Synthetic Seismograms for Cascadia Magnitude 9 Earthquakes from 3D Simulations: Amplification of Seattle and Tacoma Basins

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The M9 Project: University of Washington funded for 4 years by NSF

USGS/UW has produced a large set of broadband (0-10 Hz) synthetic seismograms for M9 Cascadia earthquakes; considering a range of rupture scenarios

Ground Motions and Tsunami inundation

Synthetic seismograms produced from 3D simulations of M9 Cascadia earthquakes (Frankel, Wirth, Marafi)

Tsunami simulations for M9 Cascadia earthquakes (Gonzalez, LeVeque)

Supercomputer time provided by Pacific Northwest National Laboratory and the Texas Advanced Computing Center

Impact

Evaluation of tall building response and damage from long-duration, long-period ground shaking (Berman, Eberhard, Marafi)

Evaluation of landslides and liquefaction from ground shaking (Duvall, Wartman, Kramer, Grant)

Evaluation of tsunami effects on structures near coast (Motley, LeVeque, Gonzalez)

Assessment of effectiveness of multiple scenarios for emergency preparedness, improving community resilience (Bostrum, Abramson)

Testing of Earthquake Early Warning (Vidale, Bodin)

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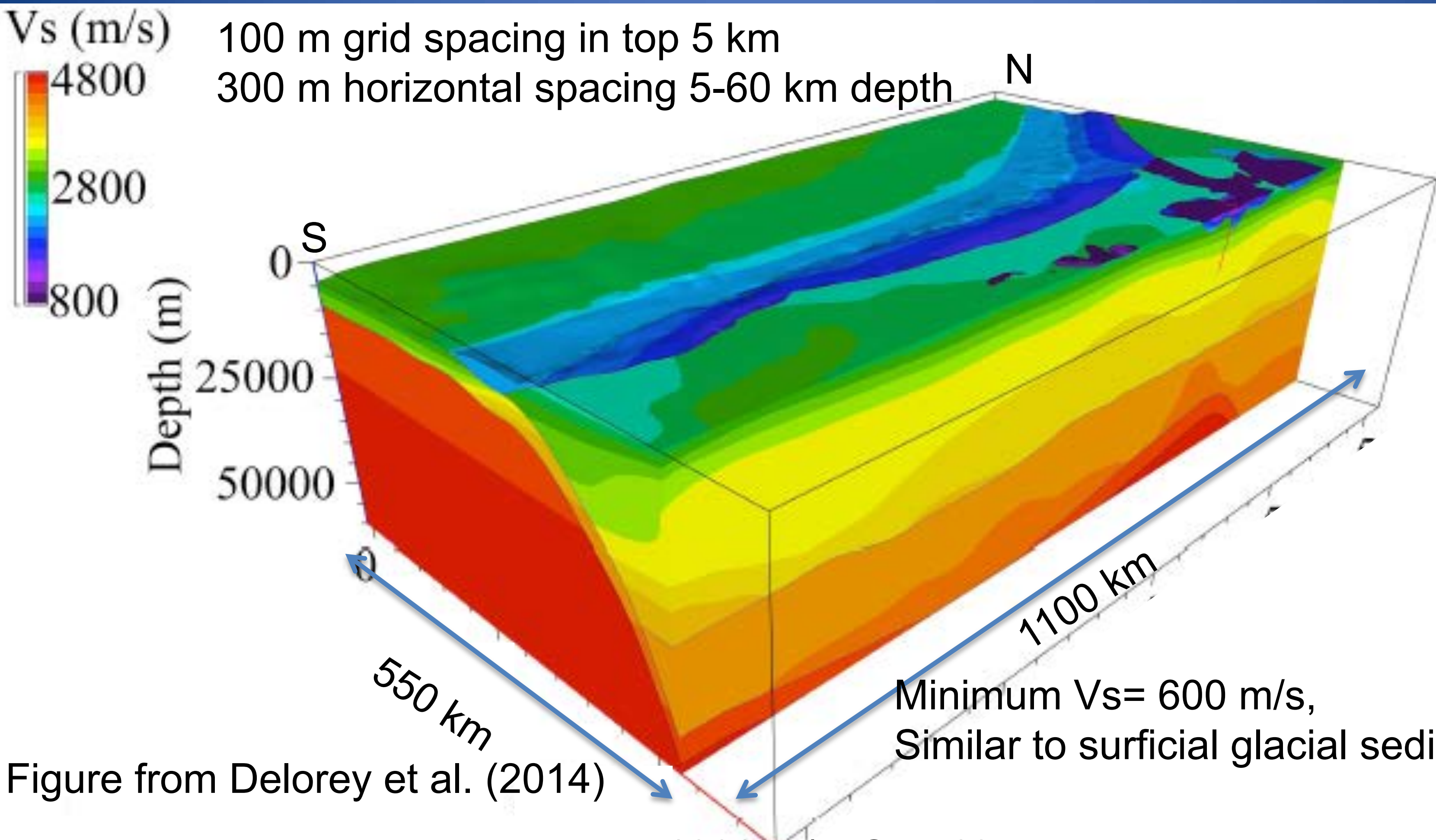
Bill Stephenson developed the 3D velocity model for Cascadia. Used seismic refraction/refraction data and tomography for Seattle basin, Moschetti et al. (2010) crustal tomography, used smoothed version of McCrory et al. (2012) plate interface

We use 3D finite difference code written by Pengcheng Liu (U.S. Bureau of Reclamation) 4th order in space, 2nd order in time., grid spacing varies with depth

100 m grid spacing in top 5 km

300 m horizontal spacing 5-60 km depth



Minimum Vs= 600 m/s,
Similar to surficial glacial sediments

Figure from Delorey et al. (2014)

We replaced water with Vs= 1000 m/s, Qs= 10
tests show insensitivity of on-shore synthetics to Vs choice

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validation of 3D velocity model for Seattle basin

- Modeled observed amplification of Fourier spectral amplitudes (1 Hz) by Seattle basin for four local earthquakes and modeled observed waveforms (2-4 s) for a M4.8 event and the M6.8 Nisqually earthquake (Frankel et al., 2009, BSSA). Also calculated small bias between SA's from synthetics and data (1-10 s)

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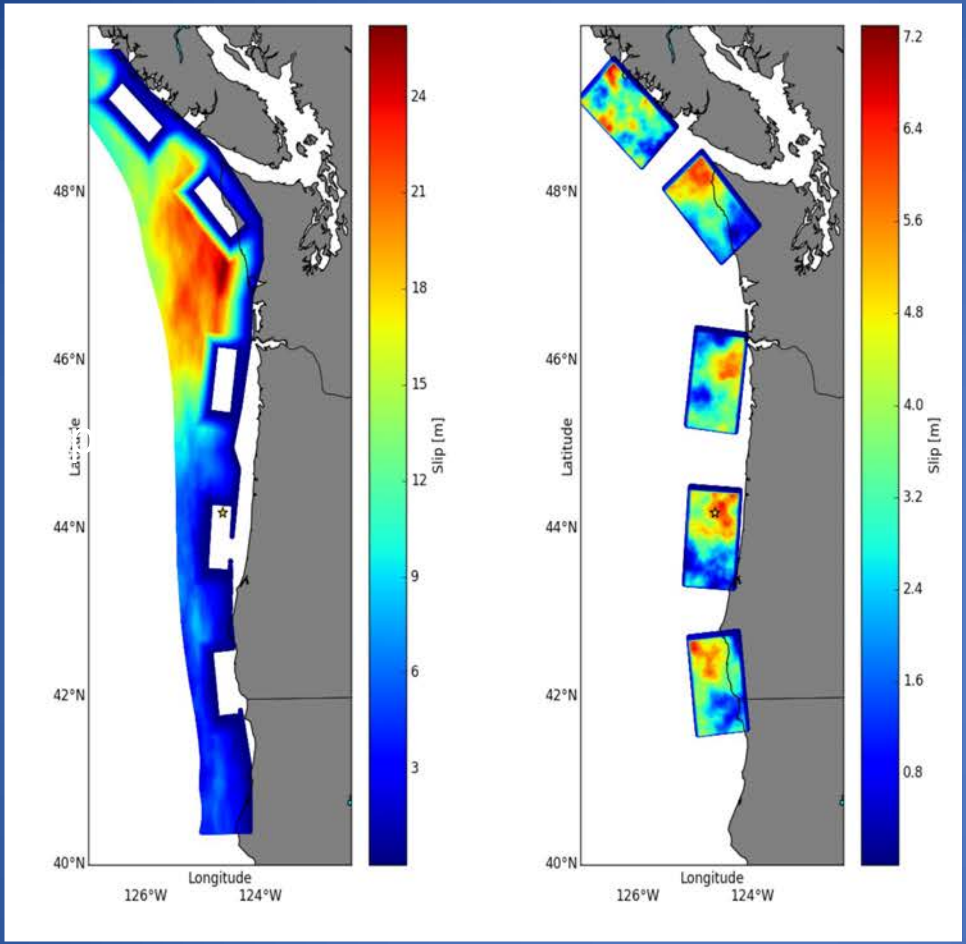
Background slip

M8.0 Sub-events ("strong-motion generation areas")



Run 21

Compound rupture model informed by observations and modeling of M9.0 Tohoku and M8.8 Maule earthquakes (see, e.g., Frankel, 2013, 2017)

About 600,000 source points (500m spacing); total Mw = 9.0

E. Wirth wrote Python script to make source model

Used McCrory et al. (2012) plate interface (smoothed)

500 x 200 km corr. distance

Slip velocity = 0.65 m/s
Max. rise time = 35 s

50 km correlation distance

Slip velocity = 5.4 m/s
Max. rise time = 2 s
For stochastic, stress drop = 200 bars

