DEEP

Fiber-optic strain-rate monitoring and source characterization: *application to stimulations in the VALTER volume at the Bedrettolab*

Presentation Schatzalp workshop

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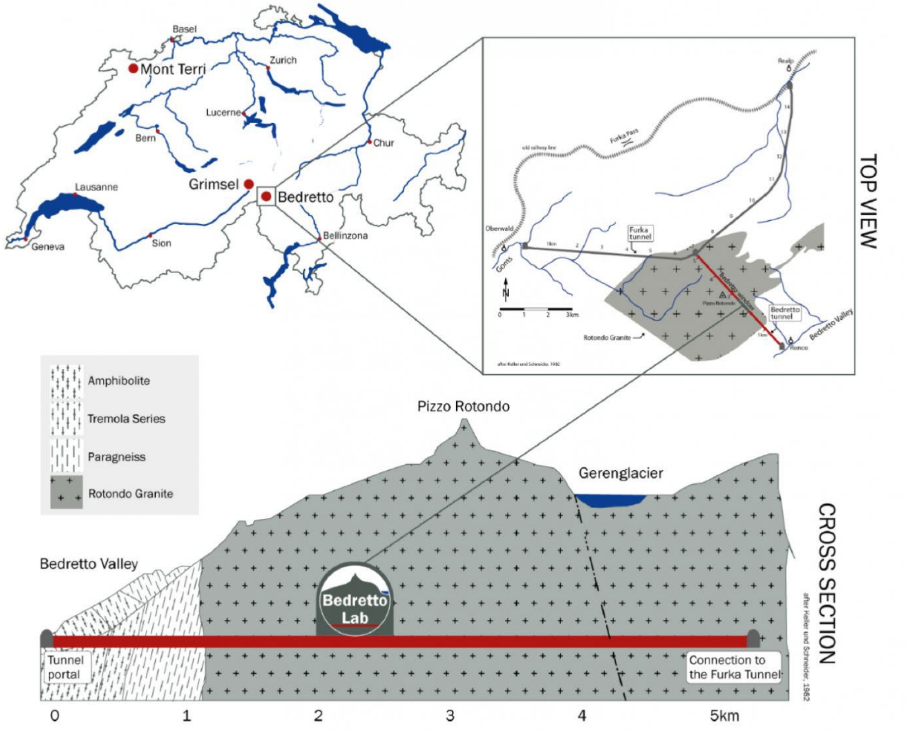
Overview

Test case: Bedretto lab in Ticino, Switzerland

Today:
Monitoring a hydraulic stimulation in the **Bedretto (BULGG)** lab with DAS, seismic **source characterization** using FWI

Goal:
- Implement fiber-optic seismology into the monitoring framework of reservoir stimulations.
- Meso-scale injection monitoring **with DAS in Bedretto**
- A fully **DAS-based** catalog and **source characterisation**
- Comparison to results from other instruments



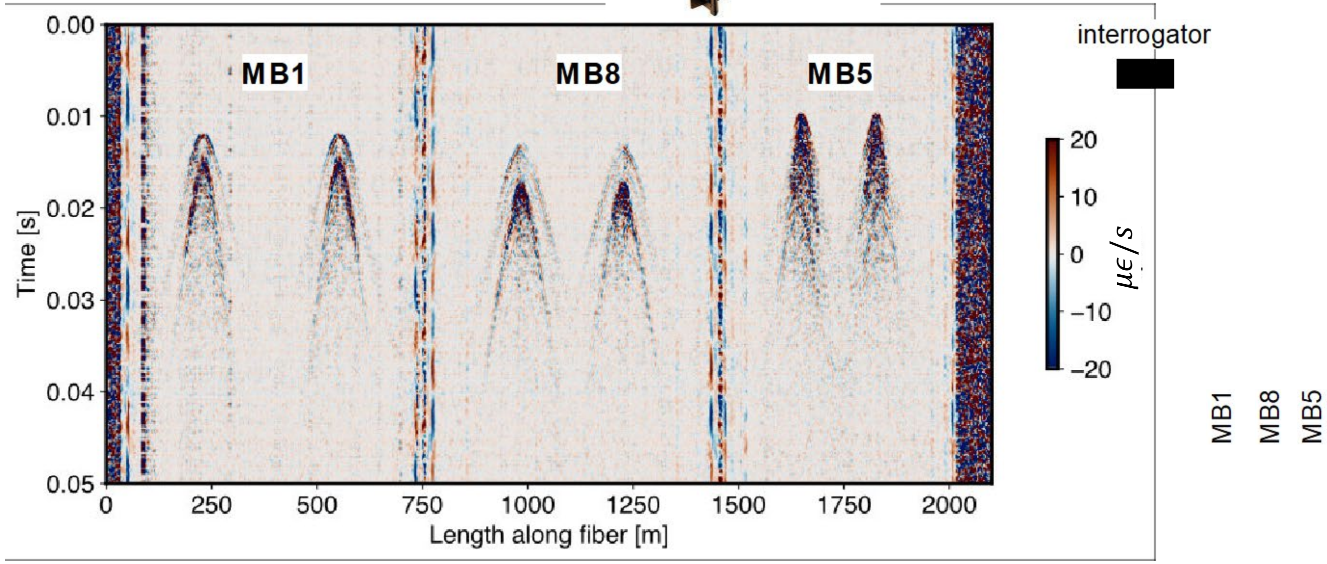
From Plenkers et al. (2023), after Keller and Schneider, (1982).

