Empirical Models of Site Effects for Simulated Ground Motions

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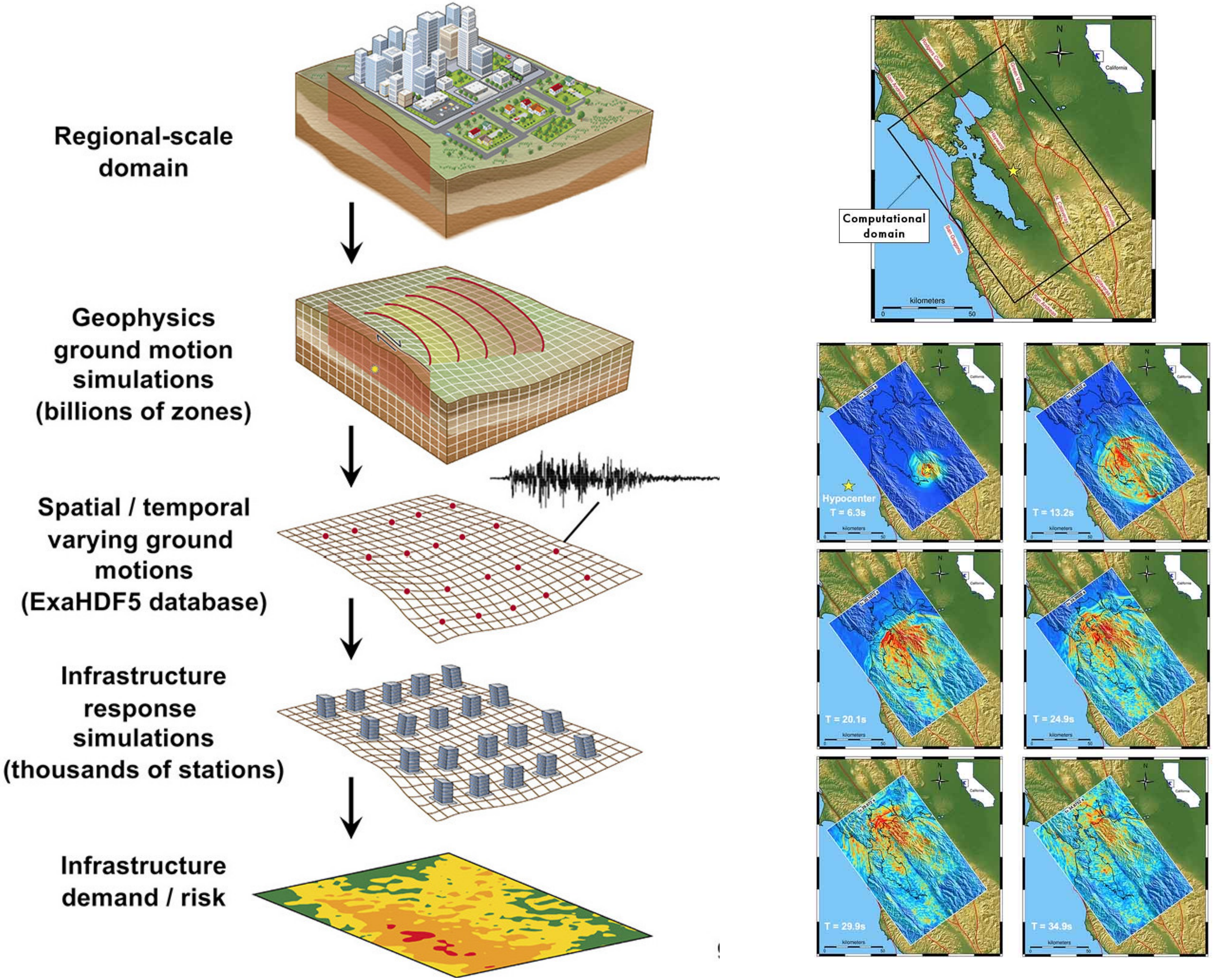
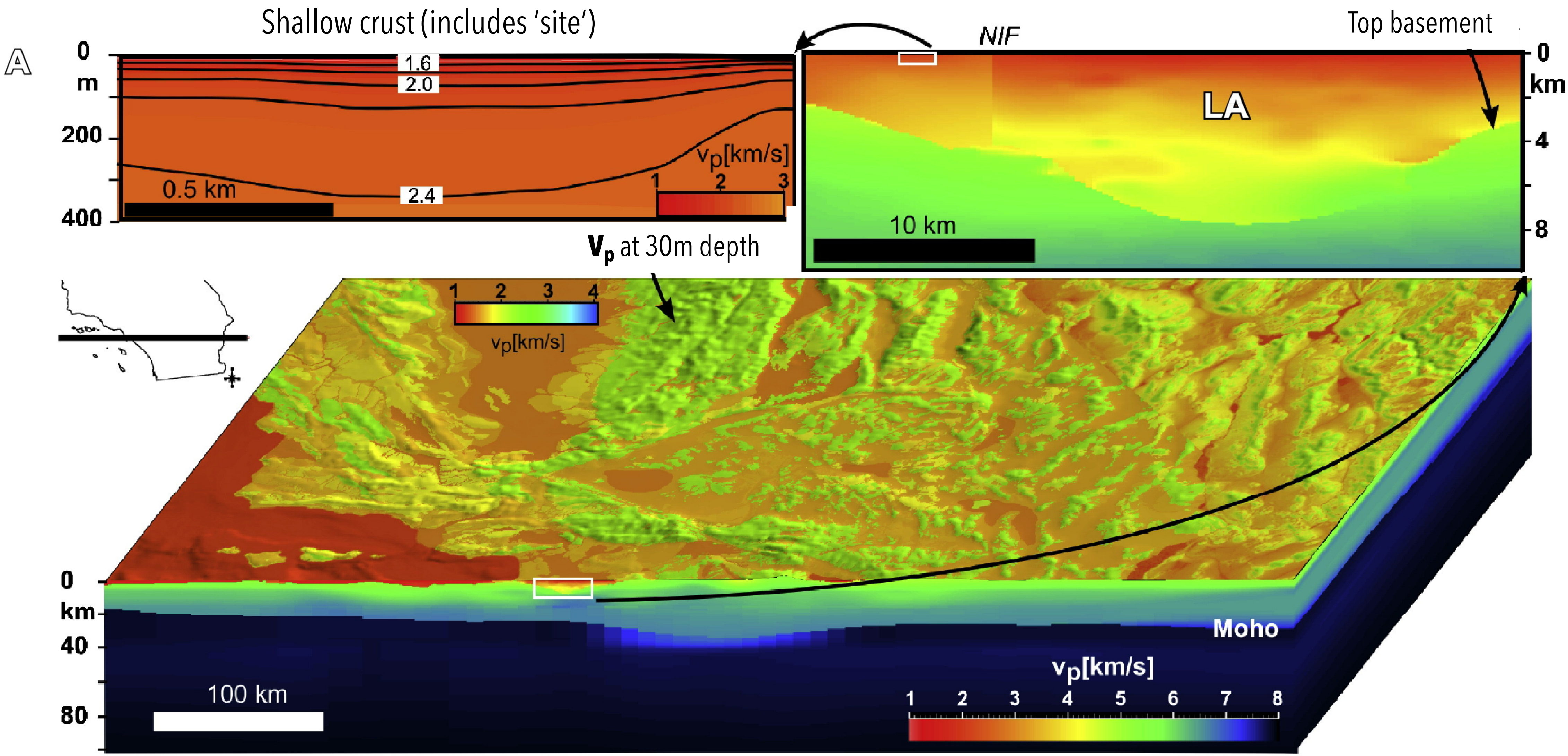
2024 PEER - LBNL WORKSHOP
Simulated Ground Motions for the San Francisco Bay Area
January 18, 2024



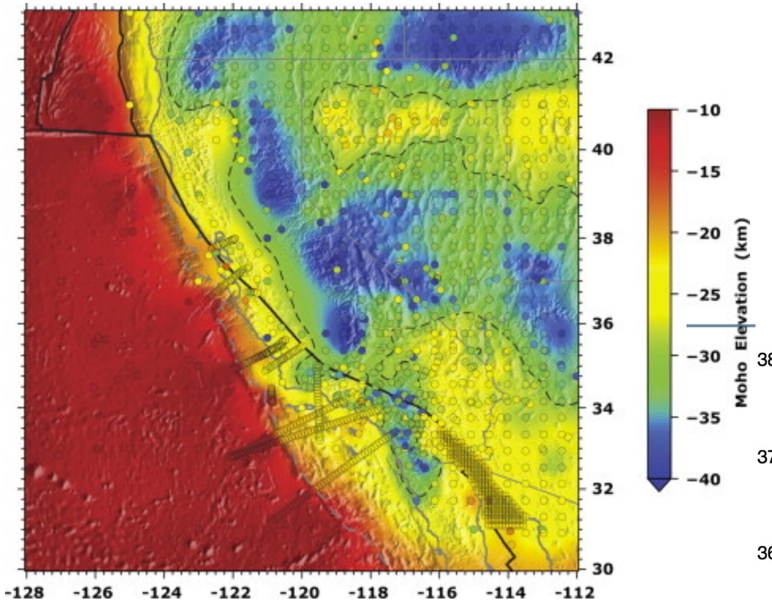
Regional-scale domain
Geophysics ground motion simulations (billions of zones)
Spatial / temporal varying ground motions (ExaHDF5 database)
Infrastructure response simulations (thousands of stations)
Infrastructure demand / risk
Computational domain
N
California
kilometers
0
50
Hypocenter
T = 6.3s
T = 13.2s
T = 20.1s
T = 24.9s
T = 29.9s
T = 34.9s

…but velocity models are coarse,



Perspective view of the northern part of the USR, showing an enlarged transect across the Los Angeles basin (Shaw et al., 2015)

…because they are 'learned' from data like this.

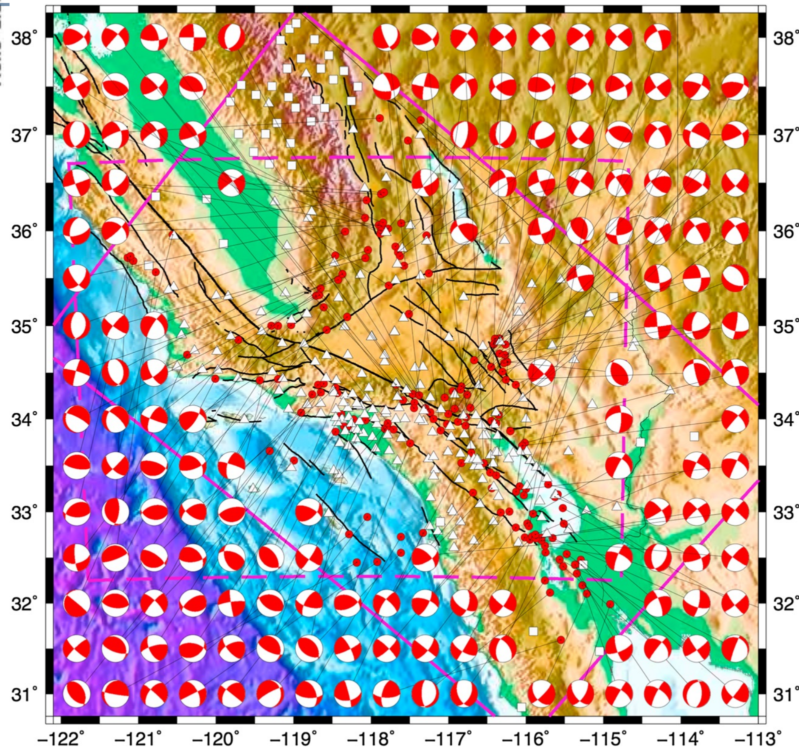


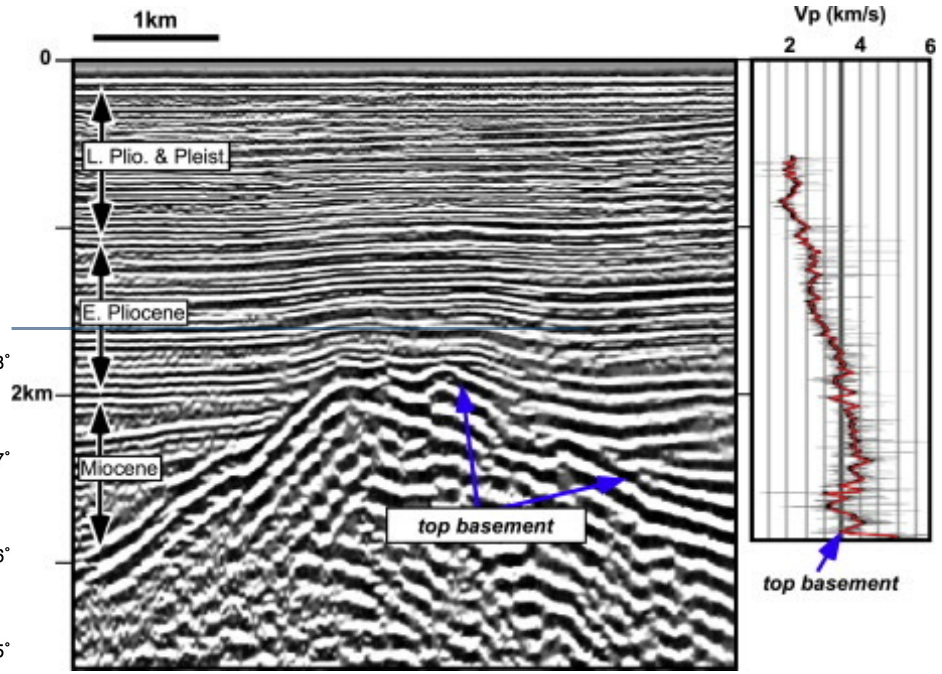
Depth of Moho in CVM
from receiver function studies
or from wide angle refraction.

