Advances in Physics-Based Modeling of High-Frequency Ground Motions and Probabilistic Seismic Hazard Analysis Using Blue Waters

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SCEC
an NSF + USGS center

Southern California Earthquake Center (SCEC)

- Mission: solve problems in earthquake system science
  - Understanding and modeling the physics of earthquake processes, from tectonic stress to fault rupture to ground motions
  - Use SoCal as our natural laboratory
- Large collaborative center
  - Multi-disciplinary Planning Committee develops yearly science plan
  - Support fundamental AND applied science
  - Over 1,000 participants
  - 18 core institutions, 44 domestic participating institutions, 13 international
- NSF & USGS funded center
- Additional support from PG&E, W.M. Keck Foundation, NSF SSI programs

Seismic Risk = 3D (Deaths, Dollars, Downtime) =

Hazard × Exposure × Vulnerability ÷ Resilience

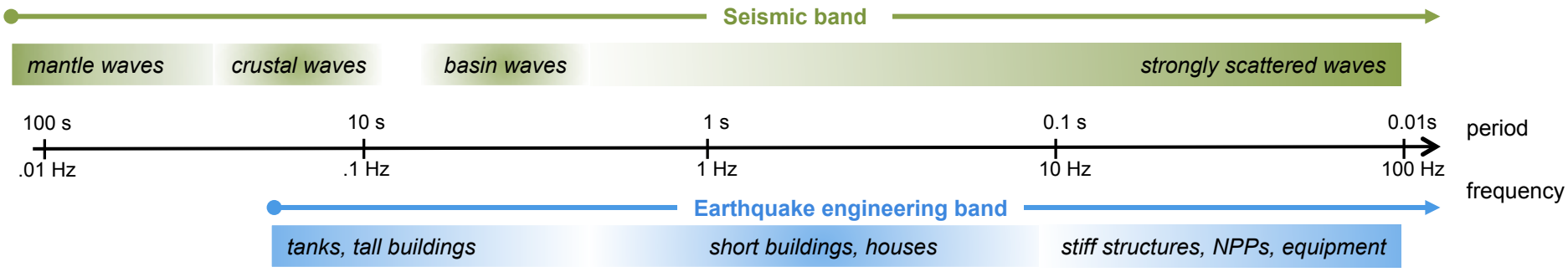
Faulting, shaking, tsunami, landsliding, liquefaction

Extent & density of built environment

Structural & nonstructural fragility

Response capabilities, insurance, cat bonds

Earthquake system science characterizes seismic hazards – key information for reducing risk and increasing resilience



Ground motion products for engineering

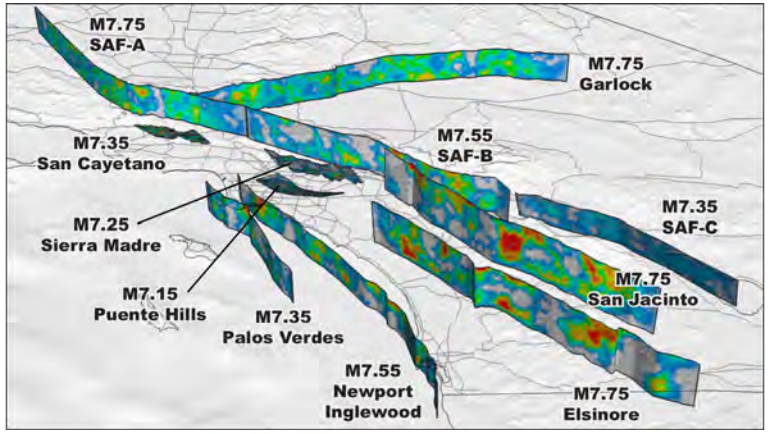
- Motivation
  - Limited data: magnitude, distance, bandwidth for scenarios that control design
- Solution
  - Simulate earthquakes and ground motions
- Still need to develop acceptance of simulations for engineering design applications
  - Extensive validation exercises help build confidence in simulated motions
  - Building code tall building sub-committee using CyberShake for next generation of code
  - USGS urban seismic hazard maps use CyberShake
  - New local (Diablo Canyon) and global (Western US, Central and Eastern US) empirical ground-motion models informed by simulations

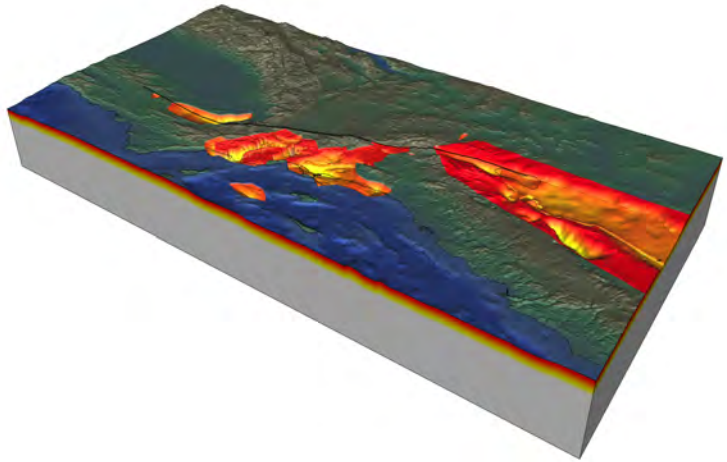
Essential ingredients for ground motion computations

1. **Earthquake source descriptions / rupture forcast (ERFs)**
   - detailed representation of fault geometry
   - rupture models that capture the complexities of dynamic fault failure

2. **Three-dimensional models of geologic structure**
   - large-scale crustal heterogeneity
   - sedimentary basin structure
   - geotechnical layer based on V_{S30}

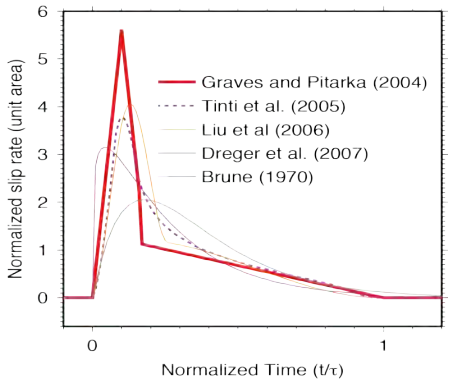
3. **Calculation of wave propagation and attenuation**
   - efficient anelastic wave propagation (AWP) codes
   - nonlinear models of near-surface response