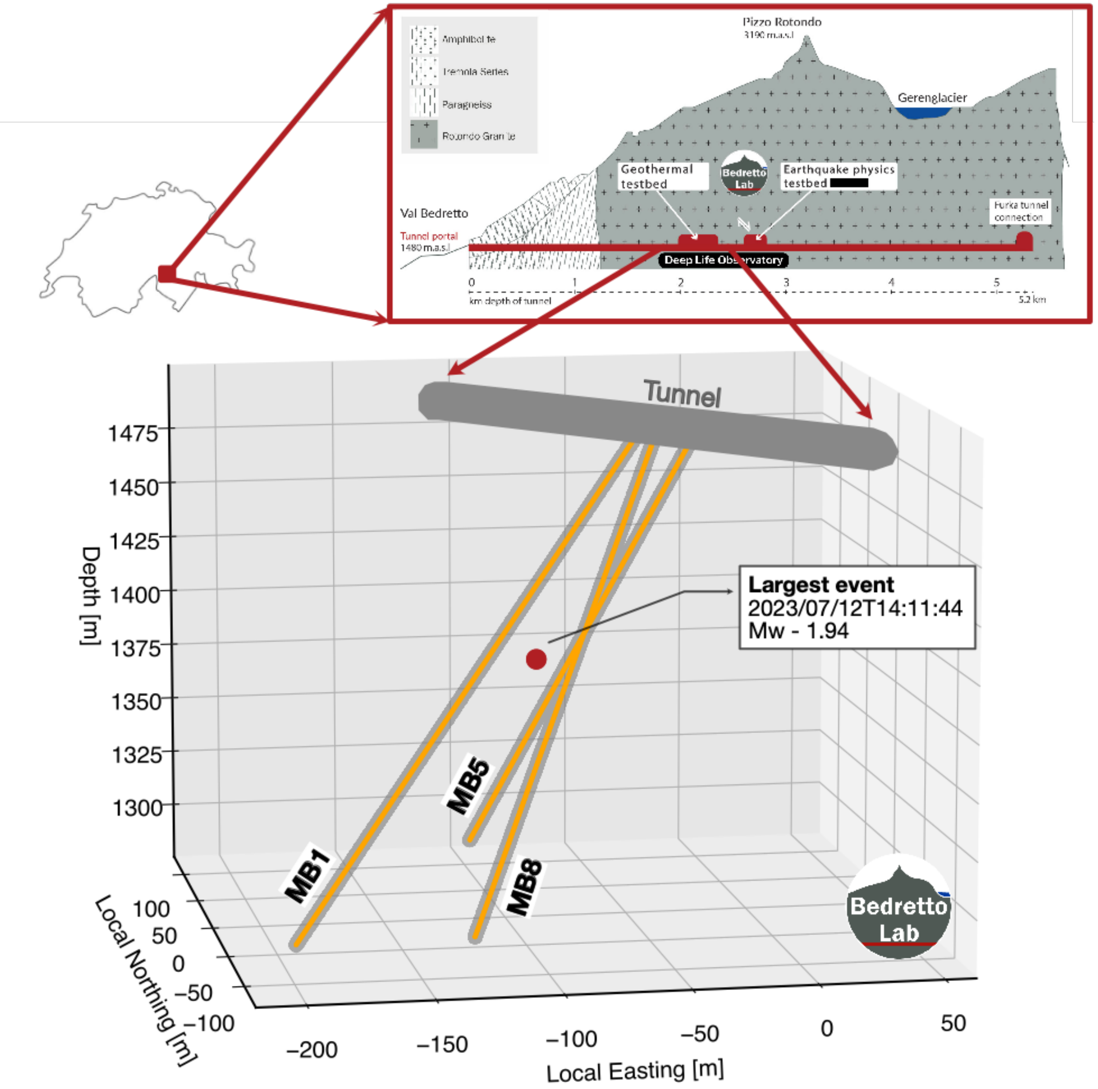
Tunnel installation

- Seismic event in between three boreholes
- Each borehole is ~400 m
- Recorded with DAS

