Deep Learning for Earthquake Monitoring

Weiqiang Zhu

University of California, Berkeley

Collaborators: Jiaxuan Li, Ettore Biondi, Jiuxun Yin, Hongyu Sun, John D. Wilding, Miao Zhang, Yongsoo Park, Yen Joe Tan, S. Mostafa Mousavi, Jennifer M. Jackson, Zachary E. Ross, Zhongwen Zhan, William Ellsworth, and Gregory Beroza

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Wide applications of deep learning

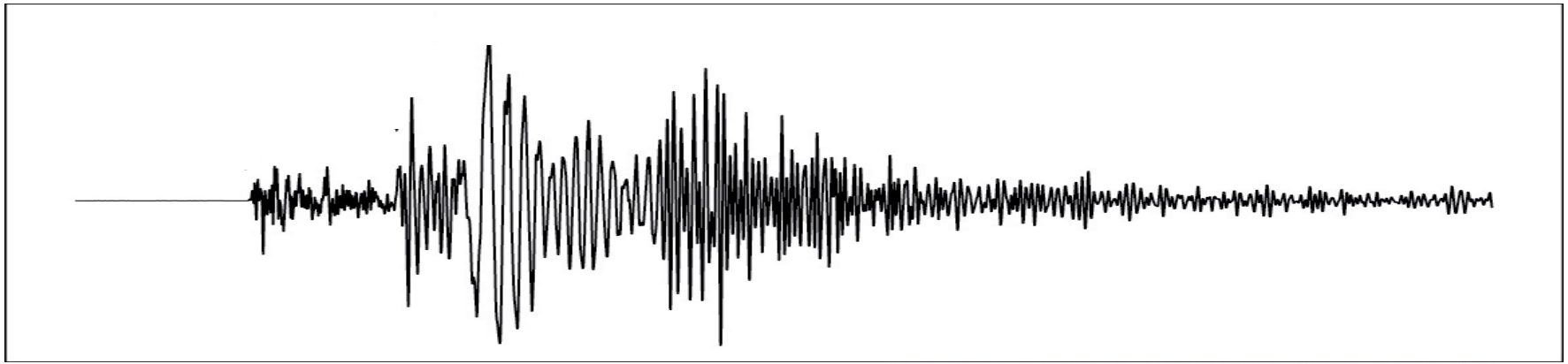
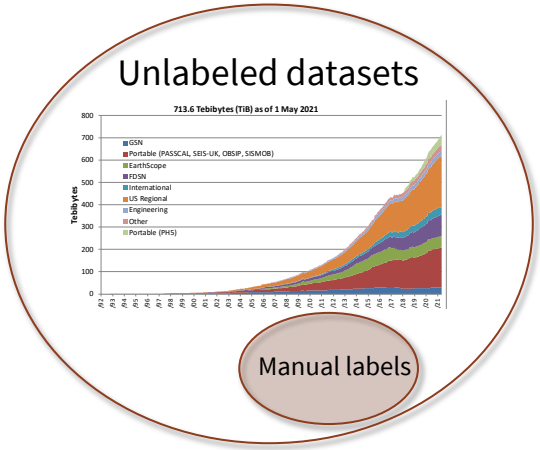


Figure sources: 1 2 3 4 5

Large datasets in seismology for deep learning

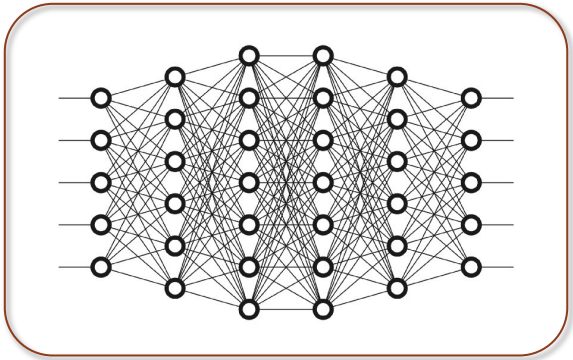
Dataset	Earthquake seismogram (×10⁶)	Noise seismogram (×10⁶)	Region	First-motion Polarity
DiTing-330 km (this study)	2.74	0	China	√
STEAD (Mousavi et al., 2019)	1.05	0.10	Global	×
INSTANCE (Michelini et al., 2021)	1.20	0.13	Italy	√
LEN-DB (Magrini et al., 2020)	0.63	0.62	Global	×
NEIC (Yeck et al., 2021)	1.30	0	Global	×
SCEDC-Phase (Ross et al., 2018a)	3.50	1.50	U.S.	×
SCEDC-Motion (Ross et al., 2018b)	2.53	2.32	U.S.	√

(Zhao et al. 2023)



Learning effective models from manual labels

Deep Neural Networks

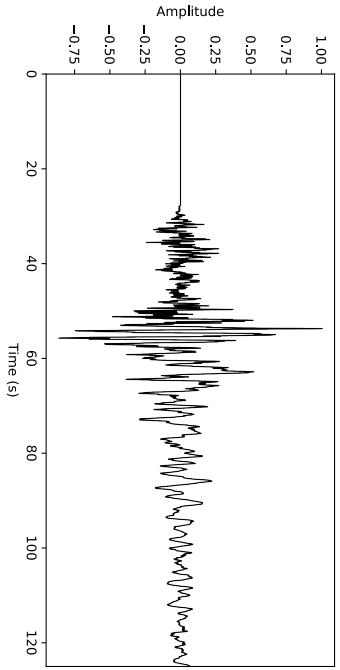


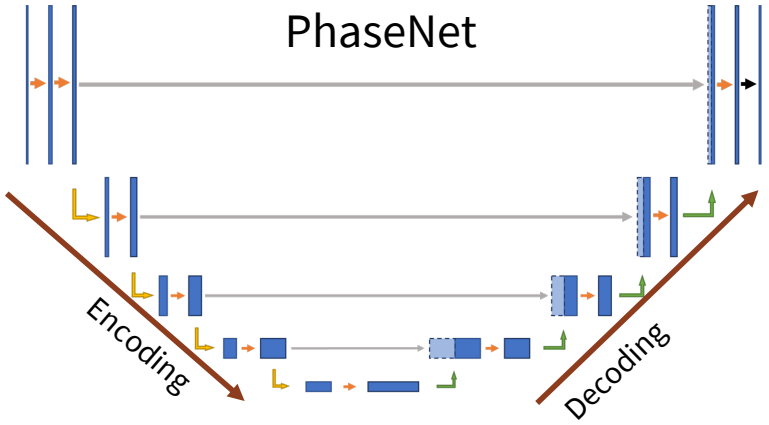
Detecting hidden signals from large datasets