Tape et al. (2012)

Distributions of the 160 earthquakes
and 258 seismic stations used for
full 3D tomography in So Cal.

Lee et al. (2014)





Migrated seismic reflection
profile in depth from the Inner
California Borderland showing
prominent top basement horizon.

Shaw et al. (2015)

10's of Hz propagate through path & site to buildings

Outline of empirical models:

a. Shallow crustal refinement of velocity models (learned from measured Vs data)

b. Site response amplification factors (learned from simulated data)

c. Nonlinear site response analyses (machine learned from data)

a. The California Sediment Velocity Model (to be)

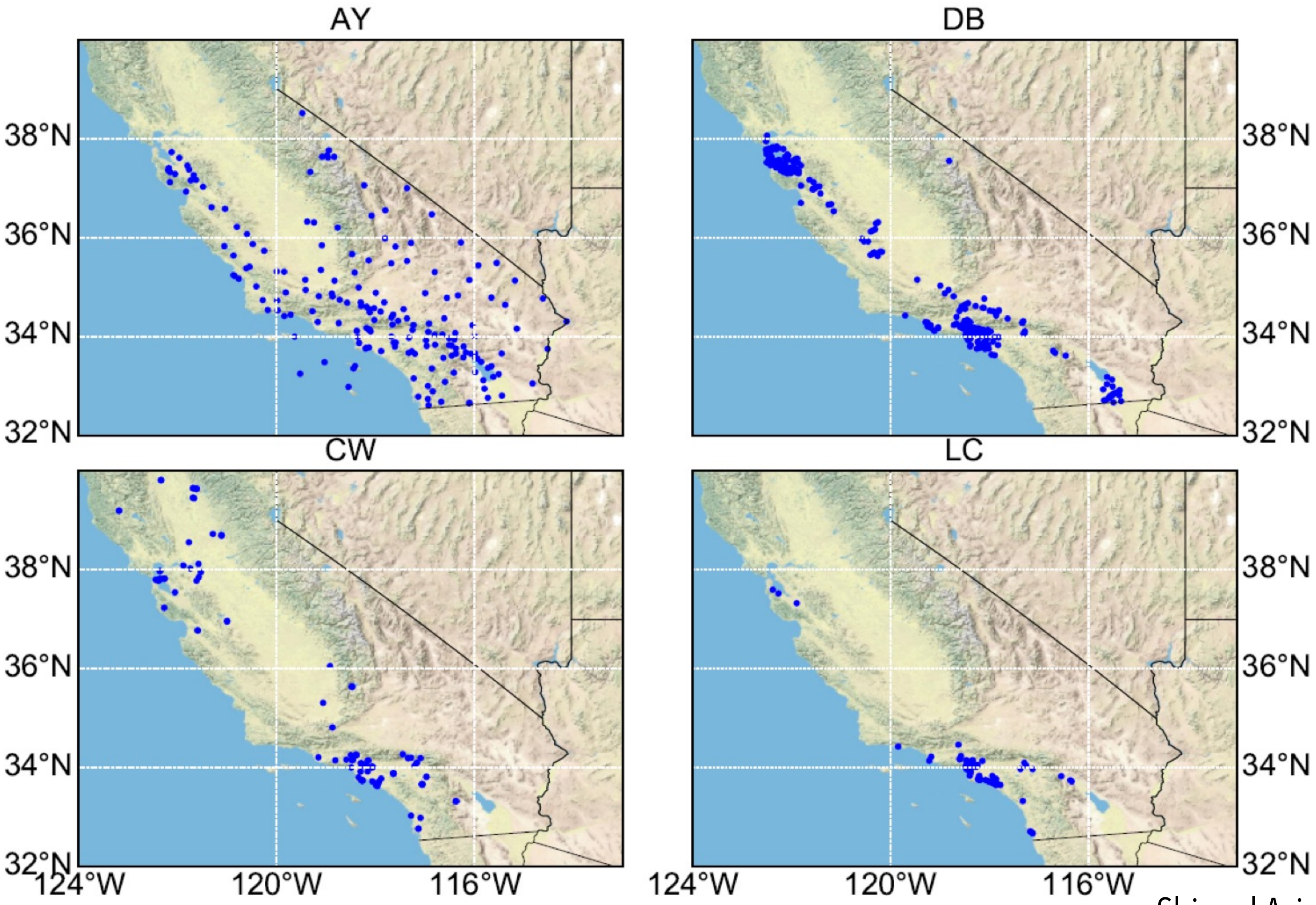
AY: Yong et al. (2013)

DB: Boore (2003)

CW: Chris Wills with CGS

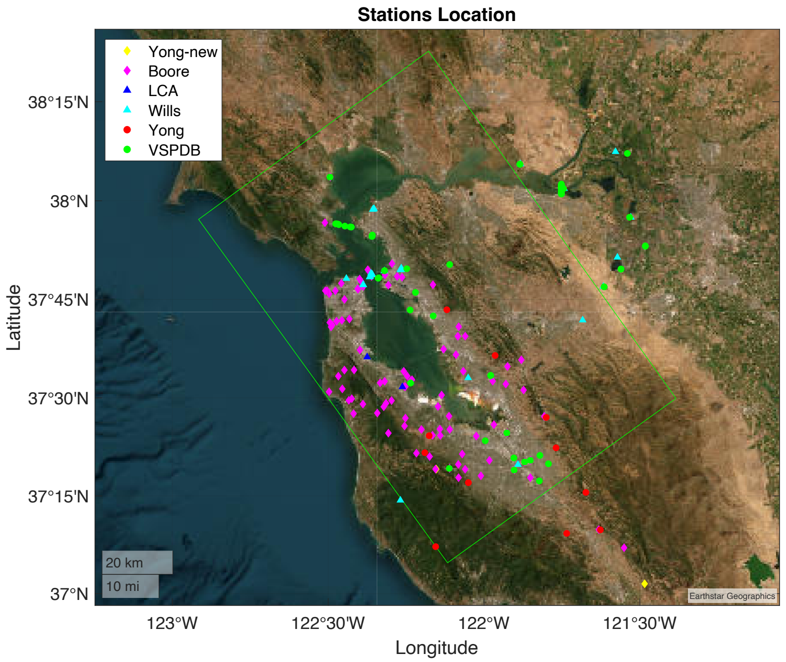
LC: LeRoy Crandall

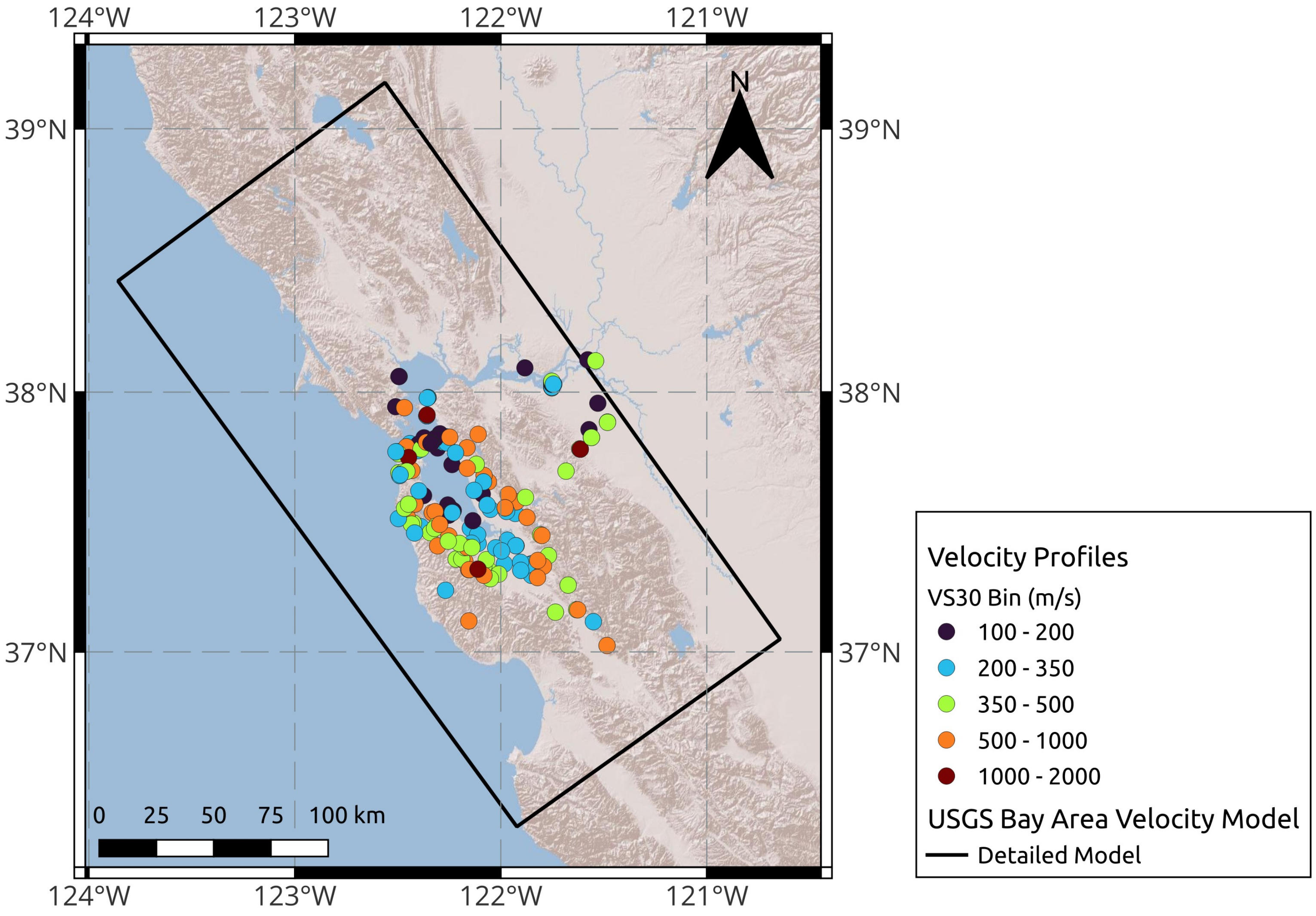
914 profiles



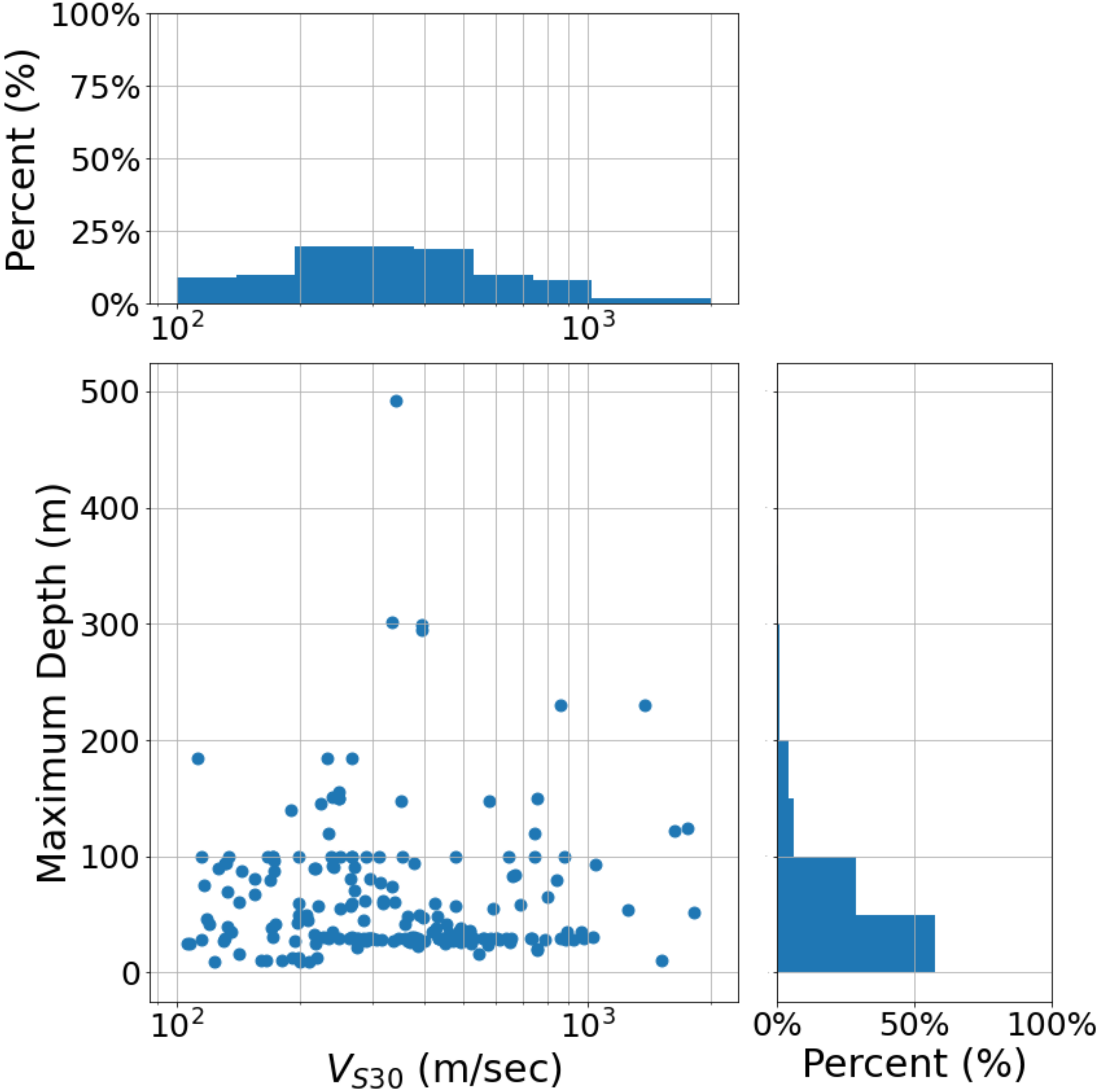
Shi and Asimaki (2018a)

