

HPC Use for Earthquake Research

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Executive Science Director for Special Projects

Southern California Earthquake Center (SCEC)

Thank to T. Jordan, P. Maechling, Y. Cui, S. Callaghan, K. Milner, K. Olsen and others

Southern California Earthquake Center (SCEC)

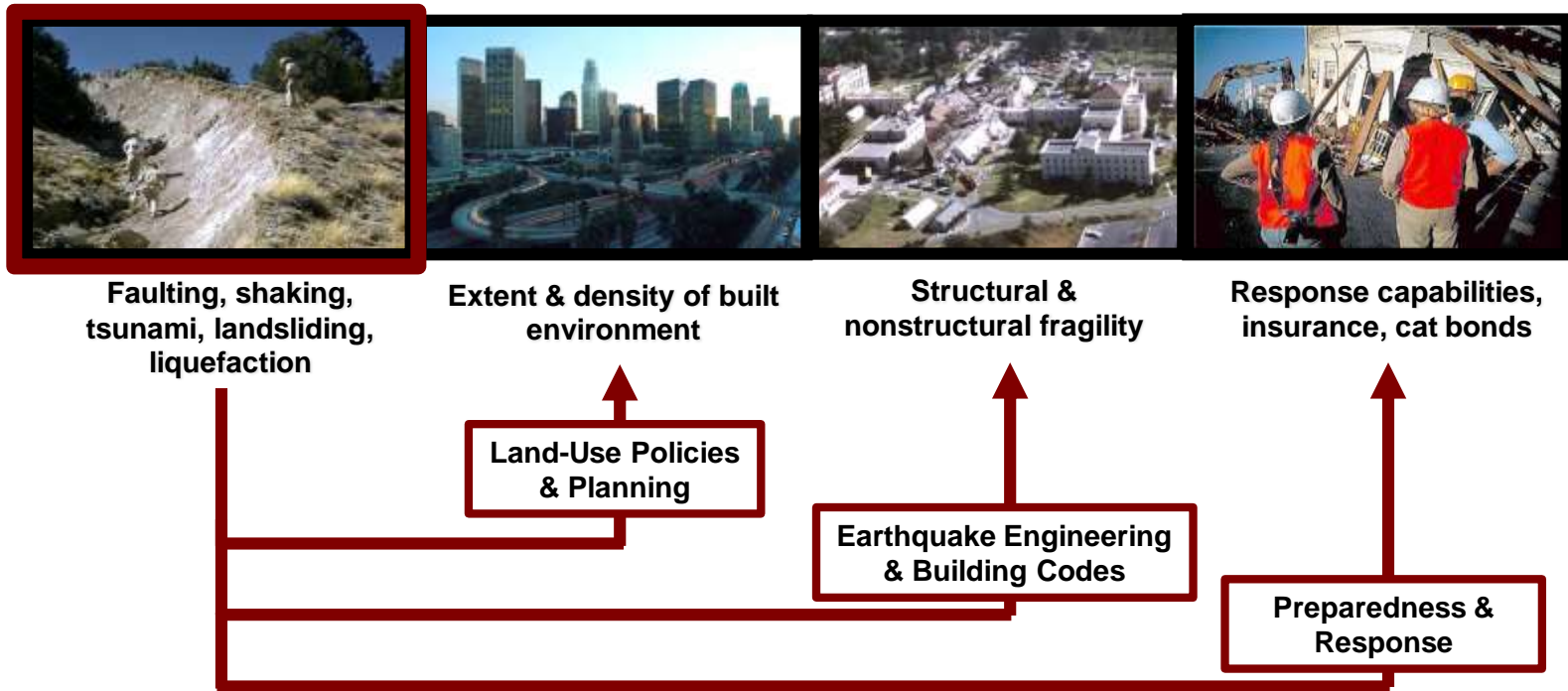
- **Mission: solve problems in earthquake system science**
 - Understand and model the physics of earthquake processes, from tectonic stress to fault rupture to ground motions
 - Use SoCal as our natural laboratory
- **Large collaborative center**
 - Multi-disciplinary Planning Committee develops yearly 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**

SCEC Institutions



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

Hazard × Exposure × Vulnerability ÷ Resilience



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

Conclusion: a paradigm shift for better resilience

Risk reduction can be achieved by

- Making risk-informed decisions (design engineers, society)
- Prioritizing risk-informed research topics: improve hazard assessment where it matters most (researchers)

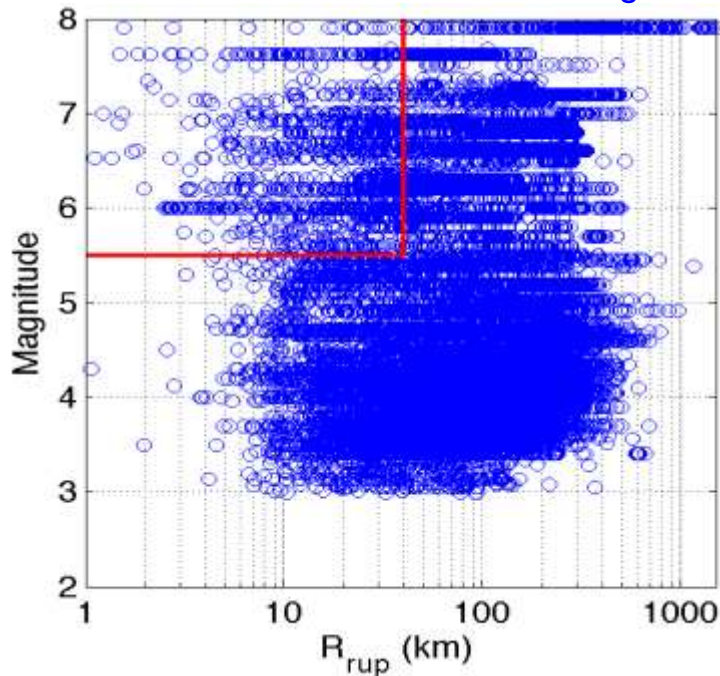
Hazard assessment will improve by

- Using validated physics-based simulation models to learn about earthquake processes
- Reducing epistemic uncertainty
 - Collect more data
 - Refine and validate models
 - Quantify uncertainty and its range

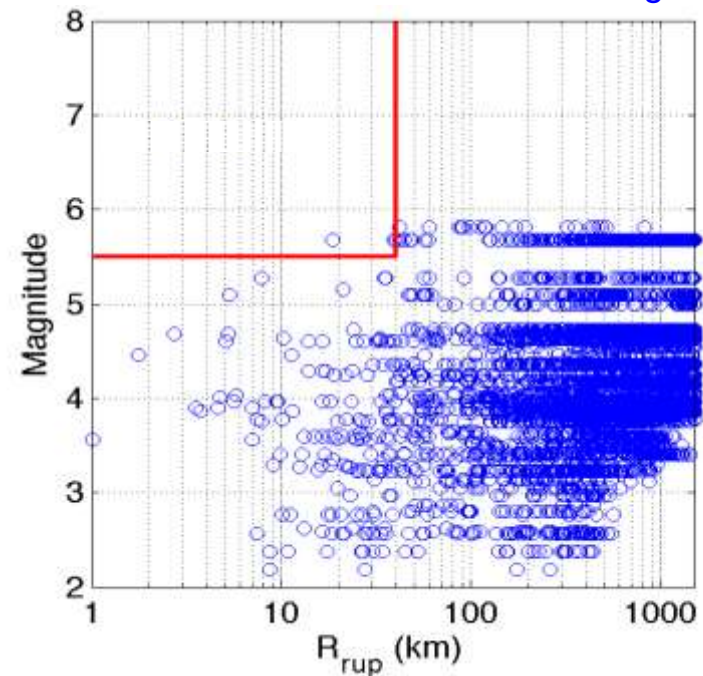
Immediate motivation

- Limited recorded datasets... Most complete record databases by PEER (UC Berkeley)

