SOUTHERN CALIFORNIA EARTHQUAKE CENTER

Using Multi-scale Dynamic Rupture Models to Improve Ground Motion Estimates

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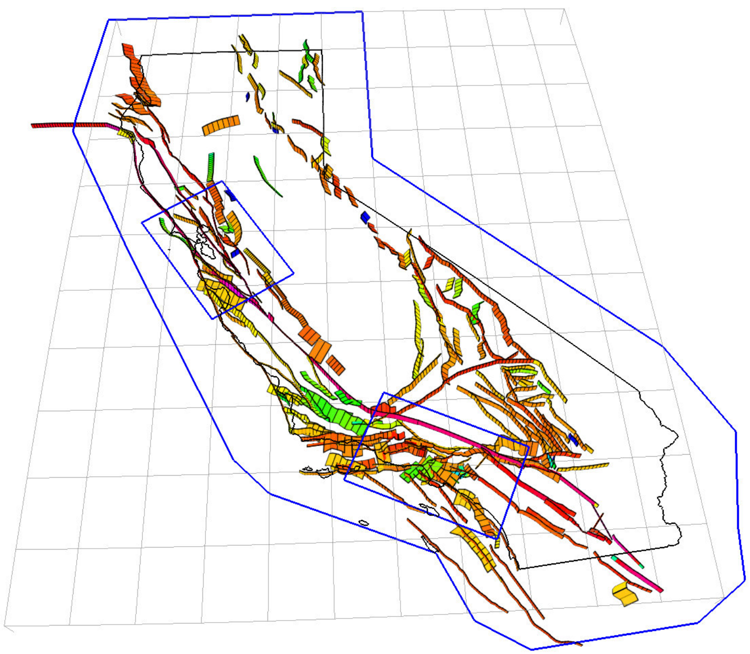
Information Technology Architect

Southern California Earthquake Center

ALCF Early Science Program Workshop

15-16 May 2012



SCEC

an NSF+USGS center

Acknowledgements

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- Computing resources are from ALCF Mira, ALCF Intrepid, ALCF Vesta, NCCS Jaguar, NCCS Titan, NICS Kraken, TACC Ranger, TACC Stampede, NCAR Yellowstone, USC HPCC
- Following contributed to the project:
  - ALCF: Geoffrey Ely, Charles Bacon, Katherine Riley, James Osborn, Robert Latham
  - SCEC: Thomas Jordan, Scott Callaghan, Kevin Milner, David Gill
  - SDSU: Kim Olsen, Daniel Roten, Steve Day, Luis Angle Dalguer
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  - OSU: DK Panda, Sreeram Porluri, Karen Tomko, Ping Lai
  - CMU: Jacobo Bielak, Ricardo Taborda, Tim Kasier, Zizhong Chen
  - Cray: John Levesque
  - NCCS: Trey White

Topics

- About the Southern California Earthquake Center
- Ground Motion Modeling Essentials
- Velocity Model Developments
- Dynamic Rupture Model Developments
- Wave Propagation Model Developments
- Probabilistic Hazard Estimates Developments
- Conclusions

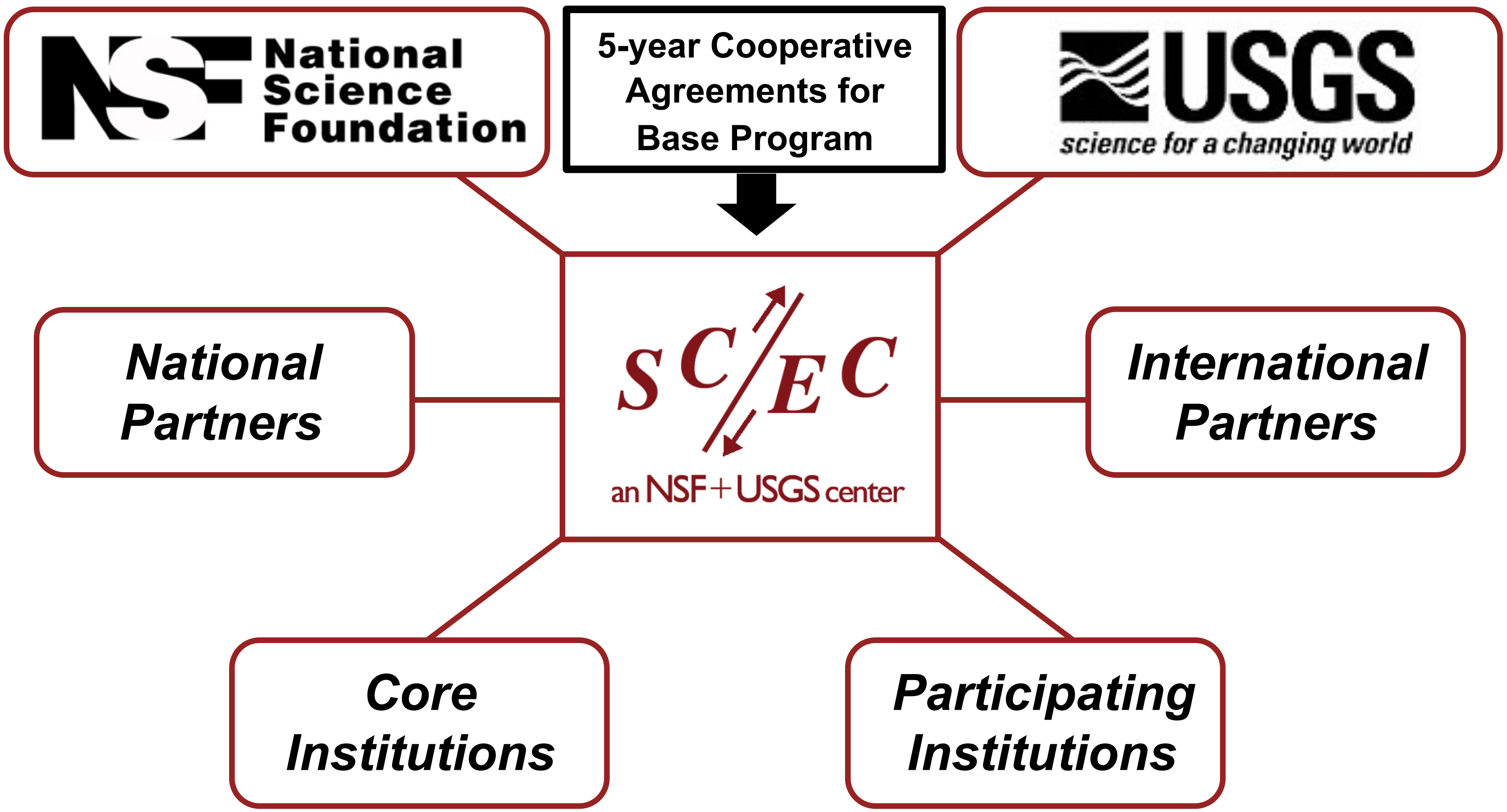
SCEC Member Institutions (Sept 1, 2011)

Core Institutions (17)	Participating Institutions (57)
California Geological Survey California Institute of Technology Columbia University Harvard University Massachusetts Institute of Technology San Diego State University Stanford University U.S. Geological Survey, Golden U.S. Geological Survey, Menlo Park U.S. Geological Survey, Pasadena University of California, Los Angeles University of California, Riverside University of California, San Diego University of California, Santa Barbara University of California, Santa Cruz University of Nevada, Reno University of Southern California (lead)	Appalachian State University; Arizona State University; Berkeley Geochron Center; Boston University; Brown University; Cal-Poly, Pomona; Cal-State, Chico; Cal-State, Long Beach; Cal-State, Fullerton; Cal-State, Northridge; Cal-State, San Bernardino; Carnegie Mellon University; Case Western Reserve University; CICESE (Mexico); Cornell University; Disaster Prevention Research Institute, Kyoto University (Japan); ETH (Switzerland); Georgia Tech; Institute of Earth Sciences of Academia Sinica (Taiwan); Earthquake Research Institute, University of Tokyo (Japan); Indiana University; Institute of Geological and Nuclear Sciences (New Zealand); Jet Propulsion Laboratory; Los Alamos National Laboratory; Lawrence Livermore National Laboratory; National Taiwan University (Taiwan); National Central University (Taiwan); Ohio State University; Oregon State University; Pennsylvania State University; Princeton University; Purdue University; SUNY at Stony Brook; Texas A&M University; **University of Alaska**; University of Arizona; UC, Berkeley; UC, Davis; UC, Irvine; University of British Columbia (Canada); University of Cincinnati; University of Colorado; University of Illinois; University of Massachusetts; University of Miami; University of Missouri-Columbia; University of New Hampshire; University of Oklahoma; University of Oregon; University of Texas-El Paso; University of Utah; University of Western Ontario (Canada); University of Wisconsin; University of Wyoming; URS Corporation; Utah State University; Woods Hole Oceanographic Institution

Proposed new SCEC4 Core Institution:

CalState Consortium

The SCEC Partnership



SCEC Mission Statement

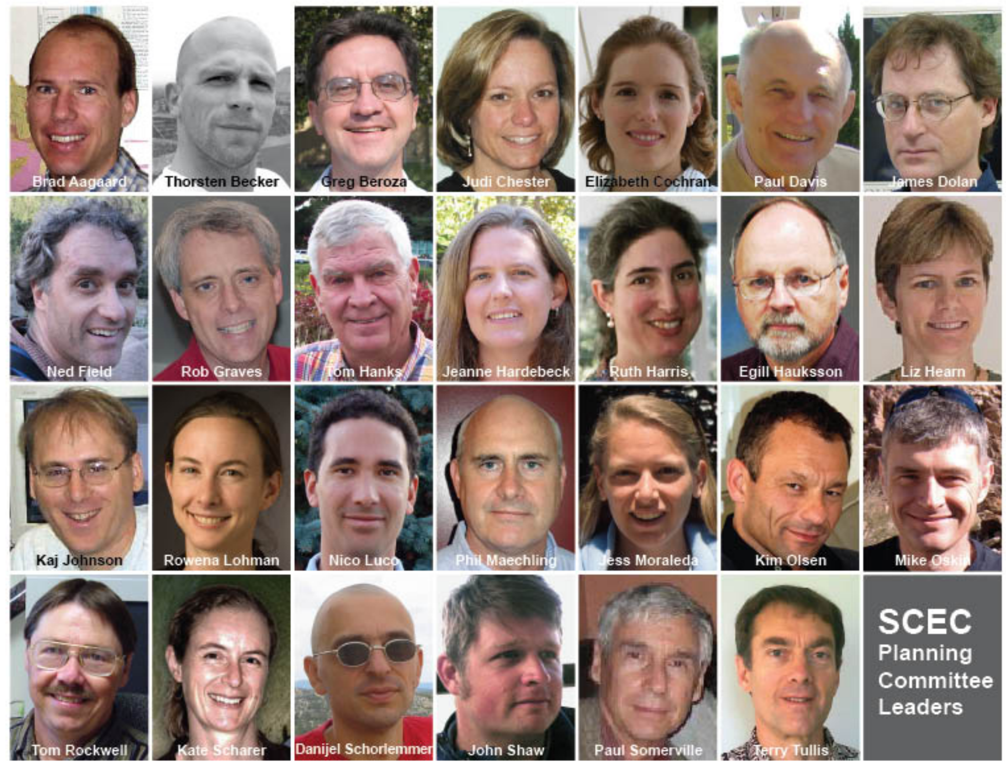
- **Gather data** on earthquakes in Southern California and elsewhere
- **Integrate information** into a comprehensive, physics-based understanding of earthquake phenomena
- **Communicate understanding** to the world at large as useful knowledge for reducing earthquake risk

SCEC's Role in Open-Science Research

- SCEC bridges basic research (NSF) and operational (USGS) organizations.
  - SCEC Mission is to translate latest research results into use with public impact
  - Apply "best available science" to established seismic hazard data calculations.
- SCEC computational acience program integrates earth structural models, and improved computational codes to produce improved computational data products
  - New earth observations are used to improve structural models
  - Updated computational codes include more realistic physics
  - Each data product has its own verification and validation requirements

SCEC Leadership Teams

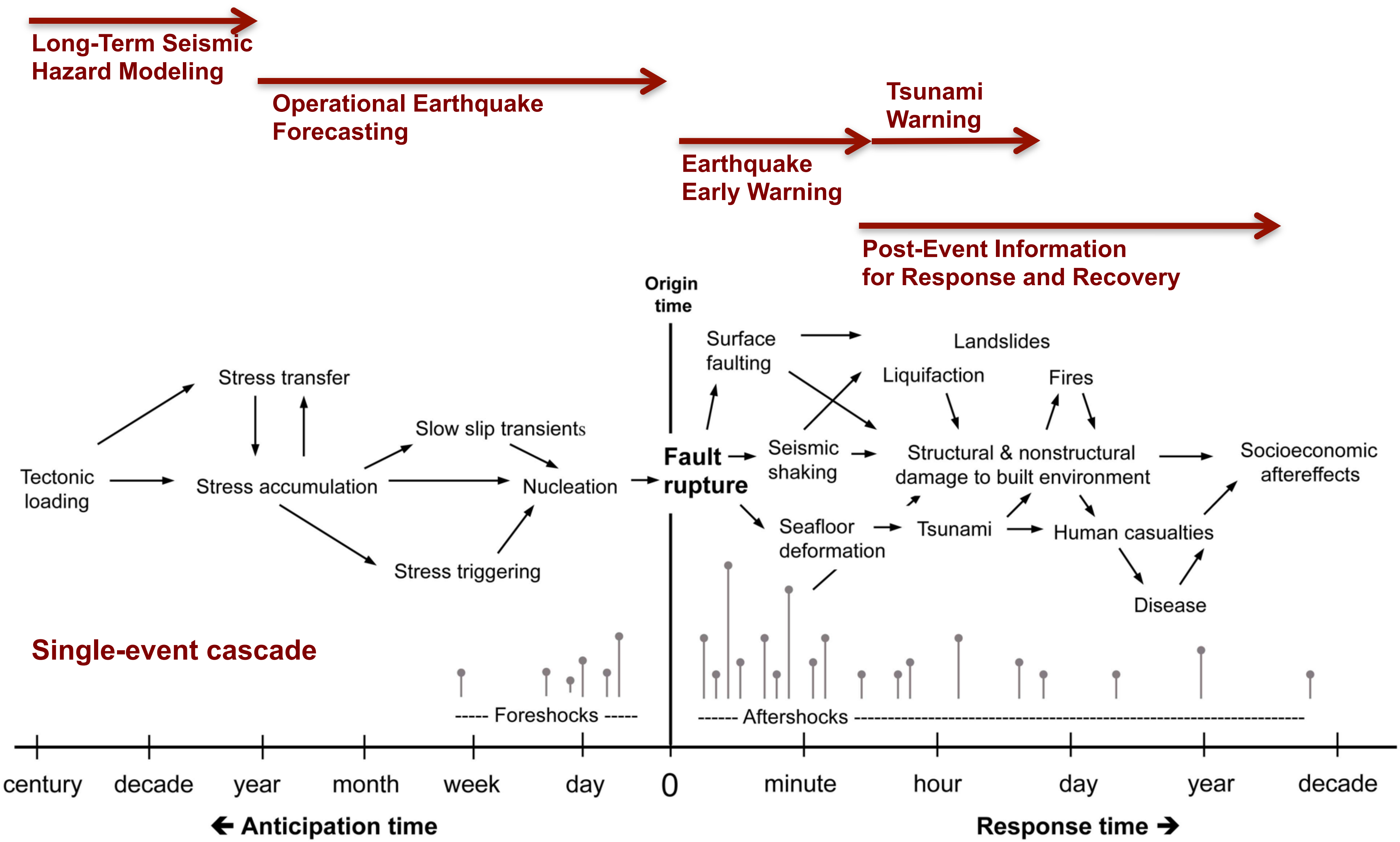
Board of Directors



Planning Committee

Staff

SCEC combines earthquake system science and computational science to improve broad impact seismic hazard computational data products across multiple time scales.



