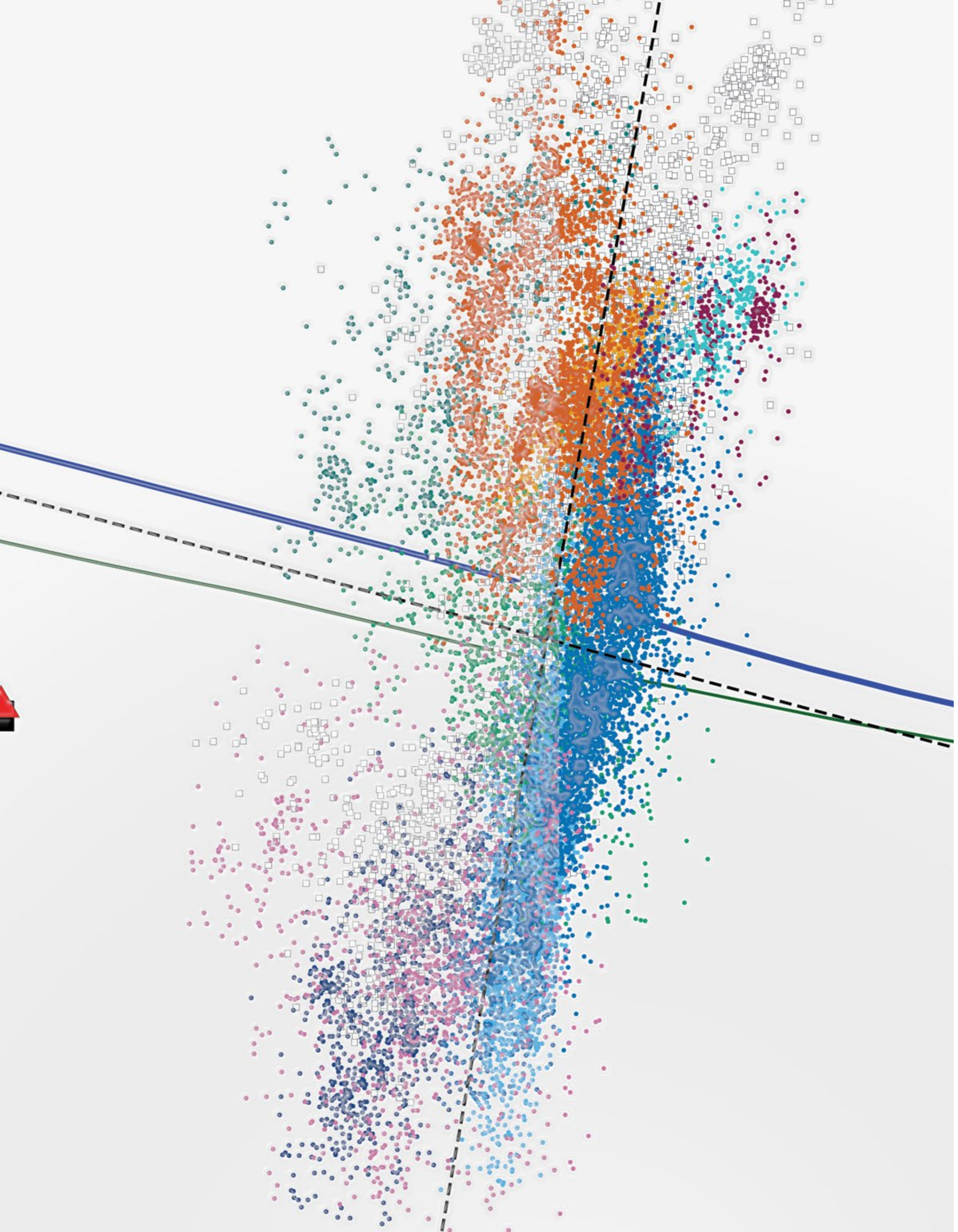


Advancing Induced Seismicity Monitoring Workflows: Insights from Utah FORGE

Federica Lanza, P. Shi, L. Passarelli, R. Schultz, A. P. Rinaldi, V. A. Ritz, S. Wiemer, and the DEEP team

UTAH FORGE U.S. Department of Energy

DEEP Innovation for: De-Risking Enhanced Geothermal Energy Projects

Schweizerischer Erdbebendienst
Service Sismologique Suisse
Servizio Sismico Svizzero
Swiss Seismological Service

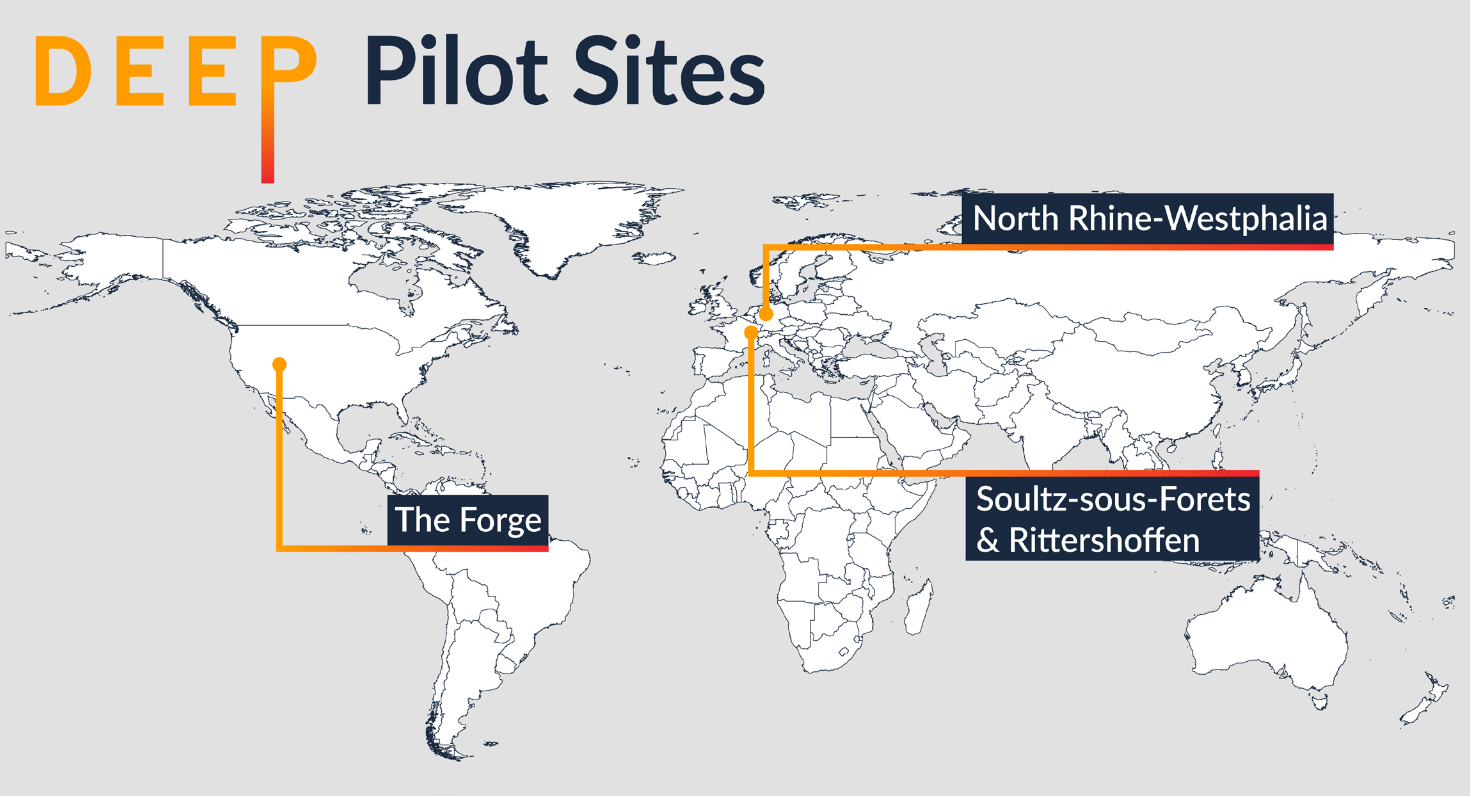
ETH zürich

Innovation for De-Risking Enhanced Geothermal Energy Projects (DEEP)

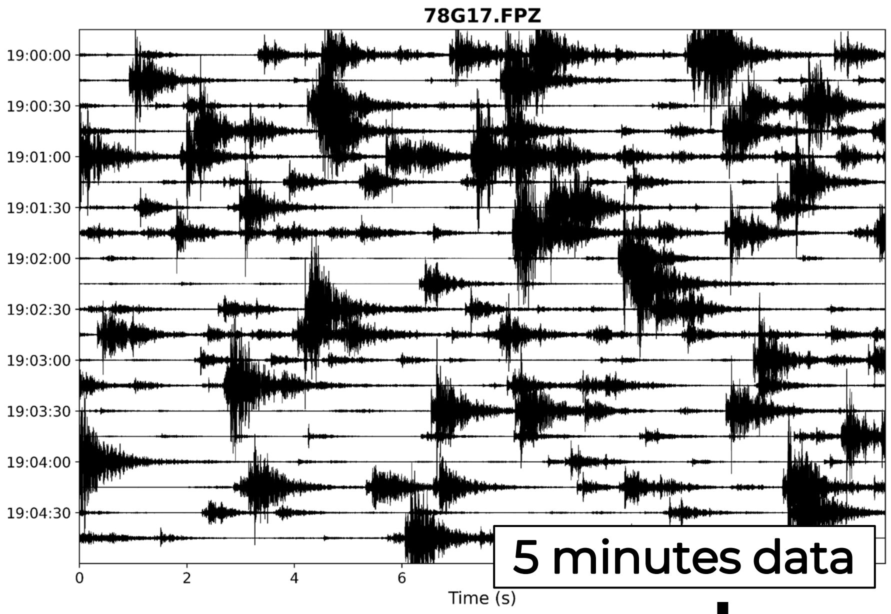
Goal: A holistic approach to **real-time monitoring, risk analysis, and mitigation** of seismicity induced by deep geothermal systems – fully open access!

- Duration: Dec. 2020 – May 2024
- DEEP consortium: 6 nations (8 academic partners, 3 industry companies)

http://deepgeothermal.org



Challenges of monitoring induced microseismicity



- High event rate (up to 100 / minute)
- Overlapping phases
- Strongly noise-contaminated events
- High sampling rates and integration of different sensors
- Large datasets (e.g., DAS)

Possible solutions?

