

S13F-0411: Quantifying the structural and site effects on microearthquake source parameter variability in a sedimentary basin across a dense array in Oklahoma

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Summary

- The basin environment and the glacial-related shallow deposits in the Central United States (US) can cause **site effects** that

- (1) **Amplify ground motions**
- (2) **Bias source parameter measurements** (corner frequency, seismic moment, and stress drop)

- The LARge-n Seismic Survey in Oklahoma (LASSO) provides a good opportunity to investigate site effects across a local scale.

- We present our two studies that quantify the influence of site effects:

- (1) In the first study, we use site amplification as a proxy of site effects and investigate the variability of source parameter measurements.
- (2) In the second study, we obtain the velocity structure using ambient noise and link the structure to the observed amplification and source parameter biases.

What are site effects?

- Near-surface unconsolidated sediment can amplify or suppress ground motions and distort the observed earthquake spectrum (Borcherdt, 1970).
- For source parameter estimation, the **corner frequency (fc)** can get underestimated due to a **higher loss of high frequency energy** while the **seismic moment (M0)** can get overestimated due to a **boosted lower-frequency level** (Abercrombie, 1995).

Induced seismicities recorded by a dense array

- The LARge-n Seismic Survey in Oklahoma (LASSO) was deployed in 2016 for about a month. The array has ~1825 stations (vertical-component only) in 25 km x 32 km (Dougherty et al., 2016).
- The array recorded reignal and local earthquakes (**Figure 1, 2**) likely induced by wastewater injection.
- The stress drop of the local events ($M = 1 - 3$) ranges between 0.83 – 54 MPa (336 events; using single-spectra fitting) or 0.41 – 96 MPa (126 events; using spectral-ratio fitting) (Kemna et al., 2020).

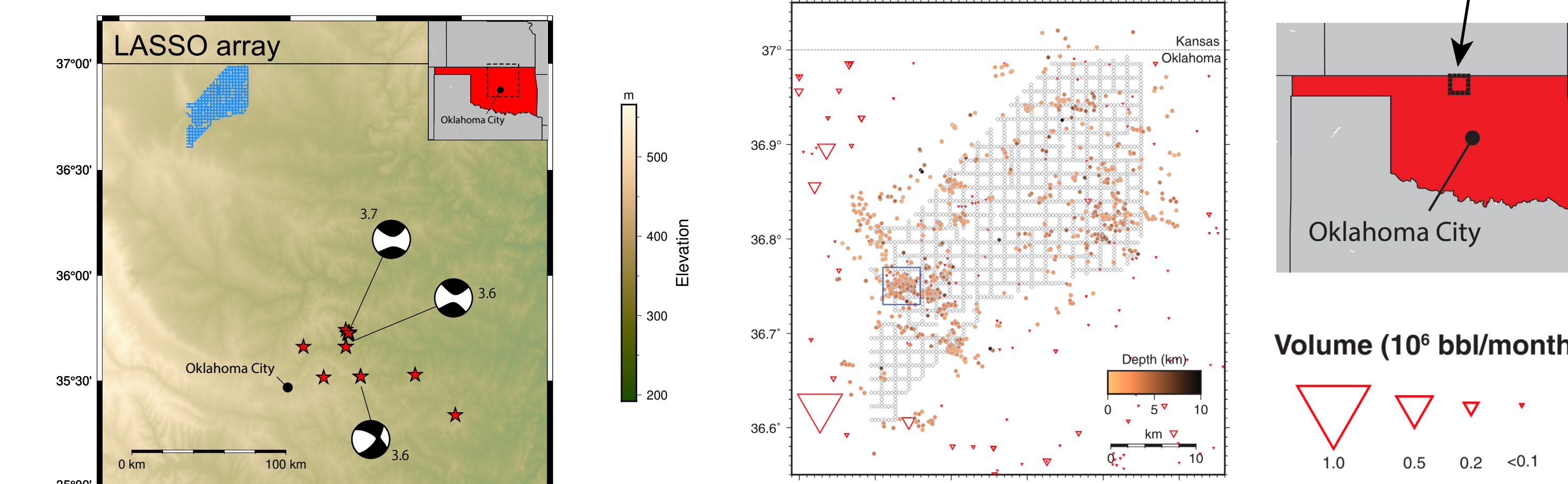


Figure 1: The LASSO array recorded regional events (red stars, $3.0 < M < 3.7$) near the Oklahoma City. The focal mechanisms are three of the largest events (numbers are magnitudes) (U.S. Geological Survey, 2022).

