Subsurface seismic properties across the southern San Andreas Fault in the Thousand Palms Canyon based on train-generated seismic waveforms

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Introduction

- We use seismic waveforms generated by freight trains in the Coachella Valley and recorded by dense seismic array sensors to image the shallow structure of the Southern San Andreas Fault Zone (SoSAFZ).
- Particle motion analysis shows that the moving freight trains generate strong Rayleigh waves across the array.
- Rayleigh wave velocities are measured using cross correlation on neighboring station pair based on the delay time and wave propagation direction.
- The amplitudes of the waveforms show strong variations across the array, including anomalies near the fault zone, which can be further utilized to estimate the Q-values across the fault zone.

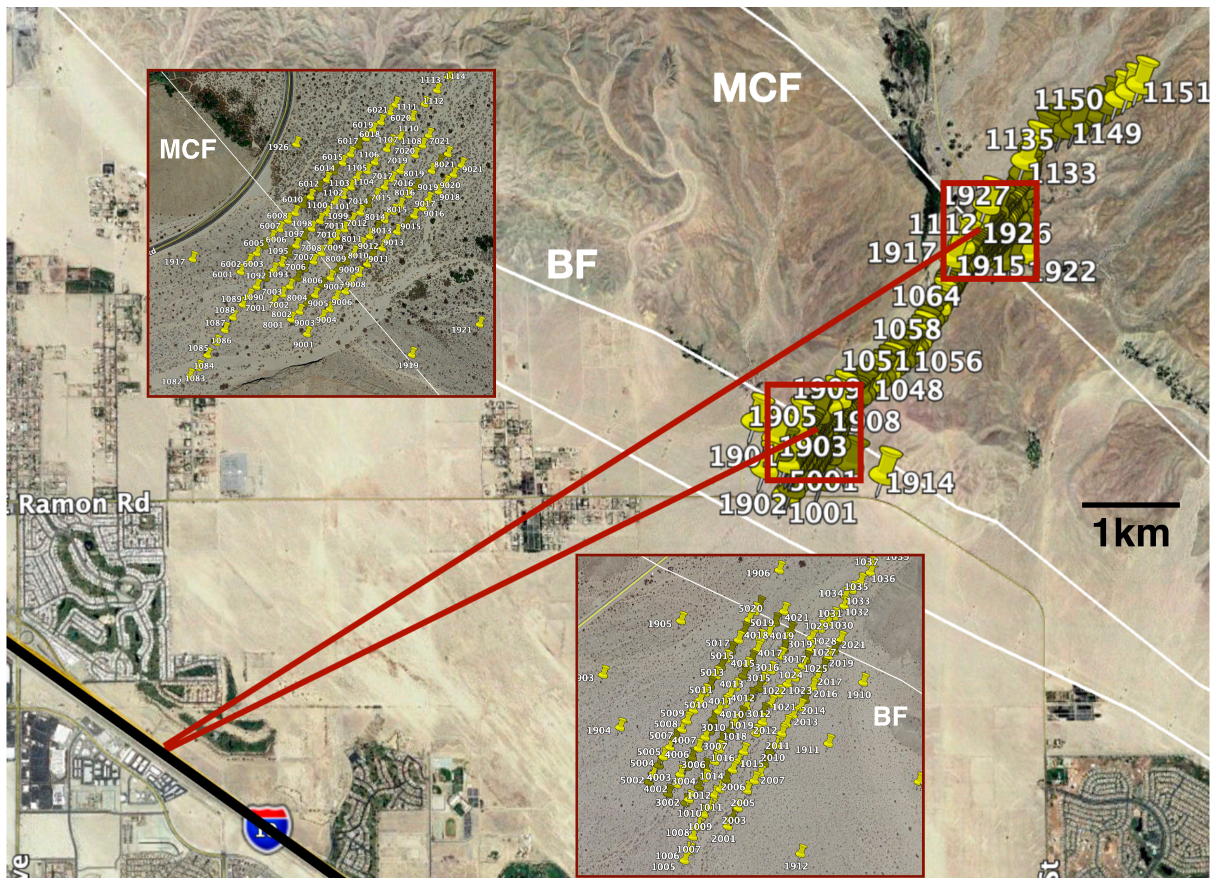
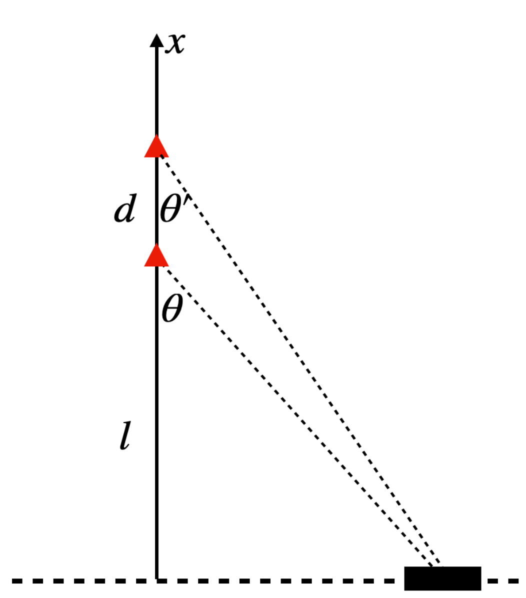