- Machine Learning approaches
- Digital twins

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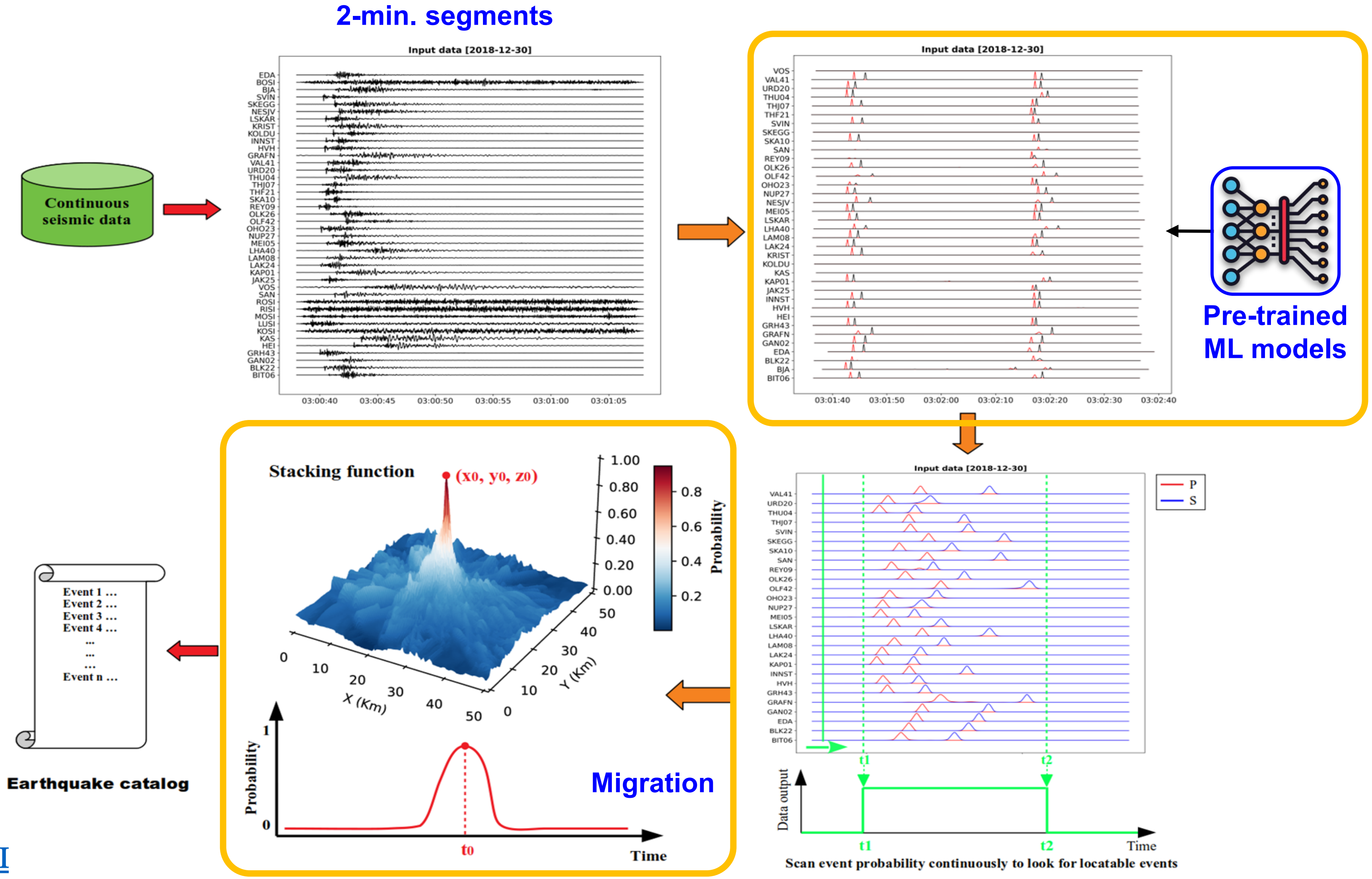
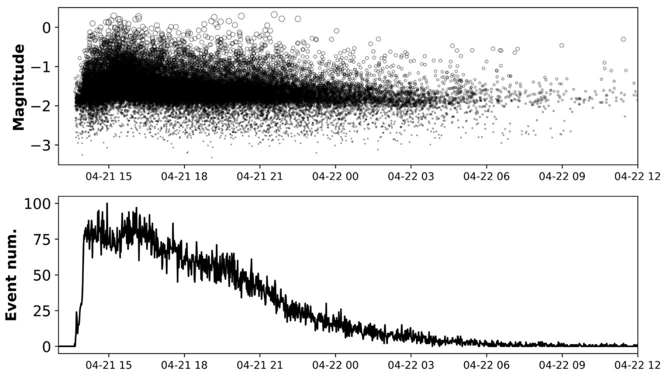
MALMI workflow

MAchine Learning aided earthquake MIgration location

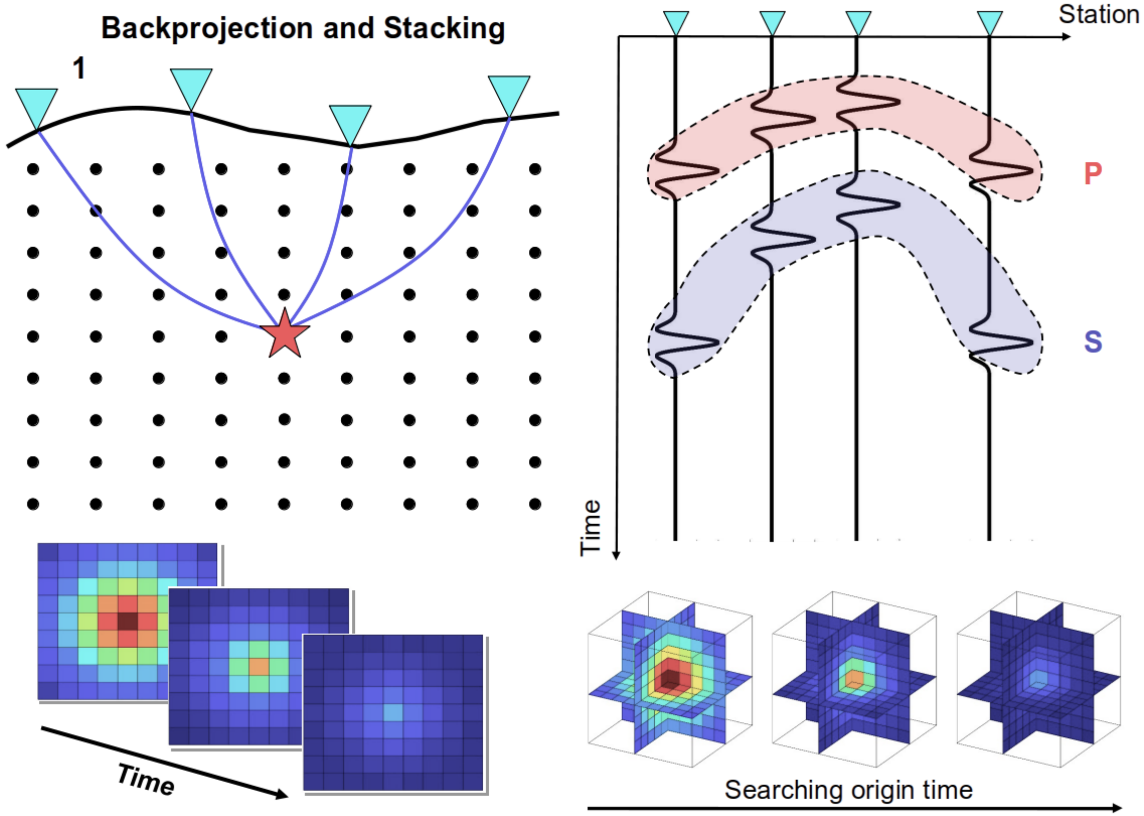
Shi et al. 2022, SRL





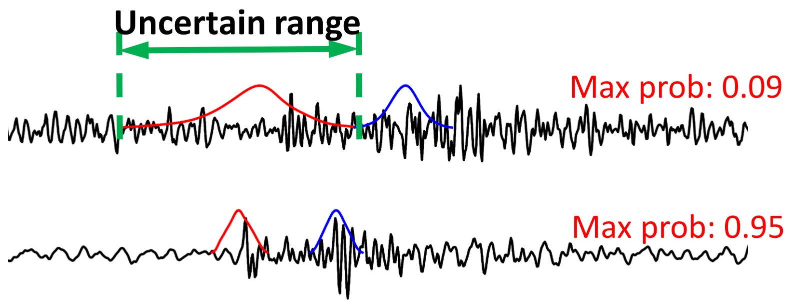
https://github.com/speedshi/MALMI

Earthquake Location using **waveform backprojection** and **stacking**



Pros:

- No phase picking (automated – use ML phase probability directly as characteristic function for backprojection and stacking);



- No phase association (great for short inter-event time and overlapping events!);
- increase SNR (from stacking);

Cons:

- Computationally expensive

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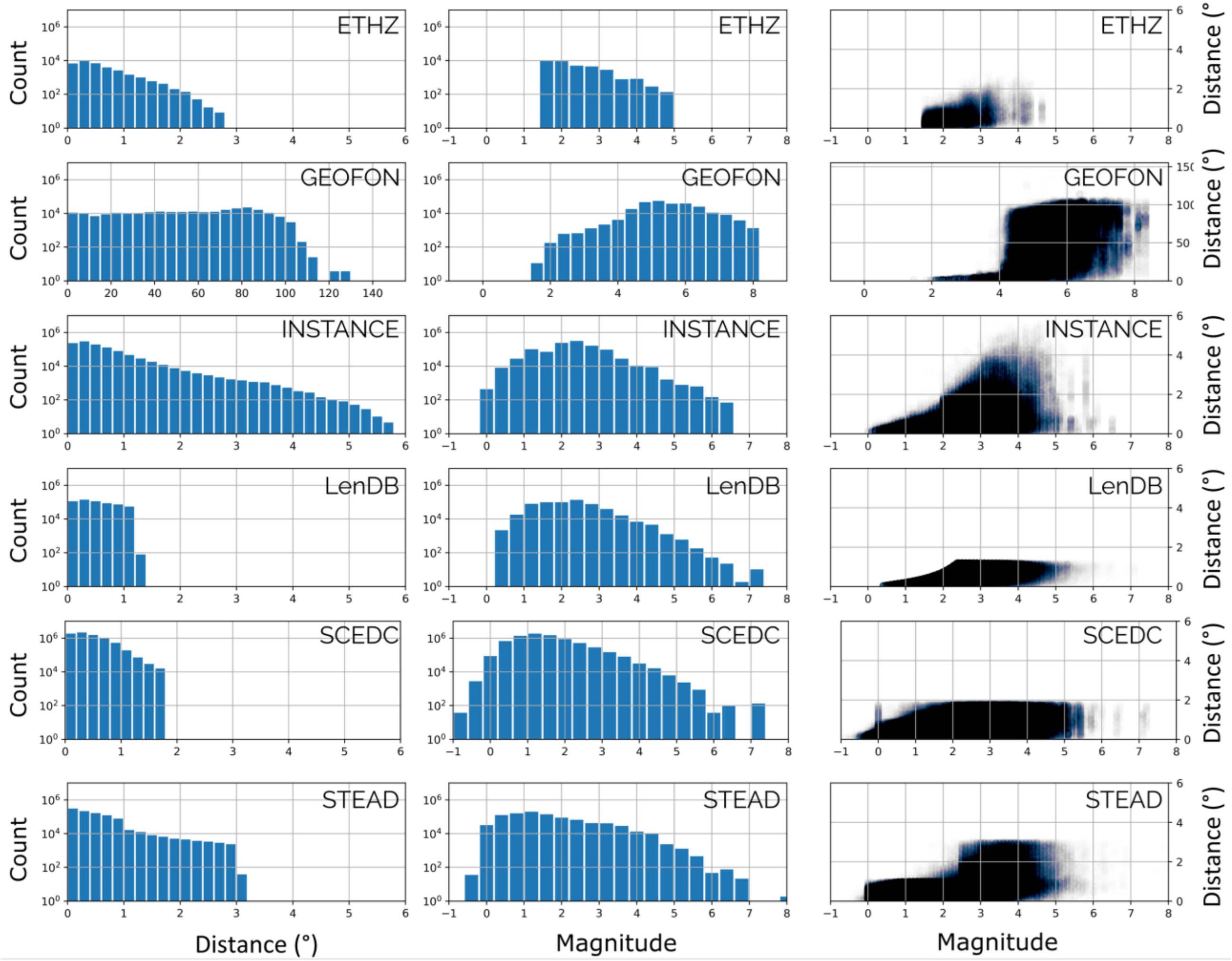
Scale Issue and Out-of-Distribution (ODD) datasets