Figure sources: 1, 2

Supervised learning to pick P/S phase arrivals

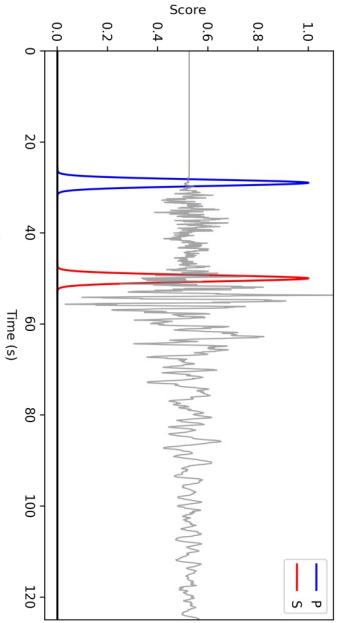
Input 3C waveform





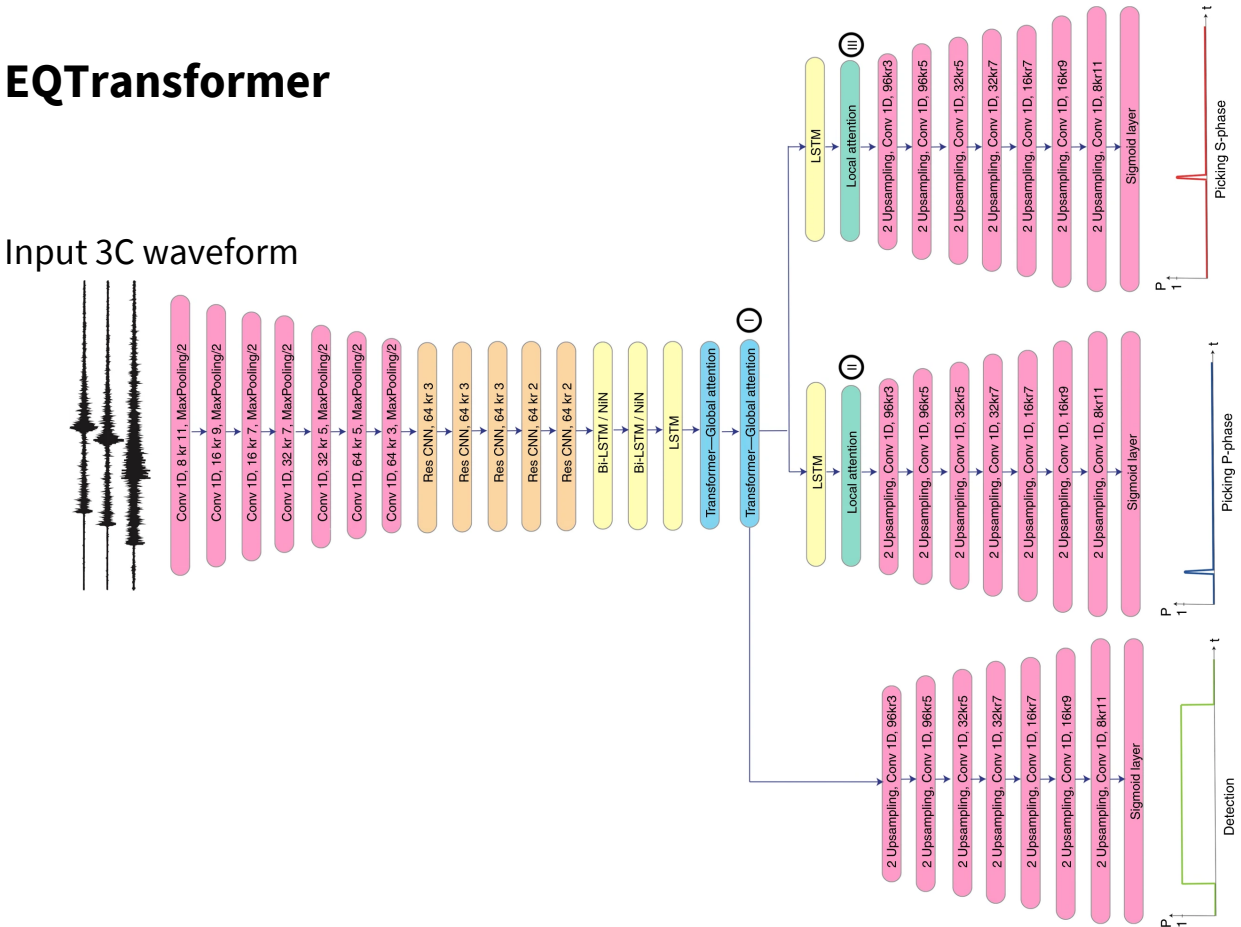
(Zhu and Beroza, 2018)

Target function



Multi-tasking detecting events and picking P/S phases

EQTransformer



Pick S-phase

Pick P-phase

Detect event window

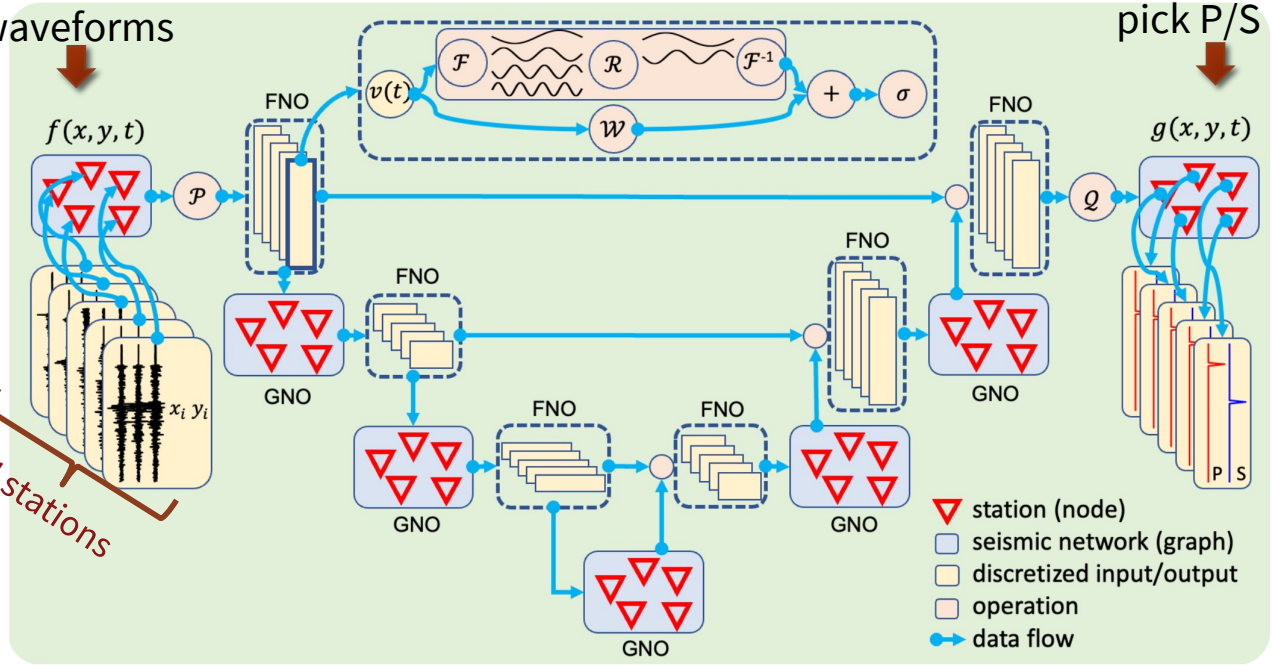
(Mousavi et al. 2020)