Figure 1. Map of the he southern San Andreas Fault in the Thousand Palms Canyon. Yellow pins denote the dense array used in this study. Yellow lines mark the fault trace in this area, include Mission Creek Fault (MCF) and Banning Fault (BF) strands. Two small panels showing zoom-in views of the two 2-D subarrays across these strands Black line denotes the I-10 railway. Red rectangles denote two 2-D dense array across the fault and red lines mark the propagation directions from a train event to these 2-D arrays (See Fig. 4).

Methodology & Workflow

- We picked event with high signal to noise ratio (SNR) and obtaining the time delay of neighboring stations using cross-correlations of band-passed vertical waveforms in a 60-sec-long moving window.
- Obtaining the propagation direction of Rayleigh wave at the two 2D subarray, then determining the location of each train event on the railway for the time window of interests.
- Rayleigh wave velocities C are measured for each neighboring station pair in dense linear array based on the delay time and wave propagation direction.
- The Q-values can be estimated by analyzing the median amplitudes of the waveforms on each neighboring station pair.



$$A_l = \frac{A_0}{\sqrt{l/\cos\theta}} \cdot \exp(-\pi f \int_0^l \frac{dx/\cos\theta}{Q(x)\cdot c(x)})$$

$$A_{l+d} = \frac{A_0}{\sqrt{(l+d)/\cos\theta'}} \cdot \exp(-\pi f \int_0^{l+d} \frac{dx/\cos\theta'}{Q(x)\cdot c(x)})$$

$$\ln A_l - \ln A_{l+d} = \frac{1}{2}(\ln\frac{l+d}{\cos\theta'} - \ln\frac{l}{\cos\theta}) - \pi f \int_0^l \frac{dx/\cos\theta}{Q(x)\cdot c(x)} + \pi f \int_0^{l+d} \frac{dx/\cos\theta'}{Q(x)\cdot c(x)}$$

$$Since\ d \ll l, \ln A_l - \ln A_{l+d} \approx \frac{\pi f}{\cos\theta} \cdot \frac{d}{Q_l \cdot c_l}$$

$$\Rightarrow Q_l \approx \frac{\pi f}{\cos\theta} \cdot \frac{d}{(\ln A_l - \ln A_{l+d})\cdot c_l}$$

Figure 2. A conceptual diagram showing how to derive Q value from amplitudes on stations. Black dash line denotes the rail way, black rectangle denotes the train. Red triangles denote a neighboring station pair, the line between them is perpendicular to the railway. The distance between the station pair d (about 25m) is much smaller than their distance to railway l (about 3 km).

References

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- K. Blisniuk, K. Scharer, W. D. Sharp, R. Burgmann, C. Amos, M. Rymer (2021). A revised position for the primary strand of the Pleistocene-Holocene San Andreas Fault in southern California. Sci. Adv. 7, eaaz5691

