Ground Motion Simulations of Magnitude 9 Cascadia Earthquakes

A. Frankel[1], E. Wirth[1], N. Marafi[2],
J. Vidale[3], W. Stephenson[1]

[1] U.S. Geological Survey

[2] University of Washington, now at RMS

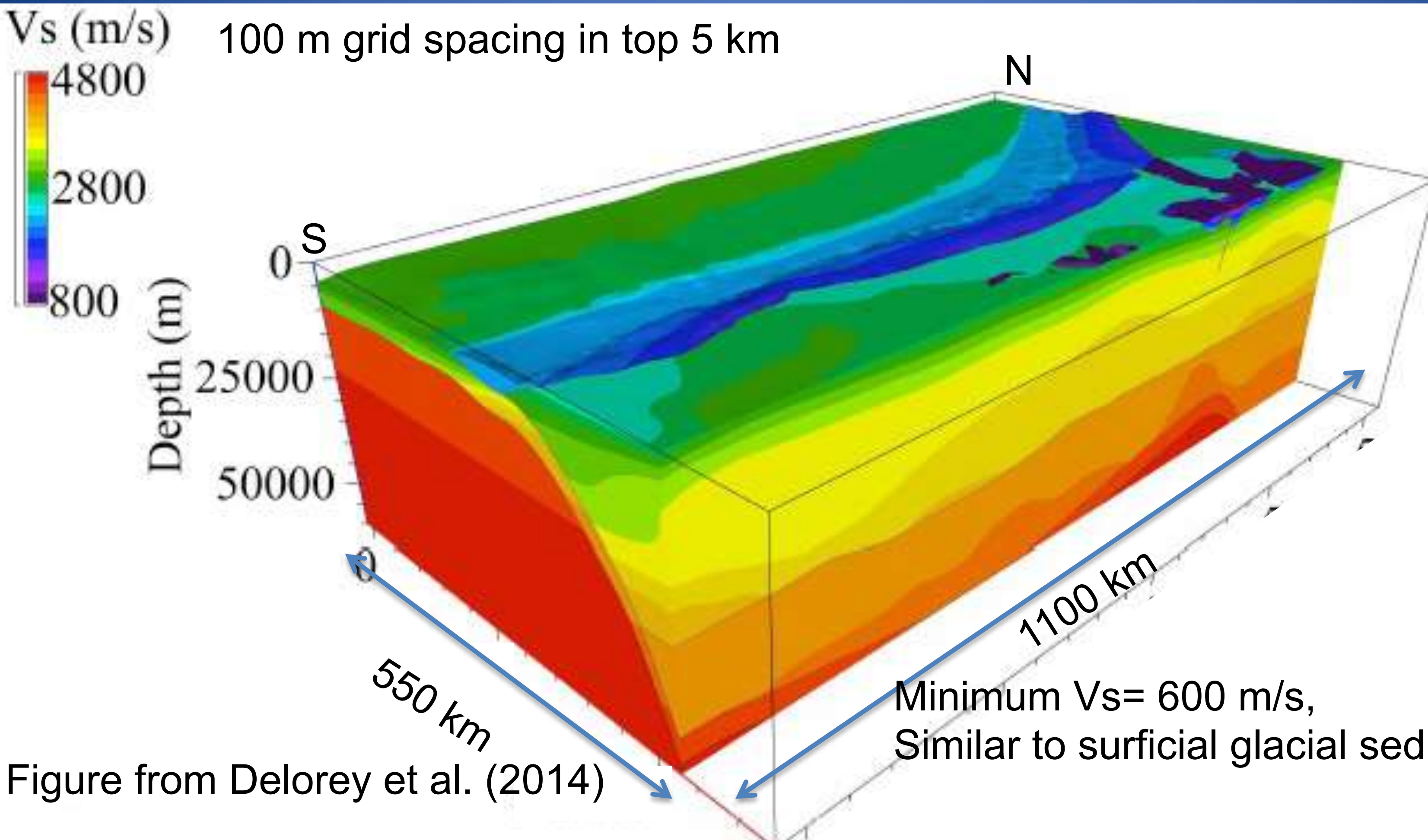
[3] University of Southern California

presentation to QuakeCoRE, Sept. 29, 2021

Stephenson et al. (2017) developed the 3D velocity model for Cascadia. Used seismic refraction/refraction data and tomography for Seattle basin (SHIPS), Moschetti et al. (2010) crustal tomography, McCrory et al. (2012) plate interface

We used 3D finite difference code written by Pengcheng Liu (U.S. Bureau of Reclamation) 4th order in space, 2nd order in time. 3D simulations run up to 1 Hz.

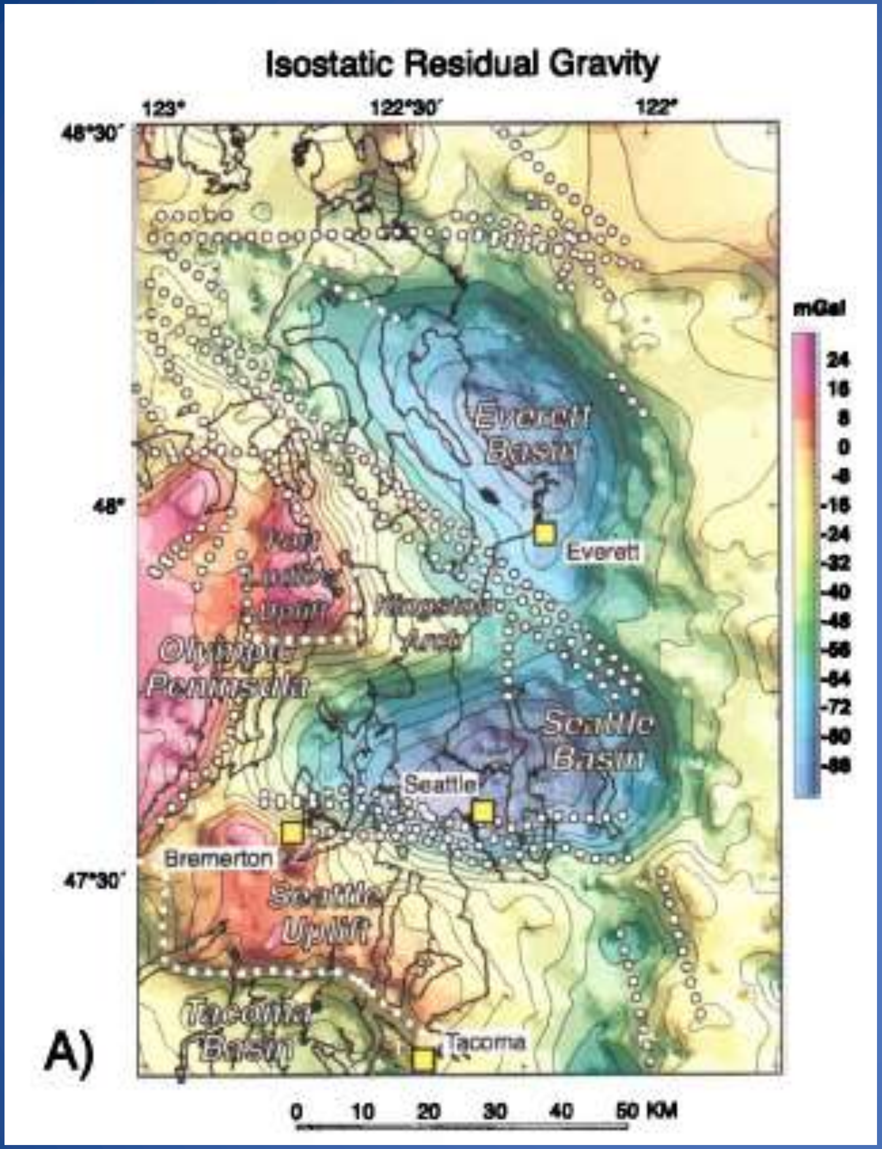
100 m grid spacing in top 5 km



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

Figure from Delorey et al. (2014)

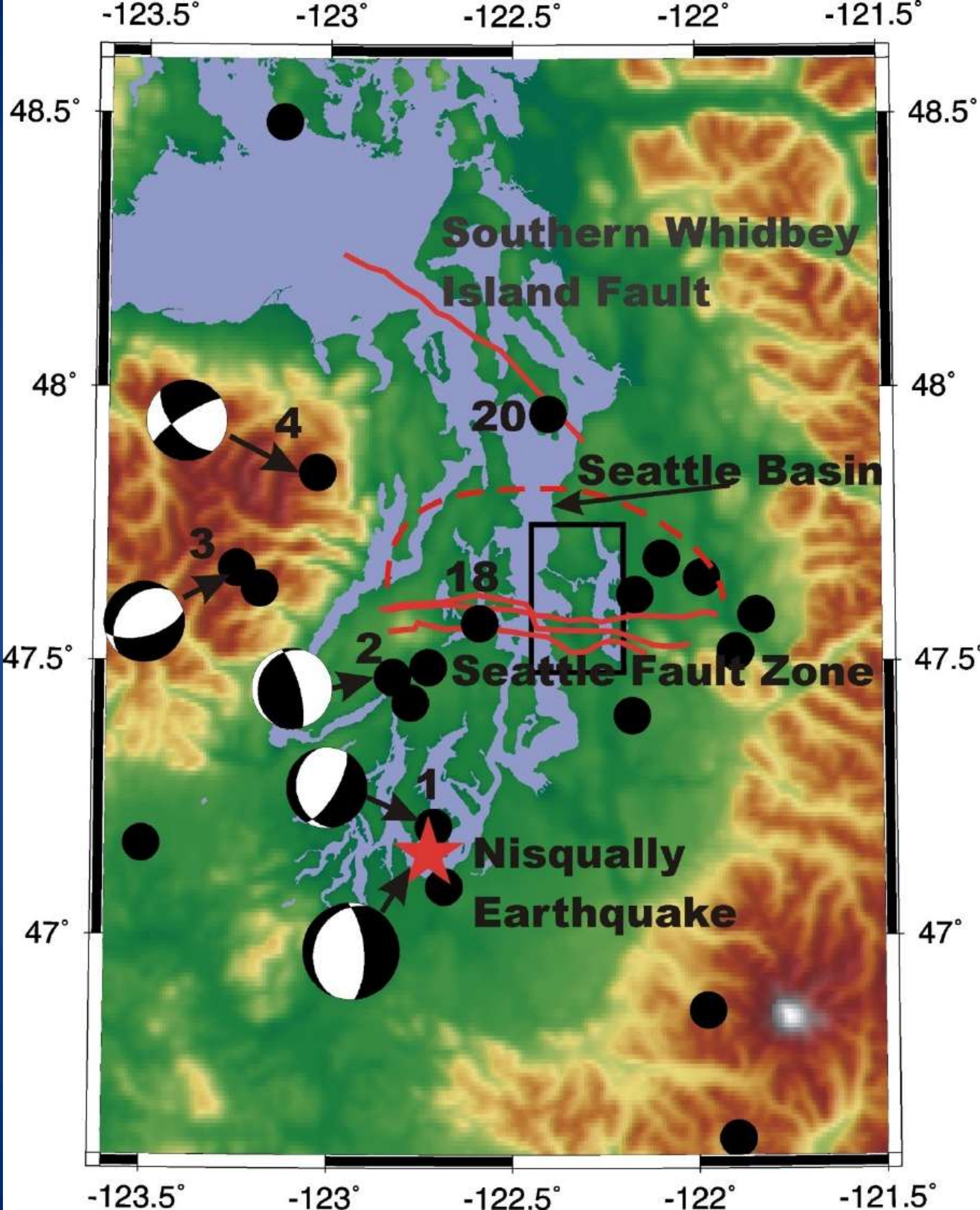
We replaced water with Vs= 1000 m/s, Qs= 10
tests show insensitivity of on-shore synthetics to Vs choice



From Brocher et al. (2001)

The Seattle basin is composed of up to 1 km thickness of glacial sediments over up to 6 km thickness of sedimentary rock.

