Use of 3D Ground-Motion Simulations for Seismic Hazard Assessment in the Pacific Northwest

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Committee on Seismology and Geodynamics, Nov. 14, 2018

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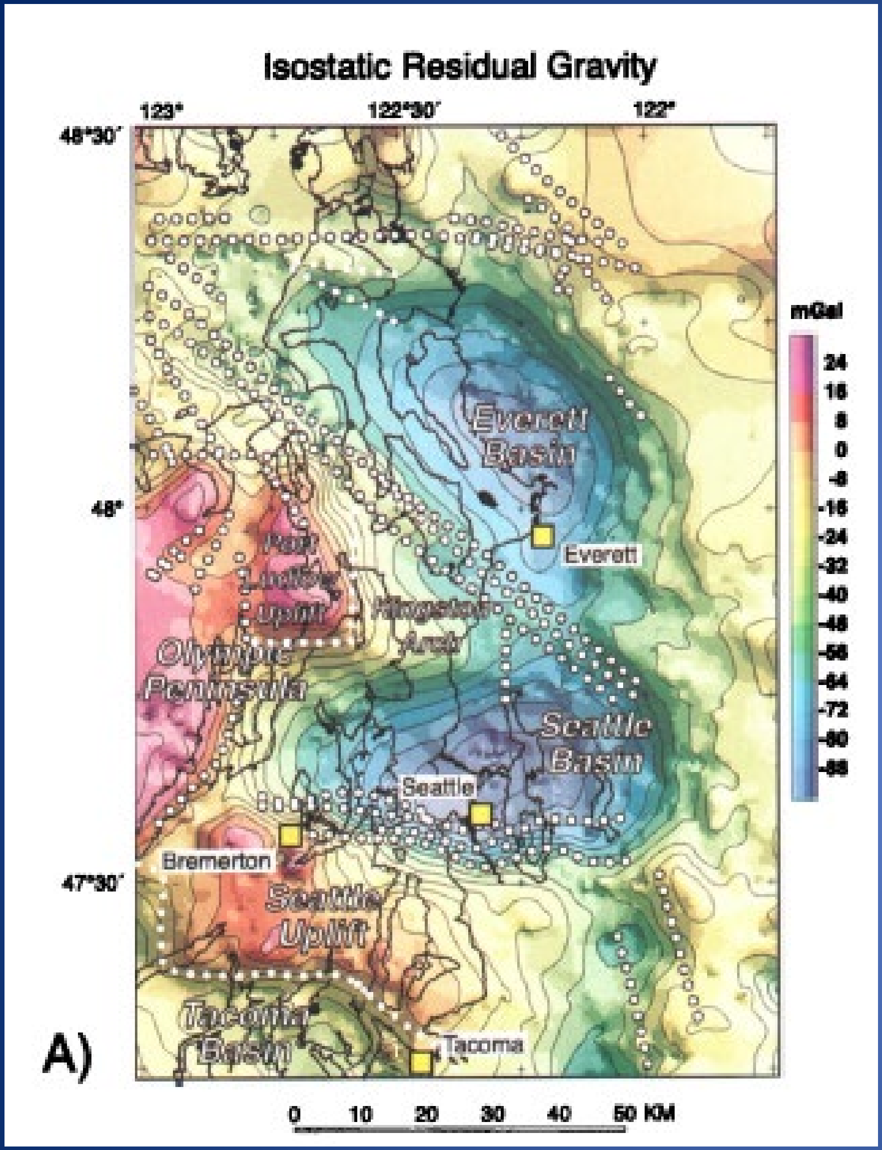
Need 3D ground-motion simulations for seismic hazard assessment to accurately quantify amplification from deep sedimentary basins

- Tall buildings ≥ 10 stories are affected by amplification and increased duration of shaking at 1-10 s caused by deep sedimentary basins. Cities are building upwards. In the past, building codes did not include deep basin amplification
- 20 story building has approx natural period of 2 s.; 50 story= 5 sec
- Sedimentary basin effects: It's more than just S-wave amplification from shallow soils
- Edges of sedimentary basins produce basin surface waves and S-wave focusing and affect damage patterns. This has been observed for Nisqually, Kobe, Northridge, and Christchurch earthquakes, and others
- 3D simulations also account for rupture directivity effects and complex path effects between source and site

Urban seismic hazard maps

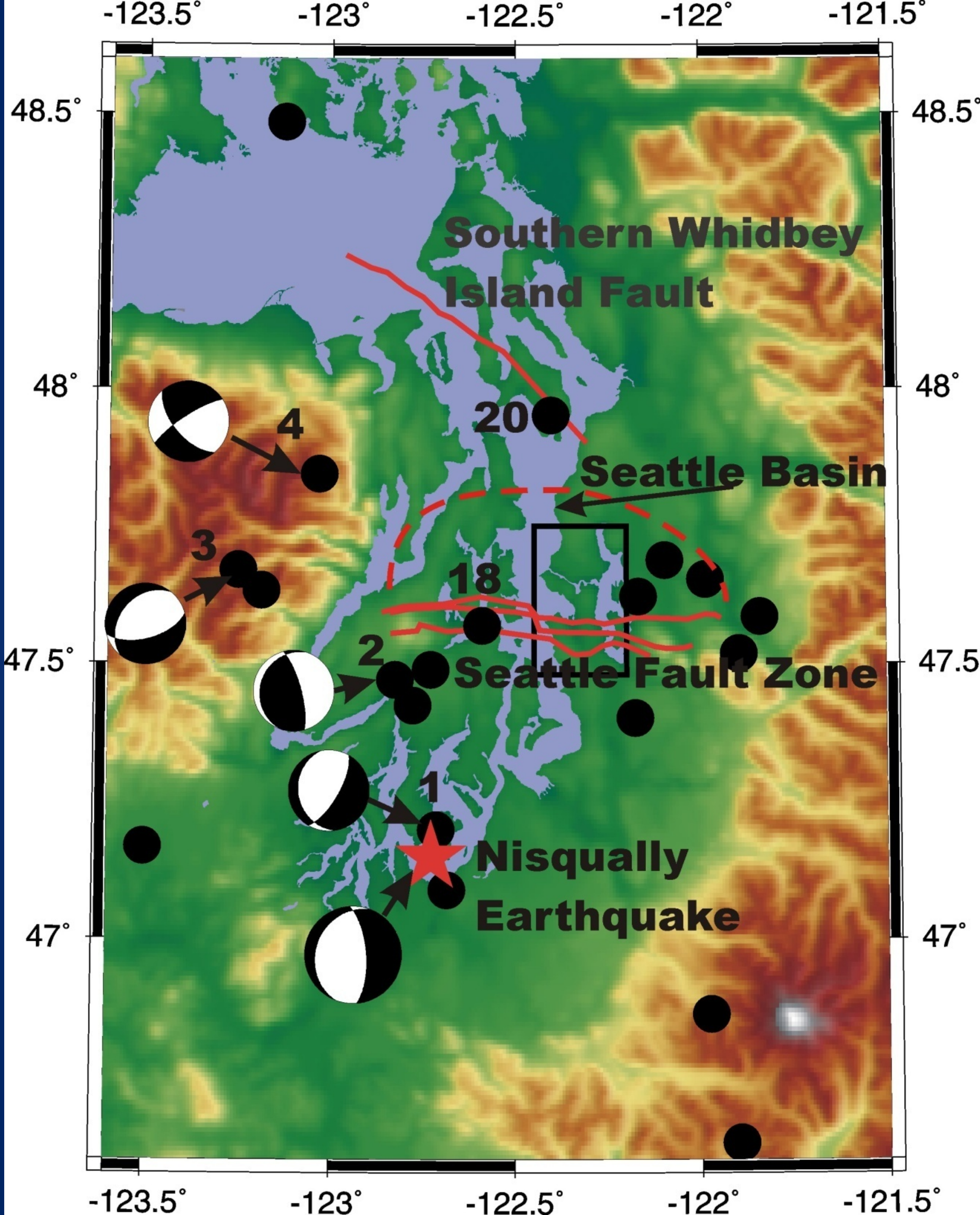
- Account for local site response (may be nonlinear), sedimentary basin effects, rupture directivity
- High level of spatial detail, depending on 3D model of seismic velocities in urban areas
- Useful for building and bridge design, emergency preparedness, urban planning



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)



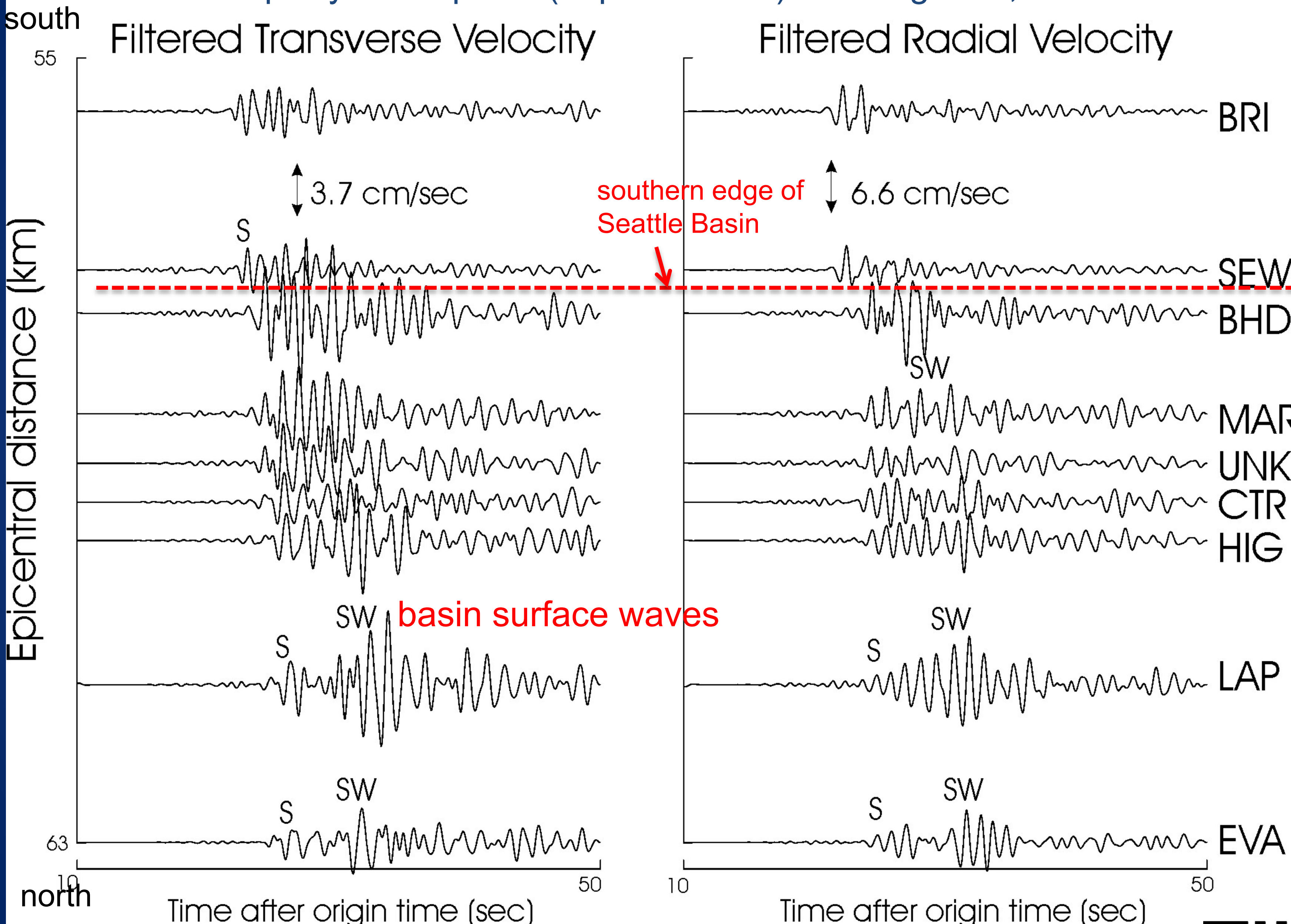
Validated 3D model for Seattle basin by comparing observed basin amplification with 3D simulations for 4 earthquakes and by modeling waveforms of a M4.8 event and the M6.8 Nisqually earthquake

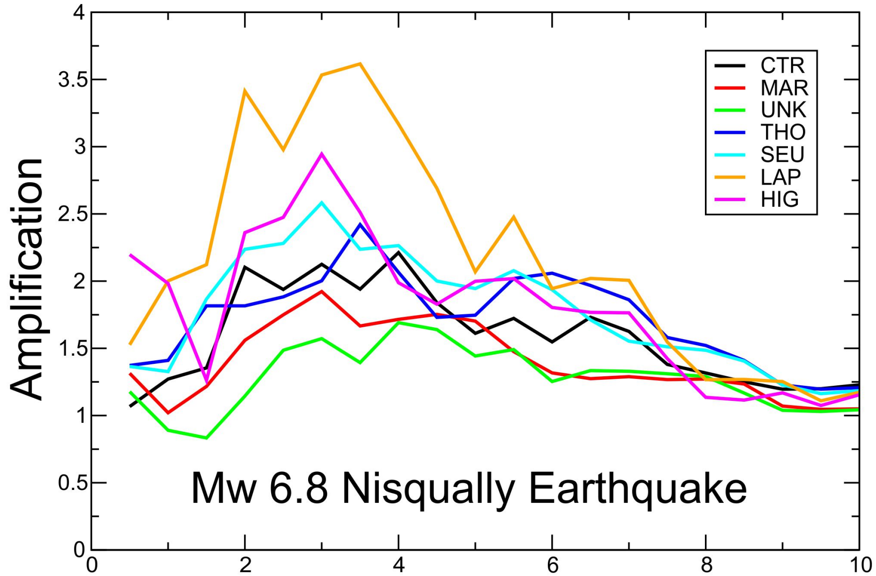
(Frankel et al., 2009)

