Contribution of a 2025m deep borehole Seismometer on characterization of induced seismicity at Balmatt Geothermal site

SCHATZALP
DAVOS
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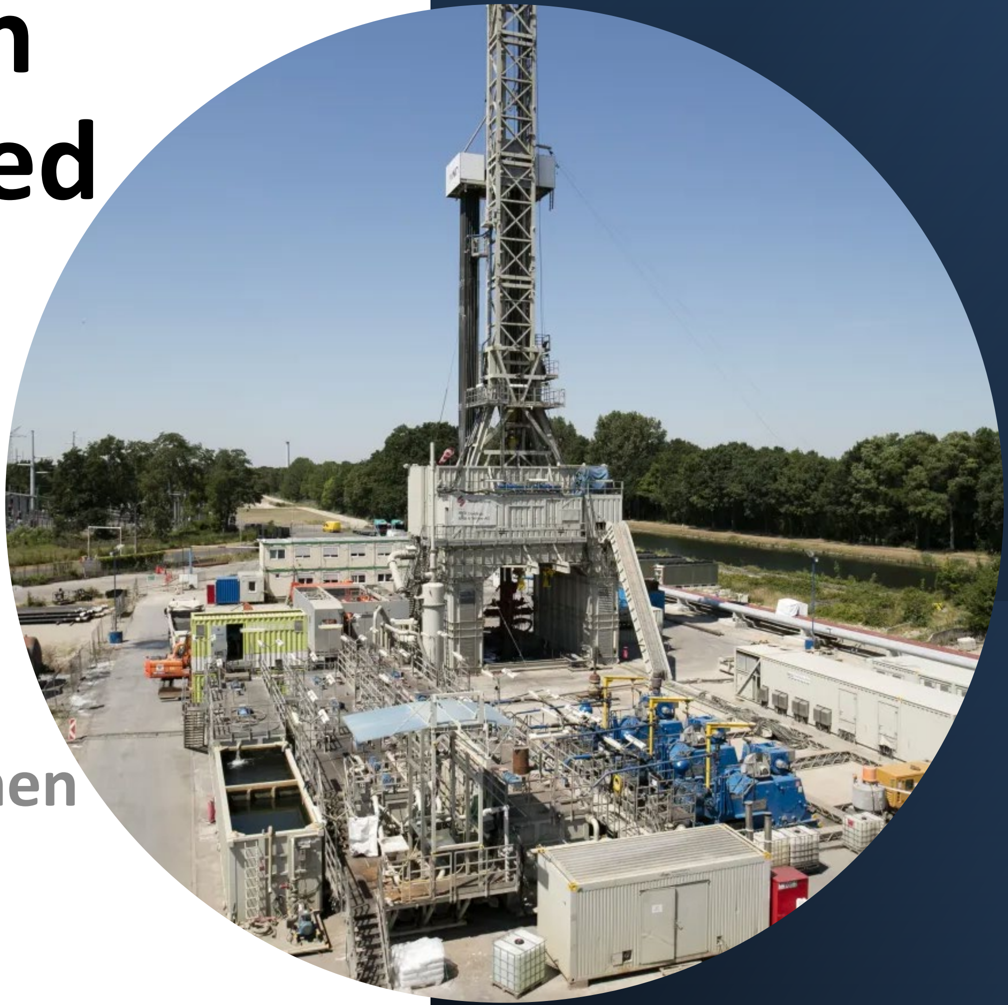
4TH INDUCED SEISMICITY WORKSHOP



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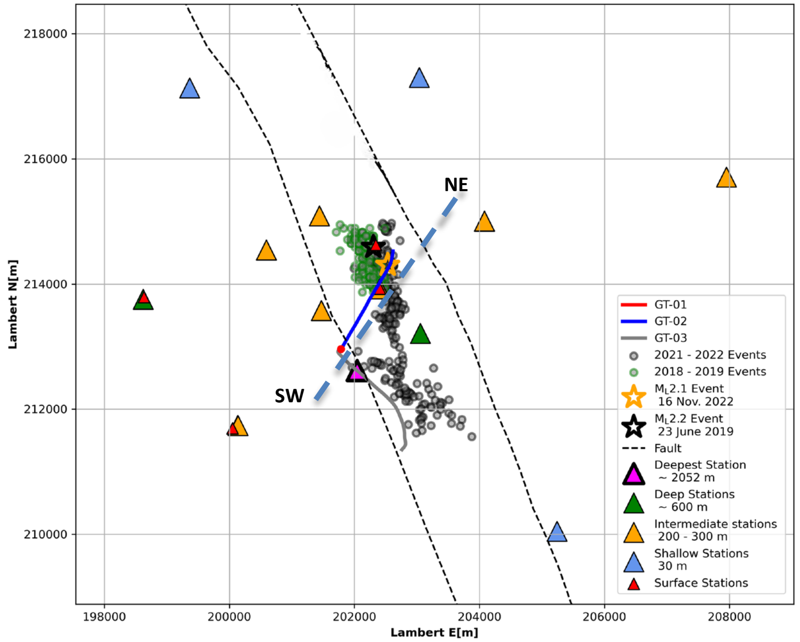
Introduction

Balmatt Geothermal Plant Mol, Belgium

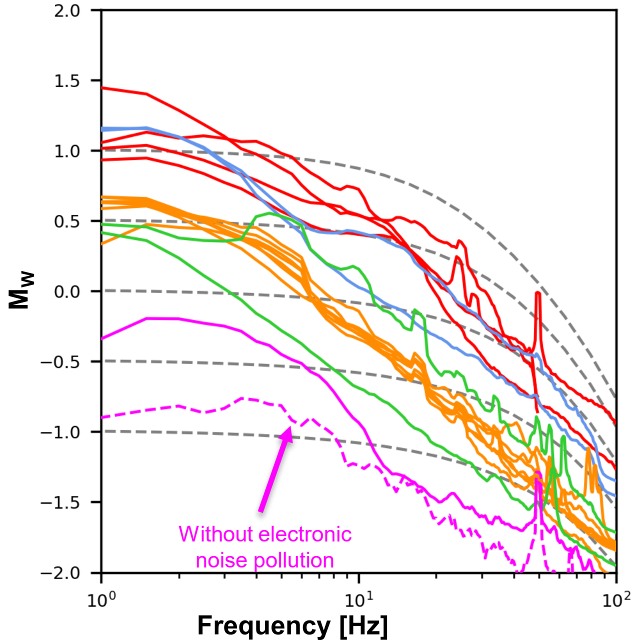
- Suspension of geothermal operation twice due to the occurrence of large induced events (M_L > 2)
- Operational phase 2019 – 2018: M_L 2.2 event
- Resumption of production in 2021-2022; suspended after the occurrence M_L 2.1 event during the 11th injection phase
- ~ 250 events recorded during the 2021 – 2022 operational phase
- This raises the questions about seismic hazard and the associated risks

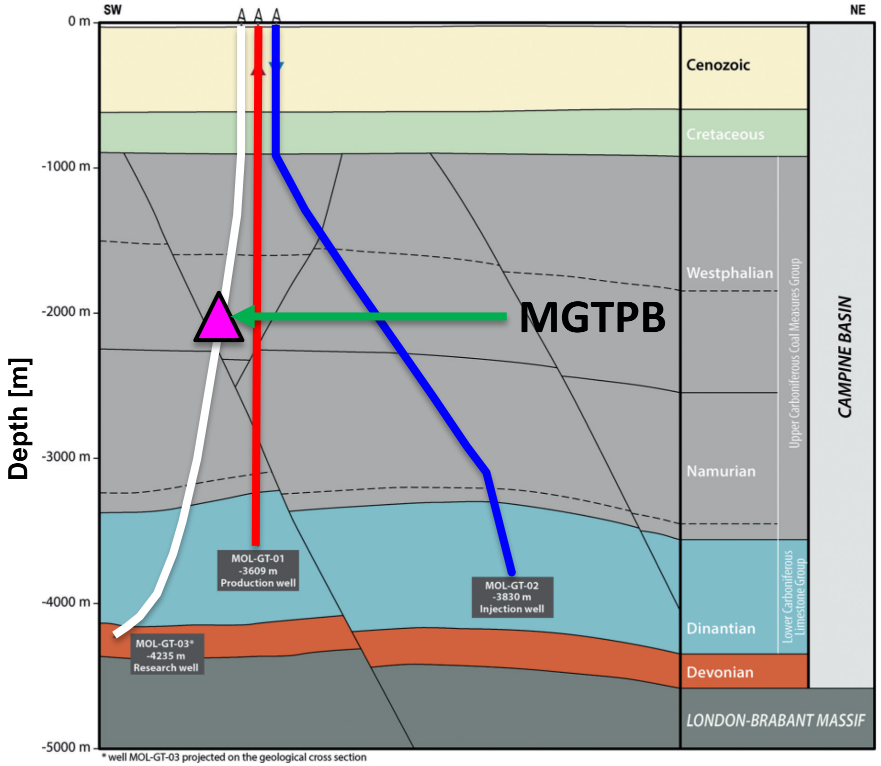


Motivation

- Utilize very deep borehole seismometer (2052 m: MGTPB) for event detection to generate high quality seismic catalogue
- Provide better insight on the spatio-temporal and energetic evolution of seismicity
- Improve probabilistic forecasting and constrain hydromechanical reservoir behaviour

