Probabilistic Seismic Hazard Maps for Seattle: 3D Sedimentary Basin Effects, Nonlinear Site Response, and Uncertainties from Random Velocity Variations

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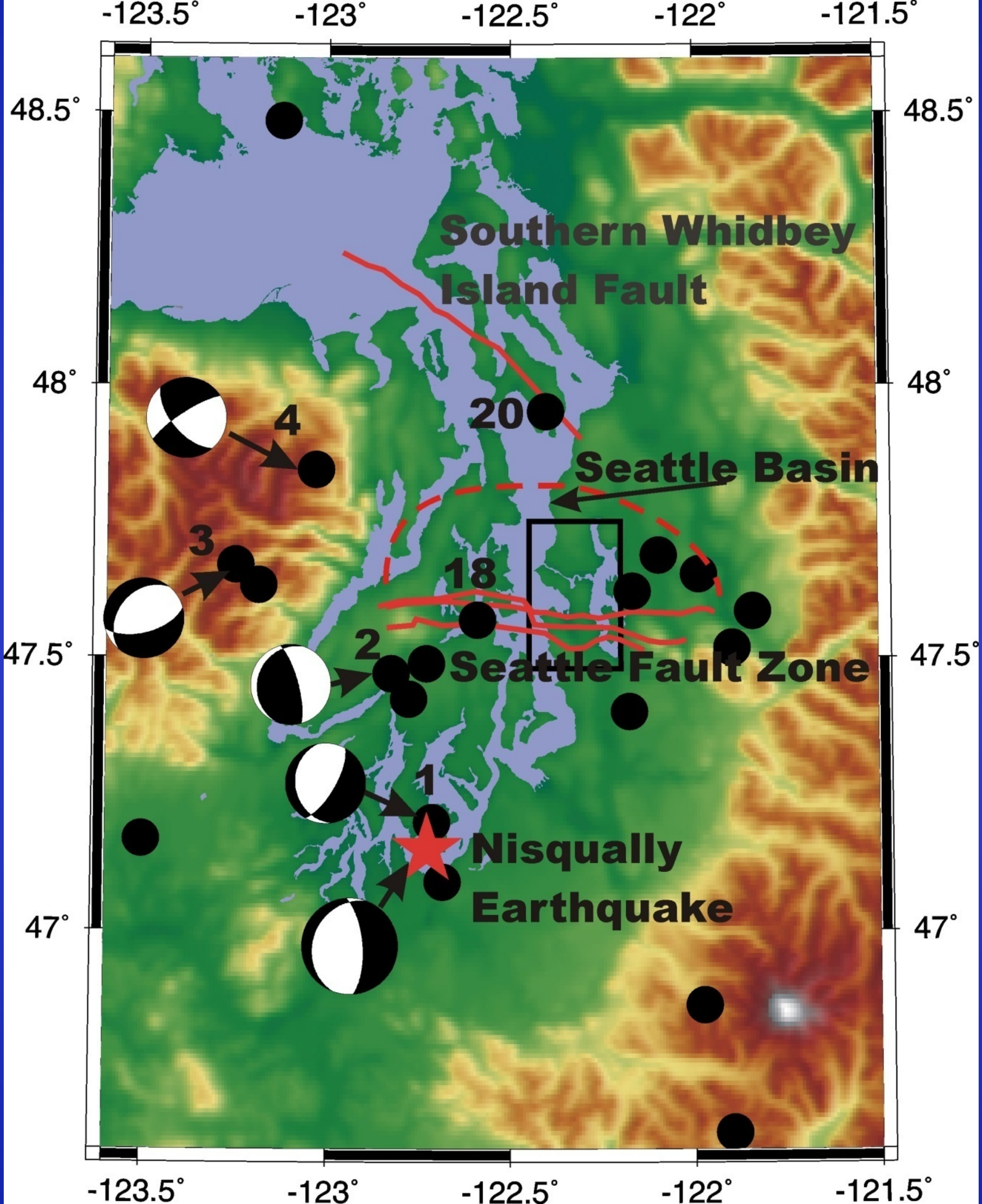
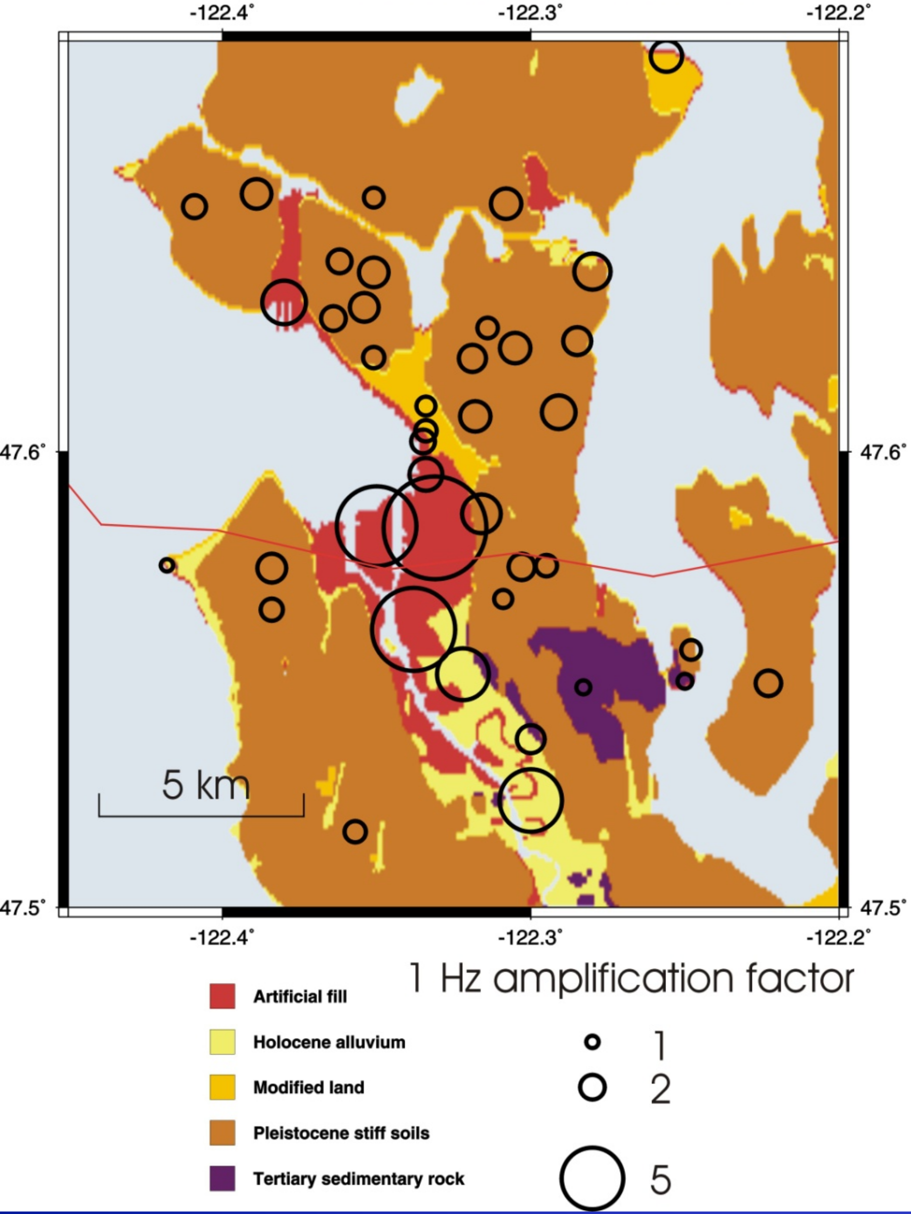
Presentation for 4th IASPEI/ IAEE International Symposium on the Effects of Surface Geology on Seismic Motion

Outline of Talk

- Observations of 3D basin effects and site response for Seattle, WA region
- Modeling basin effects with 3D finite difference simulations; validating 3D velocity model
- Methodology for producing urban seismic hazard maps for Seattle using 3D simulations
- Evaluating effects of 3D random velocity variations on peak velocities and spectral accelerations from simulations

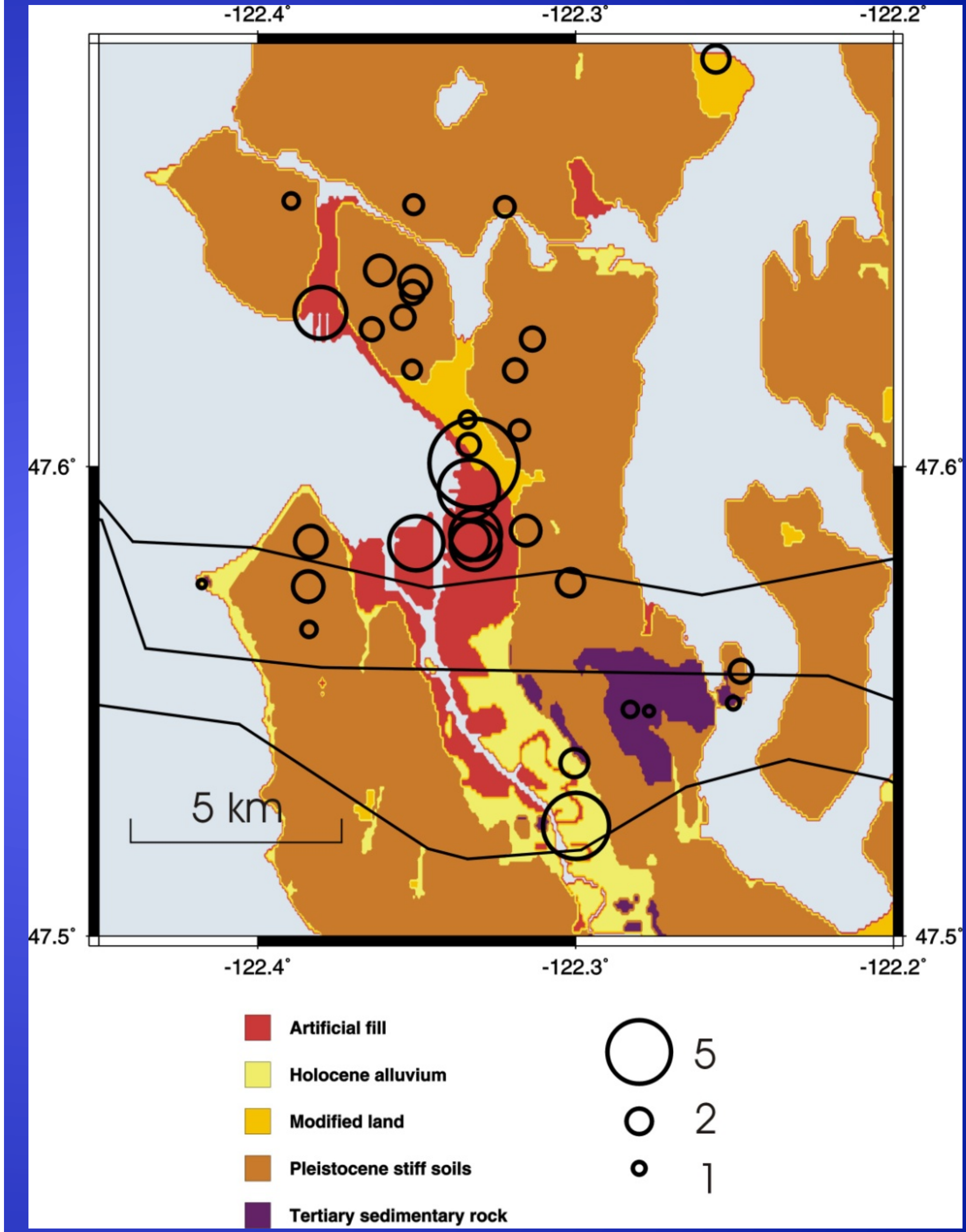

-123.5°
-123°
-122.5°
-122°
-121.5°
48.5°
48°
47.5°
47°
Southern Whidbey
Island Fault
20
4
Seattle Basin
3
18
2
Seattle Fault Zone
1
Nisqually
Earthquake

1 Hz amplification at each site determined from inversion of observed spectra. Note highest amplification is at artificial fill and Holocene alluvium sites



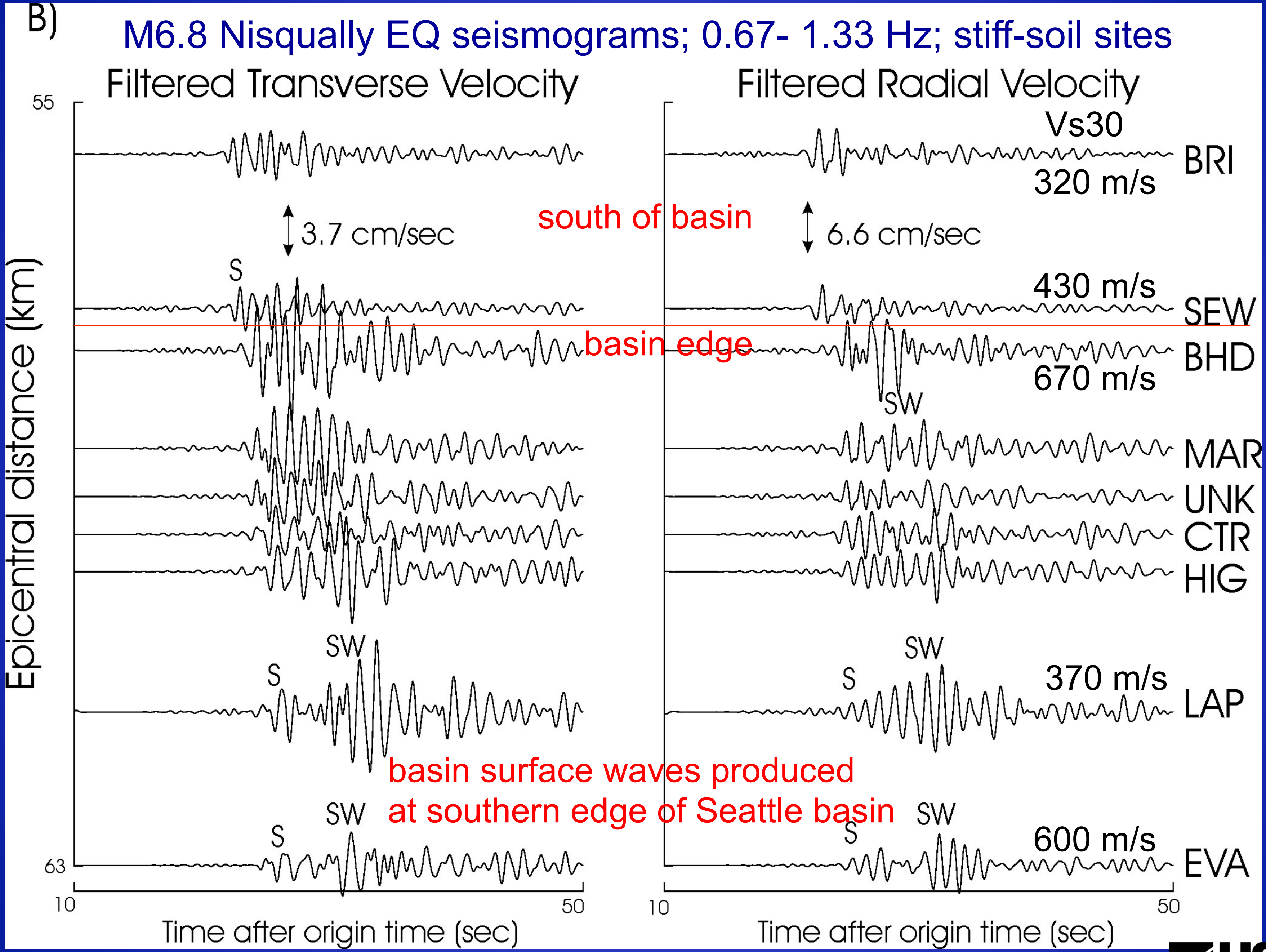
From 19 events M2.7-4.8

1 Hz amp from M6.8 Nisqually Earthquake



From M6.8 Nisqually EQ (dep=52 km)

