

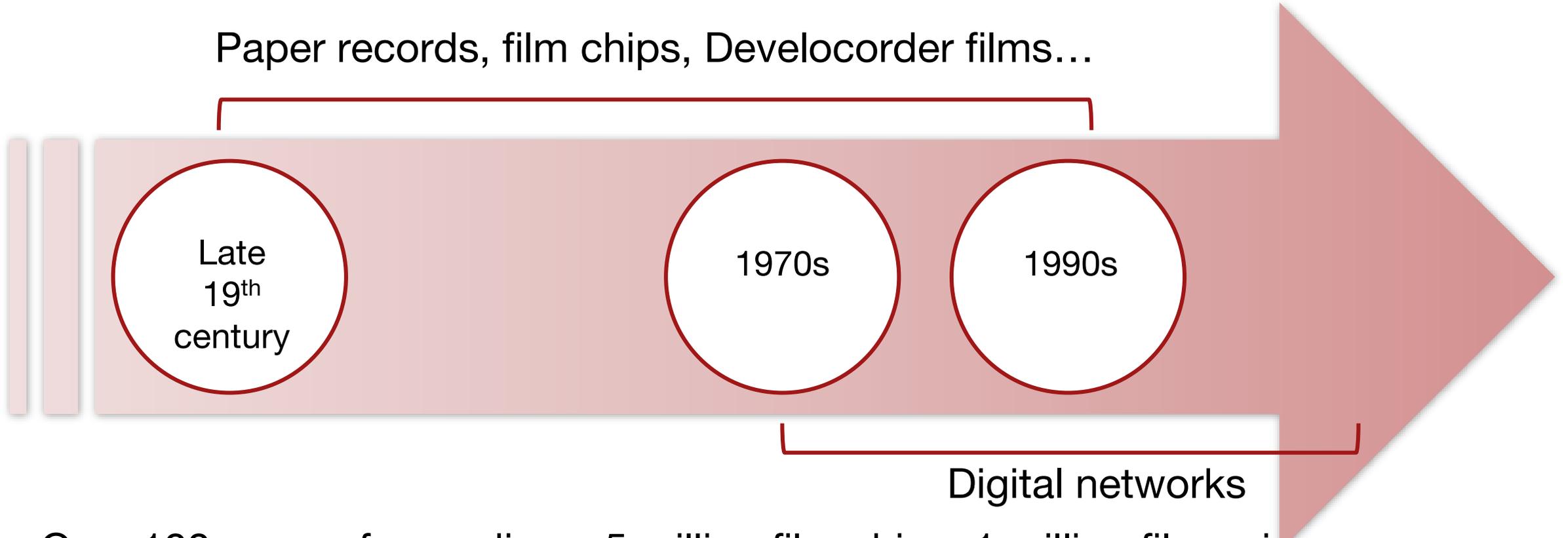
Image-Based Processing Methods in Develocorder Films Using Machine Learning: Application to the Rangely Earthquake Control Experiment