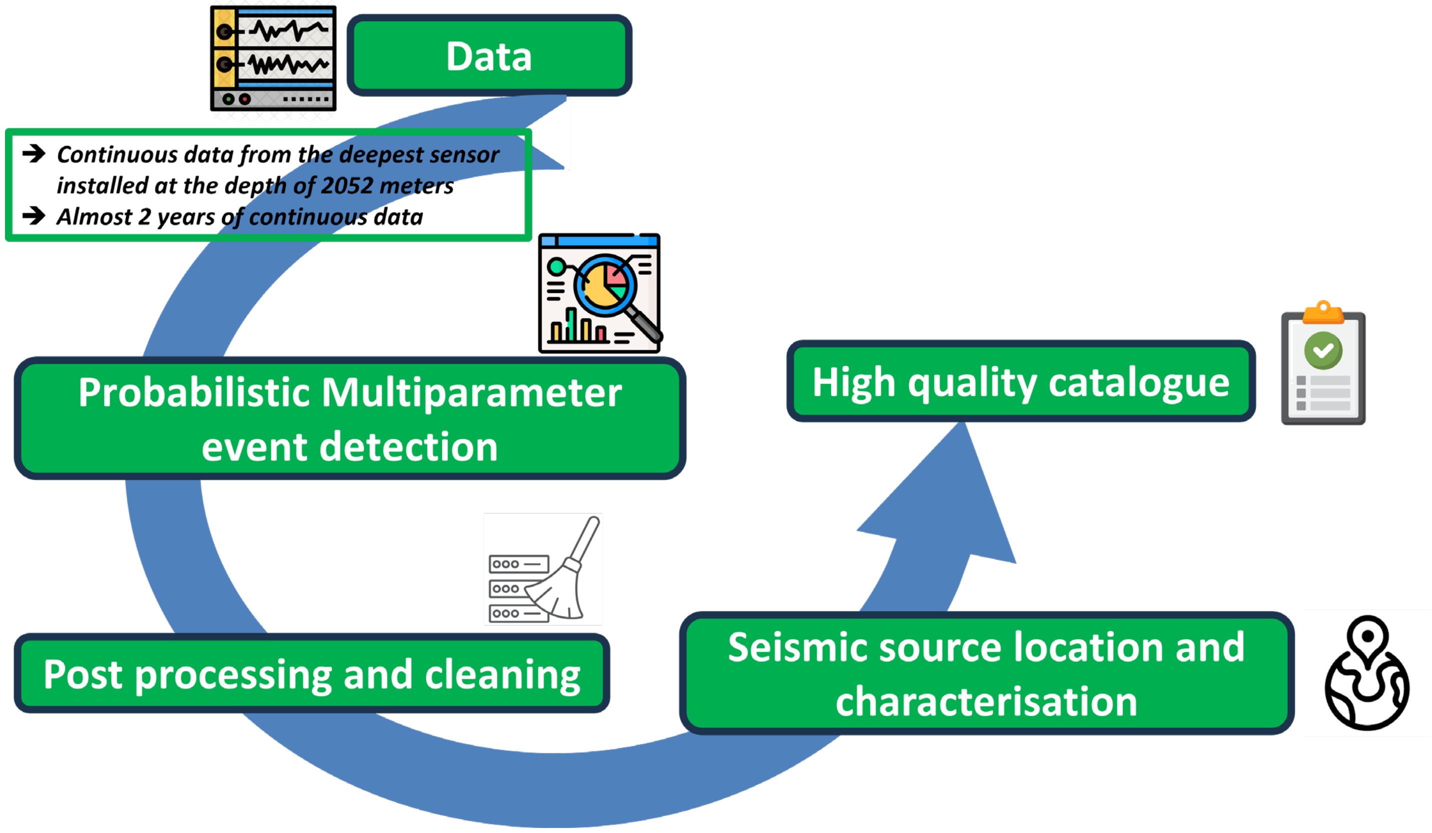
Detection sensitivity for source at 3.8 km depth below station





Objectives

Seismic Catalogue Generation Workflow



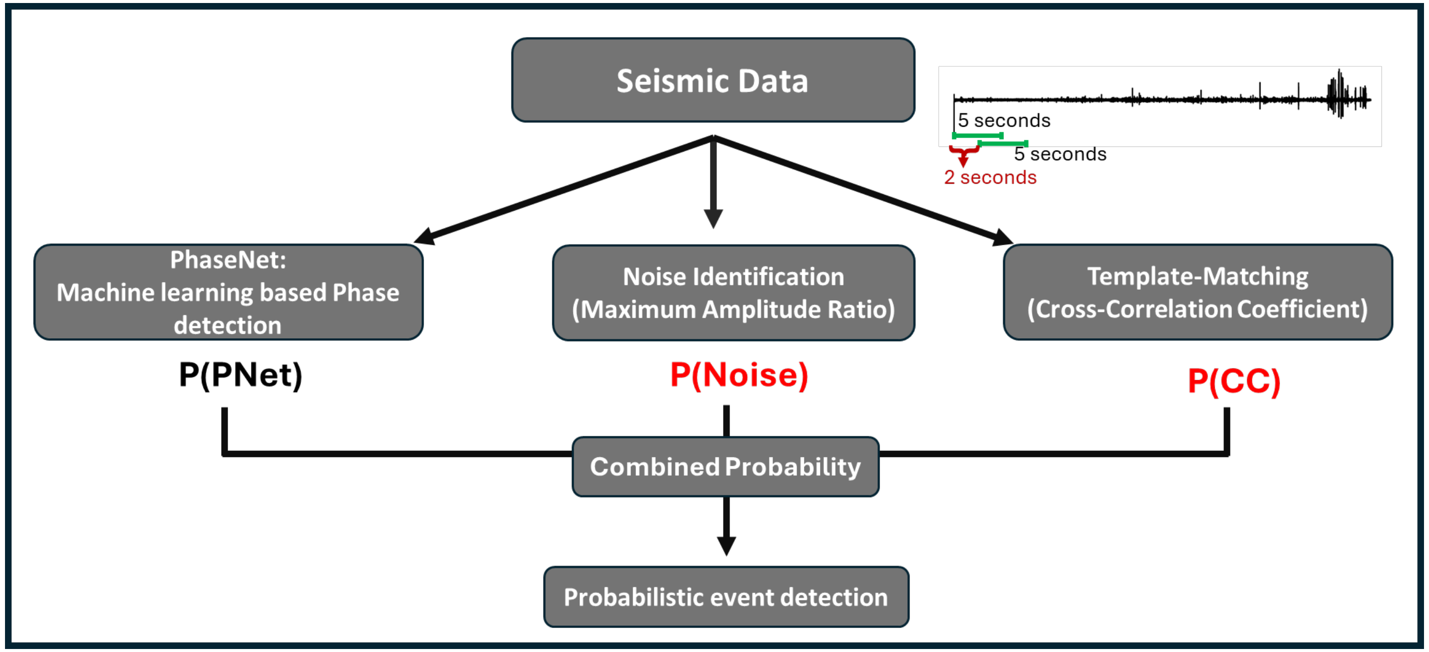
- Develop a probabilistic methodology for event detection and localization using single deep borehole seismometer

- Evaluate the contribution of (very) deep sensors in seismic monitoring and seismic hazard forecast

Data and Methods

- Continuous seismic data from a 3-component seismometer installed at the depth of 2052 m
- Almost 2 years of data from 2021 – 2022 production phase