M6.8 Nisqually EQ seismograms; 0.67- 1.33 Hz; stiff-soil sites



Vs30

320 m/s

430 m/s

670 m/s

370 m/s

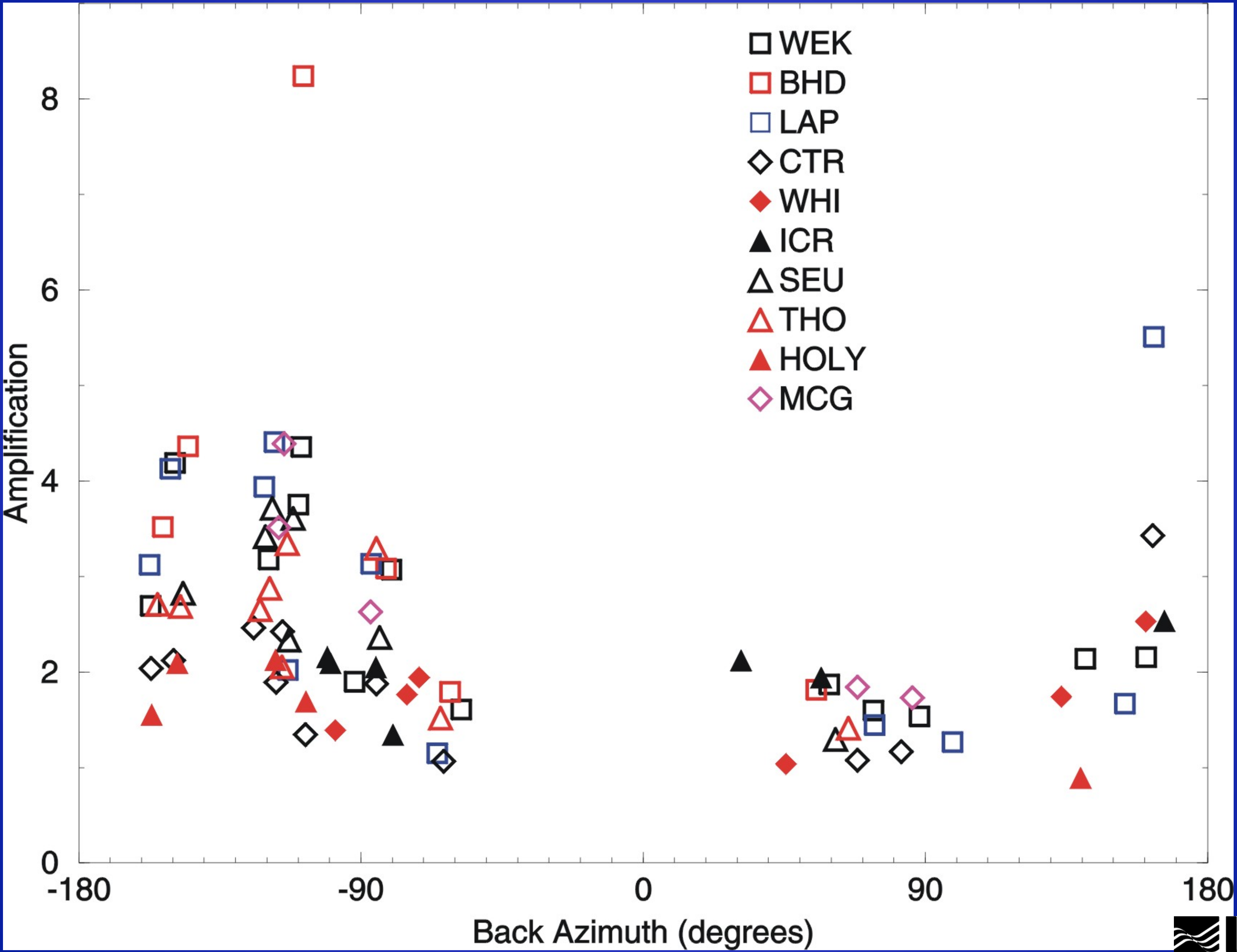
600 m/s

south of basin

basin edge

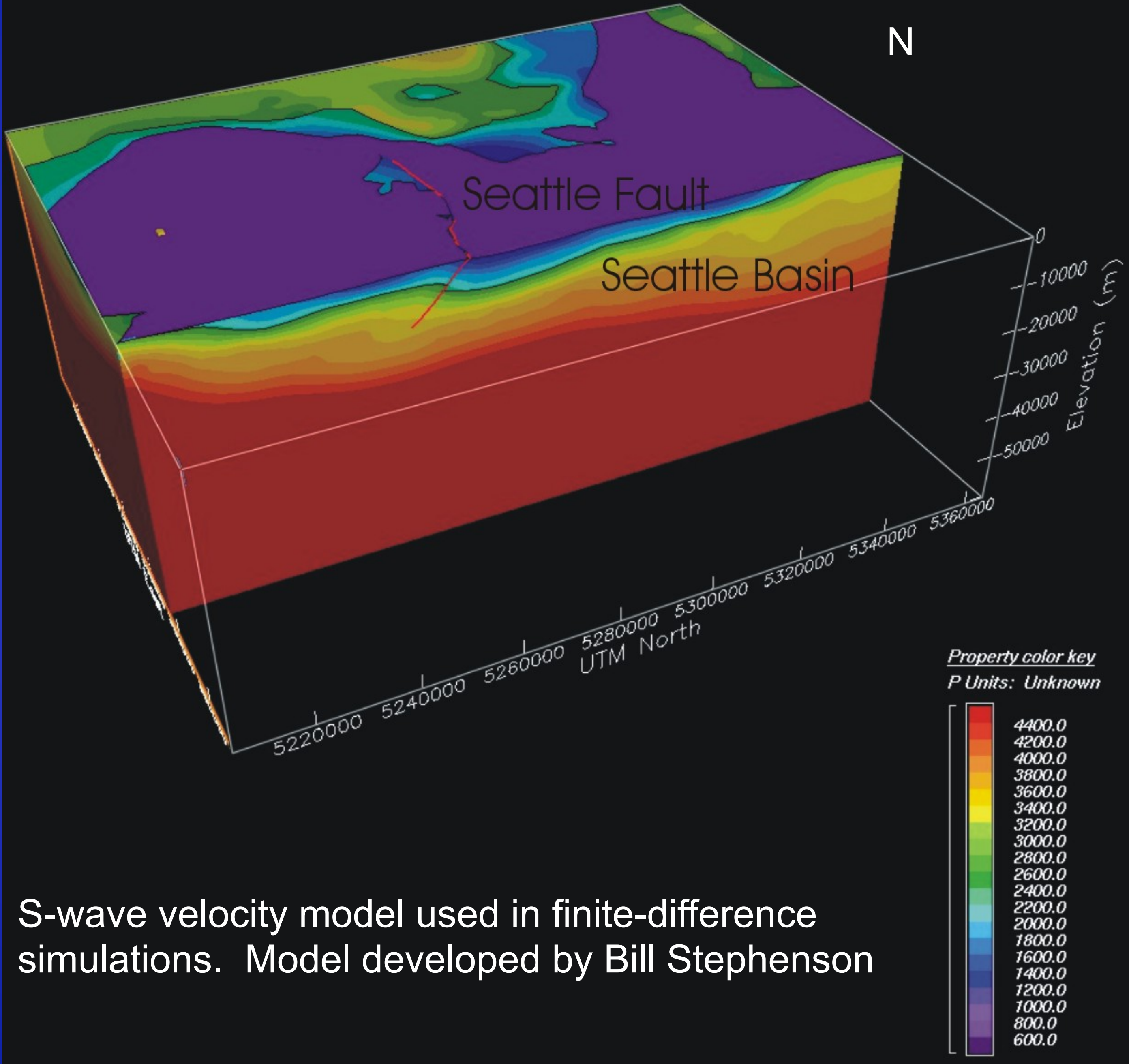
basin surface waves produced at southern edge of Seattle basin

1 Hz Amplification at stiff-soil sites in Seattle basin wrt rock site
Amplification depends on direction to earthquake

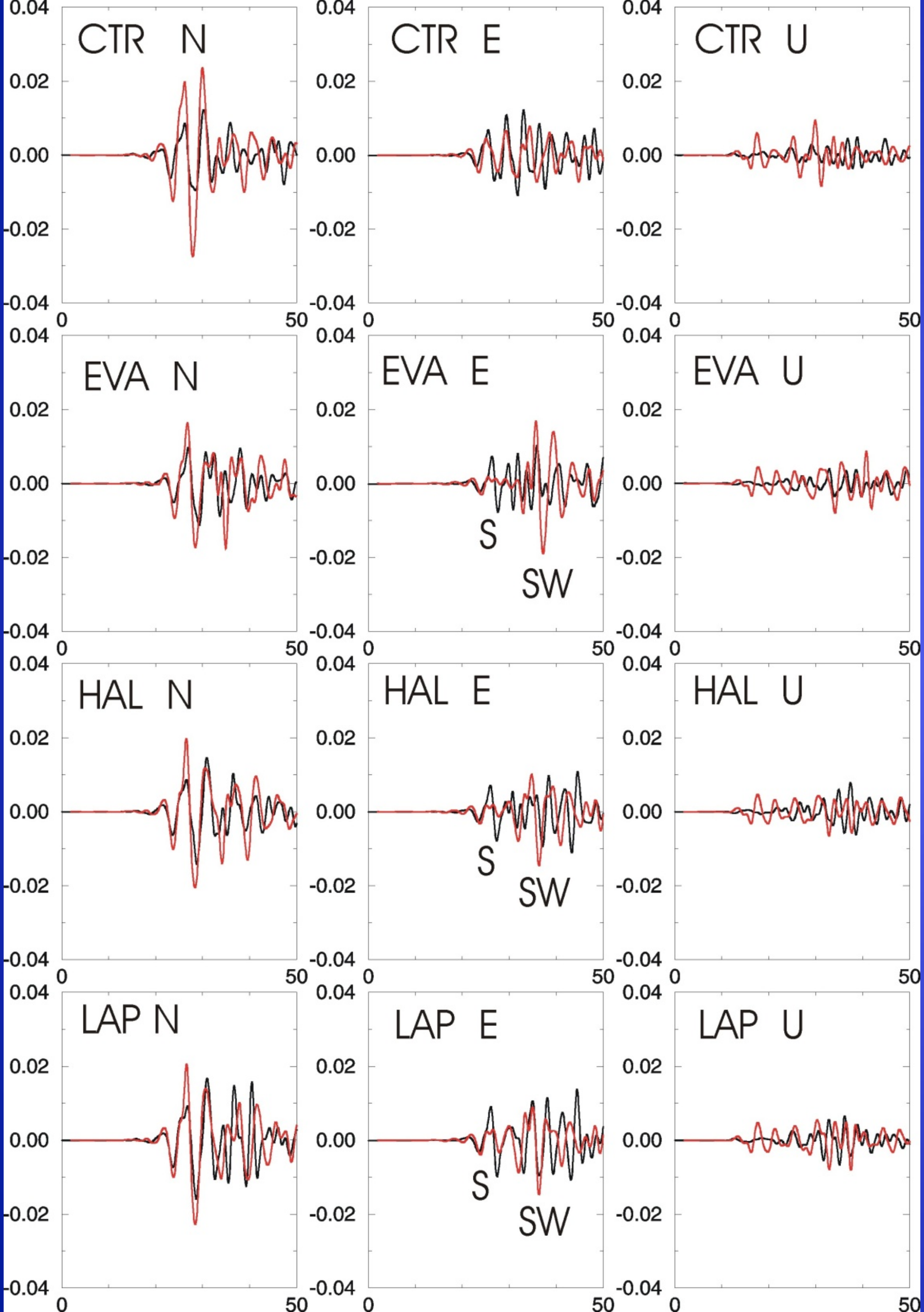


3D finite difference modeling

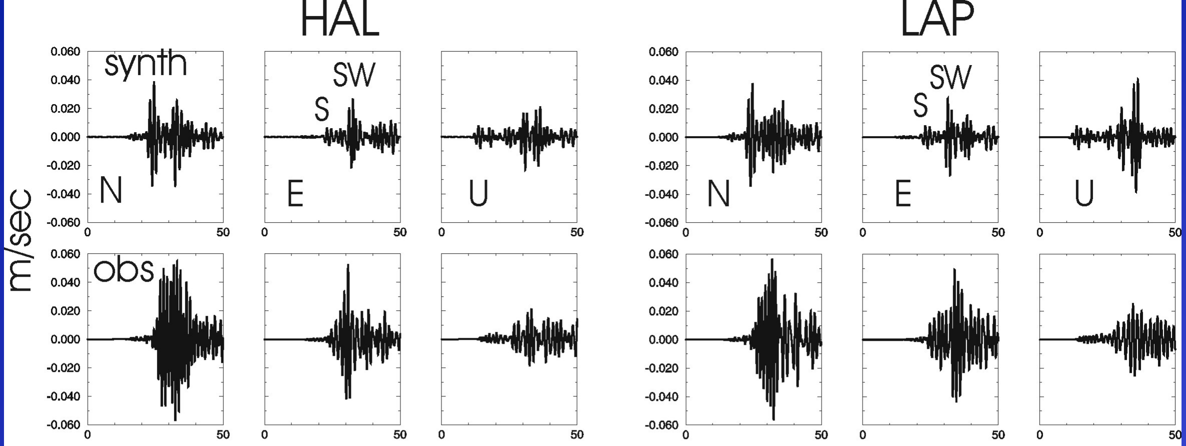
- Used viscoelastic code of Pengcheng Liu (U.S. Bureau of Reclamation); 4th order in space, 2nd order in time
- Variable grid spacing with depth; finest spacing we used was 70m
- We used minimum Vs of 600m/s, similar to observed Vs30 of glacially-overridden soils
- Accurate to at least 1 Hz (9 grid points per wavelength)
- Validated 3D model with 5 earthquakes to date



S-wave velocity model used in finite-difference simulations. Model developed by Bill Stephenson

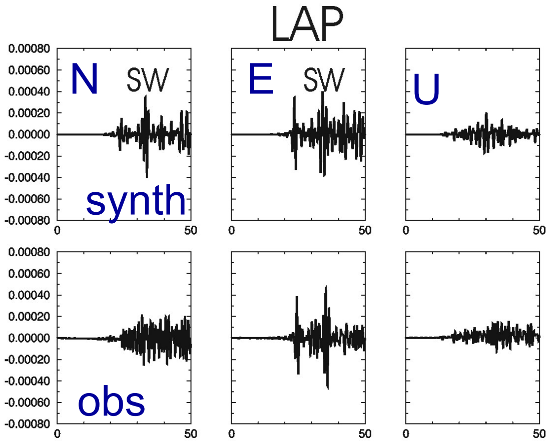


Observed (black) and synthetic (red) velocity waveforms for The Nisqually earthquake (0.2-0.4 Hz)

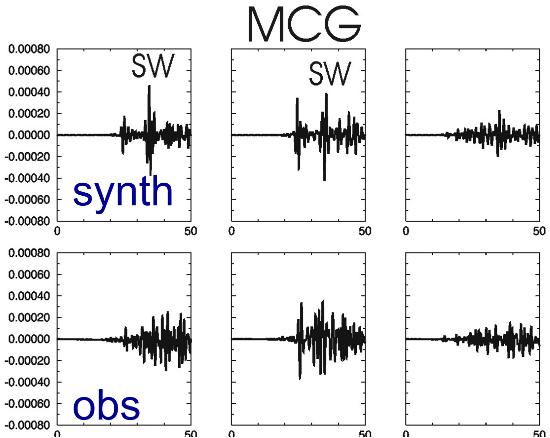


Nisqually earthquake

Examples
of observed and
predicted basin surface
waves (SW),
0.5-1.0 Hz



M4.8 deep earthquake
west of Seattle

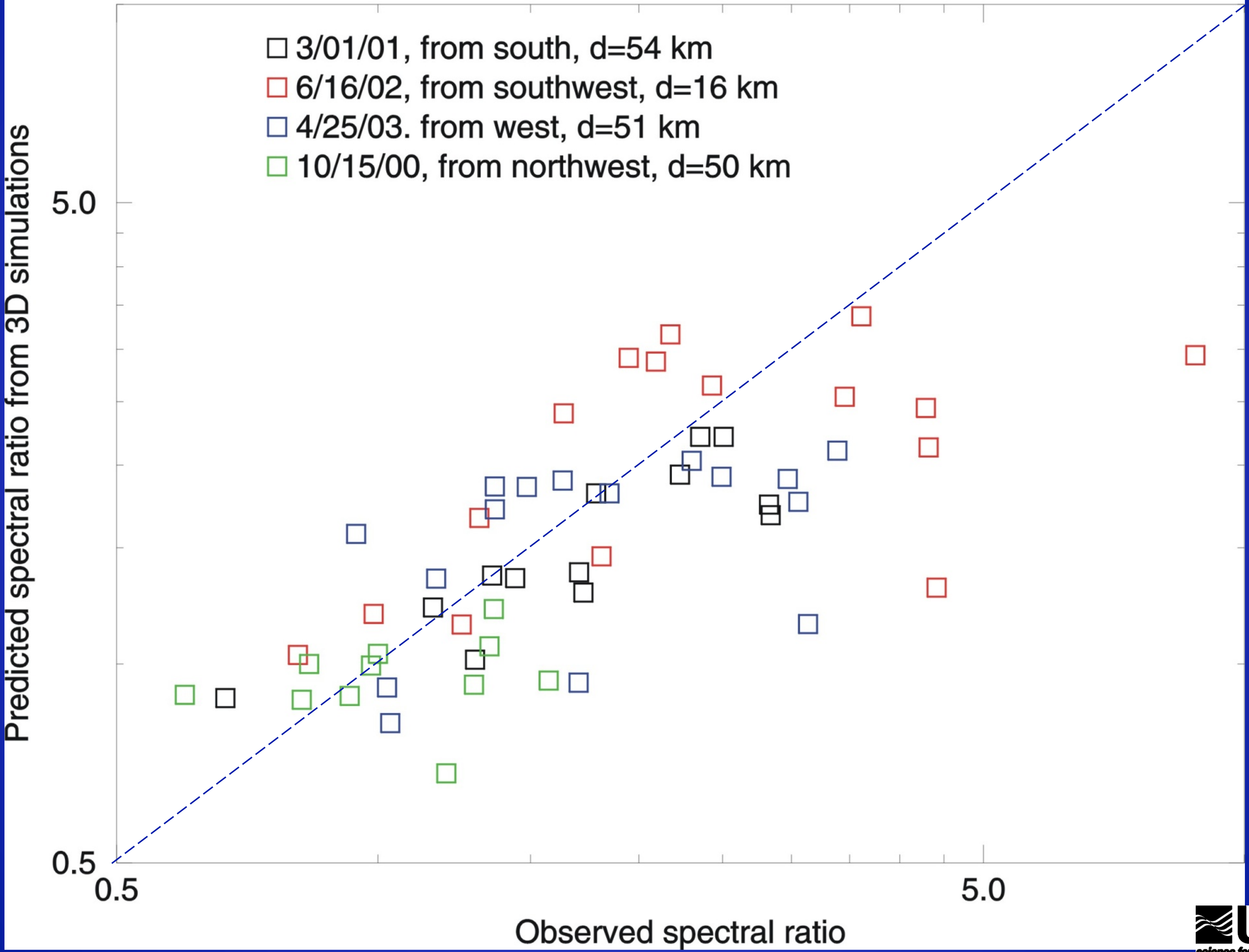


From Frankel et al. (2009)

