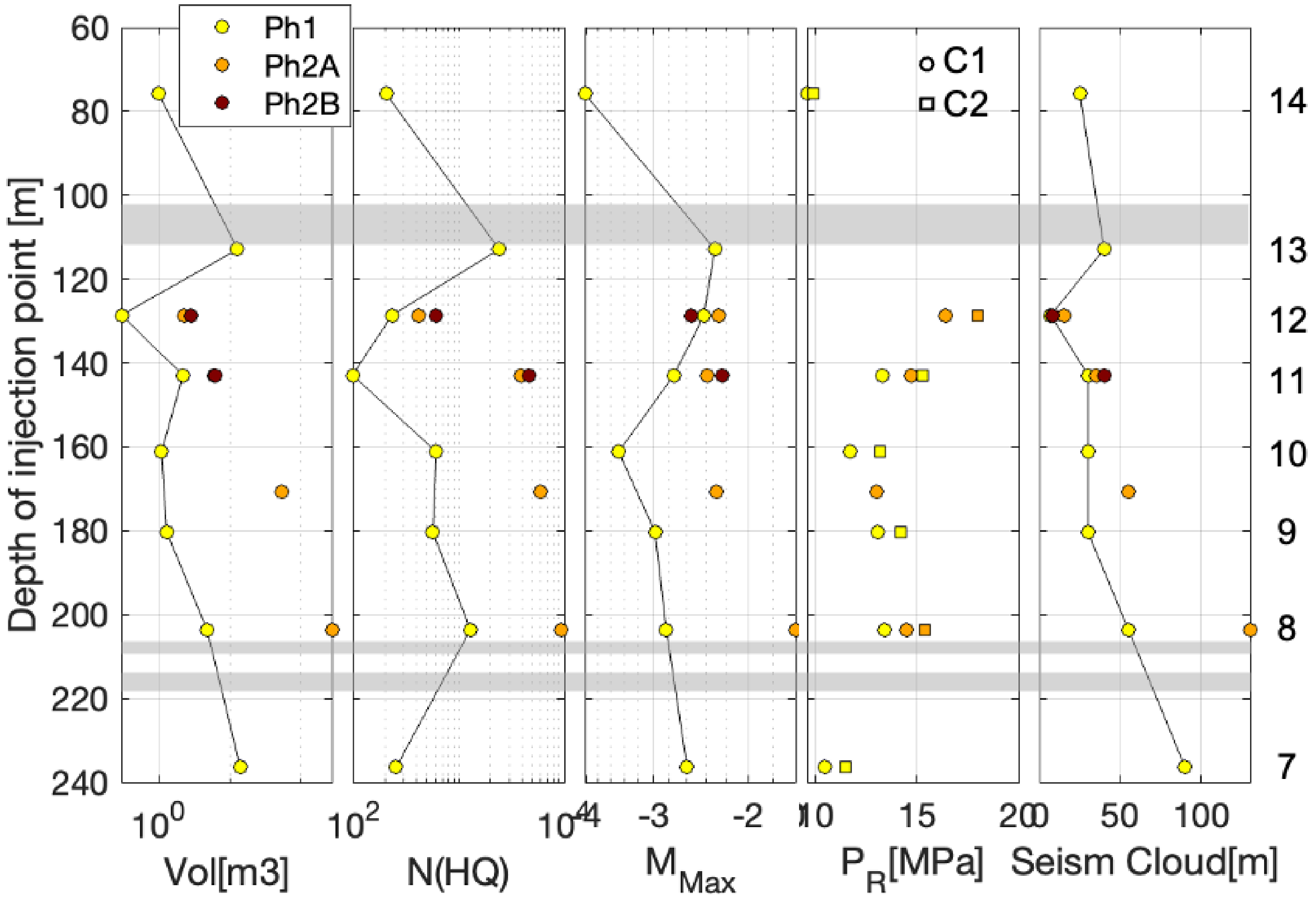
Zoom into seismicity of interval 12



Closing the gap



