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 (Dougherghty 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).

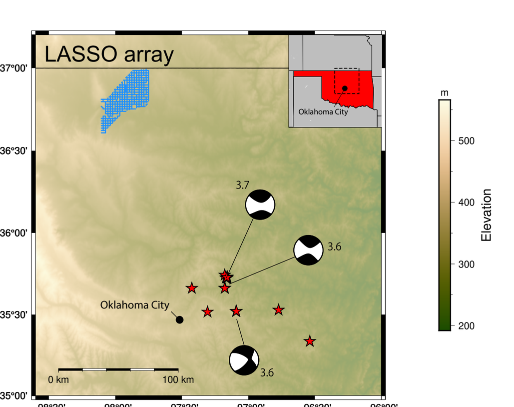


Figure 1: The LASSO array recorded regional events (red stars, 3.0 < M < 3.7) near the Oklohoma City. The focal mechanisms are three of the largest events (numbers are magnitudes) (U.S. Geological Survey, 2022).

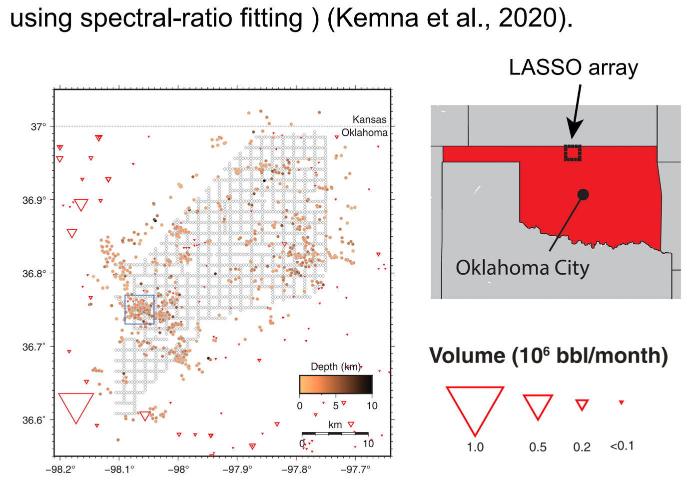


Figure 2: Local microearthquakes (dots colored by depth; M = 0.01 -- 3.0) are likely induced by wastewater injections (triangles). Modified from Cochran et al. (2020).

A large basin with local young sediments

- The LASSO array is in a sedimentary basin with Permain formations dominate the top 1 km (**Figure 3**).
- Locally, the Quaternary aluviums and terrace deposits from the massive erosion of the last ice age fill the top 10 -- 35 m (**Figure 4**, Heran et al., 2003).
- Local Vs30 (average shear-wave velocity on the top 30 m) matches the dense (CD) — loose sand (DE) categories (Wald and Allen, 2007; NEHRP, 2001).

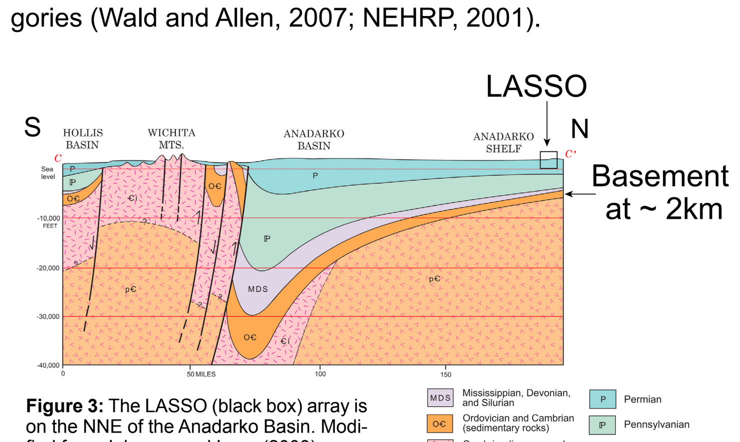


Figure 3: The LASSO (black box) array is on the NNE of the Anadarko Basin. Modified from Johnson and Luza (2008).