Predicted and Observed Spectral Ratios wrt Rock Sites

1 Hz

Stiff-soil sites



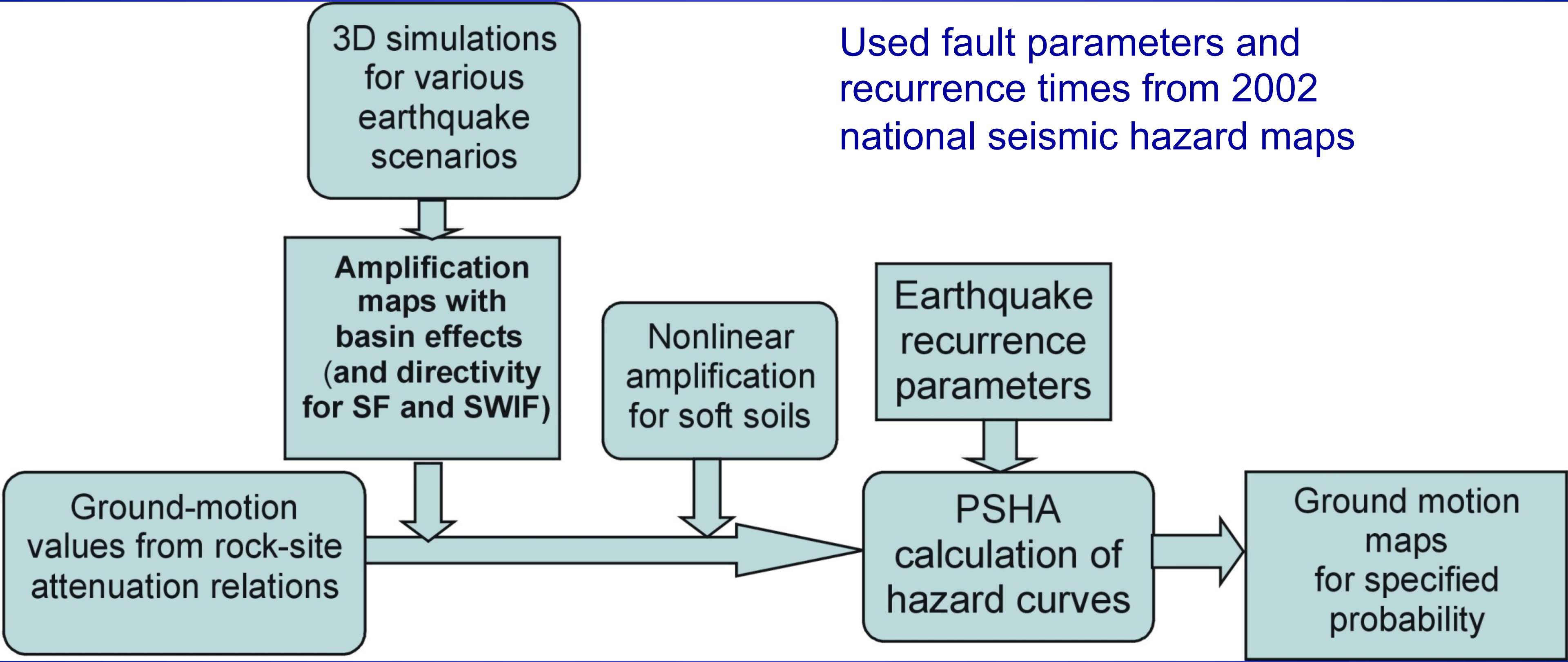
Putting the results of 3D ground-motion simulations into seismic hazard maps:

Seattle hazard maps;
USGS Open-File Report 2007-1175
Frankel, Stephenson, Carver, Williams, Odum, Rhea

541 3D finite-difference simulations used in Seattle 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

Procedure to Make Urban Seismic Hazard Maps



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

3D simulations for various earthquake scenarios

Amplification maps with basin effects (and directivity for SF and SWIF)

Nonlinear amplification for soft soils

Earthquake recurrence parameters

Ground-motion values from rock-site attenuation relations

PSHA calculation of hazard curves

Ground motion maps for specified probability

PSHA= Probabilistic Seismic Hazard Assessment

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

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

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

For stiff-soil sites: $u = u_{rock}(M,D)A_{3D}(\text{site}_i,\text{source}_j)$

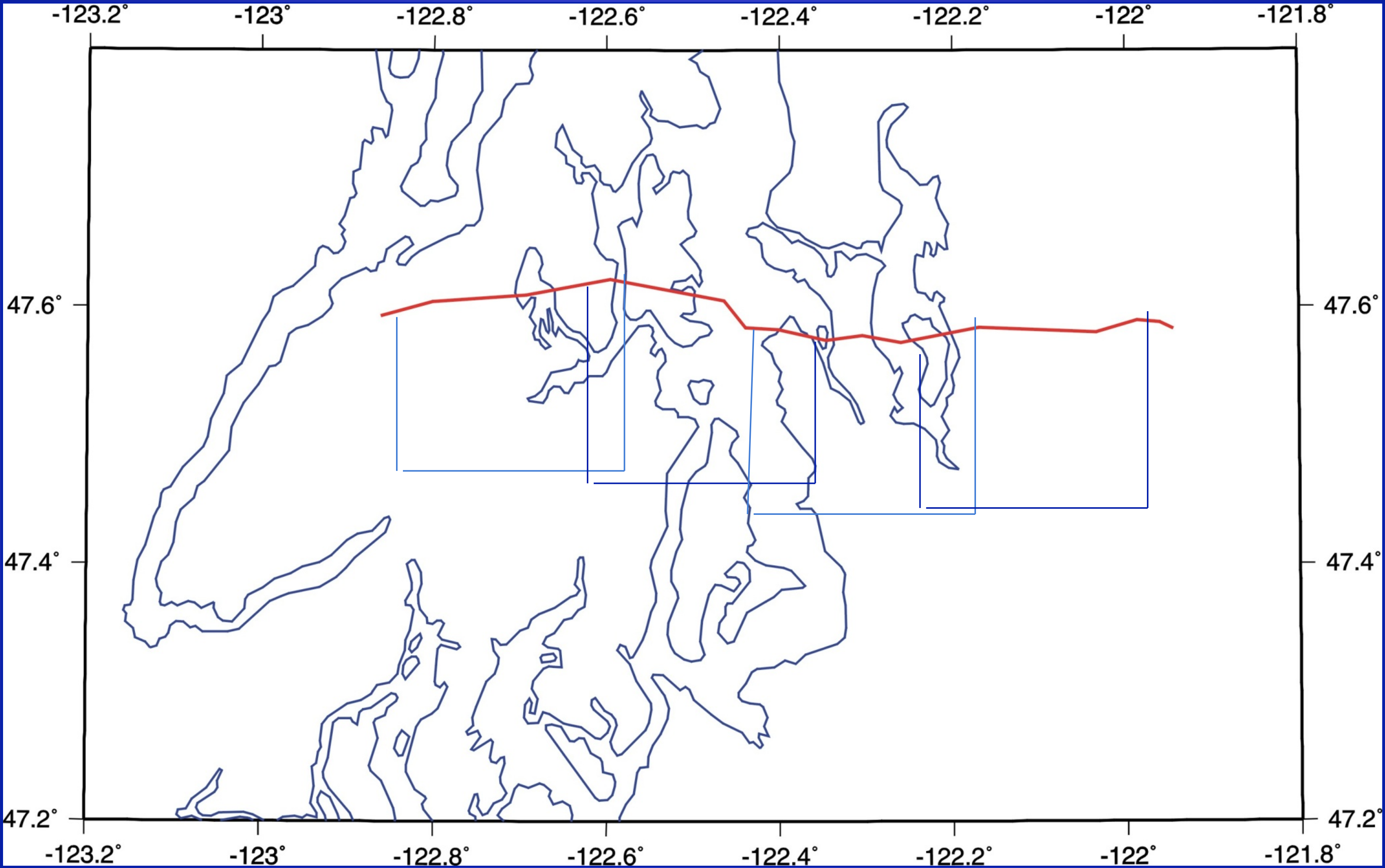
For soft-soil sites:

$u = u_{rock}(M,D)A_{3D}(\text{site}_i,\text{source}_j)A_{soft}(\text{site}_i,\text{PGA}_{rock})$

Amp factor A_{3D} contains 3D basin effects and rupture directivity determined by 3D simulations for various scenarios

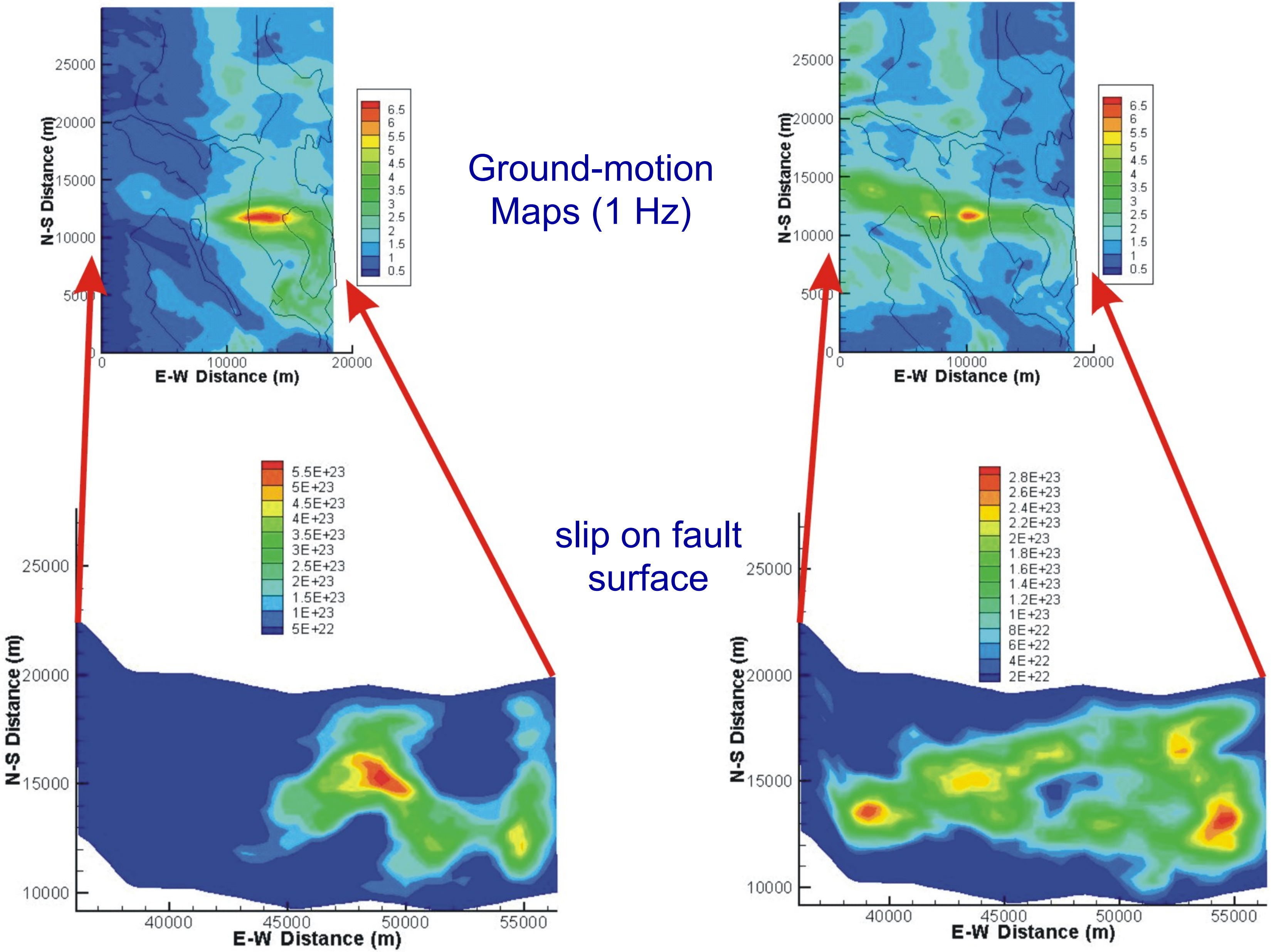
A_{soft} determined from Vs30 using Choi and Stewart (2005) empirical amplification factors

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

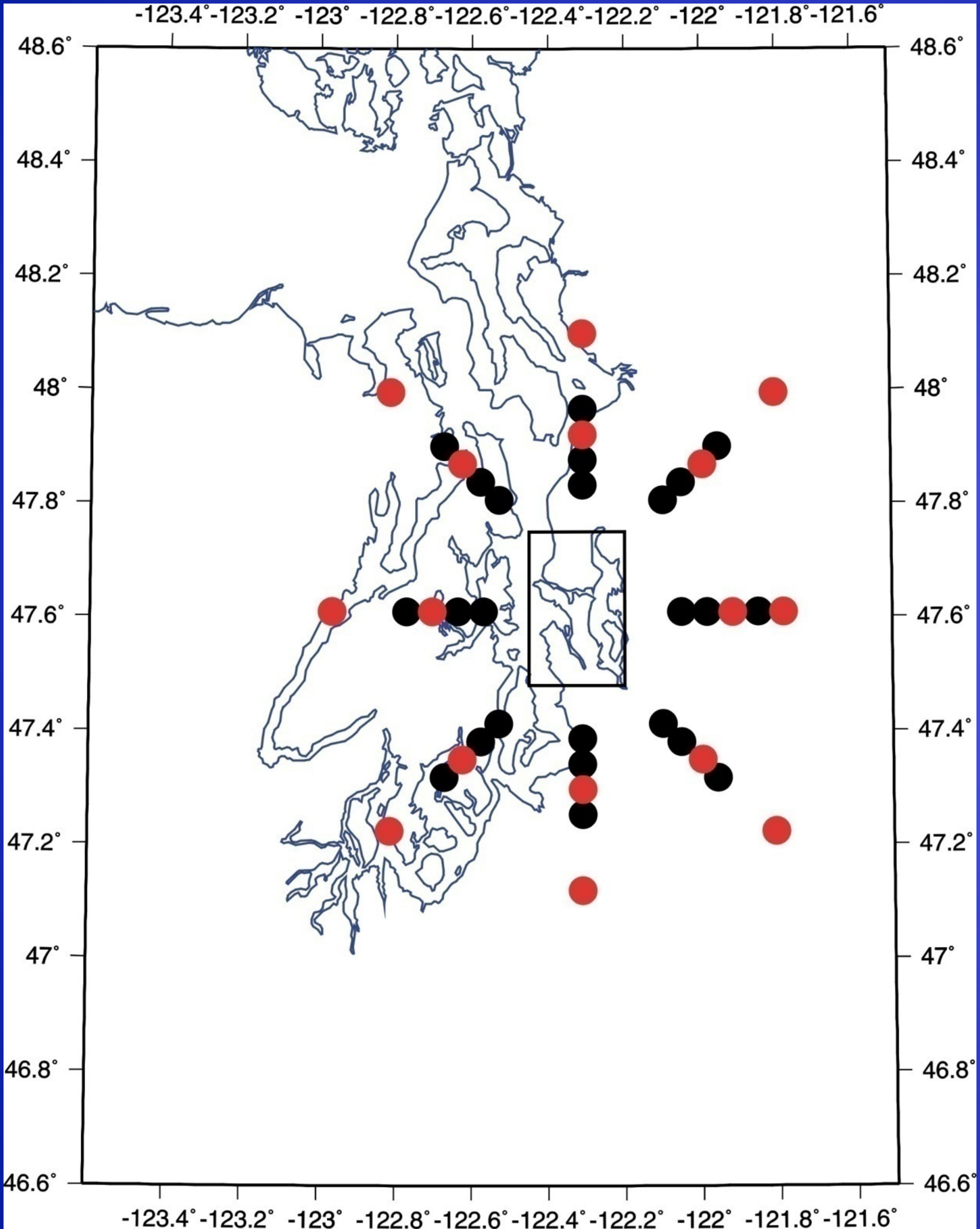
Two scenarios for Seattle fault earthquakes M6.6