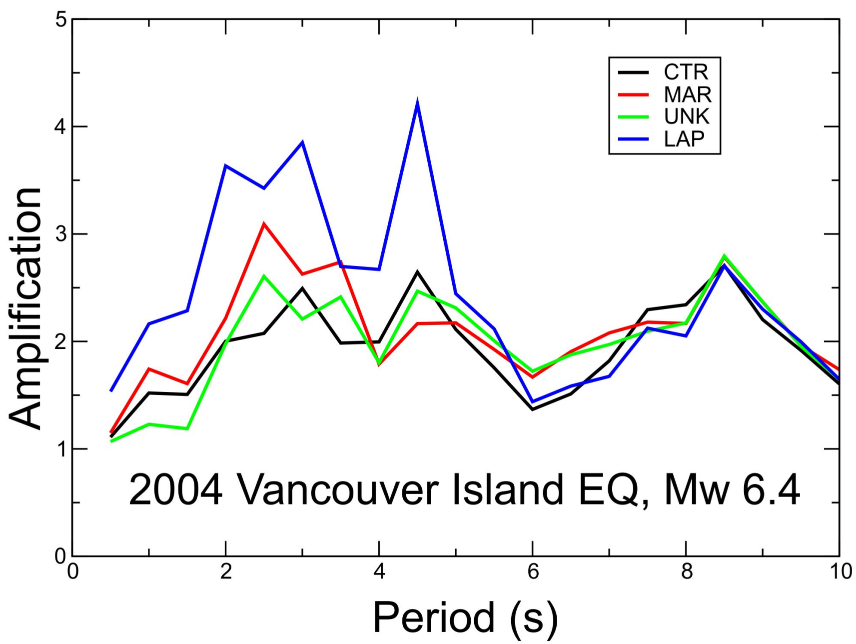
3D Simulation of M6.5 Earthquake on the Seattle Fault

From Frankel and Stephenson (2000)

M6.8 Nisqually Earthquake (depth= 52 km) seismograms; 0.67- 1.33 Hz





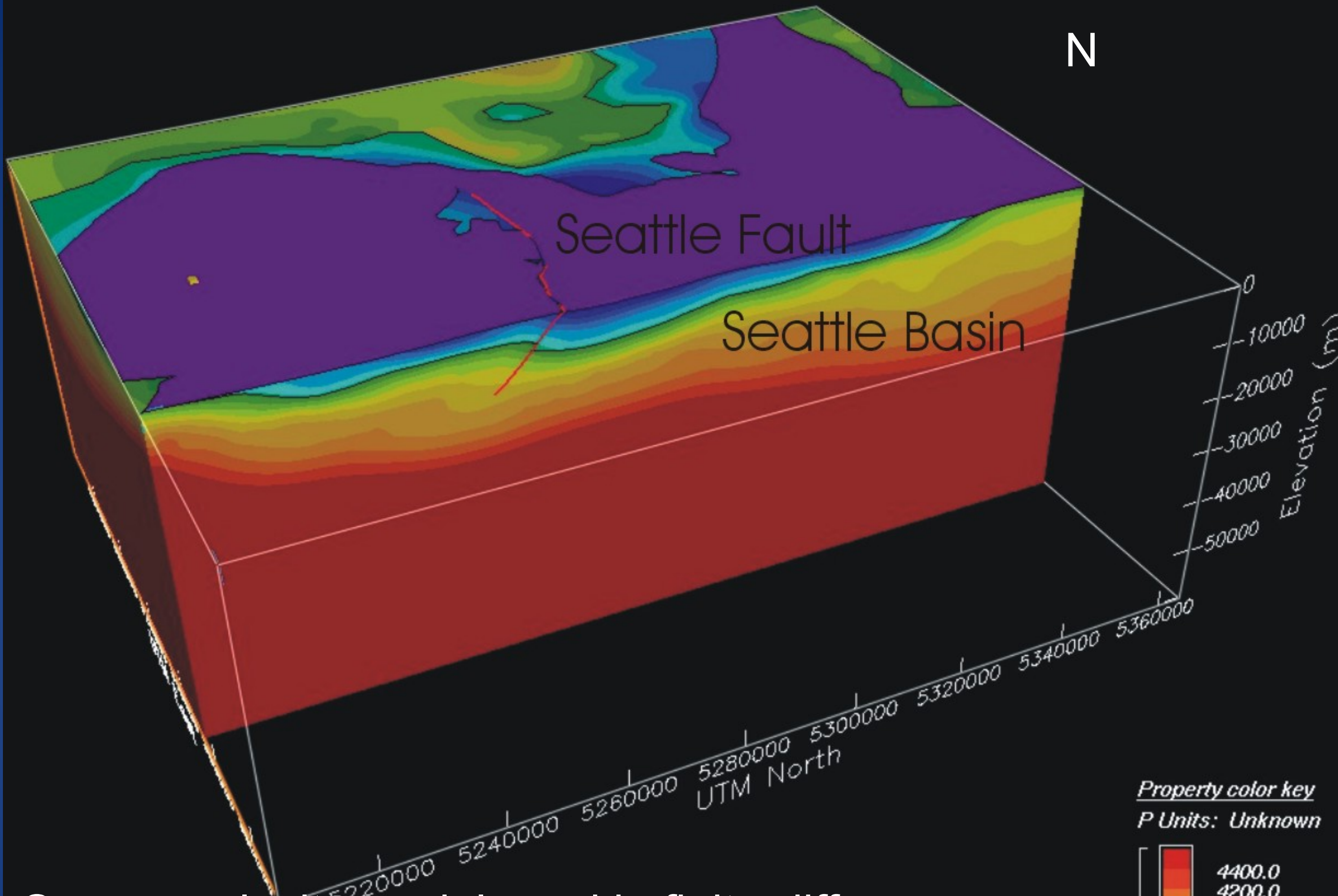


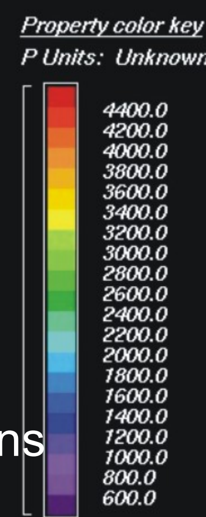
Observed amplification
of spectral response values
for stiff soil sites (C-class) in the
Seattle basin

Referenced to site with
thin soil over firm-rock
outside of basin

The basin sites and
reference site have comparable
Vs30 values; ref site Vs30= 350 m/s

Seattle basin amplification
will also affect ground motions
from Cascadia great earthquakes

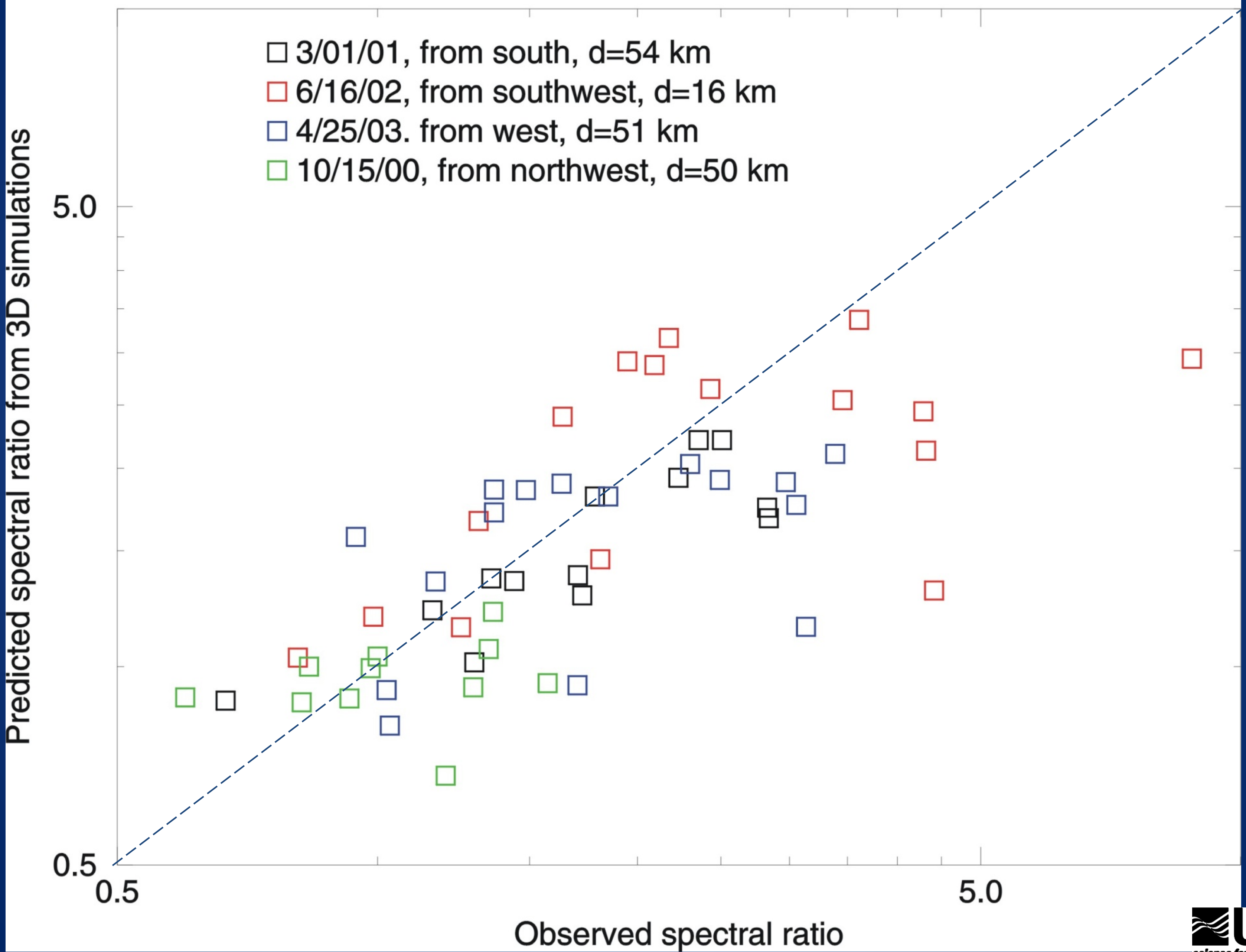




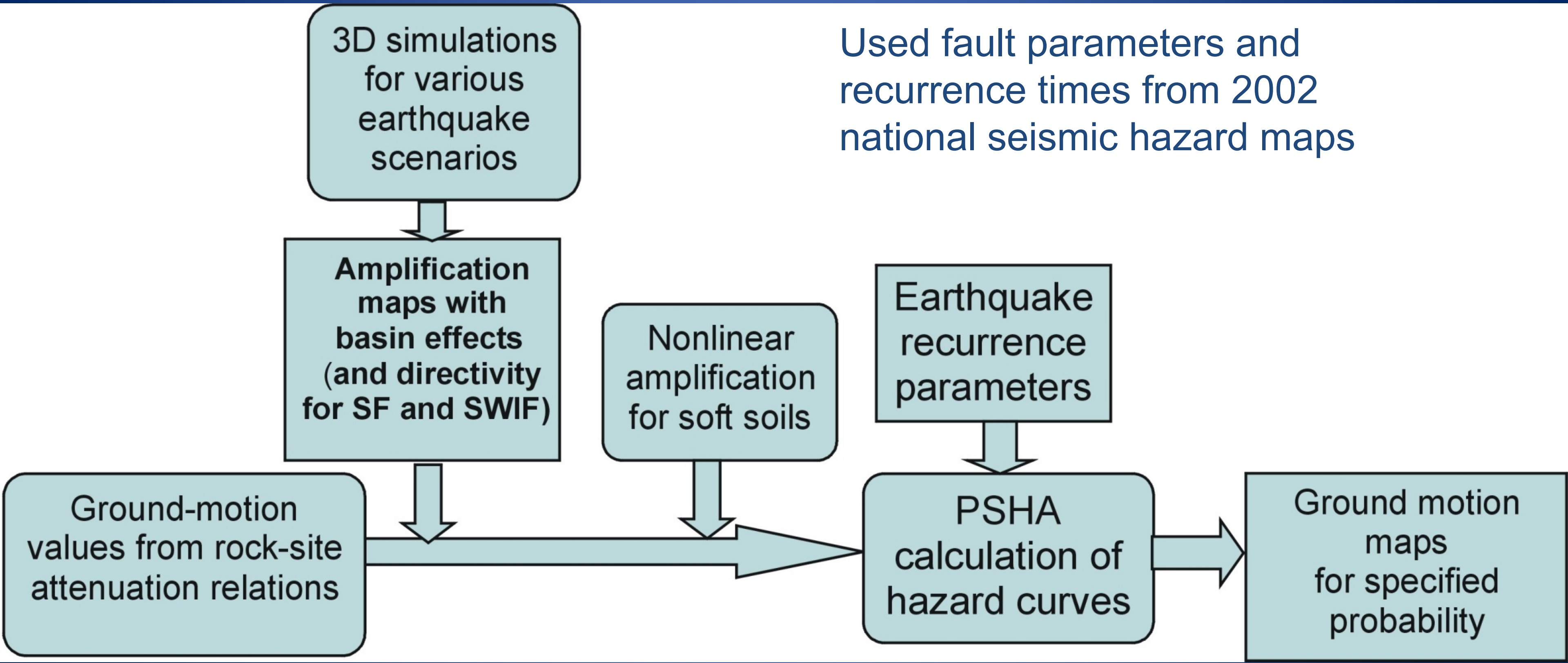
S-wave velocity model used in finite-difference simulations (2007-2009) .
Model developed by Bill Stephenson (2007); based on P-wave tomography , borehole, and seismic reflection data; very similar to Stephenson et al. (2017) model used in M9 simulations

Predicted and Observed Spectral Ratios wrt Rock Sites

1 Hz   Stiff-soil sites



Procedure to Make Seattle Urban Seismic Hazard Maps (2007)
Combine 3D simulations and earthquake recurrence parameters



Used fault parameters and recurrence times from 2002 national seismic hazard maps