Woollam et al., 2022

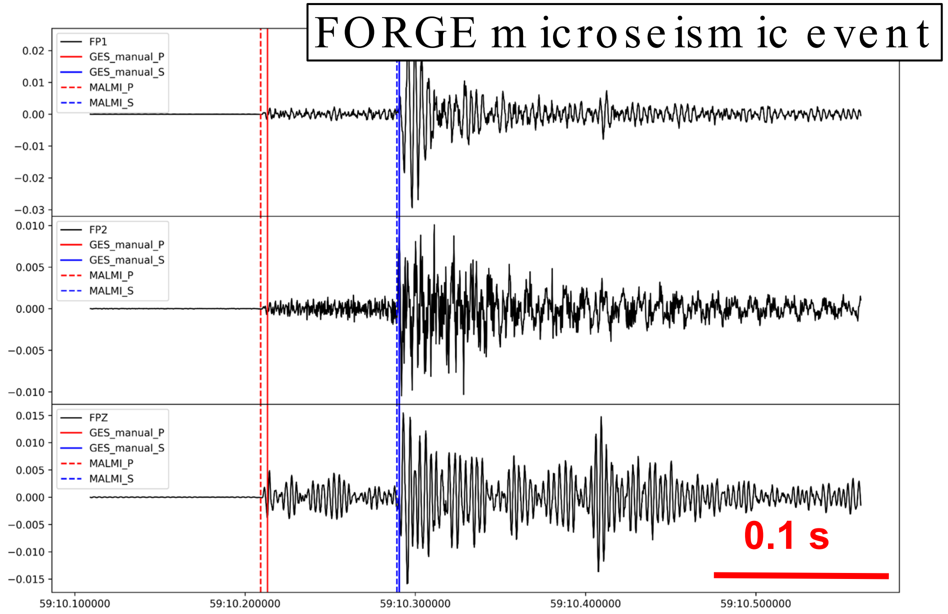


Pre-trained models:

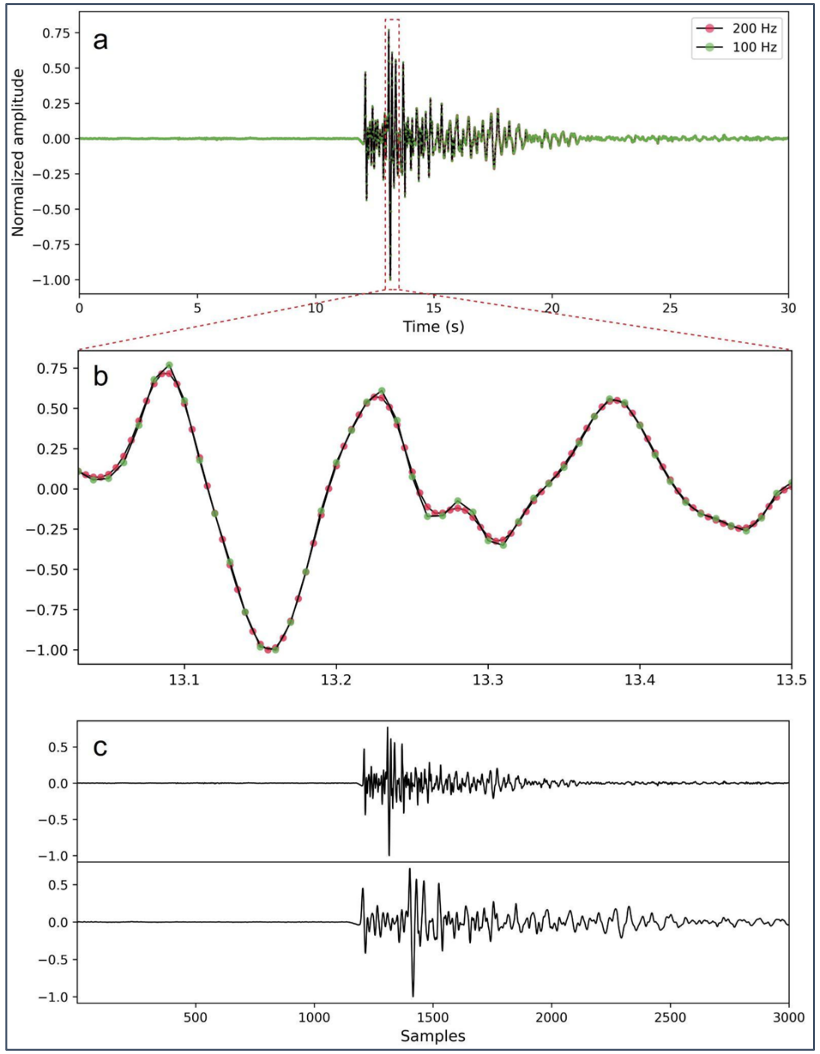
- **Magnitude range: 0 - 6;**
- **Event duration: 5 - 60 s @ 100-200 Hz;**

FORGE MS events:

- **Magnitude range: -3 to 0.6;**
- **Event duration: ~0.5 s @ 4000 Hz;**



Rescale data for augmenting ML model performance



Rescaling scheme

- Self-similarity of large and small EQs;
- Systematically stretch or squeeze waveforms to match the training data;
- Scale-independent property for most ML architectures;

Affect two aspects:

- P-to-S samples (distance);
- Samples per cycles (frequency);

Two directions:

- Upscaling (zoom-in) – up-sampling (for small EQs);
- Downscaling (zoom-out) – down-sampling (for large EQs);

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Rescale data for augmenting ML model performance

When to Up-scale:

- Small events;
- Near field recordings;

When to Down-scale:

- Large events;
- Remote events;
- Relatively far field recordings (compared to training sets)

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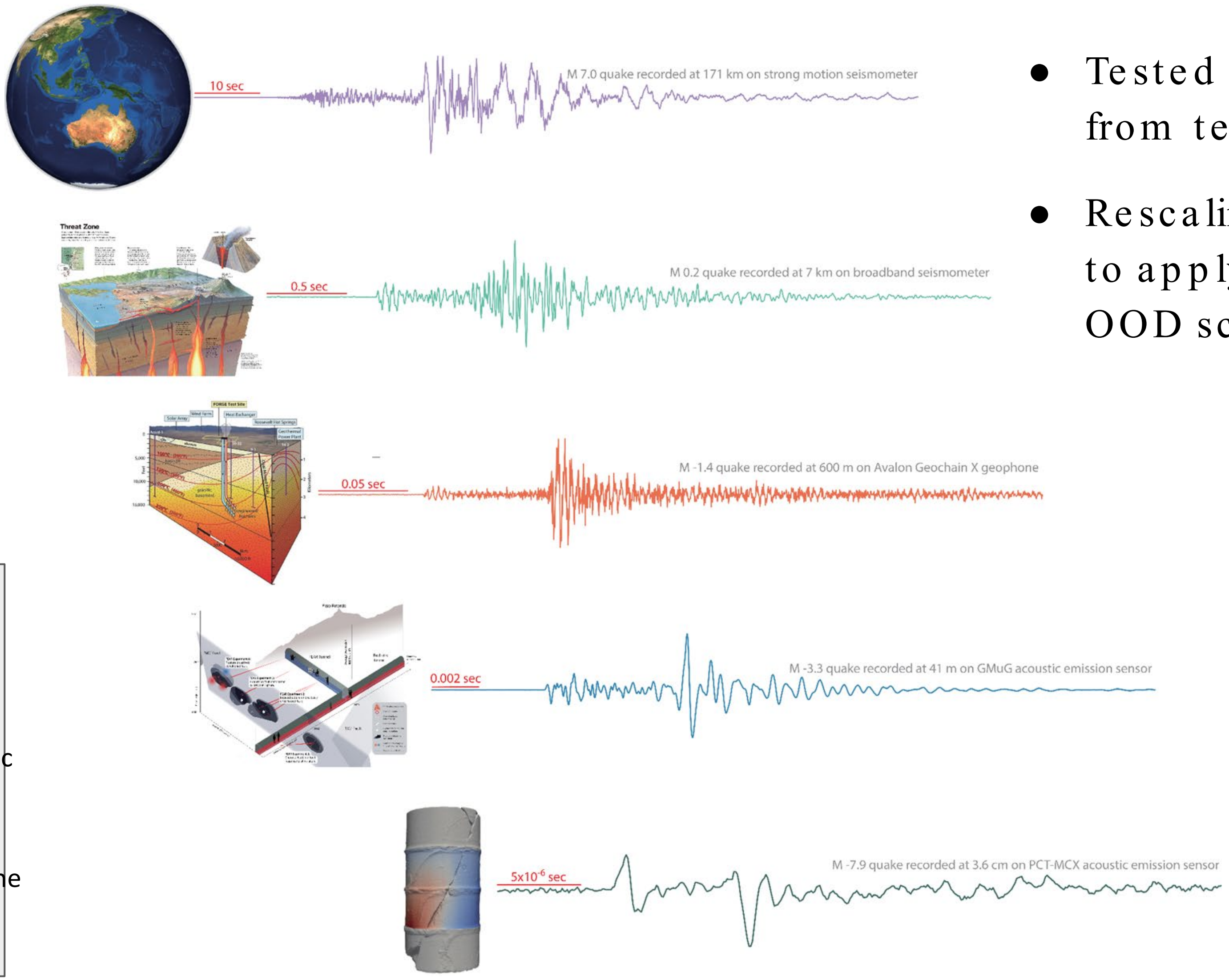
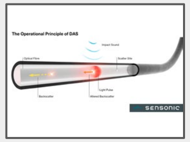
Verify cross-scale monitoring ability

