Analyzing Key Earthquake Questions with Nodal Array of Arrays around the San Jacinto Fault

Technical Report for SCEC Award # 25253

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Abstract:

Clarifying the relationship between frequent small earthquakes and the much rarer large earthquakes is fundamental to understanding fault mechanics and earthquake nucleation, yet this connection remains elusive. More complete catalogs allow us to address key questions such as the prevalence and characteristics of foreshocks, the spatiotemporal evolution of swarms, and the fine-scale structure of faults. Despite recent advances in event detection using template matching and machine-learning techniques, the detection threshold for tiny ($M < 0$) earthquakes has not yet been reached, leaving a hidden frontier of microearthquakes largely unexplored.

Beamforming applied to waveforms from small-scale nodal seismic arrays can substantially improve signal-to-noise ratios relative to single stations, enabling the detection of very small events. However, most previous array studies have used a single array, limiting location accuracy due to wavefront distortion from heterogeneous velocity structures. In this project, we deployed five 81-element nodal arrays around an active section of the San Jacinto Fault for four months through February 2025. Each array consisted of a 9 × 9 grid of sensors with 100 m aperture, which facilitated installation and maintenance while providing high signal-to-noise levels for small-earthquake detection.

By combining stacked array waveforms with nearby SCSN data, we build a seismic catalog by applying machine-learning phase picking and association. We also apply template matching event relocation from waveform cross-correlation results. Using this new catalog, we examine foreshock and aftershock statistics for small earthquakes near the San Jacinto Fault. This multi-array experiment pushes the limits of microseism detectability, offering new insights into fault mechanics and seismicity.

Progress to date:

After pulling the instruments in February 2025, we downloaded the data and loaded it onto our server for efficient processing. The array geometry is shown in Figure 1. Arrays 1, 4, and 5 had the best signal-to-noise. Arrays 2 and 3, sited on thick alluvium and relatively poor signal-to-noise, making them less useful for small-event detection.

Processing consisted of the following steps:

(1) Using selected calibration events, use waveform cross-correlation to determine P-wave timing corrections for the array elements. Because of the small size of the arrays, we decided that a single set of average timing corrections for each array was adequate; we did not need to estimate source-specific timing corrections.

(2) Stack the traces from each array using the timing corrections to generate a single three-component time series with improved signal-to-noise.