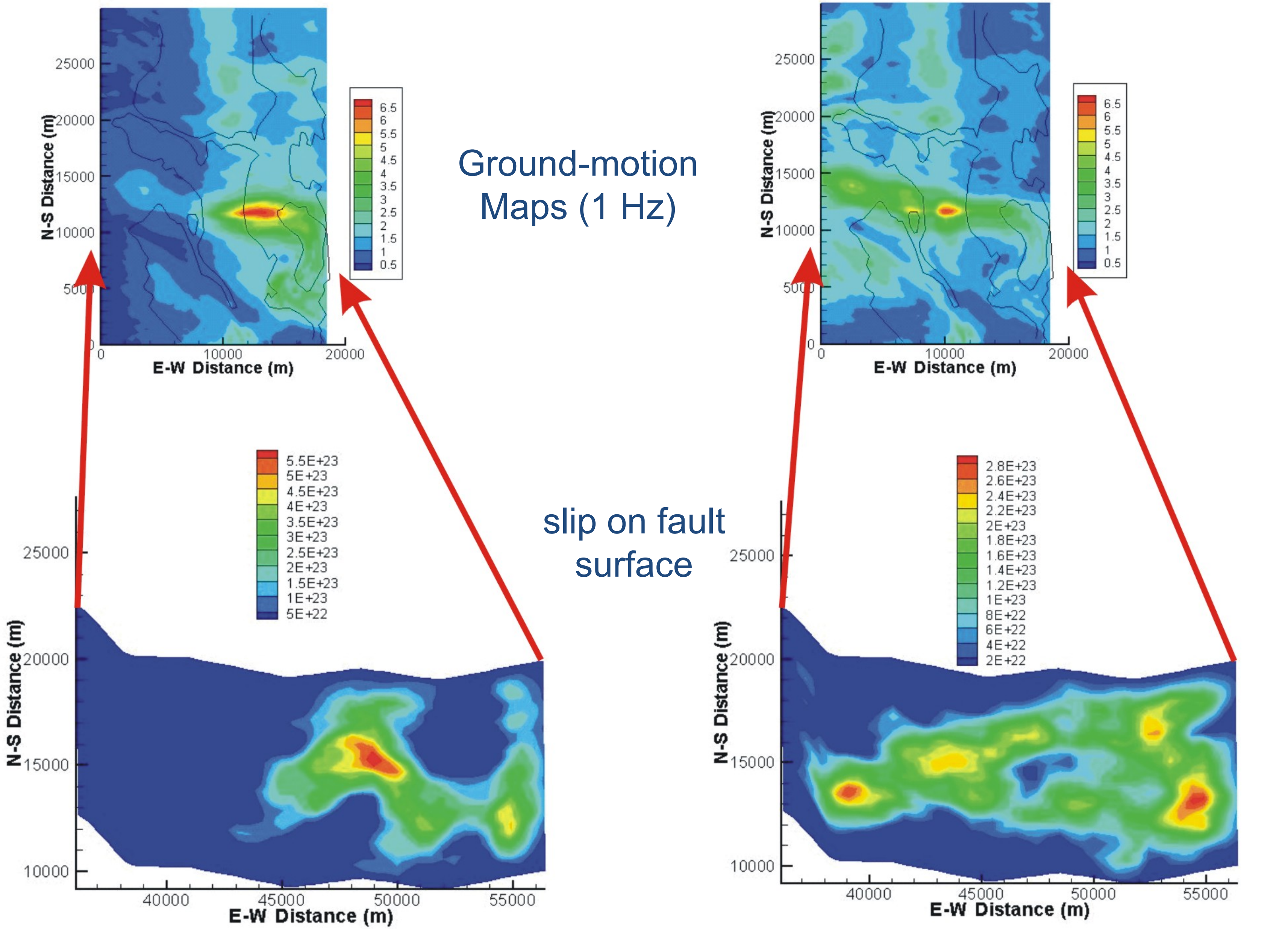
PSHA= Probabilistic Seismic Hazard Assessment

From Frankel et al. (2007)

541 3D finite-difference simulations used in Seattle urban seismic hazard maps

- 458 simulations for earthquakes in Seattle fault zone (M6.6-M7.2)
- 9 simulations for earthquakes on Southern Whidbey Island fault
- 10 simulations for point sources on Cascadia subduction zone
- 48 simulations for shallow earthquakes: 8 azimuths, 3 distances and two depths (10 and 15 km)
- 16 simulations for deep earthquakes (50 km depth): 8 azimuths and 2 distances
- Calculated synthetics at 7236 sites, with 280m spacing
- Used about 7.8 million synthetic seismograms
- 3D finite difference code written by Pengcheng Liu

Two scenarios for Seattle fault earthquakes M6.6



Used kinematic description of rupture on fault surface

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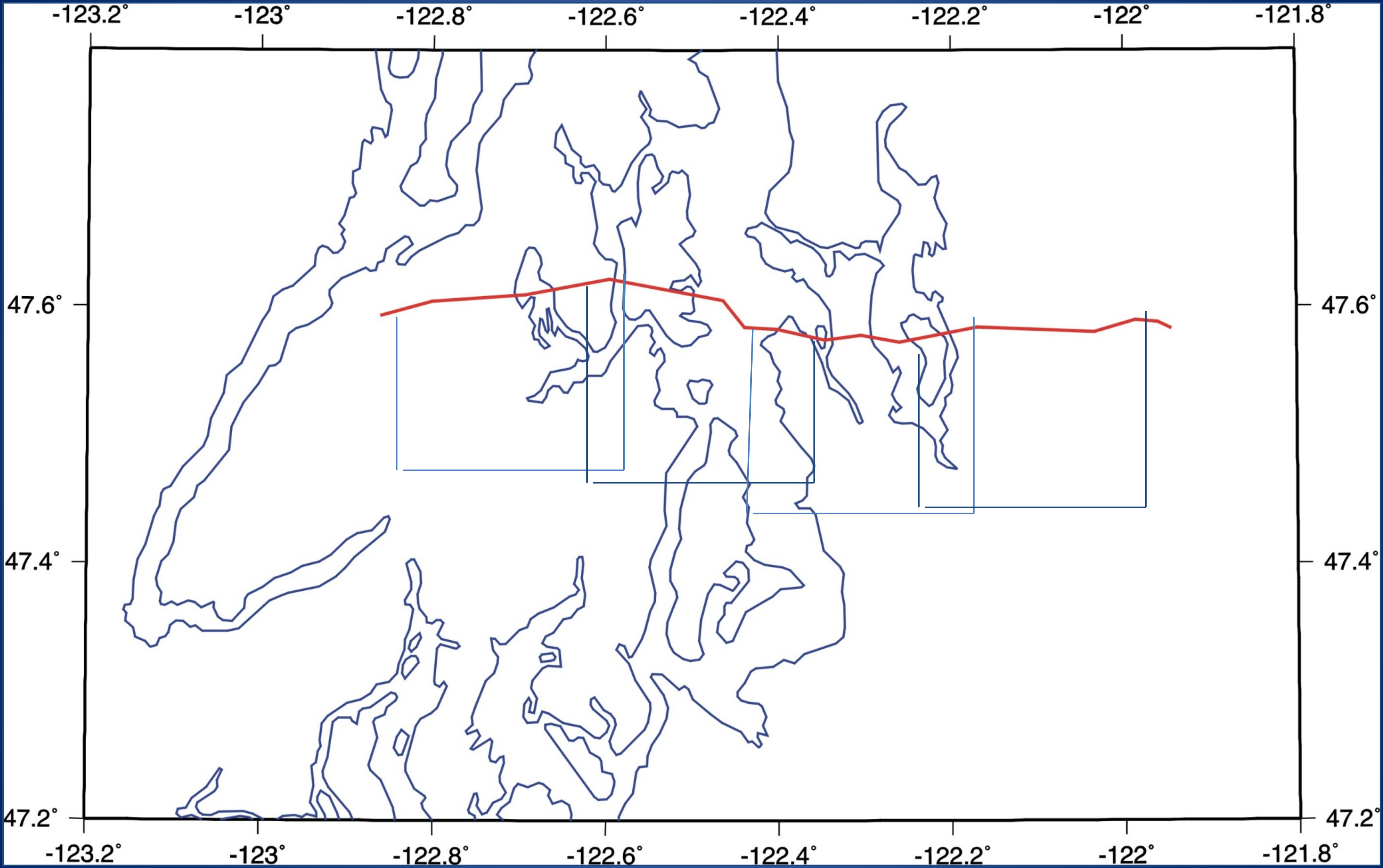
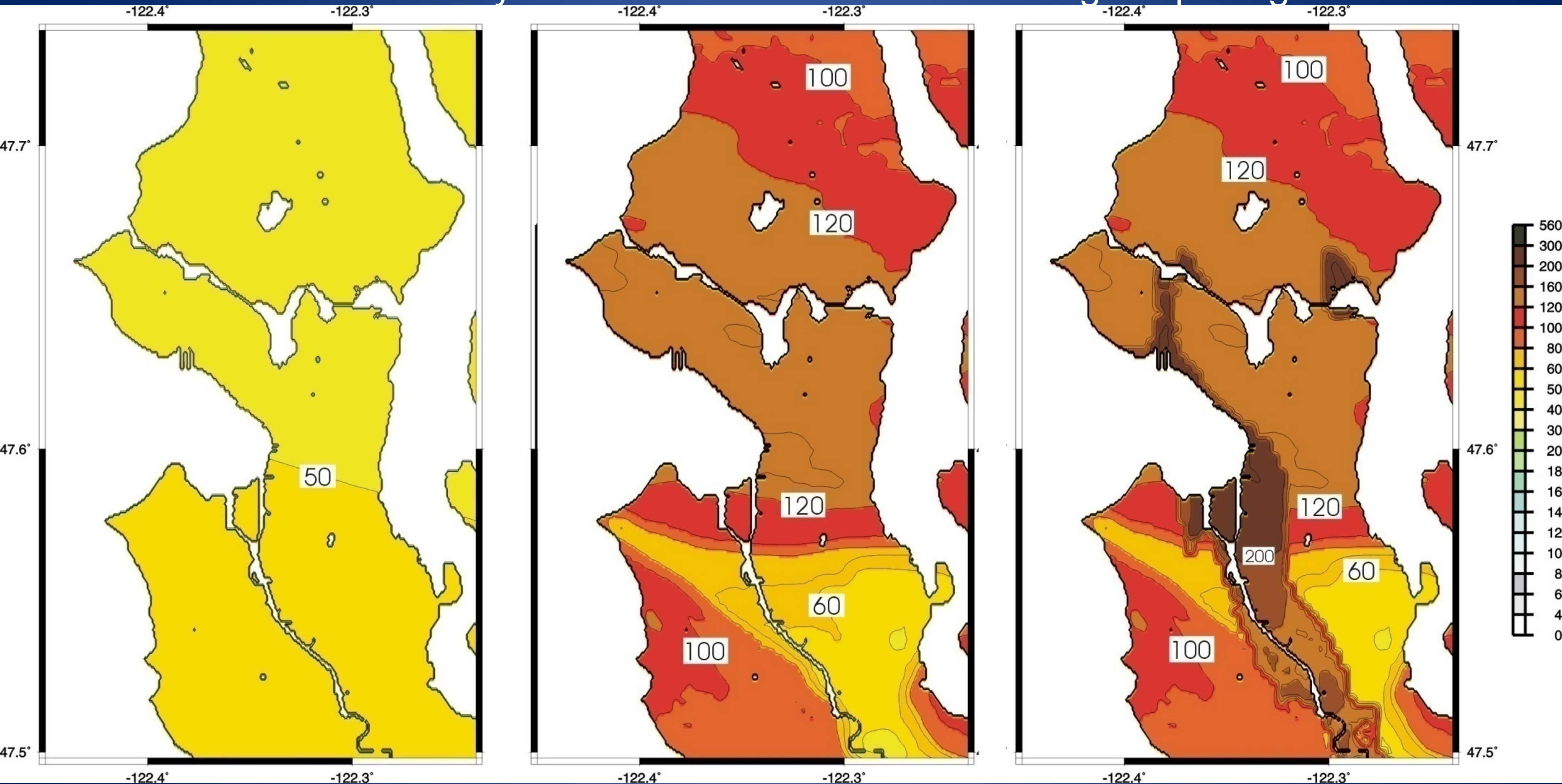
Float rupture zones along Seattle fault traces, do nine 3D simulations for each rupture zone (3 slip distributions, 3 hypocenters)



37 rupture zones M6.6-M7.2 on each of three fault traces, two dips

1 Hz Spectral Acceleration (%g)
with 2% chance of being exceeded in 50 years
Based on synthetics at 7200 sites with 280m grid spacing



one of 2002 national seismic hazard maps; rock site condition

Using 3D simulations with basin effects and directivity

Using 3D simulations and nonlinear ampl. for fill/alluvium

From Frankel et al. (2007)