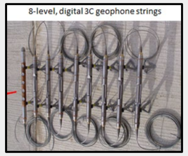


- Tested across different scales, from tectonic to labquakes;
- Rescaling is a very effective way to apply pre-trained models to OOD scales;

Acoustic emission sensor

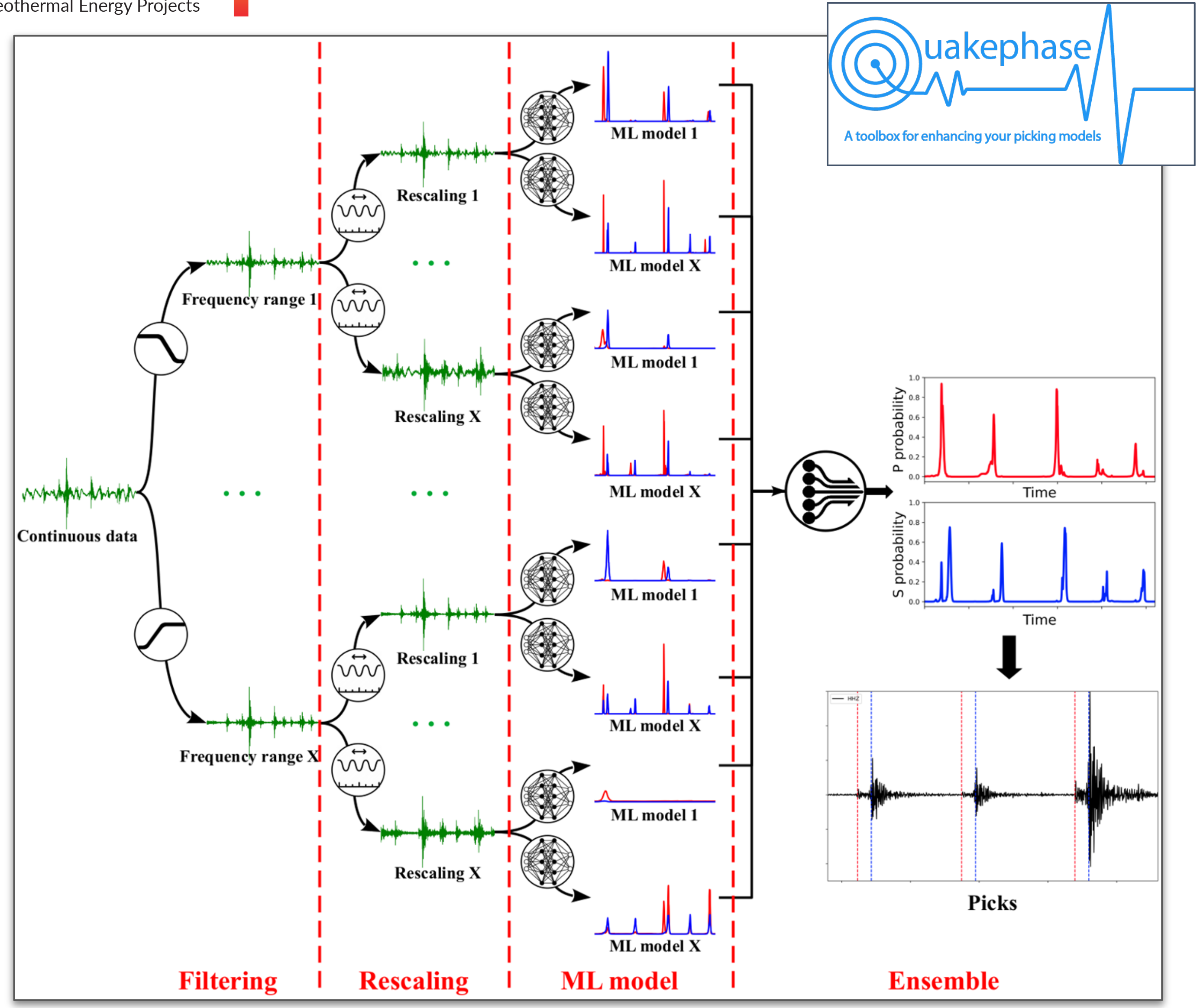


Distributed acoustic sensor



Downhole geophone chain

Quakephase: a unified platform for ML model augmentation



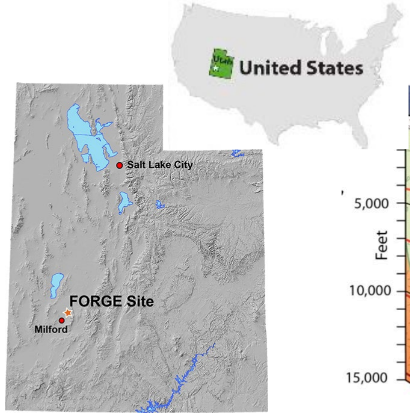
Shi et al. 2024, JGR-Machine Learning and Computation

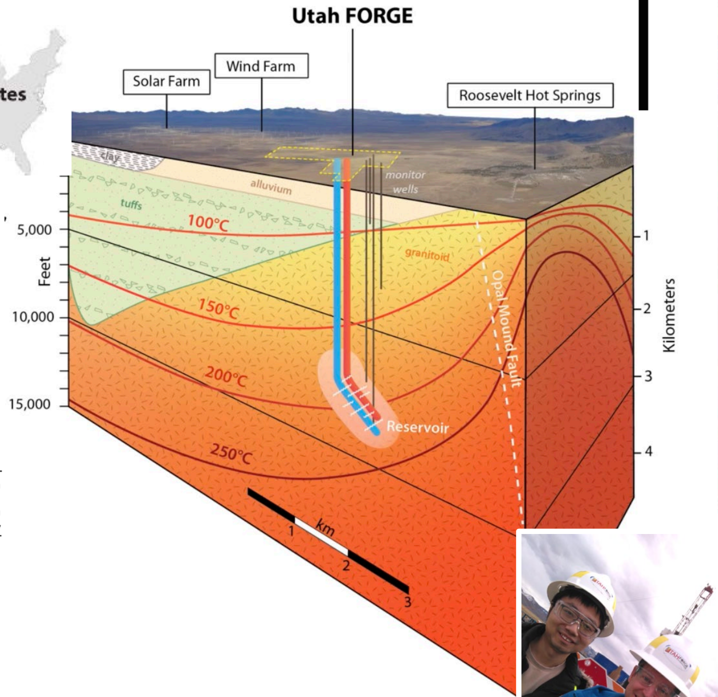
https://github.com/speedshi/quakephase

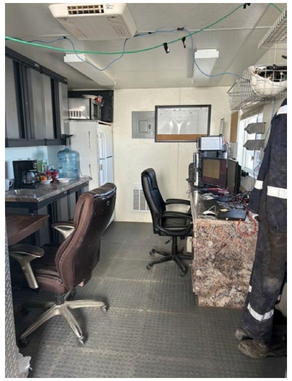
- Ensemble the predictions from different strategies into a unified prediction
- Select ensemble methods (e.g., PCA, max, semblance, median, mean, probability and minimum) according to the user purpose

Finally ready to apply to FORGE!

Utah Frontier Observatory for Research in Geothermal Energy (FORGE)







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16A-32 April 2022 stimulation

- Demonstrate reservoir growth
- Use the seismic imaging to guide location of second well

Stage 1

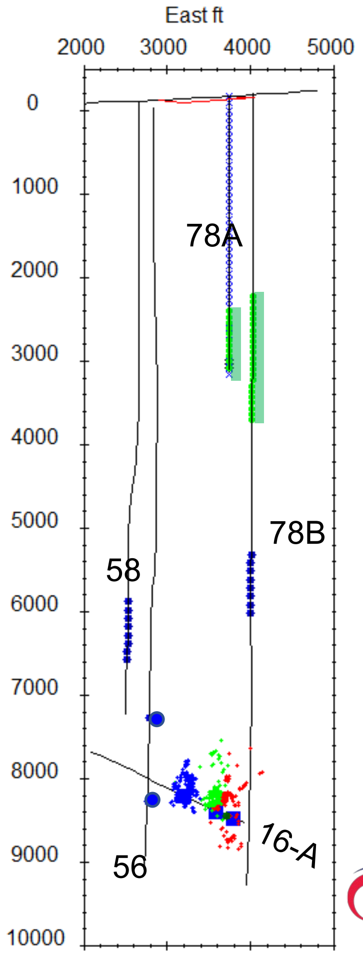
- 677 m^3 volume injected in a 200 ft open hole section at the toe of the well.
- 823 events, largest: M 0.04

Stage 2

- 443 m^3 volume injected in a 20ft long perforated interval (2570 m depth)
- 1322 events, largest: M -0.33

Stage 3

- 480 m^3 volume injected (with proppants) in a 20 ft long perforated interval (2510 m depth)
- 5283 events, largest: M 0.52



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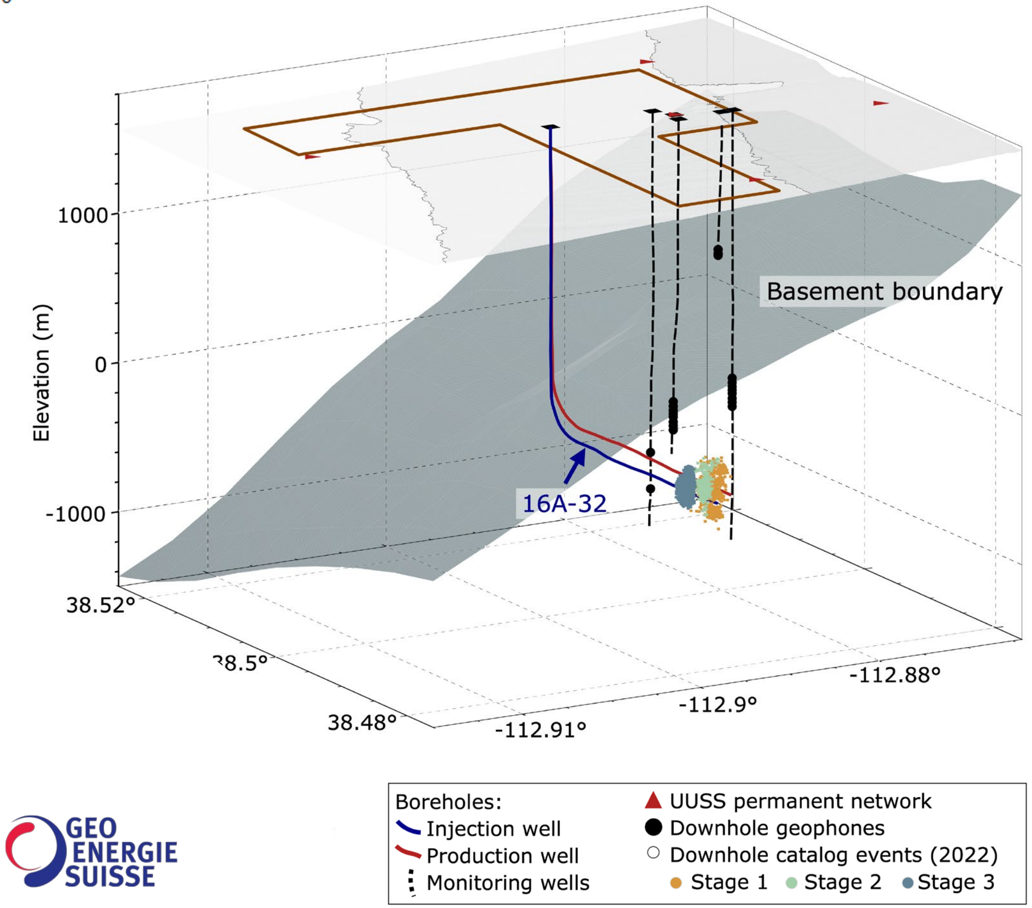