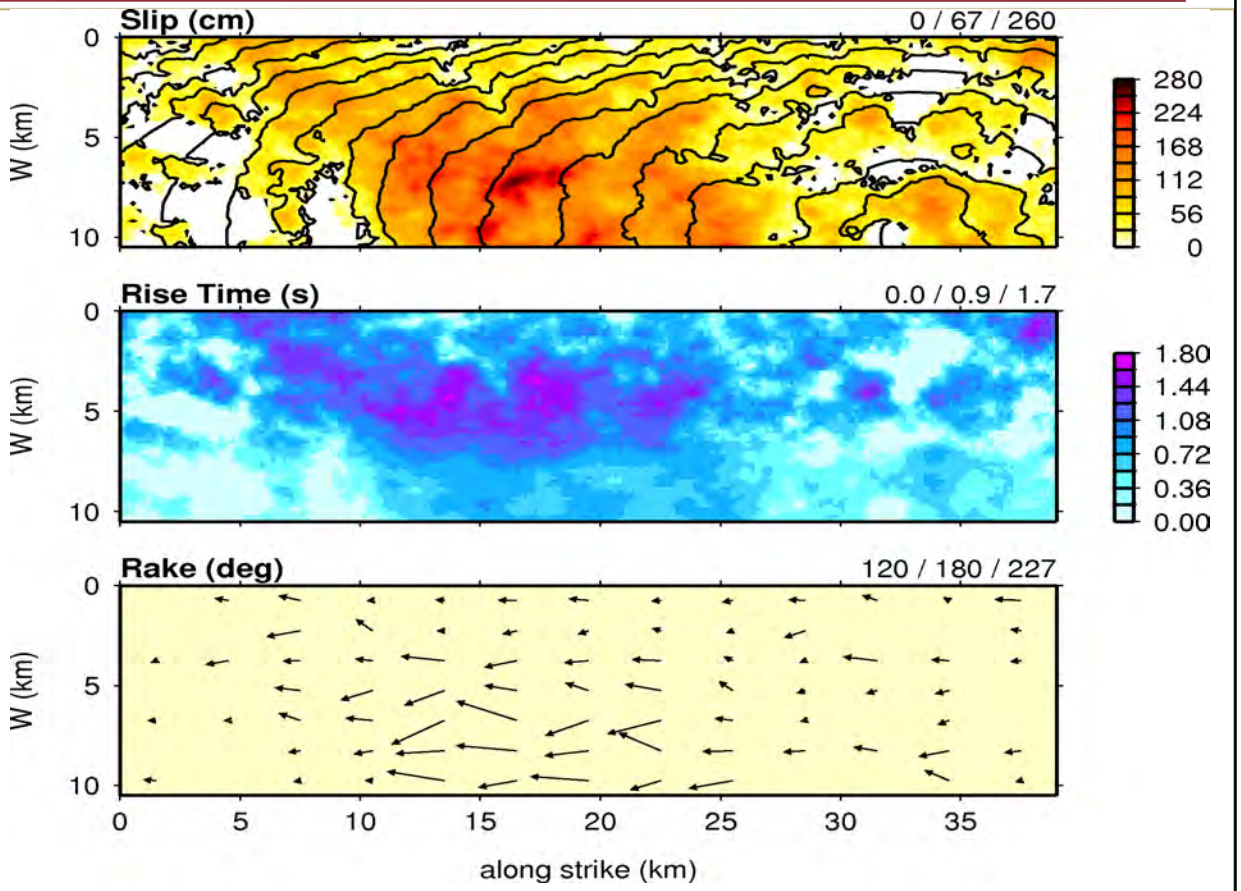




Source improvements
Graves and Pitarka rupture generator

- Unified scaling rules for rise time, rupture speed and corner frequency
- Depth scaling of rise time (increase) and rupture speed (decrease) required to model shallow (< 5 km) moment release





Graves and Pitarka 2016

Source improvements
Graves and Pitarka rupture generator

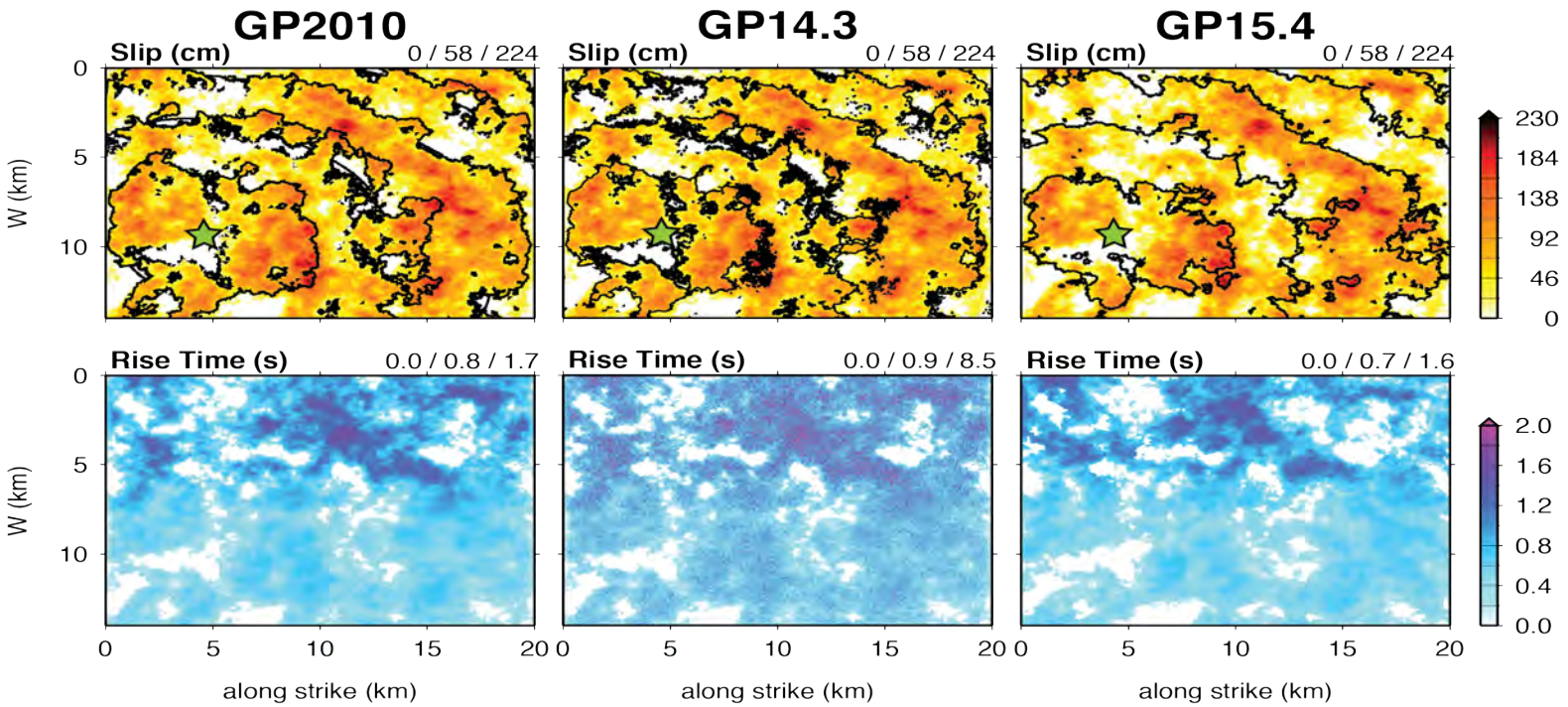
GP15.4 (Graves and Pitarka, 2016): Incorporate features to obtain better fit to data as the deterministic approach is pushed to higher frequencies.

- Relax correlation structure among slip, rupture speed, and rise time
- *Incorporate geometric complexities in fault surface*
- *Add stochastic 3D perturbations to velocity structure*
- *Incorporate near-fault low velocity region: "damage zone"*

Graves and Pitarka 2016

Can you see the differences?