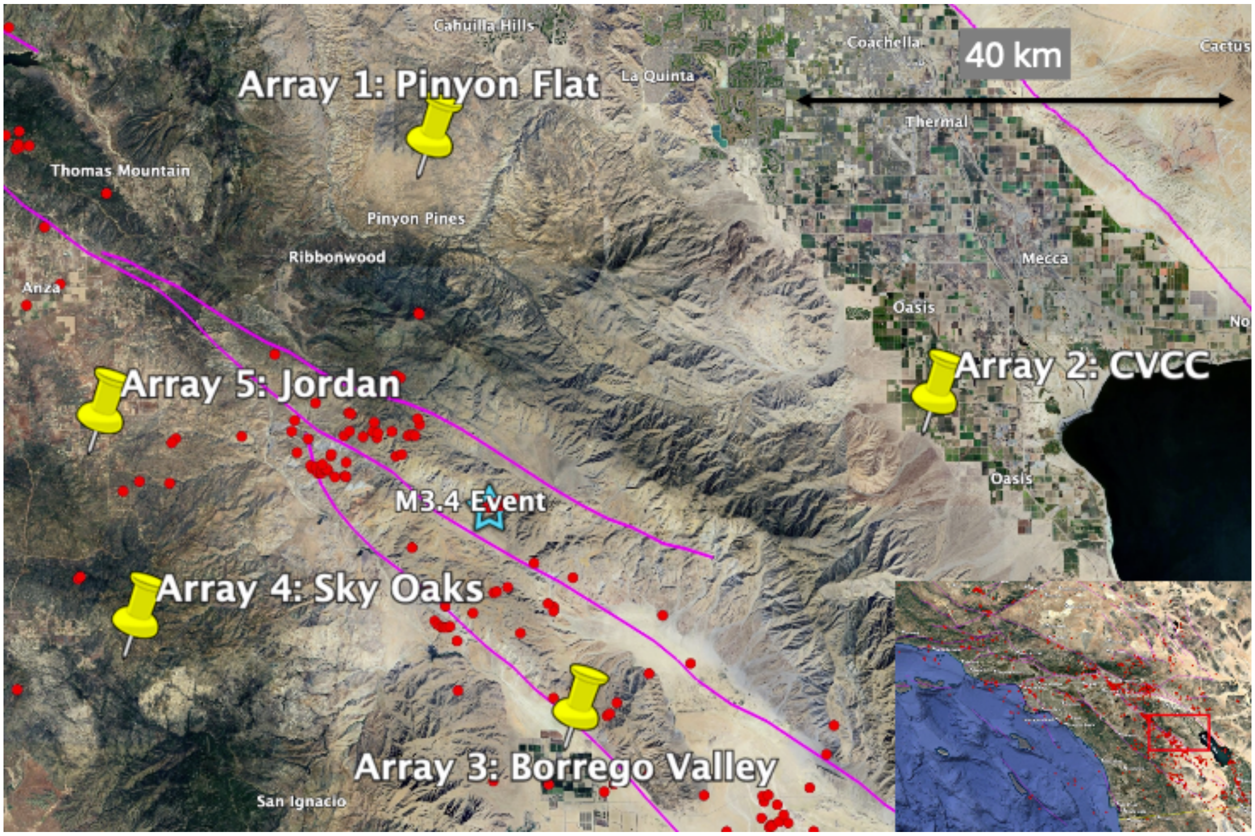

Figure 1. Map of the five arrays (pins) installed in this experiment with M ≥ 1 seismicity in our observation period as red dots [1]. Pins show the location of the Pinyon Flat Observatory, CVCC, Sky Oaks, Borrego Valley and Jordan arrays. Pink lines show the fault lines around the SJF. Blue star at the center of the map shows epicenter of M 3.35 event in Borrego Spring on November 7th, 2024.

(3) Using these results and continuous data from 10 nearby SCSN stations, run the machine learning-based event detection program EQ transformer [2] and the event association program GaMMA [4] to generate an earthquake catalog, which has 7 times more events than the SCSN catalog for our study region.

(4) Generate event templates from the beams for Arrays 1, 4, and 5, and run the template matching program MatchLocate2 [3] to detect additional events. Requiring detections by at least 2 of the arrays leads to 2927 additional events for our catalog.

(5) Estimate magnitudes for the template-matched events using their relative amplitudes compared to known events.

Figure 2 shows a frequency-magnitude plot, comparing the SCSN catalog, the machine-learning catalog, and the catalog including the template detections. As expected, we are detecting many very small earthquakes (M < 0) within our study regions. We are now using our catalog to study earthquake statistics, including estimating the fraction of the events that can be characterized as foreshocks or as being in swarms, and testing ETAS-like models to characterize earthquake clustering.

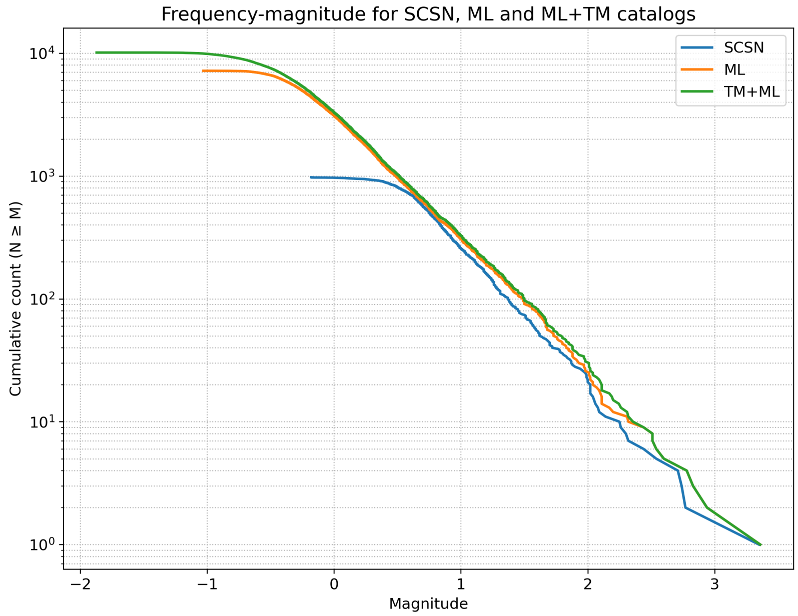

Figure 2. Frequency-magnitude plot for SCSN, ML (Machine Learning) and ML+TM (Template Matching) catalogs, shown in blue, orange and green curves, respectively.

A search for tremor finds none

Tremor was seen in this area during the 2002 Alaskan earthquake [5] and our arrays are well suited to investigate with greater sensitivity. We searched the entire dataset for tremor by visually searching the spectrograms for each 10 minutes as shown in Figure 3. Myriad local earthquakes were visible, as were local windstorms and numerous unidentified signals on individual arrays. There were dozens of events with emergent and prolonged arrivals across most of the arrays, such as the one shown, but all could be identified as small earthquakes at regional distances. No candidates for local tremor were identified.