Below the basin is volcanic rock (crystalline basement rock)



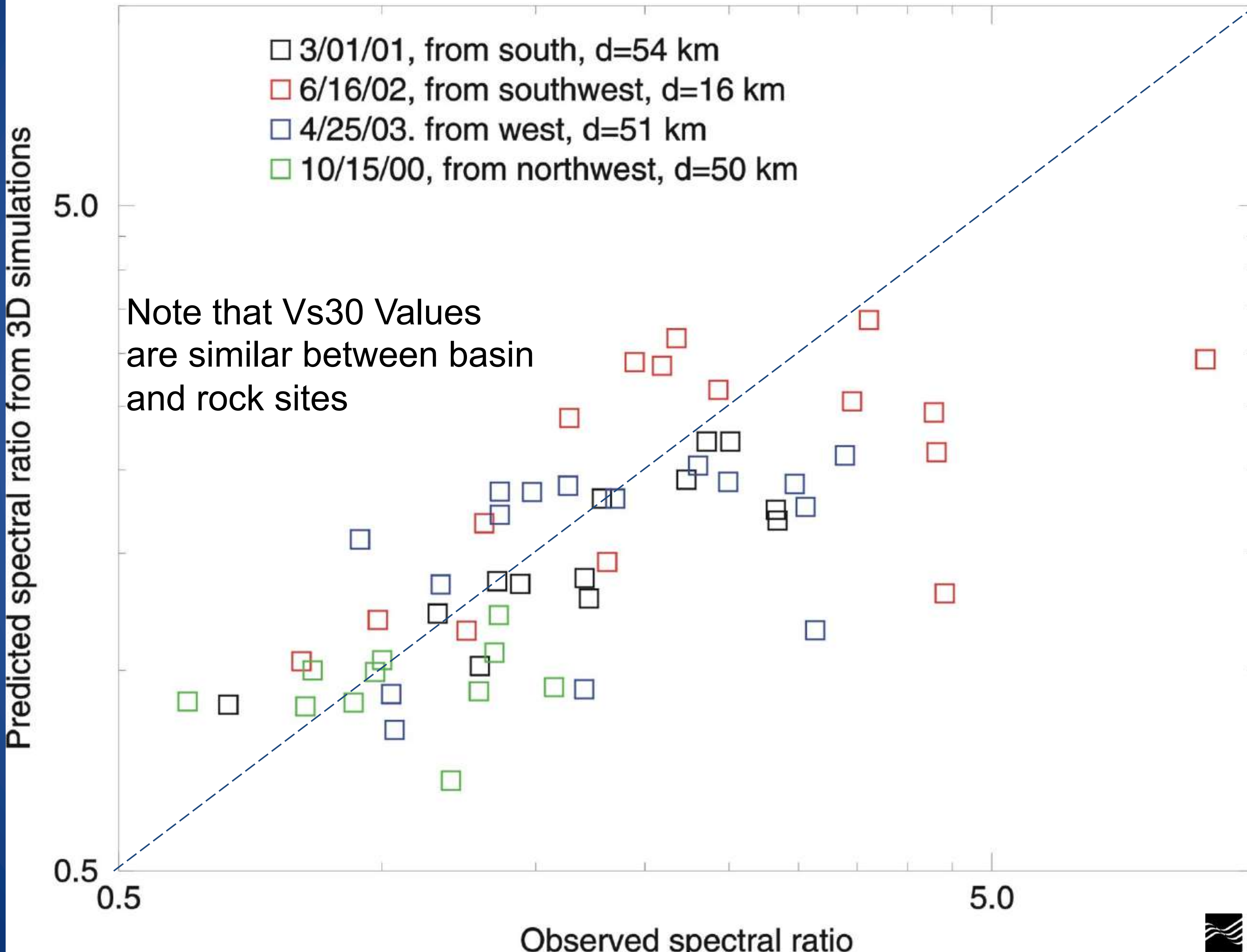
Validated 3D model for Seattle basin by comparing observed basin amplification with 3D simulations for 4 earthquakes and by modeling waveforms and response spectra of a M4.8 event and the M6.8 Nisqually earthquake (Frankel et al., 2009)

Also compared observed and predicted waveforms and response spectra for 3 additional earthquakes (Thompson et al., 2020).

USGS science for a changing world

Predicted and Observed Spectral Ratios wrt Rock Sites

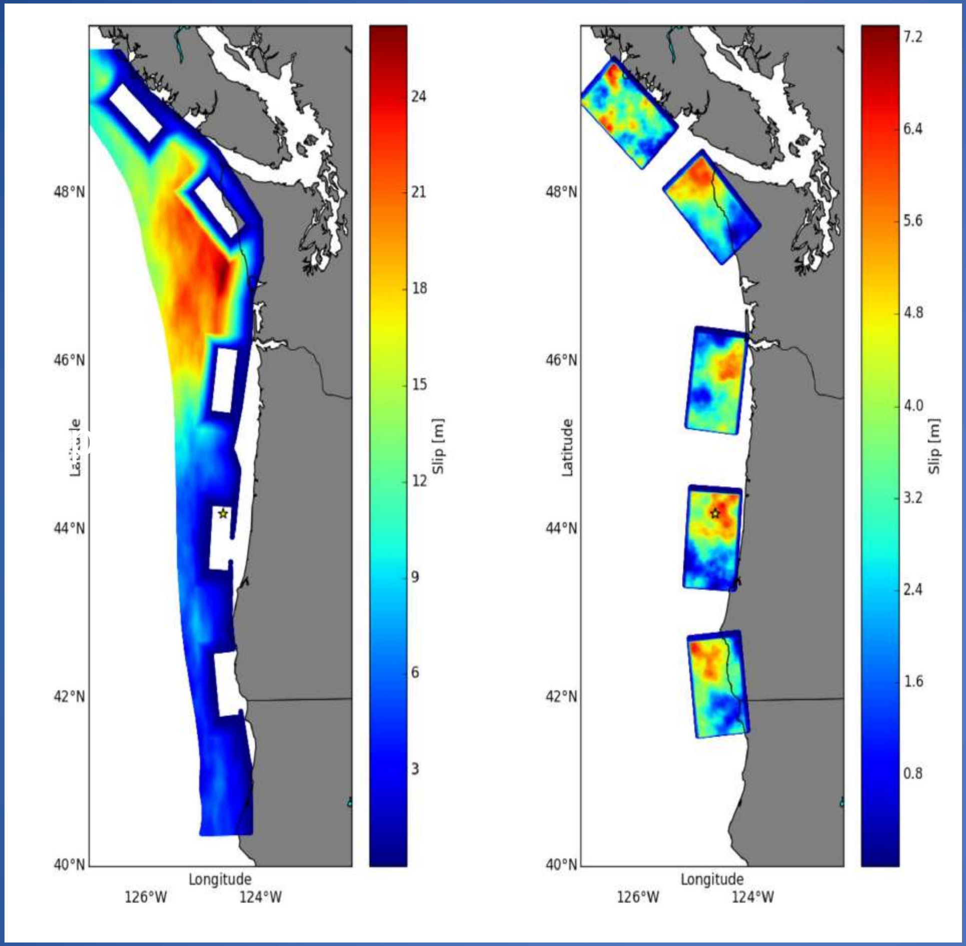
1 Hz Stiff-soil sites



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 Frankel, 2013, 2017)

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

Saved seismograms on 1 km grid

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)

USGS science for a changing world

Approach for Cascadia M9 simulations

- Started with rupture parameters (slip velocities; sub-event magnitude, average rupture velocity, standard deviation of rupture velocity) that worked for modeling response spectra from strong-motion recordings of M8.8 Maule earthquake
- Compared SA values from Cascadia M9 synthetics (non-basin sites) with observed values from Maule earthquake and with BC Hydro ground motion prediction equations (Abrahamson et al., 2016) based on recordings of M5.0-9.0 subduction zone earthquakes. Made modifications to some rupture parameters to lower bias with respect to BC Hydro GMPE at longer periods (> 6 s)
- Ran 30 3D simulations with varying hypocenter, sub-event locations, slip distribution, down-dip rupture edge
- Ran 20 3D simulations for sensitivity study to investigate dependence of response spectra to rupture parameters

USGS
science for a changing world

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

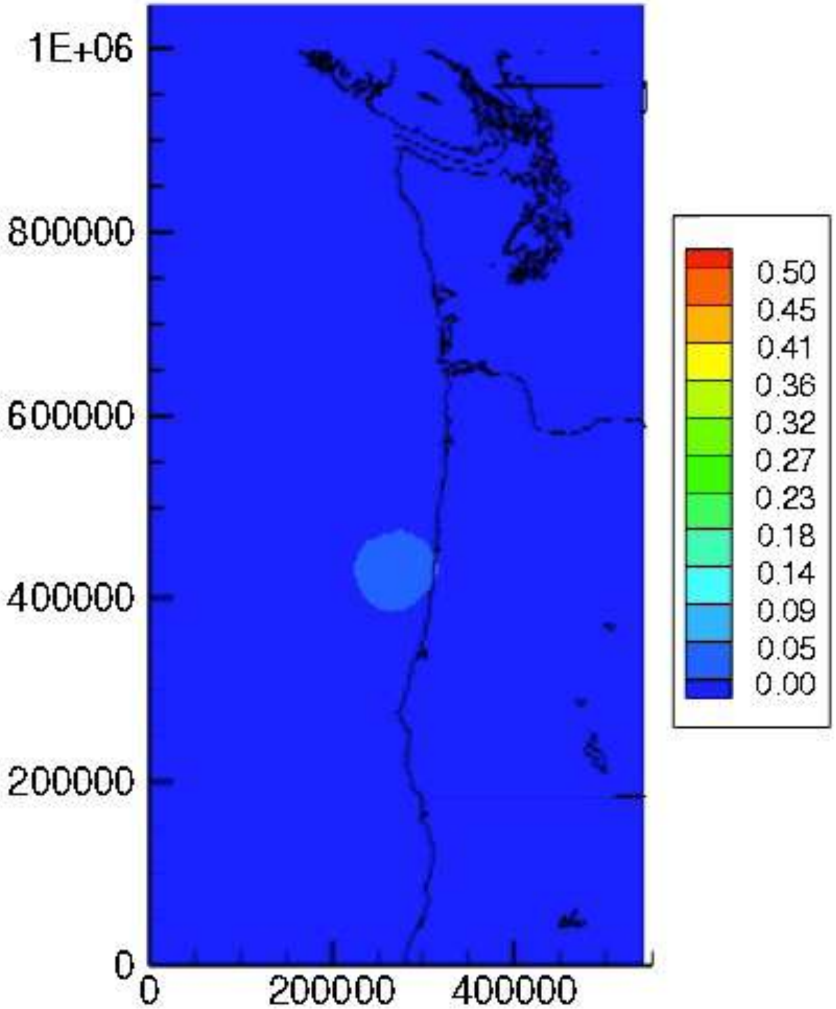
Broad band
Synthetics
(0-10 Hz)

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

USGS
science for a changing world



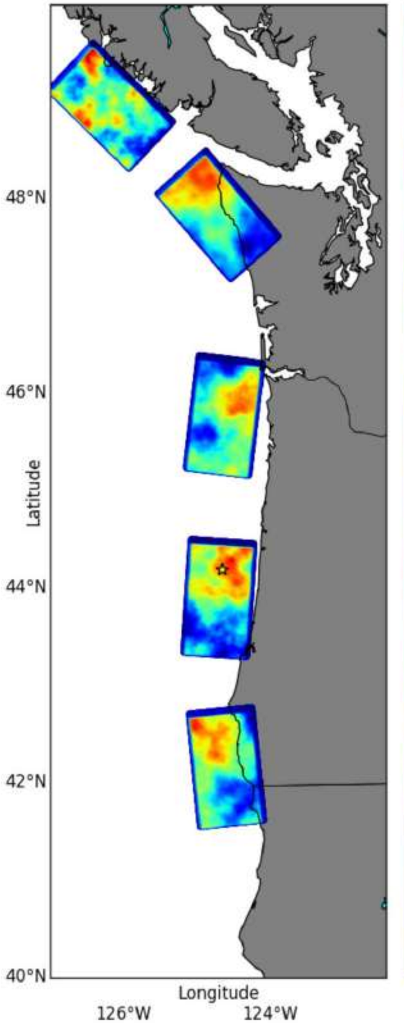
Animation of simulated ground motions for run 21

300 second movie duration

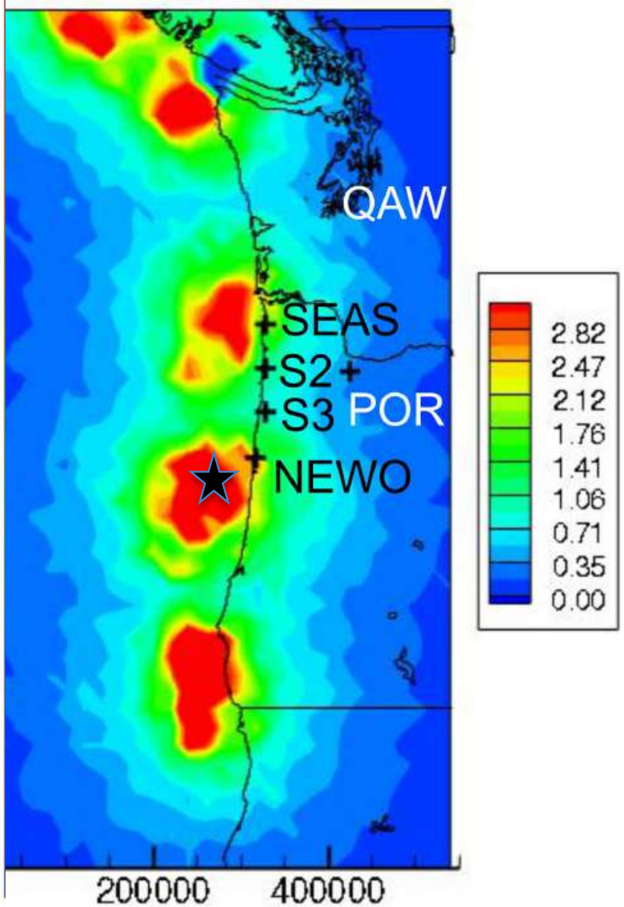
Shows magnitude of horizontal velocity vector (m/s)

Example from Run 21

Sub-event slip

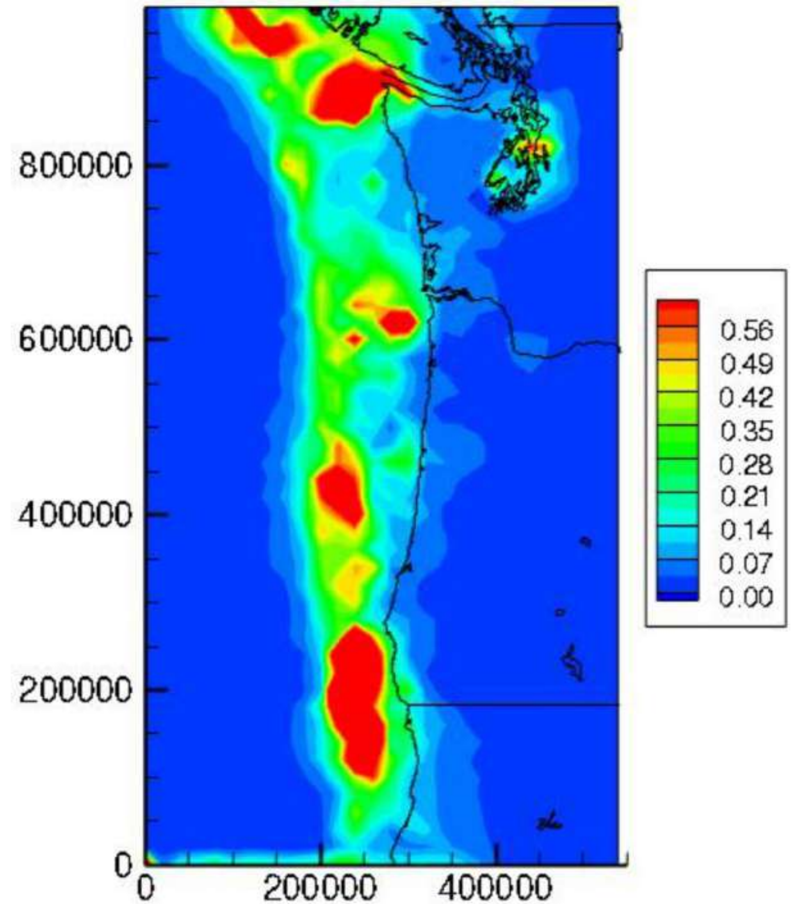


0.2 s SA (g)