211 measured and unified profiles in SFBA





Tehrani et al (2023); Lavrentiadis et al (202X)



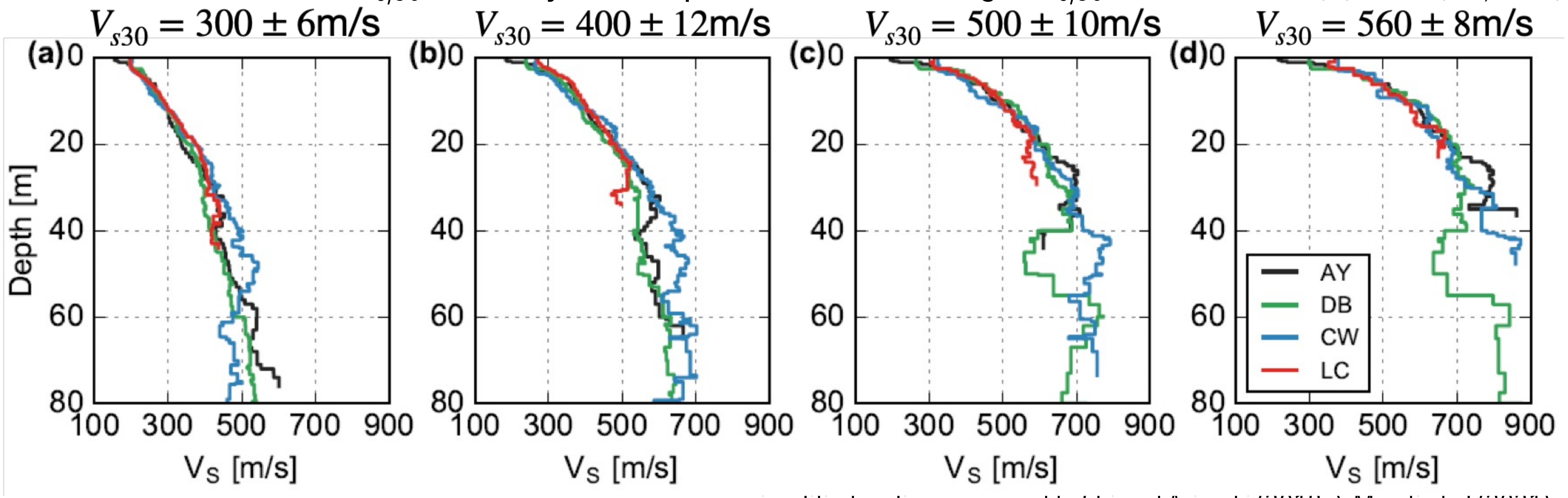
Percent (%)
100%
75%
50%
25%
0%
10^2
10^3
Maximum Depth (m)
500
400
300
200
100
0
V_{S30} (m/sec)
0%
50%
100%
Percent (%)

Scaling relationships for the median profile

$$\bar{V}_S(z) = \begin{cases} V_{S0} & \text{for } z \leq z^* \\ V_{S0}(1 + k(z - z^*))^{1/n} & \text{for } z > z^* \end{cases}$$

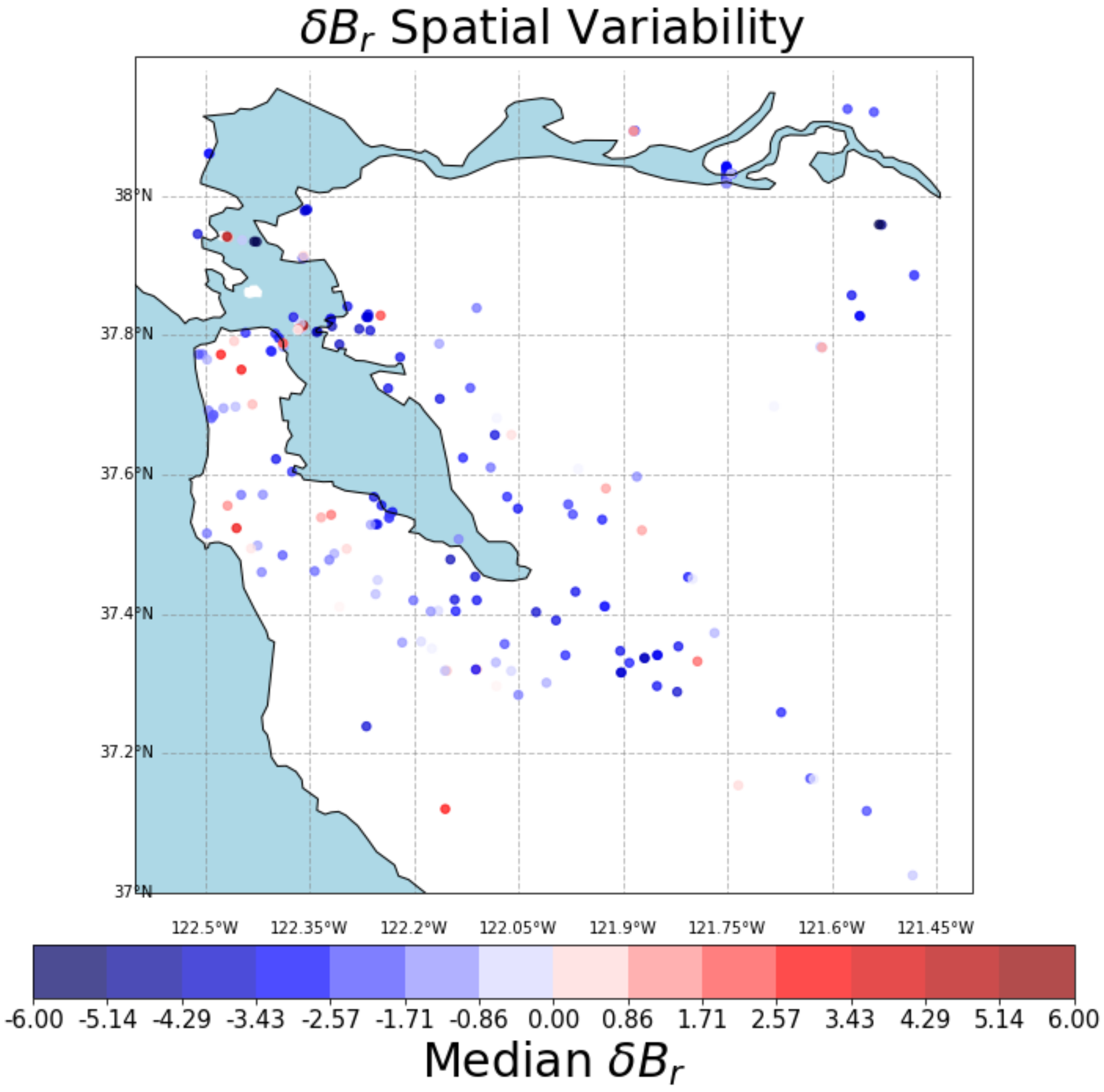
based on Shi and Asimaki (2018a)

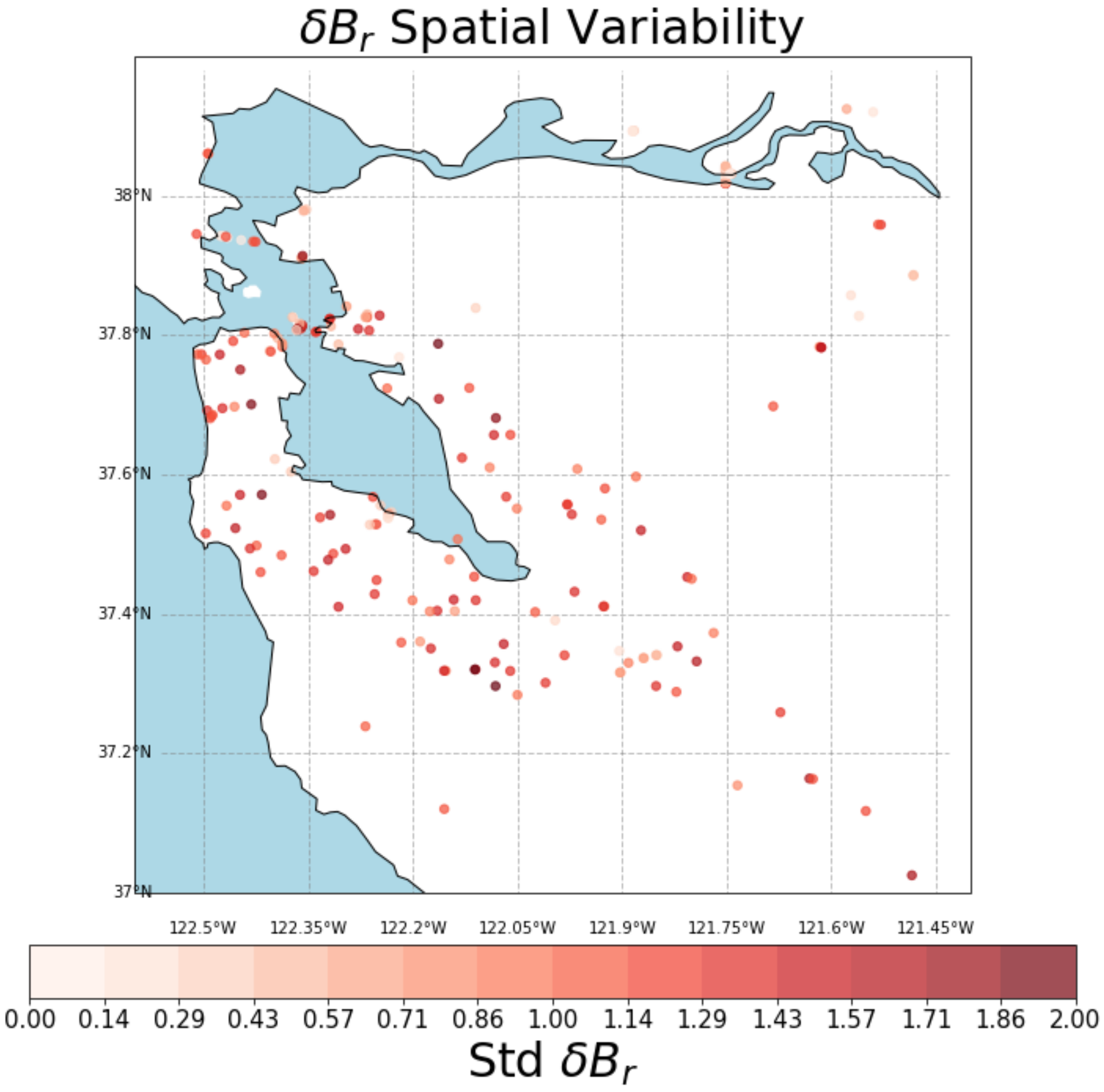
When we constraint the $V_{s,30}$ of the synthetic profile to fit the target $V_{s,30}$, we have $\bar{V}_S(z) = f(V_{s,30}, z)$