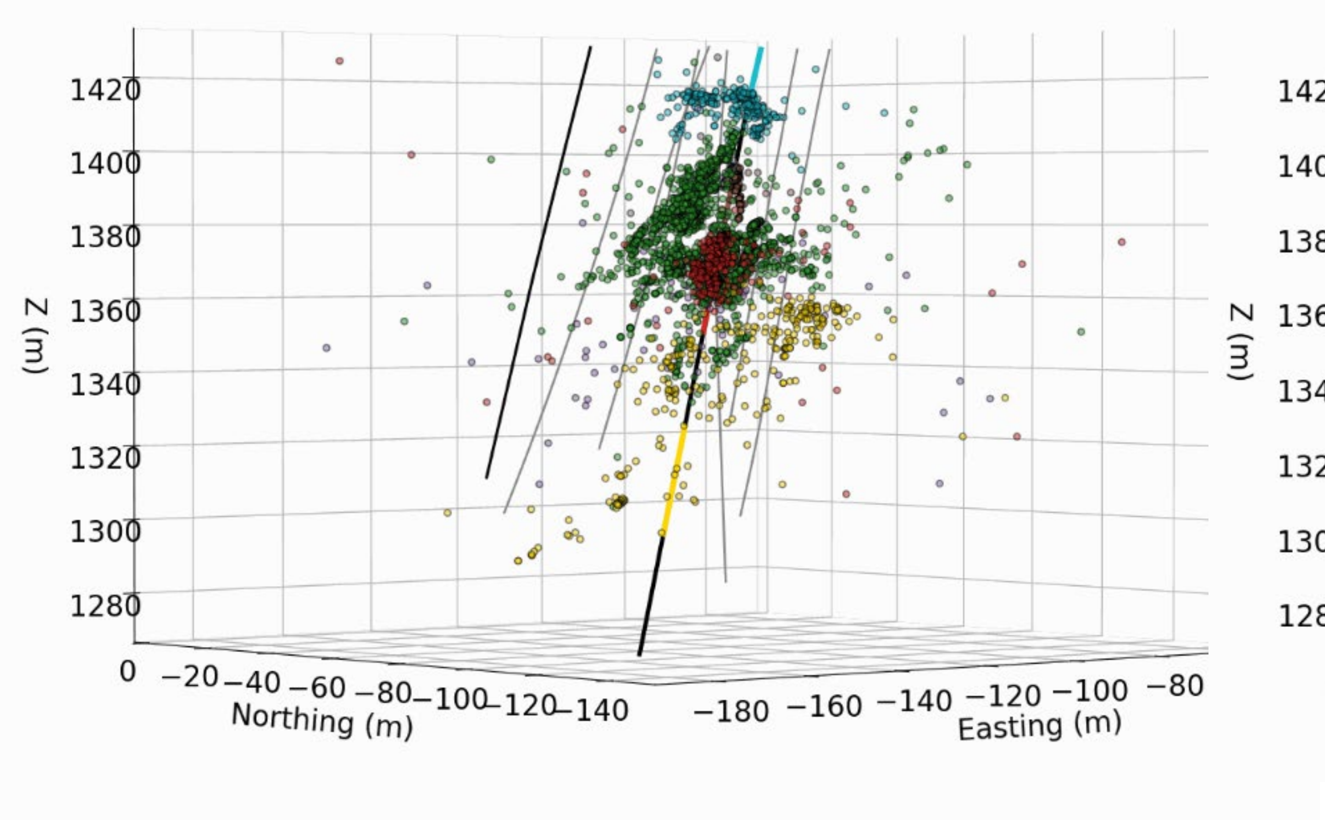
Summary of seismic behavior with hydraulic data