Data Processing

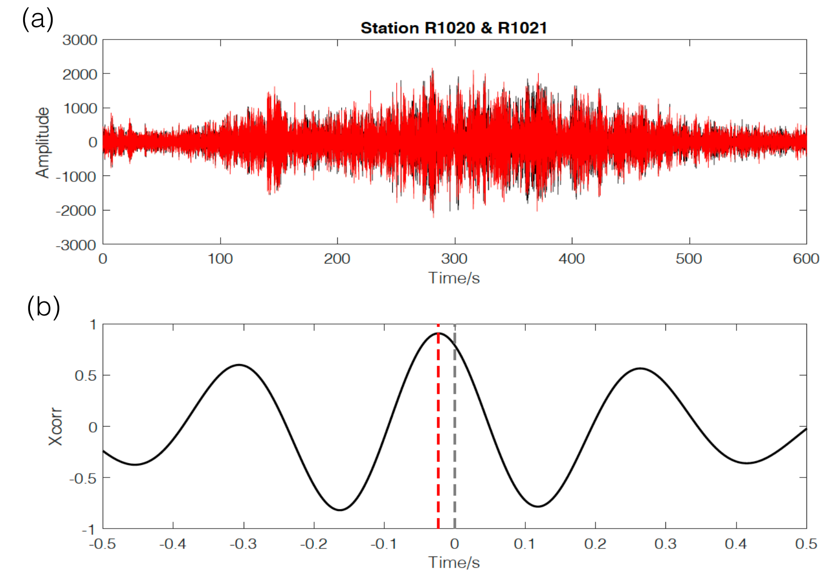
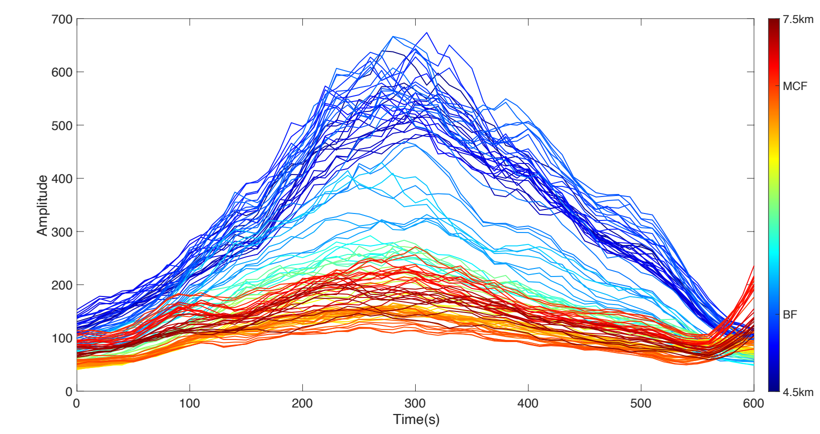


Figure 3. (a) An example of train event waveforms on a neighboring station pair R1020 (red) & R1021 (black). Train events can continued for hundreds of seconds. (b) The cross correlation of the wave forms on this station pair. The cross correlation could be near to 1 and have a time lag. (Red dash line marks the highest cross correlation.)