Site effects across a local scale (25 km x 32 km)

- The ground motions vary a lot across the small region (with a range of 2 – 3 times the array median; **Figure 5**).
- The site amplification patterns correspond to the Quaternary formations (Chang et al., 2023).

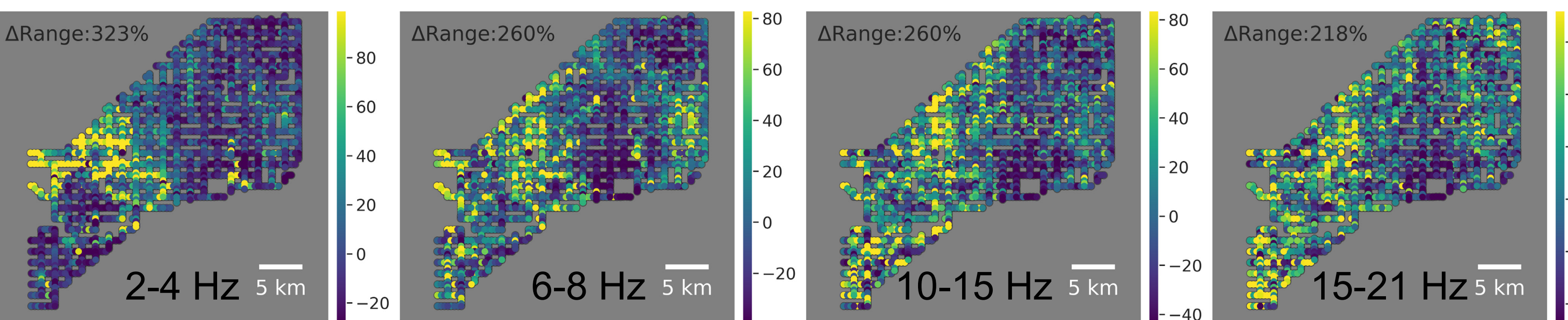


Figure 5: The median Peak-Ground-Velocity (PGV) of regional earthquakes (Figure 1) during the S-wave arrivals and codas. $\text{dev}(\text{PGV}) = (\text{PGV} - \text{median}(\text{PGV})) / \text{median}(\text{PGV})$. The range numbers are values at 99% minus values at 1%. The color bars are cut at values at 3% and 93% for visualization. The Root-Mean-Square amplitudes (RMS) have similar patterns.

- Source parameter estimated using a conventional approach (**Equation 1 – 3**) consistently correlate with ground motions:

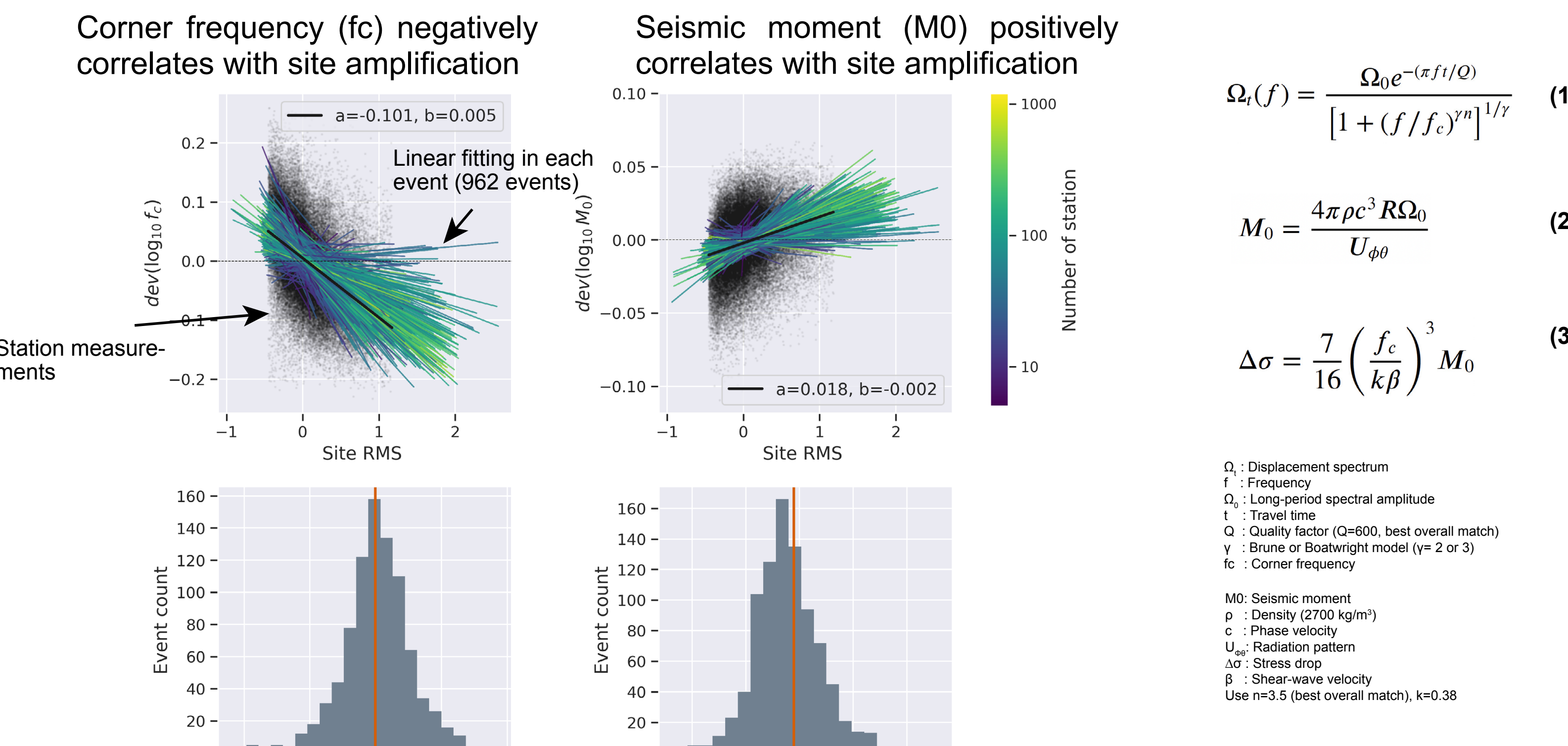
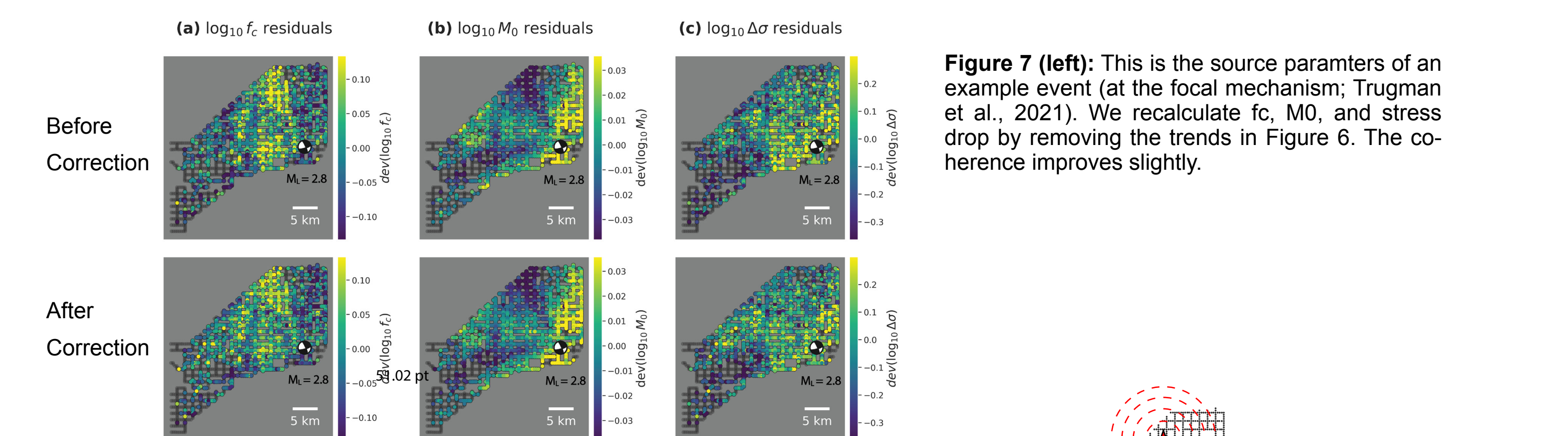


Figure 6: Correlation between measured source parameters and site amplification (site RMS) suggest potential influence from site effects.