Earthquake System Science Predicts Ground Motions

SCEC's earthquake system science research program develops and improves predictive computational models of earthquake processes. Each computational data product represents an interface between seismology and external user groups. Data product improvements have potential broad impact. Each data product requires specialized computational tools and techniques.

- **Earthquake early warning ground motion alerts (Used by: Public in Japan, Mexico, Turkey)**
- **Scenario earthquake peak ground motion estimates (Used by: Emergency response planners, building engineers, insurance companies in loss estimates)**
- **Scenario broadband seismograms (Used by: Building engineers including energy production companies)**
- **Probabilistic forecast of peak ground motions in decades to centuries (Used by: Building code developers, insurance companies in loss estimates)**

Computational Science Challenges

As a computational science group, we acknowledge non-technical challenges we face. These may be shared with other groups at this meeting.

- Integration across science domains, across disciplines, across computational codes is our path forward, in opposition to a trend towards specialization.

- People and skills involved in projects extend beyond PI and post-doc roles into a larger eco-system that includes domain scientists, computer scientists, software developers, systems administrators, …

- As projects get larger, credit and visibility is harder to manage. Very difficult to credit the right people.

- Research activities are distributed among researchers, and resource providers. Harder to credit a specific machine for an advance.

ESP Meeting Topics

- Science enabled by ESP and access to Mira
- Status of completed and ongoing run campaigns
- Preliminary results

Research Advances Supported by ESP

1. Southern California CVM tomography improvements
2. Southern California CVM with small-scale heterogeneities to support 1Hz+ ground motion simulations
3. Tools for defining complex fault geometry meshes
4. Dynamic Rupture Code (SORD-Ely) ported to BG/Q
5. Dynamic Rupture Code (SORD-Ely) added OpenMP threading and communications techniques
6. Dynamic Rupture Code (SORD-Day) with plasticity
7. Dynamic Rutpure Code (SORD-Day) simulating 10Hz on rough faults
8. GPU Solvers simulating 10Hz ground motions

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Ground Motion Computational Modeling

Three essential elements for accurate ground motion predictions:

(1) Accurate 3D structural model of earth (geologically-based velocity model and fault models)

(2) Accurate representation of slip on a fault (earthquake source description) over time.

(3) Accurate wave propagation calculation including attenuation of ground motions with distance (wave propagation simulation software)

From Single Ground Motion Simulations to Ensembles

Individual ground motion simulations are used to verify and validate simulations.

- Currently, 1Hz deterministic ground motions simulations are near the state-of-art.
- Above this frequency stochastic simulations are used to add high frequencies.

Probabilistic seismic hazard anayslis (PSHA) studies require ensembles of ground motion simulations.

- PSHA studies may require hundreds of thousands ground motion simulations.
- PSHA studies are run for lower frequencies (e.g. 0.5Hz)

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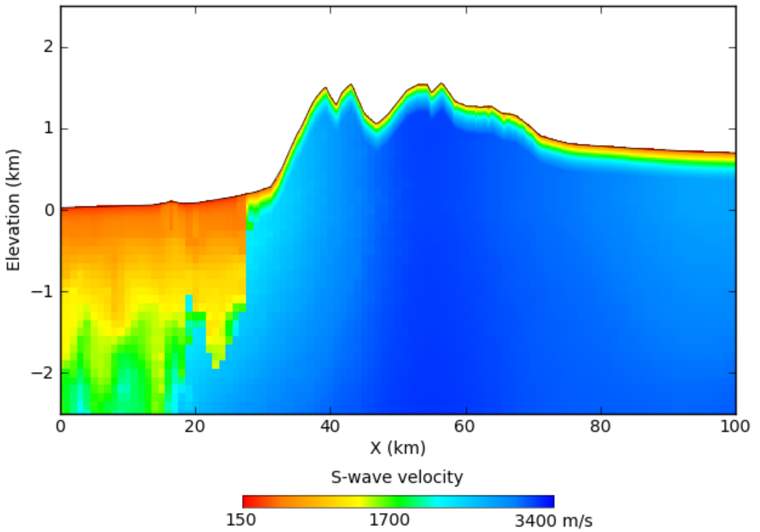
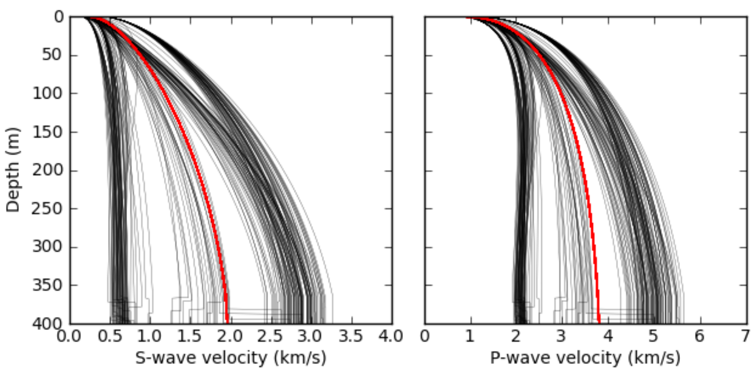
Current Research Areas for CVMs

- High resolution, near surface, properties (geotechnical layer)
- Tomographic inversions (comparing simulations to observations) improve exisisting CVMS
- Introduction of small-scale heterogeneities to better replicate observed variations in earth
- Frequency dependent attenuation models

Vs-30-based Geotechnical Layer for CVM's

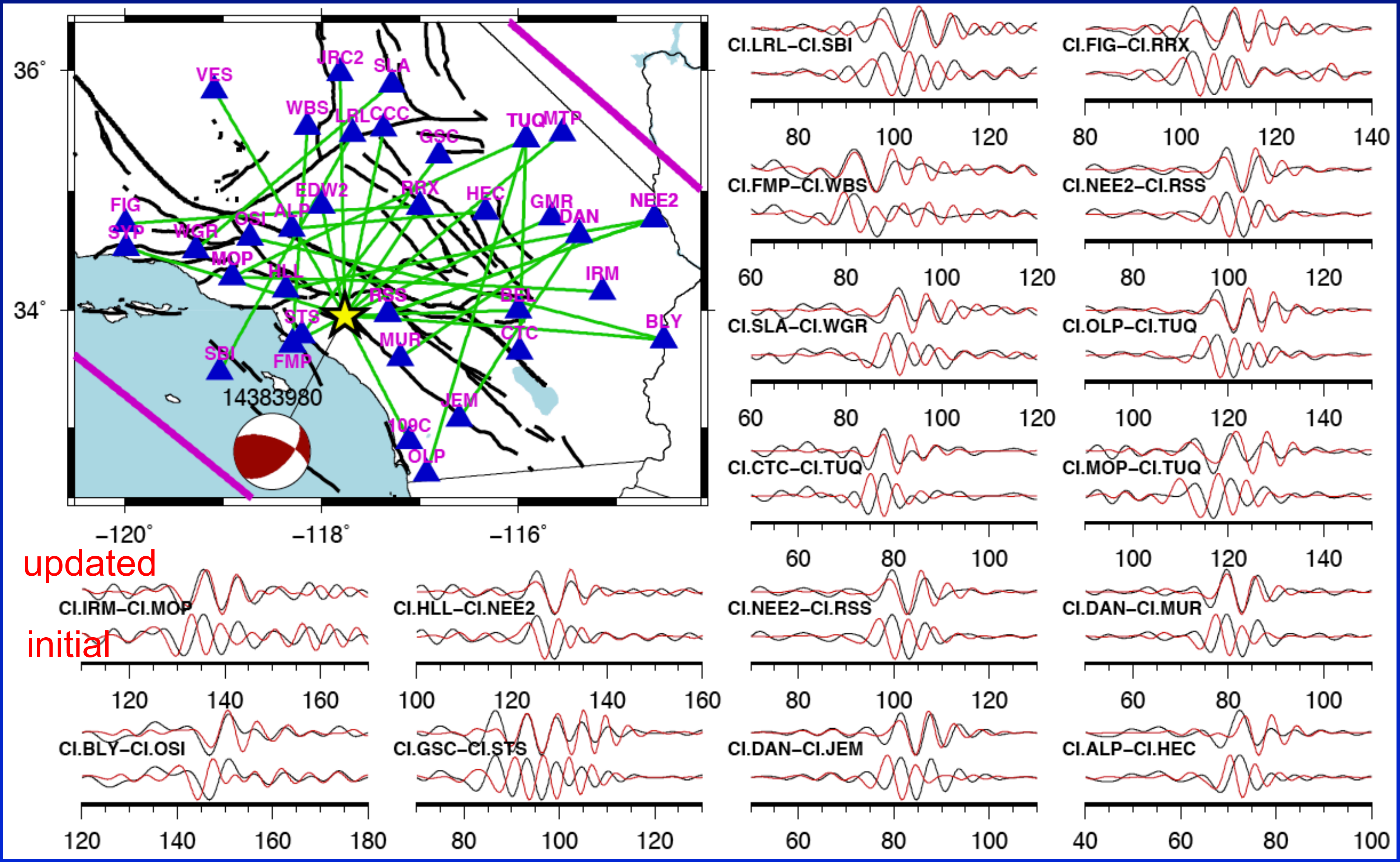


CVM-H v6.3 + GTL S-wave velocity cross-section through the Los Angeles basin and San Gabriel Mountains.



Designed and implemented a method for defining a geotechnical layer (GTL) implementation based on Vs-30 maps or topography-based Vs30 methods.

Waveform improvements



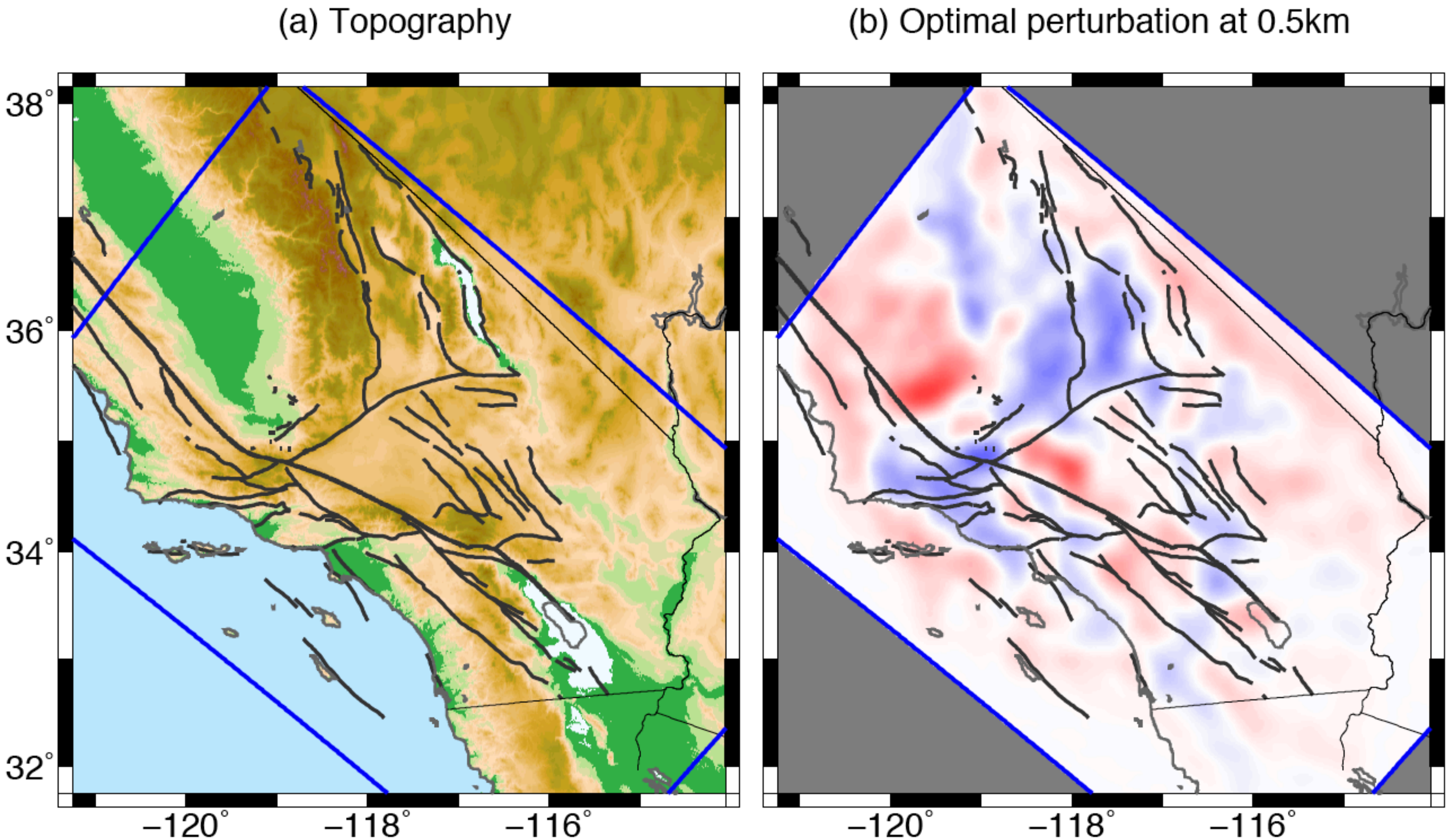
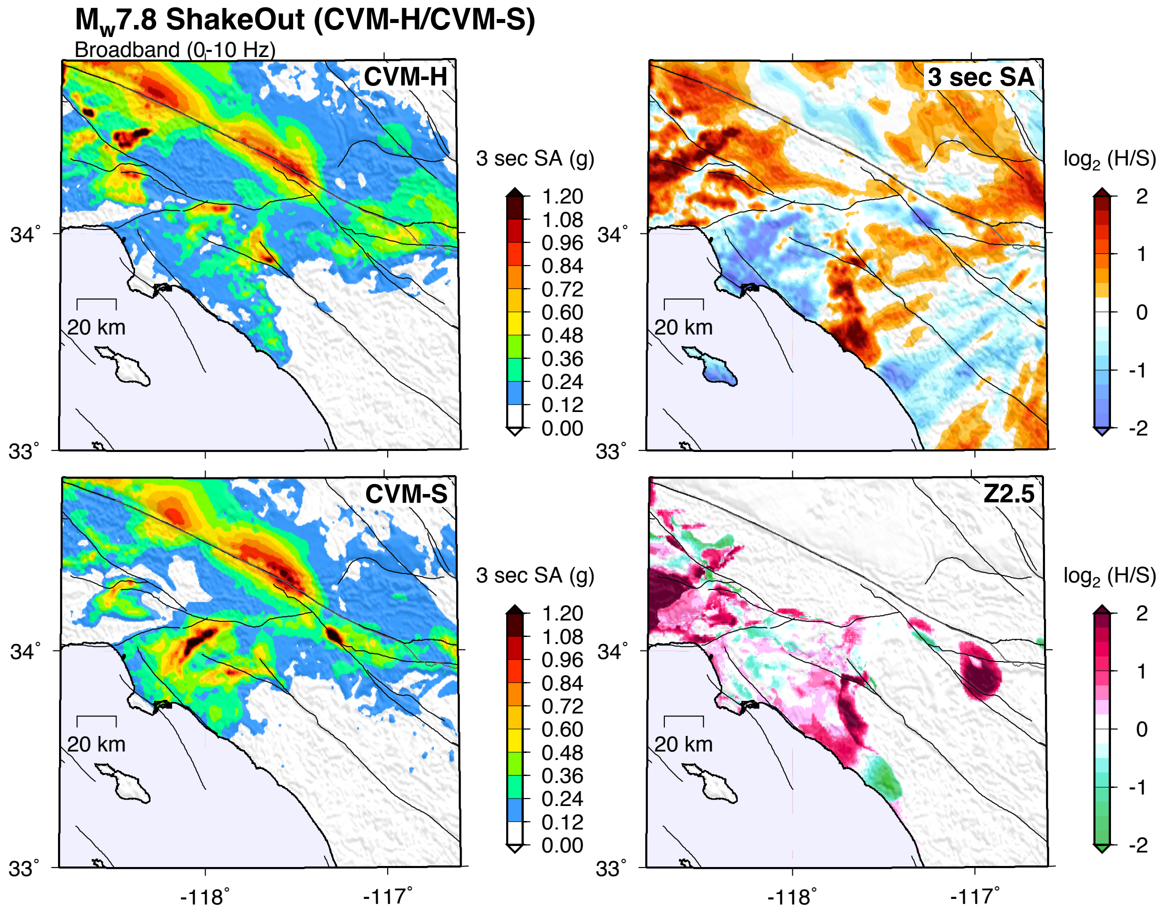


Figure 3: (a) Map of topography and major faults (thick black lines) of southern California. (b) The optimal perturbation results of the southern California tomographic inversion including iteration CVM-S4.21 performed on Yellowstone. In perturbation maps, the red regions represent velocity reduction areas and the blue regions represent velocity increase areas.