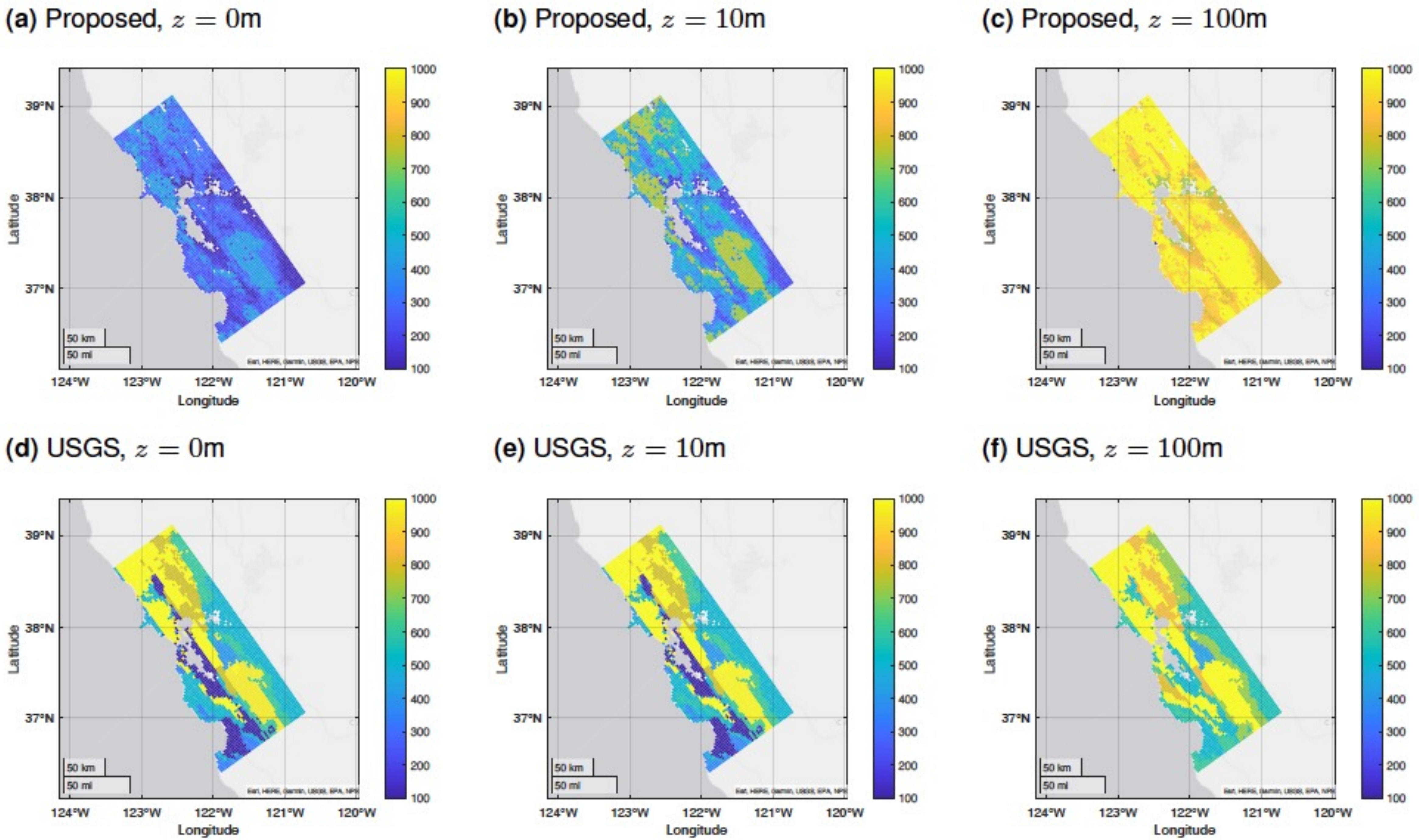


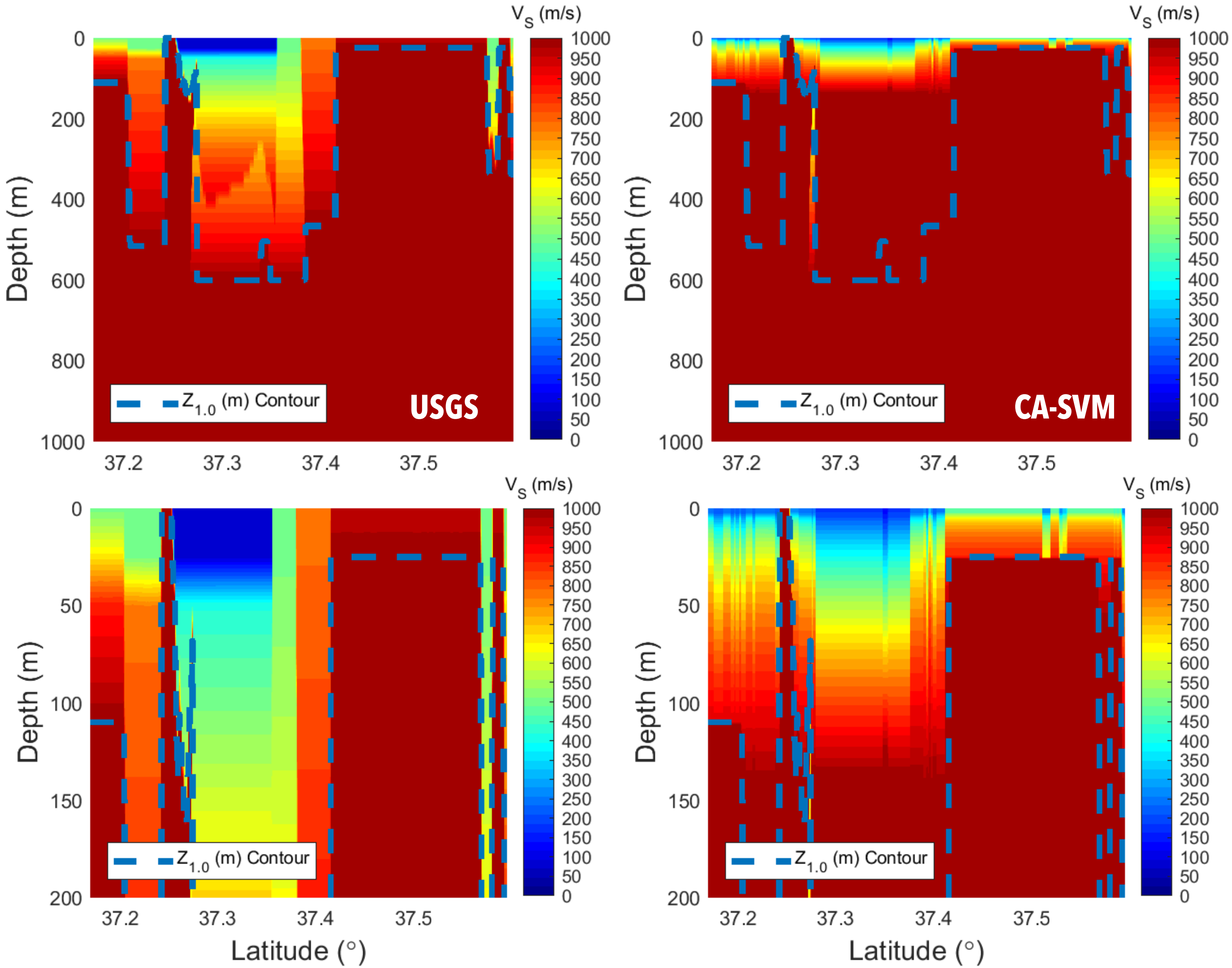
simplified scaling compared to Shi and Asimaki (2018a), Marafi et al (2021)

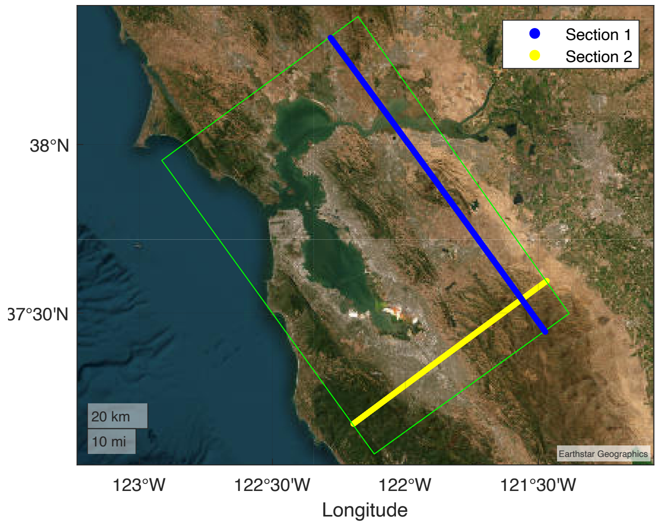
Within-profile variability varies in space (via *k*)






(a) Proposed, $z = 0$m
(b) Proposed, $z = 10$m
(c) Proposed, $z = 100$m
(d) USGS, $z = 0$m
(e) USGS, $z = 10$m
(f) USGS, $z = 100$m
Latitude
Longitude
39°N
38°N
37°N
124°W
123°W
122°W
121°W
120°W
50 km
50 mi
1000
900
800
700
600
500
400
300
200
100

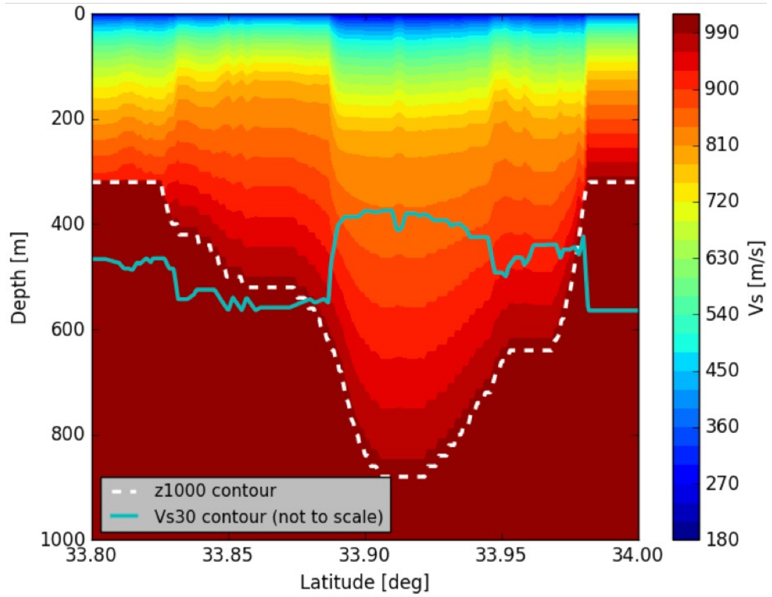


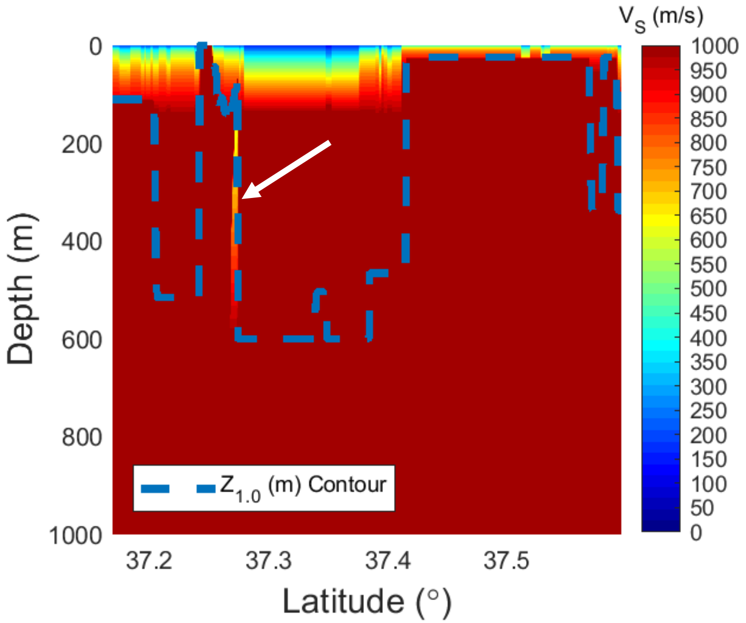


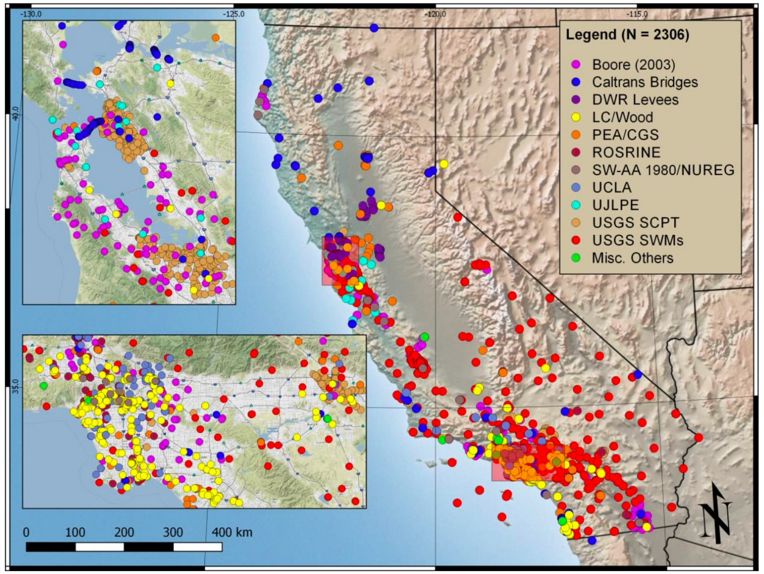
Shallow-crust velocity for **Section 2**

In progress…

- Criteria for 'stitching' with USGS model at 1km/sec, especially at basin edges.
- Eliminate median scaling (grandfathered in from S&A18) → Gaussian Process
- Expand to So Cal and Central Valley using e.g. Ahdi et al (2017).
- Analyze residuals from 1D and 3D analyses vs. GMMs.