Multi-station phase picking

Input multi-station waveforms

PhaseNO

Simultaneously pick P/S phases



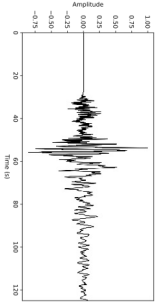
FNO: Fourier neural operator
- Learning temporal information
- Encoding seismic waveforms

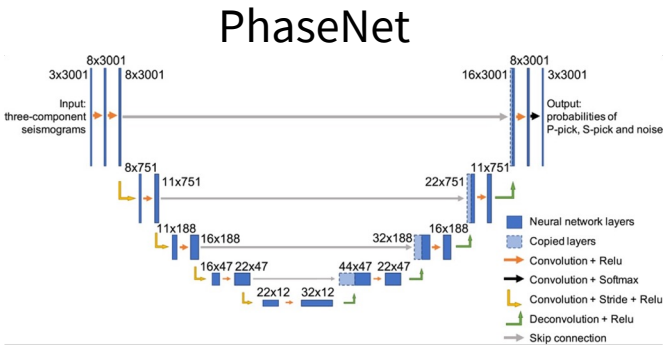
GNO: Graph neural operator
- Learning spatial relationship
- Modeling spatial-temporal moveouts

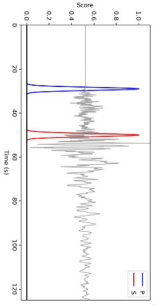
(Sun et al. 2023)

Generalizing to Distributed Acoustic Sensing (DAS)

- Seismometer (3 components)

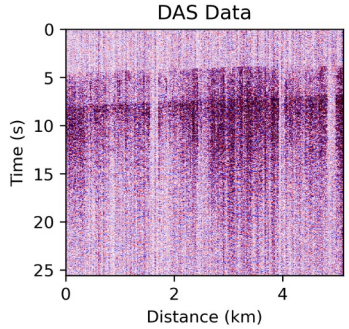


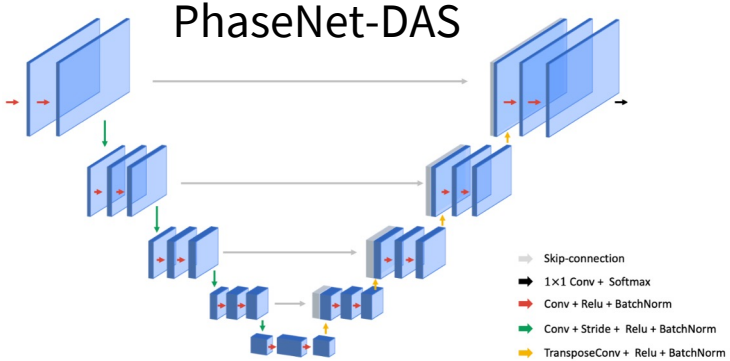


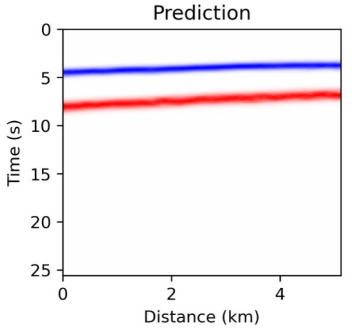


(Zhu and Beroza, 2018)

- Distributed Acoustic Sensing (>1,000 channels)

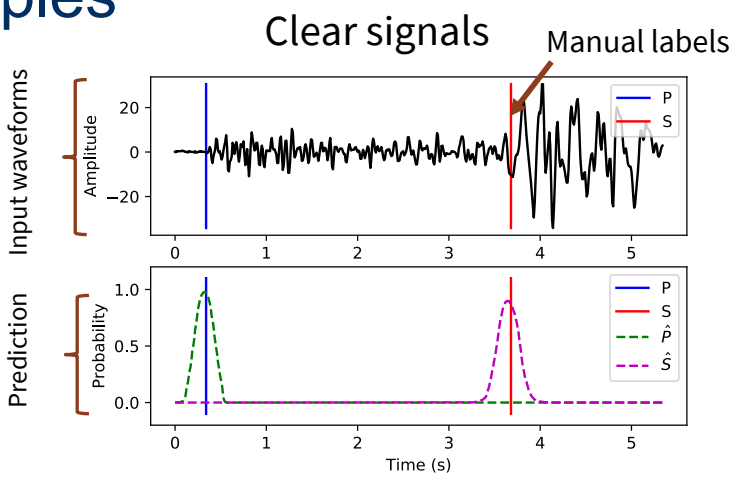


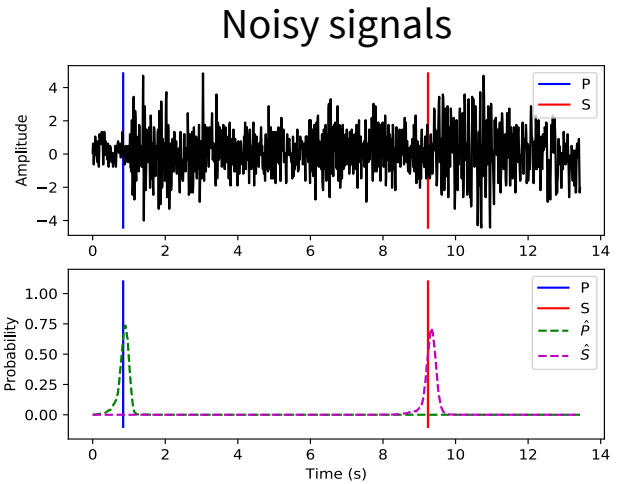


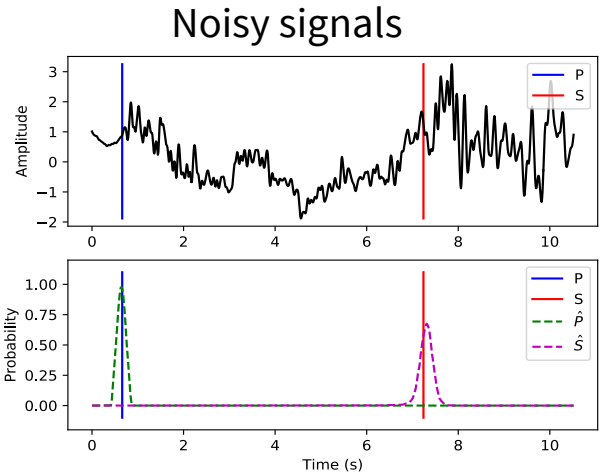


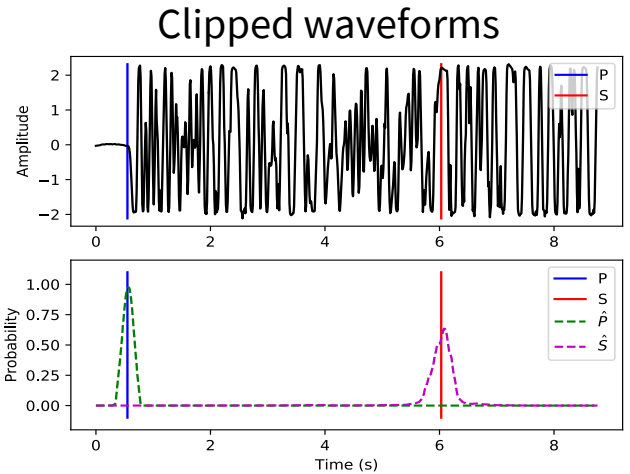
(Zhu et al., 2023)