KAIWEN WANG, WEIQIANG ZHU, WILLIAM L. ELLSWORTH, GREGORY C. BEROZA

DEPARTMENT OF GEOPHYSICS, STANFORD UNIVERSITY

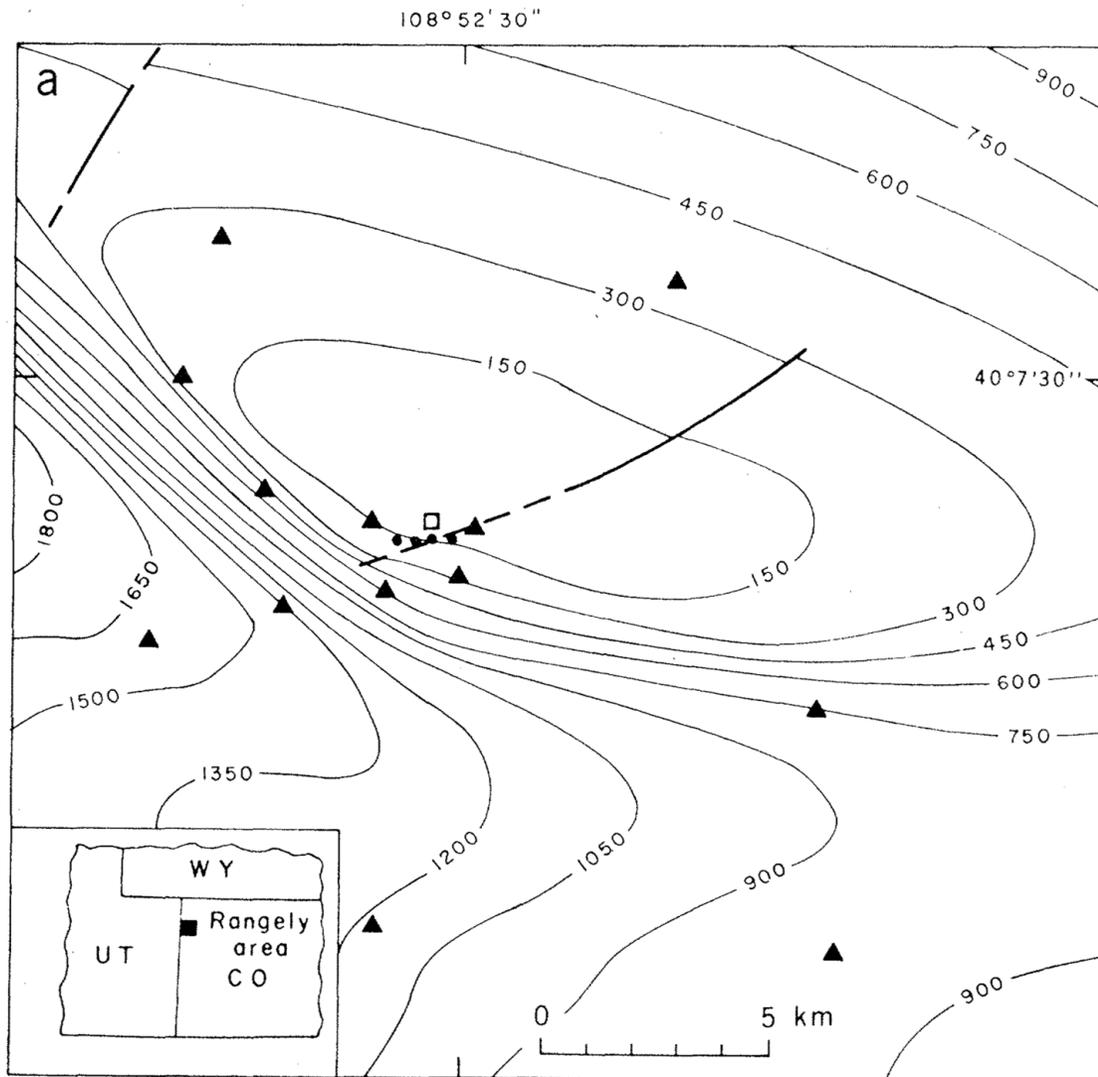
The value of analog data

Paper records, film chips, Develocorder films...



- Over 100 years of recordings. 5 million film chips. 1 million film seismograms.

(IRIS Seismo Archives)

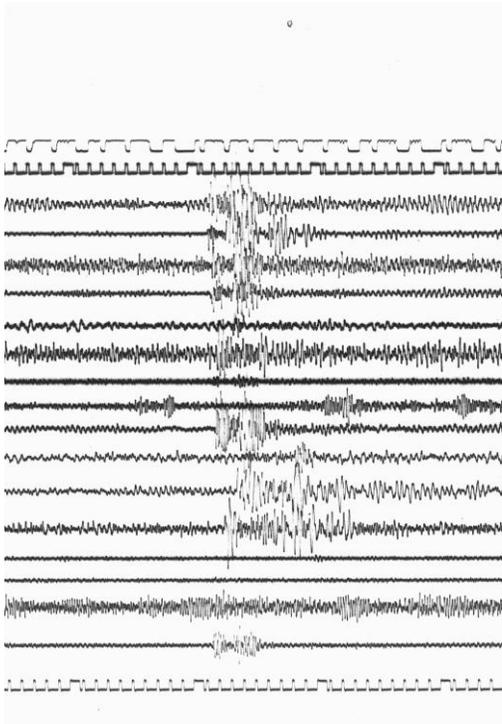


Raleigh et. al., 1976

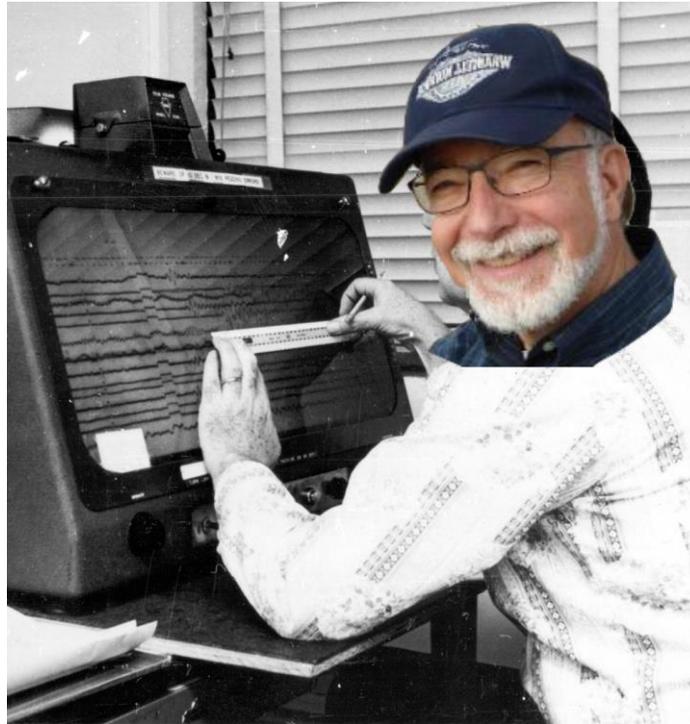
The Rangely earthquake control experiment

- A typical anticline oil field. Seismicity induced by water flooding started in the early 1960s.
- The first human controlled experiment to induce earthquakes. The goal was to test the effective stress hypothesis.
- The original earthquake catalog has been lost over the years. While the 16 mm Develocorder films are still available.