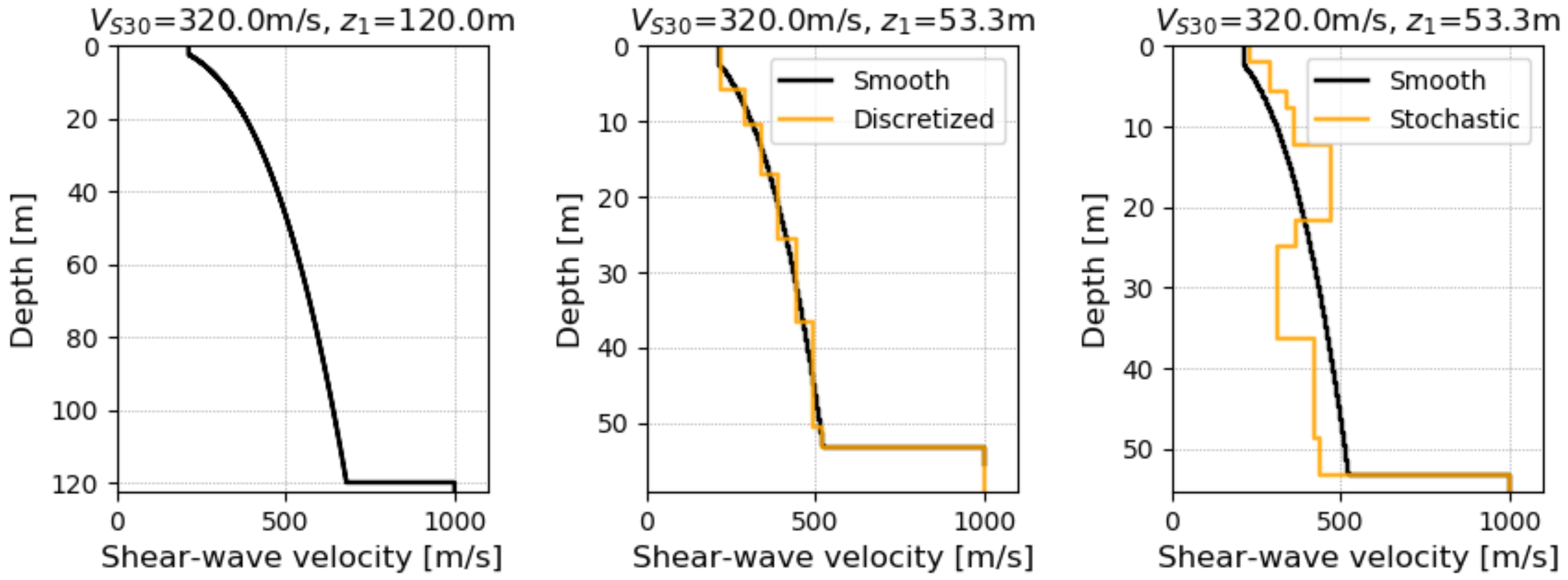


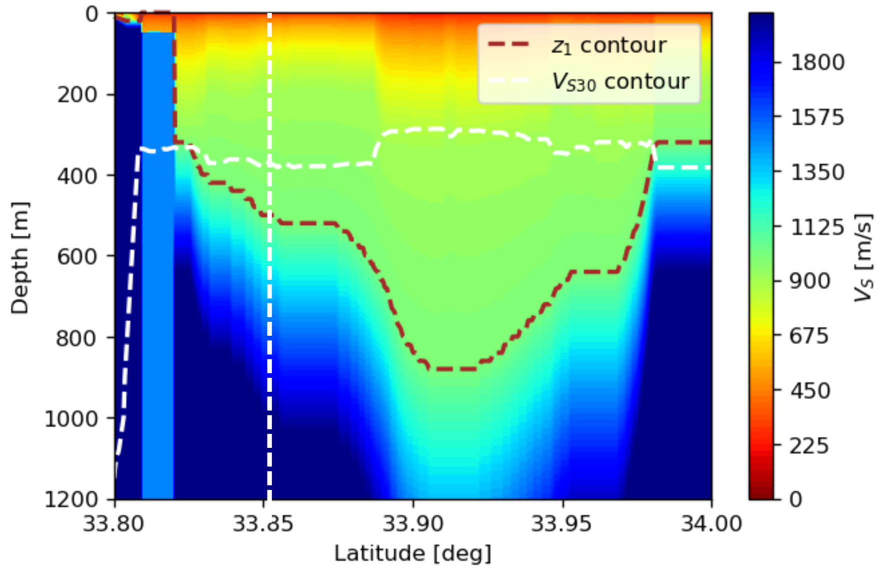




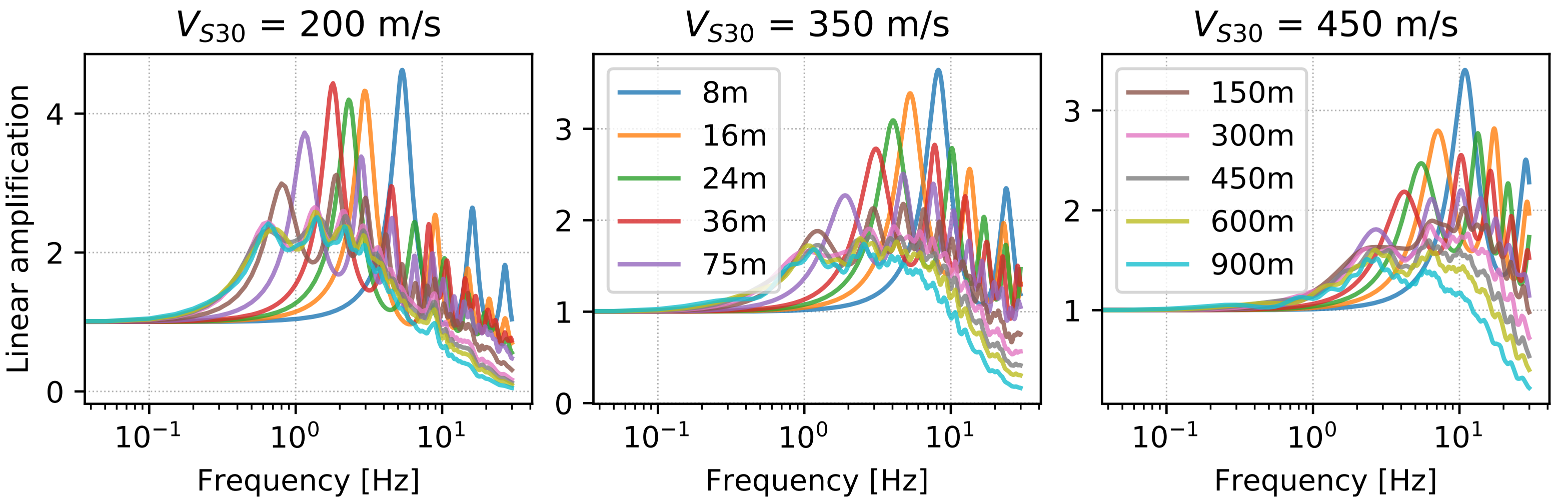
b. Complex site amplification factors

If velocity model doesn't include SVM (and perturbations thereof), integrate nonlinear site response (1D) using only $V_{s,30}$ input.

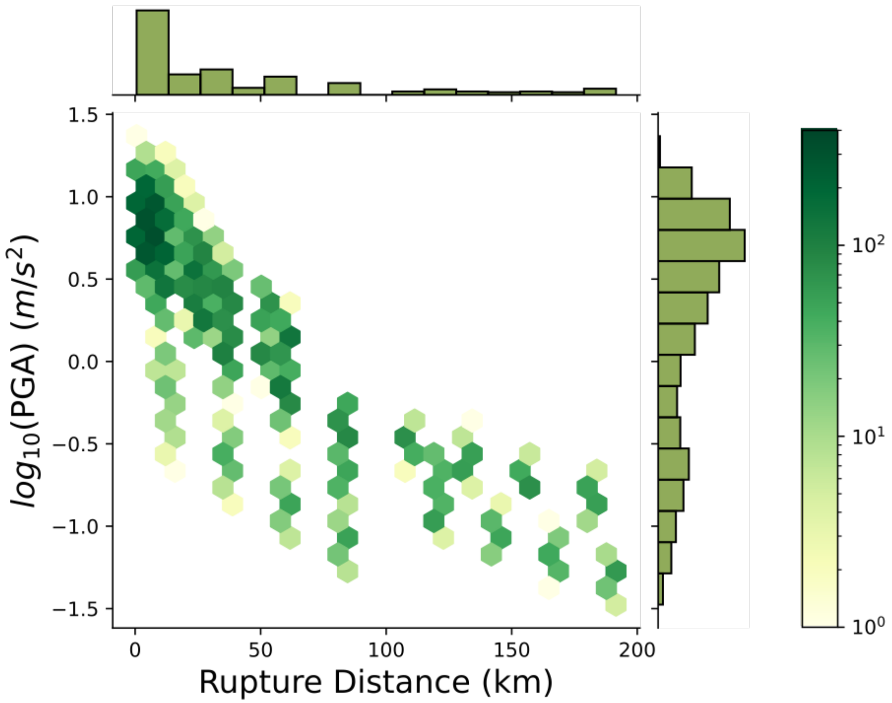


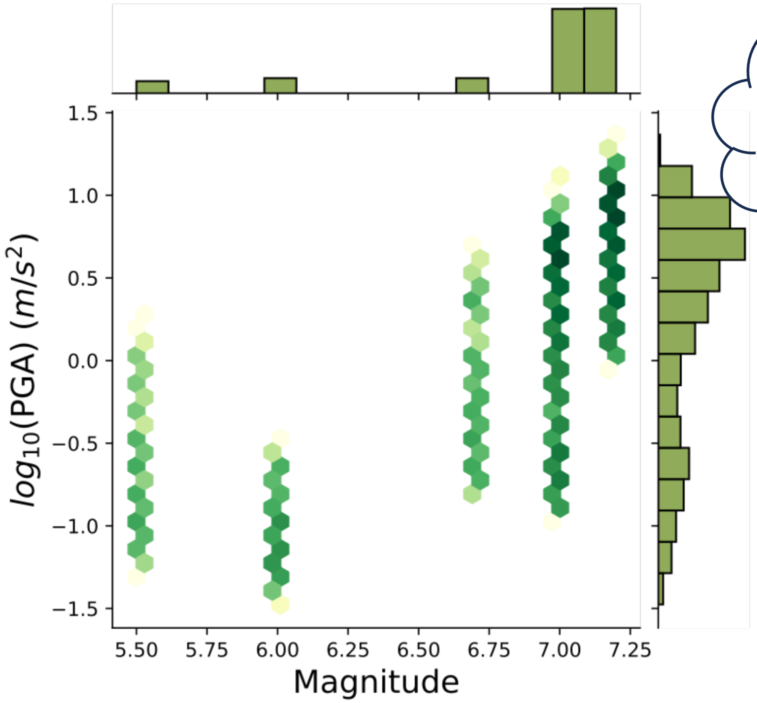


Shi and Asimaki (2021) developed precomputed complex amplification factors based on Shi and Asimaki (2018) So Cal SVM.



Generated range of SS and reverse simulated ground motions using the SCEC BBP





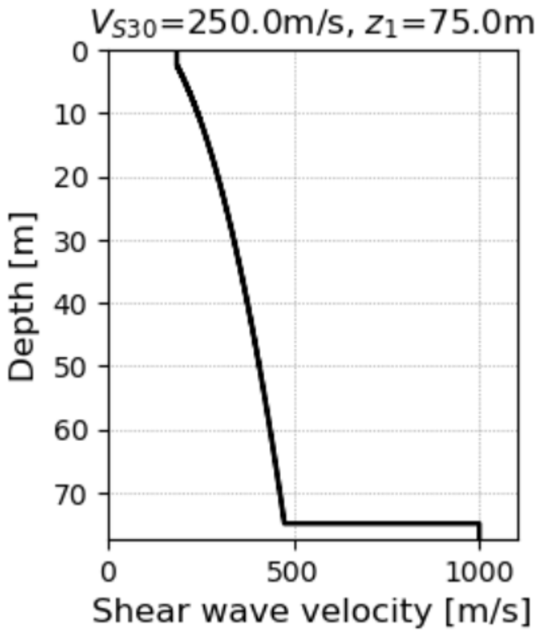
With many thanks to Rob Graves!

PySeismoSoil: Automatically assigns NL properties to Vs(z)

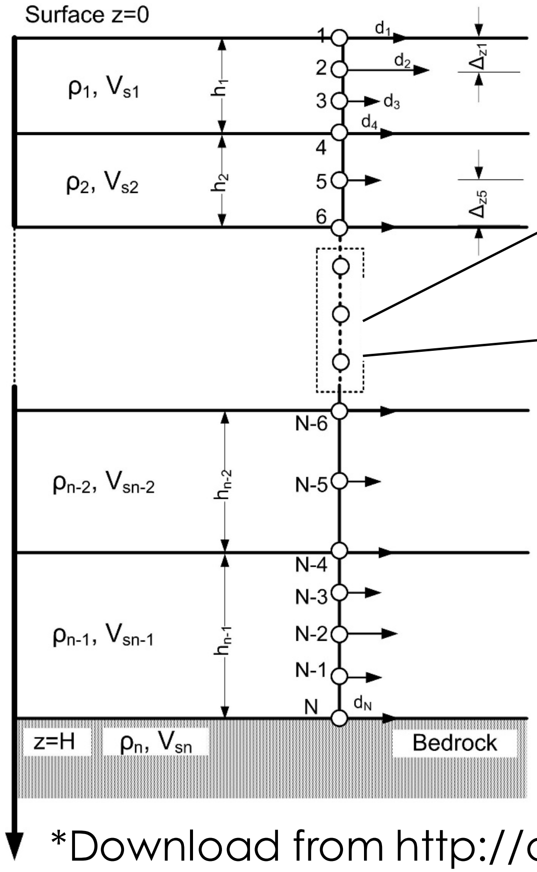
```
from PySeismoSoil.class_svm import SVM
```

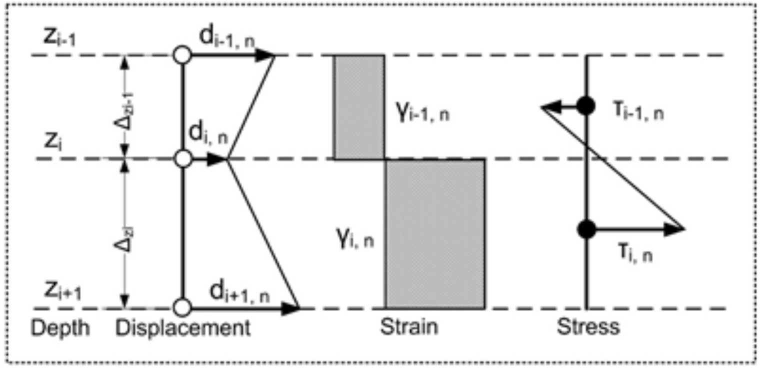
```
In [4]:  Vs30 = 250  # unit: m/s
```

```
In [5]:  svm = SVM(Vs30, z1=75, show_fig=True);
```



