DETECTING LOW FREQUENCY EARTHQUAKES IN CASCADIA WITH DEEP LEARNING

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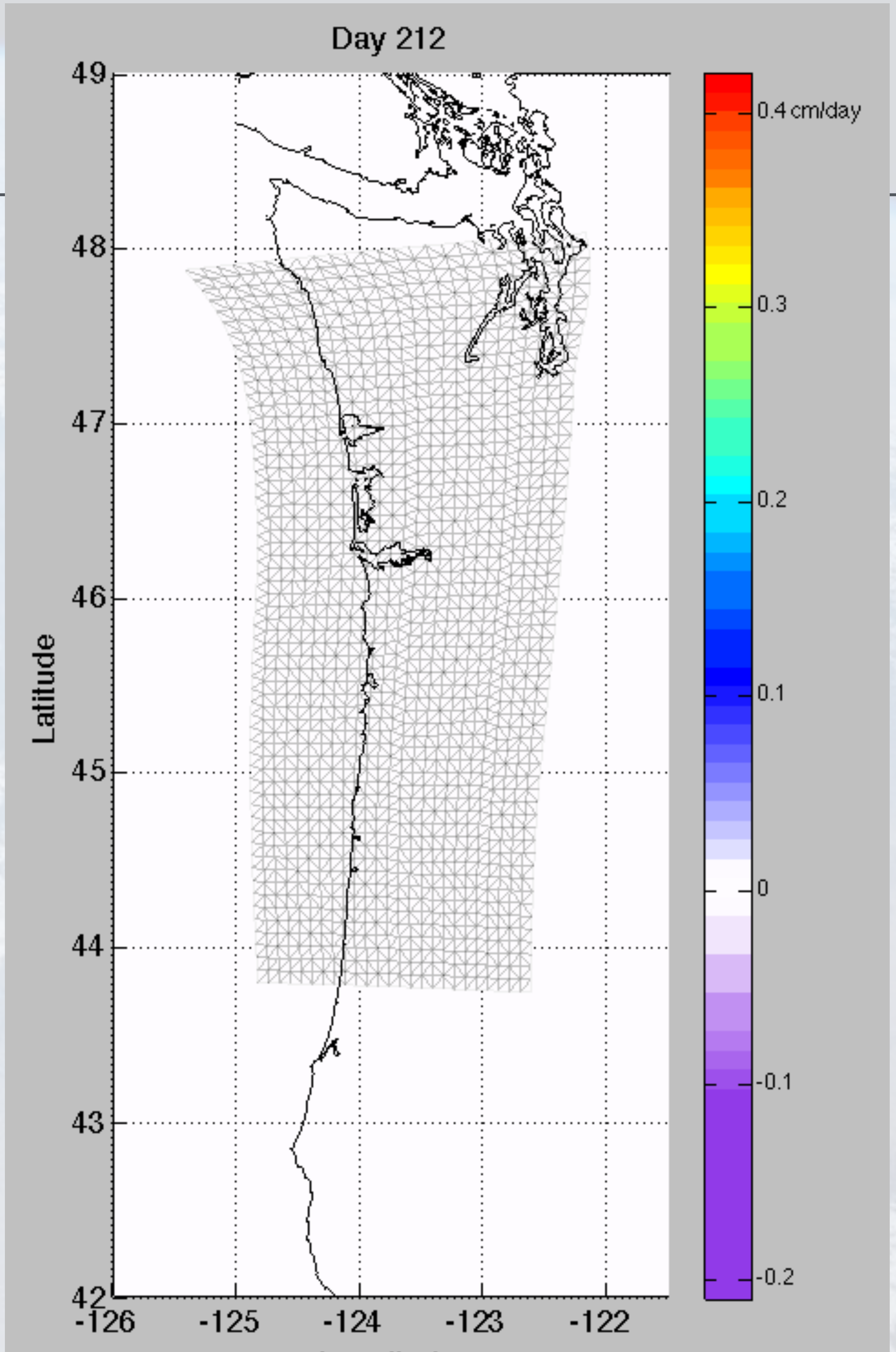
Slow slip

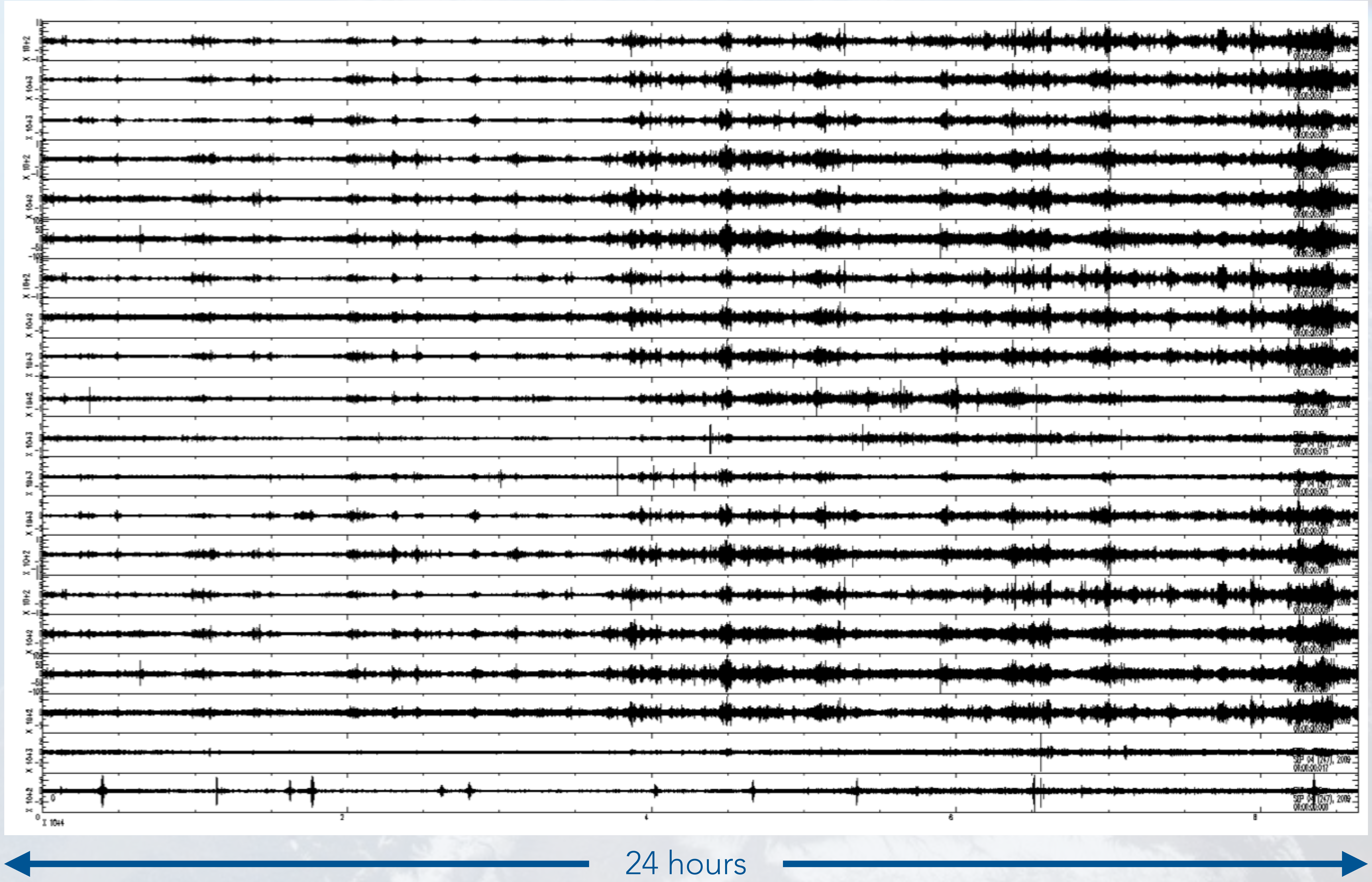
- **Fast earthquakes** have durations of fractions of a second to a few minutes
- **Slow earthquakes** have durations of days, weeks, months, and even years



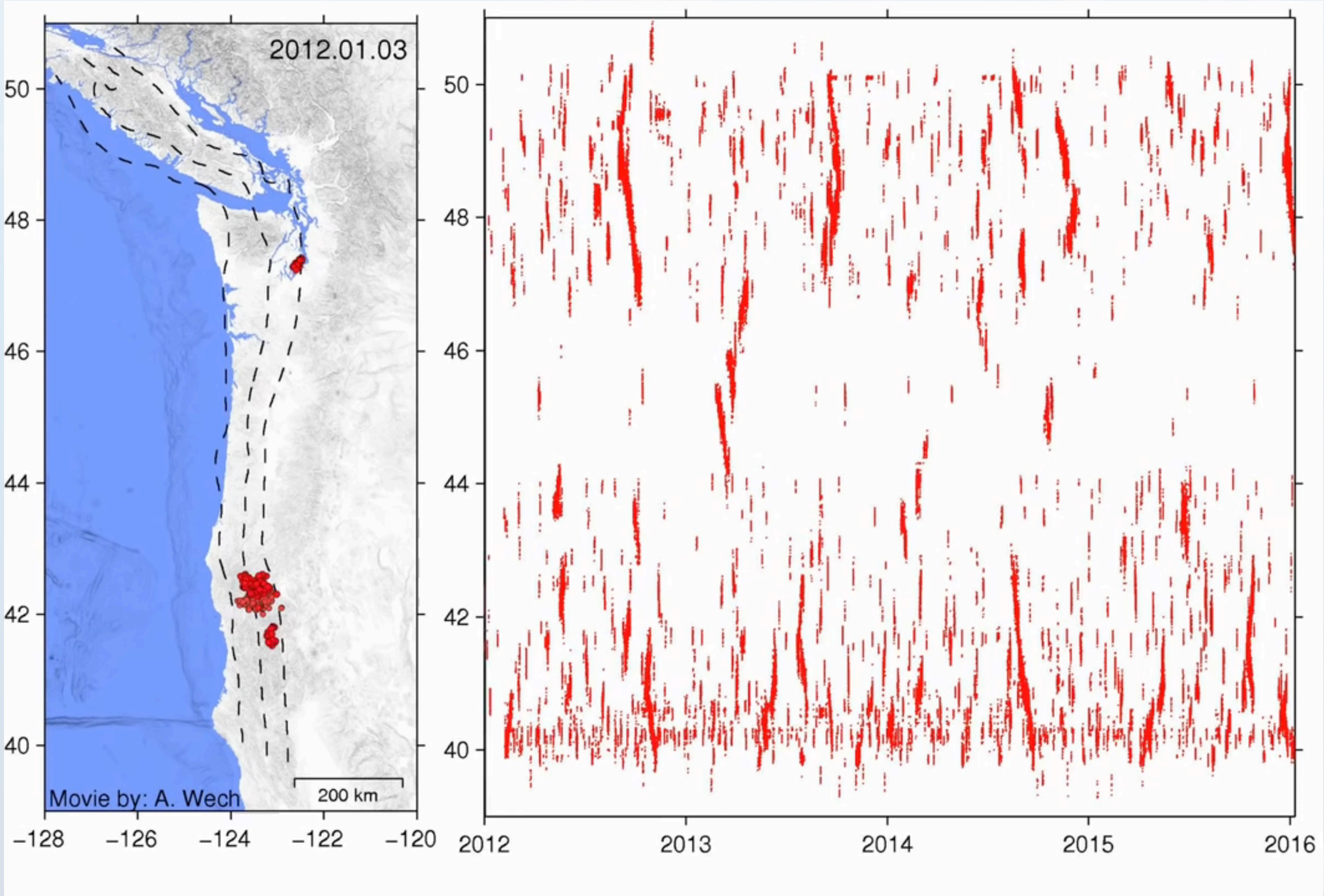
Bartlow et al. [2011]