NGA-West2: CA and similar tectonic regions

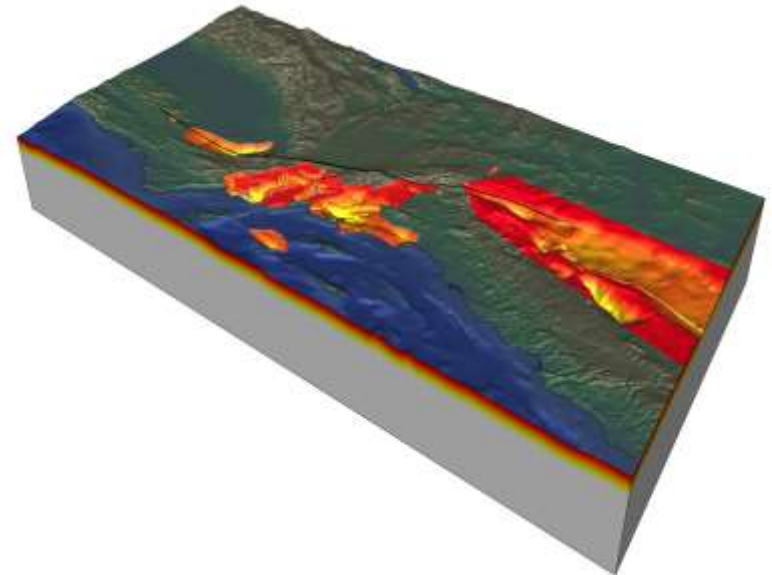
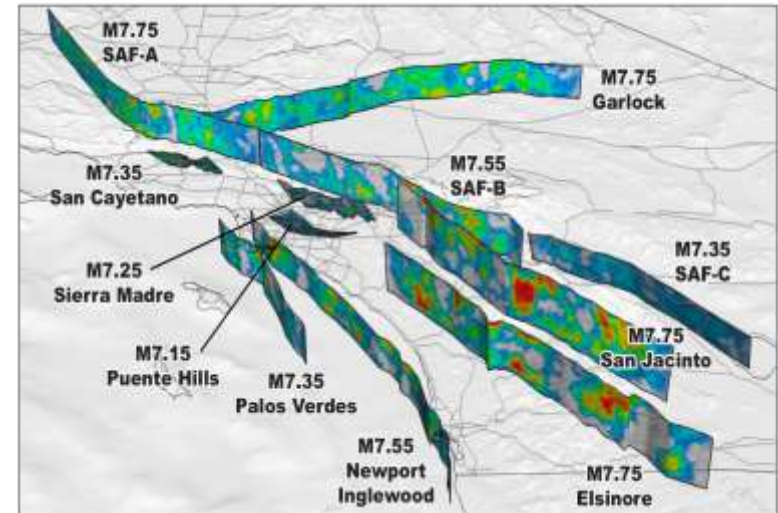


NGA-East: CEUS and similar tectonic regions



Essential Ingredients for Ground Motion Computations

1. **Earthquake rupture forecasts (ERFs)**
 - detailed representation of fault geometry
 - rupture models that capture the complexities of dynamic fault failure
 - Long-term rate of earthquakes
2. **3D models of geologic structure**
 - large-scale crustal heterogeneity
 - sedimentary basin structure
 - shallow site properties
3. **Calculation of wave propagation and attenuation**
 - efficient anelastic wave propagation codes
 - nonlinear models of near-surface response



ShakeOut Scenario

M7.8 earthquake simulation on Southern San Andreas Fault
(deterministic band $f = 0-1$ Hz; stochastic band $f = 1-10$ Hz)

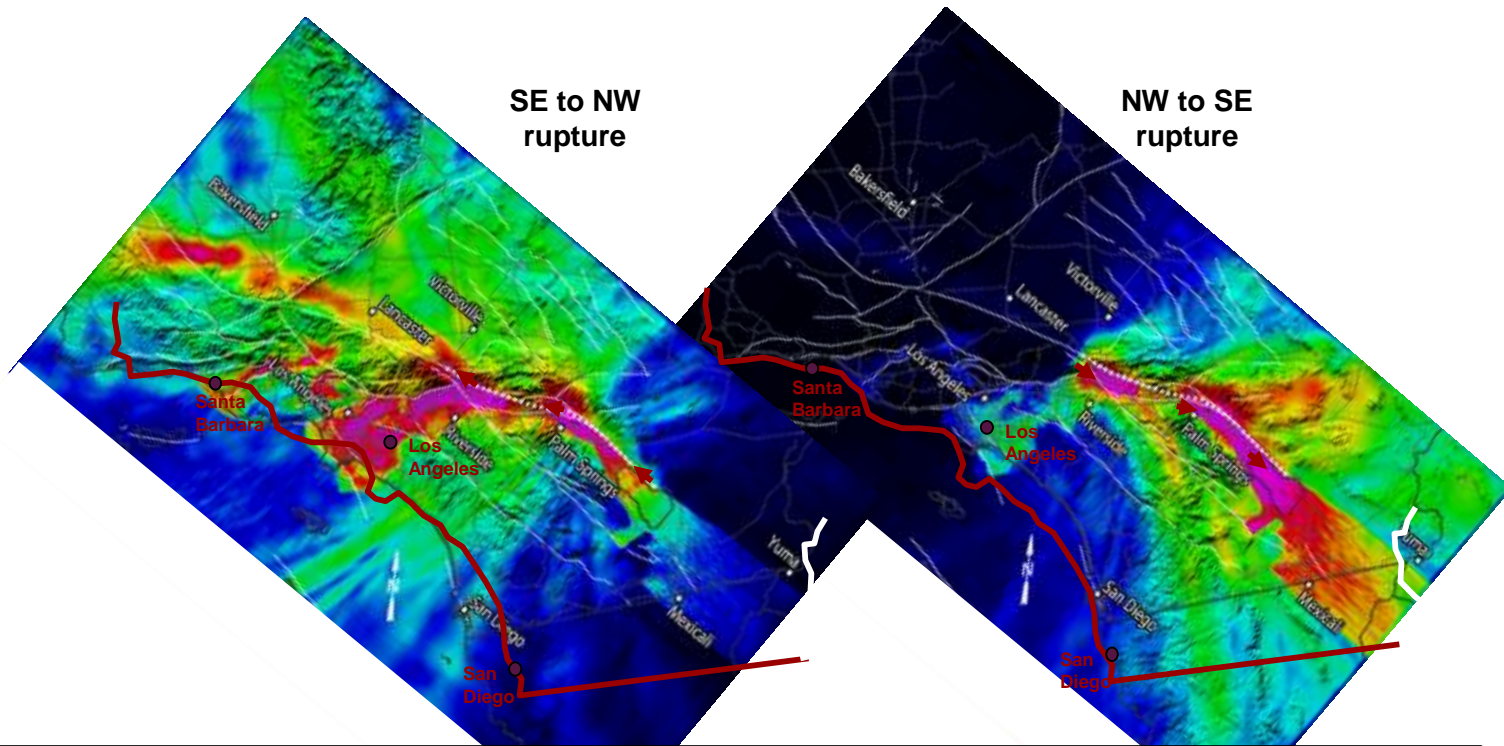


ShakeOut Scenario

M7.8 earthquake simulation on Southern San Andreas Fault
(deterministic band $f = 0-1$ Hz; stochastic band $f = 1-10$ Hz)