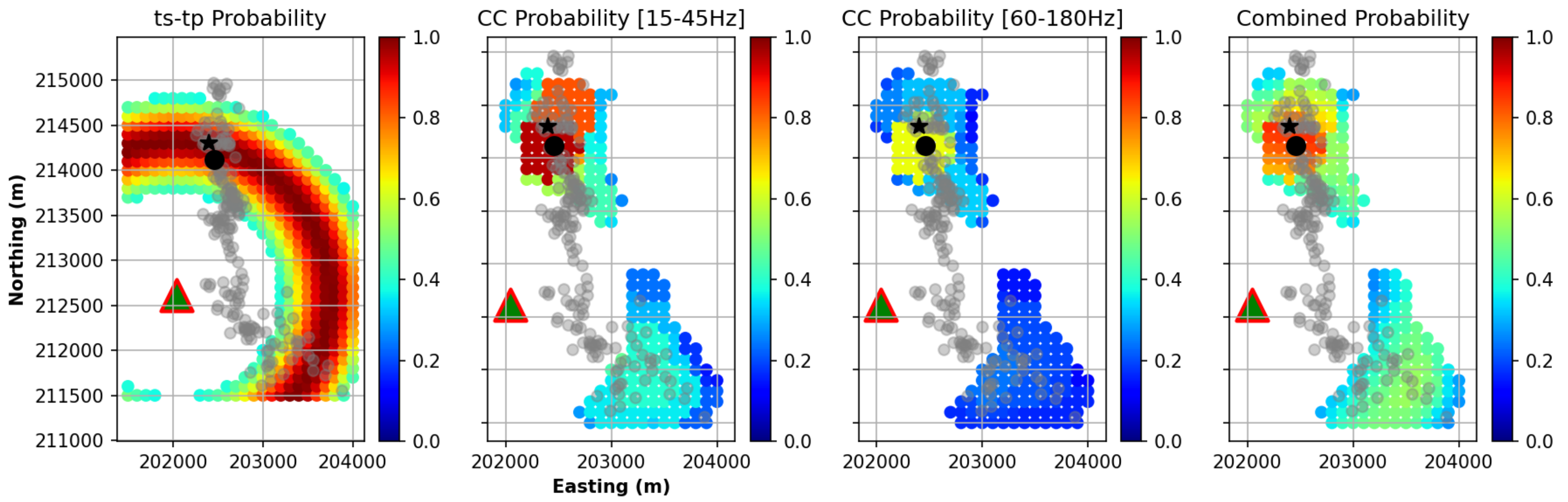
Probabilistic Multiparameter Event Detection



- Our method combines machine learning-based phase detection with empirical parameters to improve seismic event detection

Approximate Location

- NonLinLoc grid search based on the travel-time difference
- We use a constant travel-time error
- Cross-correlation with the locatable events at 2 different frequency bands
- For each grid we search the events within the given distance (e.g. 300 m) and the grid is assigned the maximum CC value among the events



Magnitude Estimation

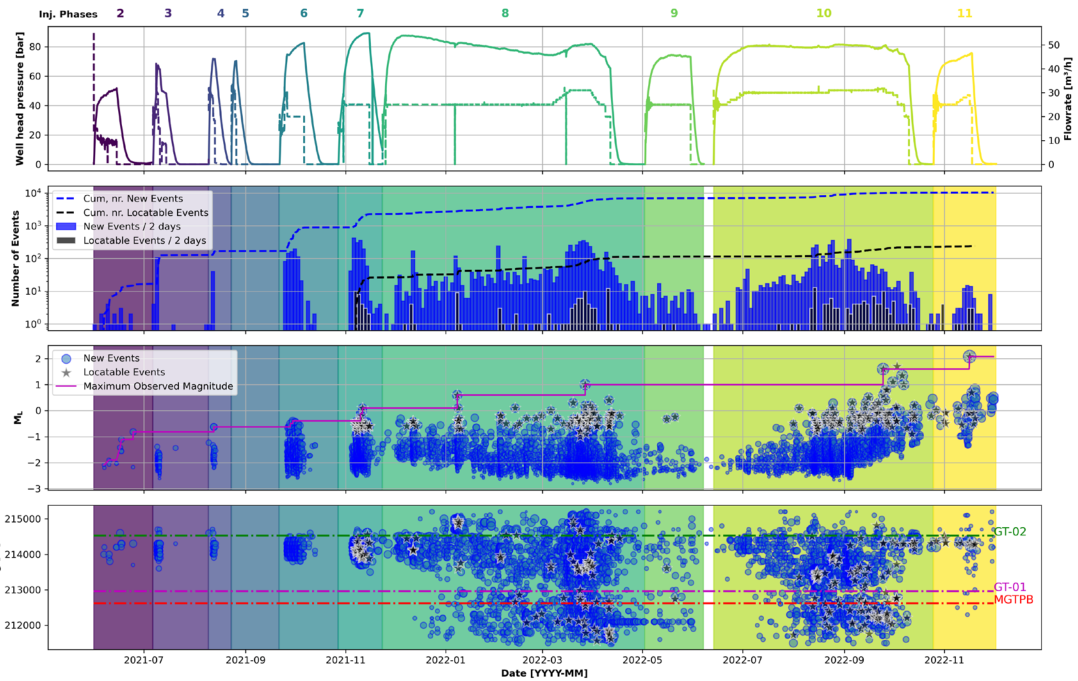
- Magnitude estimation was done using the approach from Luckett et- al. 2019

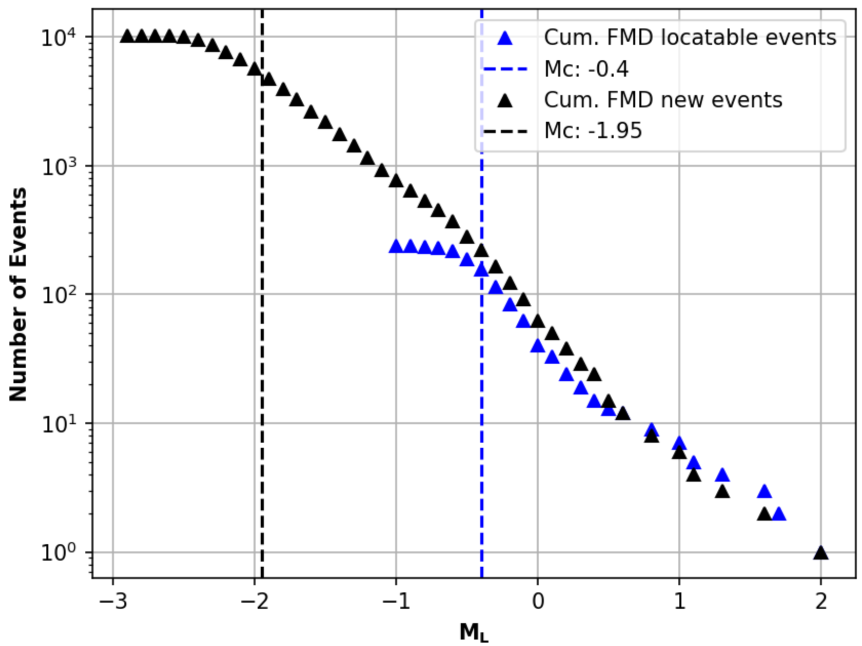
$$M_L = \log(amp) + 1.11\log(r) + 0.00189r - 1.16e^{-0.2r} - 2.09$$

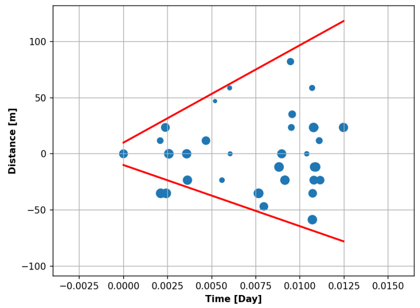
- In general magnitude estimation is done using multiple station
- Our magnitude estimations are based on single station