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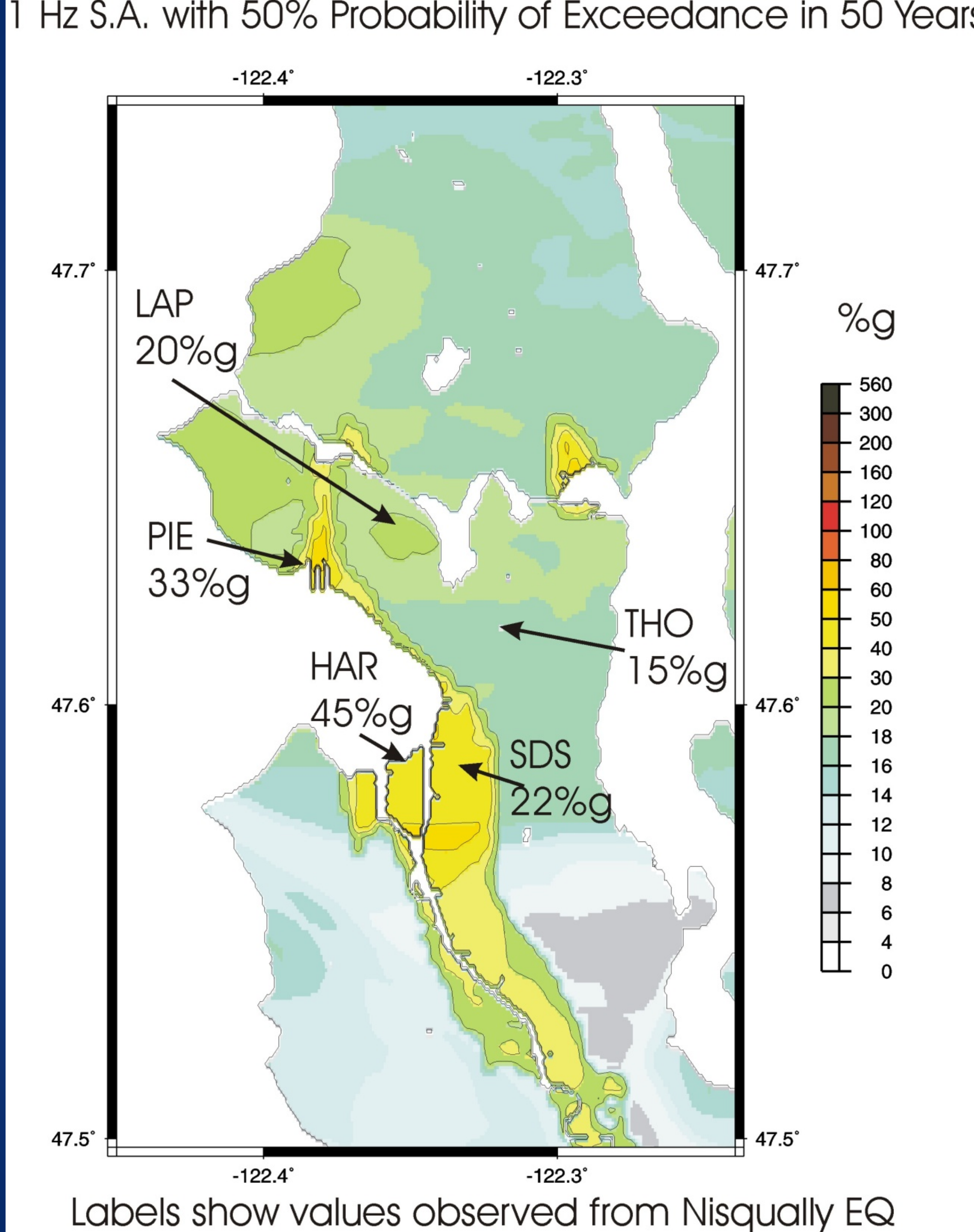
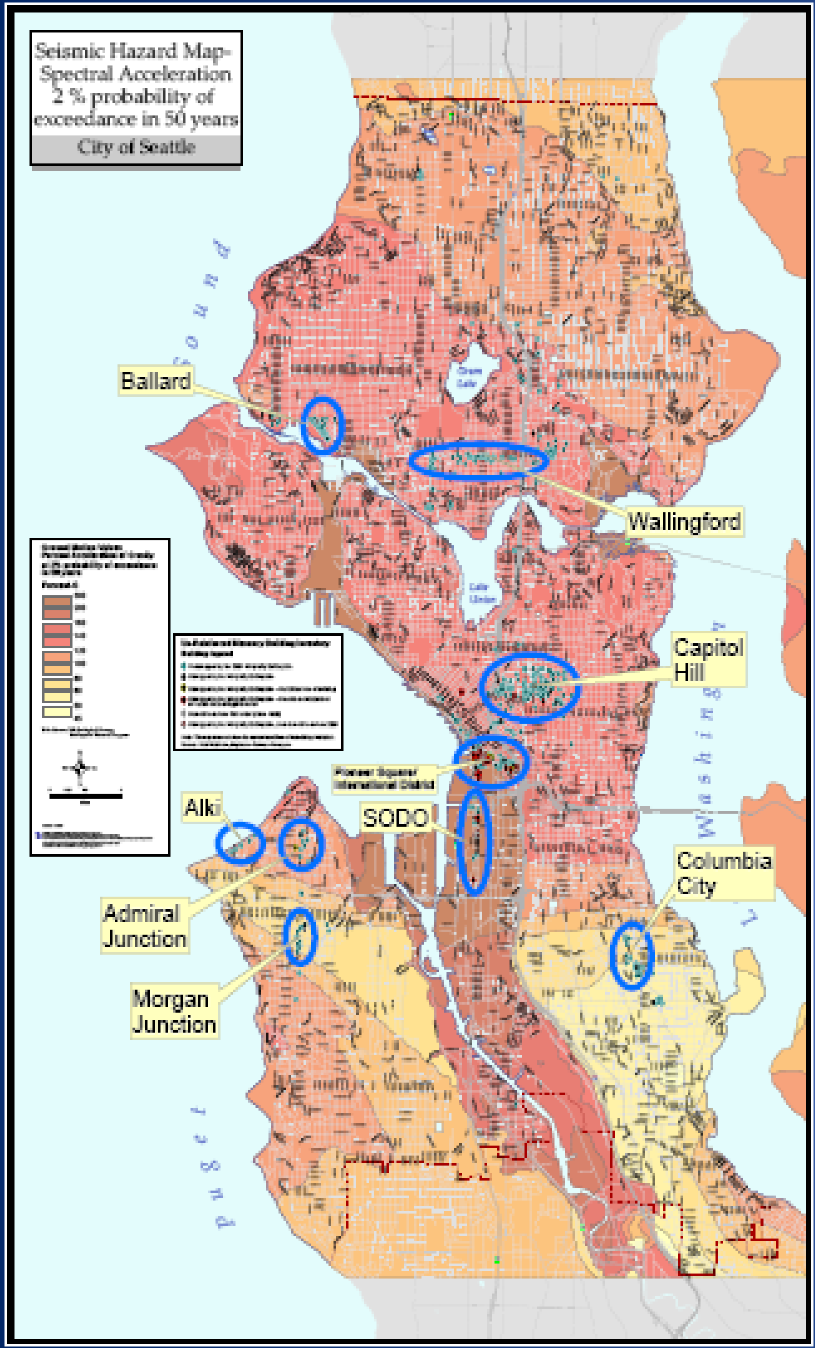


Test of hazard maps
At high probability

Map values similar to those observed during M6.8 Nisqually earthquake In 2001.
Deep M6.5-7.0 events have about 30 year recurrence time (1949, 1965, 2001)



Unreinforced Masonry Building locations in Seattle plotted on USGS urban seismic hazard map showing spectral accelerations with 2% probability of exceedance in 50 years.

Urban seismic hazard maps useful for screening purposes and as check for site-specific studies; most site-specific studies do not consider basin effects or directivity effects

Need to get basin amp terms into the building code for tall buildings

Map from City of Seattle *Unreinforced Masonry Building Seismic Hazards Study, 2007*

Synthetic seismograms for Cascadia magnitude 9 earthquakes from 3D simulations, using a range of rupture parameters

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

[1] U.S. Geological Survey

[2] University of Washington

[3] University of Southern California

USGS estimates 10-14% chance of Cascadia M9 earthquake in next 50 years based on paleoseismology

The M9 Project: University of Washington funded for 6 years by NSF

USGS/UW has produced a large set of broadband (0-10 Hz) synthetic seismograms for M9 Cascadia earthquakes; we have posted 4.5 million synthetic seismograms on DesignSafe website

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)

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 (Bostrom, Abramson)

Testing of Earthquake Early Warning (Vidale, Bodin)

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

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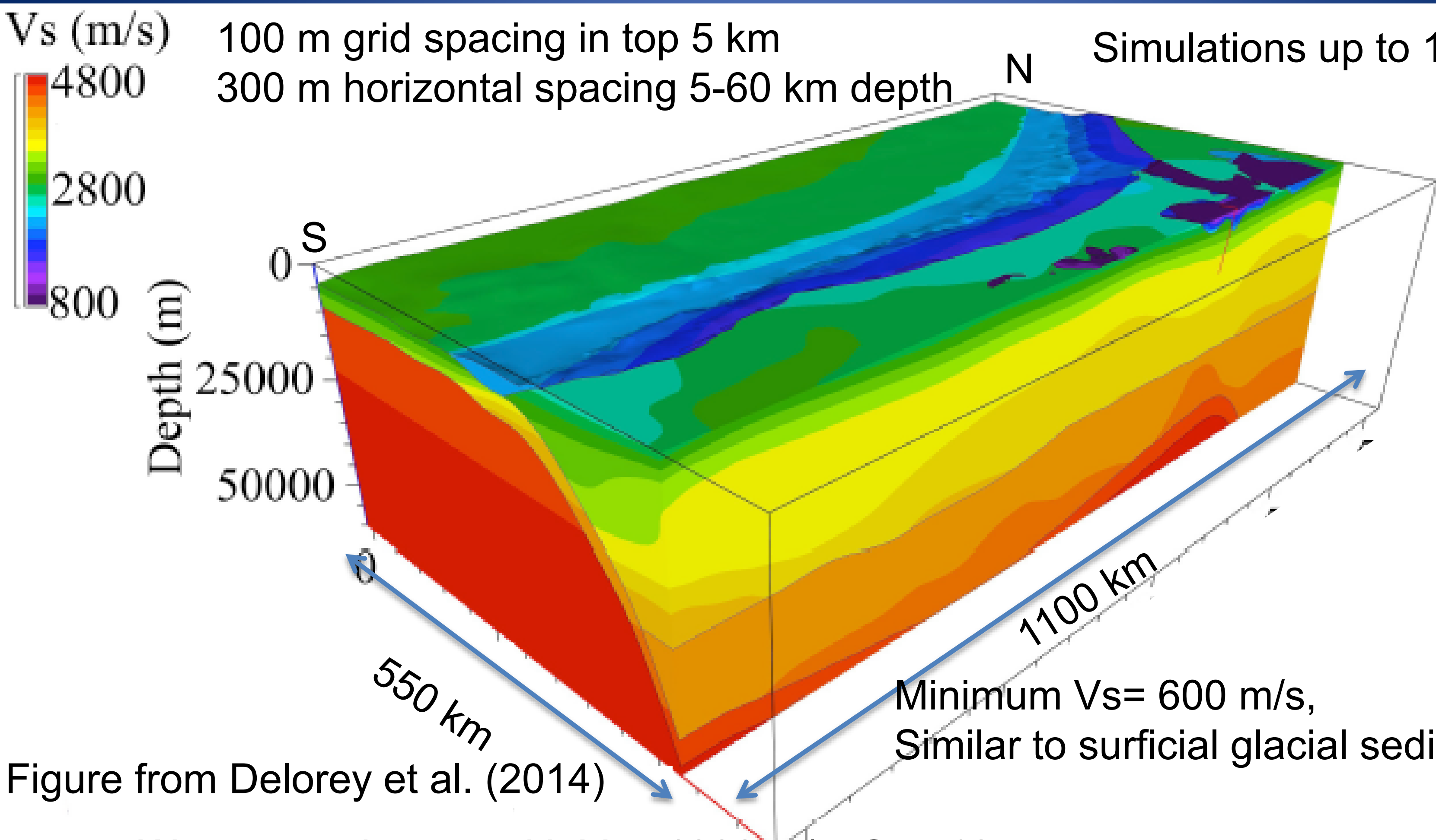
Bill Stephenson developed the 3D velocity model for Cascadia. Used seismic refraction/refraction data and tomography for Seattle basin, Moschetti et al. (2010) crustal tomography, used smoothed version of McCrory et al. (2012) plate interface

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

Simulations up to 1 Hz



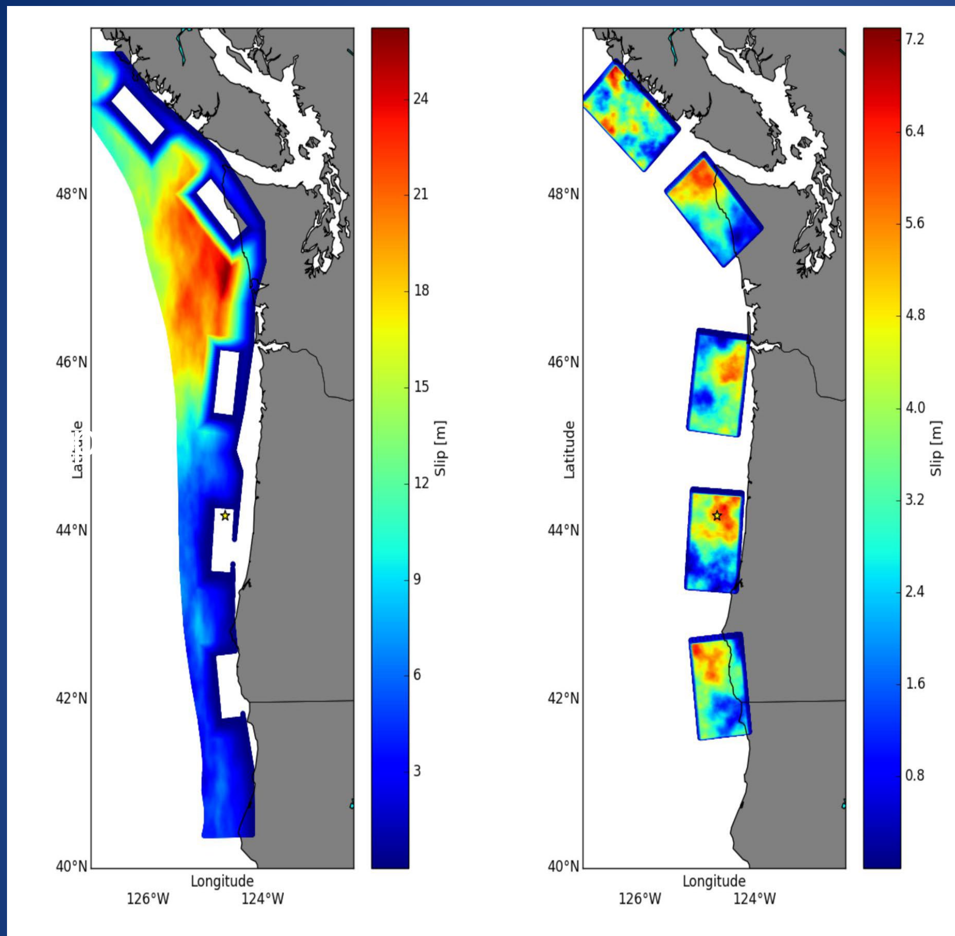
Minimum Vs= 600 m/s,
Similar to surficial glacial sediments

