Future Trends in GMPE Development

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Outline

- Expected changes in GMPEs in < 3 yrs
  - 1. Move to FAS-based models
  - 2. Improved site description – full VS profile and kappa
  - 3. Greater use of 1-D finite-fault kinematic simulations to constrain global scaling for GMPEs medians
  - 4. Move to fully nonergodic GMPEs (California example)
- Expected changes in GMPEs in 3-6 yrs
  - 5. Use of 3-D finite-fault kinematic simulations to constrain path effects
  - 6. Use of 1-D dynamic rupture simulations to constrain source scaling

1. Move to FAS-based Models

- Develop FAS models
  - Empirical GMPE for FAS (scaling with M, R, SOF, site, HW, directivity, …)
  - Apply constraints from physic-based models
- Forward application of the FAS GMPE to generate smooth FAS for wide range of scenarios
  - Extrapolation is done using the FAS models
- Convert FAS to Response Spectra (PSA)
- Develop GMPE for PSA from the simulated data
  - Mainly curve fitting as extrapolation was addressed in FAS model

Using Estimating PSA from FAS

Method 1	Method 2
FAS Model	FAS Model
Duration model & Random phase	Phase derivative distribution (allows including near-fault directivity and fling)
Standard RVT	Modified RVT (non uniform phase)
PSA	PSA

Advantages of the FAS approach

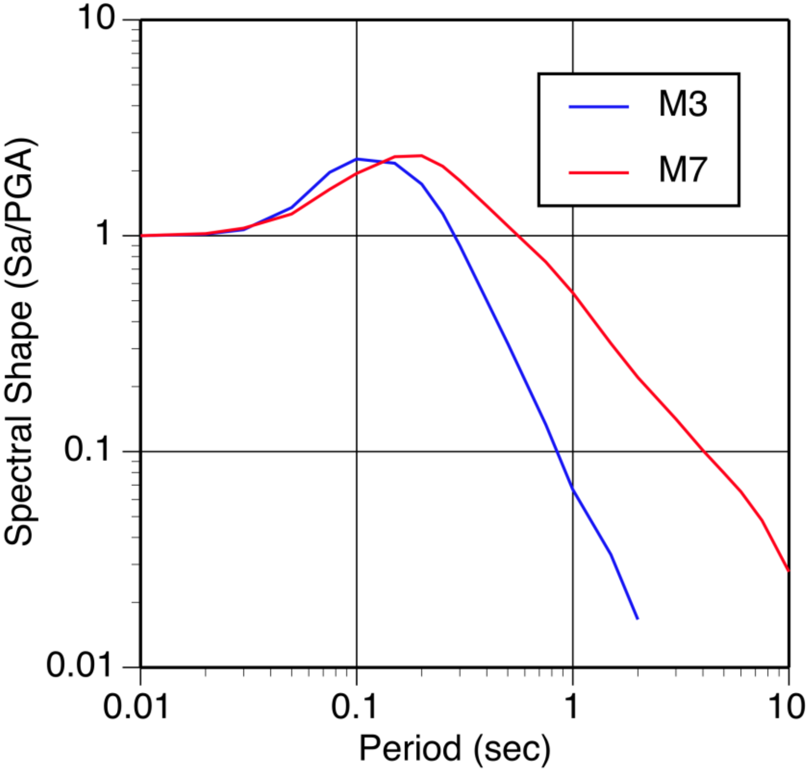
- GMPE – Seismology interface
  - FAS provides a better interface with seismological models than PSA
  - Much better for incorporating Finite-Fault Simulations
- Estimation of site terms
  - FAS site terms are simple (Linear site amplification is linear in FAS, but not always for PSA)
    - For FAS, amplification does not depend on the frequency content
  - Allows for use of the site amplification from small magnitude earthquakes more directly
  - Allows for a GMPE-specific representative VS profile (and range) to be developed
- Incorporation of Kappa
  - Straight-forward dependence on kappa

2. Improved site description

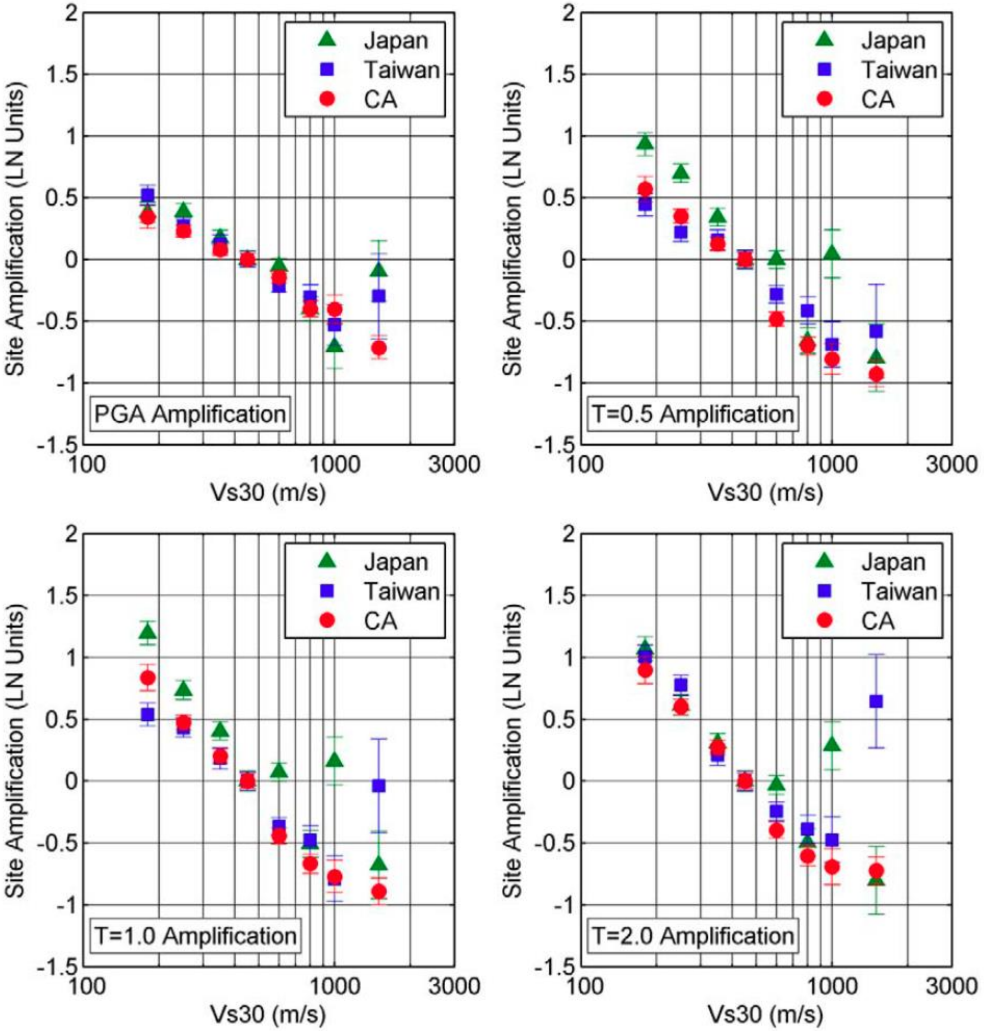
- Allows use of small magnitude data to constrain site without spectral content issue found for PSA
- Provide VS profile and kappa for VS30 values

Use of Small Magnitude Data for Site Terms

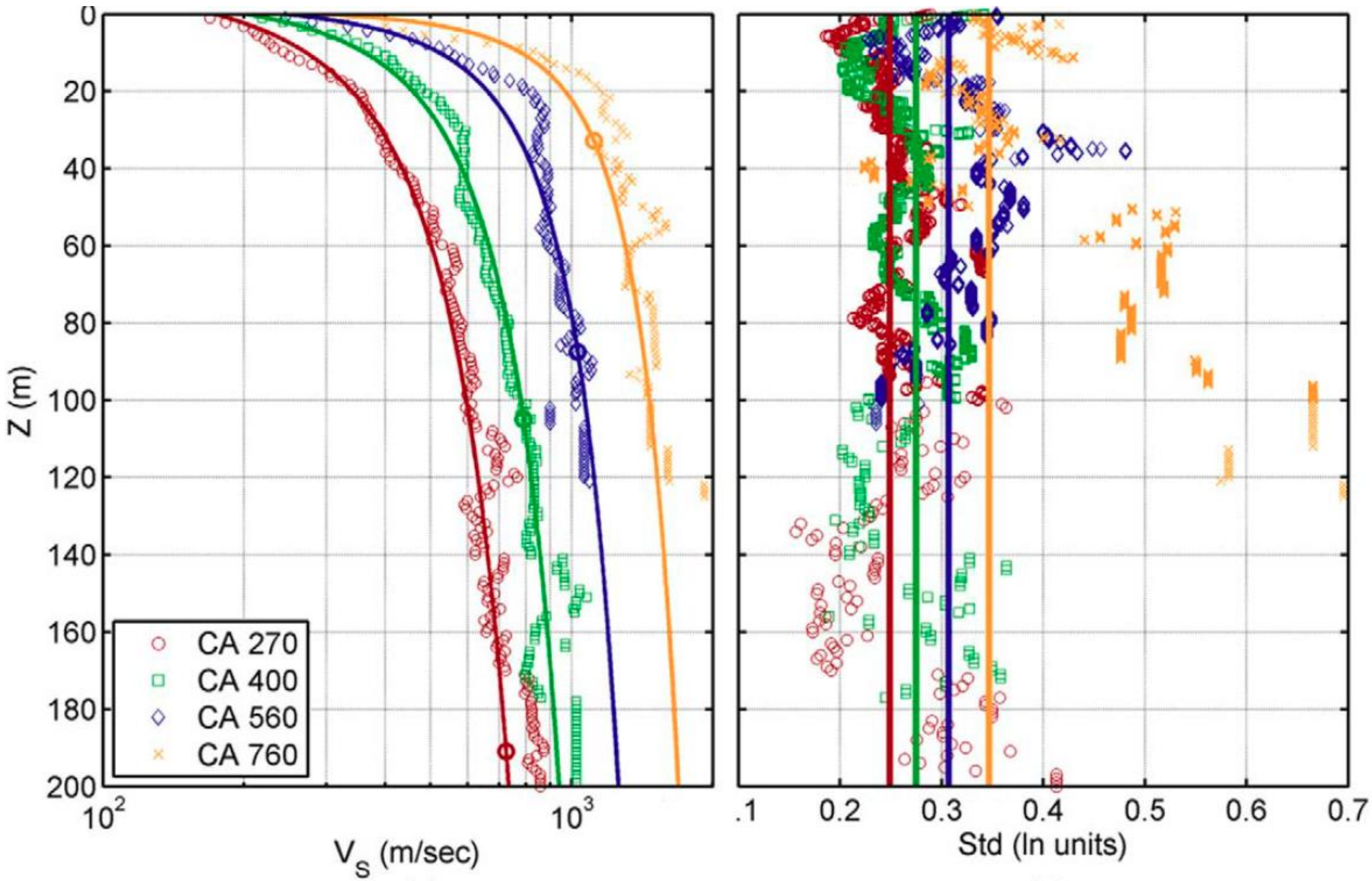
- Large data sets with small magnitude data
- Linear site response
  - Greater use of small magnitude data to constrain site amp
  - Issues of linearity of Sa scaling
  - Affected by the spectral shape, even for linear response
  - FAS does not have this issue



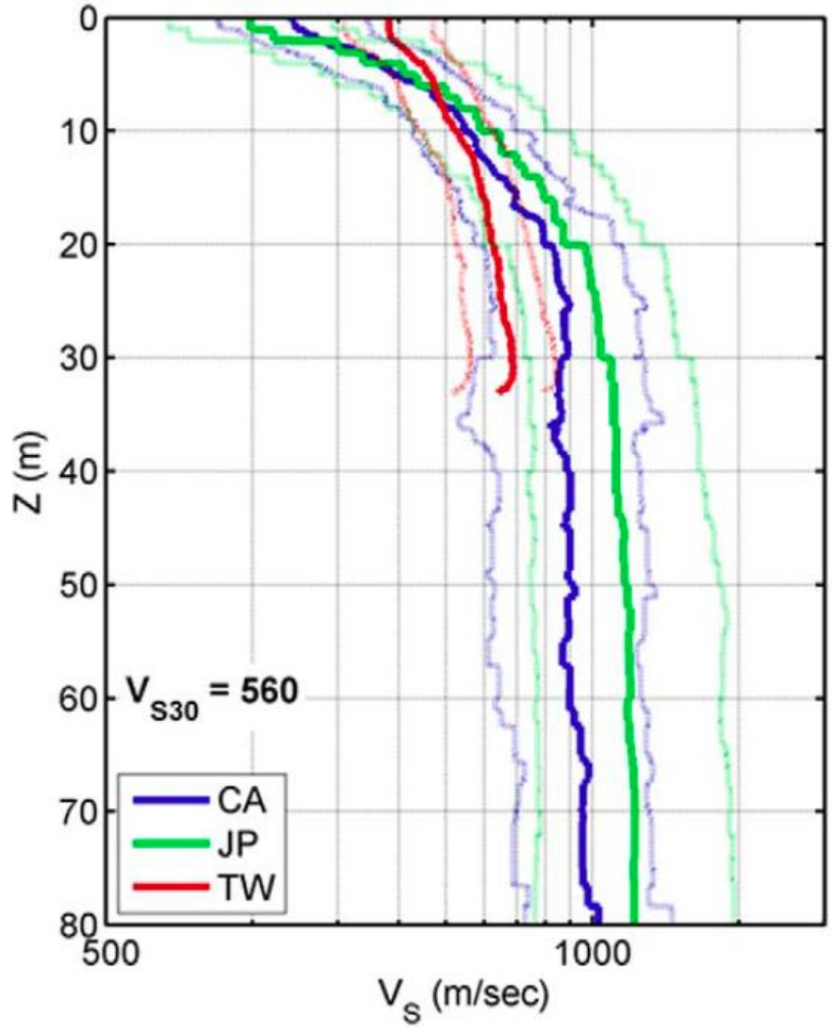
VS30 is correlated to the site amplification (>30m influence)



Correlation of VS30 and Shallow VS profile in California



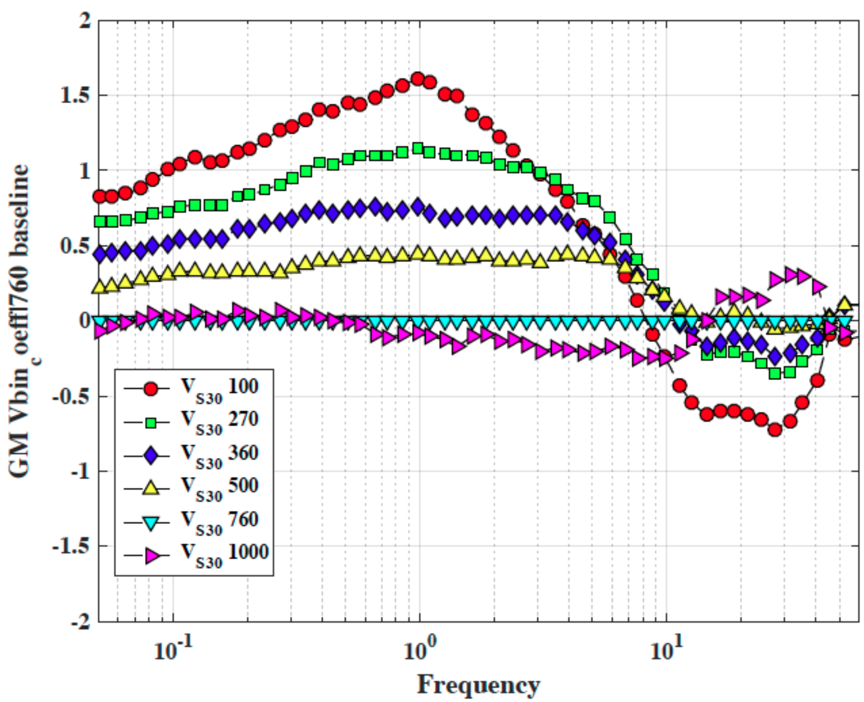
Correlation between VS30 and VS profile vary by region