Examples





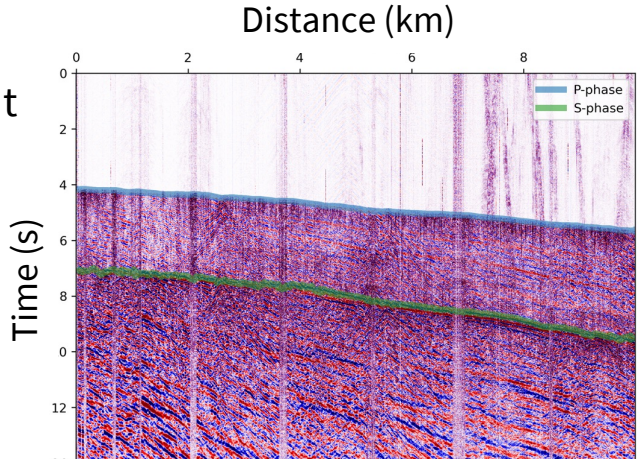




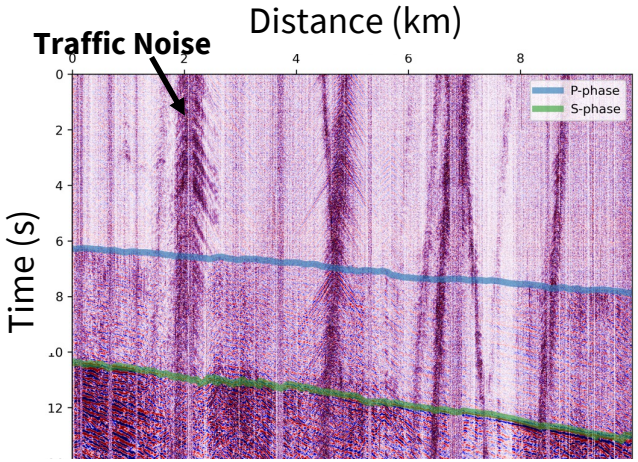
(Zhu and Beroza, 2018)

Examples on DAS

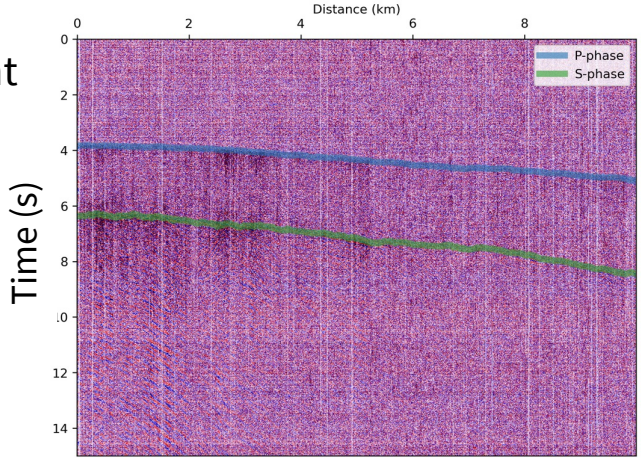
Good event signal



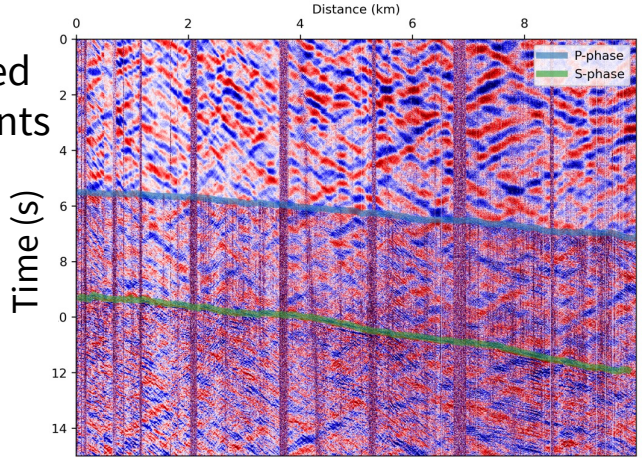
Event buried In traffic noise



Weak event signal



Event overlapped by previous events



(Zhu et al., 2023)

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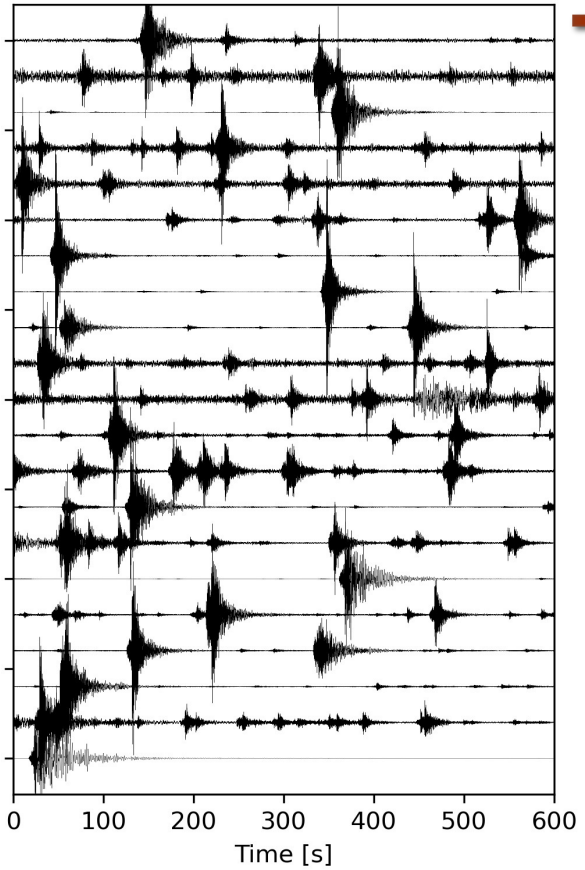