Used Von Karman correlation functions for constant stress drop scaling (k^{-2} falloff)

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Source Model Used for M9 Cascadia earthquakes

3D FD; background slip model
Max rise time= 30 sec; slip vel. = 0.65 m/s
(up to 1 Hz)

3D FD; M8 sub-event slip model
Max rise time = 2 s; slip vel. = 5.4 m/s
(up to 1 Hz)

Add
Sources
For each
3D run

Combine
With matched
Filters at 1 Hz

Broad band
Synthetics
(0-10 Hz)

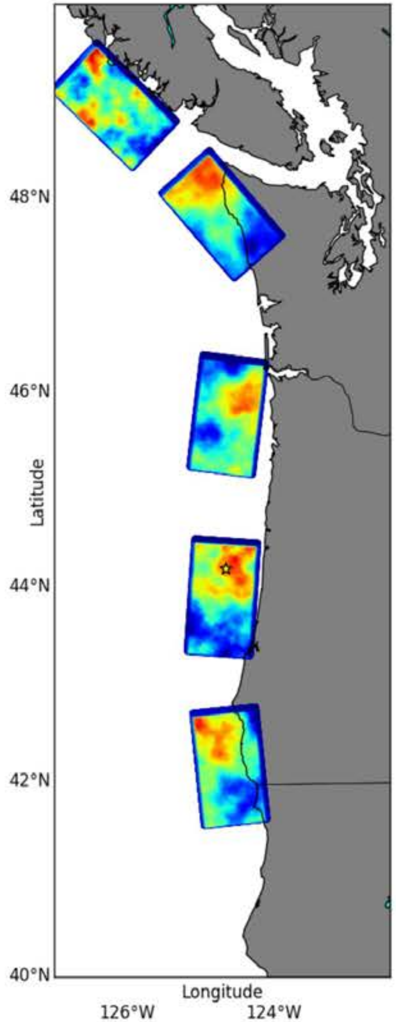
Stochastic synthetics for P and S-waves M8
sub-event slip model
200 bar stress drop
Convolve sum of point source synthetics
$G_{ij}(t)$ from SMSIM (Boore, 1982) with
relative slip velocity function *S(t)*
to get flat accel. spectrum (Frankel, 1995)
(1 Hz to 10 Hz)

$$U_j(t) = S(t) * \sum_{i=1}^{ncell} a_i \, G_{ij}\left(t - T_i - \tau_{ij}\right)$$

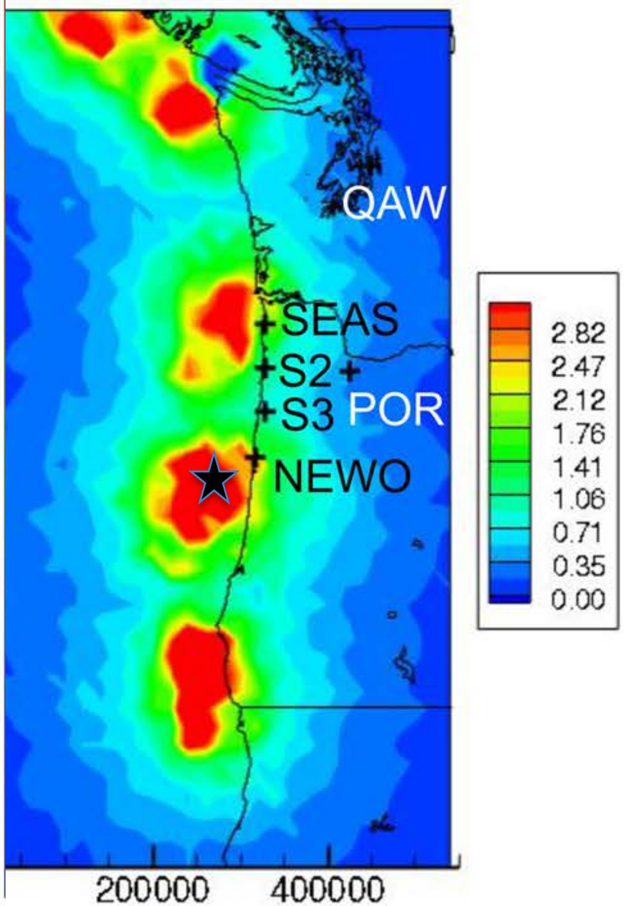
T_i is rupture time, τ_{ij} is travel time
a_i is slip within sub-event

Example from Run 21

Sub-event slip

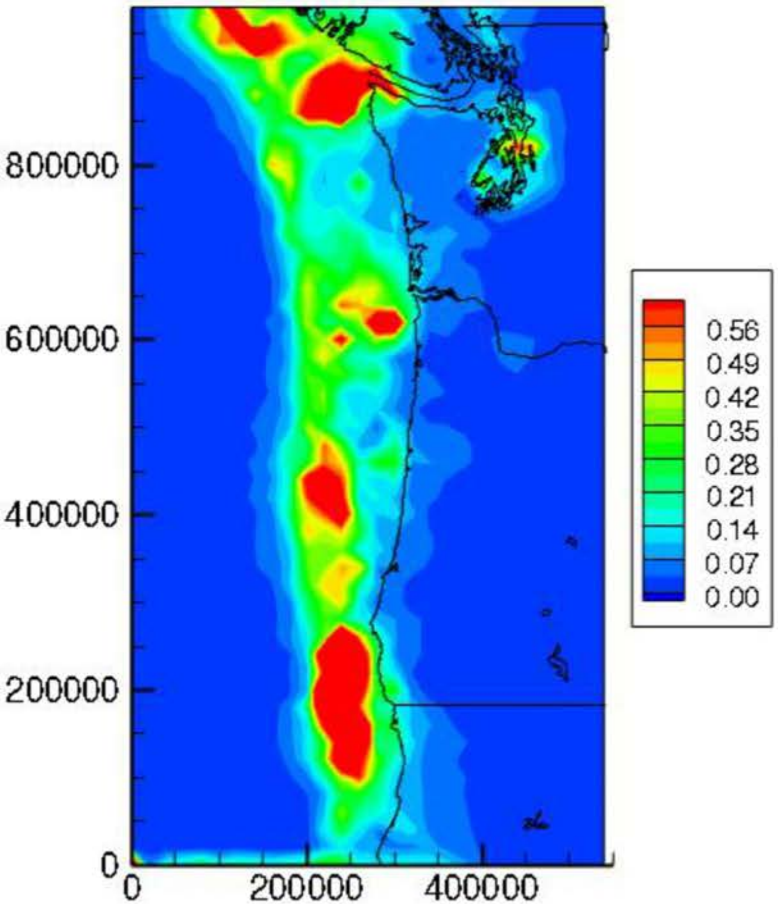


0.2 s SA (g)



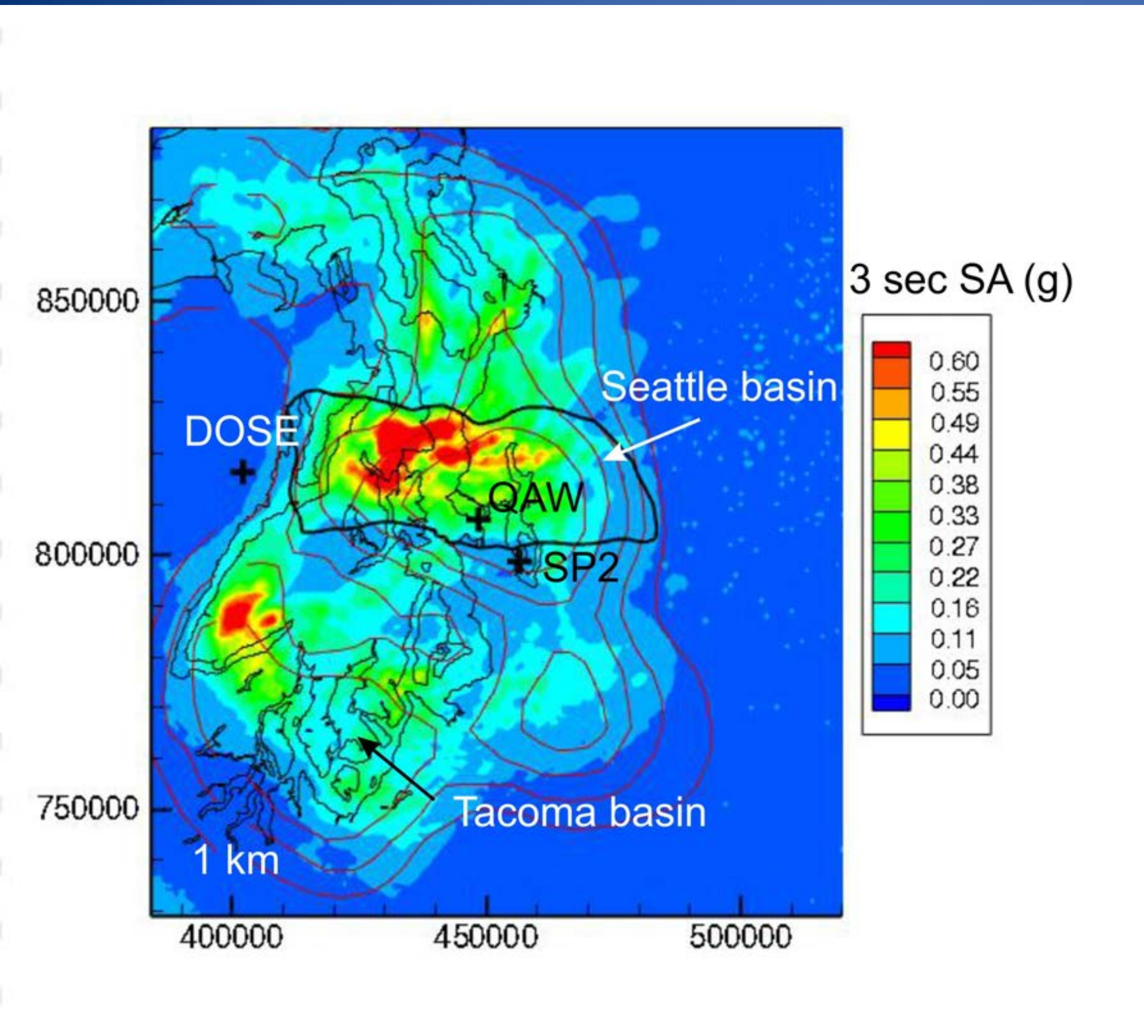
From stochastic

3.0 s SA (g)