Freq. = 5000 Hz
dx = 0.8 m
L = 4 m

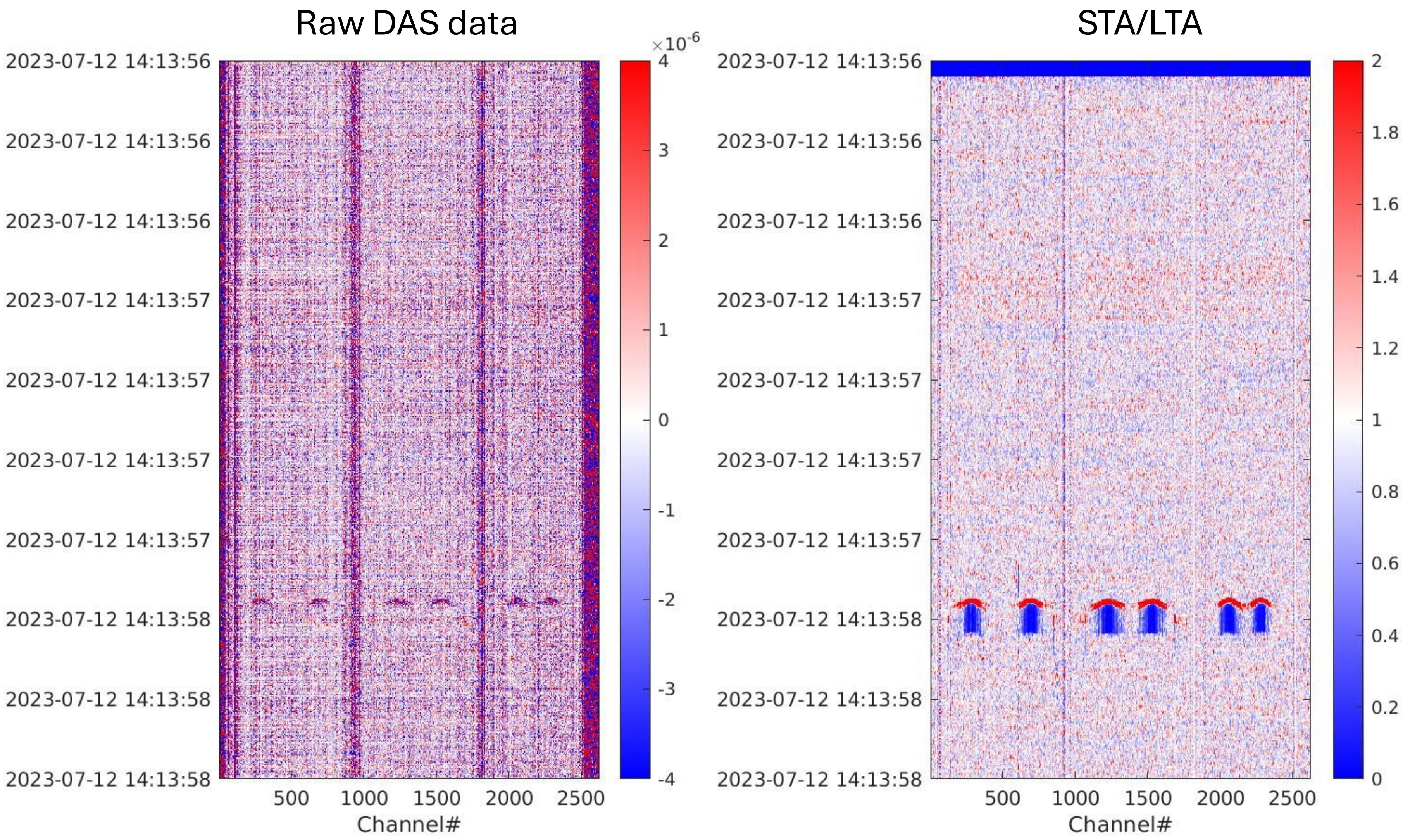
Interrogator: **FEBUS A1**





Detection: continuous STA/LTA

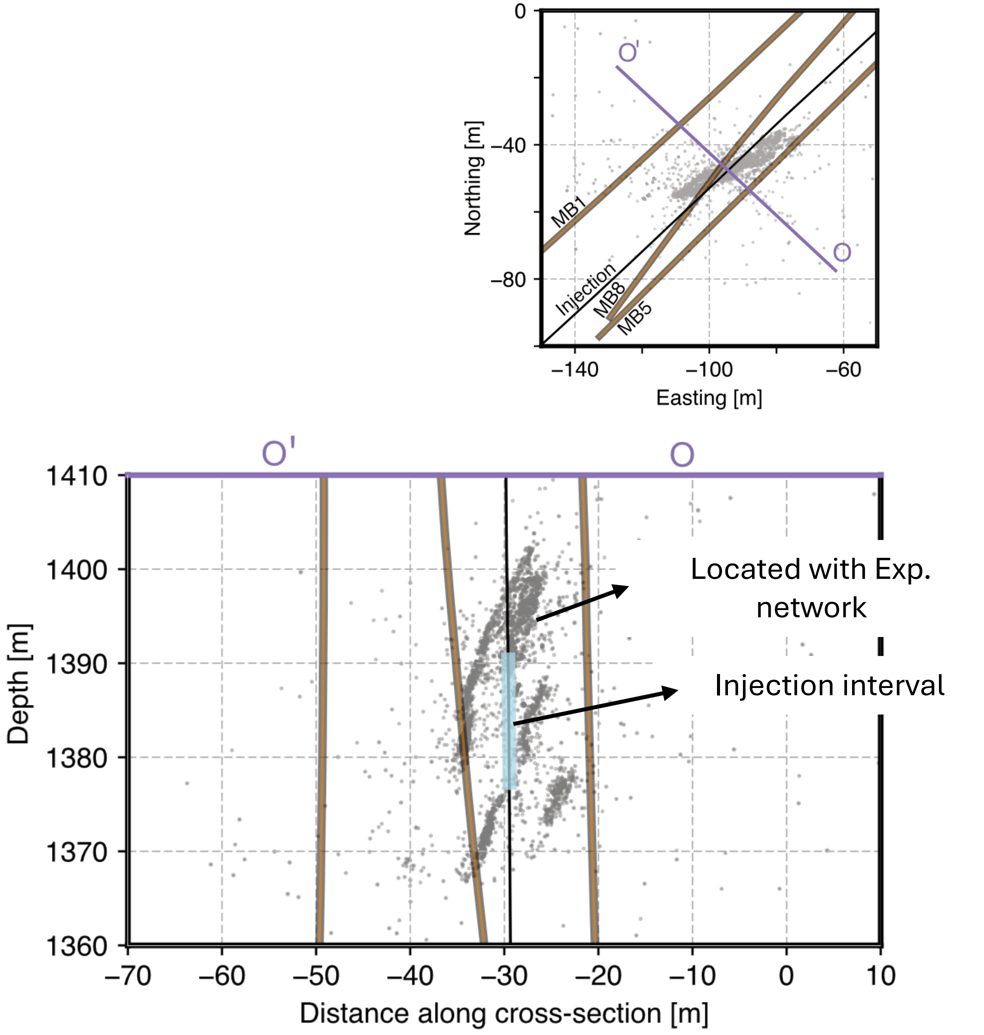
31 detections
28 quality events



Stimulation catalog

31 detections
28 quality events

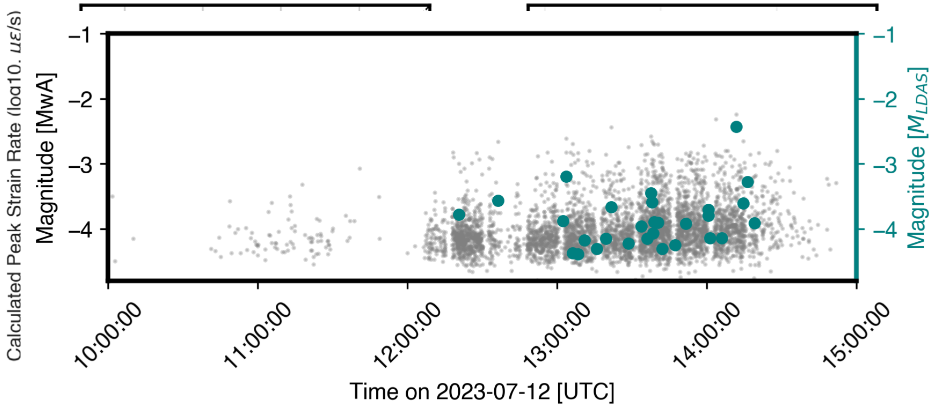
2/3 of MwA > -3 is detected

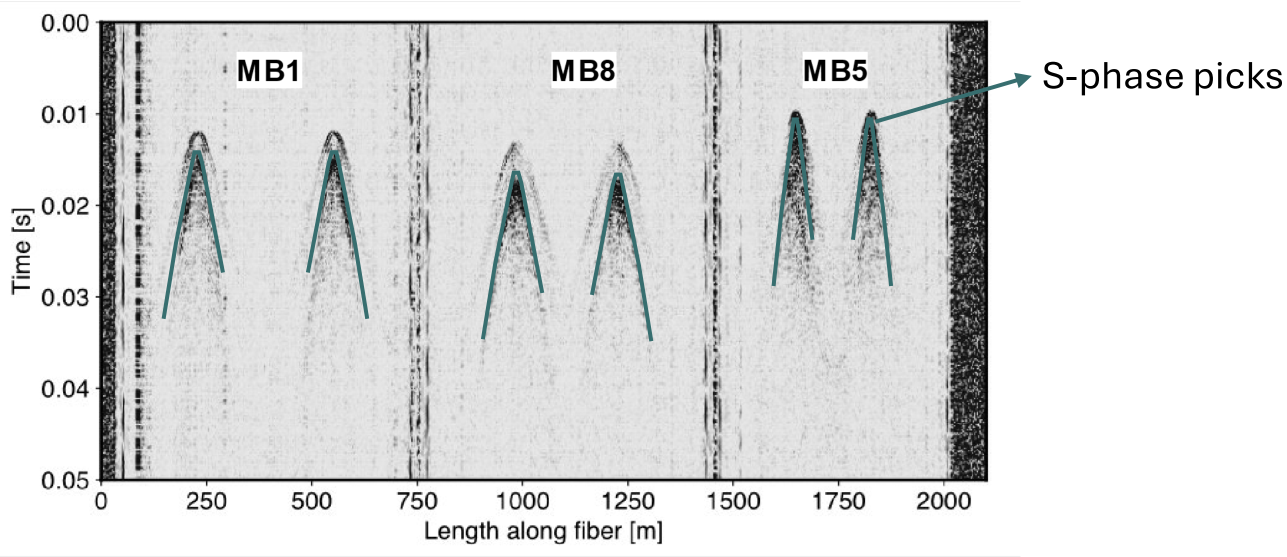


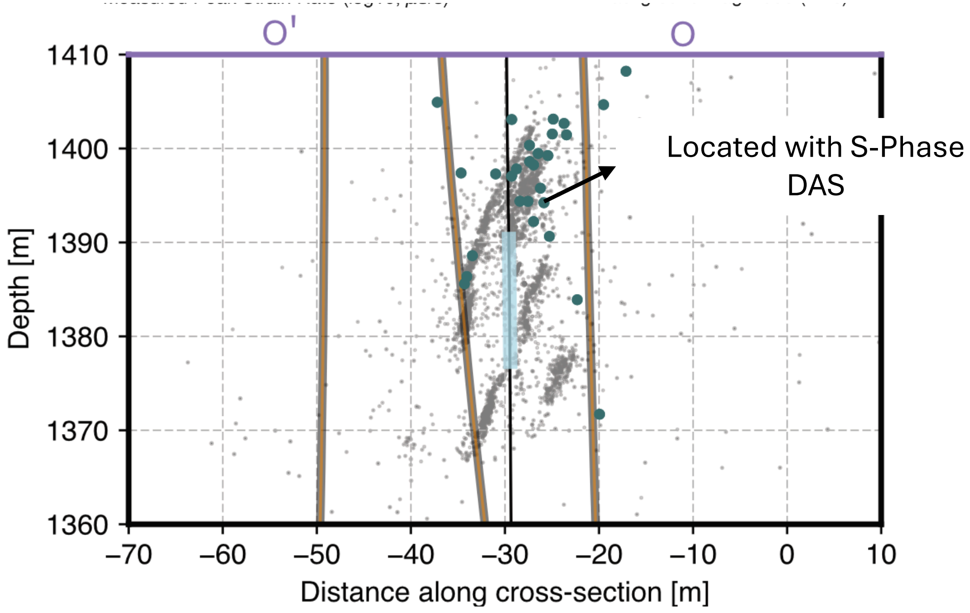
Locations by Rosskopf et al., 2024

Location and magnitude

- Locations with **HMC Lab**: Hamiltonian Monte Carlo sampler (*Zunino, A., et al., 2023*)
- Magnitude fitting based on Yin et al. (2023) using the maximum recorded strain-rate on each channel