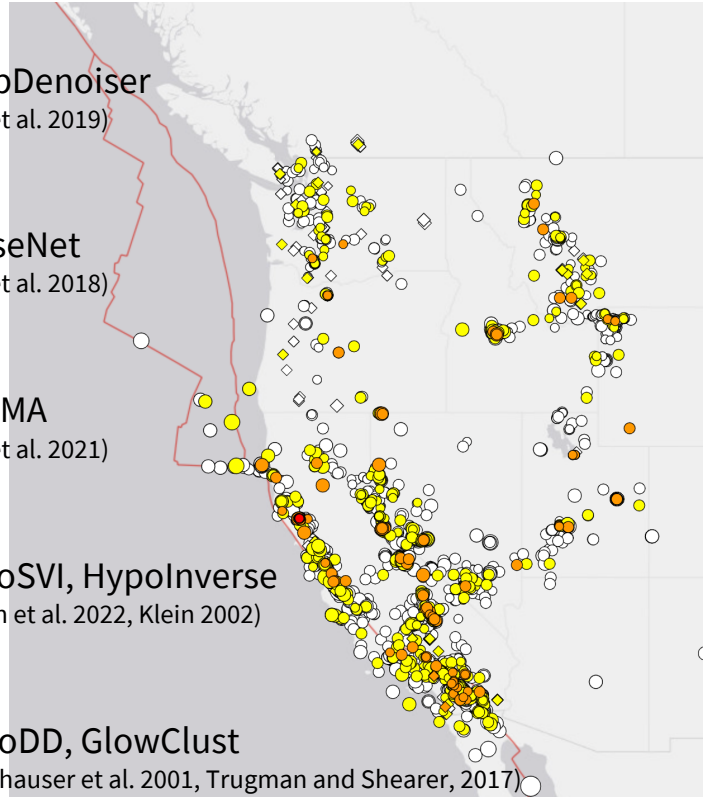
Pre-processing — DeepDenoiser (Zhu et al. 2019)

Phase Picking — PhaseNet (Zhu et al. 2018)

Phase Association — GaMMA (Zhu et al. 2021)

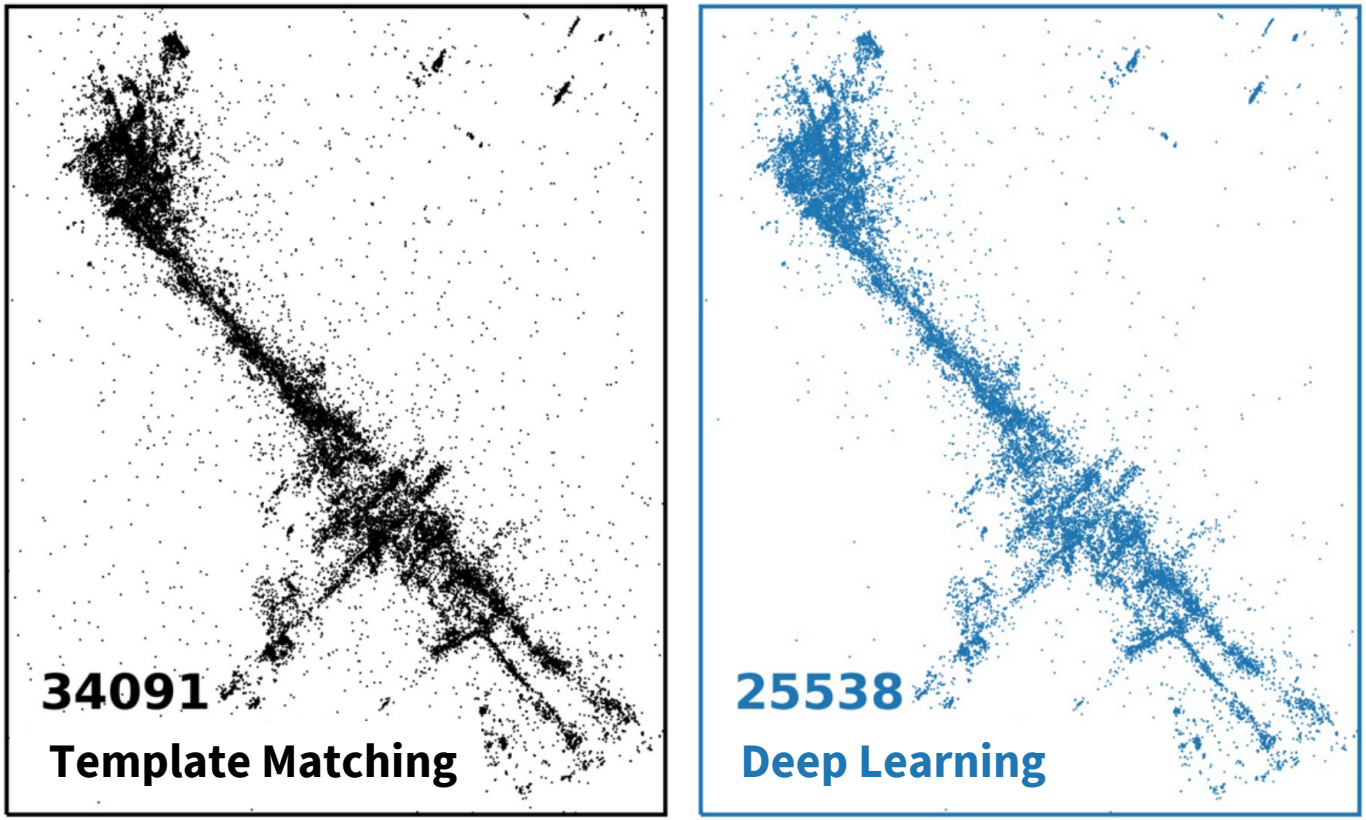
Earthquake Location — HypoSVI, HypoInverse (Smith et al. 2022, Klein 2002)

Earthquake Relocation — HypoDD, GlowClust (Waldhauser et al. 2001, Trugman and Shearer, 2017)



(staging-earthquake.usgs.gov)