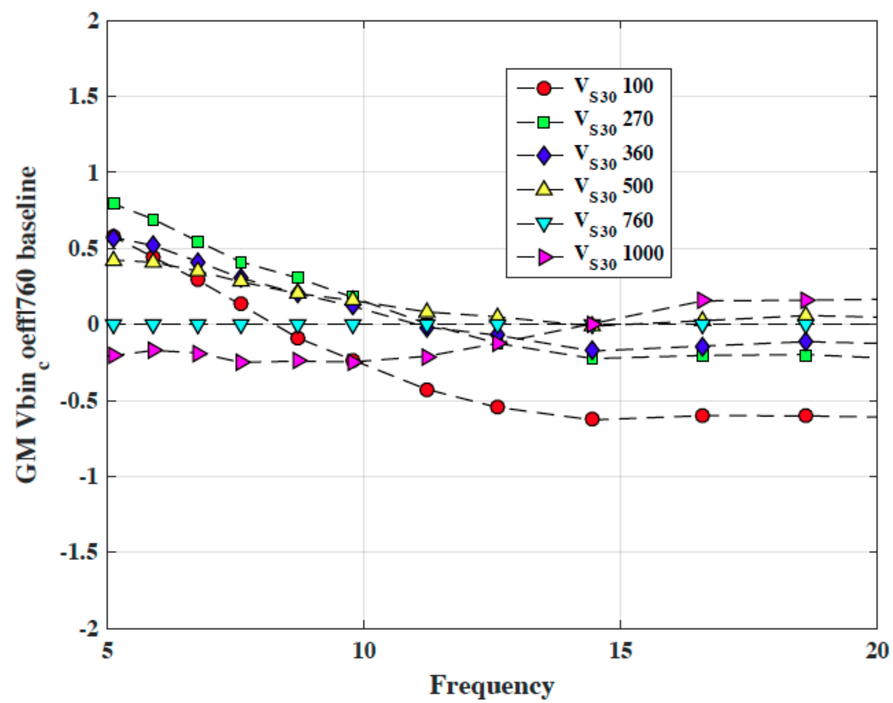


Derivation of Reference Vs Profiles for GMPE
(from work by Al Atik and Walling, 2017)

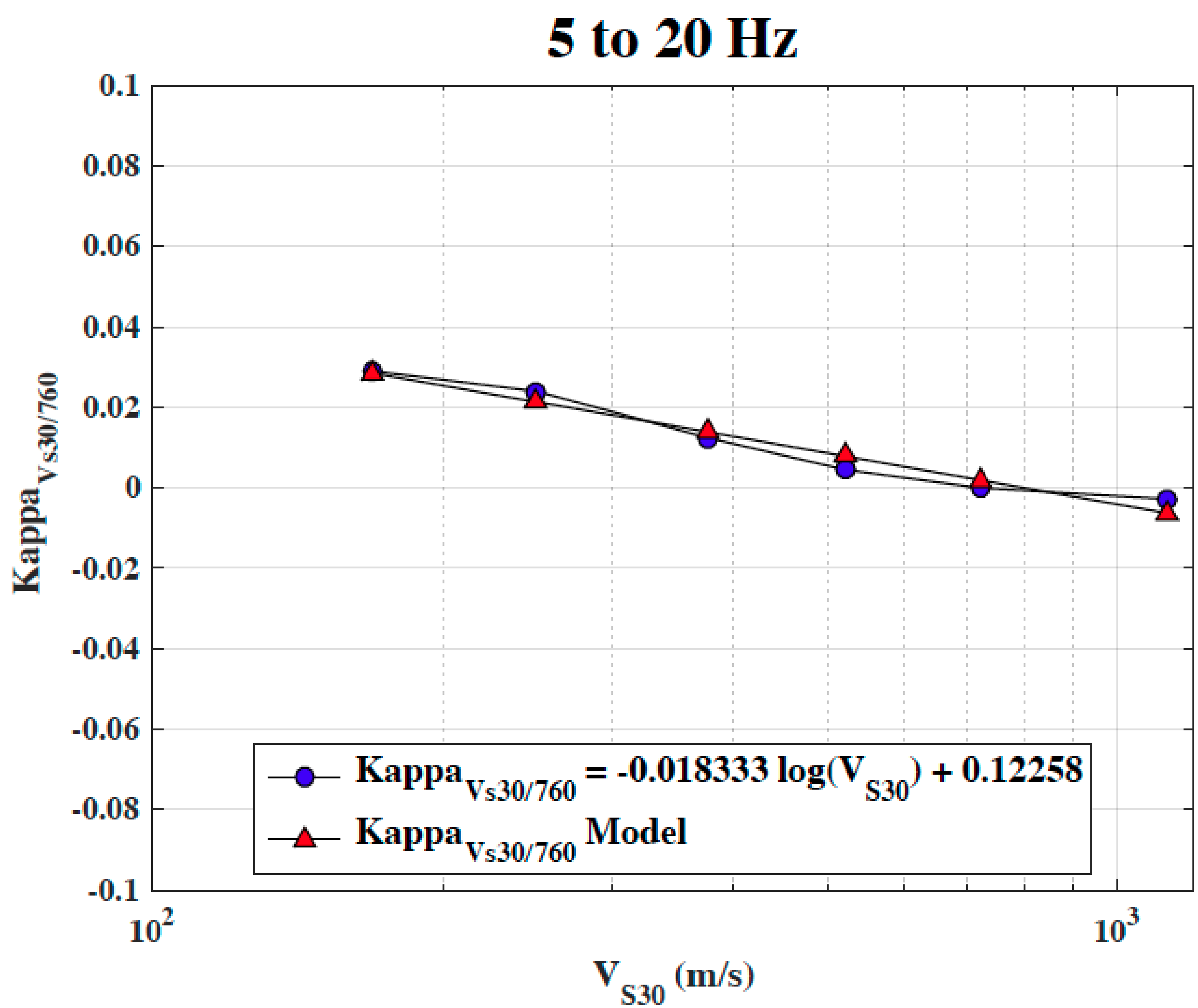
- Use FAS ground-motion model
- From regression analysis, estimate the FAS site factors for VS30 bins

FAS Site Factors from NGA-SUB Japan Subduction Data Set

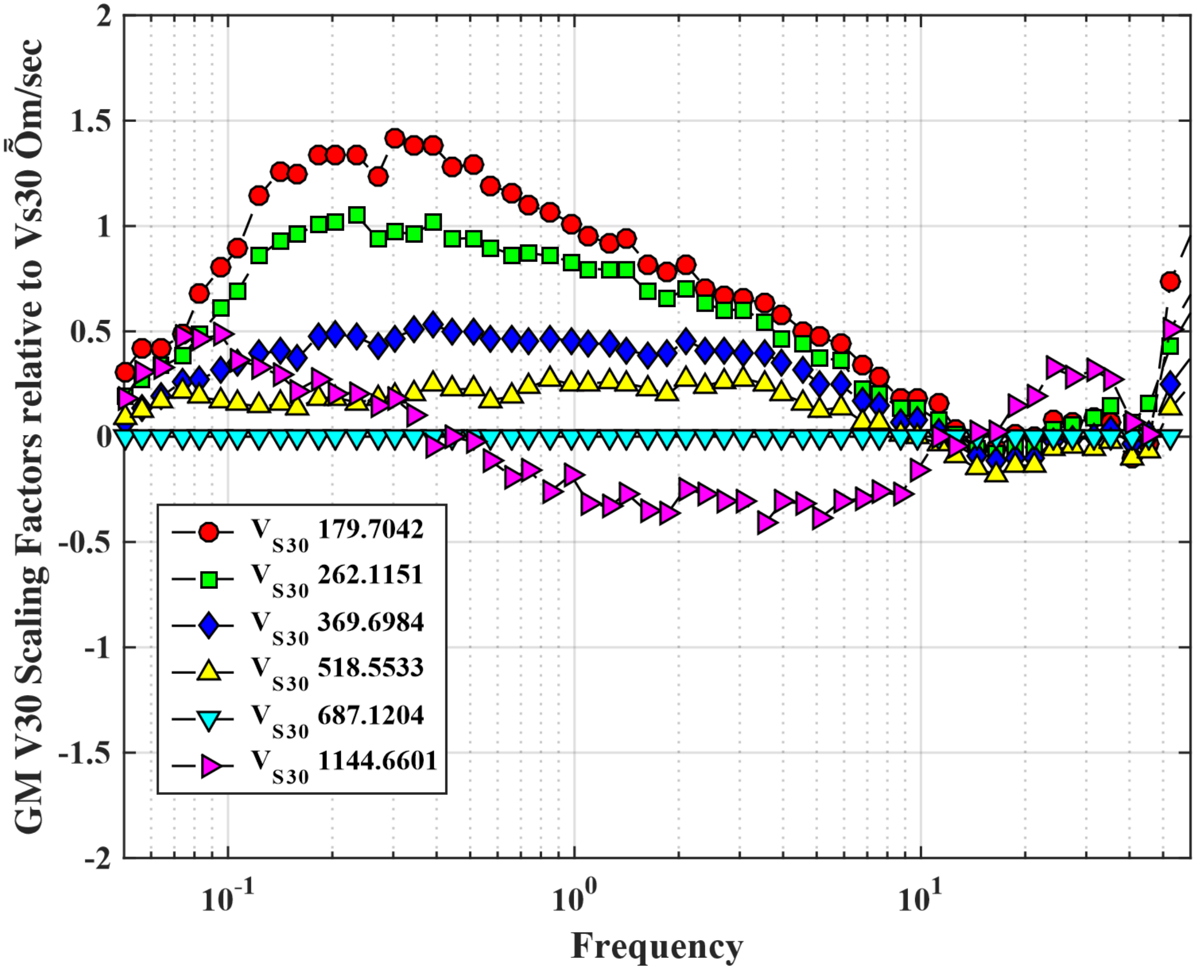




Difference in Kappa (relative to VS30=760 m/s)



Crustal: GM V_{S30} scaling relative to V_{S30} = 690 m/sec



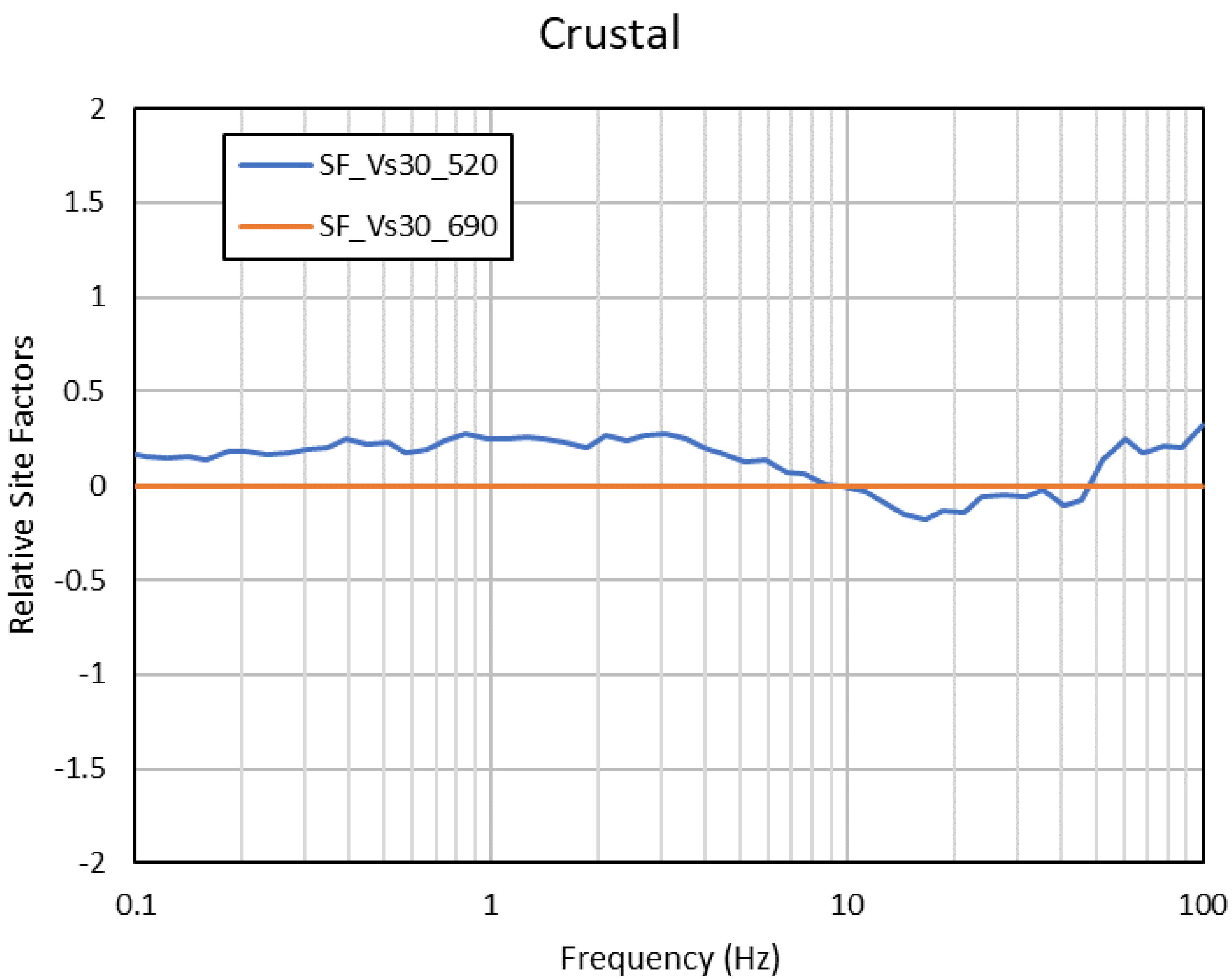
Invert for Vs profile using Quarter-Wavelength (QWL) method

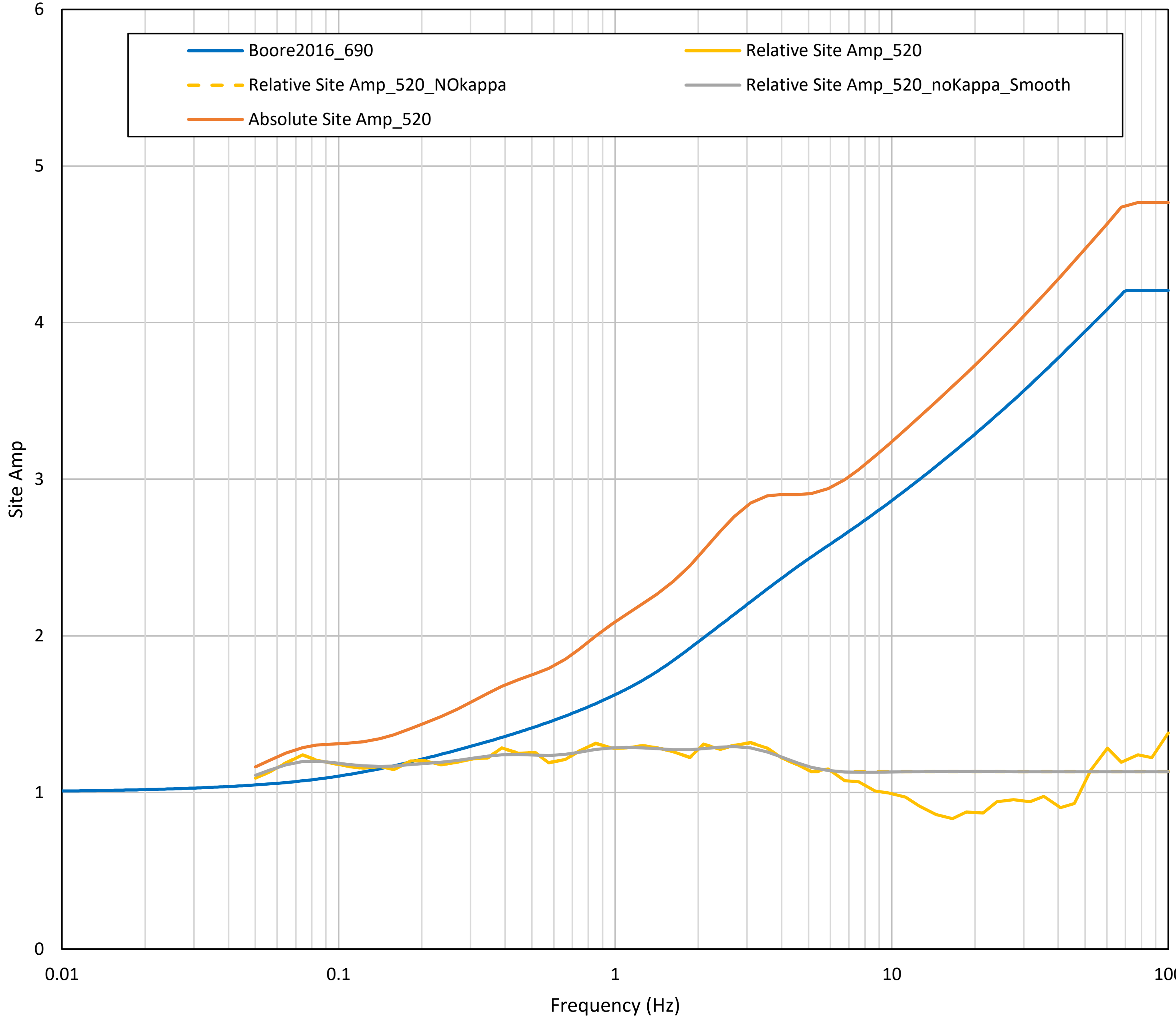
- Given site amplification factors versus frequency
- Assume ref. Vs = 3.5 km/sec, ref. rho = 2.72g/cm3
- Assume angle of incidence = 0
- Assume simple relation between density and Vs: Rho = 1.742 + 0.2875*Vs
- For freq = high to low:

$$A(i) = \sqrt{\frac{\rho_R Vs_R}{\overline{\rho}(i)\overline{Vs}(i)}} \Rightarrow Vs(i)$$

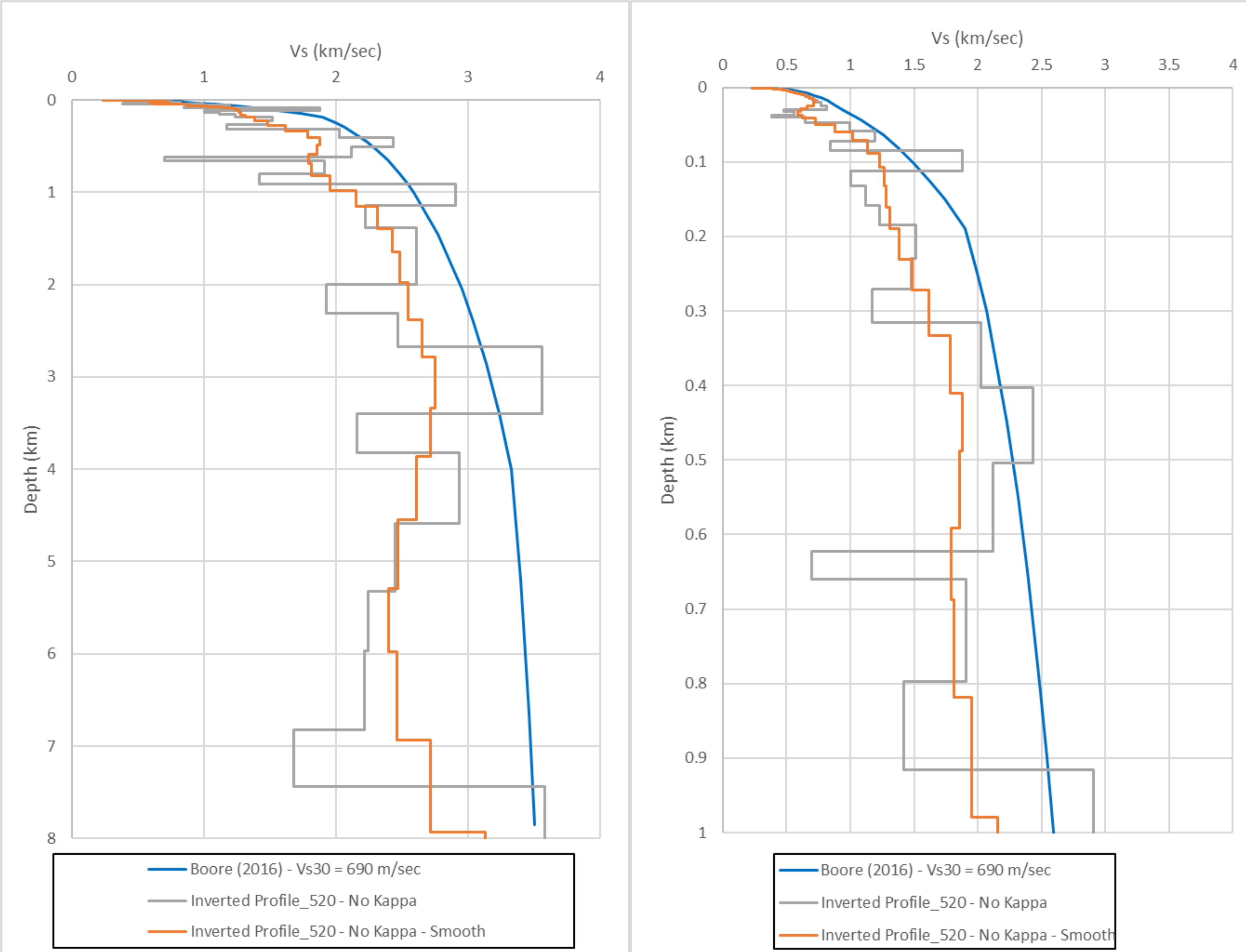
$$\overline{Vs}(i) = \mathrm{z}(i) * 4\mathrm{freq}(i) \Rightarrow z(i)$$

Example Application





Boore2016_690
Relative Site Amp_520
Relative Site Amp_520_NOkappa
Relative Site Amp_520_noKappa_Smooth
Absolute Site Amp_520
Site Amp
Frequency (Hz)
0
1
2
3
4
5
6
0.01
0.1
1
10
100


Vs (km/sec)
0
1
2
3
4
Depth (km)
0
1
2
3
4
5
6
7
8
Boore (2016) - Vs30 = 690 m/sec
Inverted Profile_520 - No Kappa
Inverted Profile_520 - No Kappa - Smooth
Vs (km/sec)
0
0.5
1
1.5
2
2.5
3
3.5
4
Depth (km)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Boore (2016) - Vs30 = 690 m/sec
Inverted Profile_520 - No Kappa
Inverted Profile_520 - No Kappa - Smooth

Improved Communication of Site Condition for Future GMPEs

- GMPEs should provide the full VS profile and kappa for a given VS30
- This profile will change by region
- Clearly shows that the VS30 is just an index to the VS profile and kappa
  - VS30 is not a fundamental parameter of the site amplification

3. Greater Use of Finite-Fault Simulations

- Empirical data remain sparse for key ranges
  - Large magnitudes at short distances
  - Sites over the Hanging wall
  - Multiple linked faults (or segments)
- Expect to see a greater reliance on Finite-Fault Simulations for GMPEs
  - Simulations are a main focus of seismic research for ground motions
  - Use simulation to sample a large range of scenarios
  - Simulation methods need adequate validation before use in GMPE development

Validation – SCEC (2015) Approach

- Part A
  - Comparing simulations for past earthquakes to data
  - Tests the model given the best source model
    - Best source model depends on the simulation method
- Part B
  - Comparing simulations to GMPEs for scenarios well constrained by the empirical data
    - M6.5 at 30 km
  - Tests the rupture generator for future earthquakes
    - Is the simulation method centered?

Uses of Finite-Fault Simulations for GMPEs

- Constrain scaling of median ground motion (current)
  - Relative scaling only (for extrapolation of empirical GMPEs)
- Provide data to derive new median model (next 3 yr)
  - Use the simulated values, not just scaling (NGA-West3)
  - Aleatory variability from empirical
- Provide data to derive aleatory variability model (3-6 yrs)
  - Parametric variability (result of different inputs to the model)
  - Non-parametric variability (result of misfit between best model and data)
    - Similar to the sigma in empirical GMPEs

Variability from Simulations

- Currently, FFS do no provide reliable constraints on aleatory variability
- Source Parameters
  - How much variability in source parameters for future earthquakes?
  - What data can constraint the source parameters?

Empirical and Simulation-based GMPEs are not Independent

- Empirical GMPEs
  - Use scaling from FFS to constrain extrapolation
  - Makes the empirical GMPEs similar to FFS
- Numerical simulations
  - Validated against empirical data
  - Makes the FFS similar to GMPE in well constrained range of data

GMPE Model Complexity

- GMPE Model complexity is driven by FFS constraints
  - Large simulated data sets will show trends not seen in empirical data
  - Capturing those trends with a parametric GMPE will likely cause complex functional forms
  - Example: complex GMPE to capture scaling for HW effects

4. Move to non-ergodic GMPEs

Ergodic GM Model

$$\ln SA(M_i, Loc_i, Site_j) = \ln GMPE(M_i, R_{ij}, VS30_j) + d_{ij}$$

Global or regional average model for the median

Assumed to apply to all sources relevant to my site

s

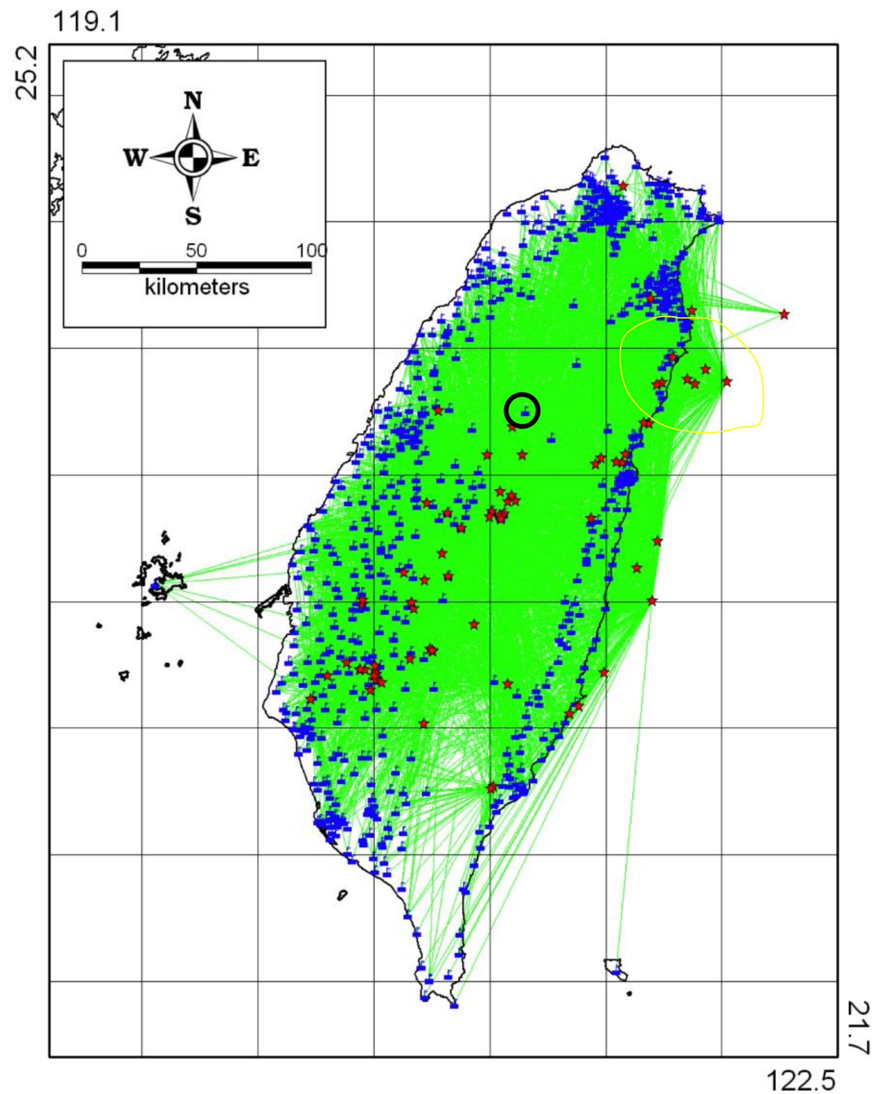
Aleatory

Mixing Epistemic and Aleatory

<u>Single Ray Path</u>

Repeatable wave propagation effects from a small source region to a single site.

Usually treated as aleatory, but should be epistemic

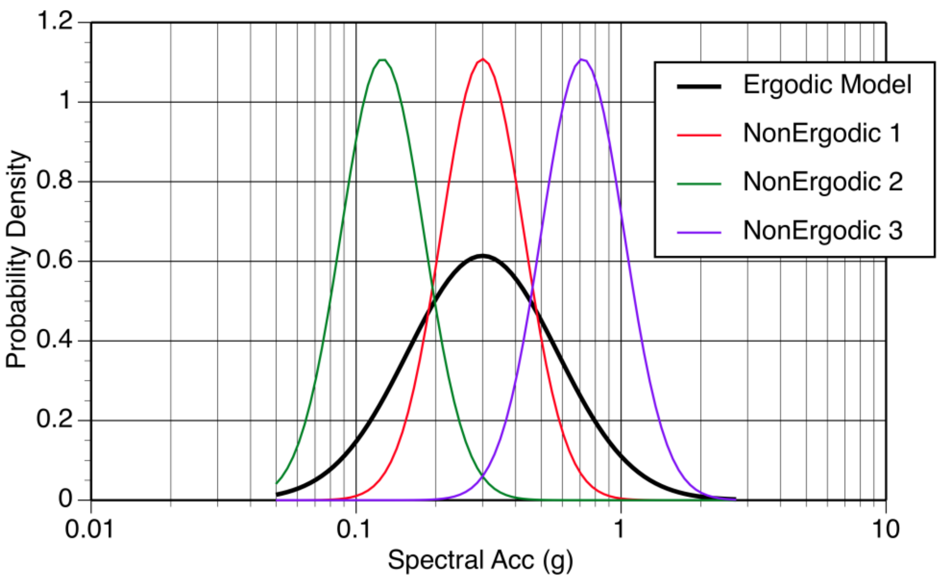


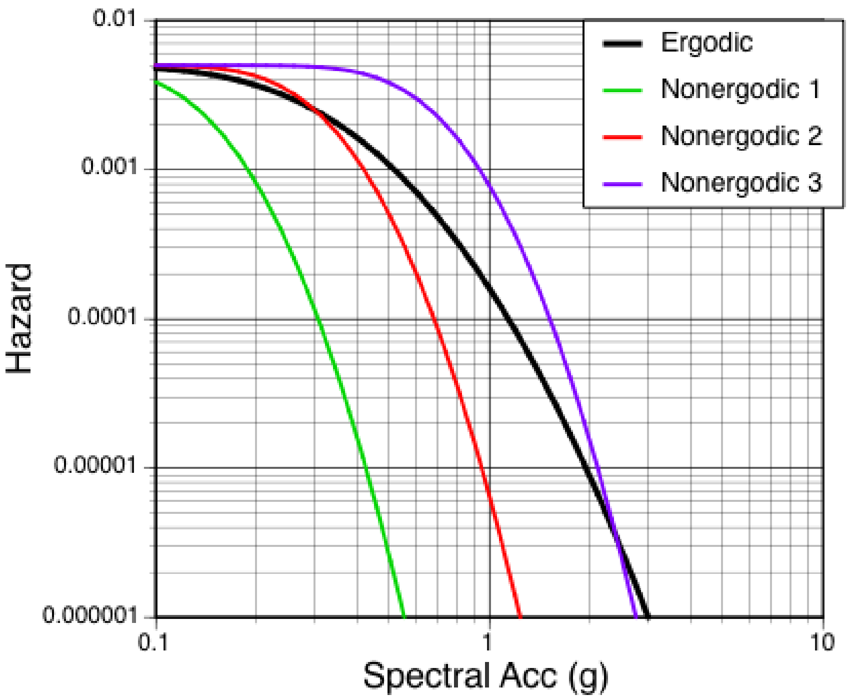
Component of GM Variability (from Taiwan)

Spectral Period (sec)	σ	ϕ_{S2S}	ϕ_{P2P}	τ_{L2L}	σ_0
PGA	0.64	0.26	0.40	0.25	0.34
0.1	0.71	0.35	0.41	0.28	0.36
0.3	0.68	0.28	0.42	0.27	0.36
0.5	0.69	0.30	0.39	0.29	0.40
1.0	0.74	0.36	0.35	0.32	0.43
3.0	0.77	0.39	0.32	0.37	0.46

From: Lin et al (BSSA, 2011)

Epistemic Uncertainty for Nonergodic GM Models





Move to Non-Ergodic GM models

Global models (NGA-W1)	Average Mag and distance scaling around the world. Gives enough data from large mag at close distances to constrain the scaling
Broad Regionalization (NGA-W2, Europe models)	Allow for differences in the large distance scaling and VS30 scaling for broad regions (such as Japan, CA, Taiwan,..). Also includes average regional differences in source (stress-drop)
Single-station sigma	Removes the systematic site terms from the aleatory variability. Requires site-specific estimates of the site response (empirical or analytical
Continuous spatial regionalization	Allow for the distance scaling to vary for each site, spatially smoothed. This is a zoneless regionalization. Path effects are isotropic
Site-specific path effects	Allows the distance scaling to vary for each site and for each source (direction)

Ergodic GMPE

$$
\begin{aligned}
GMPE_{BASE}\left(M, R_{rup}, F, V_{S30}, Z_{TOR}, \ldots\right) = \\
& q_0 + f(M) + \left(q_4 + q_5 M\right)\ln\left(\sqrt{R_{RUP}^2 + q_6^2}\right) + q_7 R_{RUP} \\
& + q_8 F + q_{10} Z_{TOR} + q_{11}\ln\left(V_{S30}\right) \\
& + f_{HW}\left(M, R_{rup}, R_x, \ldots\right) + f_{NL\text{-}site}\left(V_{S30}, PSA_{1100}\right)
\end{aligned}
$$

Nonergodic GMPE

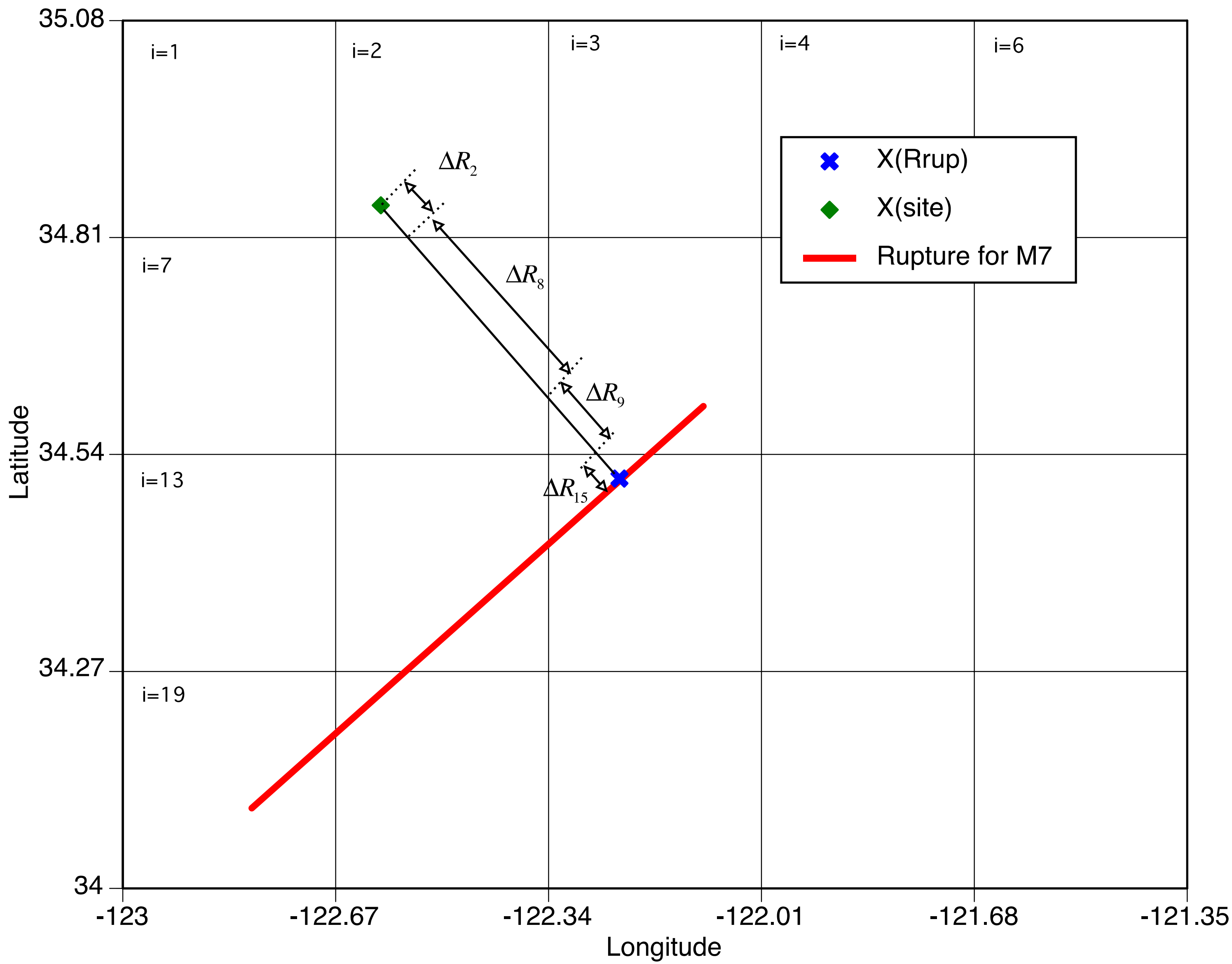
$$LN(PSA) = GMPE_{BASE}\left(M, R_{rup}, F, V_{S30}, Z_{TOR}\right)$$

$$+\delta\theta_4(\vec{x}_{Rrup})\ln\left(\sqrt{R_{RUP}^2+\theta_6^2}\right)$$

$$+\delta\theta_{0A}(\vec{x}_{site})+\delta\theta_{11}(\vec{x}_{site})\ln\left(V_{S30}\right)$$

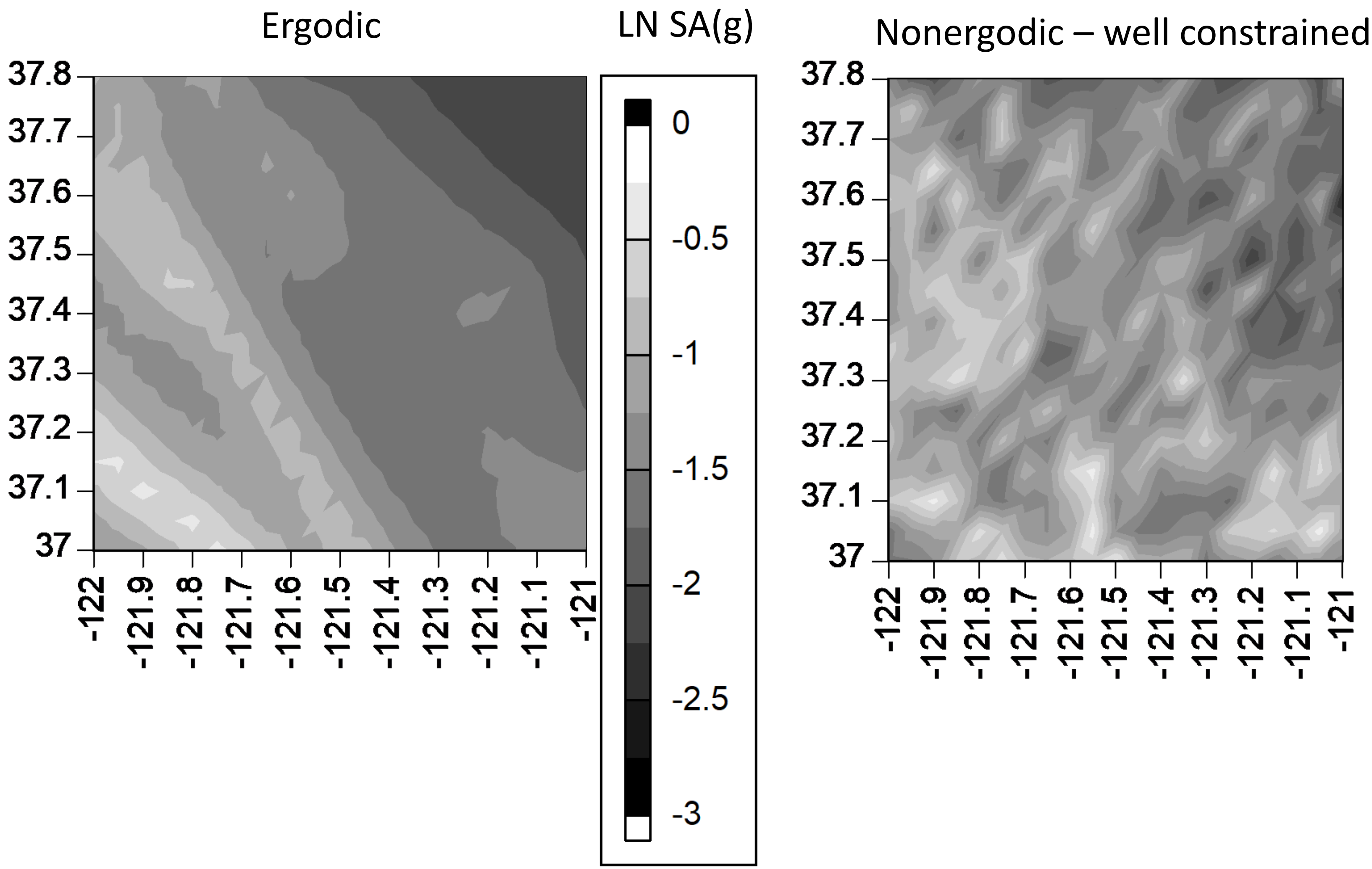
$$+\delta\theta_{0B}(\vec{x}_{Rrup})$$

$$+\sum_{i=1}^{nCell}\Delta R_i(\vec{x}_{site},\vec{x}_{Rrup})\delta\theta_{7\_i}$$



35.08
34.81
34.54
34.27
34
-123
-122.67
-122.34
-122.01
-121.68
-121.35
Longitude
Latitude
i=1
i=2
i=3
i=4
i=6
i=7
i=13
i=19
ΔR_2
ΔR_8
ΔR_9
ΔR_{15}
X(Rrup)
X(site)
Rupture for M7

Example of Potential Effects of Nonergodic GMPE on Hazard Maps

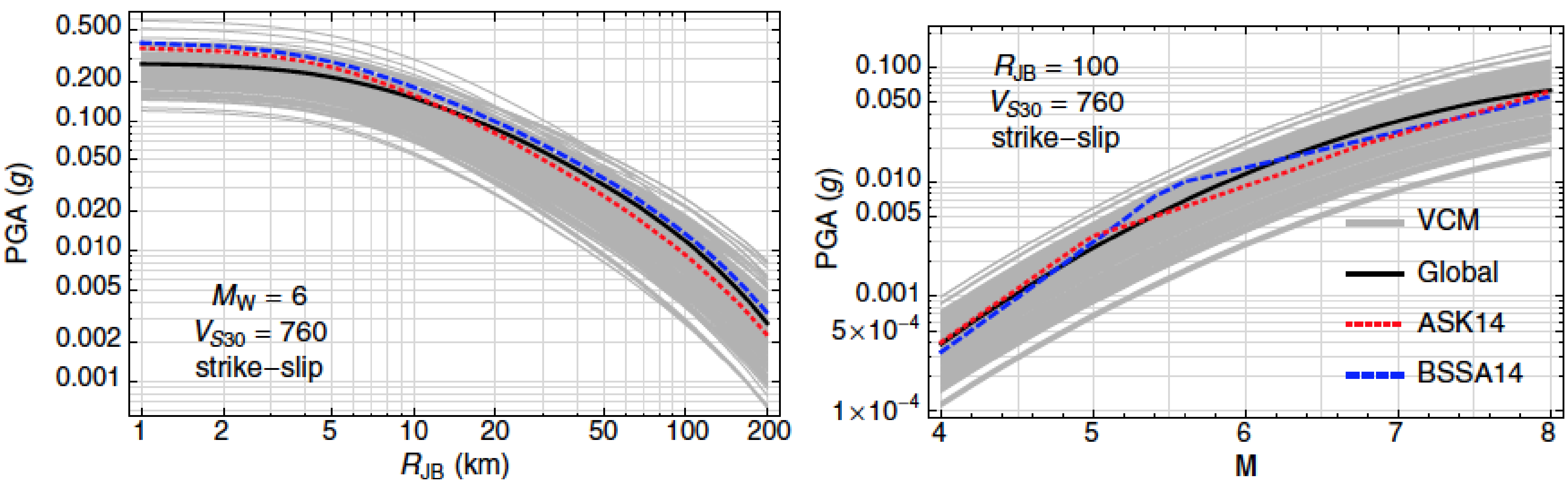


Estimating Path Terms

- Use empirical data
  - Mainly from small magnitude earthquakes
  - Currently, not dense enough station coverage
    - How to install and manage 10,000s to 100,000s of seismometers to constrain path effects?
  - Need method to extrapolate path effects from small magnitudes to larger magnitudes
- Use 3-D simulations
  - Need applicable 3-D velocity structure
  - Requires validation for the amplitudes before use
    - Need adequate ground motion data to test the simulations

Empirical Approach

Range of GM for M6 from a Continuous Coefficient Model



From Landwehr et al (2016)

Example of Results from Continuous Coefficient Model

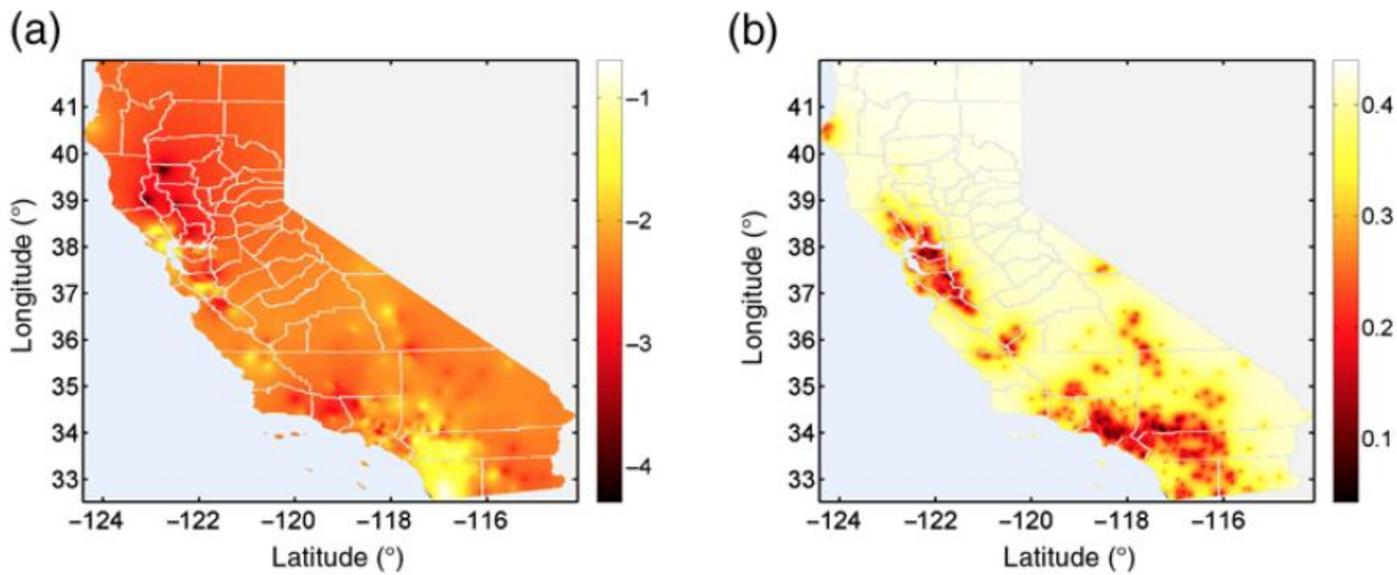
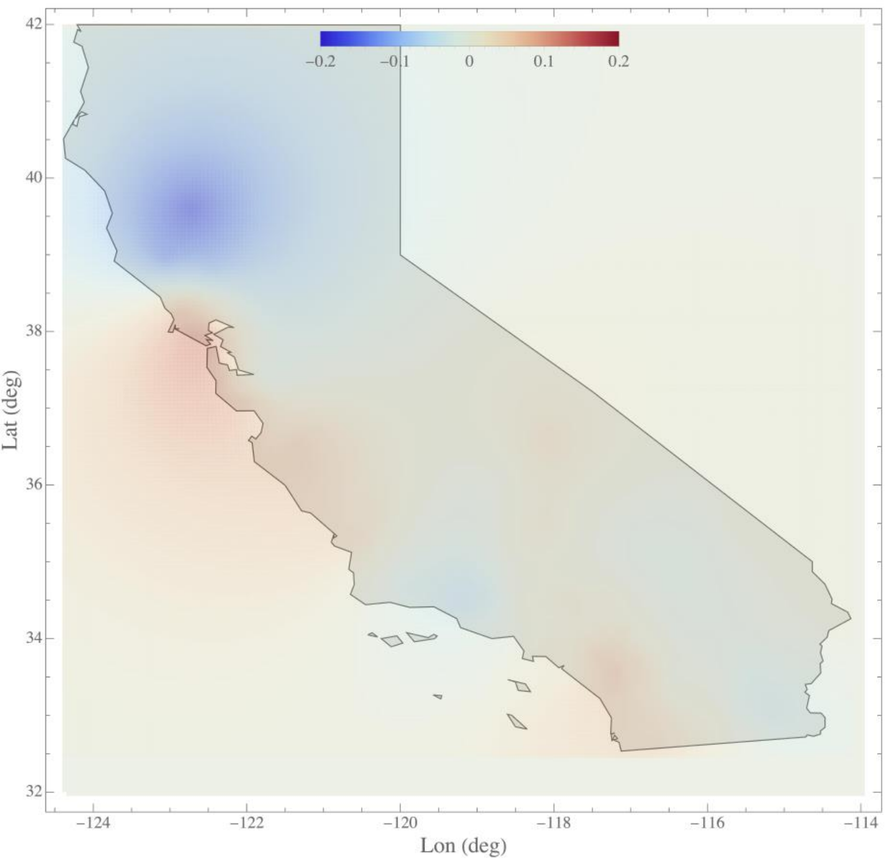


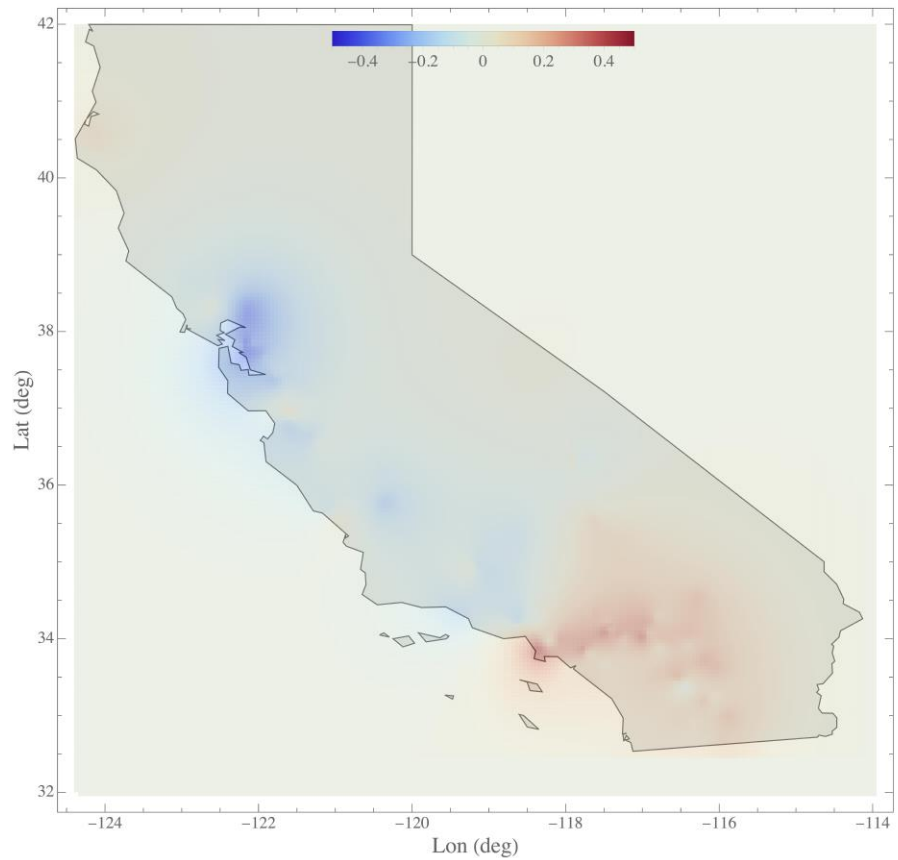
Figure 6. (a) Map of ln PGA predictions, coded by ground-motion value. (b) Epistemic predictive uncertainty ψ associated with ln PGA predictions. For simplicity, in both plots the same event–station coordinate is used for the coefficients. Predictor variables are set to $M = 6$, $R_{JB} = 10$ km, SoF = 0, and $V_{S30} = 760$ m/s, in which SoF indicates style-of-faulting. The color version of this figure is available only in the electronic edition.

Spatially Varying Coefficients

VS30 scaling Term

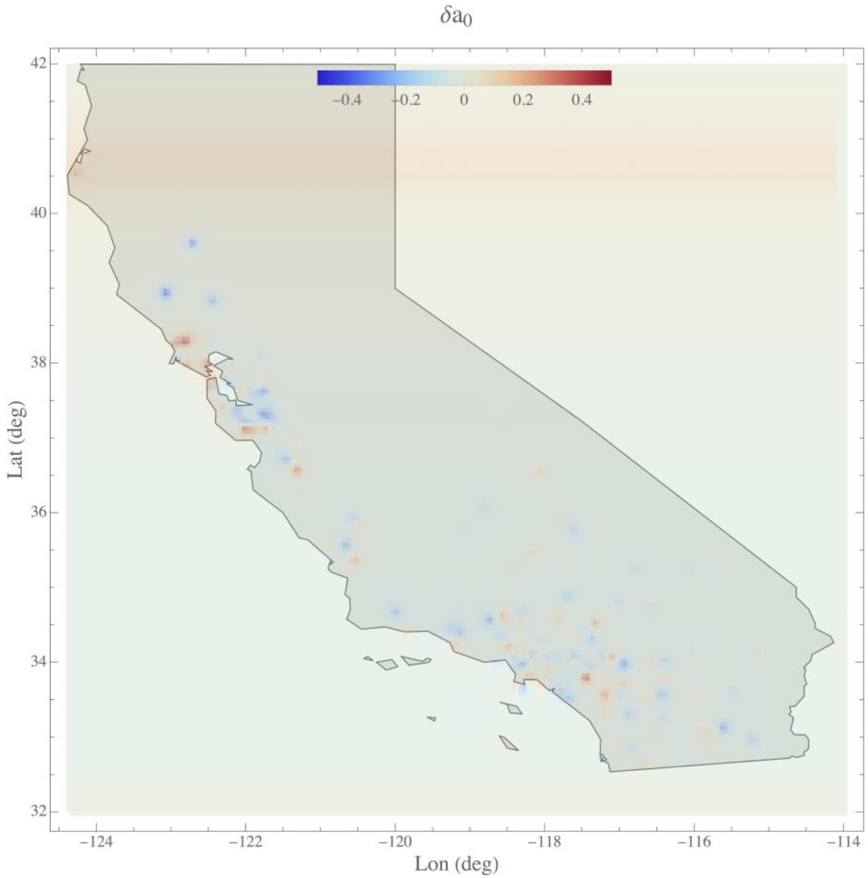


Geometrical Spreading Term

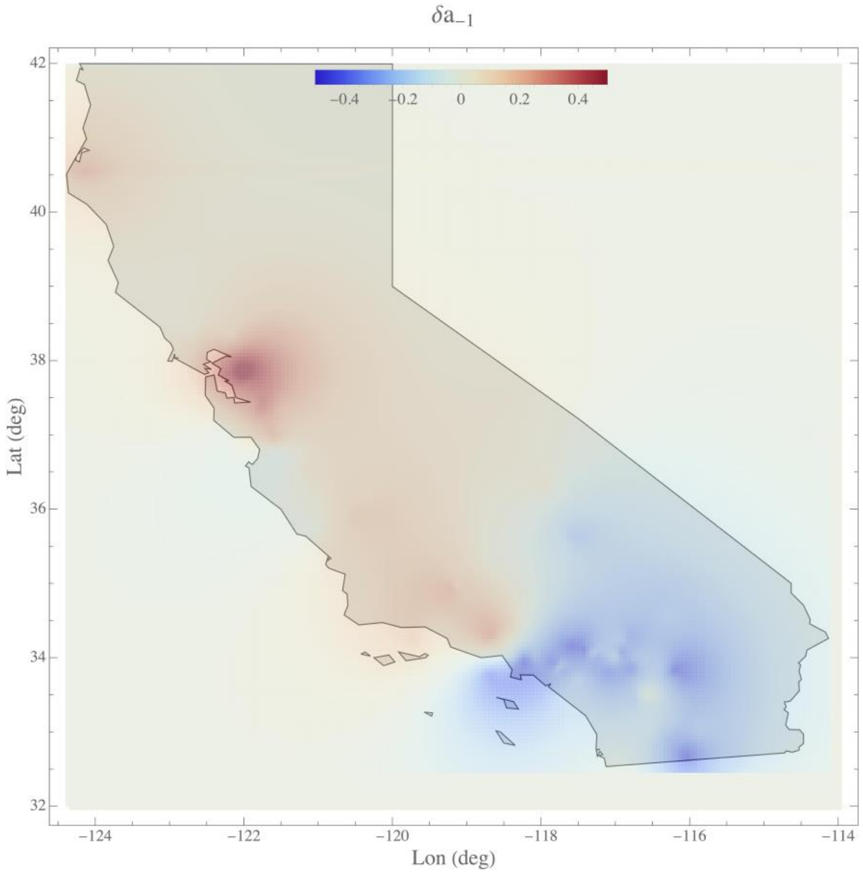


Spatially Varying Coefficients

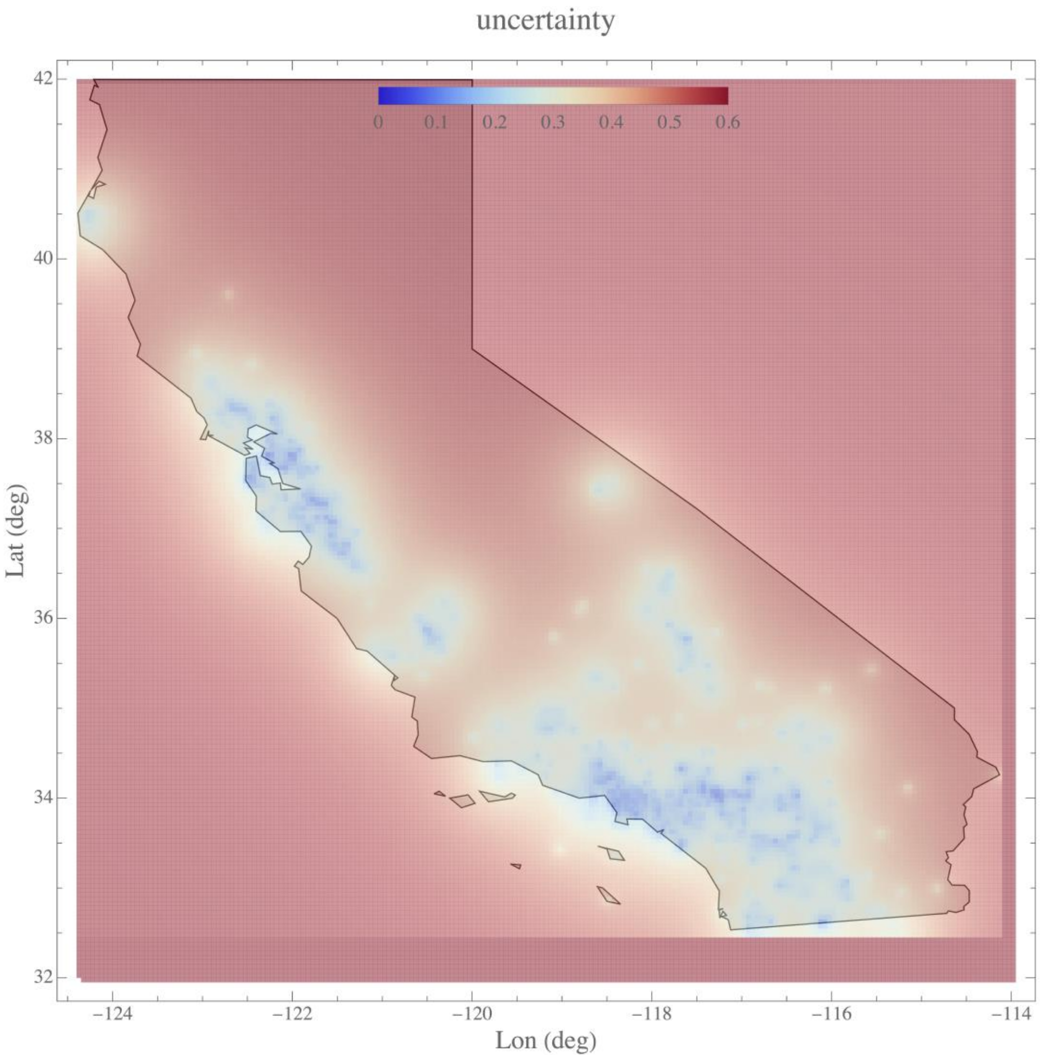
Site Term



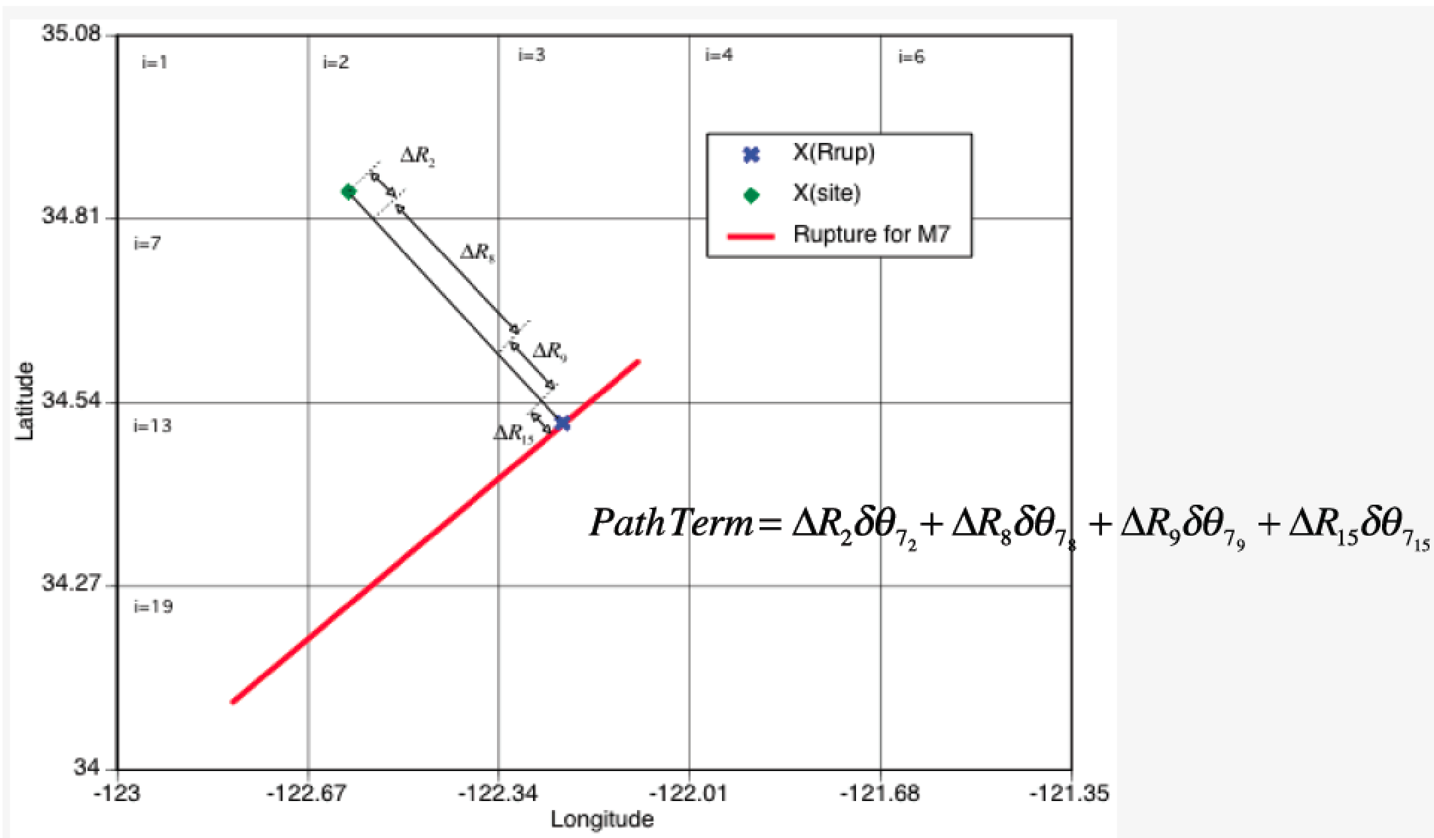
Source Term



Epistemic Uncertainty (M6m, R10)

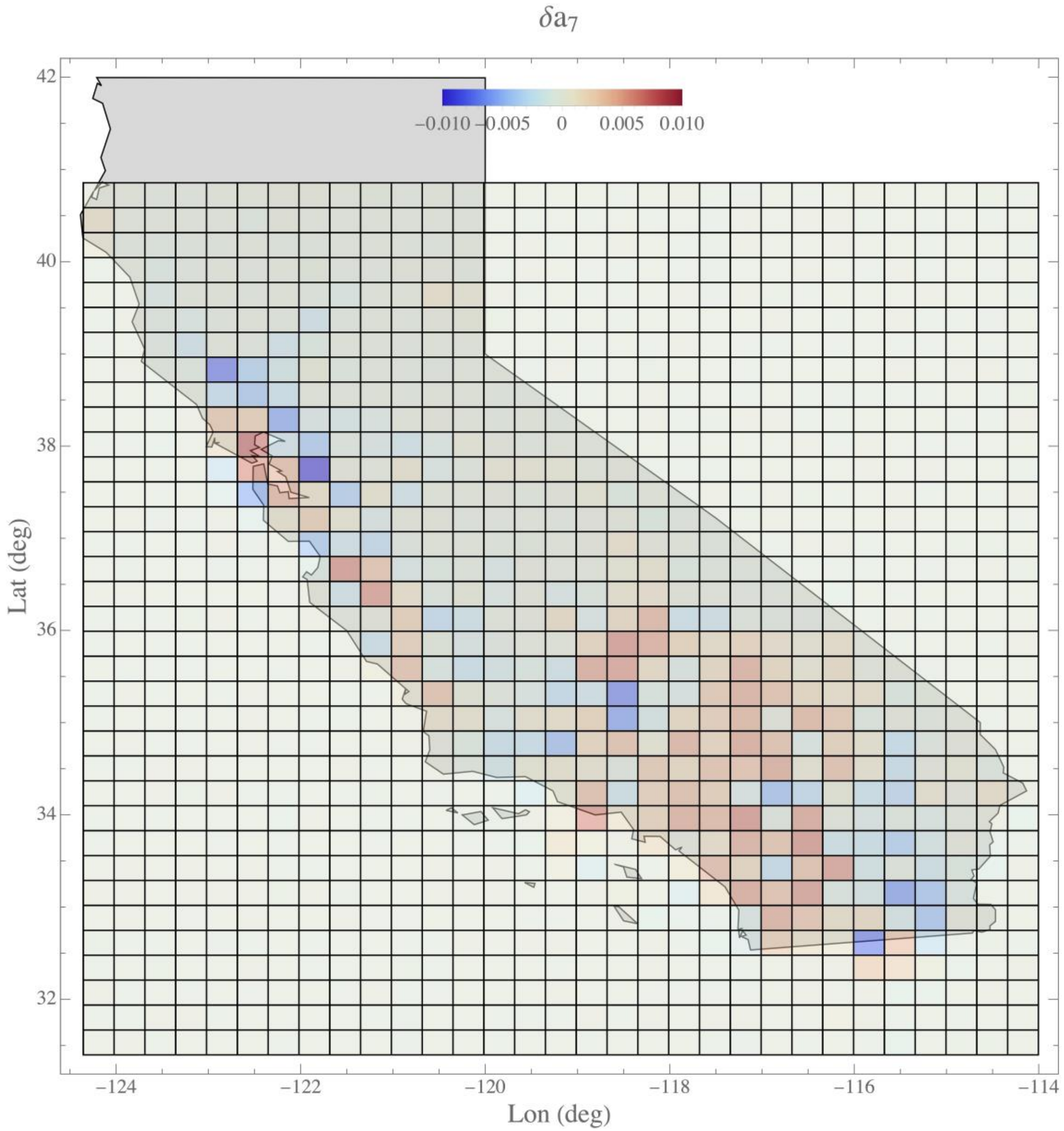


Path term (linear R) in nonergodic model



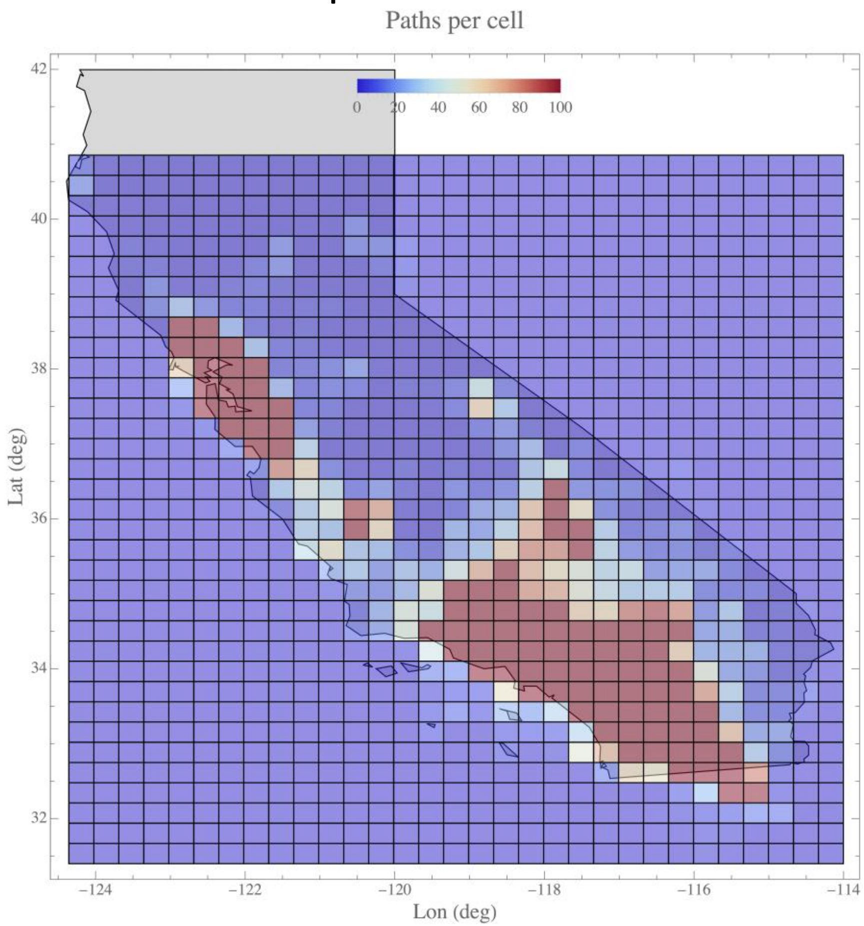
$$PathTerm = \Delta R_2 \delta\theta_{7_2} + \Delta R_8 \delta\theta_{7_8} + \Delta R_9 \delta\theta_{7_9} + \Delta R_{15} \delta\theta_{7_{15}}$$

Delta_Theta7

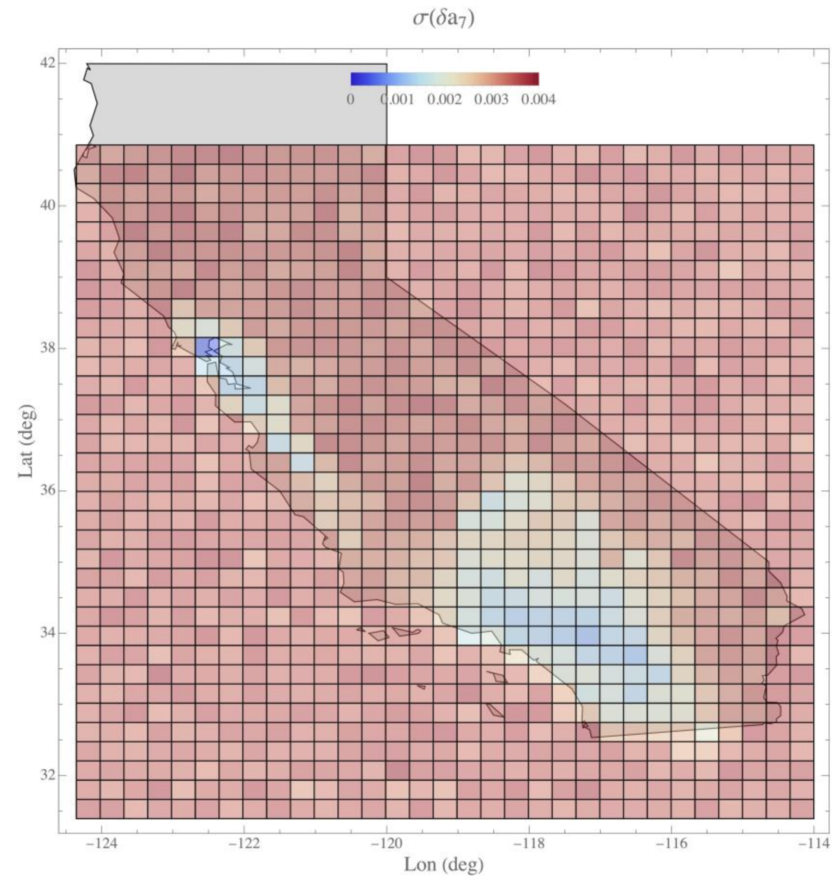


Epistemic Uncertainty in Linear R Scaling (Q)

Paths per Cell



Standard deviation of delta_Theta7

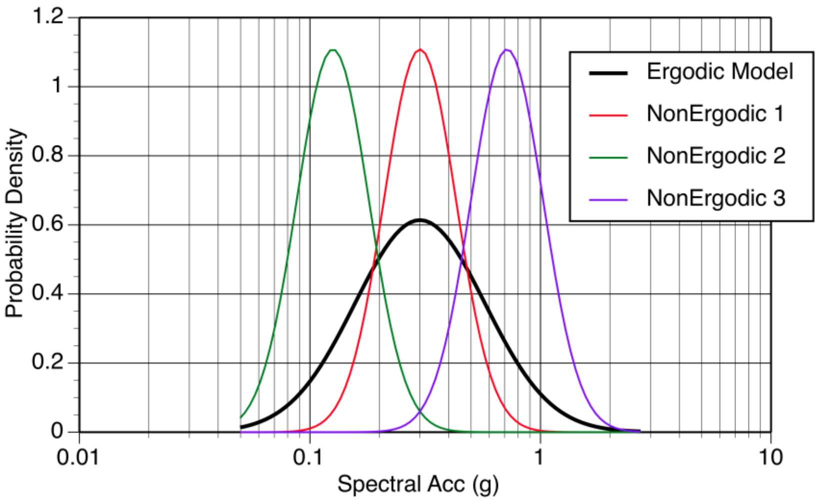


Key Issues for Moving to Non-Ergodic Ground-Motion Models

- To justify the use of the reduced aleatory variability requires:
  - Estimates of site, path, and source terms
  - Estimates of the epistemic uncertainties in the site, path, and source terms

Inappropriate use of Non-Ergodic Ground-Motion Models

- Main misuse
  - Use reduced aleatory variability,
  - But assume average path and source effects
  - And do not include the epistemic uncertainty in the estimated path, and source terms.



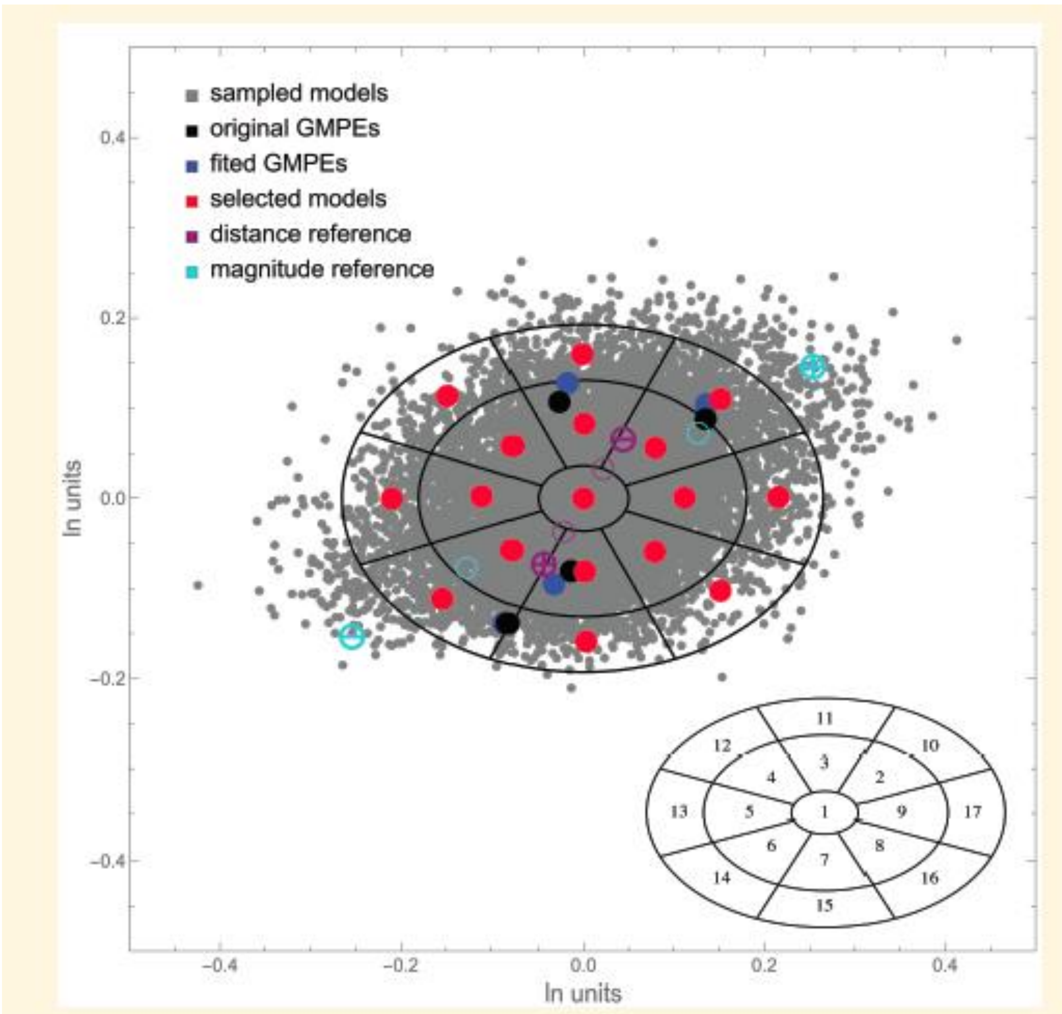
Epistemic Uncertainty

- Seismic source characterization
  - Use standard models for source logic trees
- Ground motion characterization
  - Base GMPE model (Sammon's map)
    - Alternative magnitude scaling
    - Alternative short distance scaling
  - Nonergodic – Azimuth independent
    - Alternative maps for spatial variation of coeff
  - Nonergodic – Azimuth dependent
    - Alternative maps for the attenuation by cell

Hazard Calculation

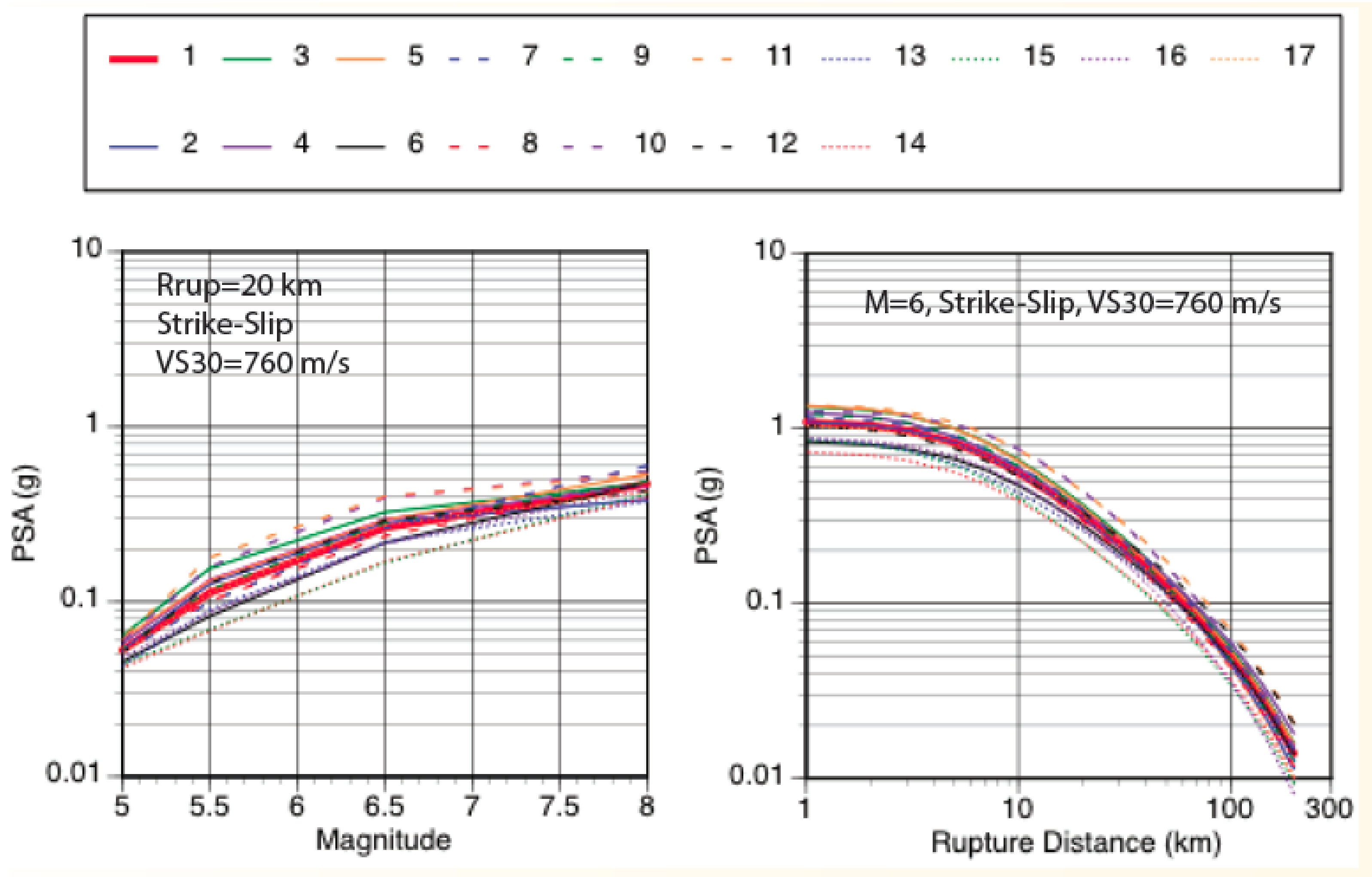
- Ergodic Case
  - sigma = 0.65
  - Epistemic uncertainty only in the average global (or regional) model
- Nonergodic case
  - sigma = 0.40
  - Epistemic uncertainty in the average global model and additional epistemic uncertainty in the nonergodic terms

Use Sammon's Maps for the Epistemic Part of Base GMPE



Based NGA-W2 models for California

Example of Epistemic Uncertainty in the Base GMPEs



Other Global Model Terms

- HW Scaling
  - Used the SWUS HW models
  - Epistemic uncertainty captured using 5 models
- Nonlinear site amplification
  - ASK14 NL model applied
  - No epistemic uncertainty included (rock site used in example)

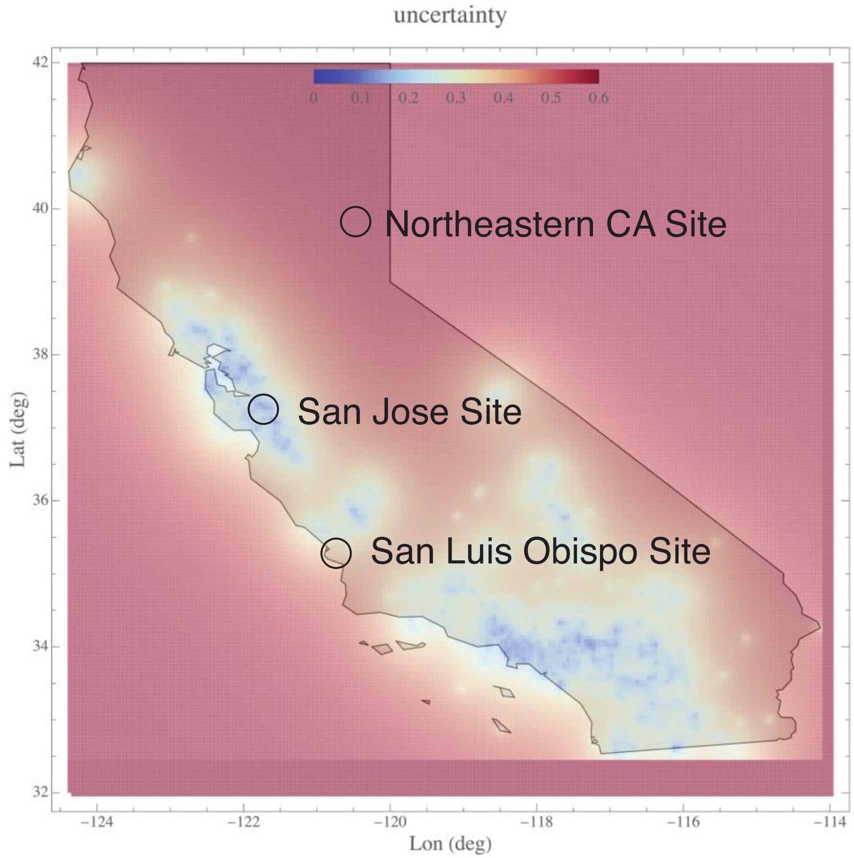
Hazard Code Modifications for Nonergic GMPEs

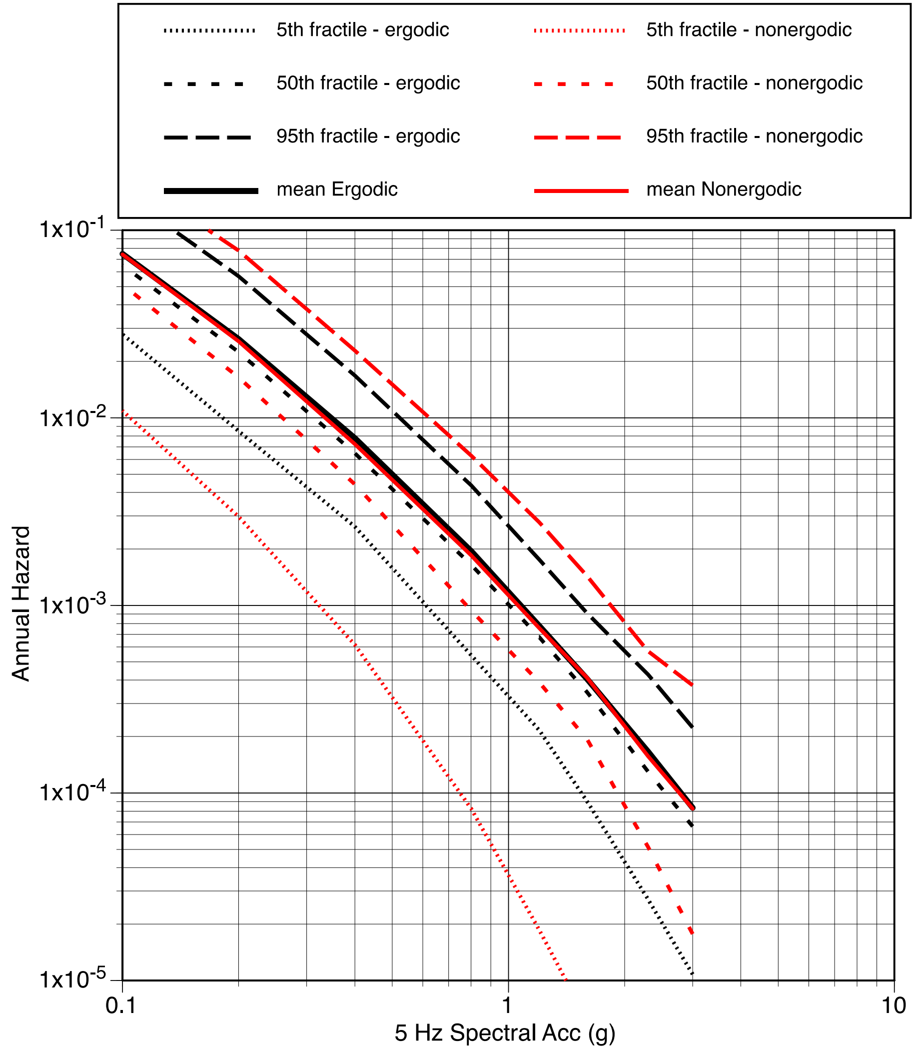
- Nonergodic terms are a function of the latitude and longitude
  - Read into lookup tables
- Compute the longitude and latitude of the closest point on the rupture to the site and pass to the GMPE
  - Previously only passed distances
- For each source location, the attenuation term is computed using the path lengths
  - Additional calculation of the path lengths though each cell

Hazard Code for Epistemic Uncertainty in nonergodic terms

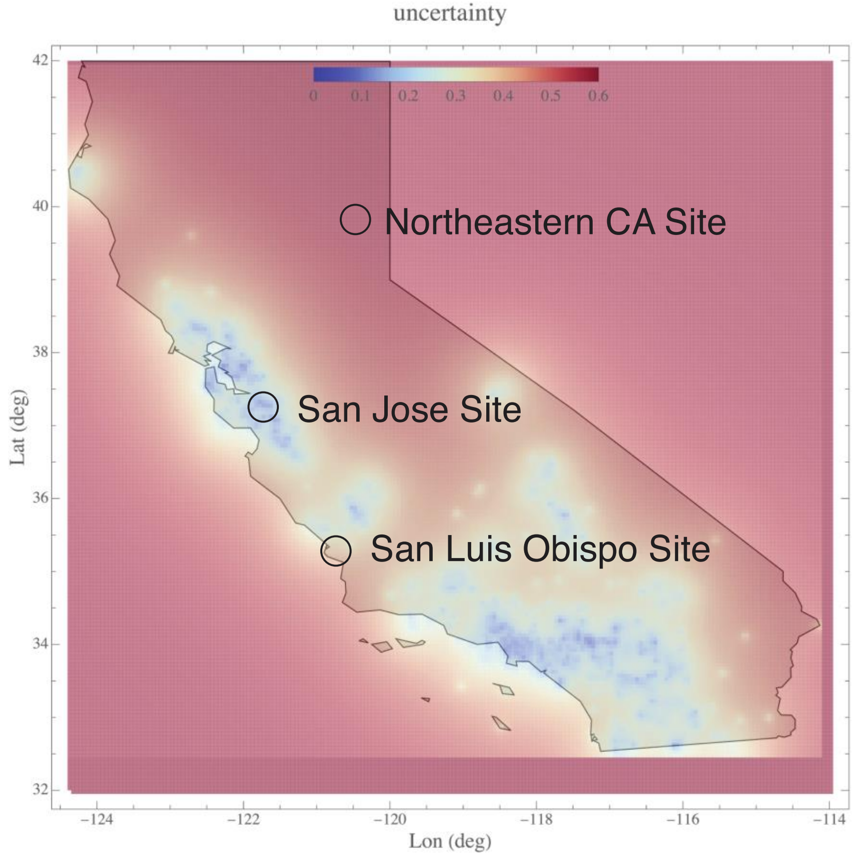
- Generate 100 samples (maps) of the nonergodic terms using spatially correlated random samples
  - Source constant: delta_theta0_B(long,lat)
  - Anelastic attenuation: Delta_theta7(long,lat)
- Only one site term needed: delta_theta0_A
- Randomly associated each of the two maps and the site constant with the base GMPEs

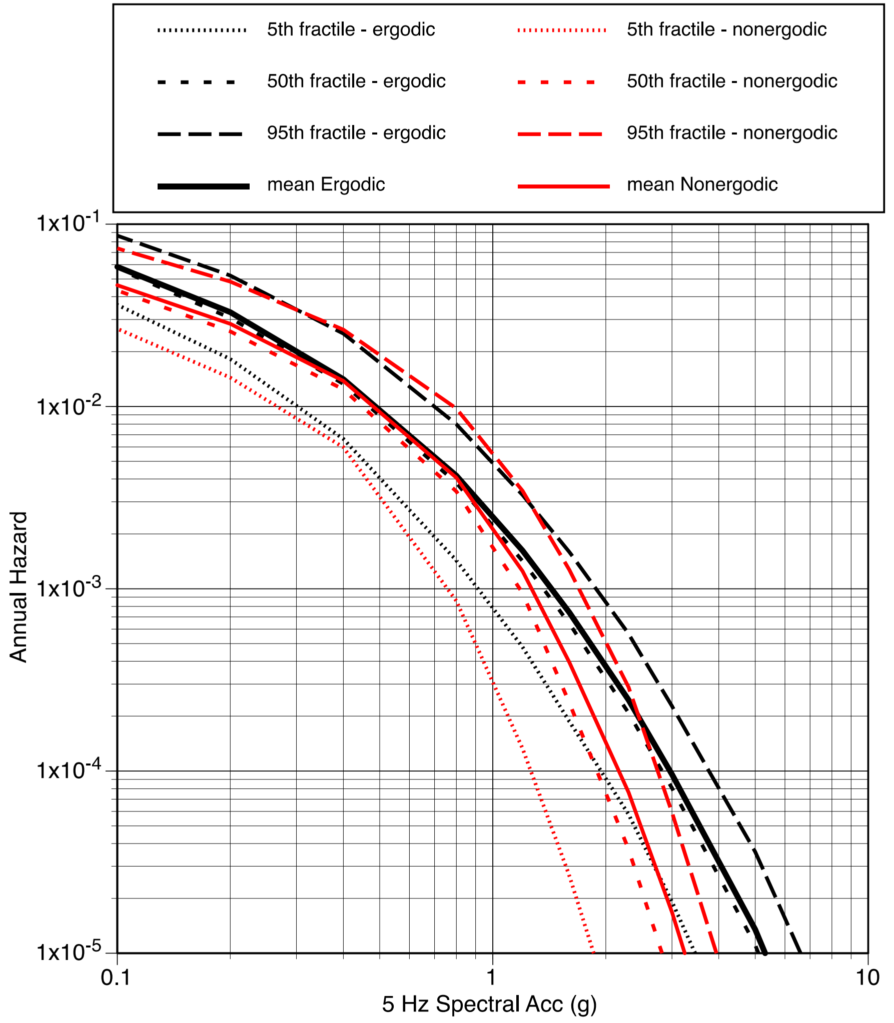
T=0.2 sec Nonergodic Hazard NE California



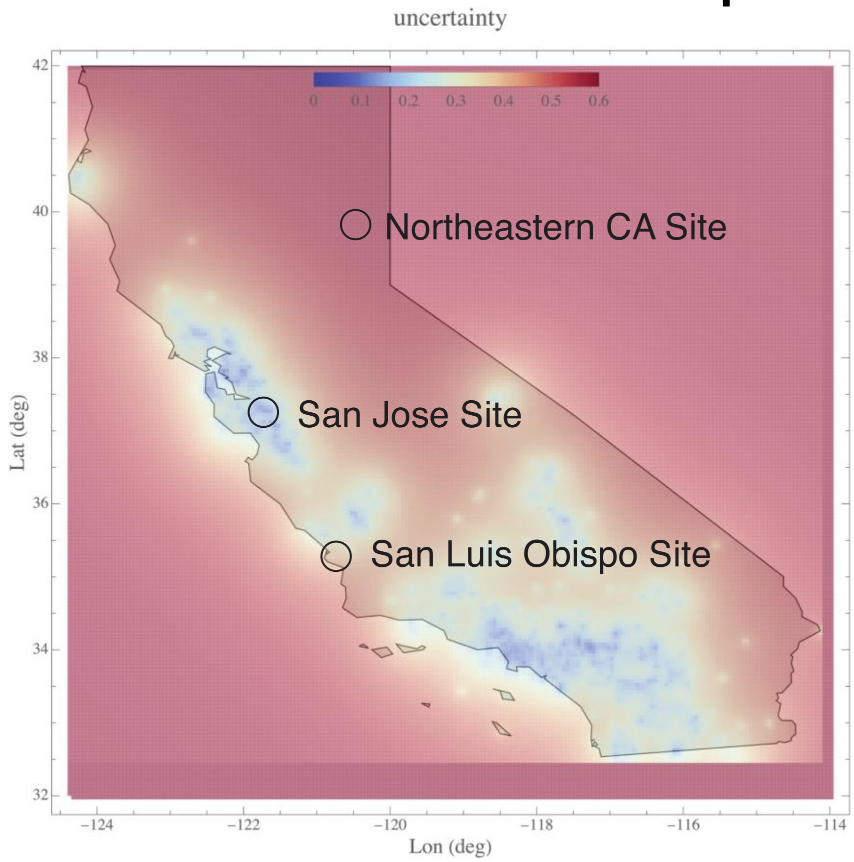


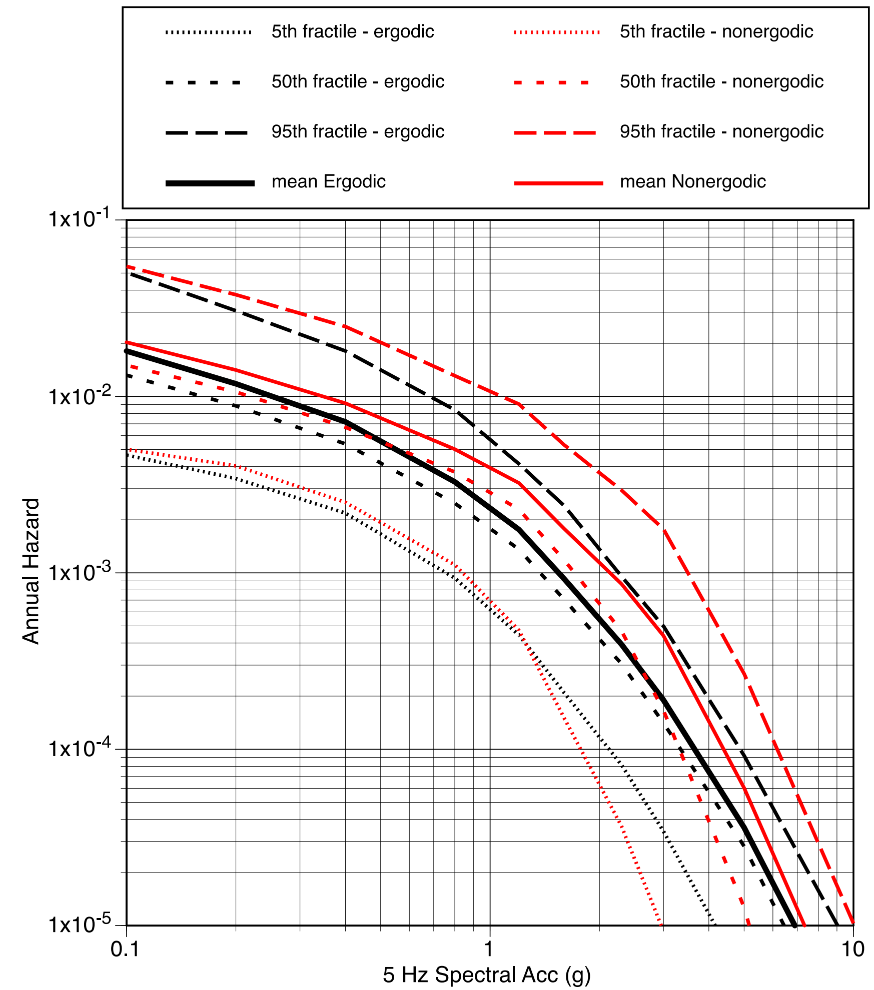
T=0.2 sec Nonergodic Hazard San Jose





T=0.2 sec Nonergodic Hazard San Luis Obispo





Site-Specific Effects

- Previous example did not use site-specific information other than the empirical site term
  - Should use site-specific site response results or recorded data at the site
- Using site response
  - Set the site term (theta0_A) to zero
  - Compute site-specific amplification with respect to the reference site condition
  - This allows site-specific nonlinear effects to be included
  - This is the same as the single-station sigma approach

Limitations of California Nonergodic GMPE

- Do the source, path, and site terms from small to moderate earthquakes to apply to large magnitude earthquakes?
- A similar assumption was also used in Taiwan SSHAC GMC when adjusting the foreign GMPEs to Taiwan moderate Mag data

Are Nonergodic Models Practical for Engineering Applications?

- Current nonergodic model for California is functional
  - Increase in hazard calculation time is less than factor of 2
  - Main cause is the number of GMPE increased from 51 (17 median & 3 sigma) to 100 (number of realizations of the nonergodic terms that are maps)
- What about regions with little data?
  - The GMPE will still be nonergodic
  - But large epistemic uncertainty in the nonergodic terms
  - Mean hazard will be similar, but larger range of epistemic uncertainty

5. Constraining Path Terms using 3-D Finite-Fault Simulations

- Numerical simulations with 3-D crustal models
  - Provides dense coverage
  - Needs validation/calibration

- Validation needs much denser station coverage than currently available

Validation Requirements for 3-D Simulations

- Median
  - Average amplitudes over a region
    - (e.g. Validation of SCEC BBP methods for 1-D)
  - Path effects for individual sites (for 3-D)
- Variability
  - Standard deviation of FAS (over a region)
- Correlation of variability
  - Period-to-Period correlations

Initial Use of 3-D Simulations for Path and Site Terms

Compute the adjustment from the ergodic GMPEs:

$$LN(SIM_{3D}) - LN(GMPE_{ERG}) = \delta\theta_4(\vec{x}_{Rrup})\ln\left(\sqrt{R_{RUP}^2 + \theta_6^2}\right) + \delta\theta_{0A}(\vec{x}_{site})$$

$$+ \sum_{i=1}^{nCell} \Delta R_i(\vec{x}_{site}, \vec{x}_{Rrup})\delta\theta_{7\_i}$$

$$+ Mean\left[\ln\left(\frac{SIM_{1D}}{GMPE_{ERG}}\right)\right]$$

Removes average source and regional path effects from the simulations

6. Simulations based Dynamic Rupture models

- Focus in last 10 years has been on the verification of programs for dynamic rupture models
- Now there is a switch to focus on the validation for dynamic rupture models
  - Expect this validation to take about 3 years

Summary of Expected Changes for GMPEs (1/3)

- Move to FAS-based models
  - Better for application of constraints from seismology
  - Better for more stable site response from small to large Mag earthquakes
  - Allows inversion of the VS profile that goes with the GMPE for a given VS30

Summary of Expected Changes for GMPEs (2/3)

- Greater use of finite-fault simulations to constrain extrapolation
  - Next 3 yrs will mainly be kinematic simulations
  - 3-6 yrs will see validation and application of simulations based on dynamic rupture models

Summary of Expected Changes for GMPEs (3/3)

- Move from partially nonergodic (single-station sigma) to fully nonergodic
  - As data become available to constrain the nonergodic terms, this will lead to the largest changes in site-specific hazard since the inclusion of GM sigma in the 1990s
- Methods to constrain path effects
  - 3-D simulations
  - Dense arrays

Summary from 2013 Talk on Same Topic

- GMPE Changes in < 3 yrs
  - More regionalization as data sets grow
  - Kappa added as basic site term
  - Improved regression methods to account for correlations in ground motions
  - FFS used as constraints on scaling
    - Extrapolations and unusual source geometries
  - Single station sigma models
- GMPE Changes in 5 yrs
  - FFS (1-D and 3-D) used for the median (combined with empirical)
  - FAS GMPEs as in termediate step providing better interface with seismological models
- GMPE Changes in 10 yrs
  - FFS used for the aleatory variability (single station and single path)
  - Single path terms (maps for a given site) for major projects
  - Single path sigma

Simplify Path from Extended Ruptures

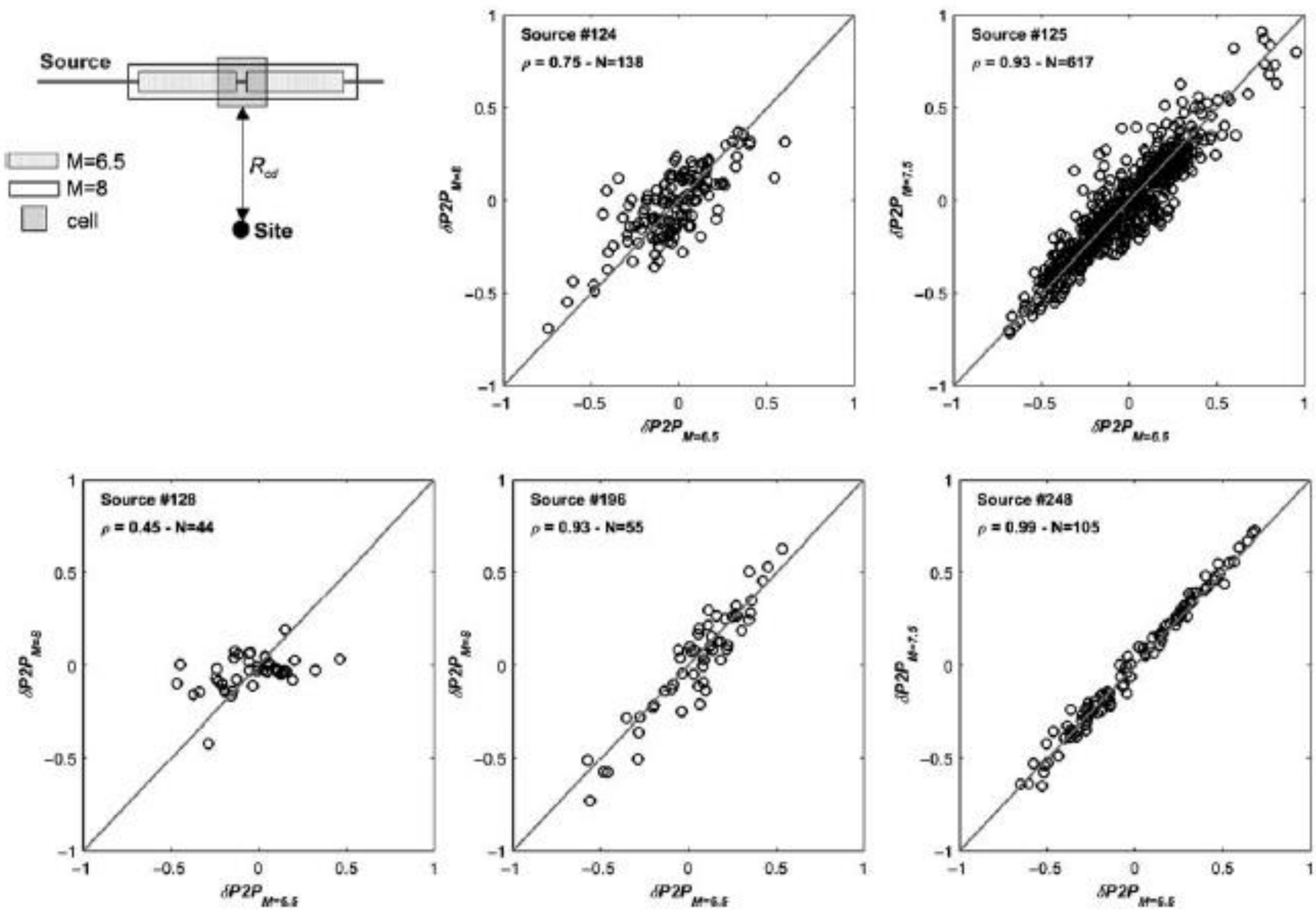
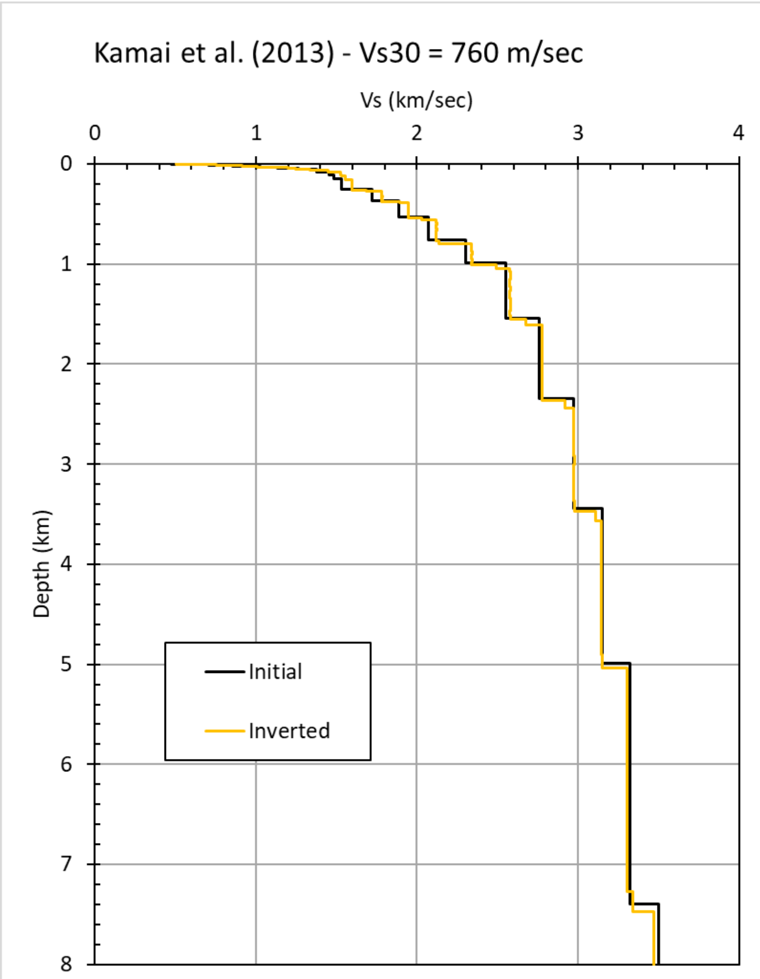
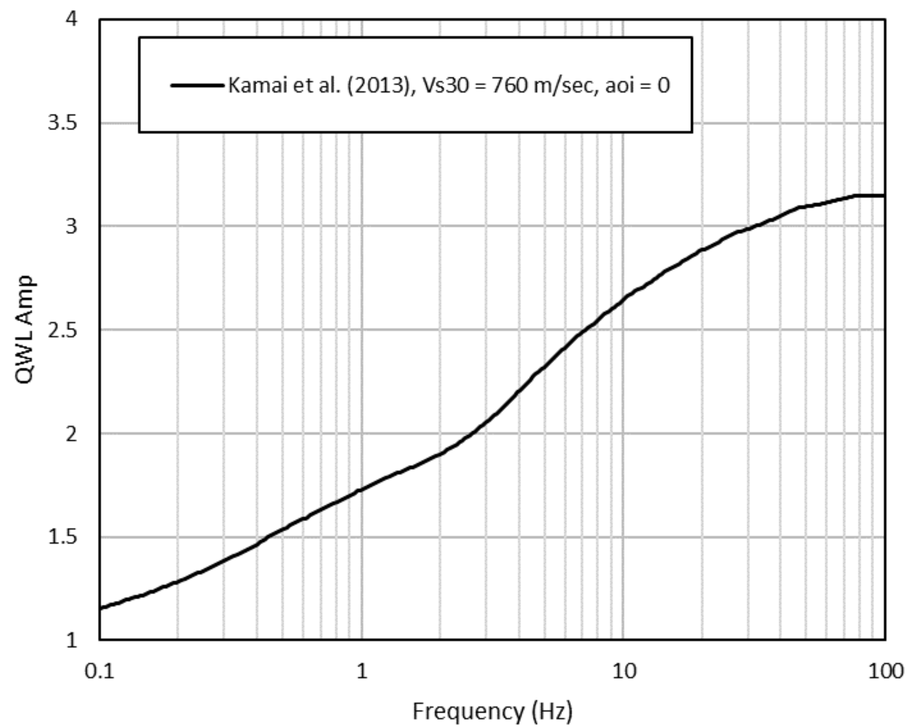


Figure 10. Correlation between the path terms from moderate-magnitude events (M_w 6.5) and those from large-magnitude events for selected CyberShake sources. The path terms are computed dividing the source by cells $0.1° \times 0.1°$. ρ is the correlation coefficient, whereas N is the number of points available for the correlation.


Kamai et al. (2013) - Vs30 = 760 m/sec
Vs (km/sec)
0
1
2
3
4
0
1
2
3
4
5
6
7
8
Depth (km)
Initial
Inverted


Kamai et al. (2013), Vs30 = 760 m/sec, aoi = 0
QWL Amp
4
3.5
3
2.5
2
1.5
1
0.1
1
10
100
Frequency (Hz)