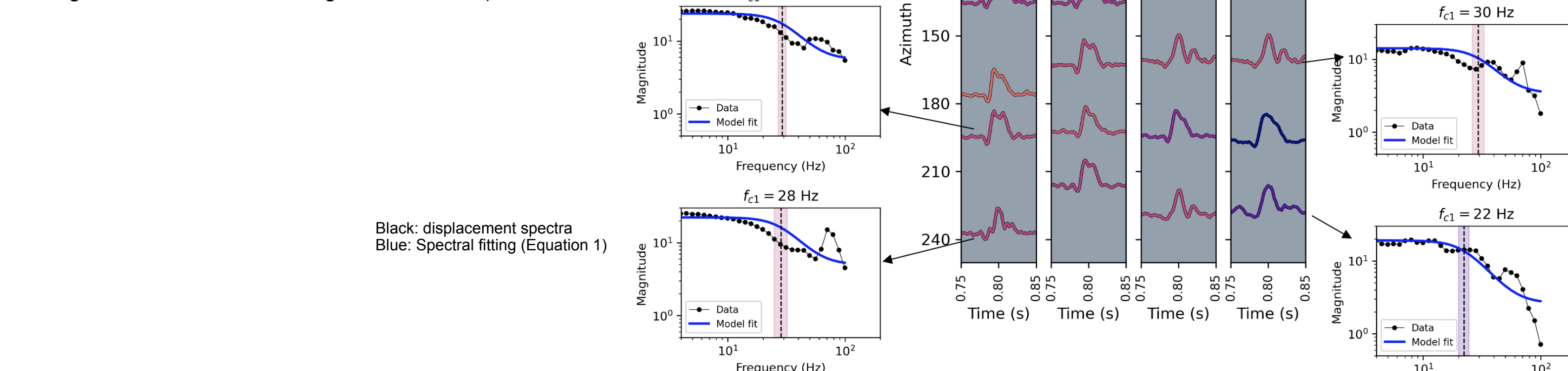
Results: Variability of source parameters include site-effect bias + source model misfit uncertainty

- We correct the source parameters by removing the trends in Figure 6. The correction improves the coherence (**Figure 7**).
- For events with the true fc being 30 – 60 Hz, the site-effect bias is about 1 – 3 Hz at this study scale.



- The rest of the variabilities (> 85% of the standard deviation of the measurements) likely come from simplification of the source model (**Figure 8**).

Figure 8 (right): We find local events have complicated source time functions that change their shapes around the epicenter despite their small magnitudes (agree with Trugman et al., 2021, Pennington et al., 2022).



Obtaining the velocity structure using ambient noise

- We investigate the shear-wave velocity (V_s) beneath LASSO to further link the structure to the observed site effects. The analysis includes 3 steps:

1. Extract surface waves
2. Estimate:
 - Phase velocity (V_{ph}) and anisotropy
 - Group velocity (V_g)
3. Convert to shear-wave velocity (V_s) structure

Using ambient-noise cross-correlation (5-min correlation window, stack over 1 month)

Using double-beamforming and seismic tomography (Seislib; Magrini, et al., 2022)

By jointly invert V_{ph} and V_g (Computer Program in Seismology; Herrmann, 2013)

- We obtain clear Rayleigh wave energy in ambient noise (**Figure 9**):

Figure 9 (right): An example virtual shot-gather (virtual source is marked as the red dot in the inset. The fundamental mode propagating with velocity near 1 km/s has a broader frequency range than the higher modes.

- The phase velocity shows the apparent influence from the basin basement that dips gently (< 1°) toward the SW of the array (**Figure 10**).
- The anisotropy does not align with the maximum stress direction in the previous study (e.g., Alt and Zoback, 2017) at 1 Hz but rotates to a closer alignment at 3 Hz.