Ground-motion Maps (1 Hz)

slip on fault surface

Used kinematic description of rupture on fault surface

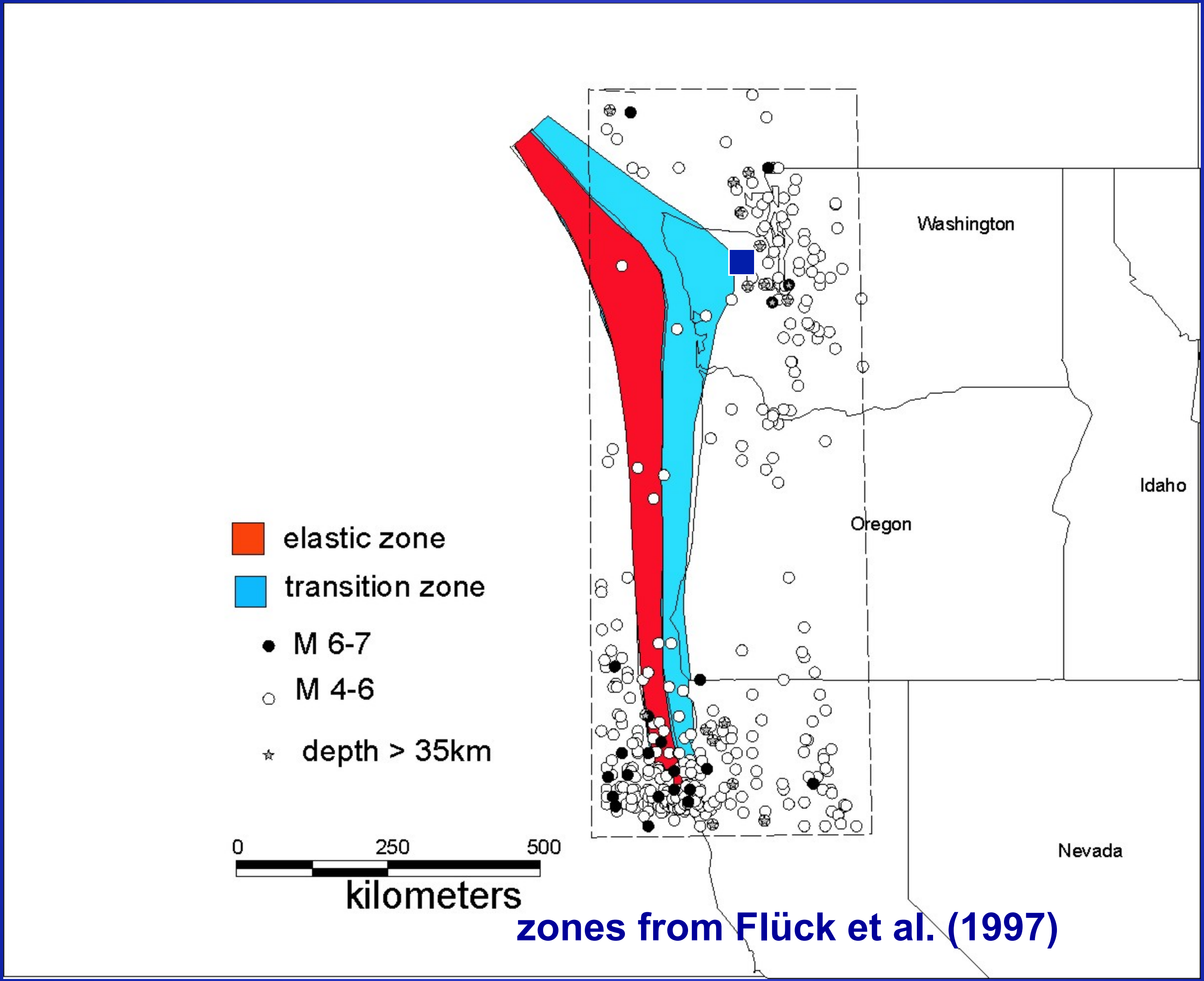


Epicenters used in simulations to determine azimuthal dependence of amplification for hazard from background earthquakes

Black shallow: 10, 15 km depth
Red: 50 km depth

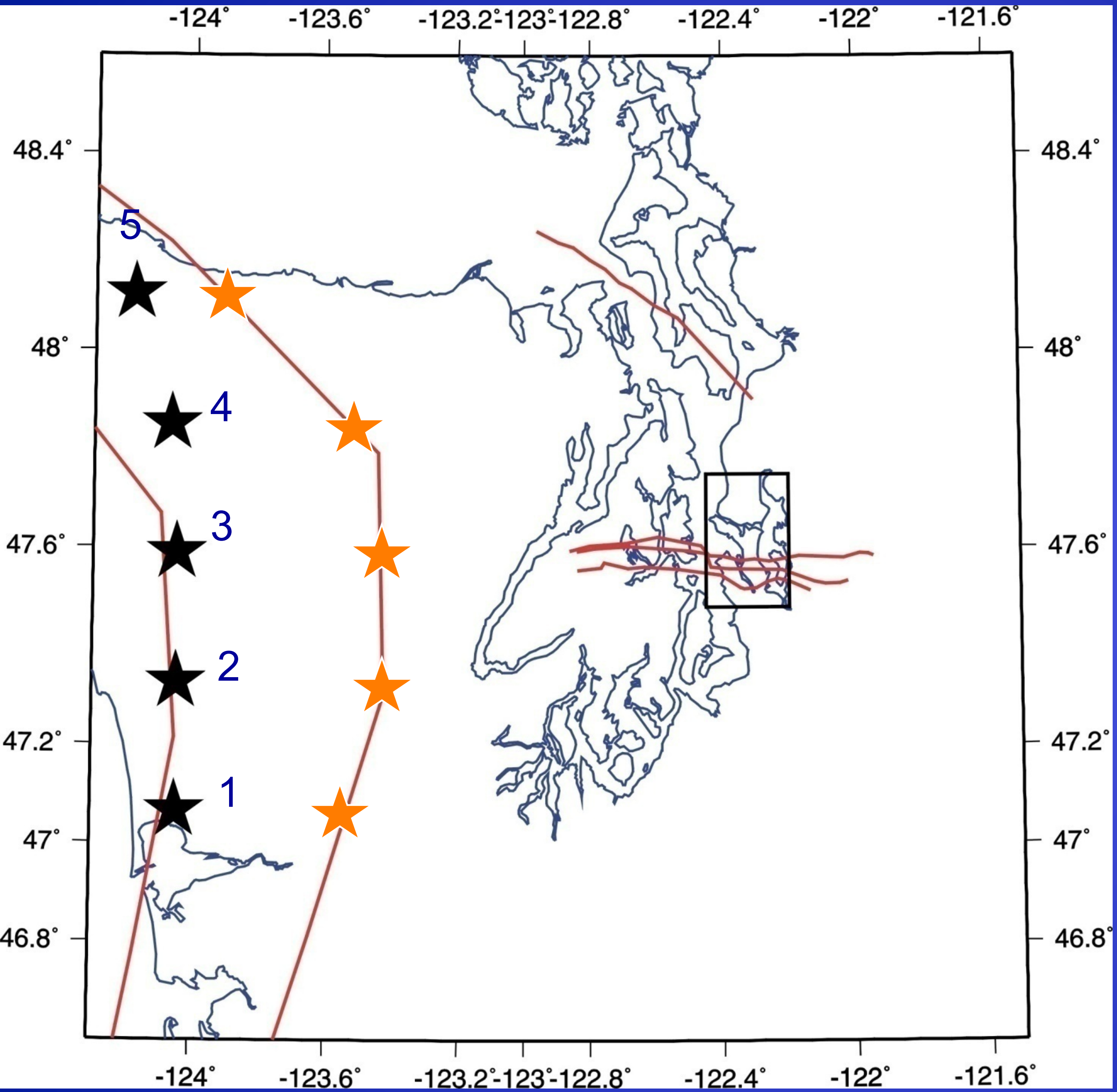
Distances chosen from dominant values from hazard deaggregation

Possible configurations for rupture zone of great Cascadia Earthquake

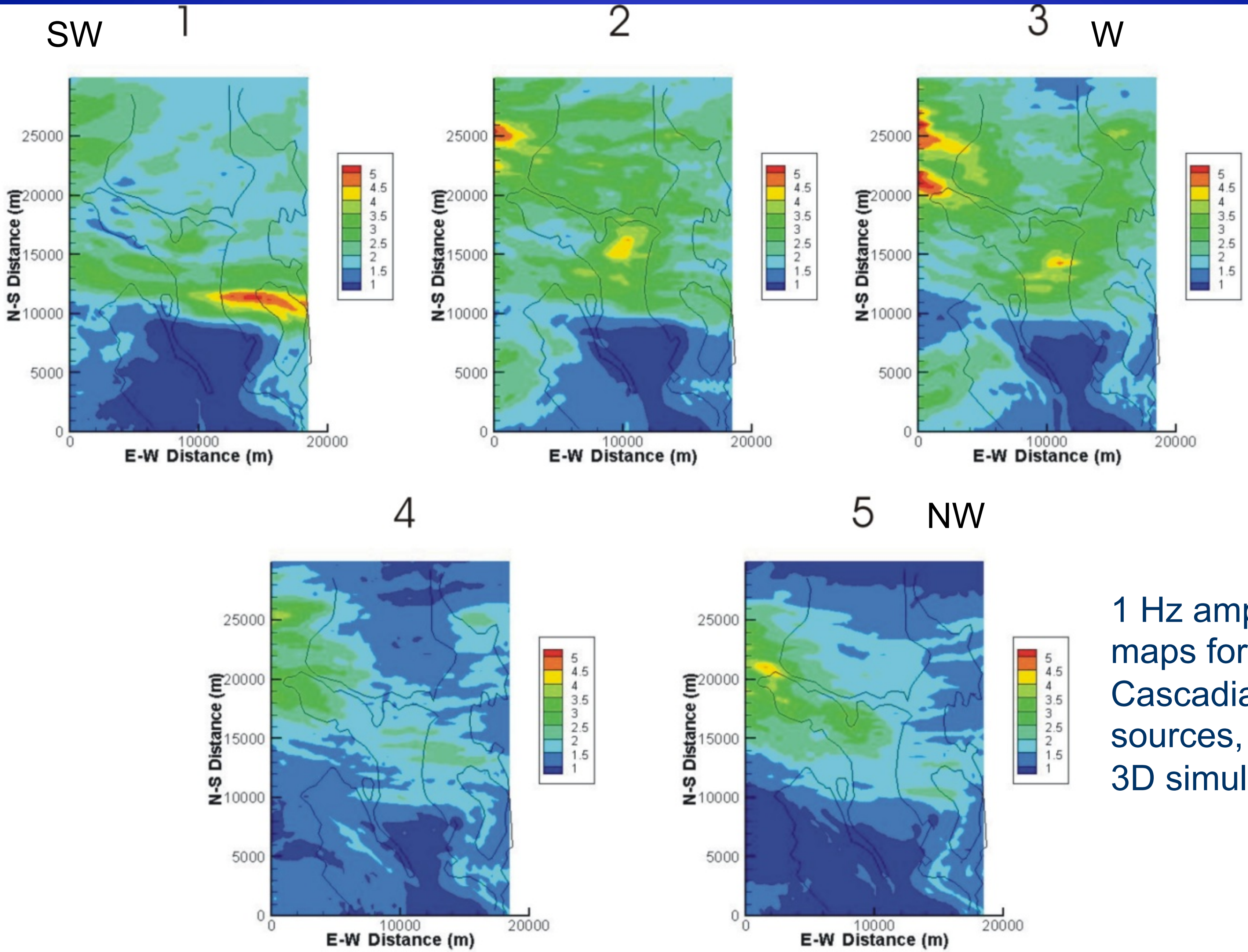


zones from Flück et al. (1997)

Figure from Petersen et al. (2002)



Point sources used to quantify amplification expected from great Cascadia earthquakes



1 Hz amplification maps for Cascadia point sources, from 3D simulations

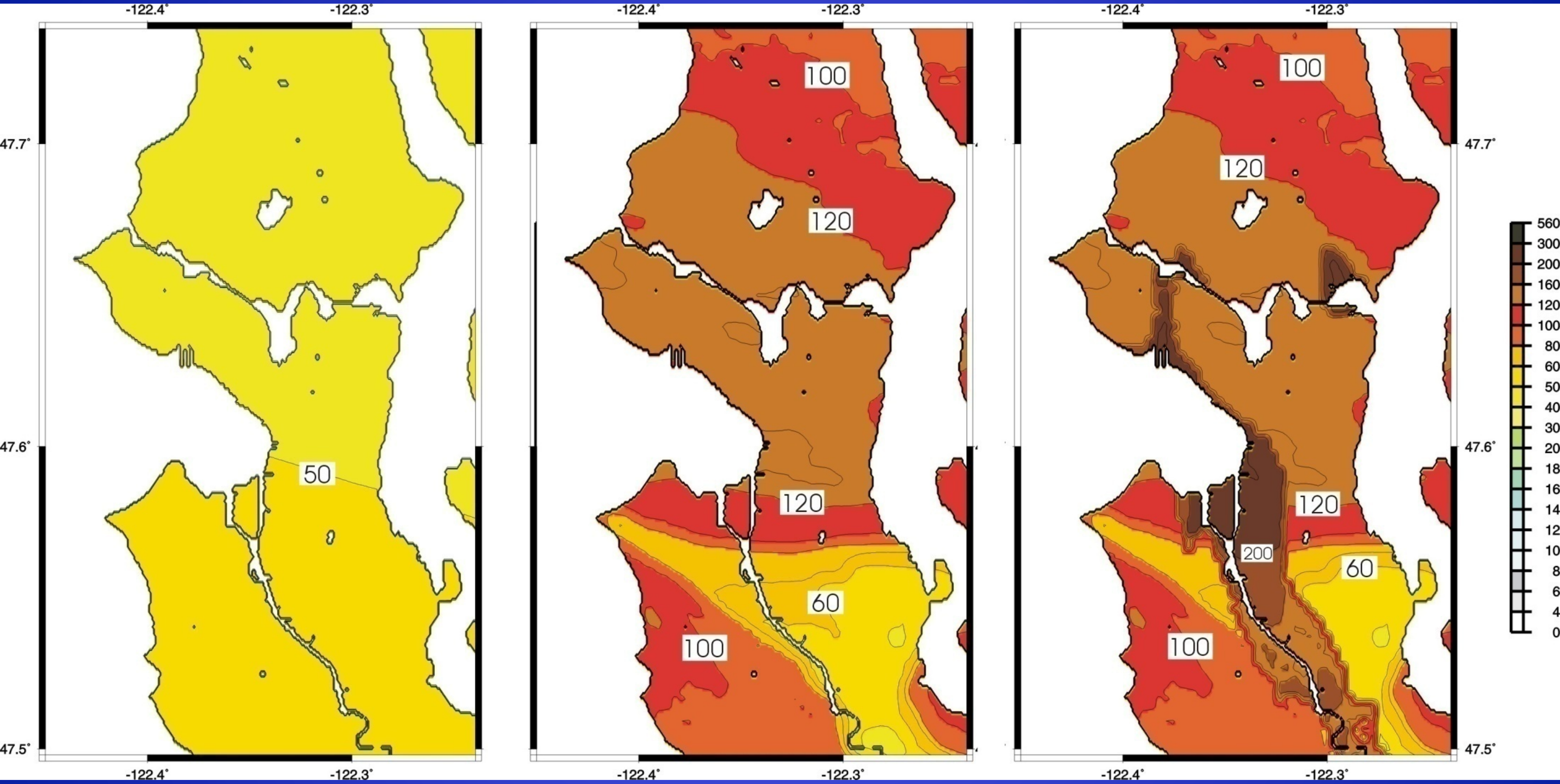
Aleatory Uncertainty

To calculate hazard from each source grid cell or each rupture scenario we applied aleatory sigma from empirical GMPE’s for firm-rock site condition

We also tried applying aleatory sigma to median of 1 sec S.A. for the 9 scenarios for each rupture zone. This produces very similar results at 10% and 2% PE as first approach.