TeraShake Simulations of M7.7 Earthquake on the San Andreas Fault



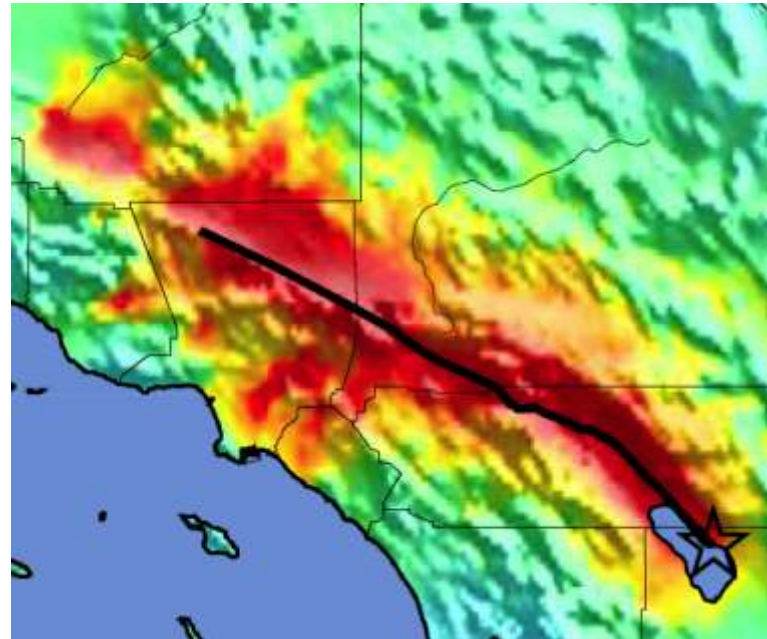
Simulations indicated strong 3D focusing of ground motions from strike-slip faults in Southern California
Quantified the importance of source directivity and basin excitation effects in earthquake forecasting and PSHA

The ShakeOut Scenario

M7.8 Earthquake on Southern San Andreas Fault

Scenario Results

- M7.8 mainshock
 - Broadband ground motion simulation (0-10 Hz)
- Large aftershocks
 - M7.2, M7.0, M6.0, M5.7...
- 10,000-100,000 landslides
- 1,600 fire ignitions
- \$213 billion in direct economic losses
 - 300,000 buildings significantly damaged
 - Widespread infrastructure damage
 - 270,000 displaced persons
 - 50,000 injuries
 - 1,800 deaths
- Long recovery time