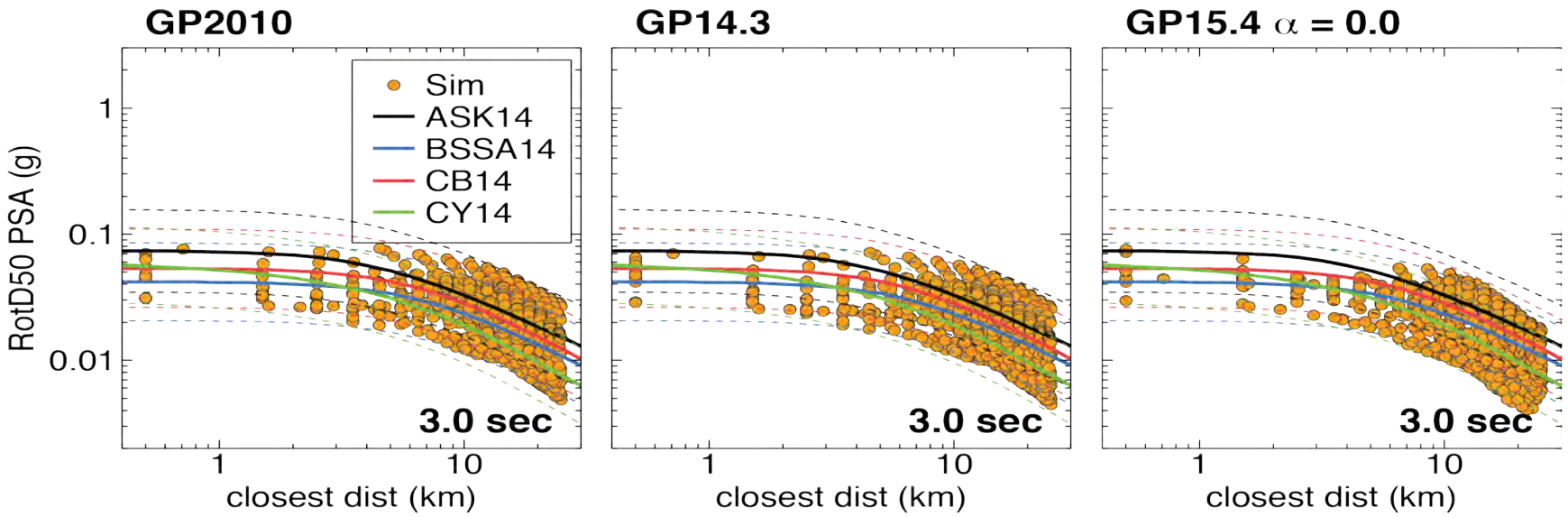
Slip distribution is the same in all models



Refinements are subtle in appearance, but lead to significant differences in radiated ground motions.

Graves and Pitarka 2016

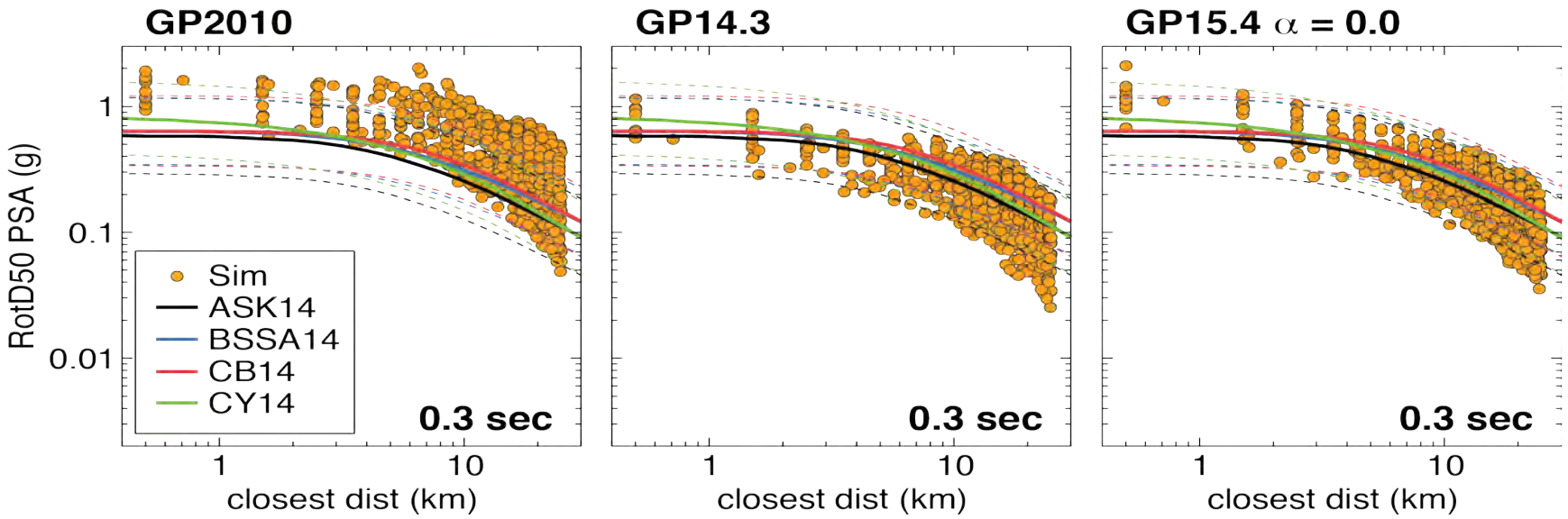
Can you see the differences?



At low frequencies (0.3 Hz), all models produce similar ground motion levels

Graves and Pitarka 2016

Can you see the differences?

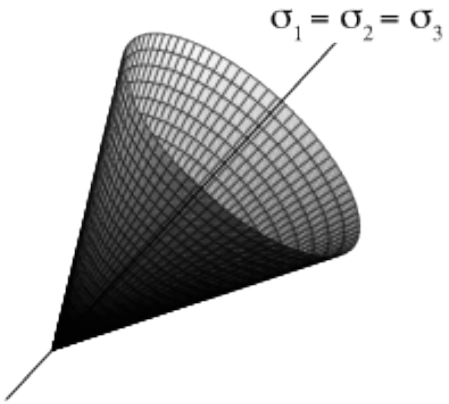


At higher frequencies (3.3 Hz), the coherence in GP2010 produces elevated ground motion levels.

Graves and Pitarka 2016

Including plasticity in near-fault material

3D Drucker-Prager plasticity with parameters from Hoek-Brown rock strength criterion include in AWP-ODC (GPU and CPU versions on BW)

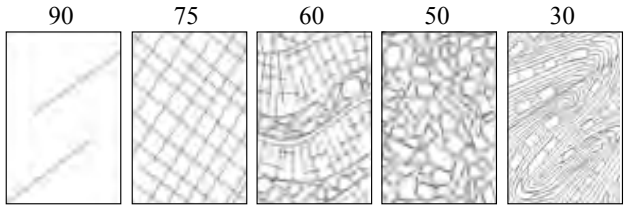


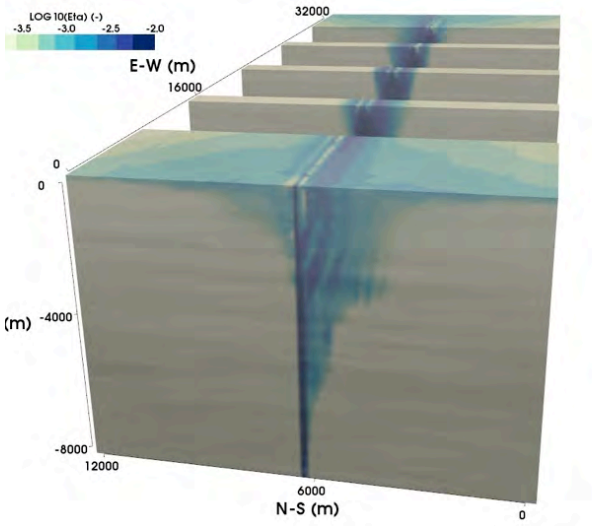
Roten et al. (2014, 2015, 2016)

m_i : tabulated by rock type, e.g.:
slate, shale, siltstone: $m_i \approx 7$
sandstones, breccias, conglomerates: $m_i \approx 17$
diorite, gabbro, granite: $m_i \approx 25$

σ_{ci} : tables with range of values by rock type
empirical equations (e.g., Chang, 2006)
descriptive grades (Brown, 1981), field estimates