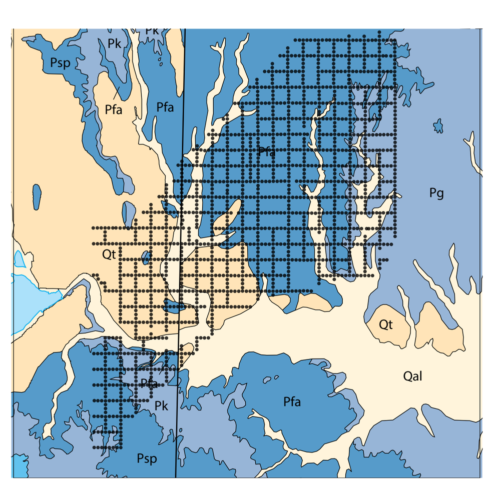


Figure 4: The Quaternary alluvium and terrace deposits (yellows) that overlay the Permian layers (blues) are prevalent across Oklahoma (Heran et al., 2003).
Qt (darker yellow) and Qal (pale yellow) are Quaternary terrace deposit and alluviums. Psp, Pk, Pfa, and Pg (various blues) are Permian shale, siltstone, sandstone, and conglomerate.

Scan this QR code for the cited references:

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).

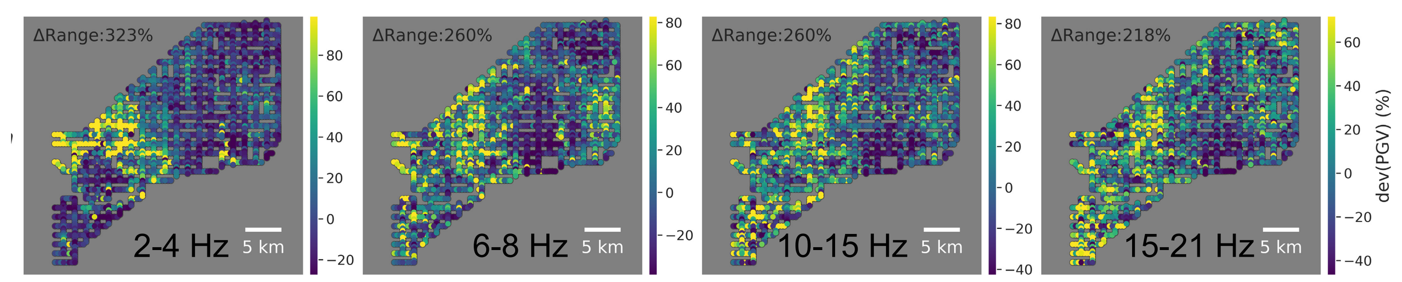


Figure 5: The median Peak-Ground-Velocity (PGV) of regional earthquakes (Figure 1) during the S-wave arrivals and codas. dev(PGV)= (PGV- median(PGV))/median(PGV).The range numbers are values at 99% minus values at 1%. The color bars are cut at values at 3% and 93% for vidualization. The Root-Mean-Square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

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

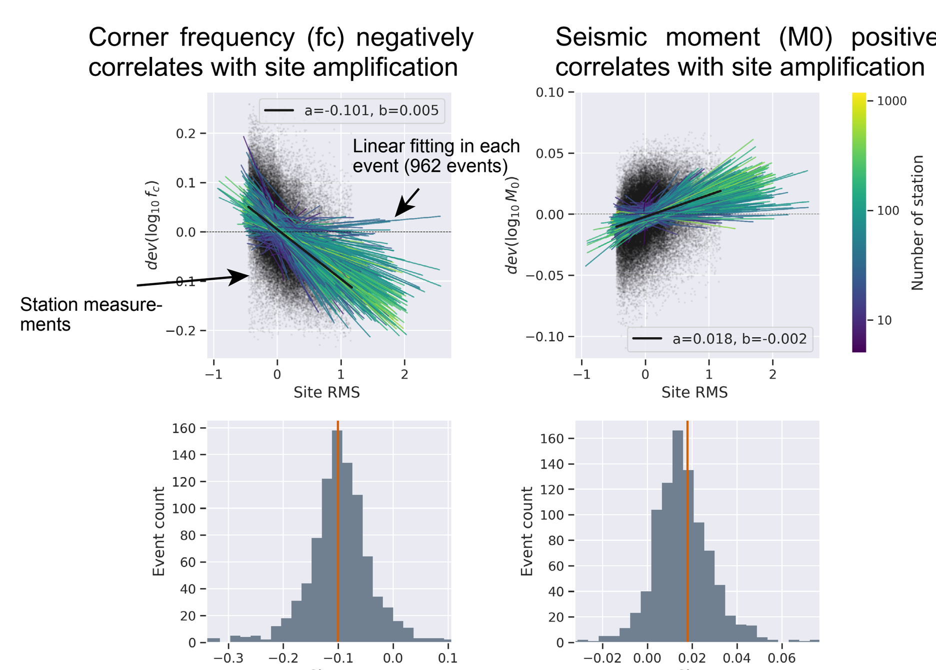


Figure 6: Correlation between measured source parameters and site amplification (site RMS) suggest potential influence from site effects.