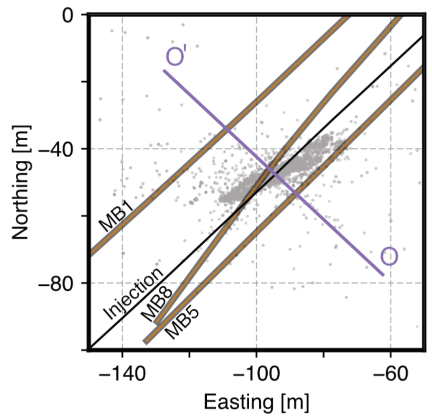


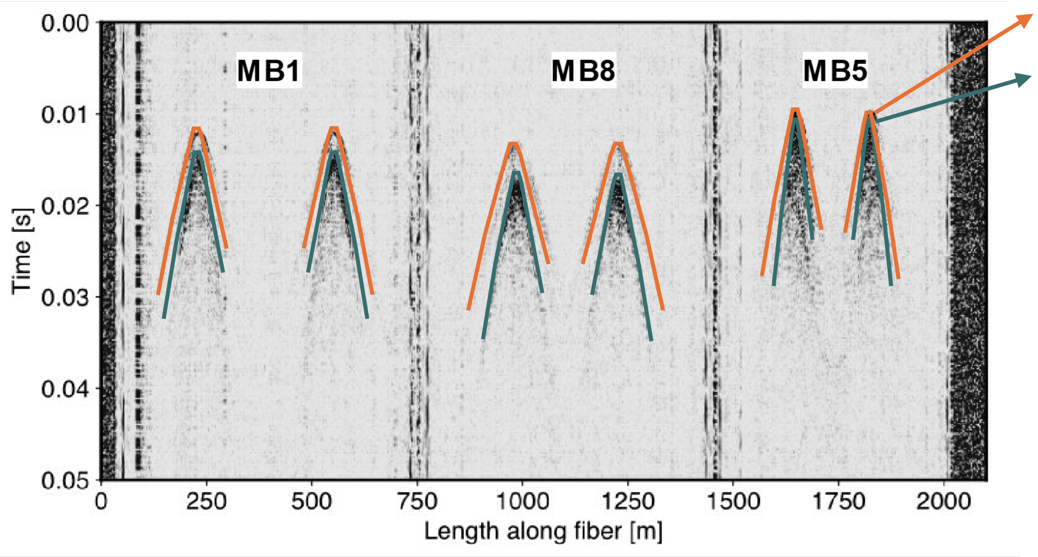


Locations by Rosskopf et al., 2024

Tunnel installation

- Locations with **HMC Lab**: Hamiltonian Monte Carlo sampler (*Zunino, A., et al., 2023*)
- Used as initial location for FWI





P-phase picks

S-phase picks

Located with DAS

Locations by Rosskopf et al., 2024

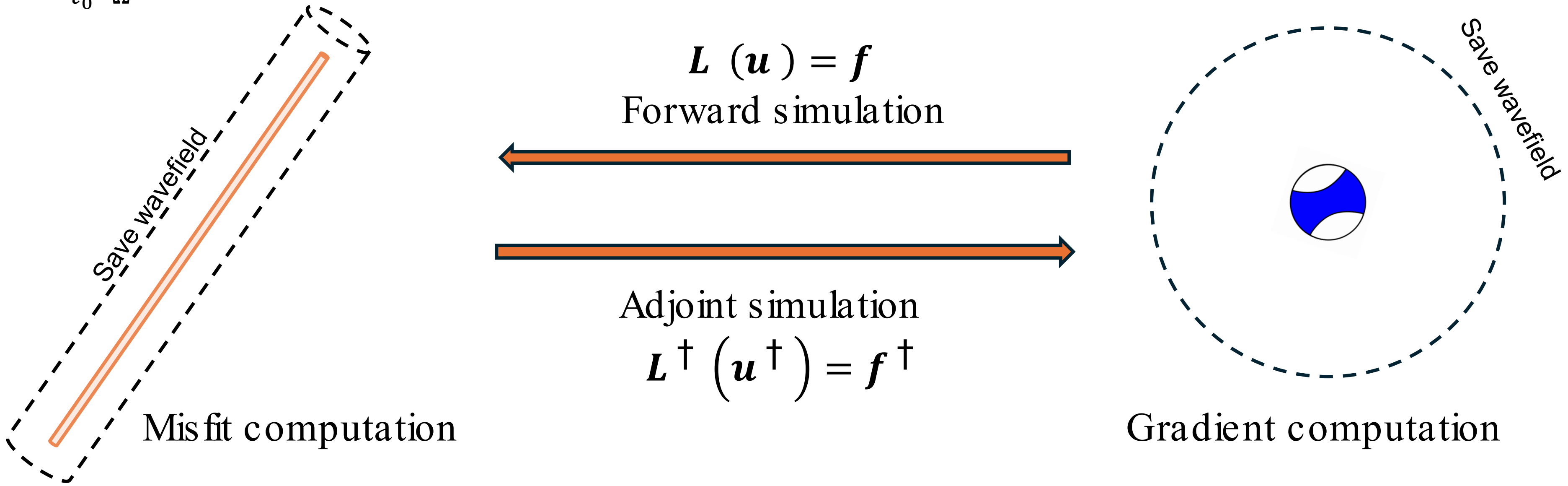
Adjoint moment tensor inversion

DAS FWI: python-package **pyber** (Noe, S. et al., *in prep*)

- Solver: Spectral-element solver **Salvus** (Afanasiev et al., 2018)
- Misfit: **L2**
- Optimizer: trust-region **L-BFGS**

$$\frac{d\chi}{dm_i} = -\int_{t_0}^{t_1}\int_{\Omega}(\dot{\boldsymbol{\varepsilon}}_{\boldsymbol{obs}} - \dot{\boldsymbol{\varepsilon}}_{\boldsymbol{syn}})\delta(\boldsymbol{x}-\boldsymbol{x}_{\boldsymbol{r}})\,\frac{d\dot{\boldsymbol{\varepsilon}}}{dm_i}\,d\boldsymbol{\Omega}dt$$

$$\boldsymbol{m} = [x, y, z, t_0, mxx, myy, mzz, mxy, mxz, mzy]$$

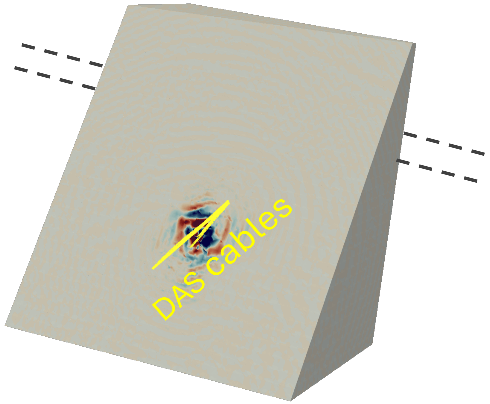


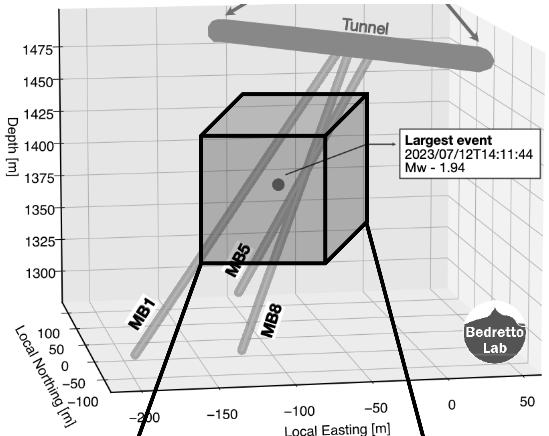
Simulation setup

Velocity model: V_p= 5400 m/s V_s= 3100 m/s

Location metrics:

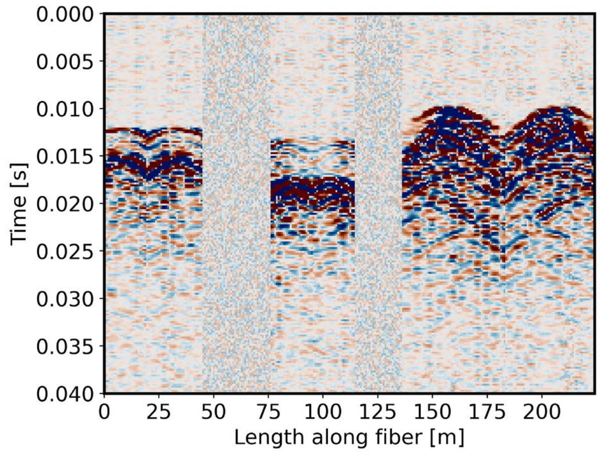
- **HMC Lab**: Hamiltonian Monte Carlo sampler (*Zunino, A., et al., 2023*)
- Back-projection of real data from the DAS cable
- Initial source location from catalogs by (*Rosskopf, M., et al., 2024*)