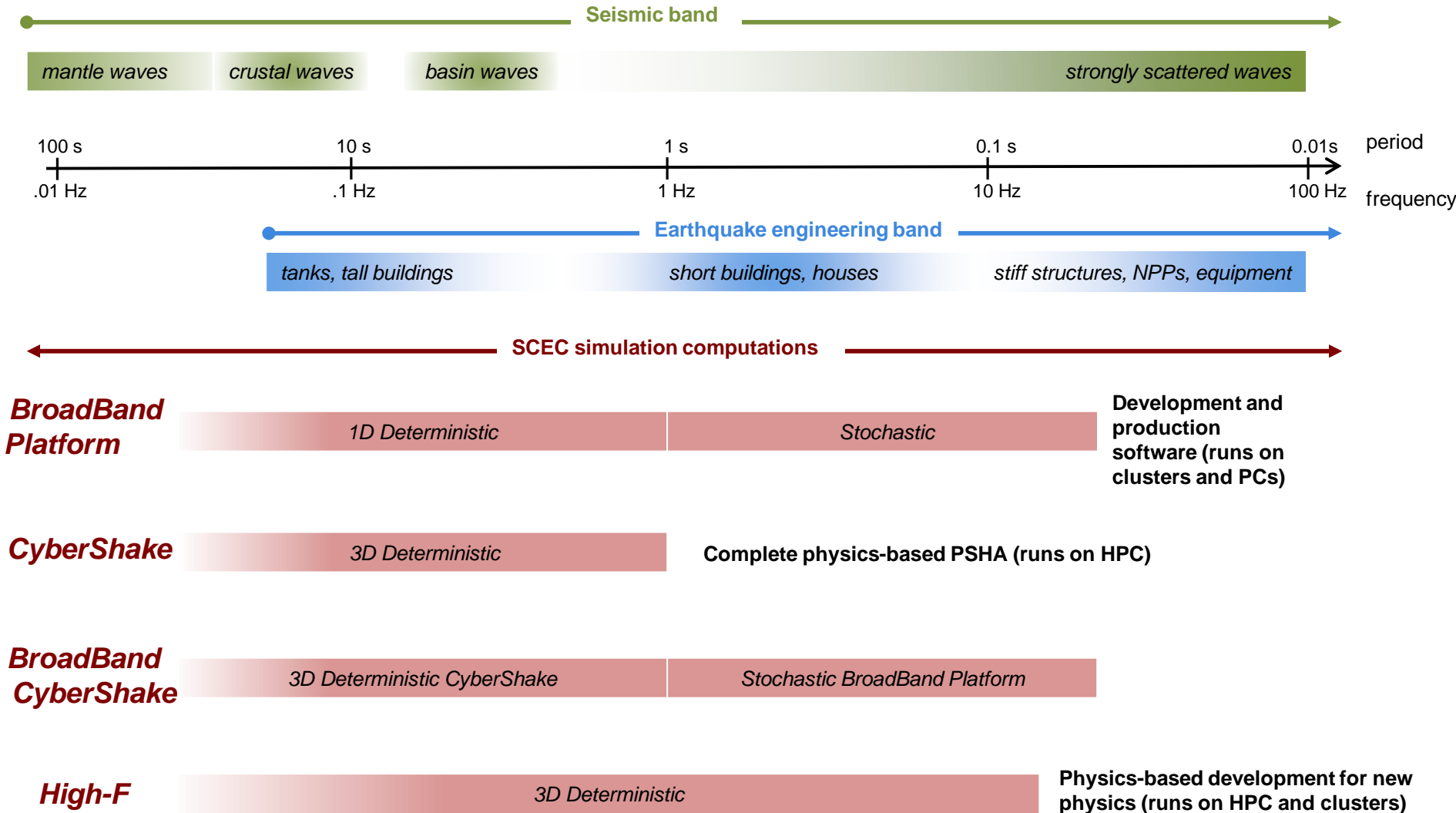
shaking intensity

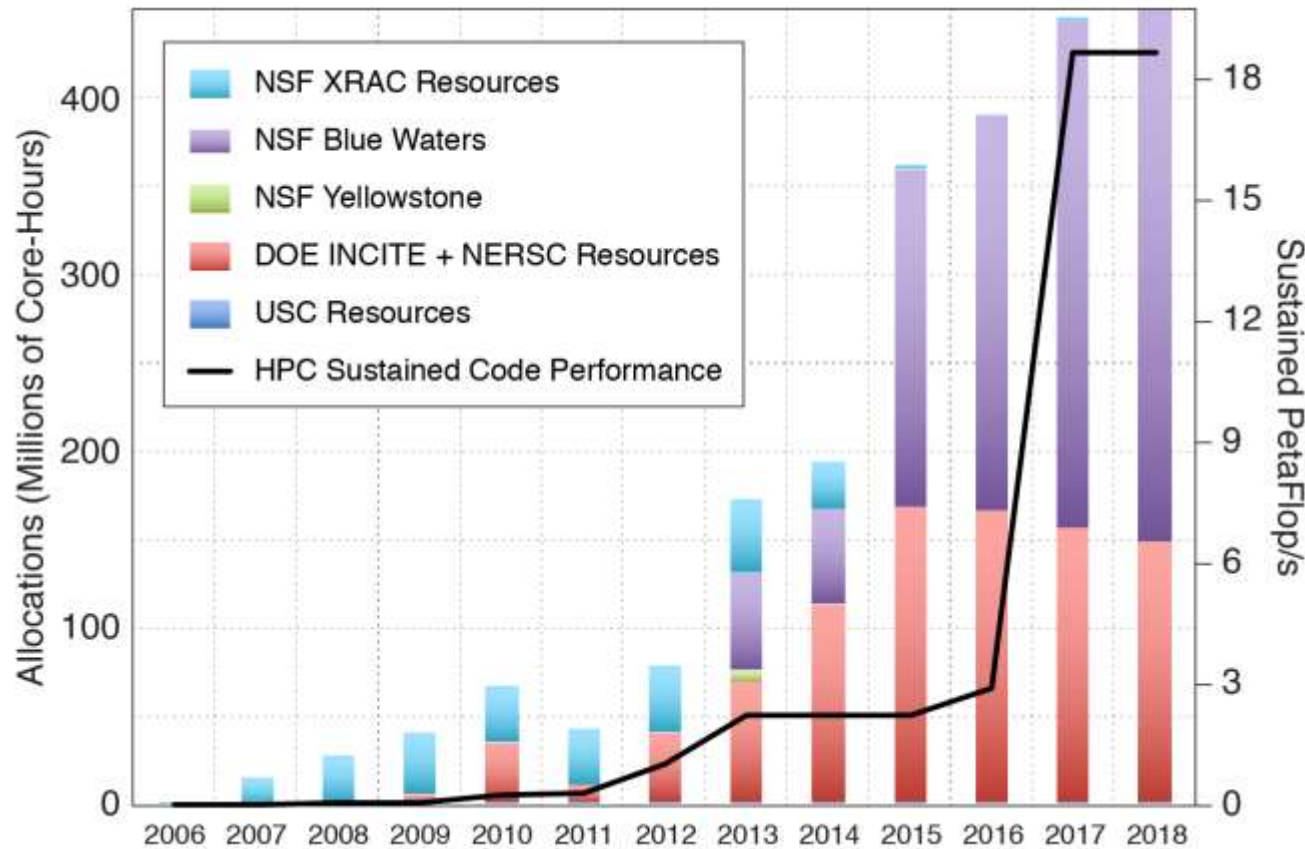
*Great Southern California
ShakeOut*

Exercise Impacts

- Largest emergency response exercise in US history
- Demonstrated that existing disaster plans are inadequate for an event of this scale
 - Motivated reformulation of system preparedness and emergency response
- Scientific basis for the LA Seismic Safety Task Force report, *Resilience by Design*

SCEC ground-motion simulation platforms





Broadband Platform (BBP)

BBP is an open-source distribution

Broadband 0.1-20+ Hz (deterministic up to ~ 1Hz)

Simple source and path (1D)

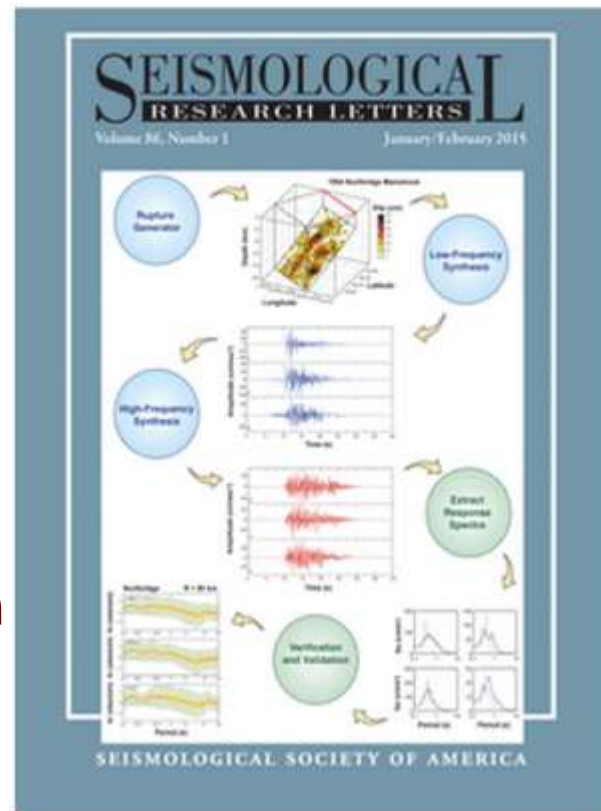
7 alternative simulation codes

Fully validated for spectral response 

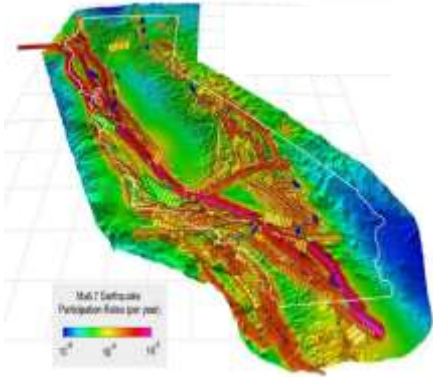
- 1.5 year validation project
- Multiple rounds of validation/improvements
- Independent review panel

Continuation of work in 2018

Used for large ground motion characterization projects

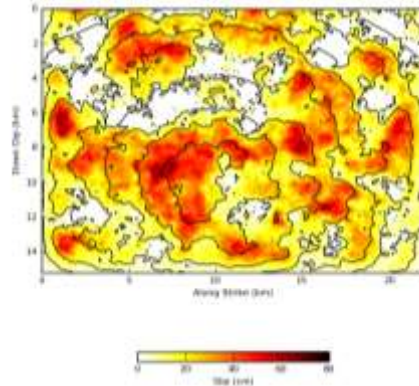


CyberShake: PSHA from Physics-Based Simulations



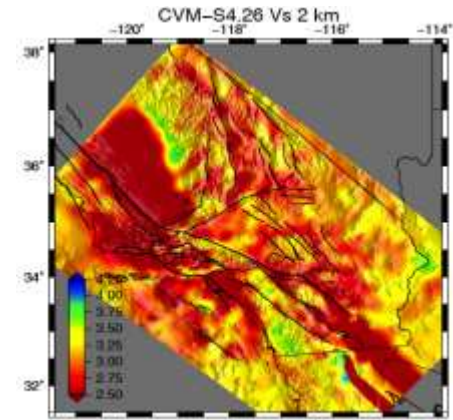
Earthquake Rupture Forecast
(e.g. UCERF)