$$\Omega_t(f) = \frac{\Omega_0 e^{-(\pi f t/Q)}}{\left[1+(f/f_c)^{\gamma n}\right]^{1/\gamma}} \quad (1)$$

$$M_0 = \frac{4\pi \rho c^3 R\Omega_0}{U_{\phi\theta}} \quad (2)$$

$$\Delta\sigma = \frac{7}{16}\left(\frac{f_c}{k\beta}\right)^3 M_0 \quad (3)$$

Ω_t : Displacement spectrum
f : Frequency
Ω_0 : Long-period spectral amplitude
t : Travel time
Q : Quality factor (Q=600, best overall match)
γ : Brune or Boatwright model (γ= 2 or 3)
fc : Corner frequency

M0: Seismic moment
ρ : Density (2700 kg/m³)
c : Phase velocity
$U_{\phi\theta}$: Radiation pattern
Δσ : Stress drop
β : Shear-wave velocity
Use n=3.5 (best overall match), k=0.38

Equation 1 -- 3: Models for getting corner the corner frequency, moment, and stress drop (Brune, 1978; Boatwright 1980; Eshelby, 1957; Madariaga, 1976). The stress drop depends on fc (strongly) and M0.

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.

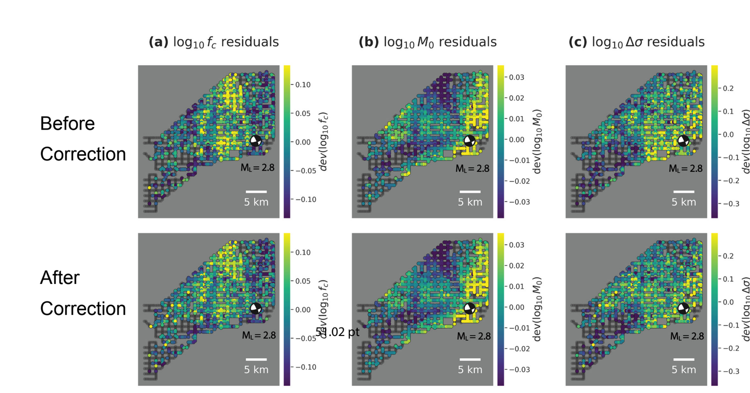
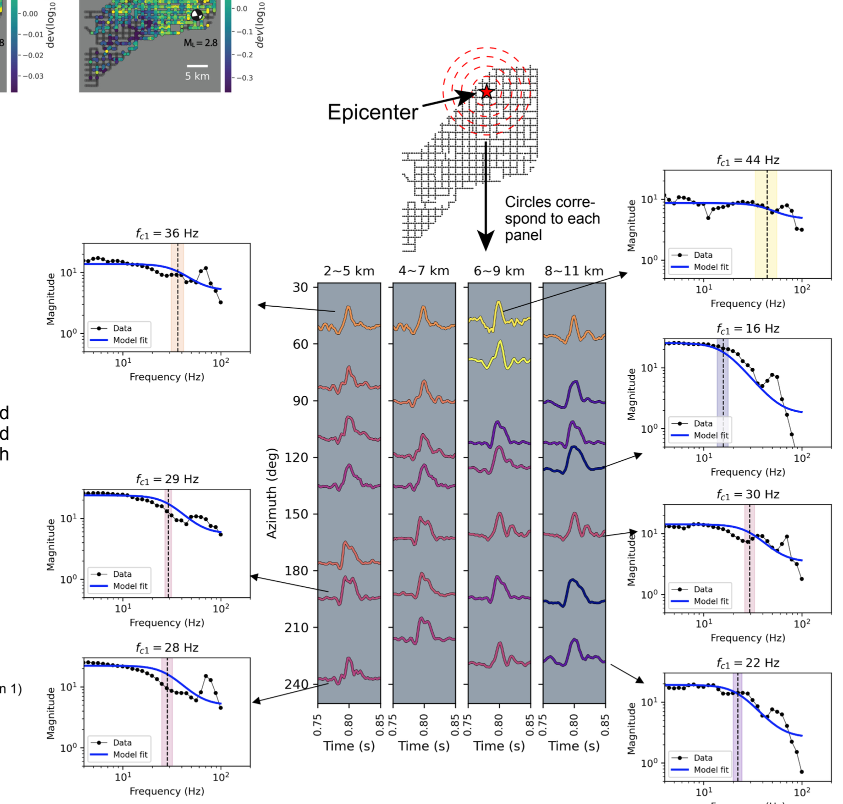