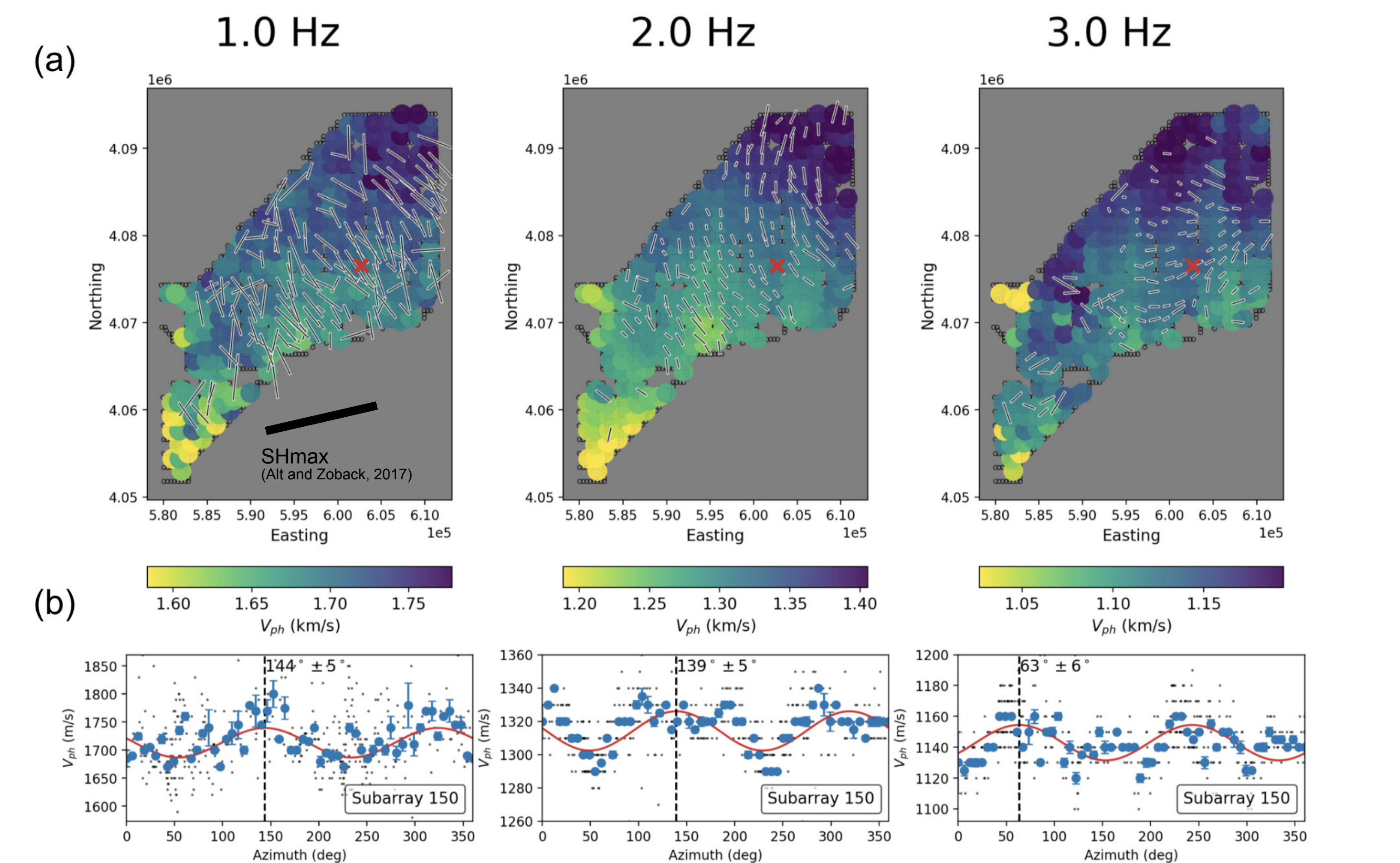


Figure 10: (a) The phase velocity (V_{ph}) and anisotropy of the Rayleigh wave fundamental mode. (b) shows the azimuthal dependence of V_{ph} at the subarray marked by a red X in (a). We bin the raw measurements from DBF (black dots) to the blue dots with errorbars indicating the deviation of raw measurements in each bin. The red sinusoidal curve is the best fit of the binned values.

- Double-beamforming (DBF) explained:

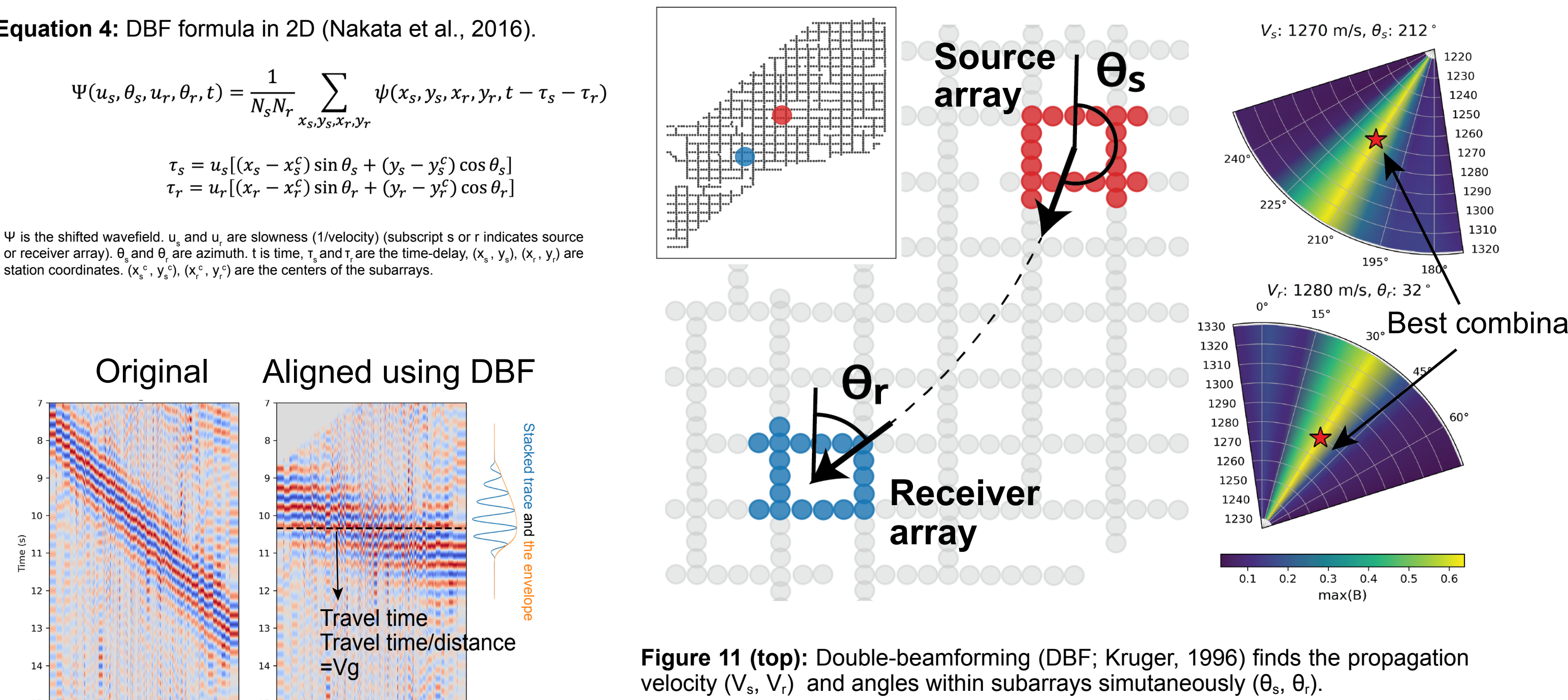


Figure 12 (left): The best velocities and angles can align the wavefield between the source and receiver arrays which result in the maximum beam.

Linking shear-wave velocity to site effects

- The shear-wave velocity reveals two trends (**Figure 13**):