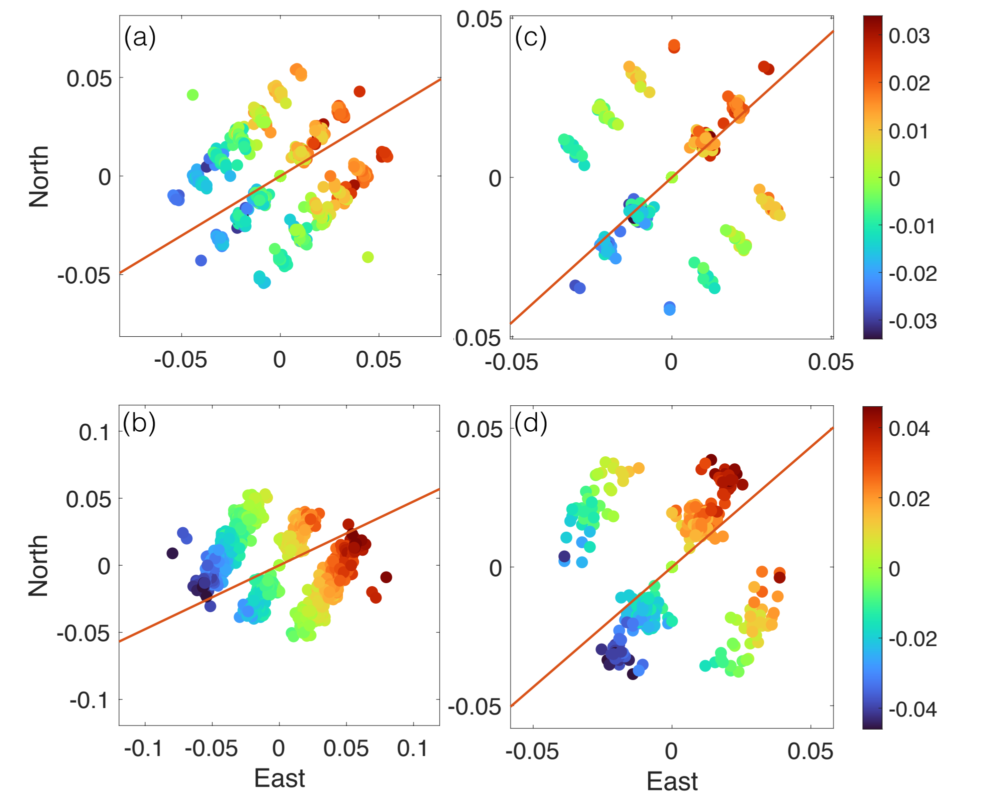


Figure 4. For each station in a 2D array, we calculate the cross correlation between it and all other stations, and plot the relative position of stations with high CC (>0.6) to this station. The color of plots denote the relative time lag between station pairs. By calculating the gradient of time lag field, propagation direction of train signal (orange line) in a time window can be determined. (a) , (b) shows 2D array across MCF and BF respectively for in a time window. Propagation directions also shown in Fig. 1 (red lines). The location of train can be determined based on the location of railway and propagation directions from train to two 2D arrays. (c), (d): same to (a), (b), but for another time window.

Figure 5. Amplitudes correlate to the location of train and stations in a train event. The x-label represents the distance between the location of the train in a time window and center of railway. Different curves represent different stations, and color bar shows the distance between station and railway.

Results & Discussion

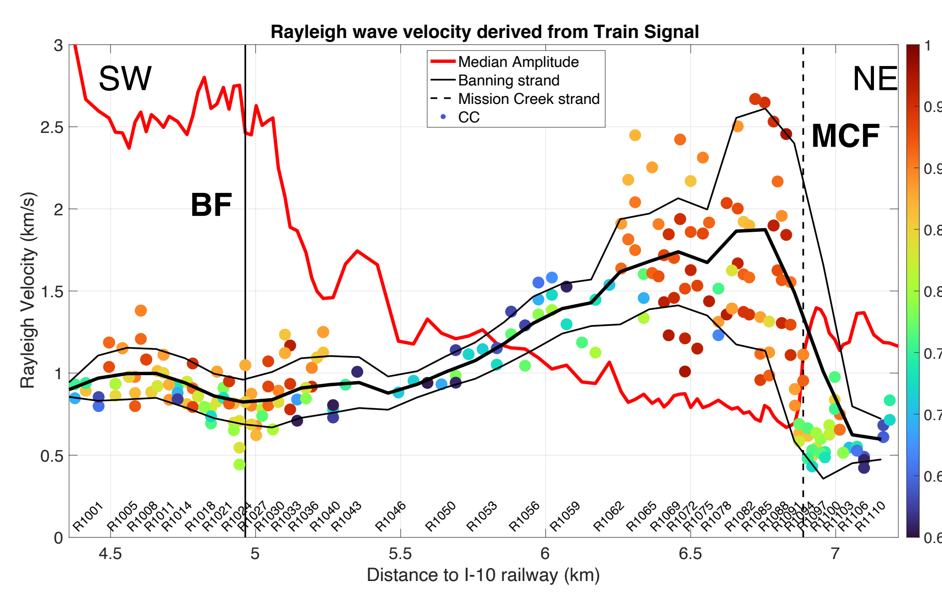


Figure 6. Amplitudes and velocities along linear array. Red curve shows the median amplitudes on stations. Colored dots denote Rayleigh wave velocities near station and color represent the cross correlation with neighbor stations. Thick black curve denote averaged velocity of events and two thin black line mark deviation. Two vertical lines mark the location of BF and MCF.