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

Background slip

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



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)

Run 21

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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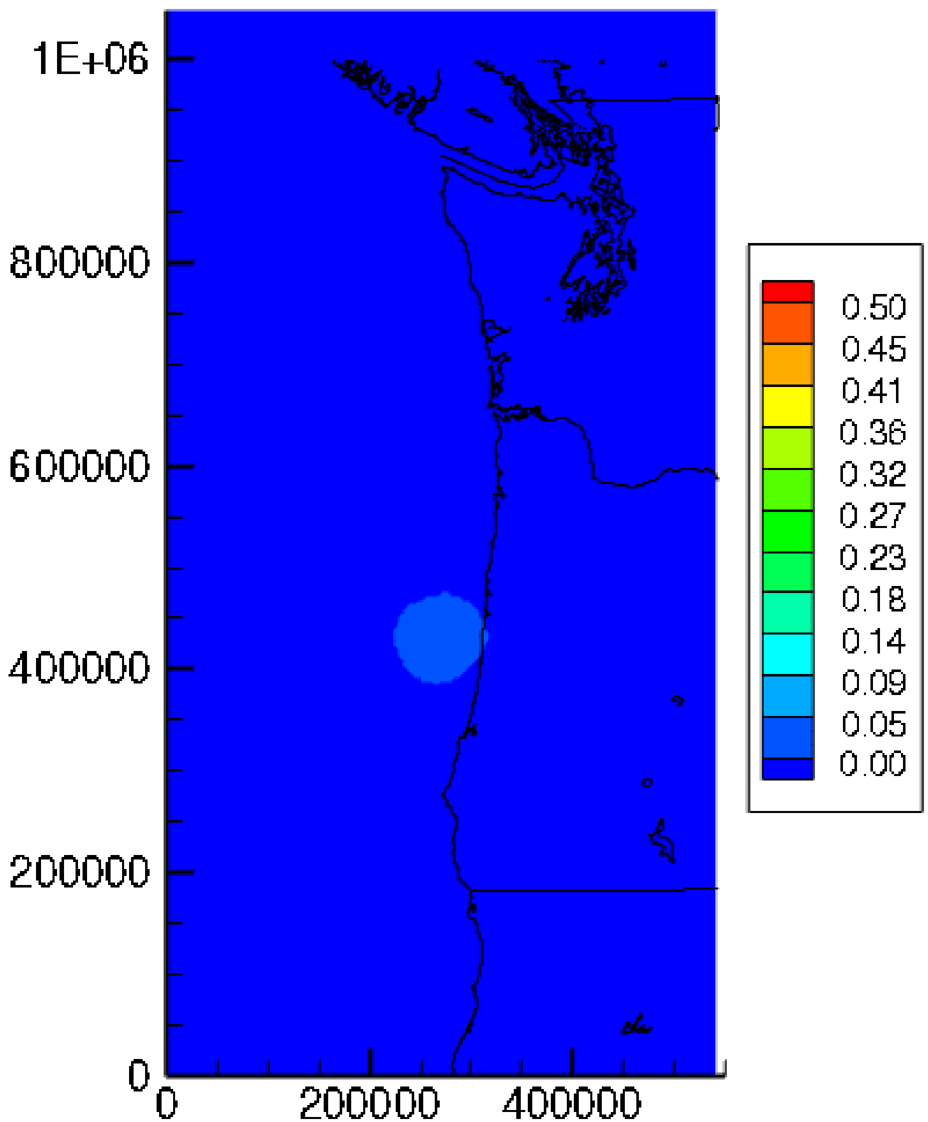

Animation of simulated ground motions for run 21

300 second movie duration

Shows magnitude of horizontal velocity vector (m/s)

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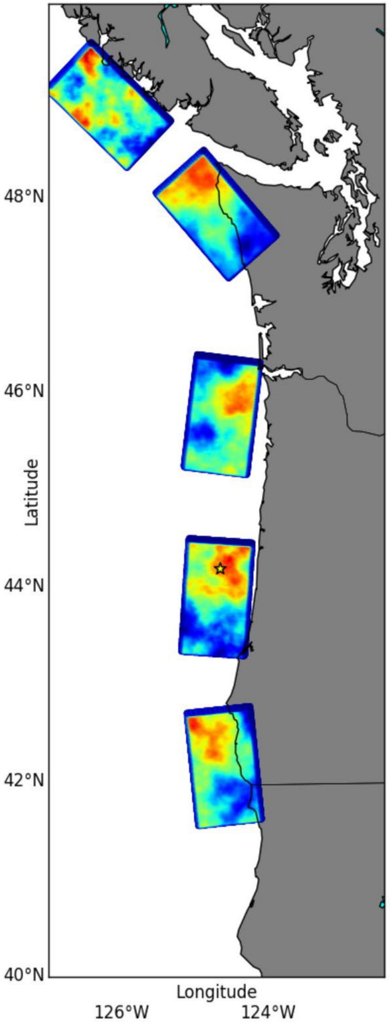
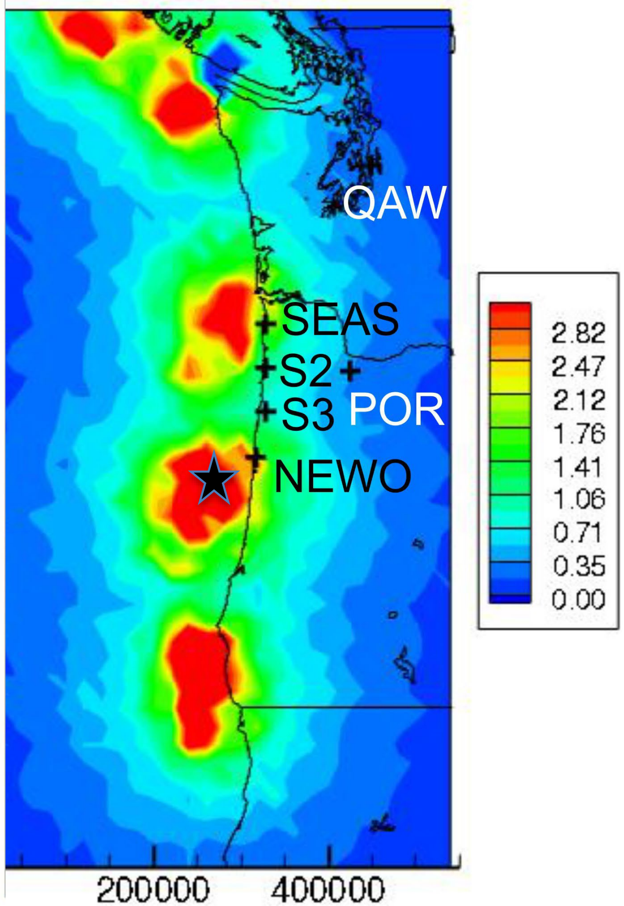
Example from Run 21

Sub-event slip

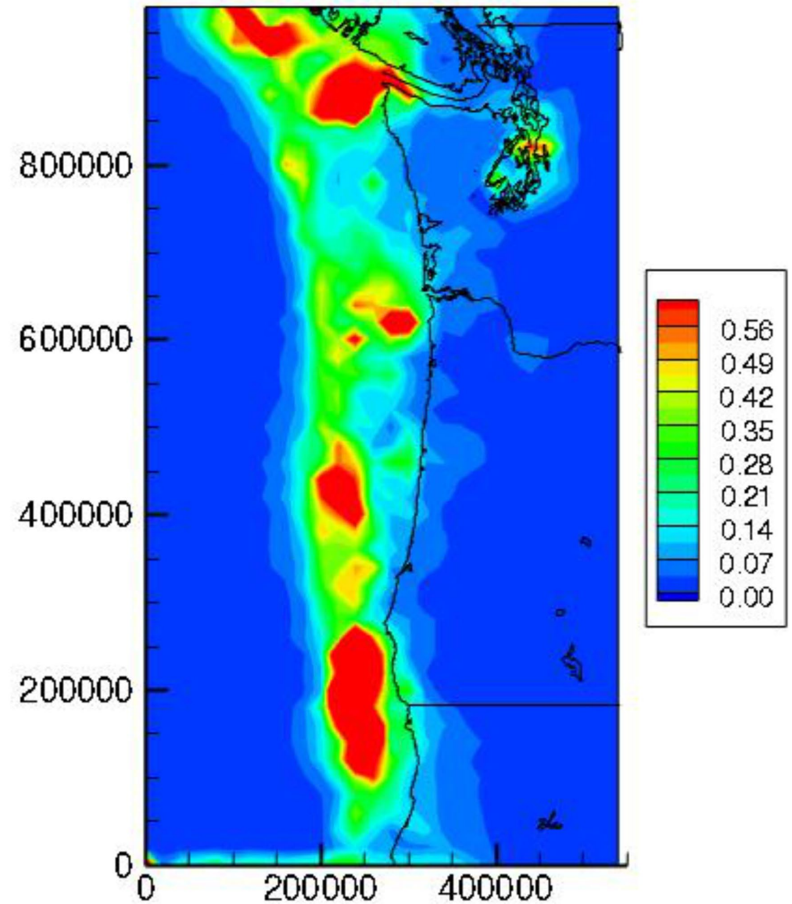


0.2 s SA (g)



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= 600 m/s

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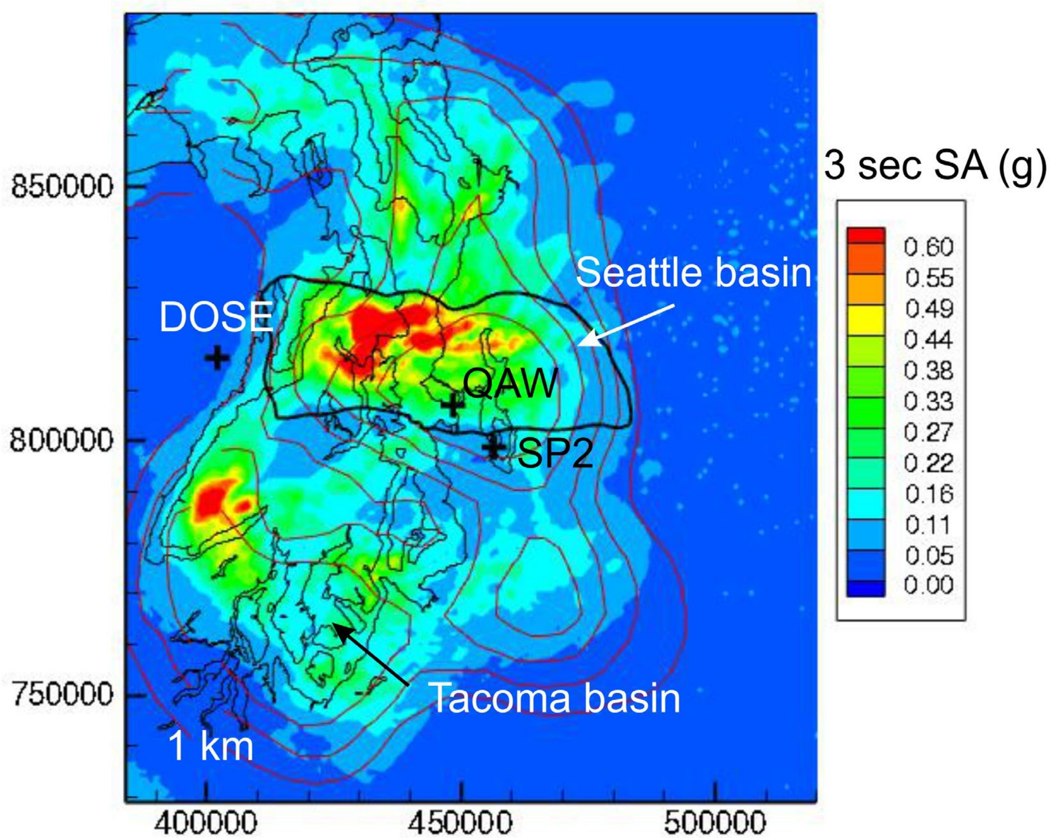
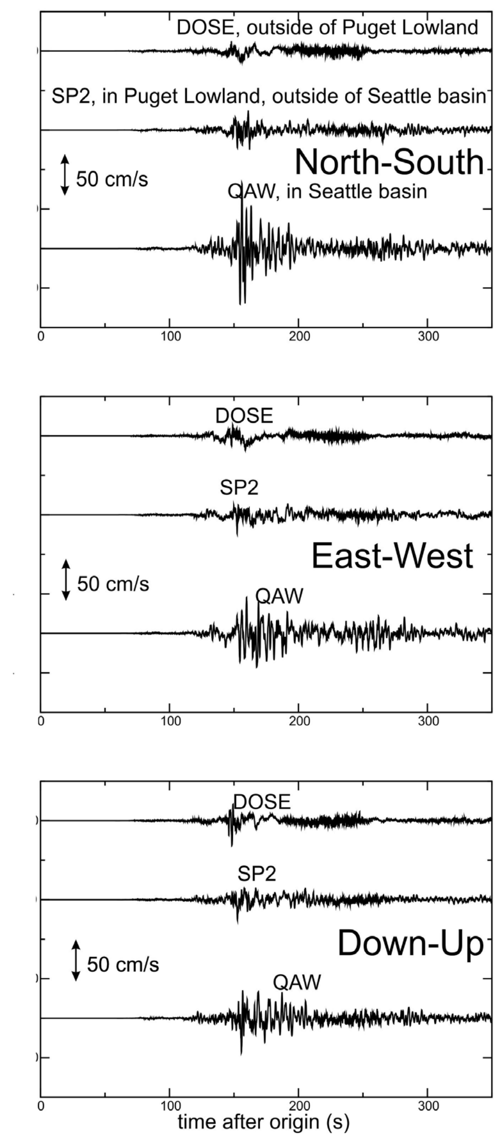
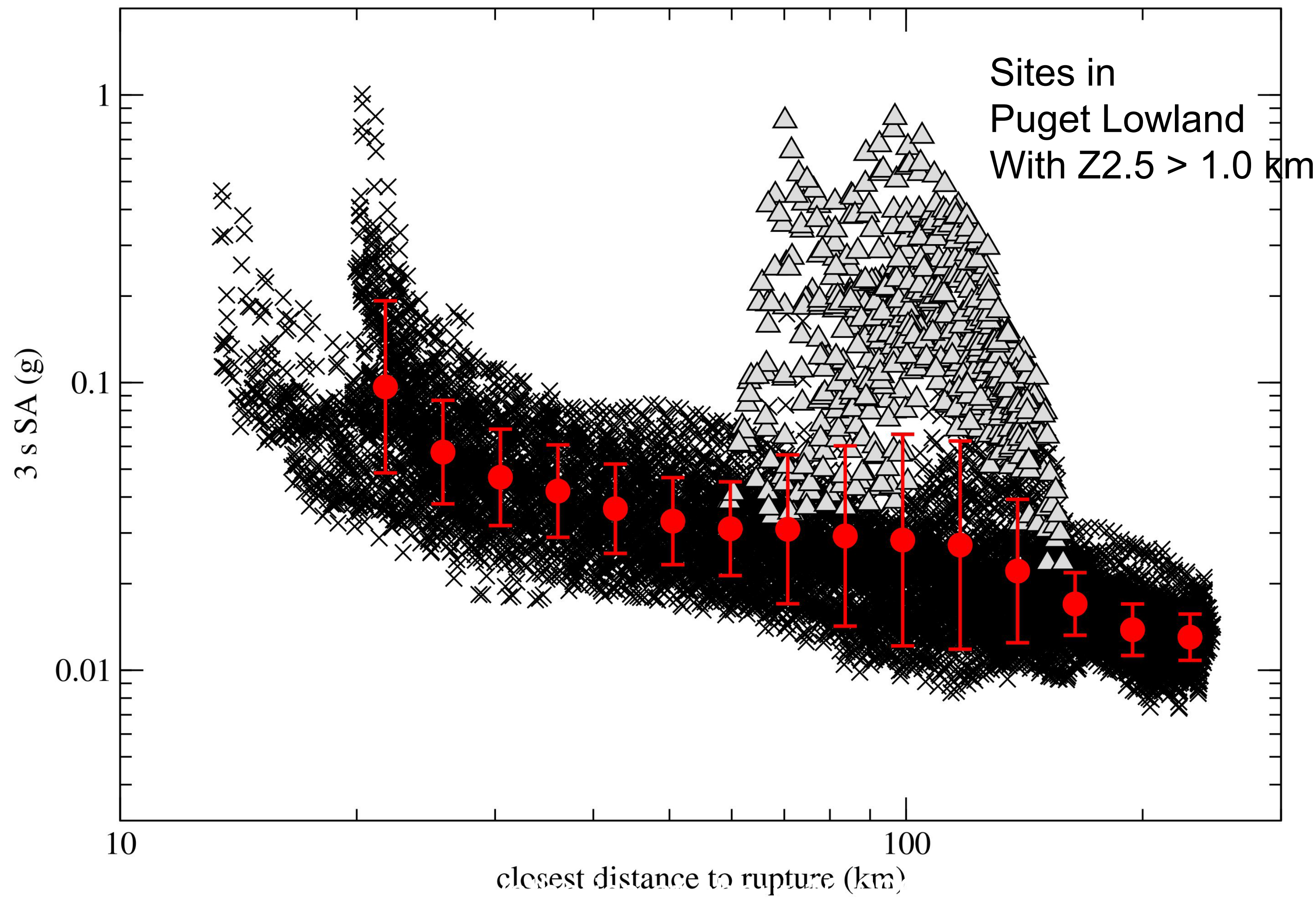
Velocity synthetics