Nonvolcanic tremor

- Slow slip events have a weak seismic signature known as tectonic tremor



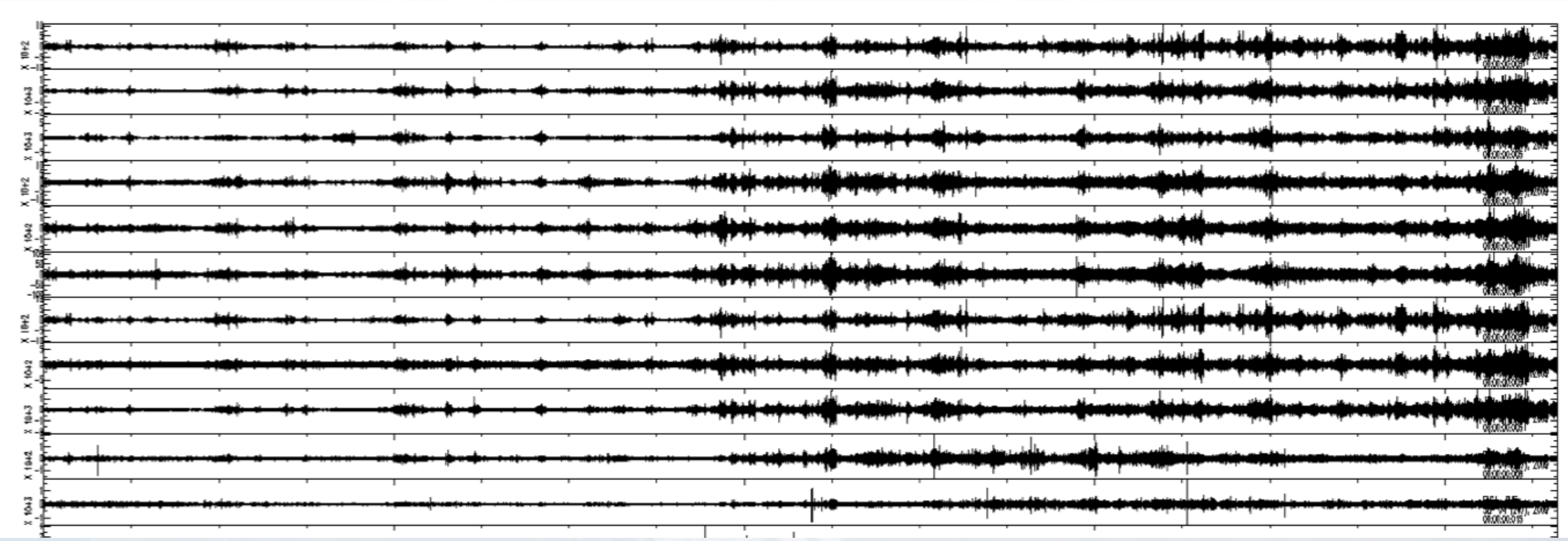
Nonvolcanic tremor



Tremor and LFEs

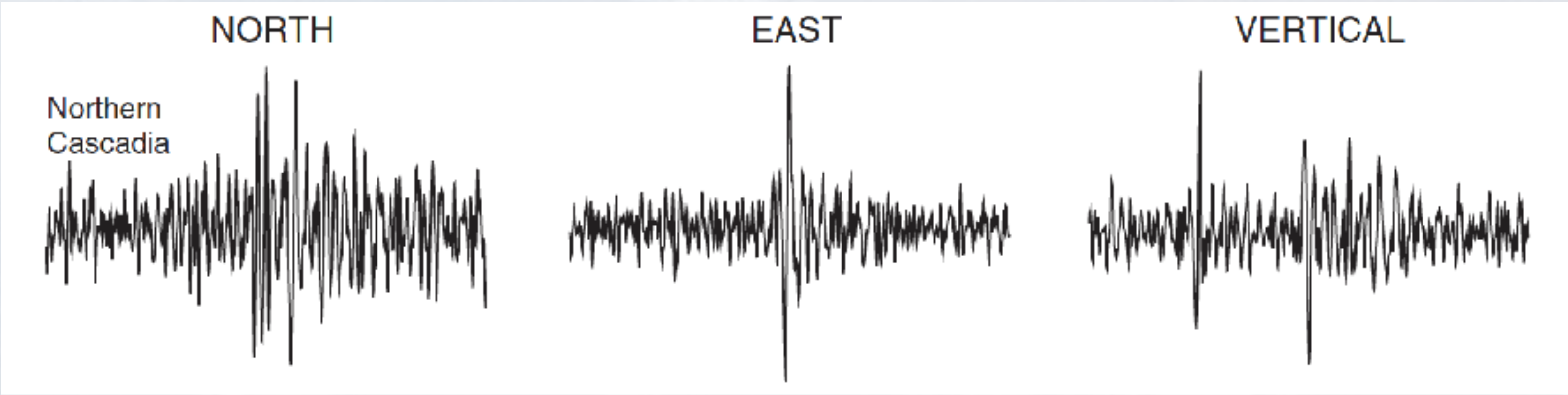
- Tremor is made up of constituent low-frequency earthquakes (LFEs)
- LFEs are **low amplitude** and **depleted in high-frequency content** relative to traditional earthquakes of the same magnitude

Tremor is an unusual seismic signal….



24 hours

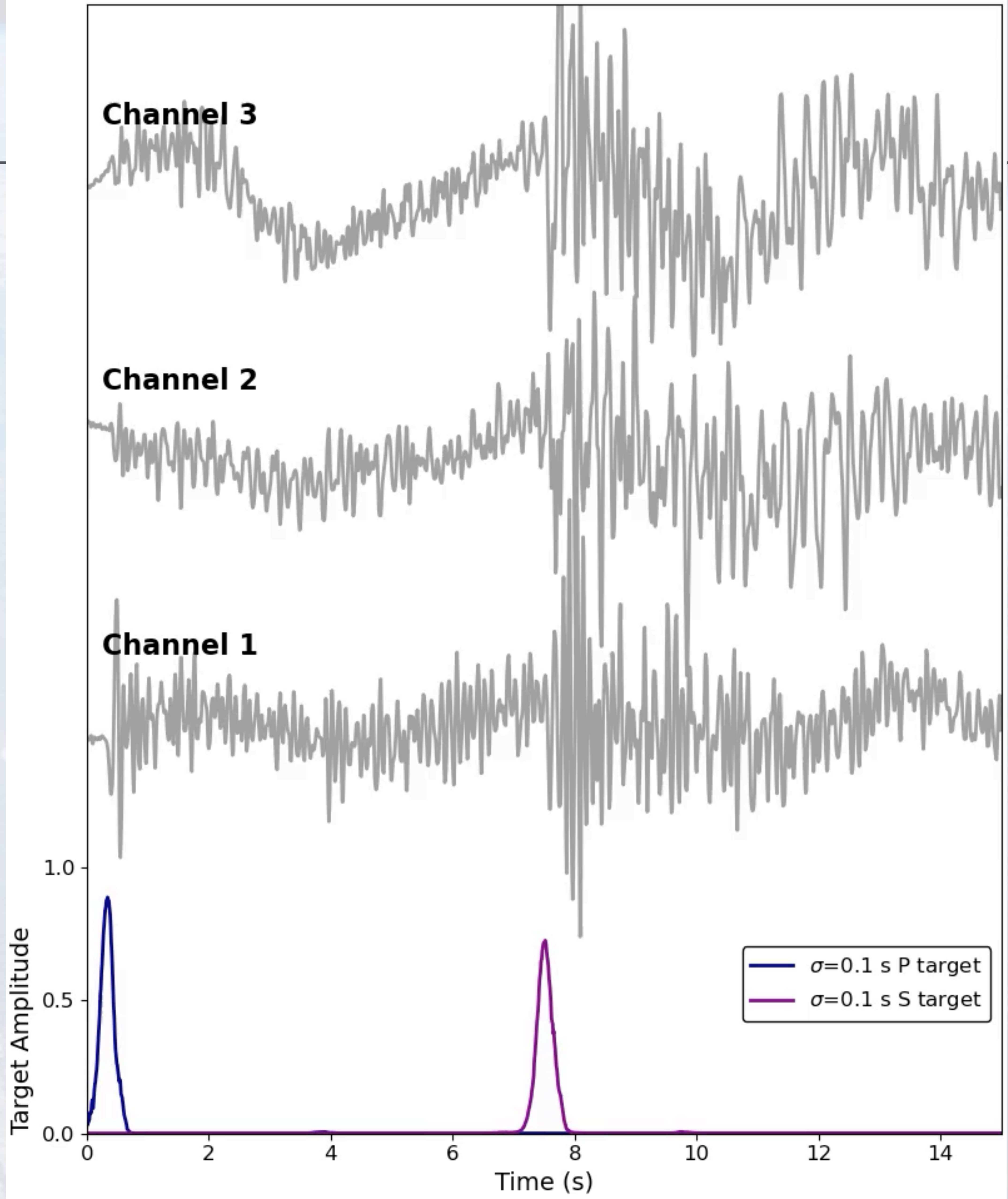
…that can be explained as a superposition of small earthquakes.