+



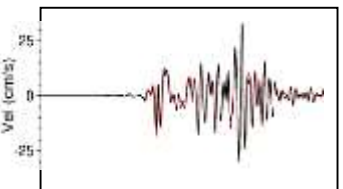
Kinematic source models

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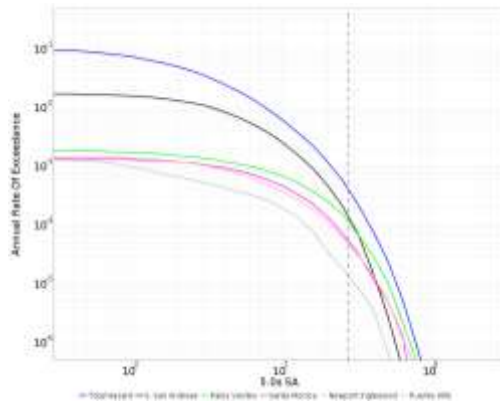


3D velocity model (from F3DT)

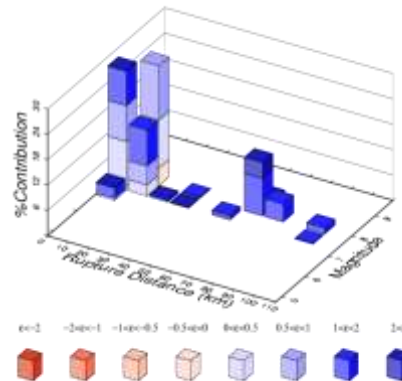
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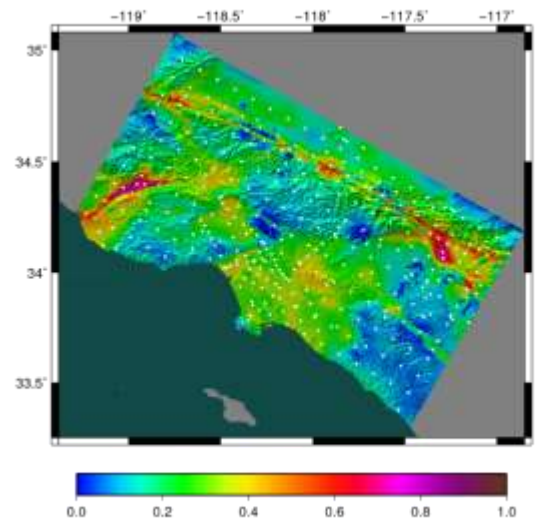
Seismograms
and intensity measures