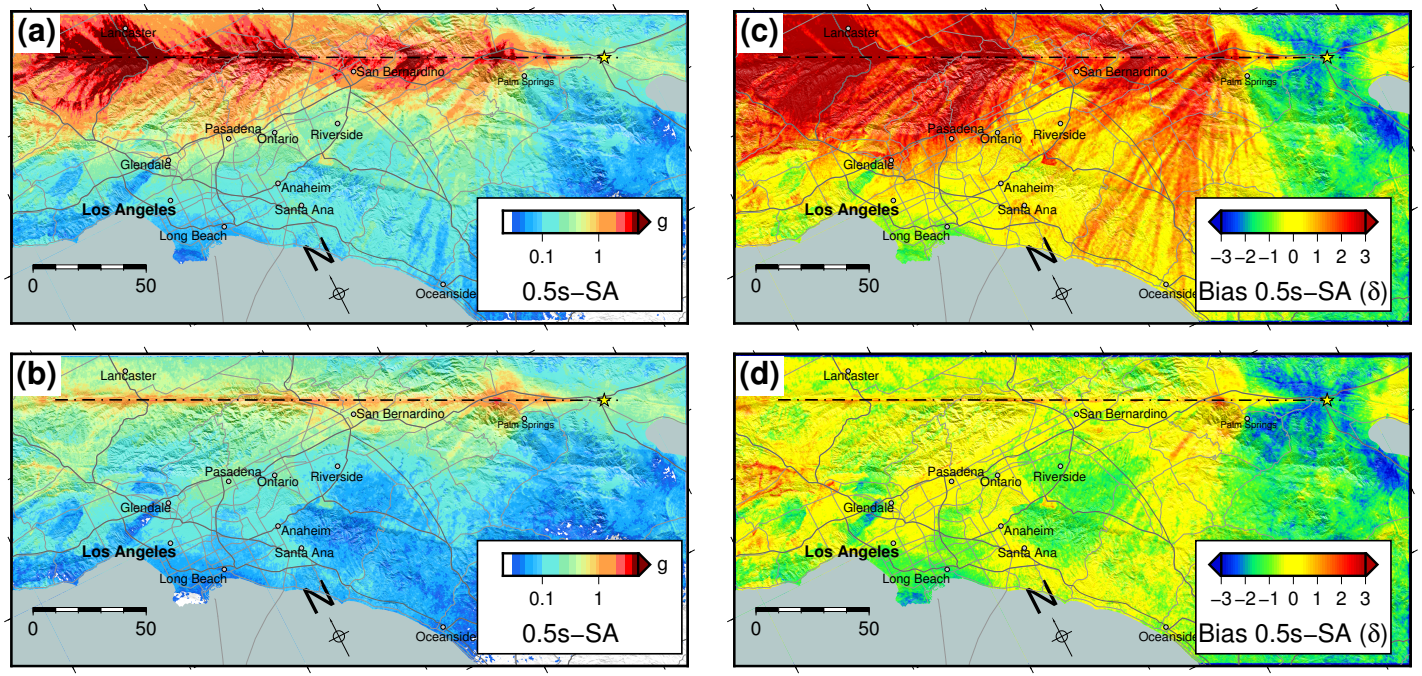
GSI: describes degree of fracturing and weathering
value (0 - 100) assigned based on charts
approximates 100 at large depth (> 1 km)





Roten et al. 2017

Including plasticity in near-fault material
4 Hz M7.7 San Andreas simulation



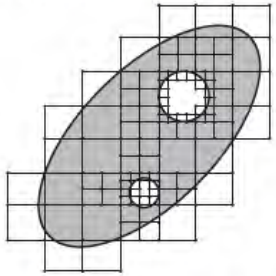
Orientation-independent spectral accelerations (SA) at 0.5 s (2 Hz) obtained from (a) linear and (b) nonlinear simulation of a M 7.7 earthquake on the southern San Andreas Fault, and bias between simulated 0.5s-SAs and the mean value predicted by the BSSA14 ground motion prediction equation for the linear (c) and nonlinear (d) model.

Roten et al. 2017

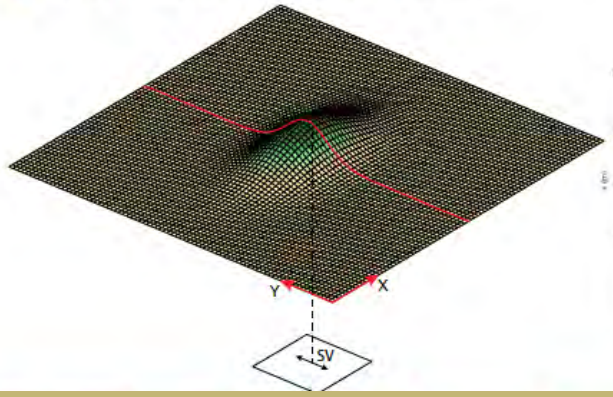
Effects of topography on ground motions

"Virtual topography" sensitivity studies using Hercules

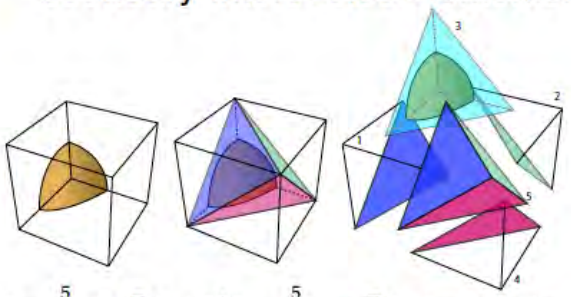
- Fictitious domain mesh following an unstructured octree approach.



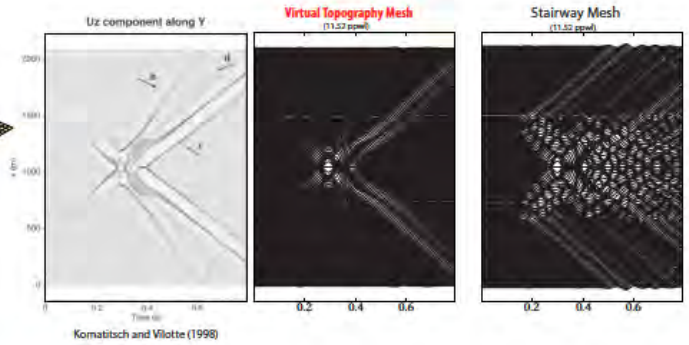
- Solve: $\mathbf{M\ddot{u} + C\dot{u} + Ku = f}$



- Cube to tetrahedra partition on boundary-intersected elements.