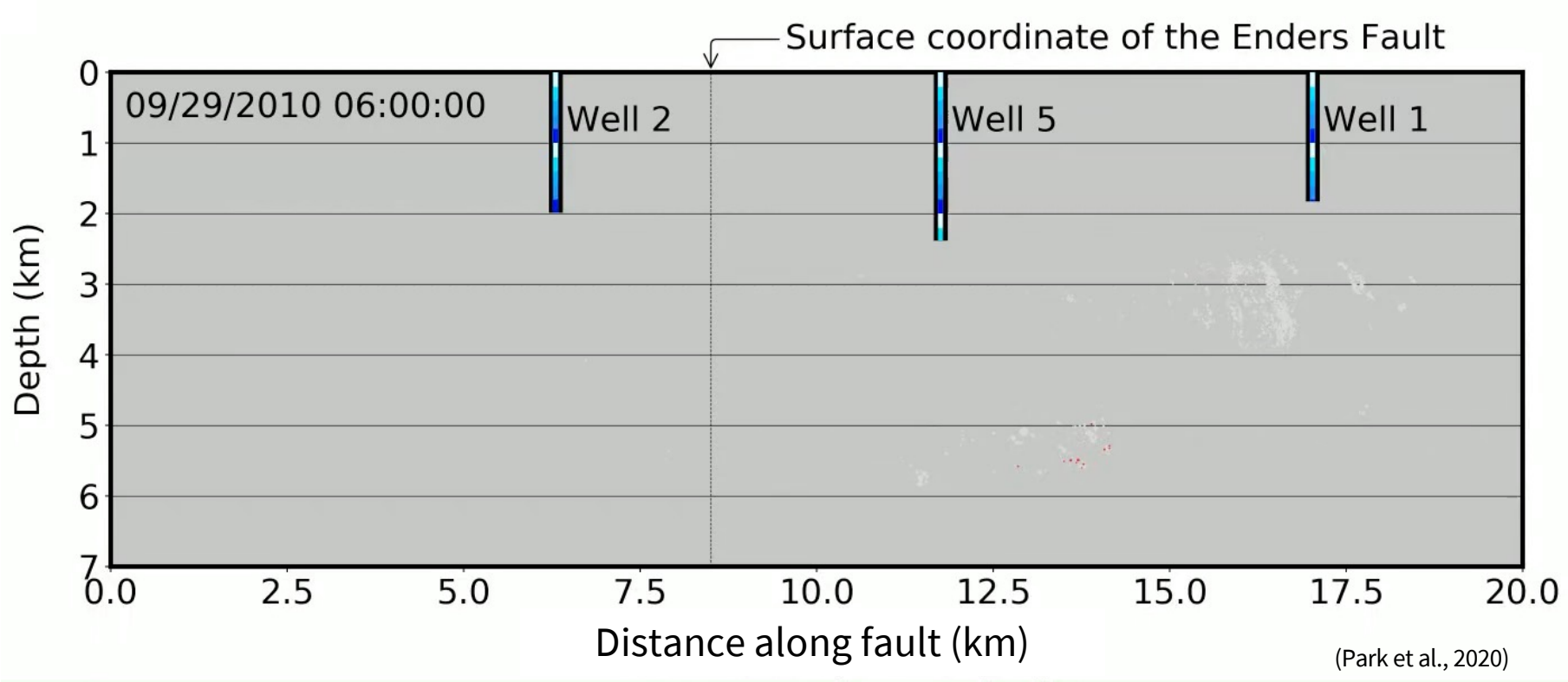
Applying to tectonic earthquakes



- Comparable accuracy
- Significantly faster
- No need for templates
- Generalizing to events beyond templates

(Park et al. 2023)

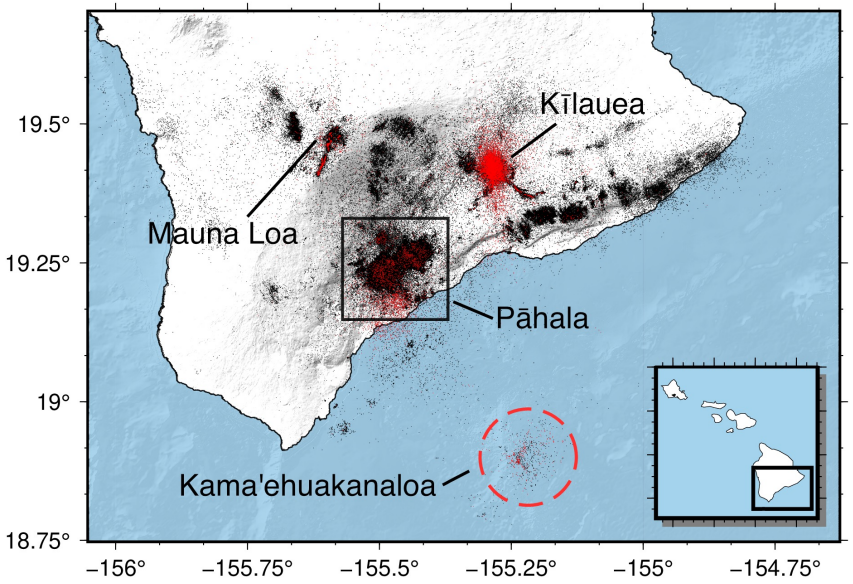
Applying to Induced Earthquakes



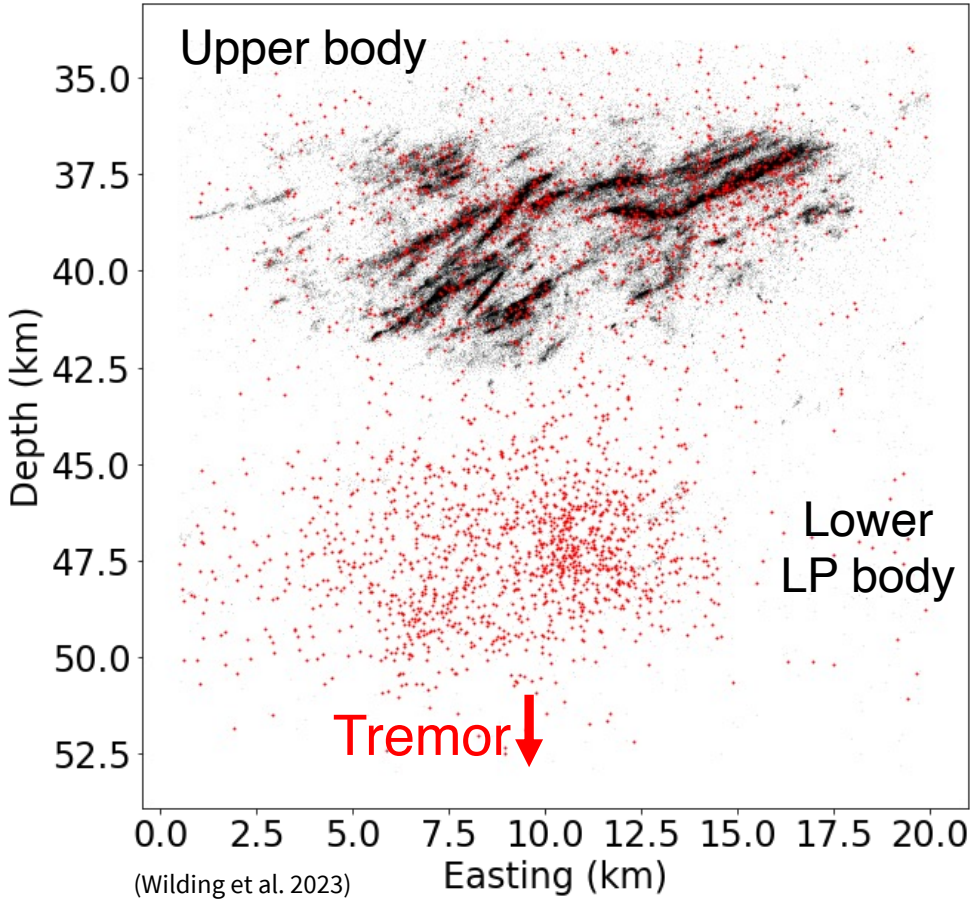
(Park et al., 2020)

- Analyzing connections between water injection and earthquakes sequences
- A clear view of the initiation and bilateral migration of the second sequence

