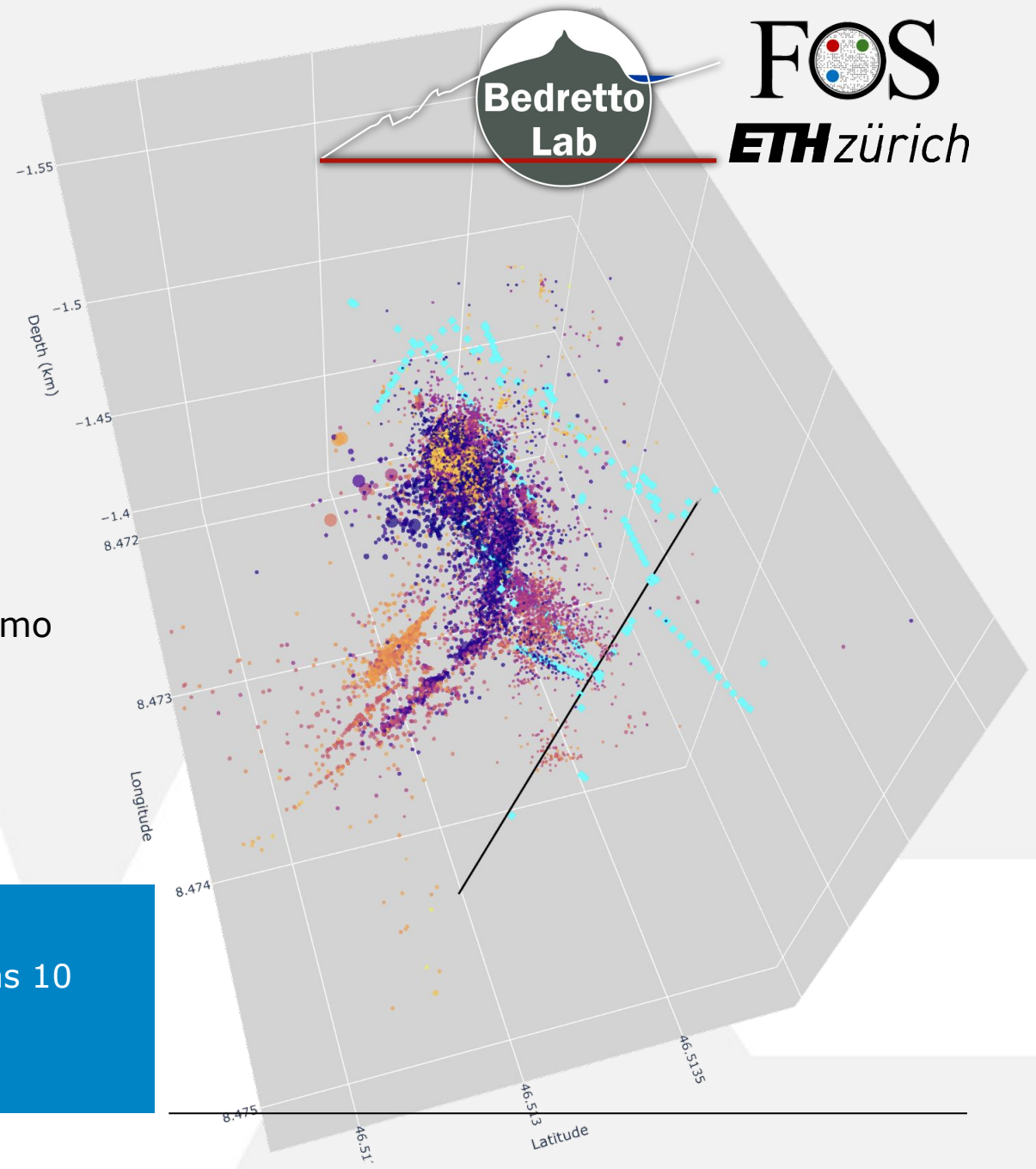
The Bedretto-Lab

Seismic Monitoring

Frédérick Massin
Mathilde Wimez, Luca Scarabello, Kacper Bilko, Thomas Haag, John Clinton, Martina Rosskopf, Khaled Ramdoun, Elisa Tinti, the *FOS-lab*, the *FEAR* and *Bedretto-Lab* seismo duty team



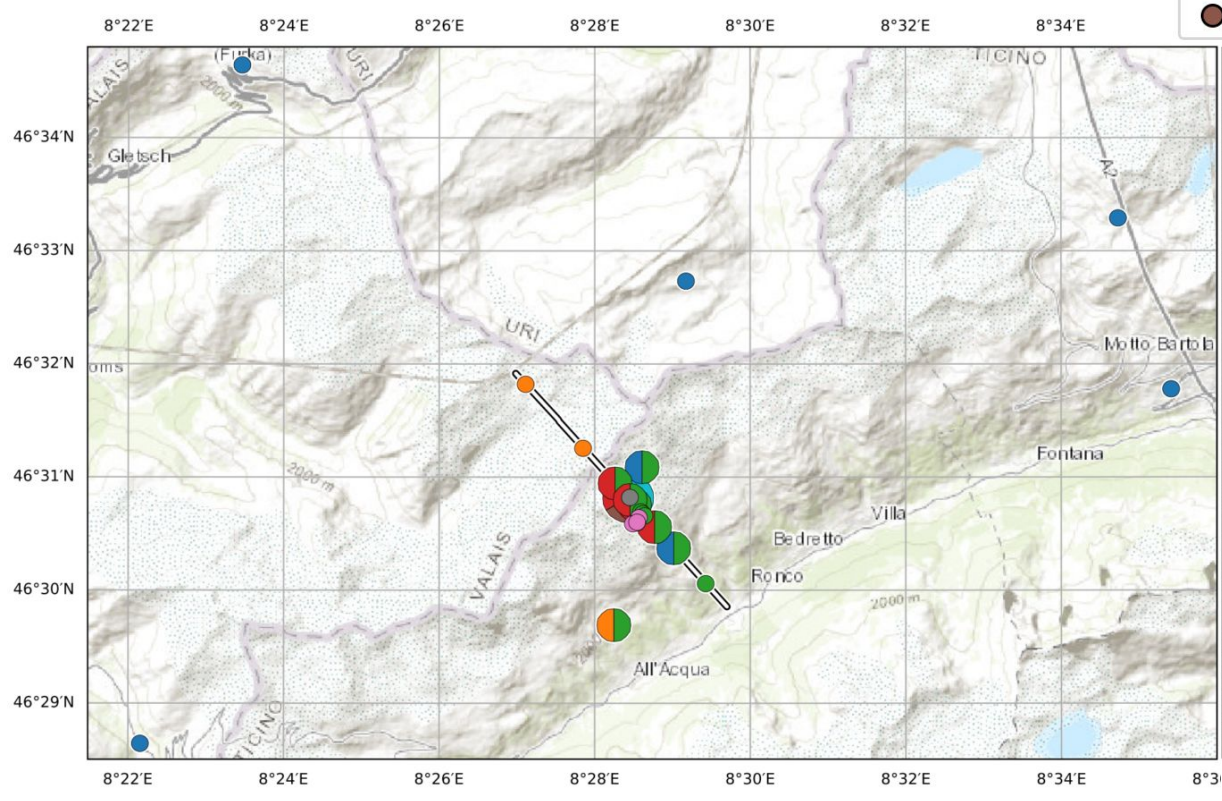
Bedretto-Lab team:
The team involves more than 30 people from ETHZ as well as 10 research institutes and companies
(see http://www.bedrettolab.ethz.ch/en/home/)

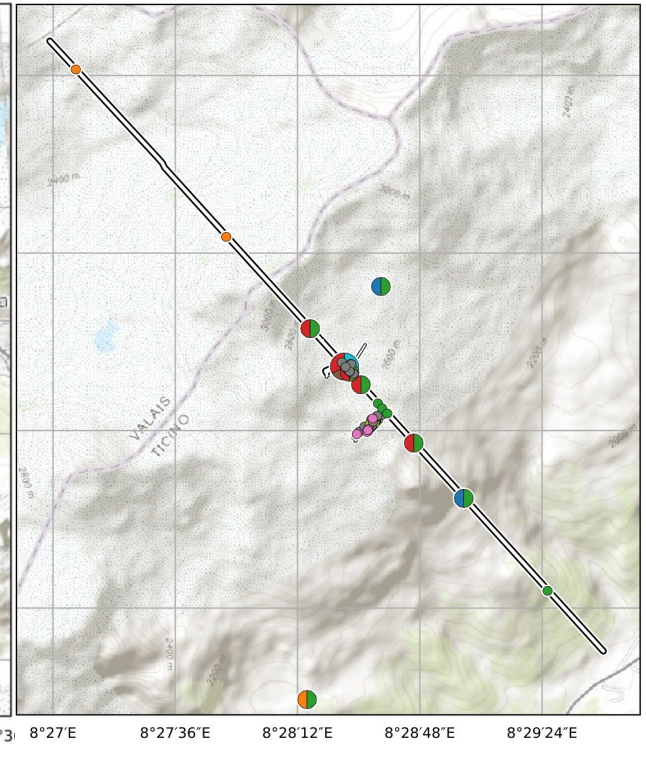
The SED national and BULGG permanent networks

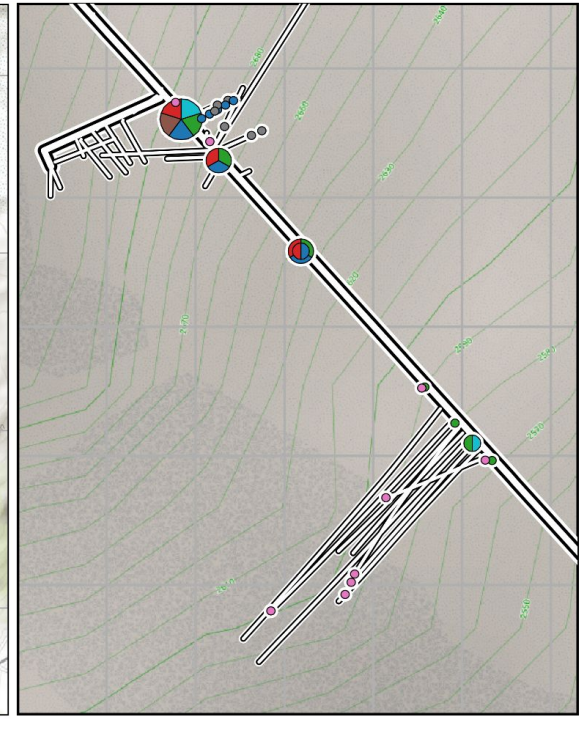
- Surface broadband sensors
- Tunnel permanent SM, BB, SP sensors
- Borehole 100/10Hz geophones

Instrument types

- Broadband seismometer
- Short period seismometer
- Strong motion accelerometer
- 2000 sps broadband seismometer
- 2000 sps short period seismometer
- 2000 sps strong motion accelerometer
- Borehole 2000 sps short period geophone
- Borehole 200,000 sps acoustic emission sensor
- Borehole 200,000 sps accelerometer
- Tiltmeter
- Distributed acoustic sensing