20 seconds

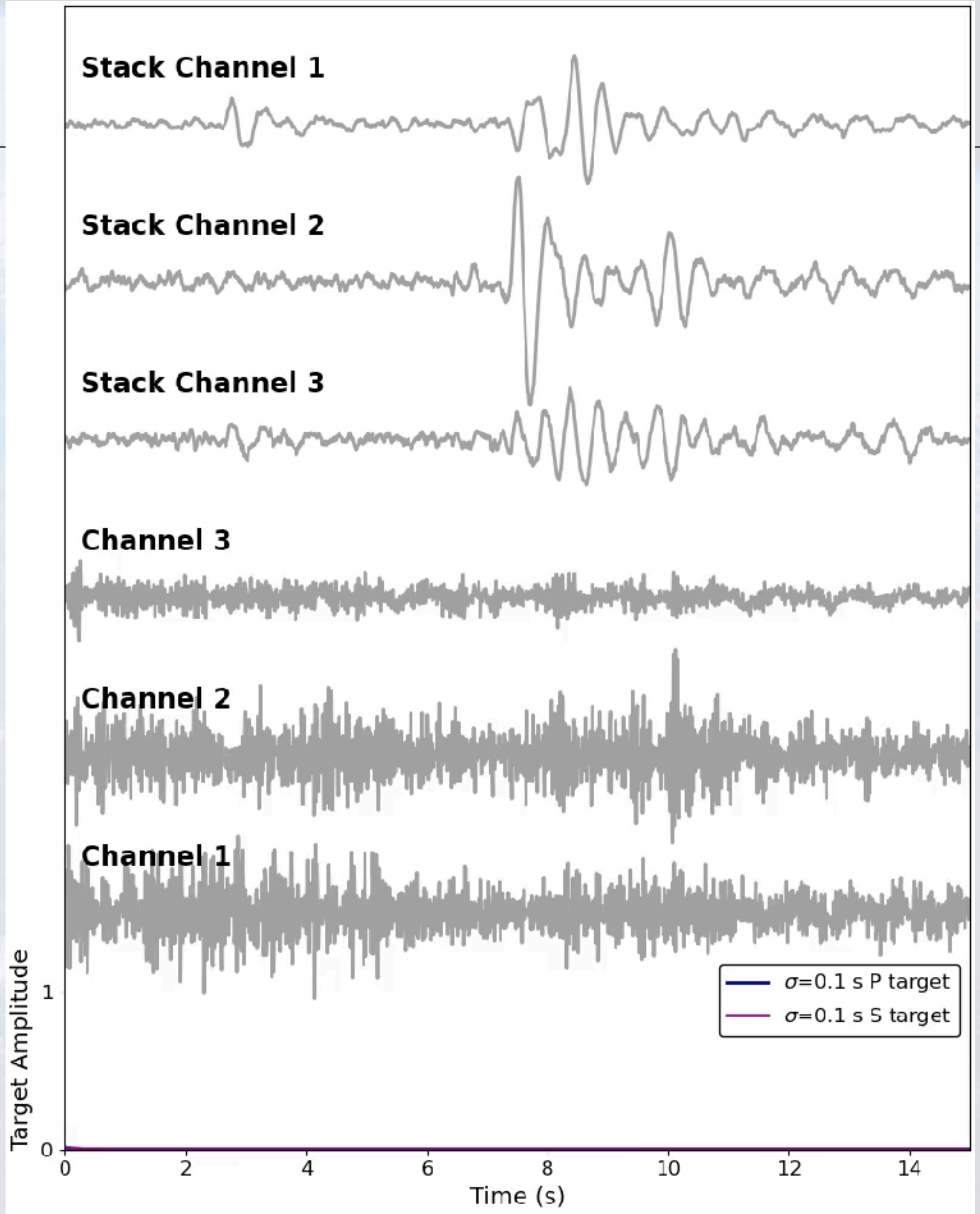
Cascadia seismicity

- We adopted the approach of Zhu and Beroza [2019] and trained a network to identify earthquakes and make phase picks
- It works really well for regular earthquakes!



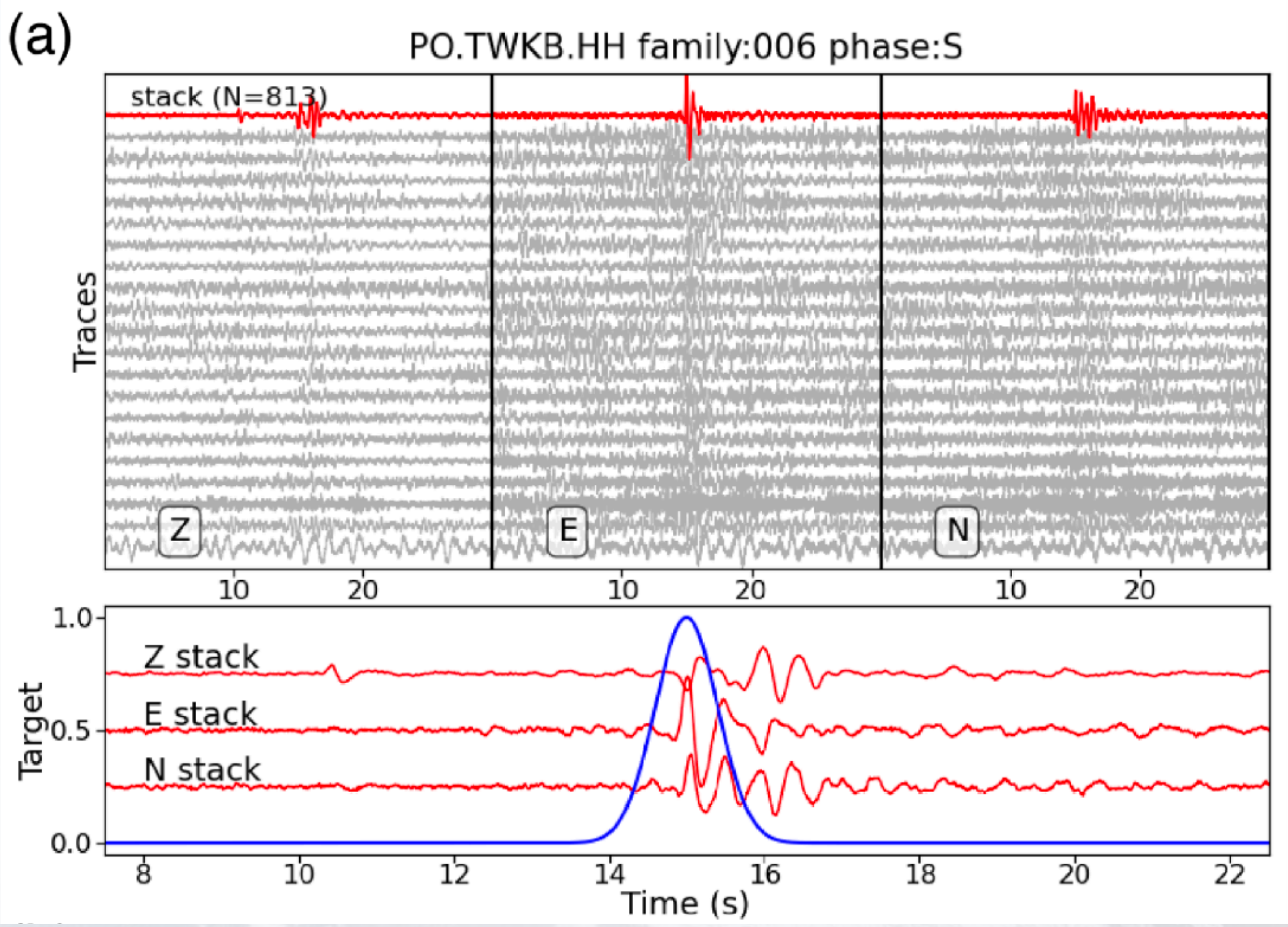
Cascadia seismicity

- We adopted the approach of Zhu and Beroza [2019] and trained a network to identify earthquakes and make phase picks
- It works really well for regular earthquakes
- Using those same pickers to detect for low-frequency earthquakes does not work very well…