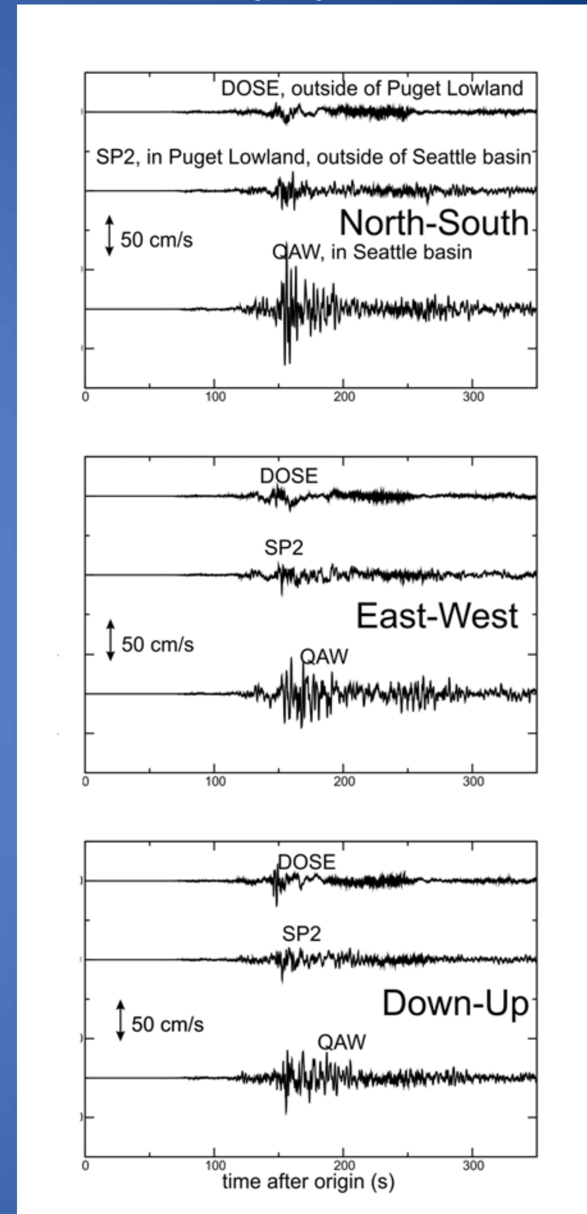


From 3D simulation

For the stochastic part we assume, for now, a uniform stiff-soil site condition; Vs30= 500-600 m/s

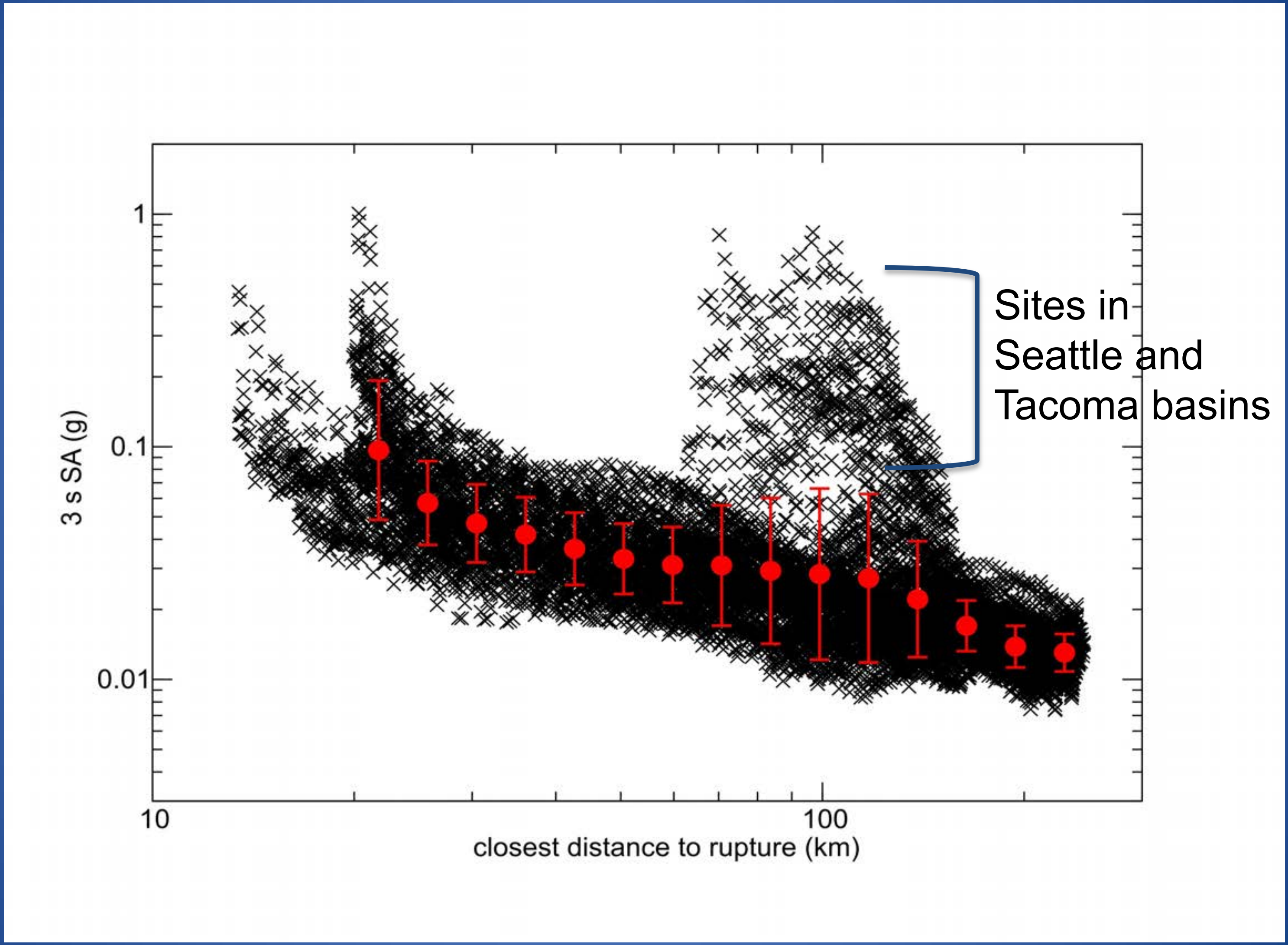


Velocity synthetics



Contours are depth to Vs of 2.5 km/s; Seattle basin outline from R. Blakely

3.0 sec S.A. for run 21; errors bars are intra-event standard deviation



Used 3D synthetics at about 10,000 onland sites

"logic tree" used for 30 rupture scenarios, Mw= 9.0 (received feedback from ground-motion modelers)