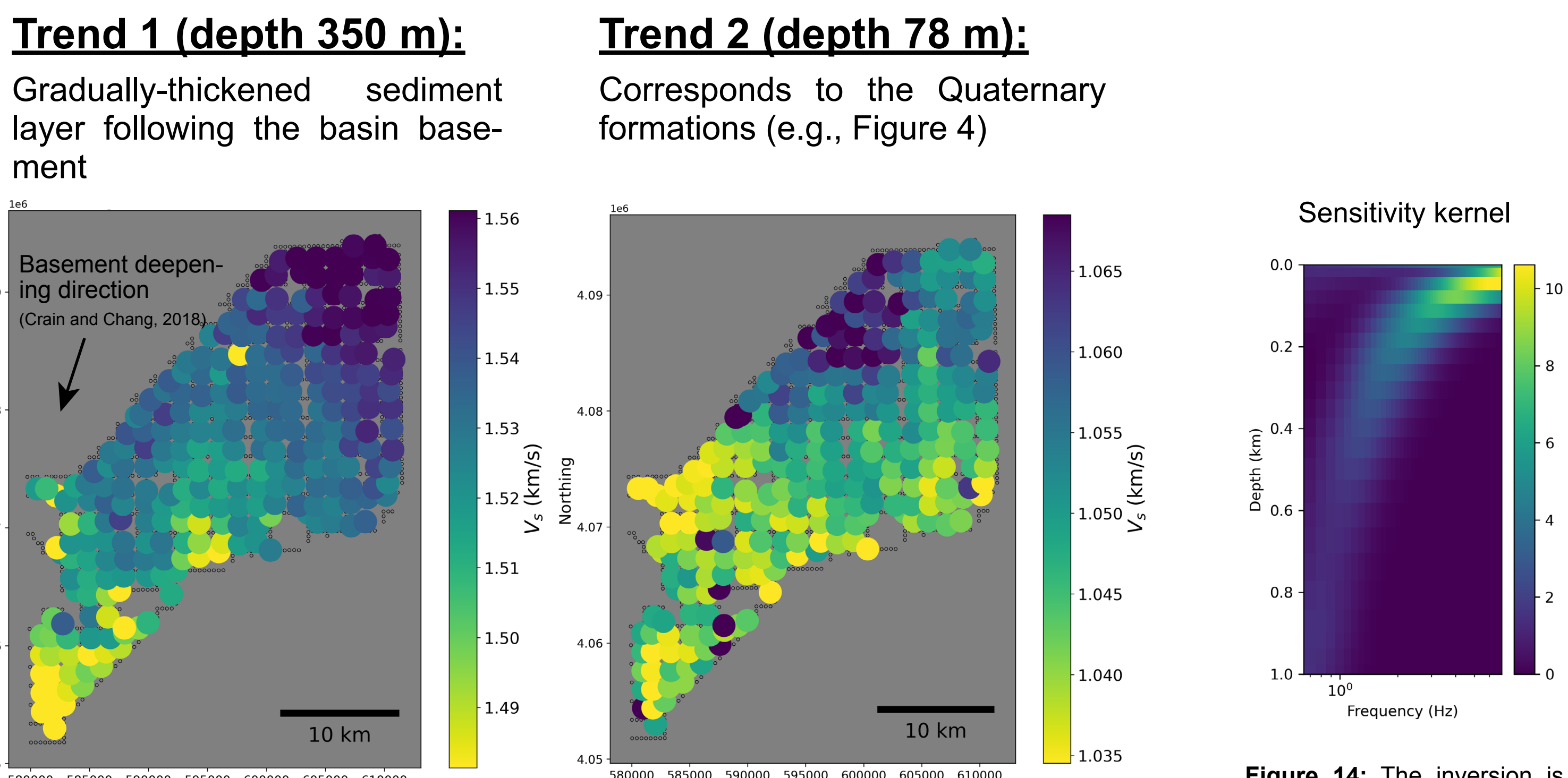


Figure 13: The shear-wave velocity (V_s) show two major trends corresponding to geology features. The colorbars are cut at values at 5% and 95% percentile for visualization.

1. Ground motions correlate both with Quaternary deposits and basin depth

- Ground motions have weak correlations with the shear-wave velocity (**Figure 15**):