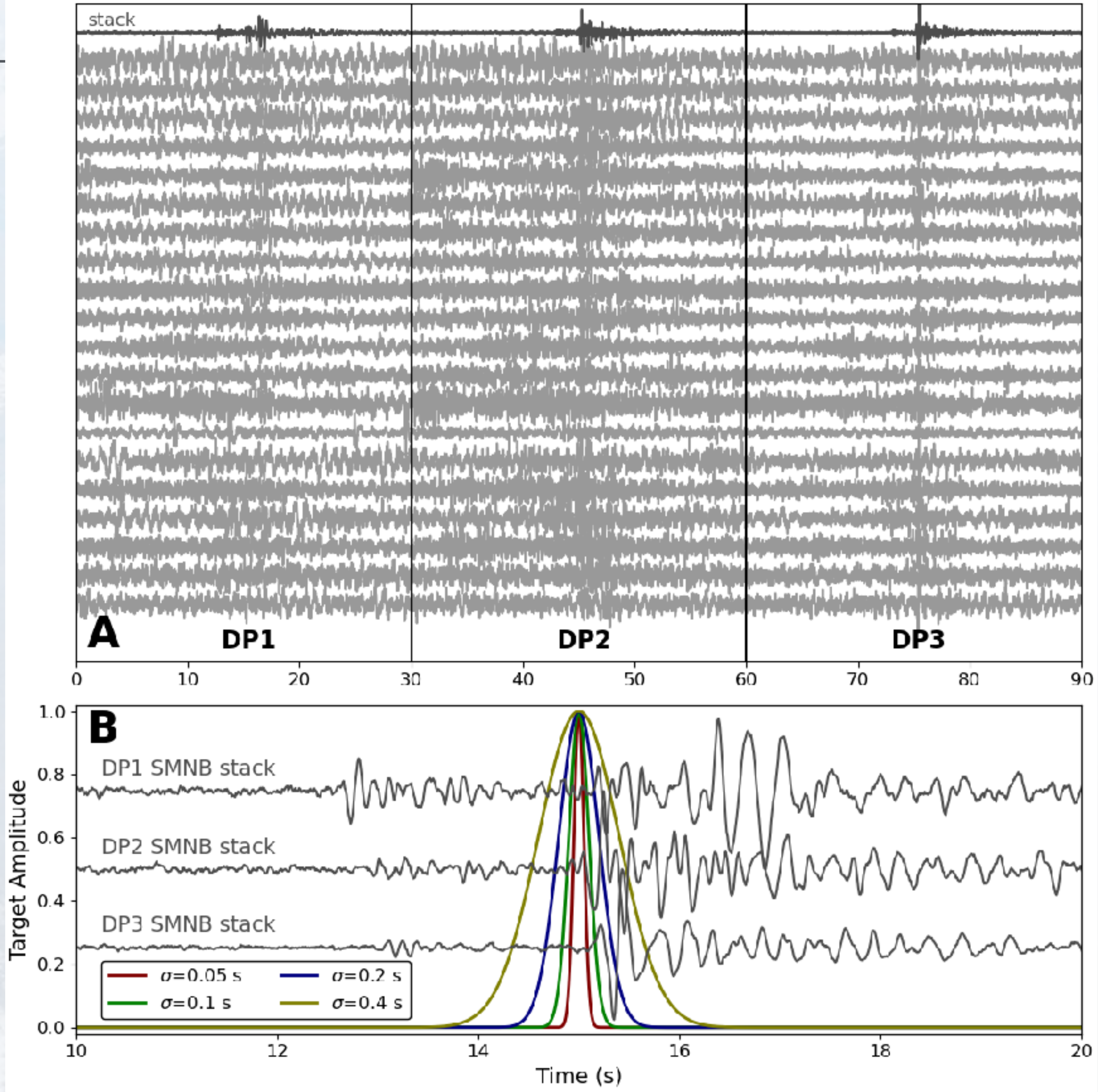
Cascadia seismicity

- Can we use the same deep learning approach we applied to regular earthquakes to detect LFEs?



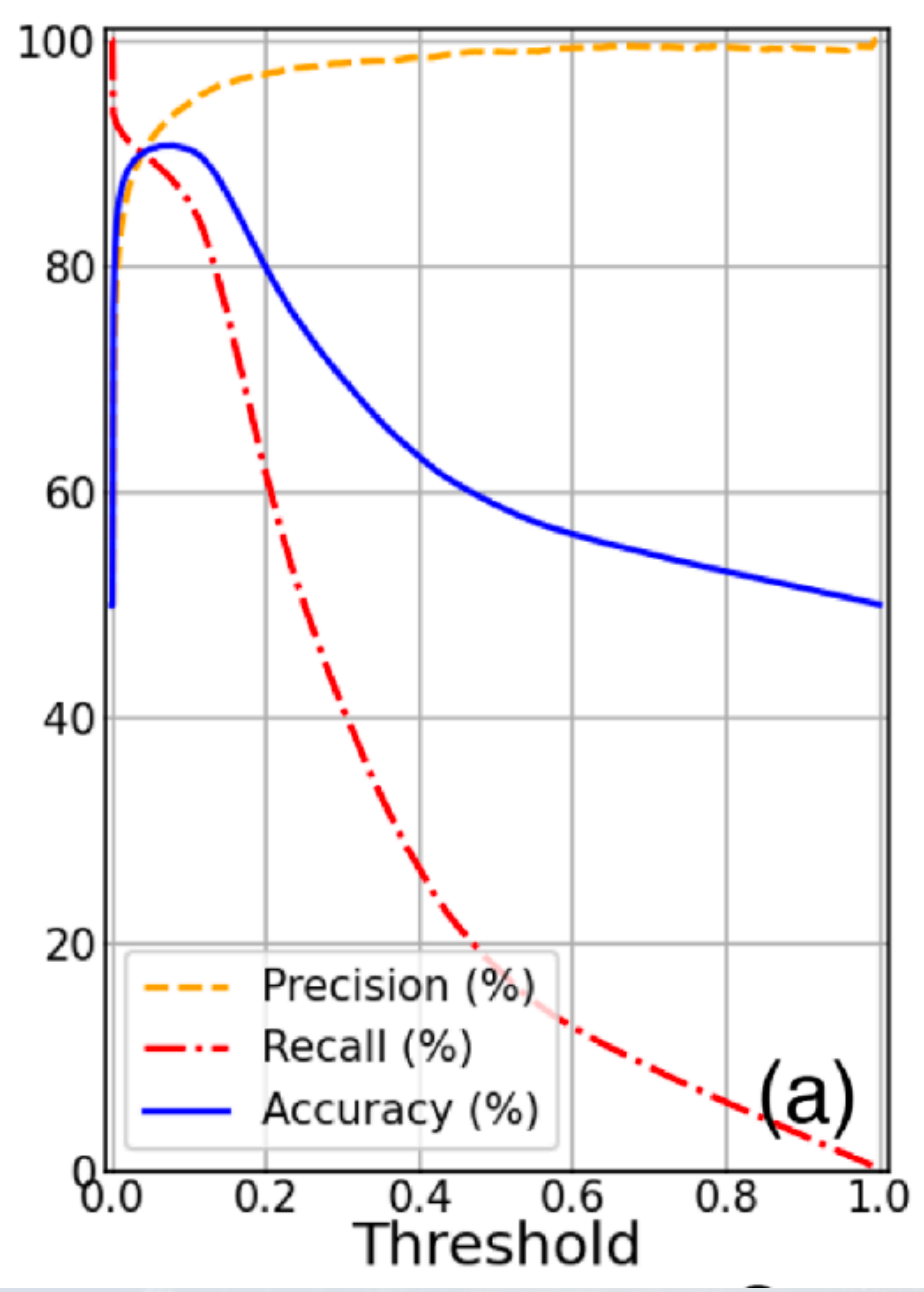
ML for LFEs

- We use the P and S-picks from LFE catalogs assembled via template matching to train our network
- Inputs are 3C waveforms; outputs are Gaussians centered on arrivals
- It’s difficult to impossible to see LFEs in the training data
- Given the low-frequency nature we add an additional target of 0.4 s