From stochastic

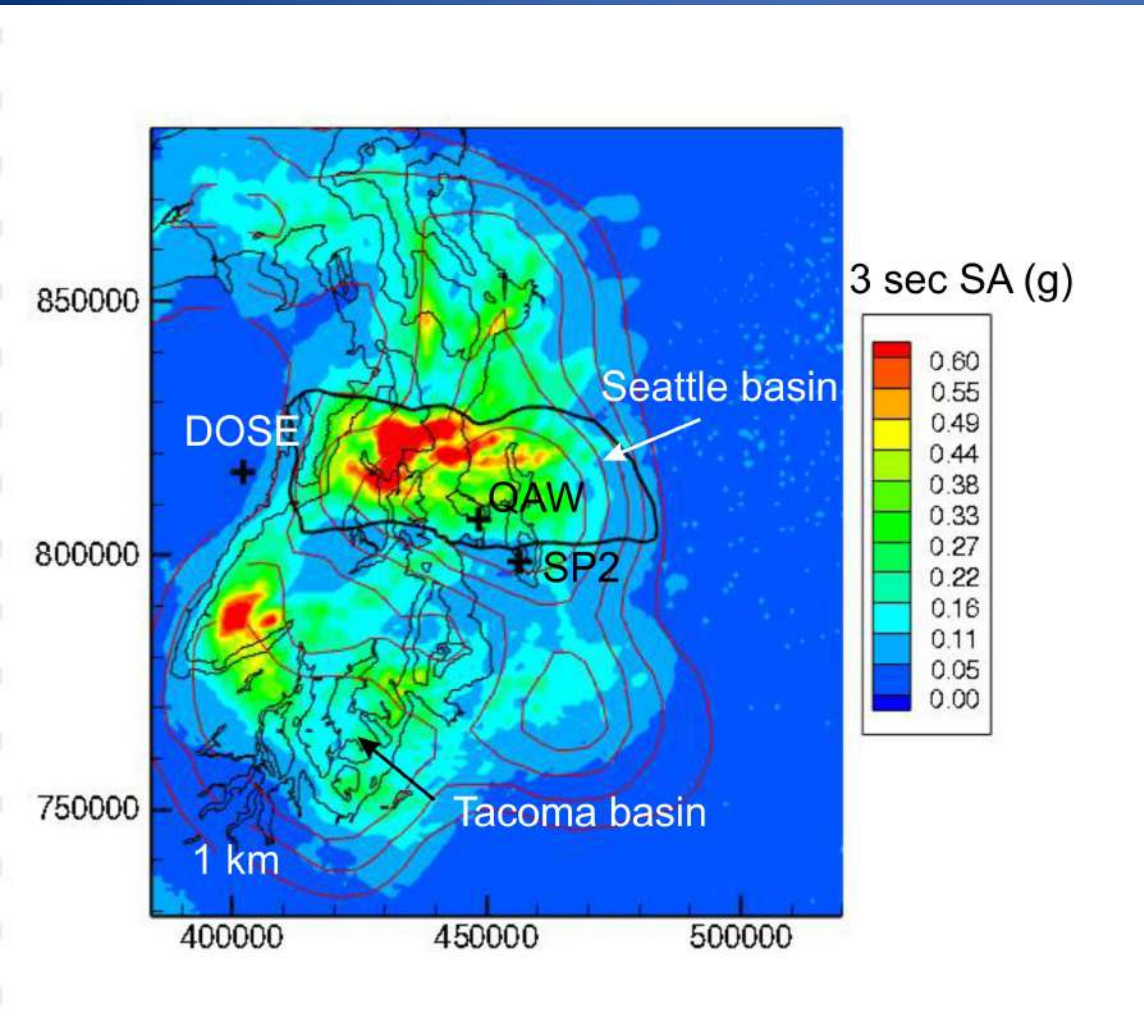
3.0 s SA (g)



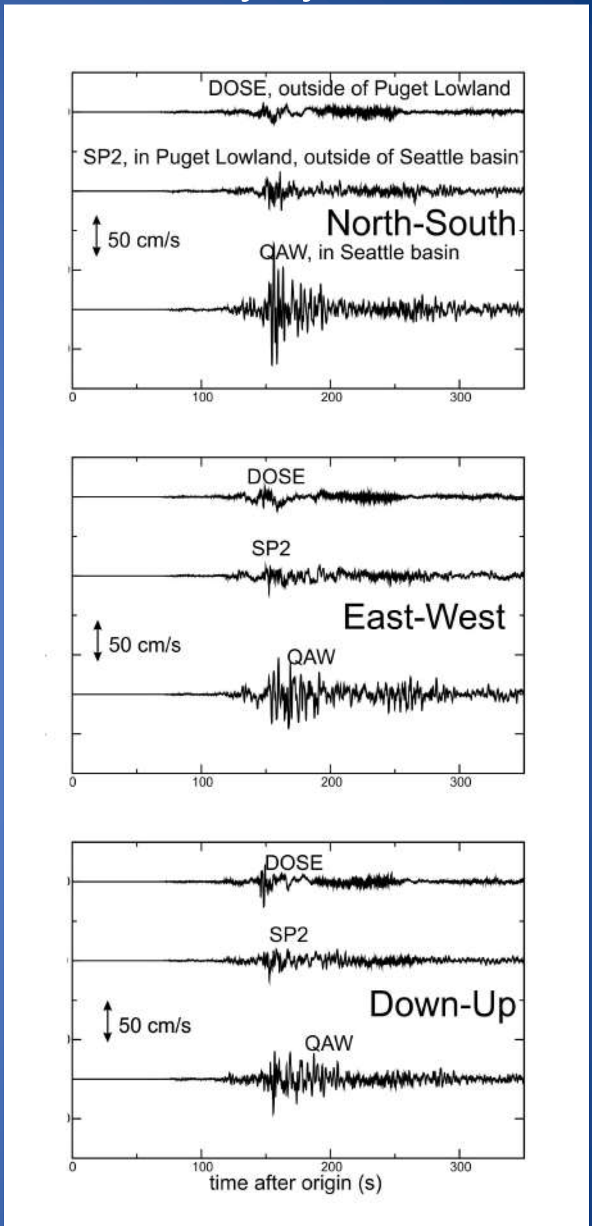
From 3D simulation

For the stochastic part we used a uniform stiff-soil site condition;
Vs30= 600 m/s, on average

3 s SA in Puget Lowland from 3D simulation

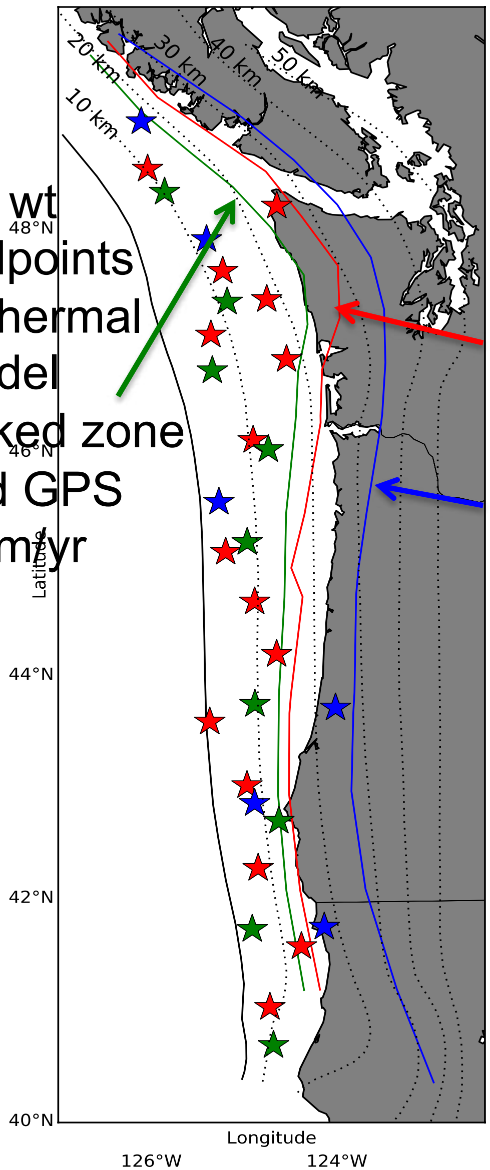


Velocity synthetics



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

Hypocenters



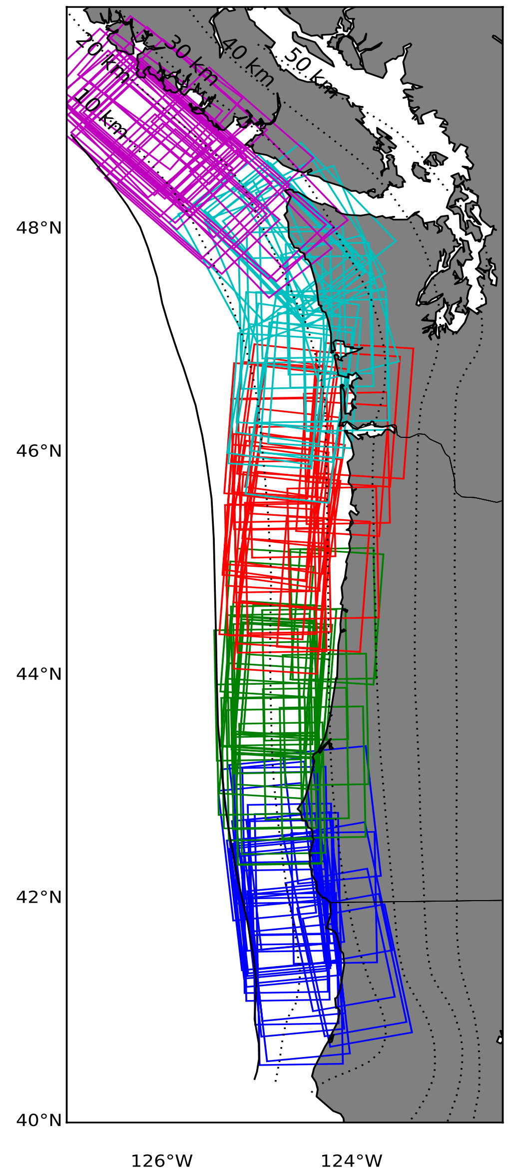
0.2 wt
Midpoints
of thermal
model
locked zone
and GPS
1 cm/yr