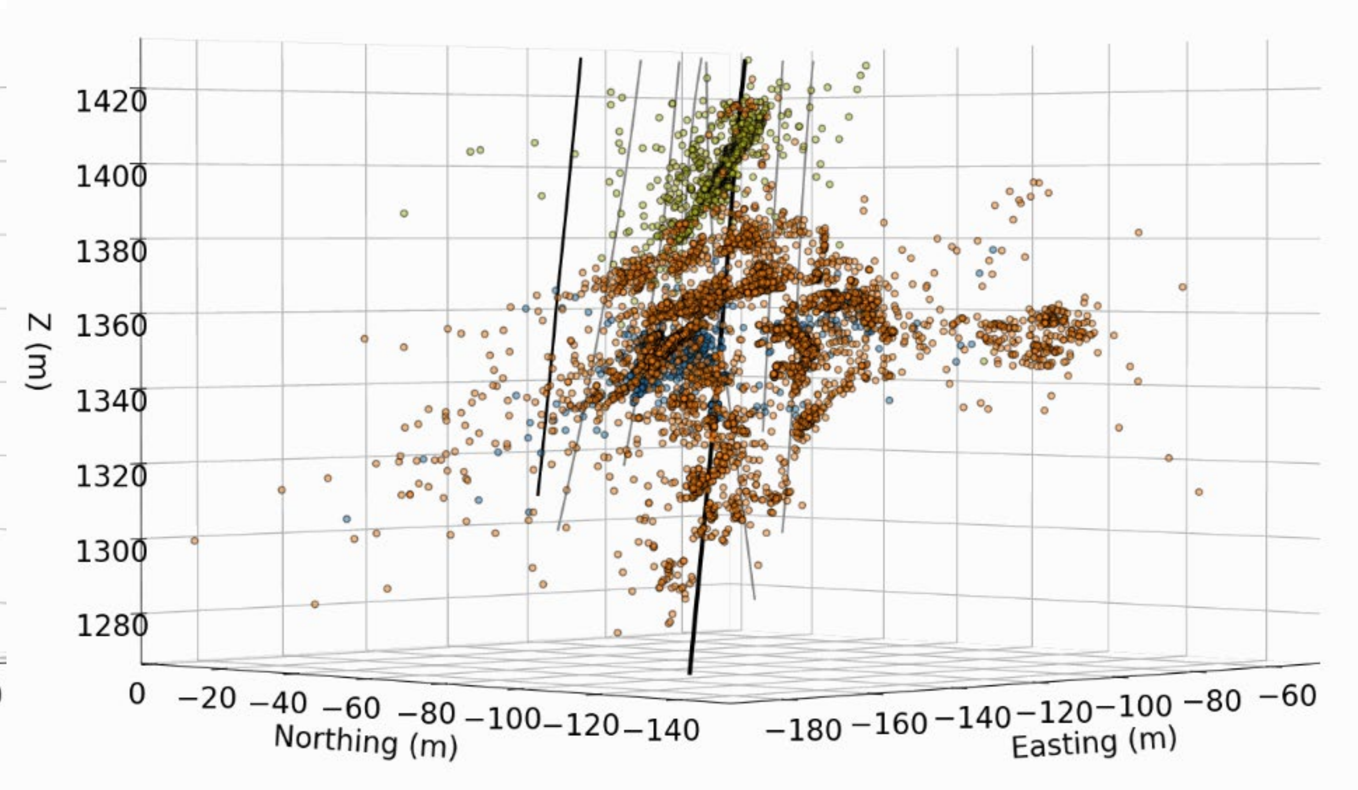


Different behaviors of different intervals

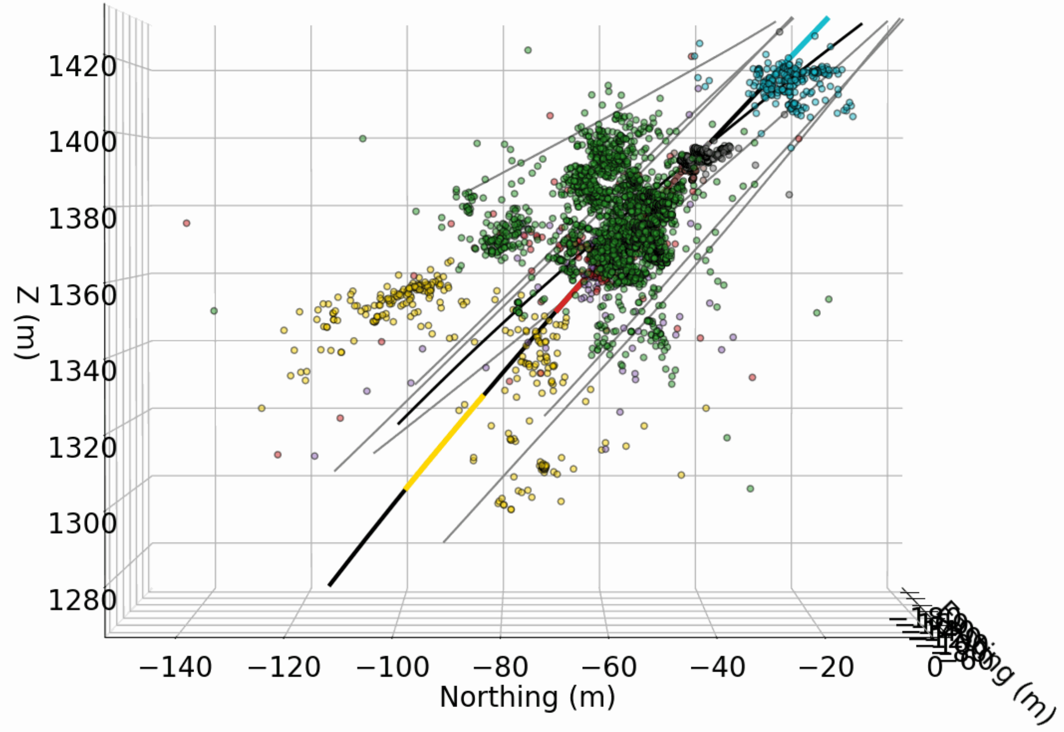
e.g. Interval 12 - low injected volume, low number events and seismic cloud extension but highest measured pressure