MALMI & Quakephase applied to FORGE

DEEP

Innovation for:
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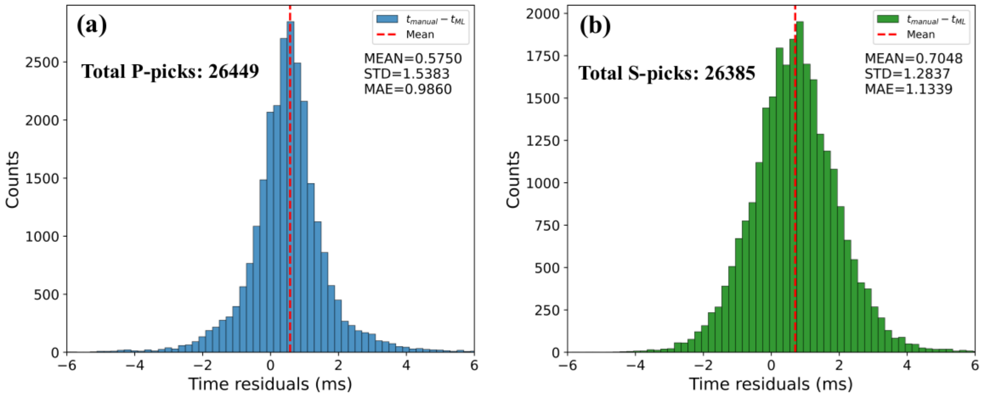
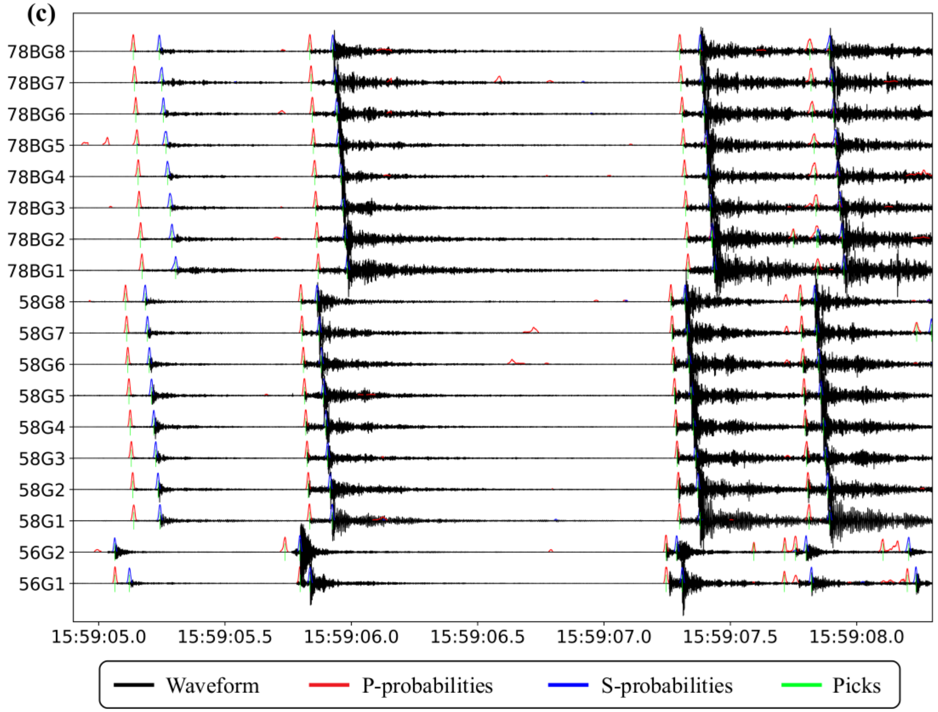
Geothermal Energy Projects

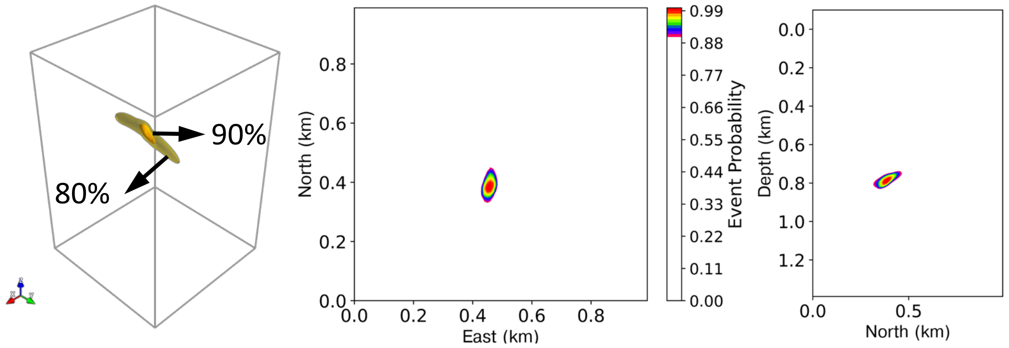
DEEP catalog
35,488 events



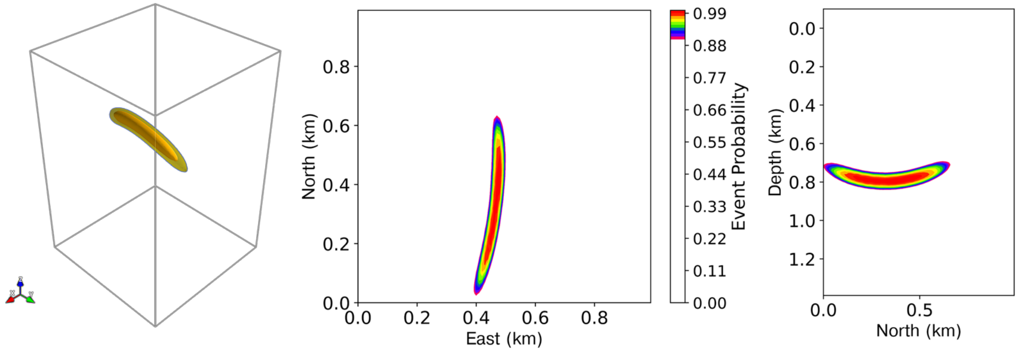


Quality	N° of events	Classification criterion
A	**11,390**	**At least one P+S picks from each well**
B	12,895	At least four picks (pick SNR>1)
C	11,203	not-locatable

Quality "A":



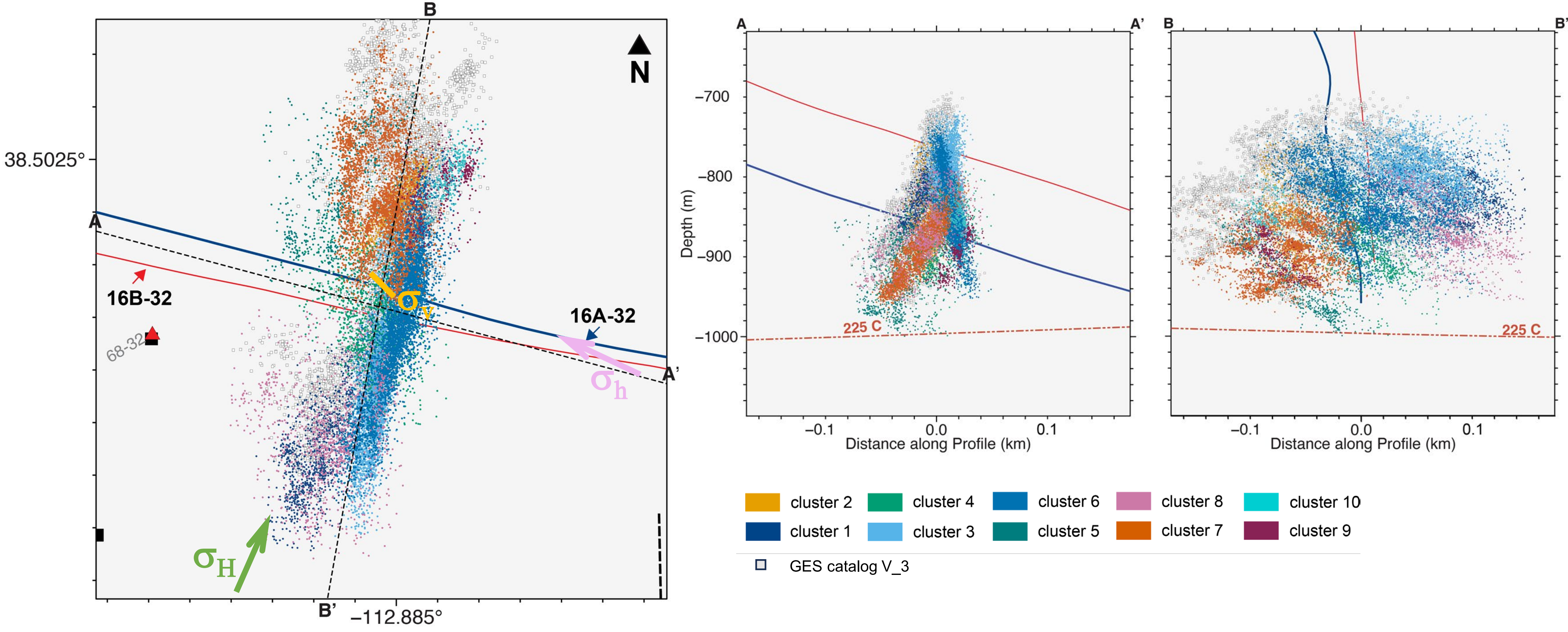
Quality "B":