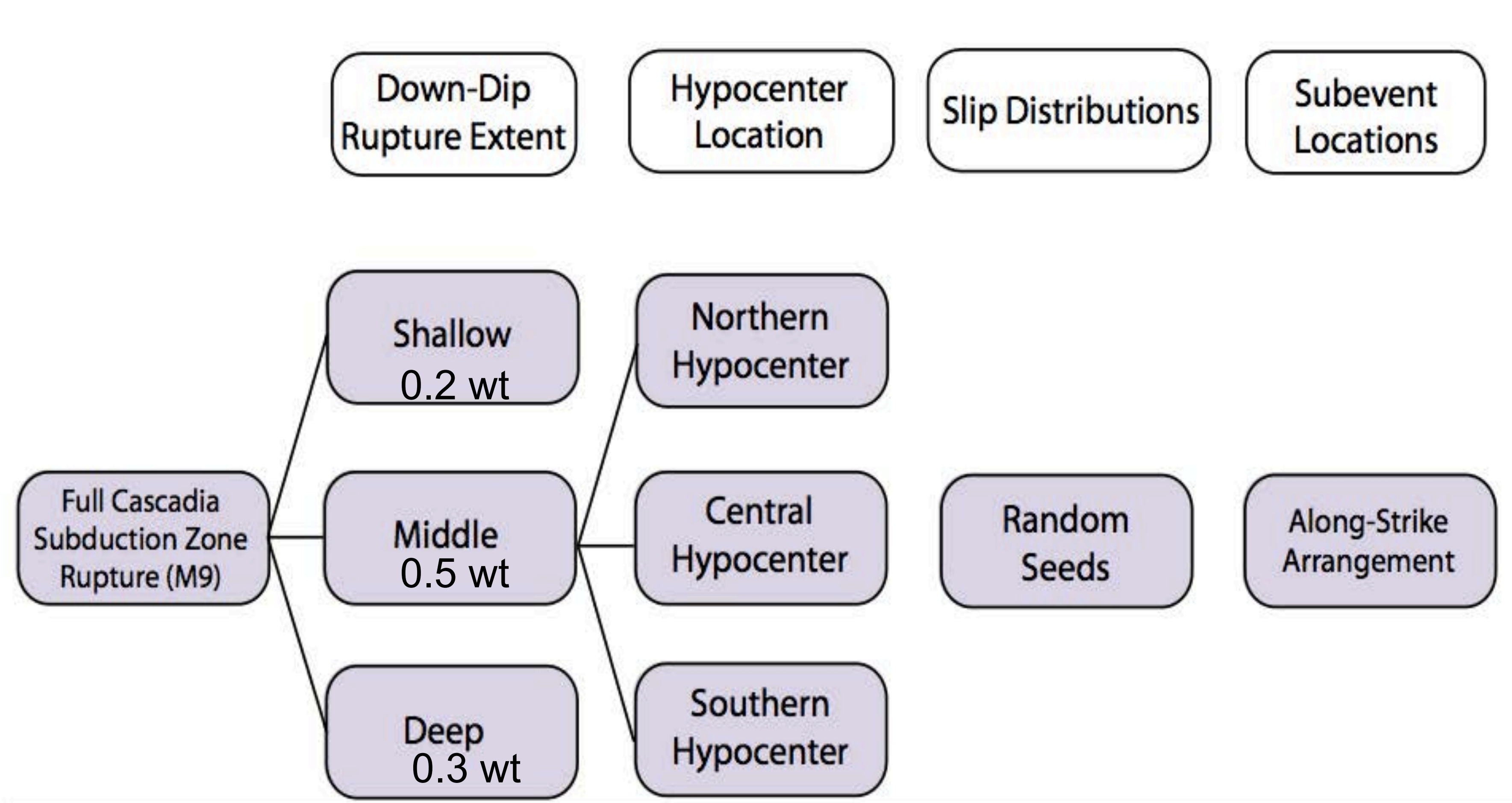
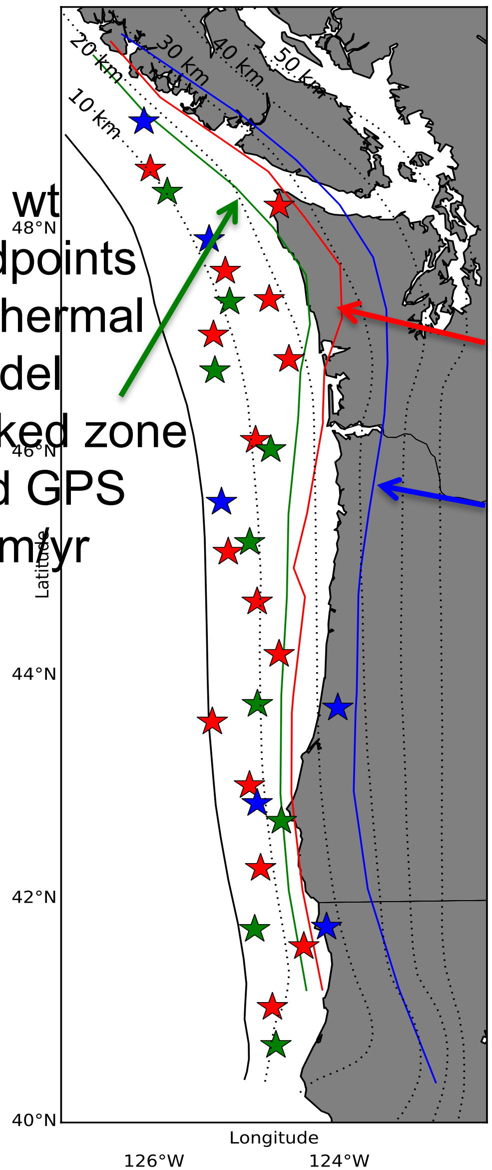


Figure by E. Wirth

Hypocenters

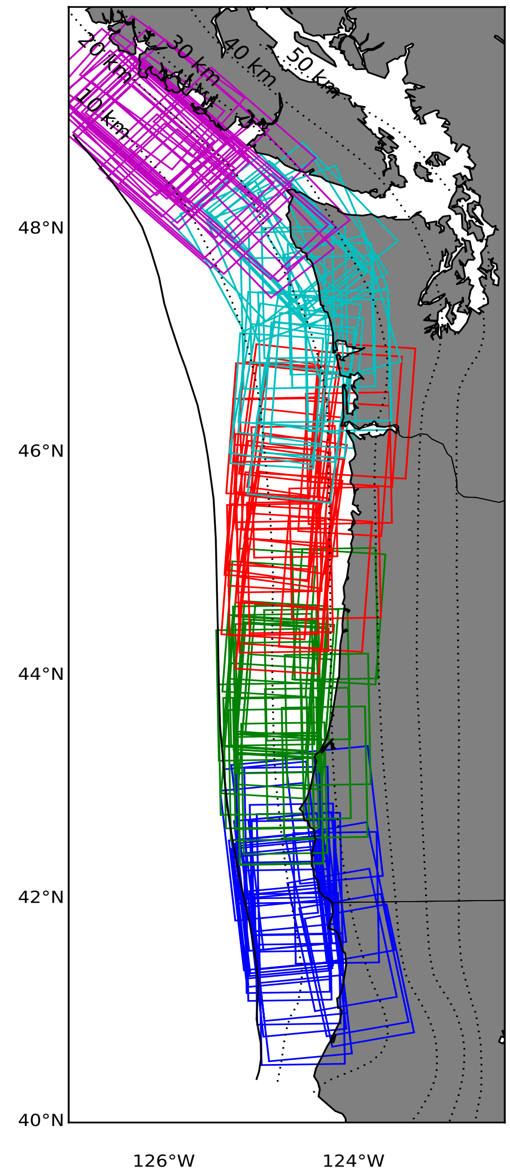


0.2 wt
Midpoints
of thermal
model
locked zone
and GPS
1 cm/yr

0.5 wt
1 cm/yr
locking
from GPS
and uplift

0.3 wt
top of
tremor
zone

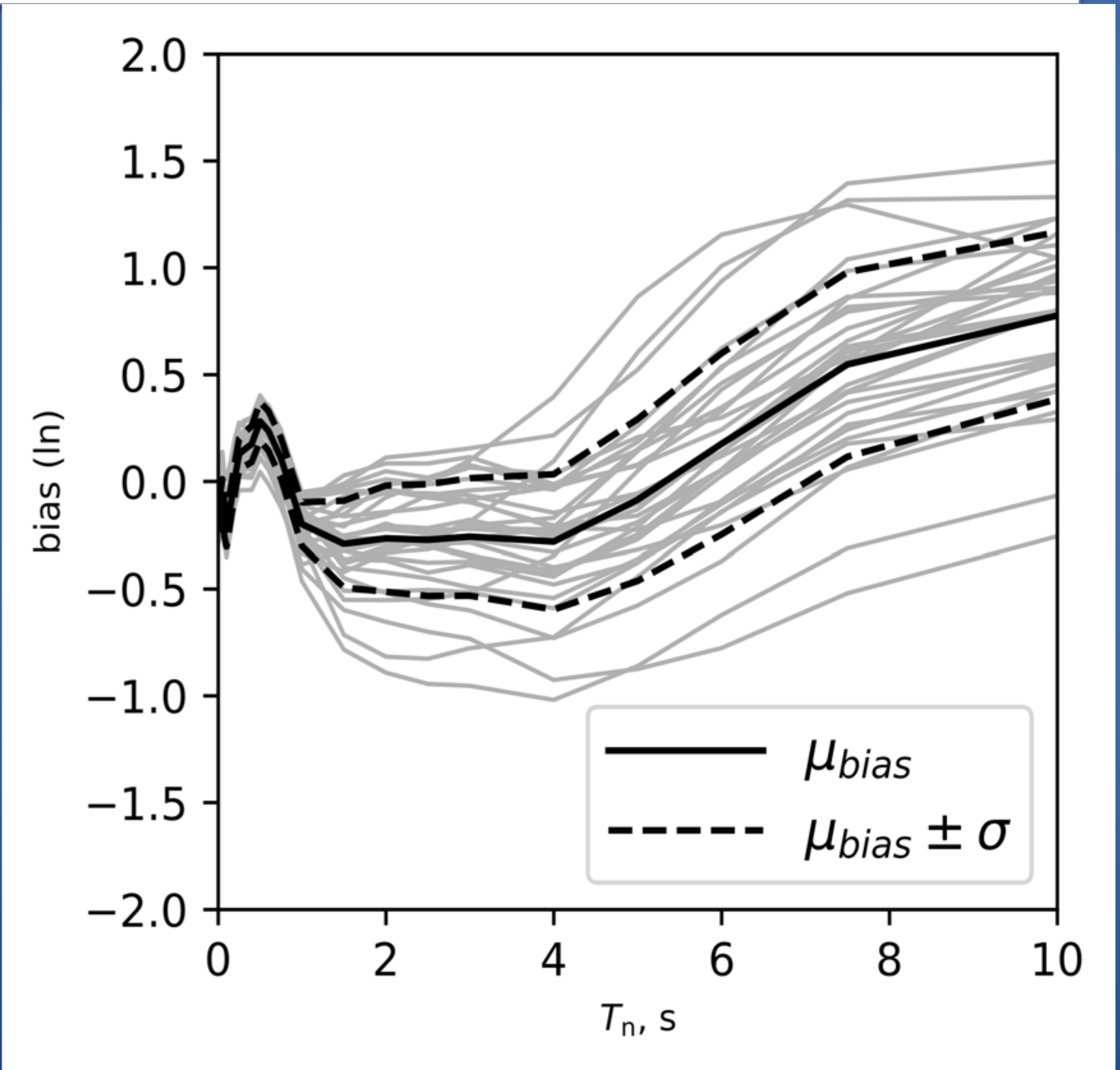
Sub-event rupture zones



Figures from Erin Wirth

Bias and standard deviation of response spectral accelerations of synthetics relative to predictions of BC Hydro ground-motion prediction equations (Abrahamson et al., 2016)