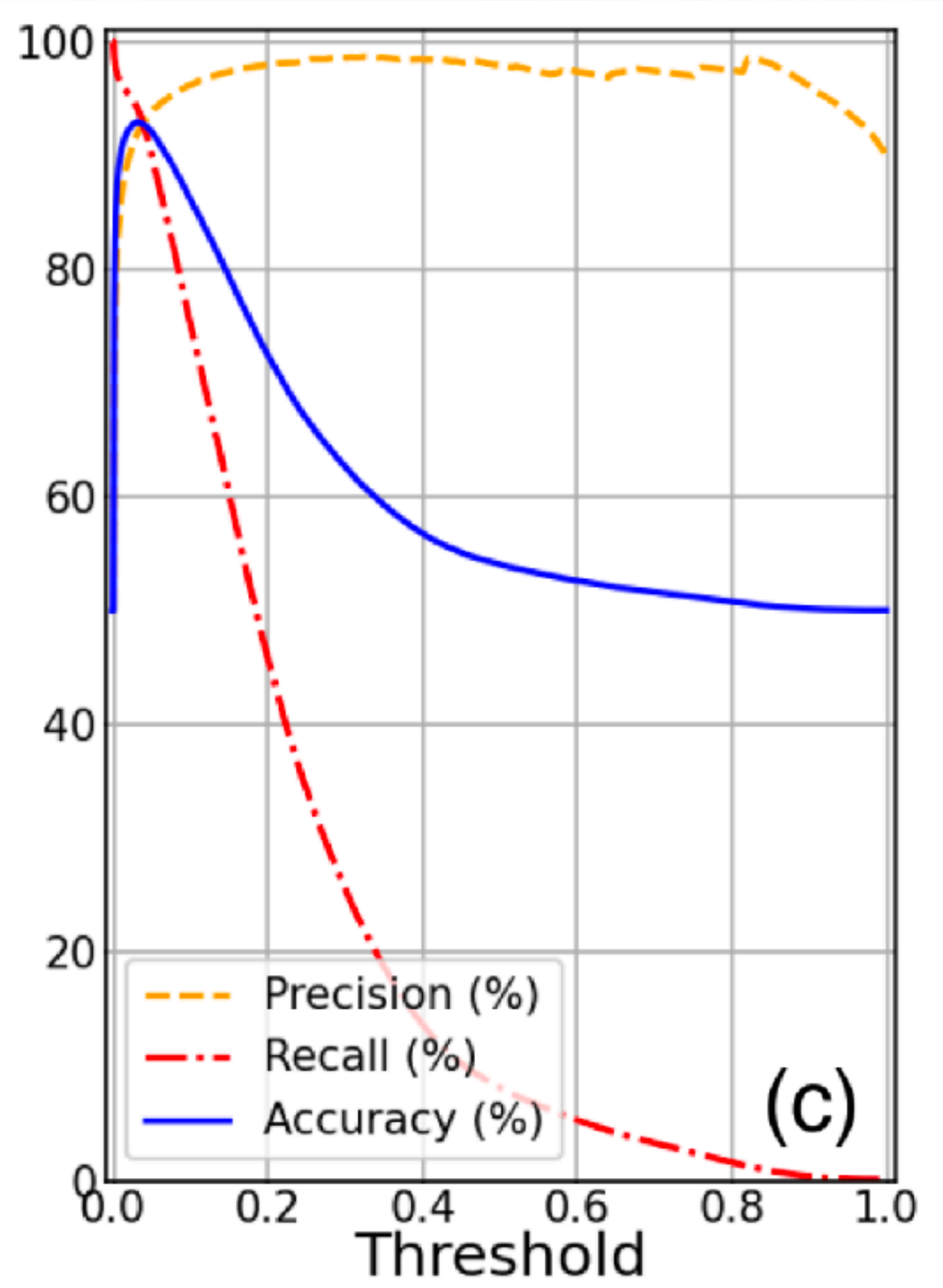


Performance metrics

P-wave model

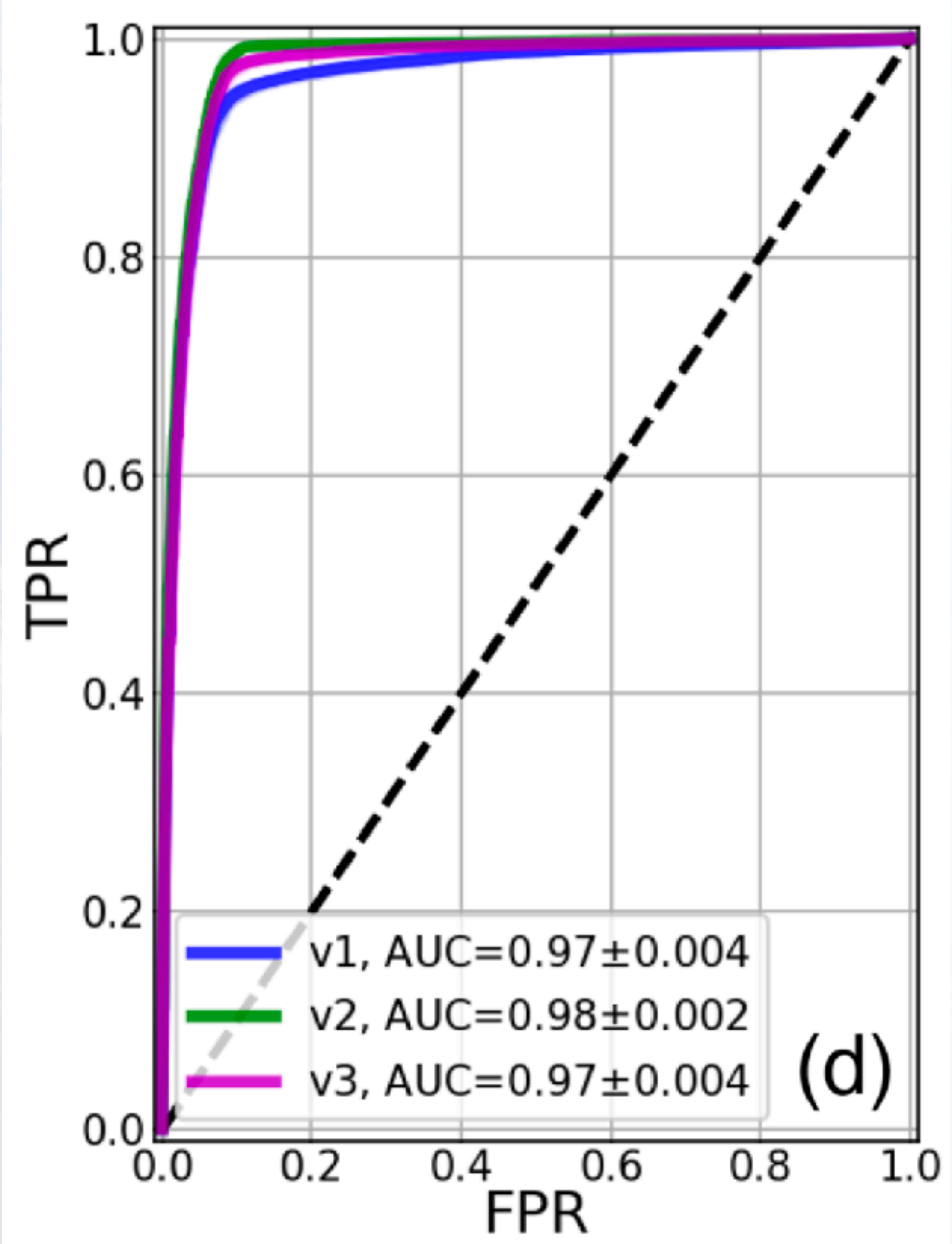


S-wave model



Model evaluation using ROC

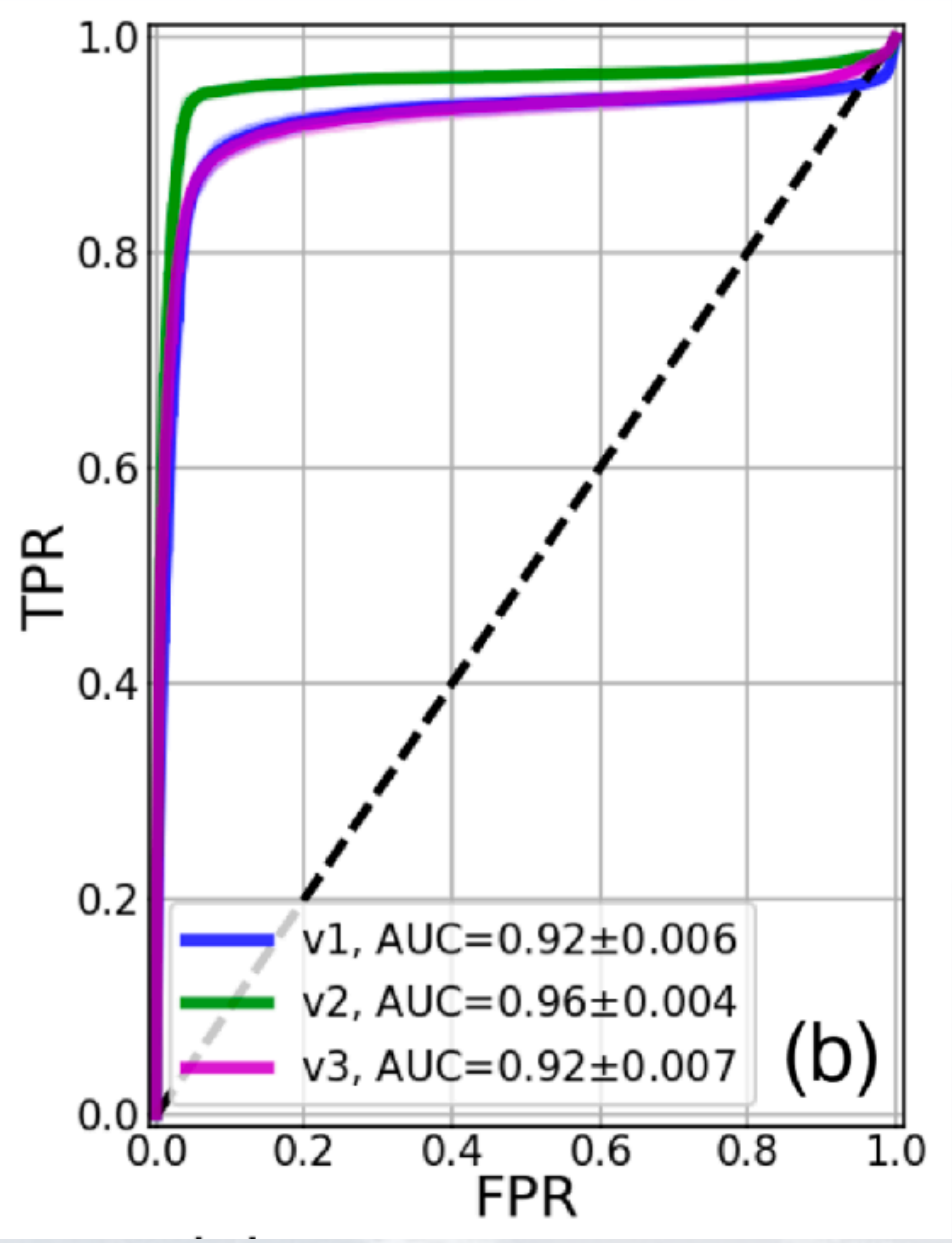
- ROC Curve: Plots true positive rate (TPR) vs. false positive rate (FPR) by varying decision thresholds.
- AUC (Area Under Curve) ranges from 0.5 (random guessing) to 1.0 (perfect model).
- Higher AUC = better model performance.



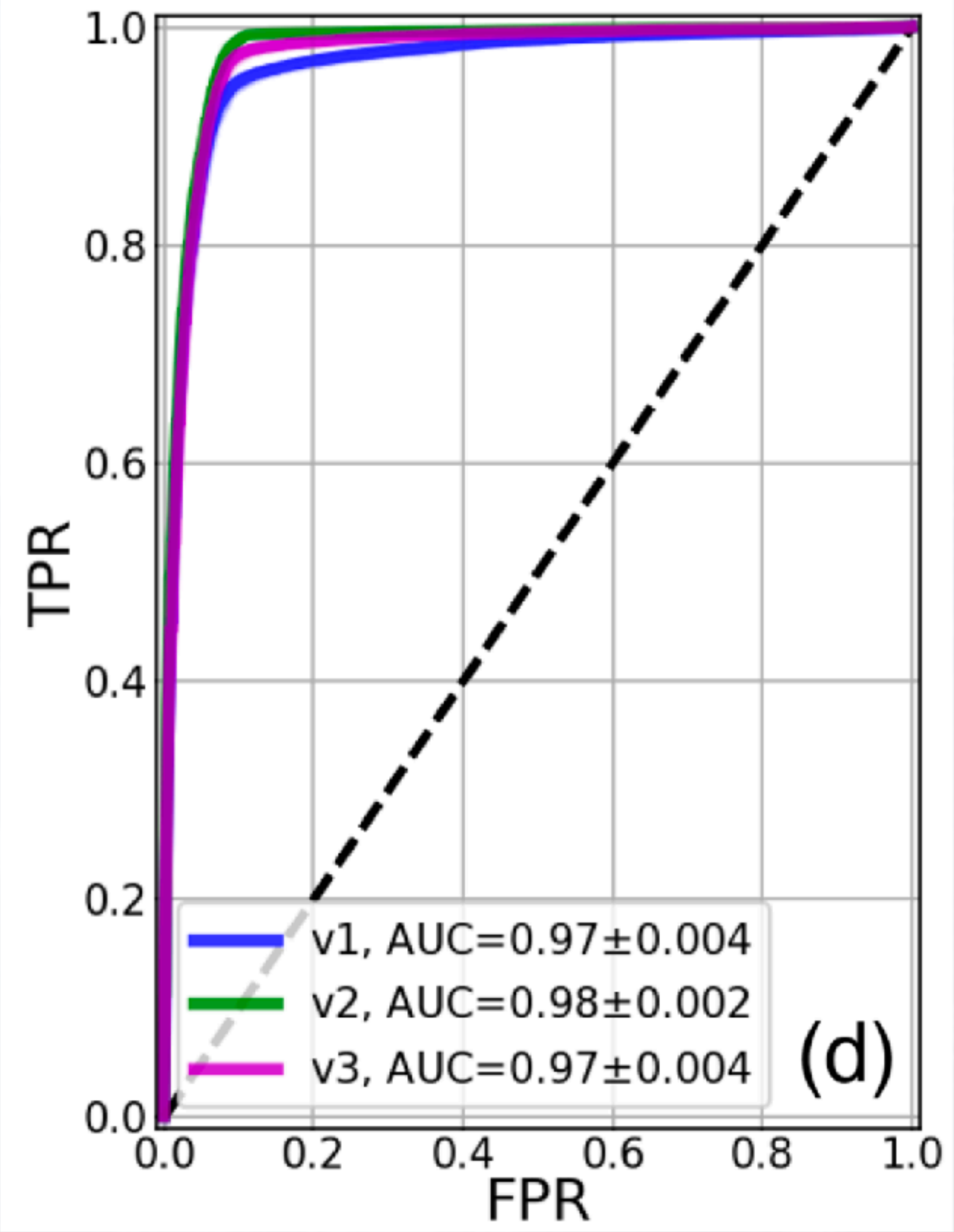
Model validation steps

- **Three evaluation setups:**
  - v1: Full test dataset.
  - v2: Only large events (M > 2.2).
  - v3: Recordings from <30 km epicentral distance.
- **For each setup:**
  - Generate 1,000 LFEs + 1,000 noise samples.
  - Repeat 20 times to get distribution of AUC values.