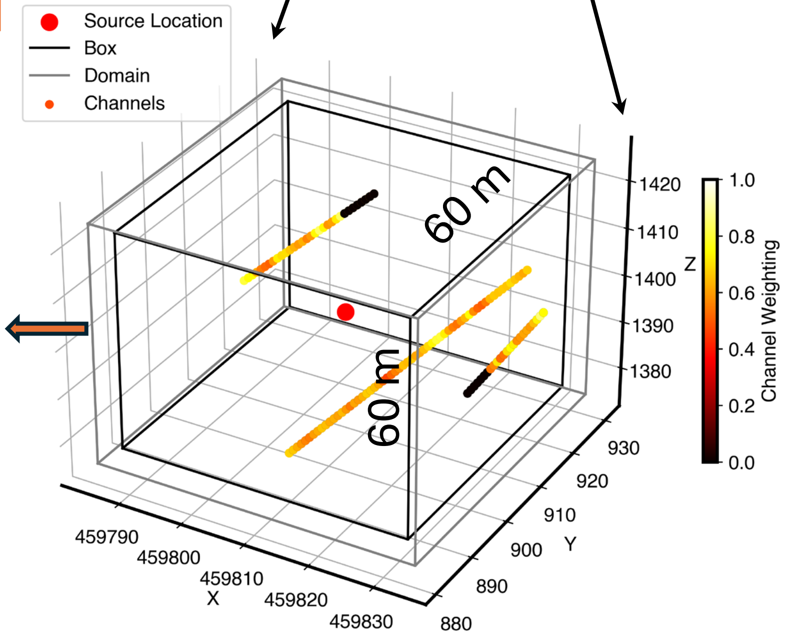




- Subdomain cut out around event
- Data cut out and **weighted** by noise

Setup parameter	Value
Frequencies [Hz]	100 - 550
Element size [m]	1
Simulation time [s]	0.025



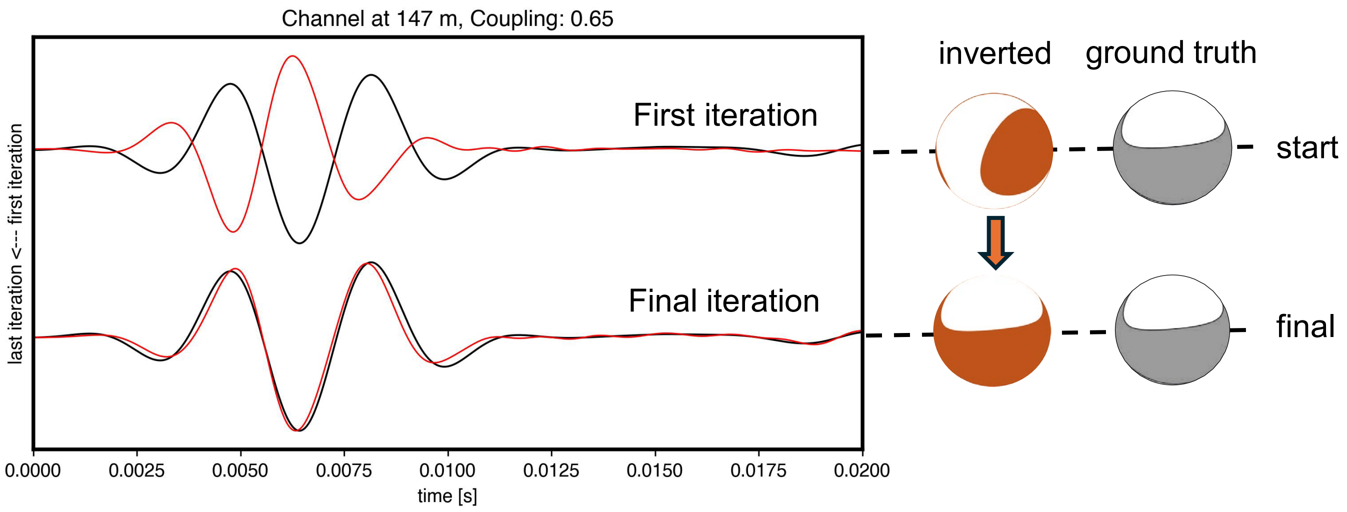


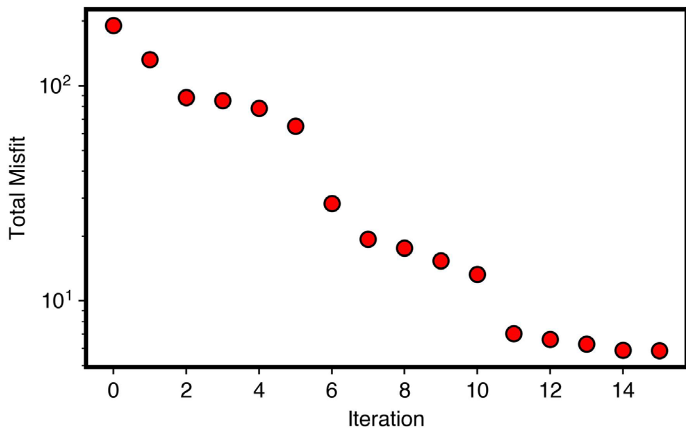
Synthetic inversion

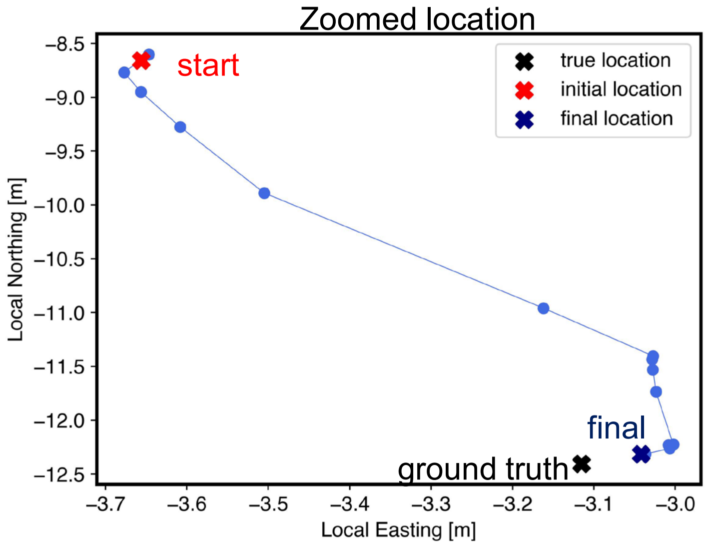
- Synthetic inversion at **400 Hz**
- 10% gaussian noise was added
- We perturb all model parameters
  - Location: 5 m
  - M_0: 1e6 Nm → 1e3 per model parameter
  - t_0: 0.0001 s
- We invert simultaneously for all model parameters:

$$\boldsymbol{m} = [x, y, z, t_0, mxx, myy, mzz, mxy, mxz, mzy]$$

→ True location recovered within 10 cm
→ Moment tensor recovered







Real data inversion

- Inversion at **550 Hz**
- We set a covariance [**x** = 2.0 m, $\mathbf{m}_{ij}$=2e3, t_0=0.0001]
- Apply channel weighting according to channel noise

Event A

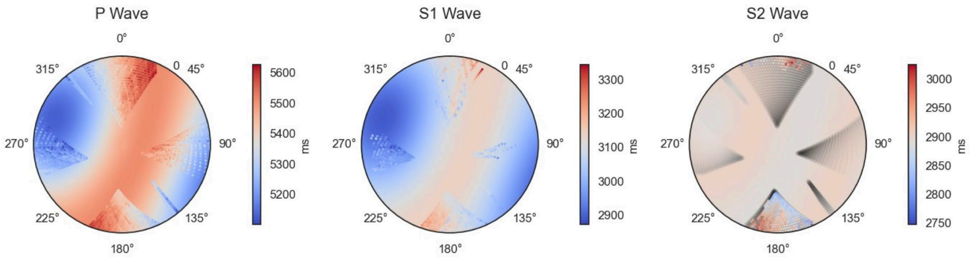
Final model fits only a portion of the data