Figure 7 (left): This is the source paramters of an example event (at the focal mechanism; Trugman et al., 2021). We recalculate fc, M0, and stress drop by removing the trends in Figure 6. The coherence improves slightly.

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

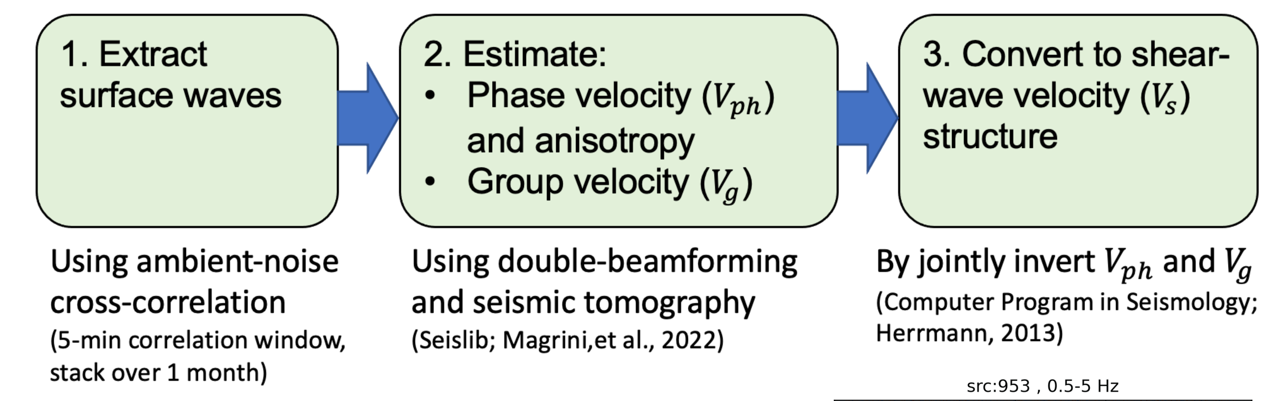
Figure 8 (right): We find local events have complicated source time functions that change their shapes around the epicenter despite their small magnitudes (agree with Trugman et al., 2021, Pennington et al., 2022).



Black: displacement spectra
Blue: Spectral fitting (Equation 1)

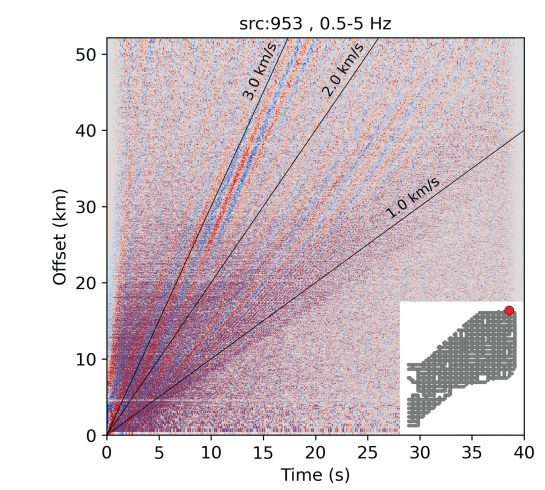
Obtaining the velocity structure using ambient noise

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



- 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.