P-wave model



S-wave model



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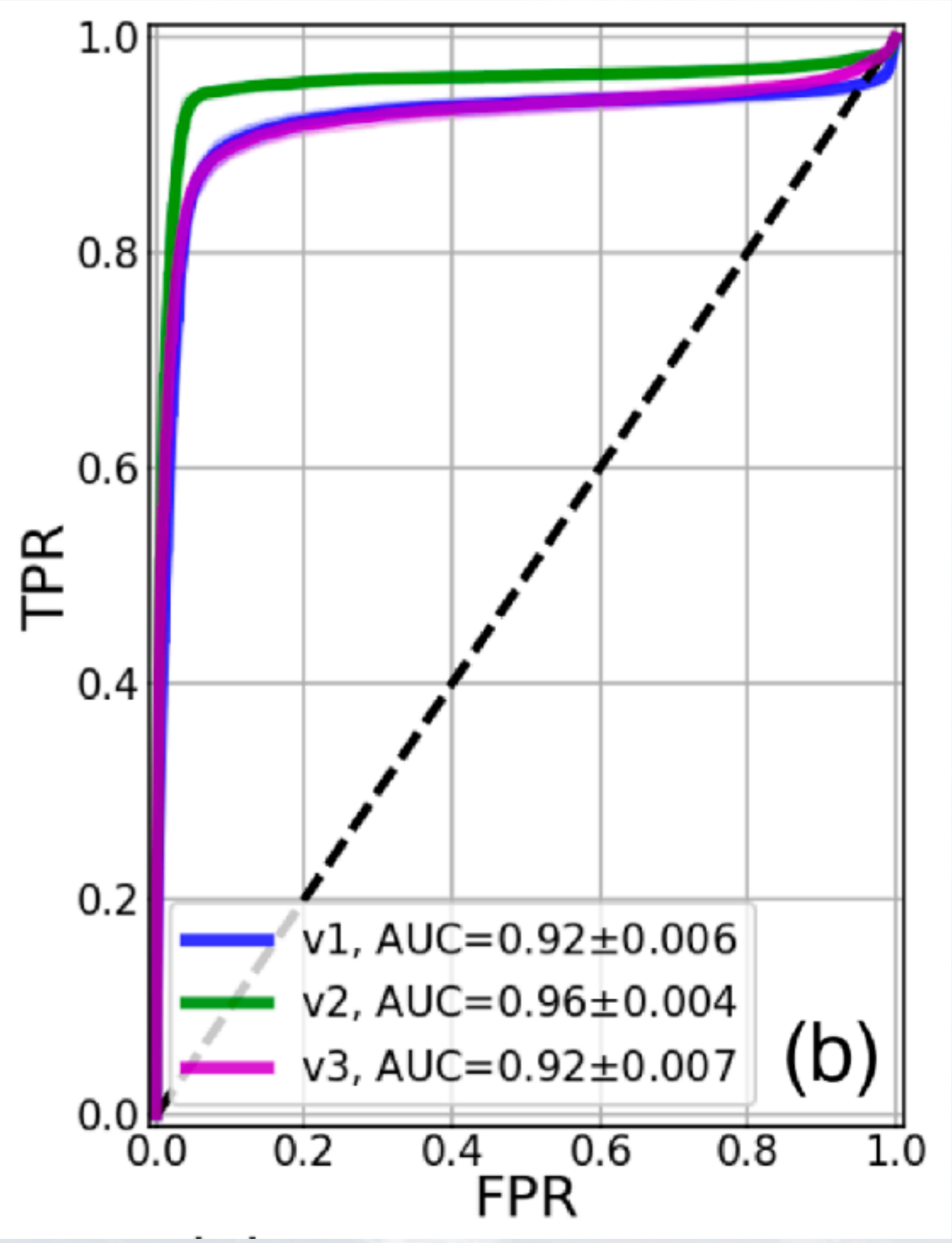