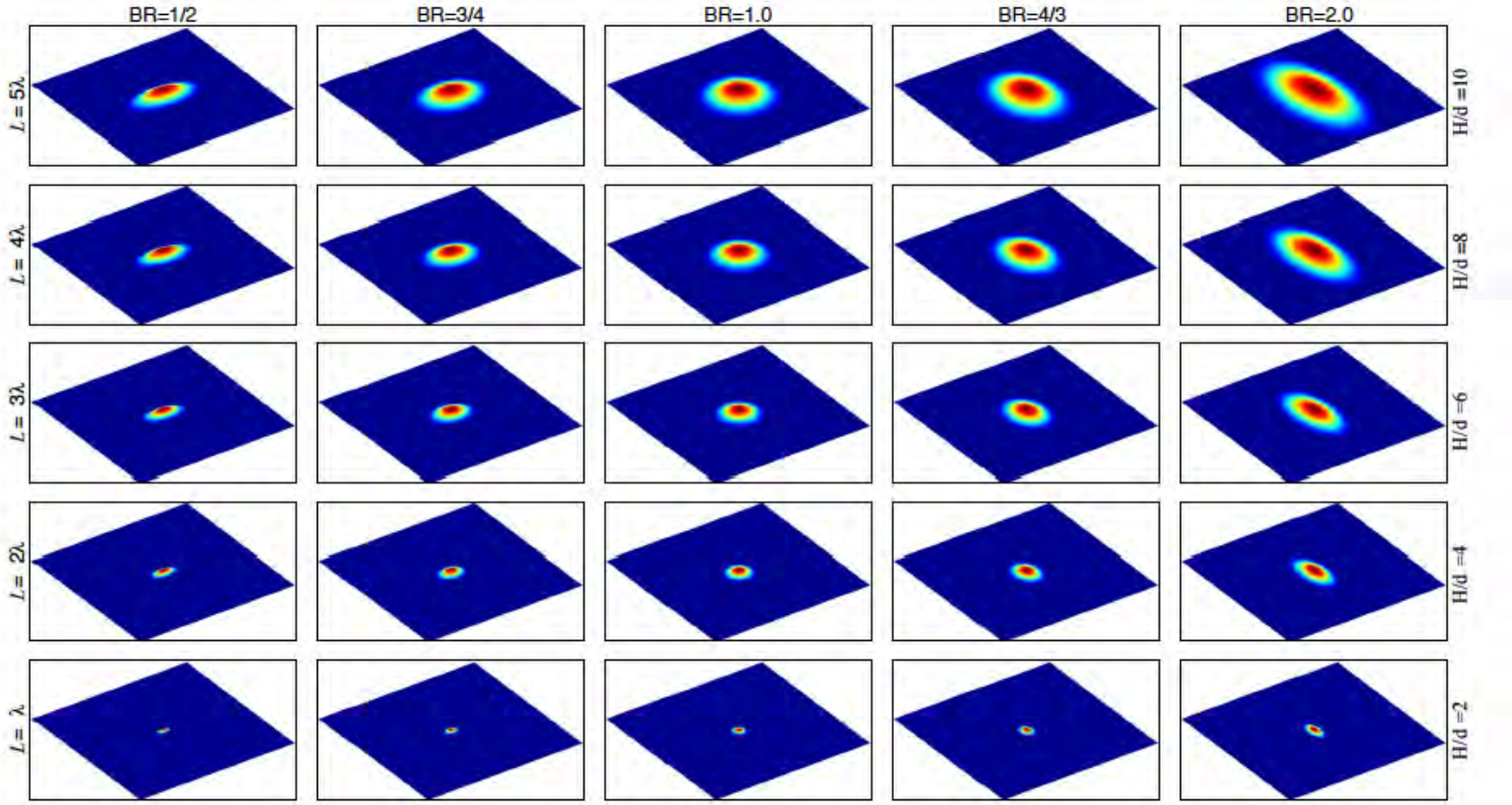


$$\mathbf{k}^{\mathbf{cube}} = \sum_{n=1}^{5} \phi_i \mathbf{k}_\mathbf{i}^{\mathbf{Tetr}},\ \mathbf{m}^{\mathbf{cube}} = \sum_{n=1}^{5} \phi_i \mathbf{m}_\mathbf{i}^{\mathbf{Tetr}},\ \phi_i = \text{void ratio}$$