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



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

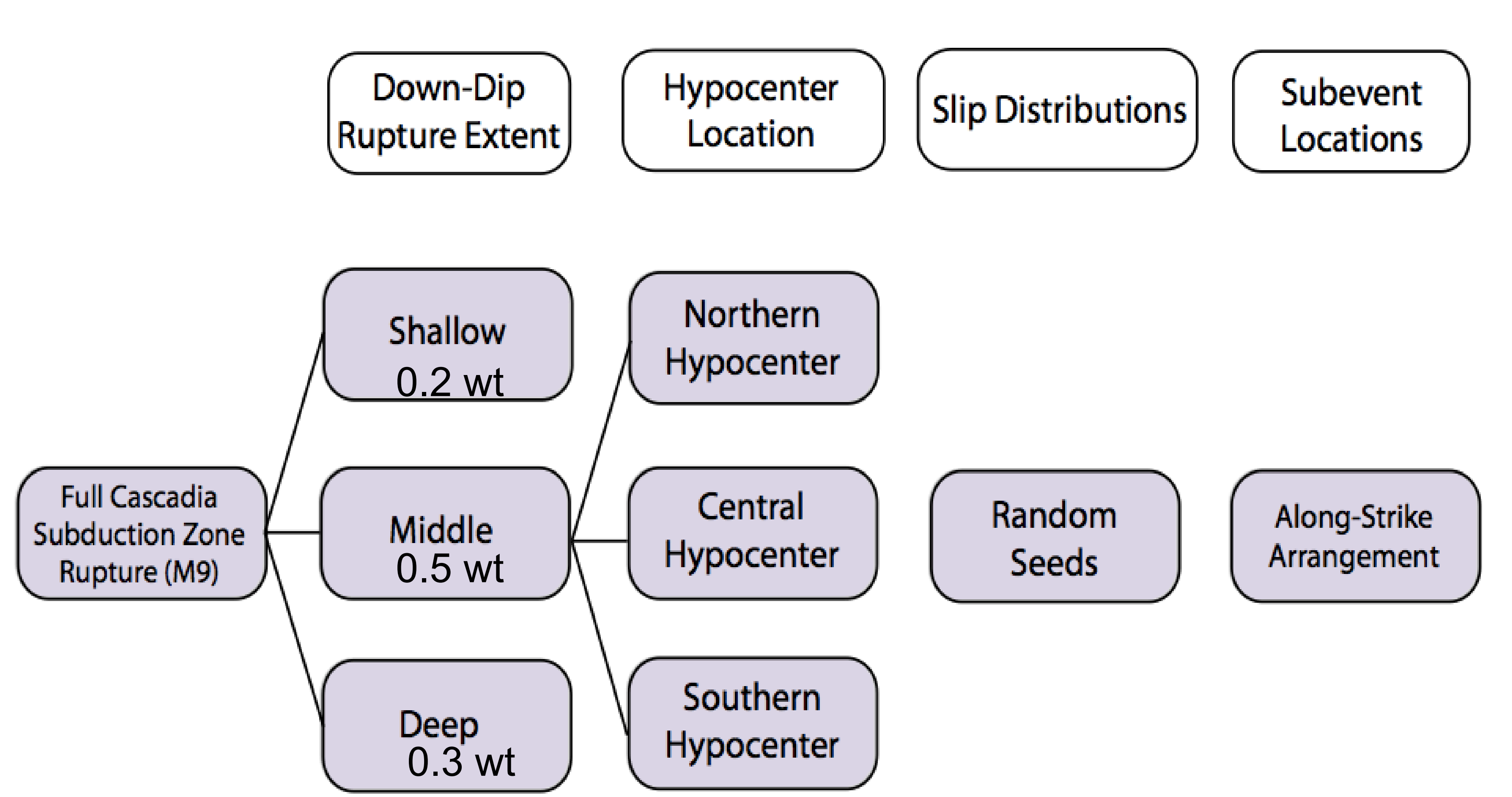
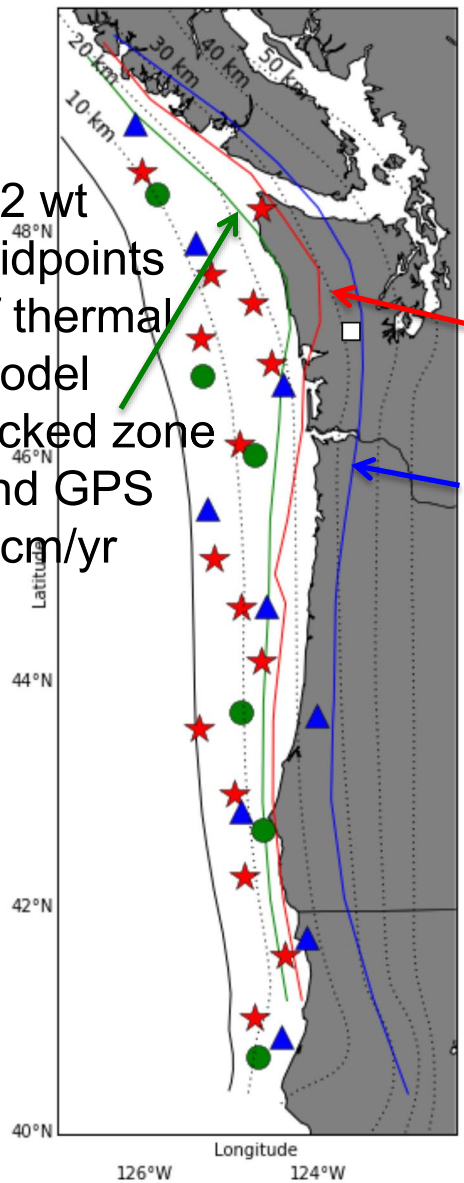


Figure by E. Wirth

Hypocenters

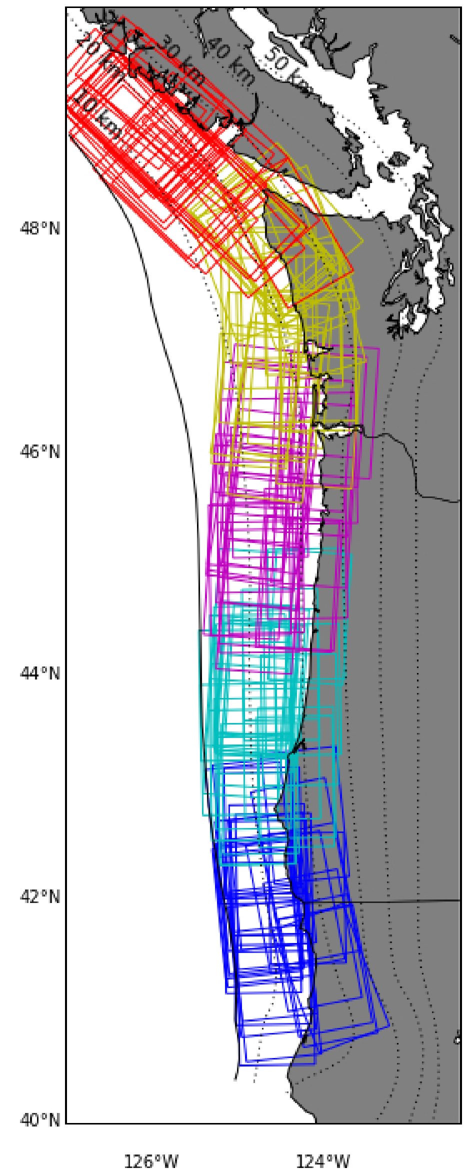


0.2 wt
Midpoints
of thermal
model
locked zone
and GPS
1 cm/yr

0.5 wt
1 cm/yr
locking
from GPS
and uplift

0.3 wt
top of
tremor
zone

Sub-event rupture zones



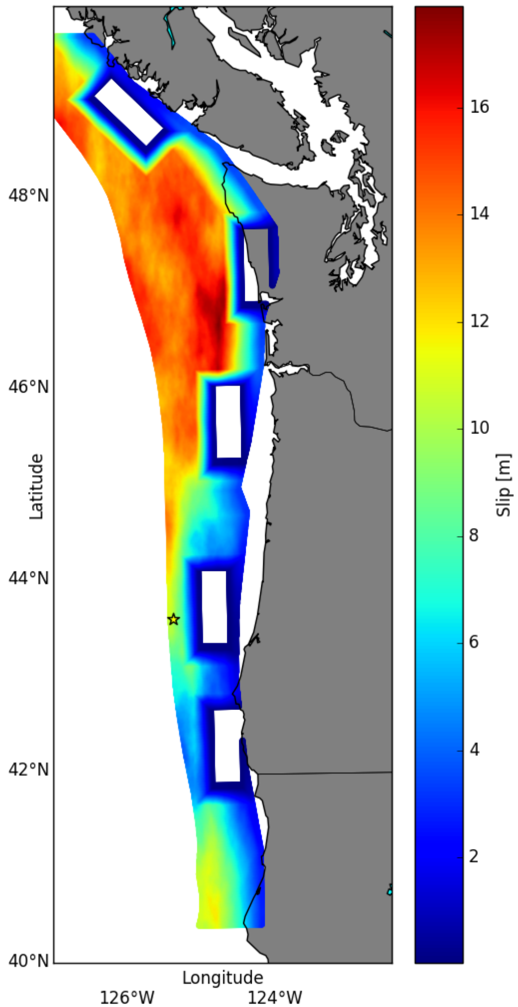
Figures from Erin Wirth

Relatively bad and good scenarios for Seattle. Both scenarios use same background slip ground motions < 8 s dominated by sub-events