Rescaling rate: 60
Frequency: 100-1800
Model: EQT_stead

High-resolution DL catalog

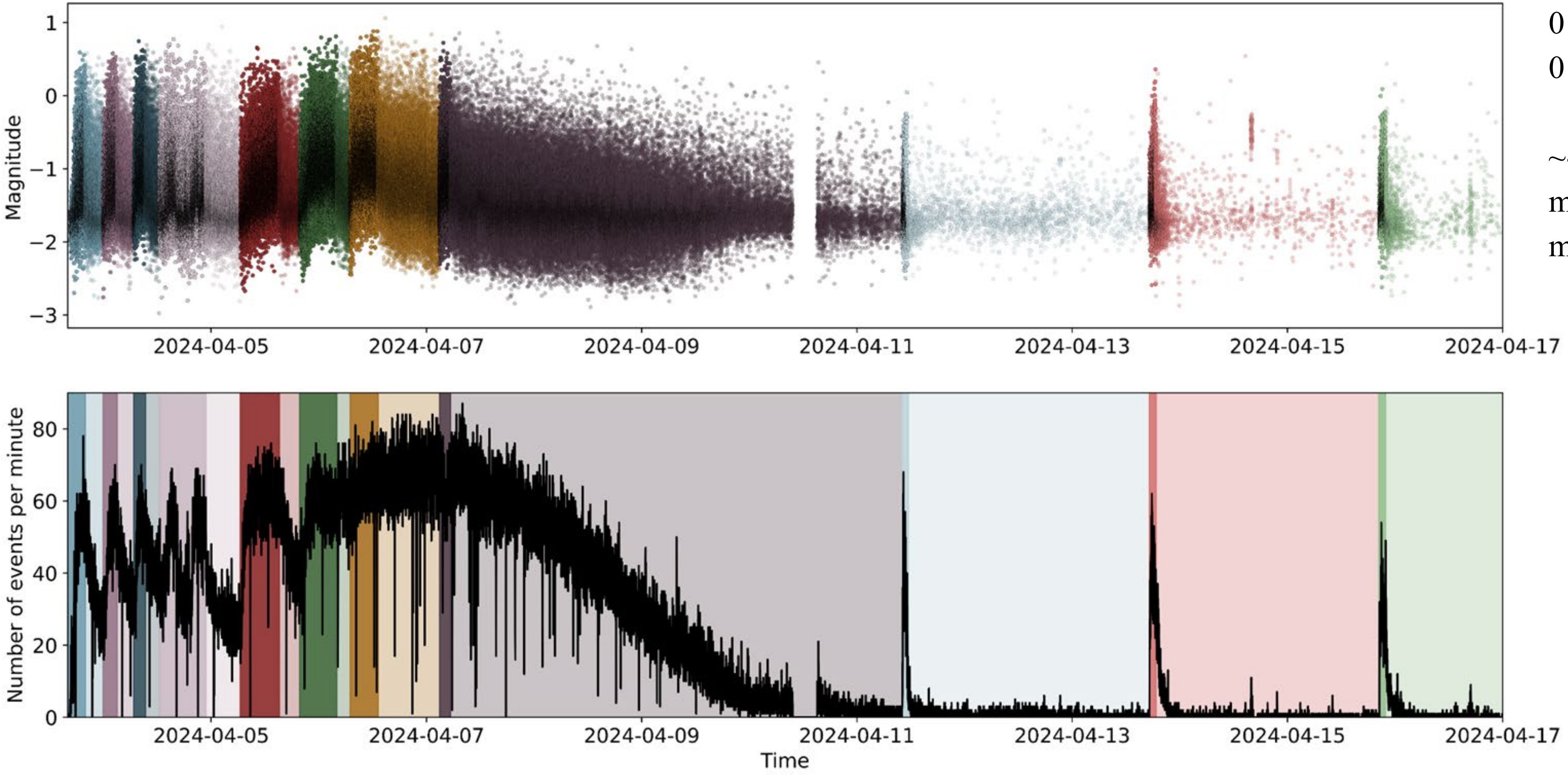
- Two-step clustering: Density-Based Spatial Clustering + Gaussian Mixture Models;
- 10 event clusters identifying distinct fracture planes



Fracturing mechanisms

- PCA analysis on DL catalog reveals strike and dip of the fracture planes;
- Independent analysis using GES catalog shows that a penny-shaped crack model is the best model during injection phase (Lanza et al., in prep)
- Seismicity cloud is likely the result of fracturing and stress change due to the opening and growing of **hydro-fractures**

2024 FORGE on-site (real-time) monitoring



04/03 16:00 to
04/17 00:00

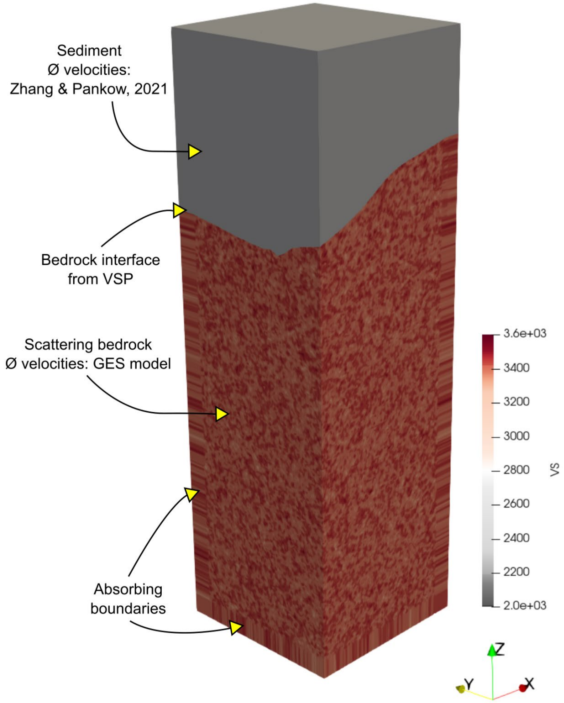
~435K events
max rate: 87/min
max mag: 1.06

Towards Digital Twins for wave propagation in EGS

How do we optimize, test, benchmark, and validate monitoring workflows?

Create an **end-to-end simulation environment** where 'ground truth' is known (e.g. FORGE site)

1. Incorporating geology



- Sediment, bedrock **velocities** (Zhang & Pankow 2021)
- **Interface** from seismic reflection data (Wannamaker et al. 2020)
- von-Kármán random **perturbations**

Towards Digital Twins for wave propagation in EGS

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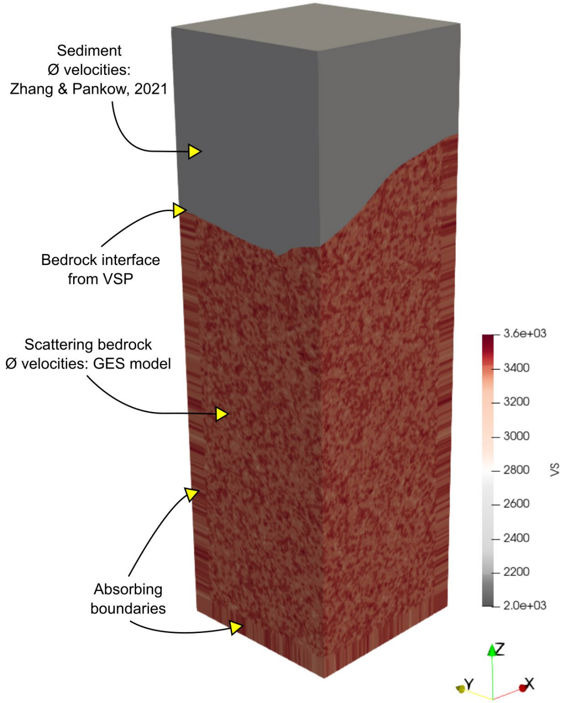
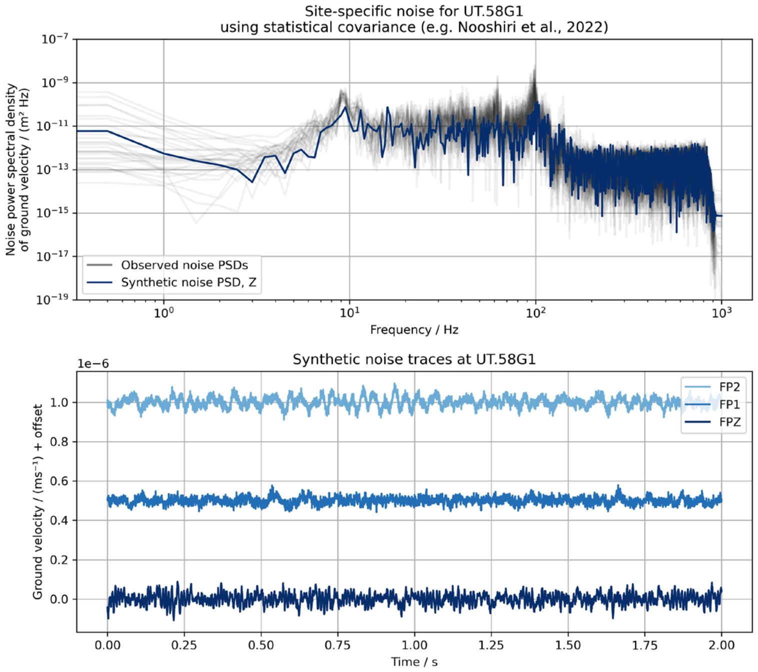


2. Site-specific noise



- Sampled site noise (Nooshiri et al. 2022)
- Estimate noise mean and covariance during pre-stimulation phase
- Later superimposed on continuous time series

Towards Digital Twins for wave propagation in EGS

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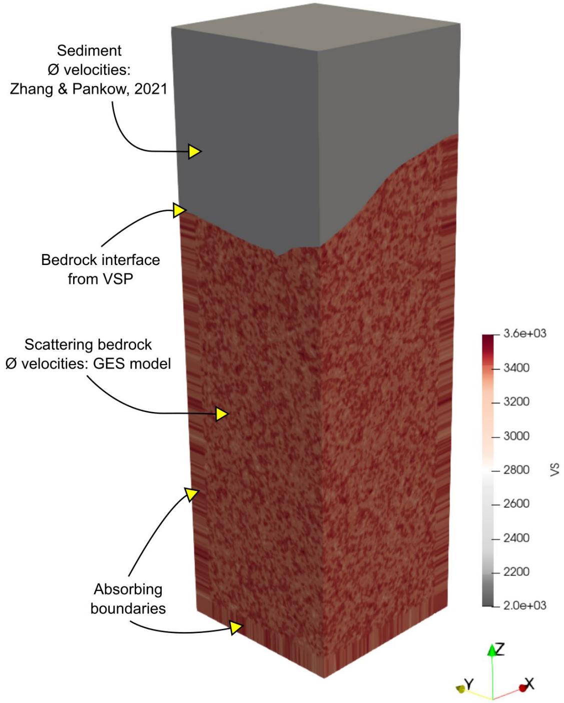