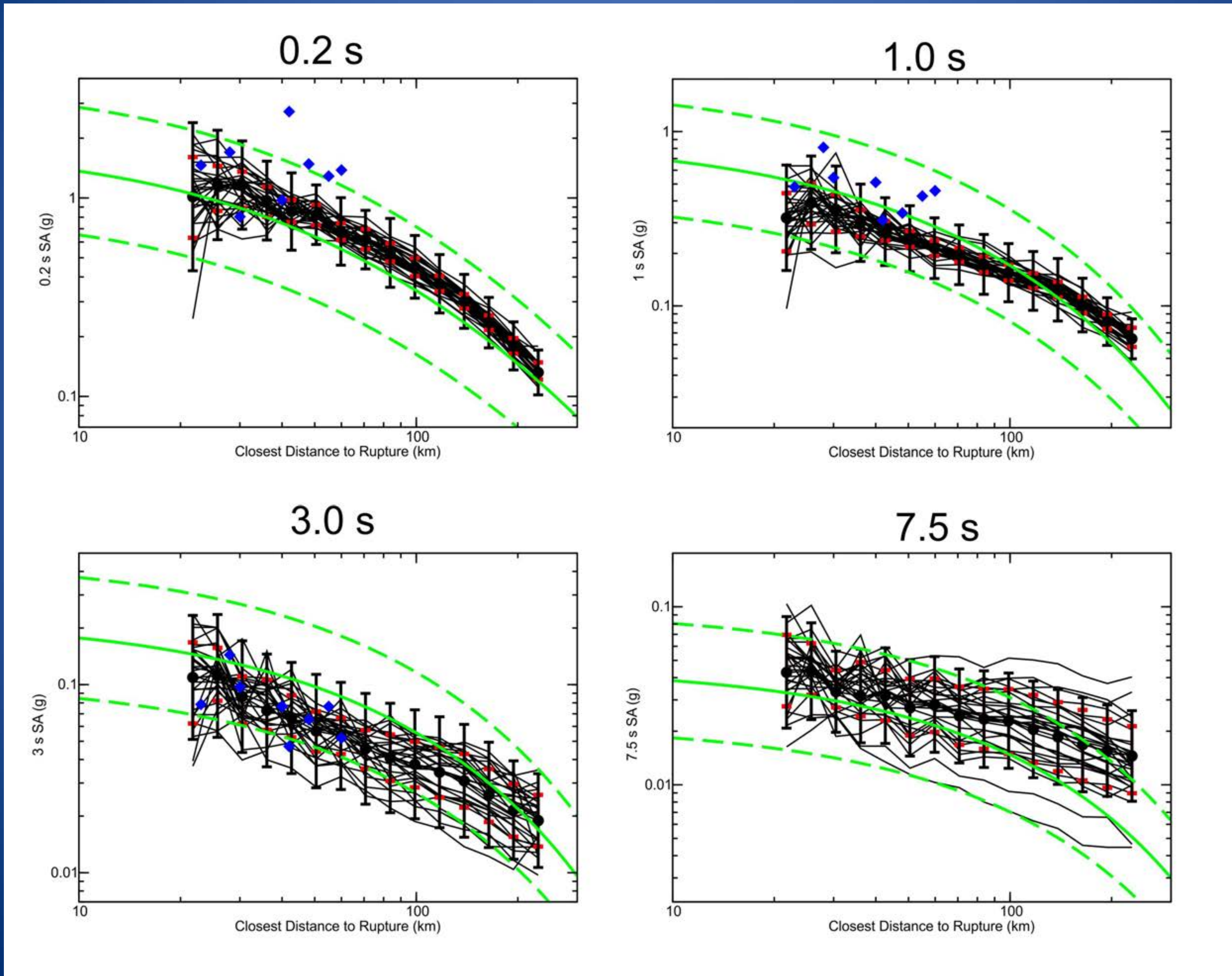
$$bias = \frac{1}{n}\sum_{i=1}^{n}(\ln synth_i - \ln gmpe_i),$$



Non-basin sites

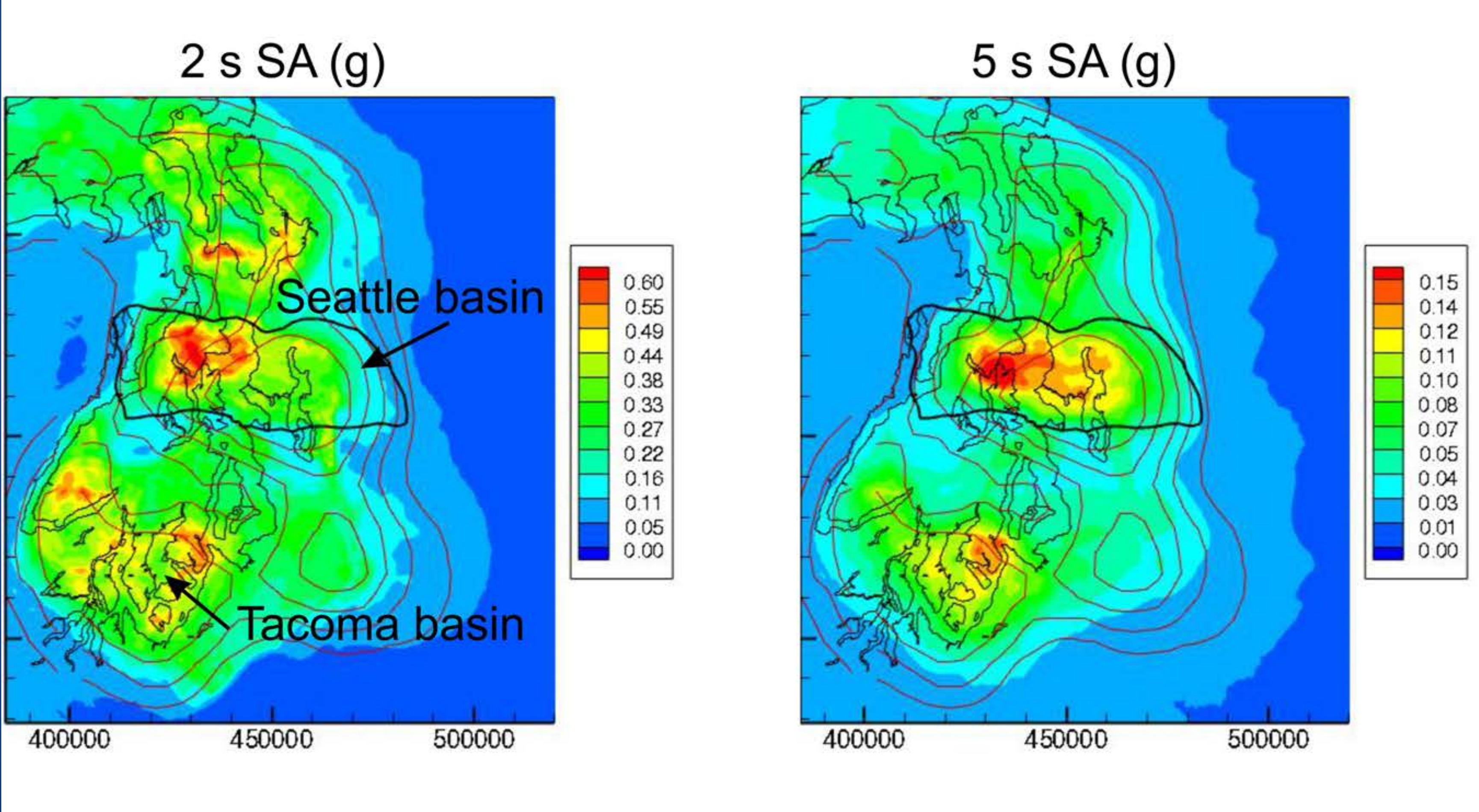
Figure by N. Marafi

SA with respect to closest rupture distance for 30 runs; non-basin sites
Green lines from BC Hydro Ground Motion Prediction Equations;
blue symbols Maule data. Black error bars: total variability; Red error bars inter-event