Hazard Curves and
fault disaggregation



M, R, ϵ
disaggregation



Hazard maps

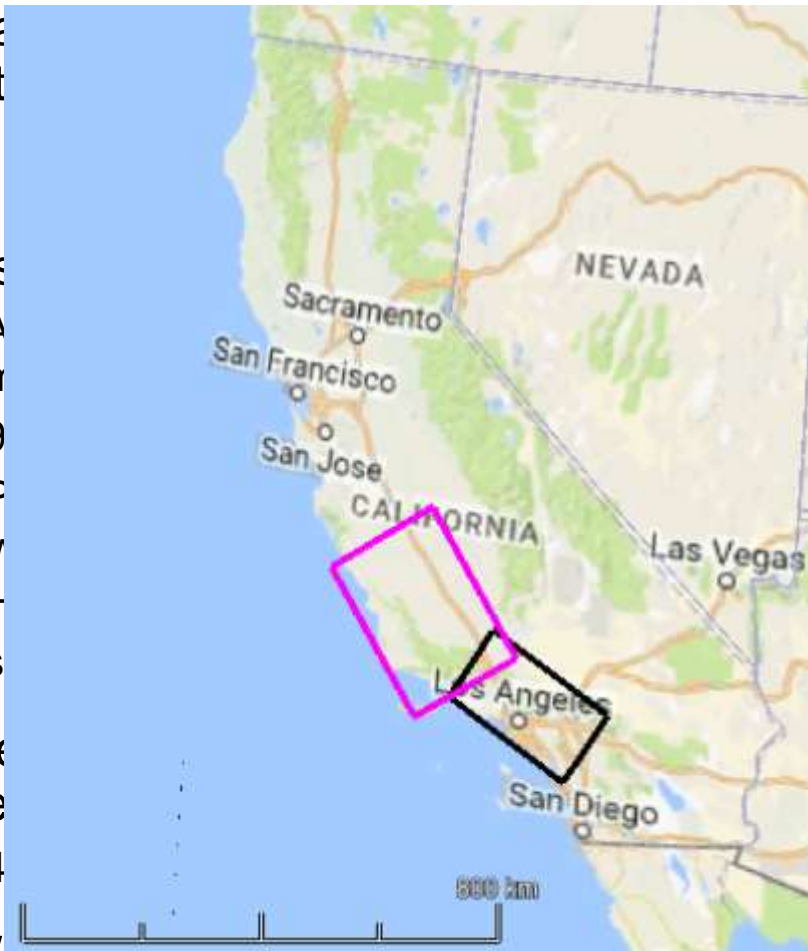
CyberShake Study 17.3, Central CA

- Ca
sit
- each of 438
quakes

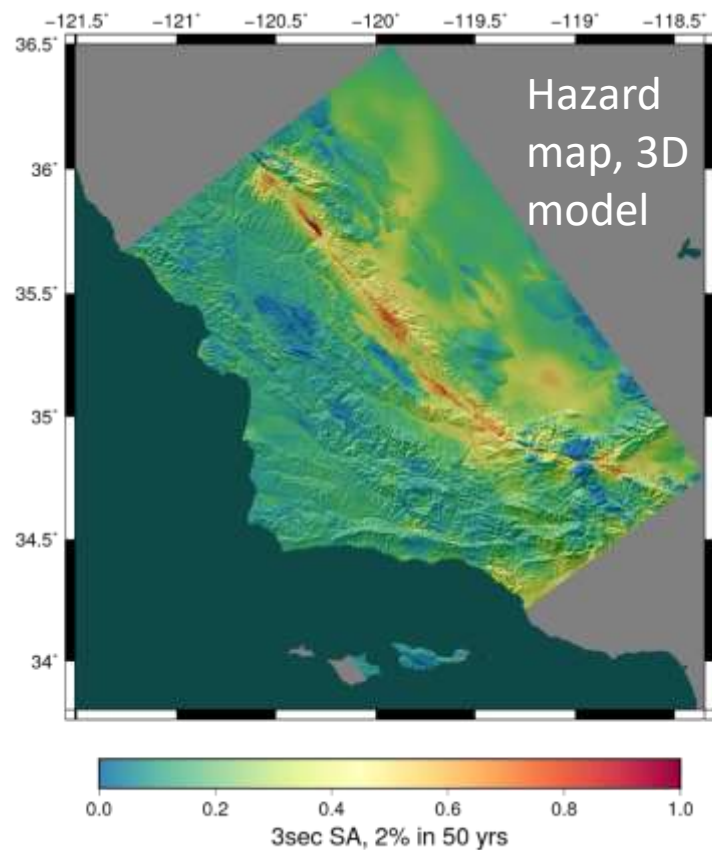
- Us
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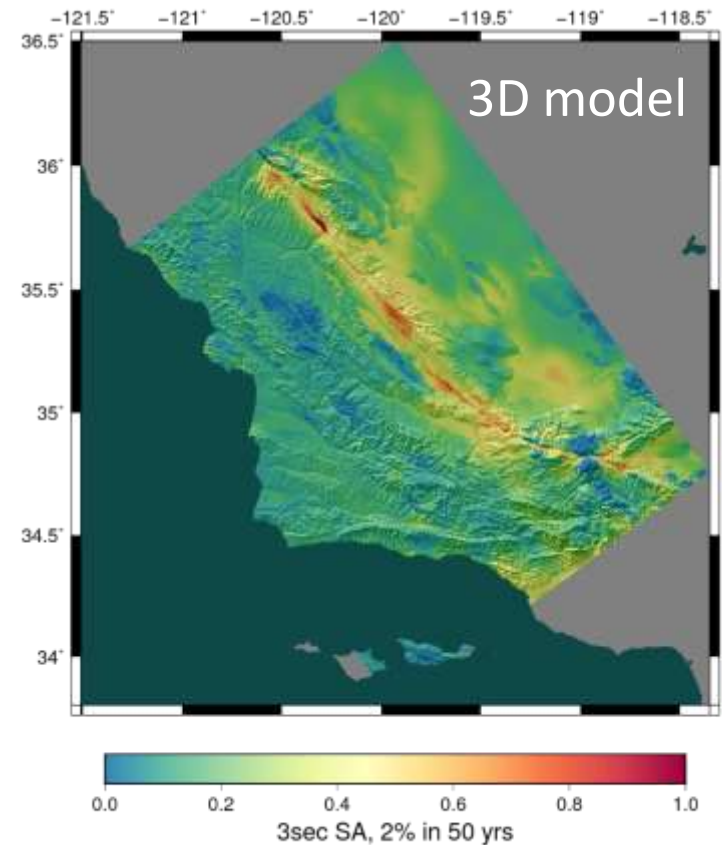
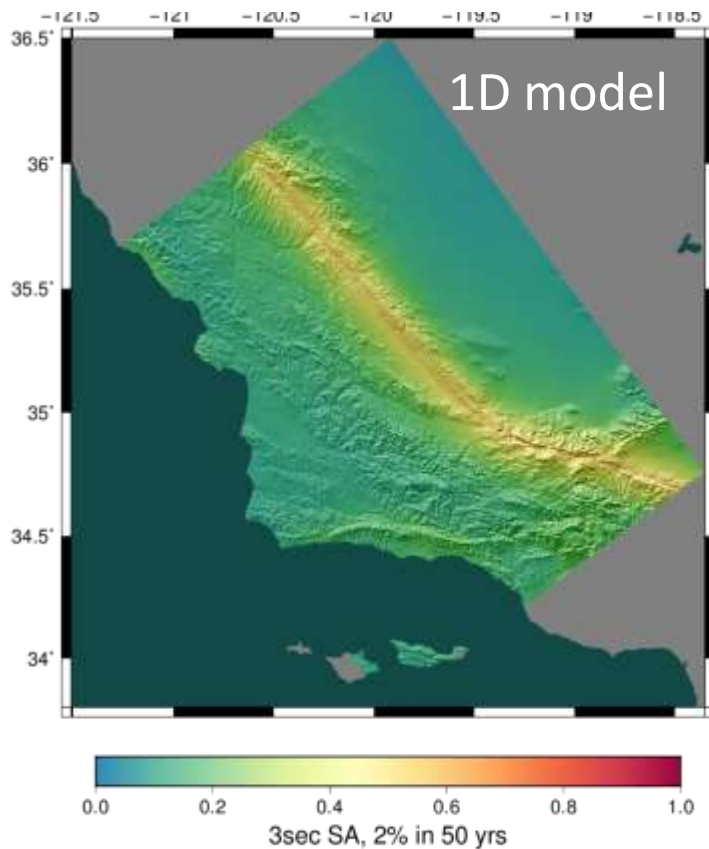
- Workflows managed 777 TB of data
- 10.7 TB of output data automatically staged back for archival storage



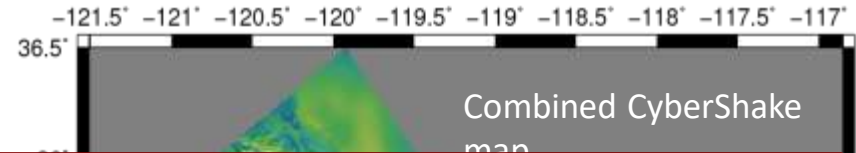
- 1000s
- days,
- (hours)
- flows
- h systems
- between the two



CyberShake Study 17.3 Results: Velocity Model Comparison

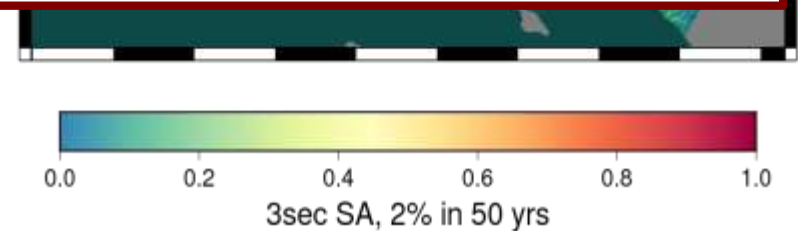
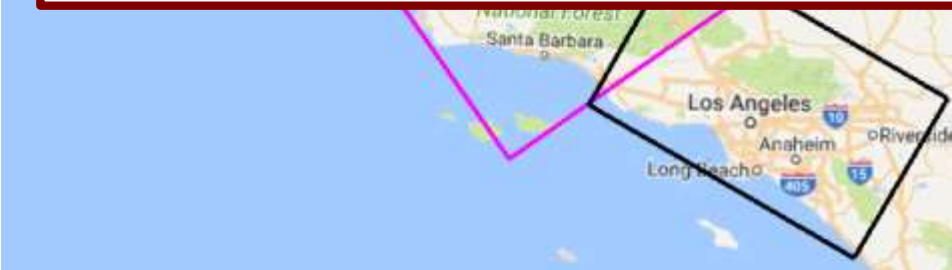


CyberShake Study 17.3 Results: CCA and LA



CyberShake

- First simulation-based PSHA model
- Used as database for machine-learning of California Earthquake Early Warning system
- Leading model in USGS Urban Seismic Hazard Mapping Project
- Source of new design maps under consideration by building code update



High-F Project

Pushing deterministic ground-motion simulations to higher frequencies ($\sim 10\text{Hz}$) while

- Improving improving computational efficiency
- Adding more realistic physics:
 - fault roughness
 - near-fault plasticity
 - frequency-dependent attenuation
 - topography
 - small-scale near-surface heterogeneity
 - near-surface nonlinearity