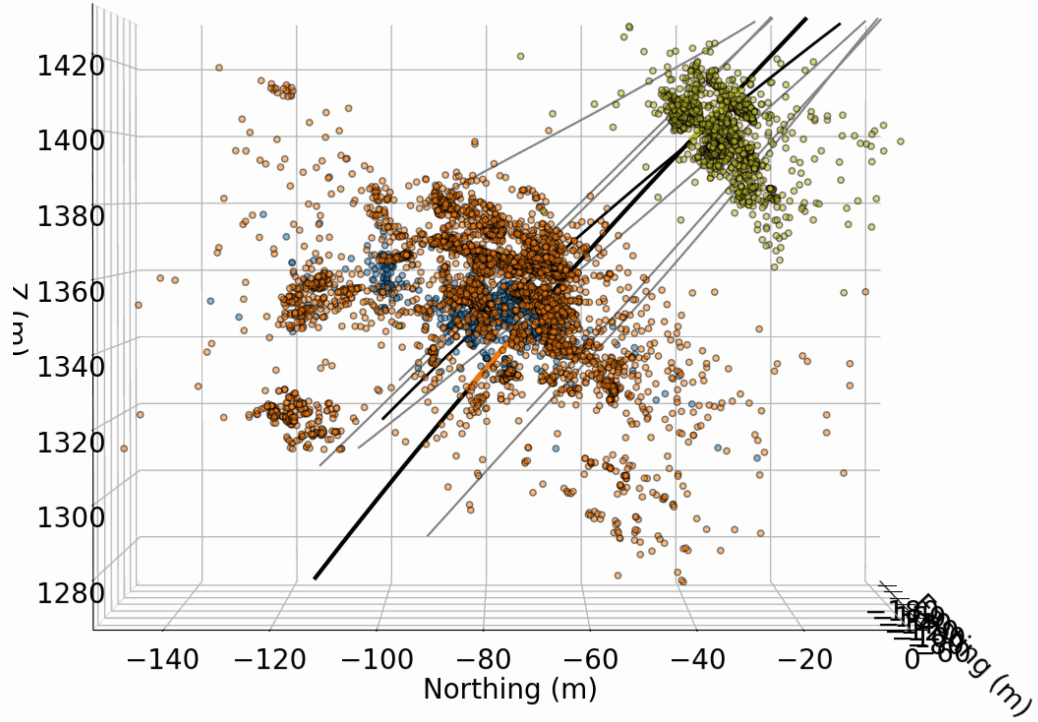
Seismicity during the stimulations