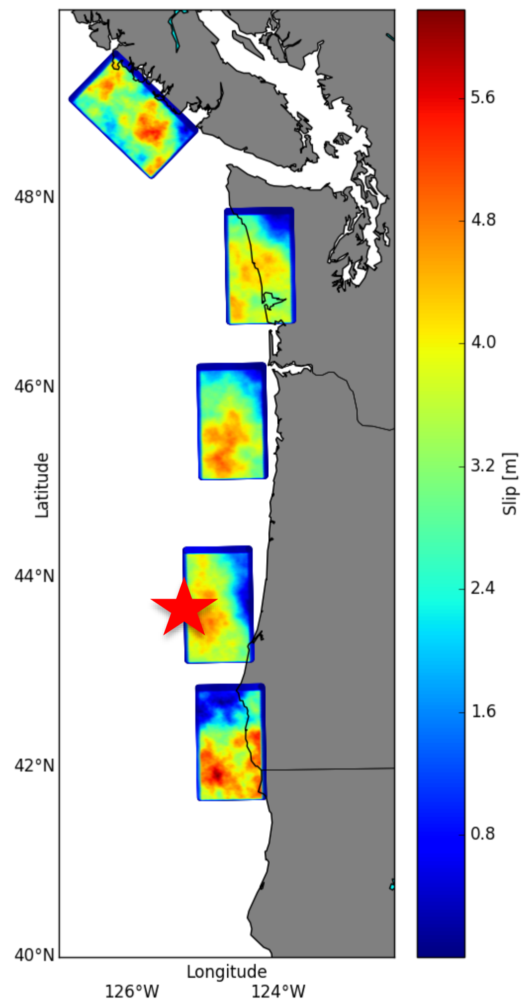
Forward rupture directivity affecting Seattle region

Rupture not directed toward Seattle region

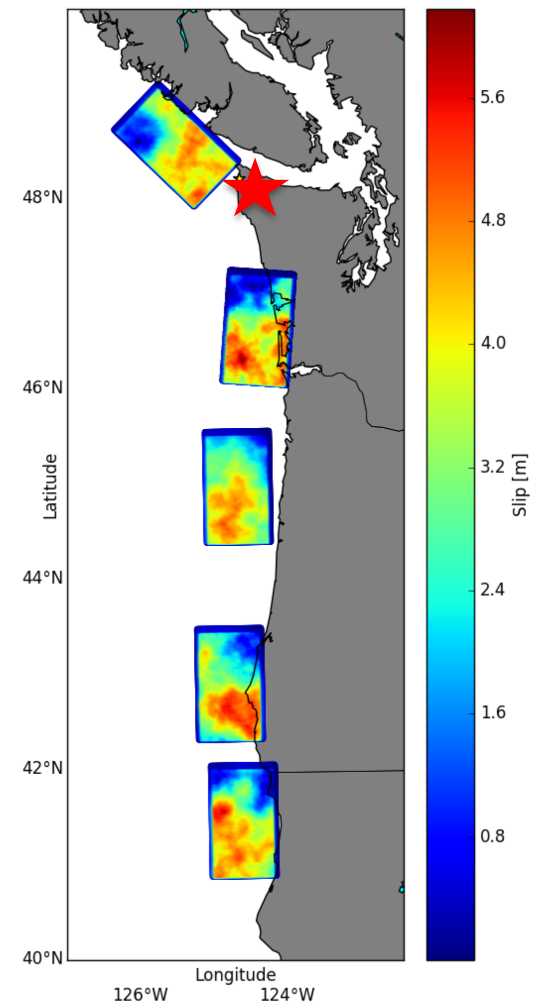
Same background slip used for both cases



M8.0 sub-events

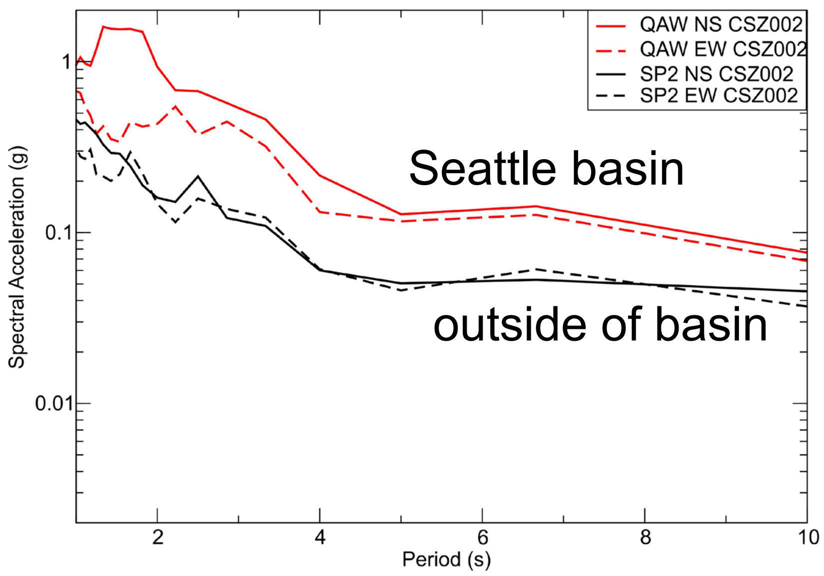


M8.0 sub-events

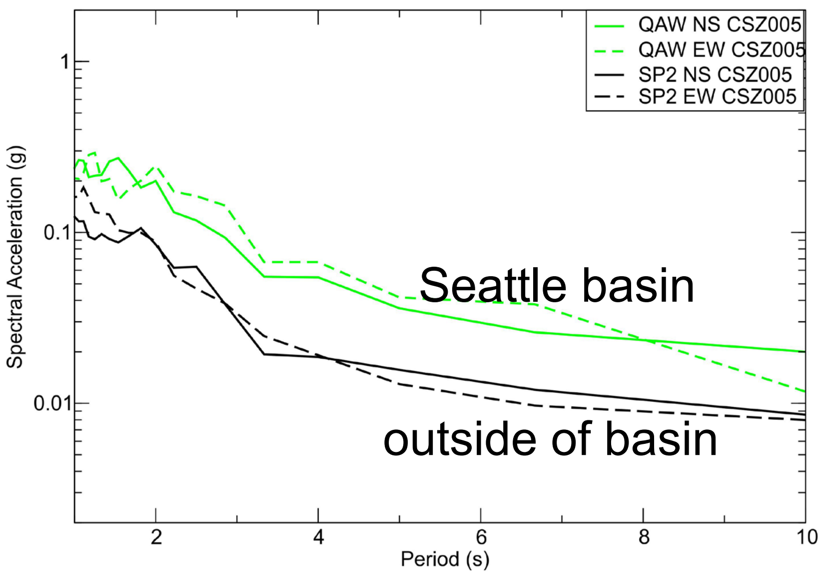


Seattle basin amplification depends on rupture directivity and azimuth of arrivals

Rupture towards Seattle
Most energy arriving from southwest



Rupture away from Seattle



Capturing this variability is key to accurately estimating seismic hazard

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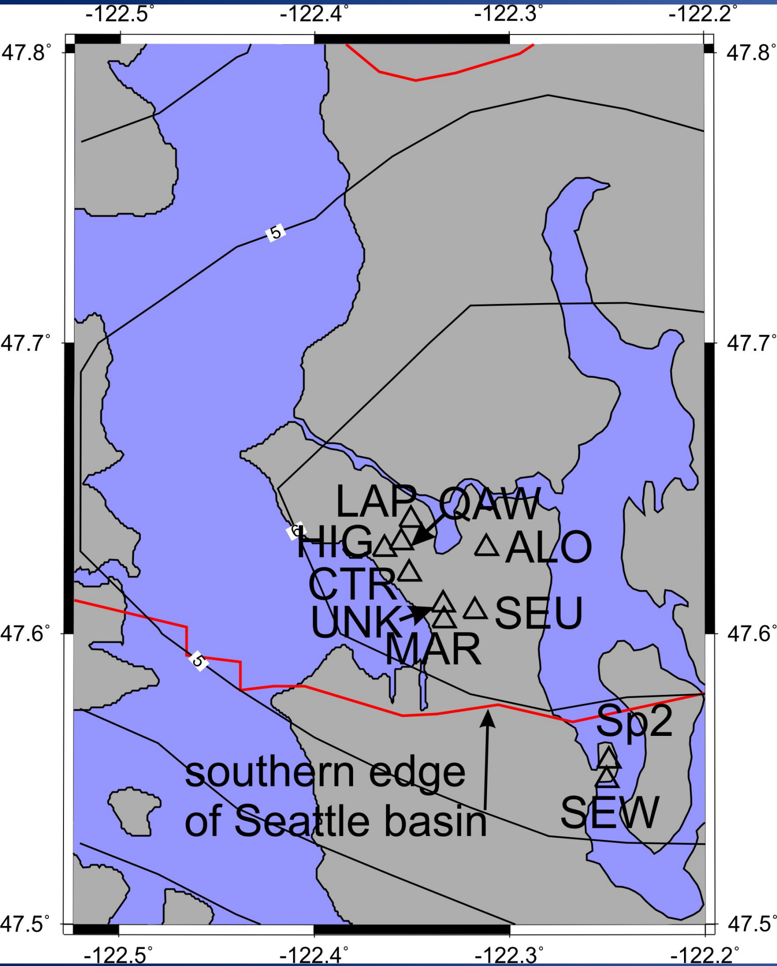
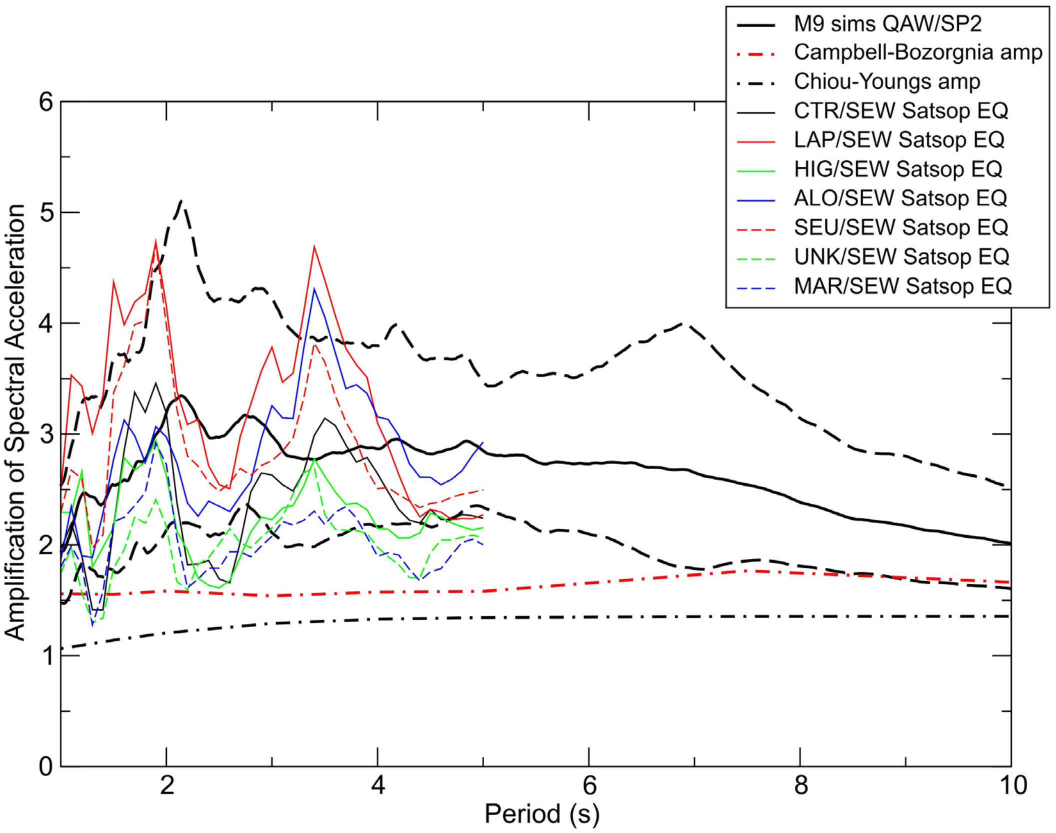
Amplification of Seattle basin sites relative to rock site outside of basin
M9 synthetics and observations from M5.0 Satsop EQ
Note that Vs30 values are similar between basin and rock sites





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

USGS-Seattle office has been actively working with city of Seattle and engineers (UW, SEAW) to conduct research to quantify basin amplification for design of high rise buildings

- In 2013, USGS co-convened workshop with city on Seattle basin amplification. Recommended using empirical basin amp terms from CA earthquakes for high rises (≥ 20 stories) in Seattle.
- 2018: USGS co-convened workshop with city on including results from M9 simulations (Frankel, Wirth) and observations. M9 simulations, as well as observations, showed higher basin amp factors than empirical data from CA crustal earthquakes.
- New Seattle city directive specifying factor of 2.0 basin amp to be used for subduction earthquakes in design of tall buildings. (USGS OFR 2018; Wirth, Chang, Frankel). City of Bellevue also has increased design of tall buildings based on M9 simulations and observations. Example of scientific research leading to practical measures to improve public safety.