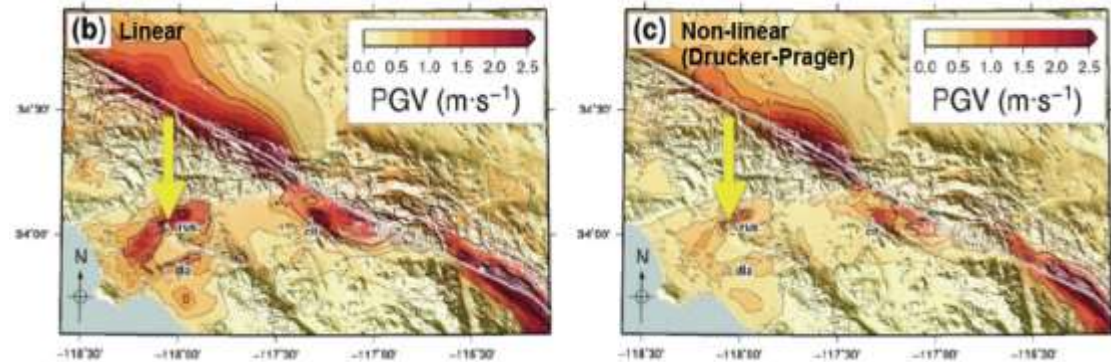


Image: Roten et al. 2015

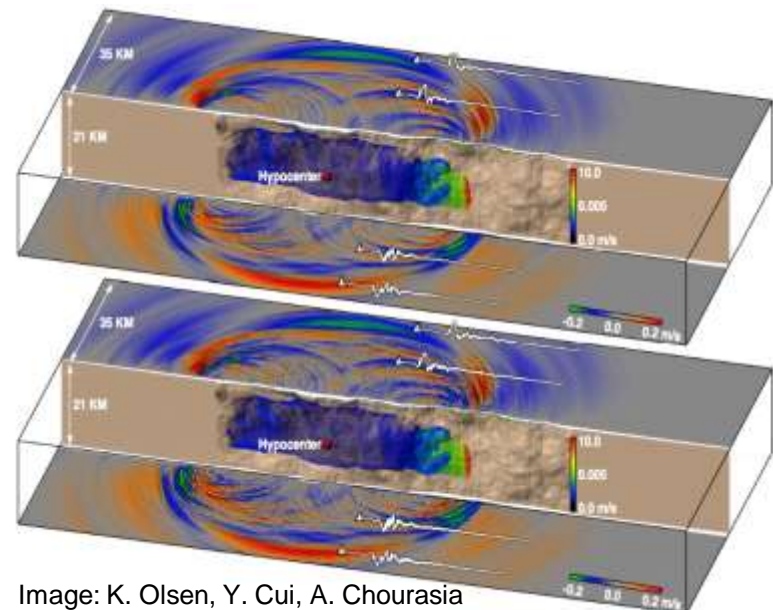
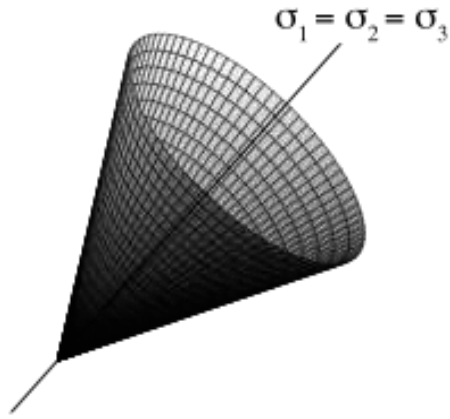


Image: K. Olsen, Y. Cui, A. Chourasia

Including plasticity in near-fault material

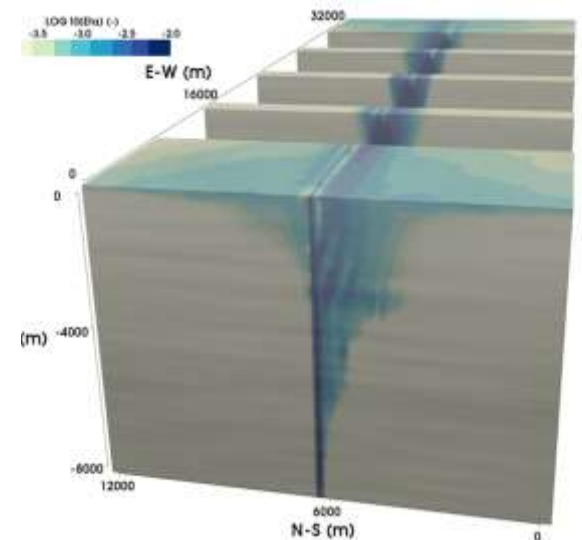
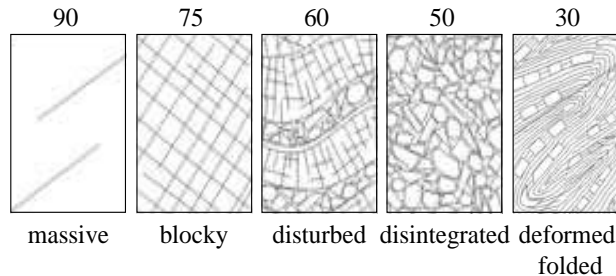
3D Drucker-Prager plasticity with parameters from Hoek-Brown rock strength criterion include in AWP-ODC (GPU and CPU versions on BW)



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: $m_i \approx 25$

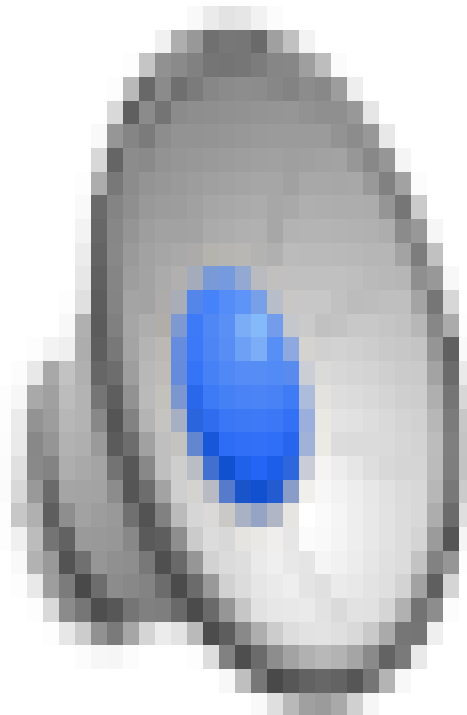
c_i : tables with range of values by rock type
 empirical equations (e.g., Chang, 2006)
 descriptive grades (Brown, 1981), field estimates

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

ShakeOut with Drucker-Prager Plasticity (Roten et al., 2016)