Finite difference method



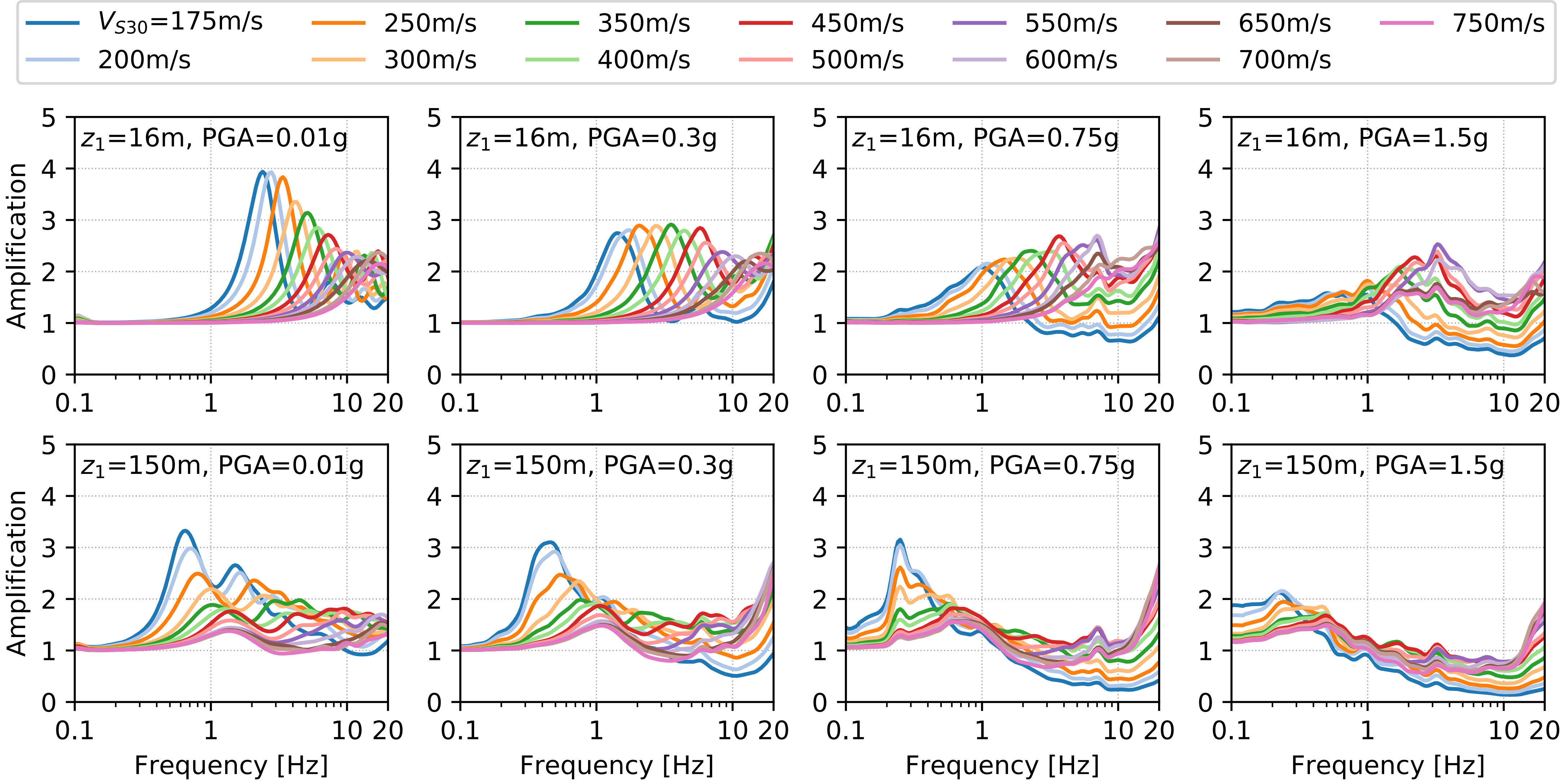


Monotonic loading	Hybrid hyperbolic model (*Shi & Asimaki, 2017*)
Hysteresis behavior	Modified Muravskii (2005) (*Li & Asimaki, 2009*)
Low strain damping	Frequency independent (*Asimaki et al, 2009*)

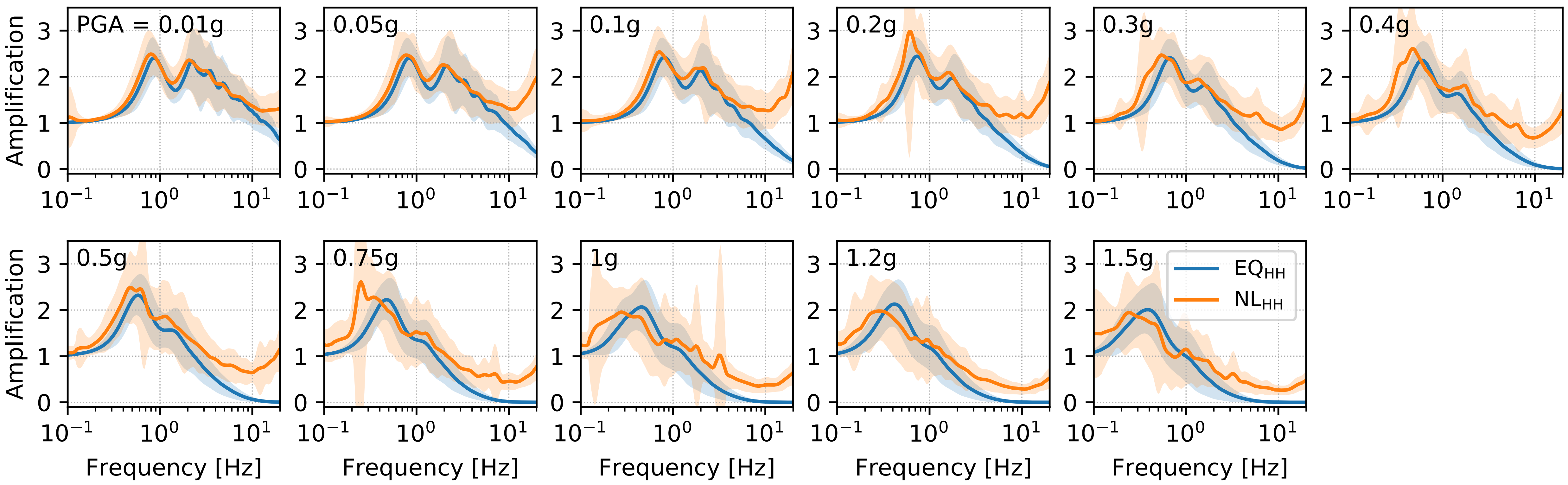
*Download from http://asimaki.caltech.edu/Resources

Shi and Asimaki (202X)

Fourier surface/rock outcrop ratios: Amplitude

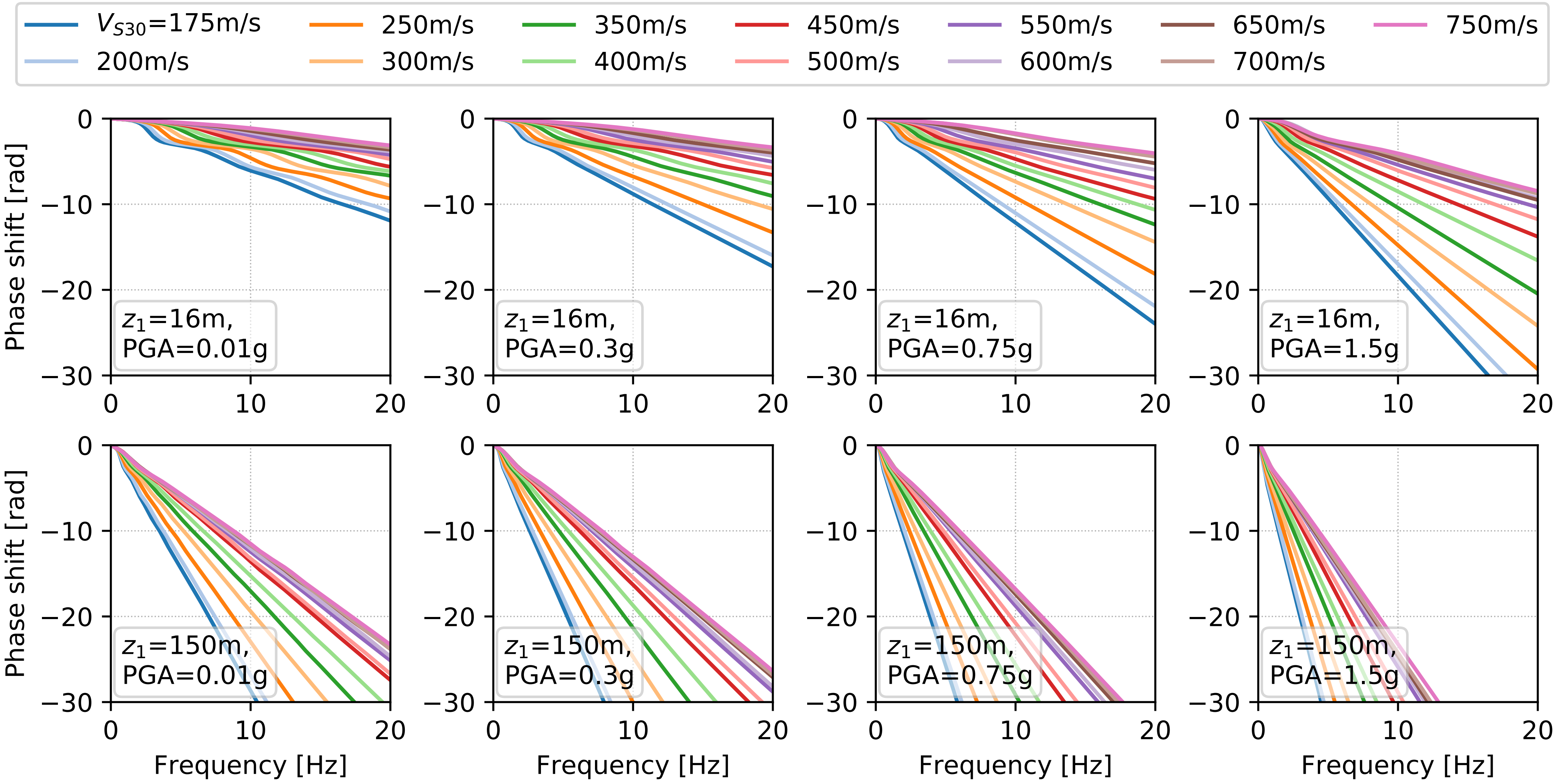


Fourier S/RO amplitude: EQ linear vs. nonlinear

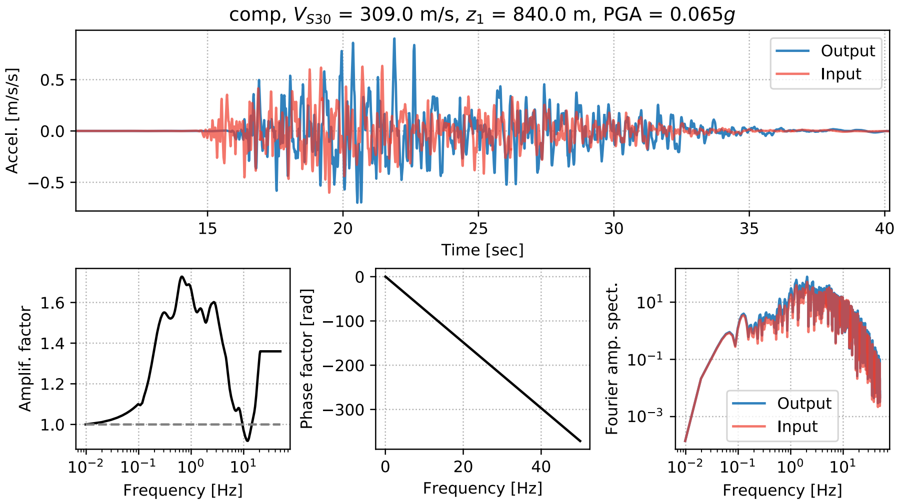


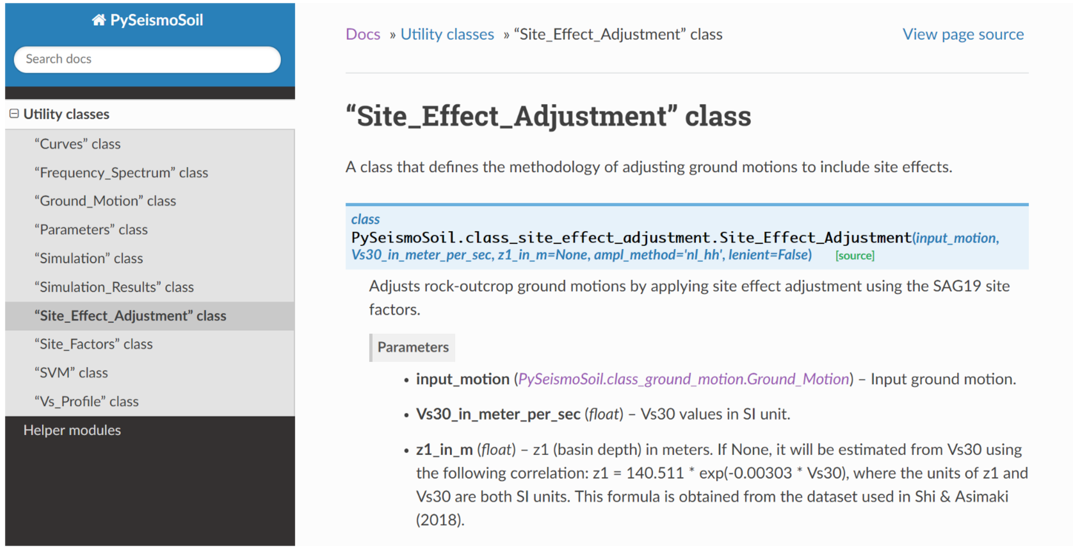
Example for $V_{s,30}$ = 250m/sec; Z1.0 = 150m