Data: original 16 mm Develocorder films



An example of Rangely microfilm

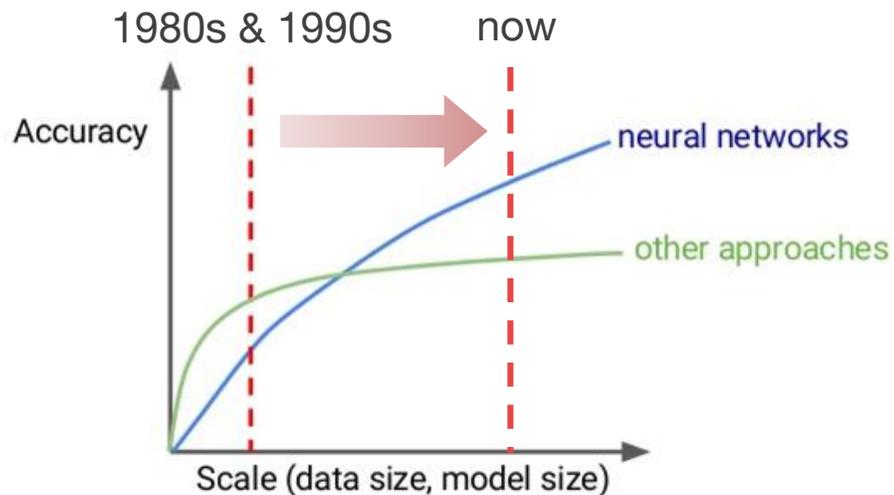


Bill viewing a film, modified from <https://en.wikipedia.org>

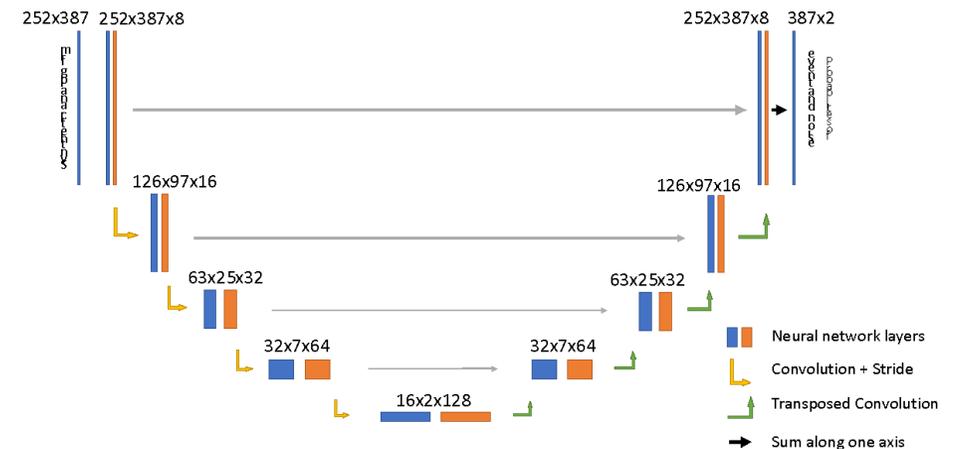
- Analog seismograms were originally analyzed by hand to measure arrival times and amplitudes.
- It is not practical to create digital time series with semi-automatic software due to trace crossing and fading intensity.
- New approaches are needed.
- We are developing image-based methods for detection and analysis.

Training a neural net to detect local earthquakes

- Thousands of labels are needed to apply deep learning methods.
- Main challenge: lack of labels for events and noises on Develocorder films.



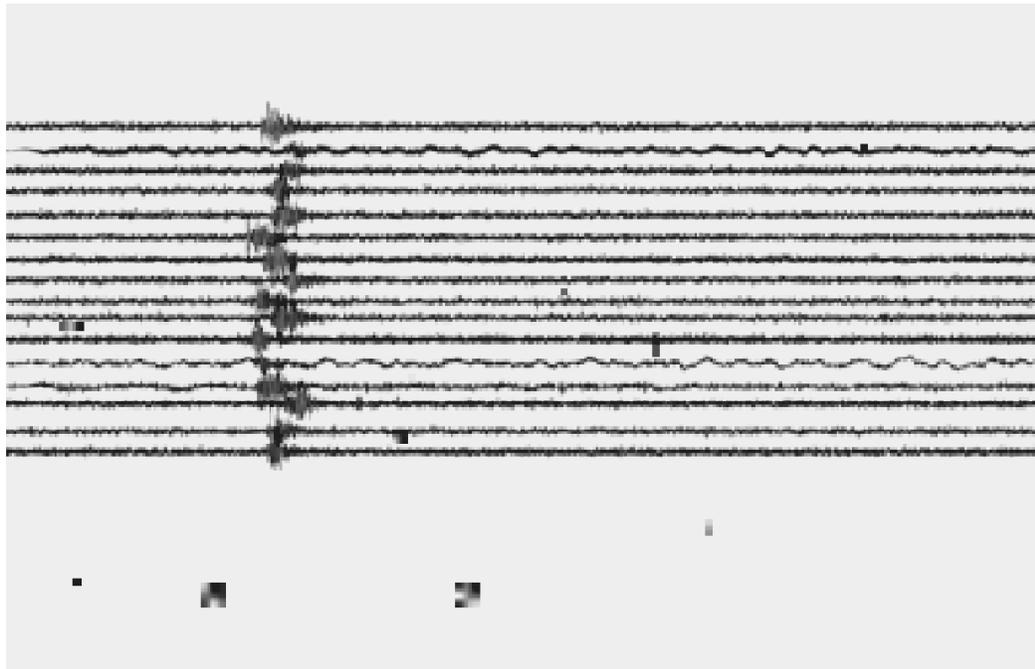
Jeff Dean at AI Frontiers: Trends and Developments in Deep Learning Research



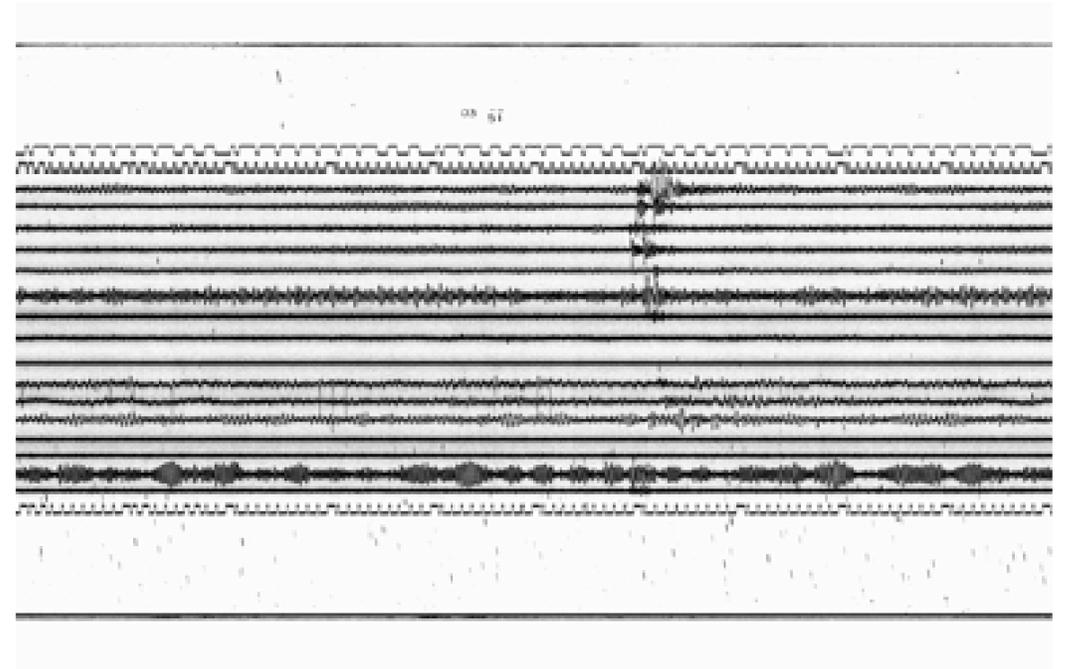
Network structure

Training a neural net to detect local earthquakes

- Main challenge: lack of labels for events and noises on Develocorder films. Thousands of labels are needed to apply deep learning methods.
- Solution: to synthesize Develocorder film images using well-labeled digital waveforms.