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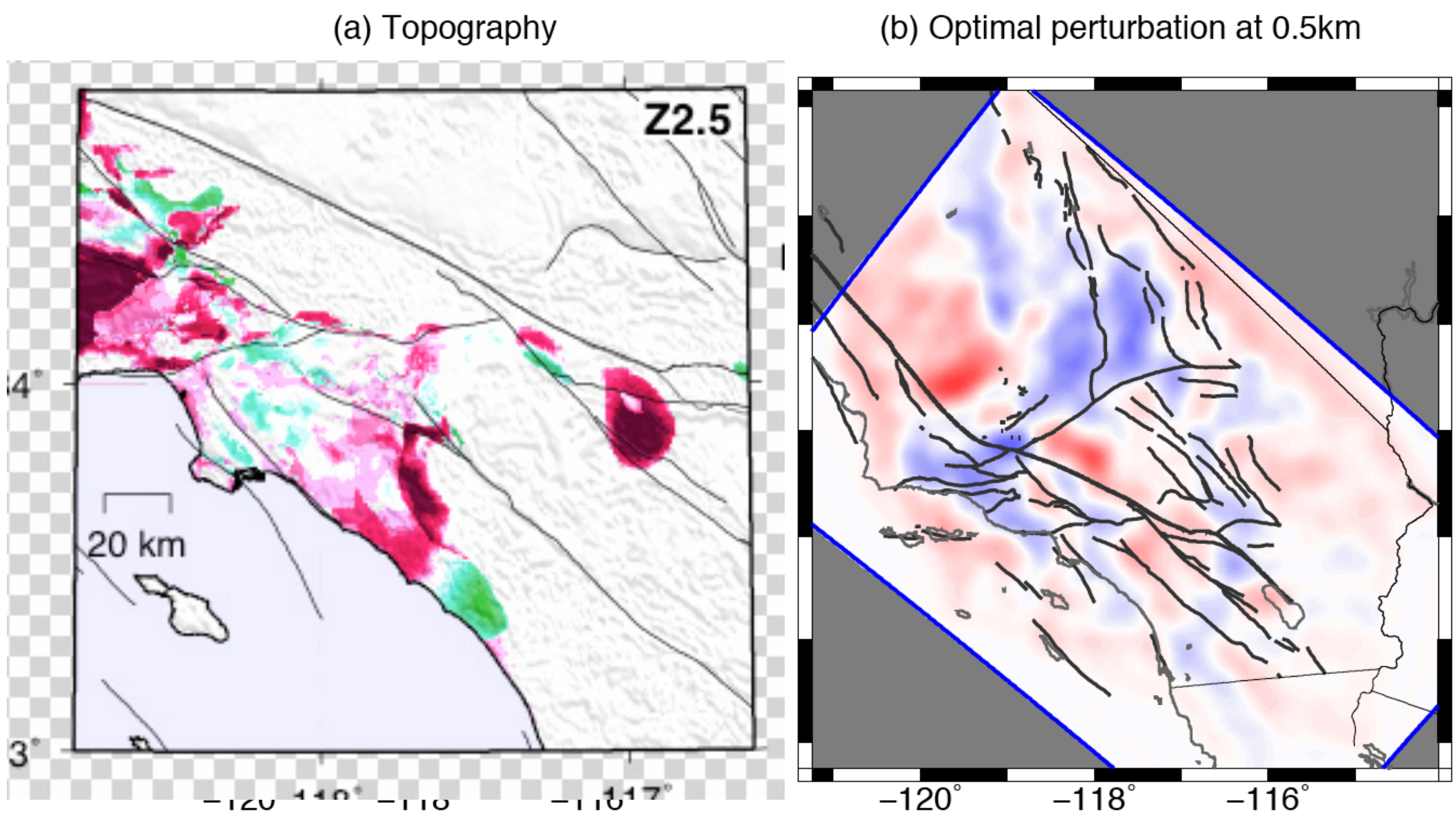

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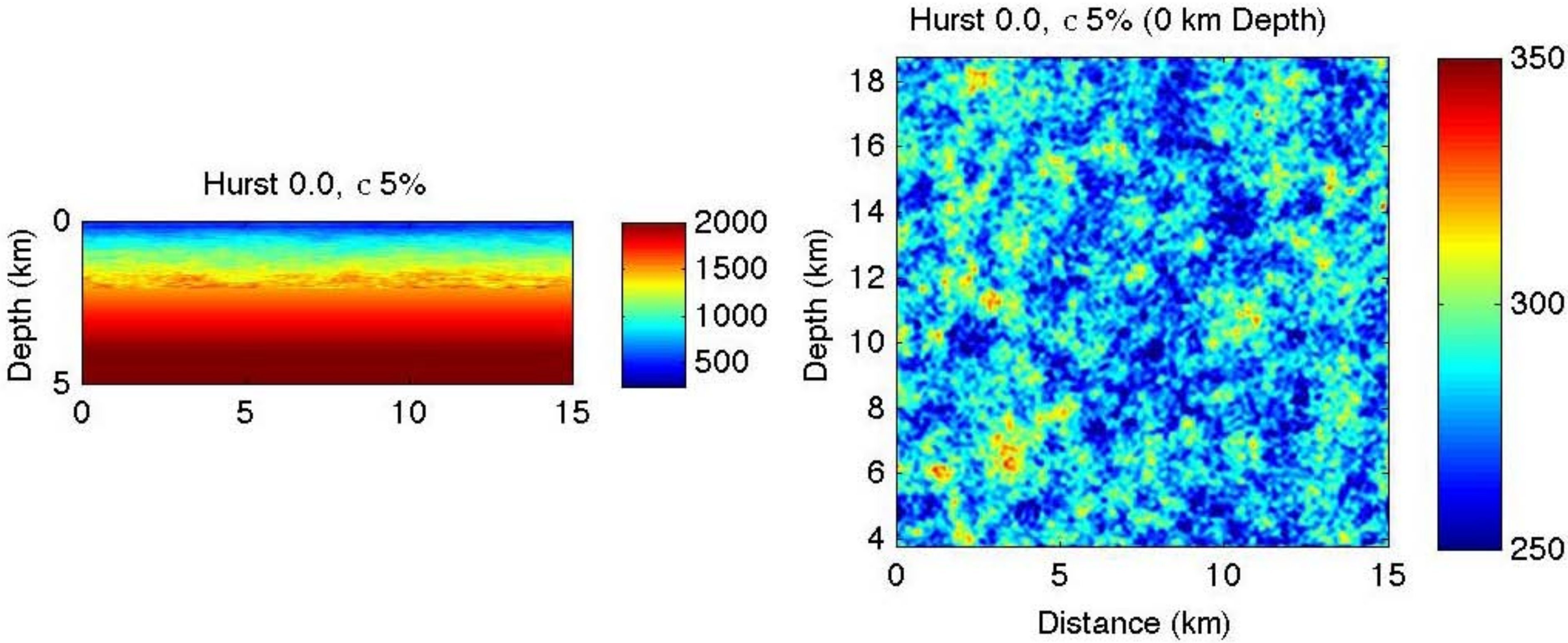

Figure 4: Illustration showing how a fractal model of small-scale heterogeneities is added into a 3D velocity model. The vertical section (left) and surface slice (right) of Vs velocity model including a fractal model with H=0.0 and σ=5%.

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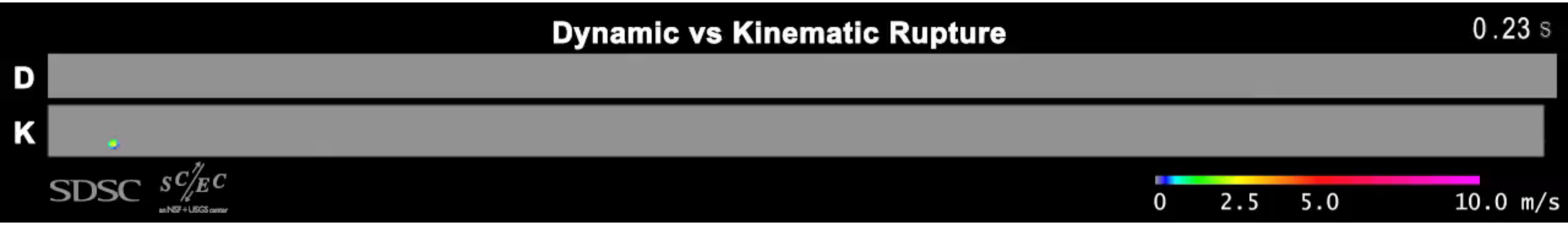
Fundamental Earthquake Physics Problem to be Investigated on Mira: Dynamic Ruptures

"The problem of frictional sliding in earthquakes is one of the most fundamental problems in all of Earth science. There are many reasons to believe that something exotic is happening." - Caltech and SCEC geophysicist Thomas Heaton

Current Research Areas for Ruptures

- Migration from kinematic ruptures (not constrained by friction laws) to dynamic ruptures (constrained by one or more friction laws)
- Definition of appropriate friction laws
- Development of supershear ruptures
- Simulations on complex (non-planar) fault geometries
- Rough fault generation of high frequency motions
- Moderation of strong ground through plasticity of earth