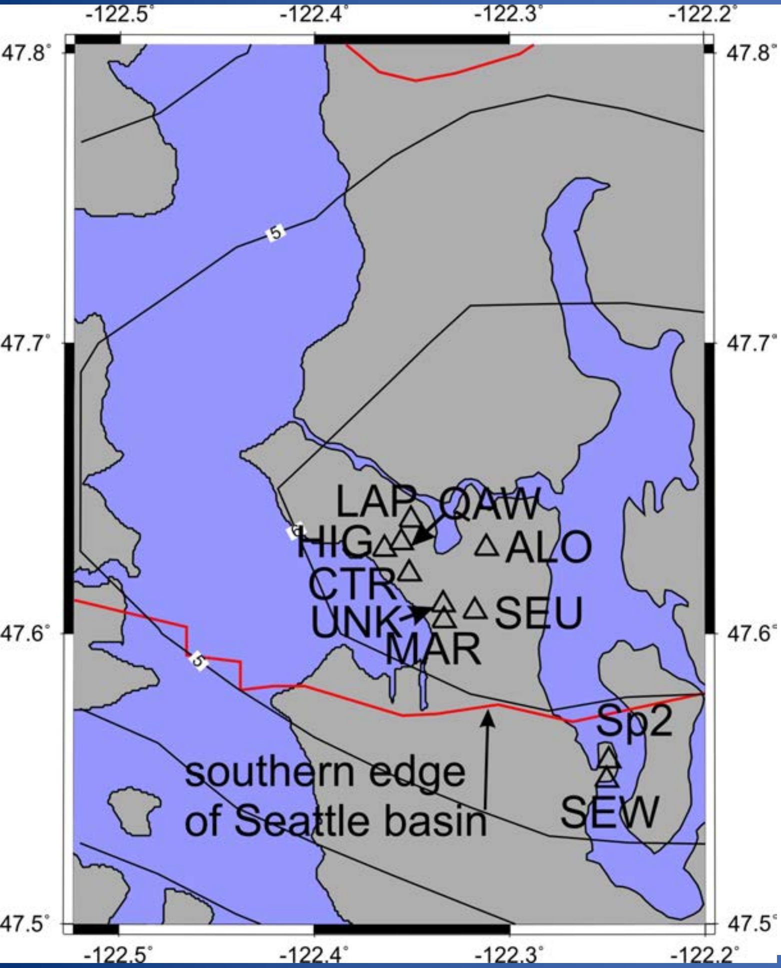


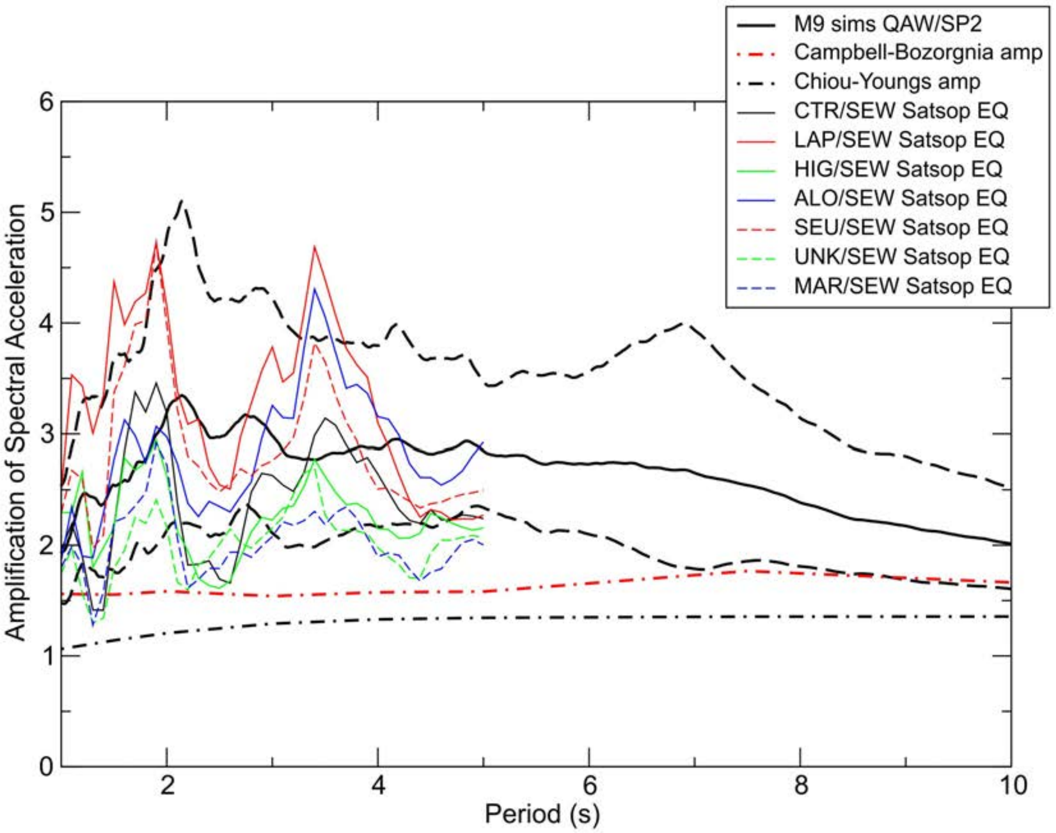
Q issue?
source
depth
effect?

Log averaged SA values from 30 scenarios



Amplification of Seattle basin sites relative to rock site outside of basin
M9 synthetics and observations from M5.0 Satsop EQ
Note that Vs30 values are similar between basin and rock sites



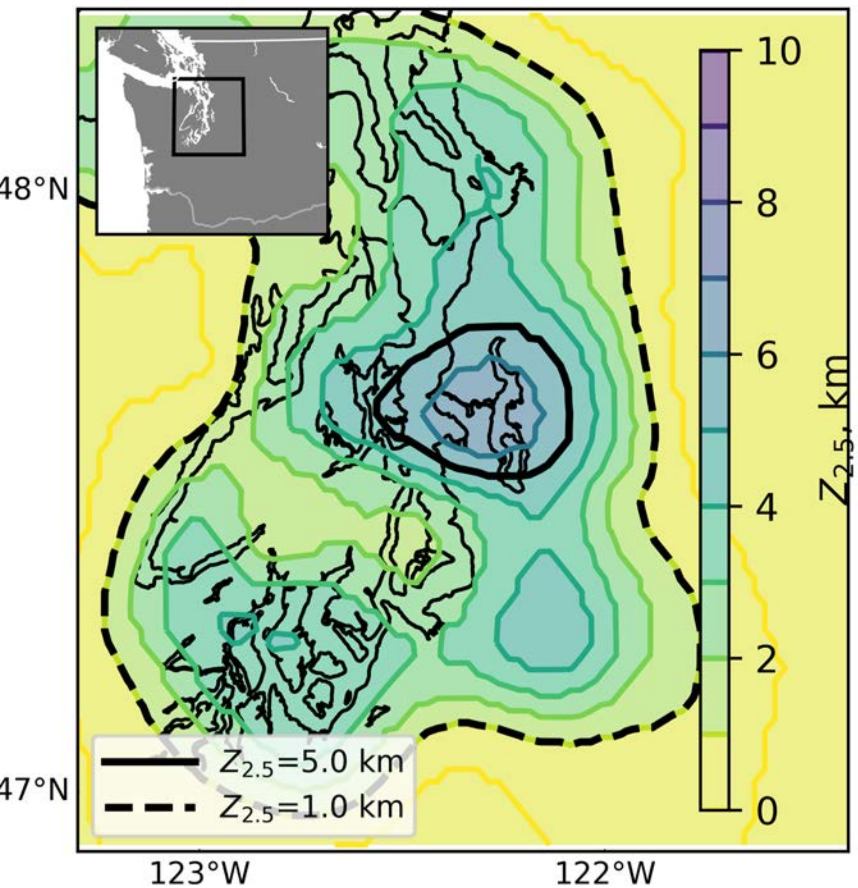


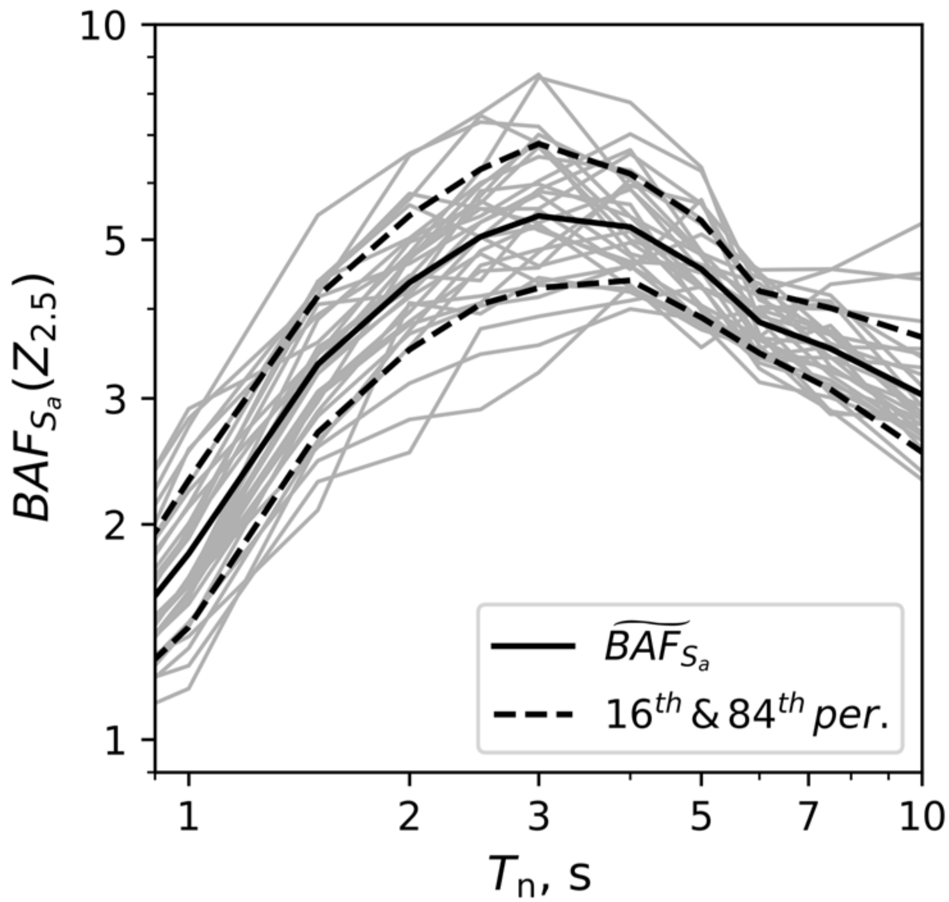
CB NGA West 2 uses Z2.5- 3 km   Seattle basin max Z2.5= 7 km

CY NGA West 2 uses Z1.0 – Zref.   Zref= 200m for Vs30 = 500 m/s

Seattle basin max Z1.0= 1000m

Basin amplification factors for sites with Z2.5 ≥ 5.0 km
With respect to sites with Z2.5 < 1.0 km outside of Puget Lowland