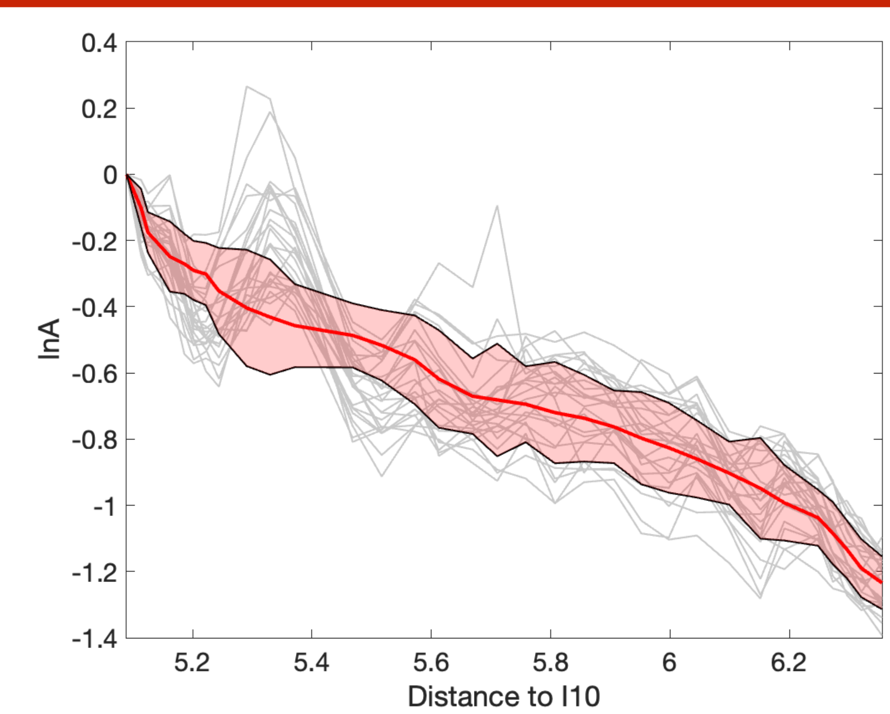


Figure 7. Each gray line denotes logarithm of normalized median amplitudes between BF and MCF of a train event in a specific time window. The red line shows the amplitude after linear stacking and smoothing, pink area denote confidence interval. The stacked and smoothed curve shows the amplitude is monotonically decreasing while distance increases.

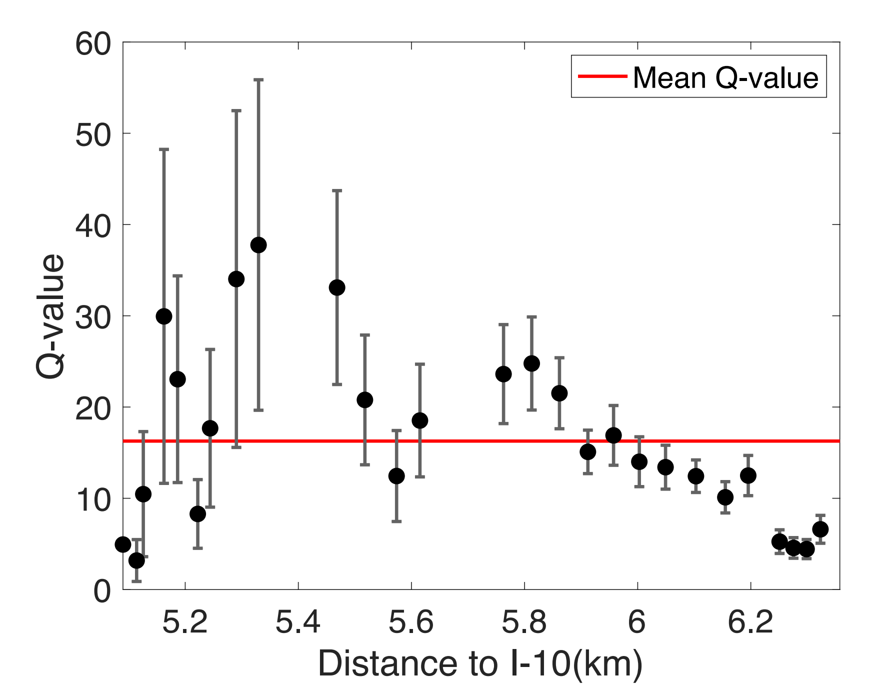


Figure 8. Q value between BF and MCF strands derived by amplitudes of train event signals, varies from 10-50, error bar shows uncertainty. Redline marks the average level of Q-value.

Conclusions

- Train signals can be tracked by the dense array, and provide stable waveforms to observe near surface structure.
- The results of train events in different window indicate a consistent low-velocity zone around BF and a strong velocity reduction across MCF towards the northeast.
- The median amplitudes of the waveforms show strong variations across the array, including anomalies near the BF and MCF strands.
- The Q values of shallow structure between the BF and MCF strands vary from 10-50.

Key limiting factors

- How to use the amplitude anomalies near the BF and MCF to indicate the structure of faults, include velocity contrast and Q value change.
- Before smoothing, there are rises in the stacked curve of amplitude. That's probably caused by local structure with low speed.
- The amplitude may also be influenced by local topography change.