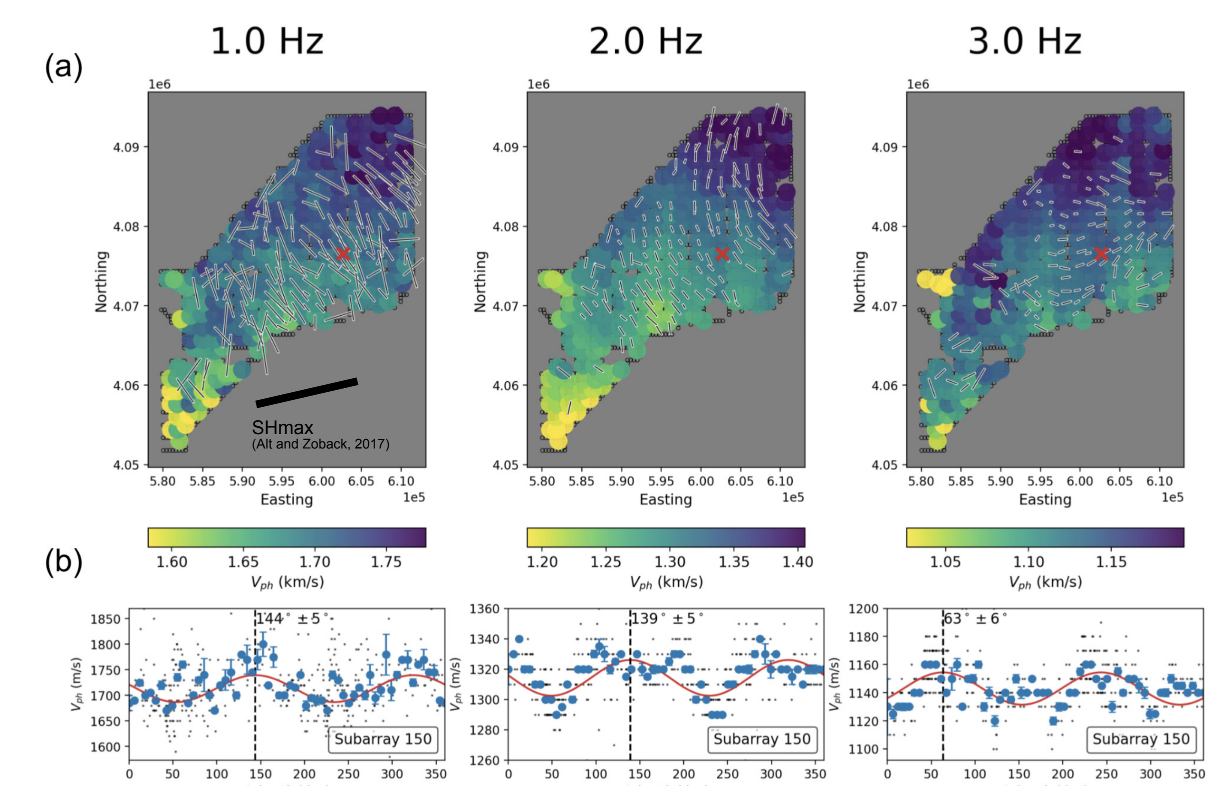


Figure 10: (a) The phase velocity (Vph) and anisotropy of the Rayleigh wave fundamental mode. (b) shows the azimuthal dependence of Vph at the subarray marked by a red X in (a). We bin the raw measurements from DBF (black dots) to the blue dots with errorbars indicating the deviation of raw measurements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

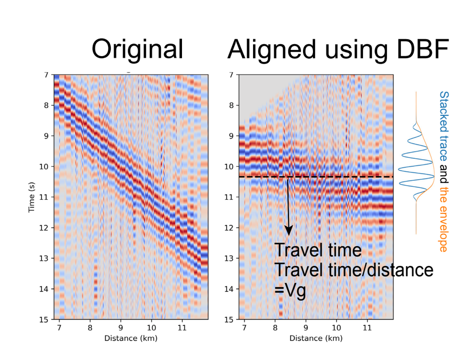
- Double-beamforming (DBF) explained:

Equation 4: DBF formula in 2D (Nakata et al., 2016).

$$\Psi(u_s,\theta_s,u_r,\theta_r,t) = \frac{1}{N_s N_r}\sum_{x_s,y_s,x_r,y_r}\psi(x_s,y_s,x_r,y_r,t-\tau_s-\tau_r)$$

$$\tau_s = u_s[(x_s - x_s^c)\sin\theta_s + (y_s - y_s^c)\cos\theta_s]$$
$$\tau_r = u_r[(x_r - x_r^c)\sin\theta_r + (y_r - y_r^c)\cos\theta_r]$$

Ψ is the shifted wavefield. u_s and u_r are slowness (1/velocity) (subscript s or r indicates source or receiver array). θ_s and θ_r are azimuth. t is time, τ_s and τ_r are the time-delay, (x_s, y_s), (x_r, y_r) are station coordinates. (x_s^c, y_s^c), (x_r^c, y_r^c) are the centers of the subarrays.