M8 Dynamic Rupture Simulation Compared to Kinematic Rupture



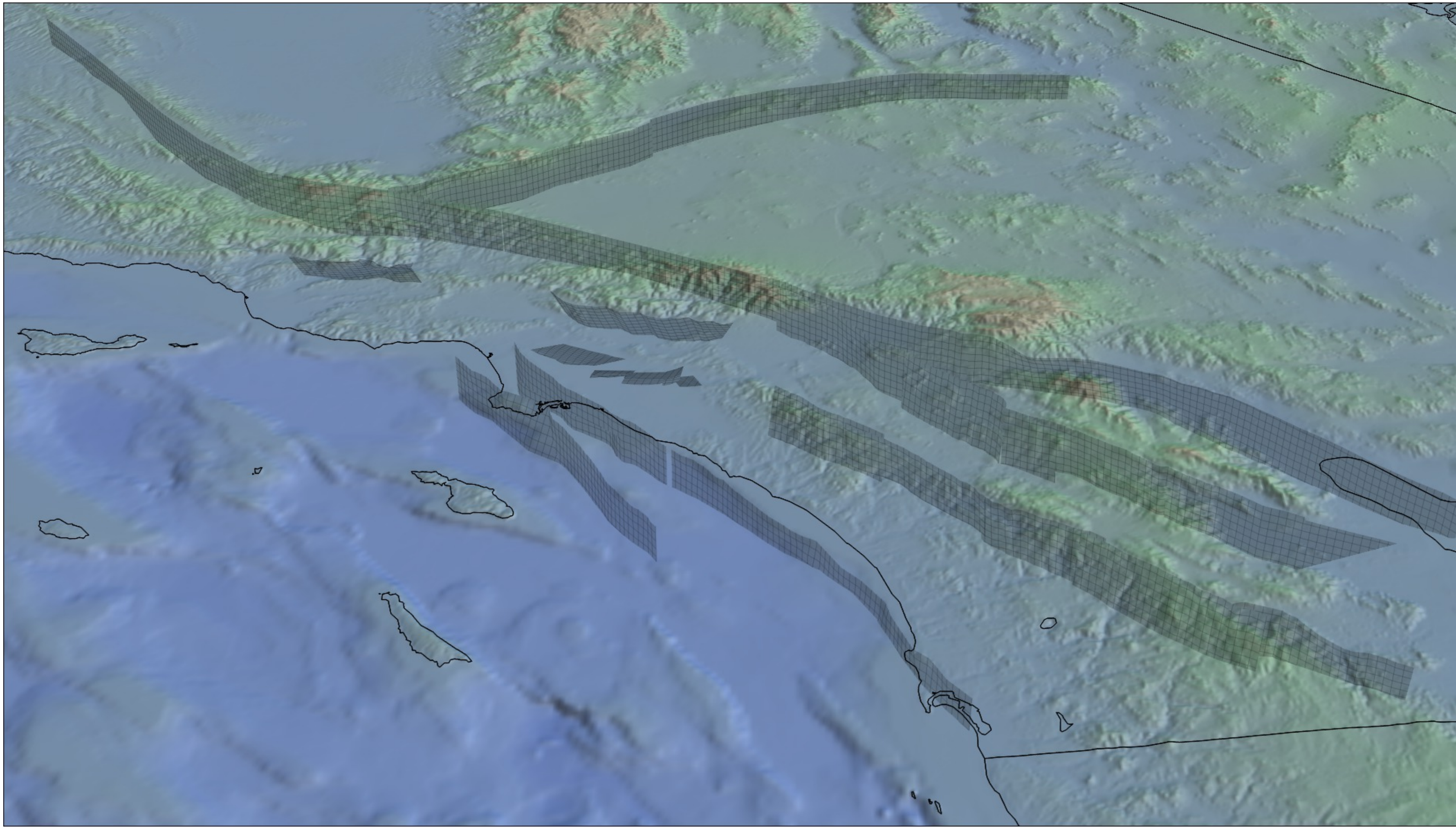
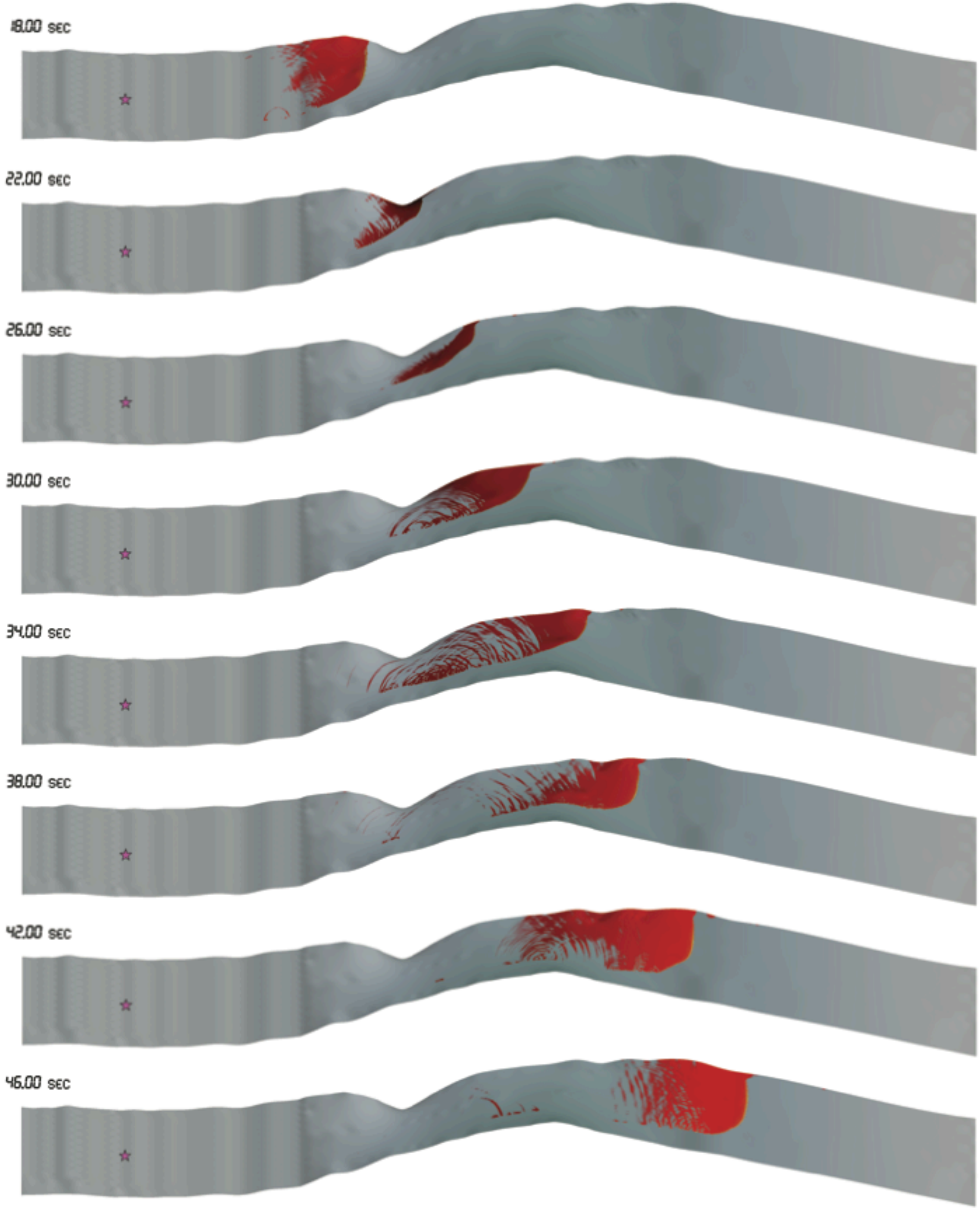
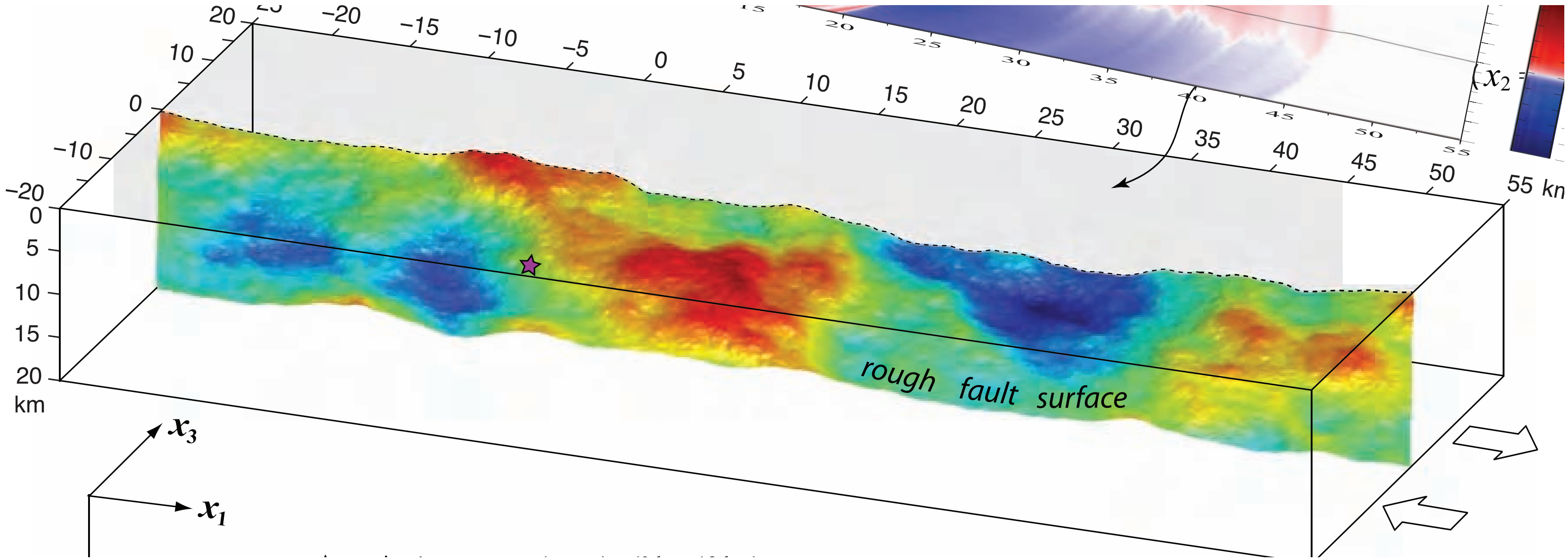


Figure 3: Quadrilateral meshes generated for the "Big Ten" rupture surfaces from the SCEC Community Fault Model.



Examples of the non-planar fault geometry in current San Andreas Fault Model.



Generation of high Frequencye (>1Hz) ground motions using SORD and a rough fault.

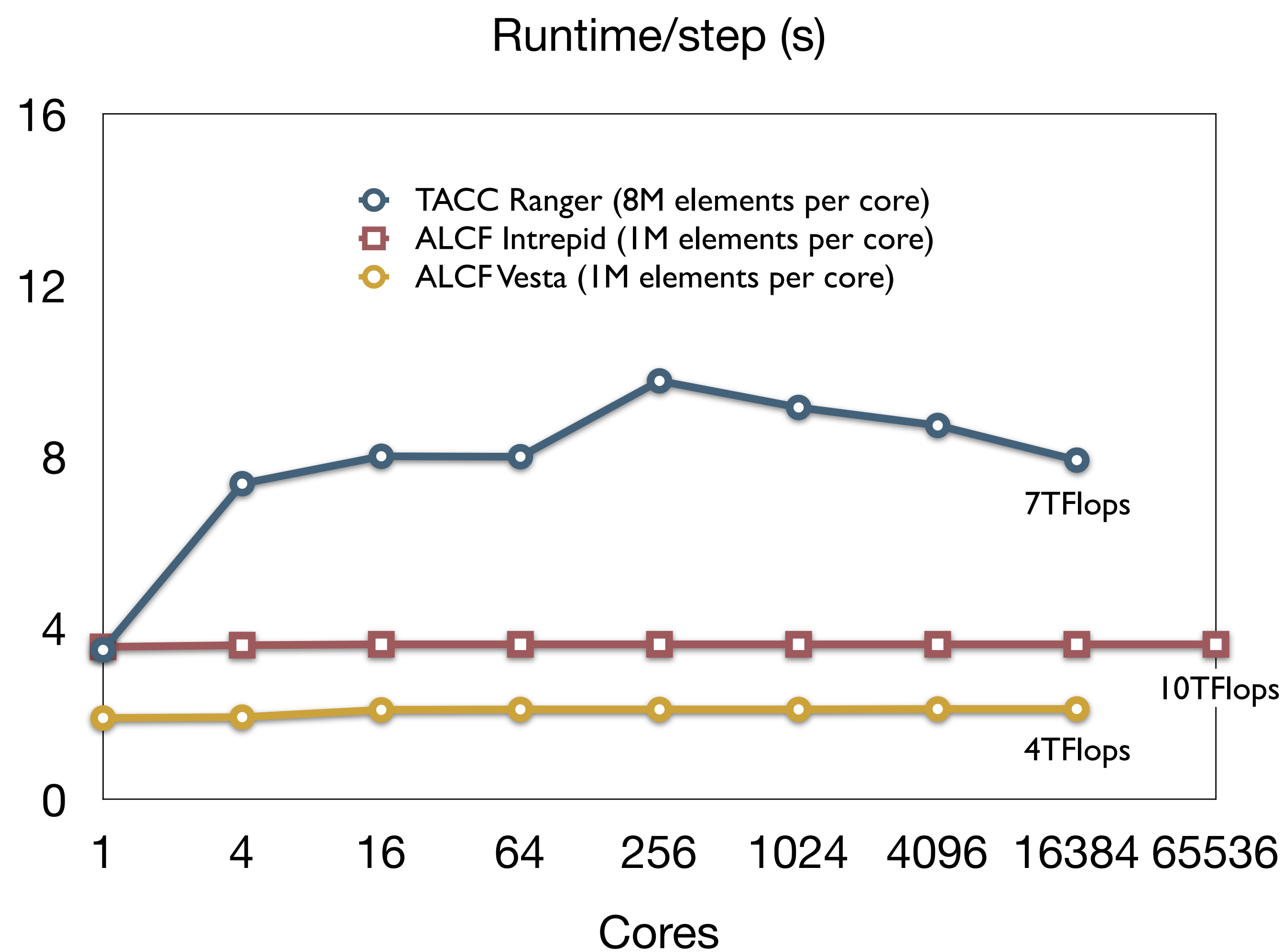
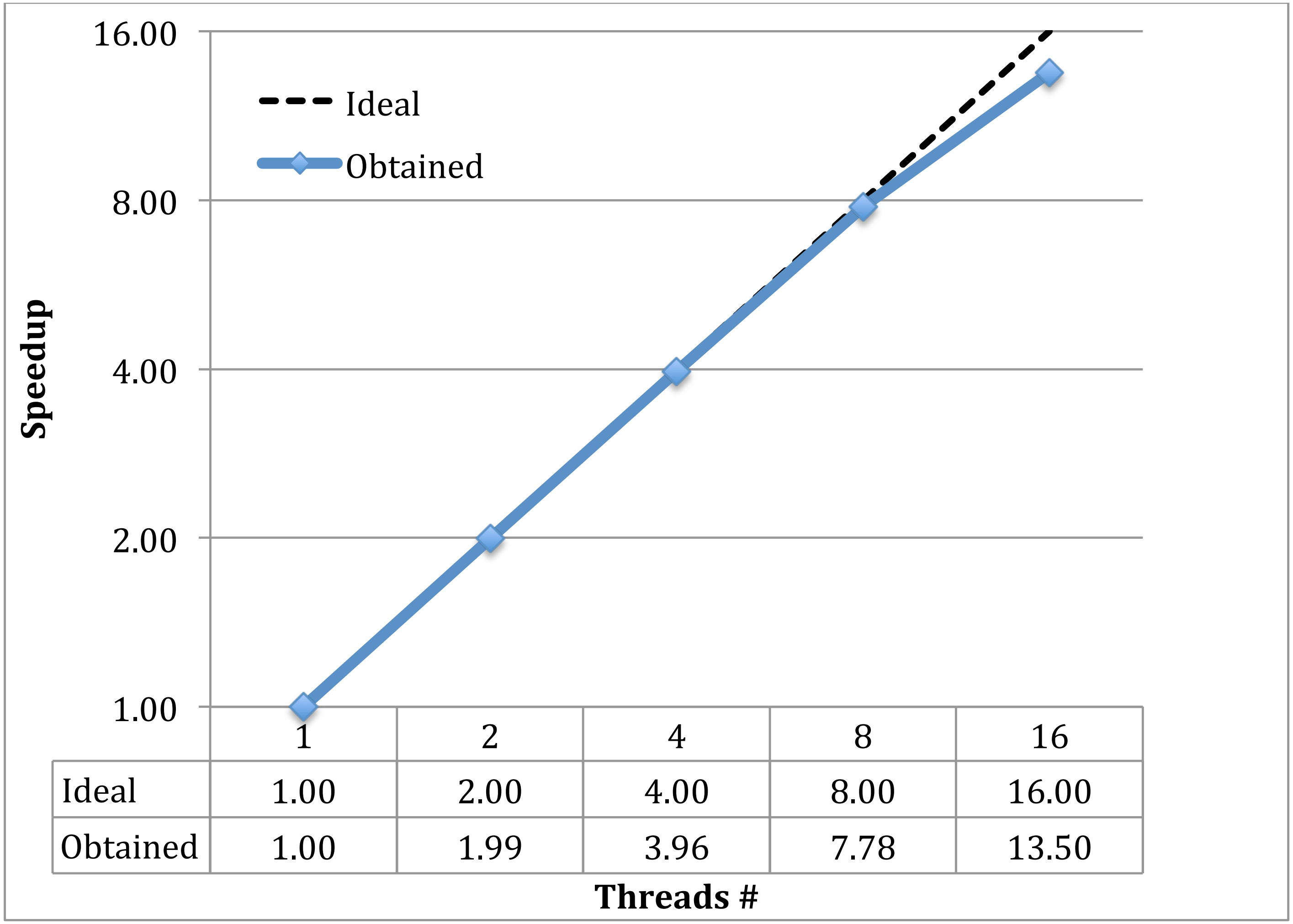


Figure 1: Weak scaling benchmark for SORD in pure MPI mode (no multi-threading). ALCF Intrepid (Blue Gene/P) and Vesta (BG/Q) demonstrate near ideal weak scaling, with BG/Q clock speed increase giving a factor of two speedup relative to BG/P.



Threads #	1	2	4	8	16
Ideal	1.00	2.00	4.00	8.00	16.00
Obtained	1.00	1.99	3.96	7.78	13.50

Figure 2: SORD OpenMP strong scaling benchmark for single node Blue Gene/Q.