Our approach ensures hazard values of new maps will be consistent with NSHM’s for firm-rock sites outside of Seattle basin

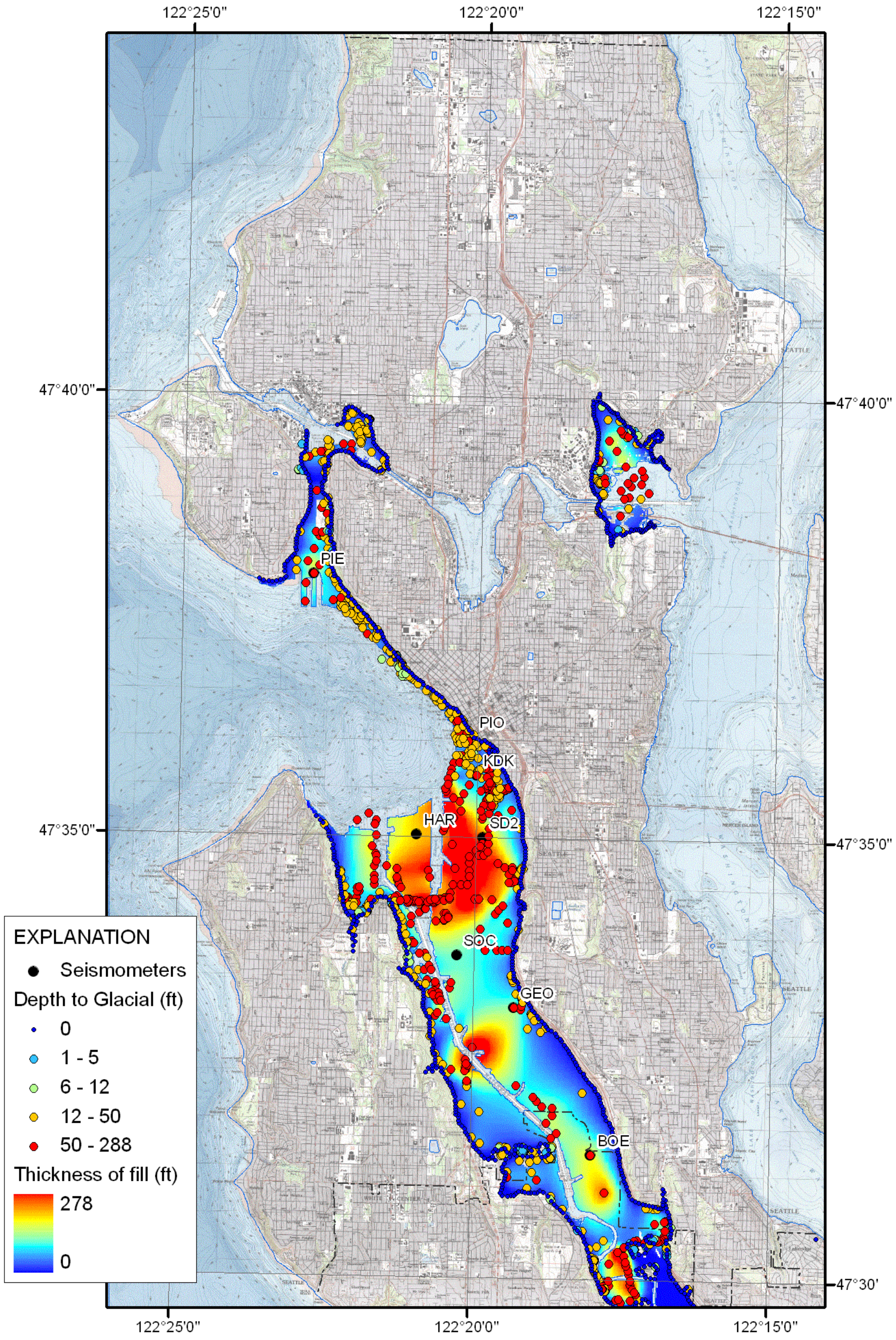
1 Hz Spectral Acceleration (%g)
with 2% chance of being exceeded in 50 years



one of 2002 national
seismic hazard maps;
Firm-rock site condition

Using 3D simulations with
basin effects
and directivity

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

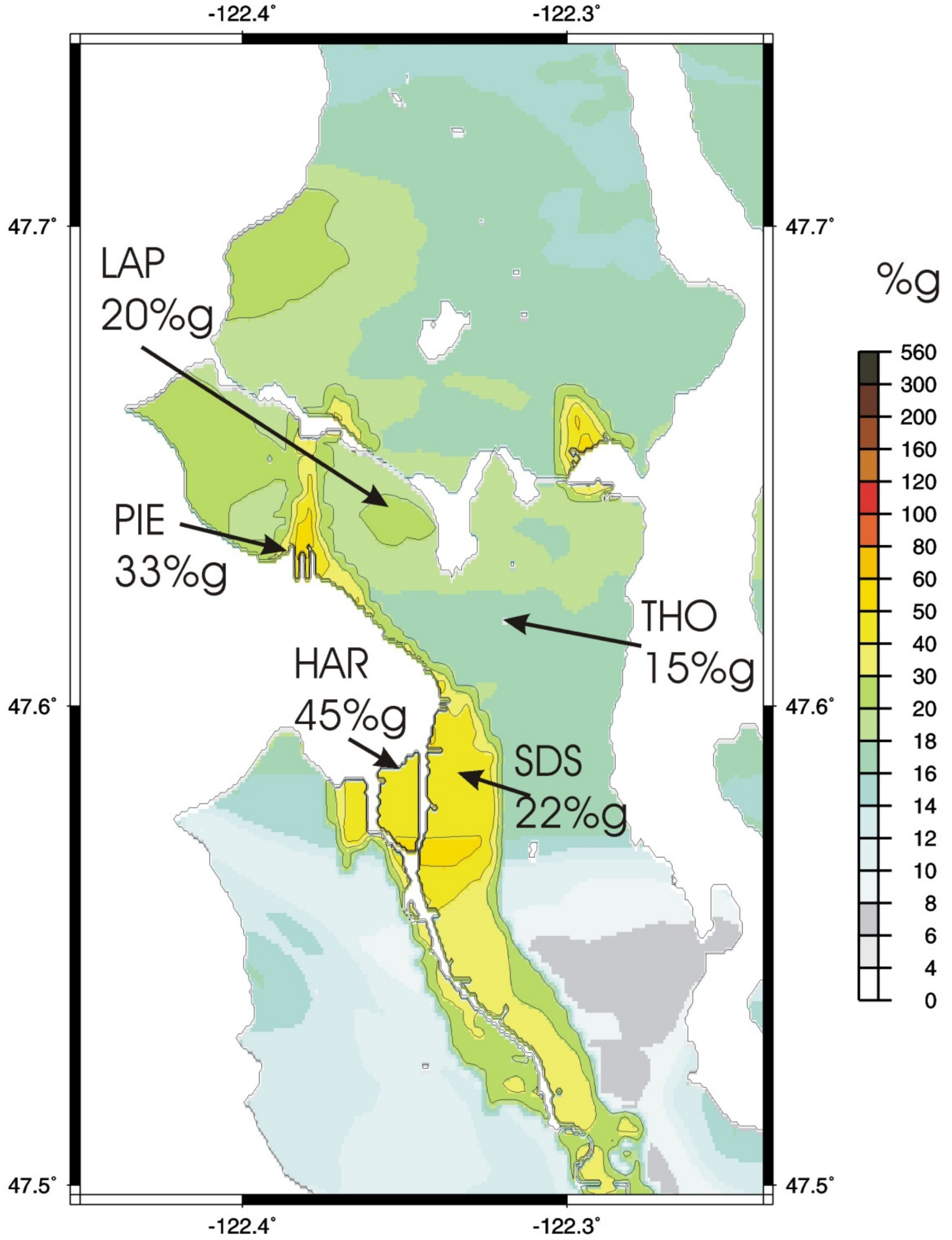


Map of thickness of fill/alluvium,
determined by Susan Rhea
using compilation of borehole data
by Kathy Troost (Univ. of WA)

This map of thickness was then used
to make a map of Vs30,
using an average
Vs profile for fill/alluvium sites

Amplification at soft-soil sites
determined from Vs30 using
Choi and Stewart (2005)
empirical amplification factors

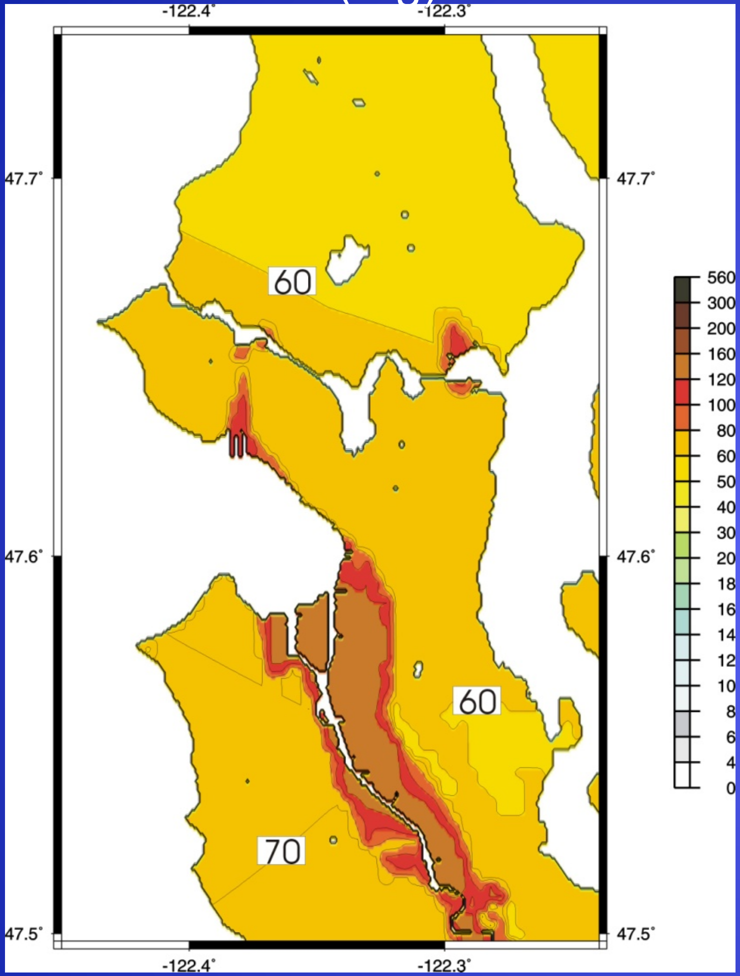
1 Hz S.A. with 50% Probability of Exceedance in 50 Years



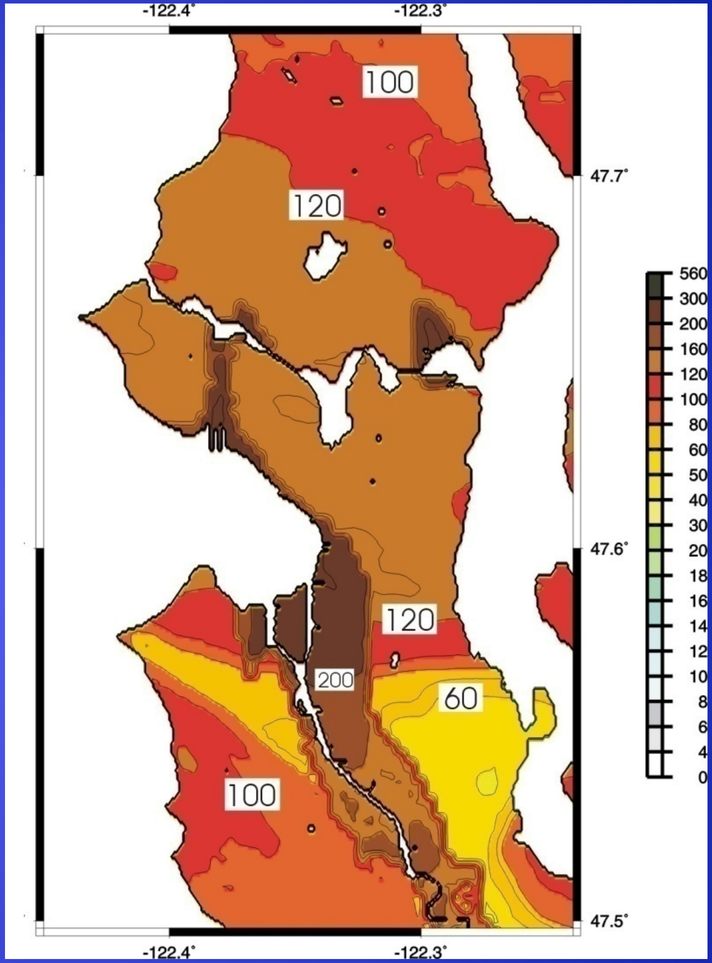
Labels show values observed from Nisqually EQ

We need to include basin amplification terms in building codes

1 Hz S.A. (%g) with 2% Prob. Of Exceedance in 50 Years

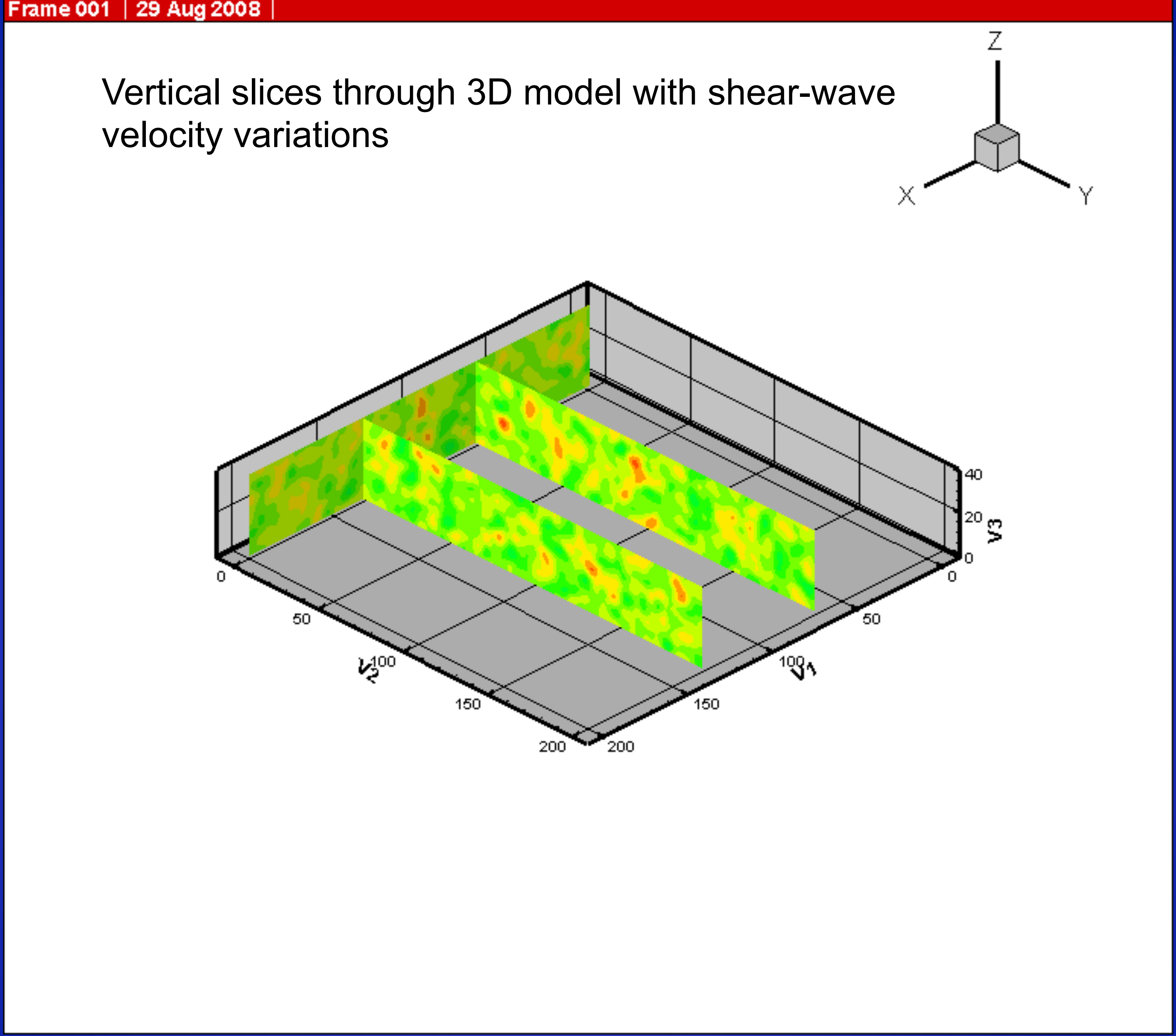


From 2002 national seismic hazard maps and NEHRP amplification factors based on Vs30 from surficial geology



New map with basin effects, rupture directivity, and nonlinear soil response at soft-soil sites

What are the effects of realistic 3D random spatial variations of Vs and Vp on the ground motions in the 3D simulations?