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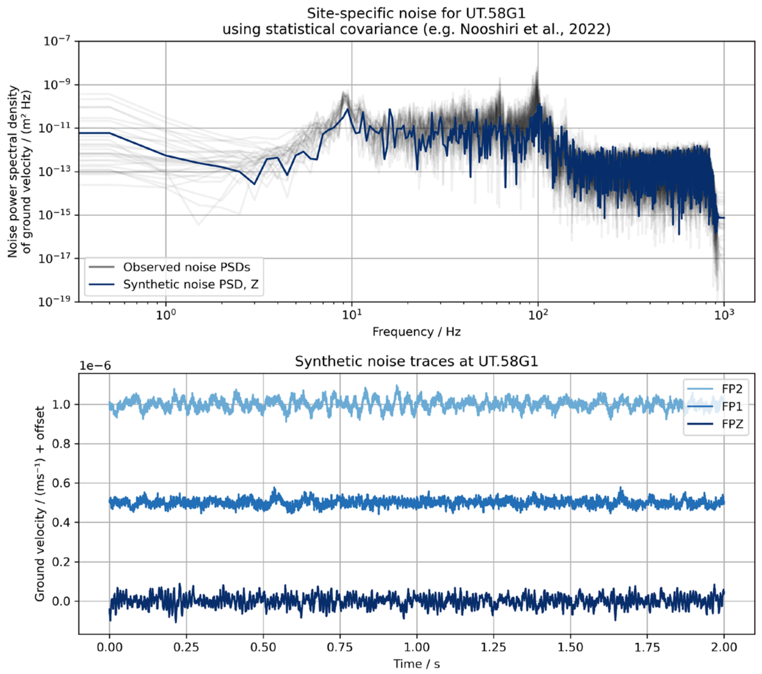
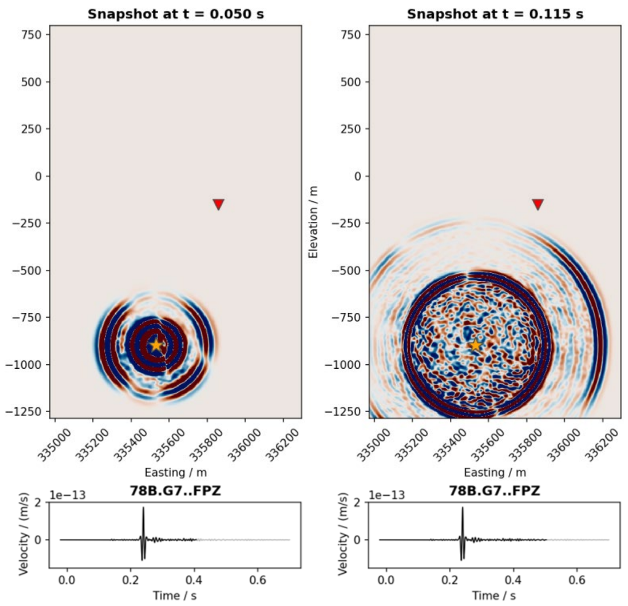


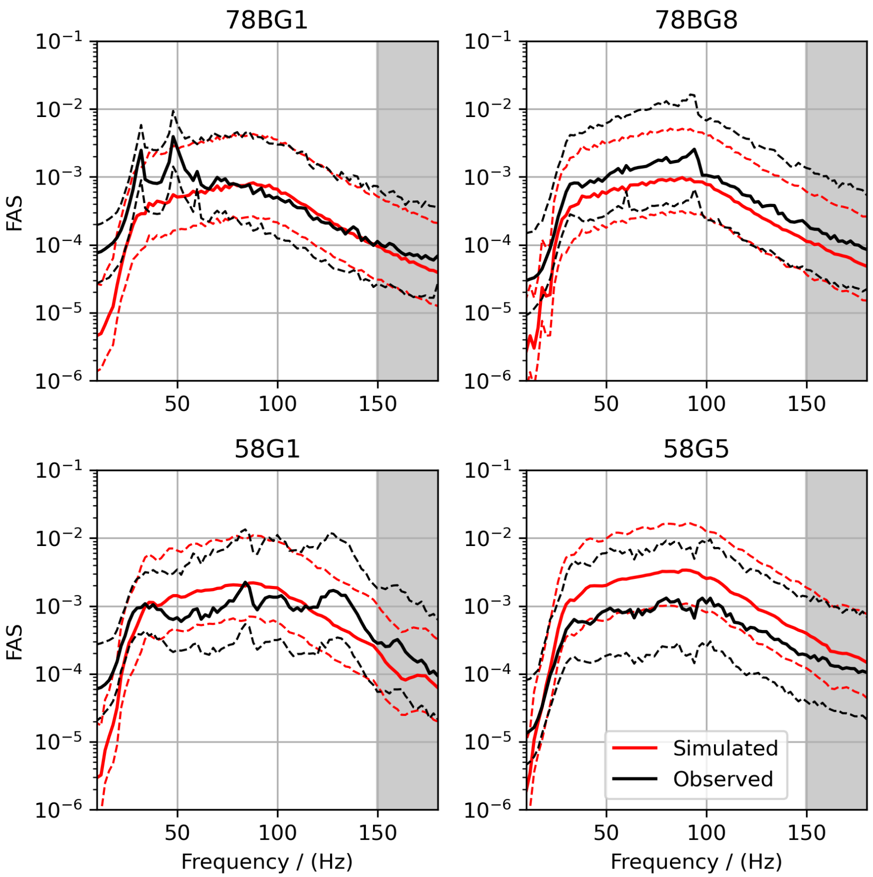
3. Numerical Solution

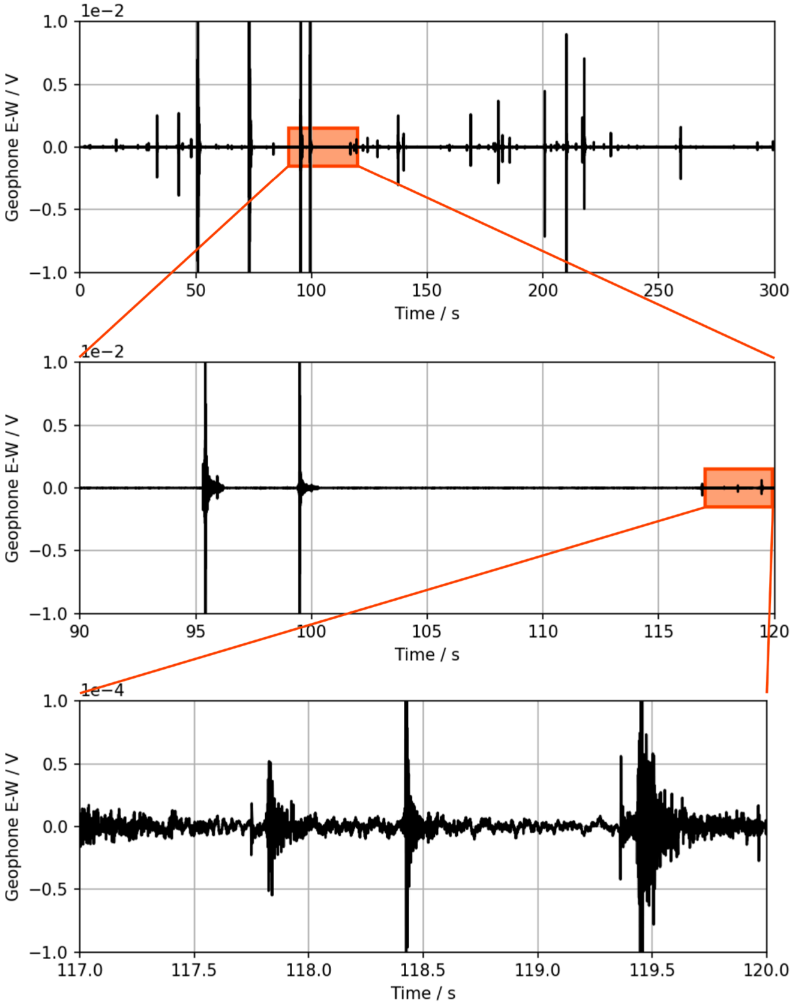


spectral-element solver **Salvus** (Afanasiev et al. 2019)

Realistic synthetic continuous waveforms

Comparison of observed and synthetic amplitude spectra



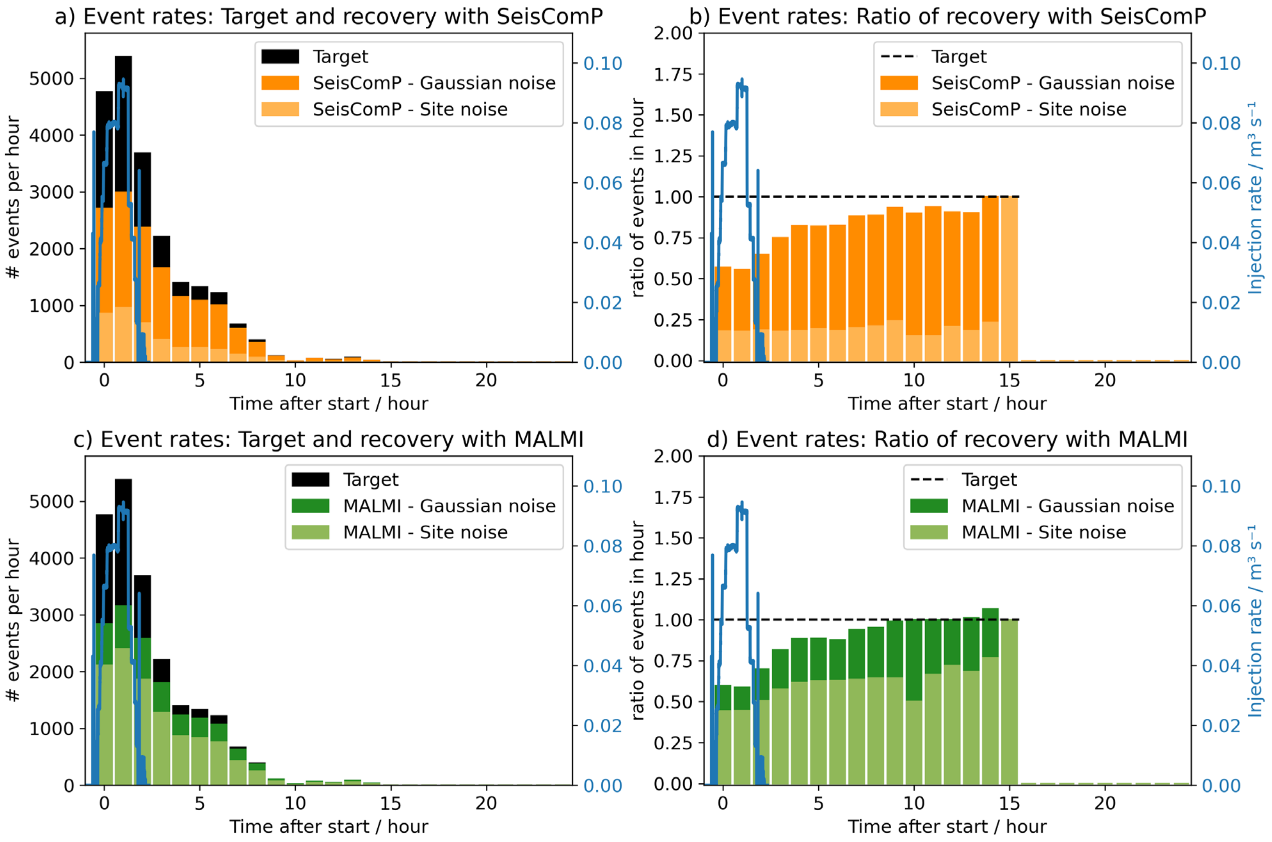


Synthetic data with site noise from a synthetic stochastic catalog based on observed seismic catalog from Stage 3 of FORGE 2022 stimulation (~20,000 events with Mw -2.5 to 0.44)