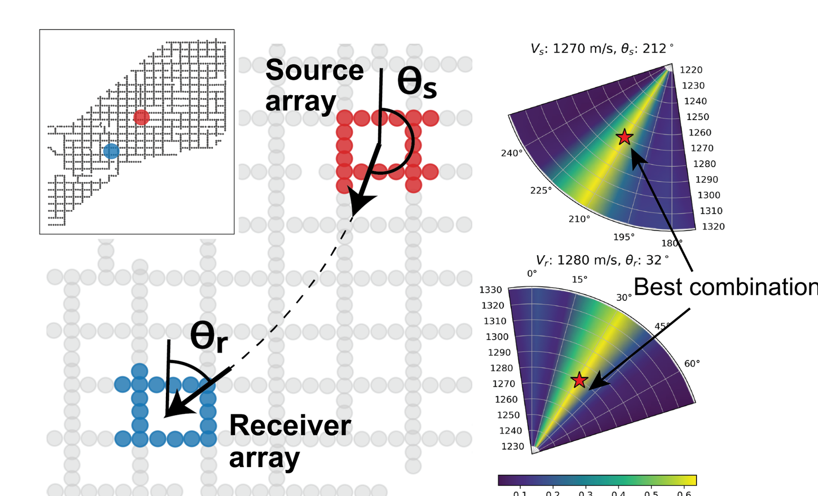


Figure 11 (top): Double-beamforming (DBF; Kruger, 1996) finds the propagation velocity (V_s, V_r) and angles within subarrays simutaneously (θ_s, θ_r).

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**):

Trend 1 (depth 350 m):
Gradually-thickened sediment layer following the basin basement

Trend 2 (depth 78 m):
Corresponds to the Quaternary formations (e.g., Figure 4)

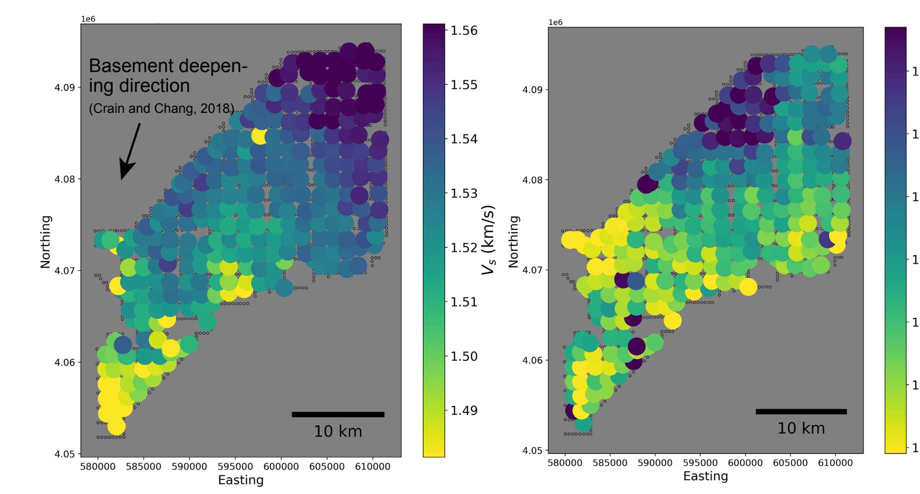


Figure 13: The shear-wave velocity (Vs) show two major trends corresponding to geology features. The colorbars are cut at values at 5% and 95% percentile for visualization.

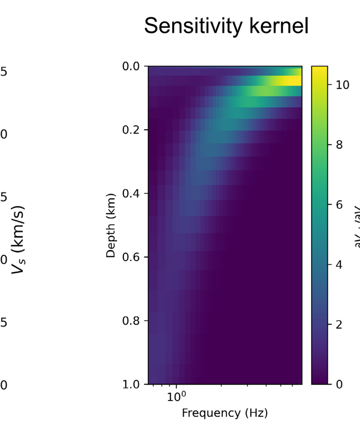


Figure 14: The inversion is sensitive to the depth range mostly between 50 m -- 1 km.