Vertical slices through 3D model with shear-wave velocity variations

Colors represent shear wave velocity variations

- Von Karman correlation function, stddev of Vs = 10% in top 1.3 km; 5% from 1.3-10.8 km depth; correlation distance of 5 km
- Randomness in Vs is fractal for length scales less than about 30 km (equal variance of Vs over equal log increments of wavelength
- Vs and Vp variations are correlated
- Minimum Vs = 500 m/s; minimum of mean Vs = 600 m/s
- This stddev for shallow basin Vs is consistent with variations found in borehole studies (e.g., ROSRINE; Thelan et al., 2006)

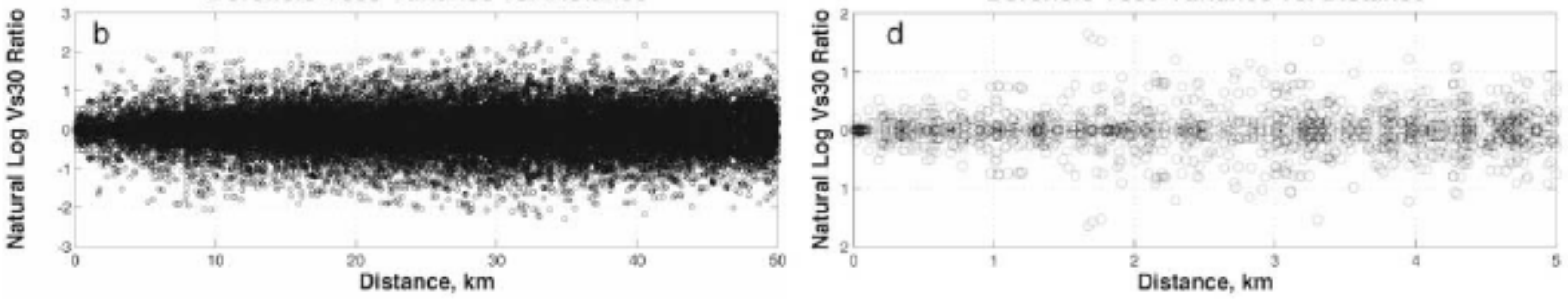


Figure from Thelan et al. (2006) showing variability in Vs30 in Los Angeles basin and San Gabriel Valley as a function of site separation; from borehole measurements compiled by Wills and Silva (1998) and Gibbs et al., (2000,2001)

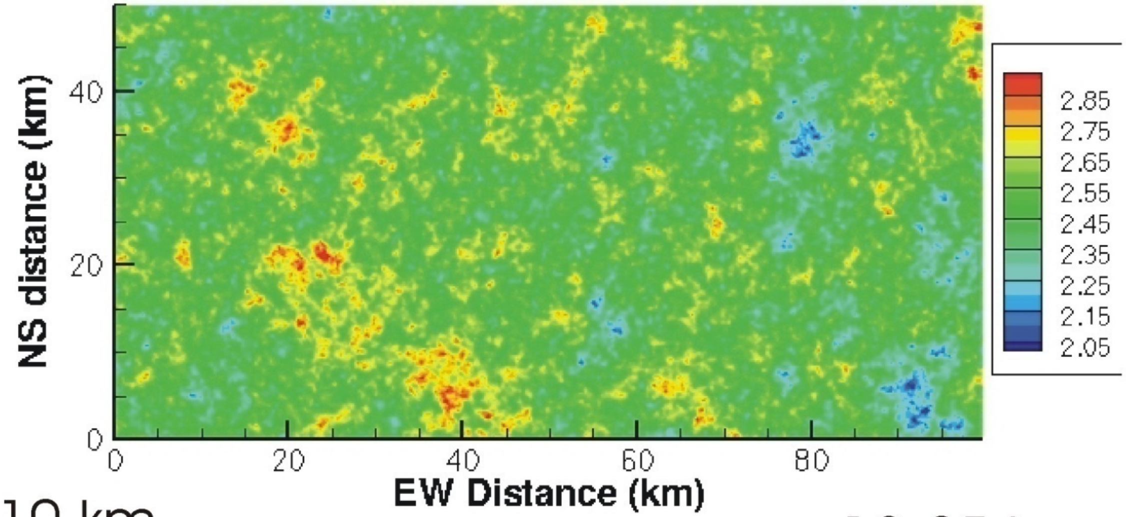
Power spectrum $P(k)$ of random variations for von Karman correlation function (with order m=0)

$$P(k) = C\,(1 + (ka)^2)^{-3/2}$$

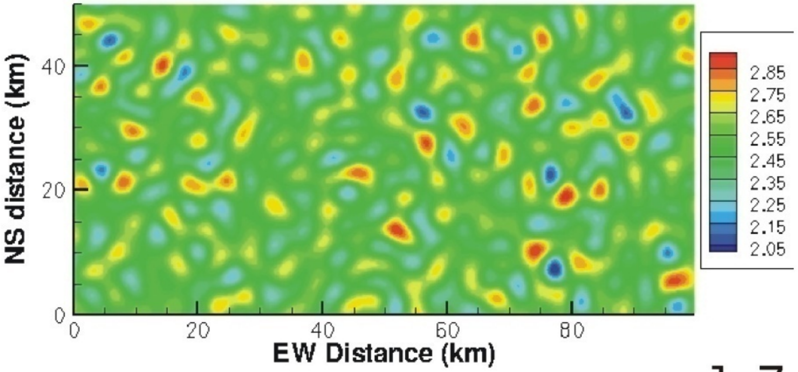
k is radial wave number for 3D medium

a is correlation distance

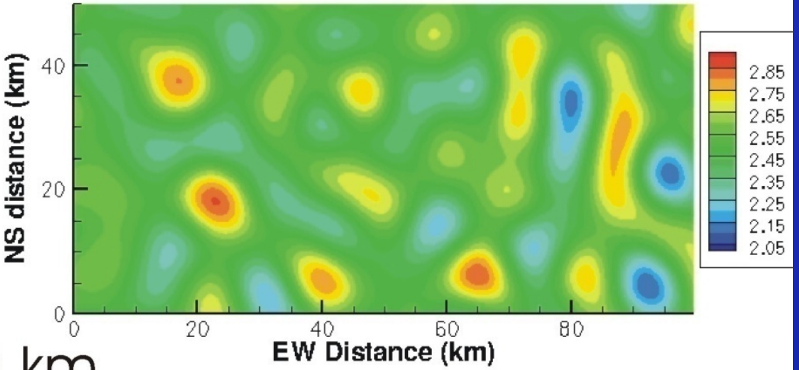
C is a constant



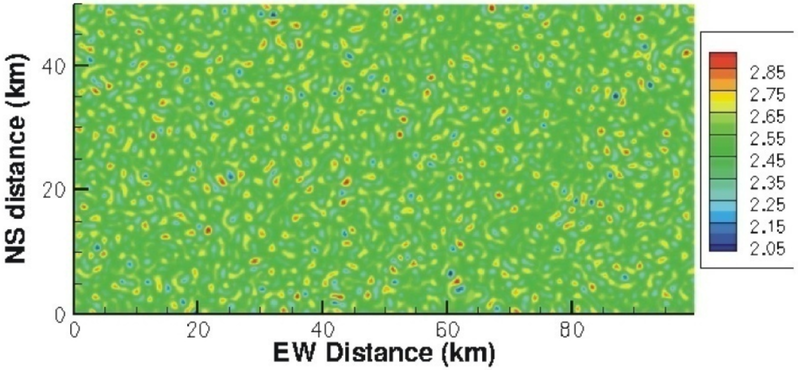
5-10 km



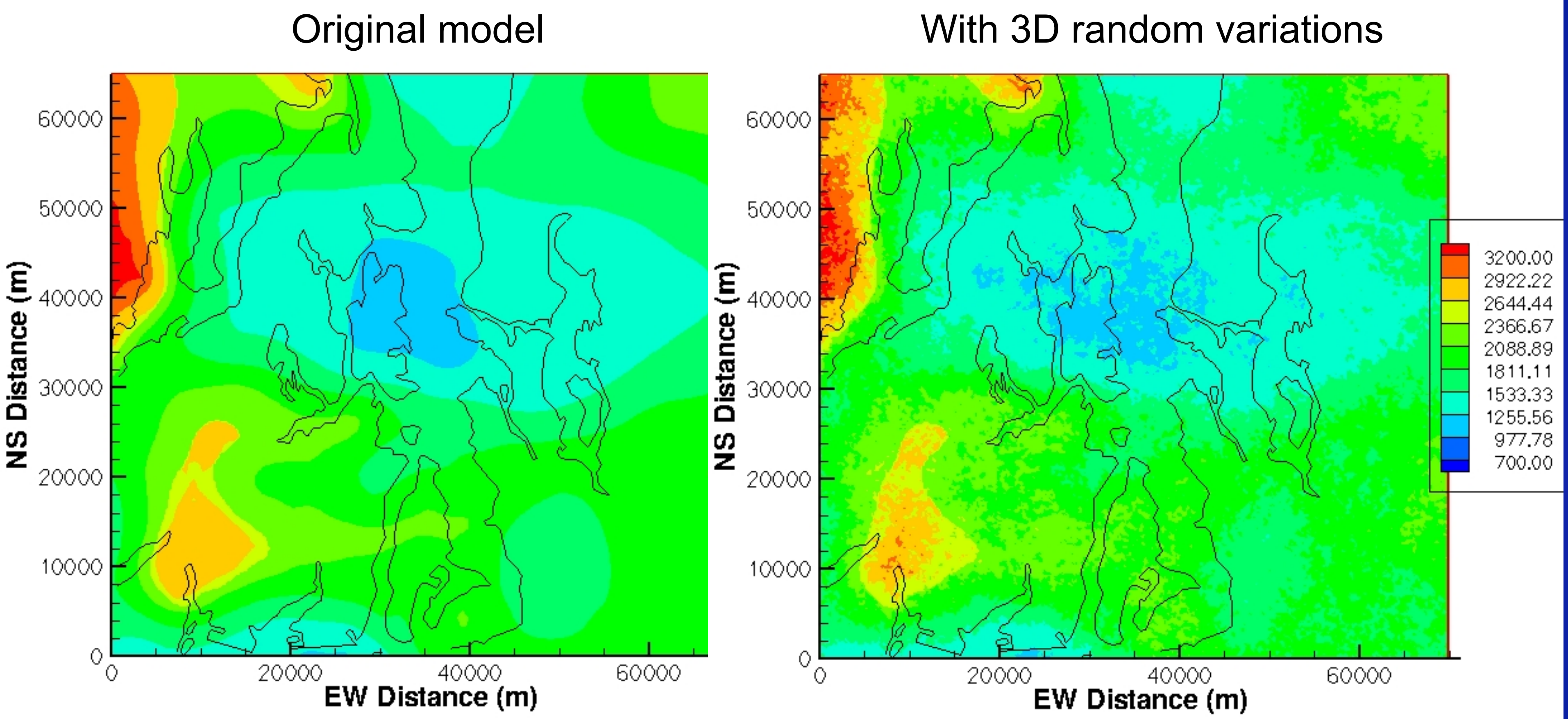
13-25 km



1.7-3.3 km



Shear-wave velocity (m/s) at 1.4 km depth

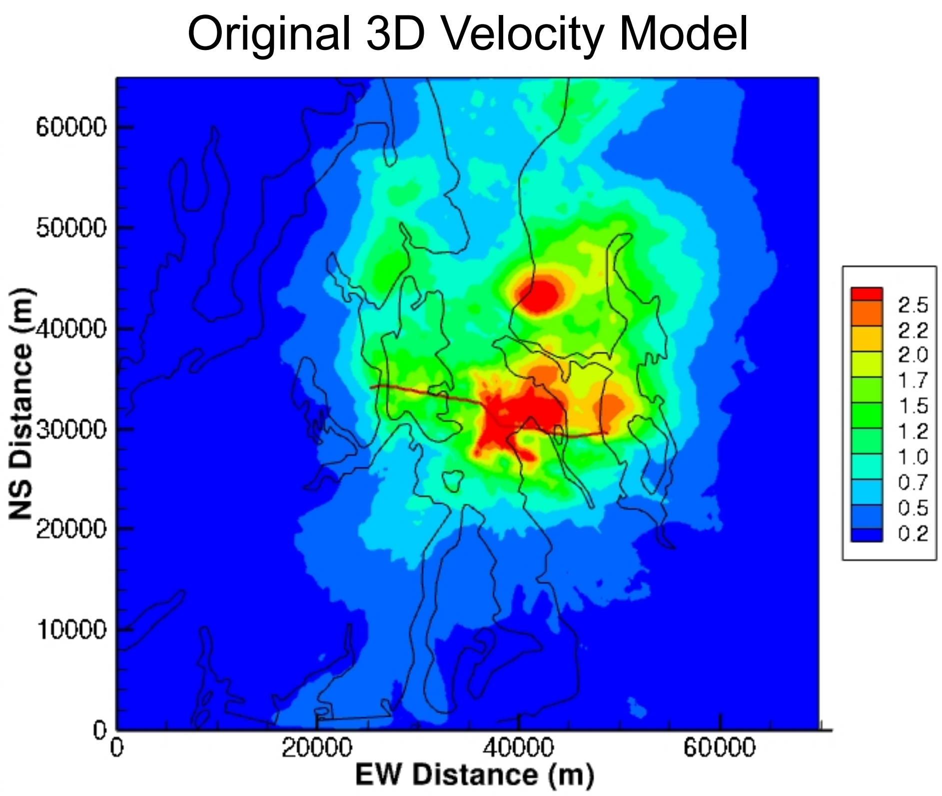


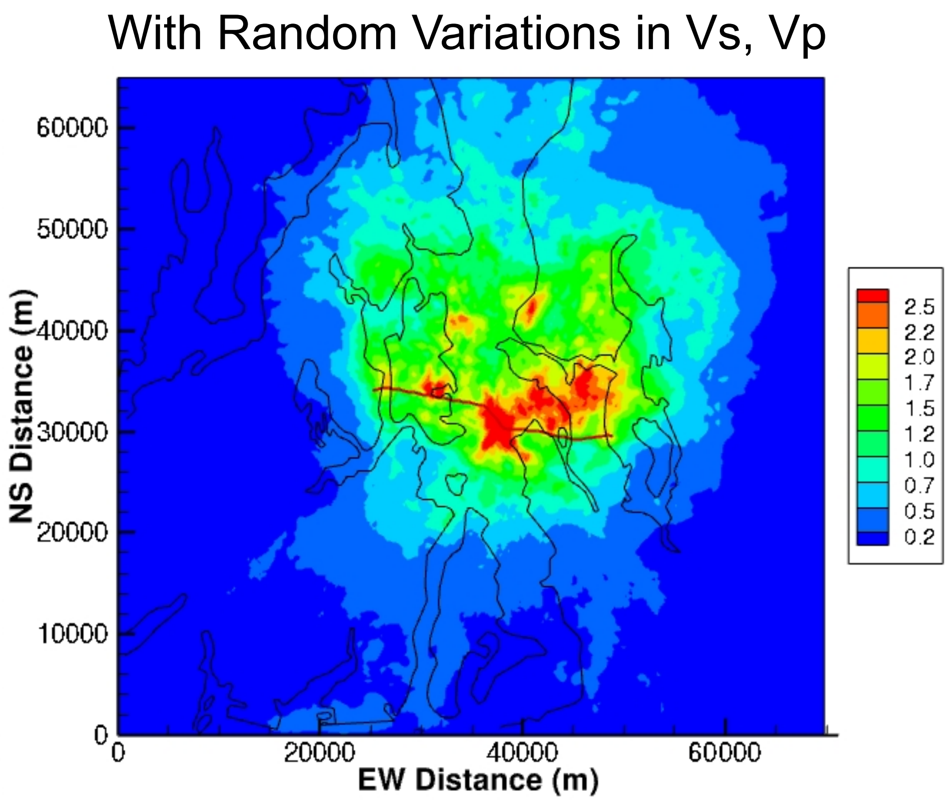
Original model

With 3D random variations

Used 10% std dev in top 1.3 km,
5% std dev from 1.3 to 10.8 km depth,
von Karman correlation function (wide range of scale lengths); Hurst exponent = 0

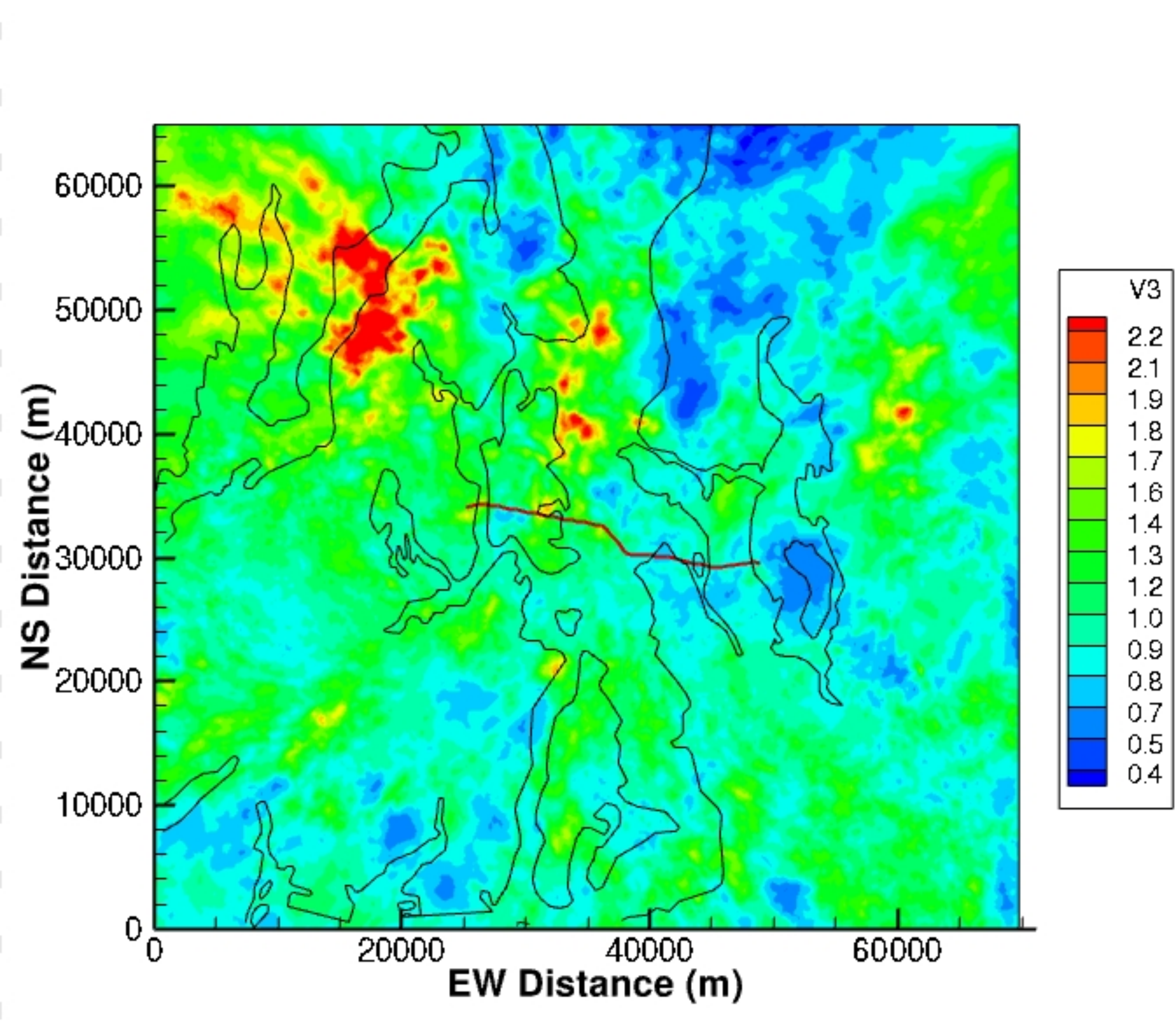
PGV’s (m/s) for simulations of M6.7 earthquake on Seattle fault