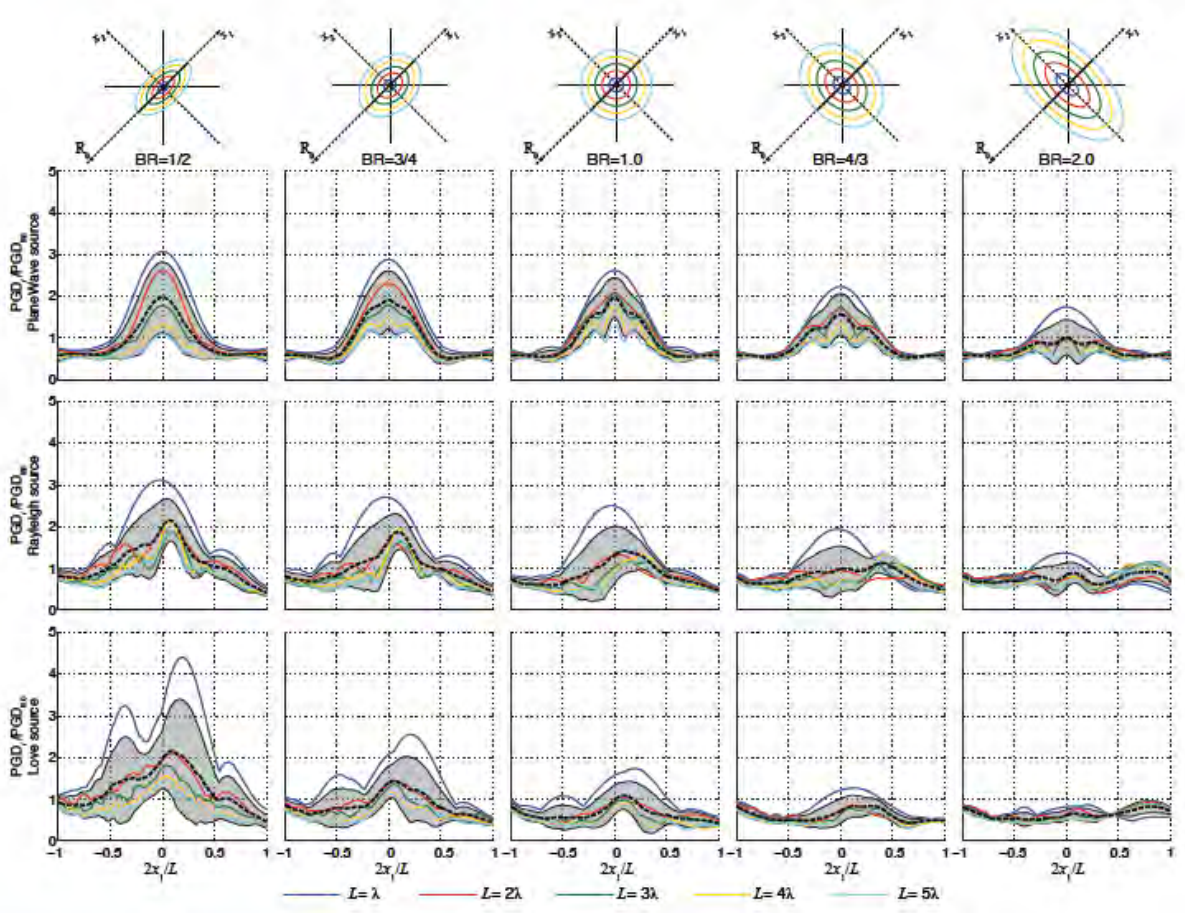
Riano et al. 2016

Effects of topography on ground motions



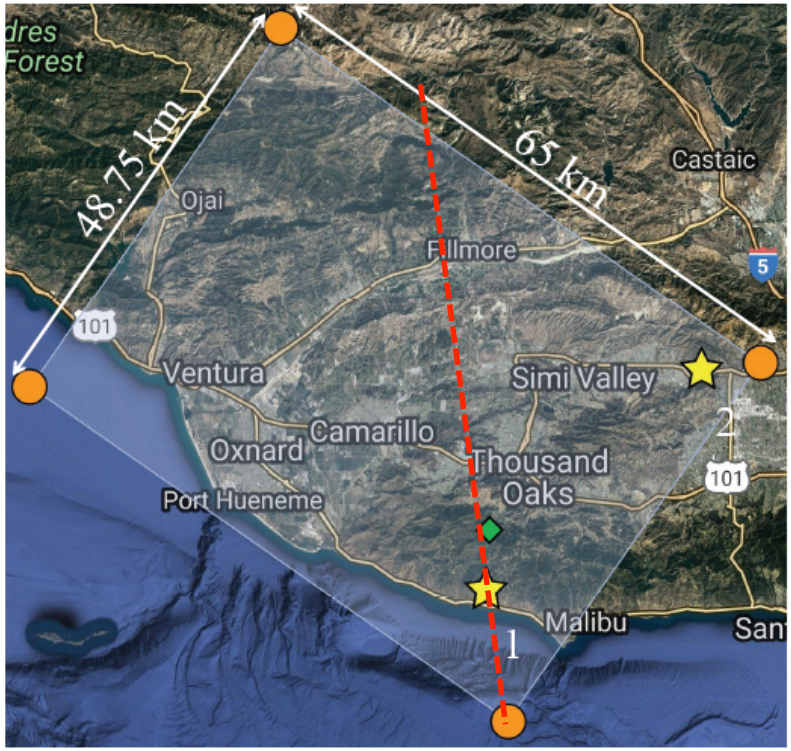
Riano et al. 2016

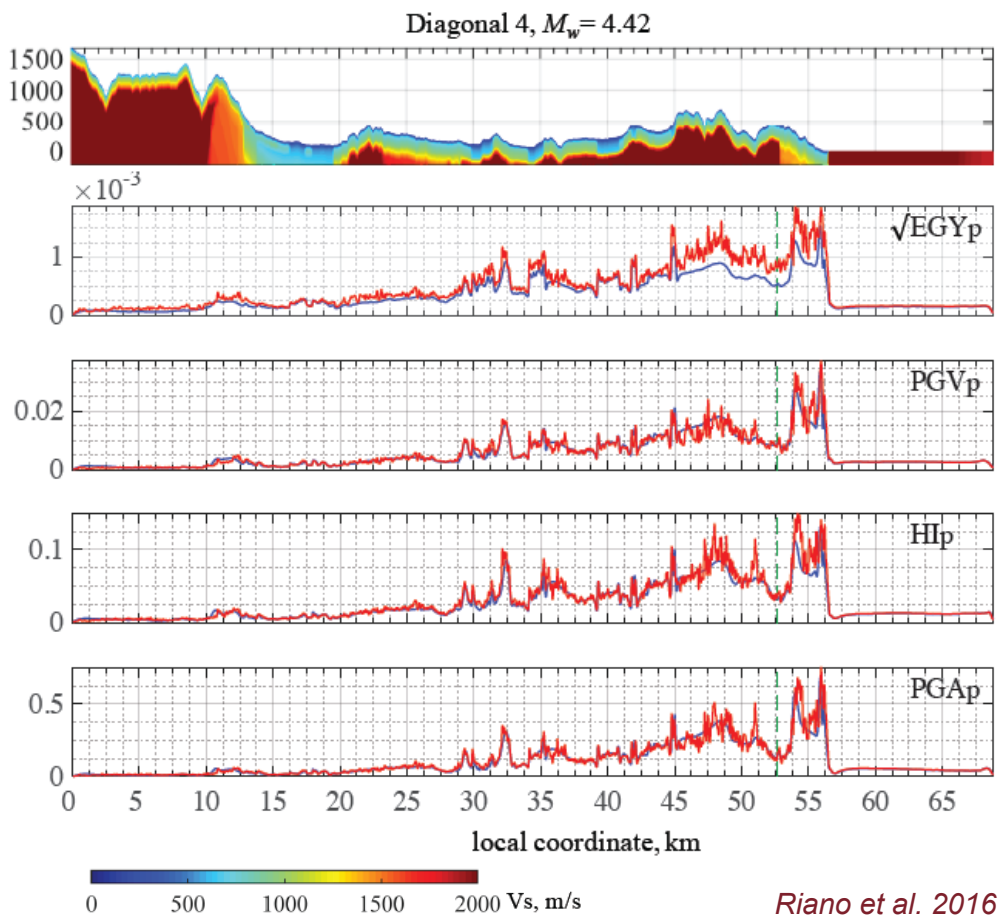
Effects of topography on ground motions



Riano et al. 2016

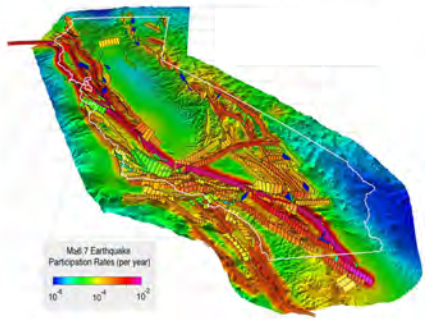
Effects of topography on ground motions





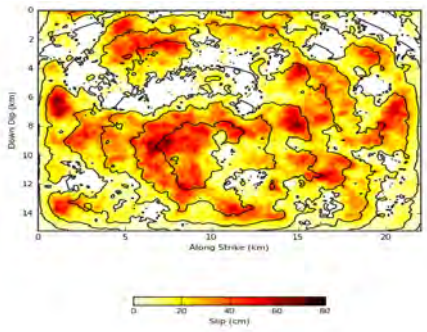
Riano et al. 2016

CyberShake: PSHA from Physics-Based Simulations



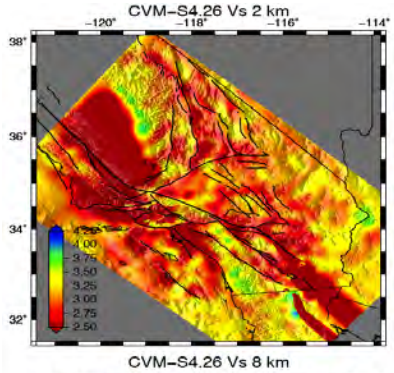
Earthquake Rupture Forecast
(e.g. UCERF)