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

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

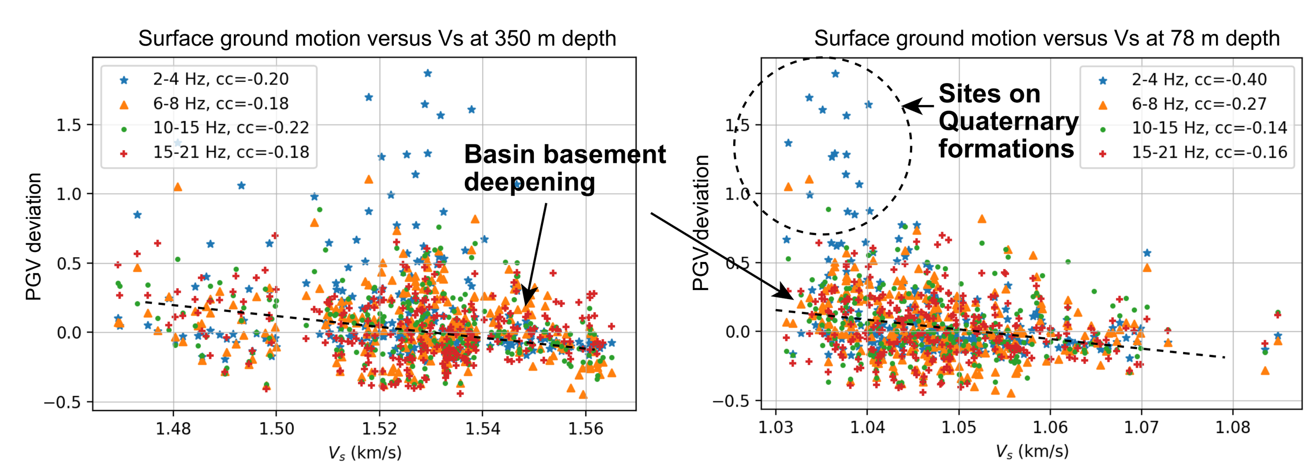


Figure 15: PGV (S waves) versus shear-wave velocity (Vs) at 350 m (left) and 78 m (right). The cross-correlation coefficients (cc) all have two-sided p-values < 5%. The PGV deviation is (PGV - median(PGV))/median(PGV).

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

- Corner frequency correlates the most with the shallowest shear-wave velocity.
- NGA-East (PEER Report, 2015-04) suggested regional soil have unexpectedly high attenuation.
- While seismic moment appears to relate more to the deeper shear-wave velocity trend:

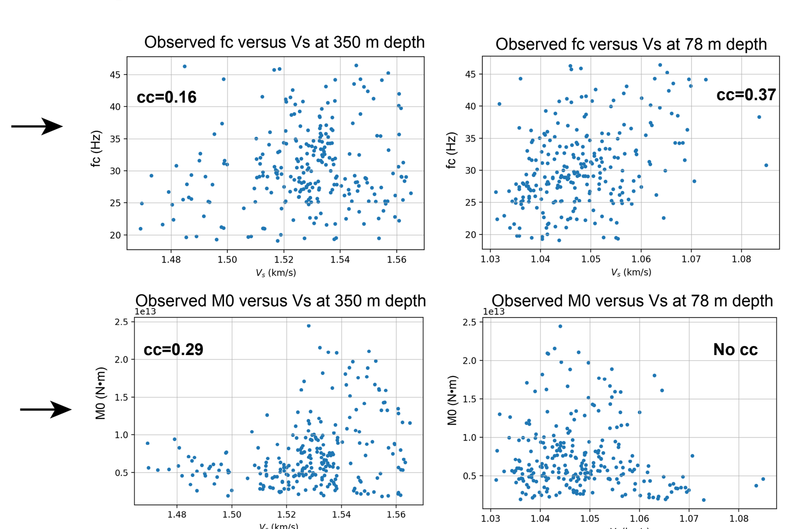


Figure 16: Sourece parameter (fc, M0 of an event) versus shear-wave velocity (Vs) at 350 m (left) and 78 m (right). The cross-correlations (cc) all have two-sided p-values < 5%.

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.