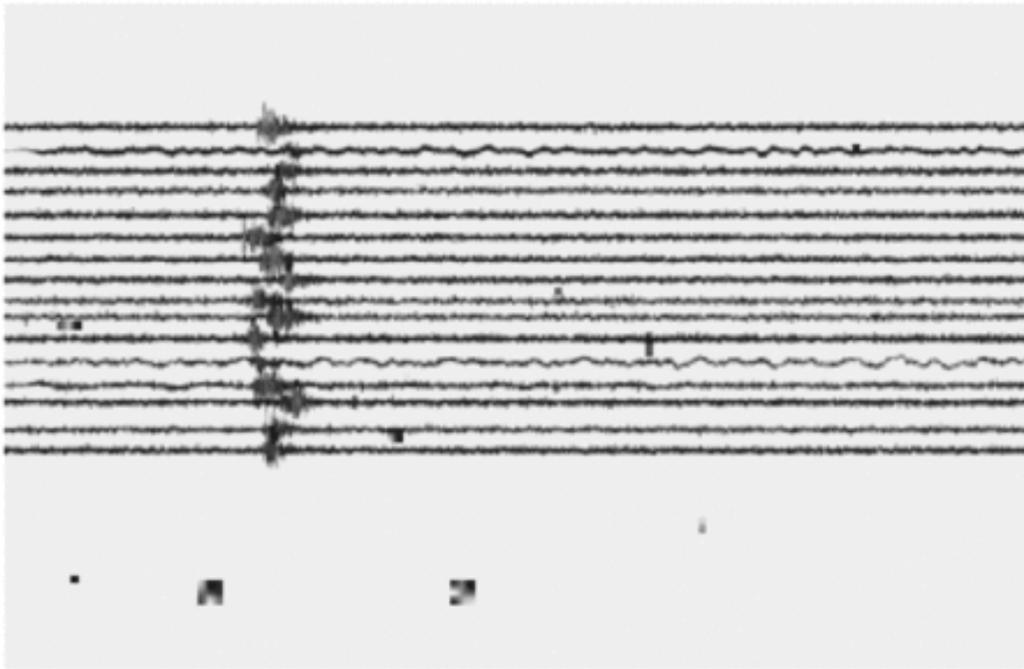
Synthetic local event



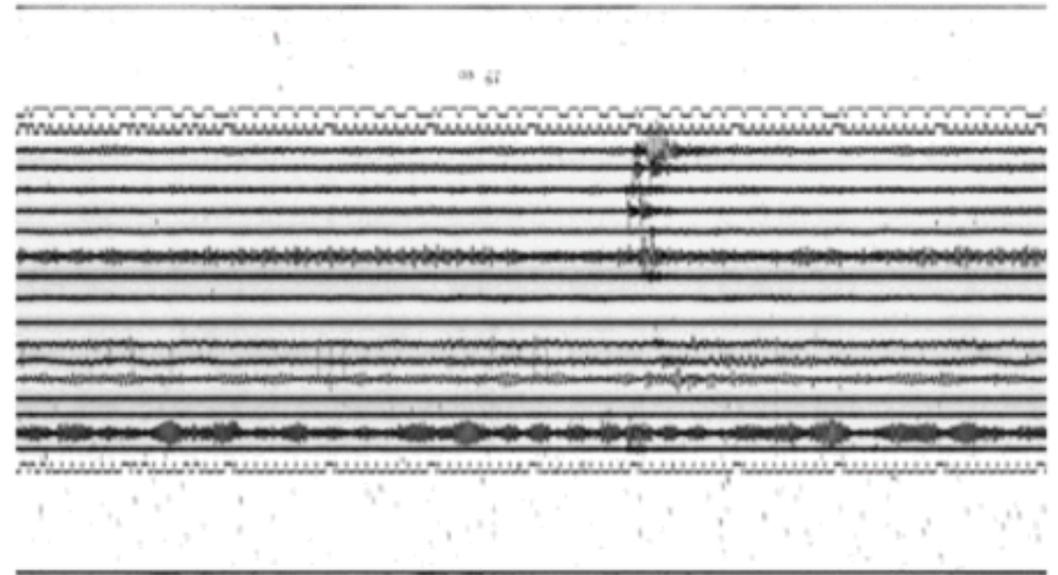
Analog local event

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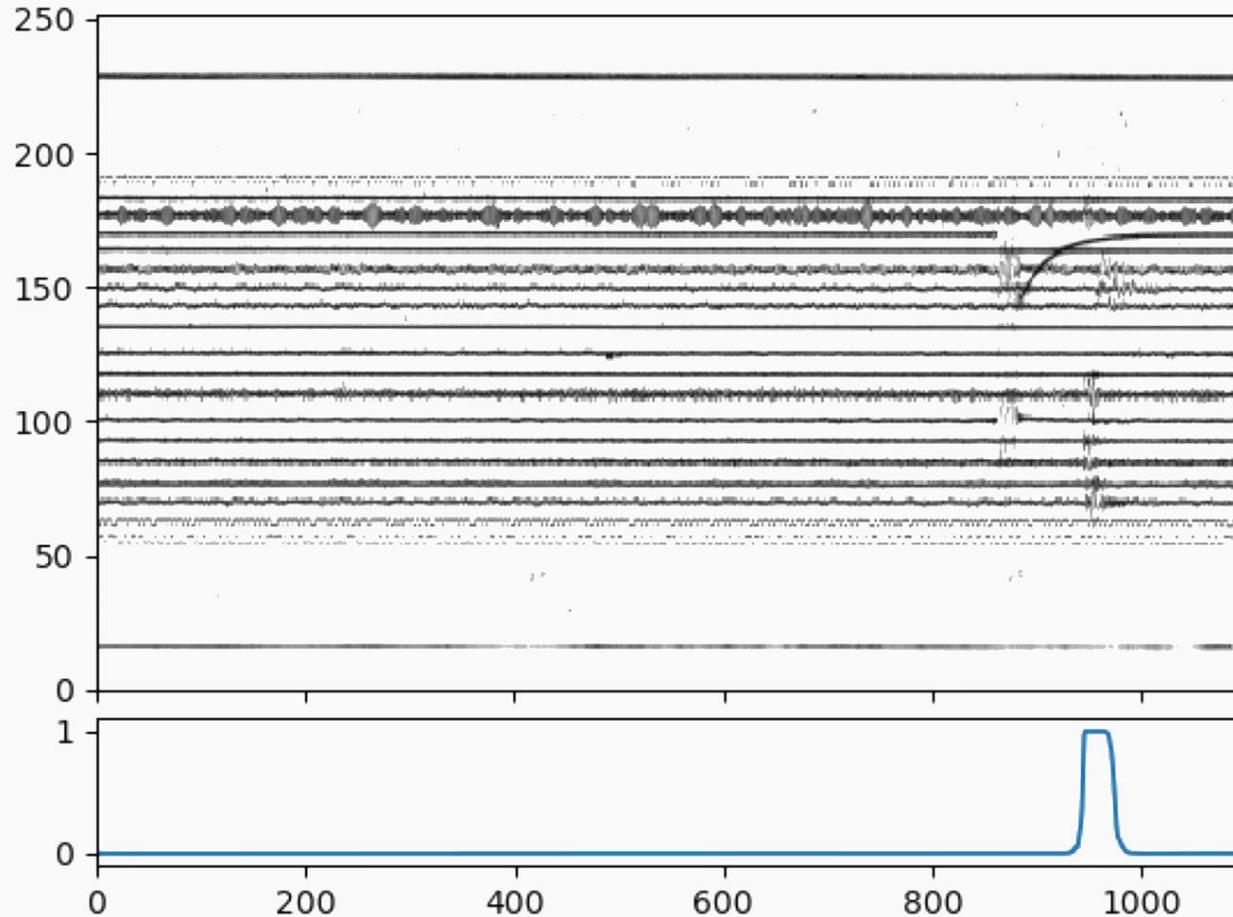


Synthetic local event



Analog local event

Model performance on validation set



Validation set: Scanned one-month films of Rangely network (Feb. 1973).

Number of images: 17622, ~ 600 films per day