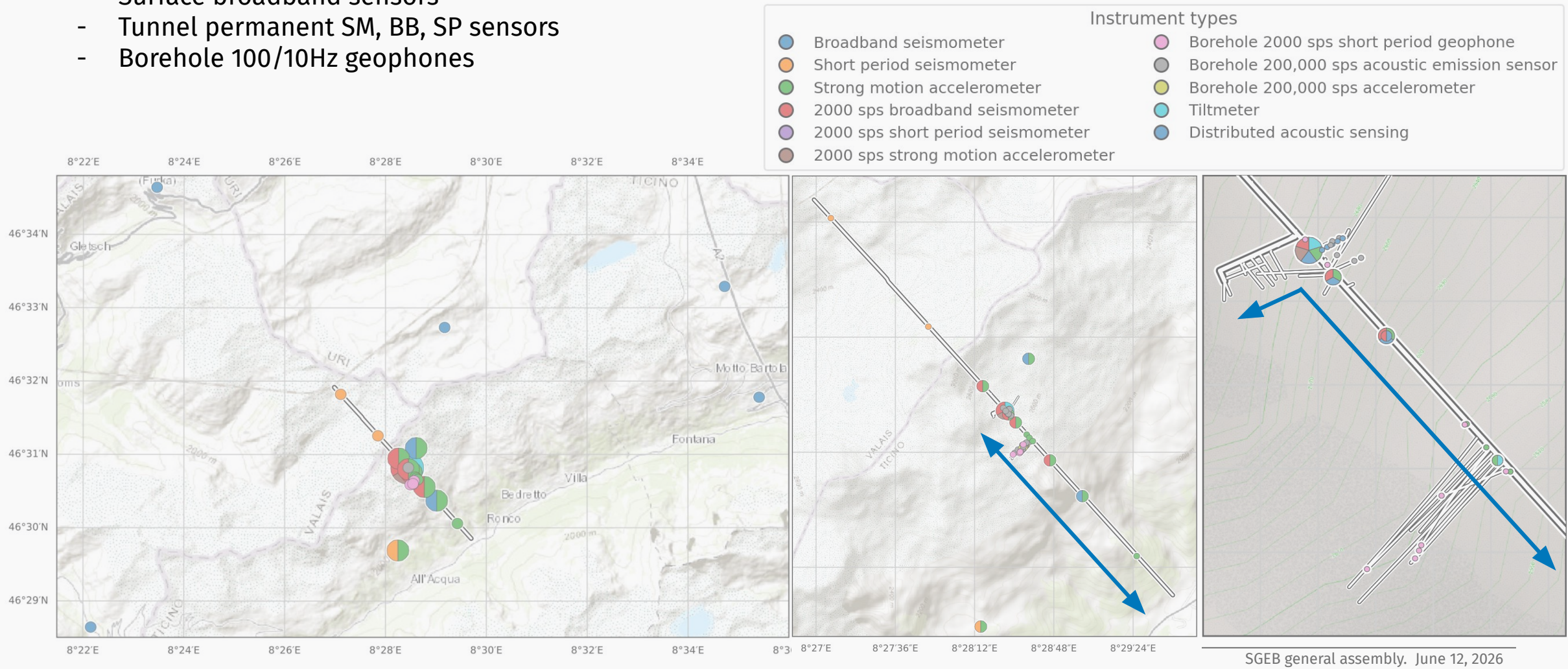




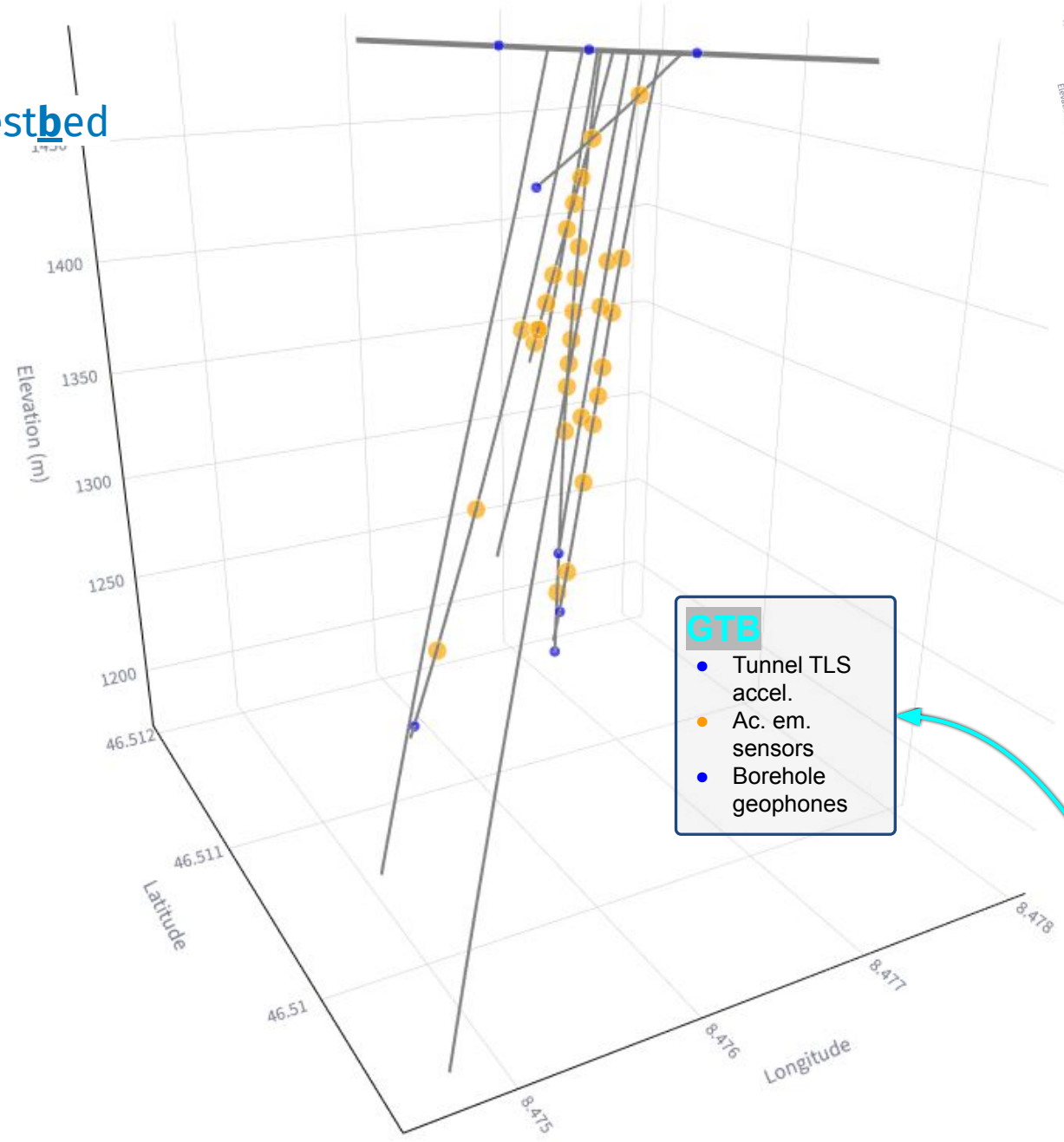


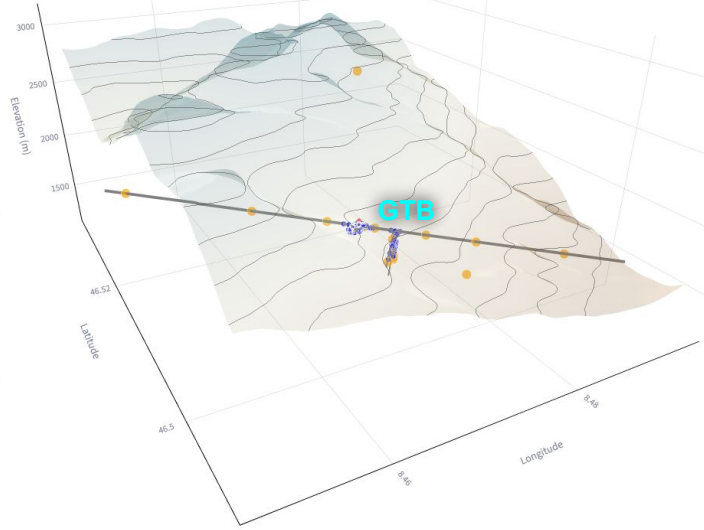
The SED national and BULGG permanent networks

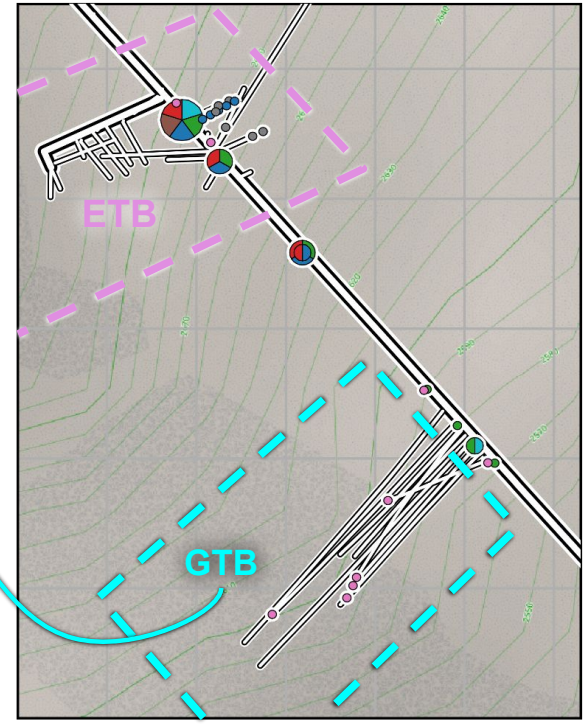
- Surface broadband sensors
- Tunnel permanent SM, BB, SP sensors
- Borehole 100/10Hz geophones



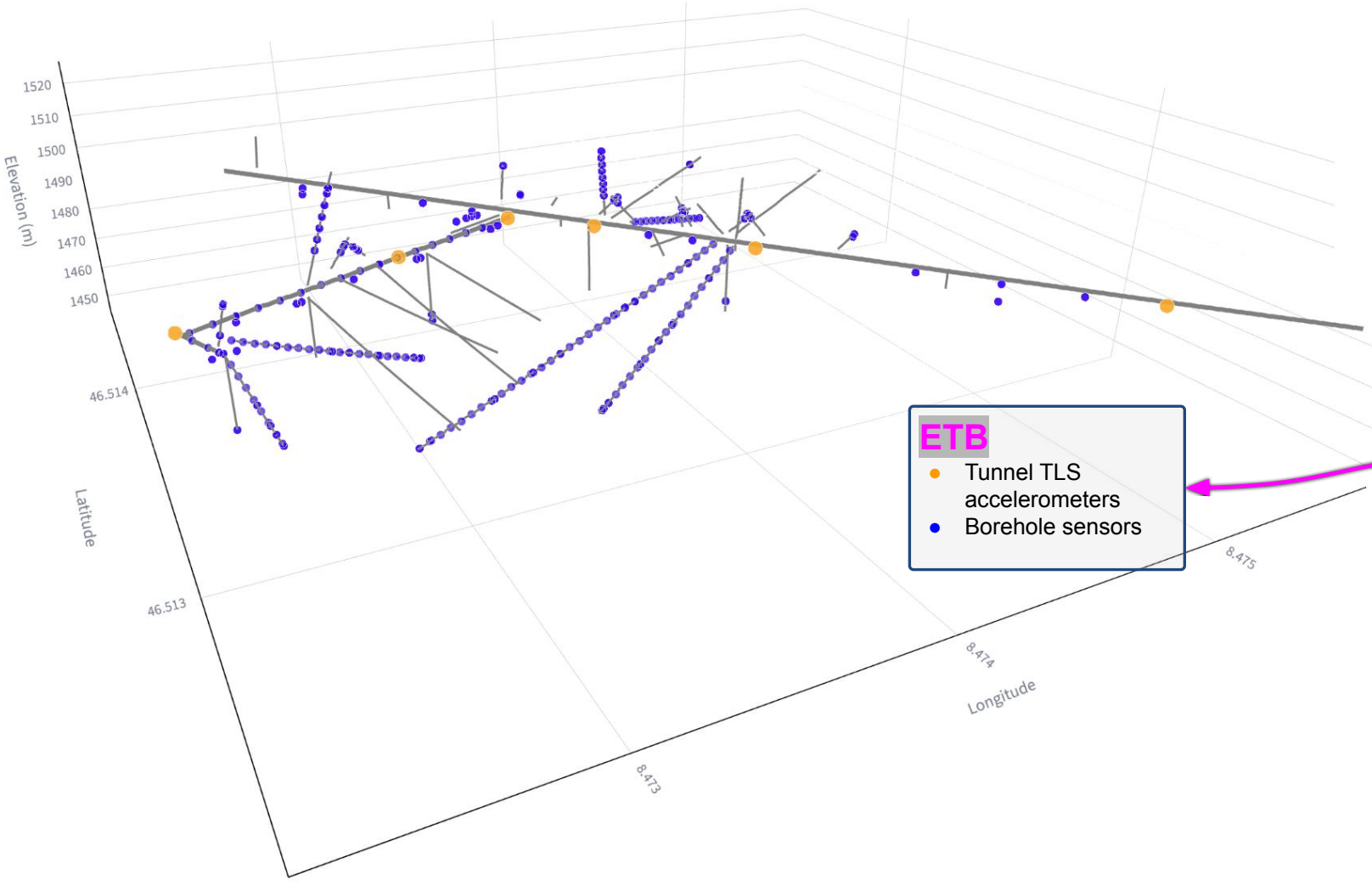
The Geothermal Testbed



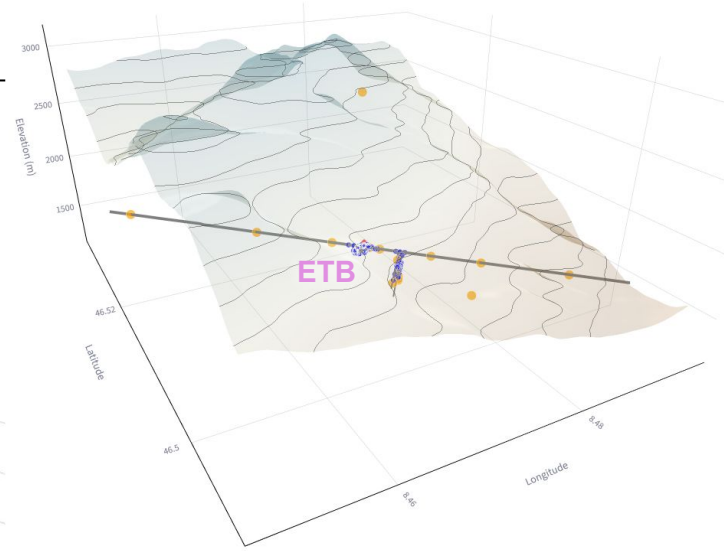


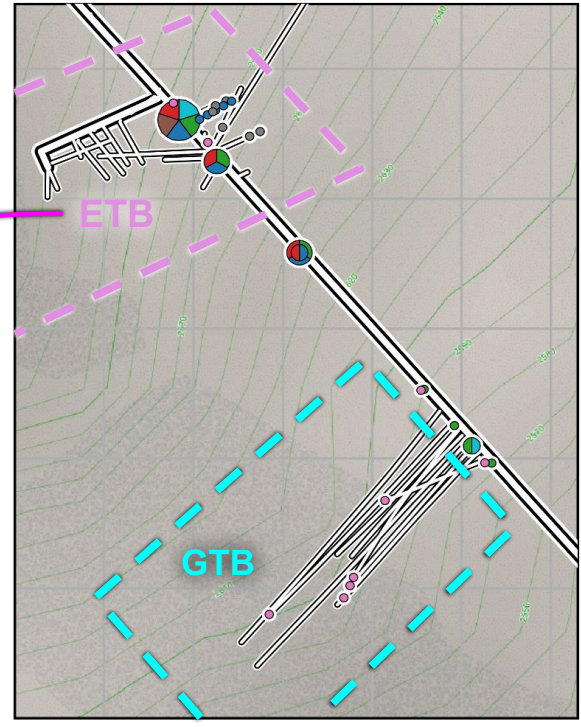


The **E**arthquake Physics **T**est**b**ed



ETB
- Tunnel TLS accelerometers
- Borehole sensors



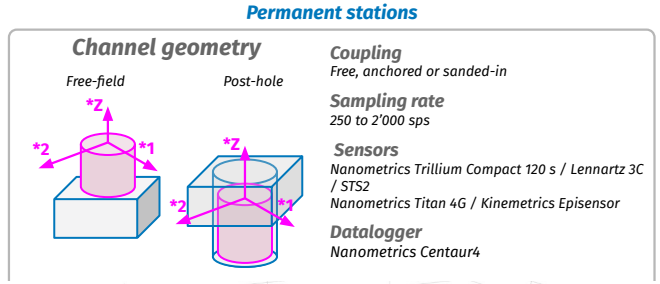


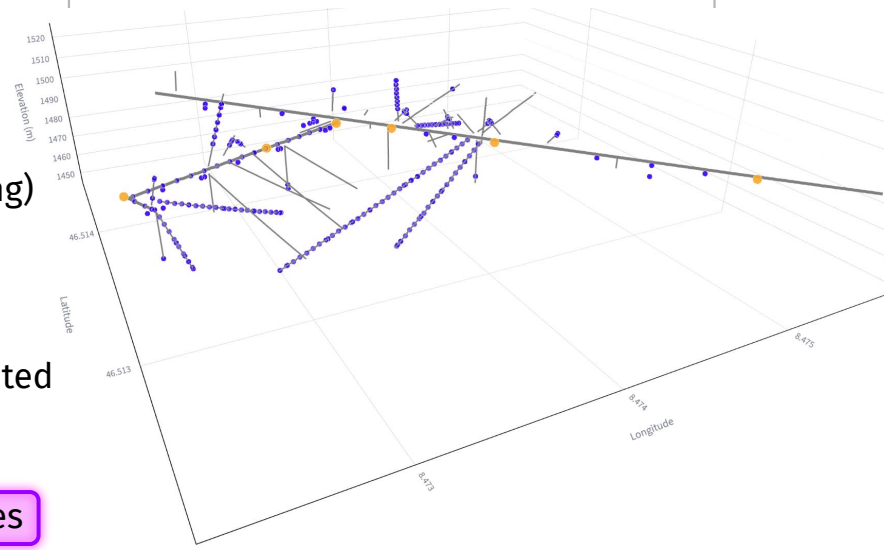
Instrumentation overview

Instrument types within the ***8R*** network:

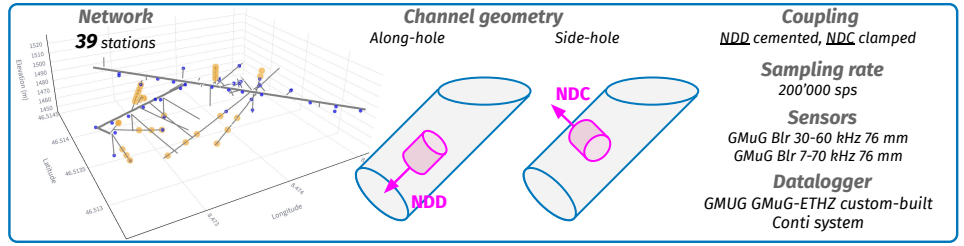
- Tunnel stations:
  - ***2 ksps:*** main tunnel
  - ***5 ksps:*** DAS cemented in tunnel floor
  - ***10 ksps:*** sanded post-hole stations (high-freq. coupling)
- Borehole stations:
  - ***5 ksps:*** DAS cemented in boreholes
  - ***10 ksps:*** Geophones
  - ***200 ksps:*** Piezo-(accelero)meters

Permanent stations

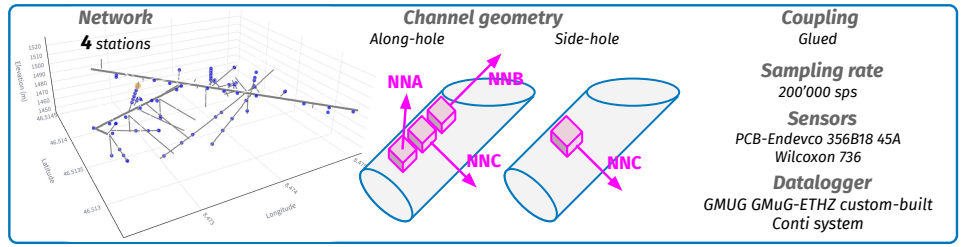




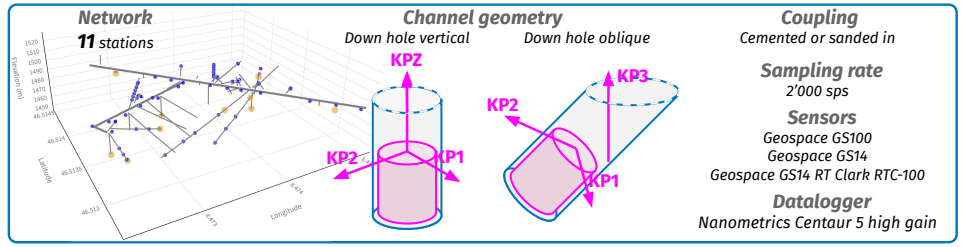
Piezometer (acoustic emission sensors)



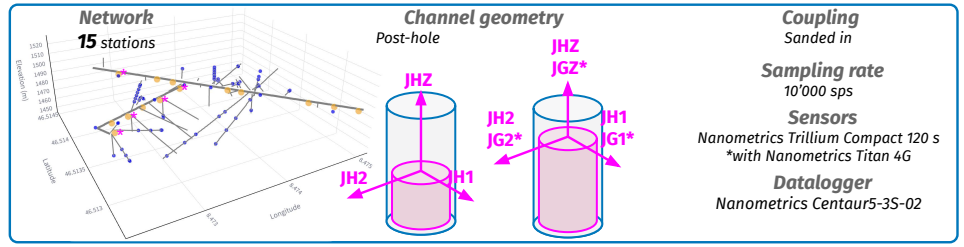
Piezo accelerometers



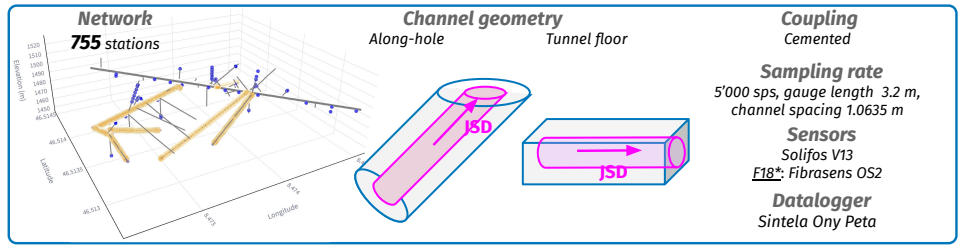
Geophones



SED-RQUIP



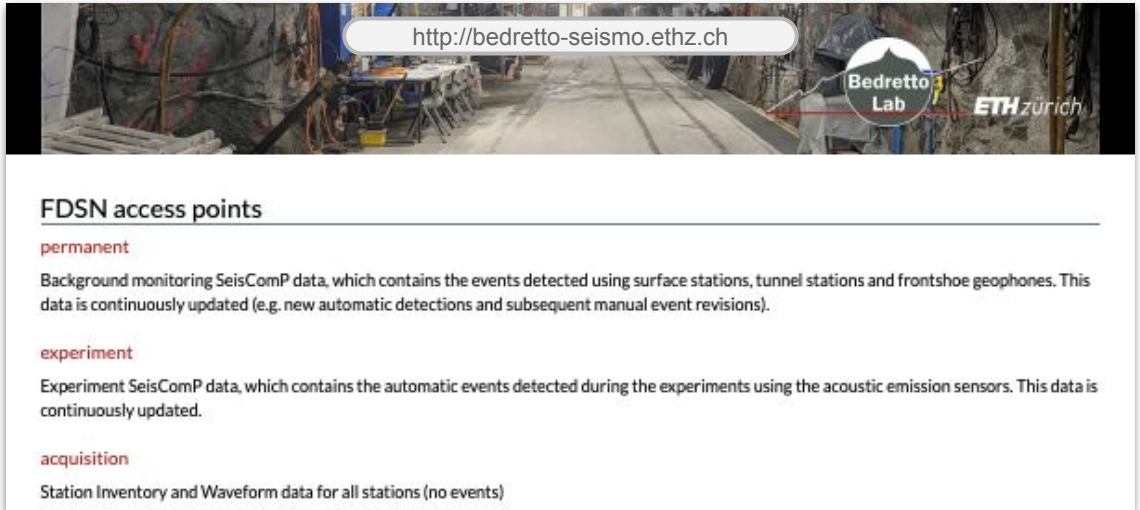
Distributed acoustic sensing

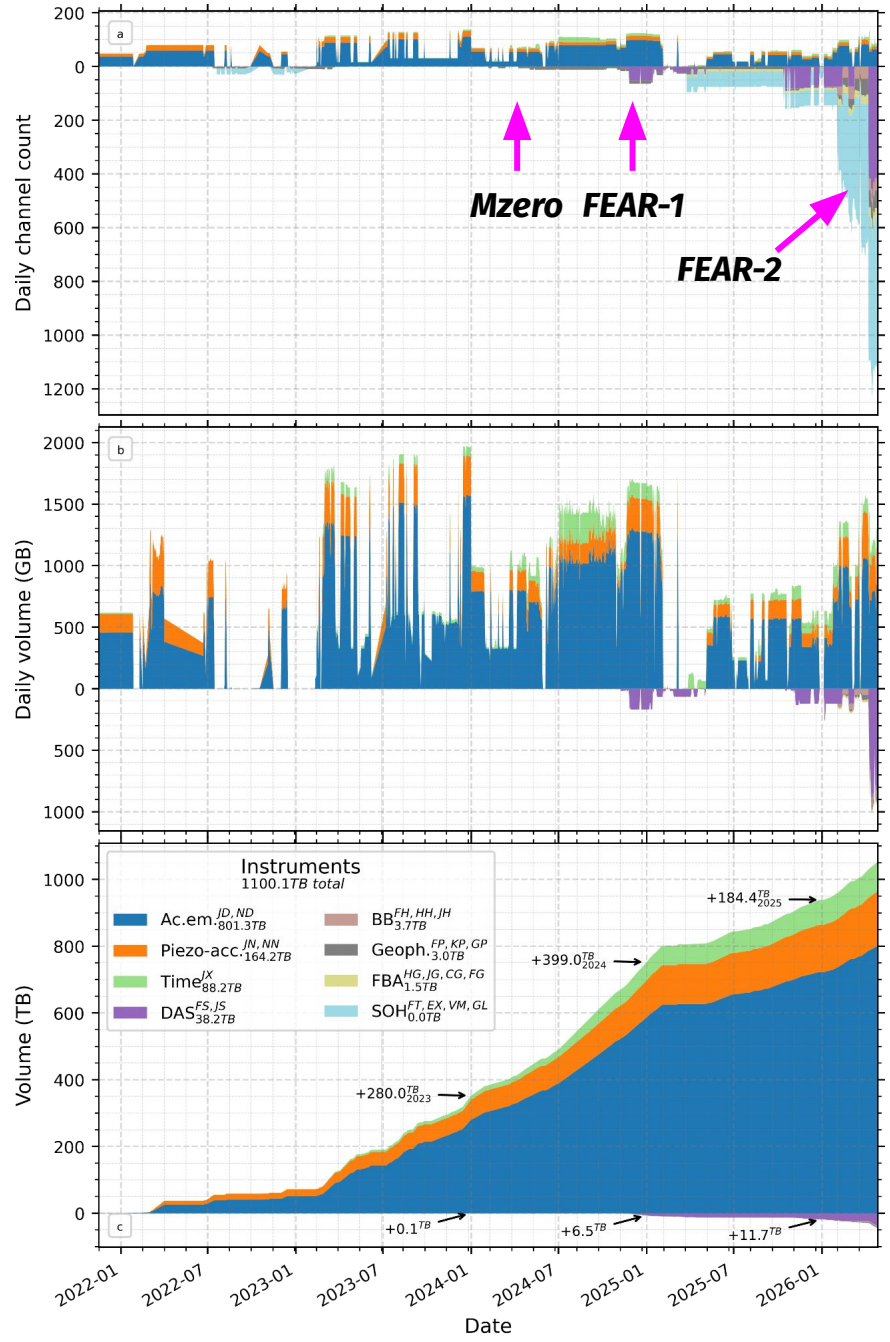


Data overview

Data volume of the ***8R*** network, ***2*** *TB per day* since FEAR-2:

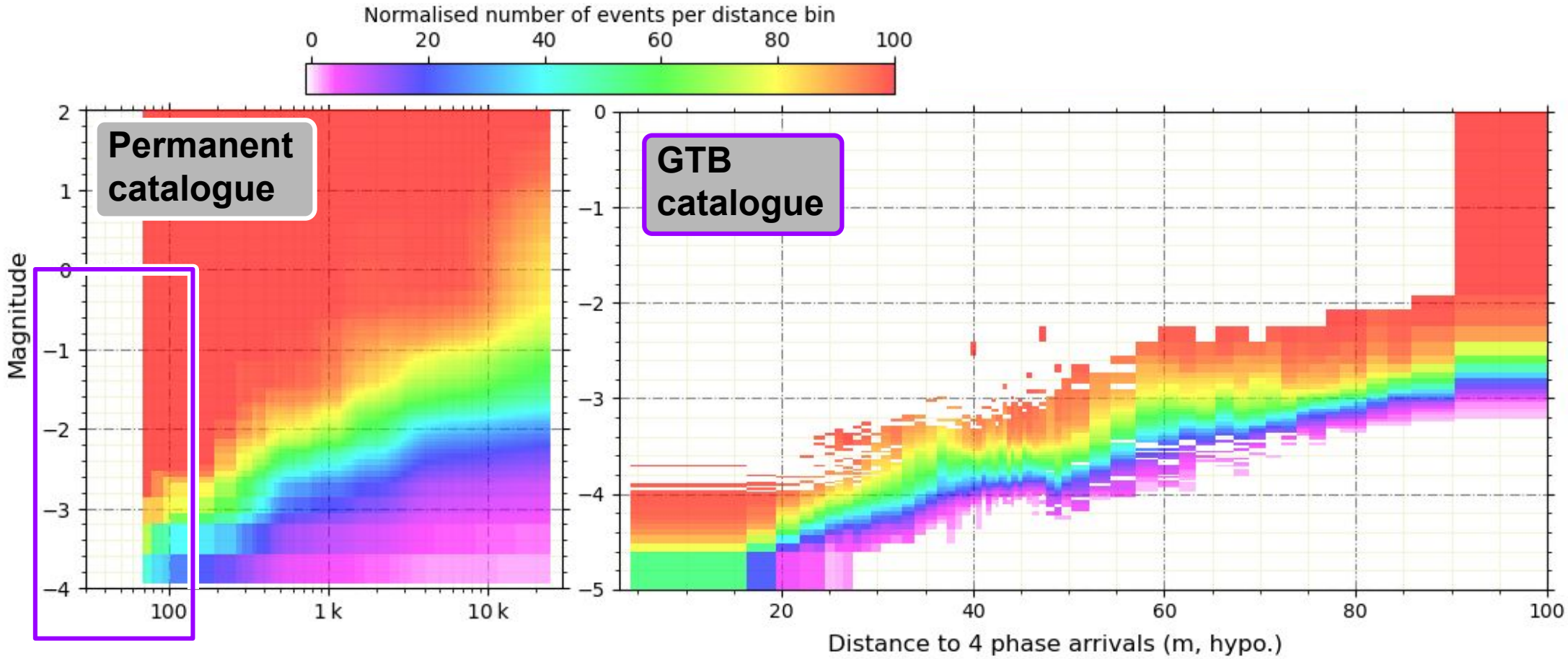
- ***1 to 1.5*** *TB per day* from borehole sensors:
  - ***~150*** *GB per day* from timing channels
- ***1*** *TB per day* from DAS since FEAR2
- **<200** *TB per day* from tunnel stations