→ Uncertainties in borehole trajectories

→ True 'model' is **anisotropic** and **inhomogeneous**

Event B

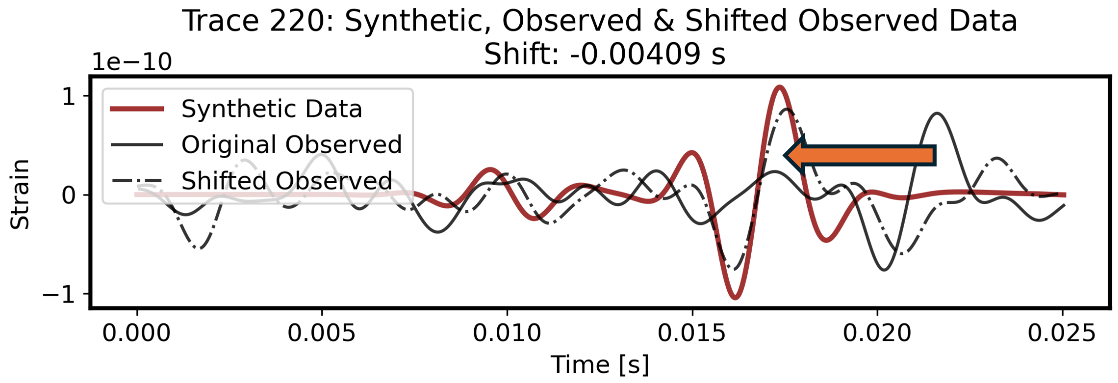
Real-world anisotropy

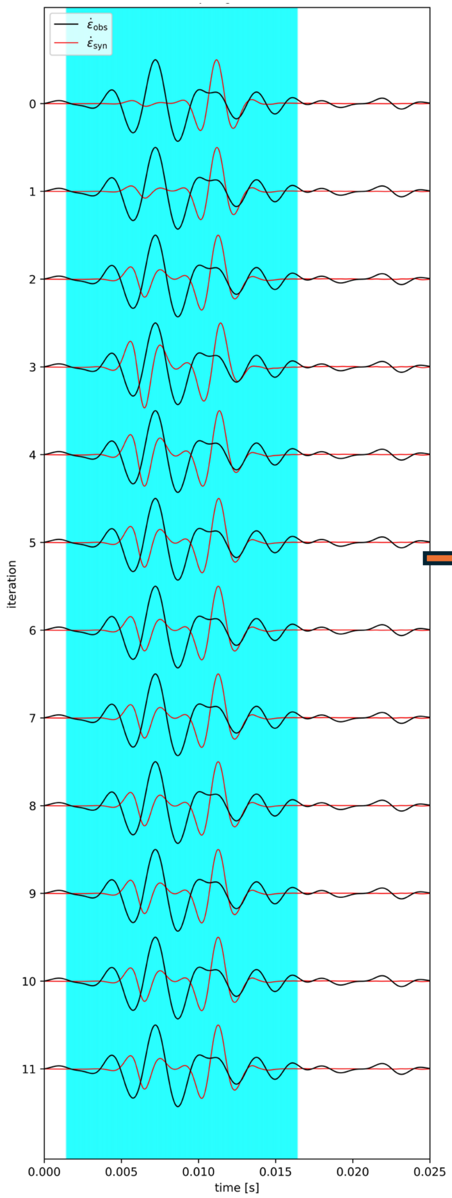


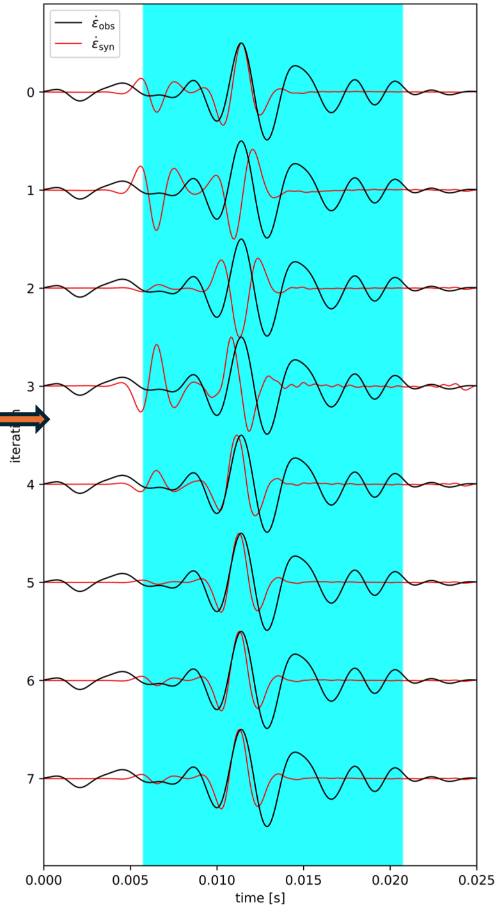
From Behnen et al. (2024)

Real data: waveform shifting

- A **factor of 4-10** remains between the amplitude of recorded and synthetic strains
- Optimising the moment tensor parameters at the final source location
- Cross-correlation shift: compensates for unknown path effects