Ermert et al. 2025, in prep

Benchmarking results

- Two datasets (gaussian and site-specific noise)
- Machine-learning based and STA/LTA detection methods
- ML has very good restitution for the site-specific noise case

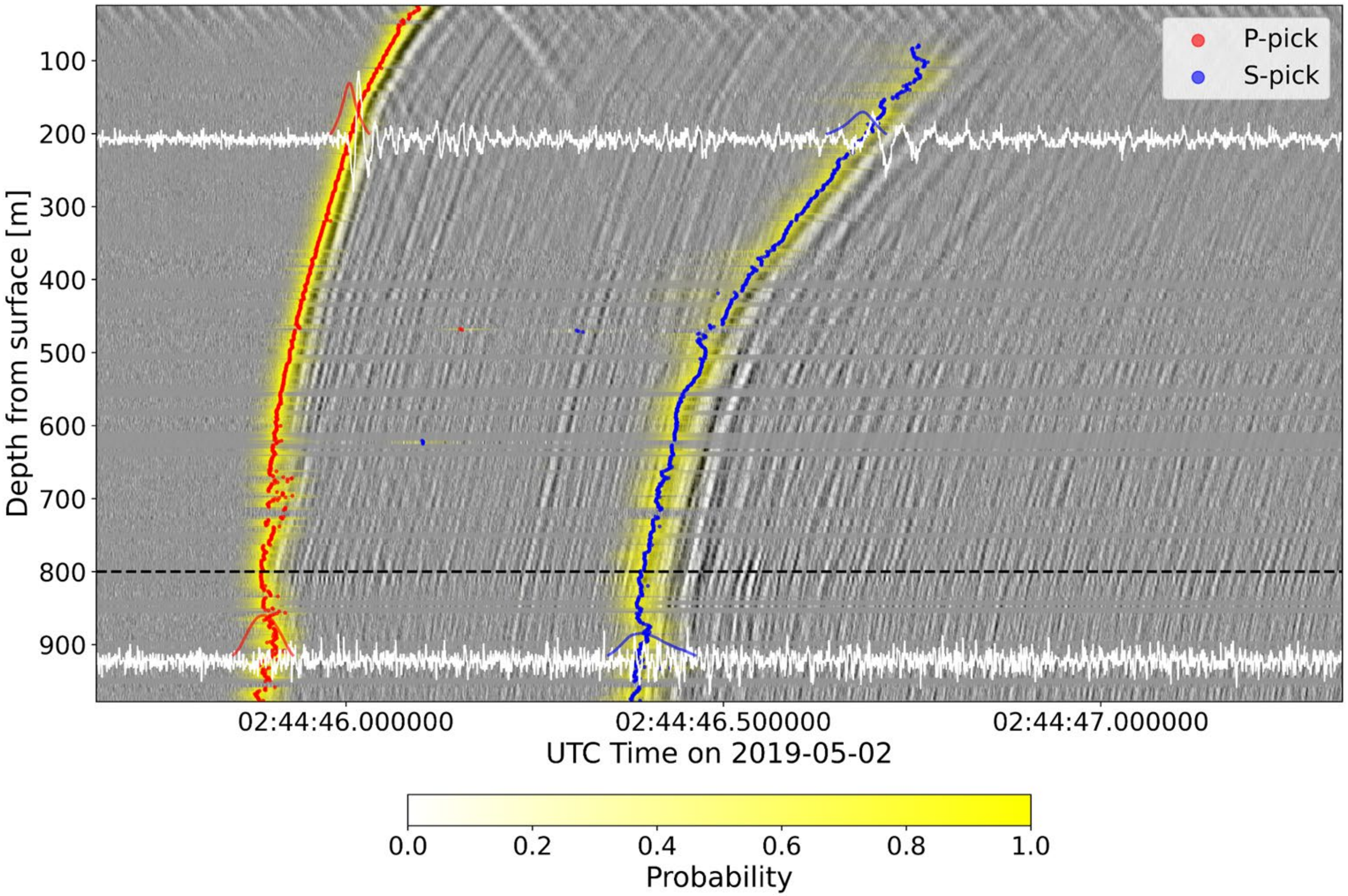


Summary

- **Rescaling and ensemble approaches** are effective in enhancing pre-trained ML models to OOD scales: applicable to entire EQ magnitude range (from labquakes of M=-9 to major tectonic earthquakes of M=8, from 10 Hz to 10 MHz);
- **High-resolution DL catalogs** hold promise for detailed investigation of fracturing dynamics in postprocessing;
- More optimization is still needed for real-time performances
- **Digital twins** of wave propagation could support decision making by enabling benchmarking of monitoring software, and beyond (e.g., monitoring network optimization, ground motion modeling)


Thank you!

QuakePhase workflow application: FORGE DAS



Dataset	Magnitude	Sampling rate	Instrument	Mode
Kumamoto	7.3	100 Hz	accelerometer	segments
COSEISMIQ	-0.6 - 3.8	100 Hz	broadband seismometer	segments
VI-EDA	-1.4 - 0.8	100 Hz	broadband seismometer	continuous
DAS	0.0	2000 Hz	downhole DAS	segments
FORGE	-2.2 - 0.6	4000 Hz	downhole geophone	continuous
Reflection survey	-2.1 - -1.5	1000 Hz	surface geophone	segments
Bedretto	-4.6 - 1.6	200 KHz	AE sensor	segments
Labquake	-7.8 - -7.0	10 MHz	AE sensor	segments

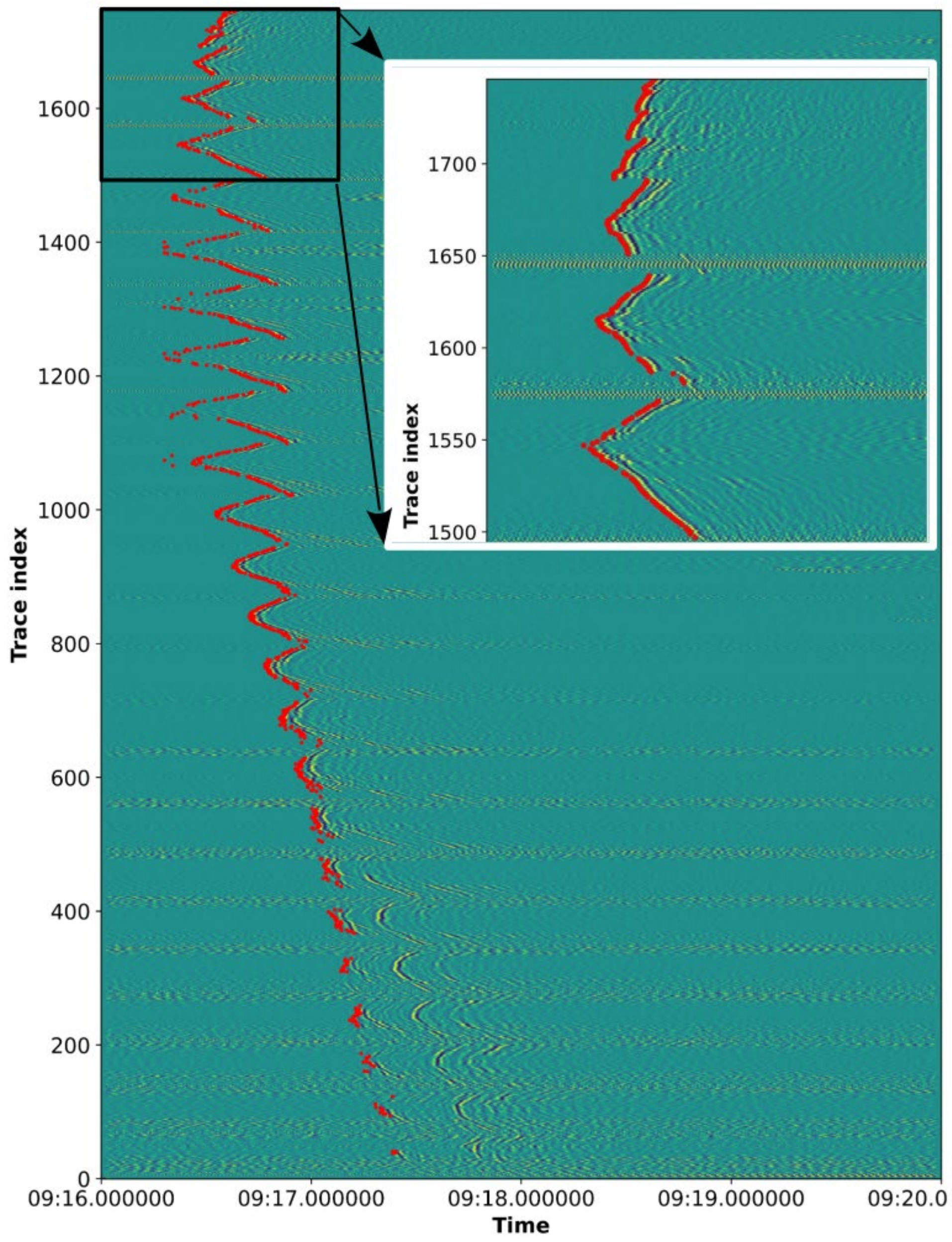
Instrument: 1-component DAS

Rescaling: 5 to 30

Model: PhaseNet_original

Frequency: 3 bands

QuakePhase workflow application: FORGE Reflection Survey



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Labquake	-7.8 - -7.0	10 MHz	AE sensor	segments

Rescaling: 17

2024 FORGE on-site real-time monitoring

Problems:

- Not able to do real-time;
- Location issue due to active borehole configuration;