Completeness and Precision in Experiment Catalogues

The magnitude completeness is a function of hypocentral distance



Alerting and response

Polygons for Ml alerts

SED

Bedretto RED

MLhc >= 2.5 (0-3km)

MLhc >= 3.5 (3-6km)

Bedretto ORANGE

1.0 =< MLhc < 1.5 (0-1km)

1.5 =< MLhc < 2.5 (1-3km);

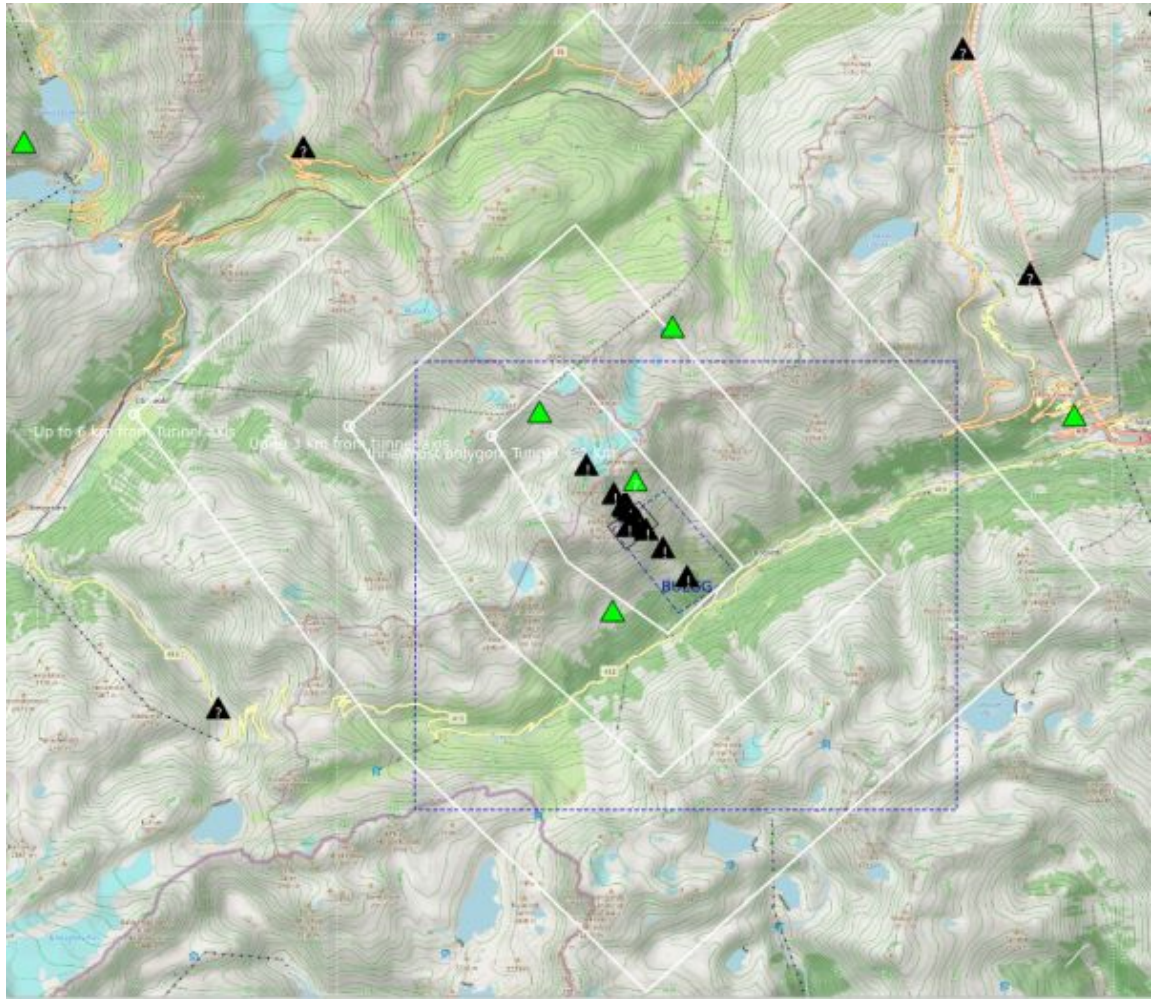
2.5 =< MLhc < 3.5 (3-6km)

Bedretto YELLOW

-0.5 =< MLhc < 1.0 (0-1km)

0.5 =< MLhc < 1.5 (1-3km)

1.5 =< MLhc < 2.5 (3-6km)



Alerting and response

Polygons for Ml alerts

SED

Bedretto RED

MLhc >= 2.5 (0-3km)

MLhc >= 3.5 (3-6km)

Bedretto ORANGE

1.0 =< MLhc < 1.5 (0-1km)

1.5 =< MLhc < 2.5 (1-3km);

2.5 =< MLhc < 3.5 (3-6km)

Bedretto YELLOW

-0.5 =< MLhc < 1.0 (0-1km)

0.5 =< MLhc < 1.5 (1-3km)

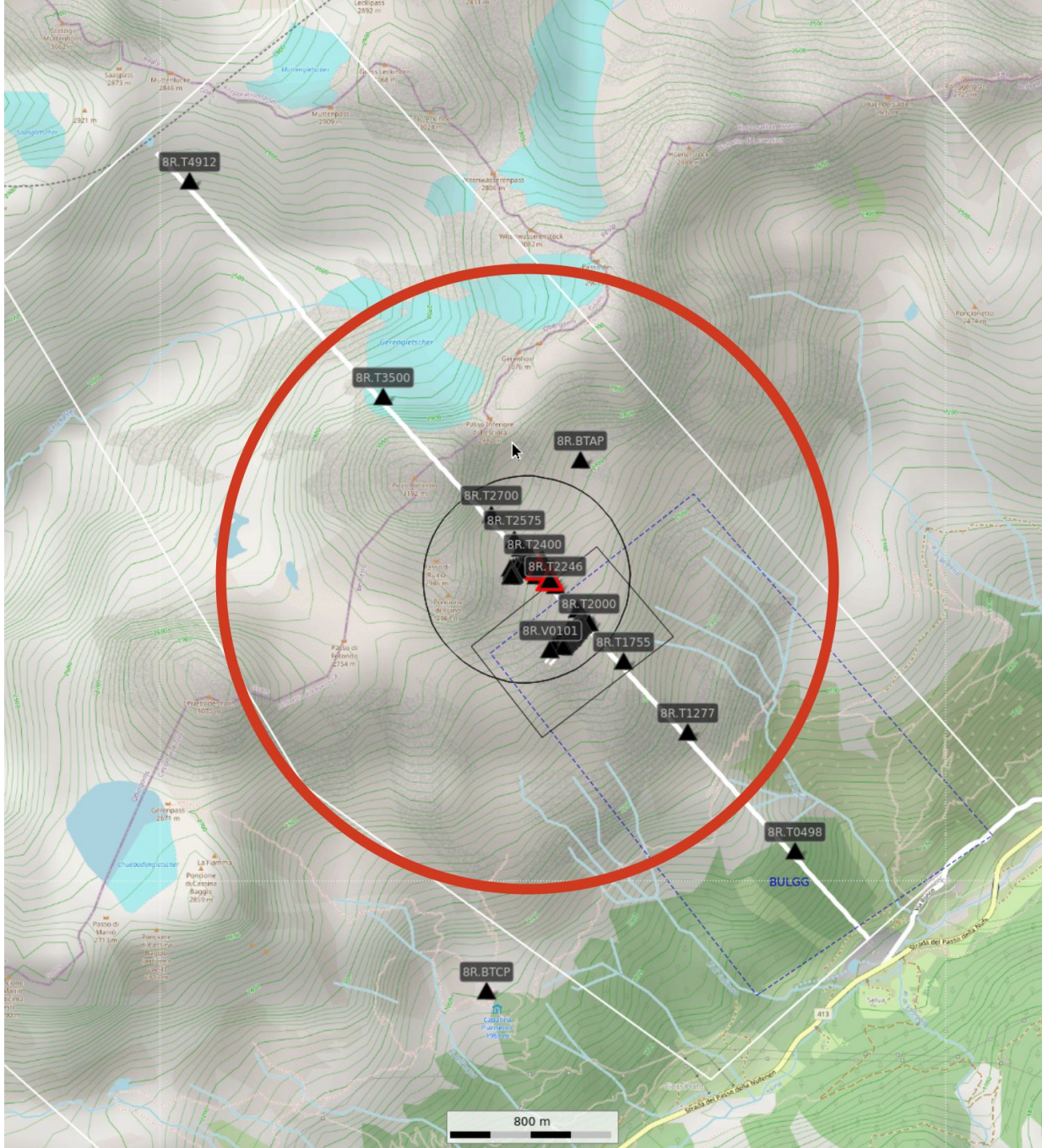
1.5 =< MLhc < 2.5 (3-6km)

BULGG

RED: MLc >= 1.3

ORANGE: MLc >= 0.5

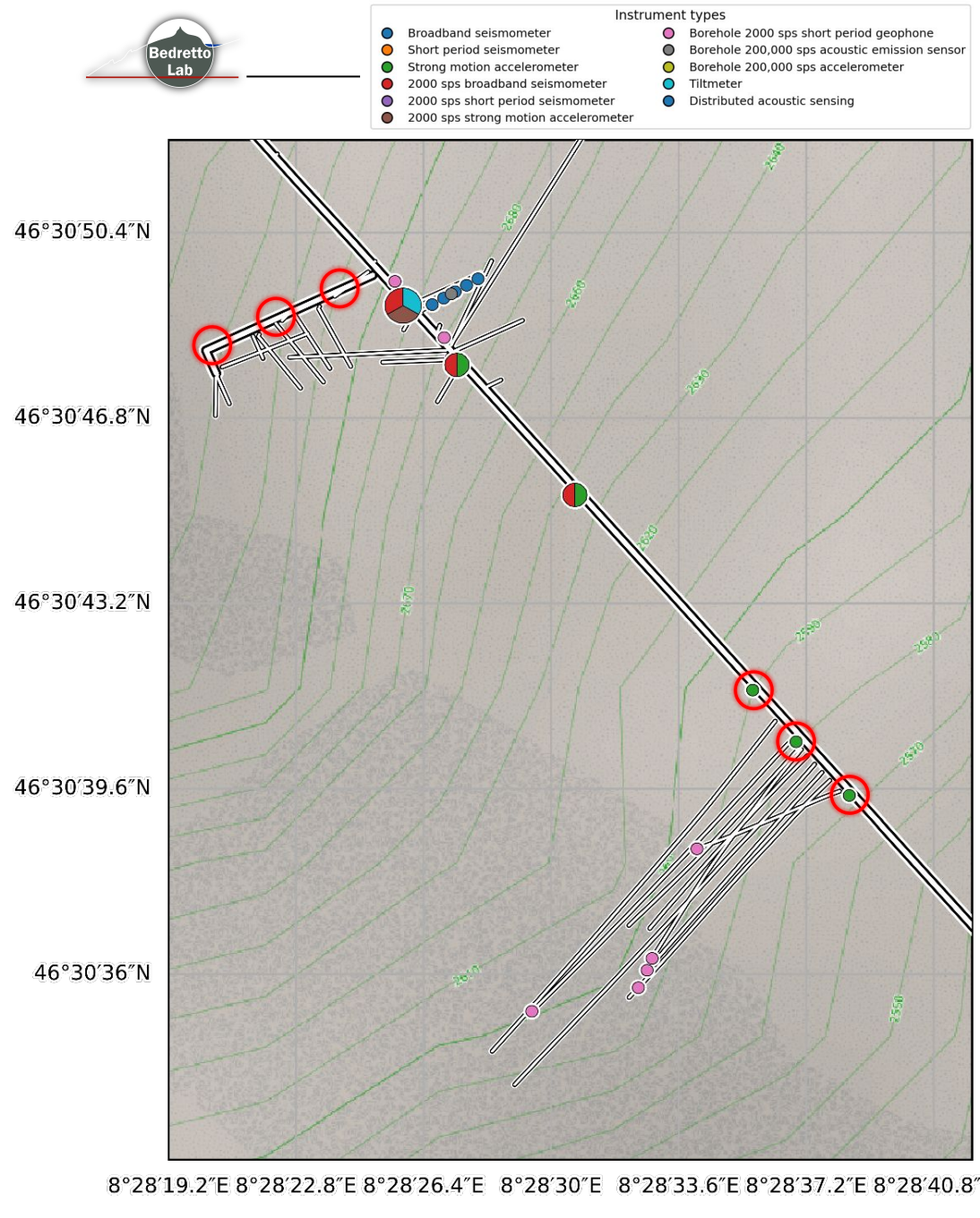
YELLOW: MLc >= -0.5



Alerting and response

QD-TLS for the ETB and GTB

- 3 Centaur-Episensor accelerographs,
- Accelerographs not useful for monitoring,
- Email and SMS notifications impossible in absence of ETHZ connectivity, the monitor display is really standalone