Applying to Volcanic Earthquakes



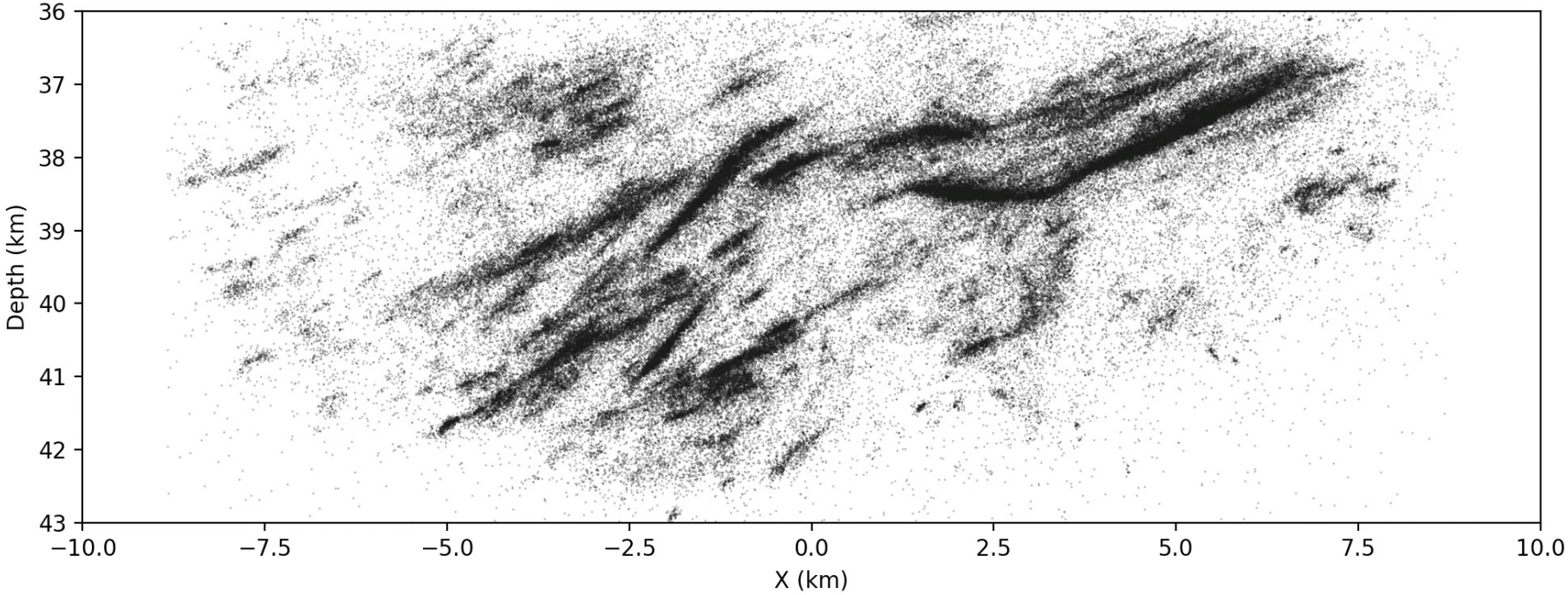
The longest and most intense noneruptive volcano-related earthquake swarm ever observed by a seismic network
(Flinders 2023)



(Wilding et al. 2023)

Volcano-tectonic earthquake
Long-period earthquake

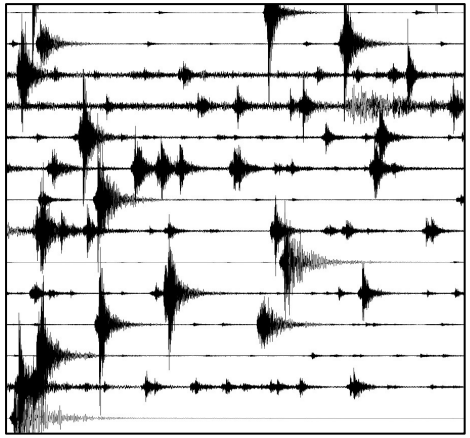
Detailed structures of Pāhala sills



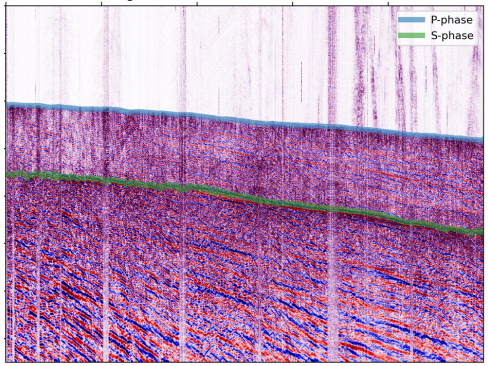
(Wilding et al. 2023)