0.5 wt
1 cm/yr
locking
from GPS
and uplift

0.3 wt
top of
tremor
zone

Also varied slip distributions
In background and sub-events

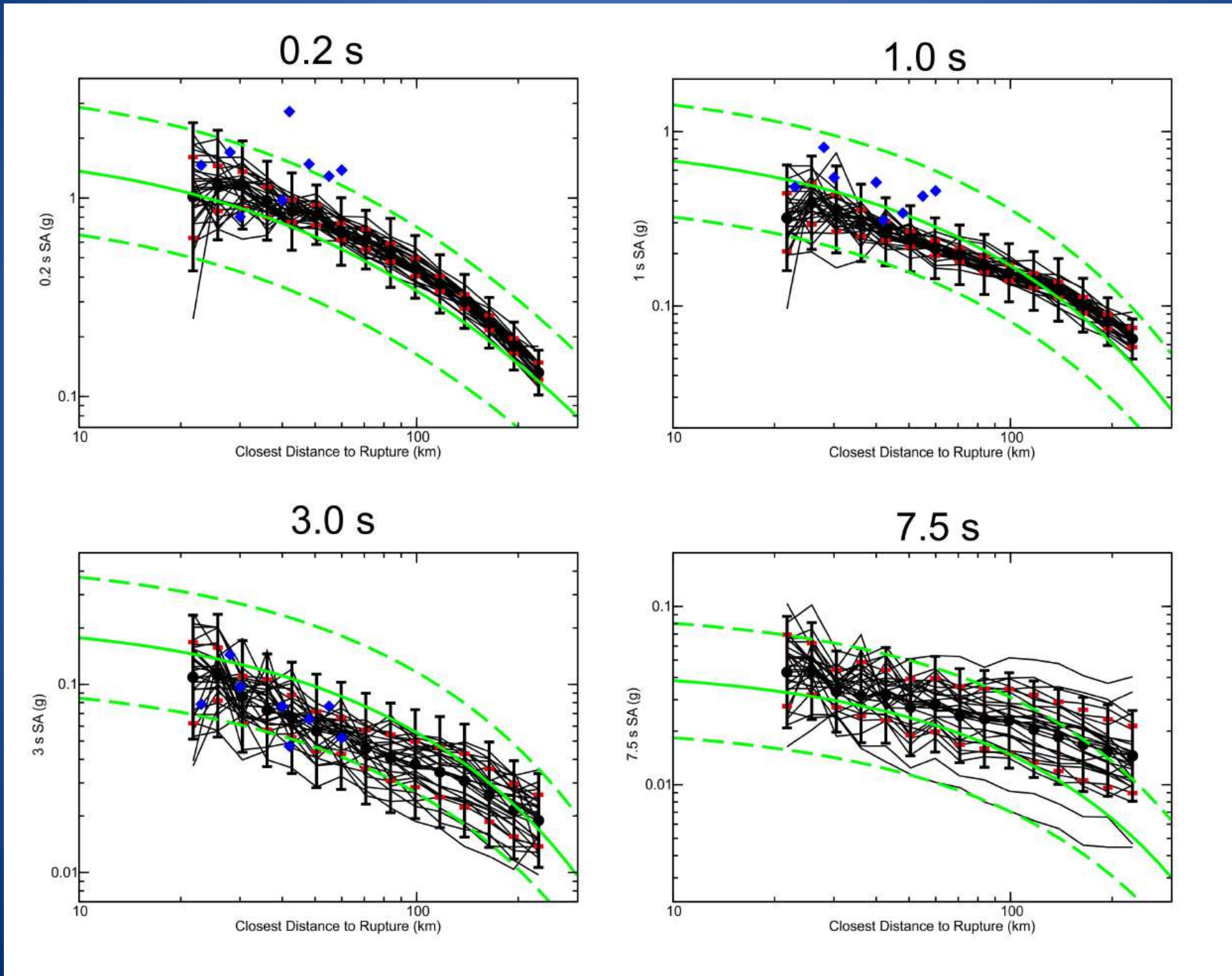
Sub-event rupture zones



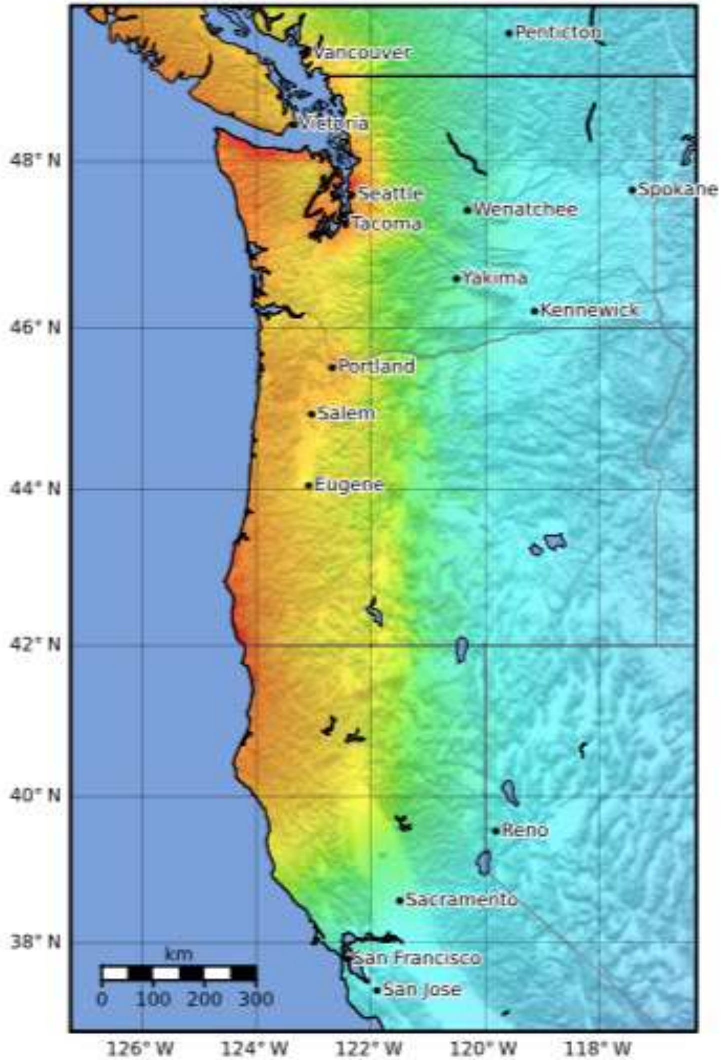
Figures from Erin Wirth

USGS
science for a changing world

SA with respect to closest rupture distance for 30 runs; non-basin sites
Green lines from BC Hydro Ground Motion Prediction Equations; Vs30= 600 m/s
blue symbols Maule data. Black error bars: total variability; Red error bars inter-event



source depth effect?



SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
DAMAGE	None	None	None	Very light	Light	Moderate	Moderate/heavy	Heavy	Very heavy
PGA (%g)	<0.0464	0.297	2.76	6.2	11.5	21.5	40.1	74.7	>139
PGV (cm/s)	<0.0215	0.135	1.41	4.65	9.64	20	41.4	85.8	>178
INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Scale based on Worden *et al.* (2012)

Ensemble Shakemap
For M_w 9 earthquake,
Median of 30 simulations

From Broadband
Synthetics

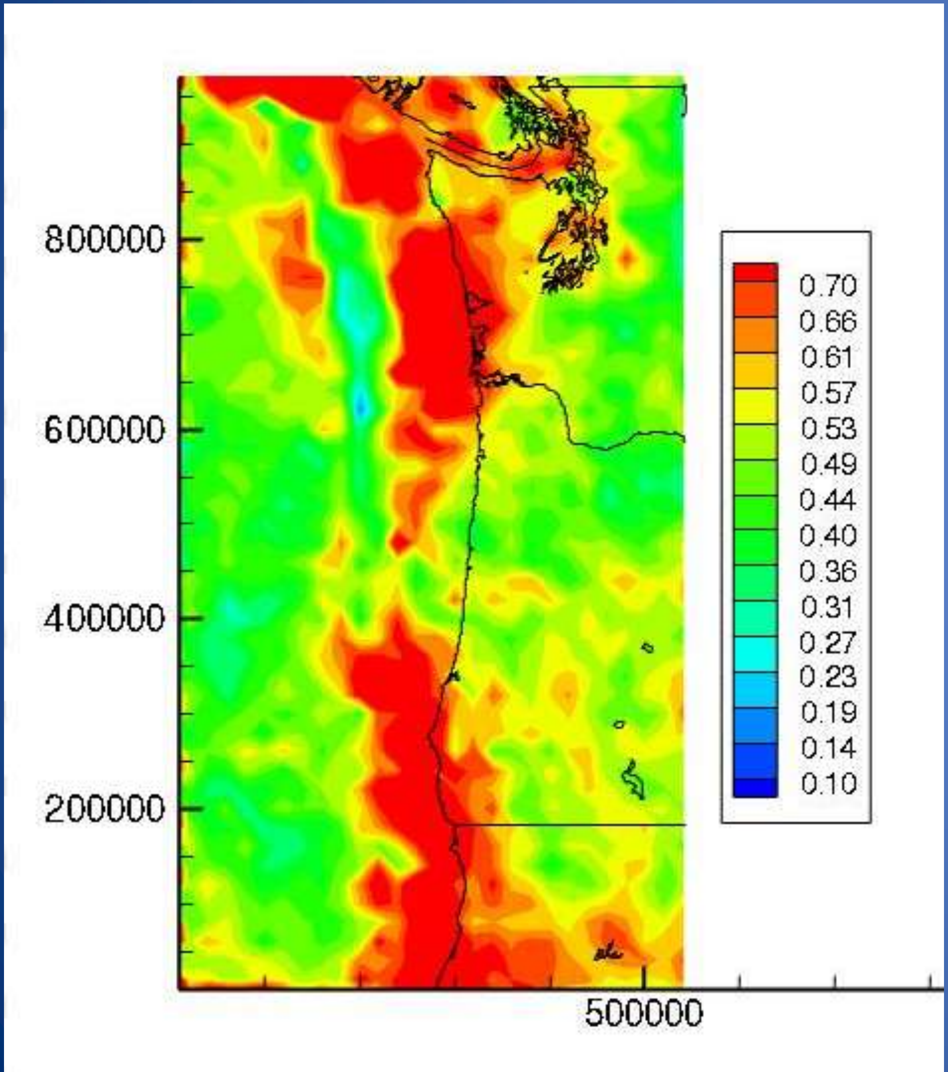
With site amplification factors
at higher frequencies
based on Vs30 map.
Pacific Northwest Vs
profiles and equivalent linear
site response used to
determine amplification
relative to Vs30=600 m/s
for simulations
(A. Grant)

Wirth, Grant, Marafi, Frankel
SRL, 2021

USGS
science for a changing world

Standard deviation (ln units) of 3 second SA for 15 M9 runs that used downdip edge based on 1 cm/yr locking depth determined from GPS measurements

This is a lower bound for single station sigma



Inter-event variability is underestimated with only 15 runs

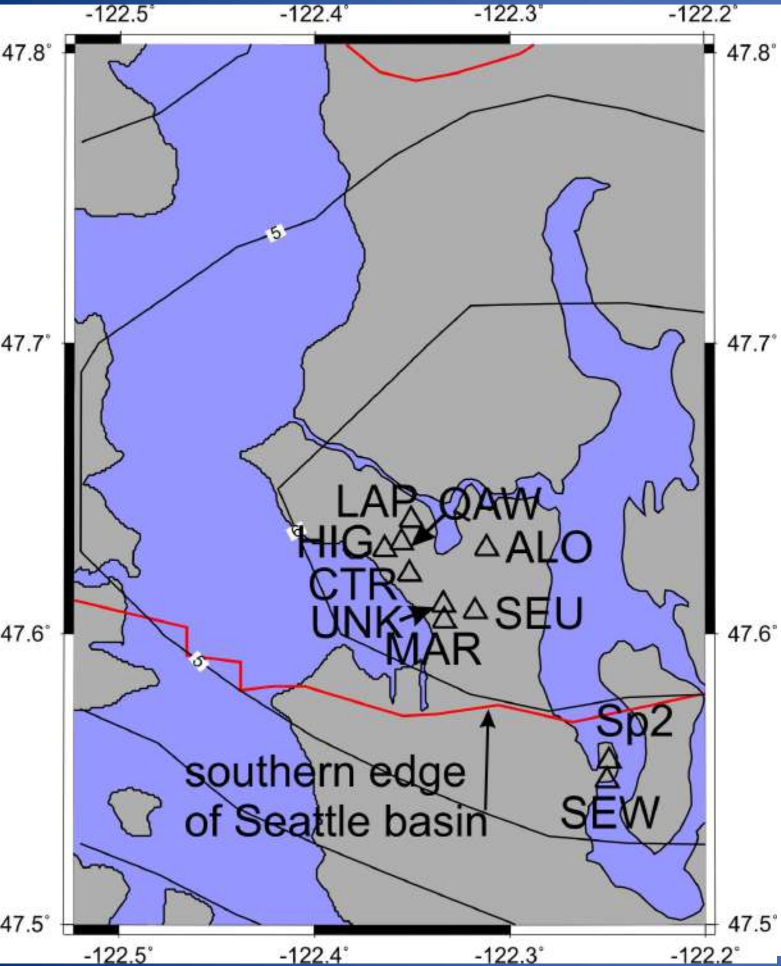
Single station sigma tends to be higher toward ends of rupture zone

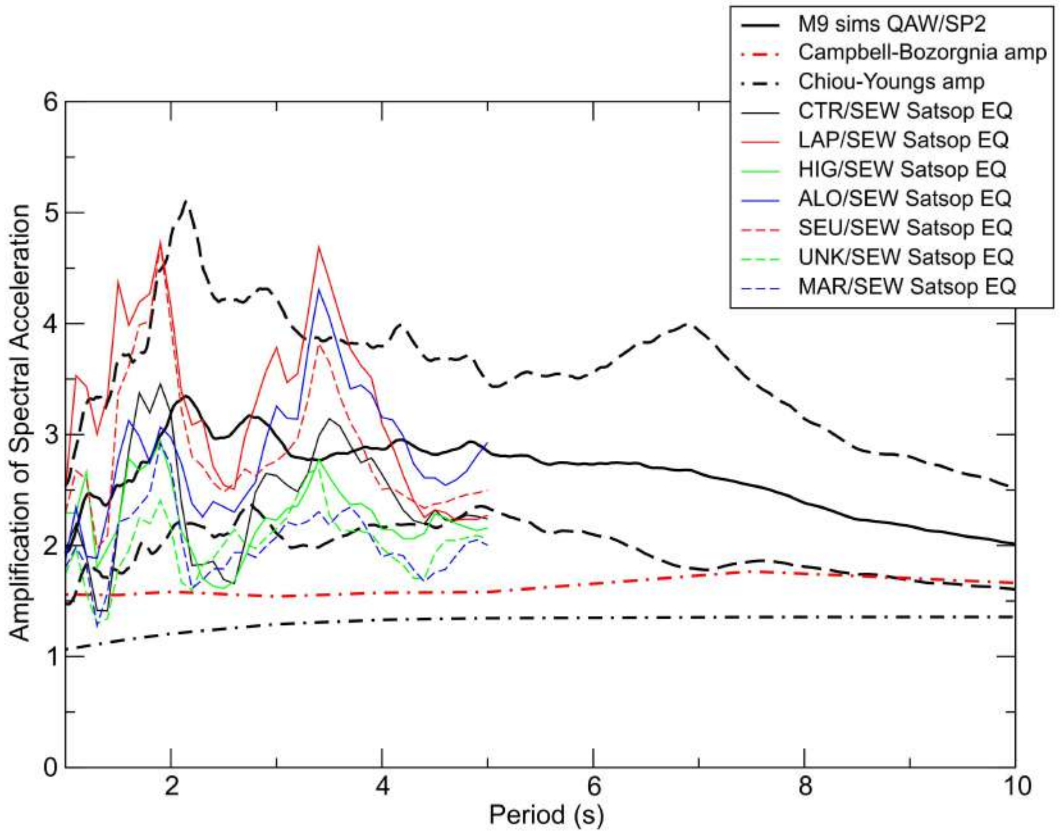
Single station sigma tends to be higher for basin sites compared to nearby non-basin sites