Magnitude Methods

Swiss National Earthquake Catalogue:

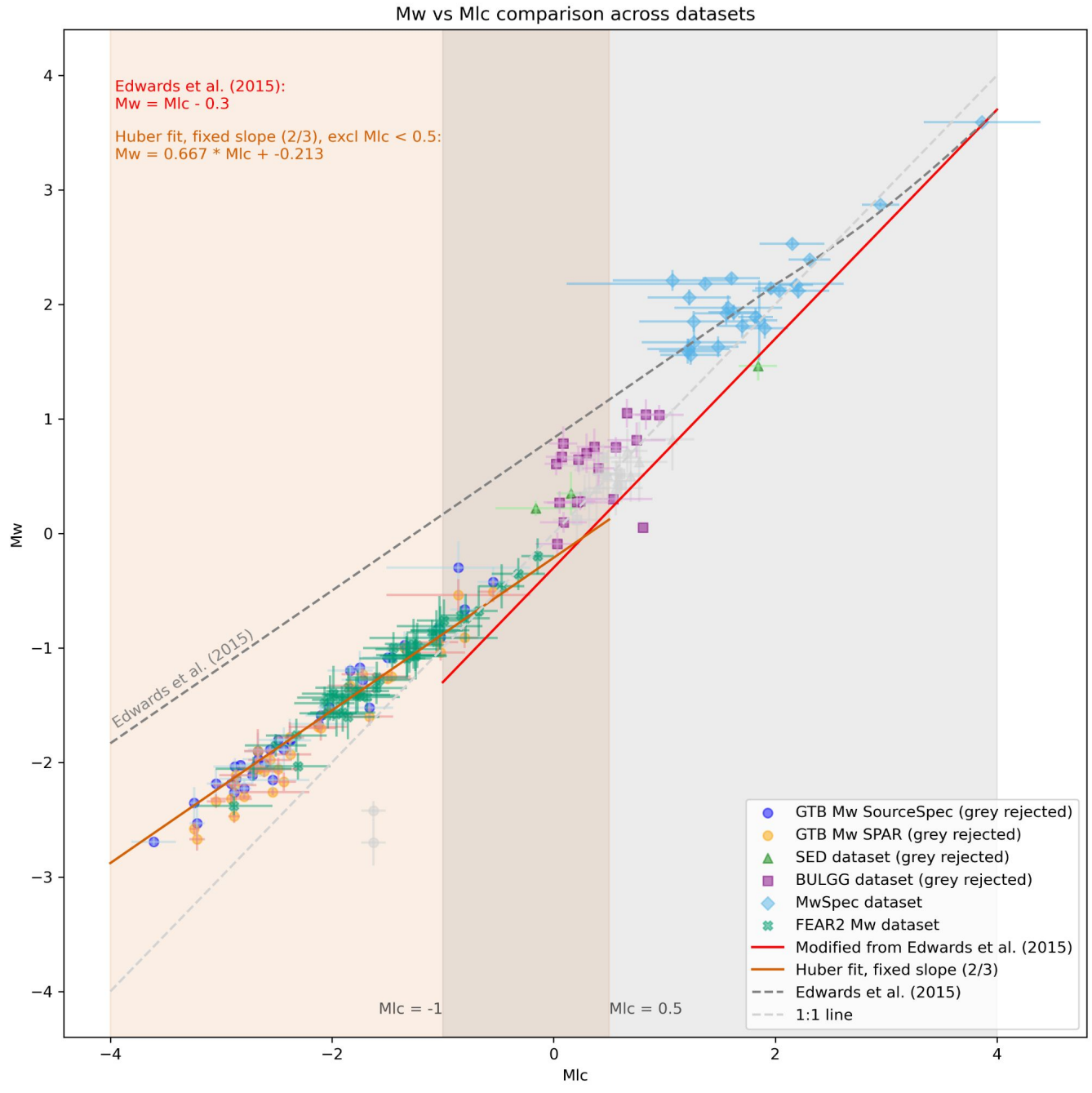
- ***Mlhc***: Swiss Local Magnitude with station corrections (**manually revised**).
- ***MwSpec***: Swiss Moment Magnitude with station corrections (**automatic**).

BedrettoLab Permanent Reference Earthquake Catalogue:

- ***MLc***: Local magnitude from Wood-Anderson amp. (**manually revised**).
- ***Mw*** **preliminary**: Seismic moment, corner frequency, and radiated energy inversion from displacement spectra (SourceSpec [rapid analysis] and SPAR [final analysis] softwares).

Borehole Arrays in Experiment Testbeds:

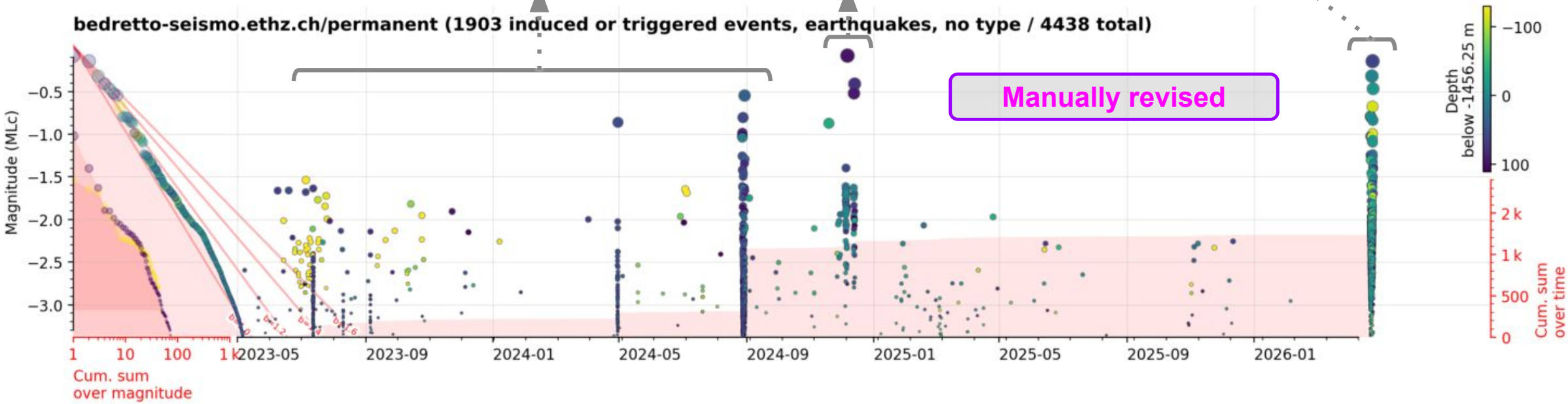
- ***MwA*** **automatic**: Magnitude regression based on amplitude ratios, calibrated against accelerometers and *Mw*.



The Permanent Reference earthquake Catalogue

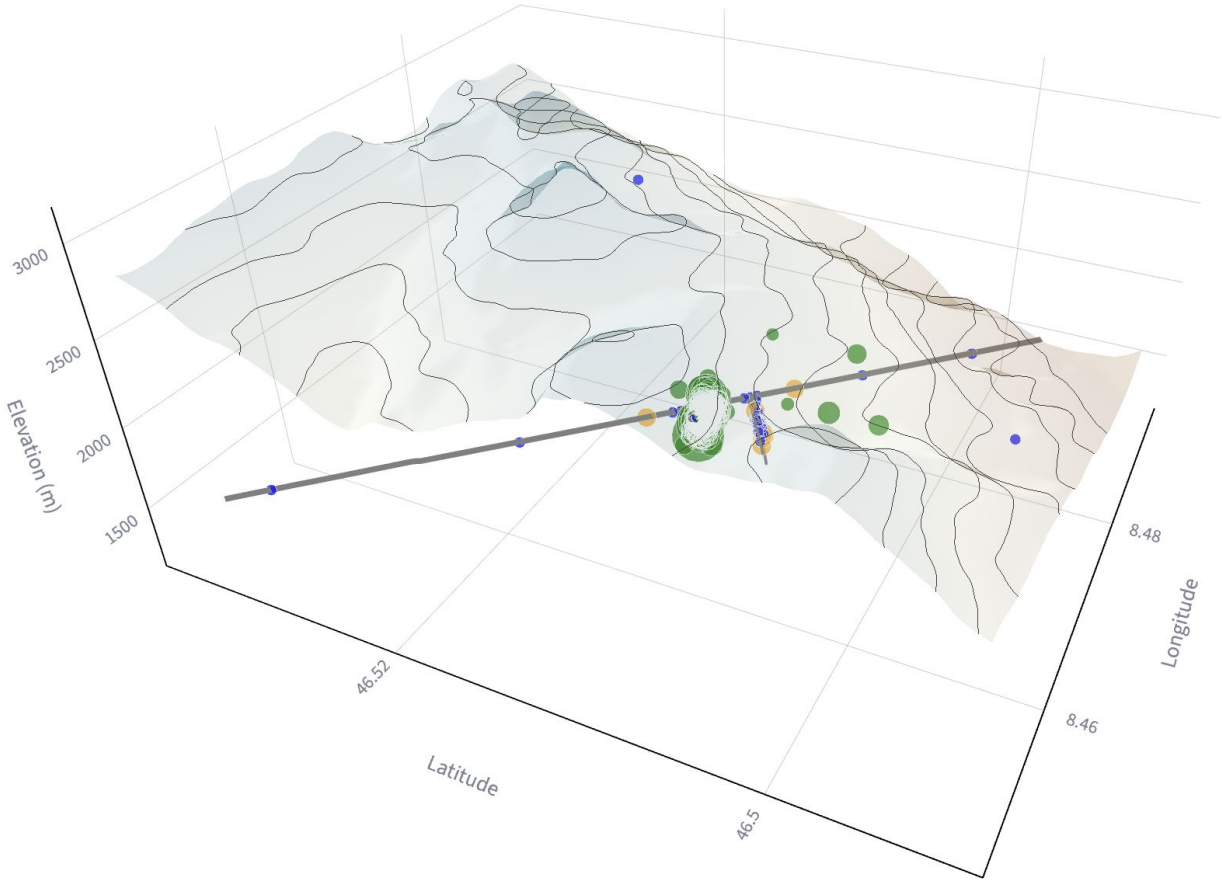
https://doi.org/10.3929/ethz-c-000789415

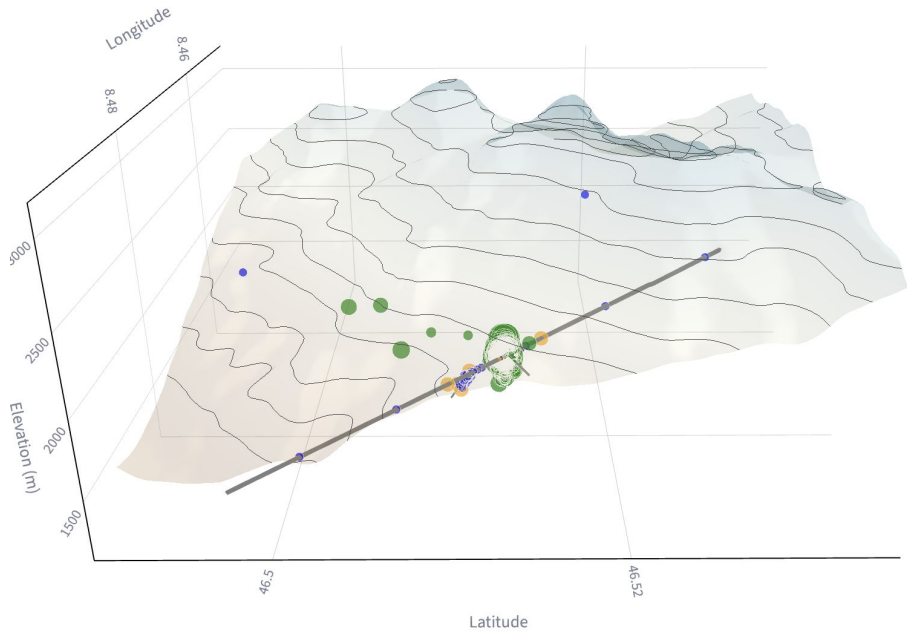
	GTB	***ETB-FEAR1***	***ETB-FEAR2***
Induced earthquakes	108’493	13’440	19’604
MLc > -1	4	5	9
Max. MLc	-0.5	-0.1	-0.1



The Permanent Reference earthquake Catalogue

https://doi.org/10.3929/ethz-c-000789415





Latest 3 months

The GTB earthquake Catalogue

https://doi.org/10.3929/ethz-c-000789401

Borehole sensors are used for operational real-time monitoring, in complement of the Permanent catalogue.