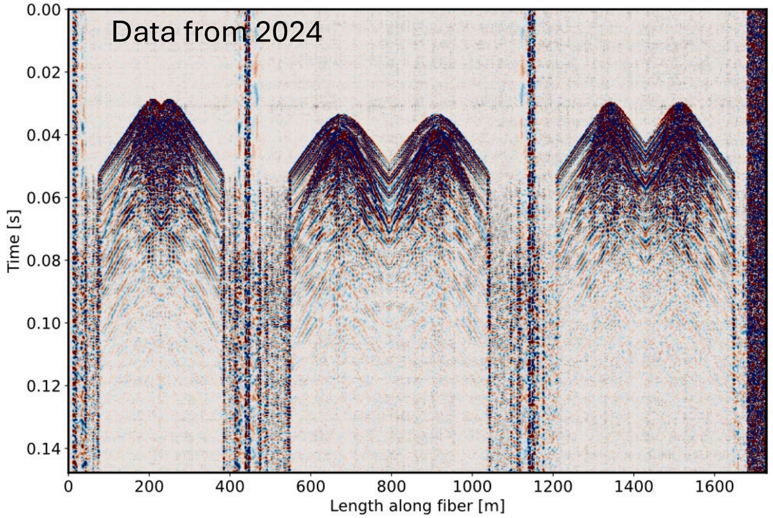




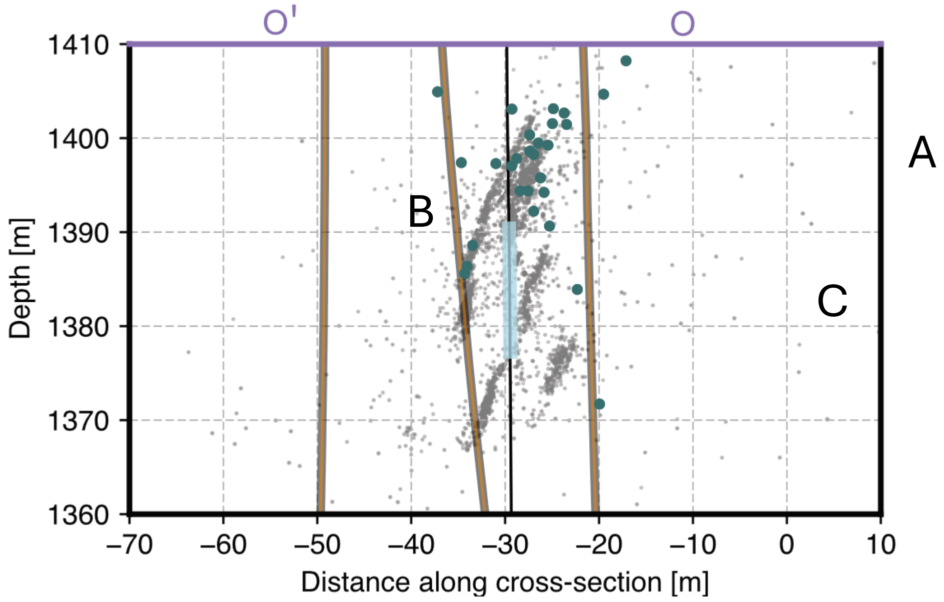


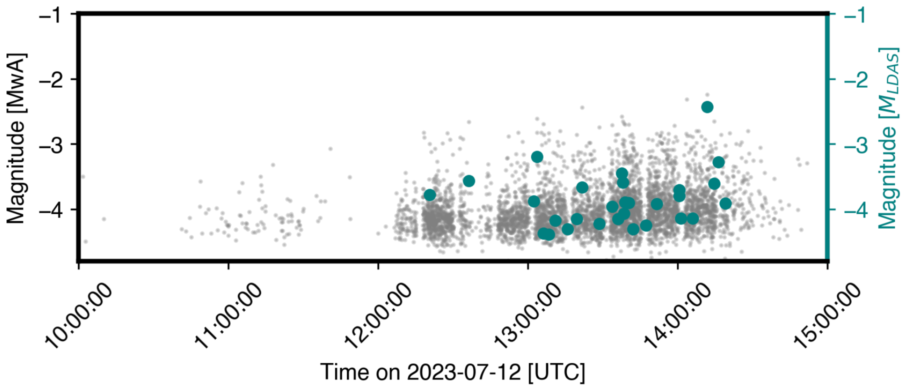
Take away message

- Meso-scale microseismic monitoring of reservoir stimulation with DAS
- Detect, lcoate and find a magnitude for most events > M -3
- FWI for source inversion gives us a homogenized moment tensor solution for three high-quality events
- We need to account for uncertainties in borehole trajectories and velocity model
- New stimulations: dozens of high-quality events



28 high-quality events





Take away message

Thank you for listening!

Take-away messages

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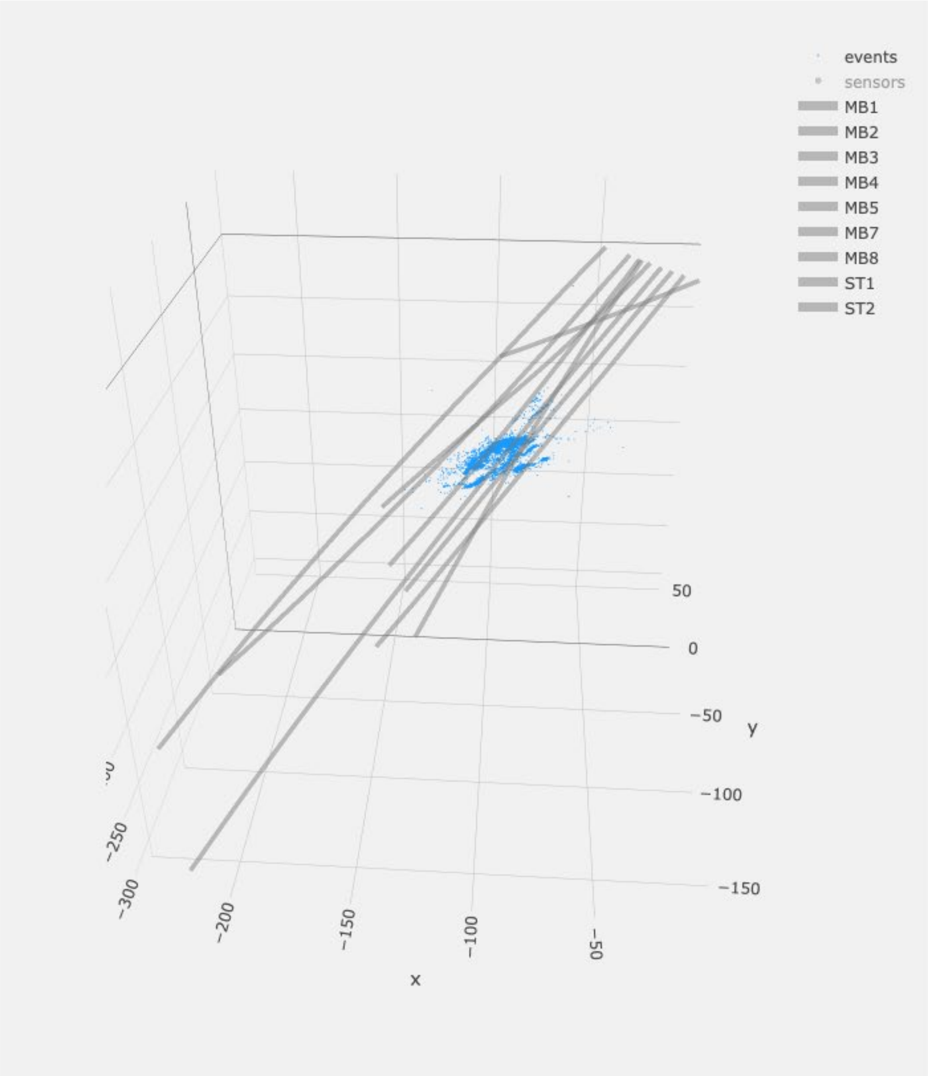
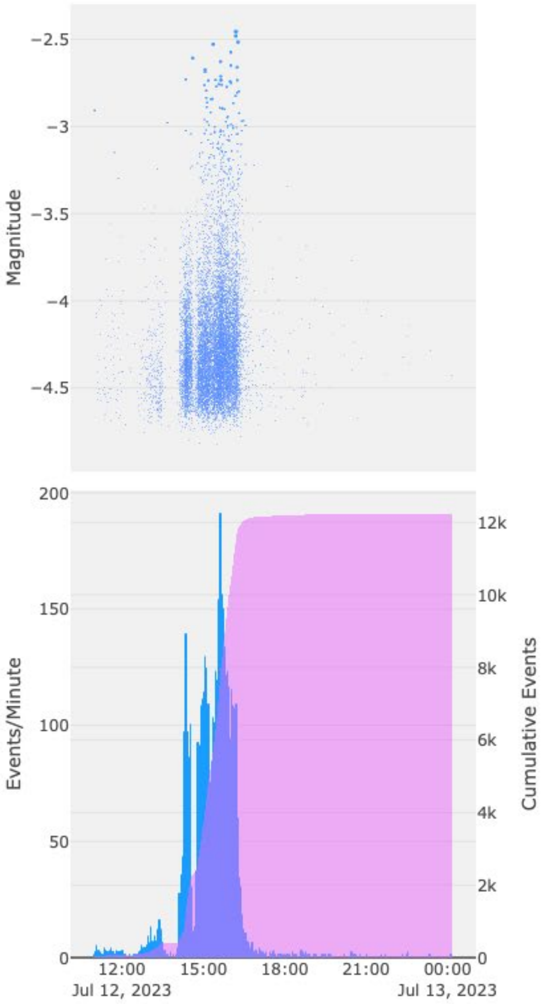
References

1. Plenkers, K, et al. (2023) "Multi-disciplinary monitoring networks for mesoscale underground experiments: advances in the bedretto reservoir project."
2. Noe, S et al., (2025, in prep.) “Theoretical Background for Full-Waveform Inversion with Distributed Acoustic Sensing and Integrated Strain Sensing”
3. Afanasiev, Michael, et al. "Modular and flexible spectral-element waveform modelling in two and three dimensions."
4. Durand, et al., (2022, May). “Analysis of the pico-seismic response of a fractured rock volume to fluid injections in the Bedretto Underground Laboratory, Switzerland.”
5. Zunino, A., Gebraad, L., et al., (2023). HMCLab: a framework for solving diverse geophysical inverse problems using the Hamiltonian Monte Carlo method.
6. Behnen, K., et al., (2024) Investigation of Seismic Anisotropy in the Rotondo Granite by Crosshole Seismic Surveys.