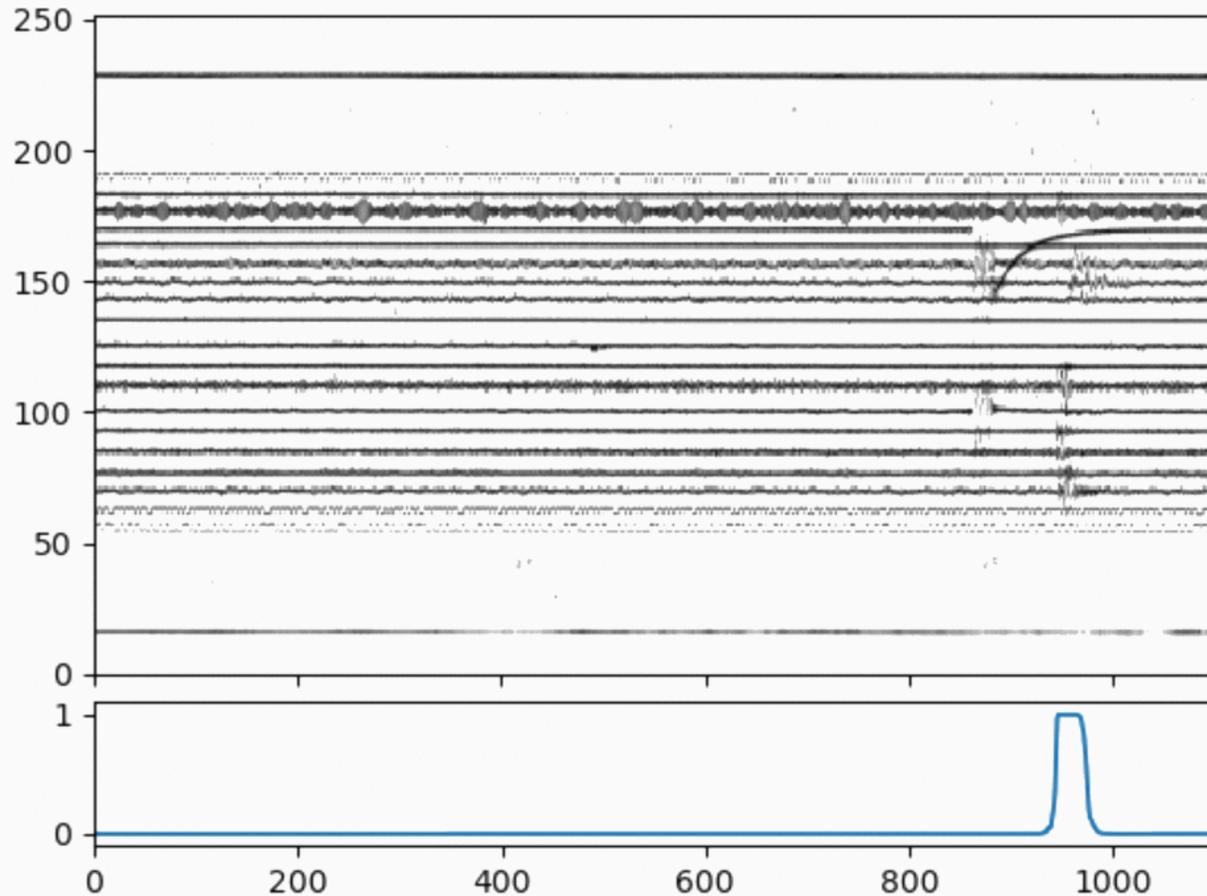
Some prediction results on the validation set (bottom panel shows probability of having a local earthquake):

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Some prediction results on the validation set (bottom panel shows probability of having a local earthquake):



Detection results

- Comparing with the number of events reported by Raleigh et al., 1976, we could detect more using our imaged based neural net.