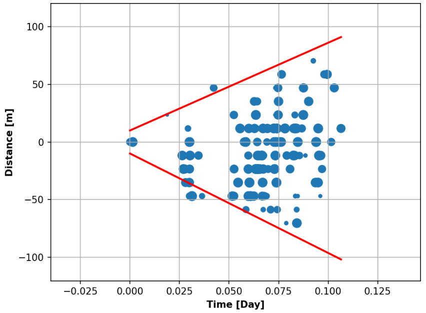
Results

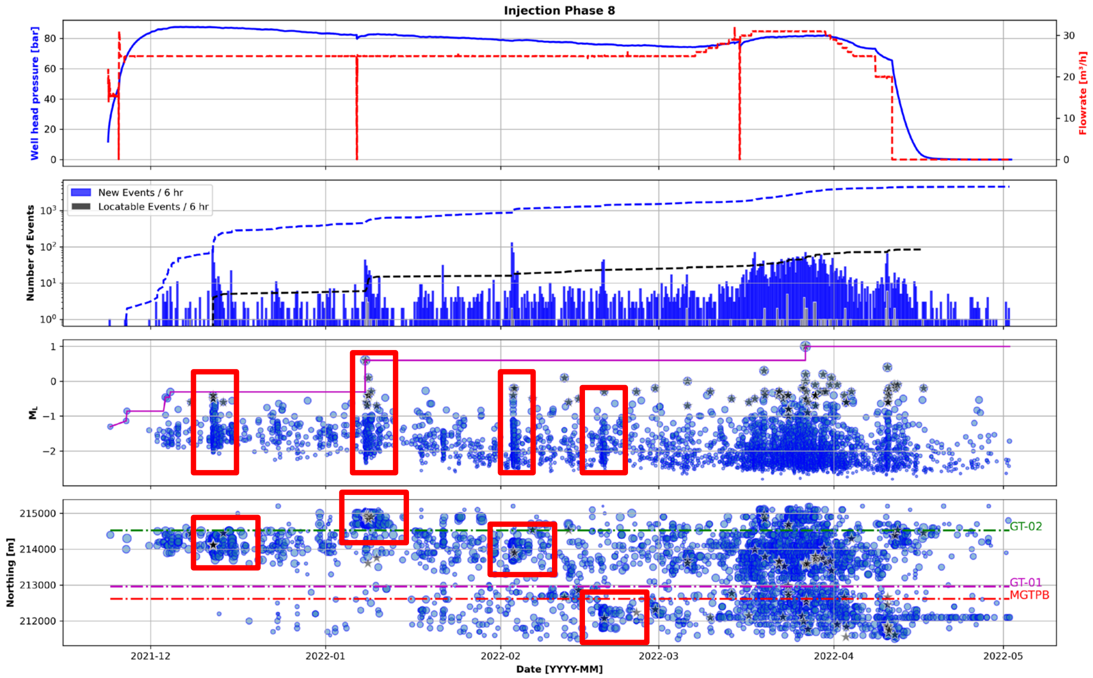
- 10290 events compared to around 250 events
- Mc from -0.4 to -1.98
- Reservoir was seismically active long before the detection of the first locatable event
- Migration of seismicity south beyond the production well occurs much earlier than shown by the previous catalogue
- Presence of highly localized (spatially and temporally) seismic bursts





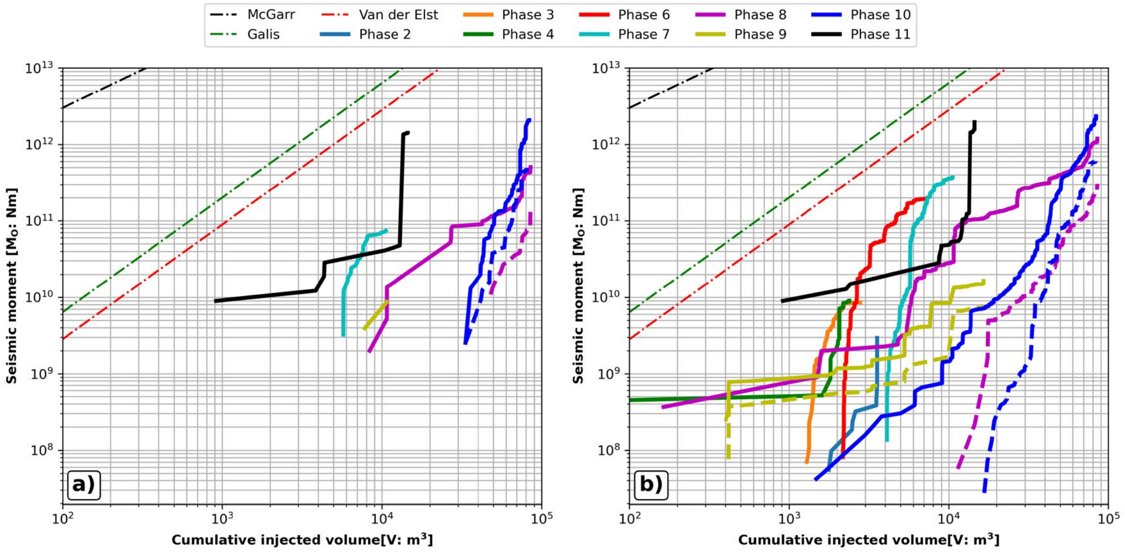






Results

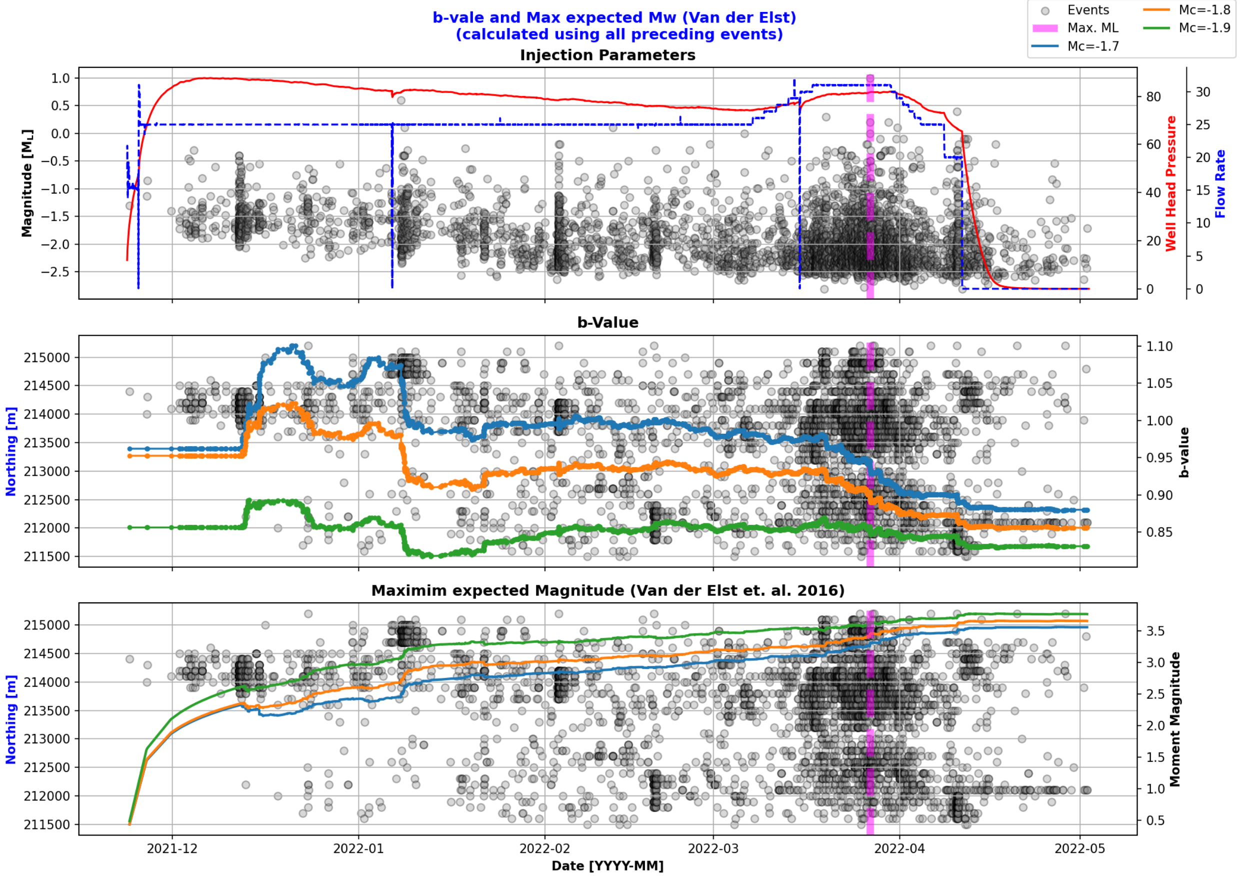
- Similar cumulative seismic moment evolution trend for the short-term injection phases (2 – 7)
  - Kaiser effect, pressure/volume memory?
  - Seismicity controlled by fluid pressure increase?
- Different trends for long-term production phases (8 – 10)
  - Different mode of energy transfer?
  - aseismic slip outpace the fluid/pressure migration?



Old Catalogue   New Catalogue

Temporal b-value evolution

- A clear relationship between the change in the change in injection parameters and the change in b-value
- The largest event occurs during the period where we observe systematic decrease in the b-value corresponding to the increase in the flow rate



On-going Work and Conclusion

- We are working on a way to integrate the new catalogue generation workflow in near-real time scenario at Balmatt
- We are working on developing a predictive Traffic Light System protocol using the observations from the detailed seismic catalogue (for example: b-value, cumulative seismic moment….)
- Further analyse in detail the spatio-temporal and energetic evolution to characterise the triggering mechanisms
- Build conceptual/predictive relationship between geothermal production and seismicity
- Combining machine learning based event detection with emperical parameters ensures that detections are supported by multiple independent criteria rather than relying solely on a single method
- We have developed a robust methodology to create a detailed seismic catalogue using a single deep seismometer
- It has a potential to be used for near-real time monitoring purpose (on the process of being implemented)
- The new catalogue provides much detailed information on the subtle changes on the reservoir

Thank you!