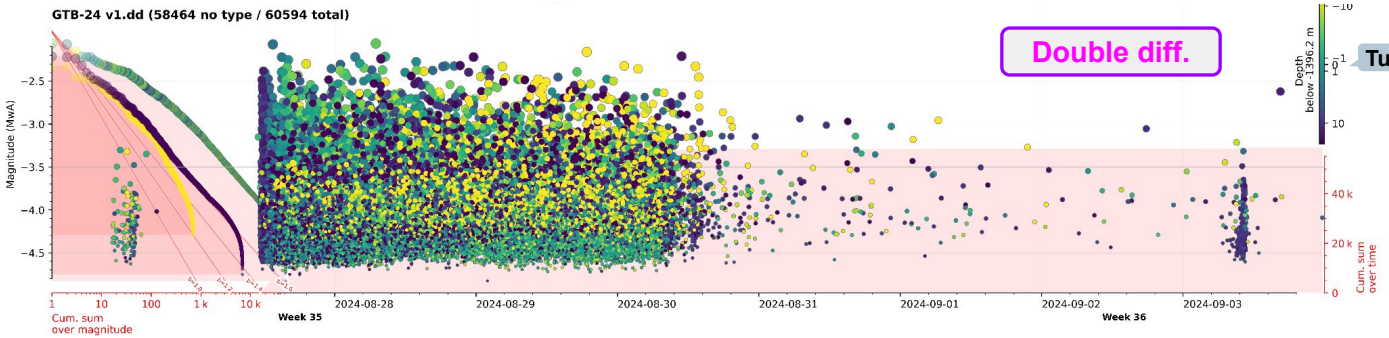
Once finalised, experiment data are integrated within an optimal experiment earthquake catalogue:

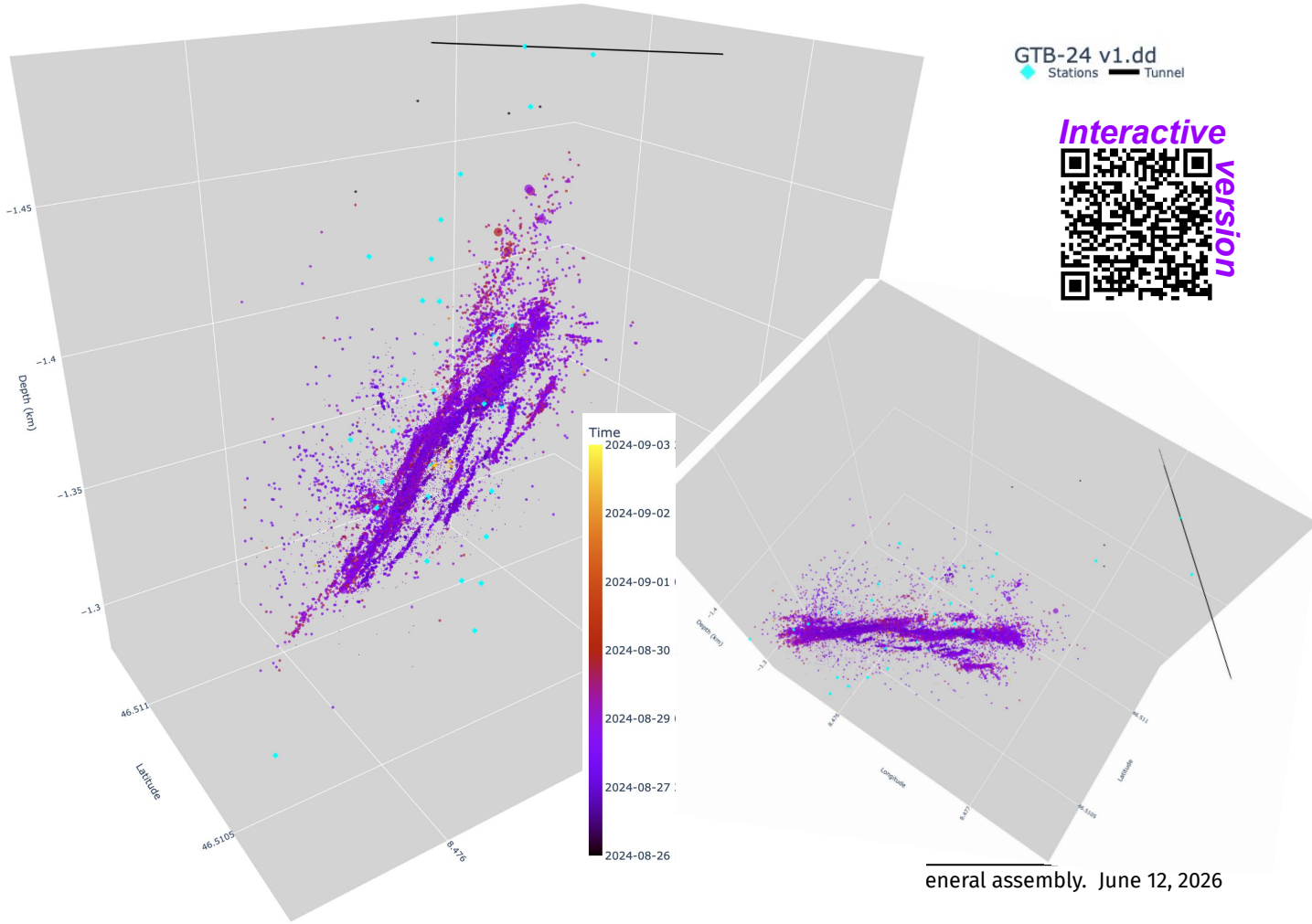
Optimization: Optimized picking, location methods and velocity models.

Precision: Fully repicked waveforms (incl. DAS), and double-difference relocations.

Completeness: Mc < -4.

Distribution: FDSN-compliant data access for the community.





The ETB-FEAR1 earthquake Catalogue

https://doi.org/10.3929/ethz-b-000743181

Borehole sensors are used for operational real-time monitoring, in complement of the Permanent catalogue.

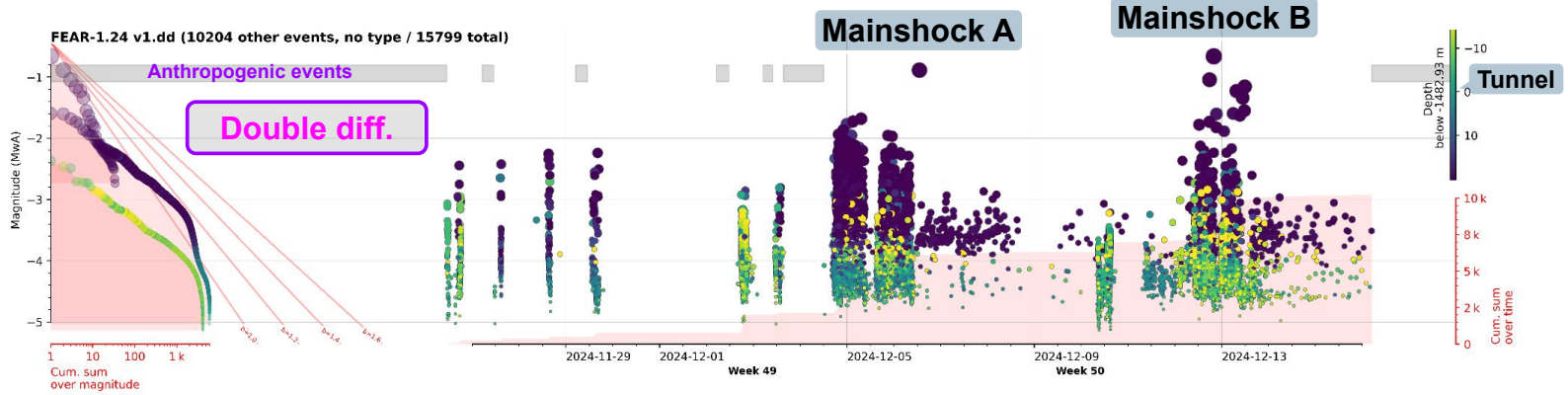
Once finalised, experiment data are integrated within an optimal experiment earthquake catalogue:

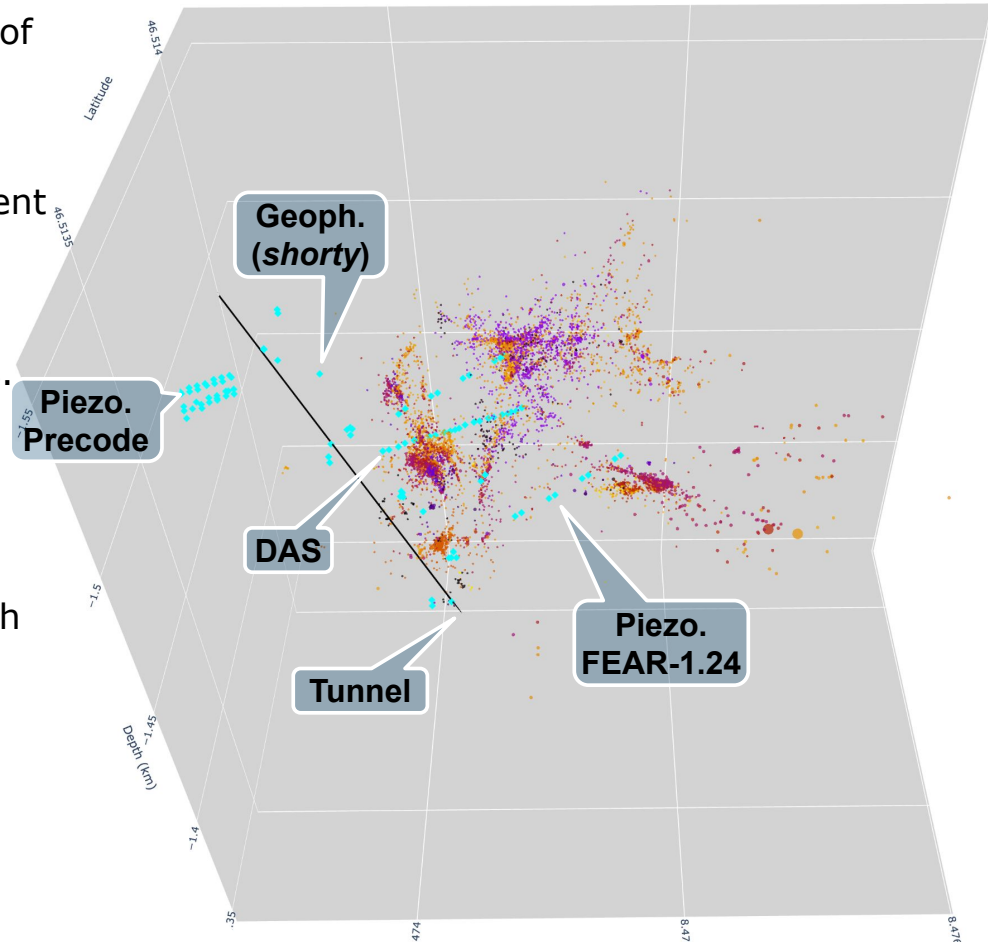
Optimization: Optimized picking, location methods and velocity models.

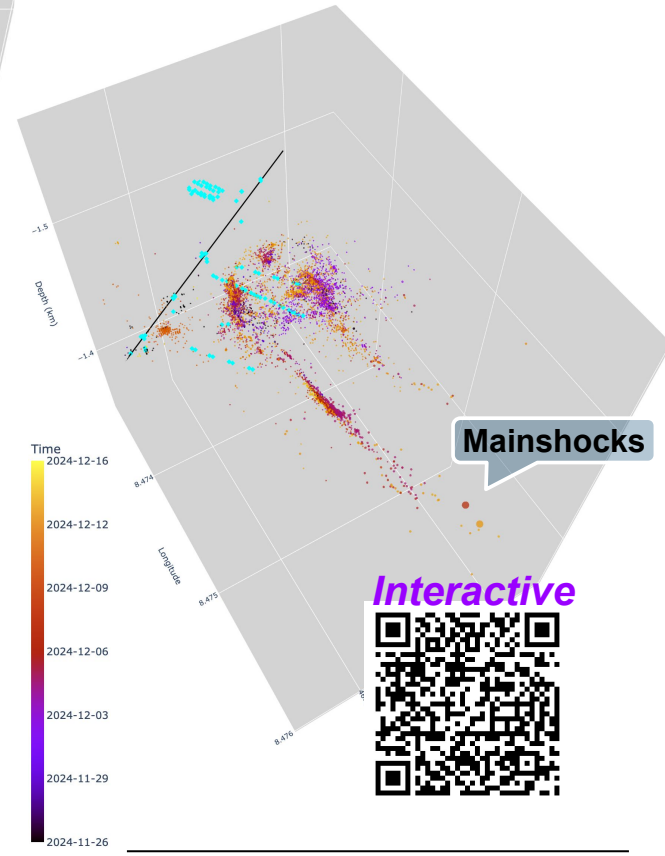
Precision: Fully repicked waveforms (incl. DAS), and double-difference relocations.

Completeness: Mc < -4, include both *MwA* and *MLc* **in FEAR catalogues**, bridging the gap between experiment arrays and the Permanent network.

Distribution: FDSN-compliant data access for the community.