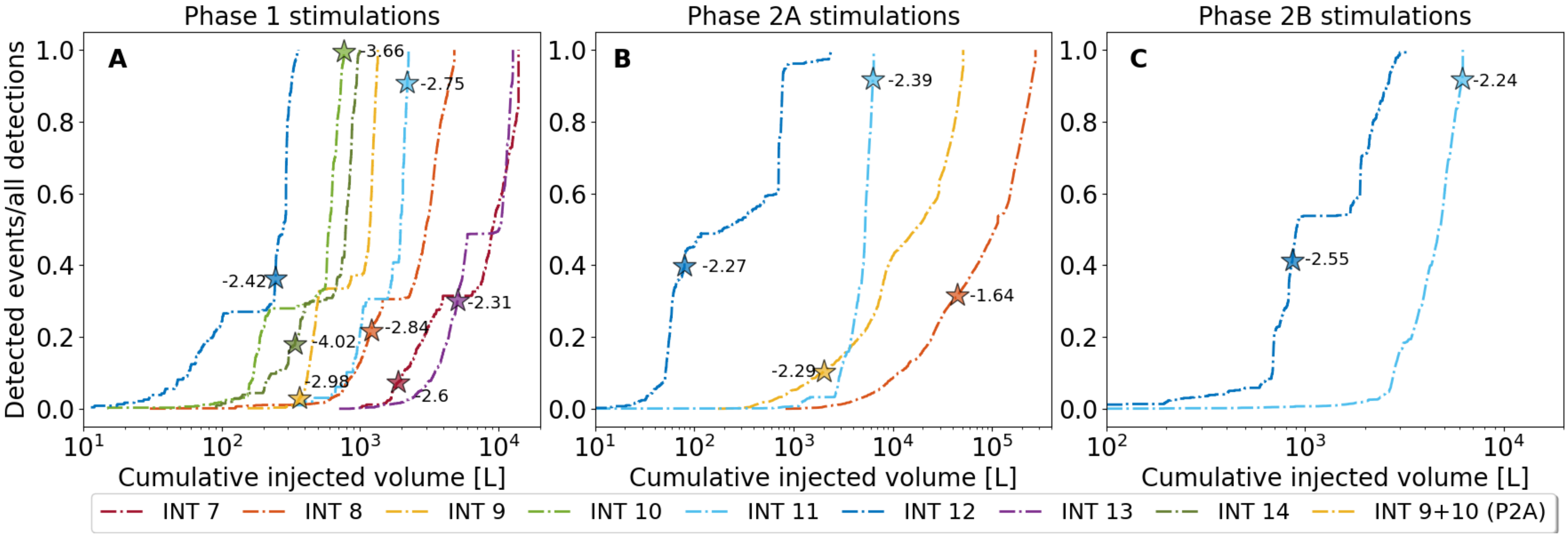


Seismicity during the stimulations

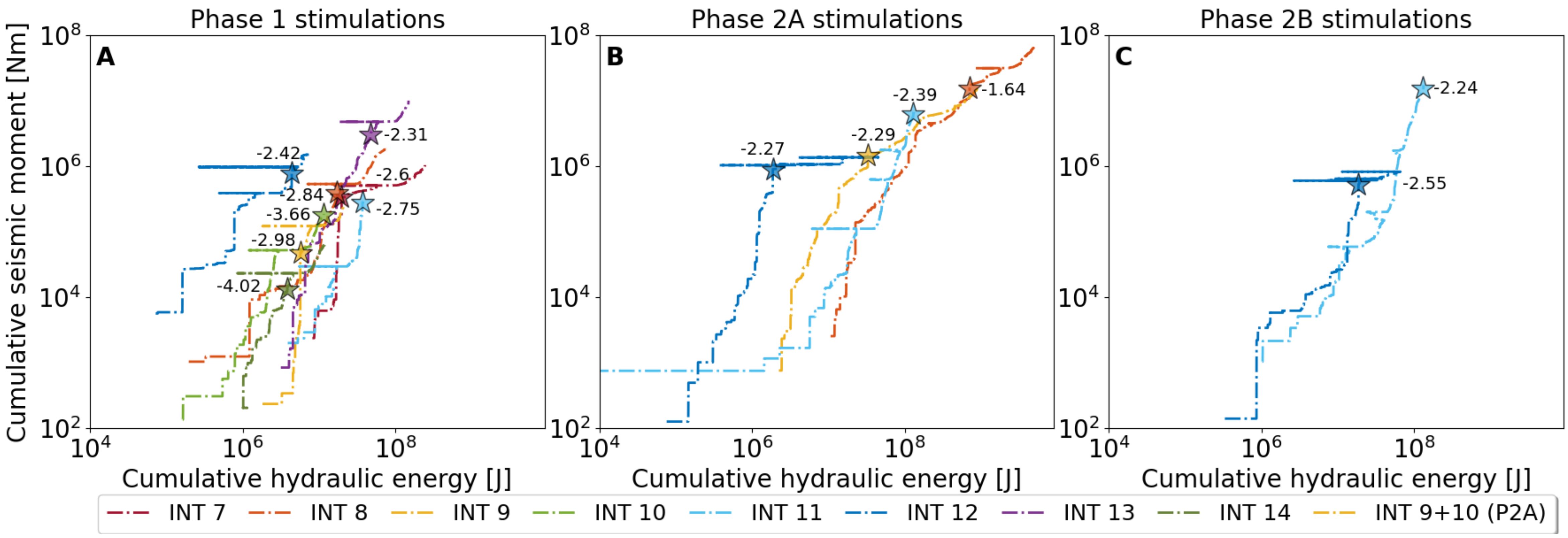