+



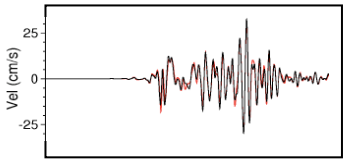
Kinematic source models

+

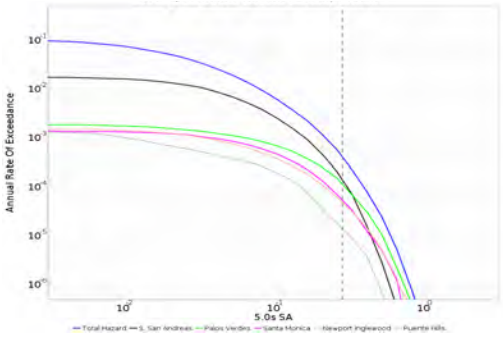


3D velocity model and wave
propagation code

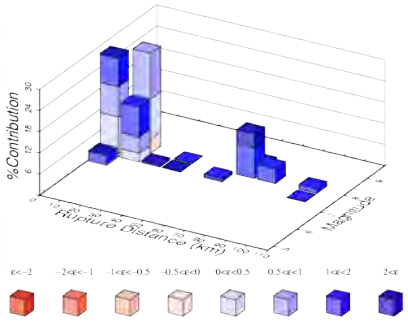
=



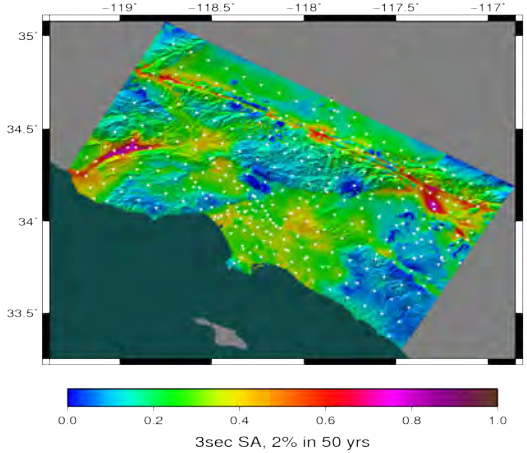
Seismograms
and intensity measures



Hazard Curves and
fault disaggregation



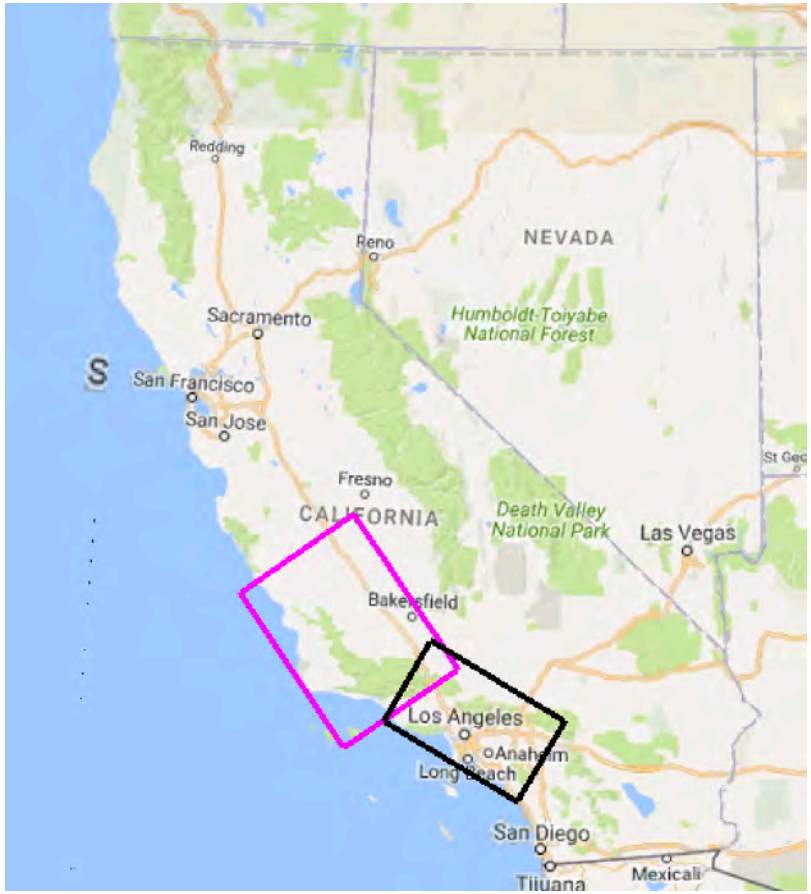
M, R, ε
disaggregation



Hazard maps

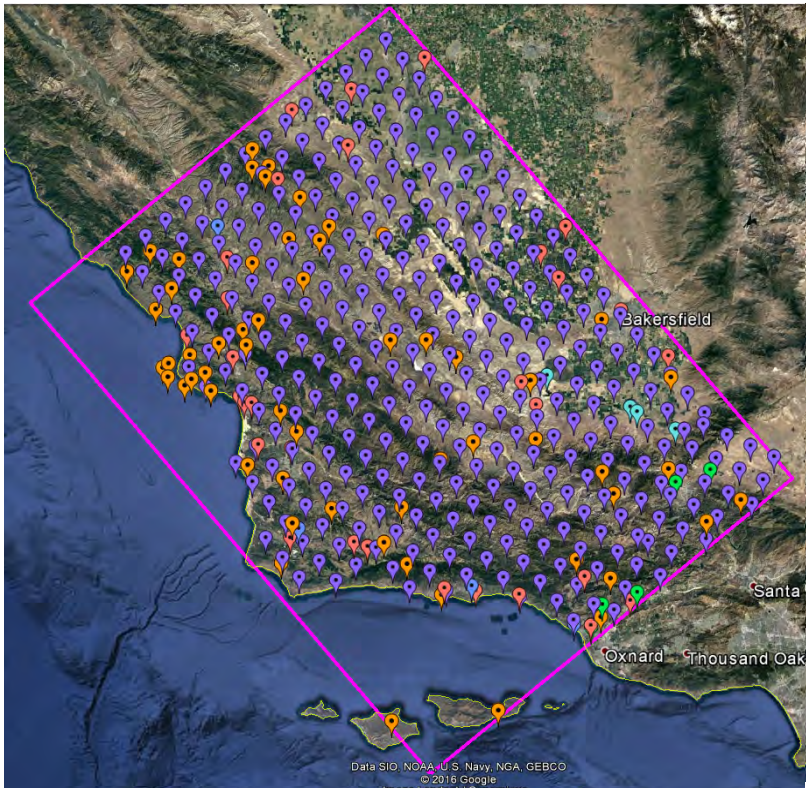
CyberShake Central California

- Proof-of-concept for expanding CyberShake to new regions
- Twice the size of CyberShake Southern California



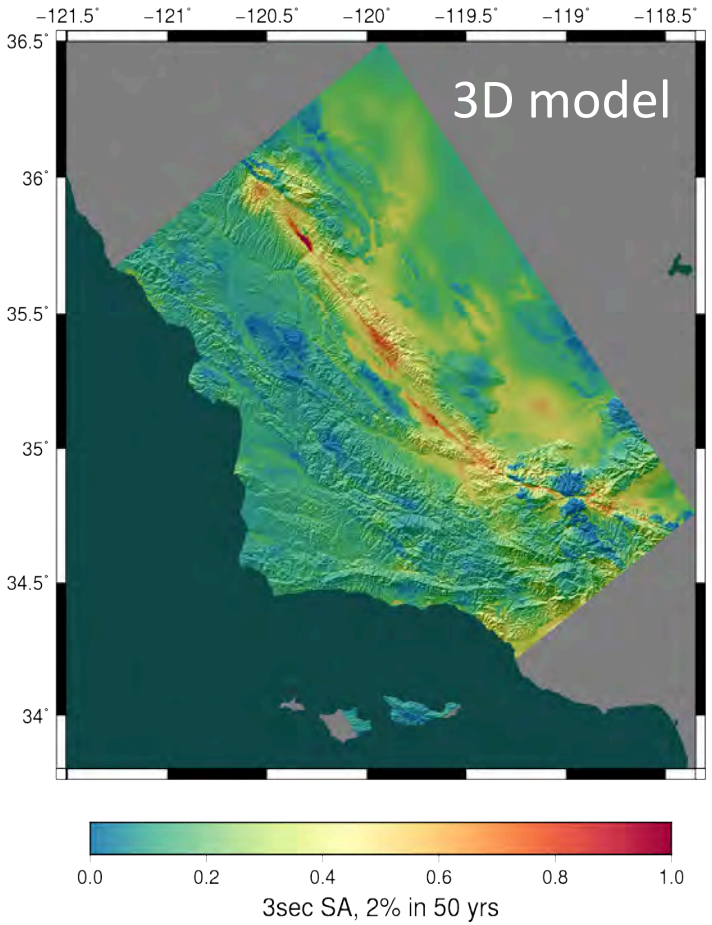
CyberShake Central California

- Proof-of-concept for expanding CyberShake to new regions
- Twice the size of CyberShake Southern California
- 438 locations
  - CISN stations
  - Water pumping sites
  - Cities from USGS Gazetteer
  - Historic missions
  - Regular grid for interpolation