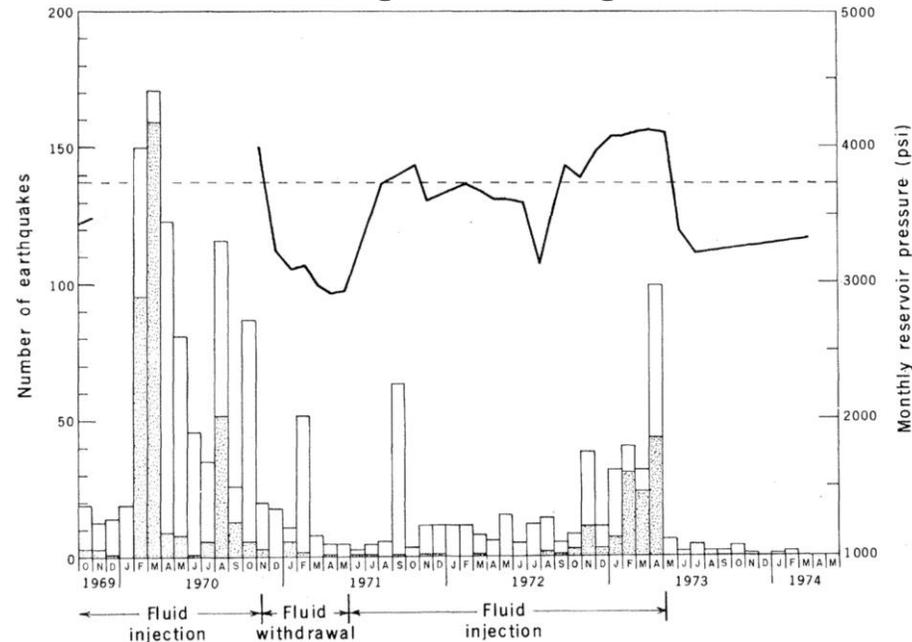
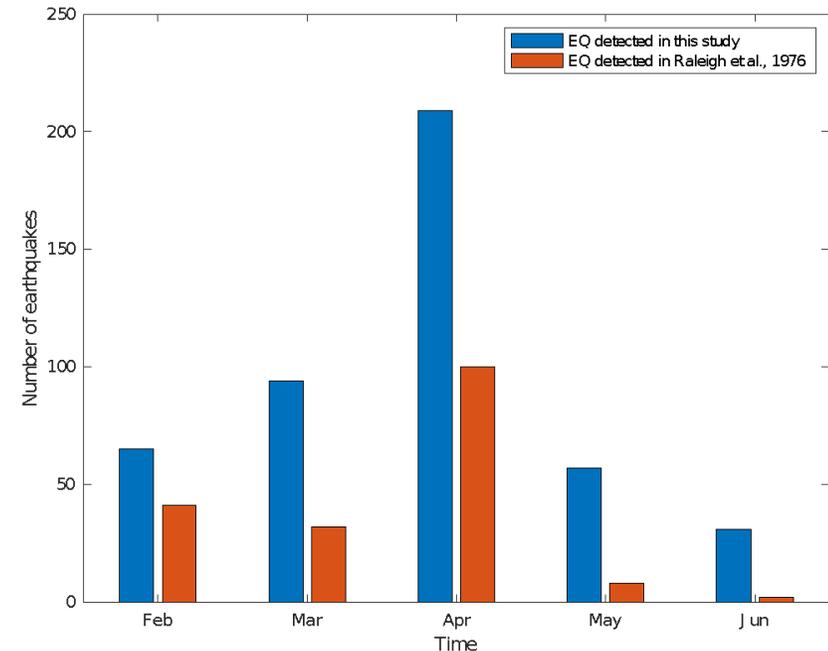
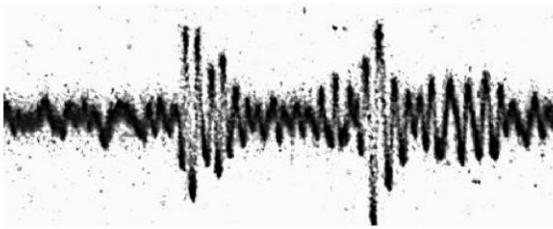


Figure from Raleigh et al., 1976 showing the number of earthquakes change with reservoir pressure.

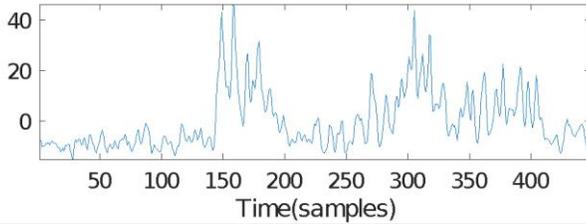


Number of earthquakes detected by the neural network in this study(Feb. to Jun. 1973) compared with the number of events reported in Raleigh et al., 1976.