Interactive

The ETB-FEAR2 earthquake Catalogue

Event catalogues based on the ***8R*** network:

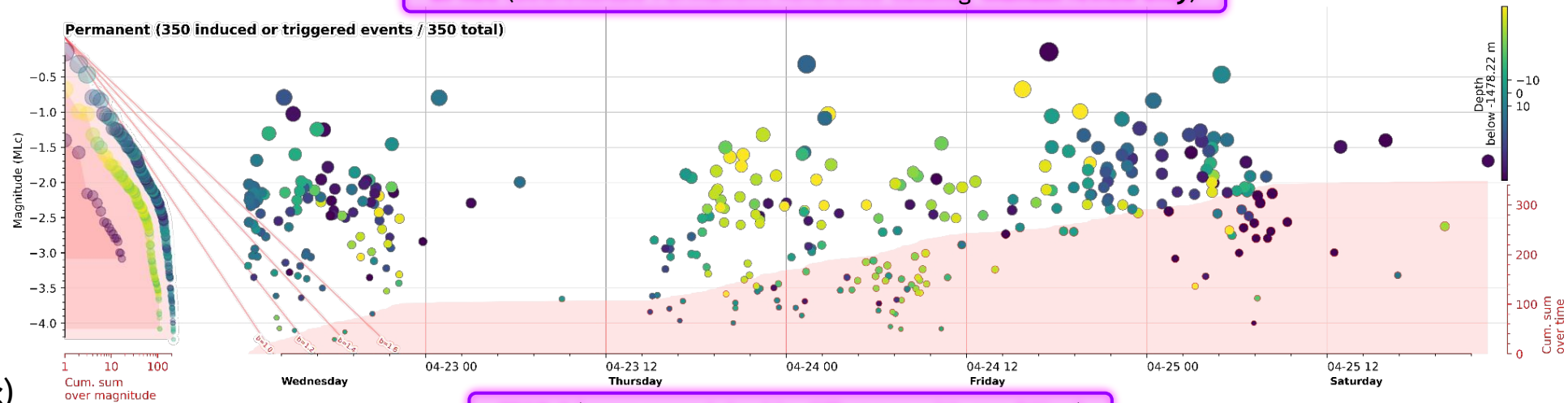
BPREC:

- ***200+ staff hours***
  24h, 6 days (3.5 red)
  2 full team 7h days
- ***350*** induced eq.
  >**M**-*0.5* 3 eq
  >**M**-*1* ~12 eq
  >**M**-*1.5* ~30 eq
  >**M**-*2* ~150 eq (**Mc**)

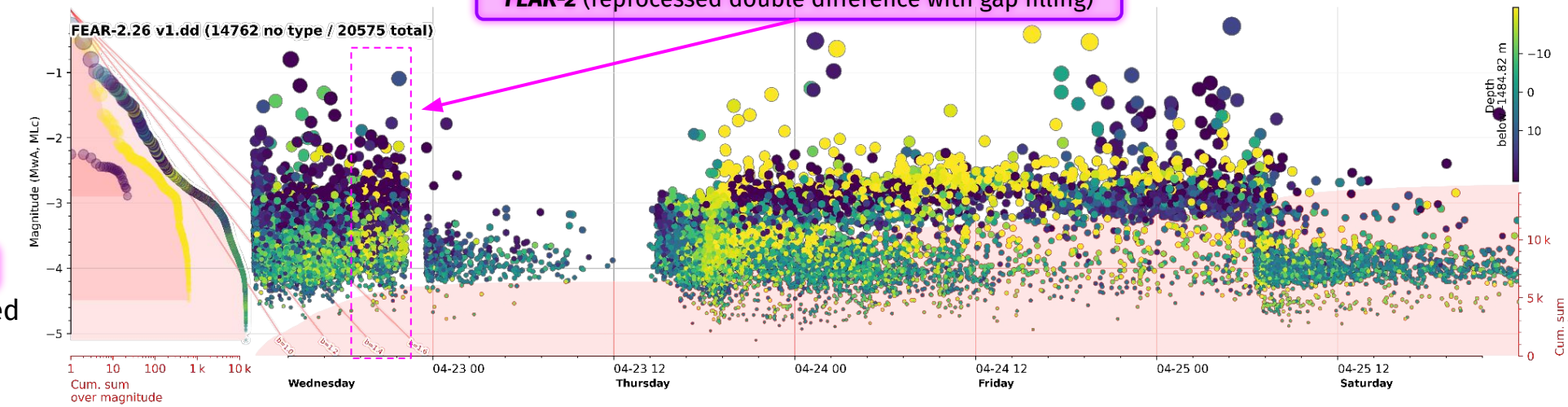
FEAR-2:

- ***~15k*** induced eq.
  from M-0.2 to -5
- Issues:
  22-23rd: Timing & gap
  <23rd: stations adjusted

BPREC (BedrettoLab Permanent Reference Catalog ***manual review only***)

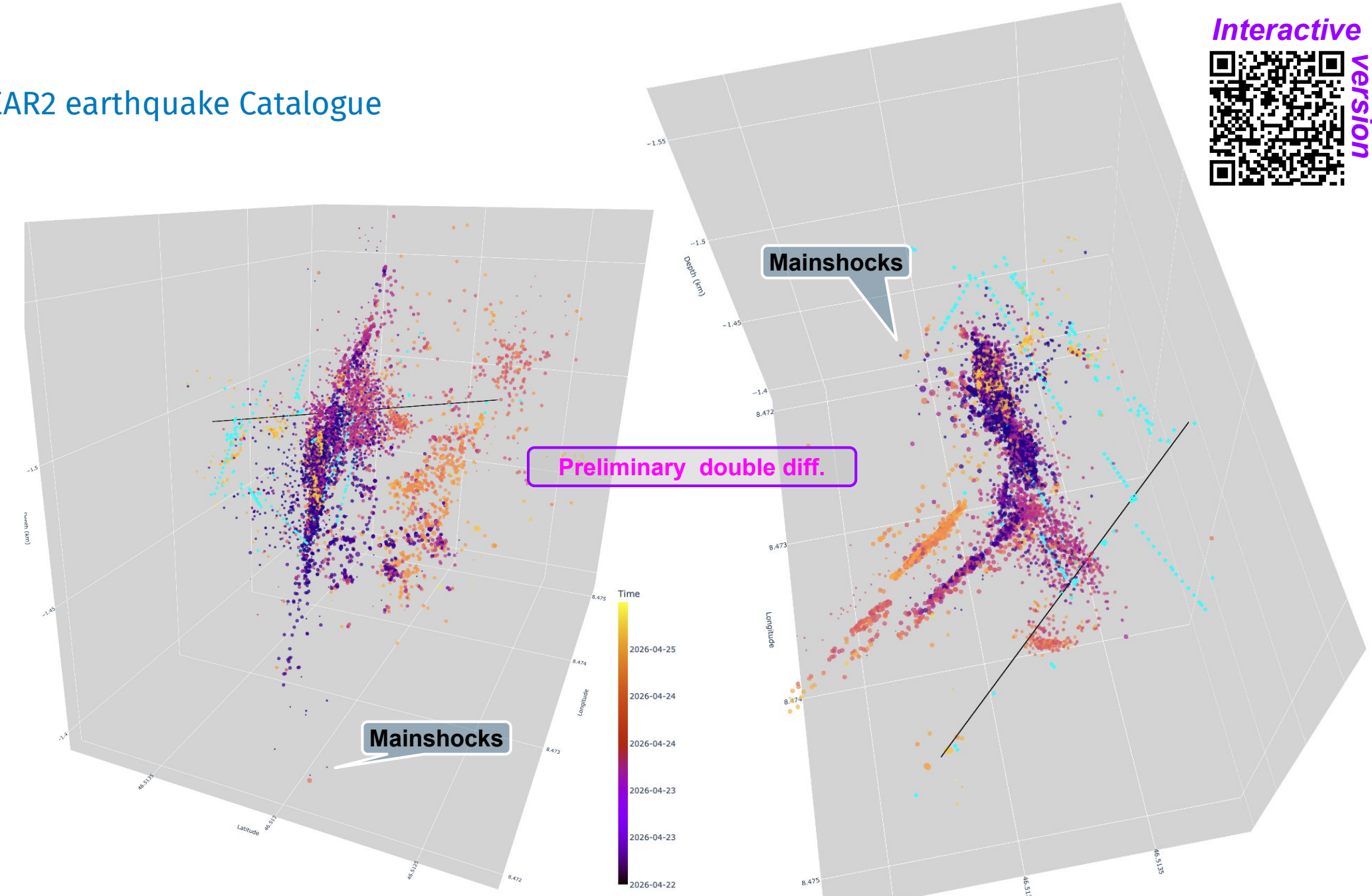


FEAR-2 (reprocessed double difference with gap filling)



The ETB-FEAR2 earthquake Catalogue

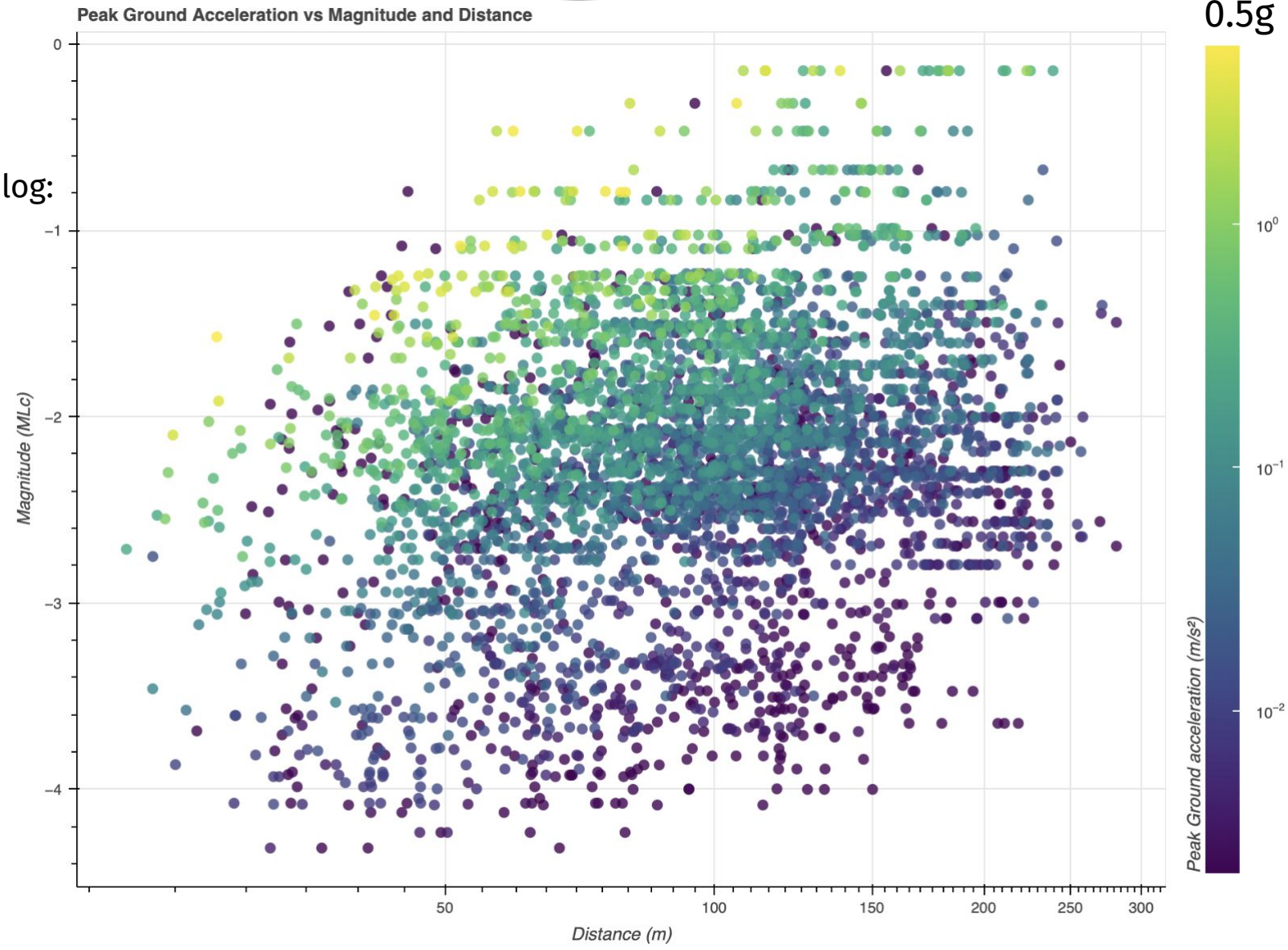
Interactive version



BPREC Peak Ground motions

Using only ***unclipped*** records manually ***revised*** events from the permanent catalog:

- PG-Accelerations:
  Max ~0.5 g for M>-1.5 and dist < 100m
- PG-Velocities:
  …



BPREC Peak Ground motions

Using only ***unclipped*** records manually ***revised*** events from the permanent catalog:

- PG-Accelerations:
  Max ~0.5 g for M>-1.5 and dist < 100m
- PG-Velocities:
  Max ~2 mm/s for M>-1 and dist < 70m