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Appendix

$$\boldsymbol{b} = \frac{\mathbf{1}}{\mathbf{2}\Delta \boldsymbol{M} \boldsymbol{ln}(\mathbf{10})} \boldsymbol{ln}\left(\frac{\left|\overline{\boldsymbol{M} - \boldsymbol{M_c}}\right| - \Delta \boldsymbol{M}'_{\boldsymbol{C}} + \mathbf{2}\Delta \boldsymbol{M}}{\left|\overline{\boldsymbol{M} - \boldsymbol{M_c}}\right| - \Delta \boldsymbol{M}'_{\boldsymbol{C}}}\right)$$

$\left|\overline{\boldsymbol{M} - \boldsymbol{M_c}}\right|$ = mean absolute deviation from the magnitude of completeness ($\boldsymbol{M_c}$)

$\Delta \boldsymbol{M} =$ the binning interval

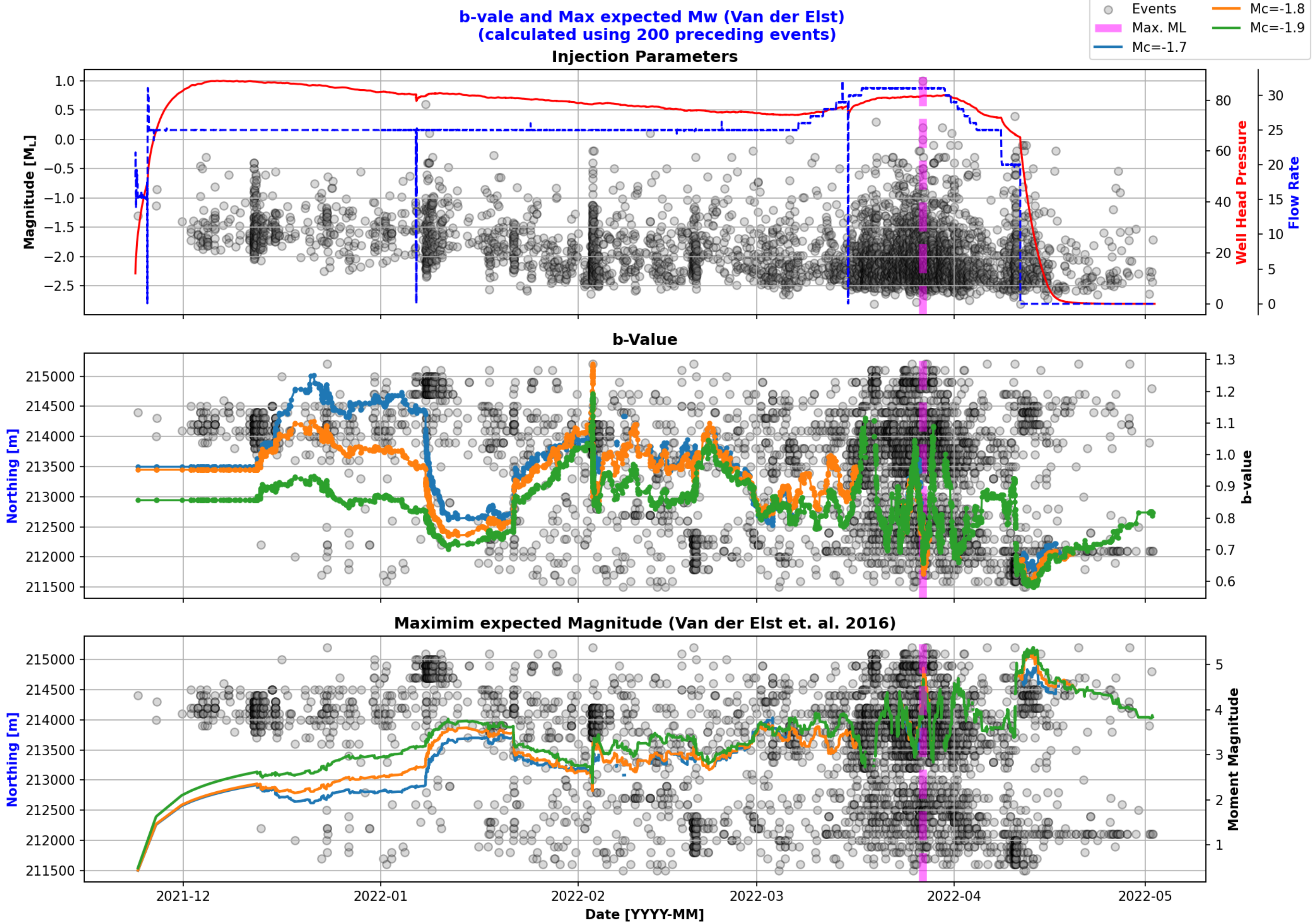
$\Delta \boldsymbol{M}'_{\boldsymbol{C}}$ = small shifted completeness threshold

$$\boldsymbol{\sigma_b} = \frac{\boldsymbol{b}}{\sqrt{\boldsymbol{N}}}$$

$\boldsymbol{N}$ is the number of magnitudes considered ($M \geq M_C$)