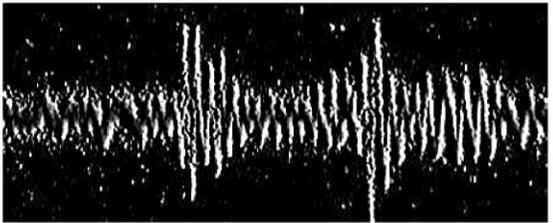
Original image



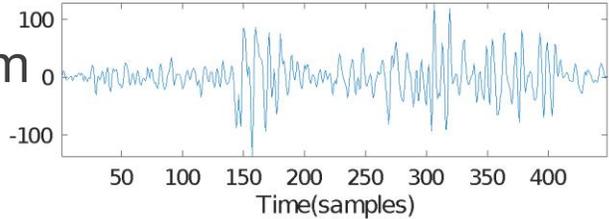
Vertical sum
 $f(t)$



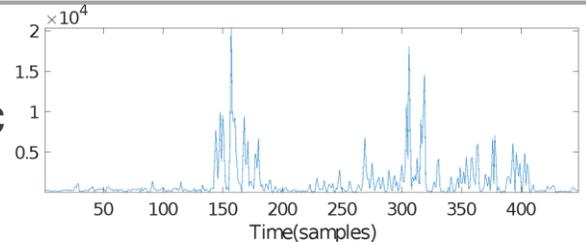
Horizontal
gradient
image



Vertical sum
 $f'(t)$



Adapted
characteristic
function

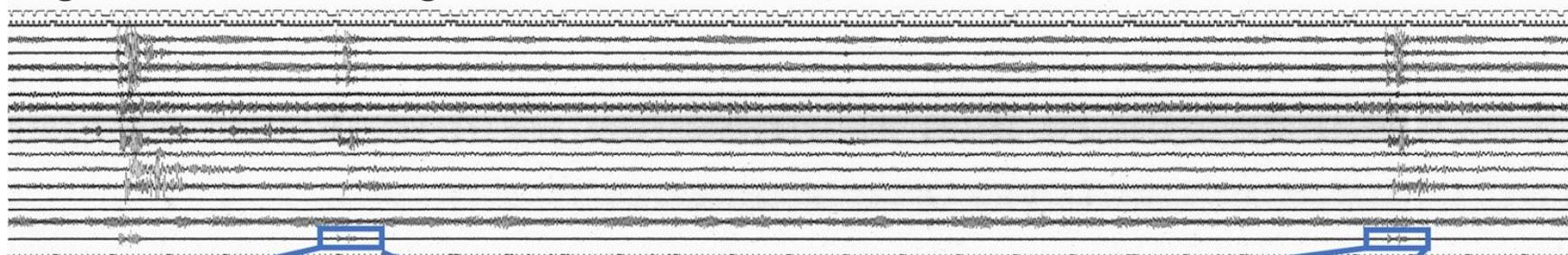


$$E(t) = Cf(t)^2 + f'(t)^2$$

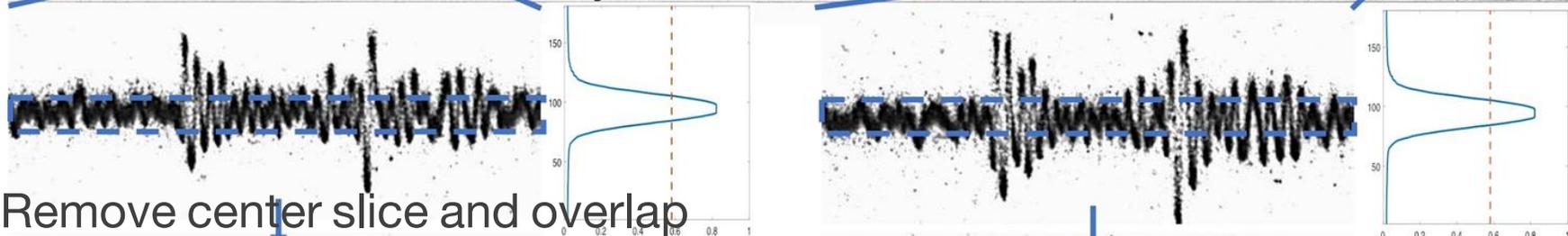
Location

- Use the detected event images:
- STA/LTA picker(adapted for image), grid-search associator
-  absolute arrival times
- 2-D image correlator
-  relative time differences between event pairs
- Those measurements are input to location programs Velest and HypoDD to give final locations.

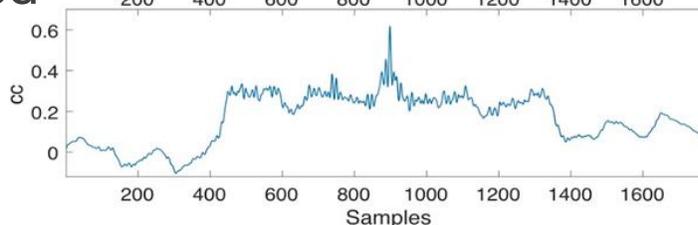
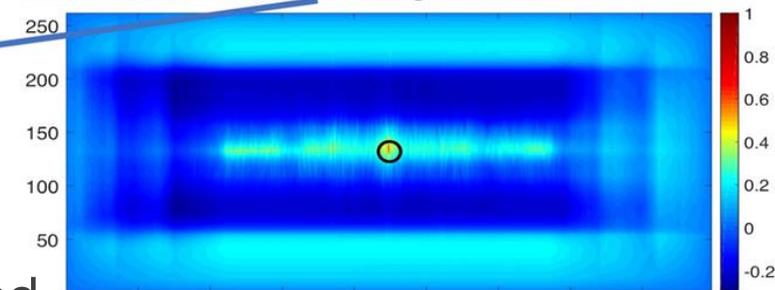
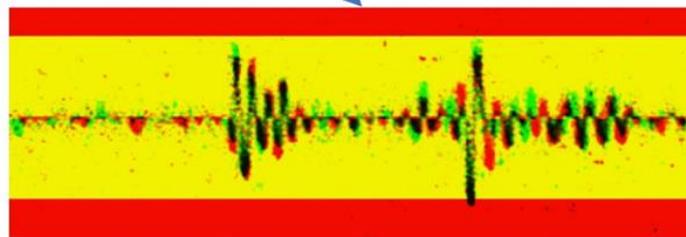
High resolution image