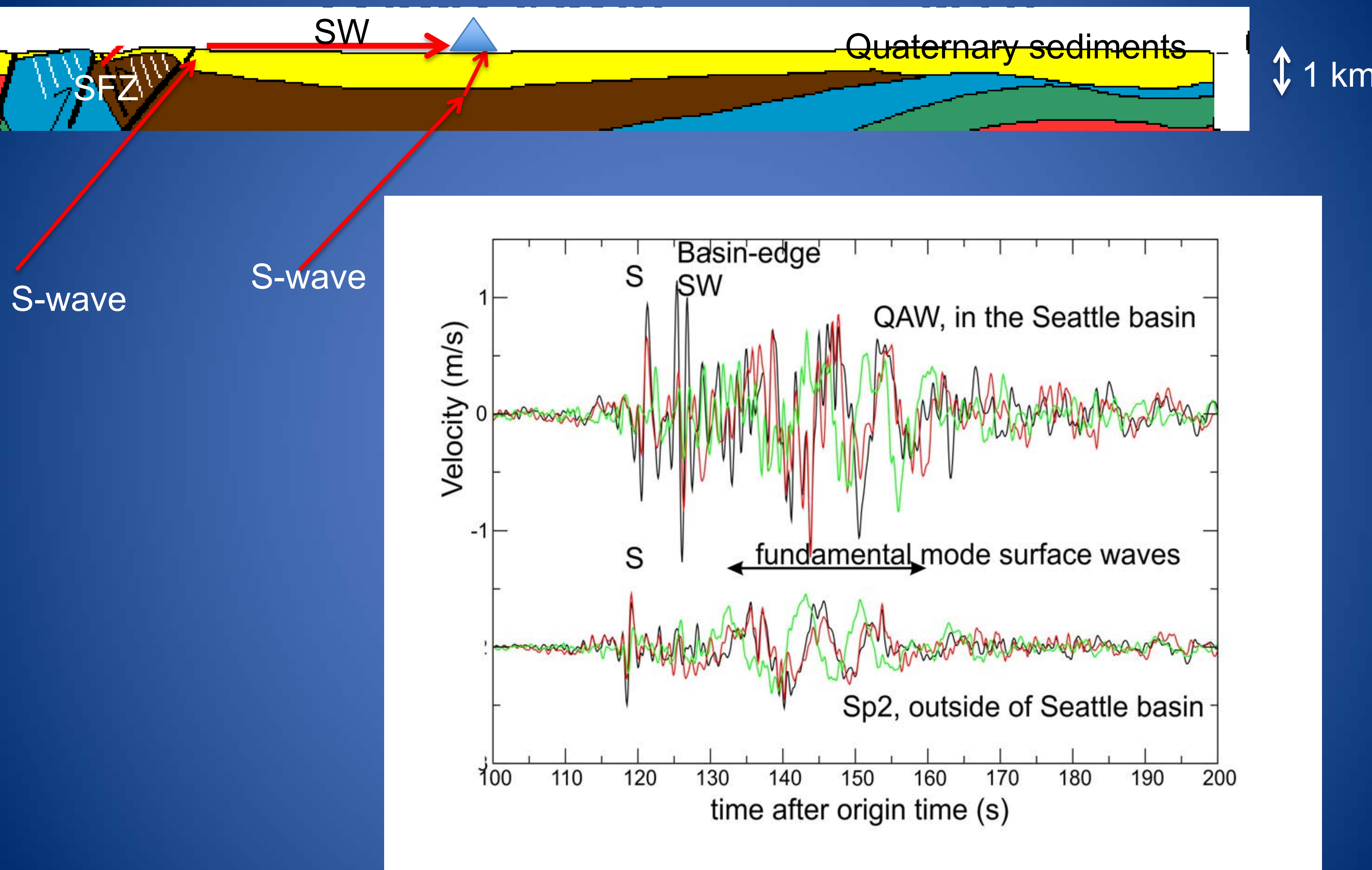


$$\ln BAF = \frac{1}{n}\sum_{i=1}^{n}(\ln synthbasin_i - \ln gmpe_i) - \frac{1}{m}\sum_{j=1}^{m}(\ln synthref_j - \ln gmpe_j),$$