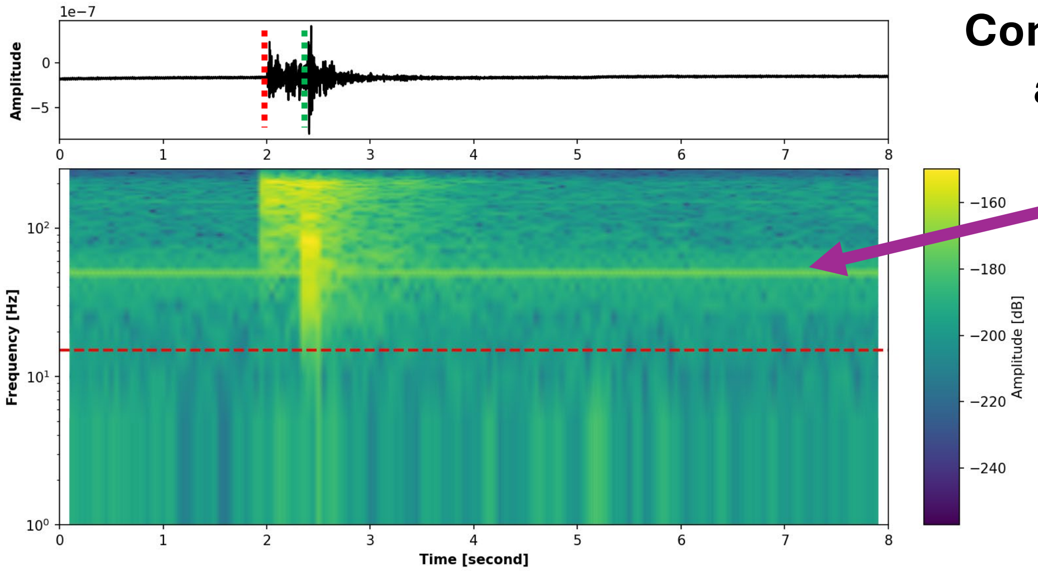
https://doi.org/10.1093/gji/

B-value evolution



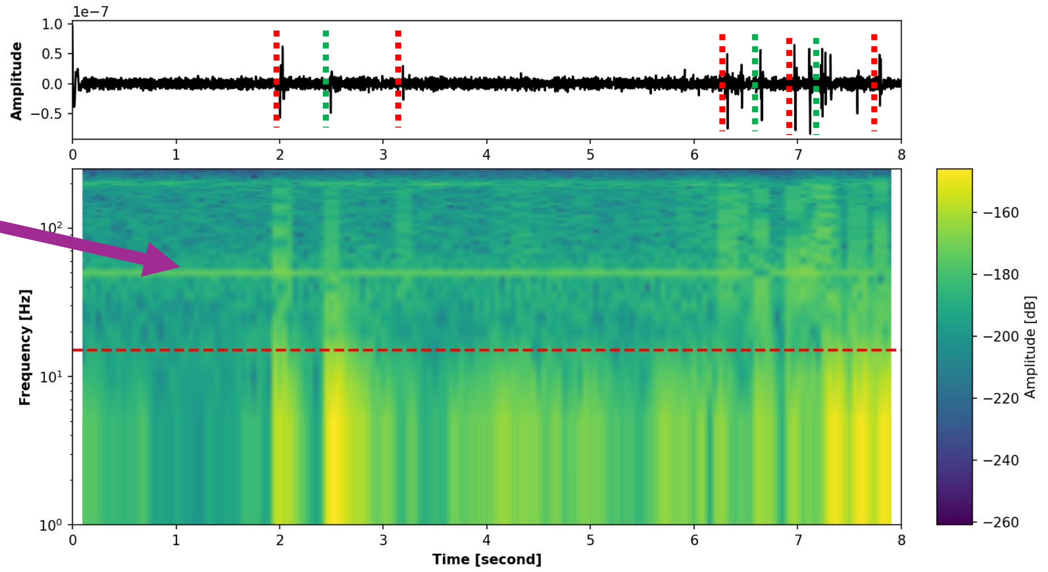
Challenges

Event

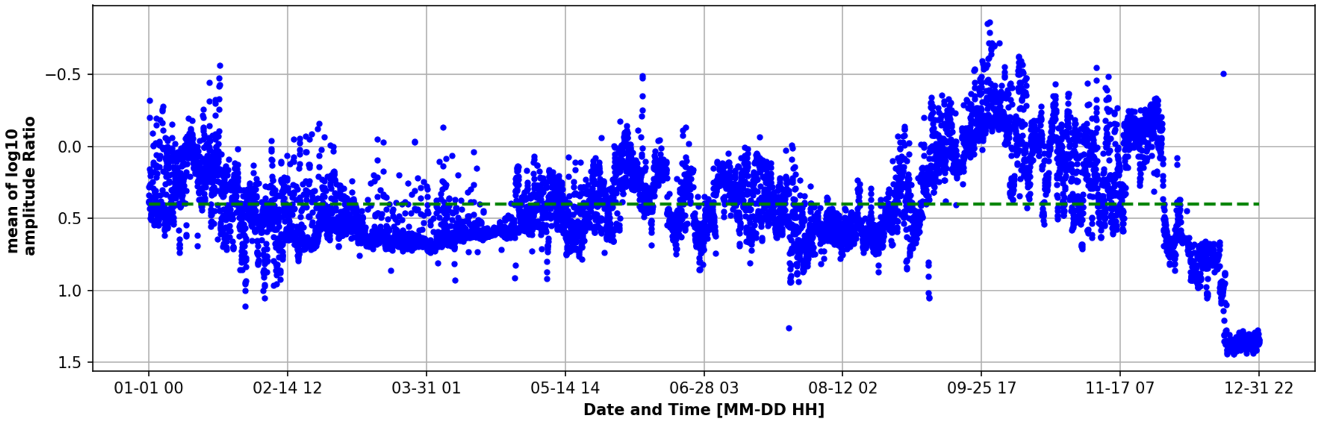


Constant noise at 50 Hz acquisition noise

Low frequency electronic noise spikes



Relative electronic noise against background noise level



- **unusually large numbers of false detections during the period where low frequency electronic noise is dominant**

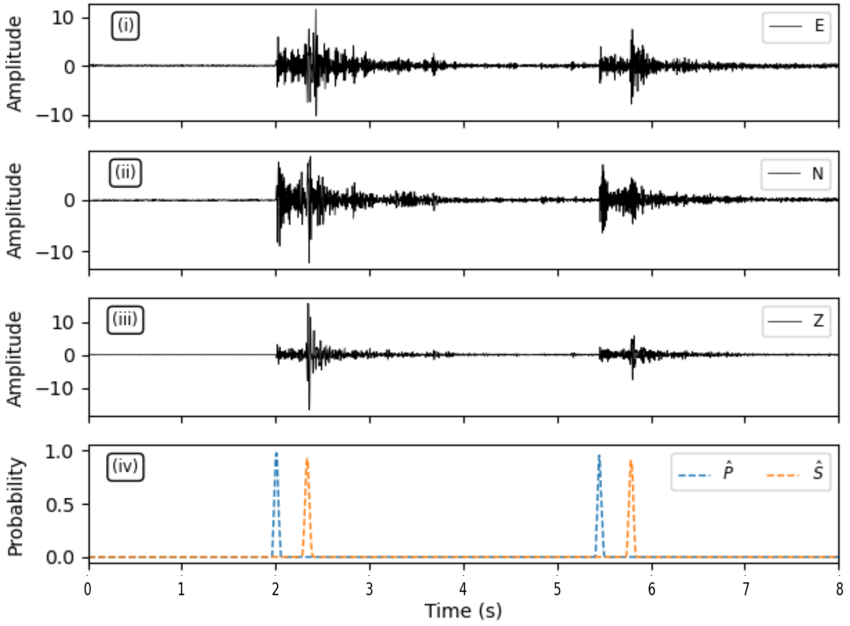
Probabilistic Multiparameter Event Detection

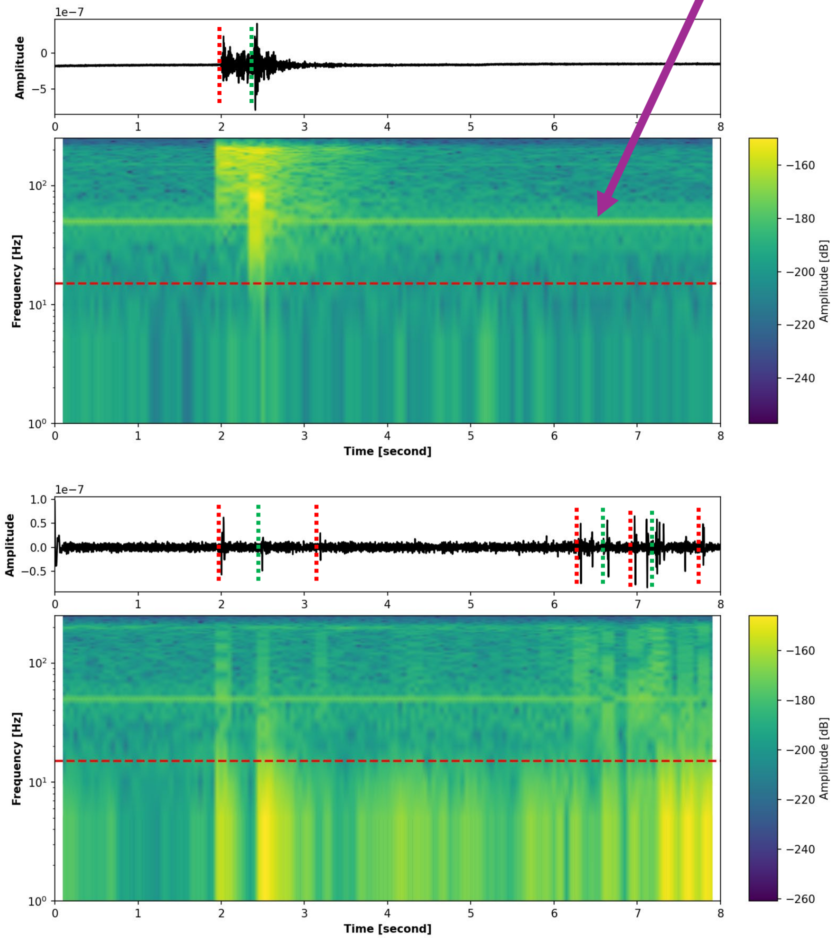
Seismic Data

Trustful? Since trained based on different sensors and different scale , tool performance not fully understood with respect to induced seismicity and using deep borehole sensor

Constant noise at 50 Hz
Instrument self-noise

PhaseNet[1]:
Machine learning based Phase detection





[1]Zhu, Weiqiang, and Gregory C. Beroza. "PhaseNet: a deep-neural-network-based seismic arrival-time picking method." Geophysical Journal International 216.1 (2019): 261-273