Need to account for this in non-ergodic PSHA

USGS science for a changing world

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



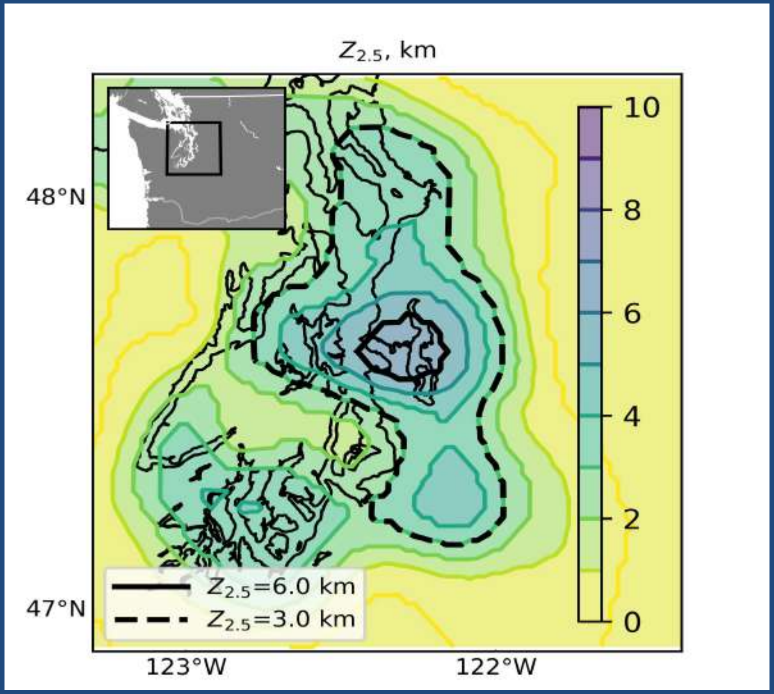


Basin amplification from Seattle basin data and M9 synthetics much larger than that predicted by GMPE's for crustal earthquakes

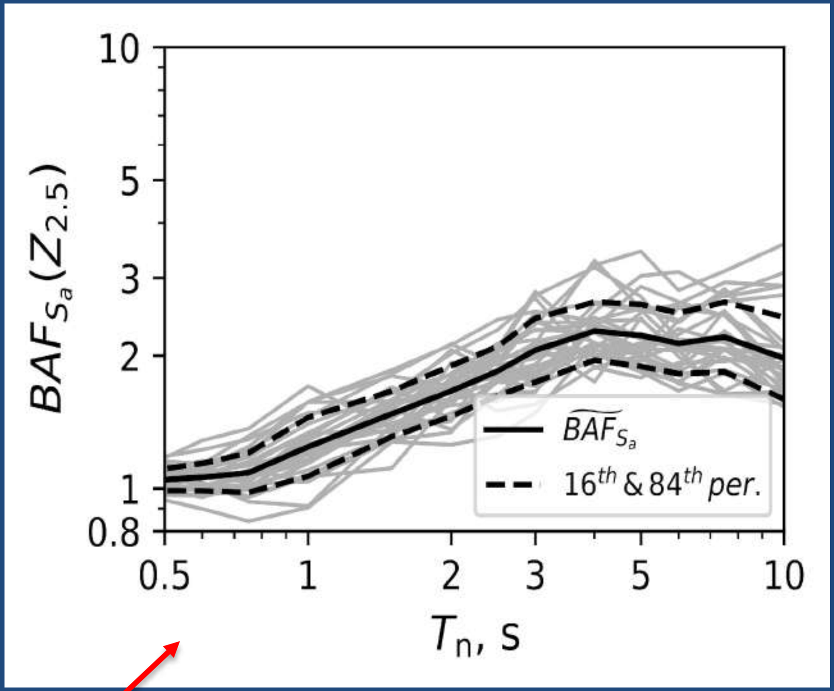
Seattle Basin Amplification Factors from 3D simulations

Figures from N. Marafi

$Z_{2.5,REF}$ = 3.0 km



Amplification for $Z_{2.5} \geq$ 6.0 km

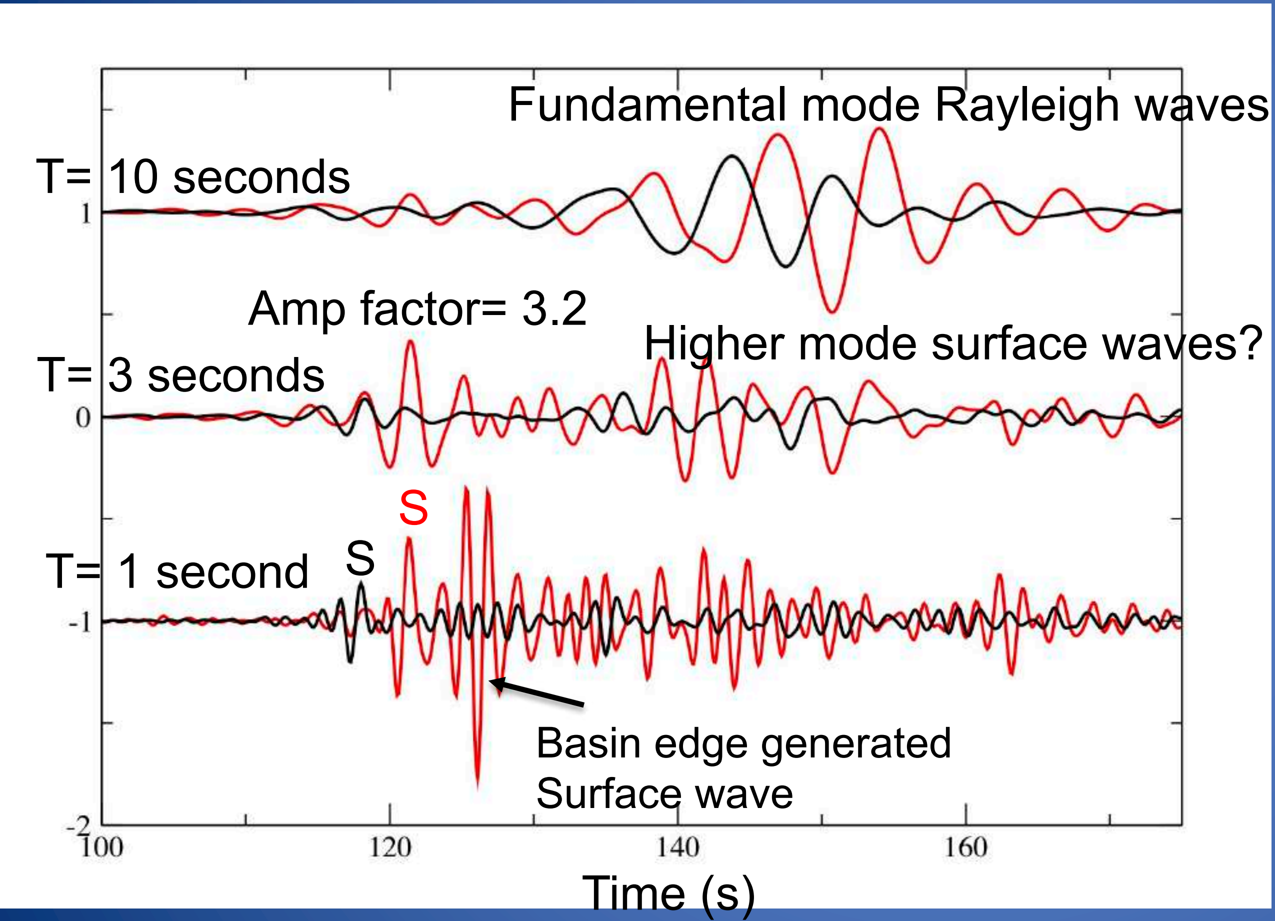


Z2.5 is depth to Vs = 2.5 km/s (crystalline basement)

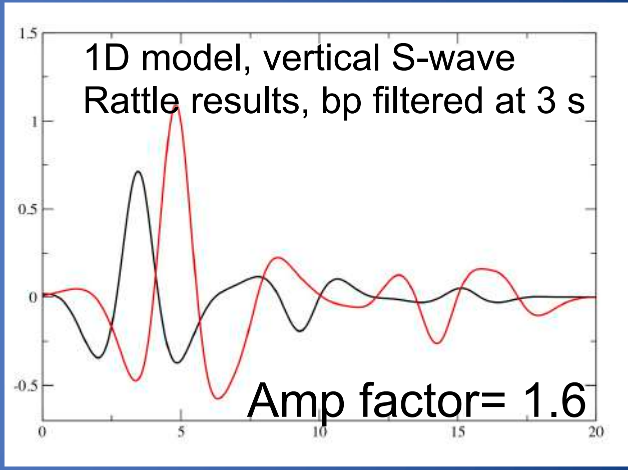
This plot was used to guide new basin amplification terms for high rise buildings in Seattle (Susan Chang, City of Seattle)
See Wirth, Chang, Frankel USGS OFR 2018-1149

Cascadia M9 synthetics (NS), 3D velocity model, bandpass filtered at 1, 3, and 10 s, run csz004

black seismograms are for station outside Seattle basin
red seismograms are for station in basin



Synthetics from
Flat layered model



Take-Home Points

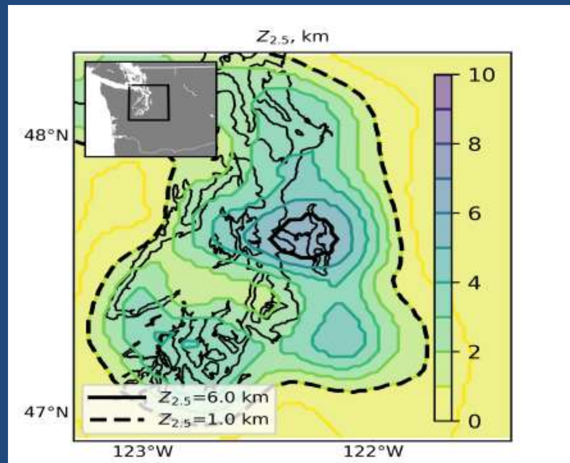
We have produced a large set of broadband synthetic seismograms of Cascadia M9 earthquakes that are being used to evaluate building response and ground failure

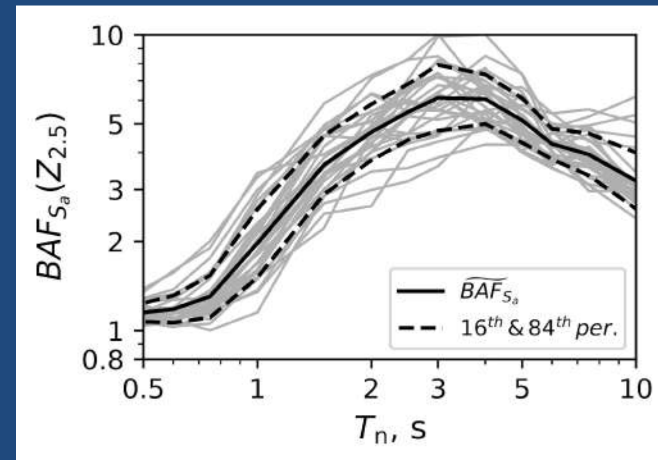
- For non-basin sites, 0.1-6.0 s spectral accelerations are similar, on average, to BC Hydro GMPE's, but exceed them at > 6 s.
- Synthetic response spectra have large variability from proximity to sub-events and, at long periods, from rupture directivity that combines with basin response
- Synthetics have amplification factors of 2-5 at 1-10 s for the Seattle basin. Factors depend on reference sites. much larger than that found for crustal earthquakes in NGA West 2 GMPE's
- Synthetics show long durations of shaking (100 s at distance of 100 km, based on 5th to 95th percentile Arias intensity)
- 2 BSSA papers: Frankel et al. (2018) and Wirth et al. (2018)
- 4.5 million synthetic seismograms are posted on DesignSafe Website: https://www.designsafe-ci.org/data/browser/public/designsafe.storage.published/PRJ-1355
- Time histories can be selected by site location using a web service in beta testing written by Nasser Marafi (UW) at: https://sites.uw.edu/pnet/m9-simulations/

Seattle Basin Amplification Factors from 3Dsimulations

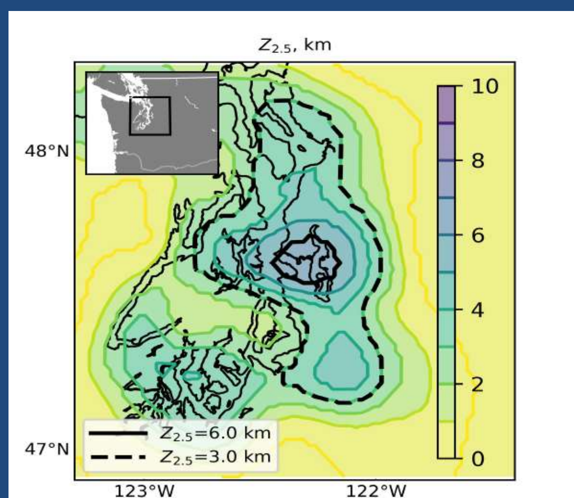
Figures from N. Marafi

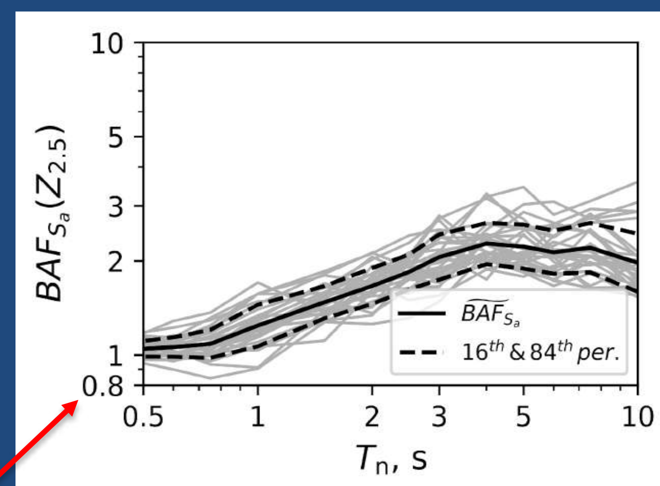
$Z_{2.5,REF}$ = 1.0 km





$Z_{2.5,REF}$ = 3.0 km





Depth to Vs = 2.5 km/s (crystalline basement)