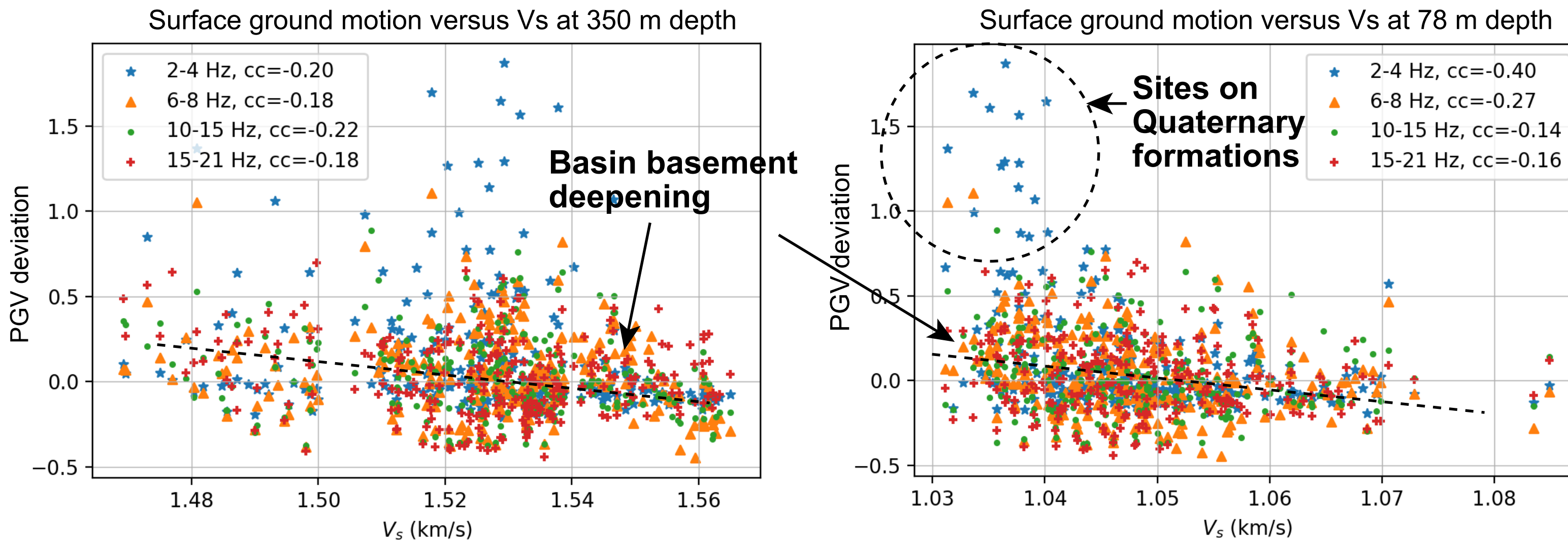


Figure 15: PGV (S waves) versus shear-wave velocity (V_s) at 350 m (left) and 78 m (right). The cross-correlation coefficients (cc) all have two-sided p-values < 5%. The PGV deviation is $(\text{PGV} - \text{median}(\text{PGV})) / \text{median}(\text{PGV})$.

2. Source parameters of an example local event (M=2.8) depend on both Quaternary deposits and basin depth

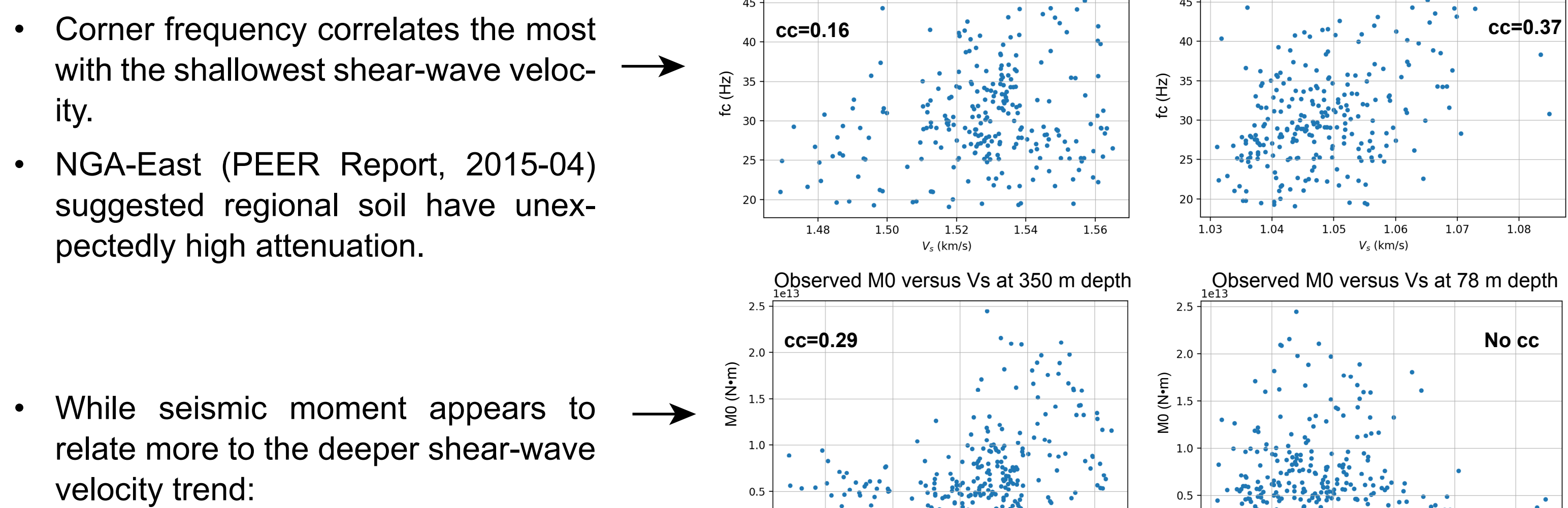


Figure 16: Source parameter (fc, M0 of an event) versus shear-wave velocity (V_s) at 350 m (left) and 78 m (right). The cross-correlations (cc) all have two-sided p-values < 5%.

Conclusions

- Source parameters can exhibit site-effect bias even across a small area.
- Attenuation in the shallowest layer (top few tens of meter) has the most important apparent influence on corner frequency bias. We are working on getting the shallow attenuation structure.
- The sediment thickness following the basin basement has apparent influences on ground motions.
- The shallow glacier-related deposits corresponds to anomalously large amplifications.