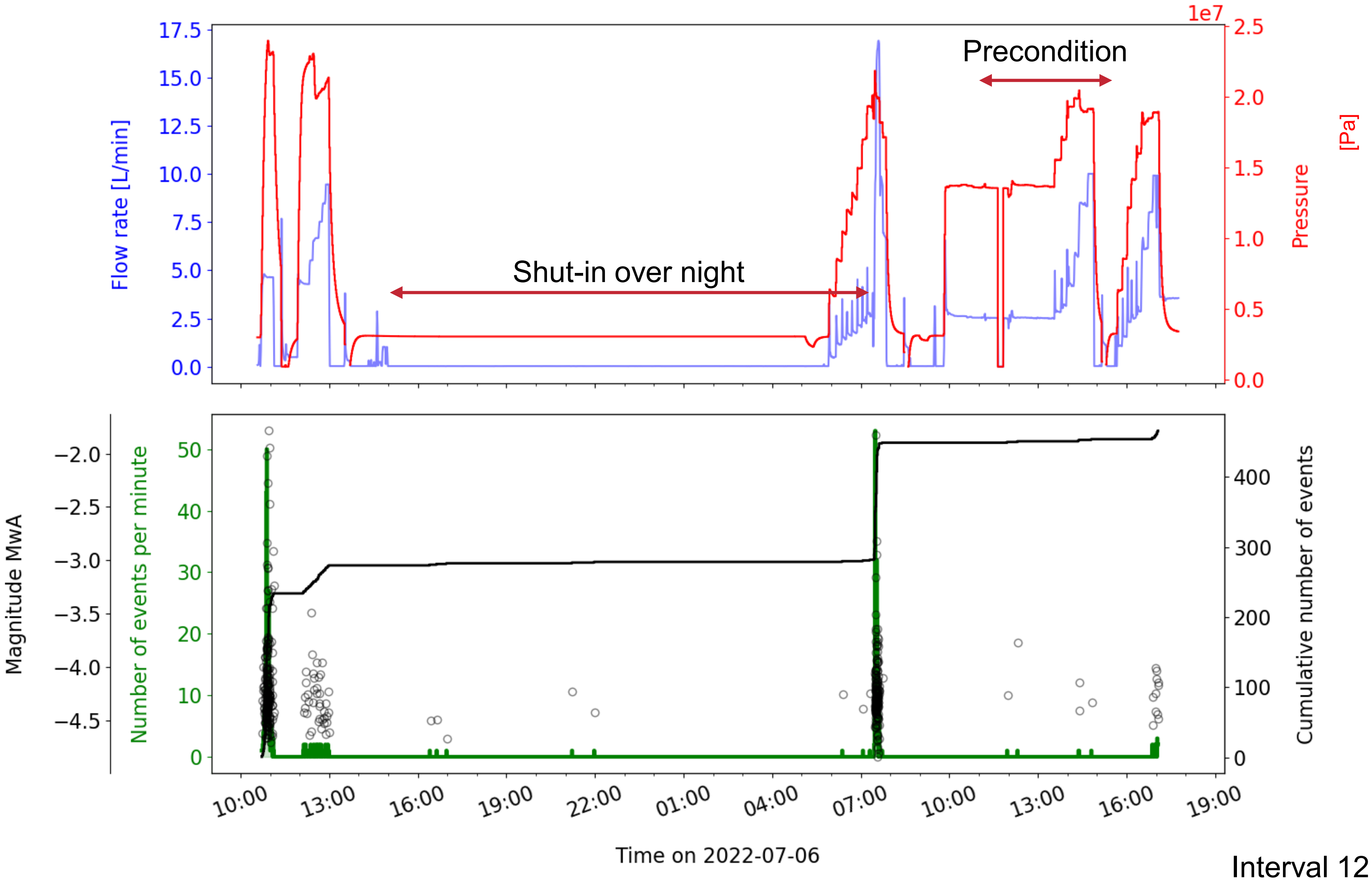
Interval behavior with increasing injected volume