This plot was used to guide new basin amplification terms for high rise buildings in Seattle (Susan Chang, City of Seattle)
See Wirth, Chang, Frankel USGS OFR 2018-1149

Comparison of M9 basin amplification (Z2.5 ref= 3 km) with NGA subduction GMMs

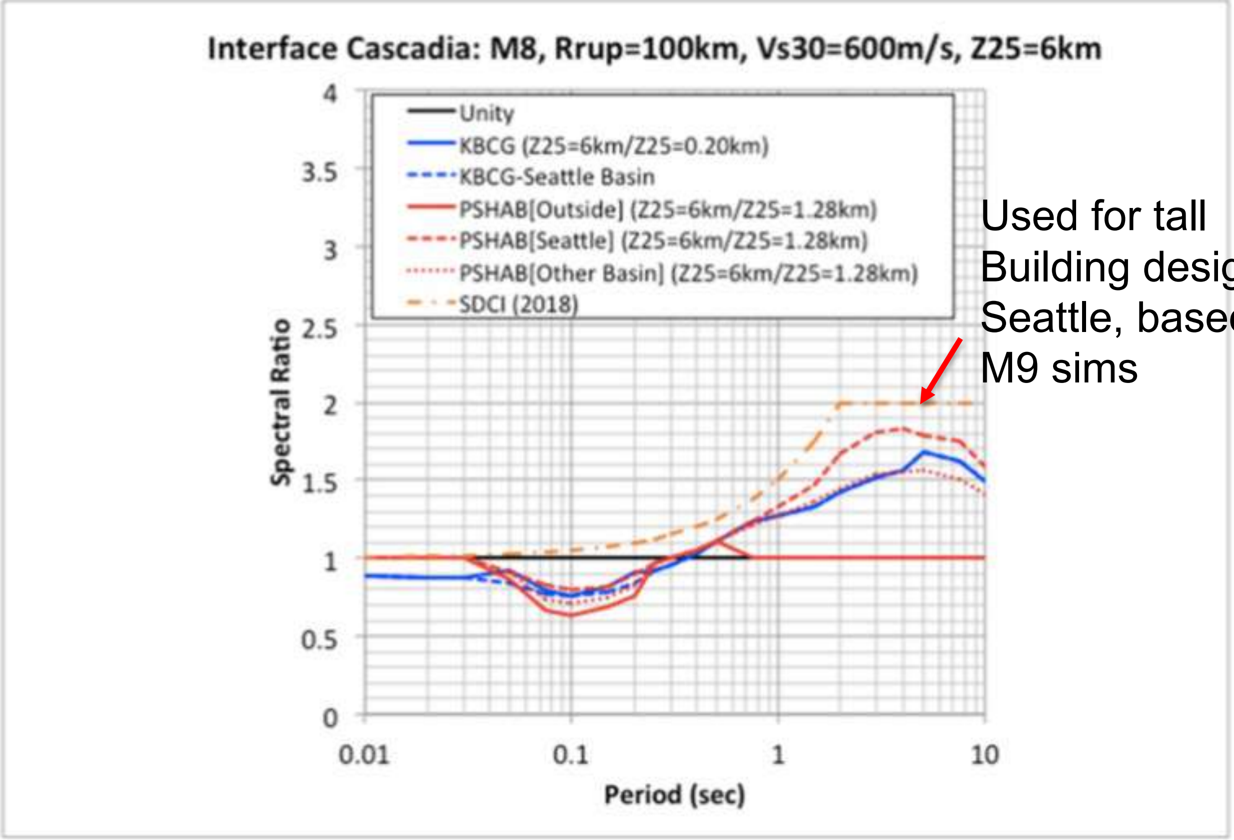
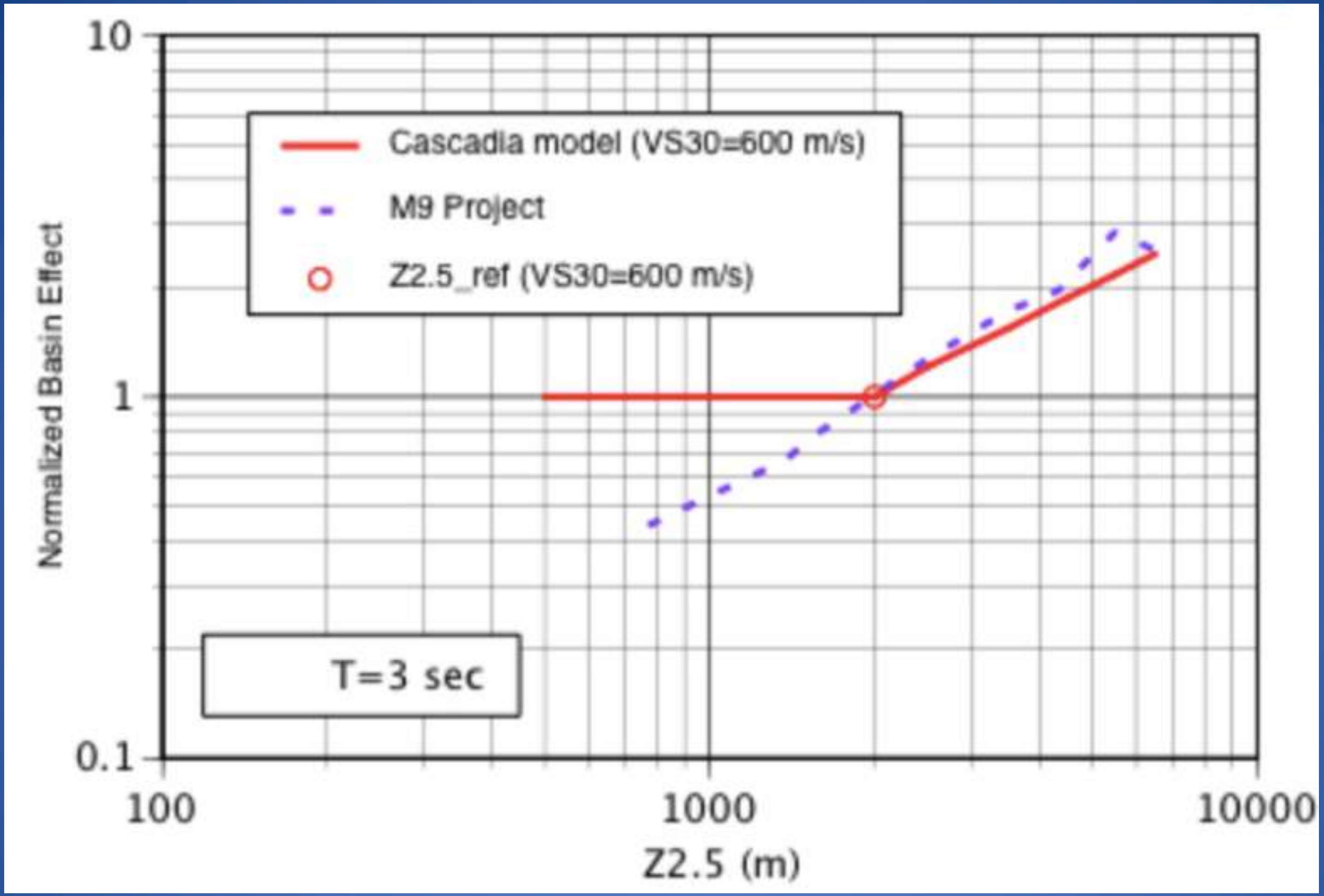


Figure 3.121 Basin amplification factors for Cascadia from a M8 interface event at a distance of 100 km and with V_{S30} = 600 m/sec and $Z_{2.5}$ value of 6 km.

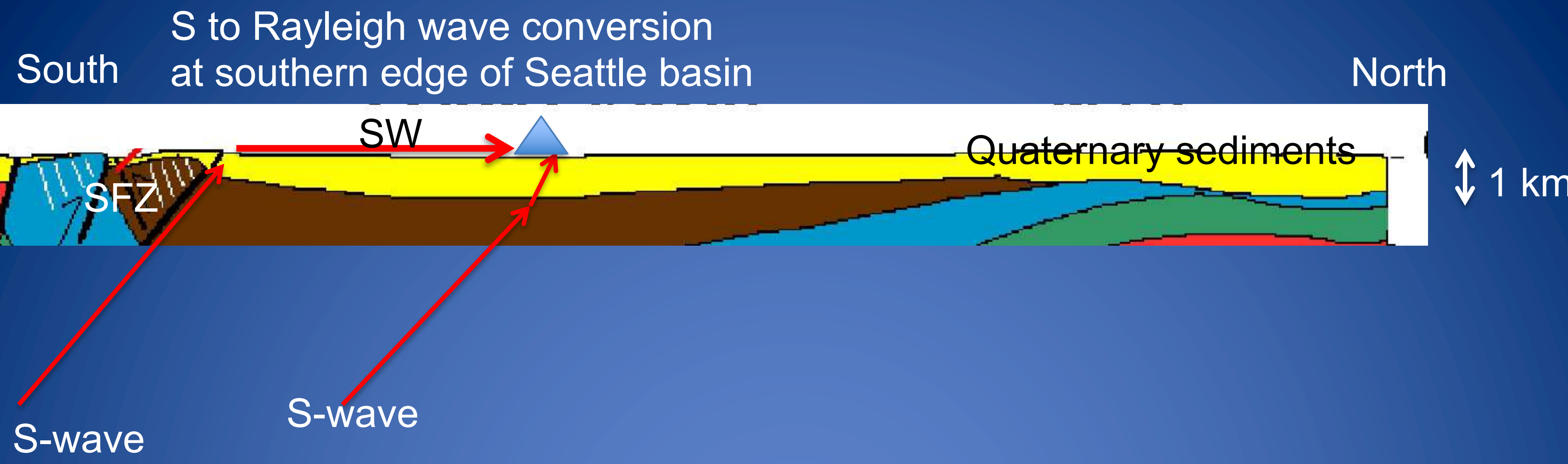
Used for tall Building design in Seattle, based on M9 sims

Figure from Gregor et al. (2021)

Note that NGA subduction database only contains slab earthquakes for PacNW. Observations indicate that Seattle basin amp is higher for earthquakes with shallow angles of incidence, such as Cascadia M9. Also found higher amplification for Mb 5.0 Satsop earthquake than Nisqually earthquake.



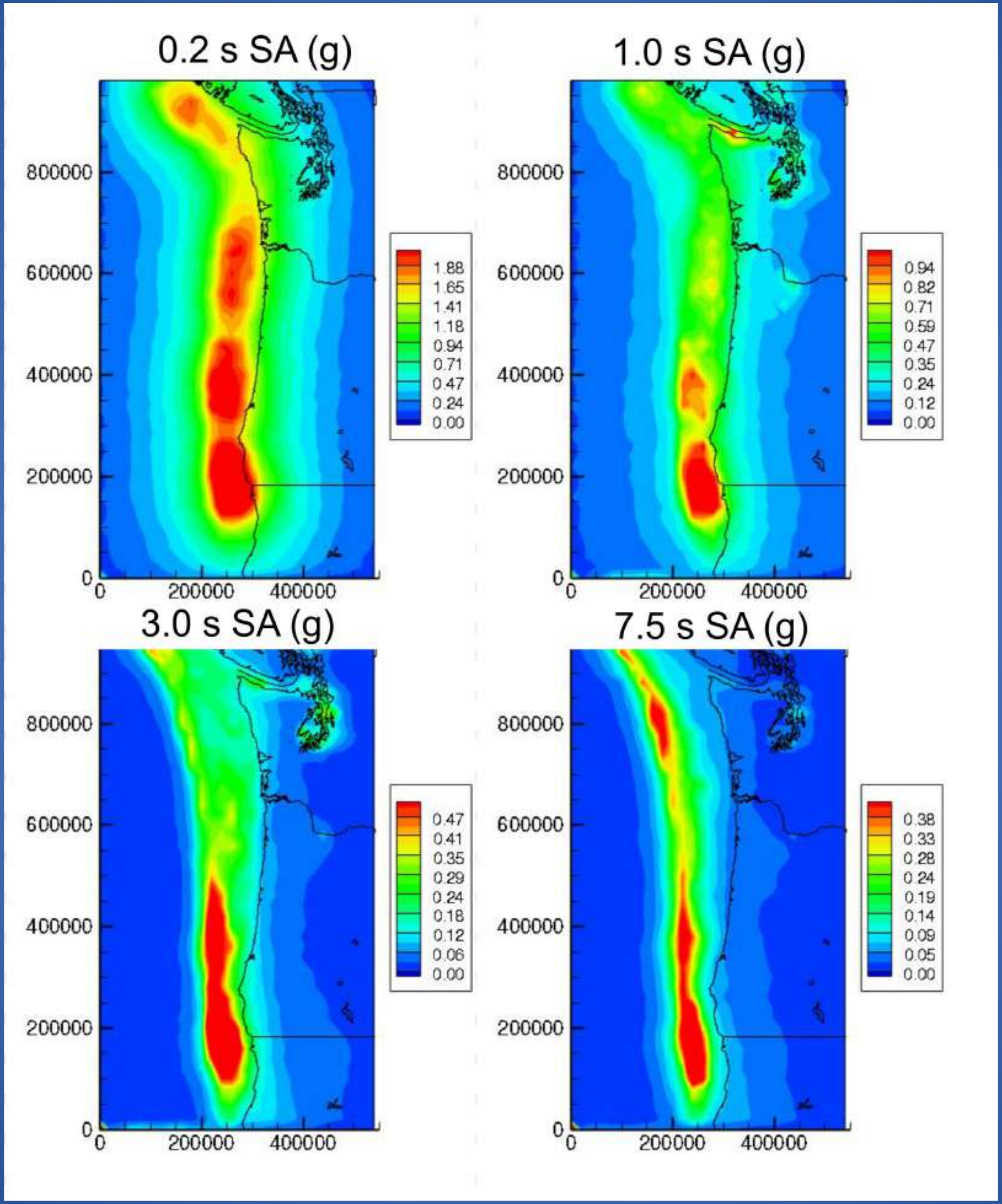
Basin amplification factors from NGA Subduction GMM of Abrahamson and Gulerce (2021) and M9 simulations