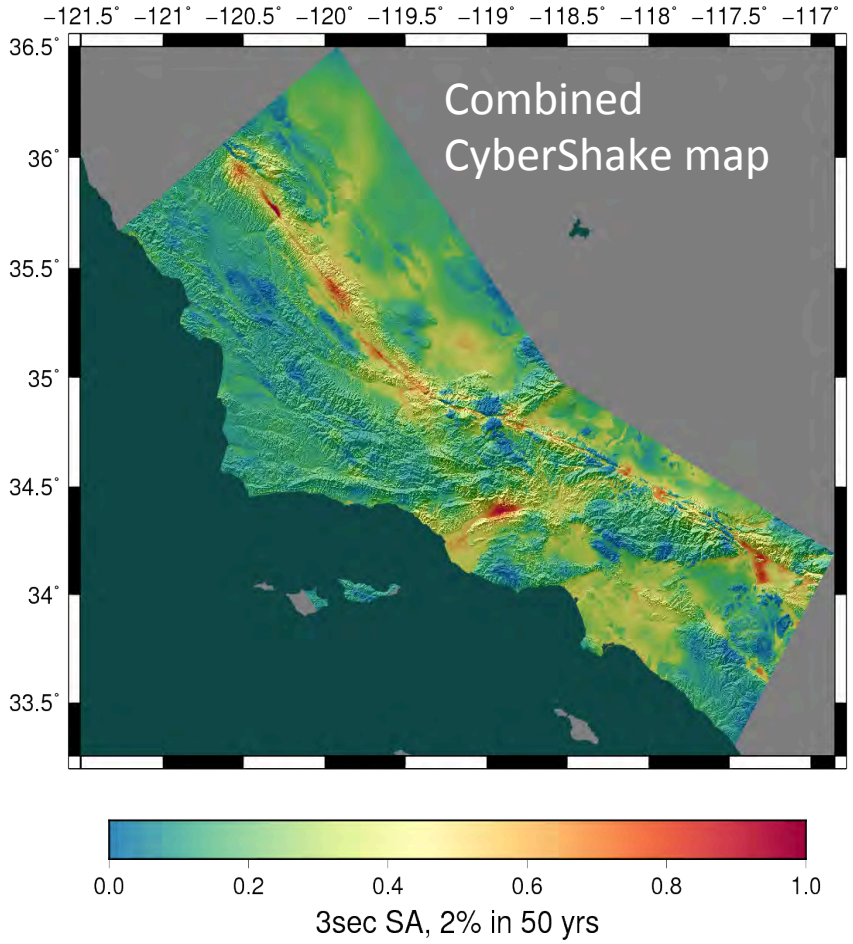


CyberShake Study 17.3

- Calculations for 2 velocity models for each of 438 sites, 1 Hz simulations, 40,000+ earthquakes
- Used OLCF Titan and NCSA Blue Waters
  - Averaged 1295 nodes (CPU + GPU) for 31 days, maximum of 5374
  - 900,000 node-hours consumed (21.6M core-hours)
  - Pegasus, HTCondor, Globus used for workflows
  - Workflow tools scheduled 15,581 jobs to both systems
  - Transferred 308 TB of intermediate data between the two systems
- Generated 285 million two-component seismograms
  - 43 billion intensity measures
- Workflow tools managed 777 TB of data
  - 10.7 TB of output data automatically staged back for archival storage



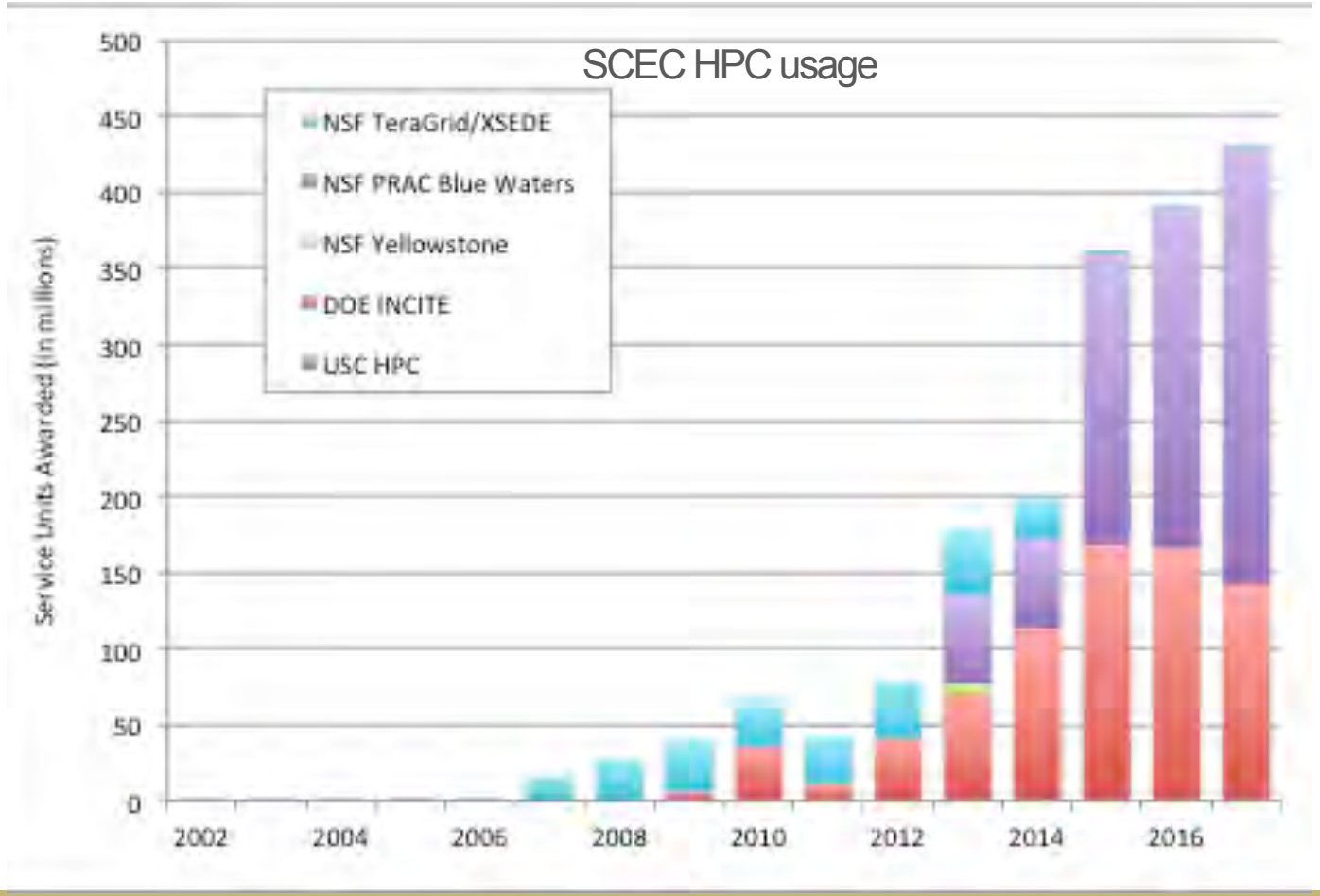
CyberShake Study 17.3 Results: CCA and LA



Tremendous scientific and societal impacts from Blue Waters allocations

- Better understanding and data fits by including complex physics
- Development of CyberShake as state-of-the-art PSHA tool
- Extensive validation exercises help build confidence in simulated motions for engineering applications

Thank you!


SCEC HPC usage
NSF TeraGrid/XSEDE
NSF PRAC Blue Waters
NSF Yellowstone
DOE INCITE
USC HPC
Service Units Awarded (in millions)
500
450
400
350
300
250
200
150
100
50
0
2002
2004
2006
2008
2010
2012
2014
2016

References

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- Roten,D., Y. Cui, K. Olsen, S. Day, K. Withers, W. Savran, W. Peng, and D. Mu. High-frequency nonlinear earthquake simulations on petascale heterogeneous supercomputers. In 2016 ACM/IEEE International Conference for High Performance Computing, Networking, Storage and Analysis (SC'16), November 13-18 2016, Salt Lake City, UT, 2016.

- Roten, D., Olsen, K. B., Day, S. M., and Cui, Y. Quantification of Fault-Zone Plasticity Effects with Spontaneous Rupture Simulations, Pure and Applied Geophysics, 1-23, 2017, doi:10.1007/s00024-017-1466-5.