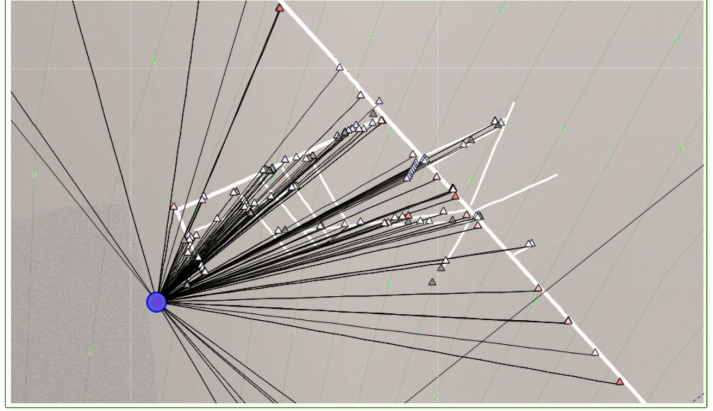


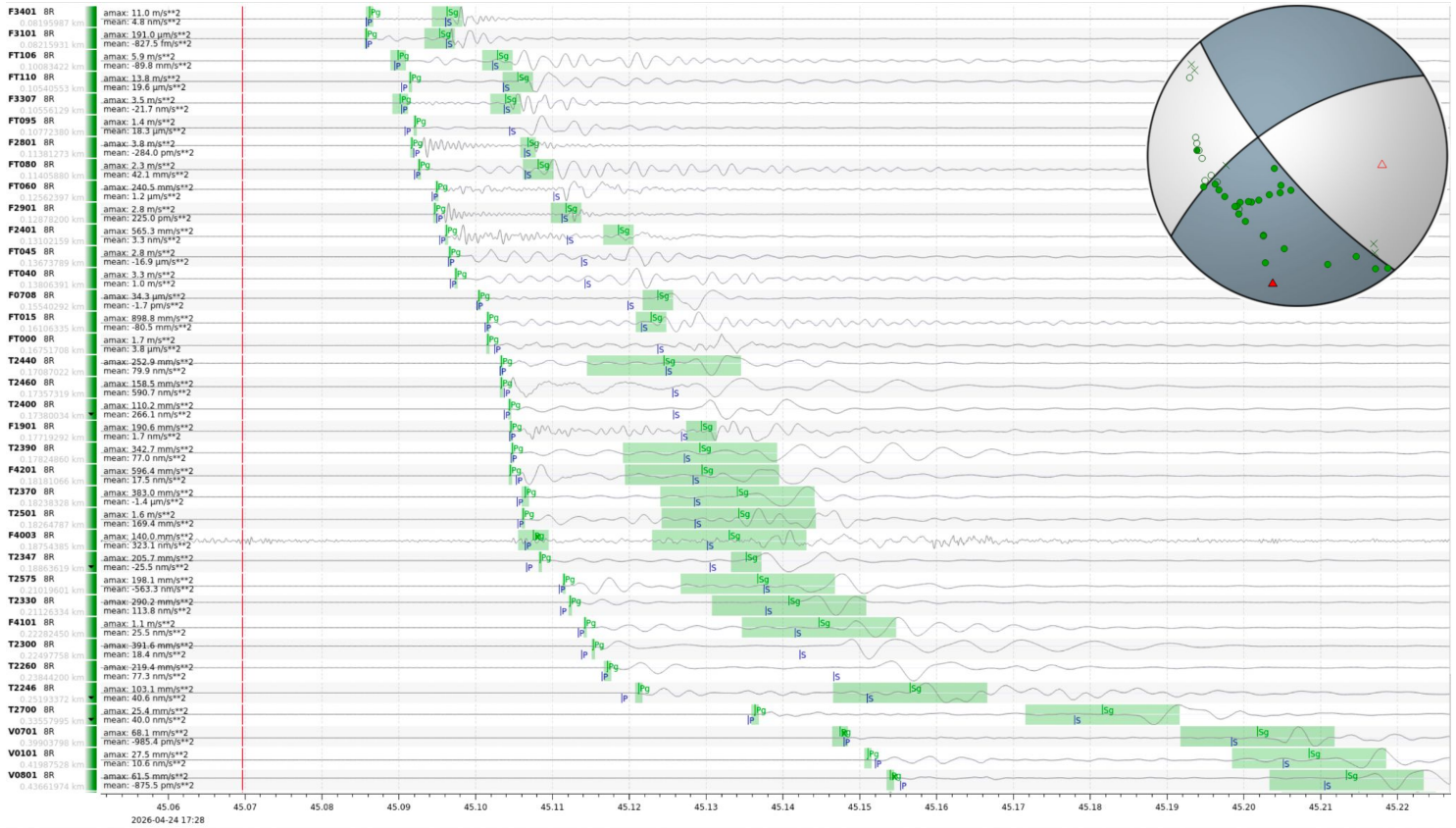
The main event

MLc -0.1 on 2026-04-24 (at 17:28:45) ***90 m*** below tunnel (1.39 km above sea level)

- Manual review with ***MLc, MwA & focal mechanism***

BPREC manual MLc -0.1 MwA -0.6

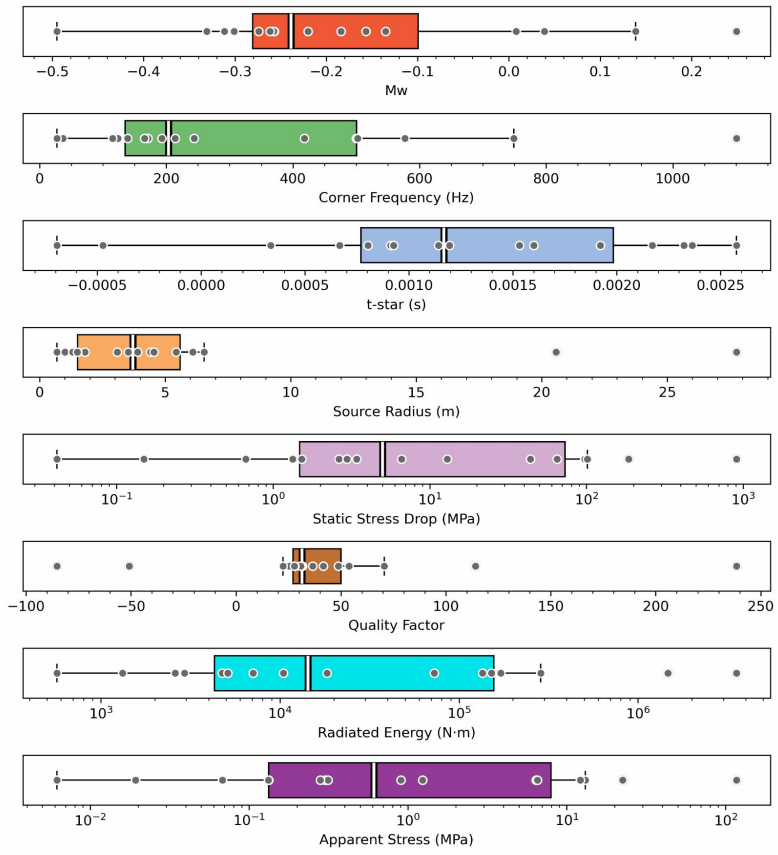


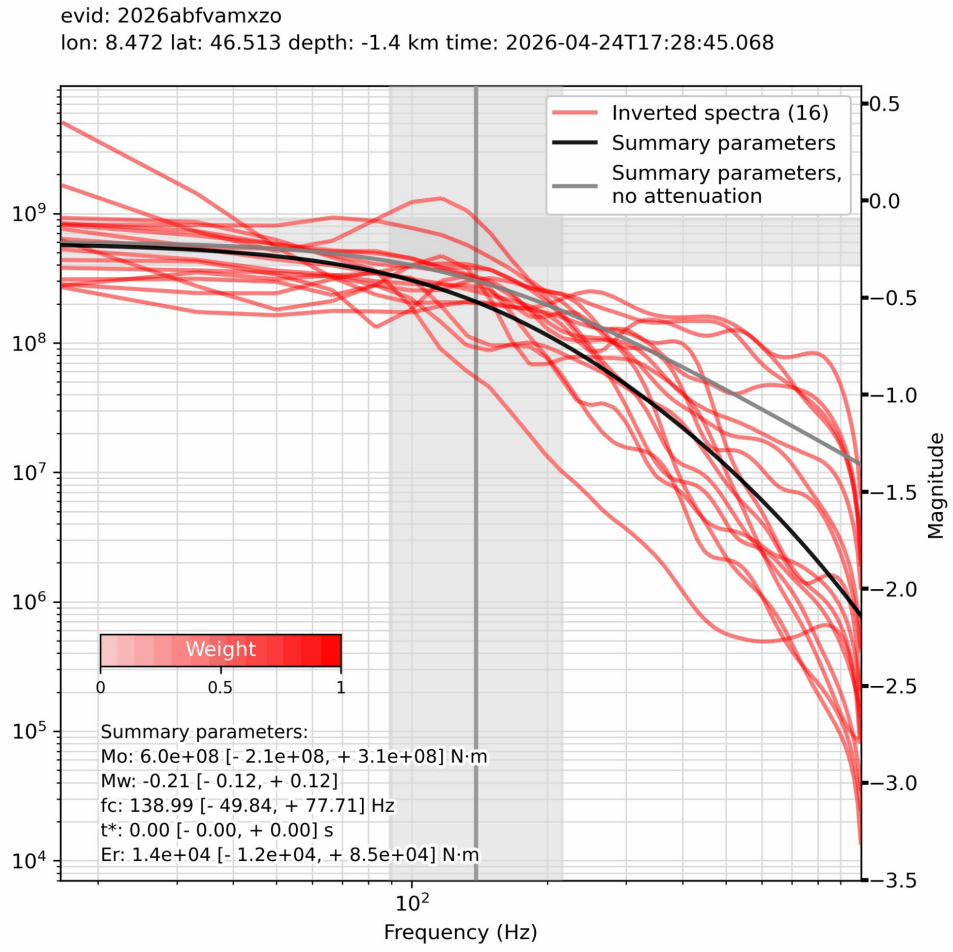


The main event

MLc -0.1 on 2026-04-24 (at 17:28:45) ***90 m*** below tunnel (1.39 km above sea level)

- Manual review with ***MLc, MwA focal mechanism***
- Preliminary ***source inversion*** from spectral analysis

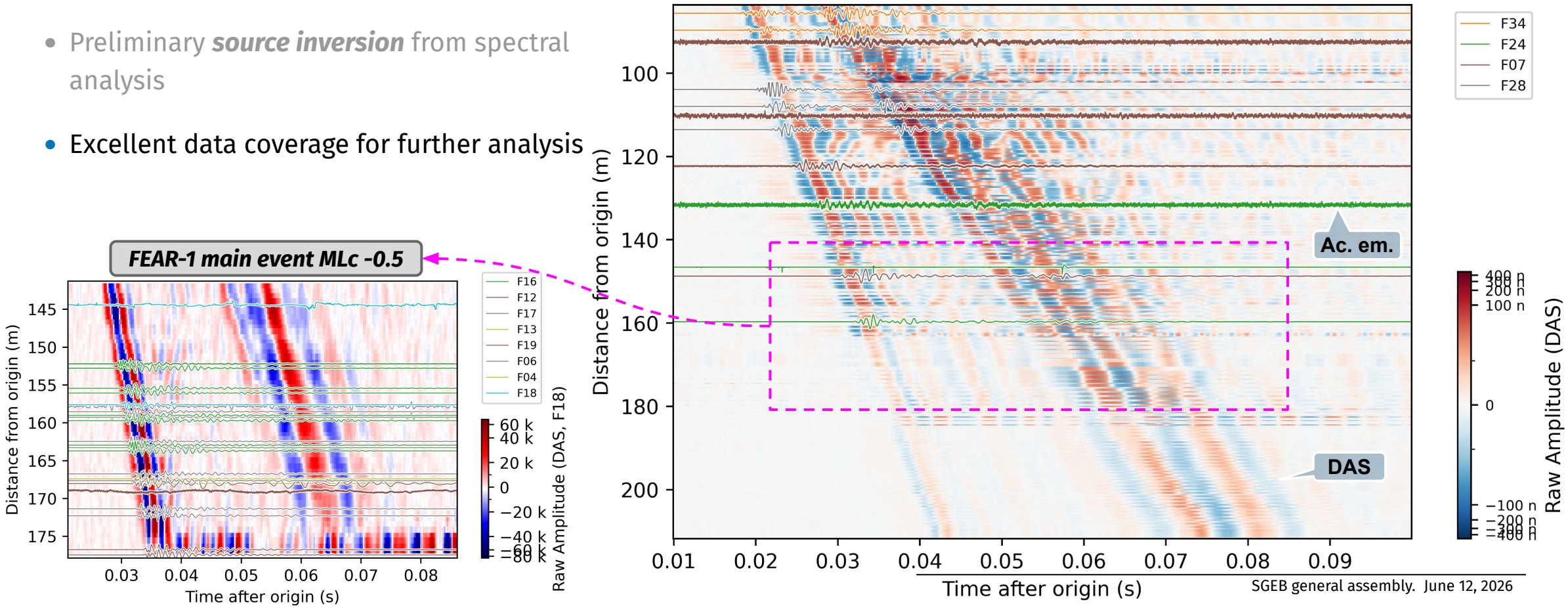




The main event

MLc -0.1 on 2026-04-24 (at 17:28:45) ***90 m*** below tunnel (1.39 km above sea level)

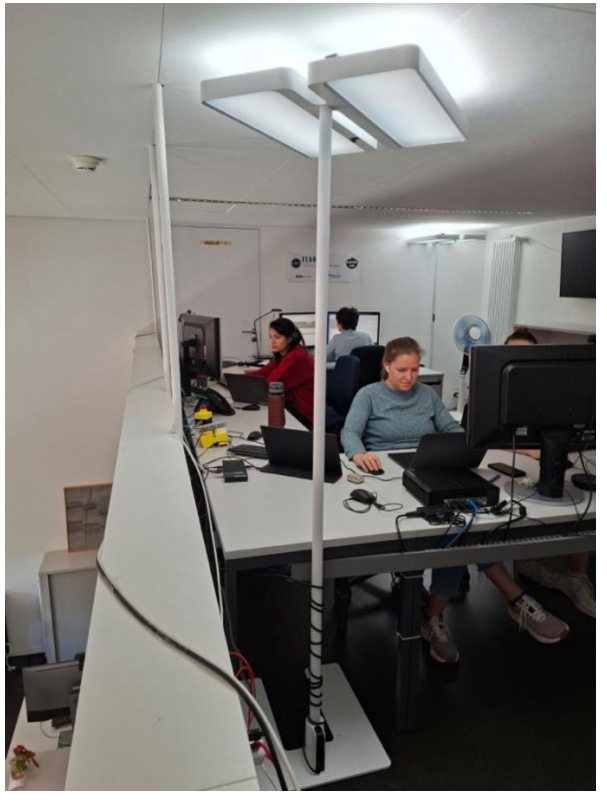
- Manual review with ***MLc, MwA & focal mechanism***
- Preliminary ***source inversion*** from spectral analysis
- Excellent data coverage for further analysis



Achievements

We have doing a lot:

- ***Quality control*** for all sensors, within a tunnel.
- Consistent ***real-time processing*** for ~2 TB data per day with national and on-site alert.
- Overlapping magnitude types (Mw, MLc and MwA).
- ***Stable DAS streaming*** with quality timing, similar volume to acoustic emission data.
- Dynamic range for ***on-scale recording up to M1 (while detecting M-5)***.



Thanks

Bibliography:

SED-ETHZ (1983). National Seismic Networks of Switzerland. doi: 10.12686/sed/networks/ch

SED-ETHZ (2018). BULGG Seismic Network, Switzerland. doi: 10.12686/sed/networks/8r

GFZ & gempa GmbH (2008). The SeisComP seismological software package. doi:10.5880/GFZ.2.4.2020.003.

Satriano, C. (2024). SourceSpec – Earthquake source parameters from P- or S-wave displacement spectra. doi: 10.5281/zenodo.3688587

Supino M. et al. (2019). A probabilistic method for the estimation of earthquake source parameters from spectral inversion: application to the 2016–2017 Central Italy seismic sequence. doi: 10.1093/gji/ggz206