Window around P-wave Grayscale distribution



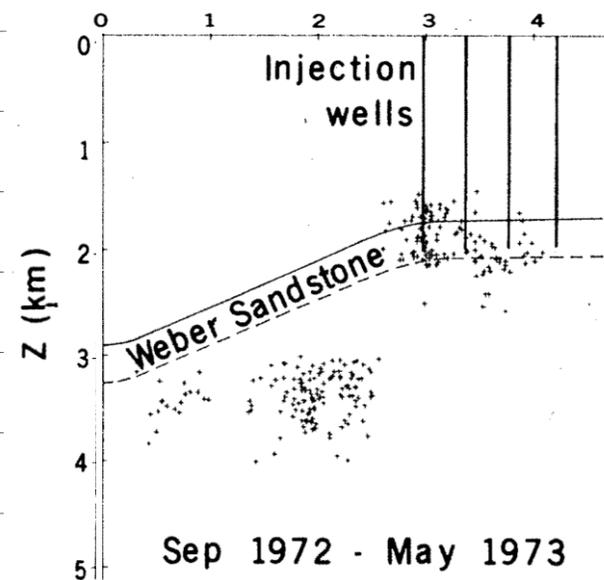
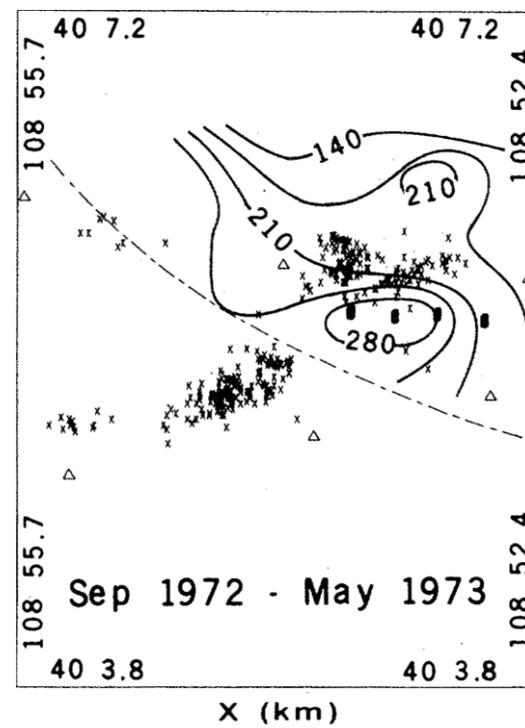
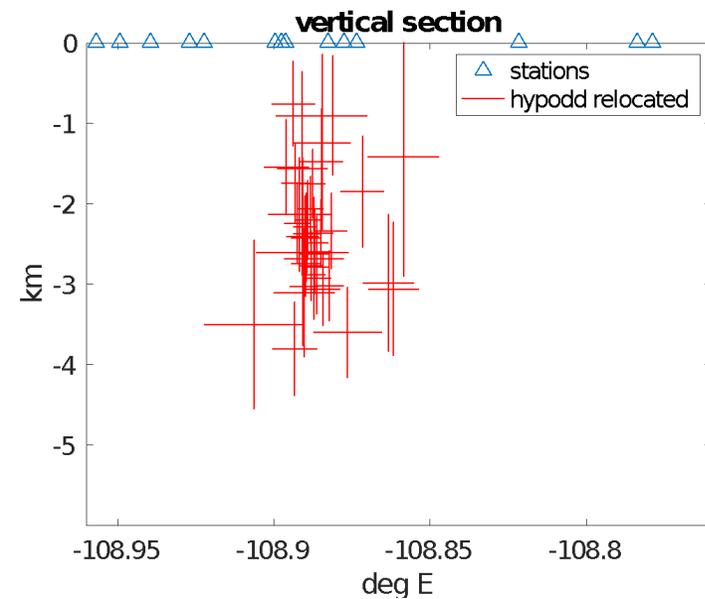
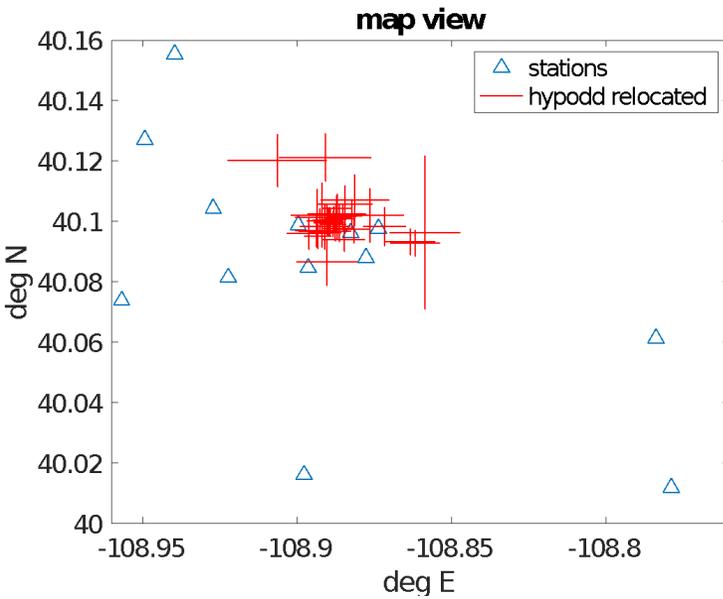
Remove center slice and overlap



Left: the two events scaled and aligned at the best fit position; Top right: correlation coefficient map; Bottom right: CC values at the center line.

Image correlation workflow

Feb 1973 events



Location Results

- We build a catalog of 40 local events from February 1973 films. This is a greater number of events than were reported in the original study (Raleigh et al., 1976).
- The events cluster at the injection wells, which is consistent with the shallow cluster in both the map view and vertical section.
- The strong consistency shows our preliminary results are already comparable to the performance of hand analysis.

Thanks