Original 3D Velocity Model


With Random Variations in Vs, Vp

PGV’s plotted are geometrical mean of PGV of two horizontal components

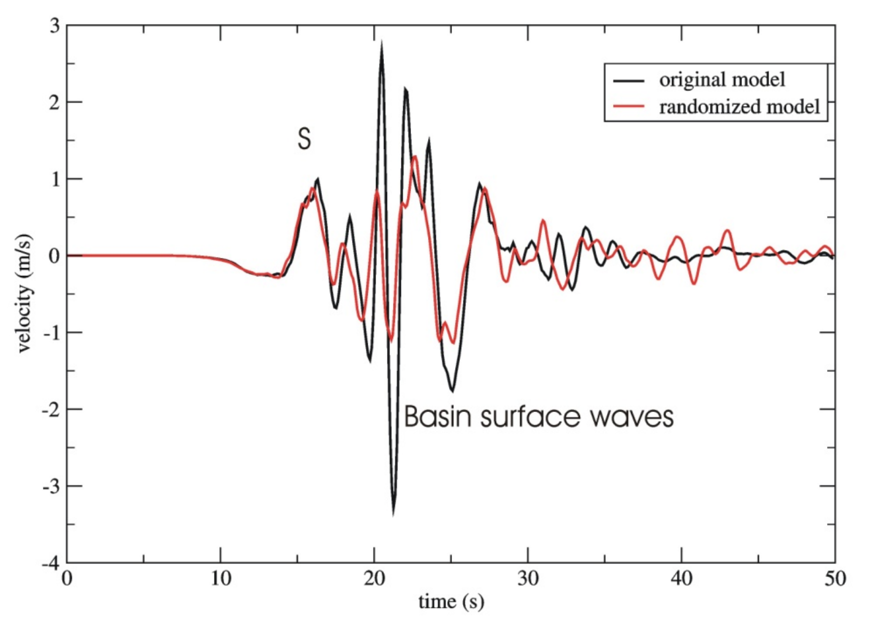
Ratio of PGV’s between randomized and original models

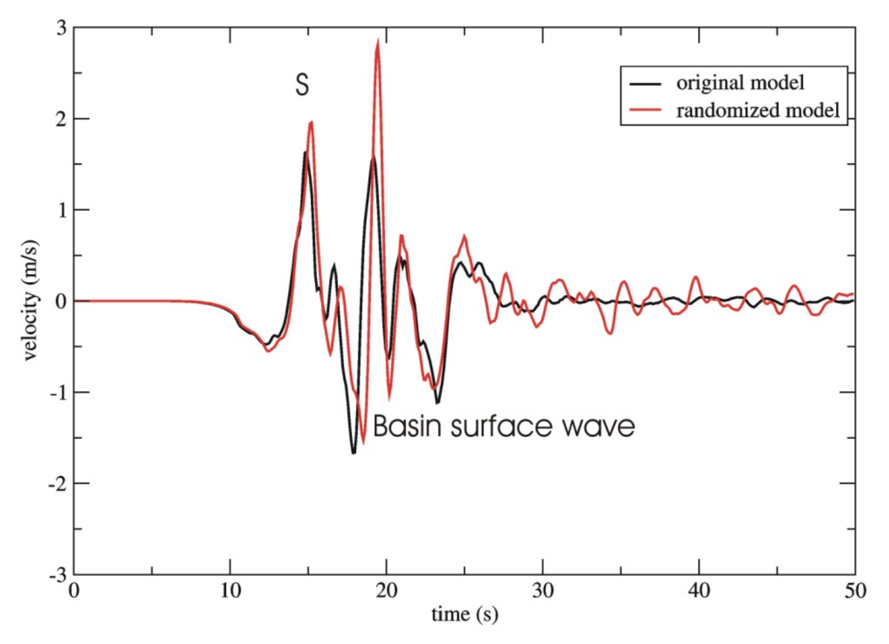


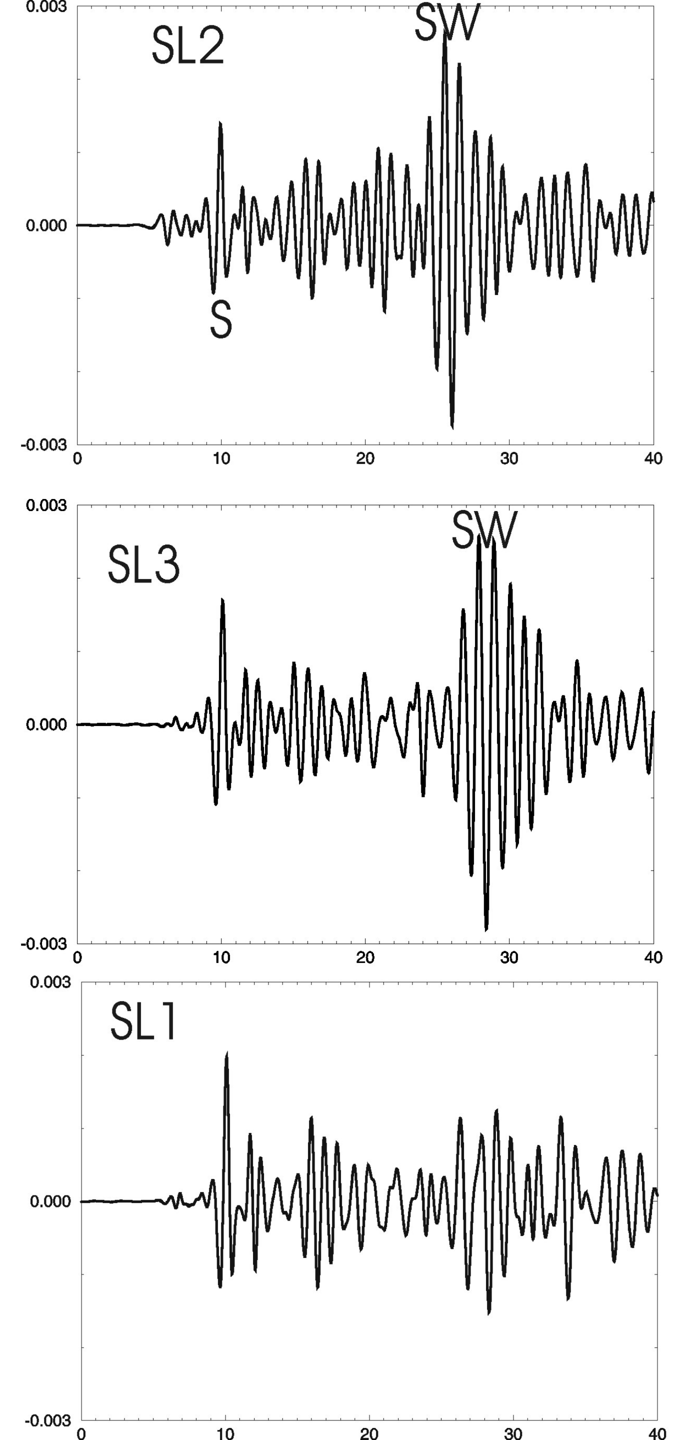
Random variations in Vs produce epistemic uncertainty in ground motions

Random variations in Vs strongly affect amplitudes of basin surface waves in simulations

All synthetic seismograms are NS velocity



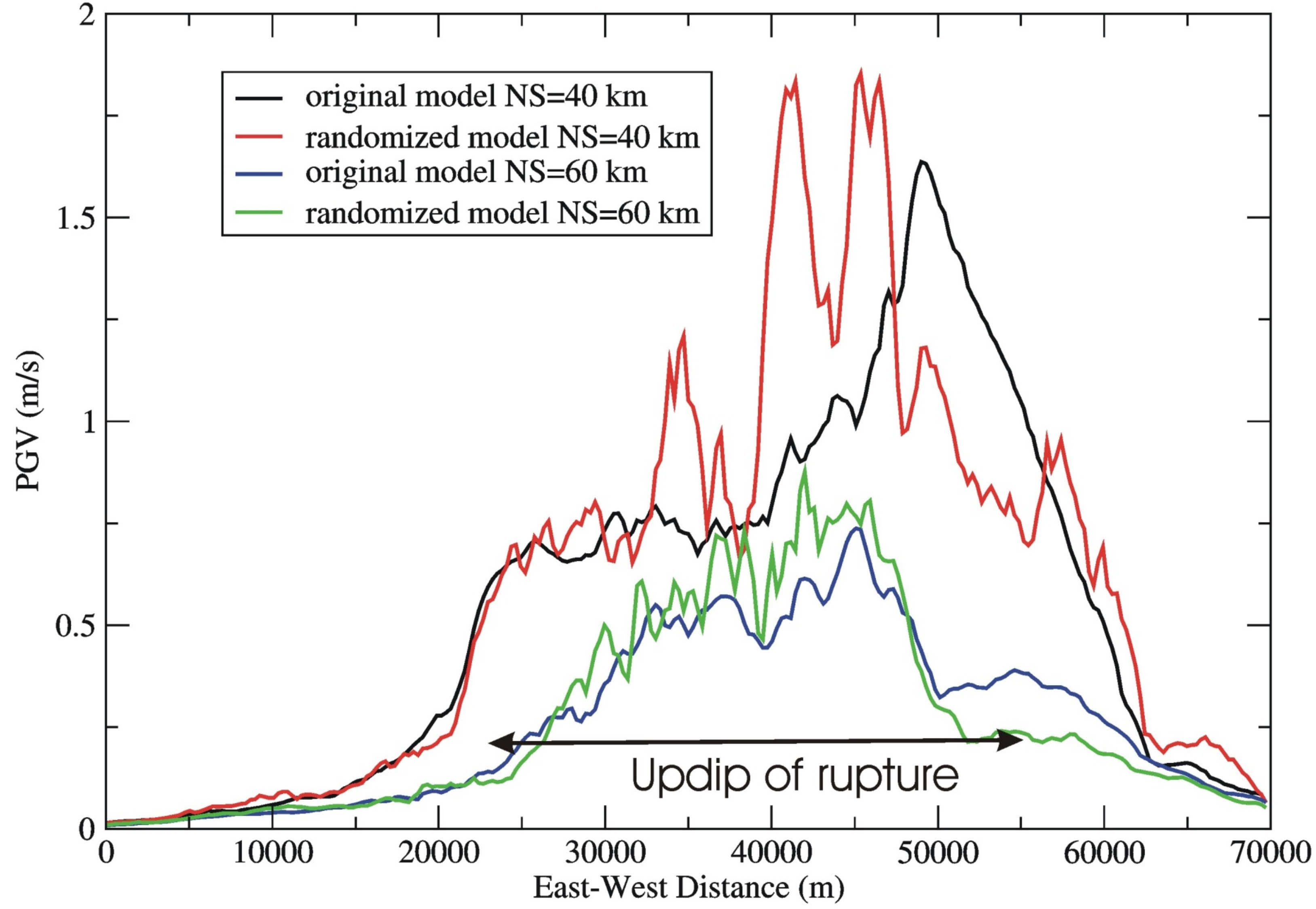




Observations of variability of basin surface waves (SW) across a 500m aperture array in San Leandro, CA (transverse acceleration records from M4.1 Alamo earthquake, filtered between 0.5 and 1.0 Hz)

Perhaps this is caused by random spatial variations of Vs in East Bay sediments

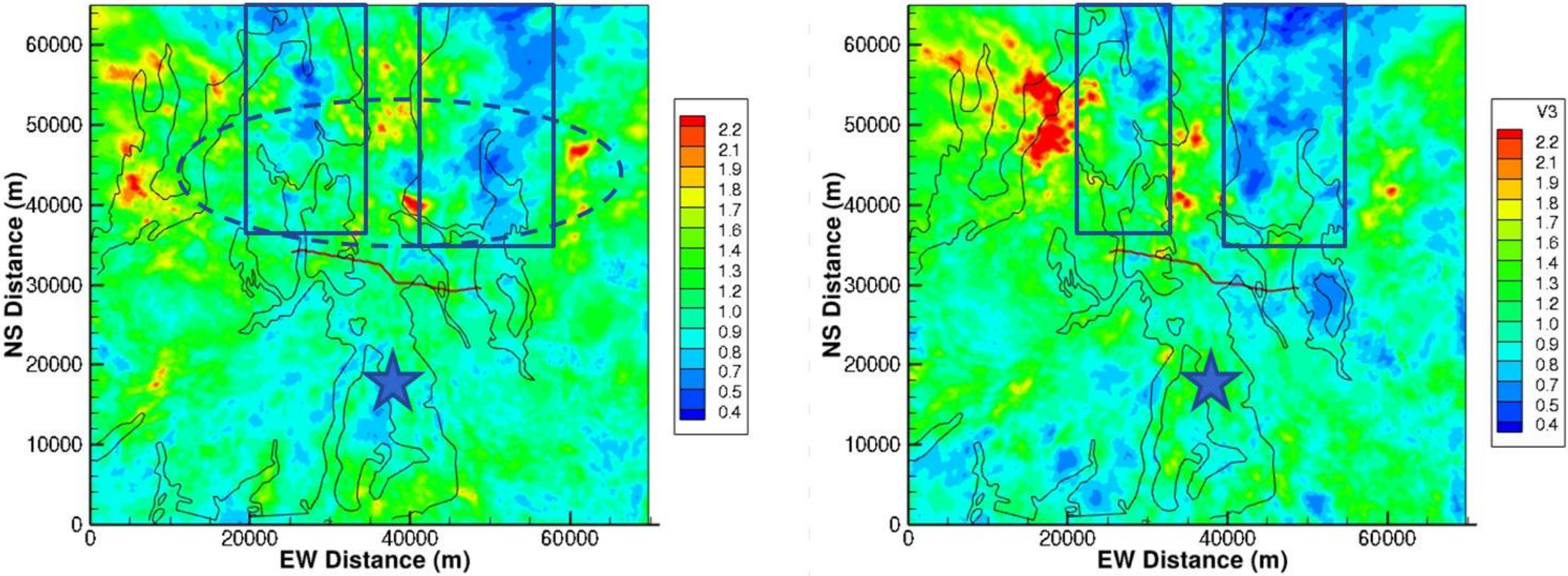
PGV in two East-West lines across basin



- Random variations in seismic velocity tend to reduce PGV and spectral accelerations in the direction of maximum forward directivity

