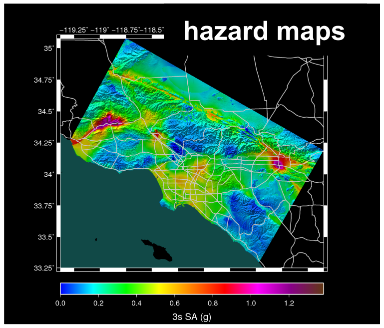
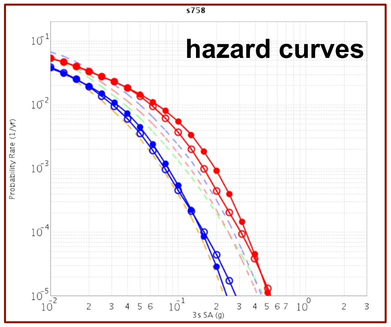
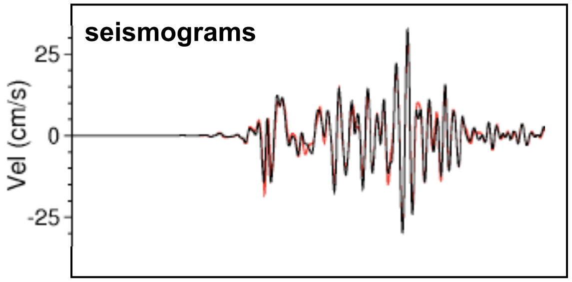
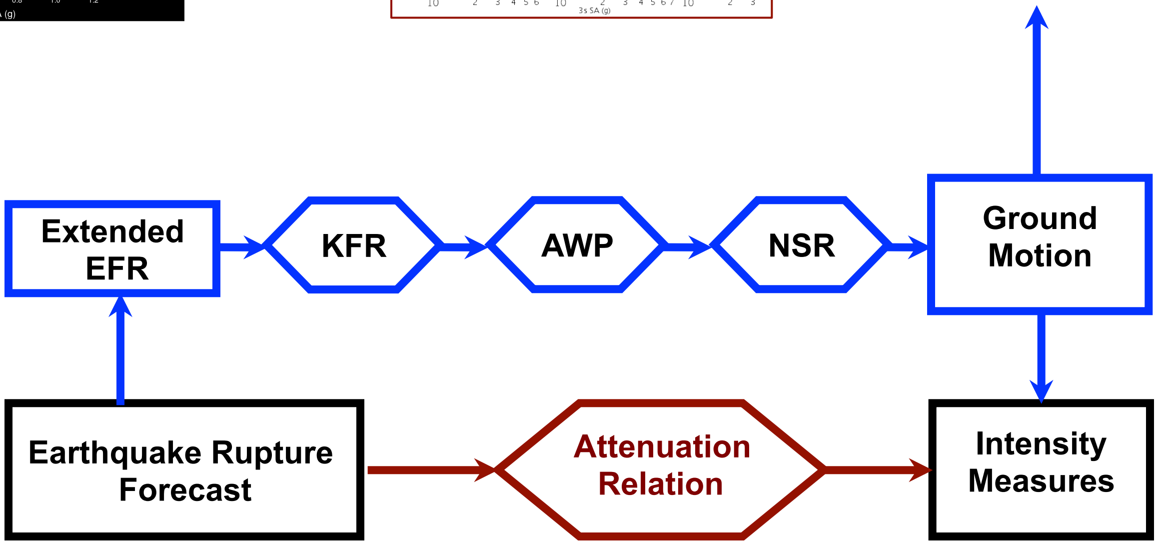
CyberShake Platform: Simulation-Based PSHA









Extended EFR → **KFR** → **AWP** → **NSR** → **Ground Motion**

Earthquake Rupture Forecast → **Attenuation Relation** → **Intensity Measures**

Physics-based simulations

Empirical model

KFR = kinematic fault rupture model
AWP = anelastic wave propagation model
NSR = nonlinear site response

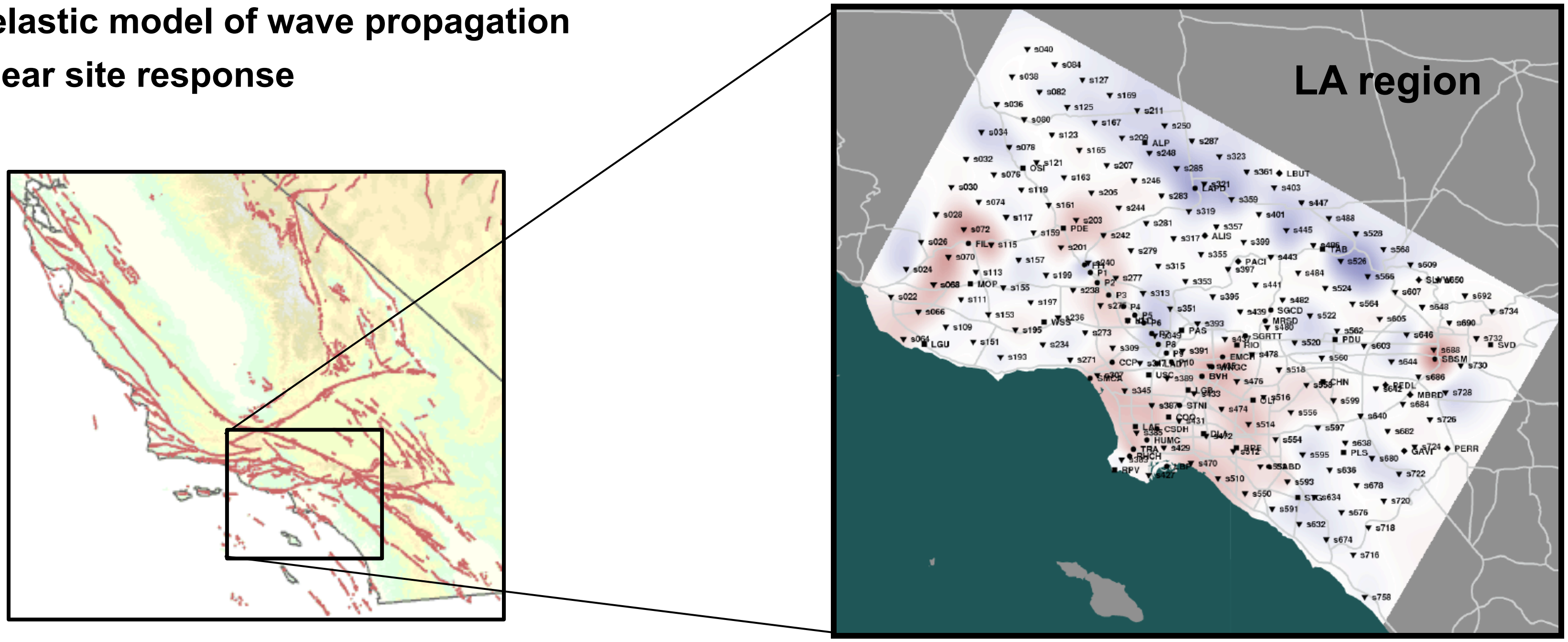
CyberShake Platform: Simulation-Based PSHA

Graves, R., T. H. Jordan, S. Callaghan, E. Deelman, E. Field, G. Juve, C. Kesselman, P. Maechling, G. Mehta, K. Milner, D. Okaya, P. Small, and K. Vahi (2011)

- **Uses an *extended* earthquake rupture forecast**
  - **Source probabilities from UCERF2**
  - **Conditional hypocenter distributions**
  - **Slip variations from pseudo-dynamic model**
- **Calculates *seismograms* efficiently using "reciprocity"**
  - **Large suites of kinematic fault ruptures**
  - **3D anelastic model of wave propagation**
  - **Nonlinear site response**

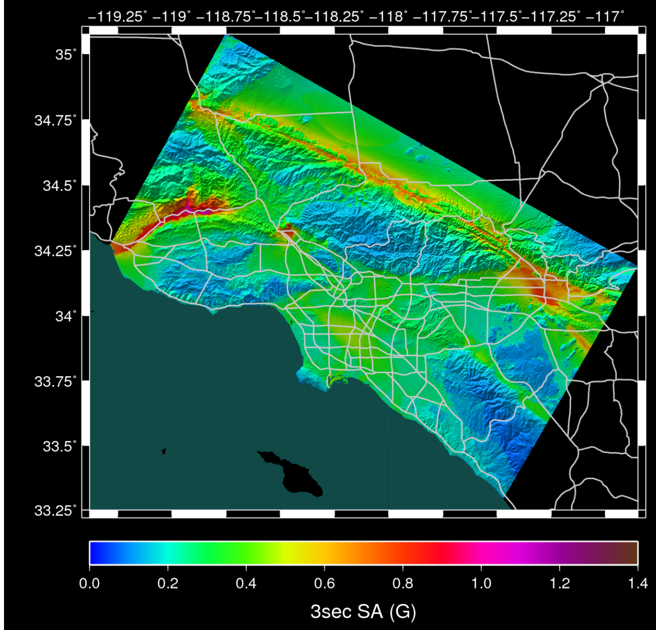
225 sites in LA region (f < 0.5 Hz)

- **440,000 simulations per site**
- **Run on TACC *Ranger***
  (5.3 million hrs, 4,400 cores, 50 days)
- **189 million jobs**
- **46 petabytes of total I/O**
- **176 terabytes of total output data**
- **2.1 terabytes of archived data**

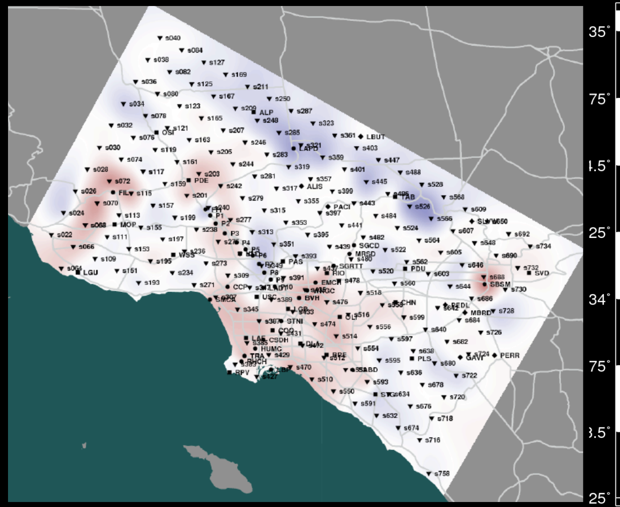


CyberShake Hazard Map Interpolation

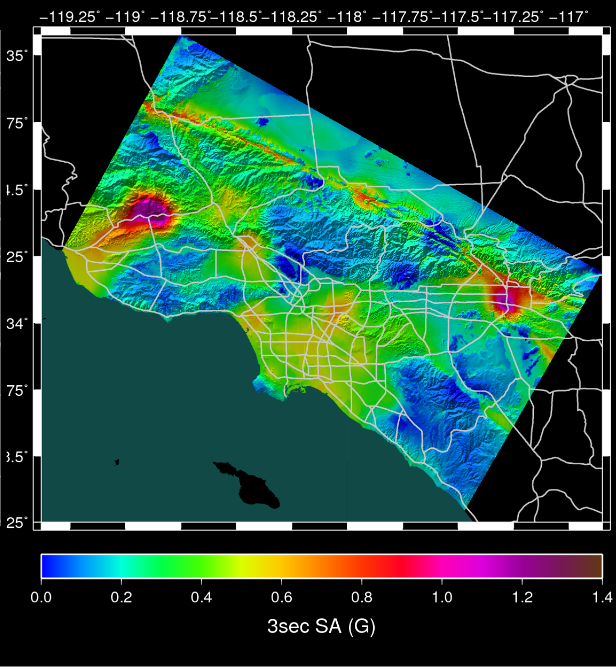
Campbell & Borzognia (2008) GMPE with CGS soil map



CyberShake (2011) differences



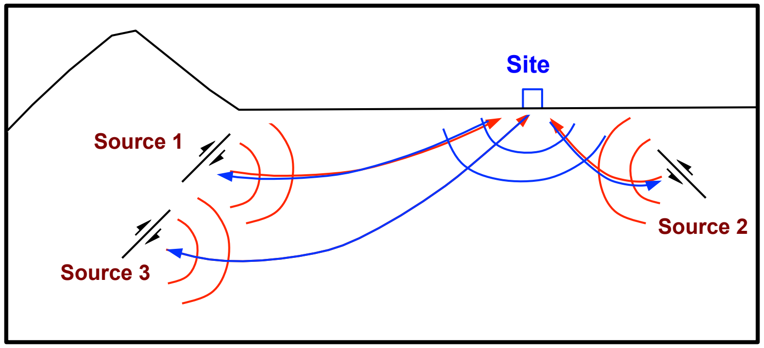
CyberShake (2011) map



3-s Spectral Acceleration (in g) at Probability of Exceedance = 2% in 50 yr

Efficiency Gained by Use of Seismic Reciprocity

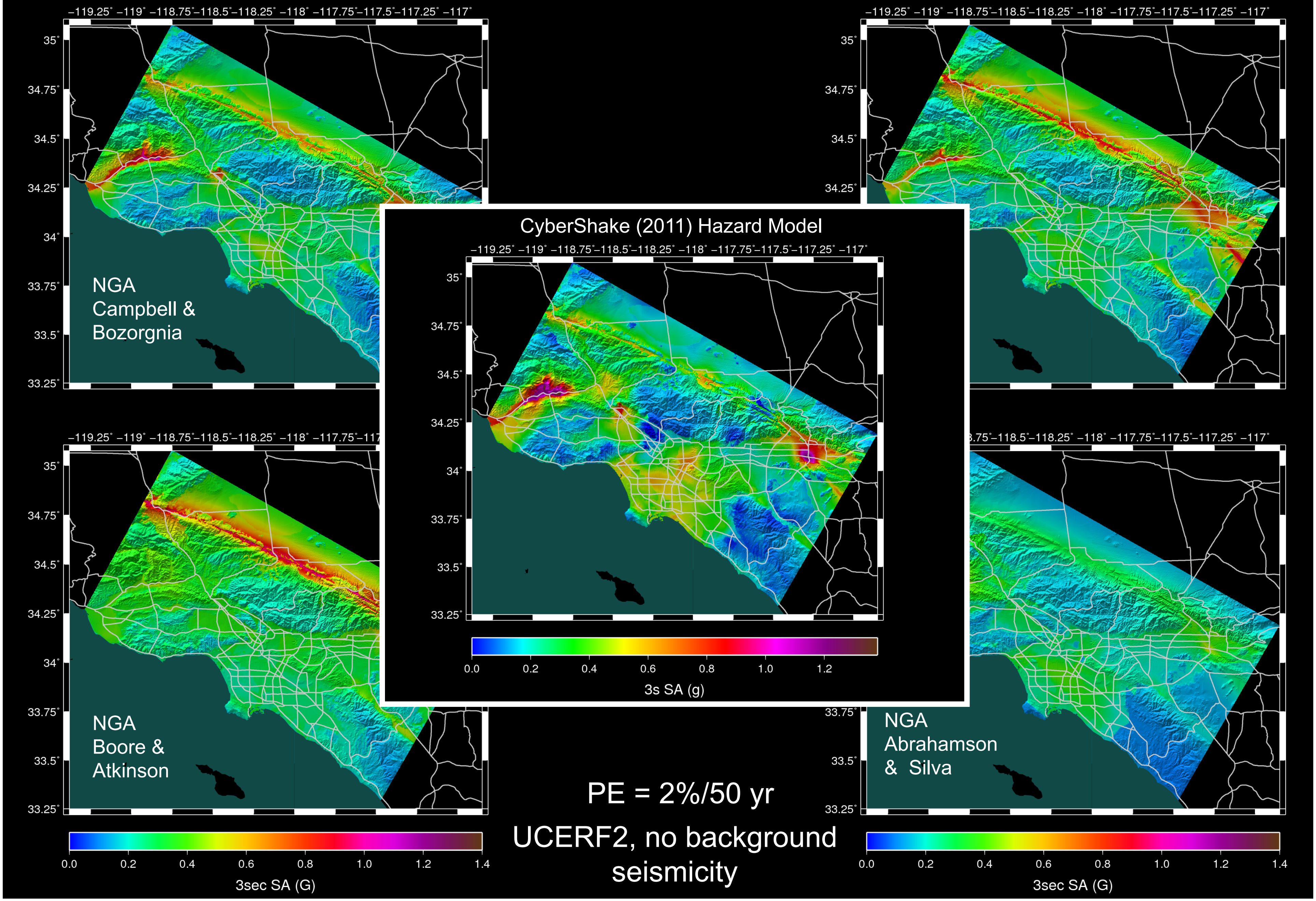
- **To account for source variability requires very large sets of simulations**
  - **40,000 ruptures in SoCal; 440,000 rupture variations to sample rupture variability**
- **Ground motions need only be calculated at much smaller number of surface sites to produce hazard map**
  - **250 in LA region, interpolated using empirical attenuation relations**
- ***Use of reciprocity reduces CPU time by a factor of ~1,000***