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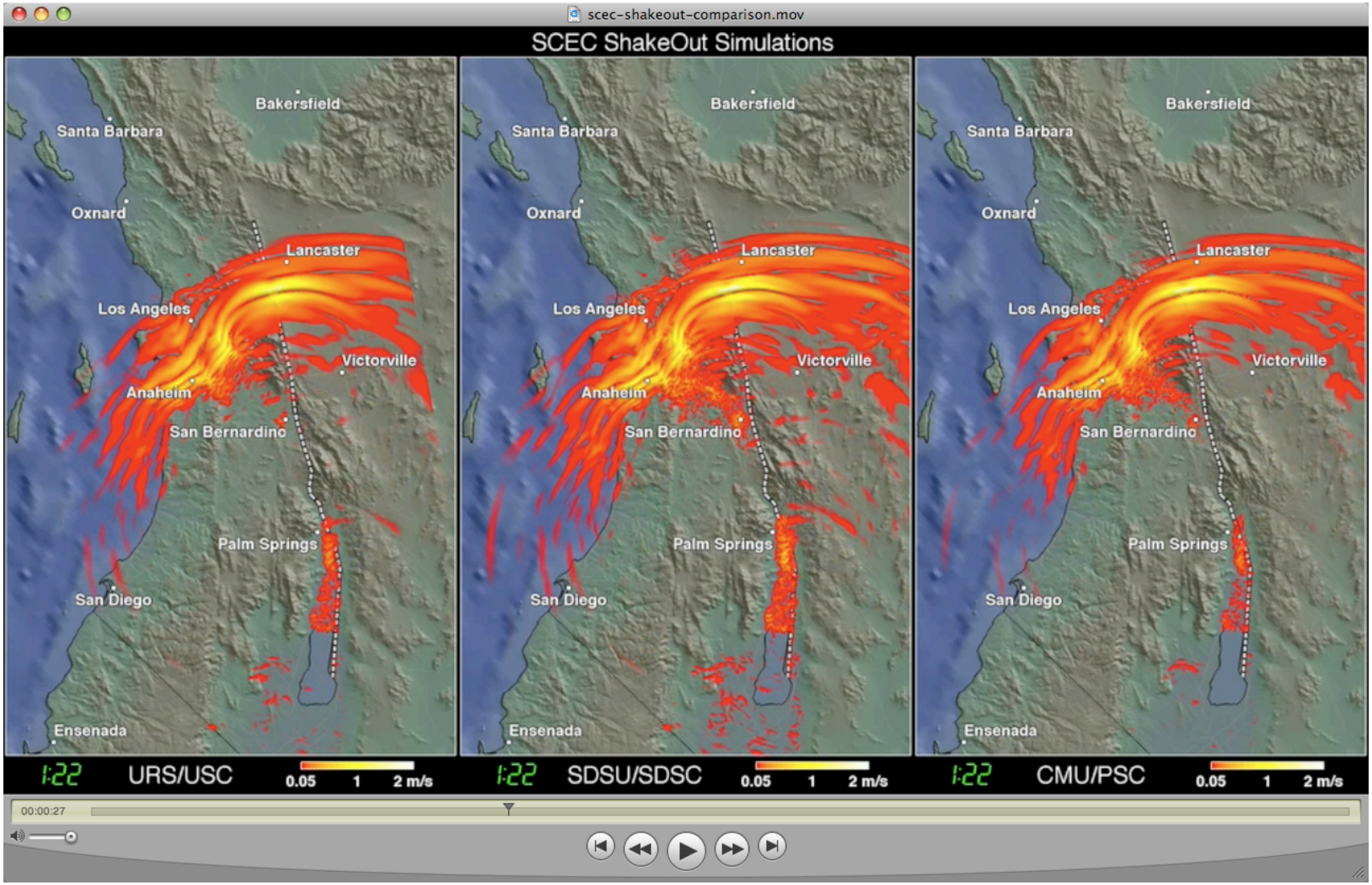
Current Research Areas for Ground Motion Simulations

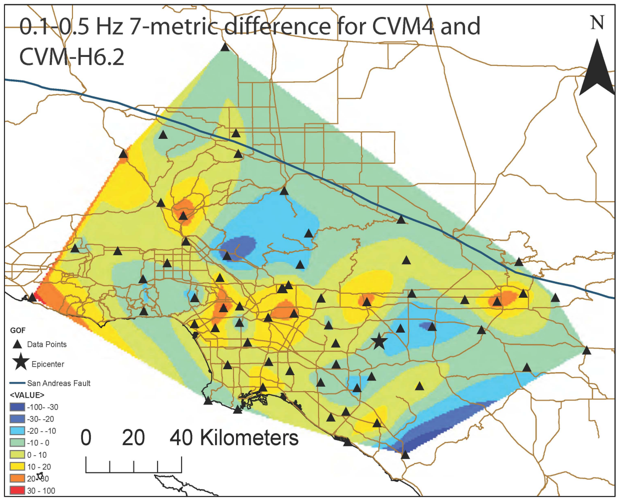
- Transition from stochastic methods to deterministic at frequencies 1Hz+
- Support for simulation volumes with topography
- Frequency dependent attenuation (Q) models
- Processing efficiency needed to support 10Hz simulations from GPUs, MICs, or others
- Use of multi-resolution meshes to reduce processing

Cross-Verification of Simulations

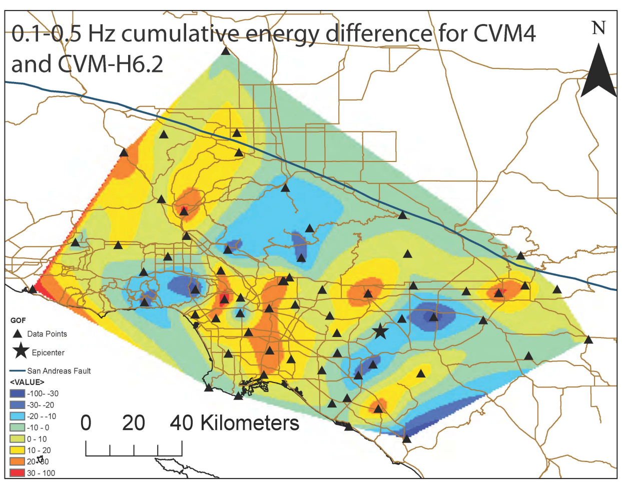


Bielak et al. (2009)

Validation Using Small Earthquakes at 0.5Hz

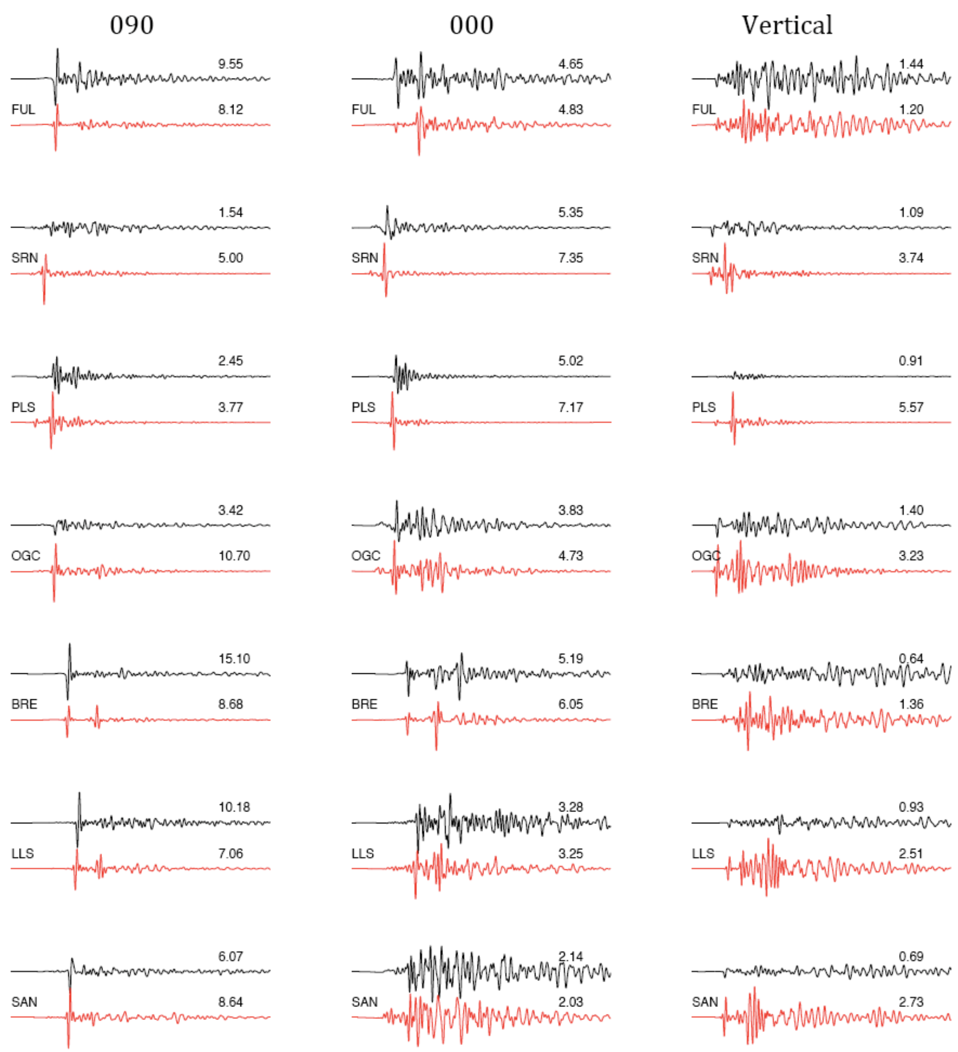


Postive (negative) values depict areas where CVM4 (CVM-H) is more accurate.

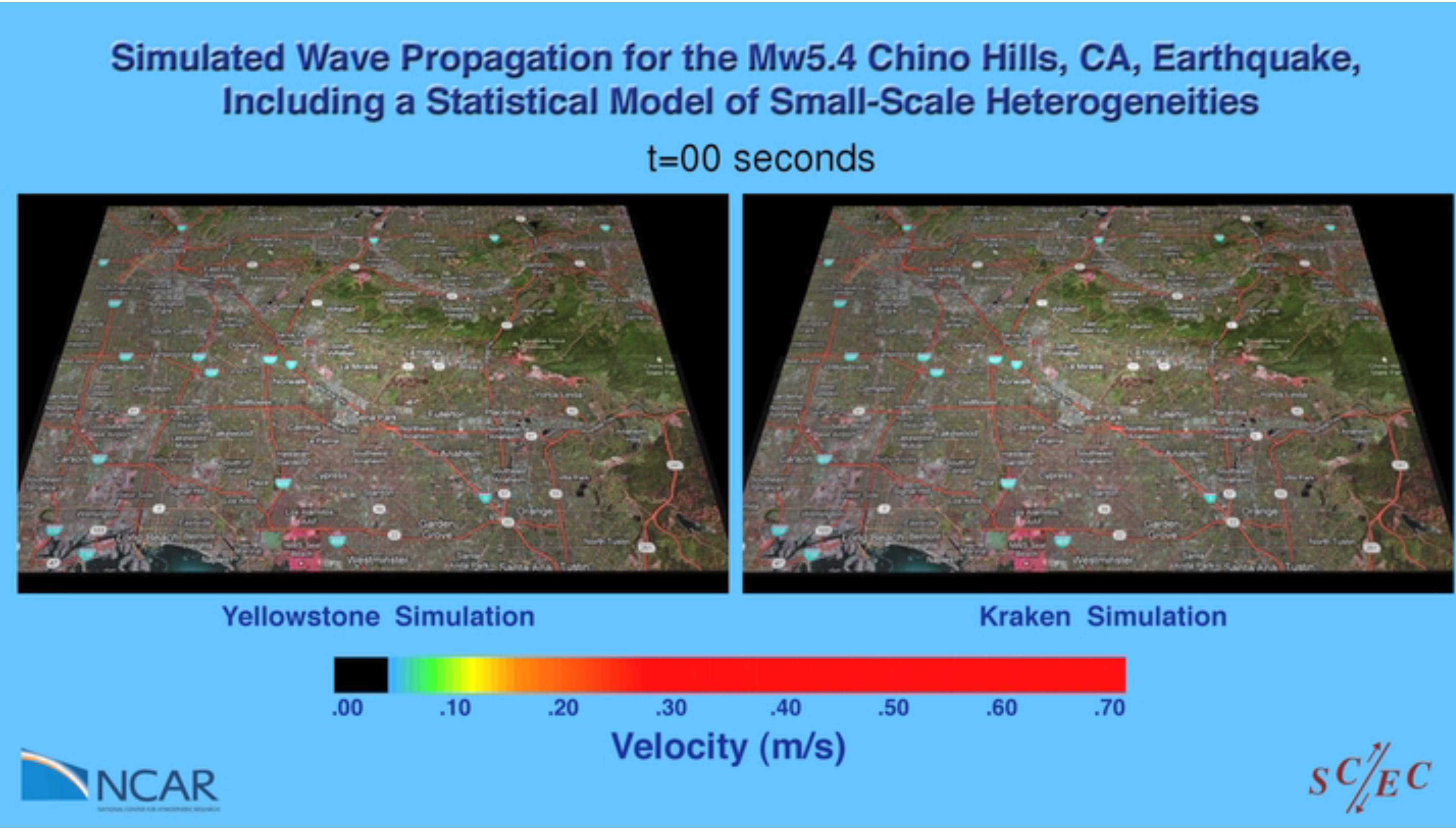


Postive (negative) values depict areas where CVM4 (CVM-H) is more accurate.

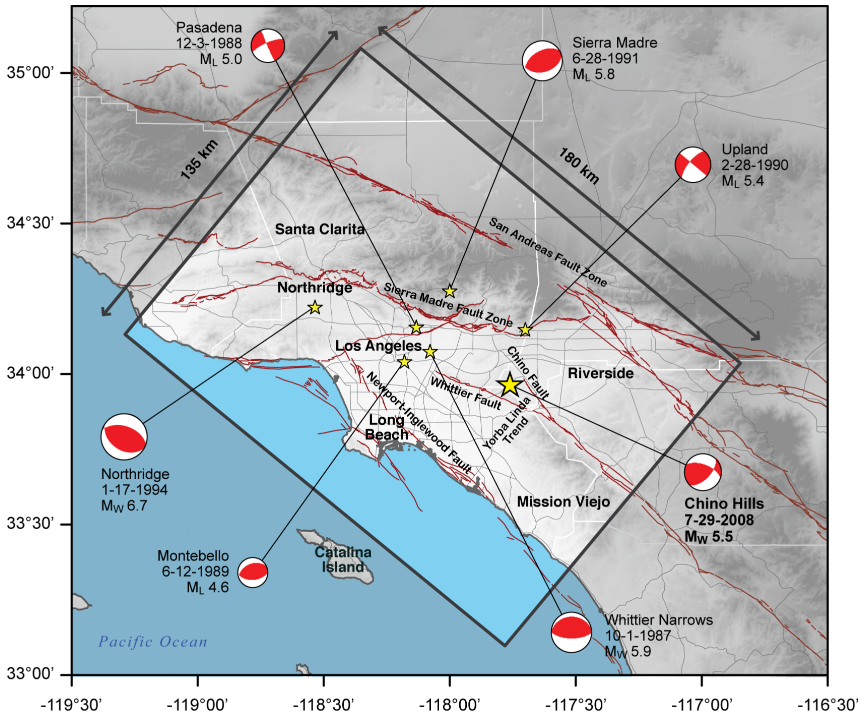
Chino Hills, M5.4, 07/29/08 (Olsen & Mayhew, 2009)