Fourier surface/rock outcrop ratios: U/R Phase



Github release and validation





PySeismoSoil

Search docs

⊟ Utility classes

"Curves" class
"Frequency_Spectrum" class
"Ground_Motion" class
"Parameters" class
"Simulation" class
"Simulation_Results" class
"Site_Effect_Adjustment" class
"Site_Factors" class
"SVM" class
"Vs_Profile" class

Helper modules

Docs » Utility classes » "Site_Effect_Adjustment" class   View page source

"Site_Effect_Adjustment" class

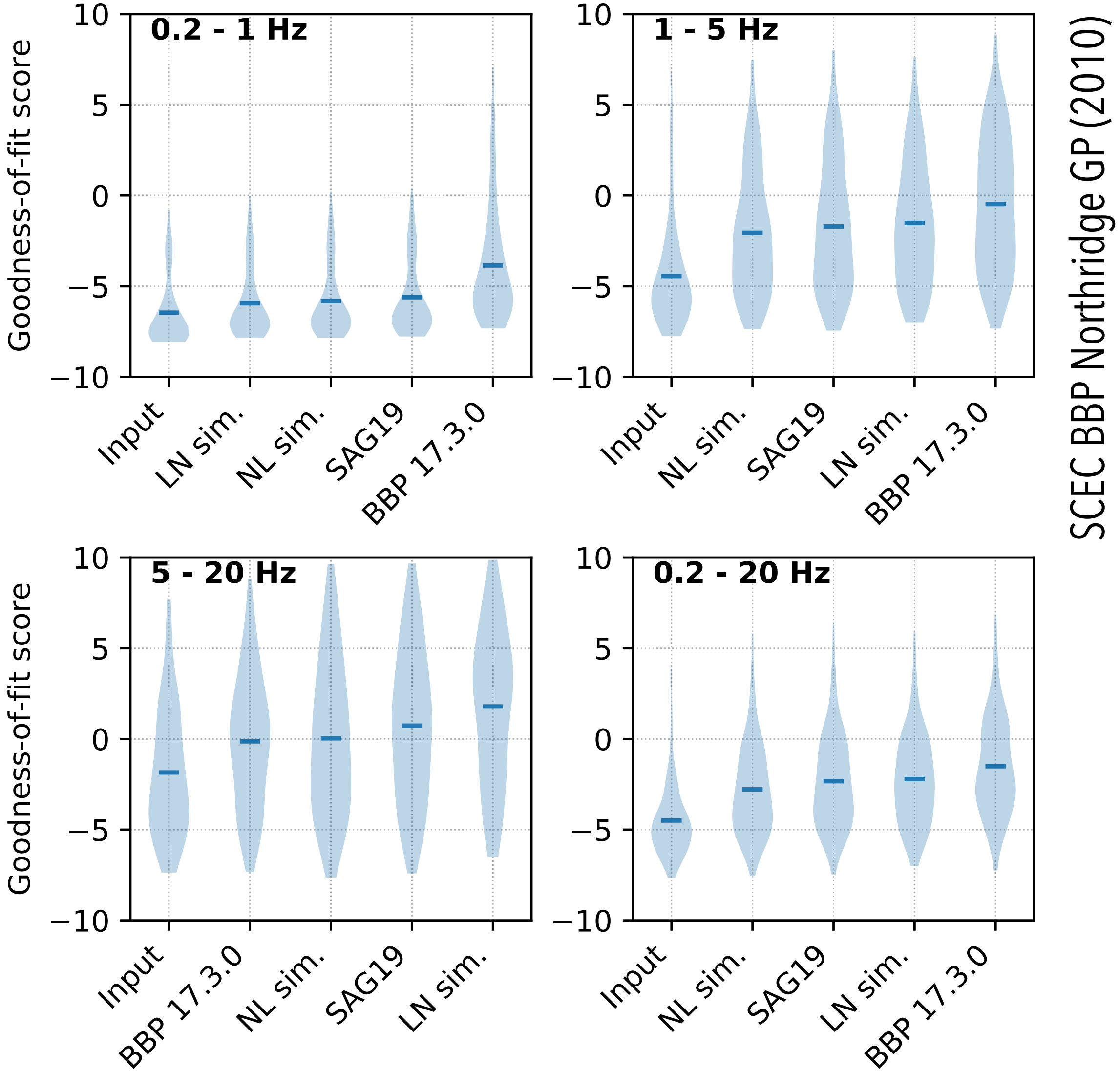
A class that defines the methodology of adjusting ground motions to include site effects.

class PySeismoSoil.class_site_effect_adjustment.Site_Effect_Adjustment(*input_motion, Vs30_in_meter_per_sec, z1_in_m=None, ampl_method='nl_hh', lenient=False*) [source]

Adjusts rock-outcrop ground motions by applying site effect adjustment using the SAG19 site factors.

Parameters

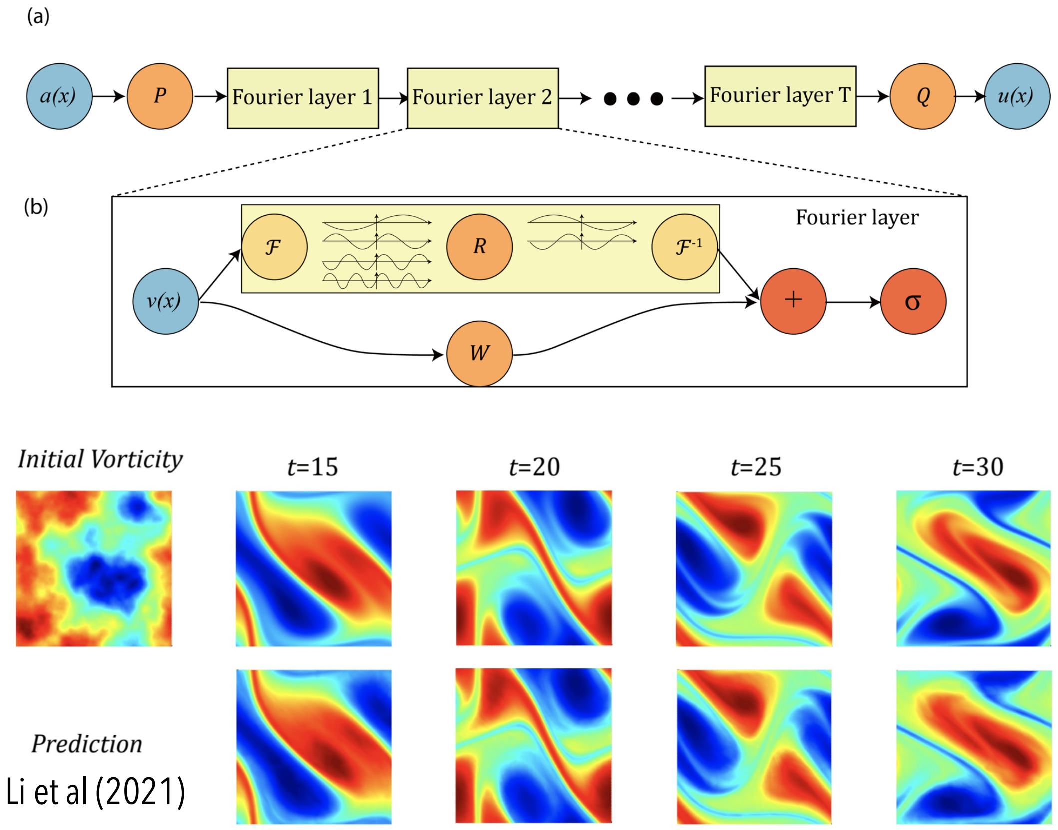
- **input_motion** (*PySeismoSoil.class_ground_motion.Ground_Motion*) – Input ground motion.
- **Vs30_in_meter_per_sec** (*float*) – Vs30 values in SI unit.
- **z1_in_m** (*float*) – z1 (basin depth) in meters. If None, it will be estimated from Vs30 using the following correlation: z1 = 140.511 * exp(-0.00303 * Vs30), where the units of z1 and Vs30 are both SI units. This formula is obtained from the dataset used in Shi & Asimaki (2018).



In progress…

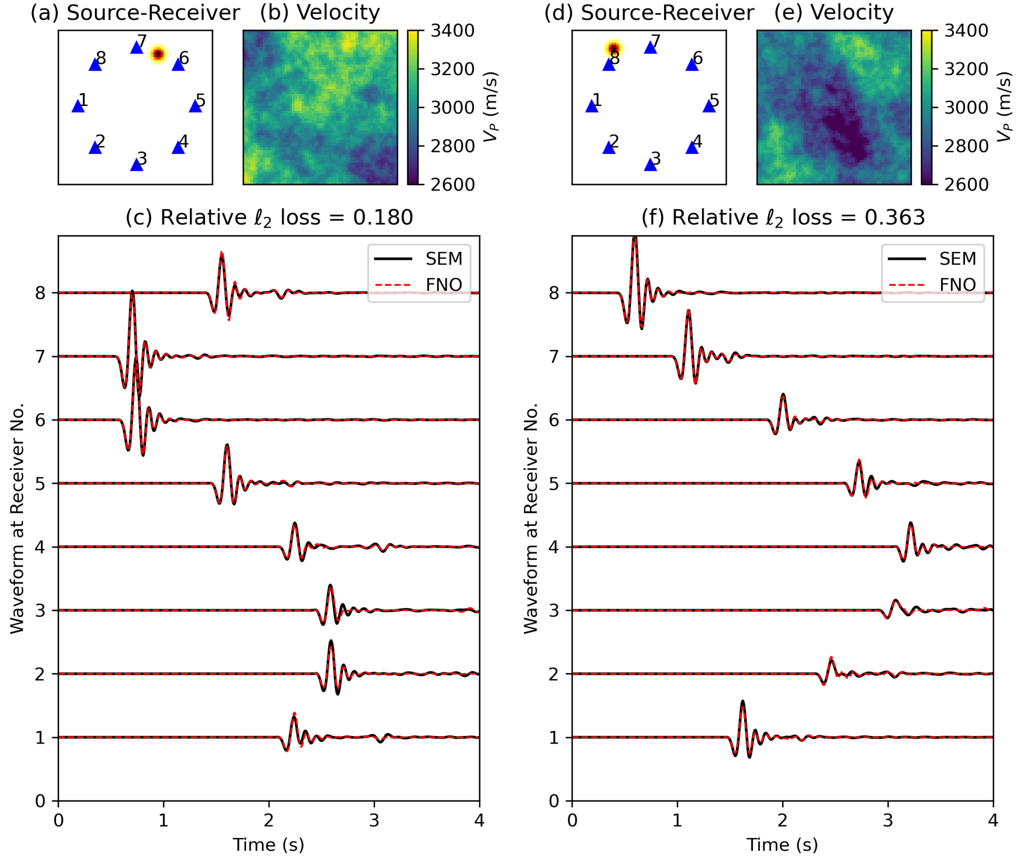
- Expand amplification factor computations for CA SVM.
- Use deterministic simulated ground motions of historic events for validation.
- Derive 3C-1D nonlinear complex amplification for the vertical component.
- Validate corrected vs. raw rare event scenarios against published GMMs …

c. Machine learning nonlinear site response w/ FNOs



Li et al (2021)

Yang et al (2021)

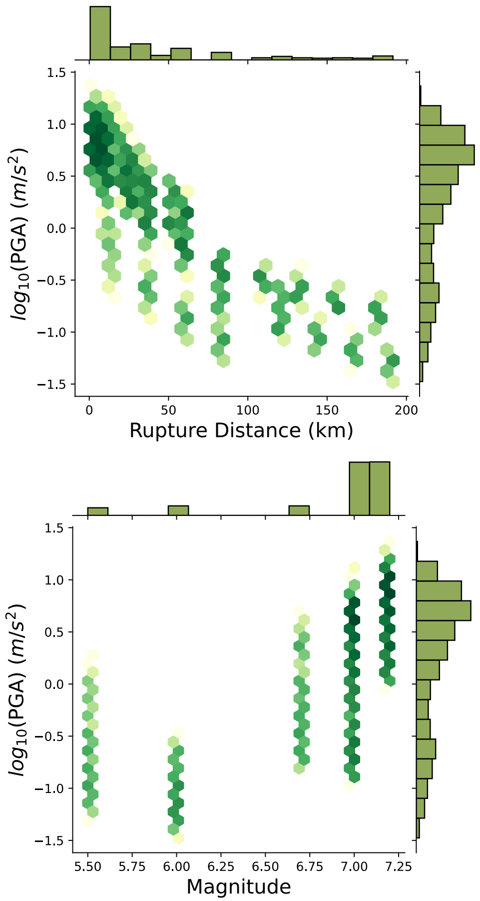


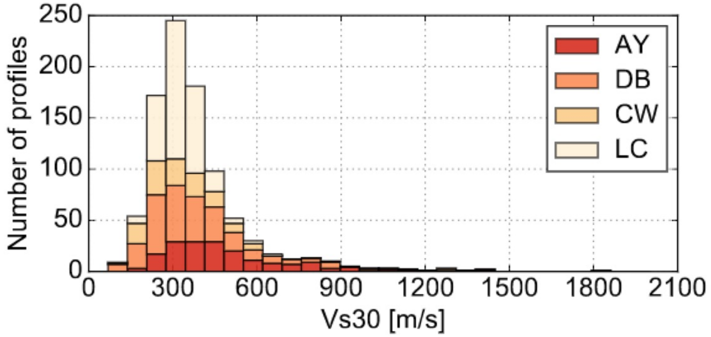
Fourier Neural Operators (FNO) are <u>mesh-independent</u>, <u>resolution-invariant operators</u>.