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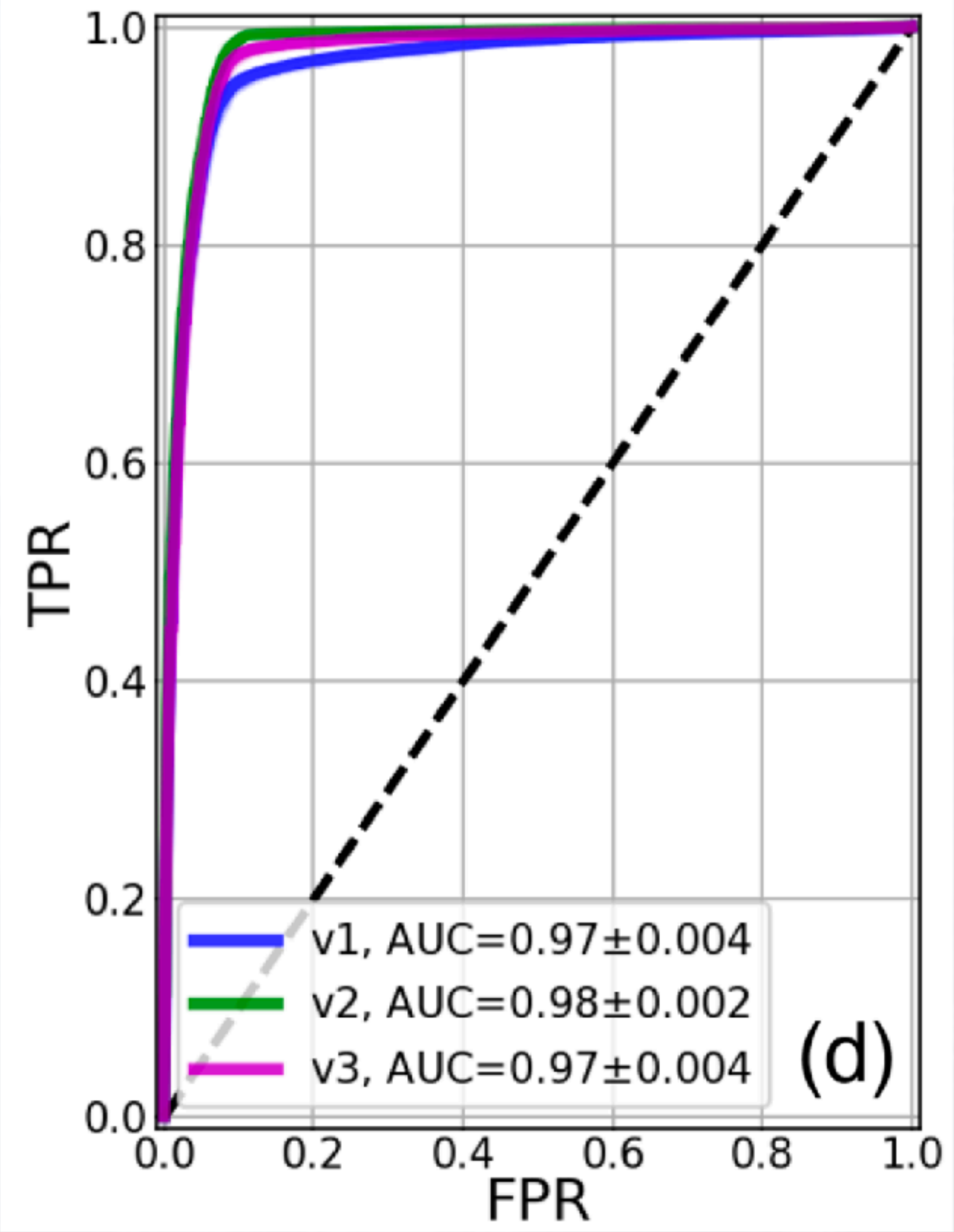
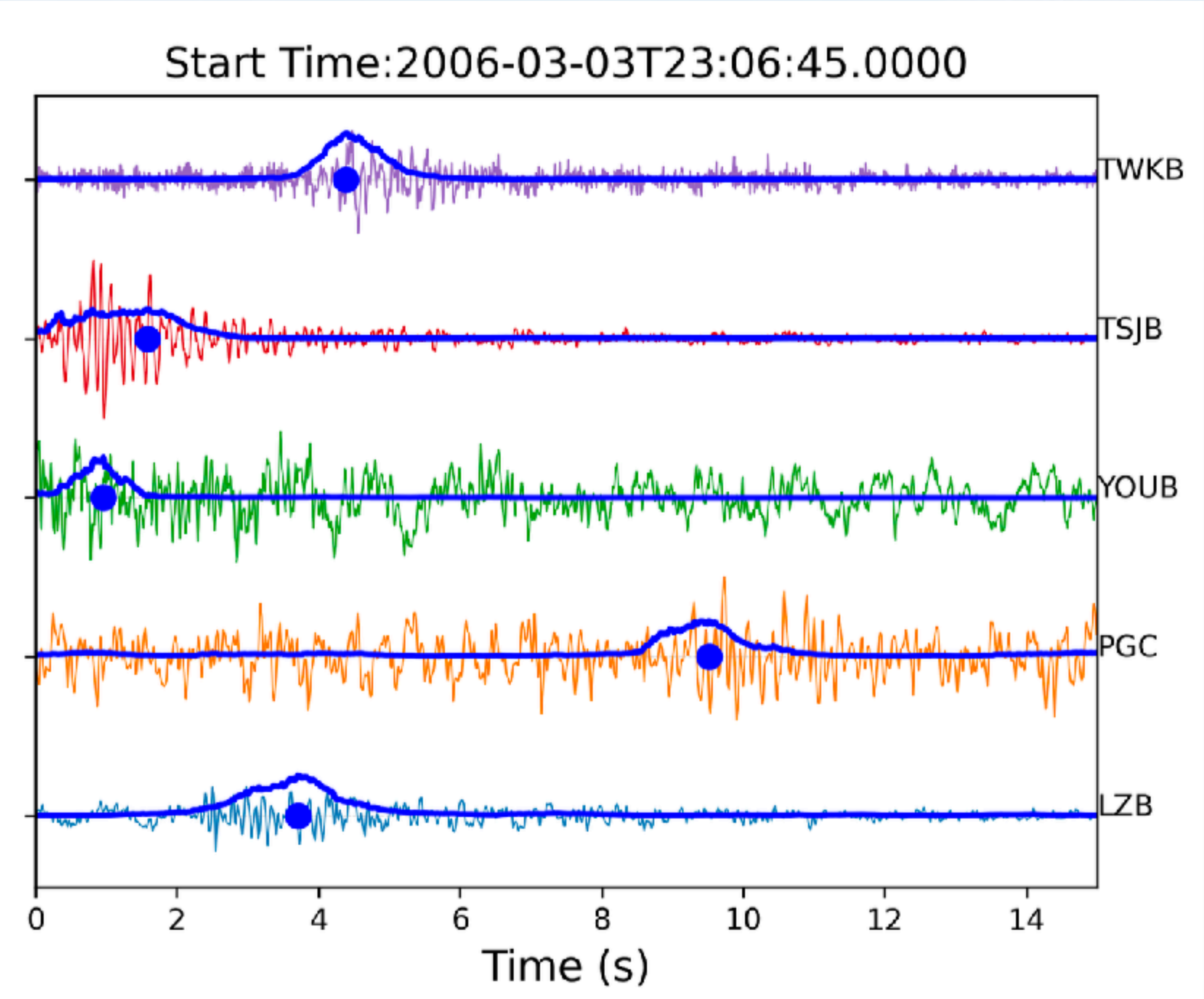
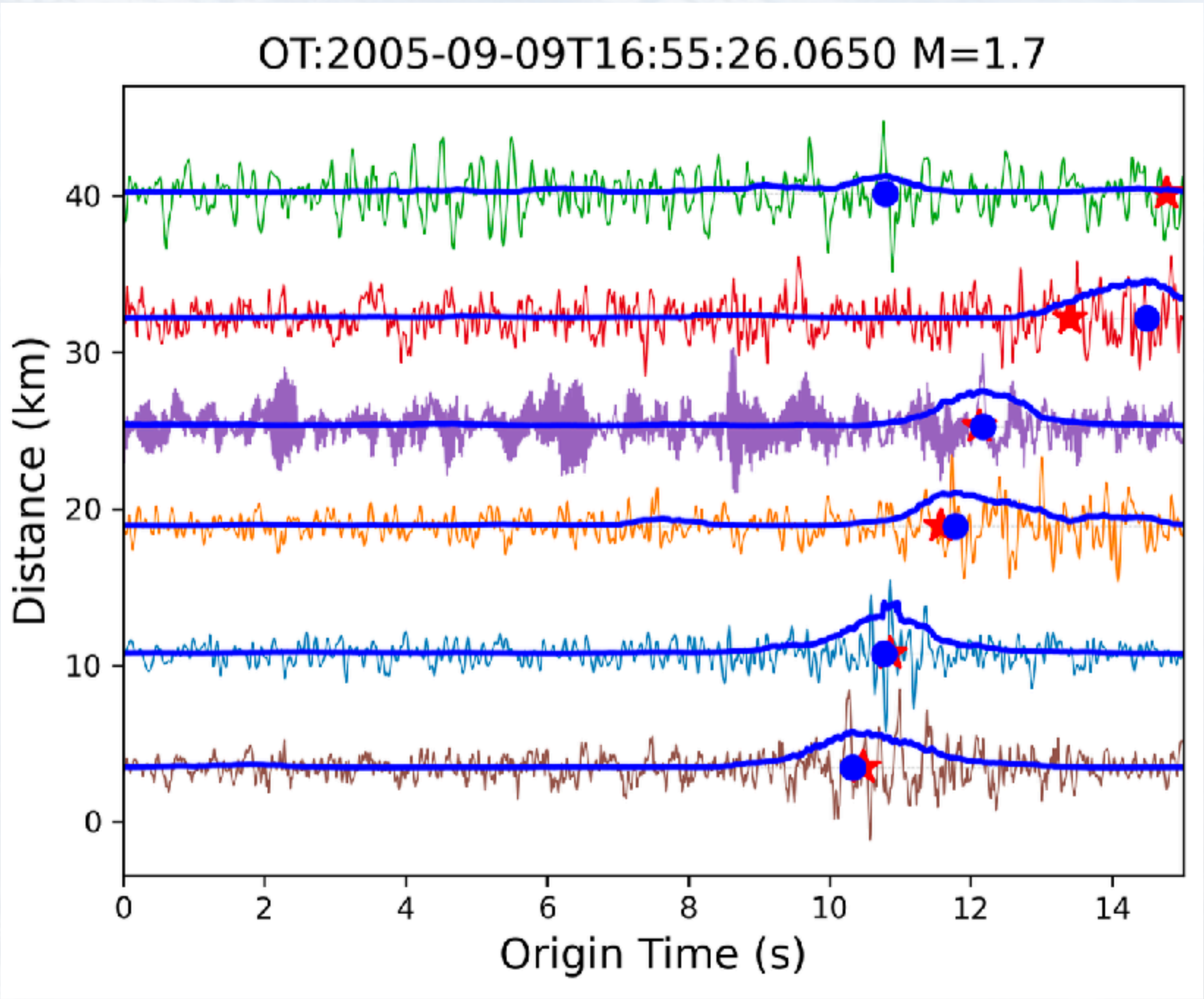
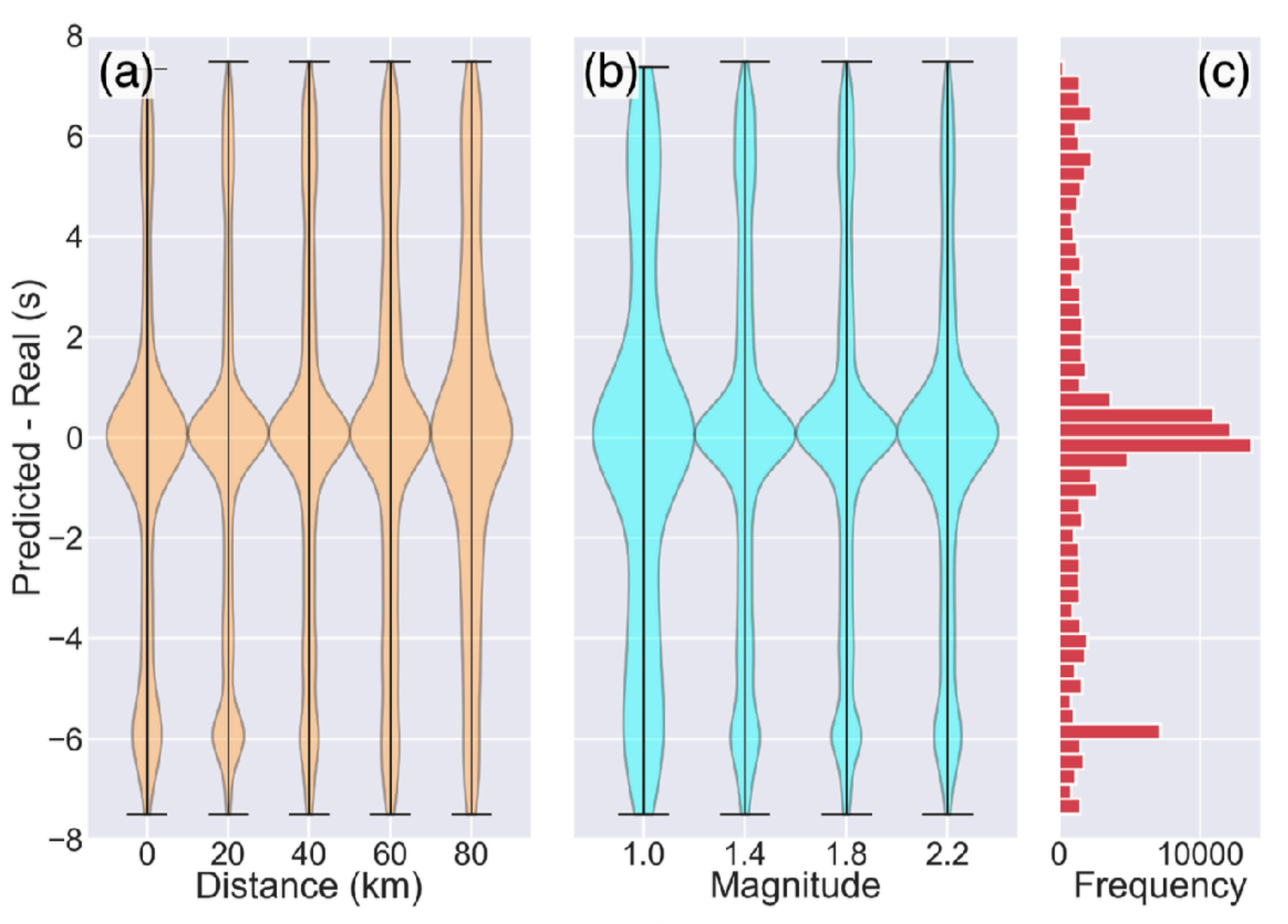