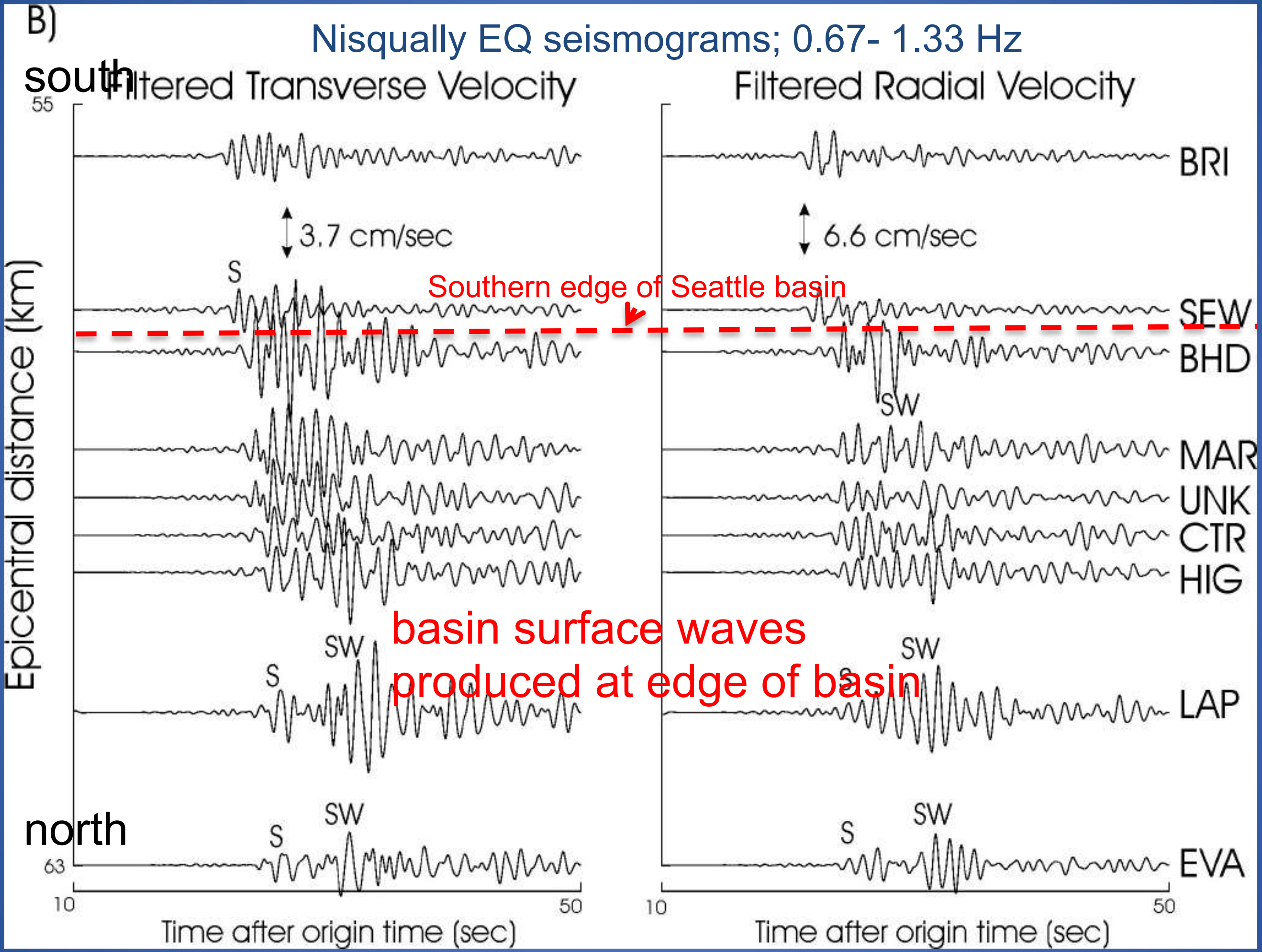


Processes that amplify ground motions and increase duration of shaking in sedimentary basins

1. S-waves amplified by low impedance of sediments and reflections within basin
2. Focusing of S-waves by curvature of base of QT sediments and also top of basement
3. Surface waves produced by conversion of S-waves at the basin edges
4. Amplification of incoming surface waves

Log averaged SA values from 30 scenarios

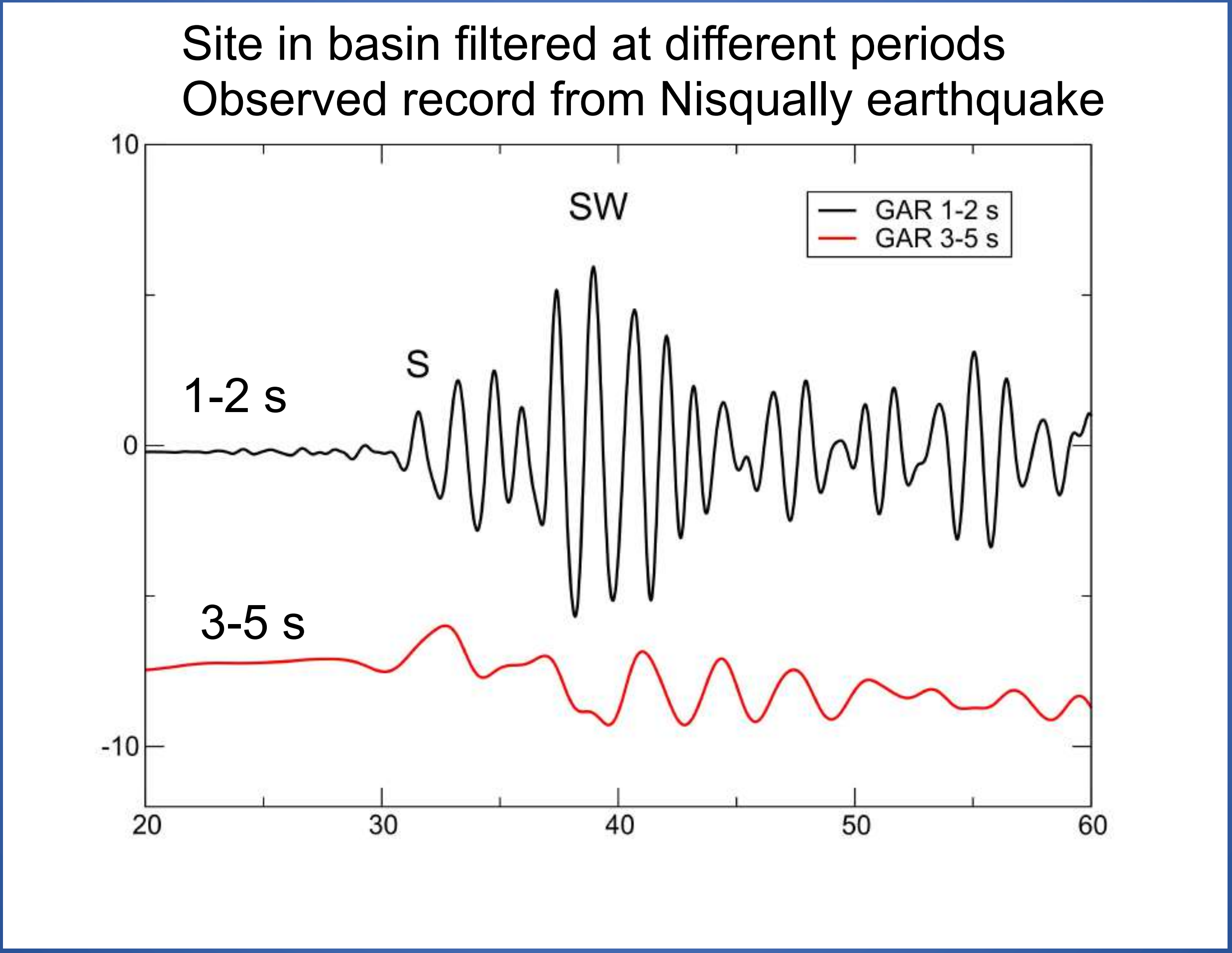


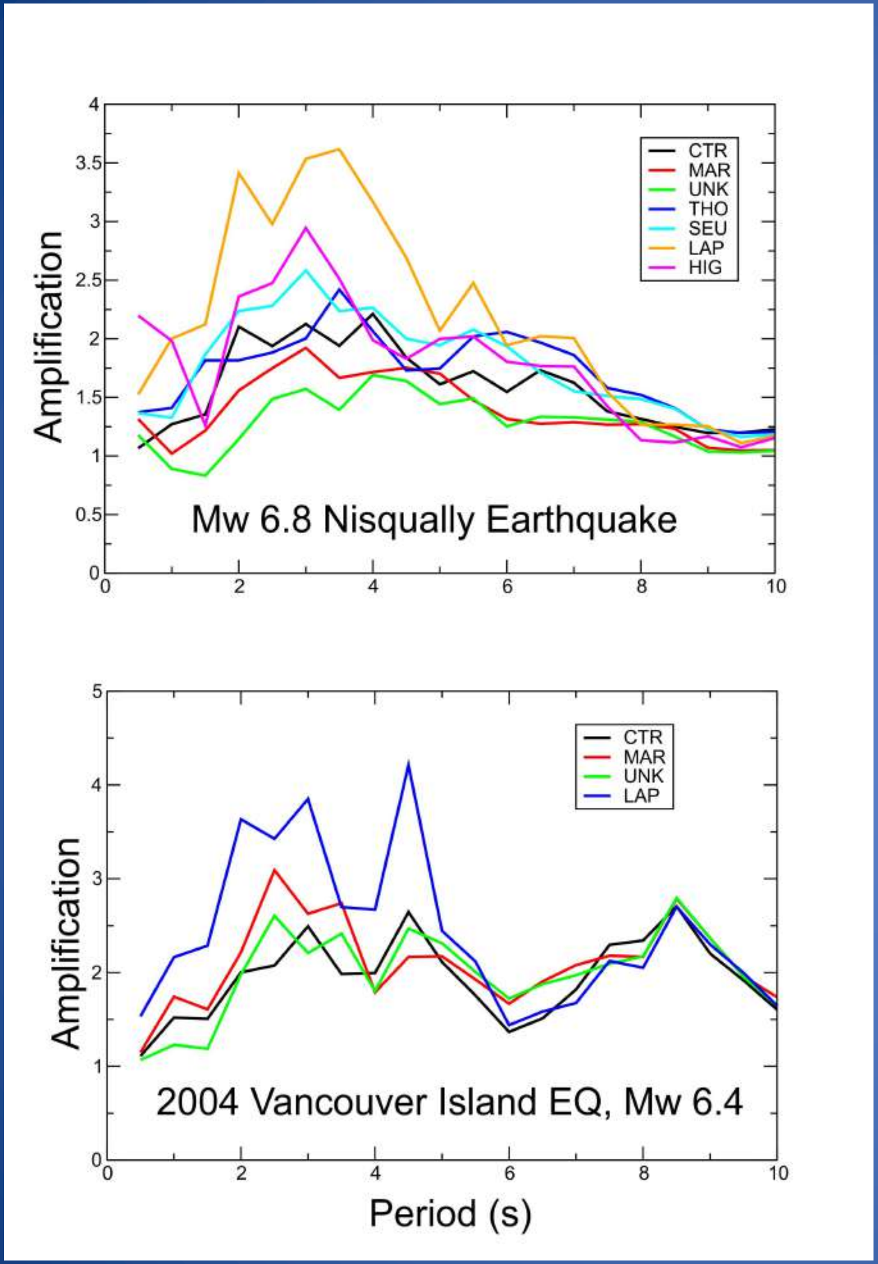


Observed Seismograms From Nisqually earthquake

Frankel et al. (2002)

Observed NS velocity records in Seattle Basin (Queen Anne) from 2001 M6.8 Nisqually earthquake, depth = 52 km.
Shows basin-edge generated surface wave (SW) has large amplitude at 1-2 s period, similar to M9 synthetics