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Future efforts to improve predictions of strong ground motions in urban areas situated on sedimentary basins

- Need to improve 3D models of Vs , Vp, Qs, Qp of crust and upper mantle, including high resolution of basins at depths of < 10 km in urban areas
- Use nodal arrays of seismometers, noise correlation
- Can we identify sub-event locations of future Cascadia M9 earthquakes from GPS data or other methods?
- Draft 2018 NSHMs include basin amplification from empirical data from crustal earthquakes (NGA West 2). 2020 NSHMs will consider 3D simulation results (M9 and Cybershake)

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Seattle Urban Seismic Hazard Maps Released in 2007

- 1 Hz spectral accelerations with 10% and 2% probabilities of exceedance in 50 years (tells you approx. the acceleration on the roof of a 10 story building); used recurrence rates from NSHMs
- USGS Open-File Report 2007-1175, Seismic hazard maps for Seattle, Washington, incorporating 3D sedimentary basin effects, nonlinear site response, and rupture directivity (Frankel, Stephenson, Carver, Williams, Odum, and Rhea), 82 pp.
- earthquake.usgs.gov/hazards/products/urban/seattle.php

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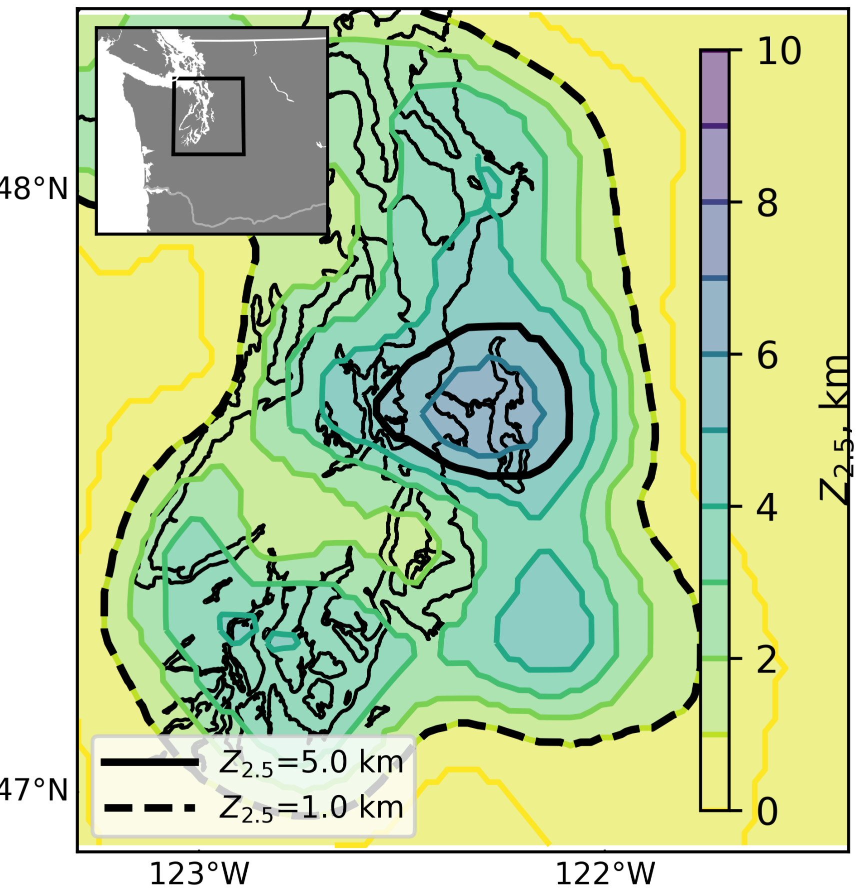
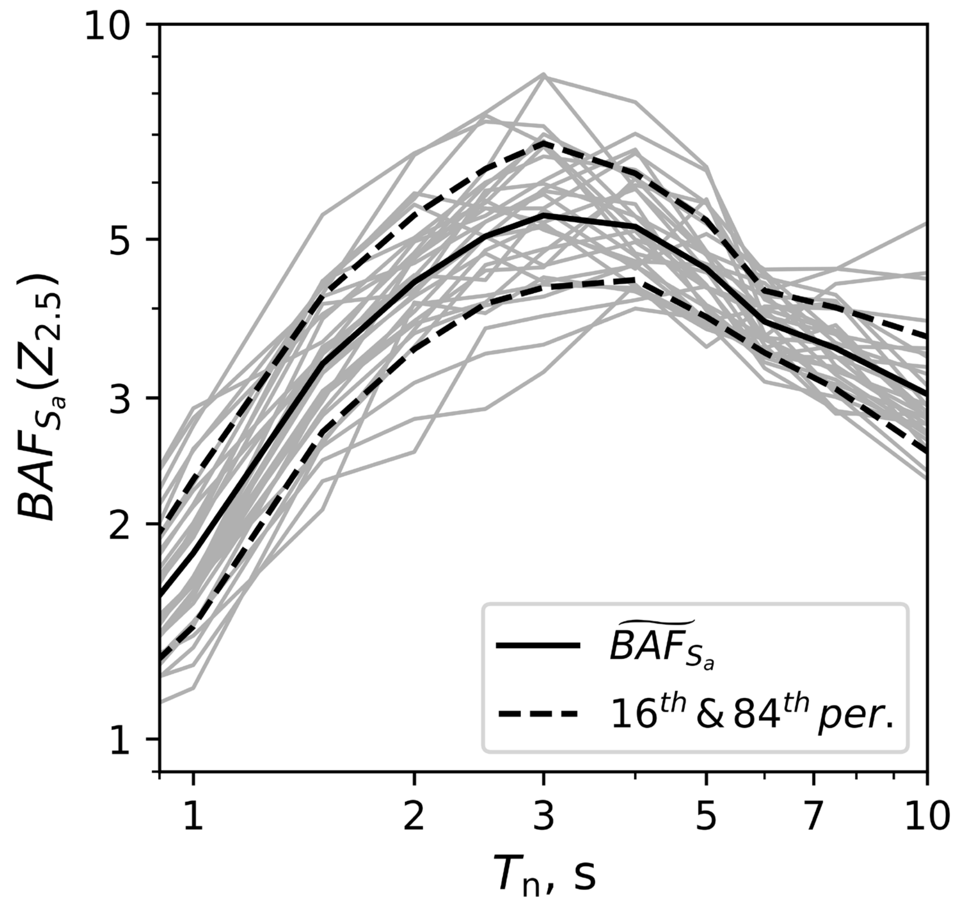
Basin amplification factors for sites with Z2.5 ≥ 5.0 km
With respect to sites with Z2.5 < 1.0 km outside of Puget Lowland

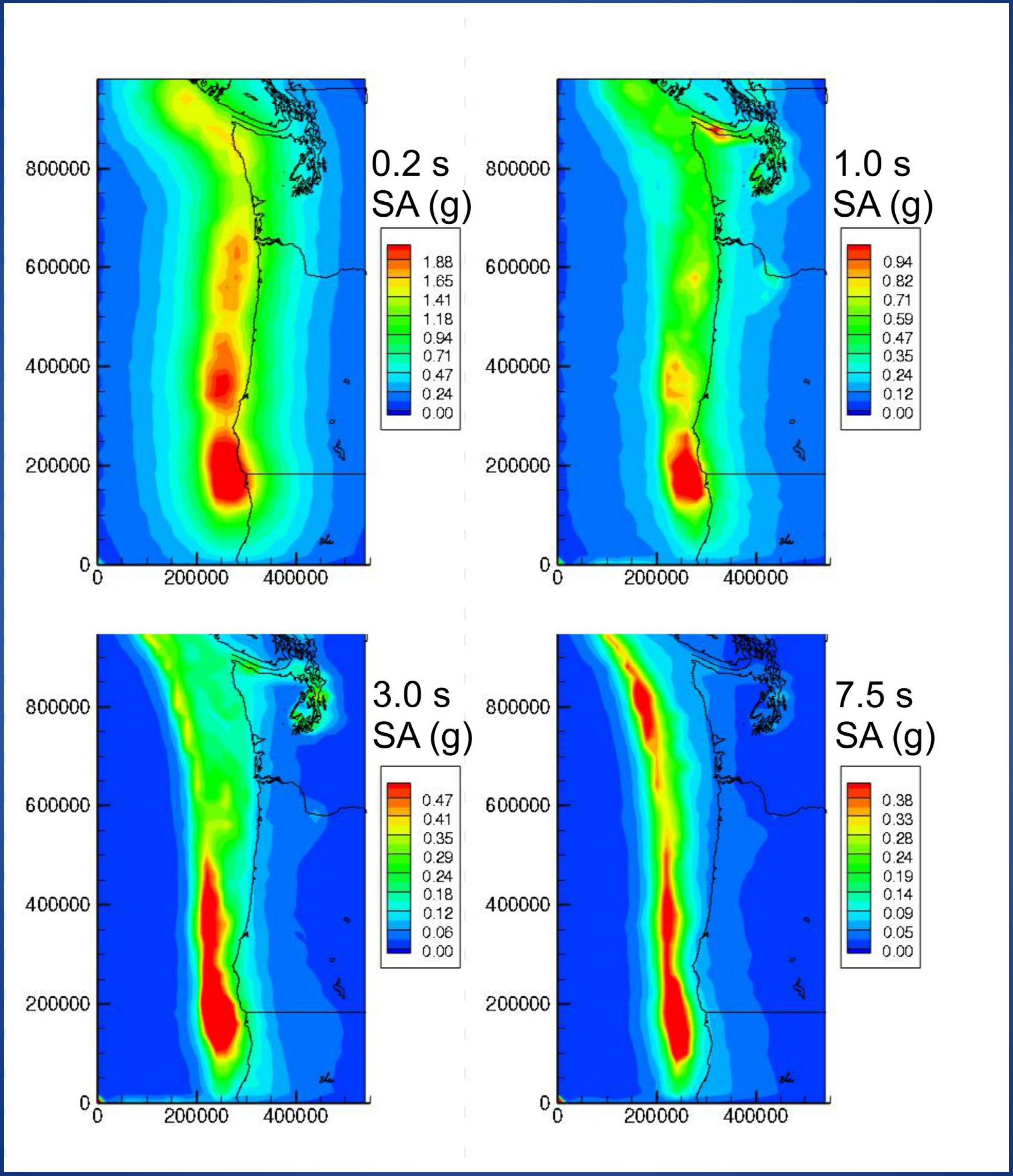




$$\ln BAF = \frac{1}{n}\sum_{i=1}^{n}(\ln synthbasin_i - \ln gmpe_i) - \frac{1}{m}\sum_{j=1}^{m}(\ln synthref_j - \ln gmpe_j),$$

Figures from N. Marafi

Log averaged SA values from 30 scenarios



Probabilistic seismic hazard with site and source dependent amplification and rupture directivity

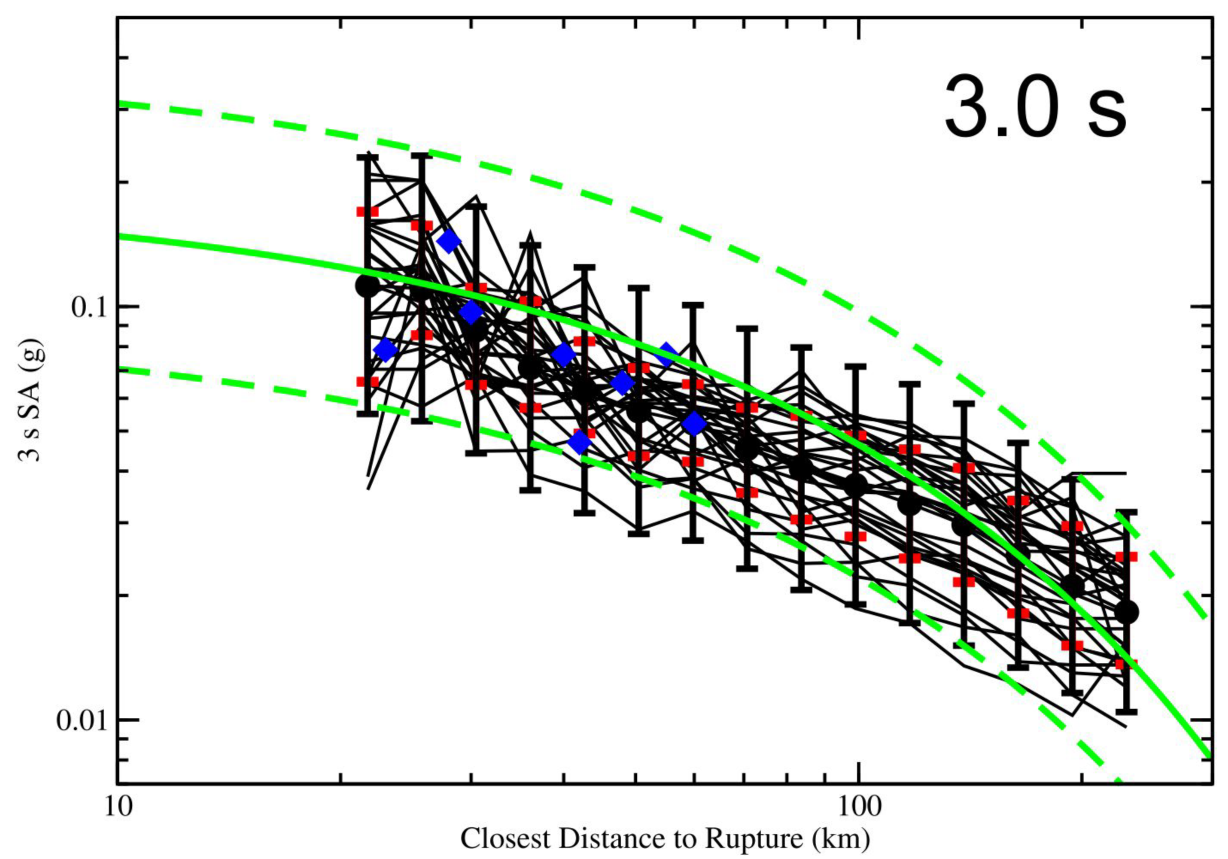
Annual probability of having ground motion exceeding u_0 at site i:

$$P(u \geq u_0) \approx \sum_{M} \sum_{\text{source}_j} \text{rate}(M, \text{source}_j)\, P(u \geq u_0 | \text{site}_i, \text{source}_j, M)$$

$$u = u_{rock}(M, D)\ \text{amp}(\text{PGA}_{rock}, \text{site}_i, \text{source}_j)$$

Amp factor contains 3D basin effects and rupture directivity
determined by 3D simulations for various scenarios
and nonlinear site response for
fill/alluvium sites determined from Choi and Stewart (2005) factors

3 sec SA with respect to closest rupture distance for 30 runs; onland, non-basin sites
Green lines from BC Hydro Ground Motion Prediction Equations (extrapolated from M5-8.4 strong-motion data from subduction zones; Abrahamson et al. 2016)
blue symbols Maule data. Black error bars: total variability; Red error bars inter-event



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

- 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
- 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 synthetics seismograms are posted on DesignSafe Website https://doi.org/10.17603/DS2WM3W

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Log averaged SA values from 30 scenarios