Effects of earthquake source geometry and site conditions on spatial correlation of earthquake ground motion hazard

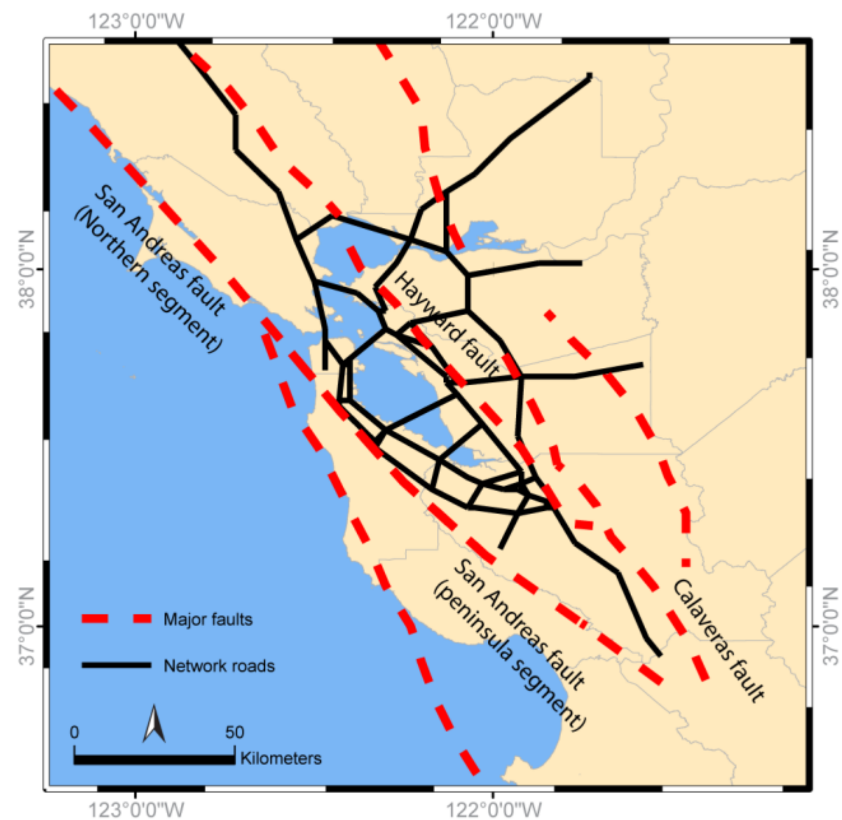
Jack W. Baker
Mahalia K. Miller
Civil & Environmental Engineering
Stanford University

Motivation

- We are interested in assessing seismic risk to distributed systems
  - Portfolios of insured properties
  - Transportation, electrical, and other infrastructure networks

- The spatial extent of these systems creates additional challenges relative to individual facilities

- Spatial variation of ground motion intensities (e.g., spectral accelerations) is a key required input for these analyses

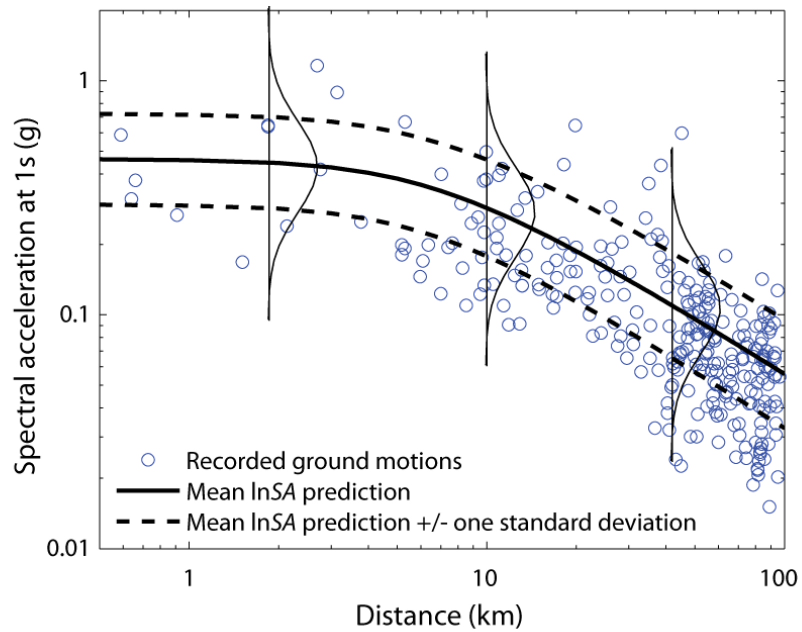


San Francisco Bay Area roadways

Background

Ground Motion Prediction ("attenuation") Models provide distributions of ground motion intensity (e.g., spectral acceleration) as a function of earthquake magnitude, source-to-site distance, etc.

Observed spectral acceleration values from the 1999 Chi-Chi, Taiwan earthquake



Model form:

$$\ln Sa_i(T) = \overline{\ln Sa_i(M, R, V_{s30}, T, \ldots)} + \sigma_i \varepsilon_i + \tau \eta$$

Spectral acceleration at site *i*

Predicted mean (log) spectral acceleration

Intra-event variability at site *i*

Inter-event variability (at all sites)

Components of correlation in ground motions

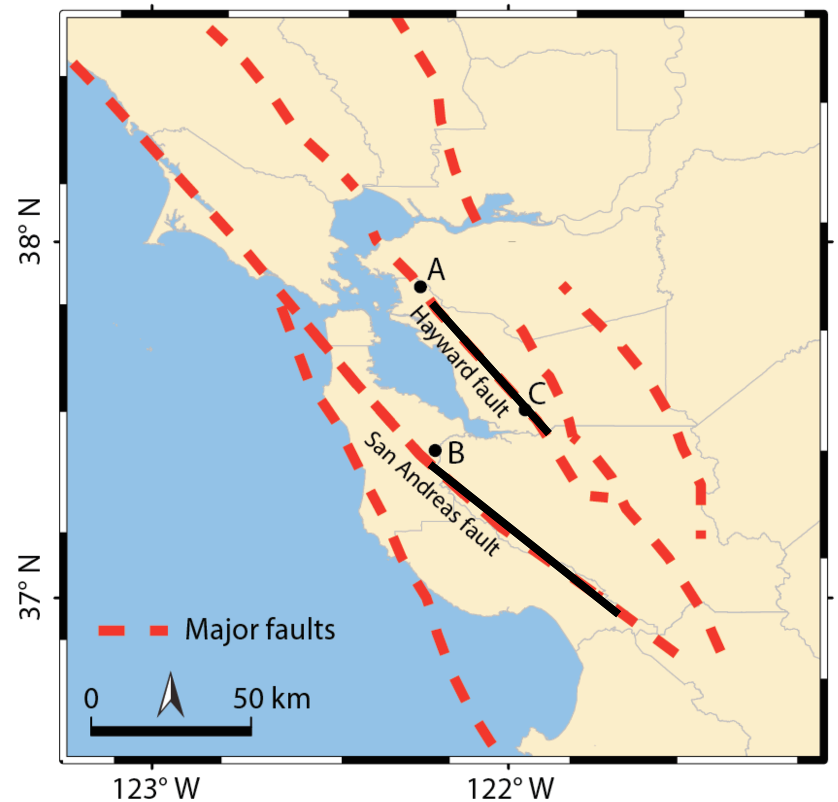
Ground motion predictions at two sites:

$$\ln Sa_{1j} = \overline{\ln Sa(M_j, R_{1j}, V_{s30,1}, T, \ldots)} + \sigma_{1j}\varepsilon_{1j} + \tau_j \eta_j$$

$$\ln Sa_{2j} = \overline{\ln Sa(M_j, R_{2j}, V_{s30,2}, T, \ldots)} + \sigma_{2j}\varepsilon_{2j} + \tau_j \eta_j$$

"Correlation in means"

"Correlation in residuals"



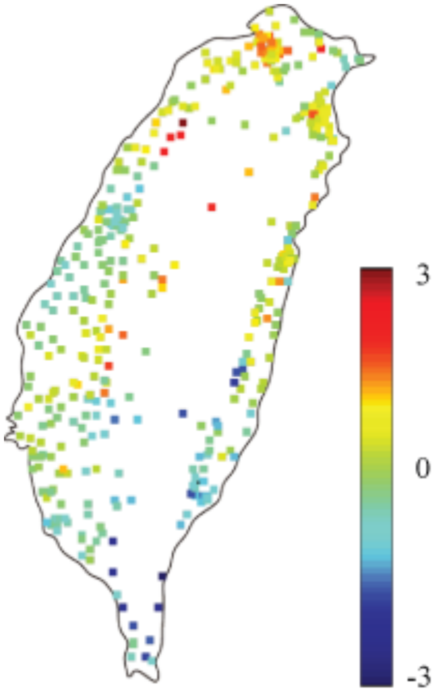
This is different than ground motion coherence

Correlation in residuals from well-recorded earthquakes

$$\varepsilon_i = \left(\ln Sa_i - \overline{\ln Sa(M, R_i, V_{s30,i}, T, \ldots)} - \tau\eta\right) / \sigma_i$$

Observations of past earthquakes shows that these residuals are correlated at nearby sites, due to

- Similar location to asperities
- Similar wave propagation paths
- Similar local site effects
- …



Observed PGA ε's from the 1999 Chi-Chi earthquake

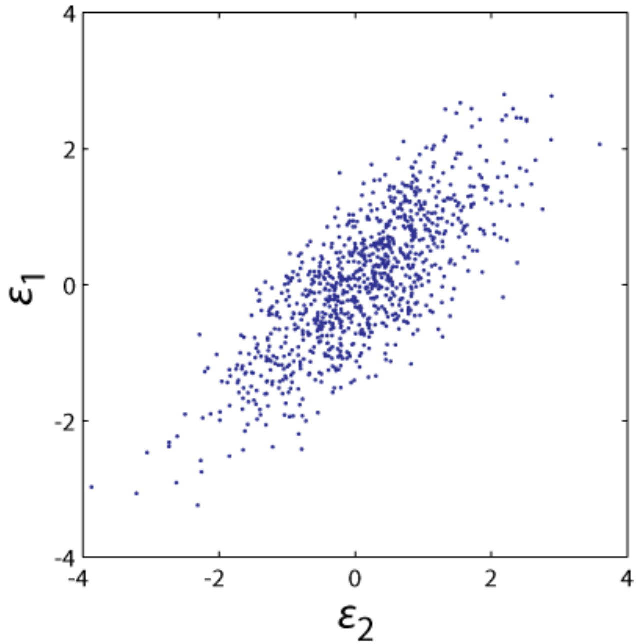
Estimation of correlation from well-recorded earthquakes

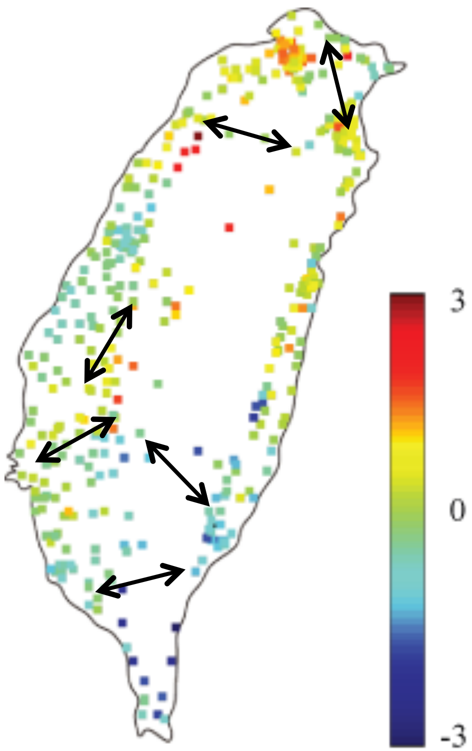
We assume that

- Any pair of sites with equal separation distance within an earthquake has the same correlation (*stationarity*)
- The correlation is independent of orientation (*isotropy*)

$$\varepsilon_i = \ln Sa_i(T) - \overline{\ln Sa_i(M, R_i, T, \ldots)} - \eta$$

We can then estimate a correlation coefficient at a given distance





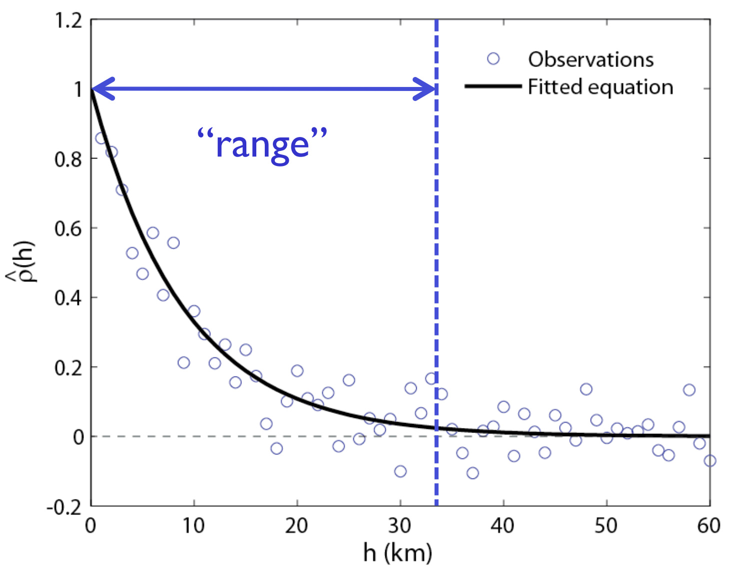
Estimation of correlation from well-recorded earthquakes

To turn these observations into a predictive model, we need:

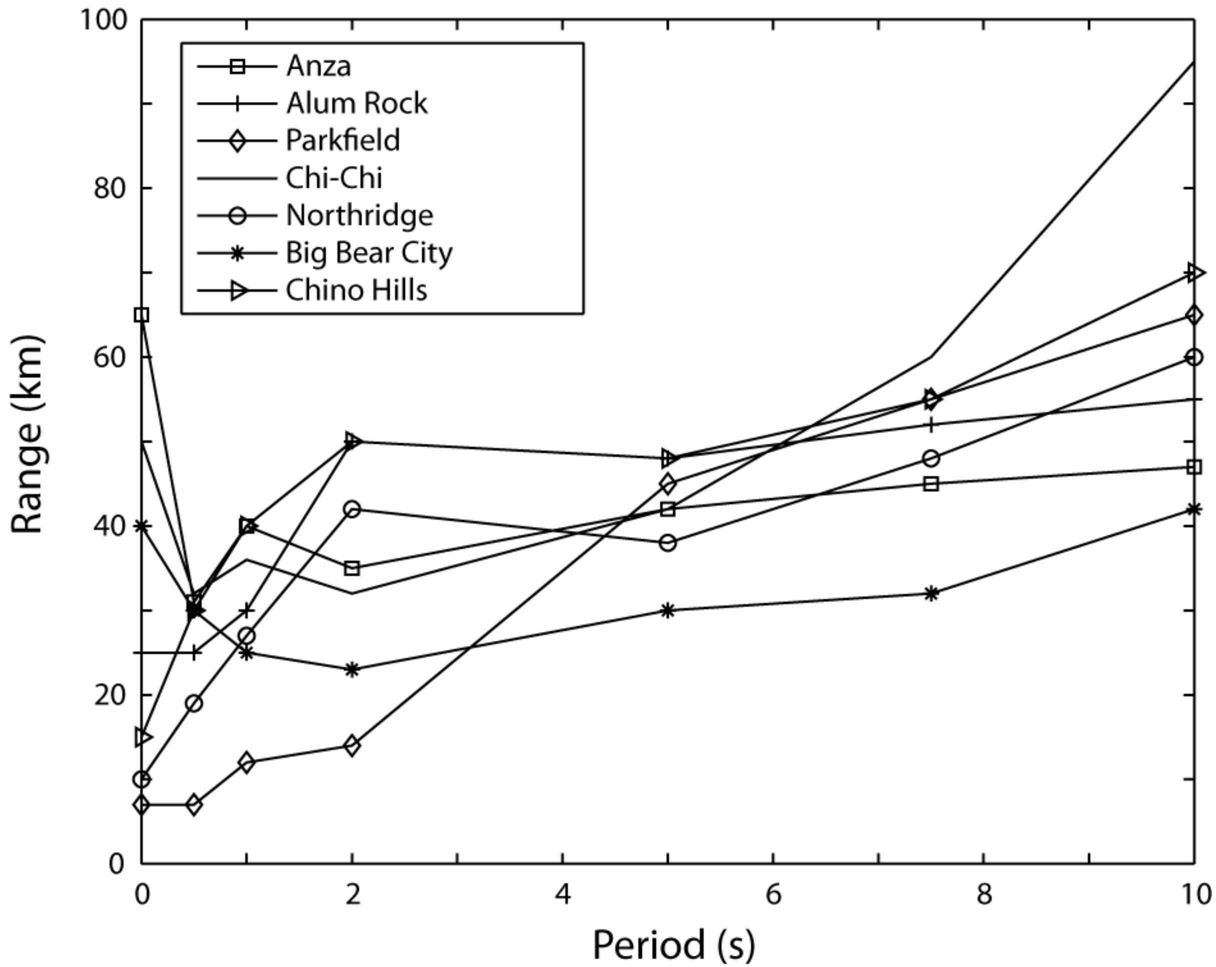
- An equation to predict correlation as a function of separation distance, *h*:

$$\hat{\rho}(h) = e^{-(3h/a)}$$

- A correlation range, a

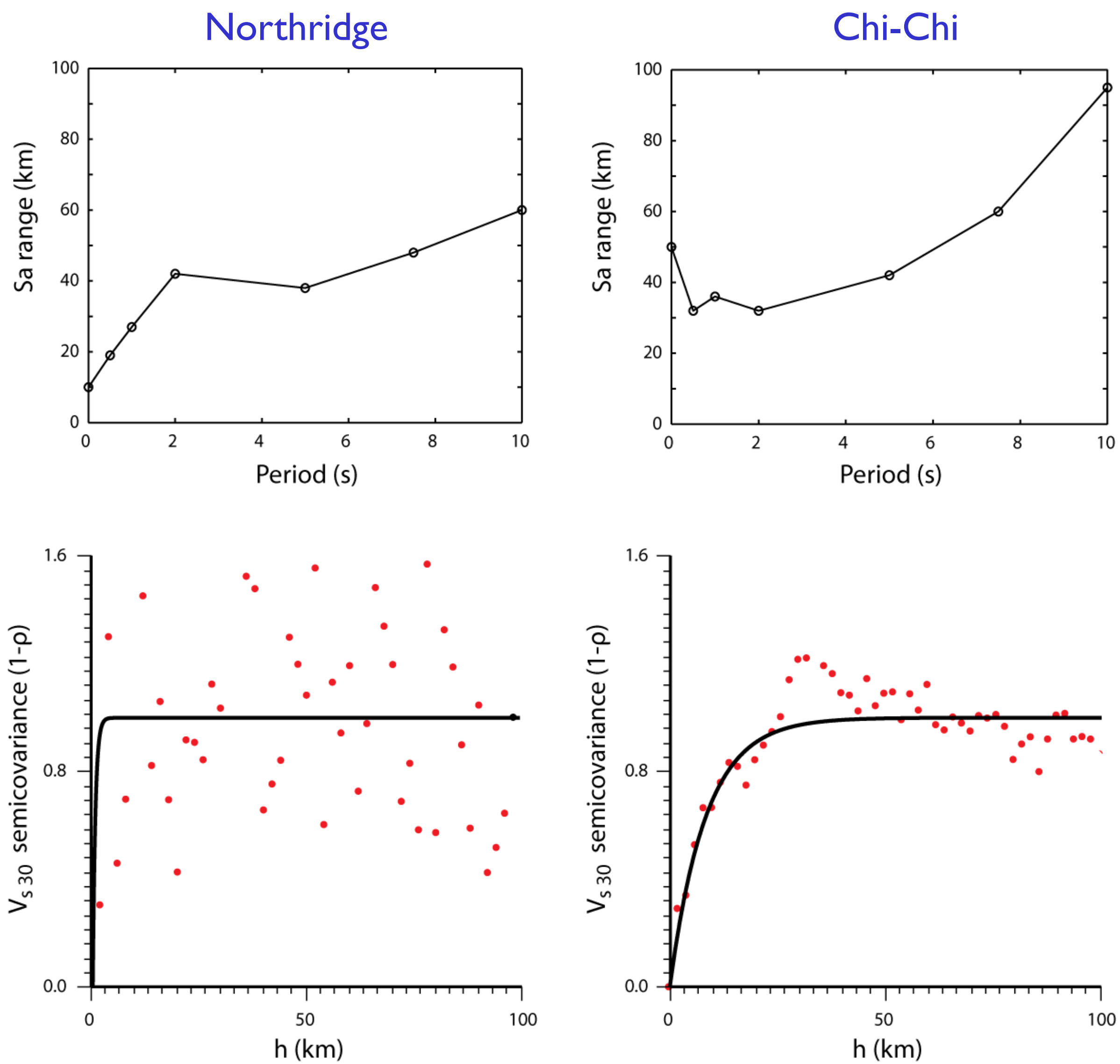


Observed ranges from several well-recorded earthquakes



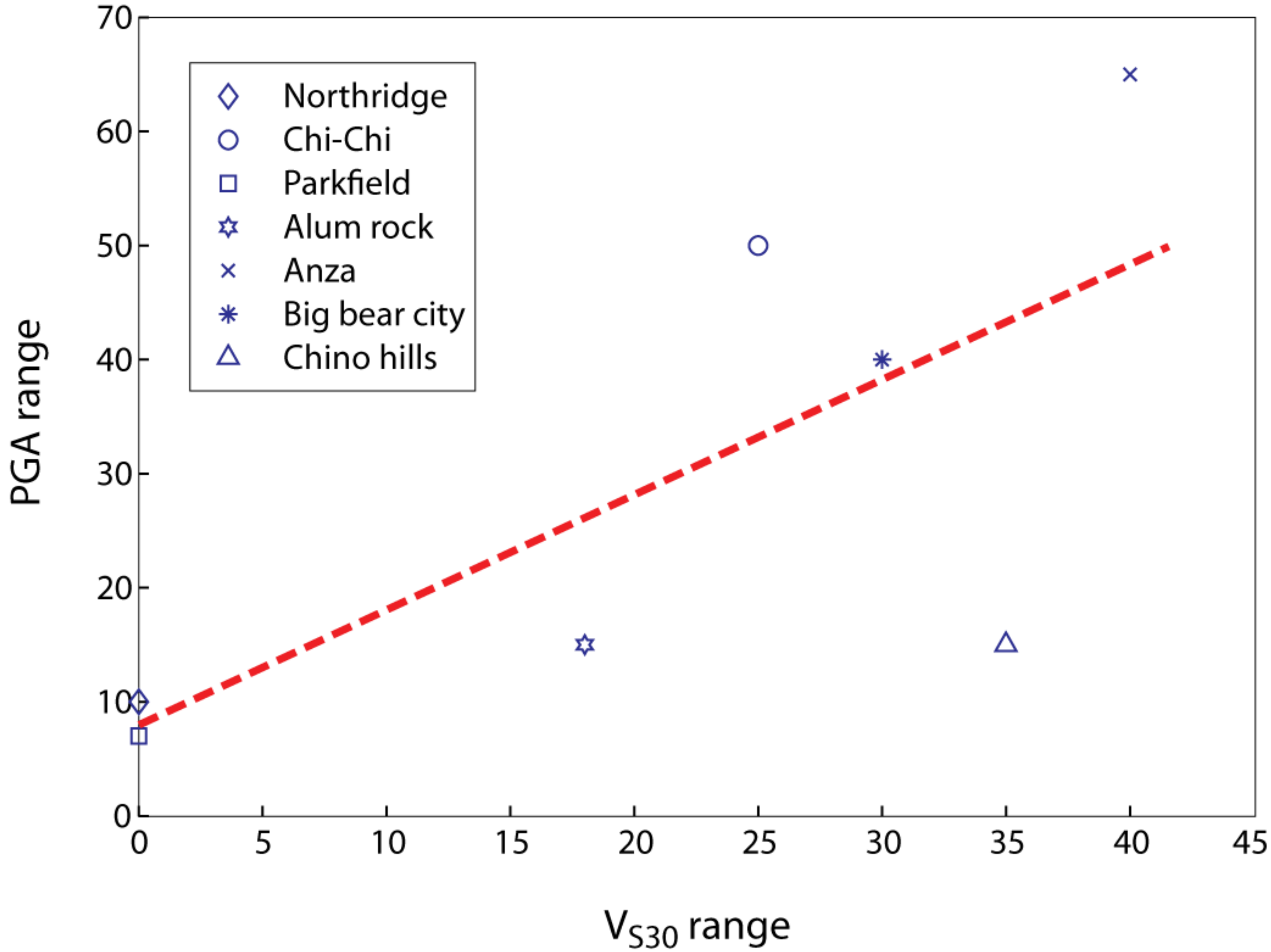
From Jayaram and Baker (2009)

Potential effect of site conditions?



From Jayaram and Baker (2009)

V_{s30} range versus *PGA* range, for seven earthquakes



From Jayaram and Baker (2009)

Correlation in residuals vs. V_{s30} variability: two possible explanations

1. V_{s30} variability is a proxy for heterogeneity in near-surface site conditions, causing heterogeneity in ground motion intensity (particularly at high frequencies?)

2. Inferred, rather than directly measured, V_{s30} values have higher correlations. In these cases, ground motion predictions at adjacent sites may have correlated errors due to incorrectly-inferred V_{s30} values

$$\ln Sa_{1j} = \overline{\ln Sa(M_j, R_{1j}, V_{s30,1}, T, \ldots)} + \sigma_{1j}\varepsilon_{1j} + \tau_j \eta_j$$

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Correlation in means is implied by the source model

Ground motion predictions at two sites:

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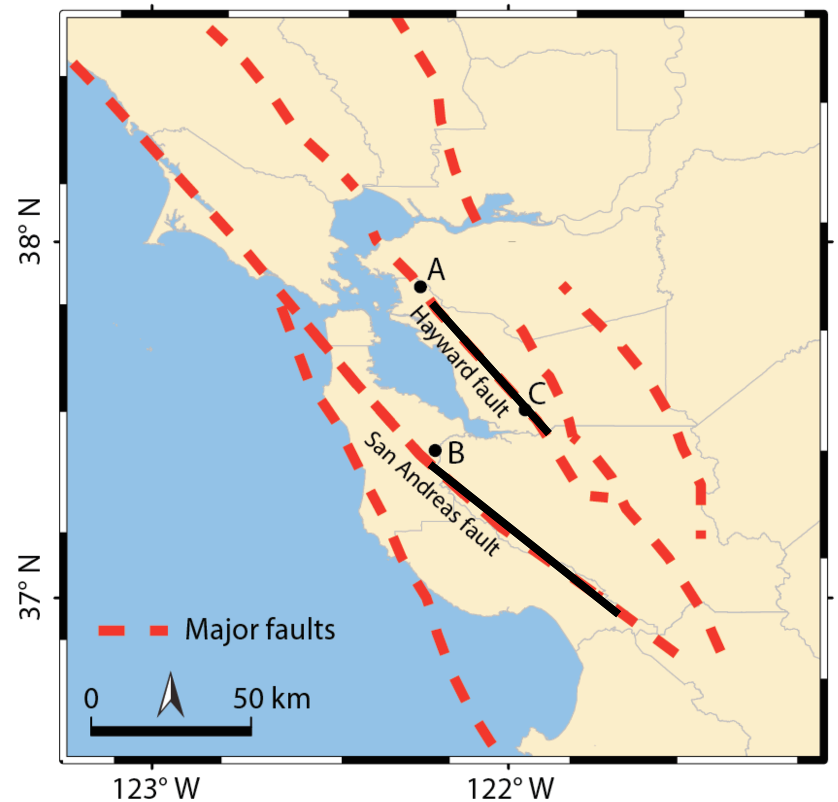
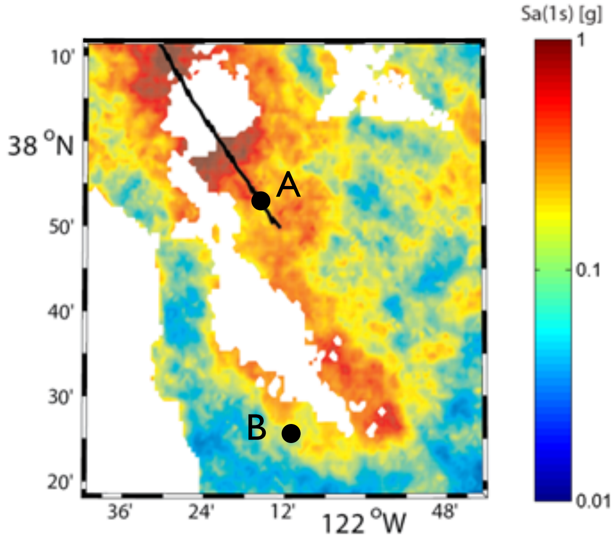
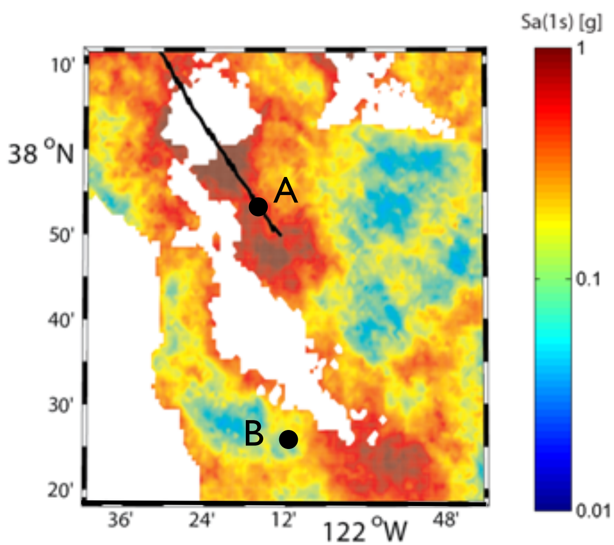
"Correlation in means"

"Correlation in residuals"



Construction of a synthetic catalog of ground motions





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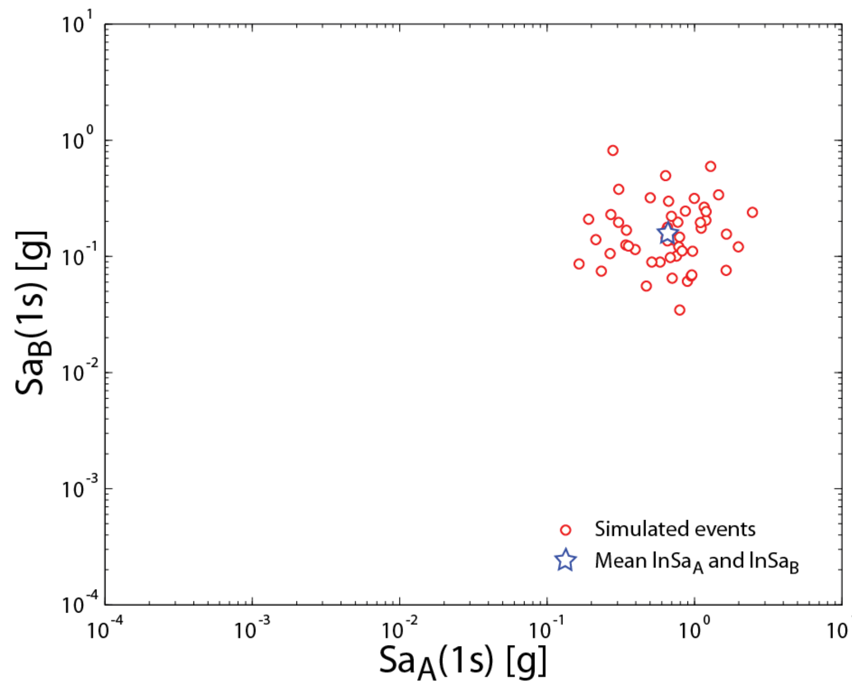

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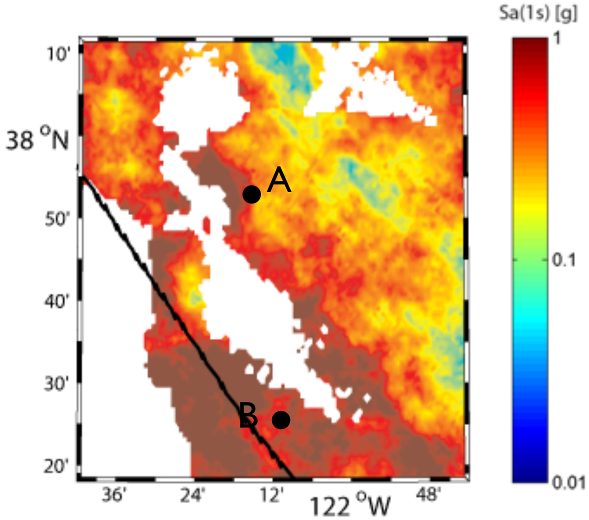

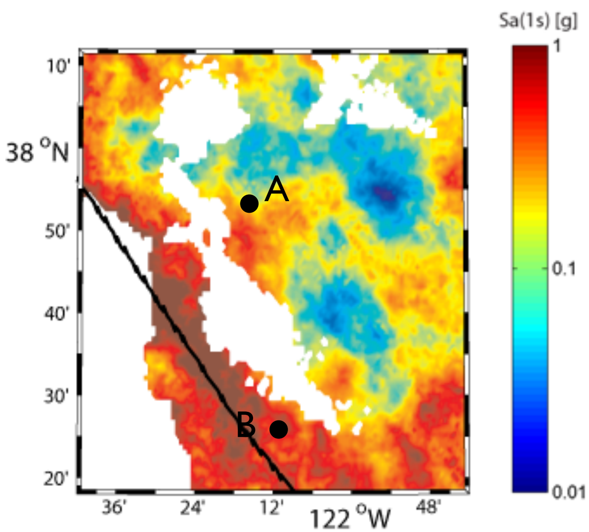

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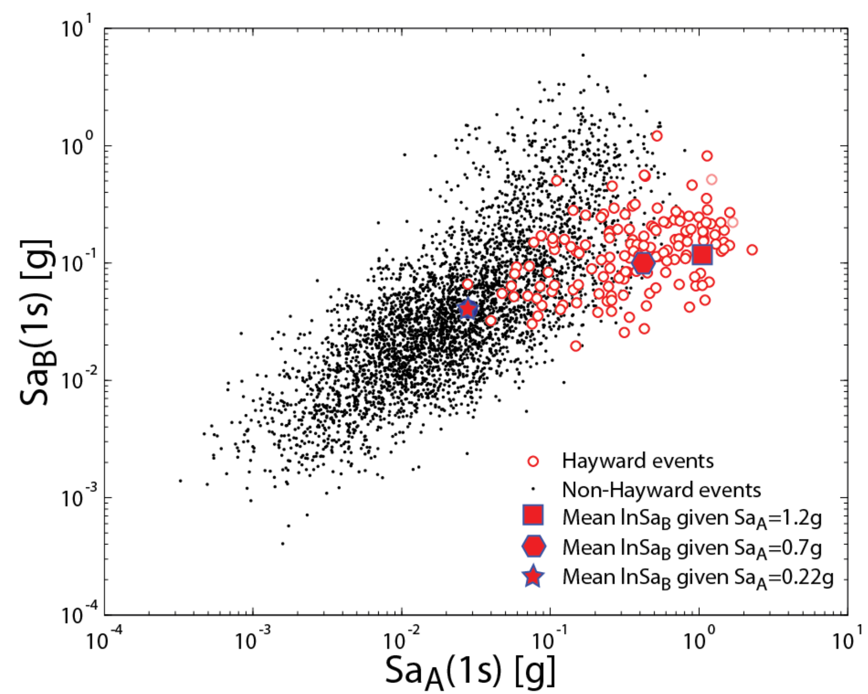
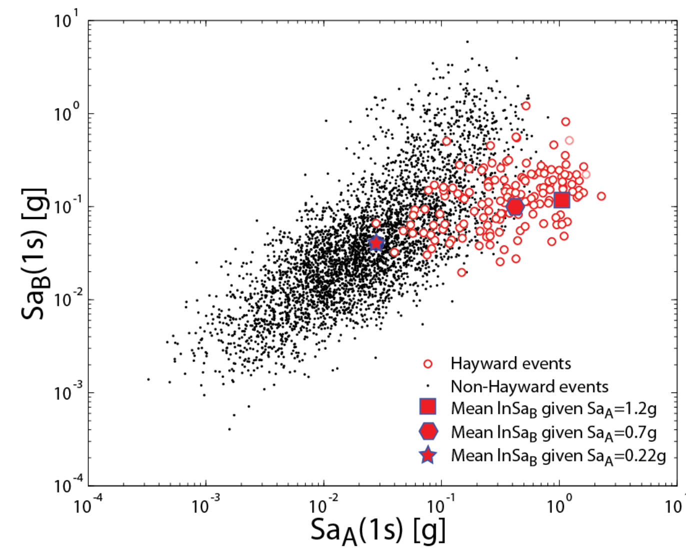


The stochastic catalog reproduces single-site hazard curves

If we look at the observed *Sa* values from these simulations at any single site, they match the distribution from traditional single-site PSHA



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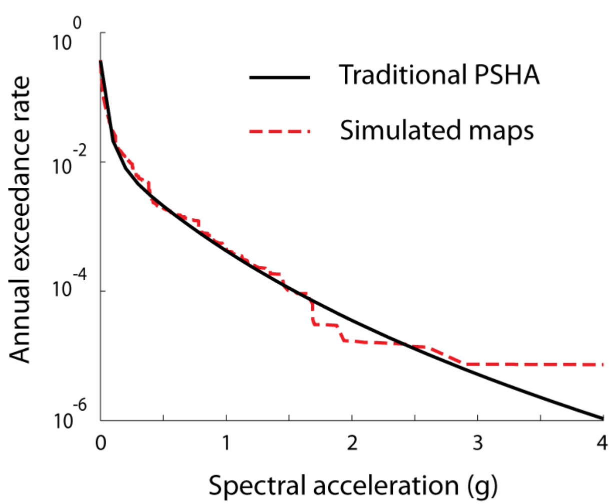
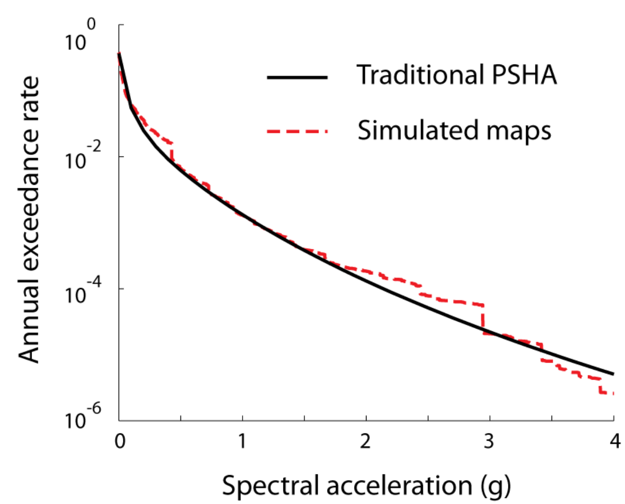
Site A:

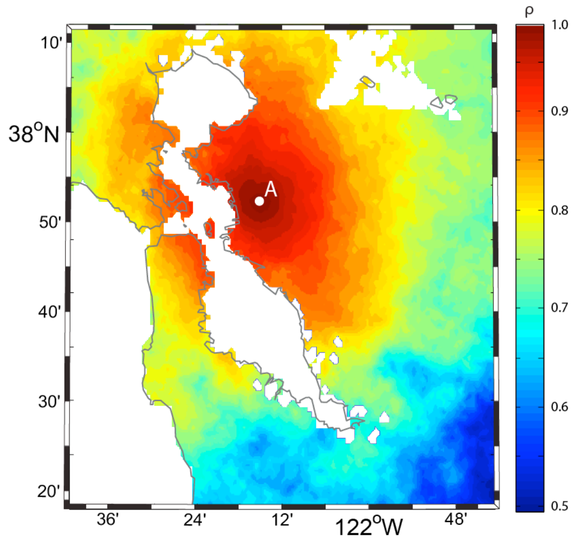


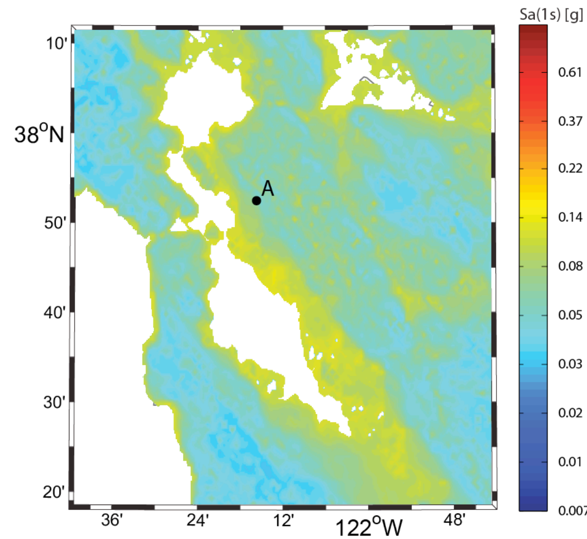
Site B:



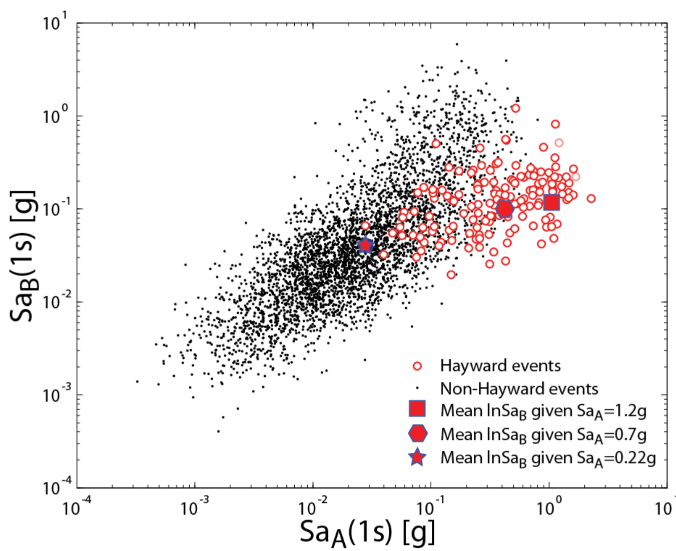
Measures of joint behavior

Correlation with $Sa_A(1s)$





Mean given $Sa_A(1s)=0.22g$



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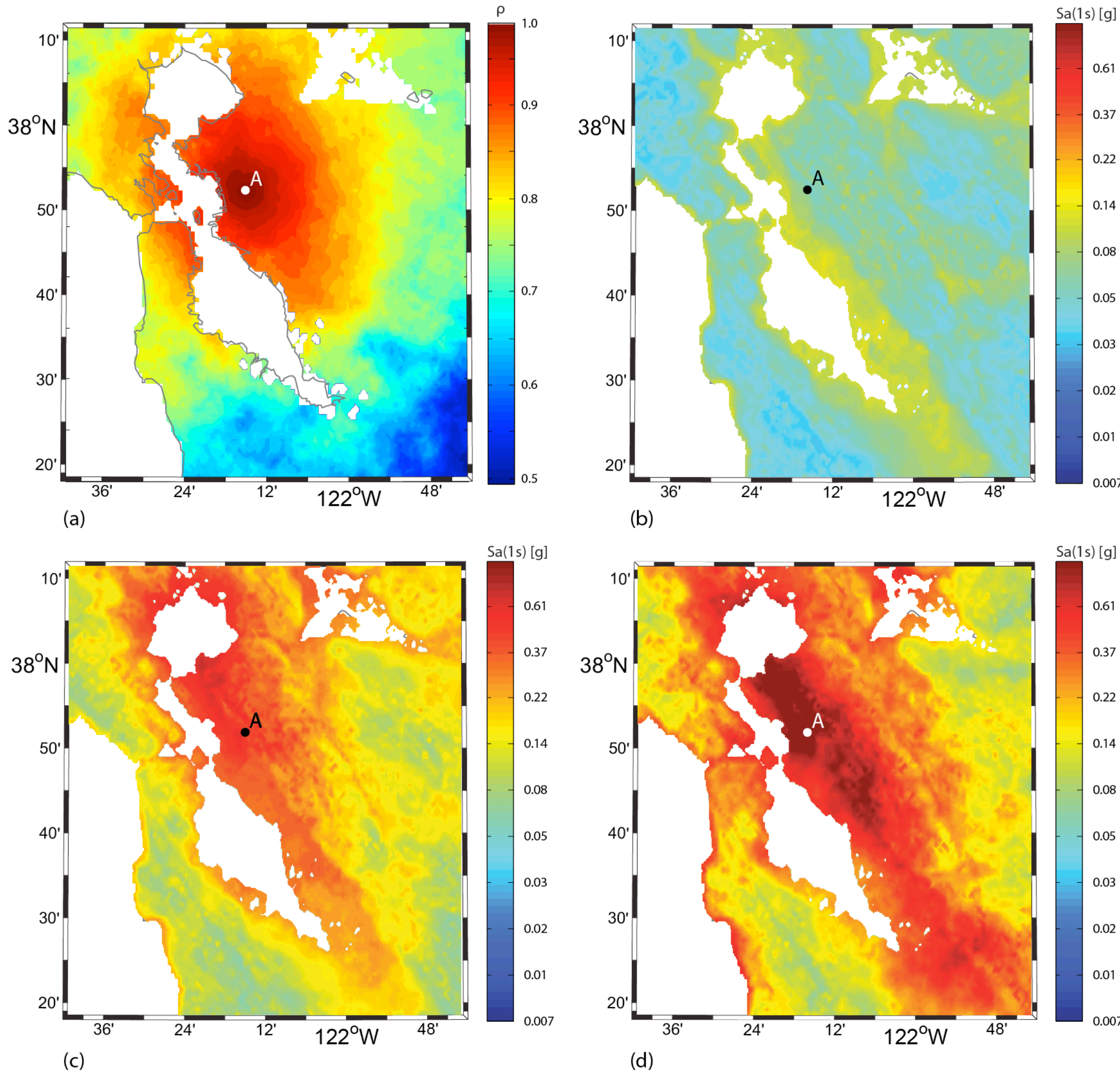
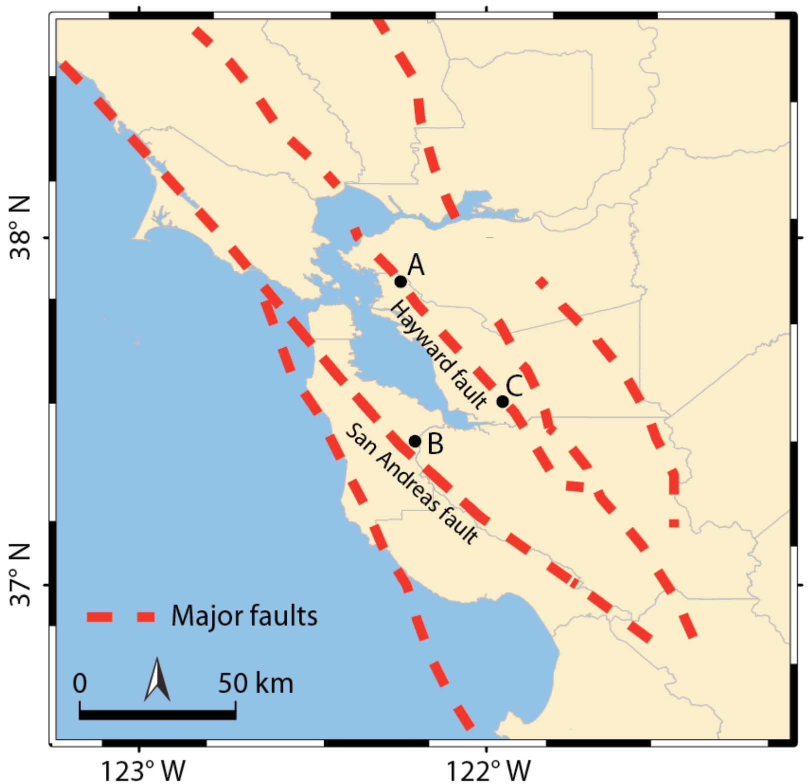
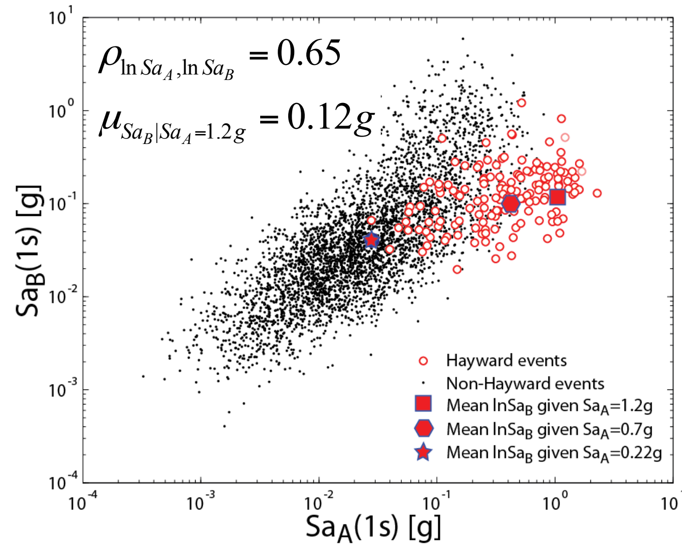


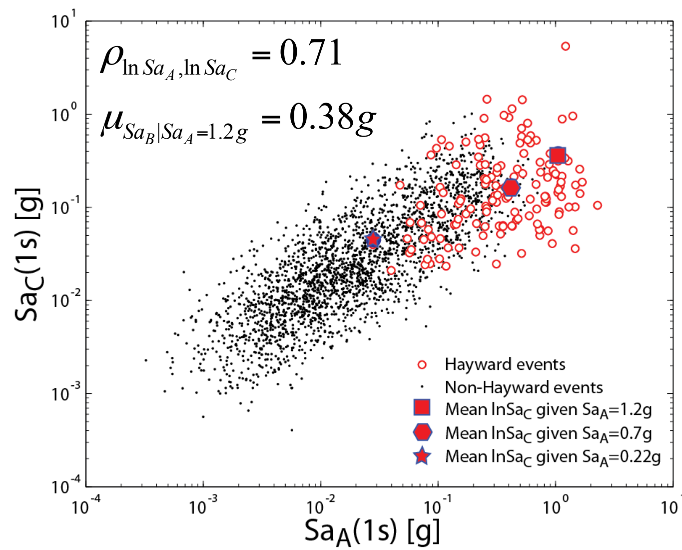
Mean given $Sa_A(1s)$=0.7g

Mean given $Sa_A(1s)$=1.2g

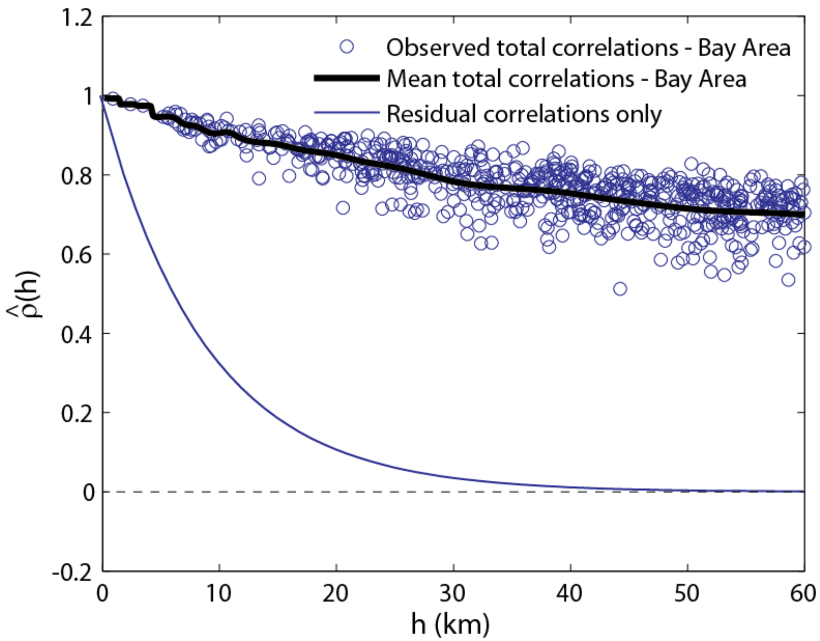
Correlation coefficients versus conditional means

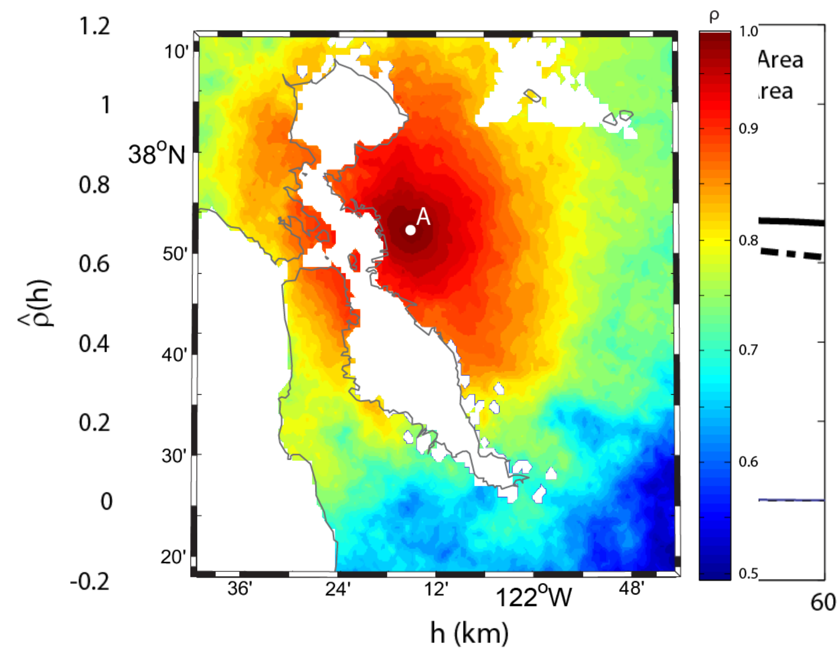






Total correlations are significant at large distance scales

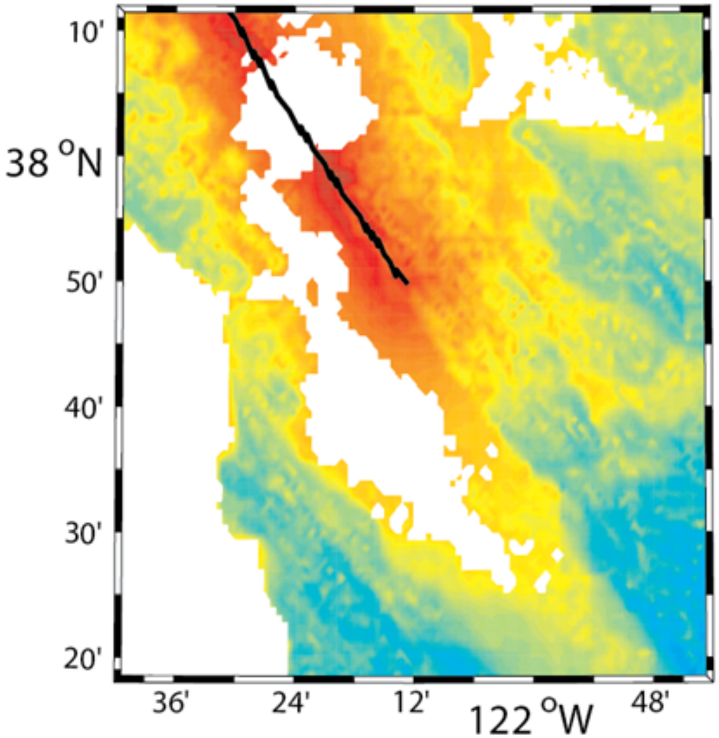




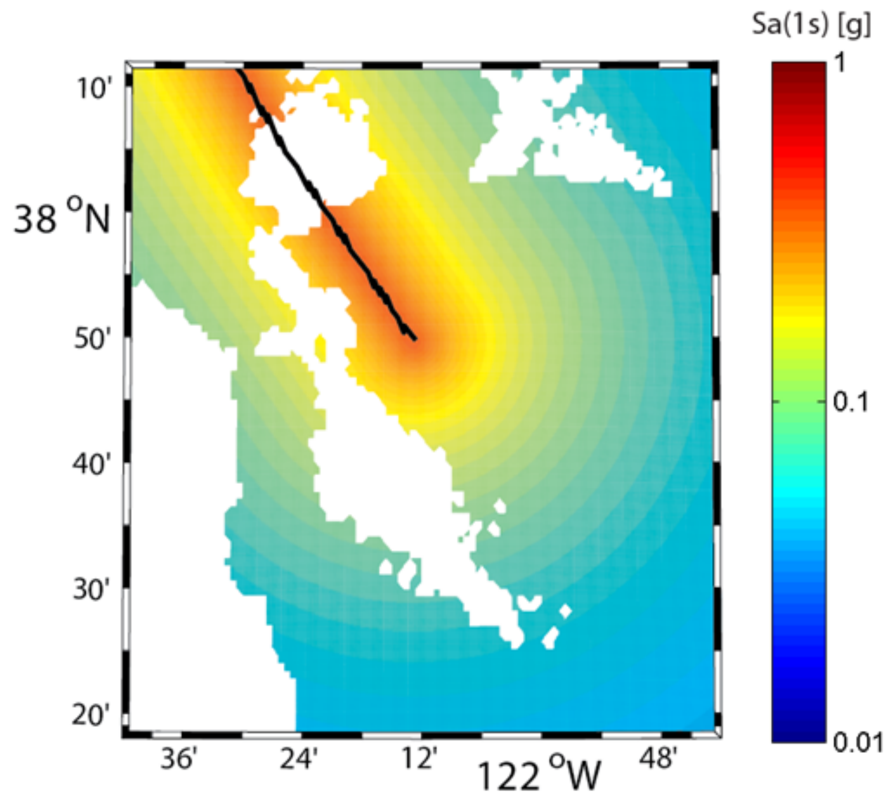
Total correlations will in general be region-dependent

Influence of site conditions

Mean ln*Sa*(1s) for a scenario Hayward event



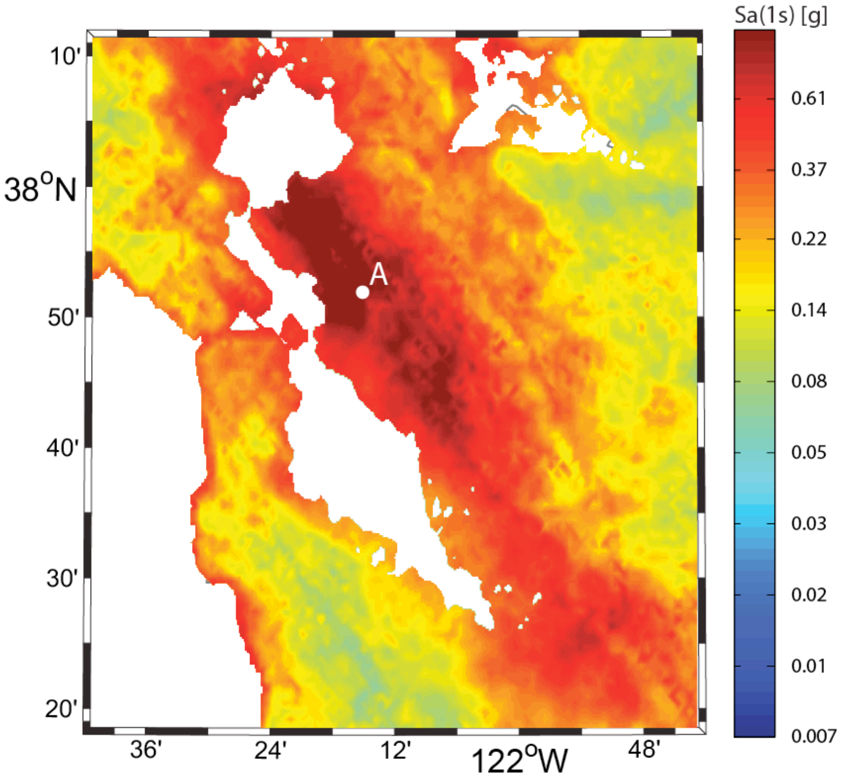
Using site-specific inferred V_{s30}



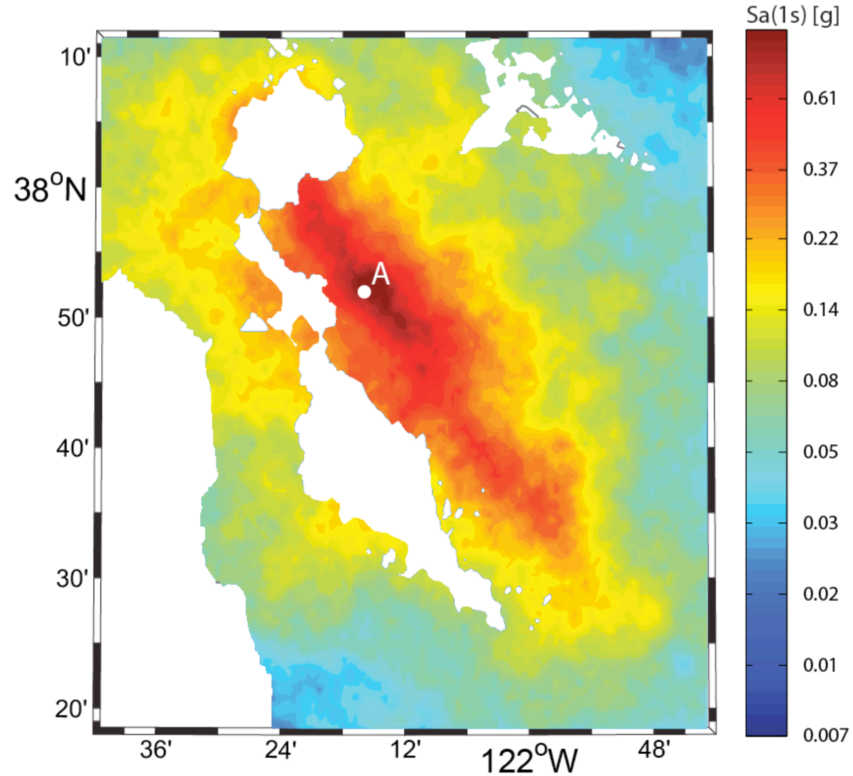
Using constant V_{s30}

Influence of site conditions

Mean $Sa(1s)$, given $Sa_A(1s)$=1.2g



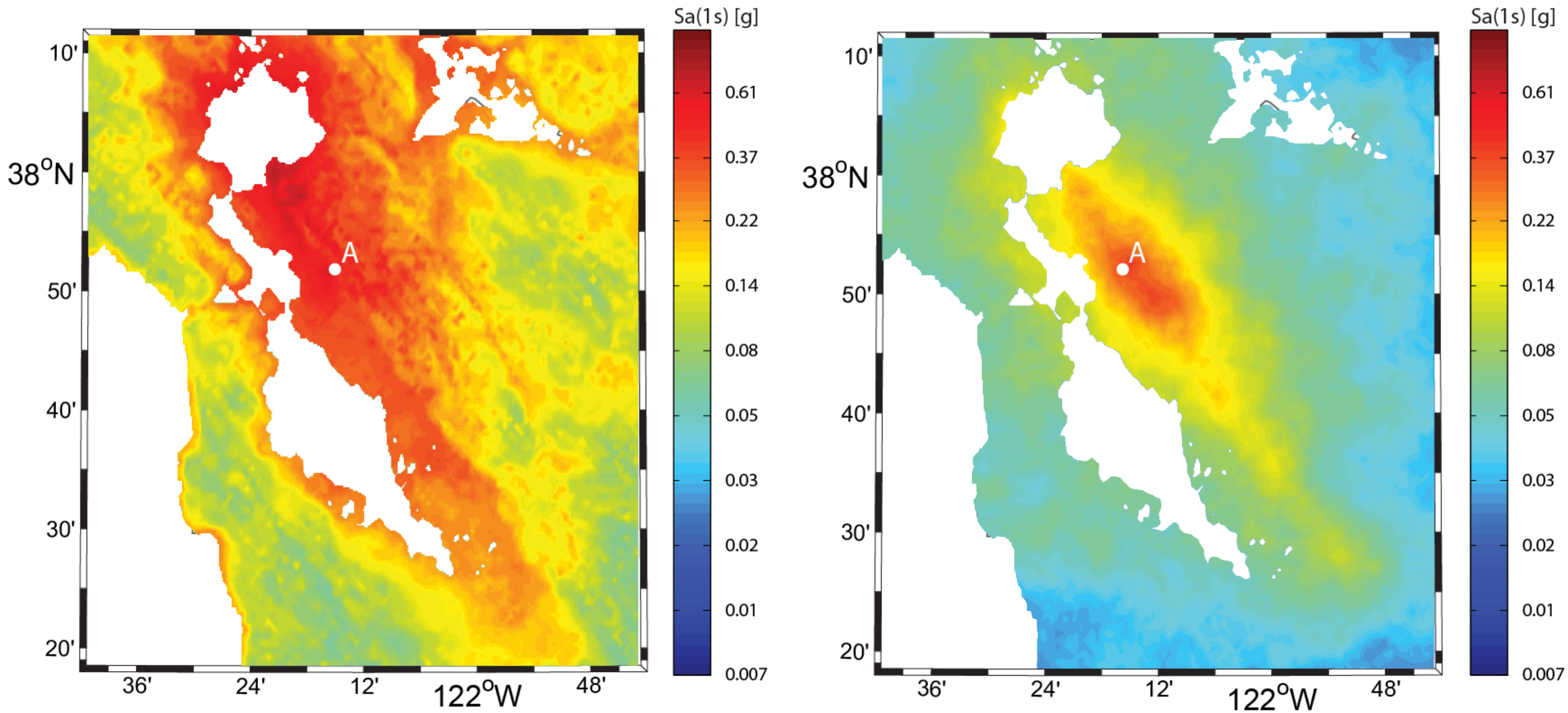
Using site-specific inferred V_{s30}



Using constant V_{s30}

Influence of site conditions

Mean Sa(1s), given Sa_A(1s)=0.7g



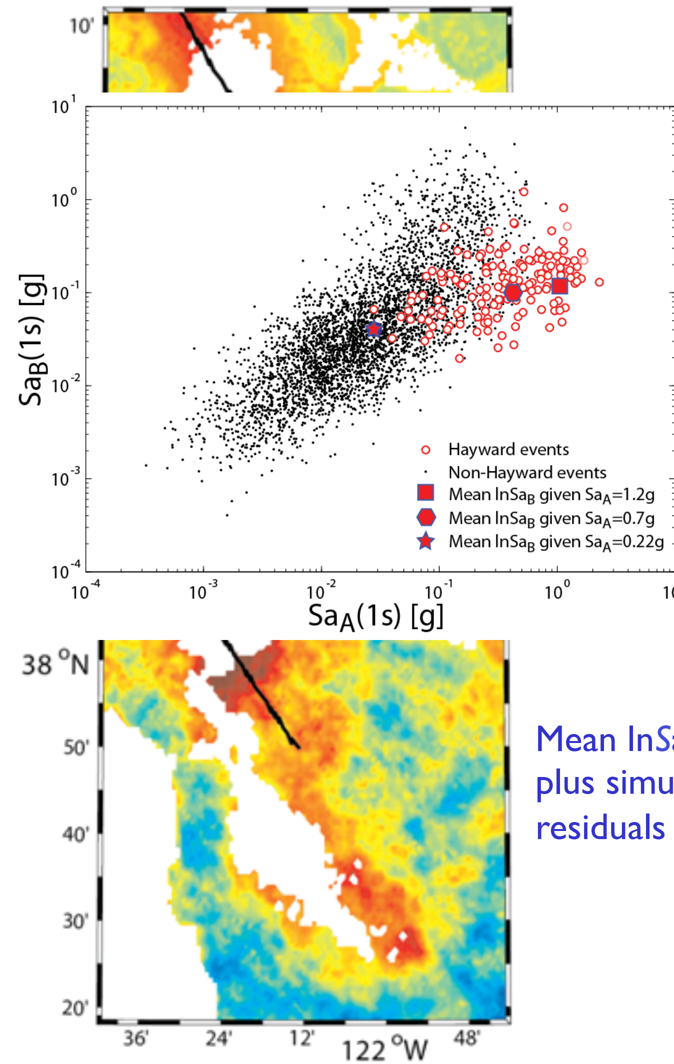
Using site-specific inferred V_{s30}

Using constant V_{s30}

Opportunities for use of simulated ground motions

- The presented results are all fully consistent with empirical ground motion prediction models
- There is a limit to the extent to which those models can capture
  - Near surface site effects
  - Basin effects
  - Topography
- We need thousands of simulations for generation of a synthetic catalog—not just a scenario event
- *An aside, observed correlations in residuals are relatively stable across past earthquakes, so this may be a useful target for validation*

Predictions from empirical models:



(1s)

Mean lnSa(1s) plus simulated residuals

Treatment of site effects: can we do better?

- Numerical site response analysis and other methods have the potential to improve on generic V_{s30}-based ground motion predictions, but for this application we need it to be scalable to thousands of sites and earthquakes
- Any implementation for this application needs to consider thousands of sites, so inference of unmeasured site conditions will be necessary

Conclusions

- Methods for studying joint distributions in *Sa* values at pairs of sites have been presented

- This formulation is fully consistent with current ground motion prediction models and seismic source models, so it simply extends single-site Probabilistic Seismic Hazard Analysis into multiple-site analysis

- In the context of empirical ground motion models, we propose decomposing this spatial variation into *correlation in means* and *correlation in residuals*
  - Correlation in means is dependent on earthquake source geometry and site condition variability
  - Correlation in residuals depends only on separation distance

- In some cases, joint distributions of ln*Sa*'s are not jointly Gaussian, and so correlations are not complete descriptors of joint behavior

- Spatial variation in ground motion spectral accelerations is an important property for assessing seismic risk at a regional scale, and advances in ground motion simulations and site effects modeling will be valuable in this field

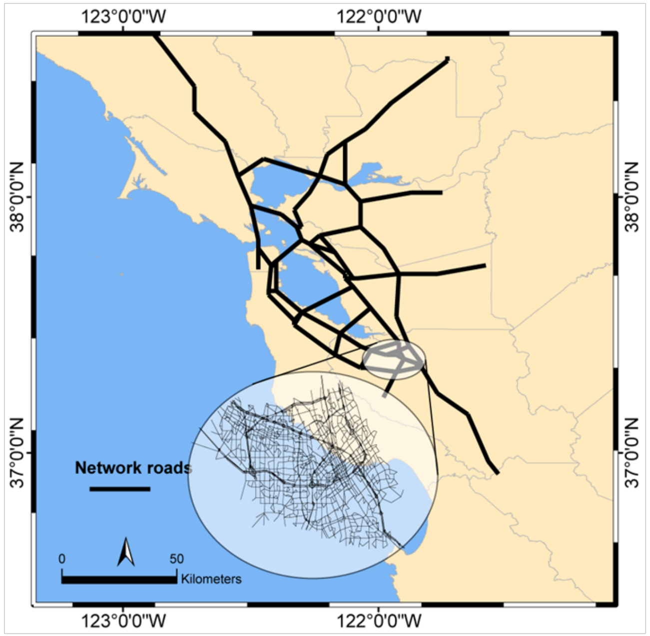
Acknowledgements

- US Geological Survey, award 07HQGR0031
- National Science Foundation, award CMMI 0952402
- Nirmal Jayaram, Paolo Bazzurro and Jaesung Park

More information available at: *http://www.stanford.edu/~bakerjw*

San Francisco Bay Area transportation network risk assessment

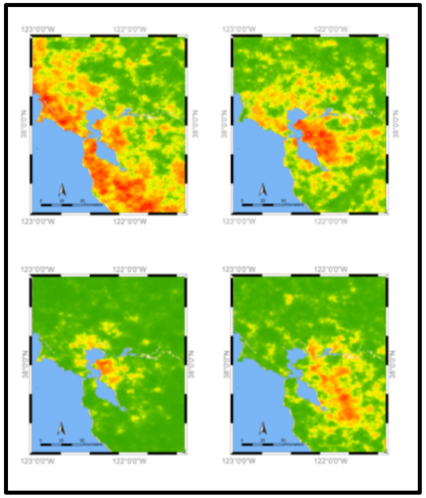
- We are studying the travel time delays induced by earthquakes
- Network data and Origin-Destination demands were obtained from Caltrans and aggregated
- Bridge damage states are estimated using HAZUS fragility functions
- Travel times are obtained using a user-equilibrium model with bridge capacities reduced due to damage (no travel demand changes)

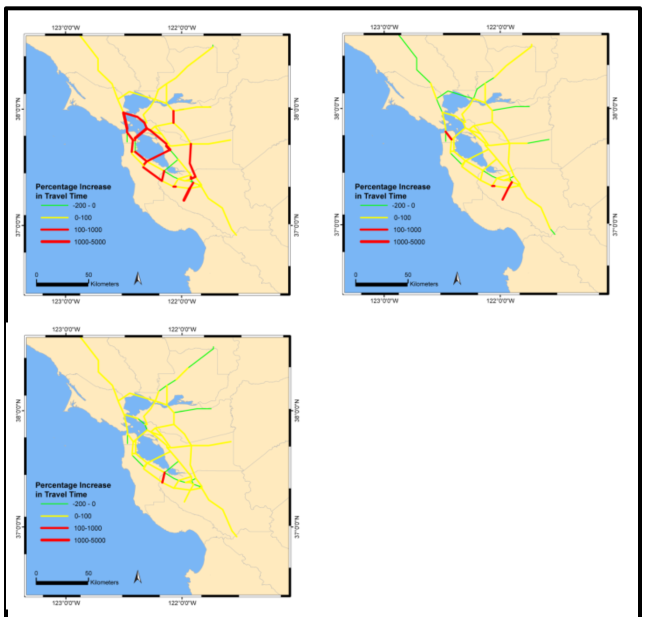


Bay area interstate highways

We use this simplified model for illustrating our methodology

Effect of spatial correlations on loss estimates





We can repeat this exercise omitting the ε correlation, to see the impact of this correlation

$$\ln Sa_i(T) = \overline{\ln Sa_i(M, R, T, \ldots)} + \varepsilon_i + \eta$$