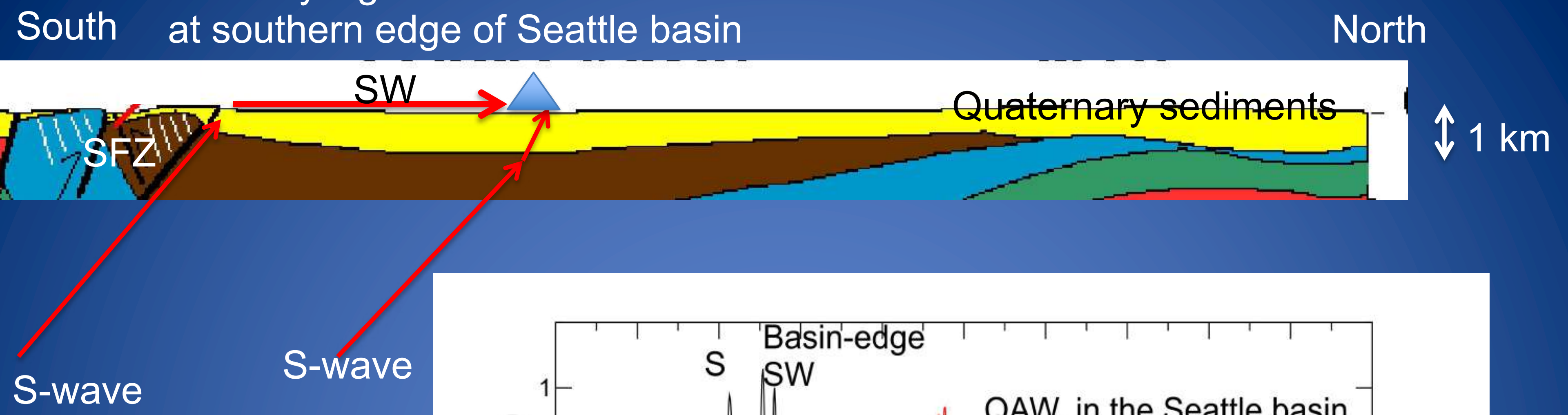
Observed amplification
of spectral response values
for stiff soil sites in the
Seattle basin

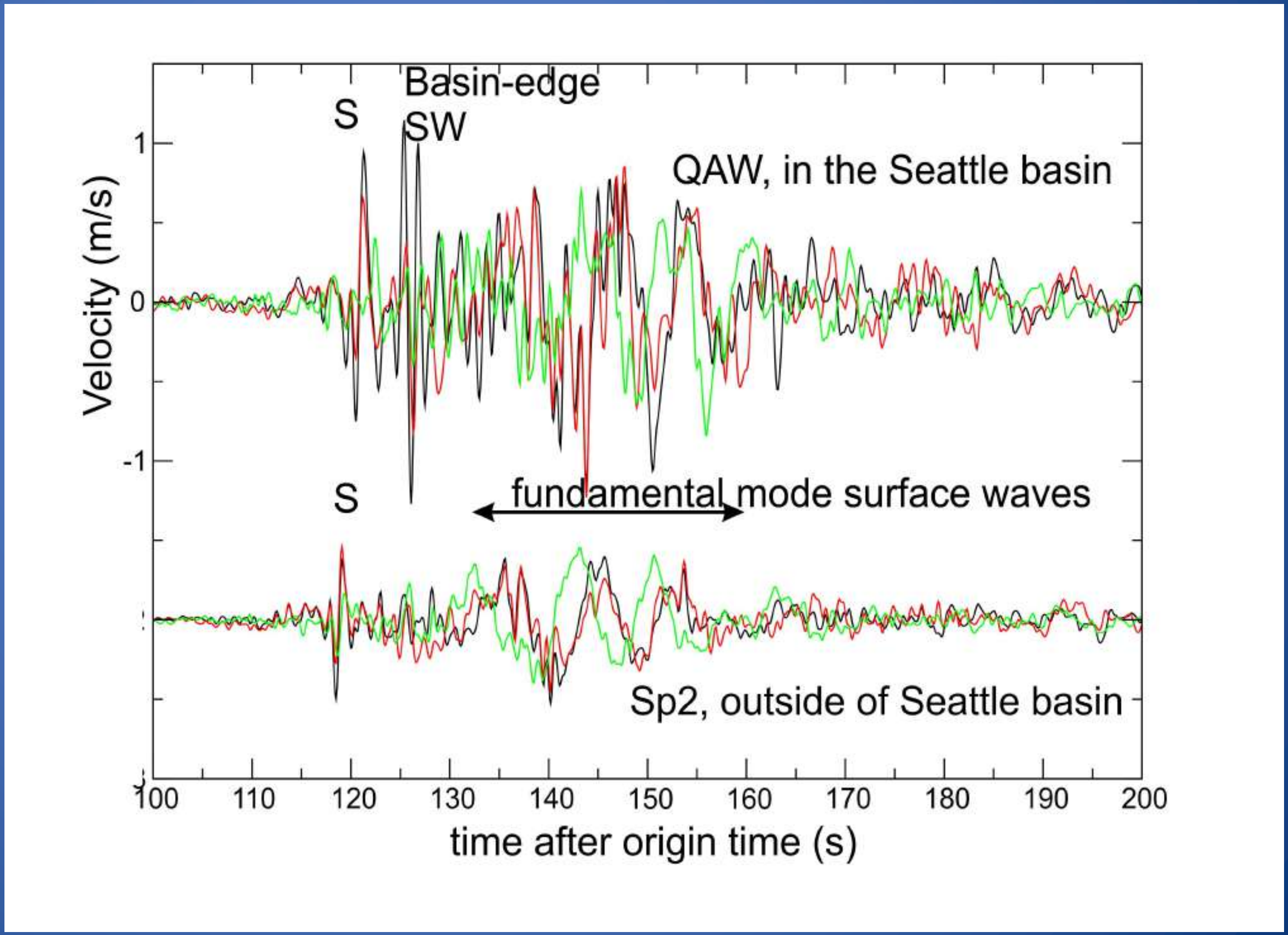
Referenced to site BRI with
thin soil over firm-rock
outside of basin (Vs30= 350 m/s)

These sites have similar Vs30
Values.

Note there is likely more
Amplification when referenced
to sites outside of Puget Lowland

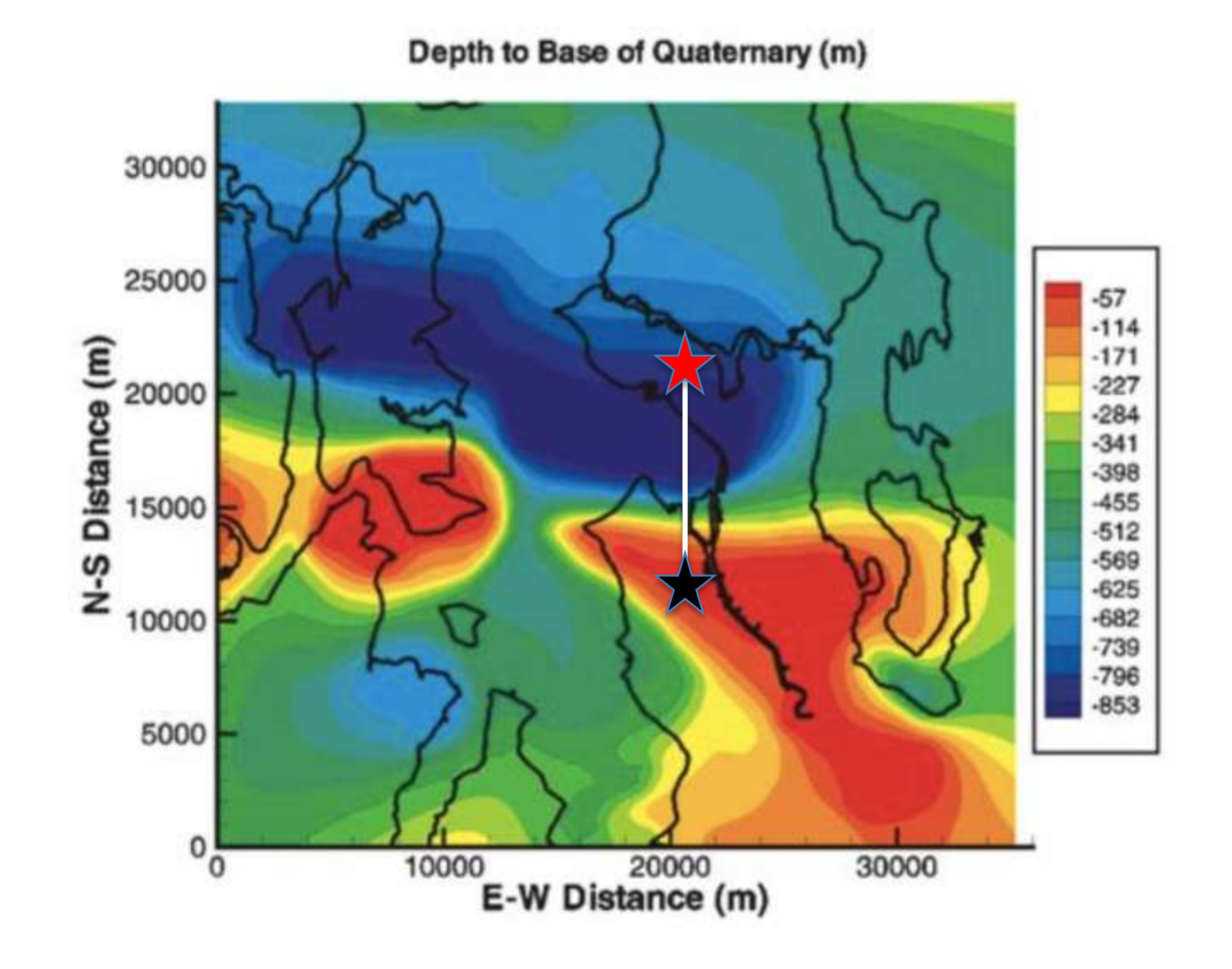
S to Rayleigh wave conversion at southern edge of Seattle basin





Synthetics from 3D simulation of Cascadia M9 earthquake

Black : NS comp
Red: EW comp
Green: vert. comp.

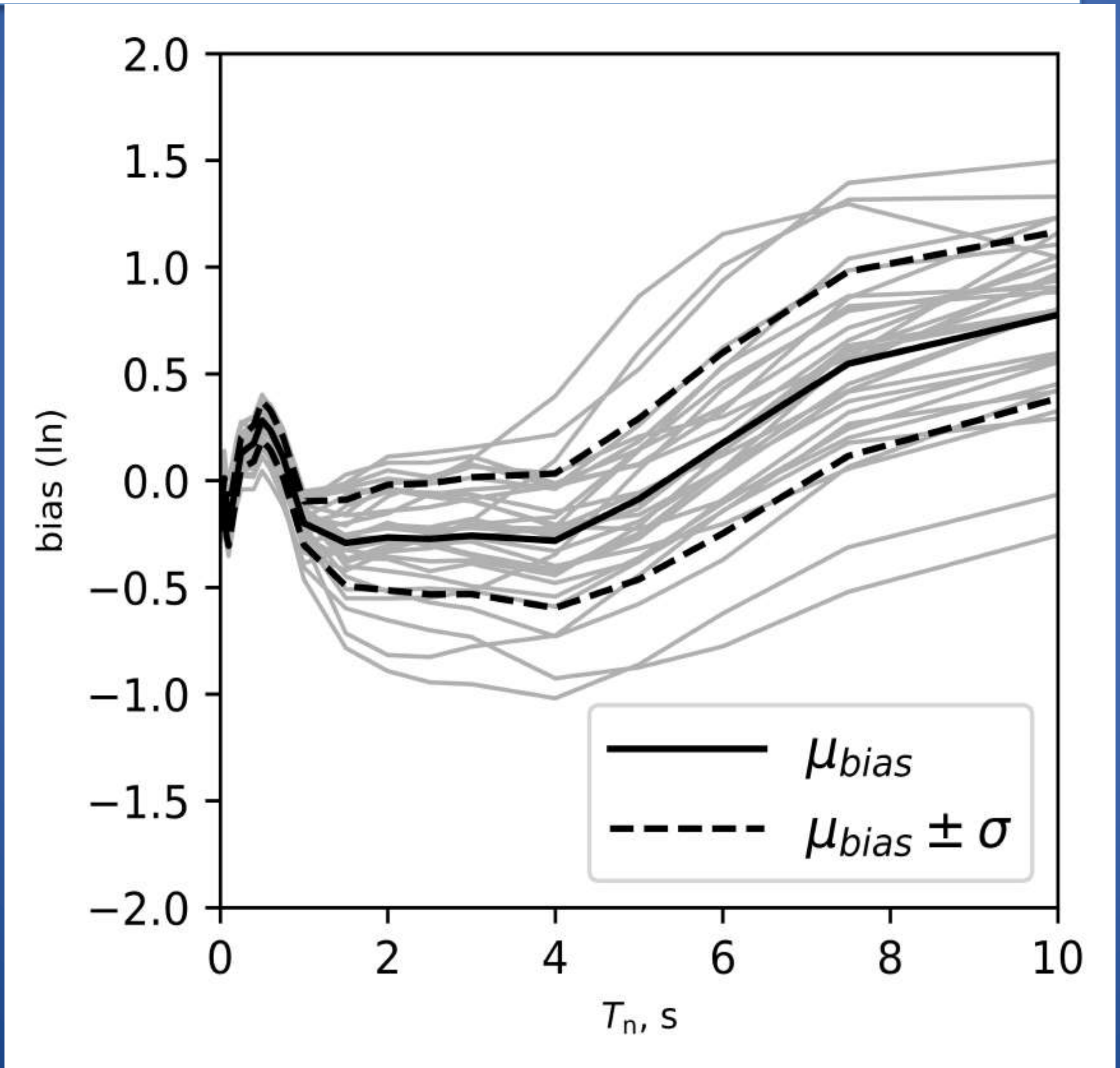


Model of Depth to top of Bedrock (m) for Seattle basin

From Stephenson et al. (2017) 3D Velocity Model; Based on Johnson et al. (1999)

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