M **sources to** ***N*** **sites requires** ***M*** **simulations**

M **sources to** ***N*** **sites requires 3*N* simulations**

NGA (2008) Attenuation Relations used in National Seismic Hazard Maps

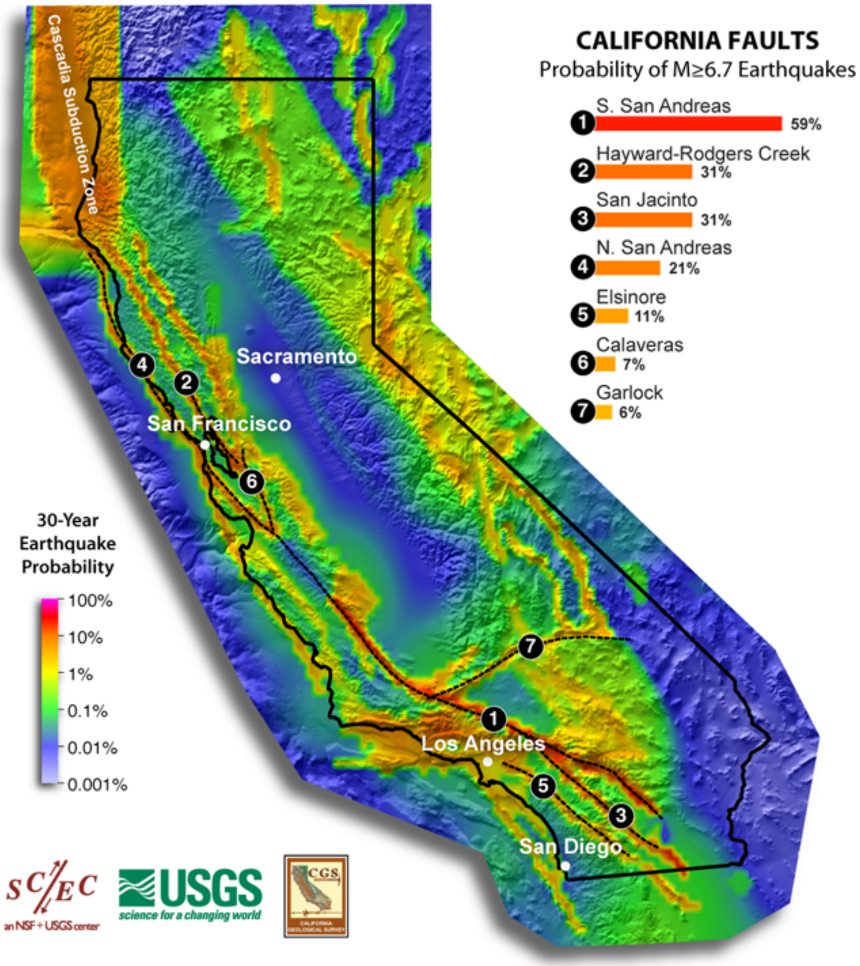


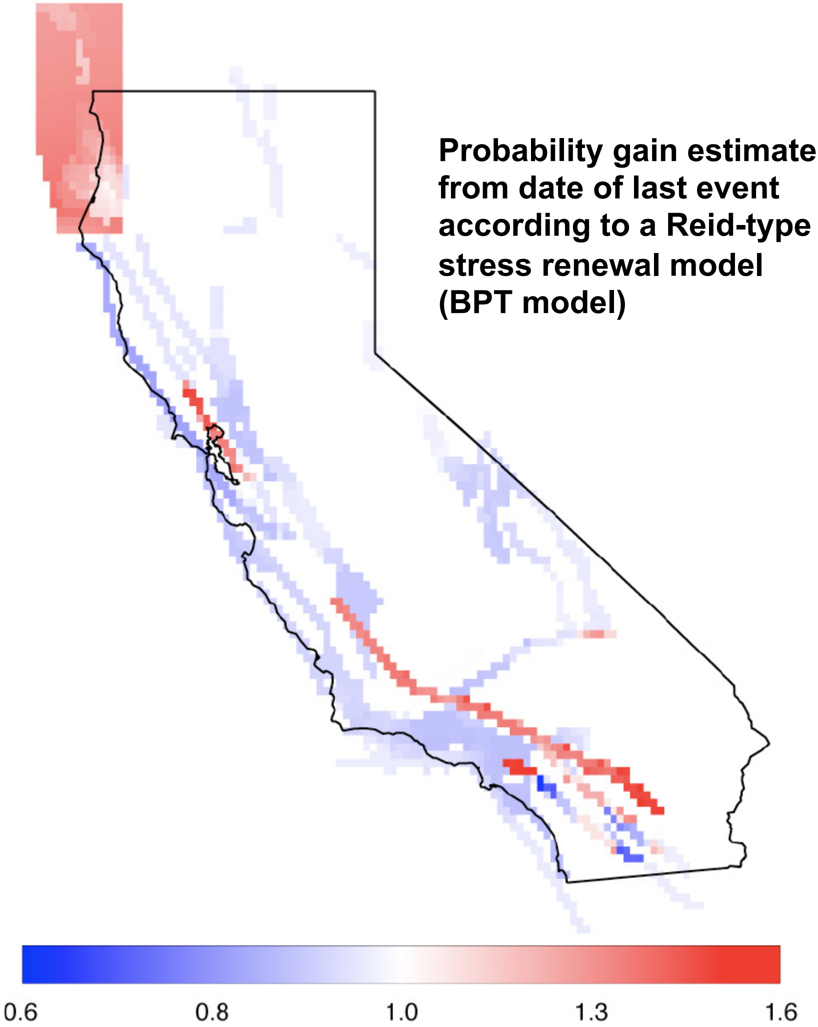
PE = 2%/50 yr

UCERF2, no background seismicity

Working Group on California Earthquake Probabilities (2007)

Uniform California Earthquake Rupture Forecast (UCERF2)

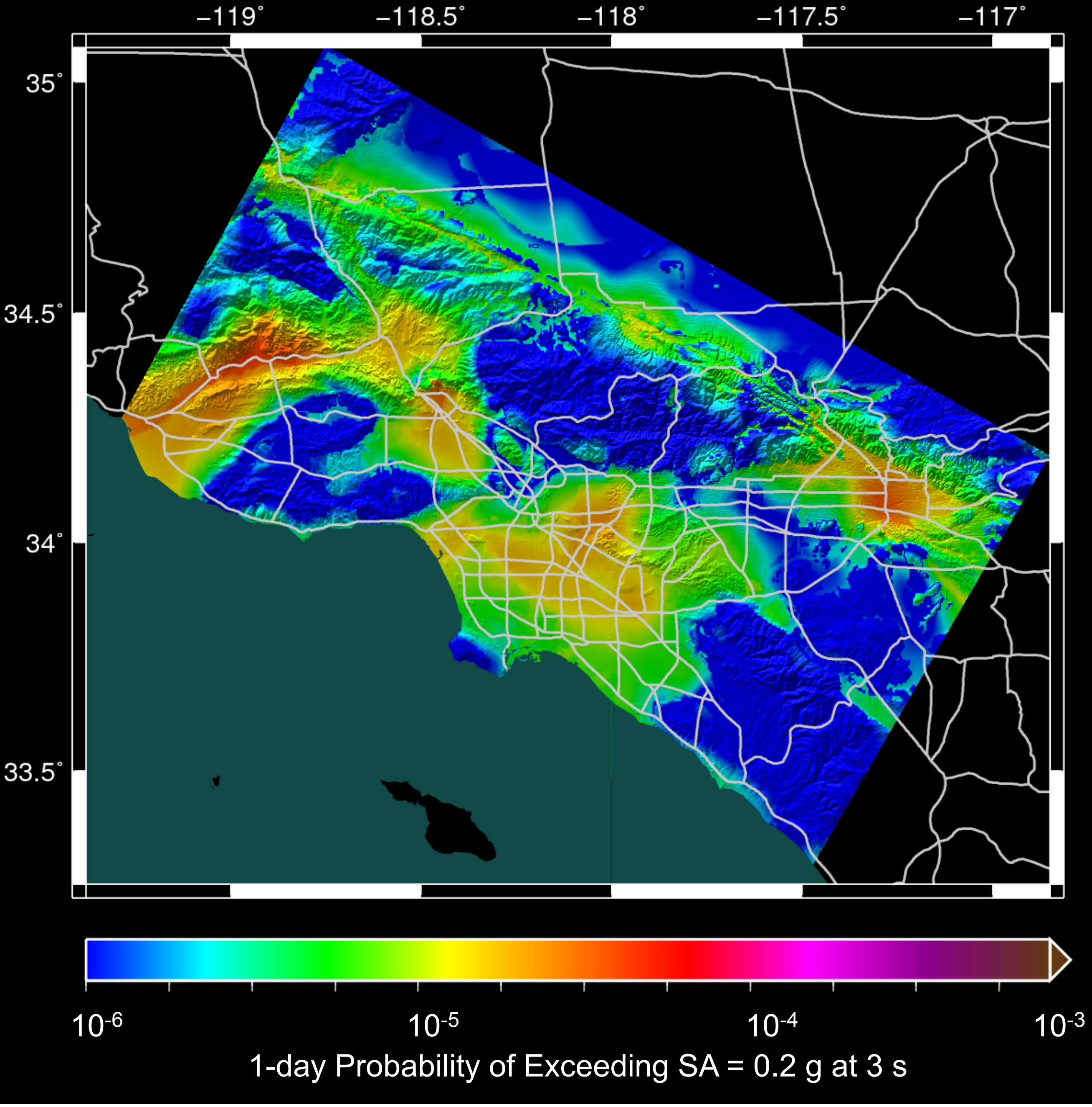




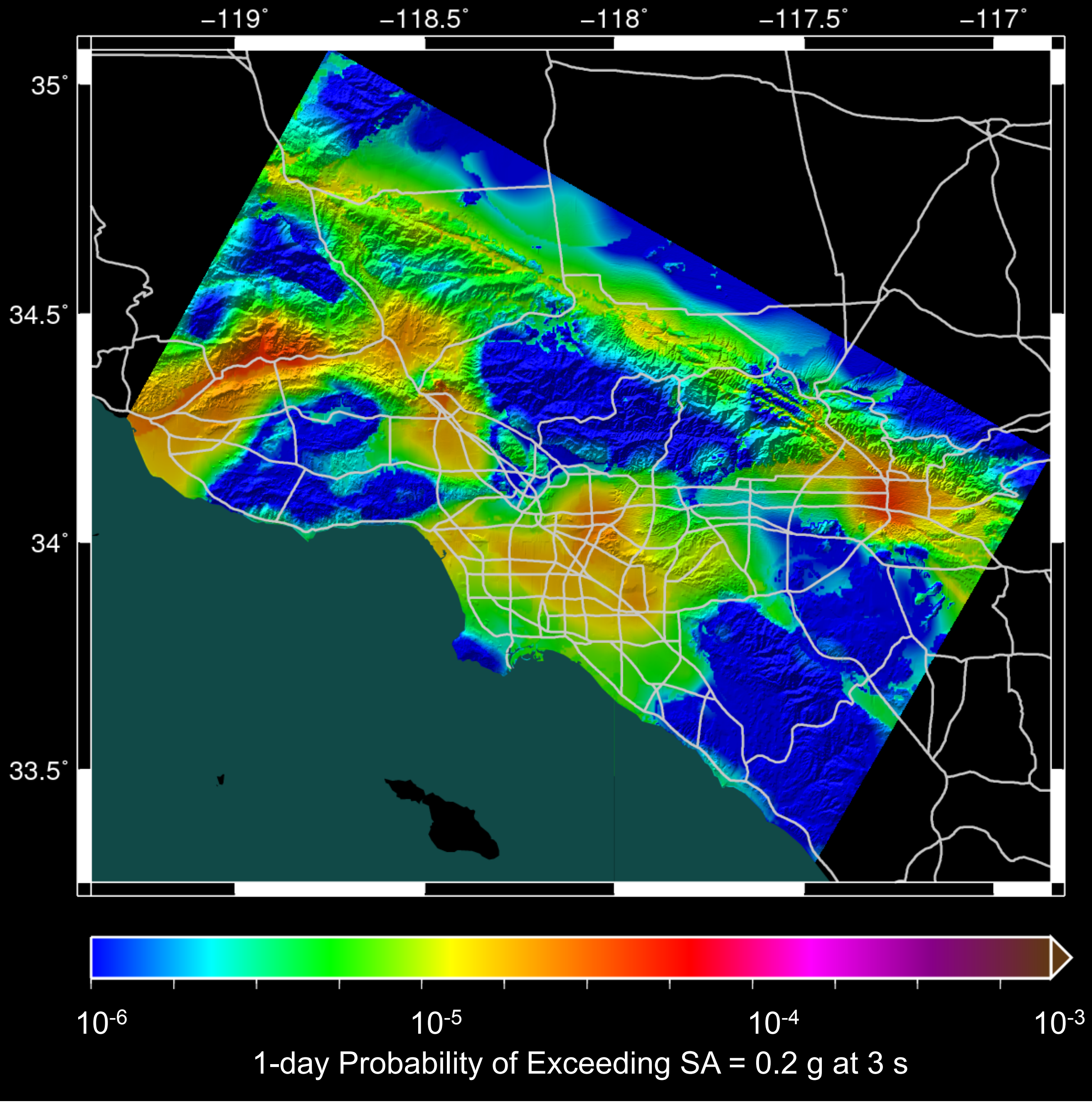
Probability gain estimated from date of last event according to a Reid-type stress renewal model (BPT model)

Ratio of time-dependent to time-independent participation probabilities for M ≥ 6.7

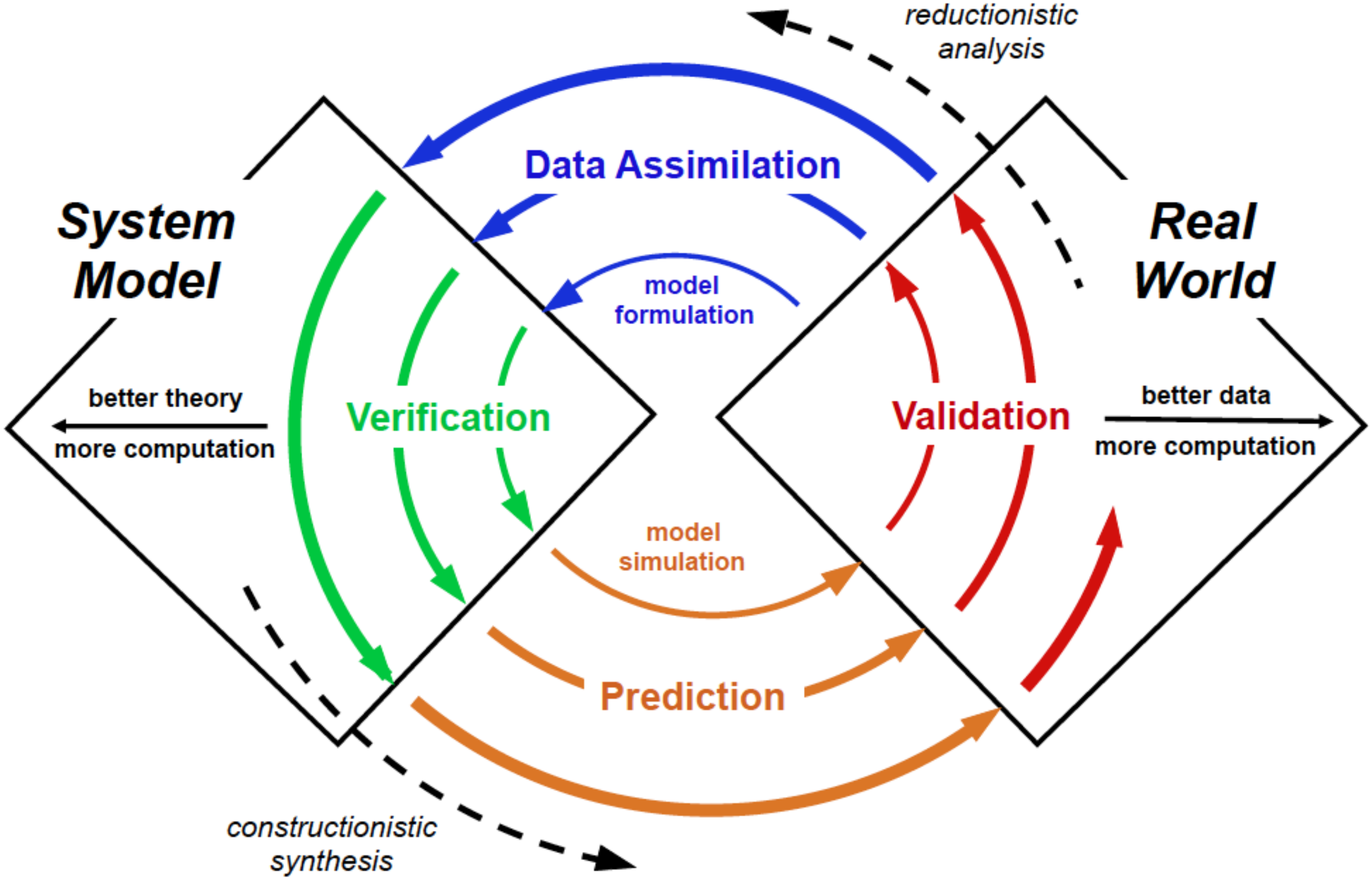
CyberShake (2011) NSHMP Time-Independent Model



CyberShake (2011) UCERF2 Time-Dependent Model

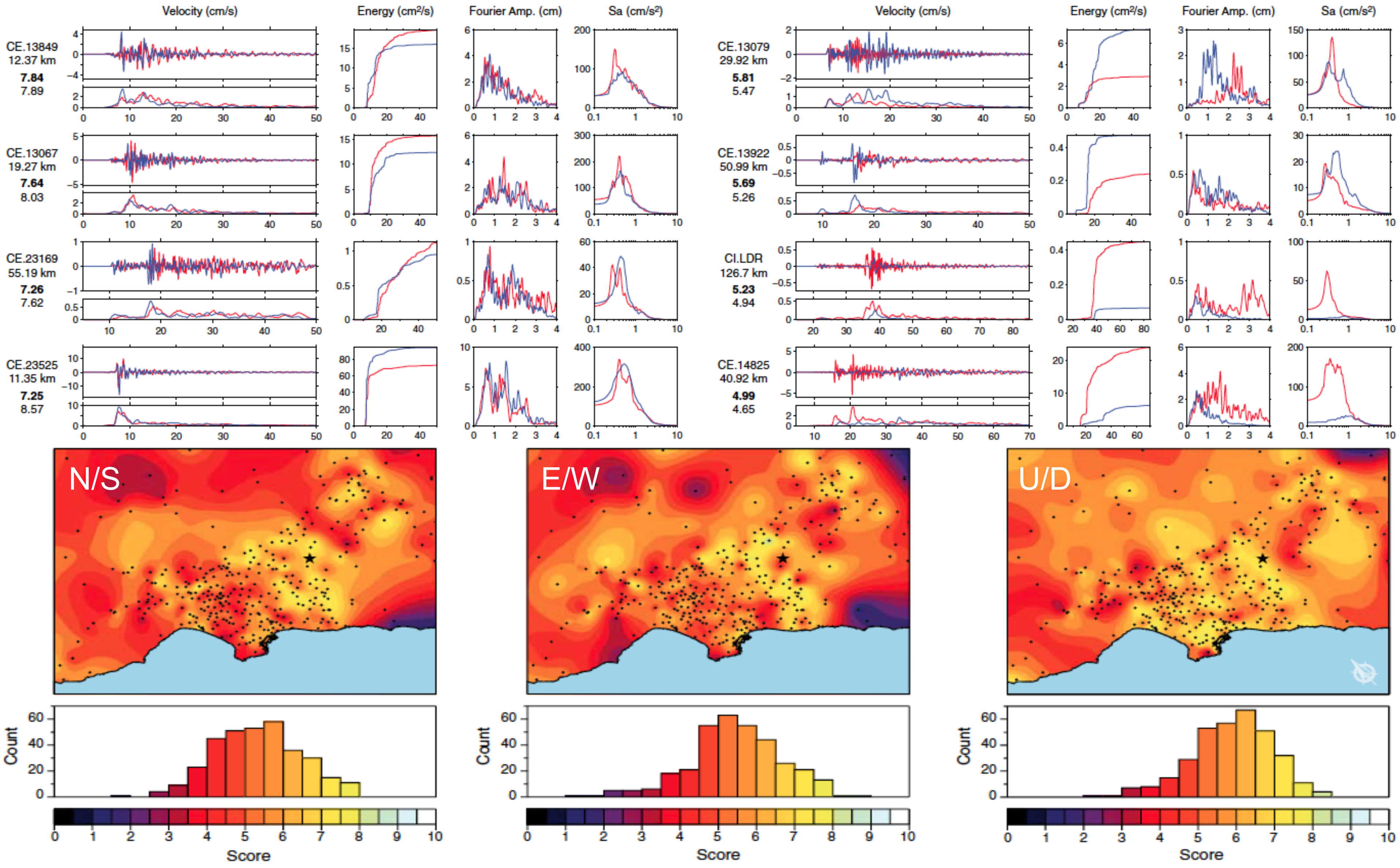


Inference Spiral of System Science



Validation Using Small Earthquakes

2008 Chino Hills, M5.4 (Taborda & Bielak, 2013)



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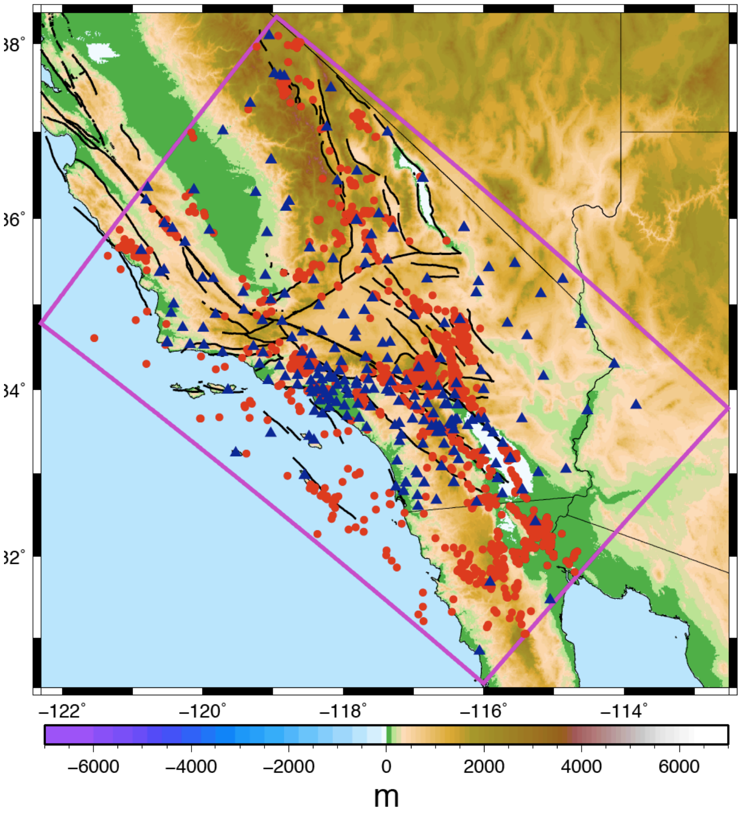
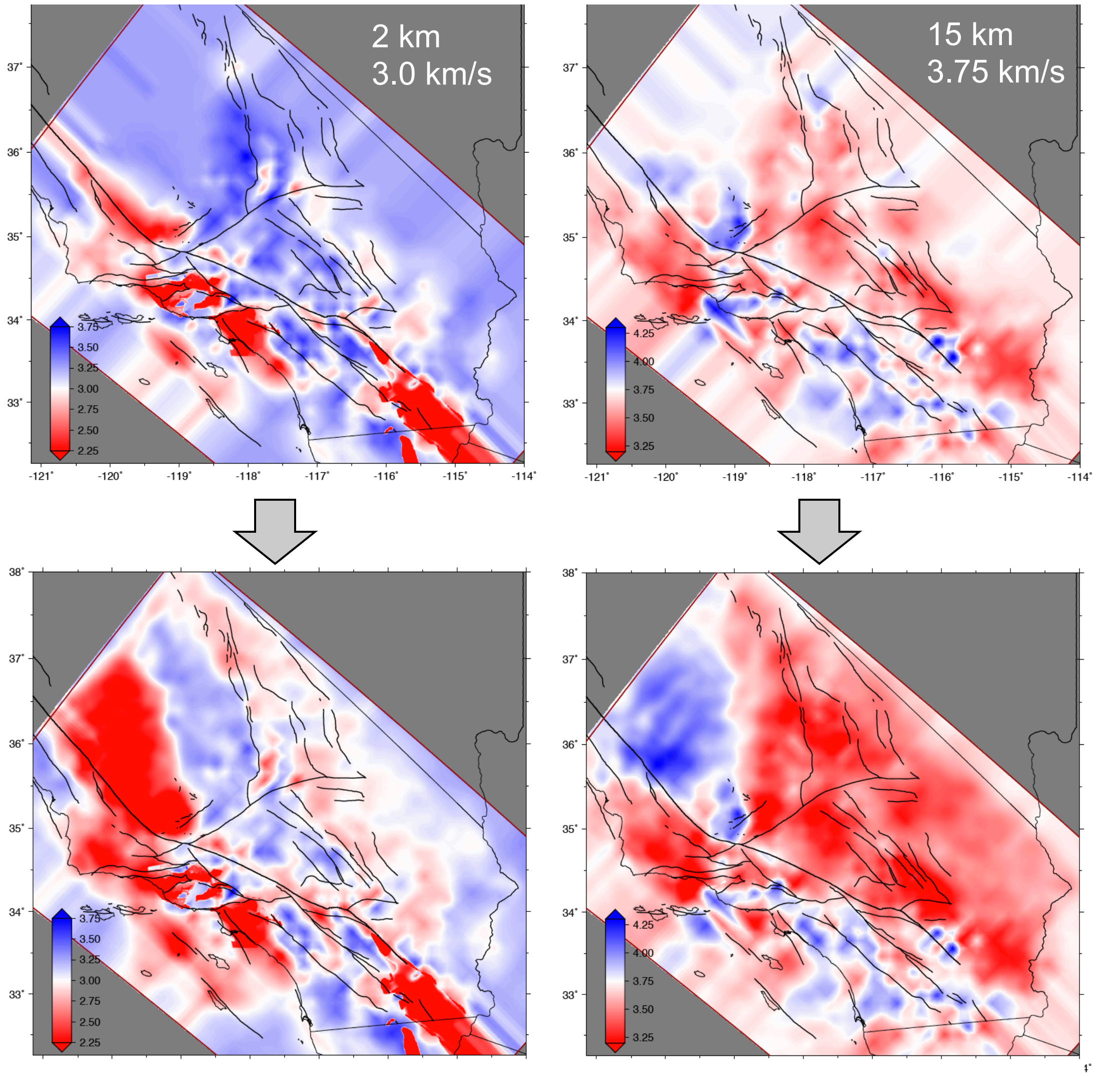
Data Assimilation Using Full-3D Waveform Tomography

Inversion of Earthquake Waveforms and Ambient-Noise Green Functions



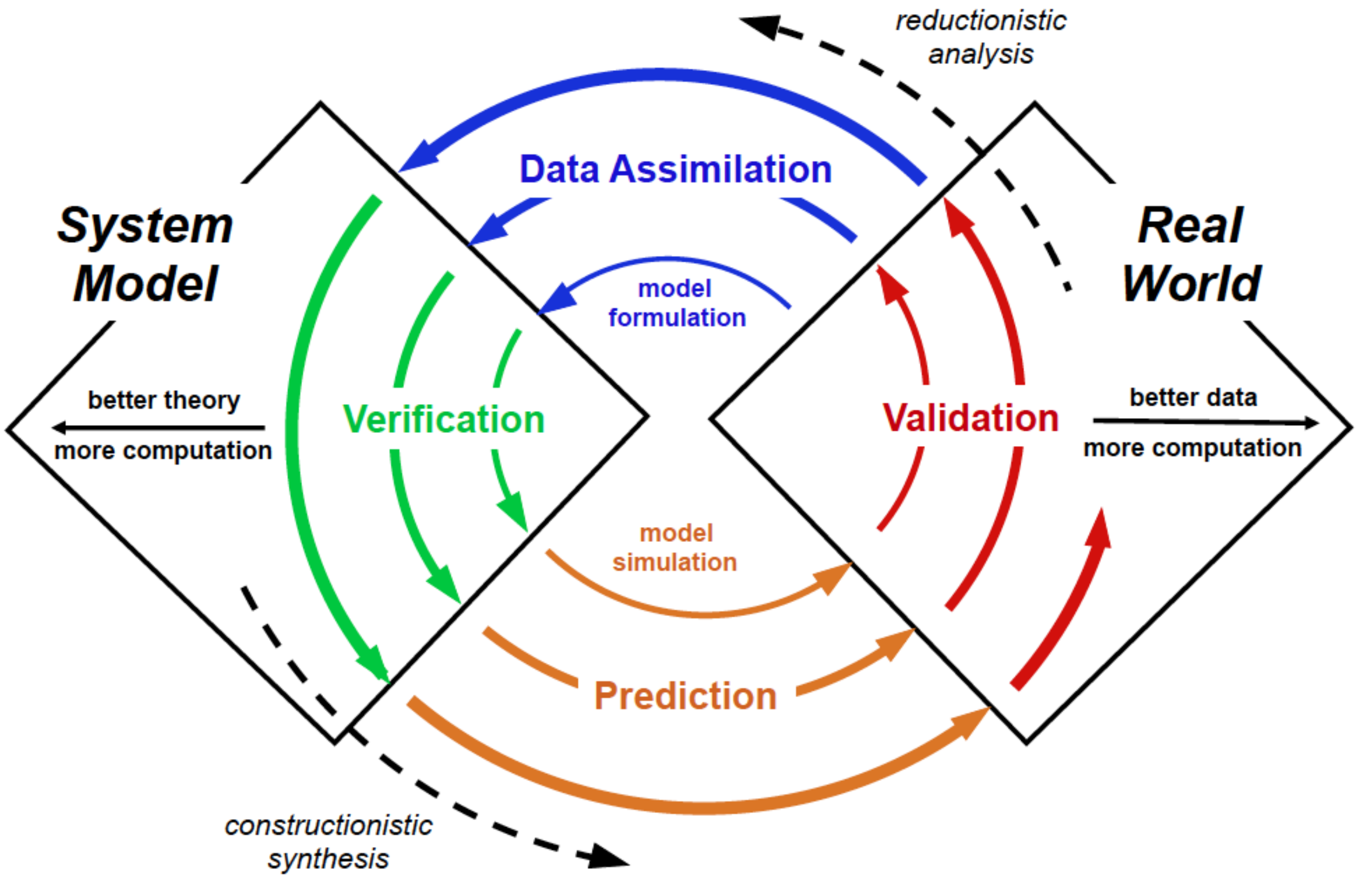
E.-J. Lee, P. Chen, T. H. Jordan, P. Maechling, M. Denolle, G. Beroza (2012)

CVM-S4

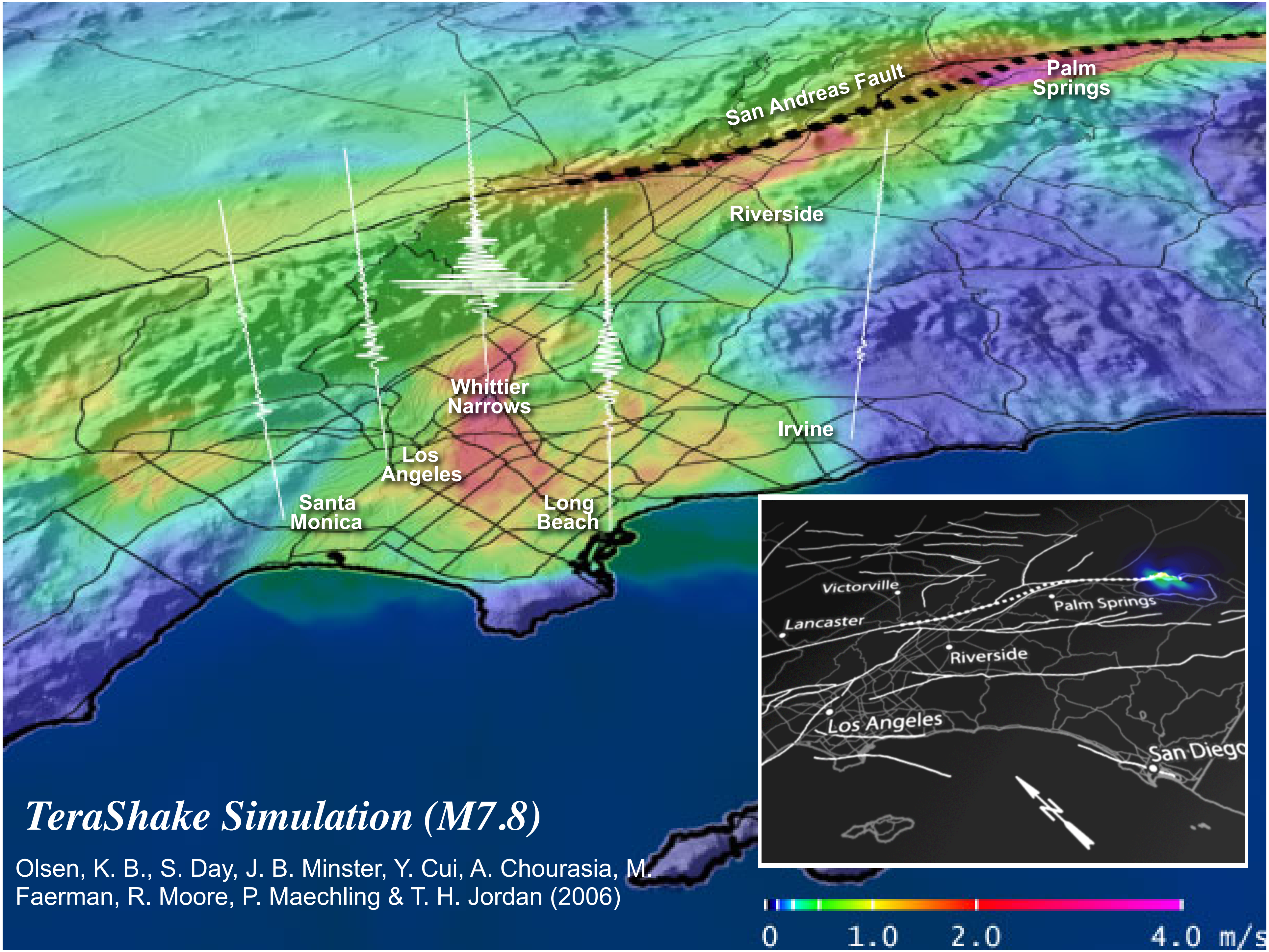


CVM-S4.20

Inference Spiral of System Science

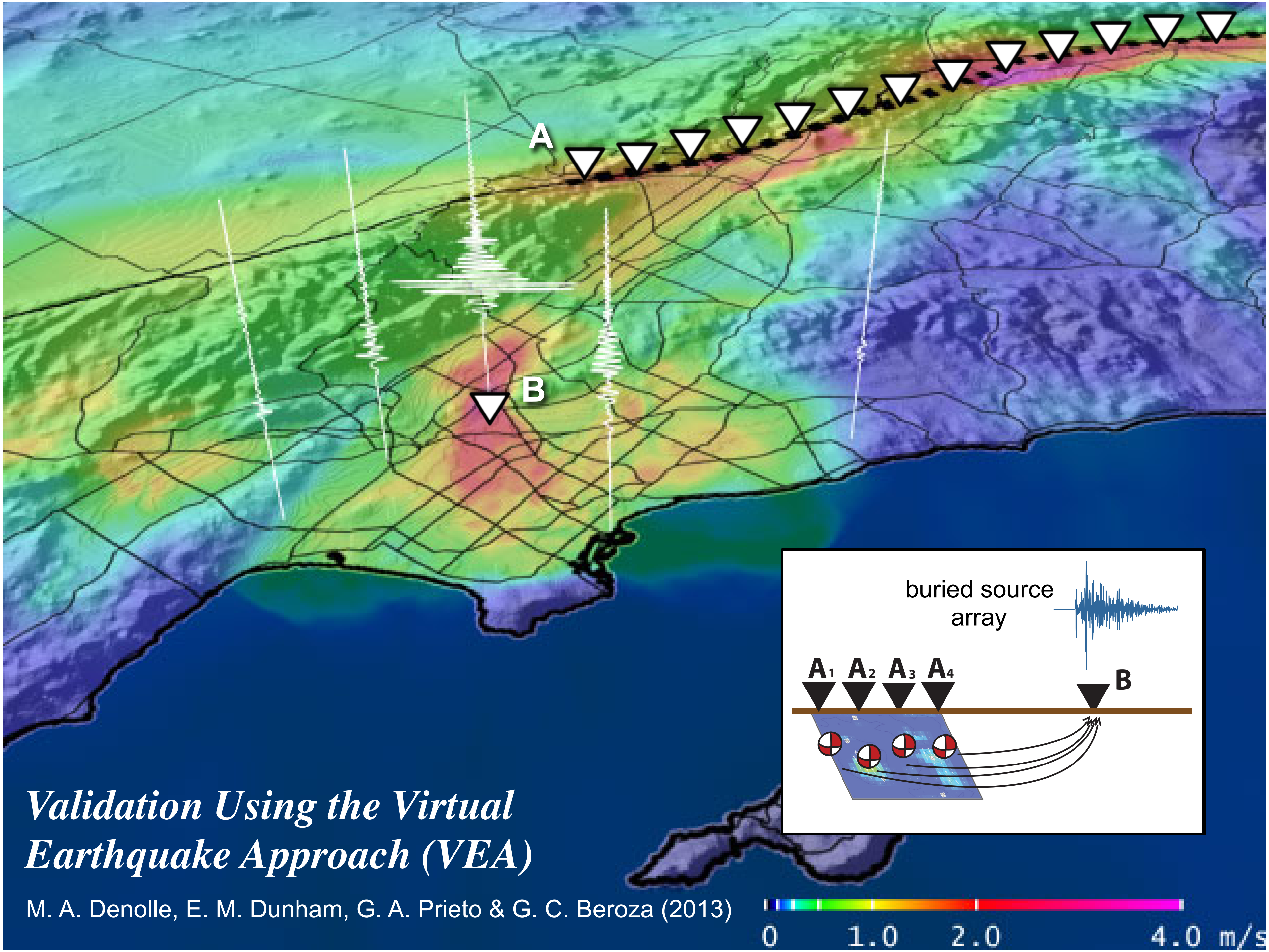


But how can we validate models of large, *unobserved* earthquakes?



TeraShake Simulation (M7.8)

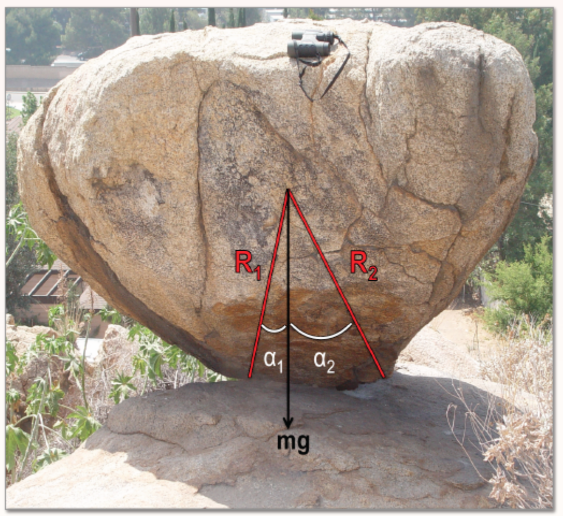
Olsen, K. B., S. Day, J. B. Minster, Y. Cui, A. Chourasia, M. Faerman, R. Moore, P. Maechling & T. H. Jordan (2006)

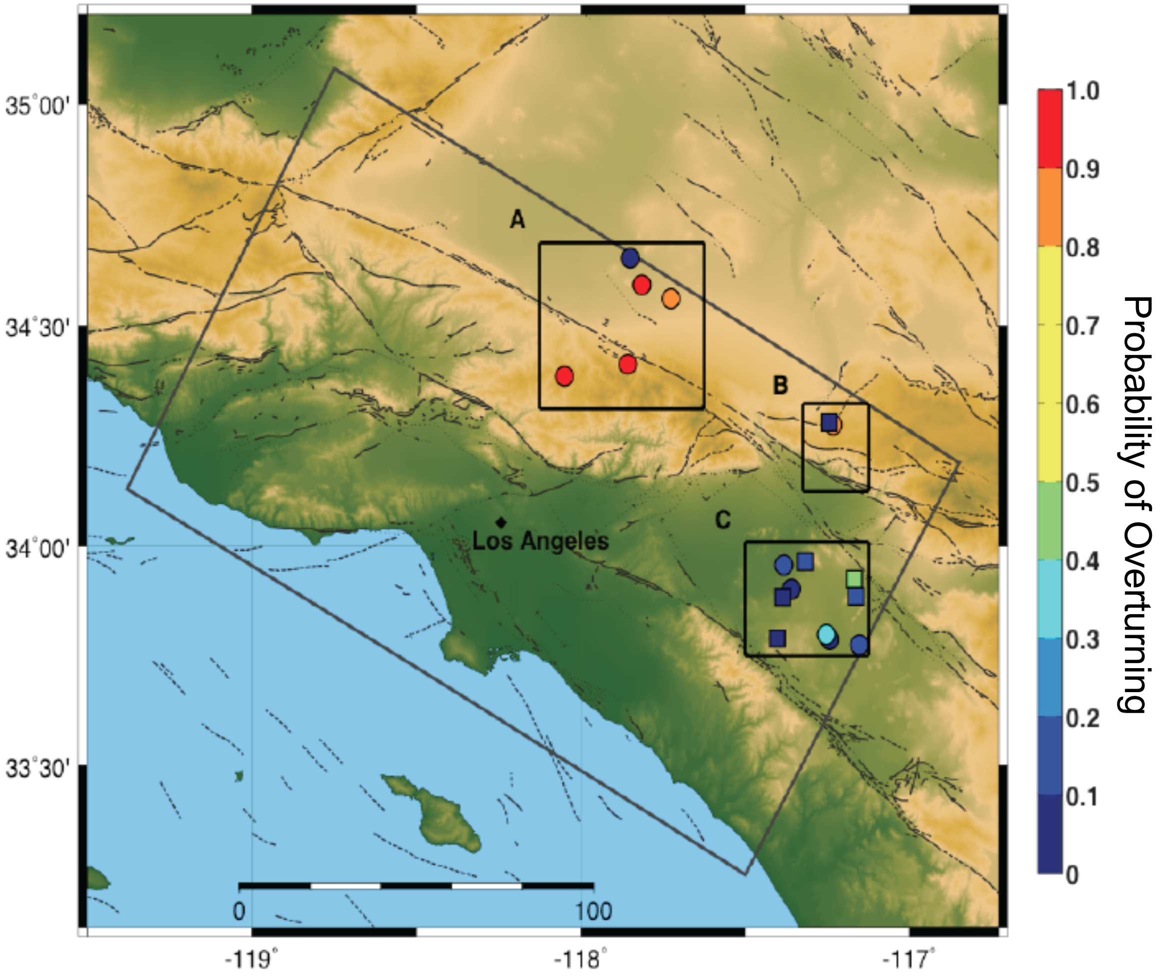


Validation Using the Virtual Earthquake Approach (VEA)

M. A. Denolle, E. M. Dunham, G. A. Prieto & G. C. Beroza (2013)

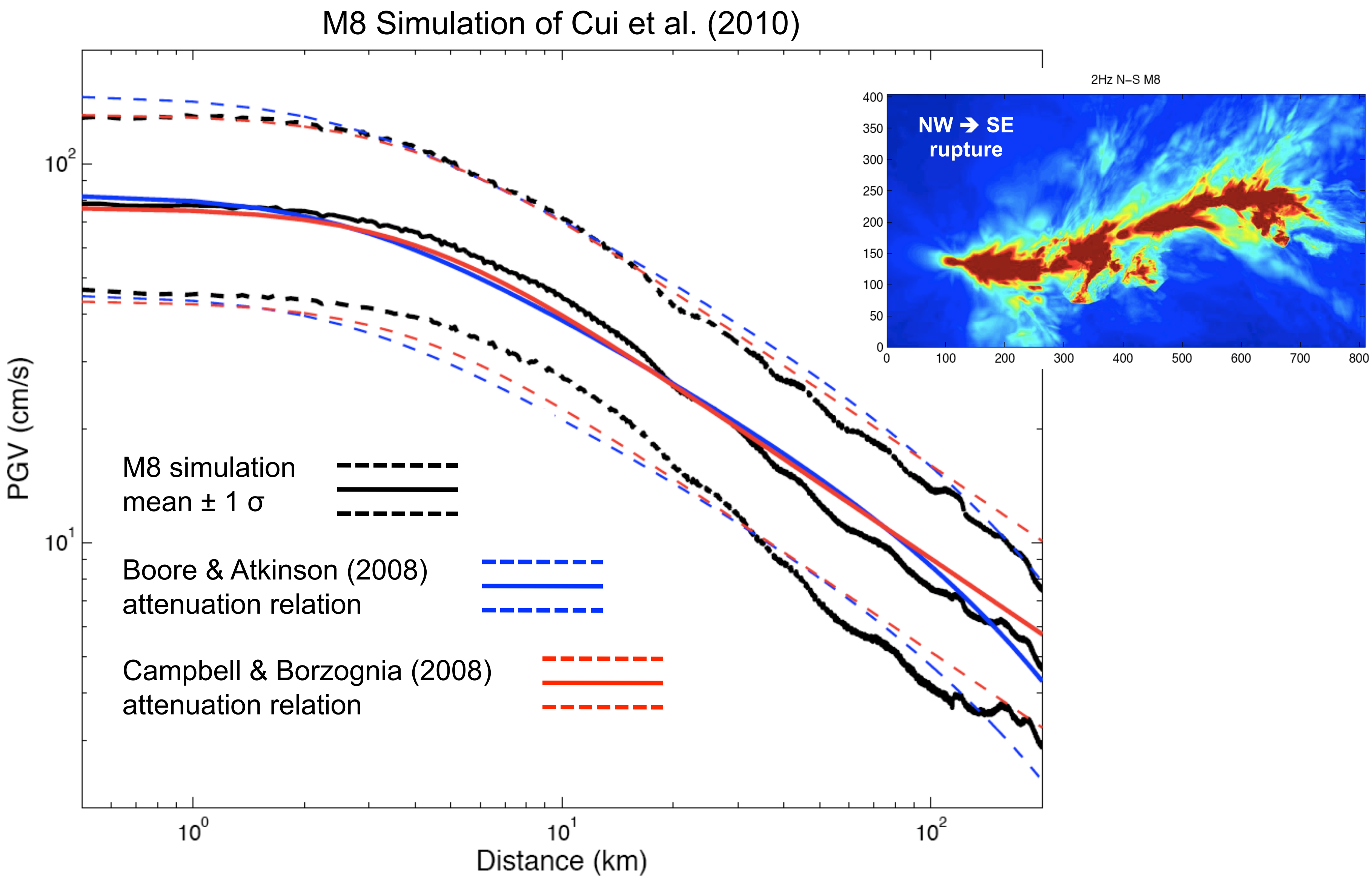
Validation Using Precariously Balanced Rocks





Probability of Overturning in 10,000 years of CyberShake Exposure
(Donovan, Jordan & Brune, 2012)

Validation Using Empirical Ground Motion Prediction Equations



M8 Simulation of Cui et al. (2010)

Comparisons of CyberShake with GMPEs

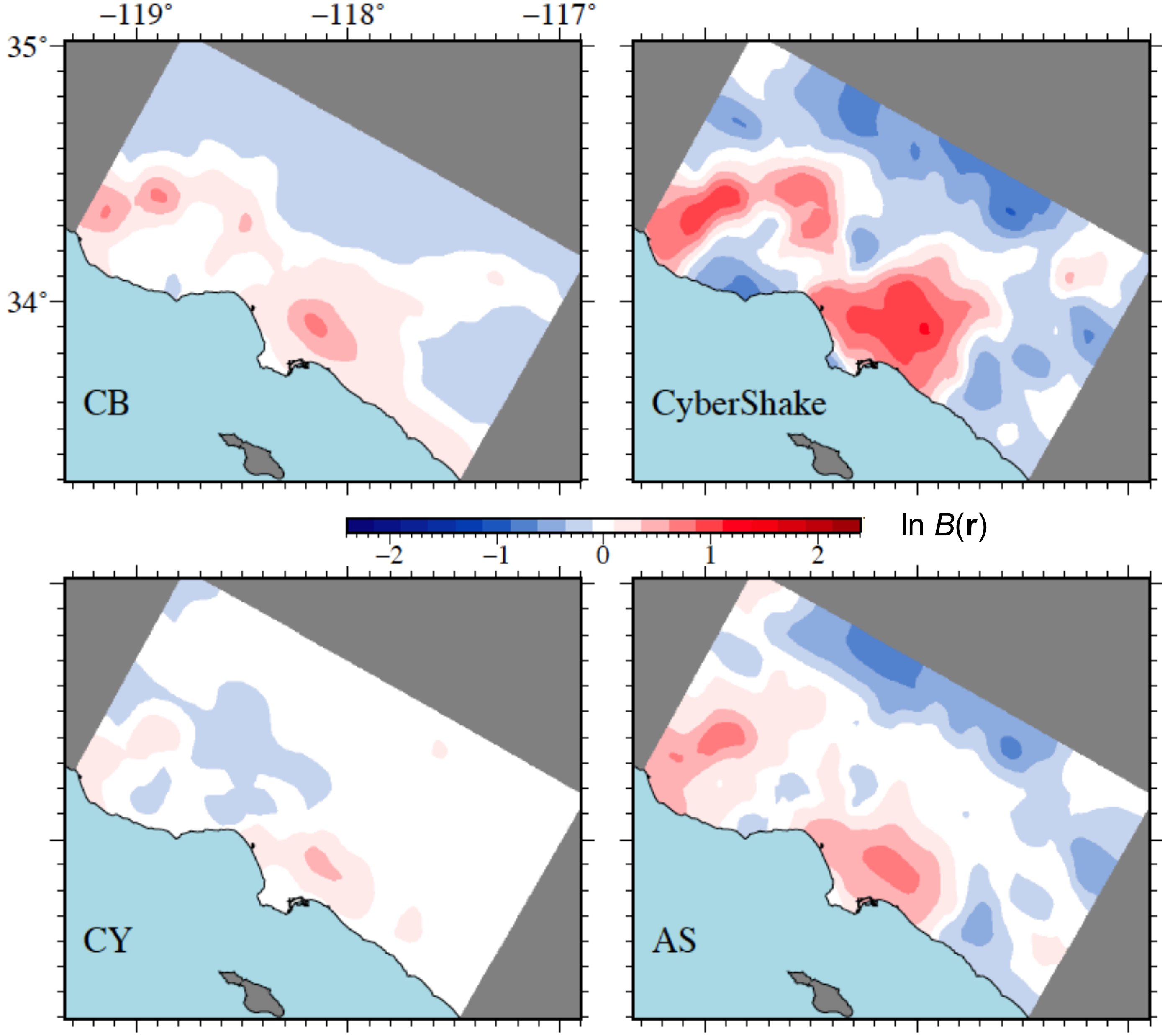
- **GMPEs are the multiplication of factors representing attenuation, site effects, directivity effects, etc.**
  - **This model-based factorization is not available for CyberShake**
- **We can compare simulation-derived models with GMPEs using "averaging-based factorization" (Wang & Jordan, 2013)**
  - **Expected shaking intensities are constructed from a hierarchy of averaging operations over slip variations (s), hypocenters (x), sources (k), and sites (r)**

$$\overset{\ln(IM)}{\overset{\downarrow}{G(r,k,x,s)}} = \underset{\text{level}}{\underset{\uparrow}{A}} + \overset{\text{site effect}}{\overset{\downarrow}{B(r)}} + \underset{\text{attenuation effect}}{\underset{\uparrow}{C(r,k)}} + \overset{\text{directivity effect}}{\overset{\downarrow}{D(r,k,x)}} + \underset{\text{slip variability effect}}{\underset{\uparrow}{E(r,k,x,s)}}$$

This averaging-based decomposition is unique and exact

Basin Amplification Maps

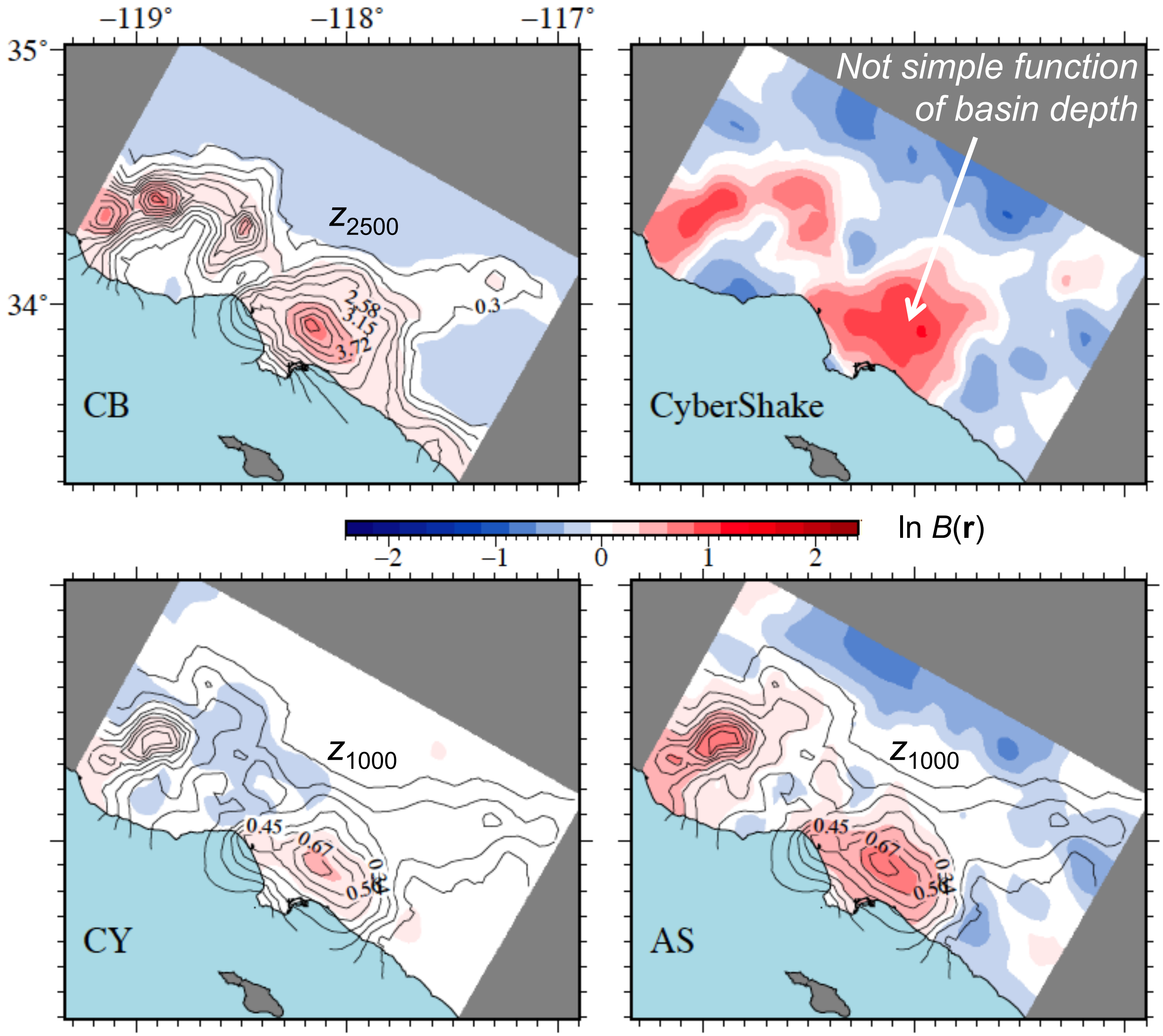
(SA-3s corrected for V_S30)



Wang & Jordan
(2013)

Basin Amplification Maps

(SA-3s corrected for $V_S 30$)



Not simple function of basin depth

Wang & Jordan (2013)

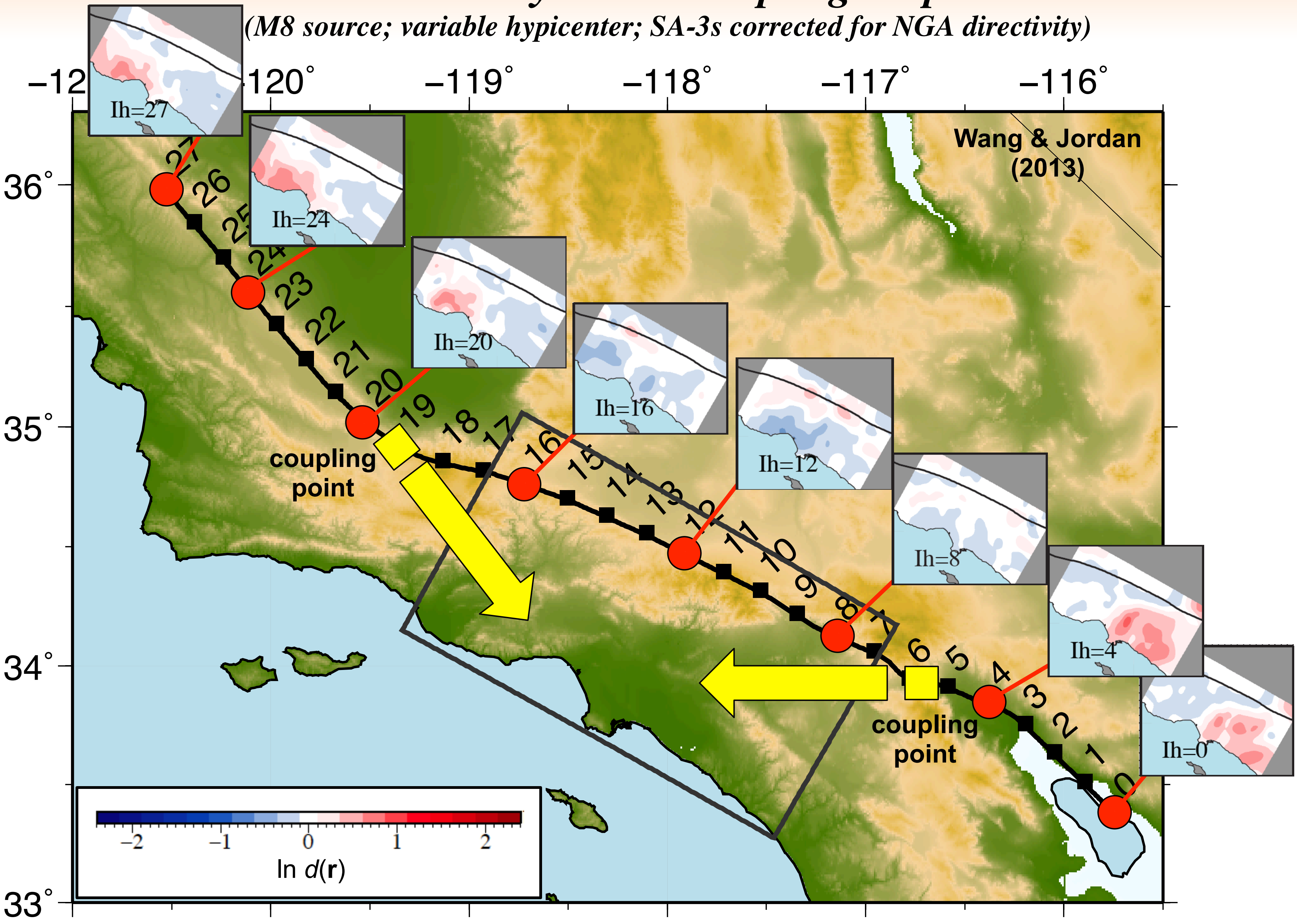
Comparisons of CyberShake with GMPEs

Averaging-based factorization provides quantitative comparisons. Low-frequency (0.1-0.5 Hz) results are:

- **V_{S30} site effects for CyberShake are comparable to NGA models**
- **CyberShake basin effects are up to an order of magnitude larger than those from the NGA models**
  - **Basin excitation not a simple function of basin depth**
- **CyberShake directivity effects are larger than the NGA directivity "add-on" of Spudich & Chiou (2008)**
  - **Directivity-basin coupling effects, which are unmodelled by NGA, are large in CyberShake**
- **Largest epistemic uncertainties in CyberShake are from the basin structure of the seismic velocity models**
  - **Coupling between rupture complexity and CyberShake response is relatively small**

Directivity-Basin Coupling Maps

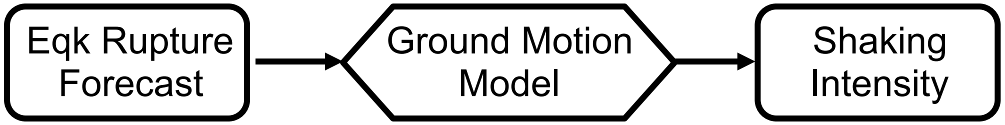
(M8 source; variable hypicenter; SA-3s corrected for NGA directivity)



Wang & Jordan (2013)

CyberShake: Application to Short-Term Earthquake Forecasting

- **Pre-computed CyberShake ground motion models are easily coupled to short-term forecasting models, such as STEP and UCERF3**
  - **Output is a time-dependent seismic hazard estimate**

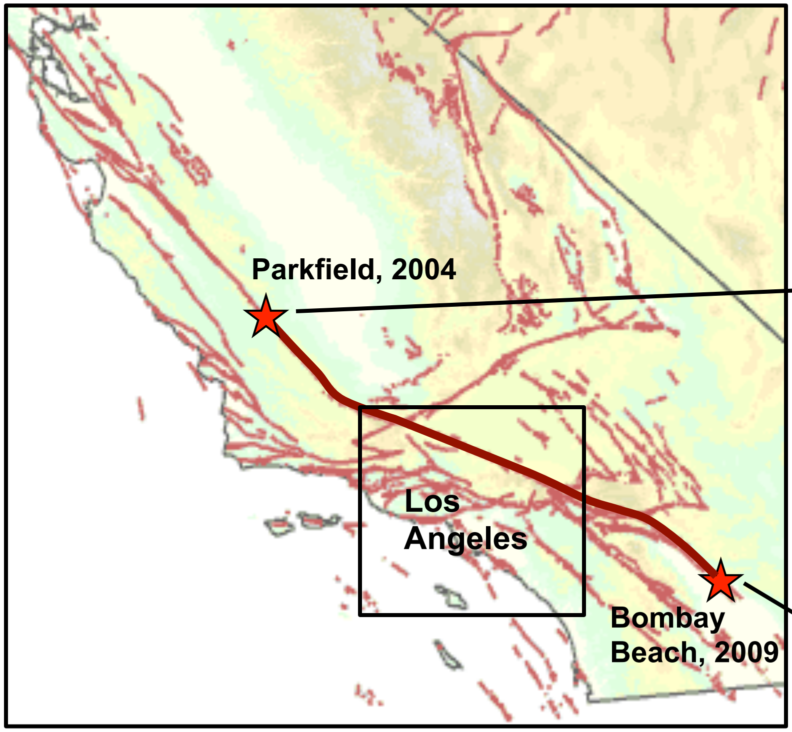


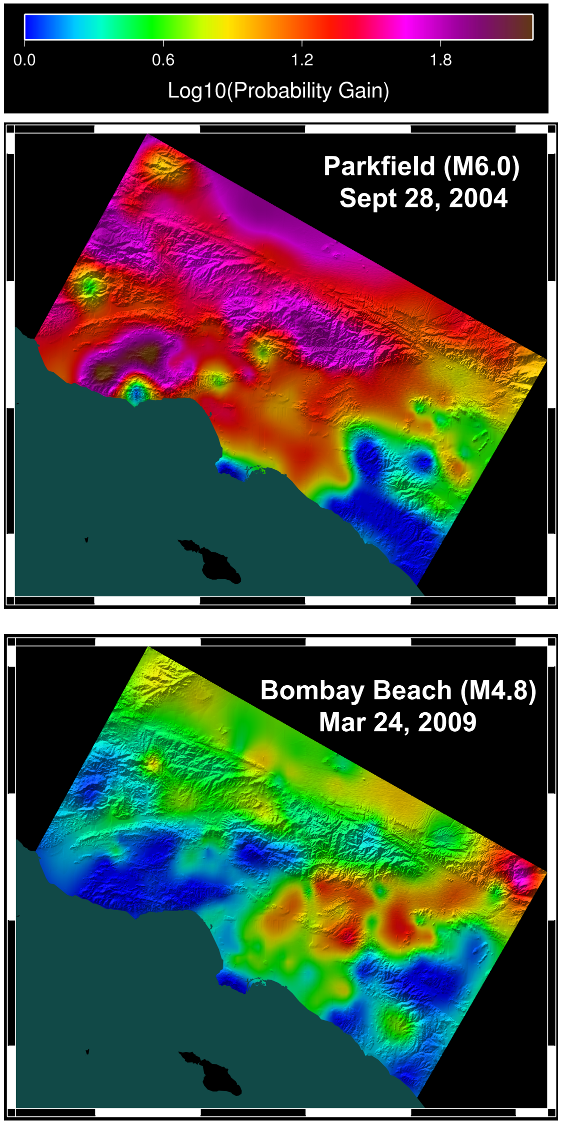
Eqk Rupture Forecast → Ground Motion Model → Shaking Intensity

$P(S_n, T)$ $P(IM_k \mid S_n)$ $P(Im_k, T)$ T = forecast time

- **Short-term forecasting localizes epicenter probabilities**
  - **Coupled model achieves significant gains in ground motion probabilities through the forecasting of source directivity and directivity-basin coupling**

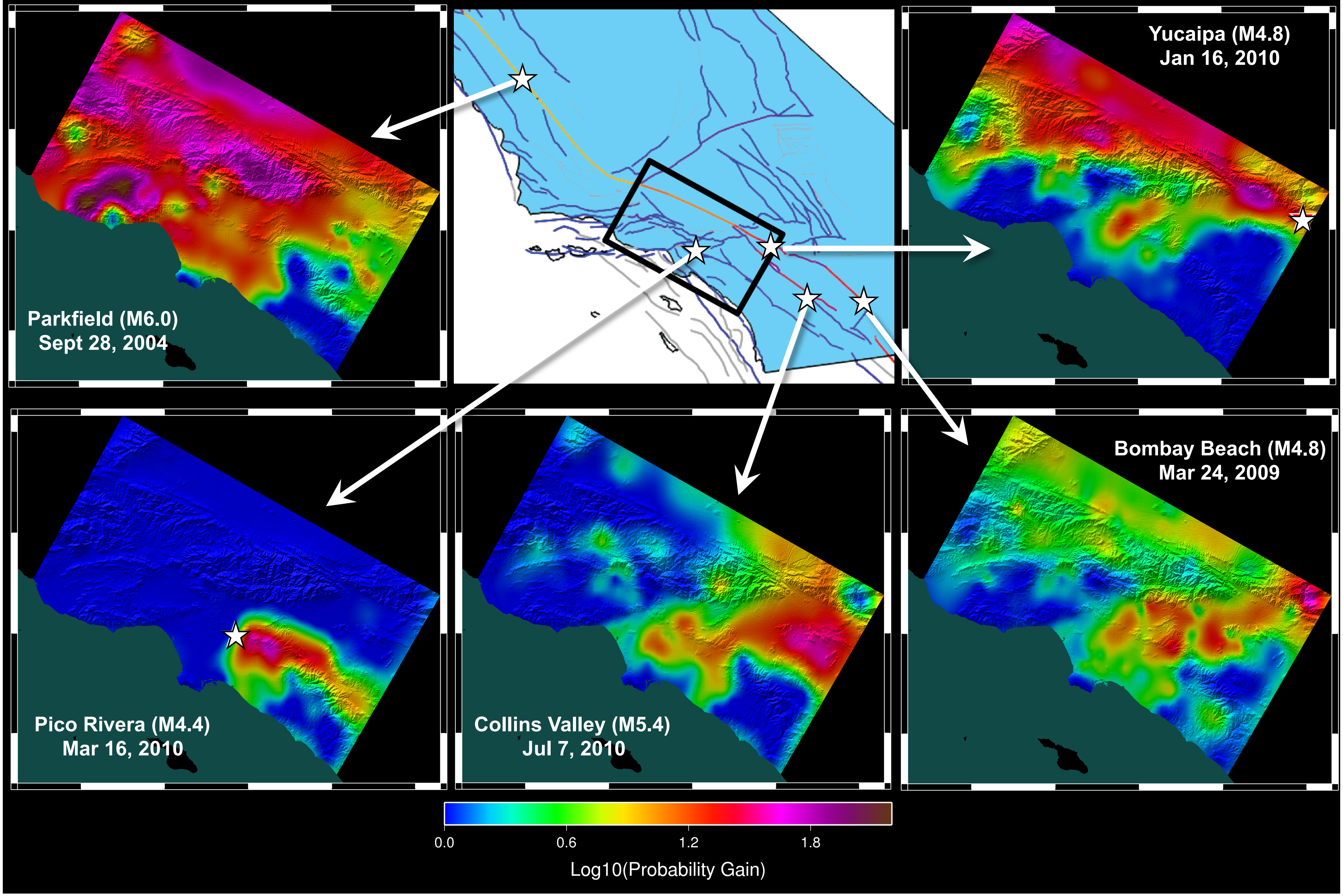
CyberShake: Application to Short-Term Earthquake Forecasting





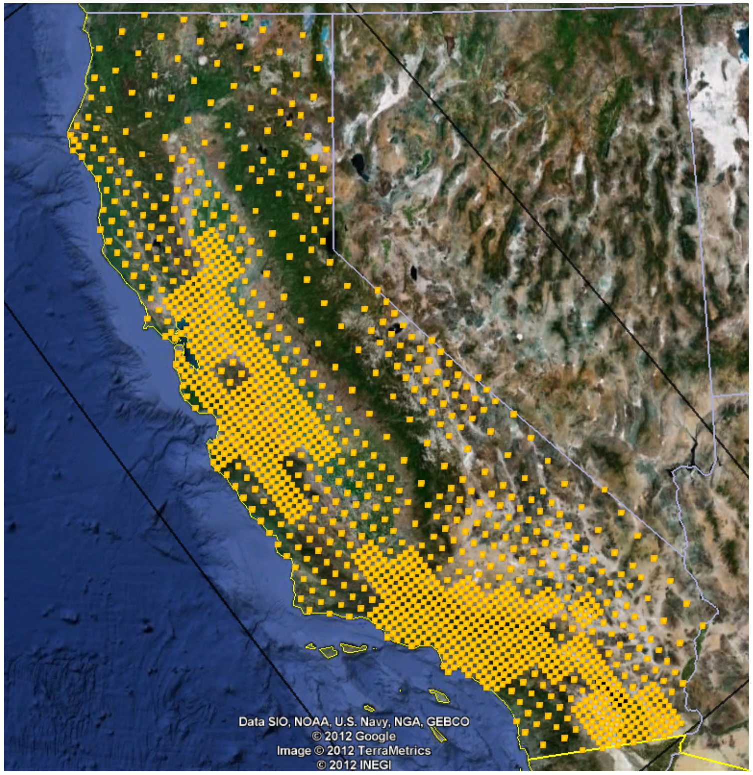
- **Compute probability gain from forecasting model. Example: $G = 1000$ for $R \leq 10$ *km***
- **Apply probability gain to CyberShake ruptures and re-compute ground motion probabilities for short interval following events. Example: 1 day**

Time-Dependent Earthquake Forecasting using CyberShake



CyberShake: Initiative to Compute a Statewide Physics-Based Hazard Model

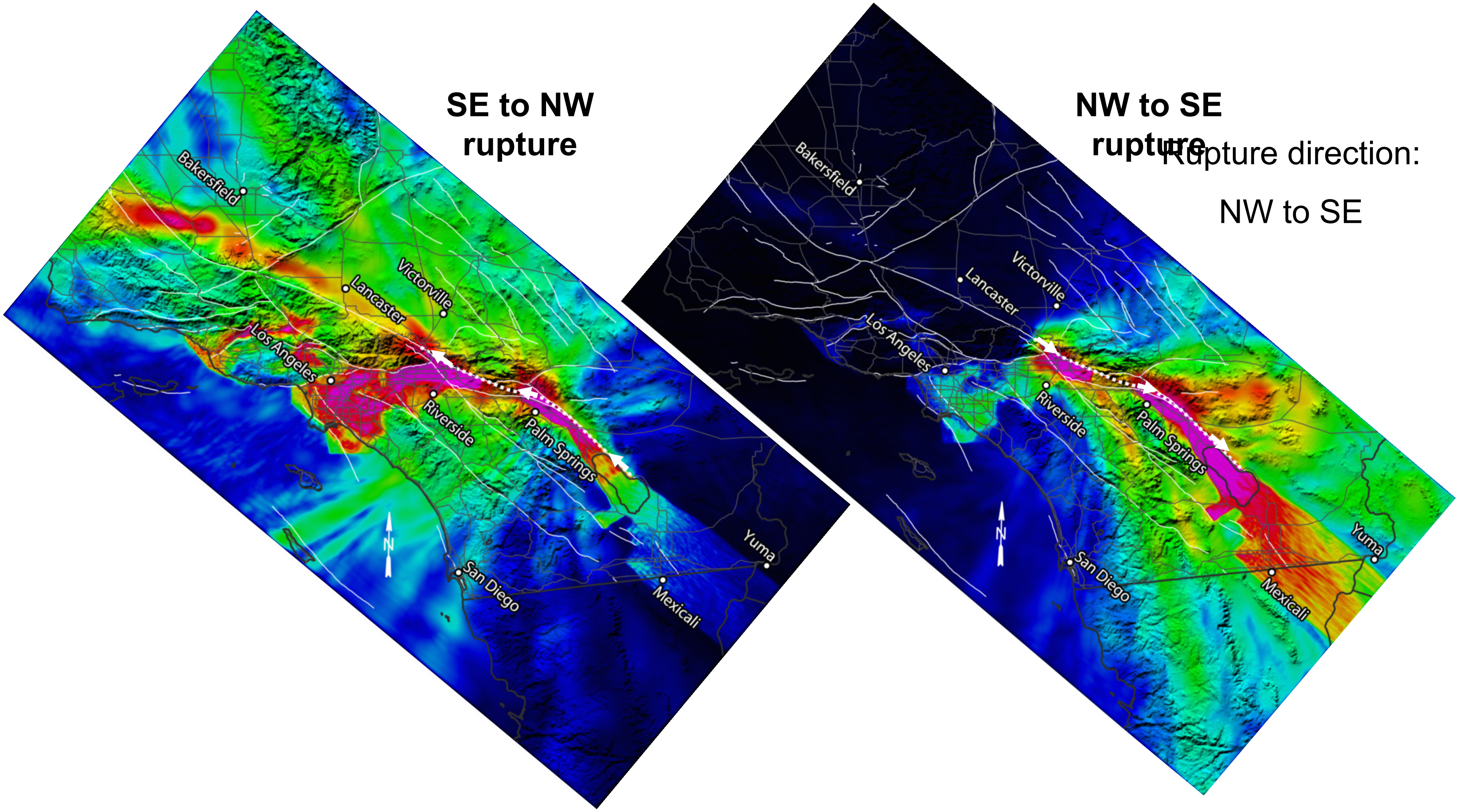
- **Extend CyberShake models to 1400 sites across California**
  - **Develop statewide Unified Community Velocity Model (UCVM)**
  - **Compute site response to 1 Hz deterministic, 10 Hz stochastic**
- **Couple time-dependent UCERF3 to CyberShake**
  - **Provide frequently updated time-dependent seismic hazard maps**
- **Extend CSEP to prospectively test ground motion forecasts against observations throughout California**



Statewide CyberShake

- Computational requirements for 1 Hz deterministic, 10 Hz stochastic:
  - Number of jobs: 23.2 billion
  - Storage: 2800 TB seismograms
  - Computer hours: 392 million

Coupling of Directivity and Basin Effects



SE to NW rupture

NW to SE rupture

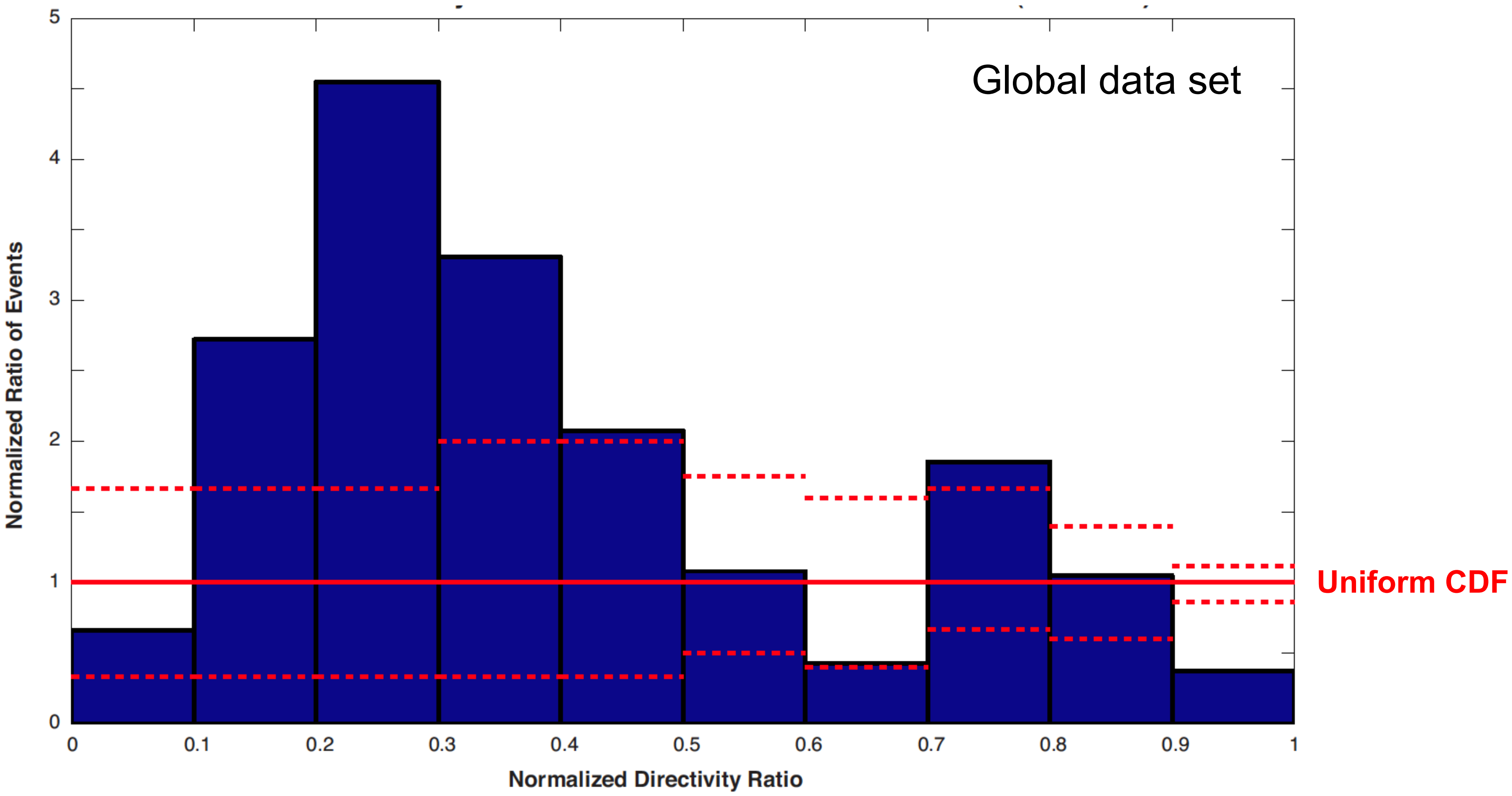
Rupture direction:

NW to SE

TeraShake simulations of M7.7 earthquake on Southernmost San Andreas (Olsen et al. 2006)

Conditional Hypocenter Distribution

Donovan & Jordan (2013)

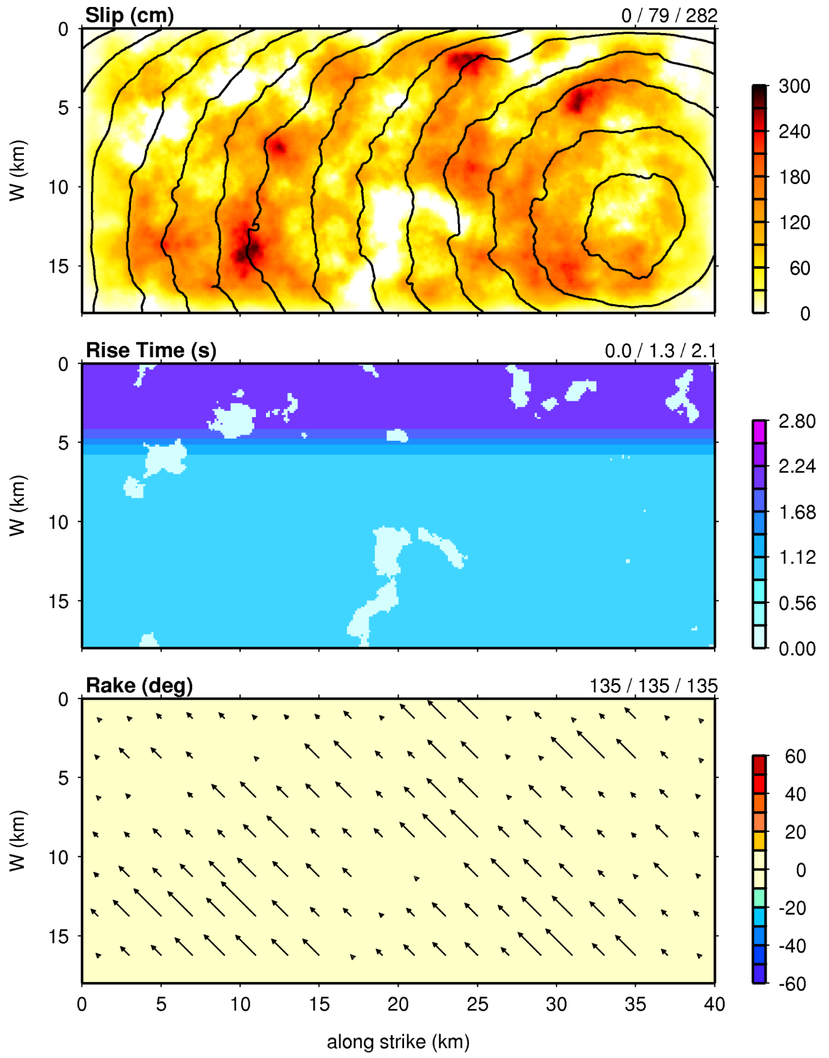


🡐 centroid biased

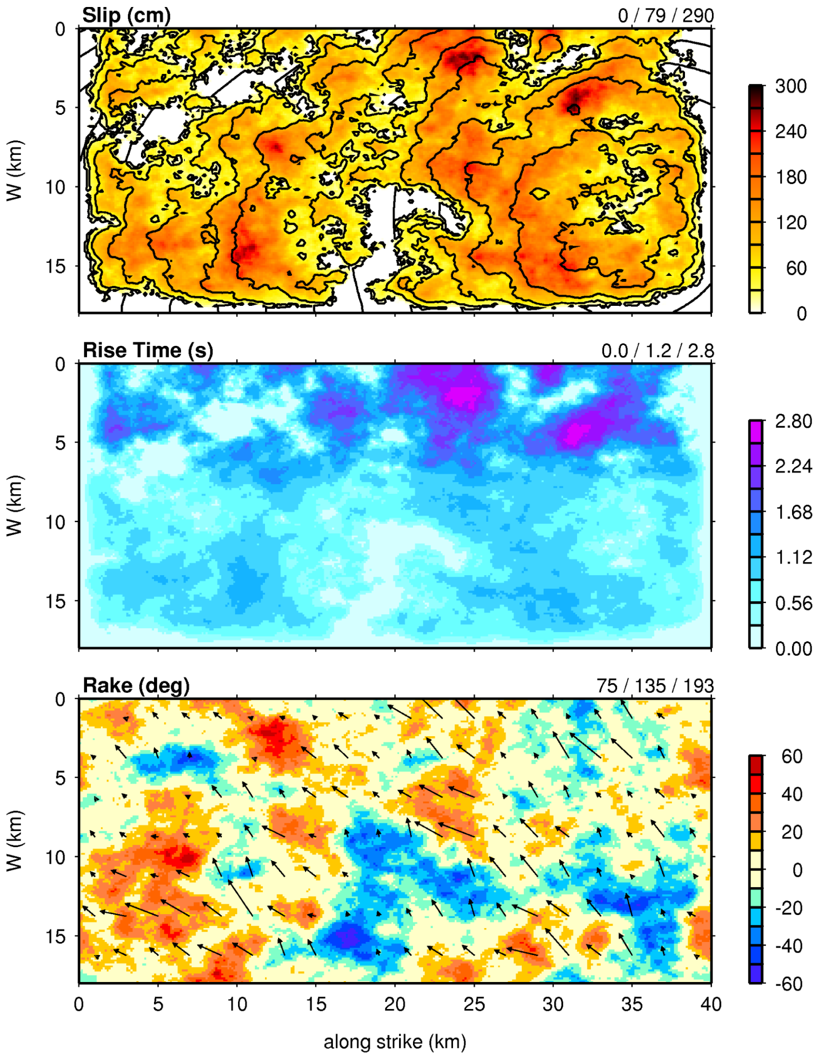
periphery biased 🡒

Graves-Pitarka Pseudo-Dynamic Rupture Models

GenSlip v2.1 (2007)



GenSlip v3.2 (2010)

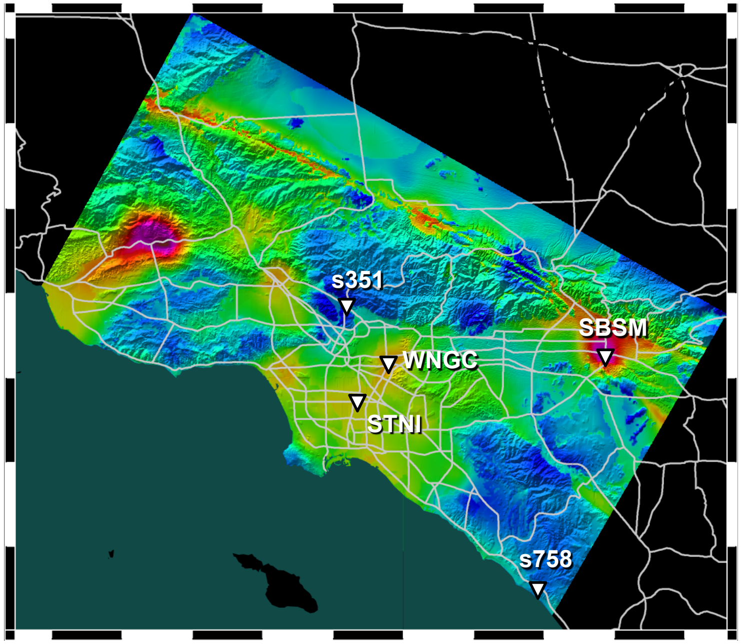


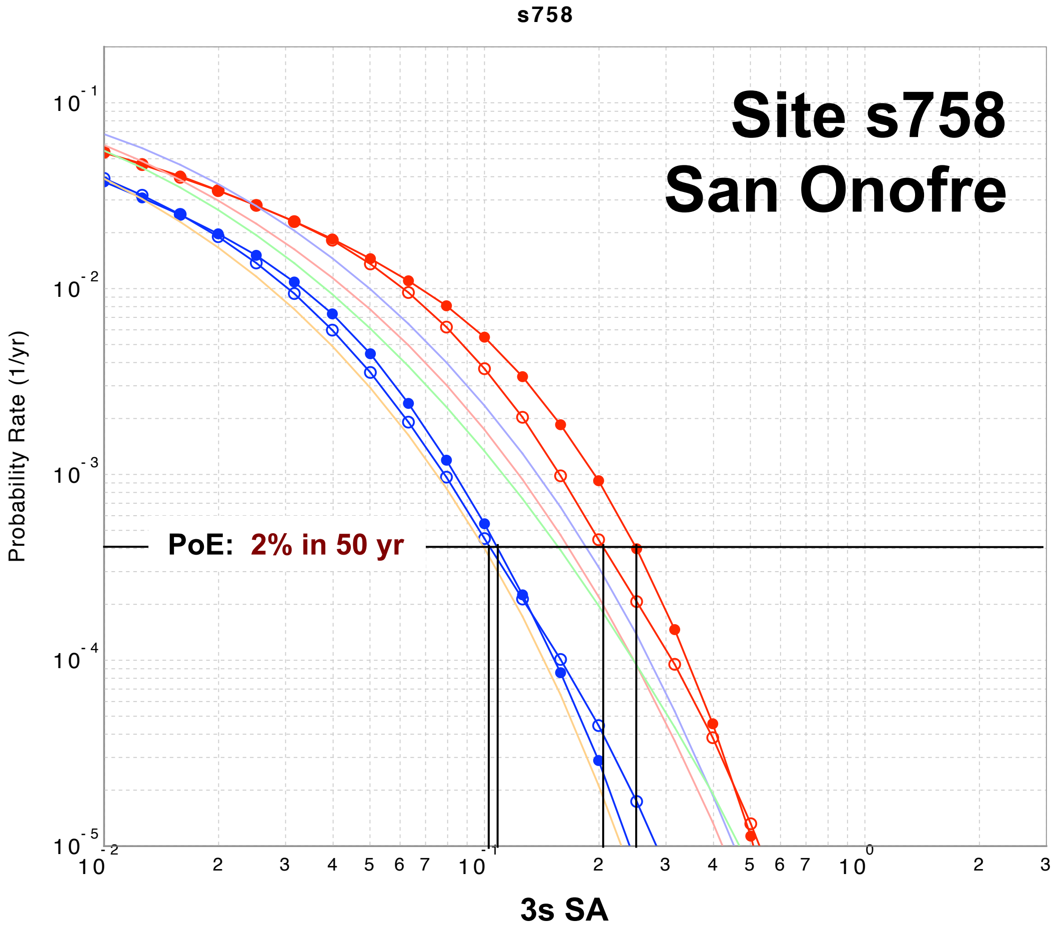
CyberShake Results

UCERF2, no background seismicity

CyberShake Versions

CS1:	**CVM-S4**	**SM-2007**
CS2:	**CVM-S4**	**SM-2010**
CS3:	**CVM-H2.11**	**SM-2007**
CS4:	**CVM-H2.11**	**SM-2010**





Site: s758, PoE: 2% in 50 yr

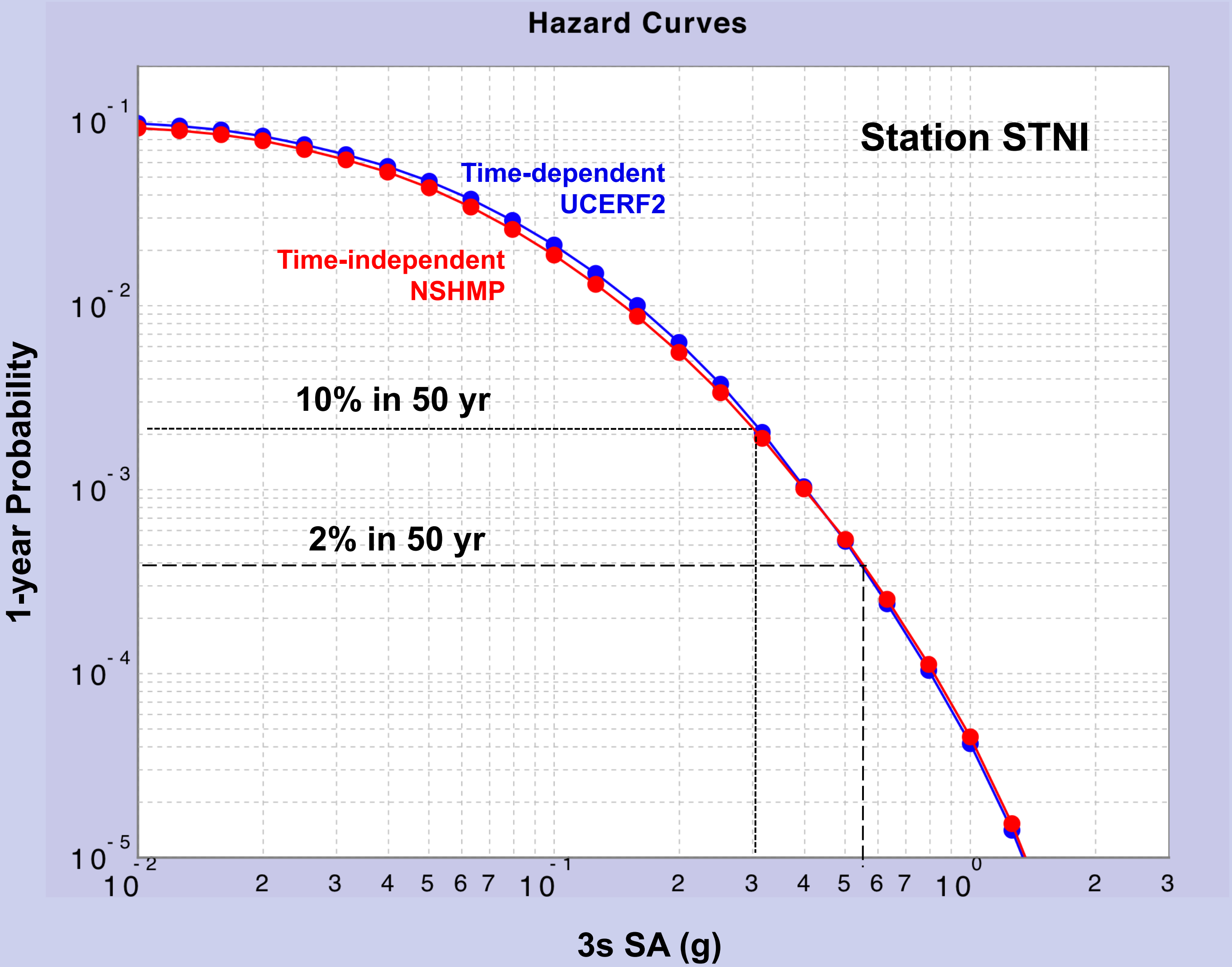
CS1: **0.10 g**

CS2: **0.11 g**

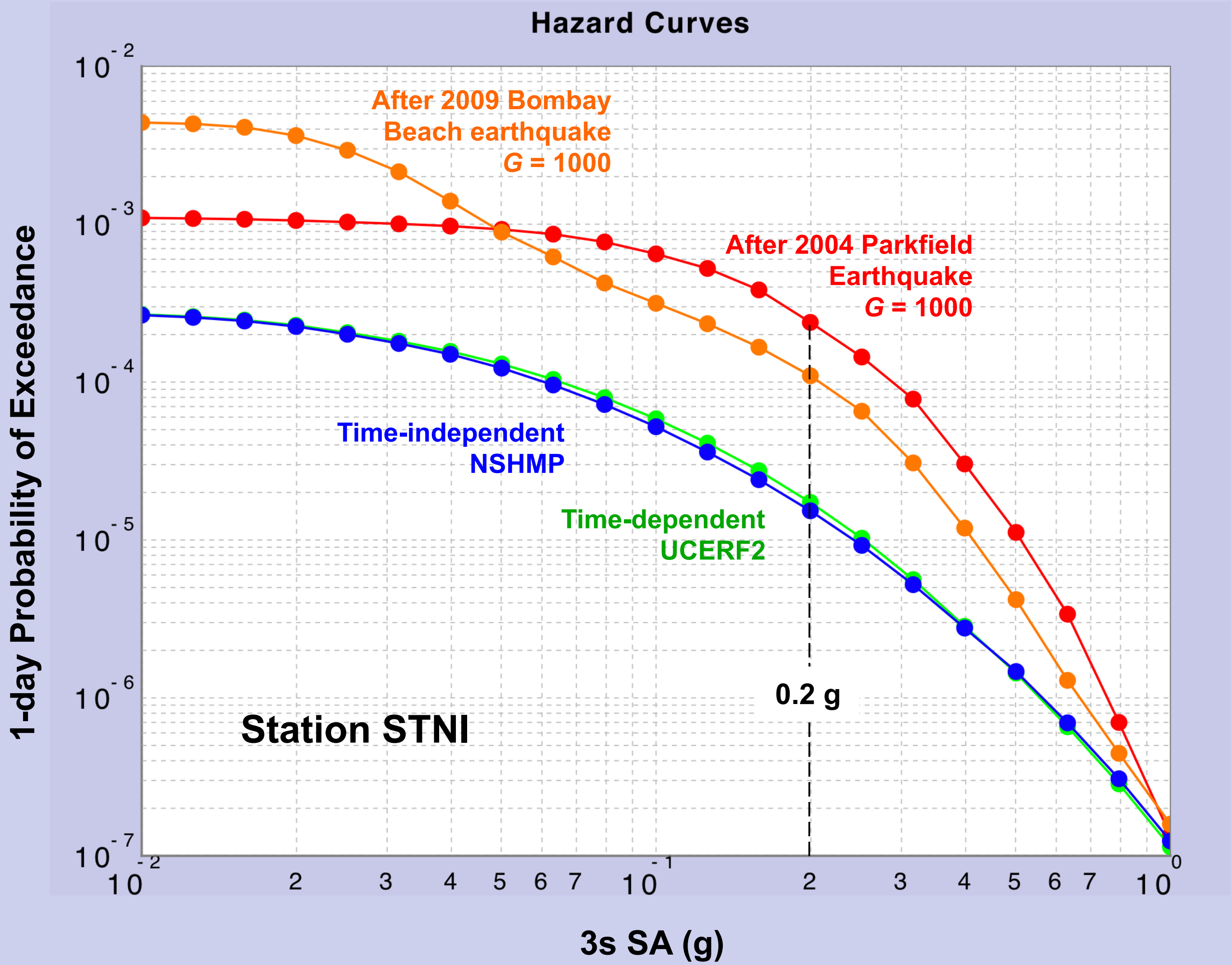
CS3: **0.20 g**

CS4: **0.25 g**

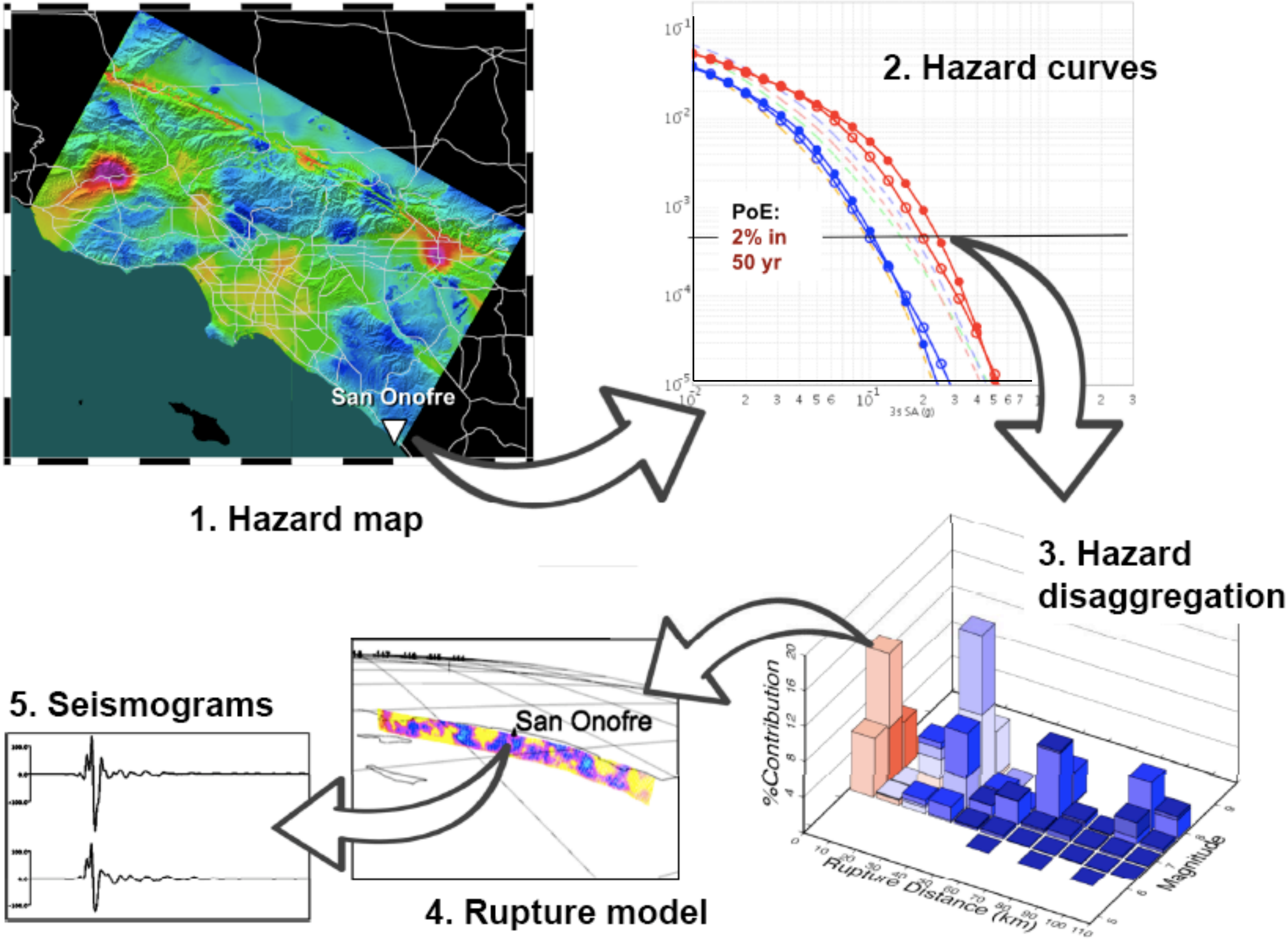
CyberShake Time-Independent Hazard Curves



CyberShake Time-Dependent Hazard Curves



CyberShake Produces a Layered Seismic Hazard Model



1. Hazard map

2. Hazard curves

3. Hazard disaggregation

4. Rupture model

5. Seismograms