Interval behavior with increasing injected volume



Exemplary Stimulation protocol for fault preconditioning

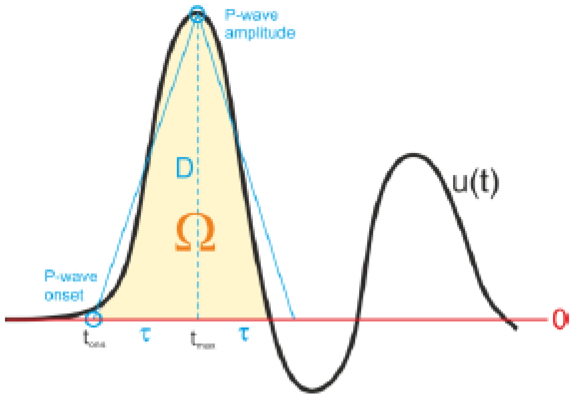


Mix of flowrate and pressure controlled cycles + long pressurization of fault

Interval 12 Phase 2A

Moment Tensor Inversion - hybridMT

Based on key parameter omega



$\Omega \approx D\tau \, sgn(u(t_{max}))$
(area of triangle)

Omega is proportional to seismic moment observed at certain station plus it gives polarity information

Uses clustered events assuming similar travel paths to suppress their influence

→ Software tries to suppress effects of erroneous stations

Resampling of input data for uncertainty assessment

→ Polarity resampling, amplitude resampling, station rejection resampling and takeoff angle resampling

Summary of the stimulations

Interval/ Phase	Number detections	Number of HQ events	Max MwA	lateral extent of seismically activated volume [m]	Injected Volume (m^3)
7/1	398	254	-2.6	90	14.1
8/1	2080	1289	-2.84	55	4.8
8/2A	12776	9369	-1.64	130	273.8
9/1	832	567	-2.98	30	1.3
10/1	922	611	-3.48	30	1.1
9-10/2A	7086	6002	-2.29	55	54.0
11/1	99	98	-2.75	30	2.2
11/2A	4087	3848	-2.39	35	6.0
11/2B	5310	4615	-2.24	40	6.2
12/1	241	233	-2.42	7	0.3
12/2A	500	420	-2.27	15	2.4
12/2B	683	599	-2.55	8	2.9
13/1	5146	2417	-2.31	40	12.9
14/1	460	204	-4.02	25	1