Example picks

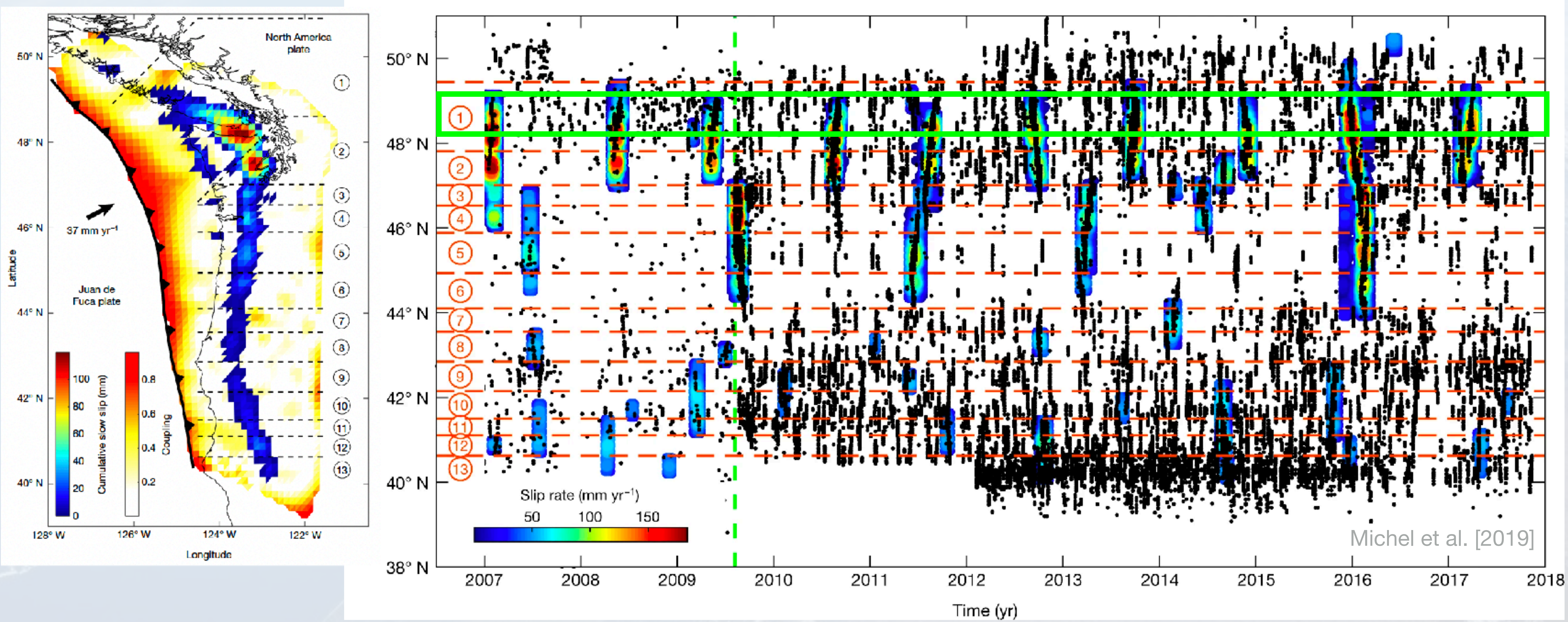




Arrival misfits

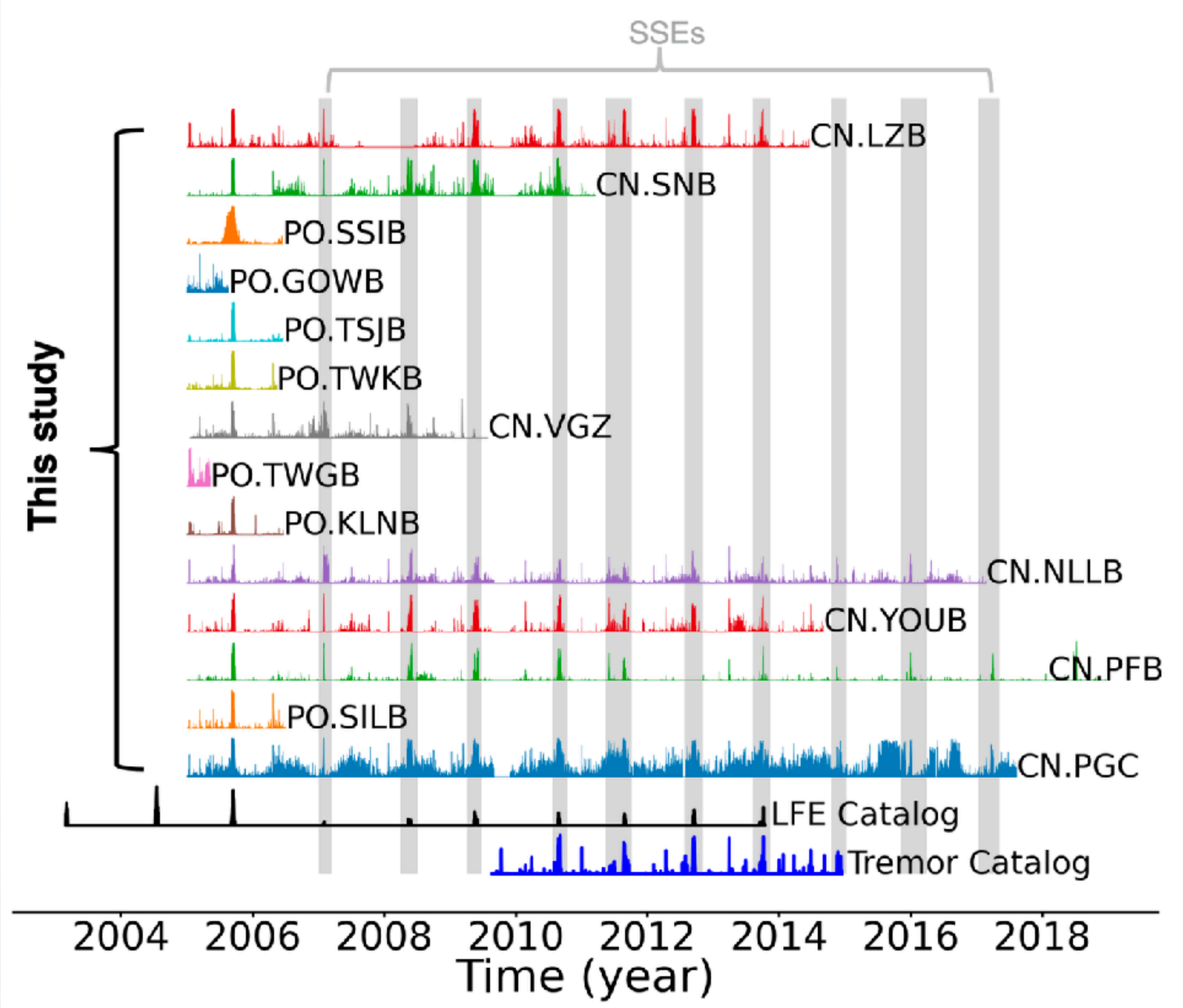


LFE data mining



LFE data mining

- Early data mining results are promising
- There are high daily detection counts across the network during times of known SSEs
- There are also many events between known SSEs — these could be real

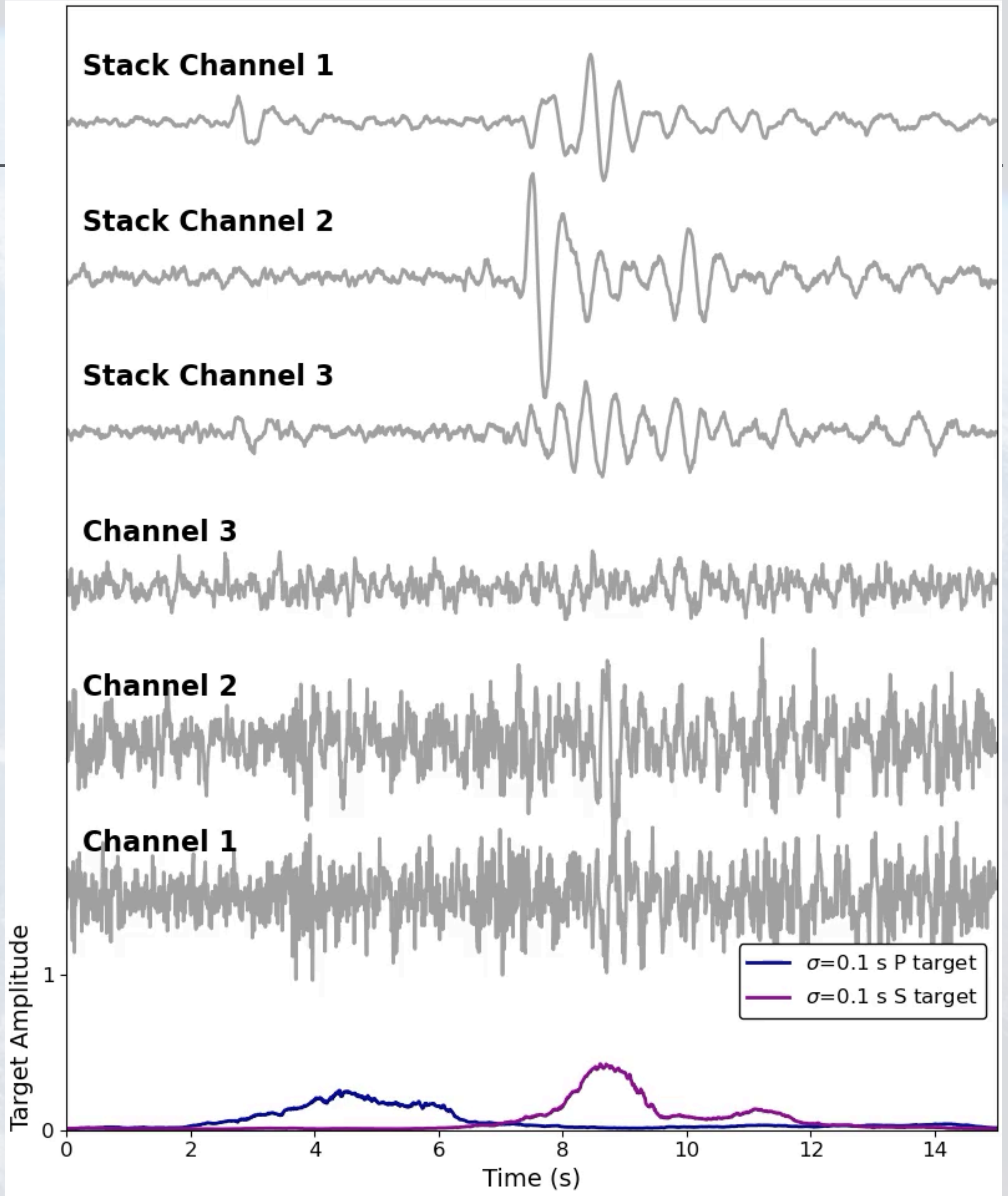


The way forward

- Deep learning can successfully identify LFEs in continuous seismic data despite their low-amplitude nature

- It is capable of identifying known and new LFEs

- Still working on validating detections but ML is a promising tool for identification and characterization of LFEs in massive datasets



Ongoing challenges

- Useful, but we're still far from ML derived LFE catalogs
- S-waves alone aren't enough
- Probably need a specially trained associator that can untangle overlapping LFEs (to the extent possible)
- Want to know more? — Lin, J.-T., Thomas, A., Bachelot, L., Toomey, D., Searcy, J., & Melgar, D. (2024). Detection of Hidden Low-Frequency Earthquakes in Southern Vancouver Island with Deep Learning. Seismica, 2(4). https://doi.org/10.26443/seismica.v2i4.1134