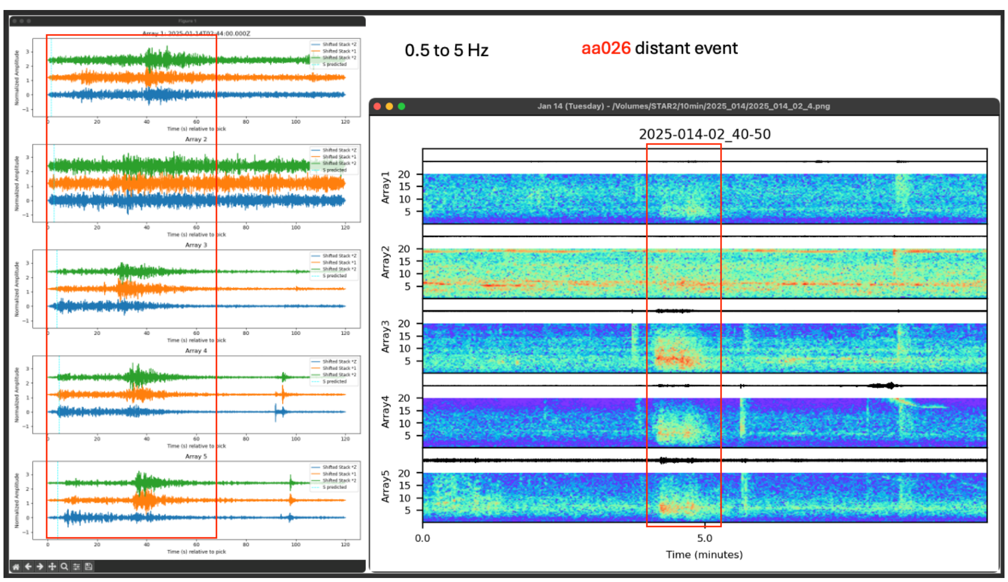

Figure 3. Example array stacks and spectrograms from our experiment. The extended and emergent signal shown is not tremor, but results from a small earthquake recorded at regional distance.

Educational aspects

The Array of Arrays experiment provided an opportunity for more than 10 students to participate in the fieldwork and gain firsthand experience with nodal seismic instrumentation. The project has also enabled one graduate student, Taiga Morioka, to attend the annual meetings of SCEC, AGU, and SSA, contributing to his PhD thesis.

References:

[1] Earthquake Hazards Program, U.S. Geological Survey. (2026). Retrieved April 10, 2025, from https://www.usgs.gov/programs/earthquake-hazards

[2] Mousavi, S. M., Ellsworth, W. L., Zhu, W., Chuang, L. Y., & Beroza, G. C. (2020). Earthquake transformer—An attentive deep-learning model for simultaneous earthquake detection and phase picking. *Nature Communications*, *11*(1), 3952. https://doi.org/10.1038/s41467-020-17591-w

[3] Zhang, M., & Wen, L. (2015). An effective method for small event detection: Match and locate (M&L). *Geophysical Journal International*, *200*(3), 1523–1537. https://doi.org/10.1093/gji/ggu466

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[5] Gomberg, J., Rubinstein, J. L., Peng, Z., Creager, K. C., Vidale, J. E., & Bodin, P. (2008). Widespread triggering of nonvolcanic tremor in California. *Science*, *319*(5860), 173-173.

Presentations:

Morioka, T., Brenguier, F., Cochran, E. S., Fan, W., Higueret, Q., Hollis, D., Shearer, P. M., Vernon, F. L., Vidale, J. E., Wang, R., & Zhang, H. (2025, 12). Probing Seismicity Secrets with Five Nodal Arrays around the San Jacinto Fault. Poster Presentation at 2025 AGU Annual Meeting.

Morioka, T., Brenguier, F., Cochran, E. S., Fan, W., Higueret, Q., Hollis, D., Shearer, P. M., Vernon, F. L., Vidale, J. E., Wang, R., & Zhang, H. (2025, 09). Probing Seismicity Secrets with Five Nodal Arrays around the San Jacinto Fault. Poster Presentation at 2025 SCEC Annual Meeting.

Morioka, T., Brenguier, F., Cochran, E. S., Fan, W., Higueret, Q., Hollis, D., Shearer, P. M., Vernon, F. L., Vidale, J. E., Wang, R., & Zhang, H. (2025, 04). Probing Seismicity Secrets with Five Nodal Arrays around the San Jacinto Fault. Poster Presentation at 2025 SSA Annual Meeting.

Morioka, T., Brenguier, F., Cochran, E. S., Fan, W., Higueret, Q., Hollis, D. D., Shearer, P. M., Vernon, F. L., Vidale, J. E., Wang, R., & Zhang, H. (2024, 09). Probing Seismicity Secrets with Five Nodal Arrays around the San Jacinto Fault. Poster Presentation at 2024 SCEC Annual Meeting.