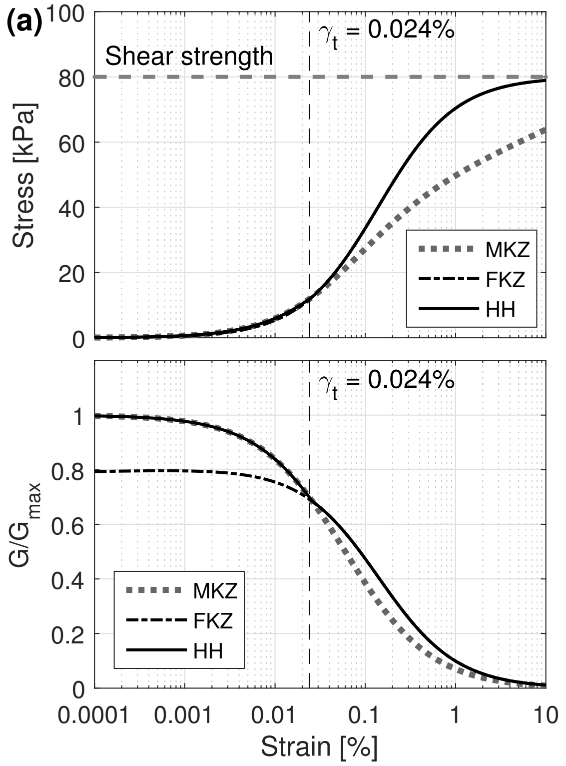
Unlike **Neural Networks**, they learn the solution to the PDEs, not snapshots of the solution.

Can be evaluated at any spatiotemporal resolution at 10^5 faster than simulations

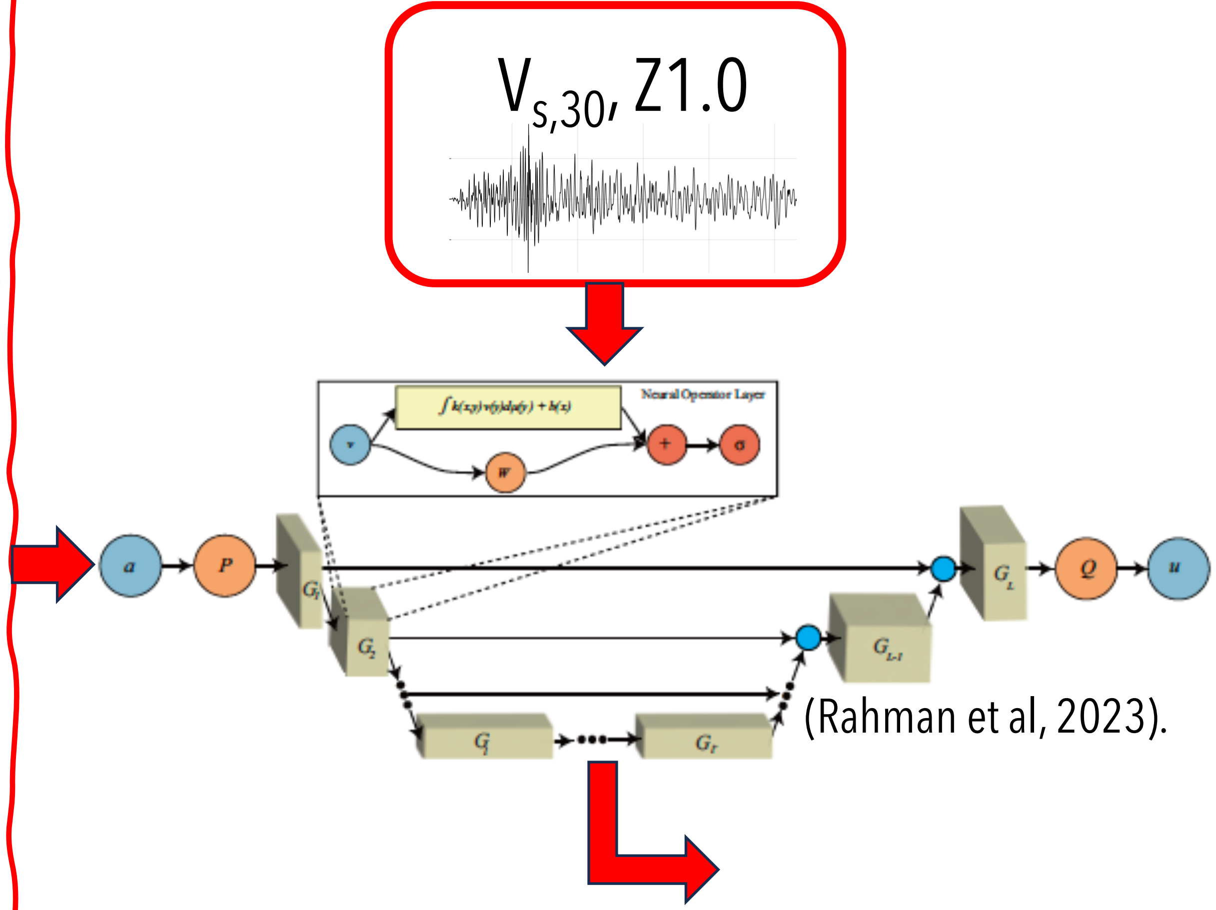
SVL, HH nonlinear model and wave equation





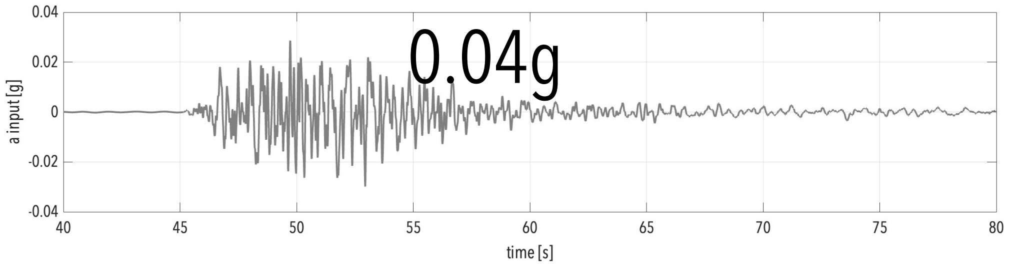


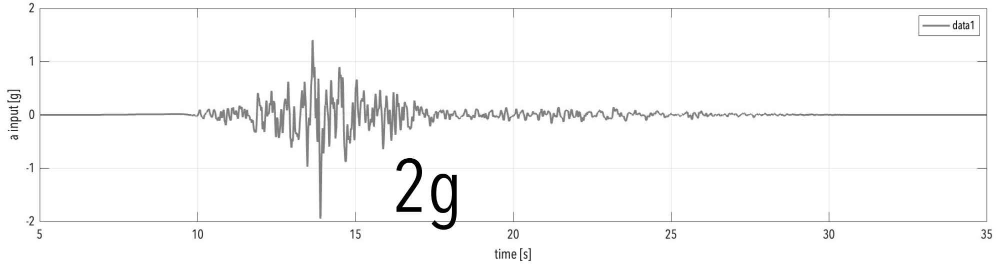
- Ground motions.
- Parameterized Vs profiles.
- Nonlinear functional form.

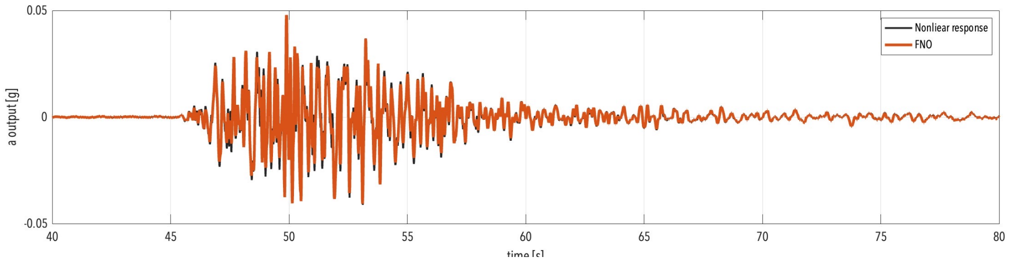


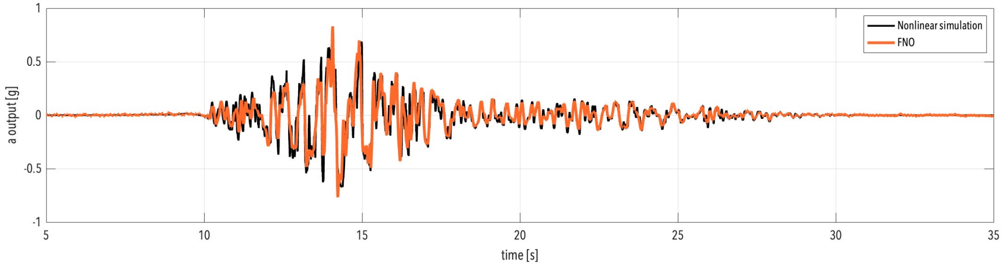
(Rahman et al, 2023).

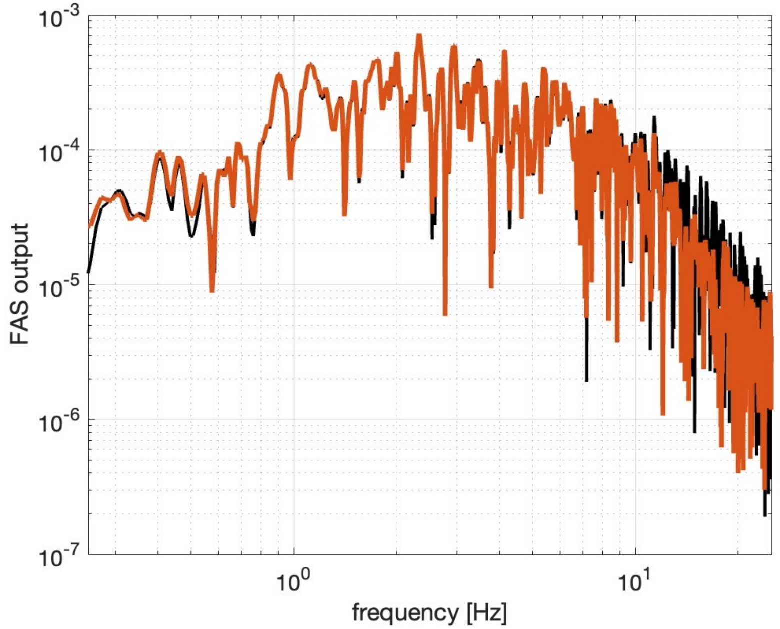
Nonlinear site response with Neural Operators (~3ms)

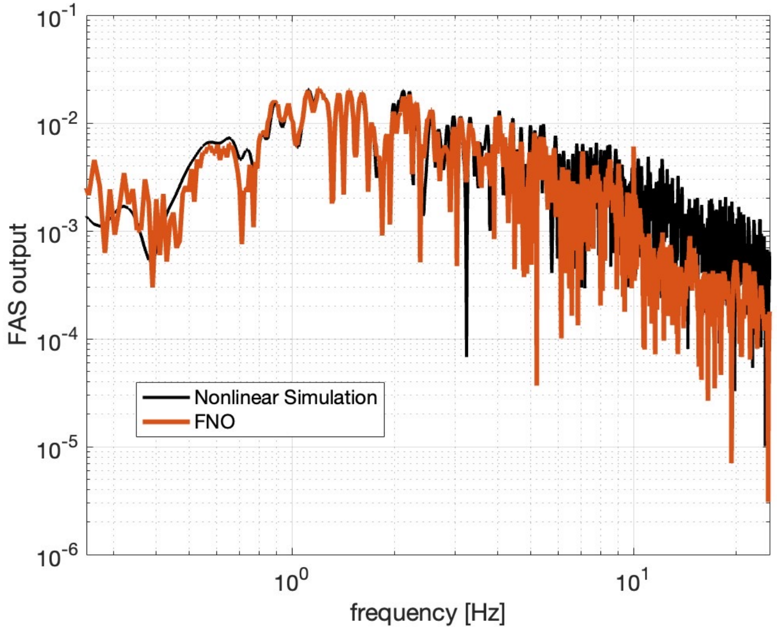












To be continued…

- Populate the shallow crust with high resolution material properties → improve 3D site effects in the high frequencies (what about the rare events?)
- Sample V_{s30} maps and adjust locally using complex FAS factors or FNO-nonlinear analyses → improve 3x1D site effects (what about surface waves?)
- Do a little bit of both?

Add **some nonlinearity to the 3D simulations** and some **high frequency realism through machine learning** to compensate for the imperfect velocity models …?

We're on it! ☺

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