Extra slides:total catalog





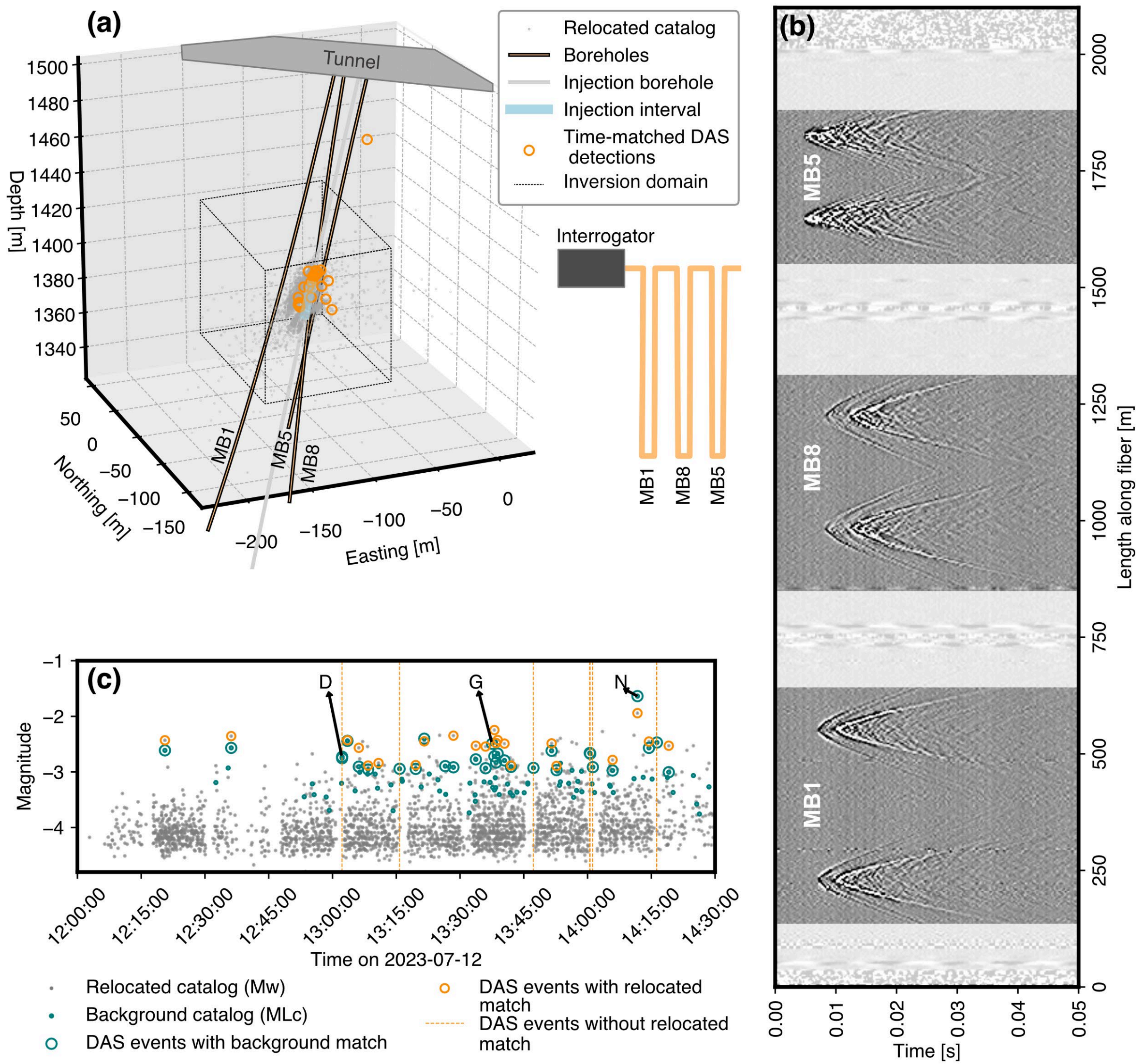
Total stimulation catalog
Rosskopf, M., Durand, V., & Obermann, A. (2024)

Extra slides: event A

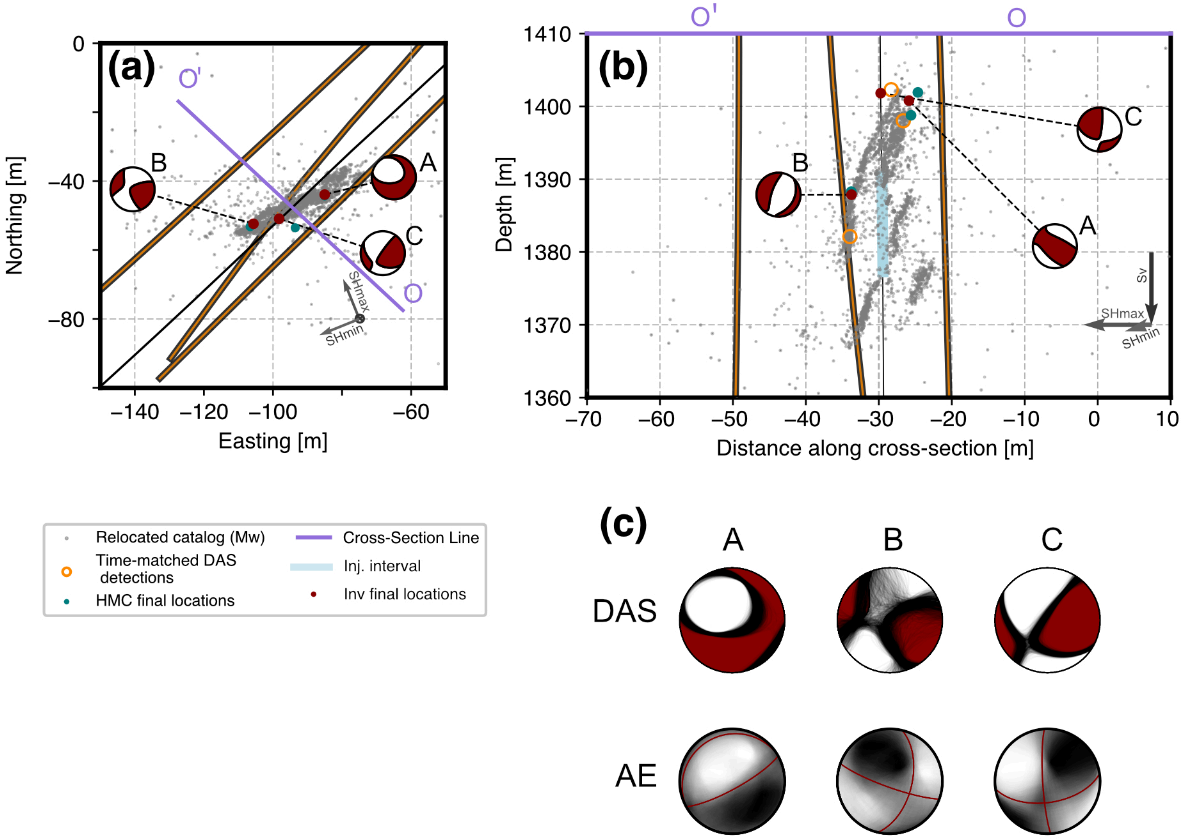
Extra slides: event B

Extra slides: event C

Extra slides: event C



Extra slides: event C



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Extra slides: event C