Deep Learning for Earthquake Monitoring

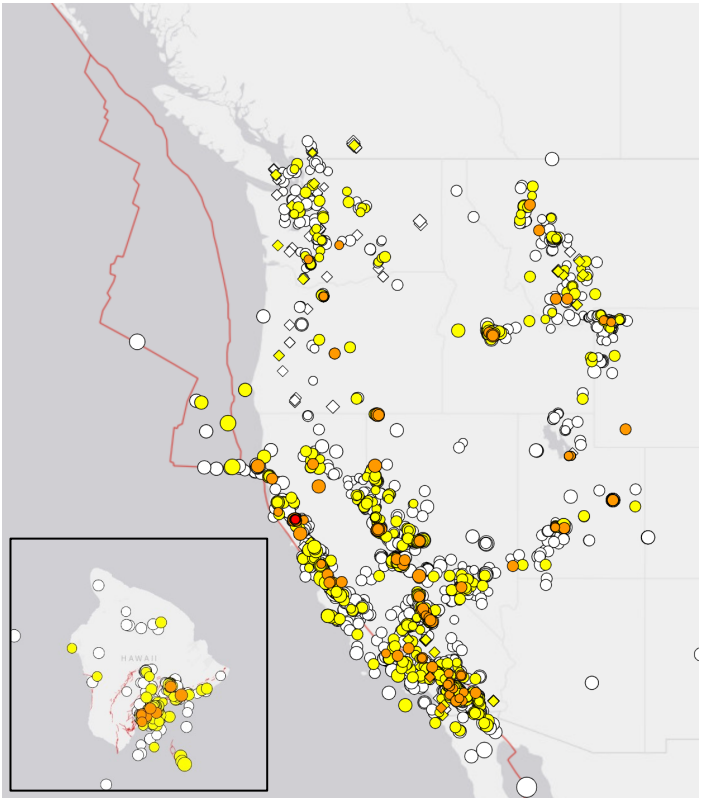
Seismic network



Fiber-optic network

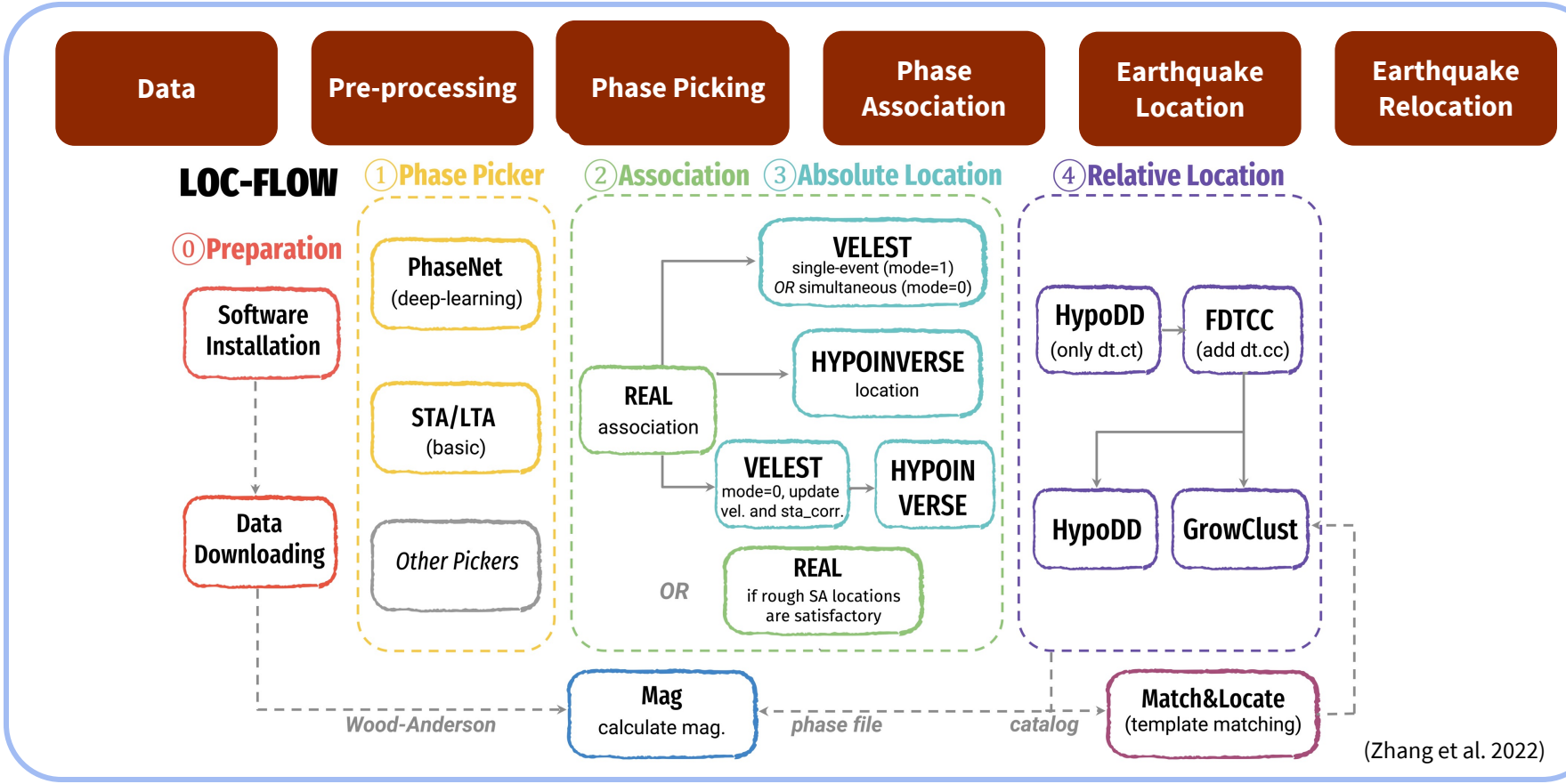


An End-to-End Network for Earthquake Monitoring



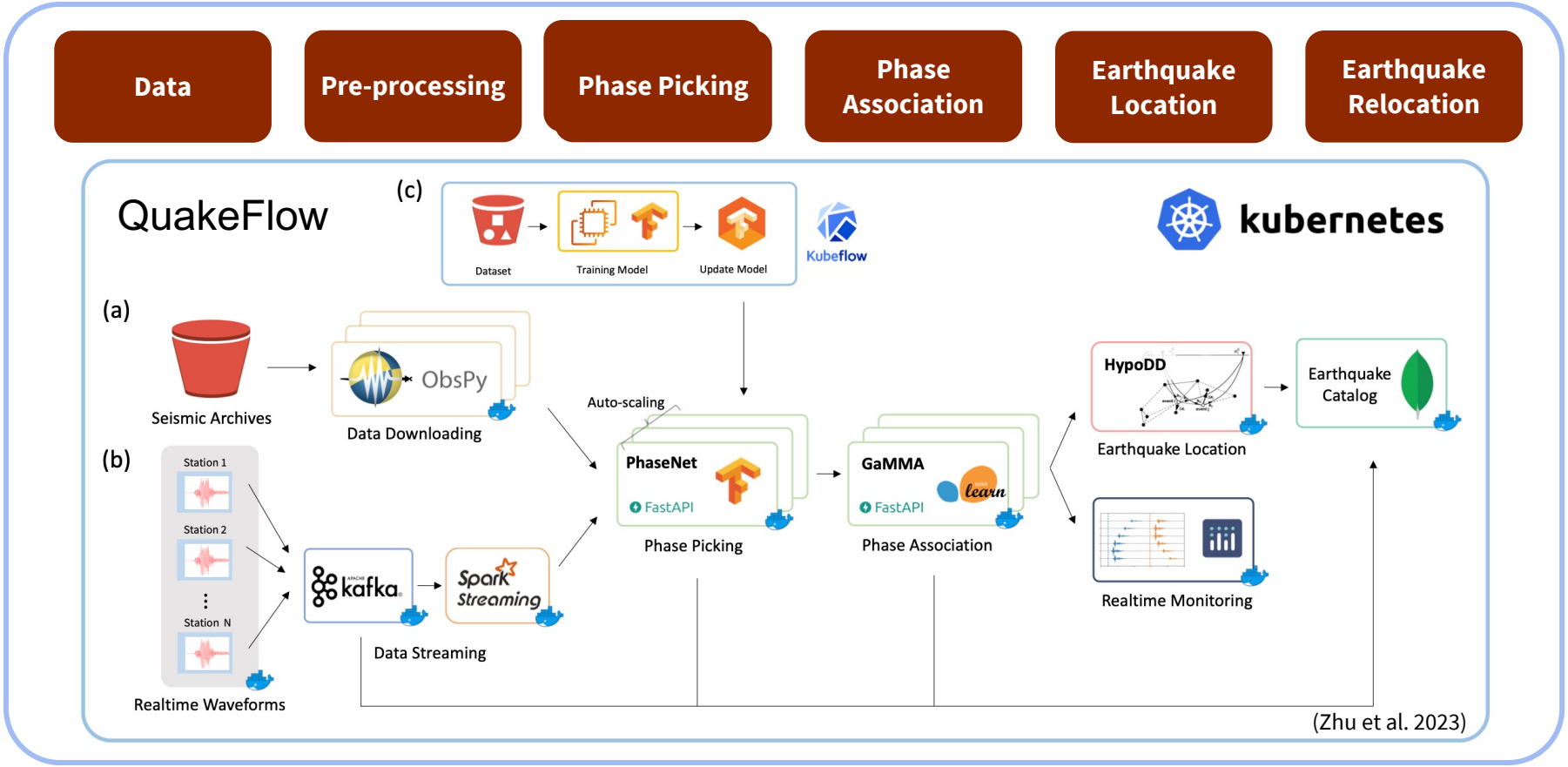
(staging-earthquake.usgs.gov)

Towards a complete deep-learning-based workflow



(Zhang et al. 2022)

Towards a complete deep-learning-based workflow



Towards a complete deep-learning-based workflow

Data | **Pre-processing** | **Phase Picking** | **Phase Association** | **Earthquake Location** | **Earthquake Relocation**

SeisBench
A toolbox for machine learning in seismology

JGR Solid Earth

Research Article | Open Access

Which Picker Fits My Data? A Quantitative Evaluation of Deep Learning Based Seismic Pickers

(Münchmeyer et al. 2021)

Performance Matrix: