Southern California Earthquake Center

An Overview of the SCEC CyberShake Project

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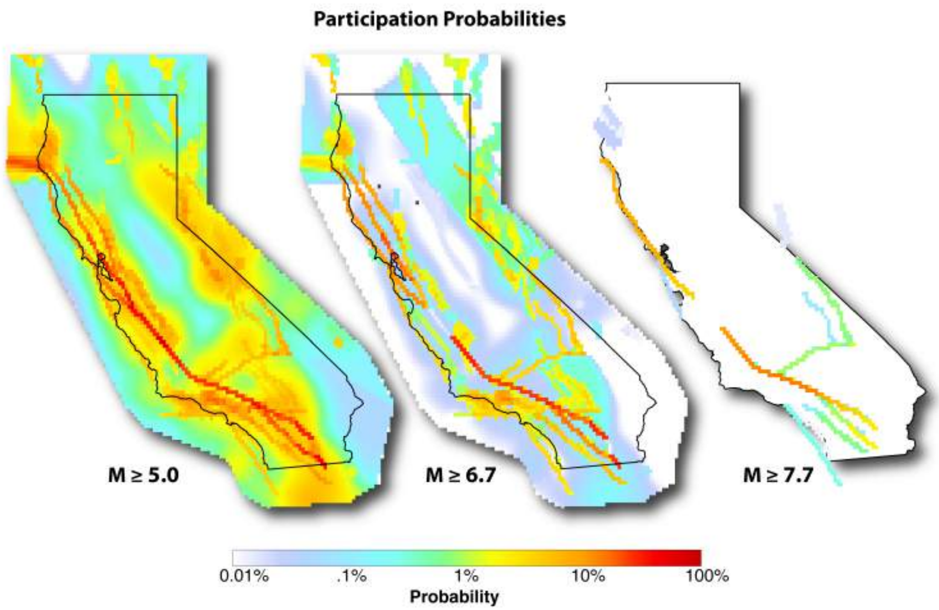
CyberShake co-developers: S. Callaghan, R. Graves, F. Wang, K. Olsen, K. Milner, and P. Maechling, E.-J. Lee, P. Chen

Meeting of the SCEC Committee for the Utilization of Ground Motion Simulations

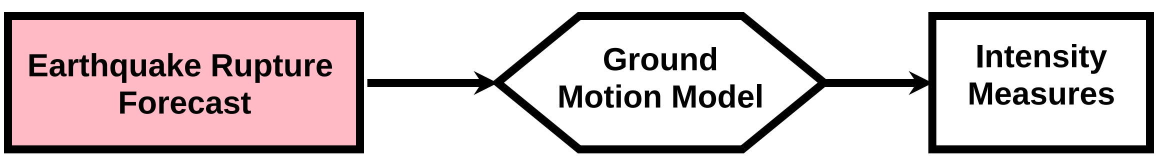
03 Nov 2014

Probabilistic Seismic Hazard Model



Working Group on California Earthquake Probabilities (2007)

Uniform California Earthquake Rupture Forecast (UCERF2)



$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

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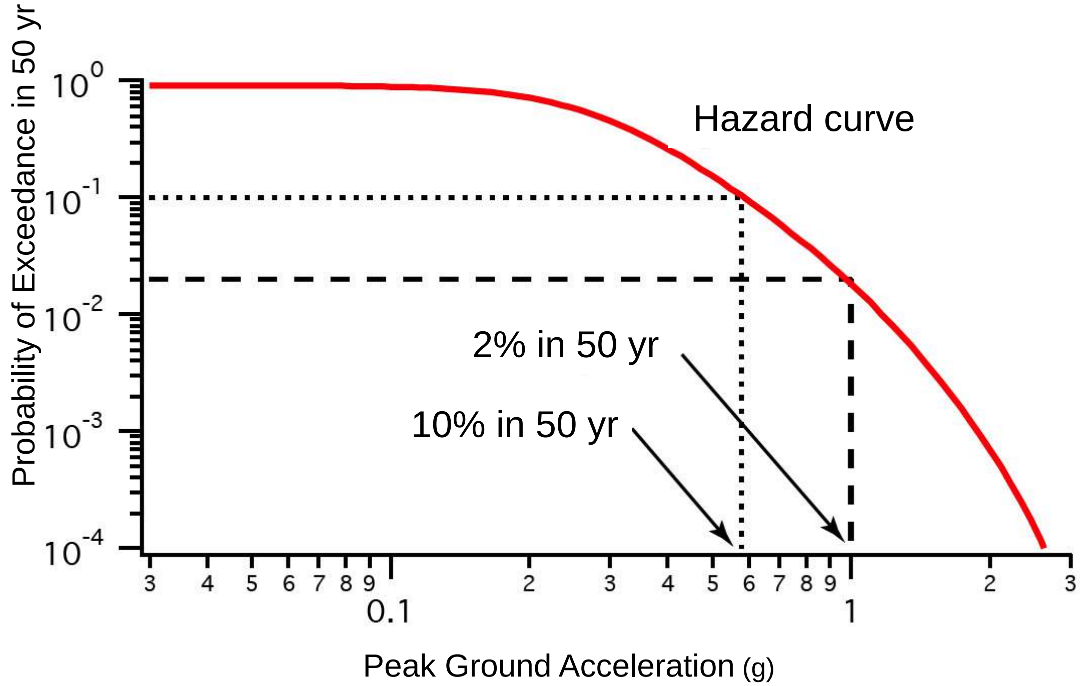
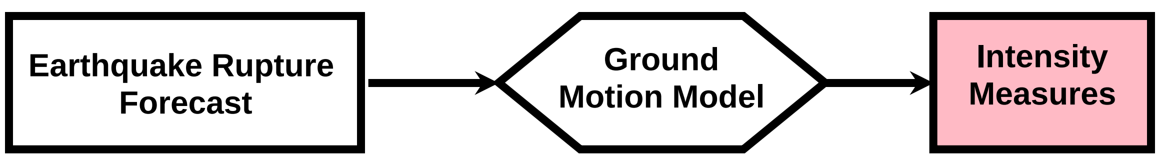
Probabilistic Seismic Hazard Model

Hazard Curve:

- **Shaking intensity: Peak Ground Acceleration (PGA)**
- **Interval: 50 years**
- **Site: Downtown LA**



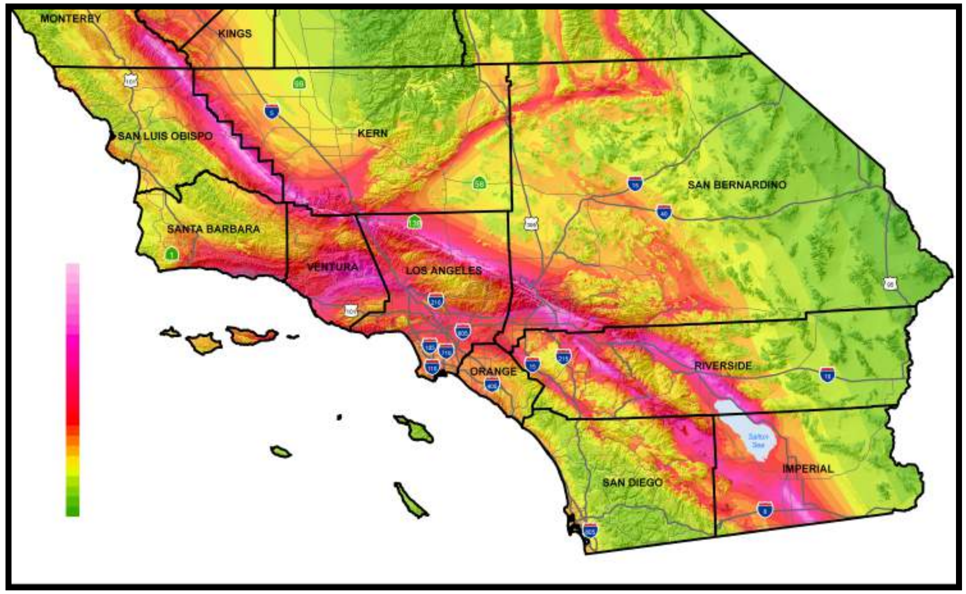


$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

Probabilistic Seismic Hazard Model

National Seismic Hazard Map

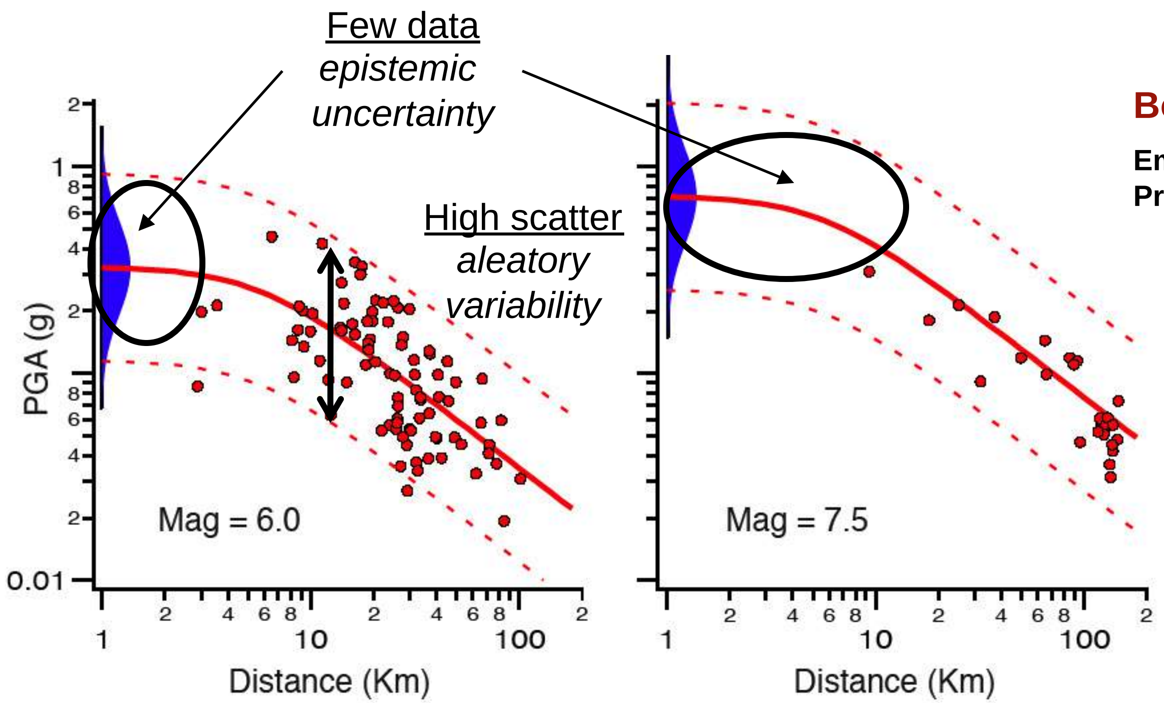
PGA (%g) with 2% Probability of Exceedance in 50 years



Earthquake Rupture Forecast → **Ground Motion Model** → **Intensity Measures**

$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

Probabilistic Seismic Hazard Model



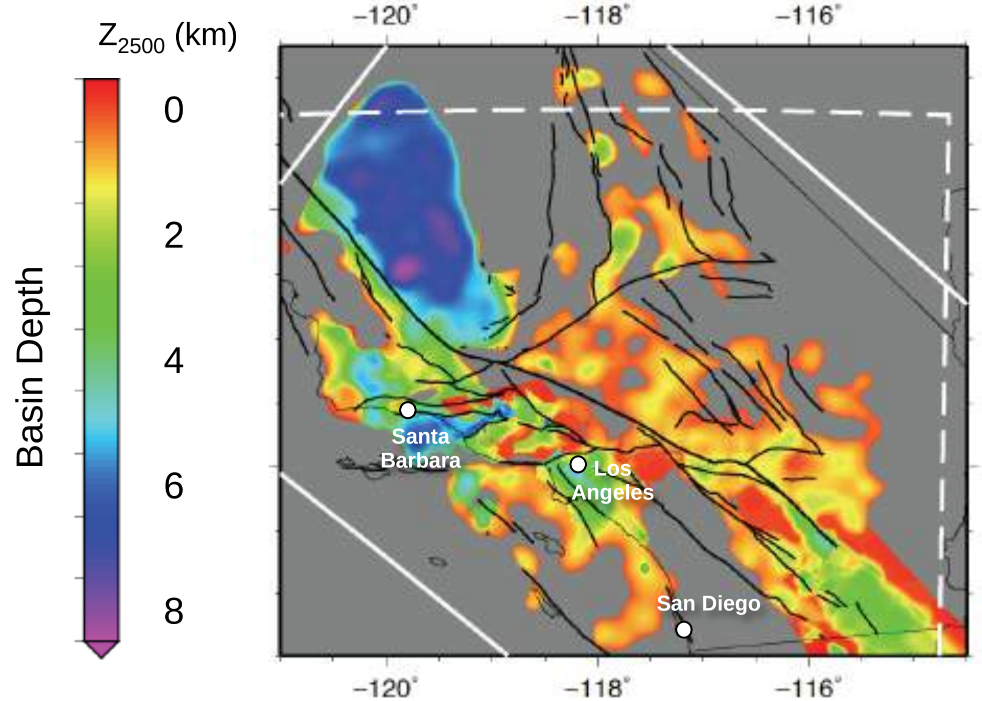
Boore et al. (1997)

Empirical Ground Motion Prediction Equations (GMPEs)

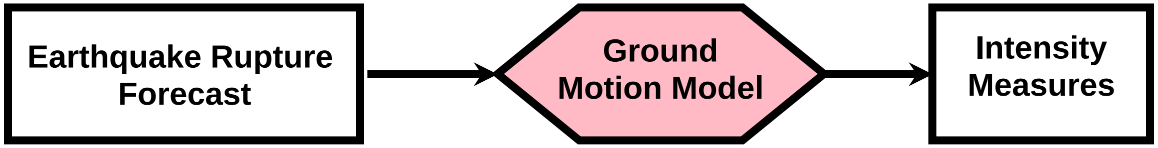
Earthquake Rupture Forecast → **Ground Motion Model** → **Intensity Measures**

$P(S_k)$ $\quad$ $P(Y_n \mid S_k)$ $\quad$ $P(Y_n)$

Probabilistic Seismic Hazard Model

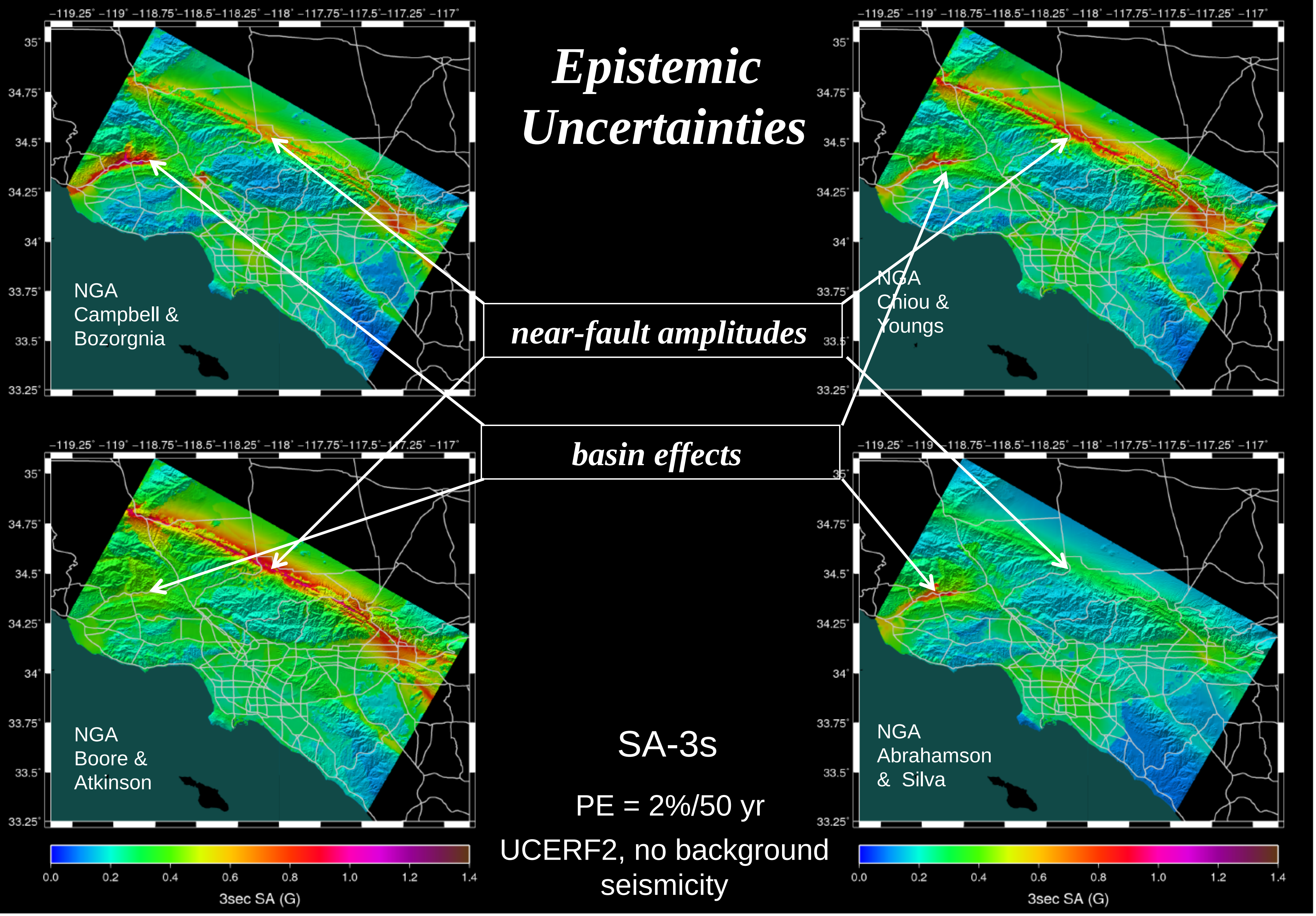


Much of the aleatory variability in the GMPEs comes from 3D heterogeneity in crustal structure



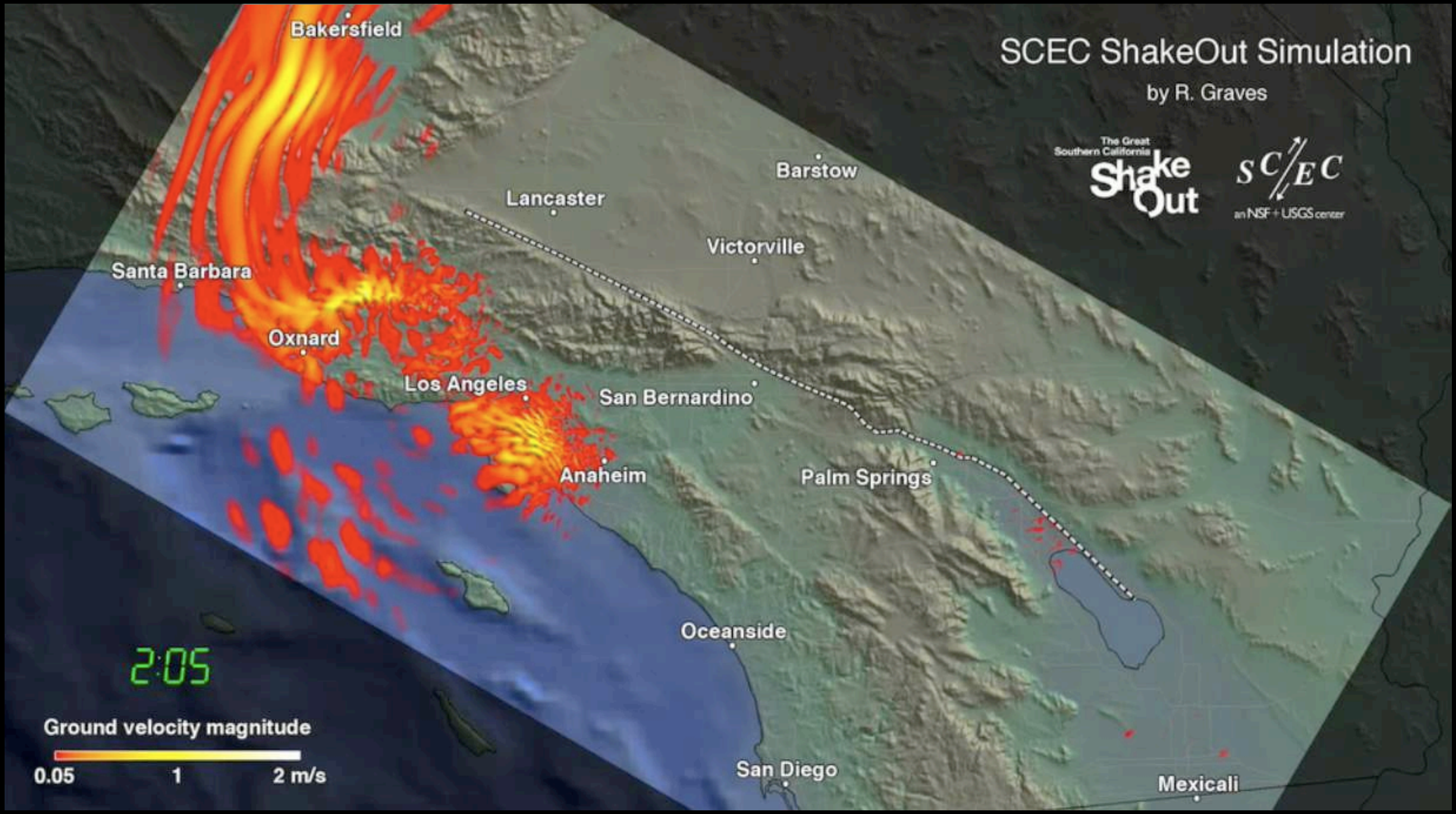
$P(S_k)$ $P(Y_n \mid S_k)$ $P(Y_n)$

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

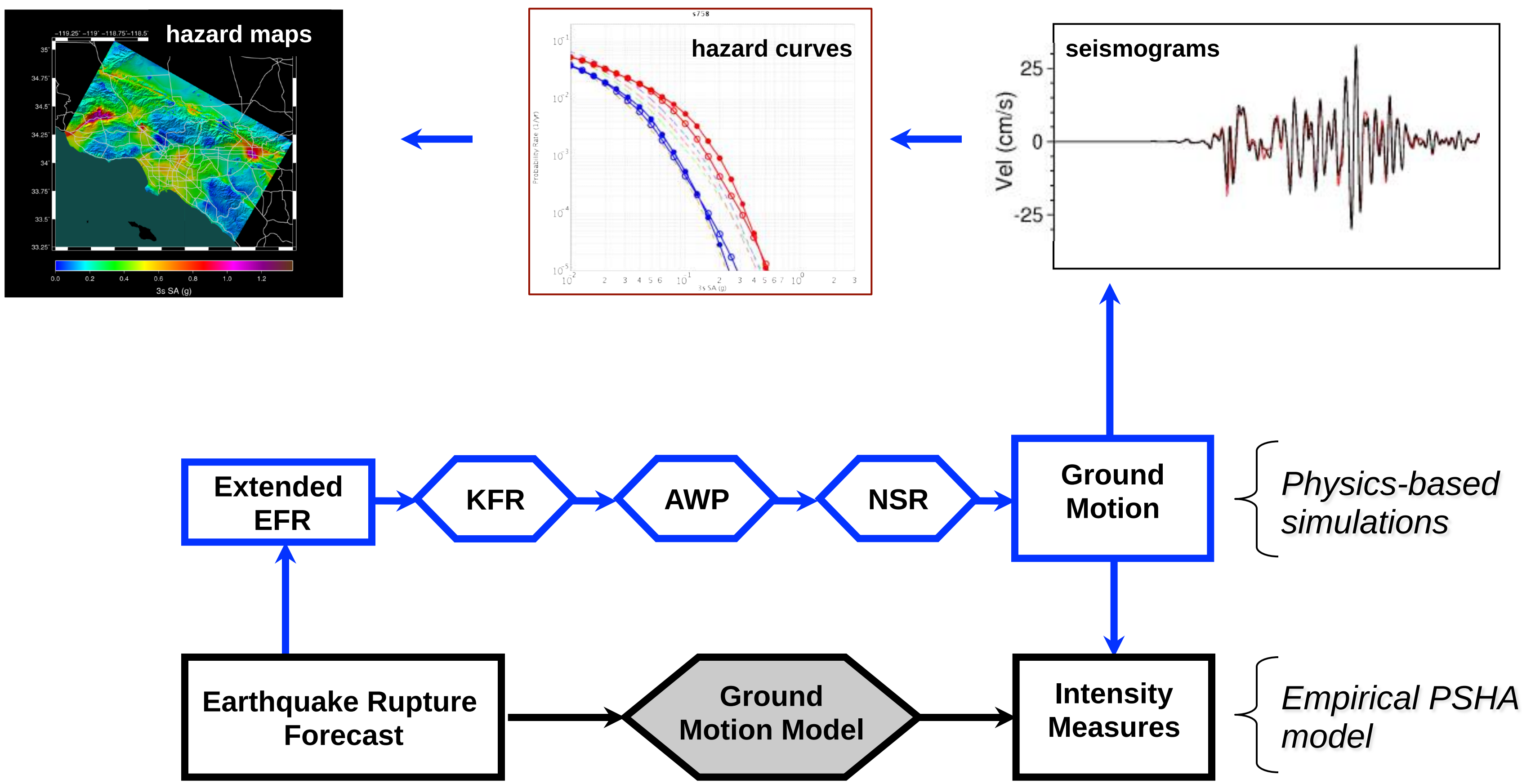


ShakeOut Scenario

M7.8 Earthquake on Southern San Andreas Fault



CyberShake Model: Physics-Based PSHA



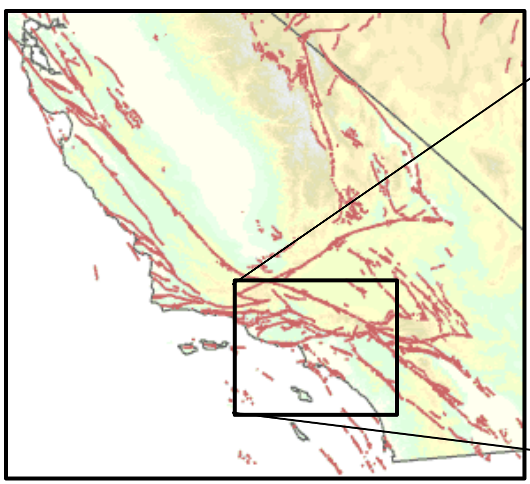
KFR = kinematic fault rupture model

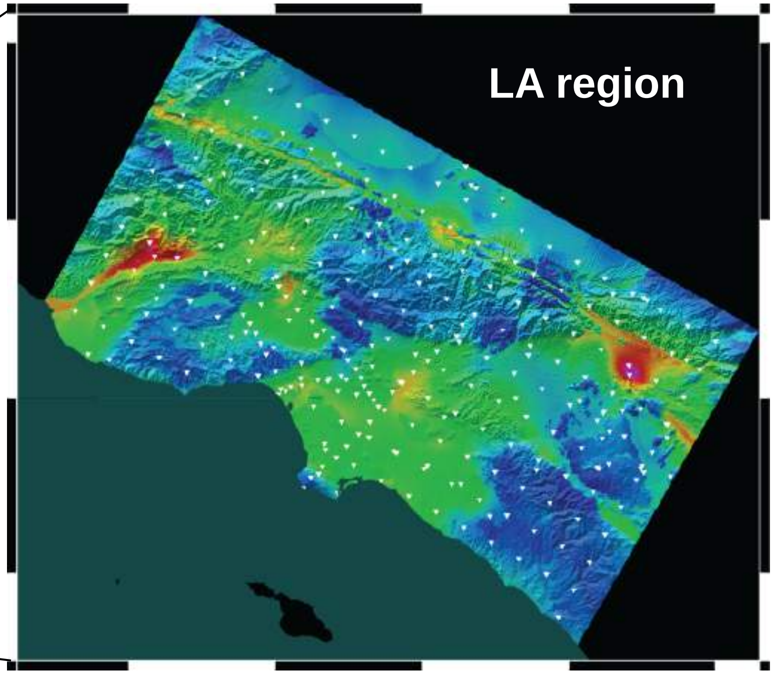
AWP = anelastic wave propagation model

NSR = nonlinear site response

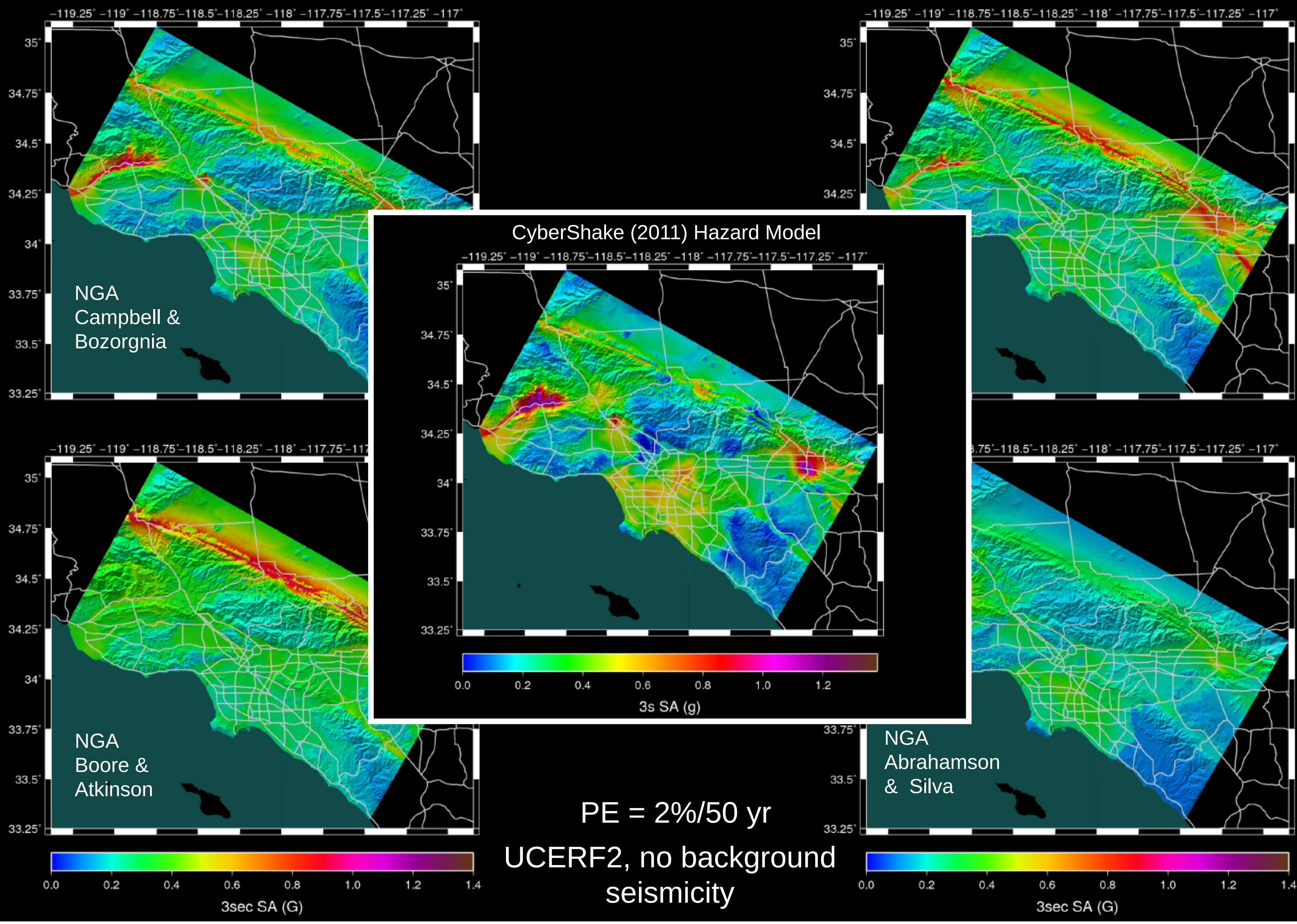
CyberShake Model: Physics-Based PSHA

- **Sites:**
  - 283 sites in the greater Los Angeles region
- **Ruptures:**
  - All UCERF2 ruptures within 200 km of site (~14,900)
- **Rupture variations:**
  - ~415,000 per site using Graves-Pitarka pseudo-dynamic rupture model
- **Seismograms:**
  - ~235 million per model





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



CyberShake Platform: Physics-Based PSHA

Essential ingredients

1. Extended earthquake rupture forecast
   - probabilities of all fault ruptures (e.g., UCERF2)
   - conditional hypocenter distributions for rupture sets
   - conditional slip distributions from pseudo-dynamic models
2. Three-dimensional models of geologic structure
   - large-scale crustal heterogeneity
   - sedimentary basin structure
   - near-surface properties ("geotechnical layer")

   } from SCEC CVMs
3. Ability to compute large suites (> 10^8) of seismograms
   - efficient anelastic wave propagation (AWP) codes
   - reciprocity-based calculation of ground motions

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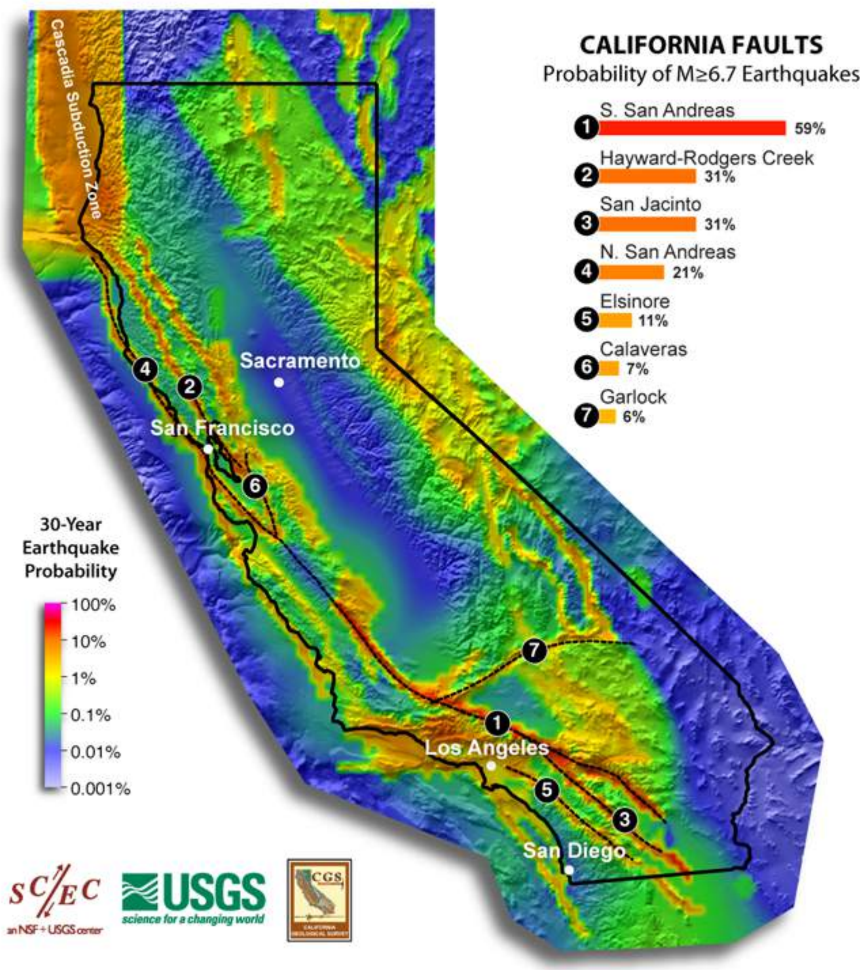
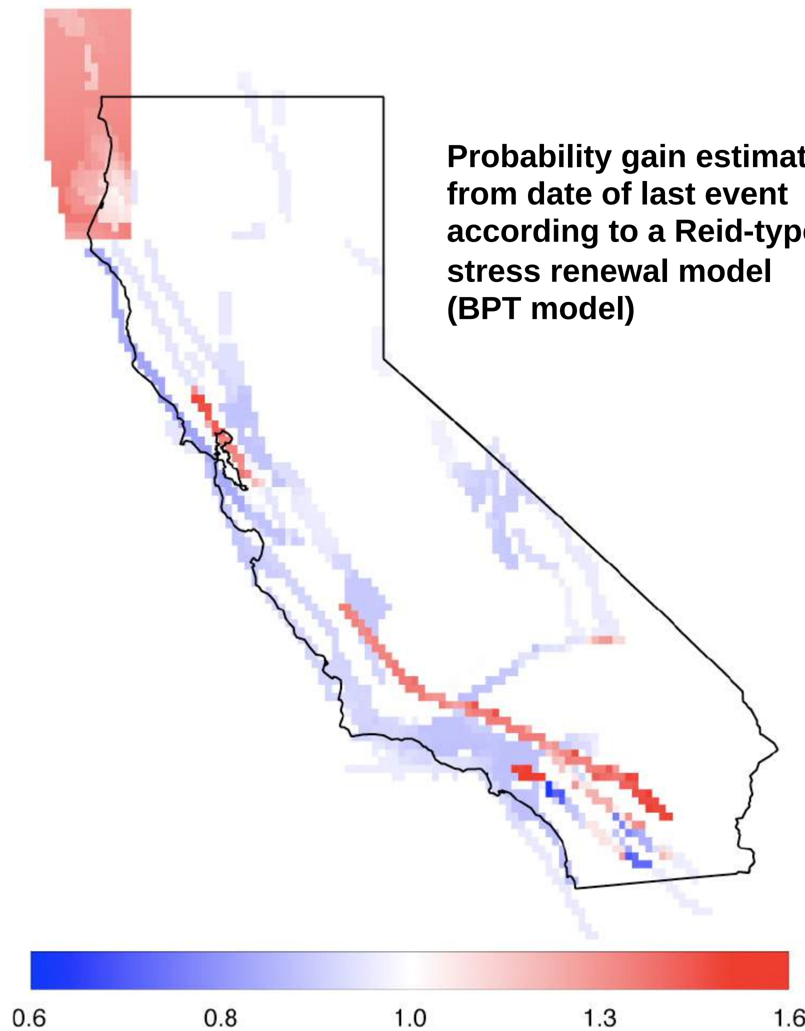
Working Group on California Earthquake Probabilities (2007)

Uniform California Earthquake Rupture Forecast (UCERF2)

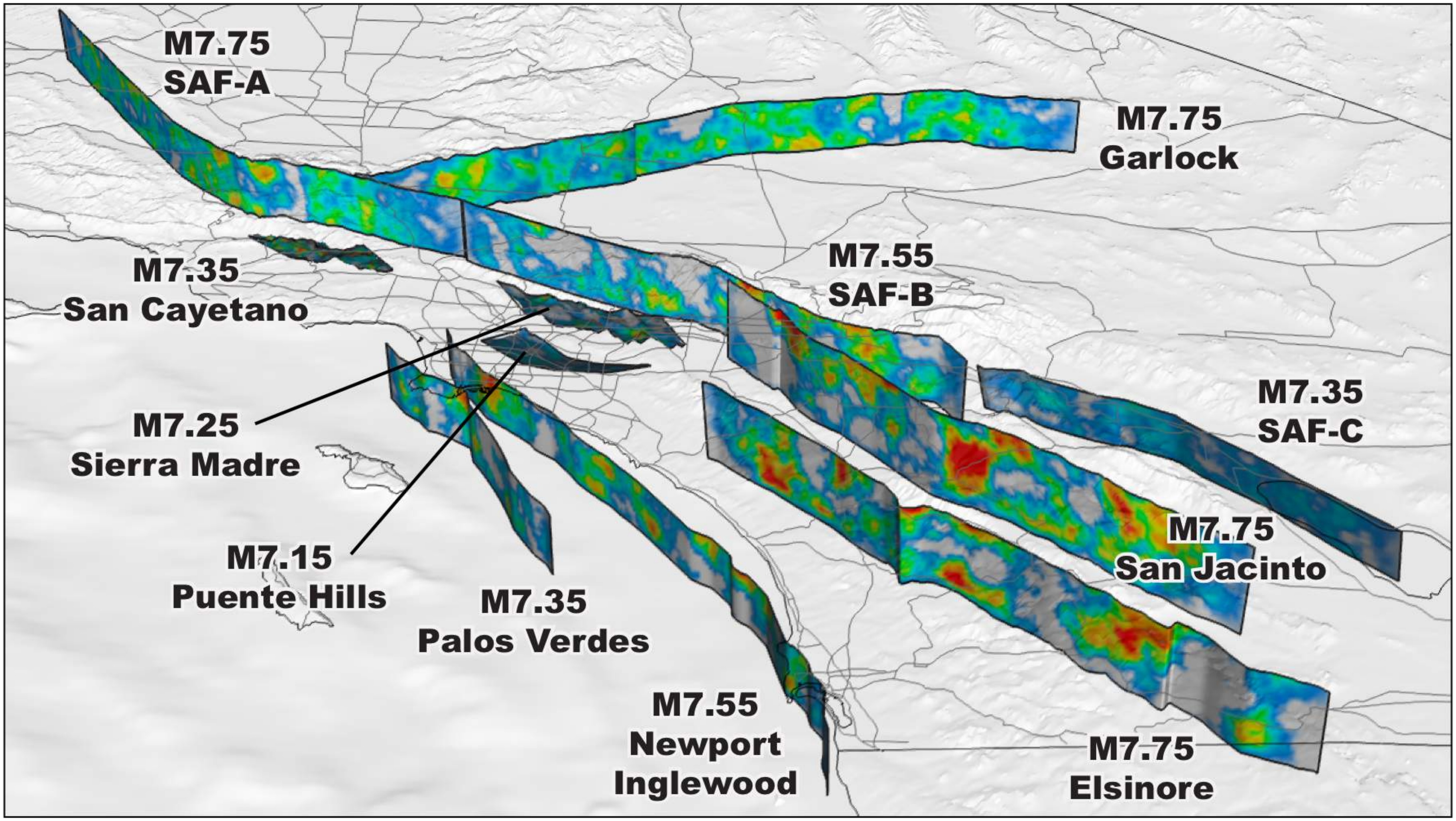


Probability gain estimated from date of last event according to a Reid-type stress renewal model (BPT model)



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

CyberShake Rupture Models



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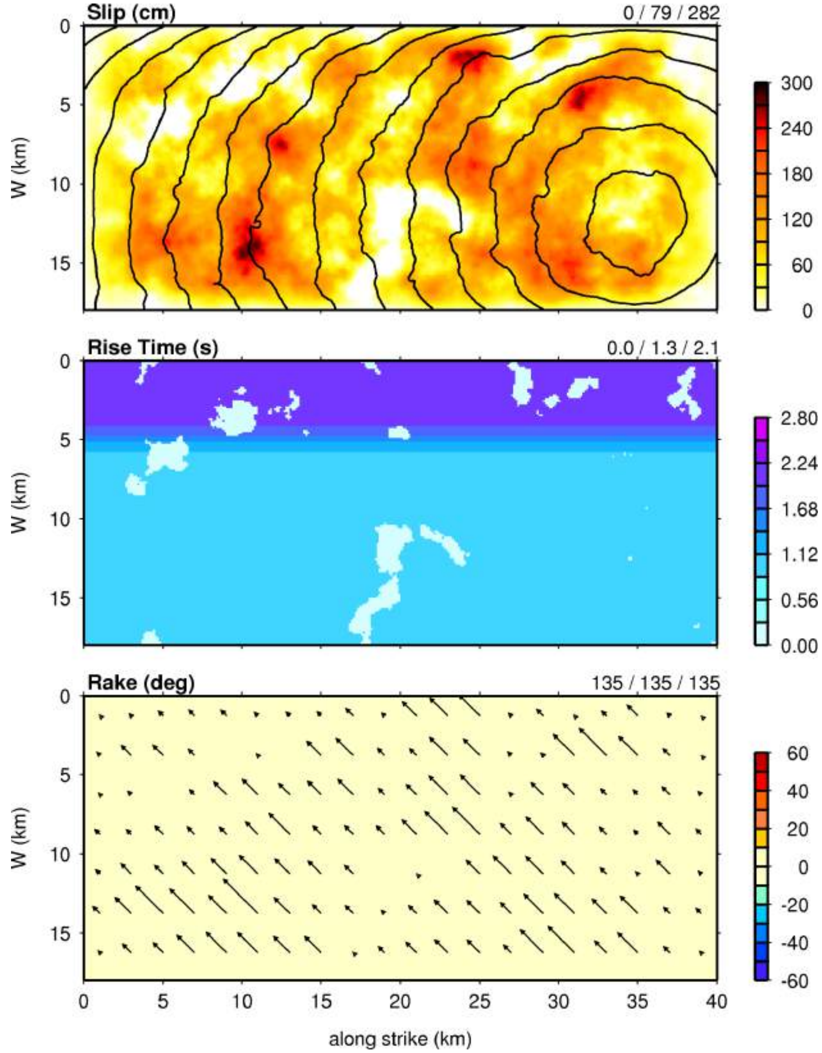
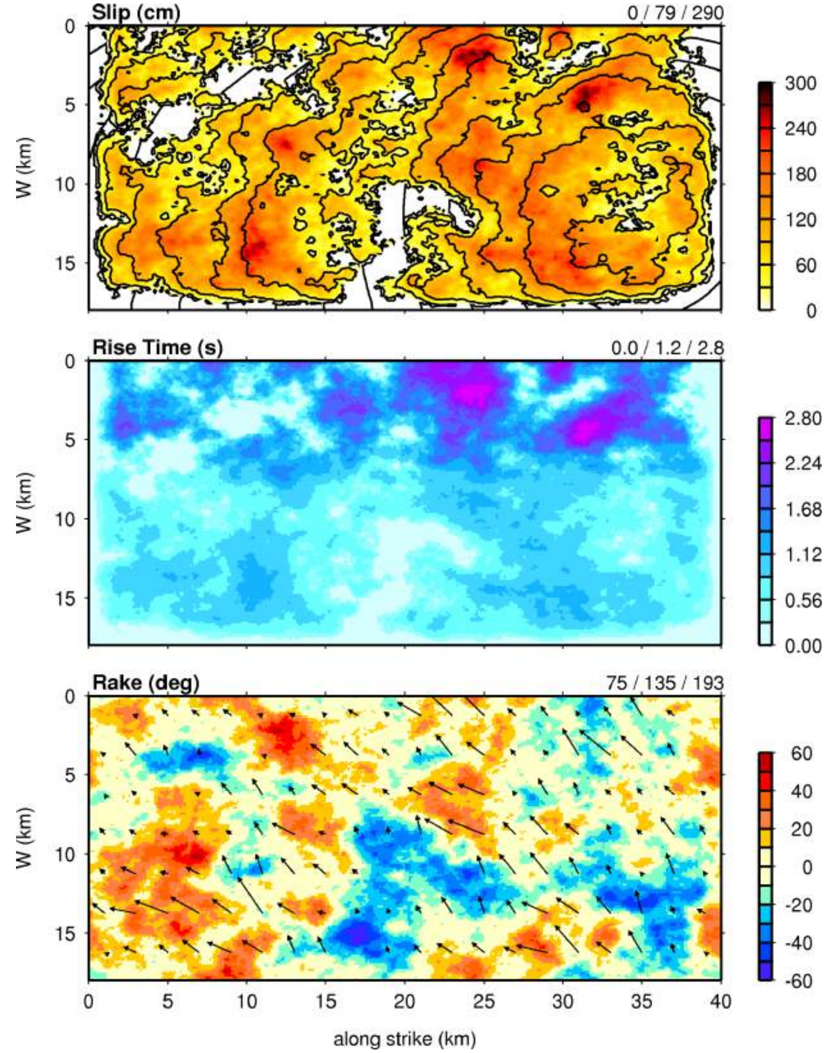
Conditional Slip Distribution

Graves-Pitarka Pseudo-Dynamic Rupture Models

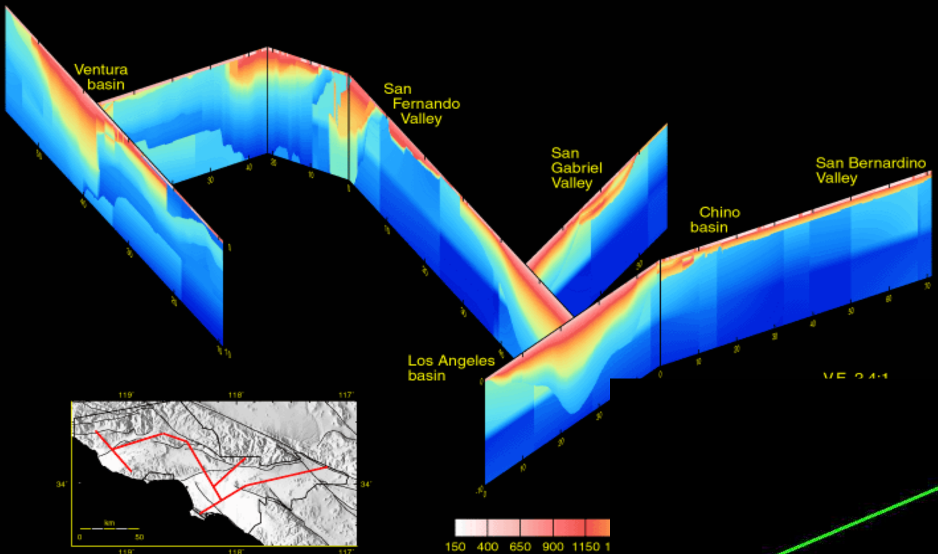
GP07
used in CS11



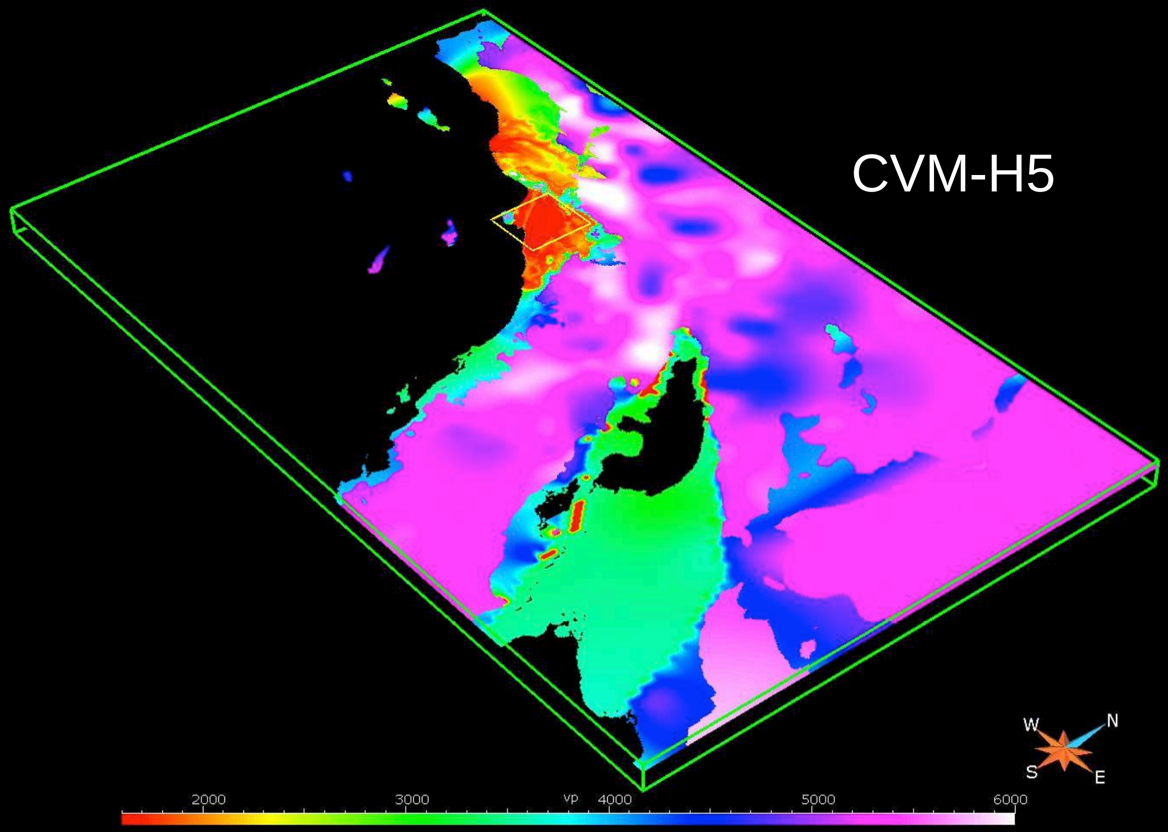
GP10
used in CS13



SCEC Community Velocity Models (CVMs)



CVM-S4

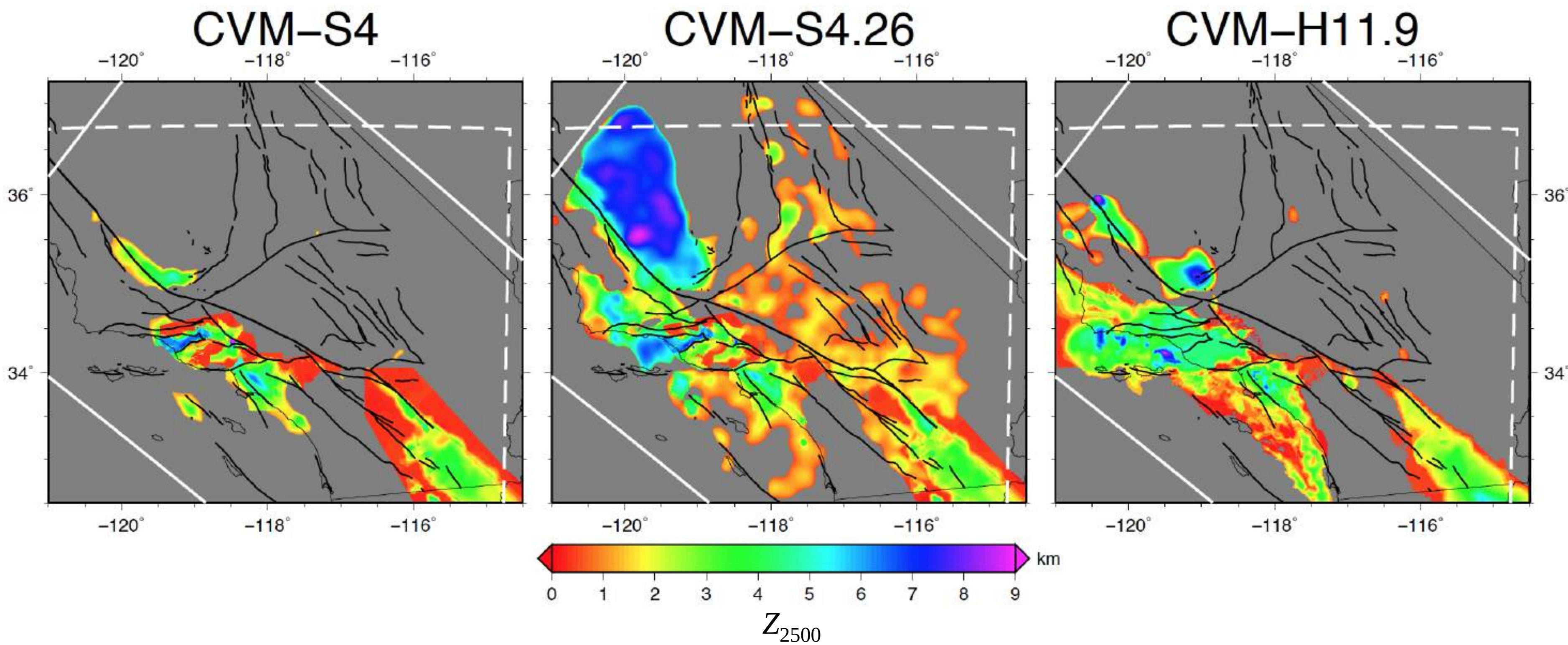


CVM-H5

Data sources

- **Surface geology**
- **Well logs**
- **Refraction surveys**
- **Reflection surveys**
- **Seismic tomography**
- **Geologic models**

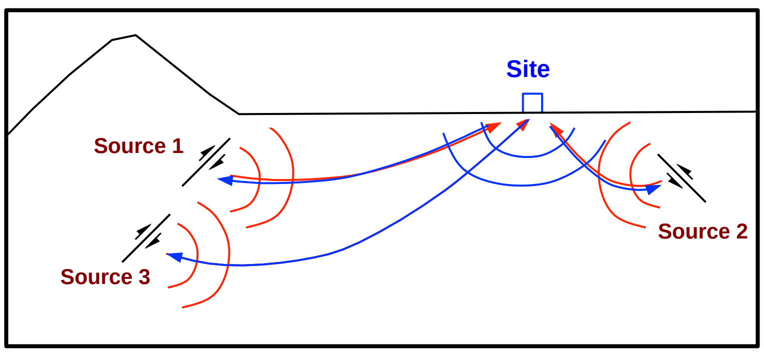
Basin Structures of Three SCEC CVMs



Z_{2500} **:** iso-velocity surfaces at V_S = 2.5 km/s

Rapid Simulation of Large Rupture Ensembles Using Seismic Reciprocity

- **To account for source variability requires very large sets of simulations**
  - **14,900 ruptures from UCERF2; 415,000 rupture variations**
- **Ground motions need only be calculated at much smaller number of surface sites to produce hazard map**
  - **283 in LA region, interpolated using empirical attenuation relations**
- ***Use of reciprocity reduces CPU time by a factor of ~1,000***

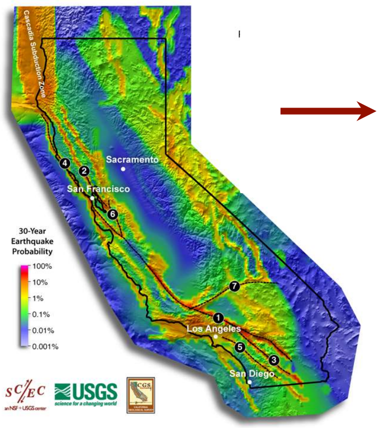


Strain Green Tensor (SGT)

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

***M* sources to *N* sites requires 2*N* or 3*N* simulations**

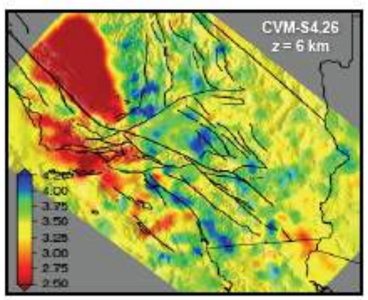
CyberShake Workflow



Uniform California Earthquake Rupture Forecast

→ **UCVM** → **AWP-ODC** → **SeisSynth** → *data transfer* → **Data Product Generation**

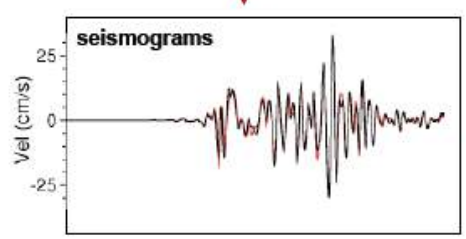
UCVM: *Mesh generation*
1 job per site
MPI, 320 cores



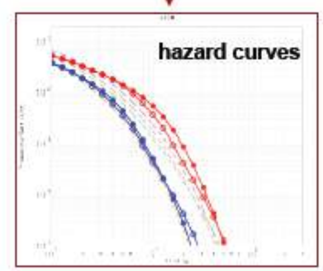
Full-3D tomographic model of S. California

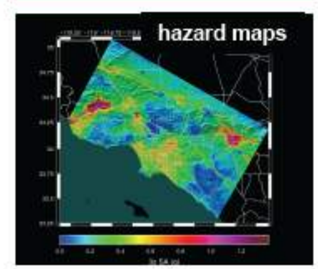
AWP-ODC: *SGT computation*
2 jobs per site
MPI, 10k CPUs or 100 GPUs

SeisSynth: *Post-processing*
415,000 jobs per site
serial



Data Product Generation: *Populate DB, construct queries*
4 jobs per site



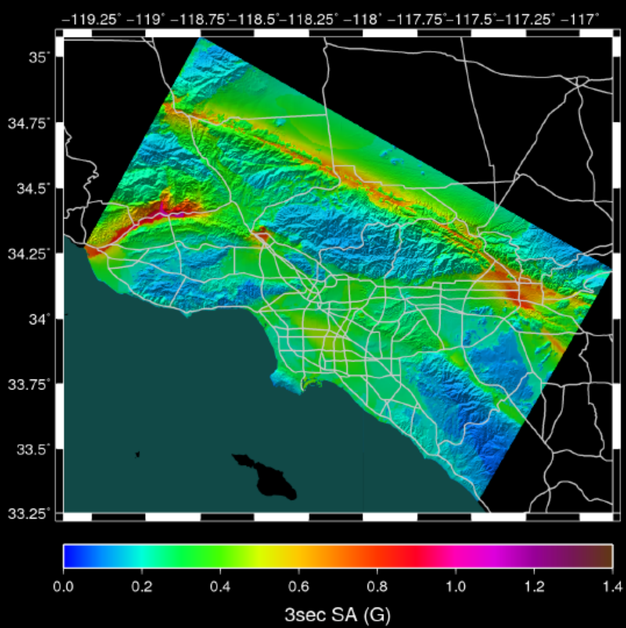


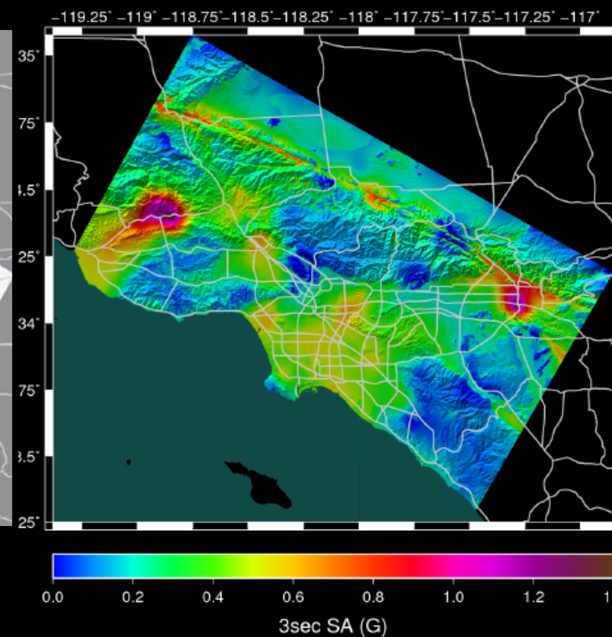
CyberShake Hazard Map Interpolation

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

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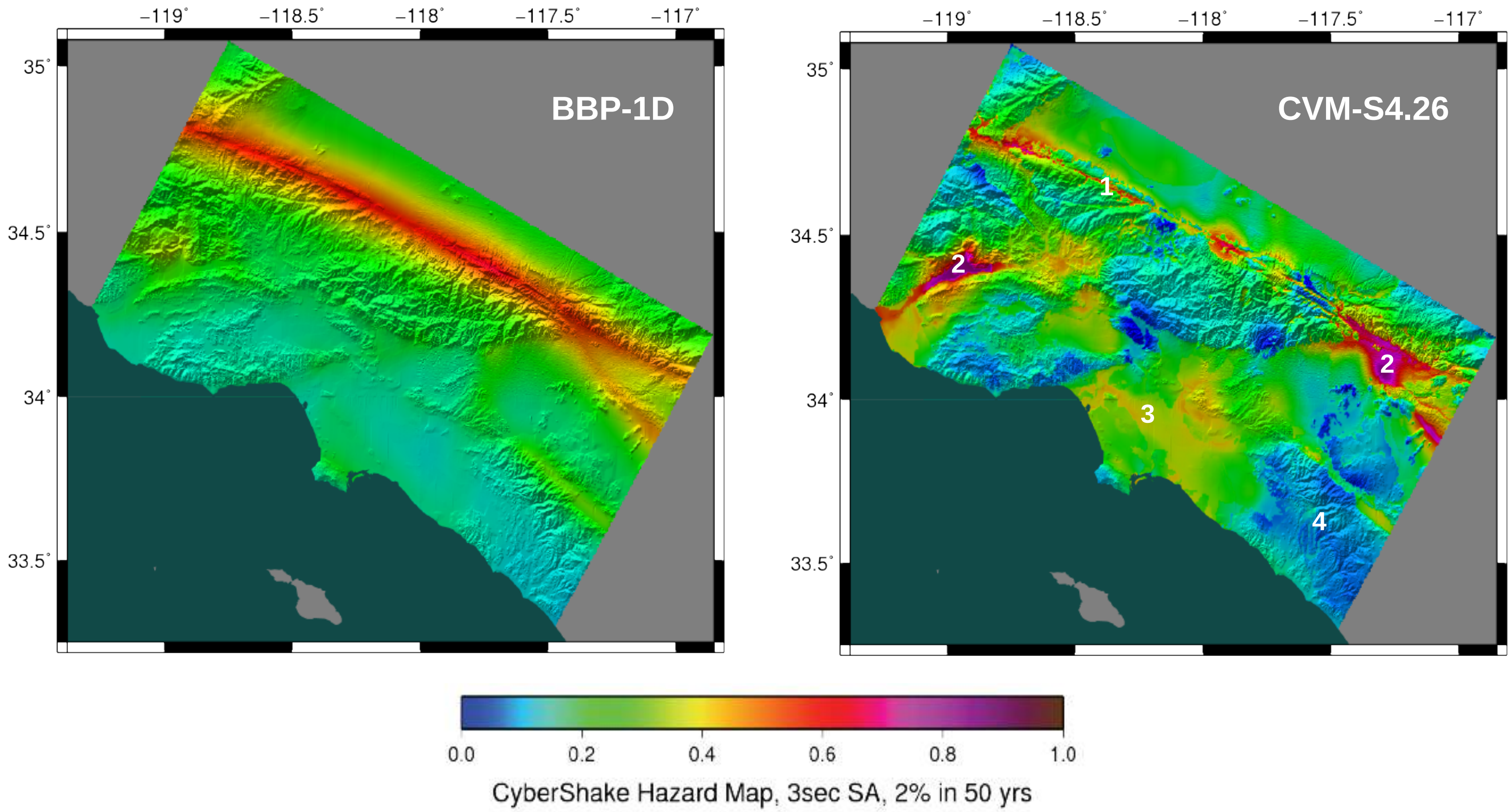
Comparison of 1D and 3D CyberShake Models for the Los Angeles Region



1. lower near-fault intensities due to 3D scattering
2. much higher intensities in near-fault basins
3. higher intensities in the Los Angeles basins
4. lower intensities in hard-rock areas

Seismological Hierarchy of CyberShake

$$G(r, k, x, s) = \ln Y(r, k, x, s)$$

- **Site set:** $r \in R$
  - 283 sites in the greater Los Angeles region
  - Elastic structures: BBP-1D, CVM-S4, CVM-H11, or CVM-S4.26
- **Rupture set:** $k \in K(r)$
  - All UCERF2 ruptures within 200 km of site (~7000 total)
- **Conditional hypocenter distribution:** $x \in X(r, k)$
  - Uniform distribution along fault strike with $\Delta x \approx 20$ km
- **Conditional slip distribution:** $s \in S(r, k, x)$
  - Pseudo-dynamic rupture models of Graves & Pitarka (2007, 2010)
  - Approximately 415,000 rupture variations per site, 235 million synthetic seismograms per model (2 horizontal components)

CHD and CSD define the "Extended ERF"

Averaging-Based Factorization

(Wang & Jordan, *BSSA*, 2014)

- **Representation of excitation functionals**

Expected shaking intensities constructed by averaging over slip variations (s), hypocenters (x), sources (k), and sites (r)

$$G(r,k,x,s) = A + B(r) + C(r,k) + D(r,k,x) + E(r,k,x,s)$$

↑ ln (Y) ↑ level ↑ site effect ↑ path effect ↑ directivity effect ↑ slip complexity effect

- **Representation of excitation variance**

$$\mathrm{Var}[G] = \bar{\sigma}_G^2 \equiv \left\langle [G(r,k,x,s) - A]^2 \right\rangle_{S,X,K,R}$$

$$= \sigma_B^2 + \left\langle \sigma_C^2(r) \right\rangle_R + \left\langle \sigma_D^2(r,k) \right\rangle_{K,R} + \left\langle \sigma_E^2(r,k,x) \right\rangle_{X,K,R}$$

$$\equiv \sigma_B^2 + \bar{\sigma}_C^2 + \bar{\sigma}_D^2 + \bar{\sigma}_E^2$$

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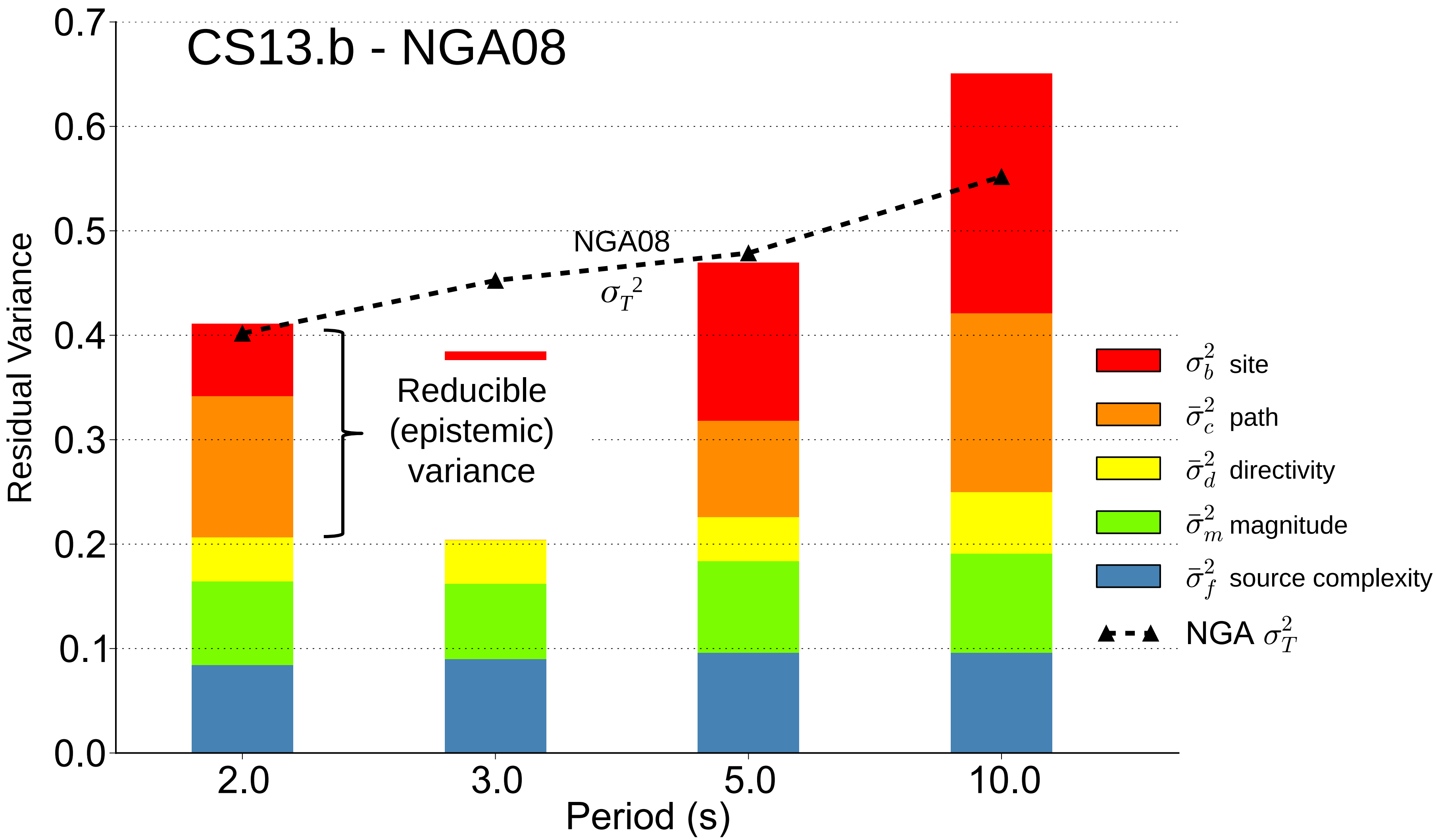
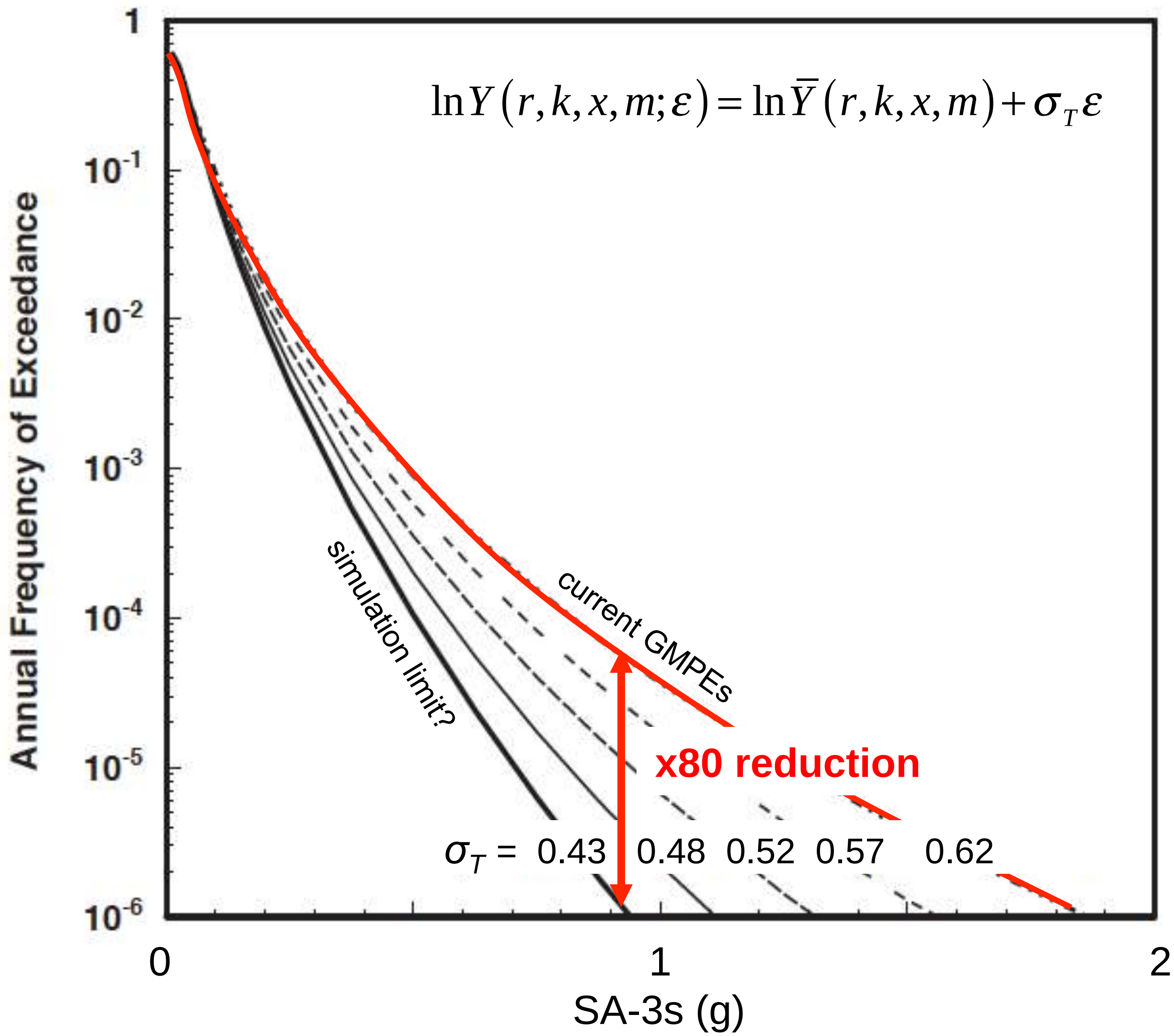
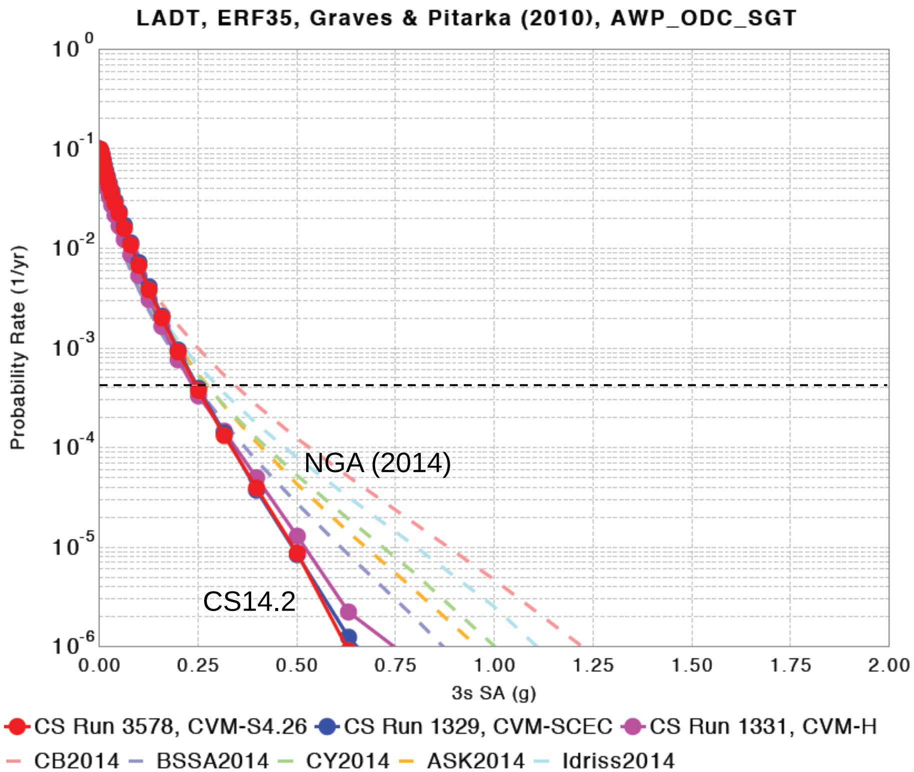
ABF Variance Analysis of the CyberShake Model



Importance of Reducing Aleatory Variability

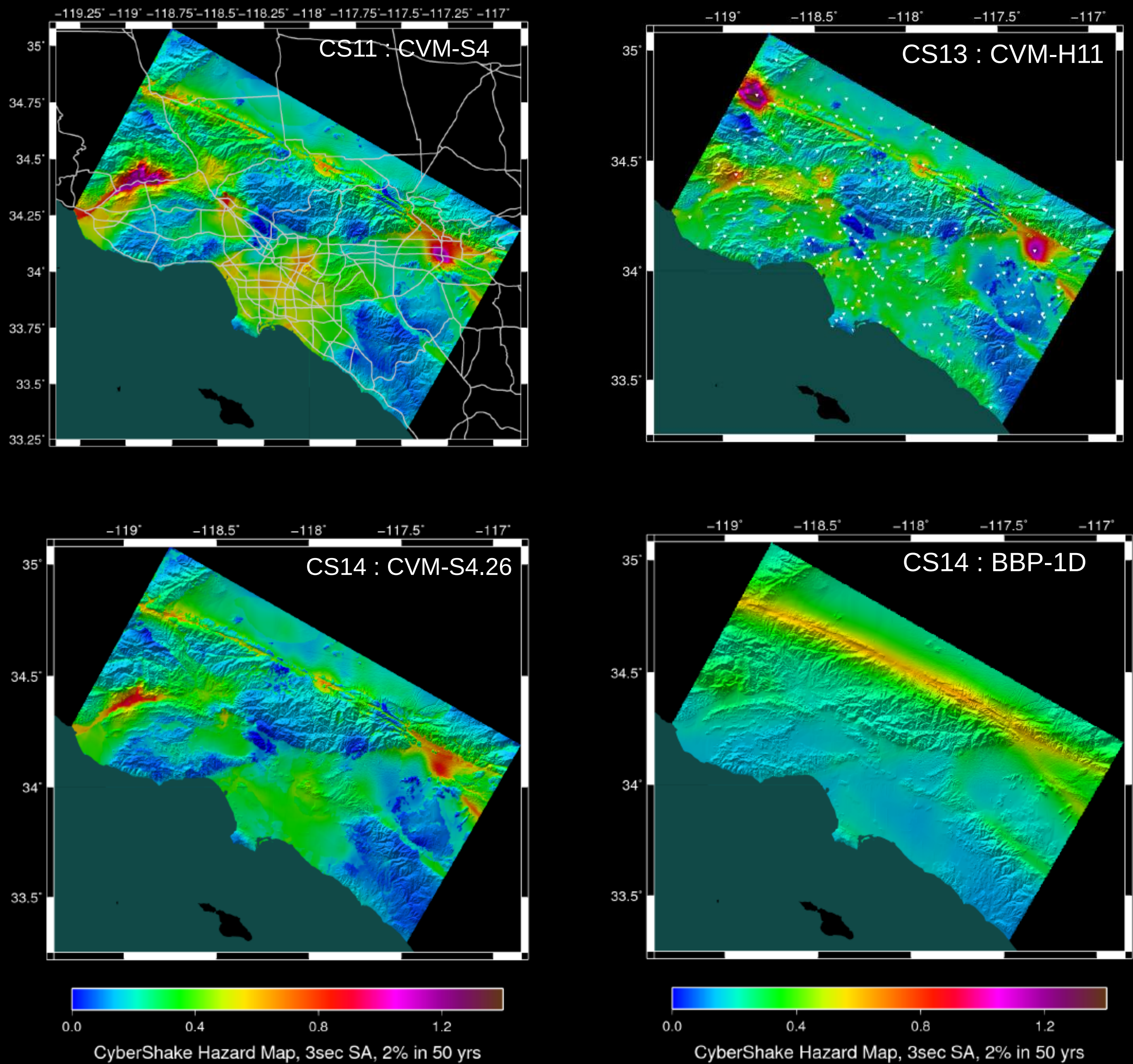


NGA(2014)-CyberShake Hazard Curve Comparisons



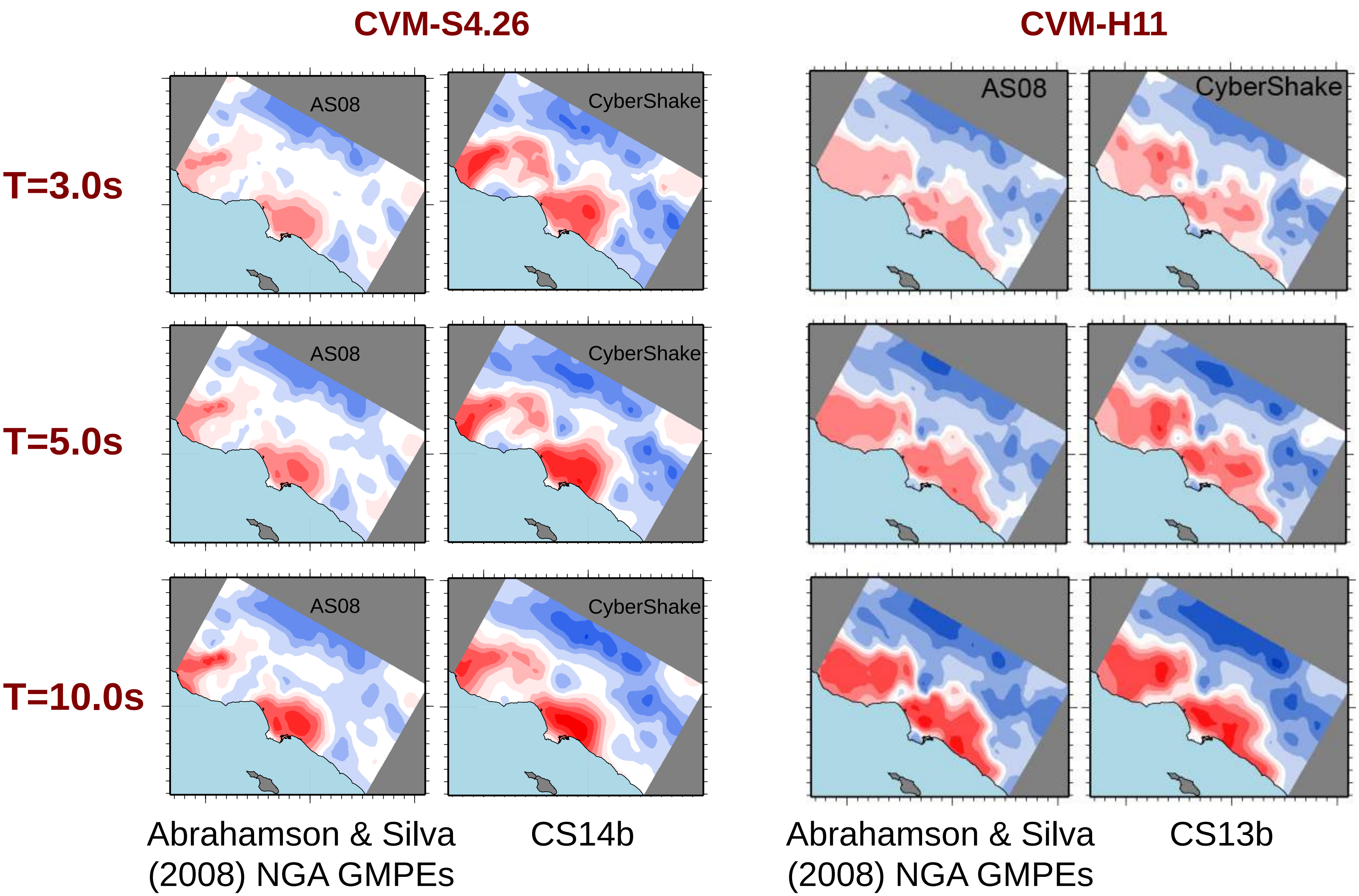
Site LADT
(Los Angeles)

CyberShake Hazard Maps from Four CVMs



Dependence of Basin Effects on Velocity Structures

(SA corrected for V_{S30} using BA08)



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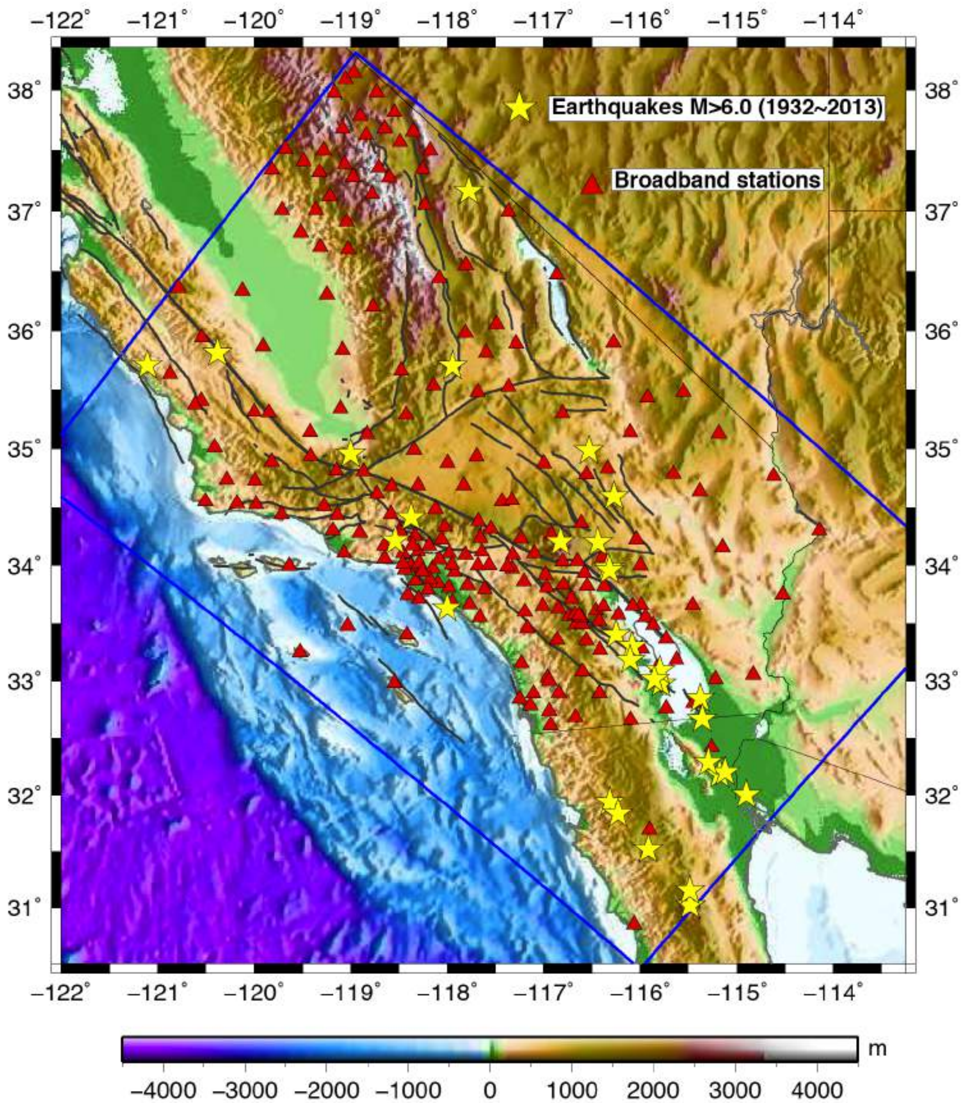
CVM-S4.26

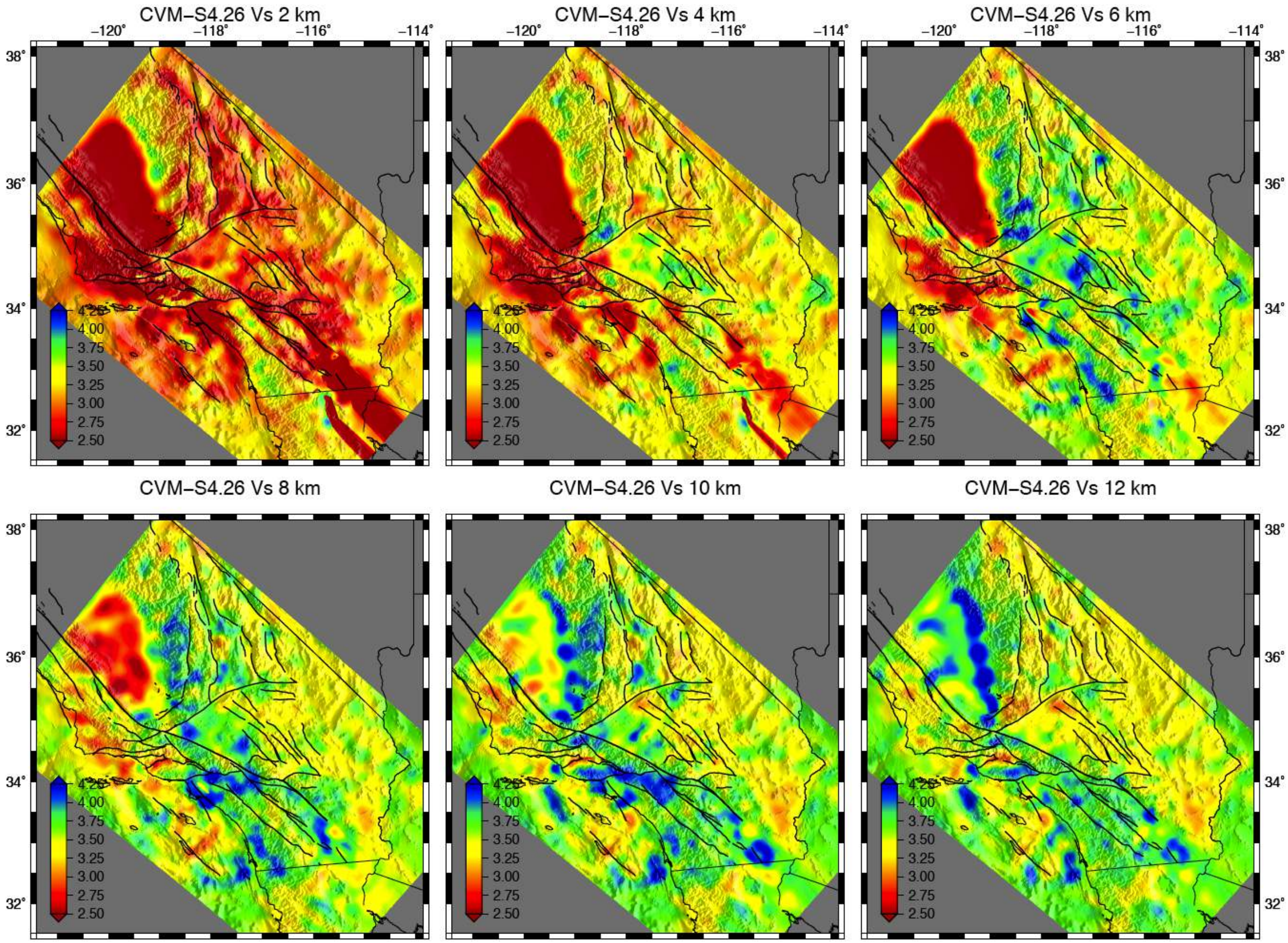
Full-3D tomography model of Southern California crustal structure



- **CVM-S4 starting model**
- **26th iterate of a full-3D tomographic (F3DT) inversion procedure (Lee et al., 2013).**
- **Data sets comprise ~ 550,000 differential waveform measurements at *f* ≤ 0.2 Hz**
  - **38,000 earthquake seismograms**
  - **12,000 ambient-noise Green functions**
- **Nonlinear iterative process involved two methods:**
  - **adjoint-wavefield (AW-F3DT)**
  - **scattering-integral (SI-F3DT)**

Full-3D Waveform Tomography

(Lee, Chen, Jordan, Maechling, Denolle & Beroza, JGR, 2014)



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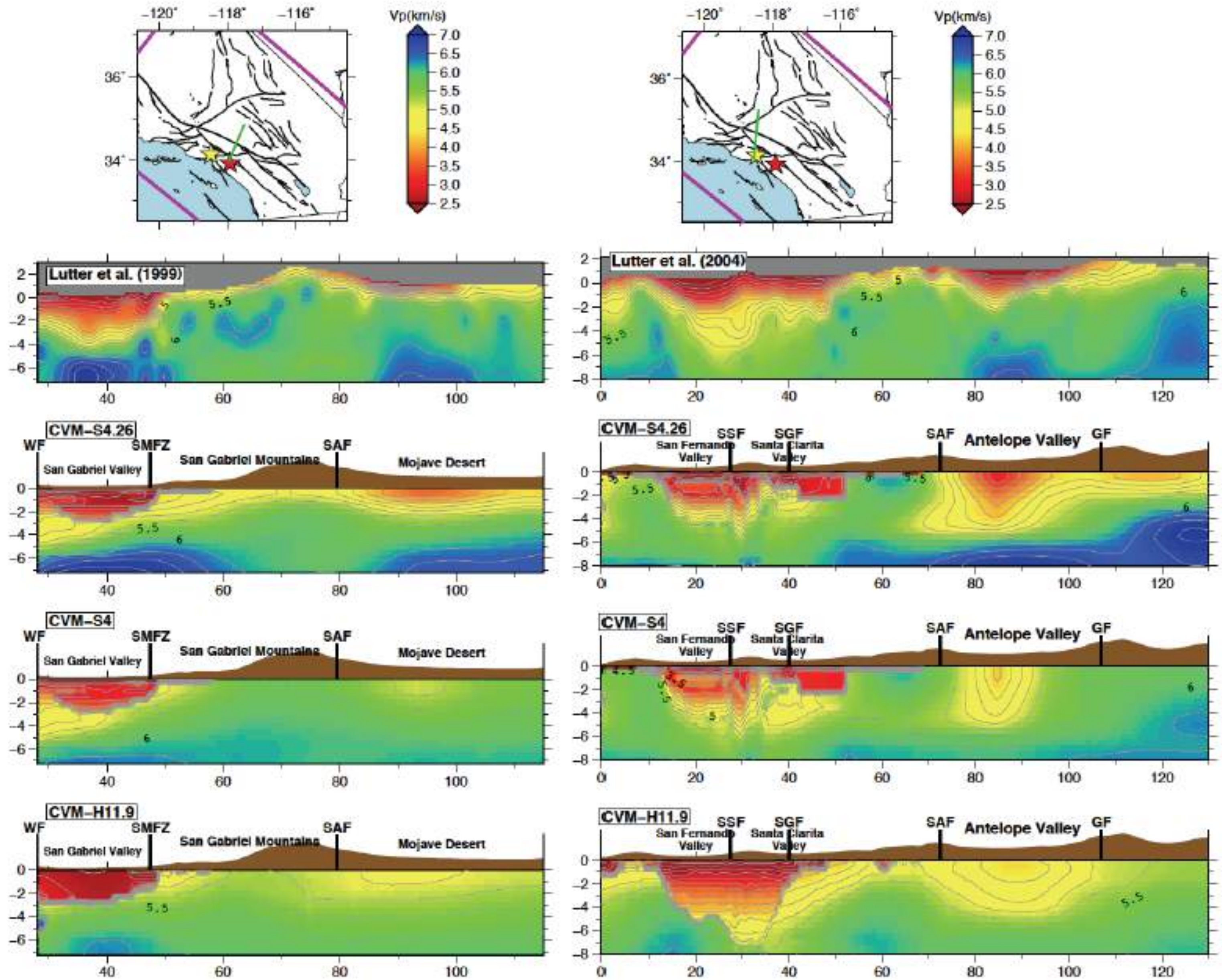
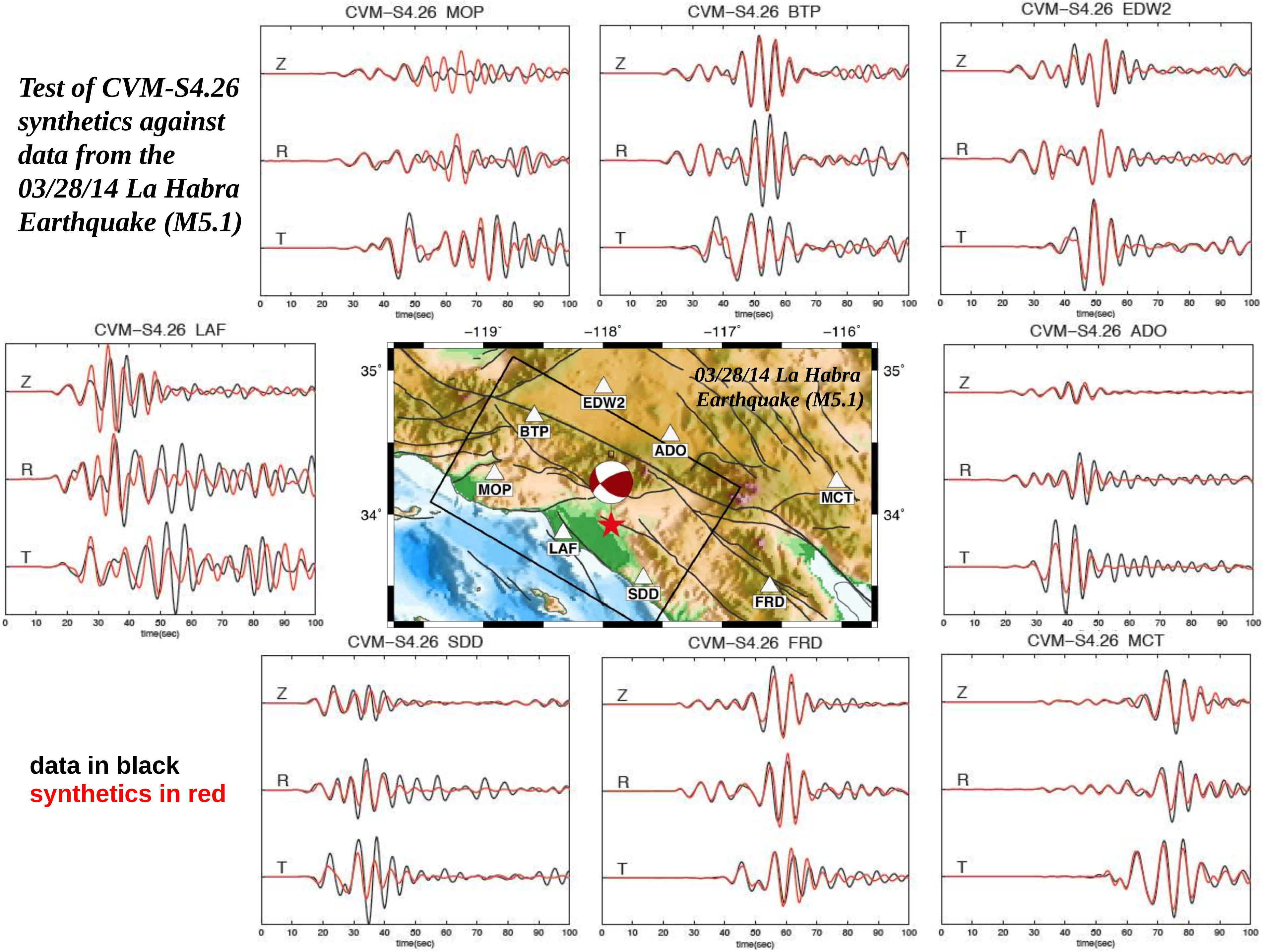
LARSE Profiles



Test of CVM-S4.26 synthetics against data from the 03/28/14 La Habra Earthquake (M5.1)



data in black
synthetics in red

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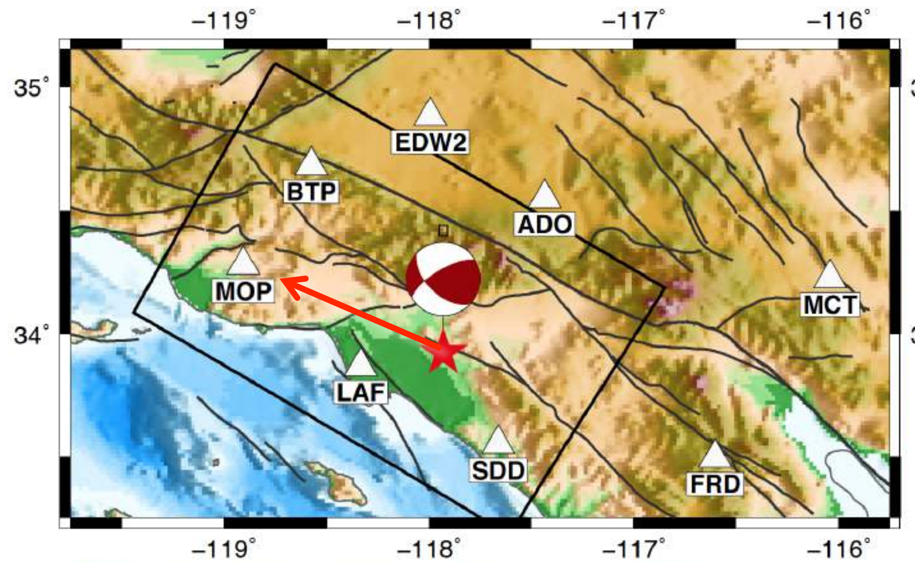
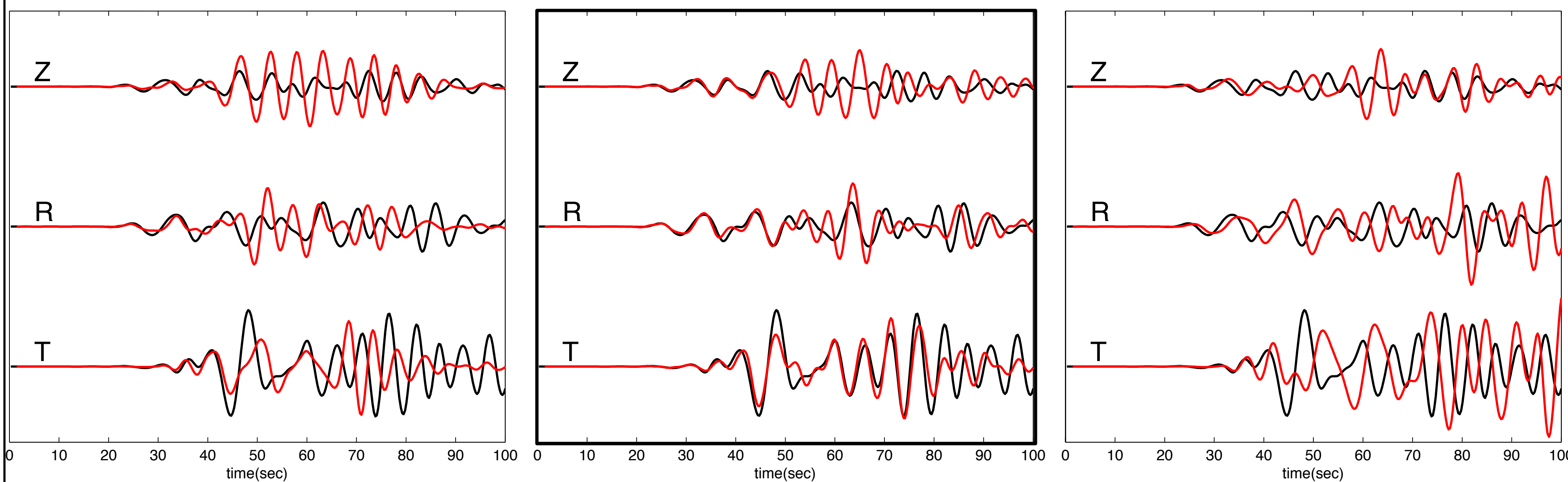
03/28/14 La Habra Earthquake (M5.1)

Station MOP
Observed in black
Synthetic in red

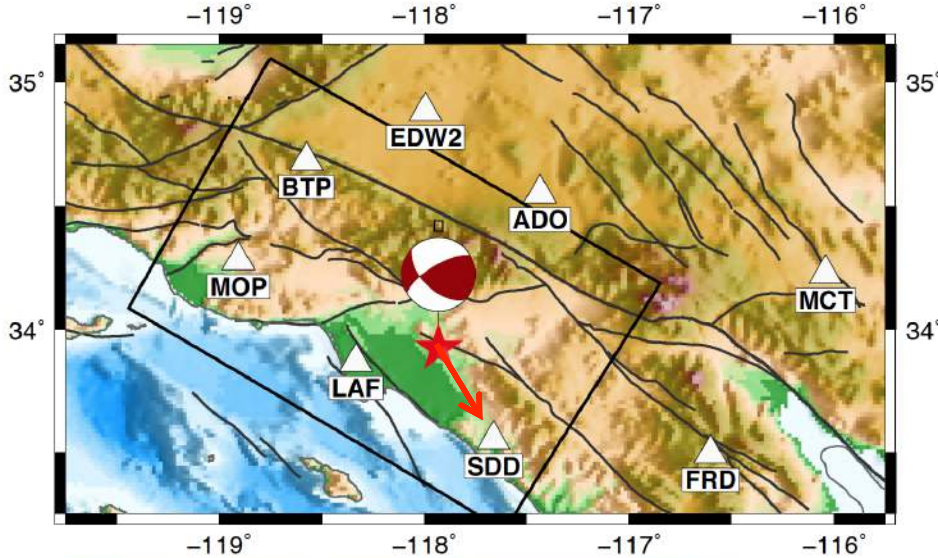


CS11: CVM-S4 | CS14.2: CVM-S4.26 | CS13.4: CVM-H11.9

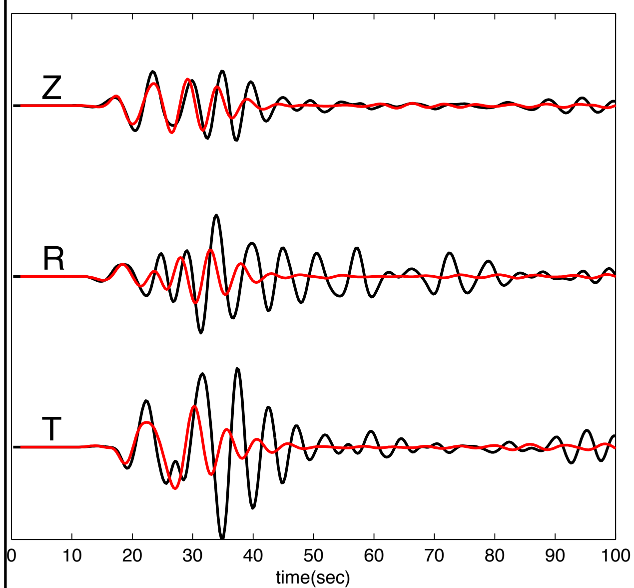


03/28/14 La Habra Earthquake (M5.1)

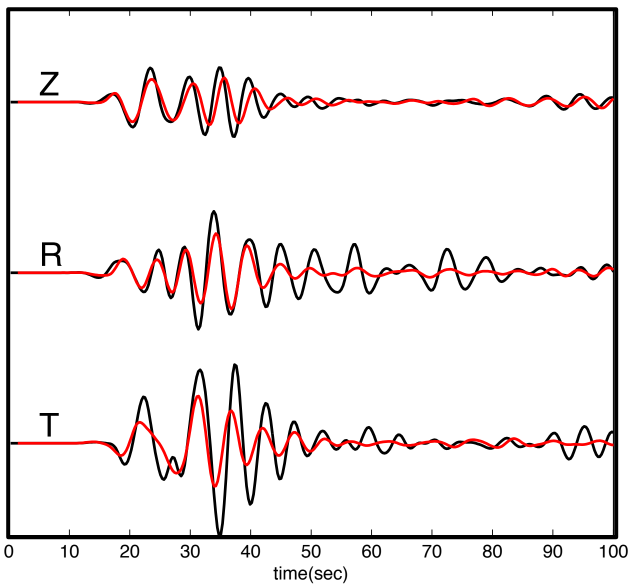
Station SDD
Observed in black
Synthetic in red



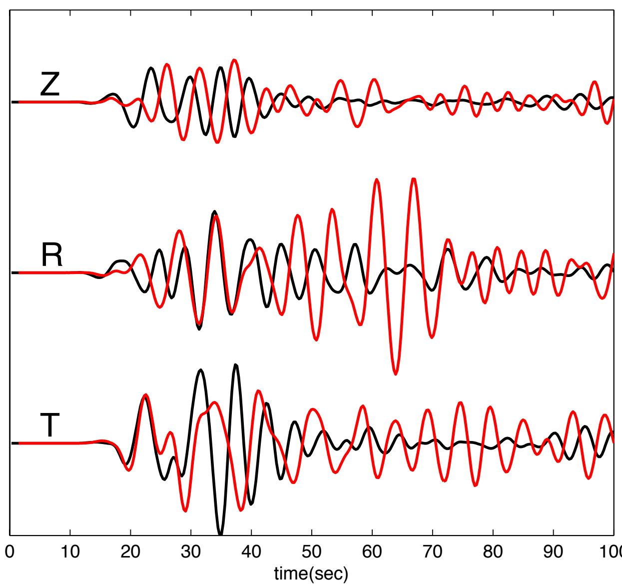
CS11: CVM-S4



CS14.2: CVM-S4.26



CS13.4: CVM-H11.9



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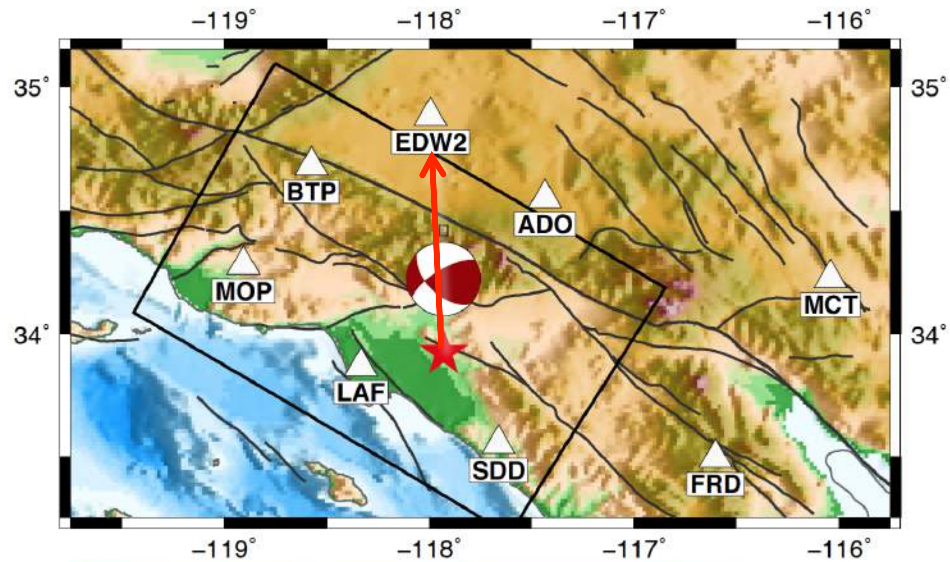
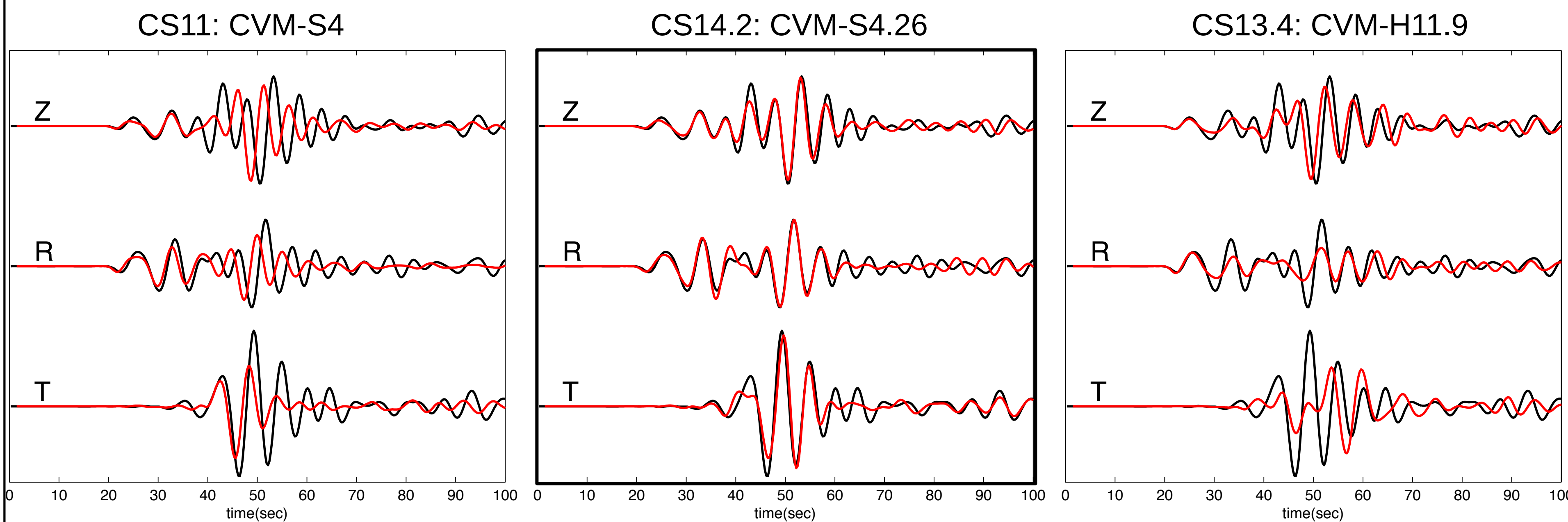
03/28/14 La Habra Earthquake (M5.1)

Station EDW2
Observed in black
Synthetic in red





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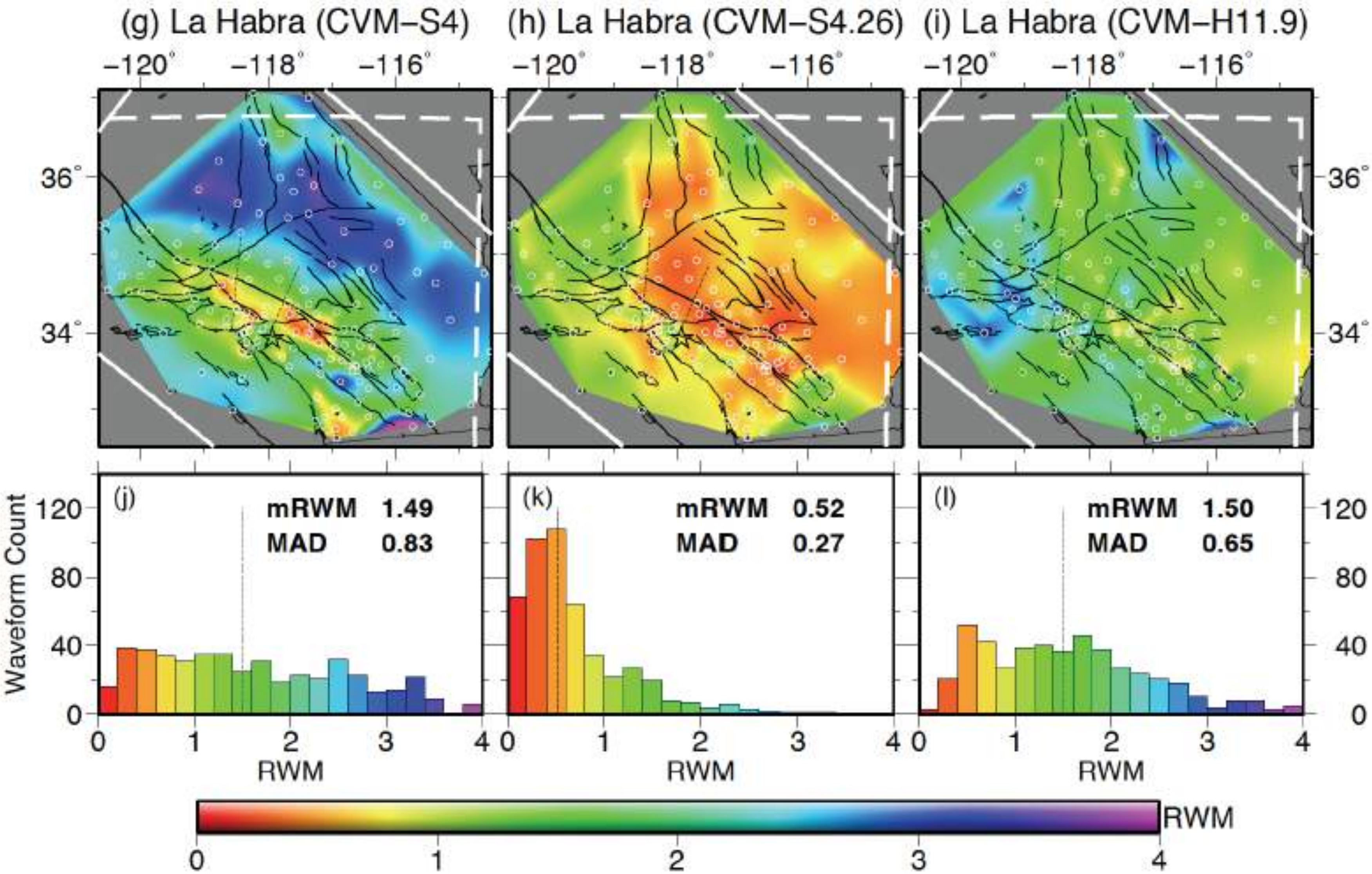
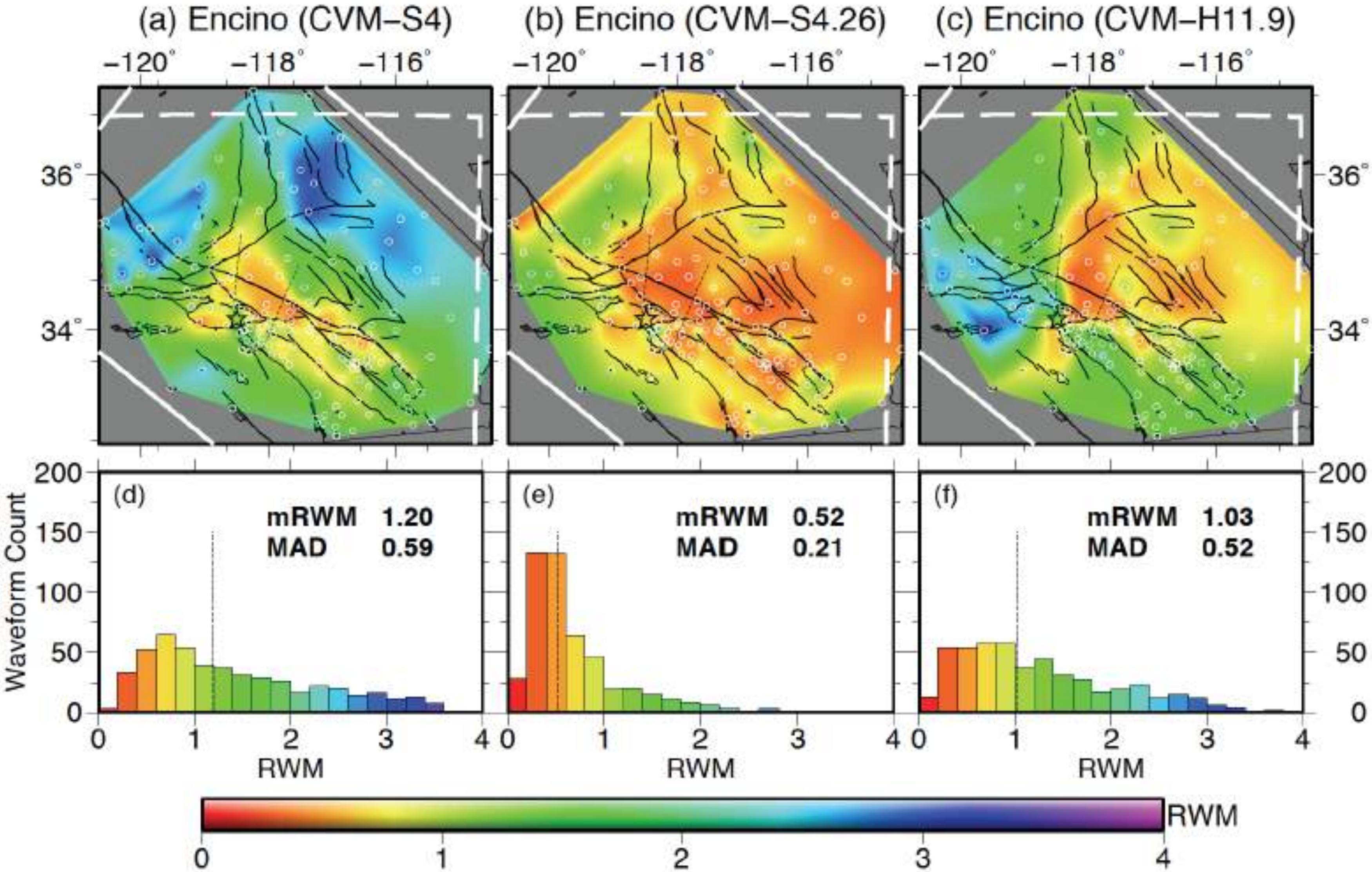
03/28/14 La Habra Earthquake (M5.1)

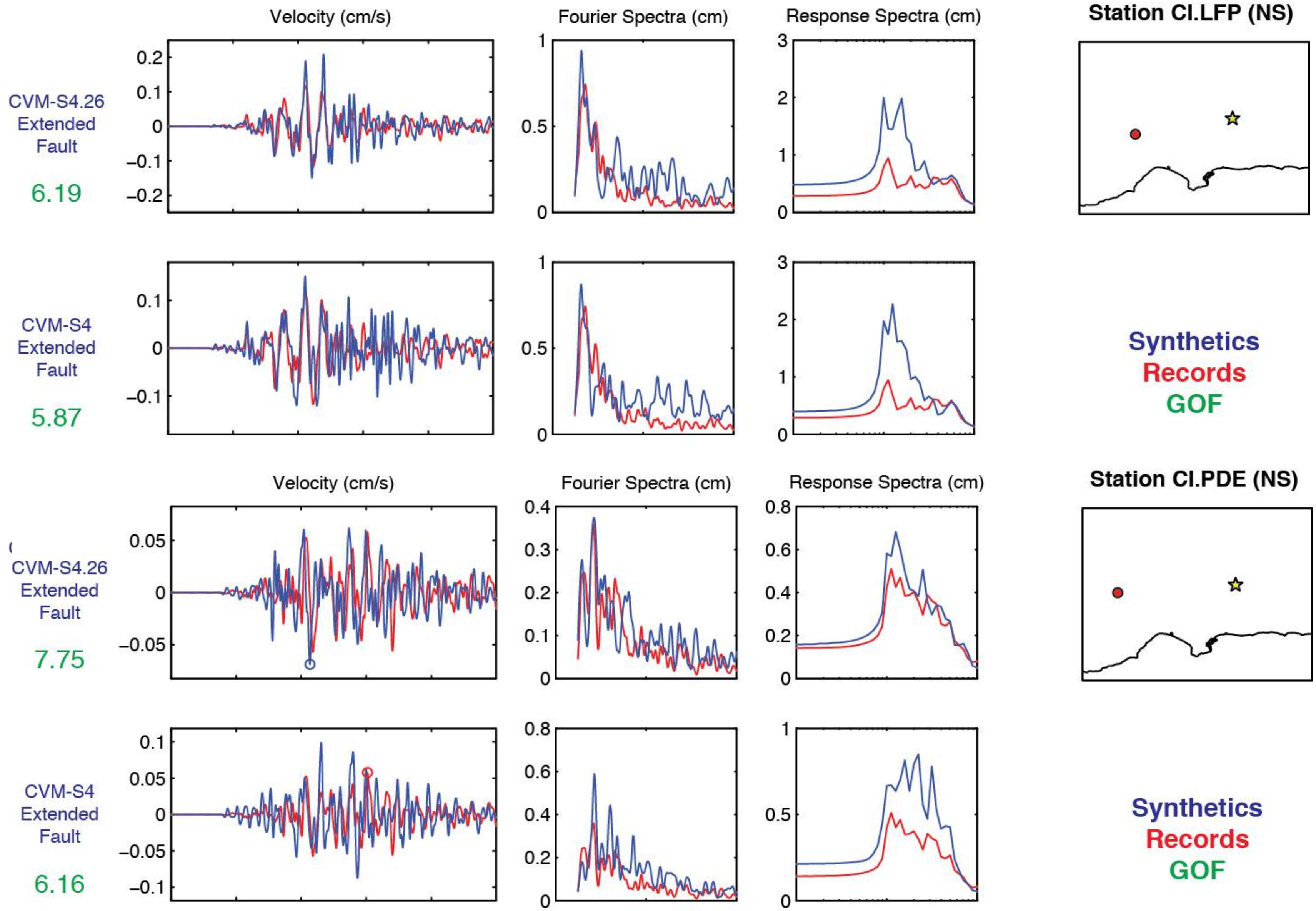


03/17/14 Encino Earthquake (M4.4)



03/18/14 La Habra Earthquake (M5.1)

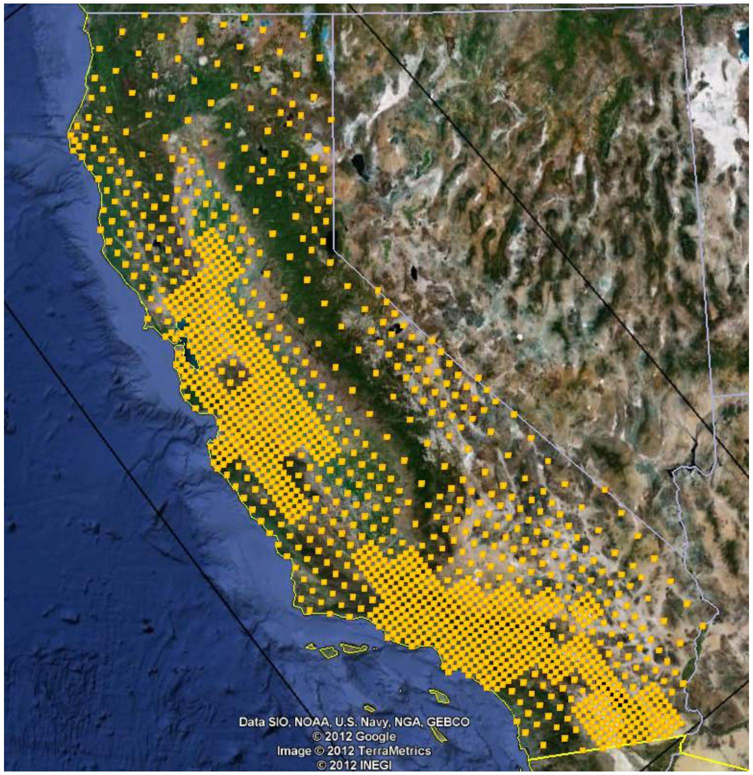
(Taborda et al., 2014)



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

Southern California Earthquake Center

- **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

End