Ratios of PGV's between randomized and original models

Different seeds for random variations; same slip distribution on fault

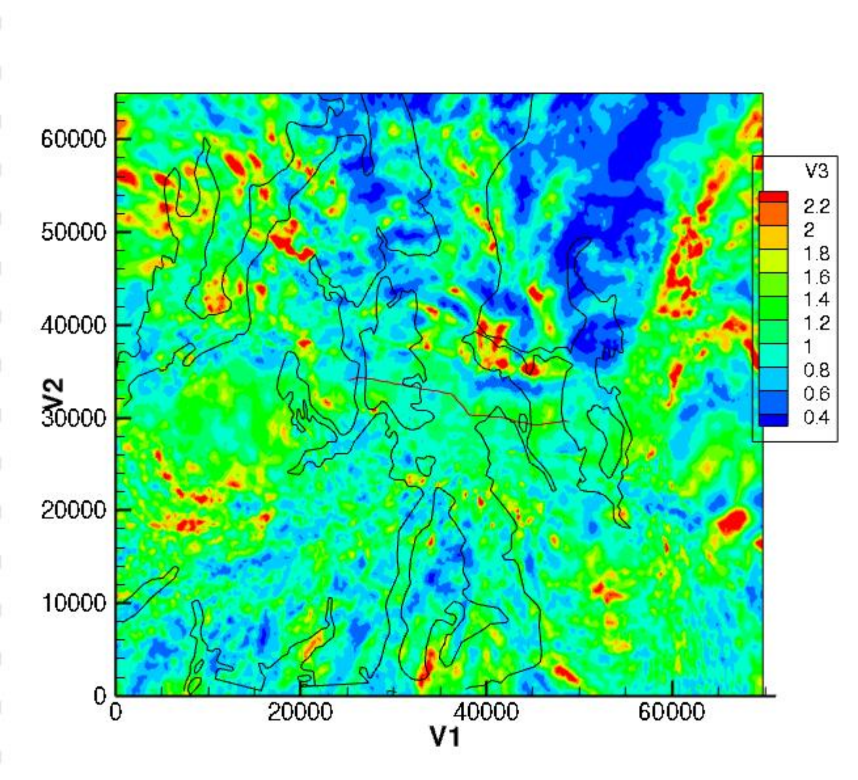


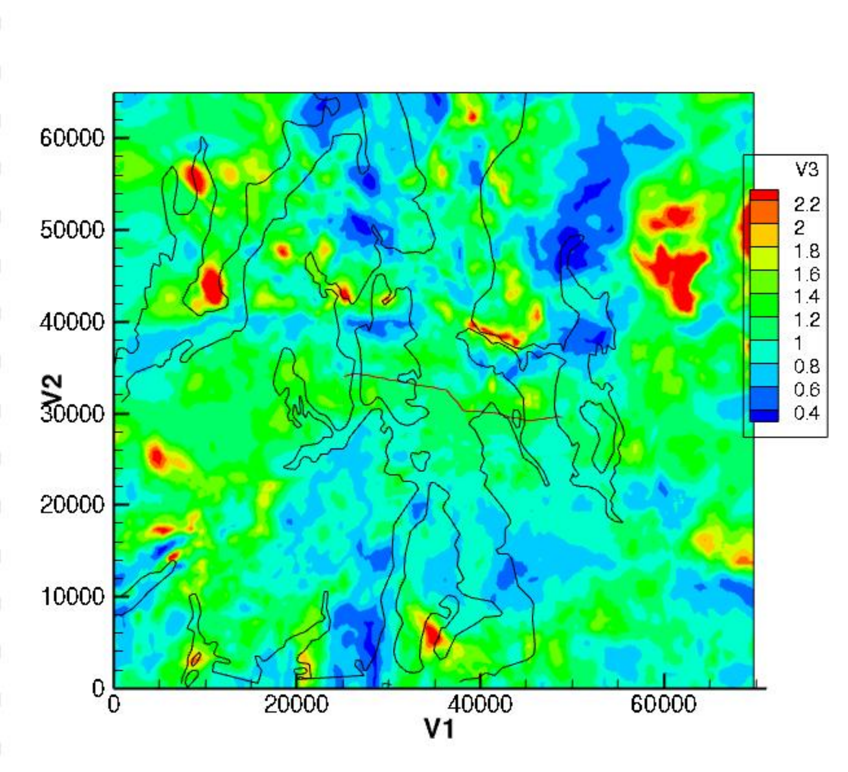
Dashed ellipse is approximate location of Seattle basin

Rectangles are areas of reduced average PGV in forward rupture direction caused by scattering from random variations

Ratio of 1.0 sec Spectral Accelerations between randomized and original models

Ratio of 3.0 sec Spectral Accelerations between randomized and original models

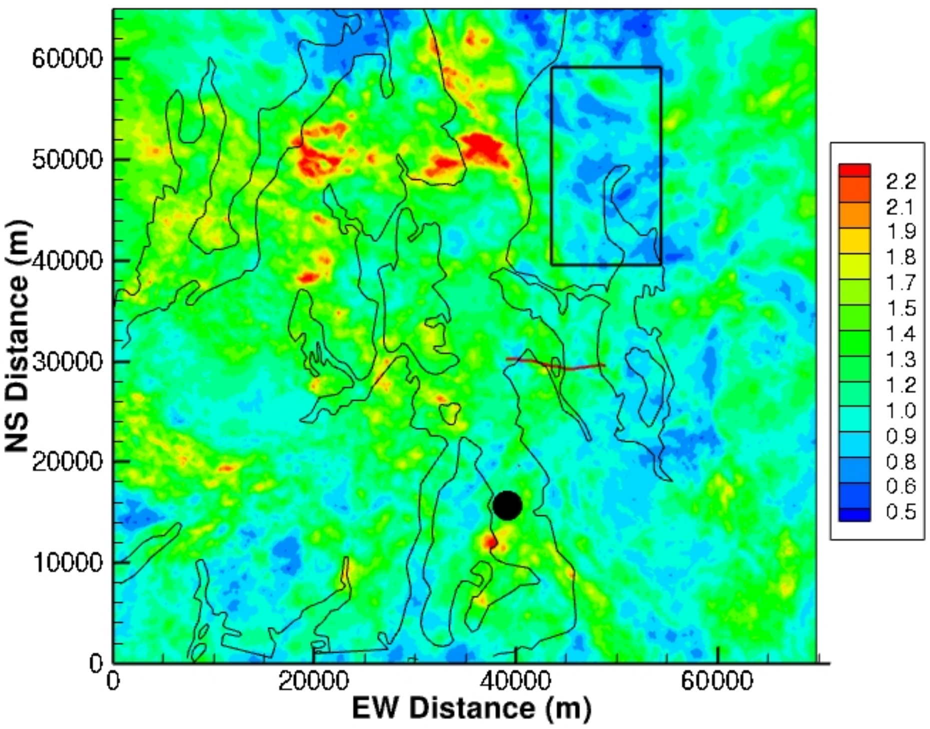


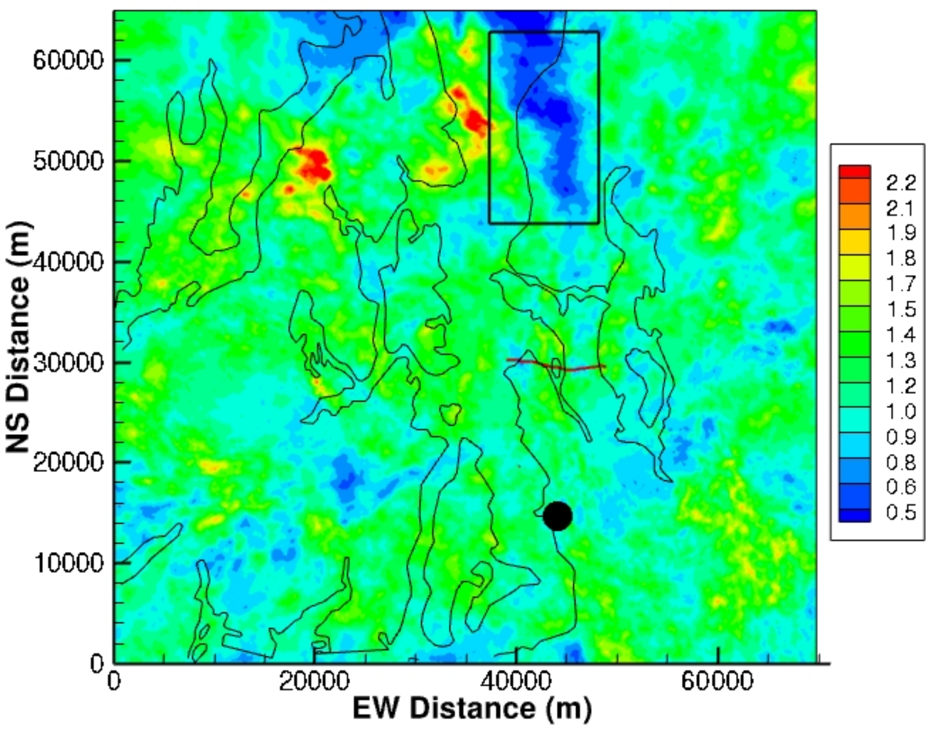


Ratios of spectral accelerations are taken from geometrical mean of spectral acceleration at each site over two horizontal components

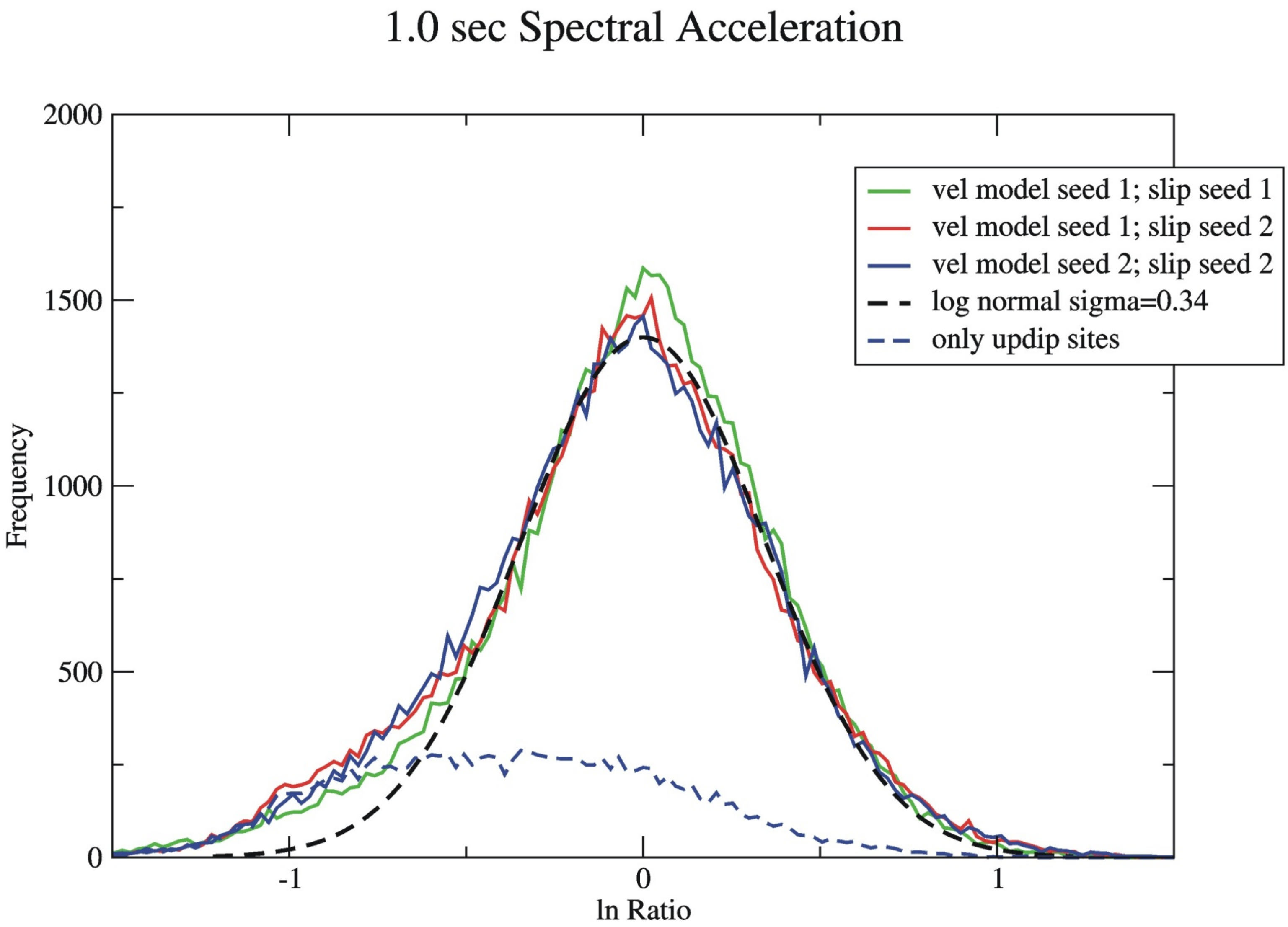
Note low ratios (deamplification) north of ends of fault at sides of basin
Higher ratios in center of basin and outside the basin

Simulations using eastern segment of fault:
Shifting hypocenter changes location of deamplification





Histograms of ratios of 1.0 sec S.A. between random and original models



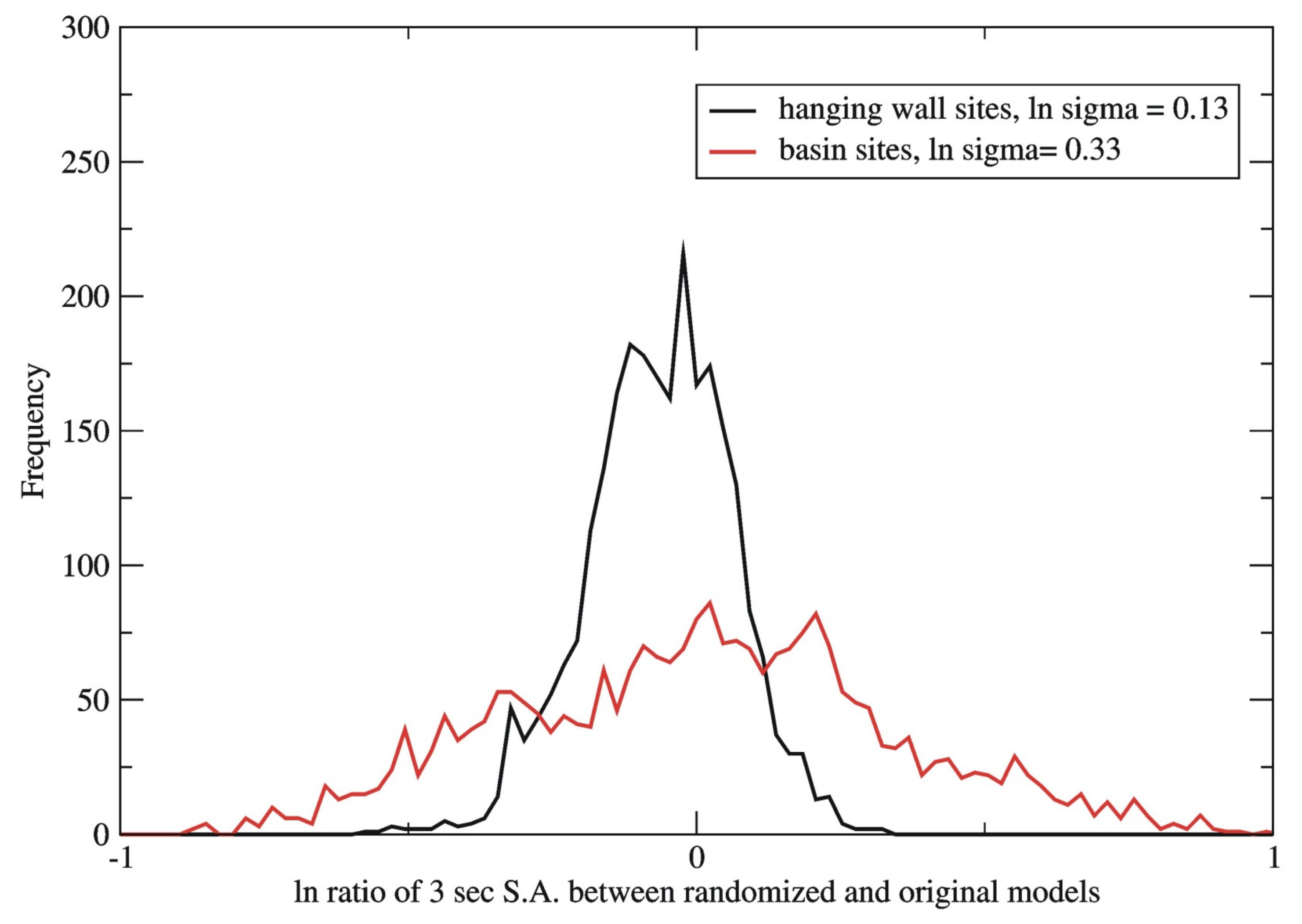
Excess of low values caused by decrease of amplitude at updip sites

- Random Vs variations produce epistemic uncertainty in spectral acceleration that is a significant portion of the so-called "aleatory" uncertainty of the misfit of GMPE's to data
- Standard deviation (ln units) for stiff-soil sites:

	1.0 sec S.A.	**3.0 sec S.A**
From random variations of Vs	0.34	0.27
Campbell and Bozorgnia (2008)	0.62	0.65

Random variations produce larger stddev (sigma) at basin sites than hanging wall sites because basin surface waves are more sensitive to random variations than are steeply propagating S-waves in hanging wall.

May be tendency to reduce median amplitude of hanging wall sites



Why Should We Care?

- Earthquake scenarios in 3D models without random variations in Vs may overestimate areas with focused basin surface waves; may overestimate PGV and 1.0 and 3.0 sec S.A. in forward rupture direction for sites and underestimate amplitudes in other directions
- Probabilistic hazard maps such as Seattle maps using hundreds of scenarios mitigate this problem
- Random variations in Vs (stddev of 10%) can produce localized amplification of a factor of two in PGV and 1.0 and 3.0 sec S.A. over distances of a km or so; could explain some cases of localized differences in damage from earthquakes

Why Should We Care?

- For PSHA: random variations in Vs produce significant epistemic (modeling) uncertainty of ground-motion values that will affect calculations of hazard; epistemic ln sigma of 0.3 for basin sites (for PGV, 1.0 and 3.0 sec S.A.), a substantial portion of observed sigma from GMPE misfit of data
- We need to better assess the variability of basin surface waves caused by small-scale fluctuations of Vs, using array observations and simulations, to improve our estimates of ground-motion uncertainty (sigma) for urban seismic hazard maps and to provide synthetic seismograms that capture the variability of basin surface waves for the design of long-period buildings