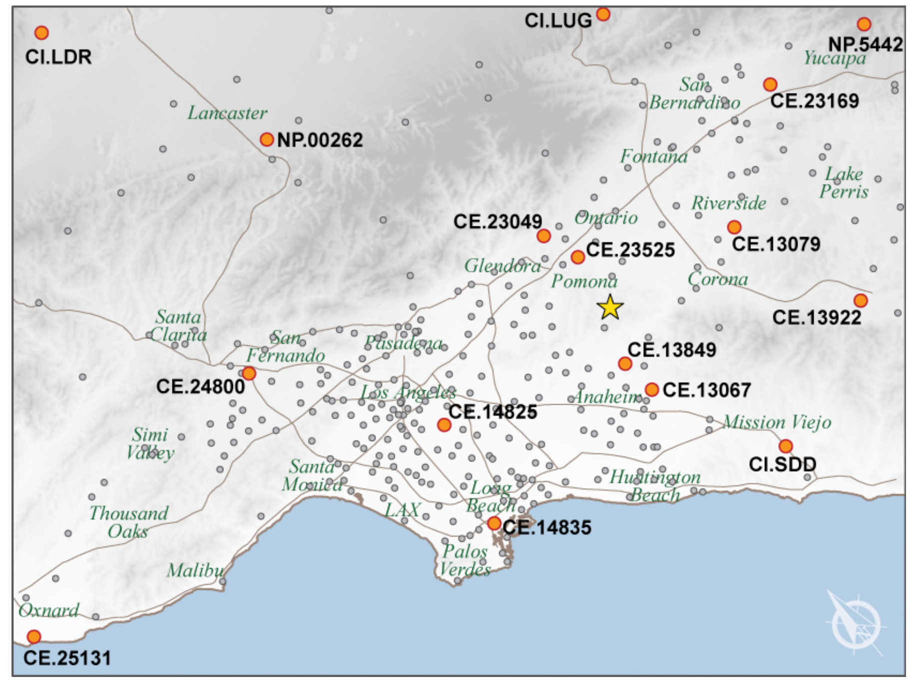


2.5Hz Chino Hills with and w/o CVM heterogeneities



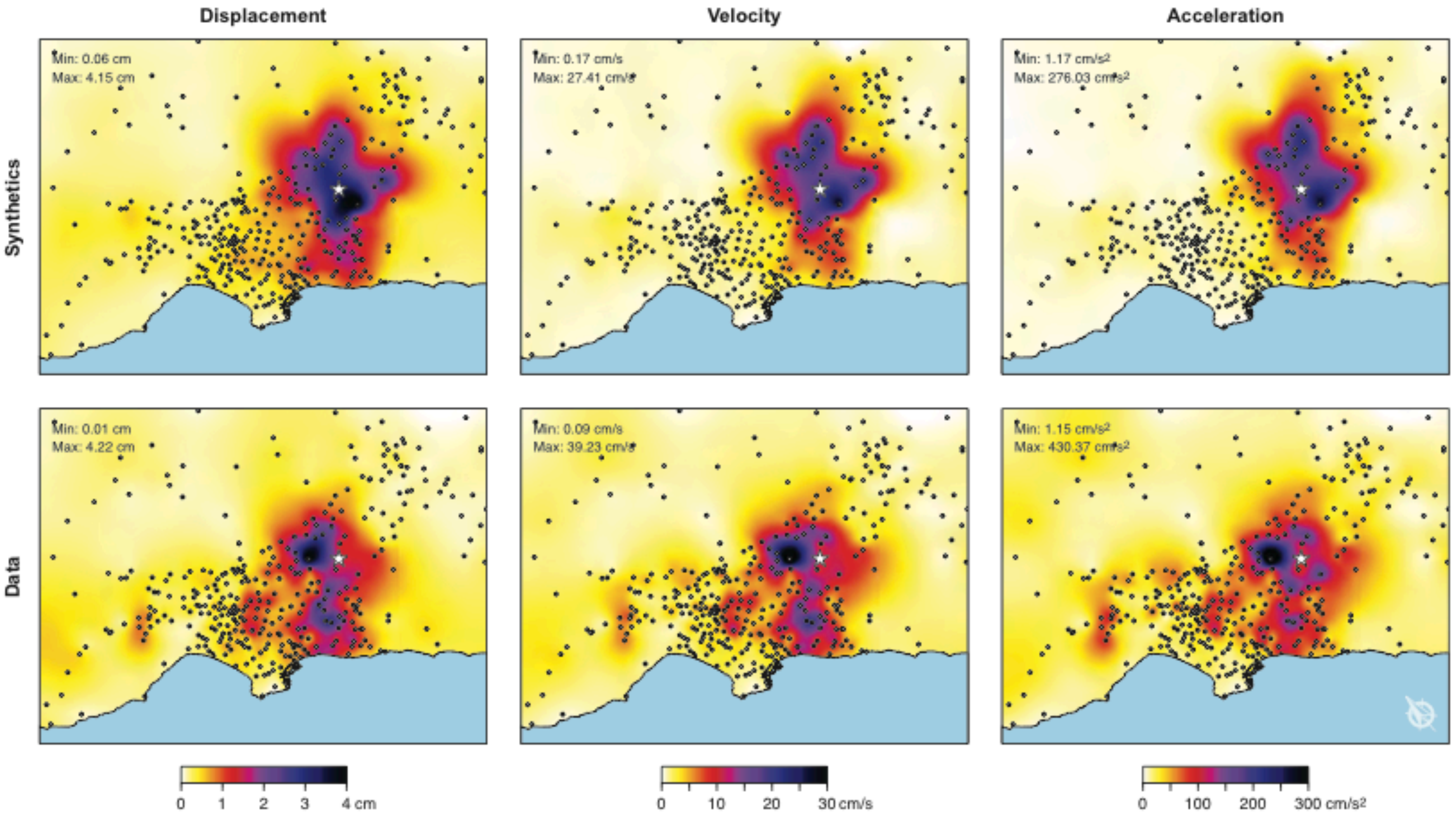
Chino Hills at 4 Hz and 200 m/s





Used ~350 stations for validation

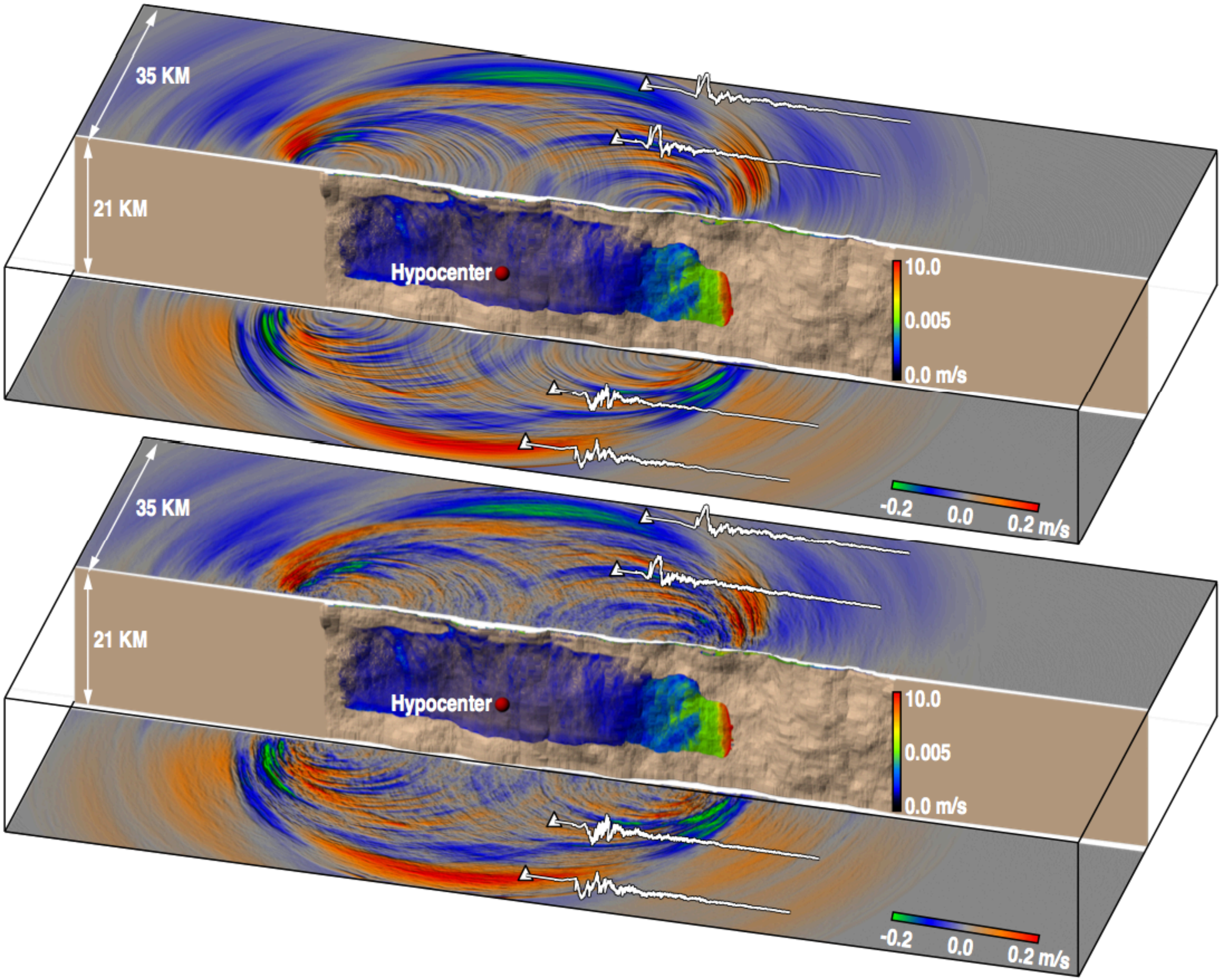
Chino Hills Validation at 4Hz



Development of CPU-GPU Code

- To exploit availability of CPU-GPU systems, we have developed prototype GPU wave propagation code.
- GPUs do floating point intensive calculations. Code was redefined to reduce data movements
- Unused CPUs (as GPUs are running MPI codes) are used to “co-schedule” high throughput, loosely coupled post-processing codes

10Hz SORD Dynamic Rupture and Wave Propagation with and without small scale Heterogeneities



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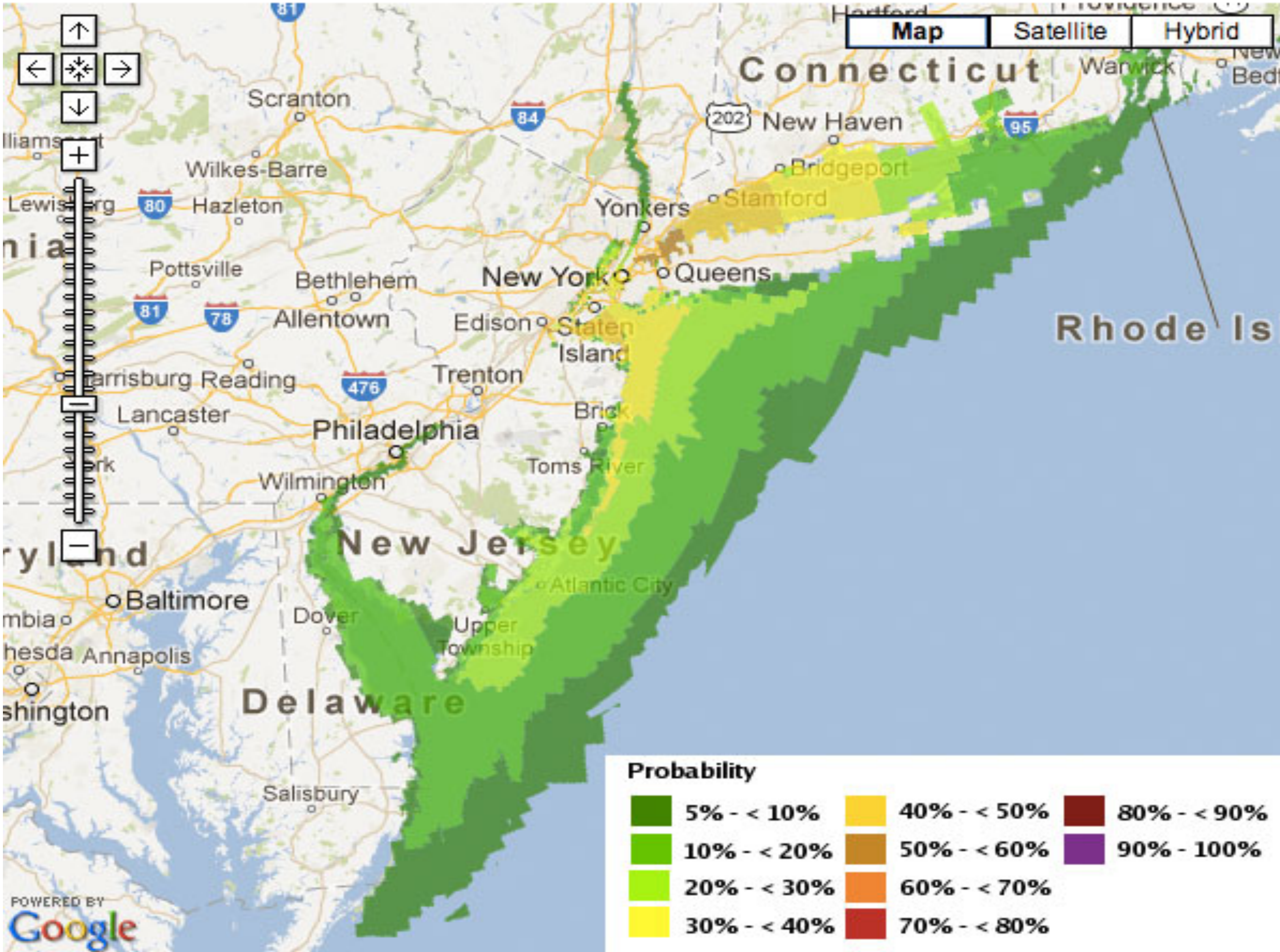
Current Research Areas for PSHA

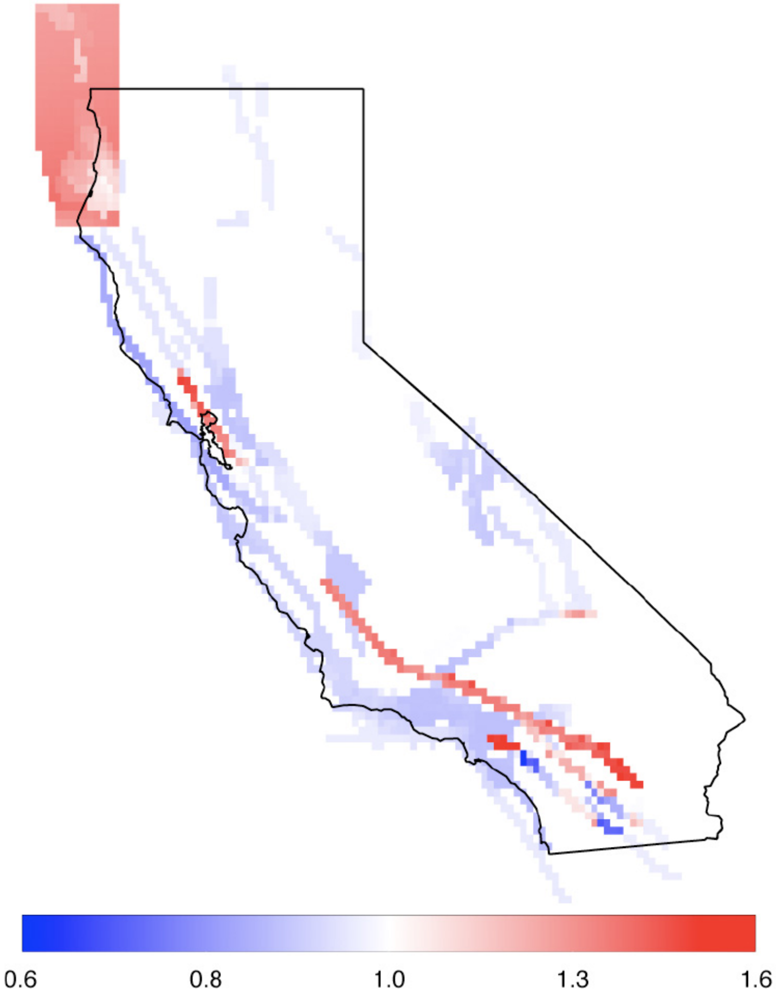
- Replace attenuation relationships with full 3D wave propagation simulations
- Increase max simulated frequency to 1Hz+
- Heterogeneous computing workflow with large MPI jobs and millions of loosely-coupled serial post processing jobs.
- Evaluation of alternative CVMs
- Integration of dynamic ruptures to include supershear ruptures
- Integration of most recent USGS Earthquake Rupture Forecast (UCERF3.0) with fault to fault ruptures and low probability but very large (M8.5+) ruptures