Seismic Data

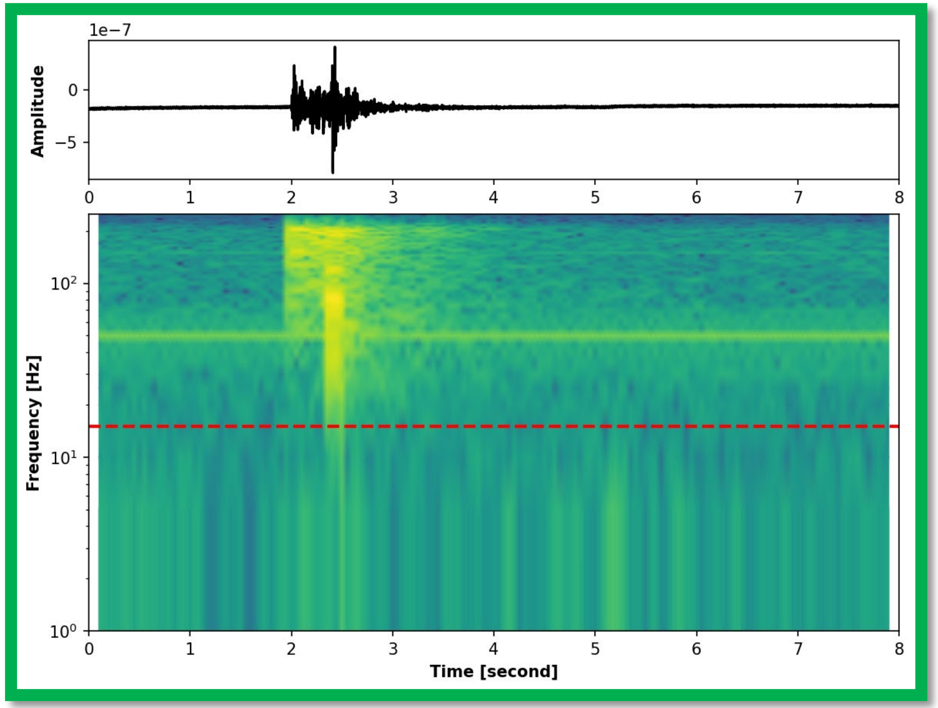
PhaseNet[1]: Machine learning based Phase detection

Noise Identification (Maximum Amplitude Ratio)

Measuring presence of electronic noise

➔ Based on amplitude ratio 60-180 Hz/1-10Hz

Seismic signal above sensor frequency (15 Hz) and acquisition noise (50 Hz)



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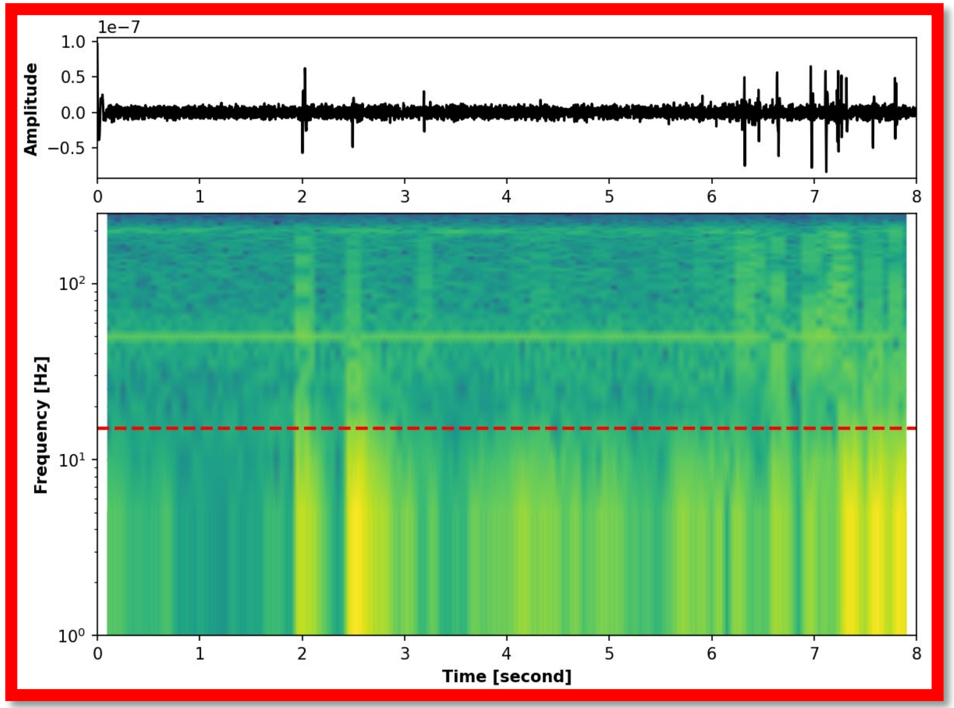
Electronic noise dominant below sensor frequency



Seismic Data

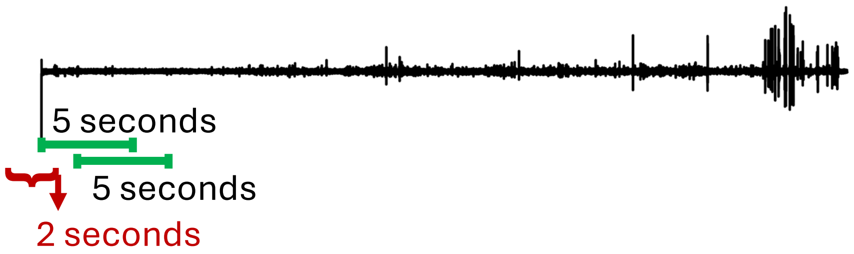
PhaseNet[1]: Machine learning based Phase detection

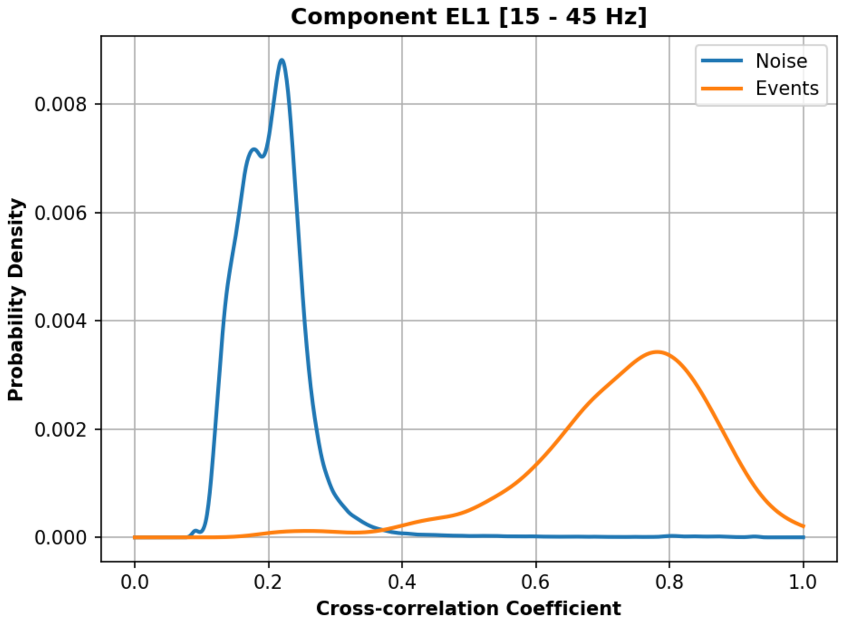
Noise Identification (Maximum Amplitude Ratio)

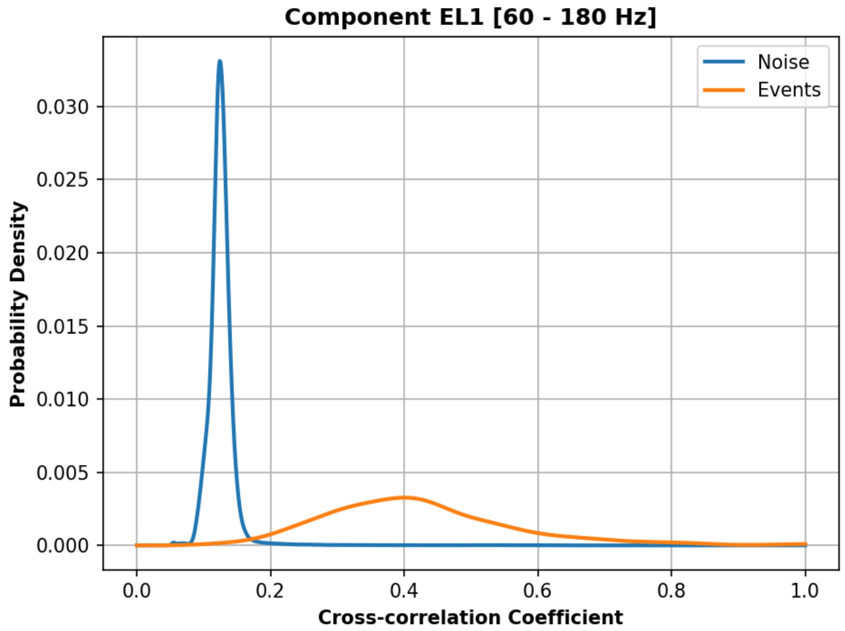
Template-Matching (Cross-Correlation Coefficient)

Identifying the repetitive and similar induced events

- ➔ In total 64 templates: best waveforms in terms of signal to noise ratio from the list of all the locatable events
- ➔ based on two frequency band: 15 – 45 Hz and 60 – 180 Hz