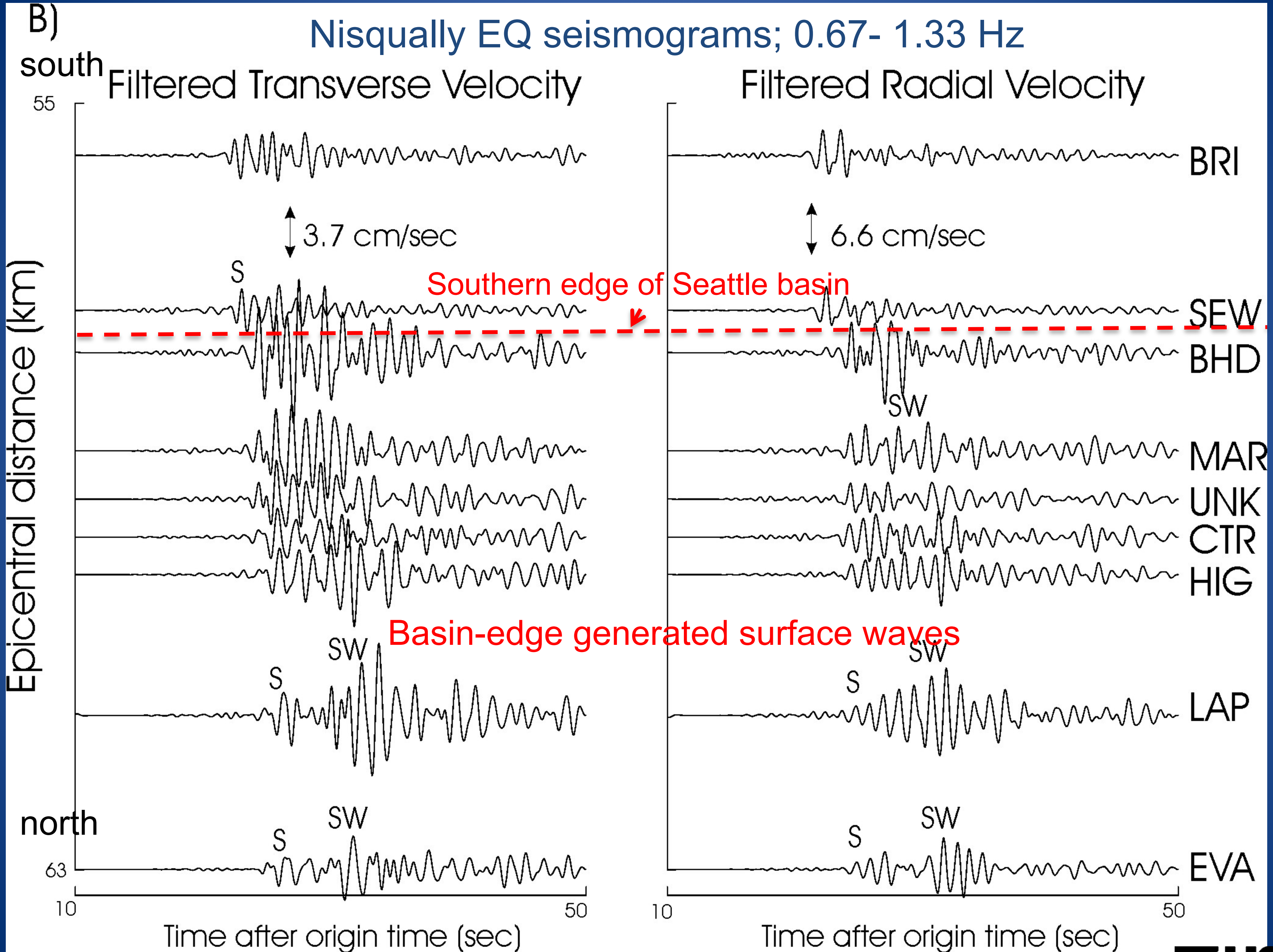
Figures from N. Marafi

CB NGA West 2 has no basin effect for Z2.5 1-3 km

S to Rayleigh wave at edge of Seattle basin



Nisqually EQ seismograms; 0.67- 1.33 Hz



Predicted 2.5 second amplification

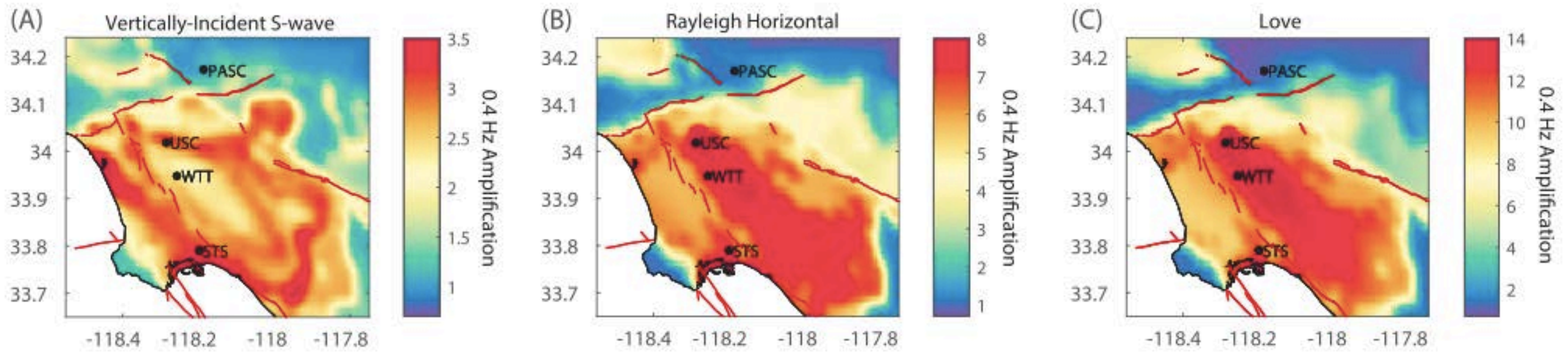


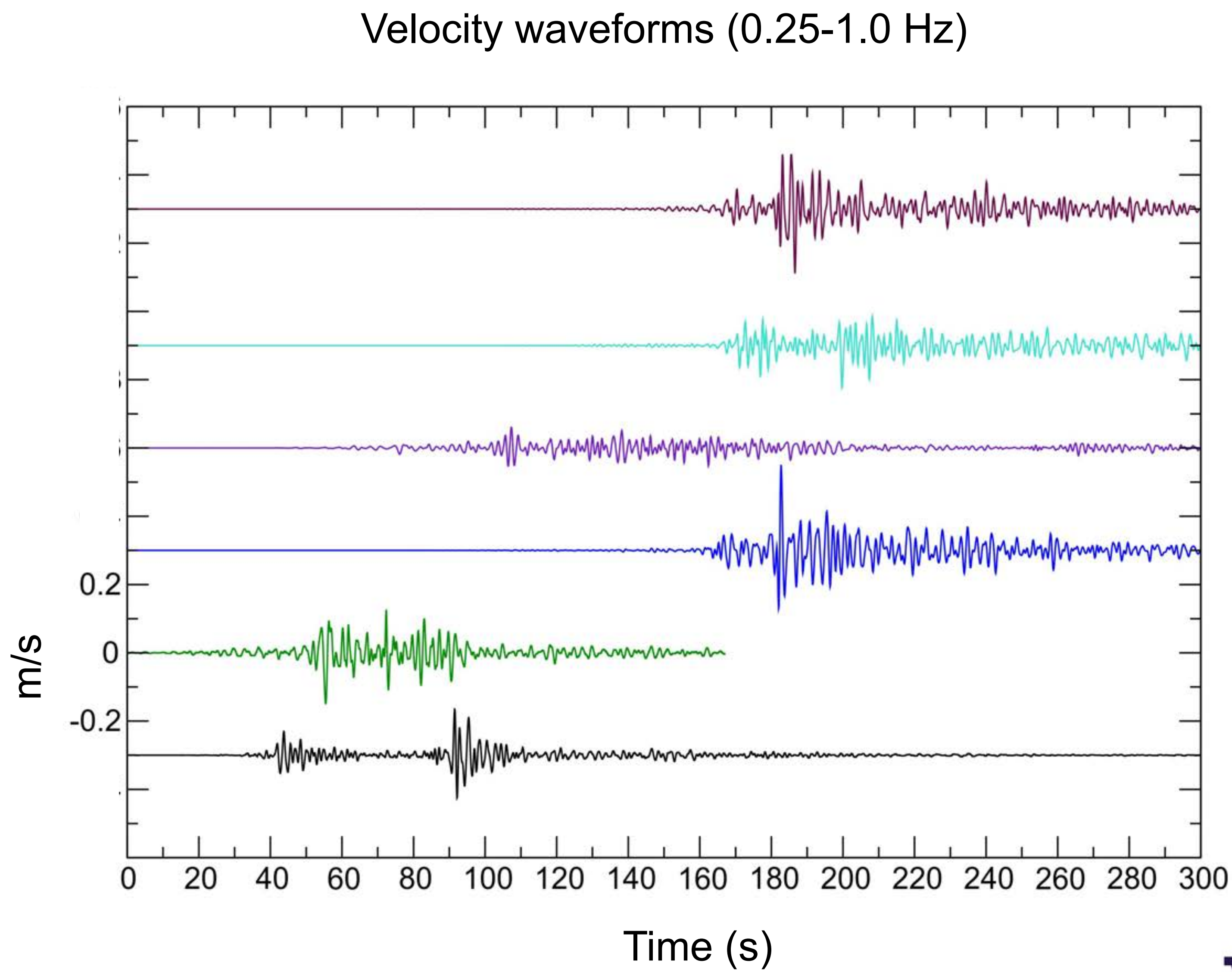
Figure 2. Maps of relative amplification for Southern California, describing 1-D amplification factors relative to the hard rock site, PASC, at 0.4 Hz for (a) vertically-incident shear waves, (b) horizontal component Rayleigh waves, and (c) Love waves. Faults from the *U.S. Geological Survey and California Geological Survey* [2006] are shown by red lines.

Figure from Bowden and Tsai (2017)

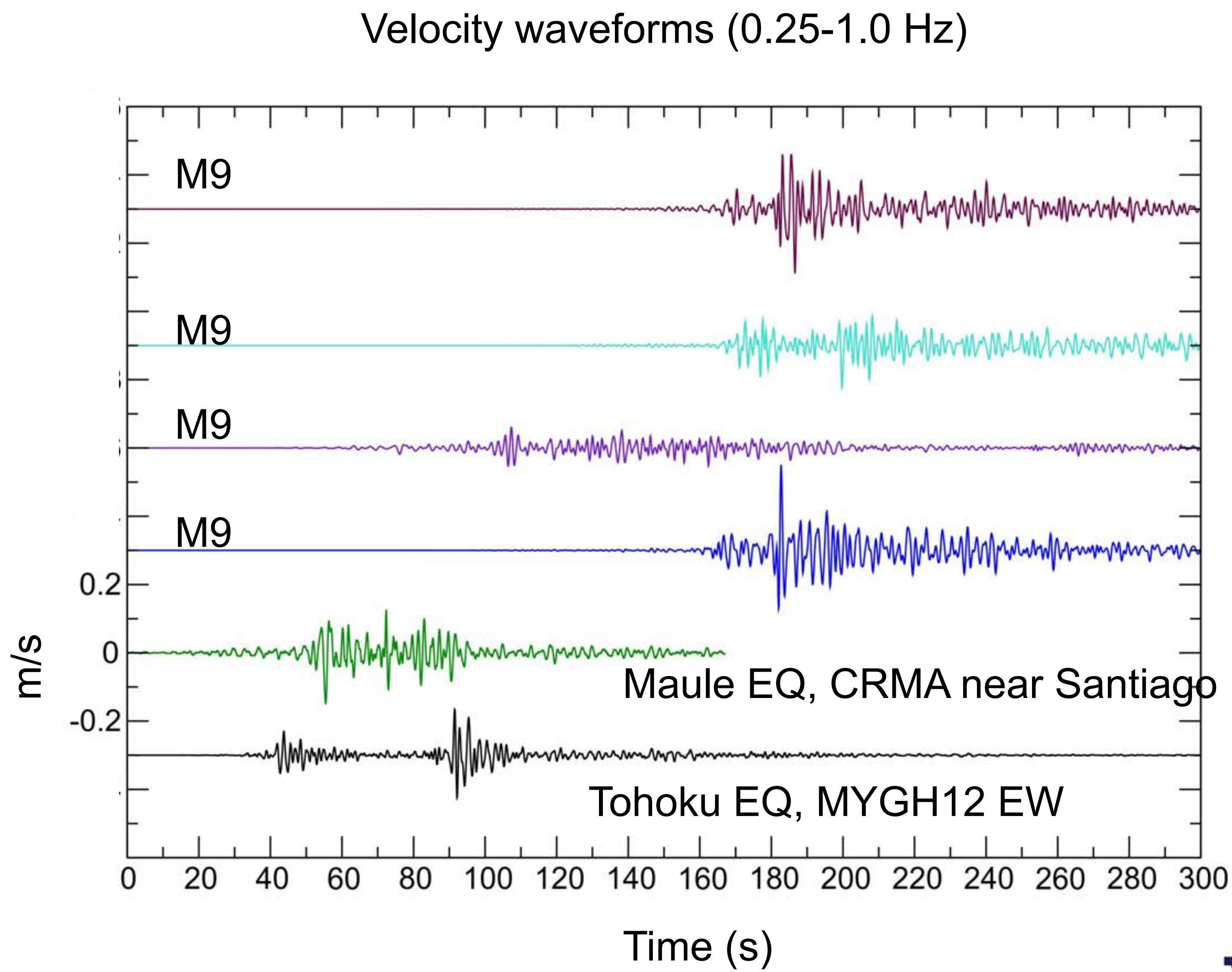
This shows predicted amplification in
L.A. Basin from simple theoretical calculations.
Surface wave amplification in basin
Is usually greater than that for vertically
propagating S-waves.

- There will be a small workshop in Seattle on March 22, convened by Susan Chang of the city of Seattle and USGS, to discuss how to include basin amplification results from M9 simulations in design of tall buildings in Seattle; follow-up to 2013 workshop

Guess the M9 synthetics (SP2; firm-rock site outside of Seattle basin) and actual records from Maule and Tohoku at comparable distances



Guess the M9 synthetics (SP2; firm-rock site outside of Seattle basin) and actual records from Maule and Tohoku at comparable distances



Take-Home Points

We have produced a large set of broadband synthetic seismograms of Cascadia M9 earthquakes that are being used to evaluate building response and ground failure

- For non-basin sites, 0.1-6.0 s spectral accelerations are similar, on average, to BC Hydro GMPE's, but exceed them at > 6 s.
- Synthetic response spectra have large variability from proximity to sub-events and, at long periods, from rupture directivity that combines with basin response
- Synthetics have amplification factors of 2-5 at 1-10 s for the Seattle basin; much larger than that found for crustal earthquakes in NGA West 2 GMPE's; should they be used in 2020 NSHM's?
- Synthetics show long durations of shaking (100 s at distance of 100 km)
- Synthetics will be posted on DesignSafe Website
- ShakeMaps will be posted on USGS Scenario ShakeMap site

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