Probability of Storm Surge Greater Than Six Feet



SCEC-USGS-CGS Working Group on California Earthquake Probabilities (2007)

Uniform California Earthquake Rupture Forecast (UCERF2)

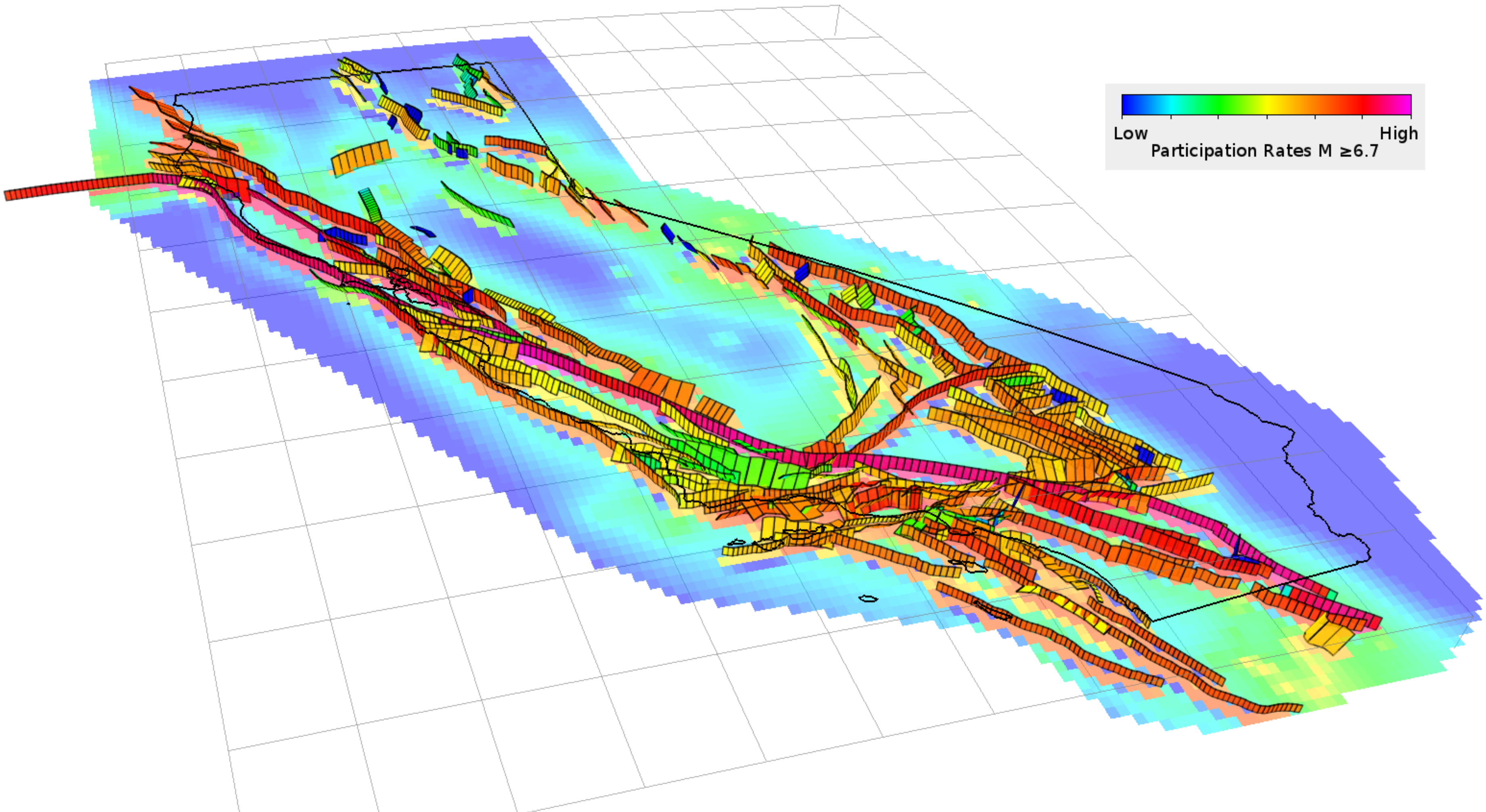


Ratio of time-dependent to time-independent participation probabilities for M ≥ 6.7

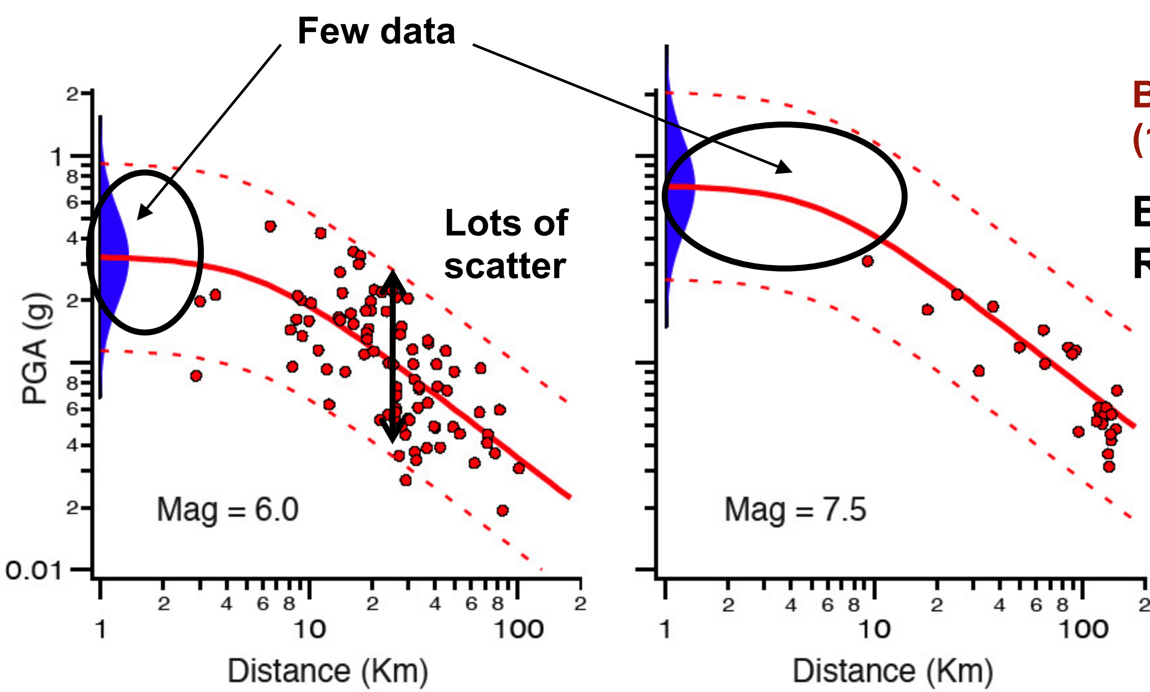
Recommendations for improvement:

- Include fault-to-fault ruptures
- Include earthquake clustering and triggering probabilities, including aftershocks
- Develop self-consistent stress-renewal models
- Understand time-dependence of historical seismicity
- Reconcile magnitude-area relationships

Uniform California Earthquake Rupture Forecast (UCERF3)

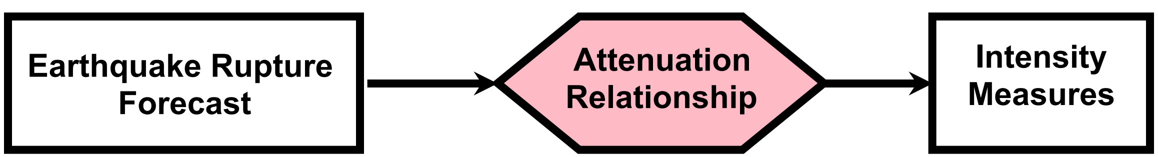


Probabilistic Seismic Hazard Model



Boore, Joyner & Fumal (1997)

Empirical Attenuation Relationship

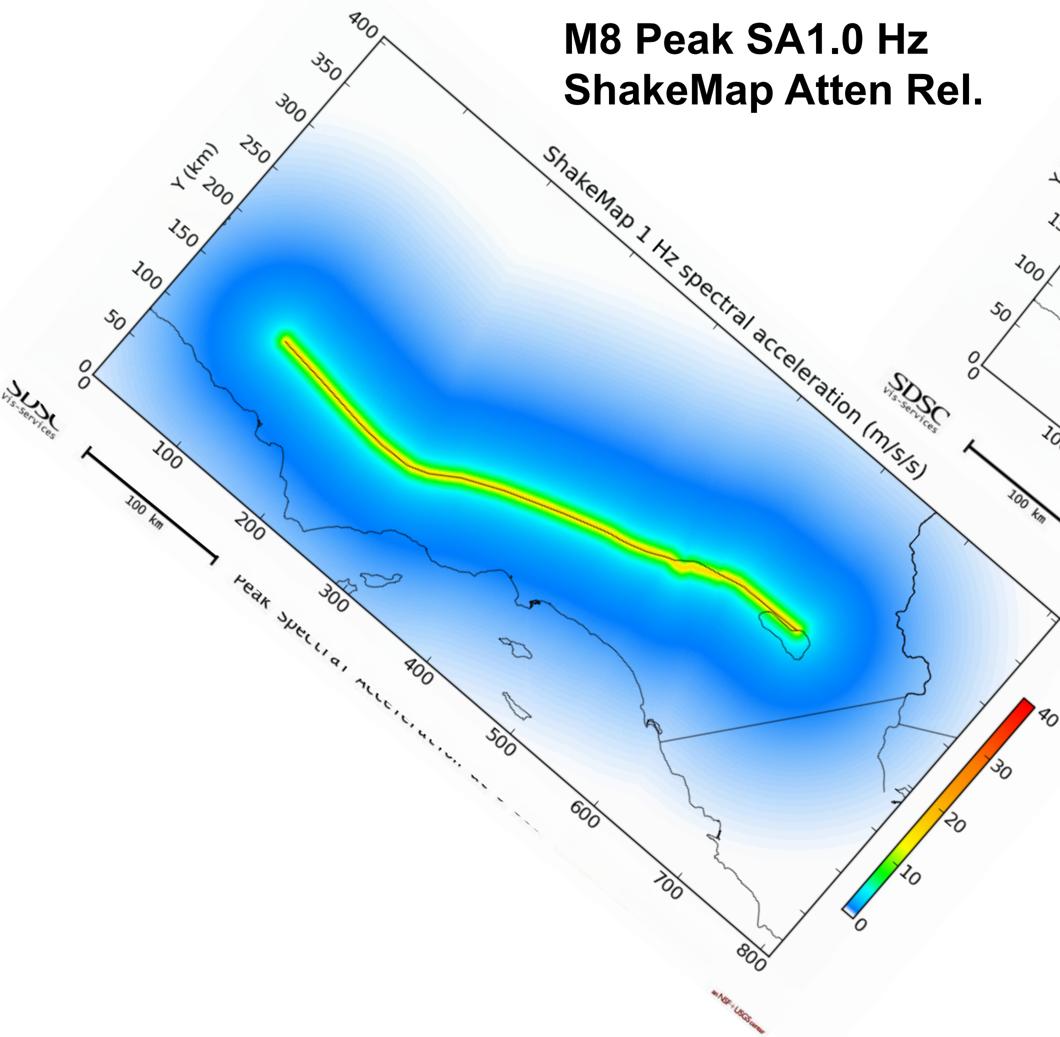


$P(S_n)$ $P(IM_k \mid S_n)$ $P(IM_k)$

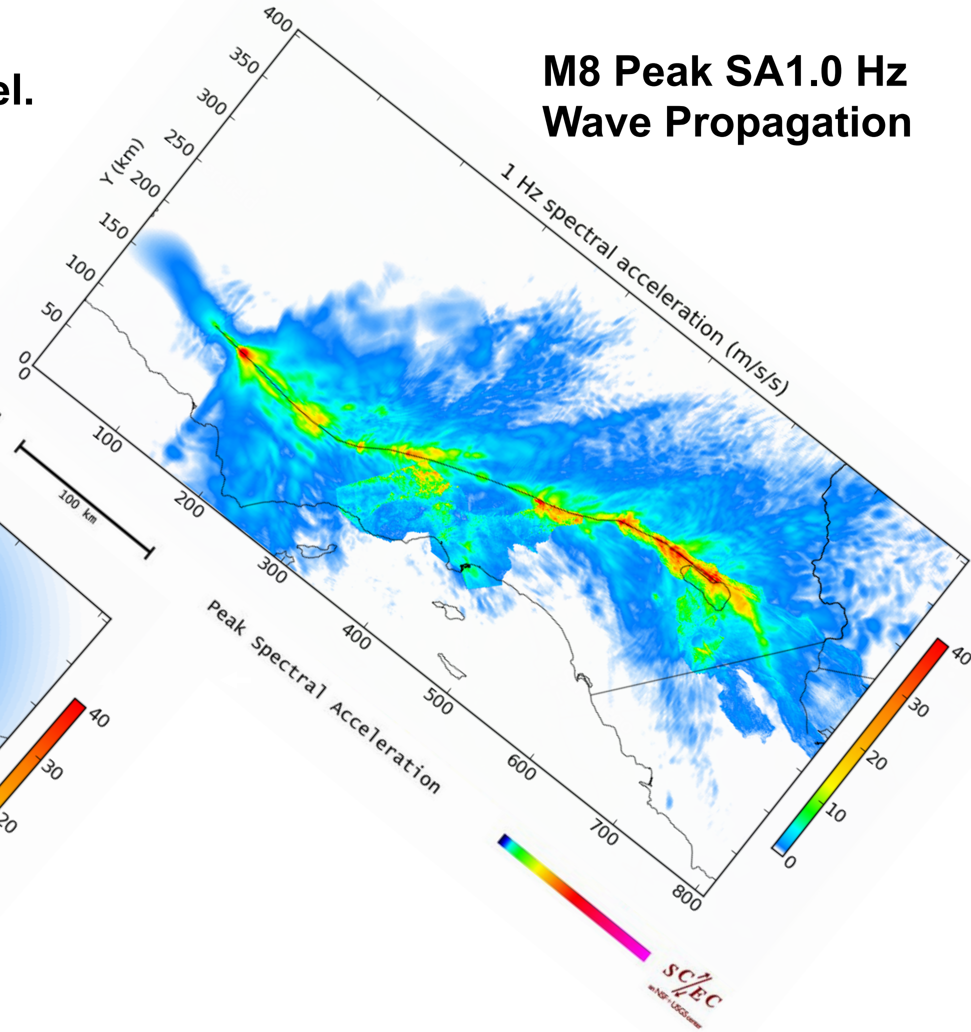
Probabilistic Seismic Hazard Analysis

M8 Comparisons – Atten Relation versus AWP

M8 Peak SA1.0 Hz
ShakeMap Atten Rel.