Data and Methods

Probabilistic Multiparameter Event Detection

- To quantify the likelihood of the test events relative to the overall data distribution (based on amplitude ratio or CC-coeficient), we employ a probabilistic approach based on empirical cumulative distribution functions (ECDFs)

$$\hat{F}_{all} = \frac{1}{N}\sum_{i=1}^{N} 1_{x_i \le x} \qquad \hat{F}_{evt} = \frac{1}{M}\sum_{j=1}^{N} 1_{x'_j \le x}$$

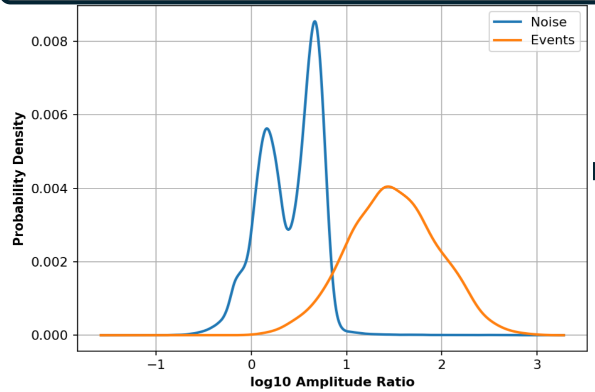
$$P_{diff} = \hat{F}_{all}(x) - \hat{F}_{evts}(x)$$

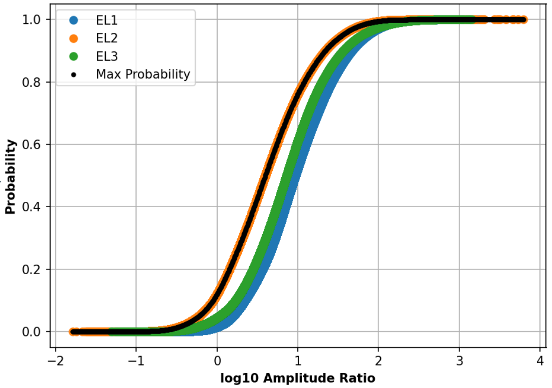
$$P_{final} = \frac{\sum_i P_{diff}\,(x_i)}{max \sum_i P_{diff}\,(x_i)}$$

- We calculate the event probability for each component based on the amplitude ratio and cc-coefficient
- The resultant event (P(Noise)) probability based on the maximum amplitude ratio is the maximum out of the three components
- In case of template matching probability, we take the mean of the event probability from two frequency bands (P(CC))
- Since PhaseNet already provides probability for P- and S-pick. The PhaseNet probability (P(PNet) for the given window if it contains an event with P- and/or S-pick is the mean between the P-and S-pick probability otherwise its 0.

$$\boldsymbol{P(Event) = \frac{P(PNet) + P(Noise) + P(CC)}{3}}$$

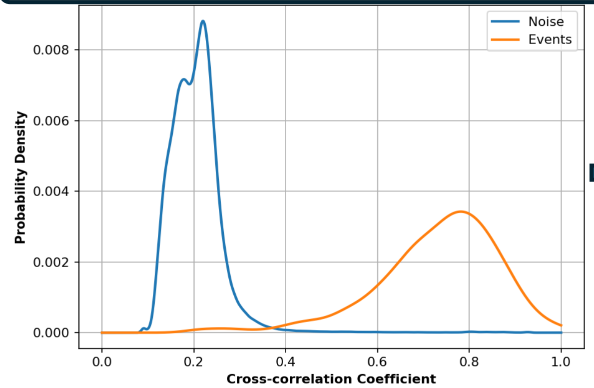
Maximum Amplitude Ratio

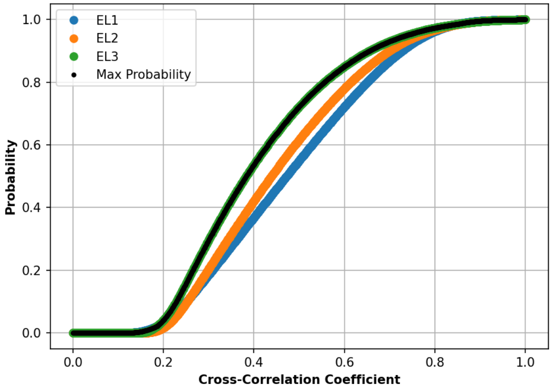




Event Probability

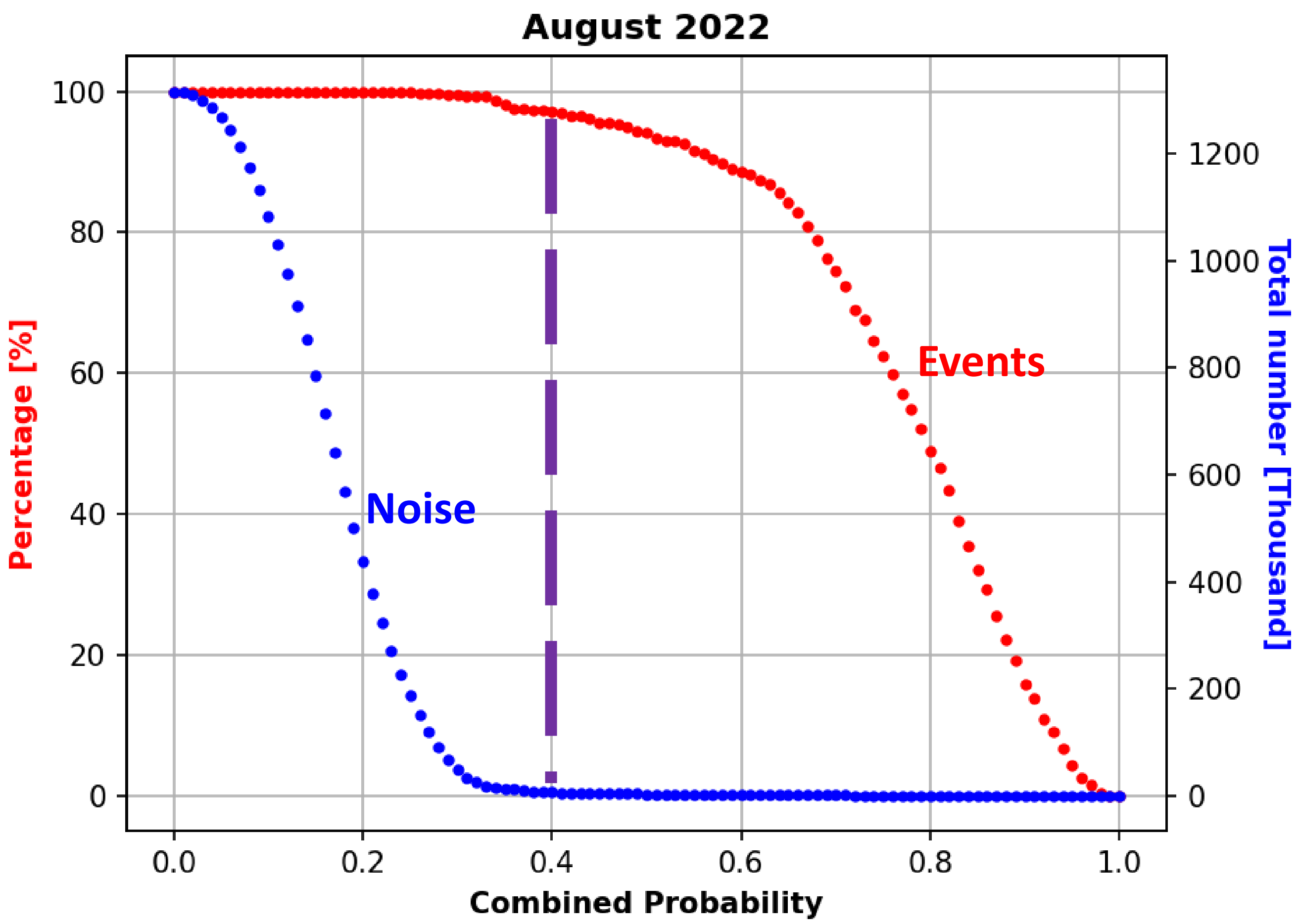
Cross-Correlation Coefficient





Performance

- ➢ **For probability of 40 % (0.4) noise decreases significantly and most events detected**
- ➢ **Everything above 40 % probability is potential event**



Spatio-temporal Evolution of Seismicity

Migration/evolution of seismicity

Are all the failures seismic and are controlled by fluid pressure increase?
Does aseismic slip outpace the fluid/pressure migration?