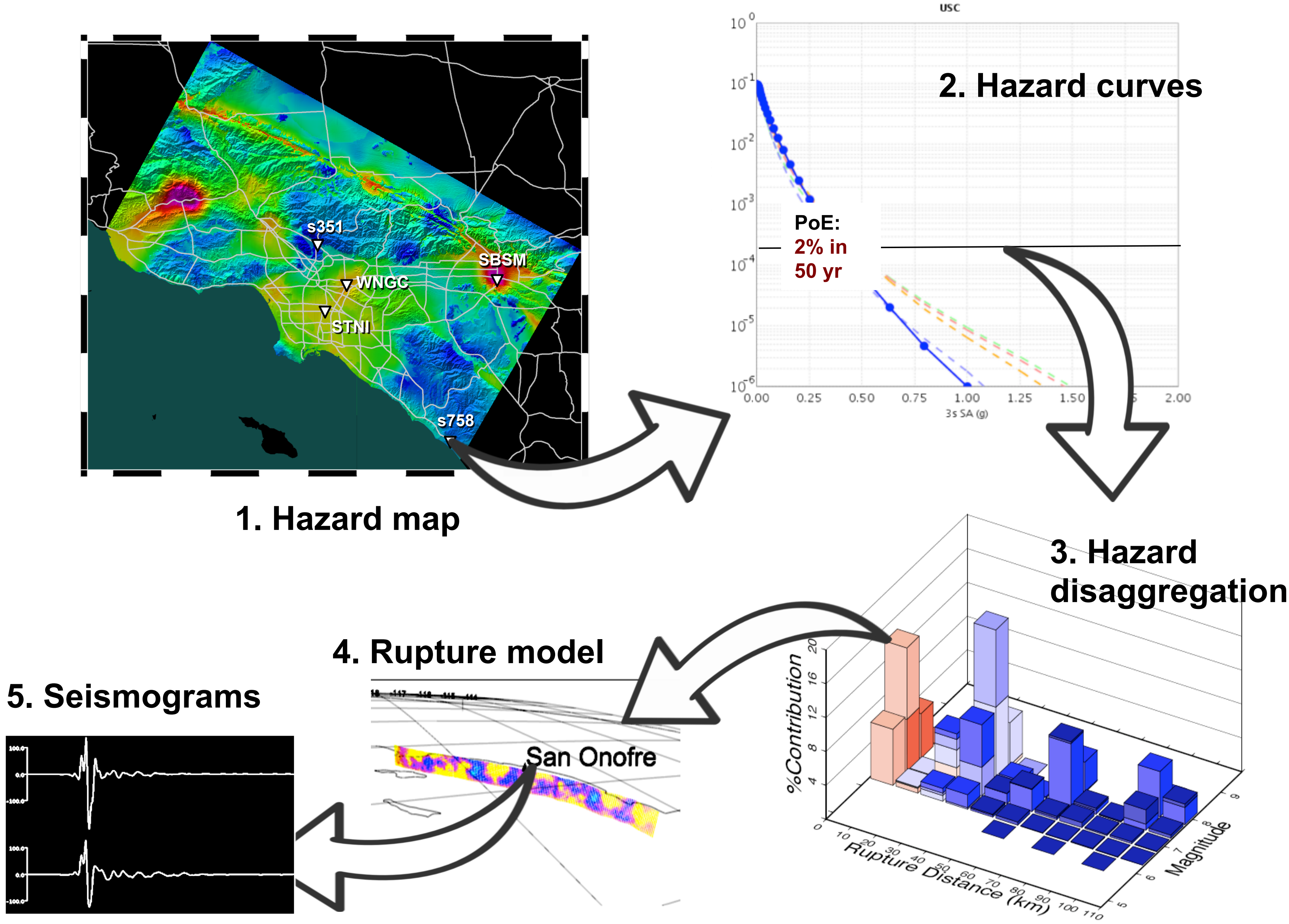


M8 Peak SA1.0 Hz
Wave Propagation

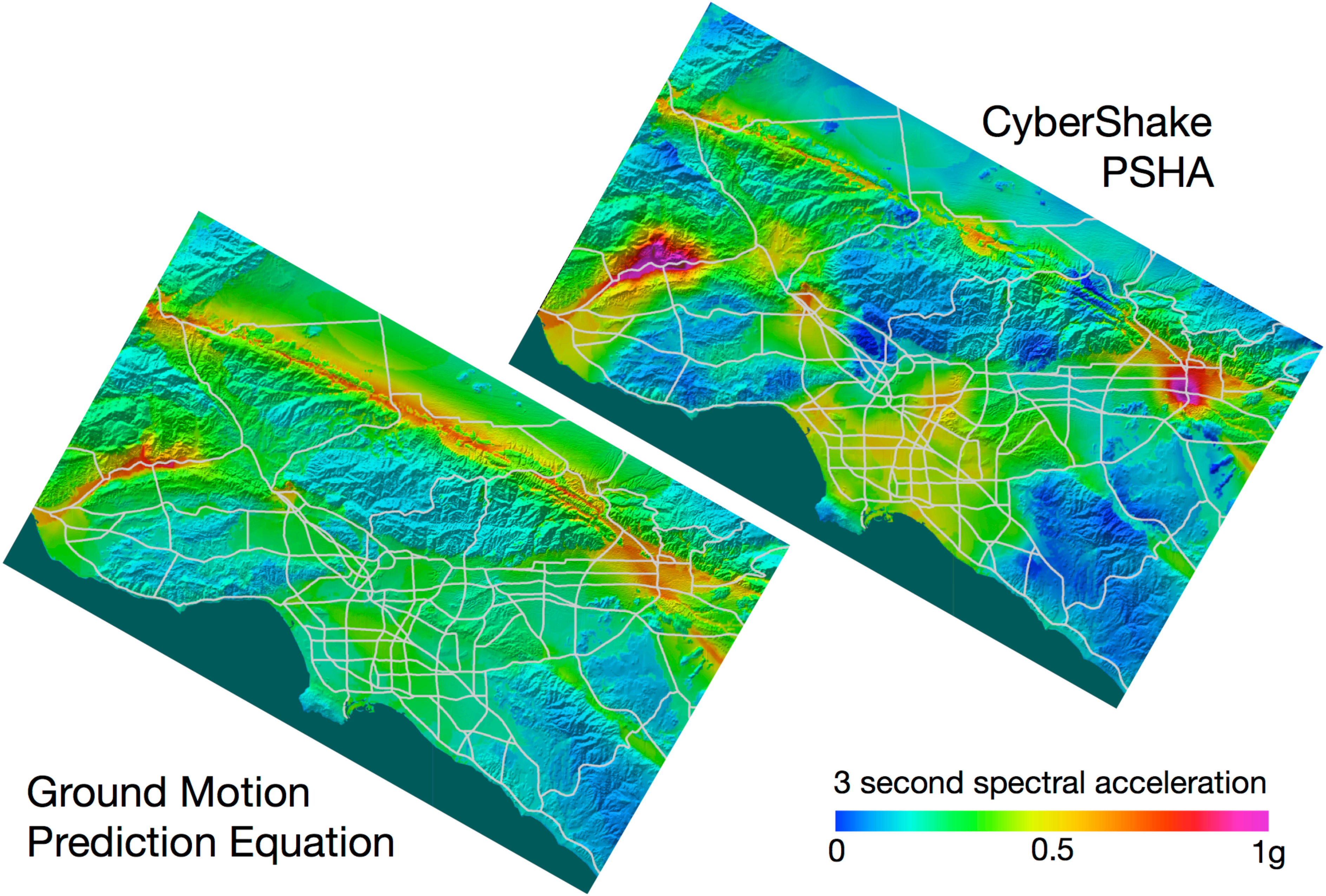


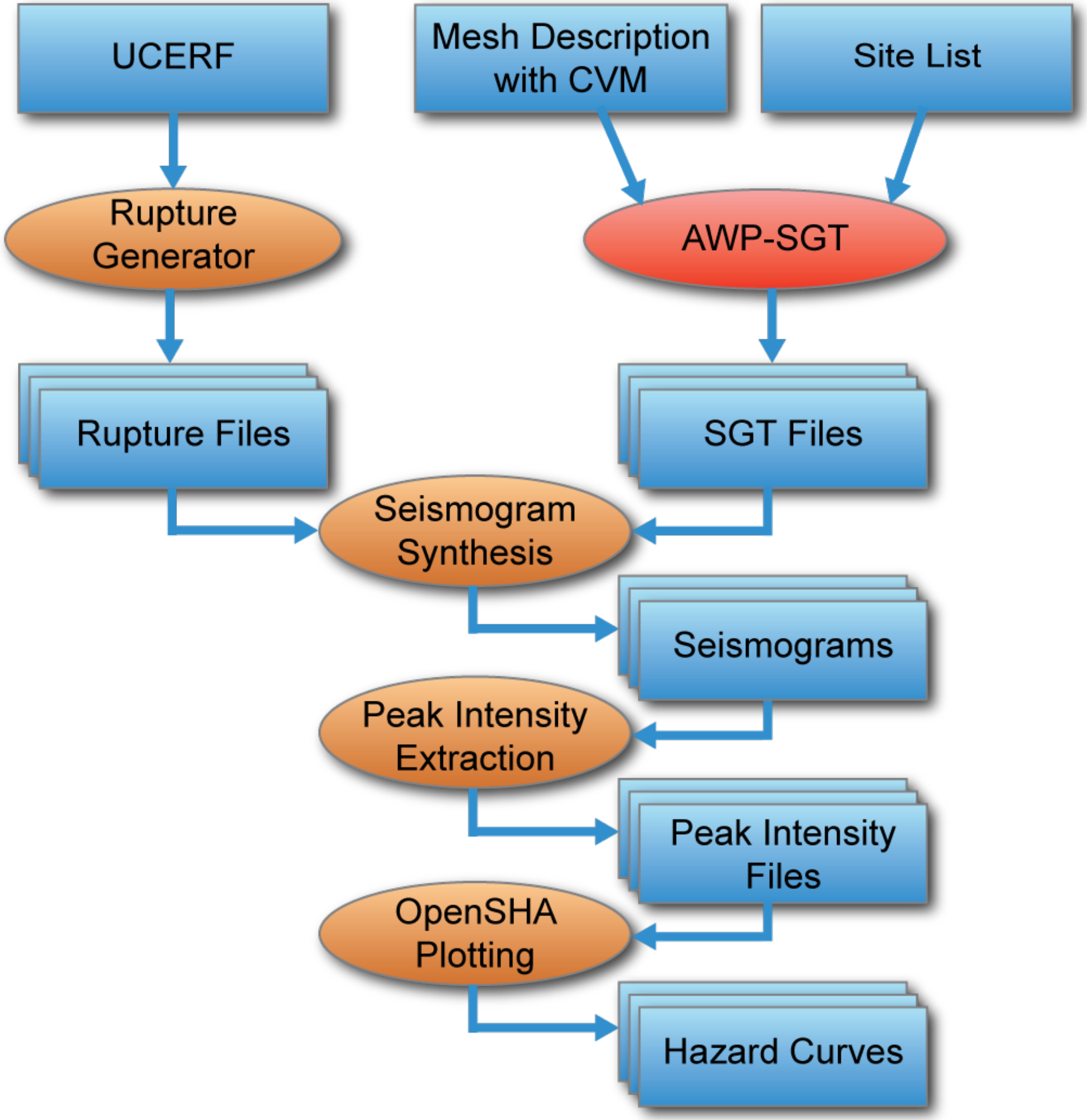
Southernmost San Andreas M7.7 (Olsen et al. 2008)

Structure of the CyberShake Hazard Model



Physics-Based Probabilistic Seismic Hazard Analysis




UCERF
Mesh Description with CVM
Site List
Rupture Generator
AWP-SGT
Rupture Files
SGT Files
Seismogram Synthesis
Seismograms
Peak Intensity Extraction
Peak Intensity Files
OpenSHA Plotting
Hazard Curves

Workflow Tool Development to Support CyberShake

Enabling Large-scale Scientific Workflows on Petascale Resources Using MPI Master/Worker

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24 IN THE PAST HOURS	JOBS STARTED	JOBS QUEUED	JOBS COMPLETED
	1624	1848	1594

About Blue Waters

The Blue Waters project provides systems and support for petascale science and engineering. The Blue Waters supercomputer - one of the most powerful systems in the world - achieves sustained performance of 1 petaflop on a range of science and engineering codes and offers more than 25PB of usable storage. View complete system specs

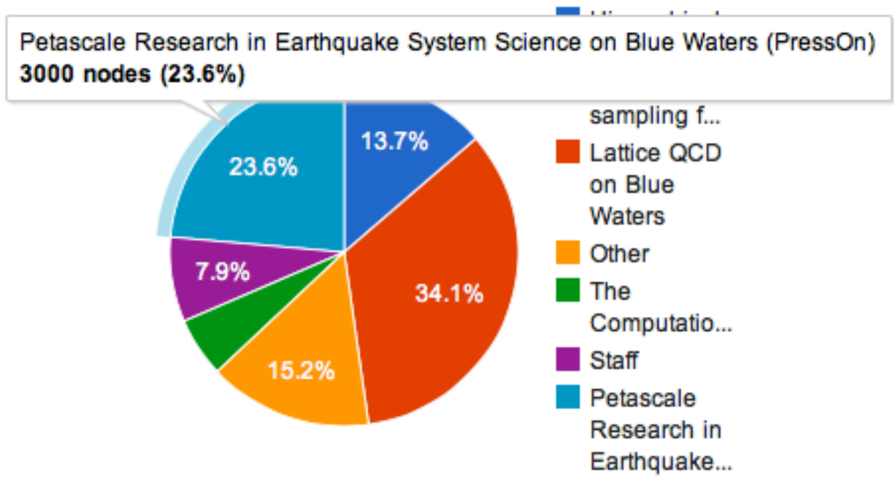
Blue Waters is supported by the National Science Foundation. Researchers can apply to use the system through NSF's Petascale Computing Resource Allocation process; time is also allocated by the Great Lakes Consortium and the University of Illinois at Urbana-Champaign.

The Blue Waters project also includes education and training activities and engagement with industry.

Find out more about the science and engineering impact of the Blue Waters project at https://bluewaters.ncsa.illinois.edu/impact-overview.

Questions? Contact help+bw@ncsa.illinois.edu .

Current Running Jobs



Agenda

- About the Southern California Earthquake Center
- Ground Motion Modeling Essentials
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Conclusions

- **Numerical simulations of large earthquakes have now advanced to the point where they can usefully predict the strong ground motions from anticipated earthquake sources.**
  - Collaboration with SCEC on use of simulations from USGS (ERF,PSHA), Energy Companies (high frequency simulations), and Building Code developers (PSHA)
- **Current PSHA production runs are smaller than scientific goals**
  - Simulation region will expand from 200 (Los Angeles area) to 5000 sites (California)
  - Simulation frequency will increase from 0.5Hz to 1.0Hz (typically a factor of 16 to double simulation frequency with current FD codes)
  - Dynamic ruptures will be used to generate rupture variations
- **SCEC and ALCF should continue to collaborate on producing these new seismic hazard data products.**
  - SCEC INCITE 2013 award (CyberShake 3.0) proposes a 1Hz California Hazard Map.
  - Practical solutions are needed to keep the computational cost within practical limits

End