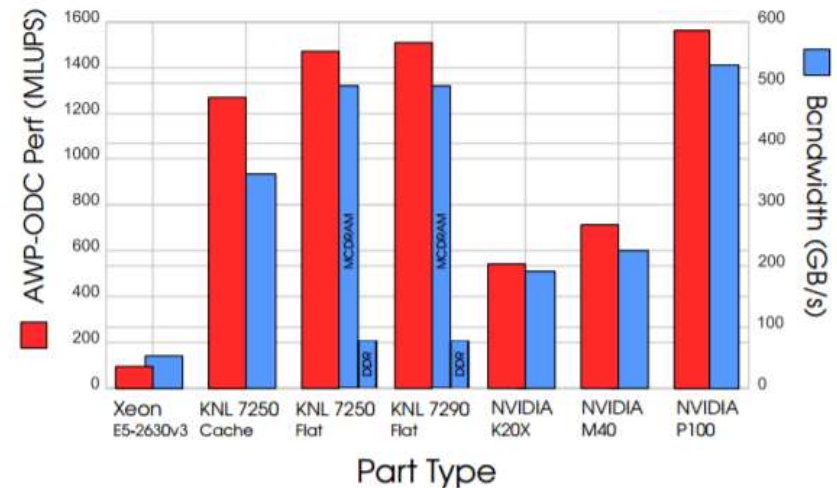
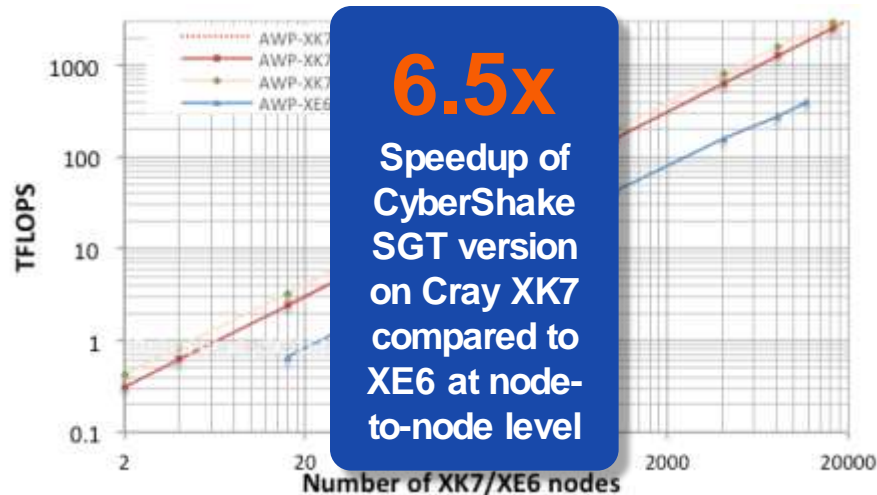
AWP-ODC

NVIDIA GPUs

- A first 4-Hz nonlinear M7.7 earthquake simulation on the southern San Andreas Fault conducted using 4,200 Blue Waters GPUs
- 100% of parallel efficiency achieved for both linear/ nonlinear versions of AWP-ODC up to 8,192 GPUs
- Accelerated time-to-solution from original nonlinear 0.68sec to 0.29sec per iteration
- Blue Waters PAID project provided additional support.

Intel Xeon Phi

- **Mega Lattice Updates per Second (MLUPS):** Xeon Phi KNL 7290 achieves 2x speedup over NVIDIA K20X, 97% of NVIDIA Tesla P100 performance
- **Performance on 9,000 nodes of Cori-II equivalent to performance of over 20,000 K20X GPUs at 100% scaling**
- **Open Source:**
<https://github.com/HPGeoC/awp-odc-os>



SDSC Achieves Record Performance in Seismic Simulations With Intel

March 7, 2017

March 7 — Researchers at the San Diego Supercomputer Center (SDSC) at the University of California San Diego have developed a new seismic software package with Intel Corporation that has enabled the fastest seismic simulation to-date, as the two organizations collaborate on ways to better predict ground motions to save lives and minimize property damage.

AWP-ODC on Sunway TaihuLight

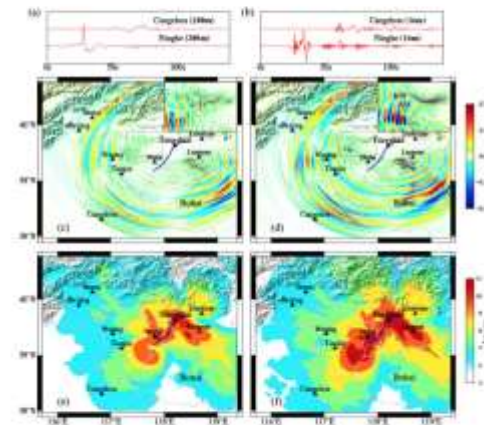
- Tsinghua University/Wuxi SC Center ported open source AWP-ODC using Sunway OpenACC and fully optimized the code on TaihuLight
- Sustained 15-Pflop/s or 12.5% of the peak achieved, a ACM Gordon Bell Finalist in 2017
- 1976 Mw7.2 Tangshan earthquake scenario and high-fidelity simulation using 10 million cores
 - A spatial resolution of 25m
 - 320km x 320km x 60km
 - Frequency of up to 10Hz
 - Included non-linear near-fault physics

(Haohuan Fu, Conghui He, Bingwei Chen, Zekun Yin, Zhenguo Zhang, Wenqiang Zhang, Tingjian Zhang, Wei Xue, Weiguo Liu, Wanwang Yin, Guangwen Yang, Xiaofei Chen (2017) 15-Pflops Nonlinear Earthquake Simulation on Sunway TaihuLight: Enabling Depiction of Realistic 10 Hz Scenarios, SC'17, Nov 13-16, Denver, 2017)

Earthquake Codes Developed by SDSC, SDSU, SCEC Used in 2017 Gordon Bell Prize Research

Chinese Team Recognized for Simulating 20th Century's Most Devastating Earthquake

Published December 4, 2017



Simulated ground motions of the 1976 Tangshan earthquake that resulted in a 12-member team of Chinese researchers being awarded the 2017 Gordon Bell prize. Image courtesy of Haohuan Fu, Tsinghua University, et al.

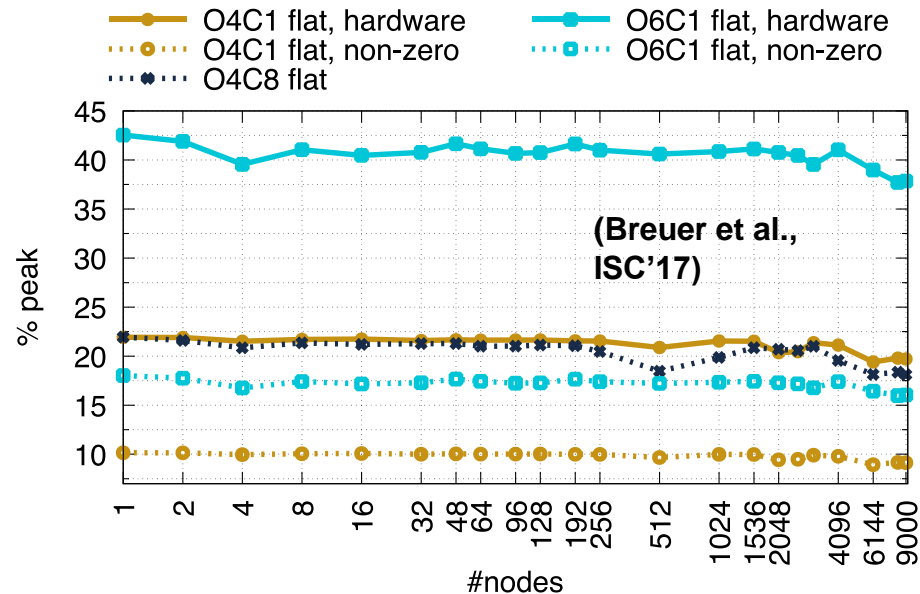
for 'Anelastic Wave Propagation, Olsen, Day, and Cui.'

A Chinese team of researchers awarded this year's prestigious Gordon Bell prize for simulating the devastating 1976 earthquake in Tangshan, China, used an open-source code developed by researchers at the San Diego Supercomputer Center (SDSC) at UC San Diego and San Diego State University (SDSU) with support from the Southern California Earthquake Center (SCEC).

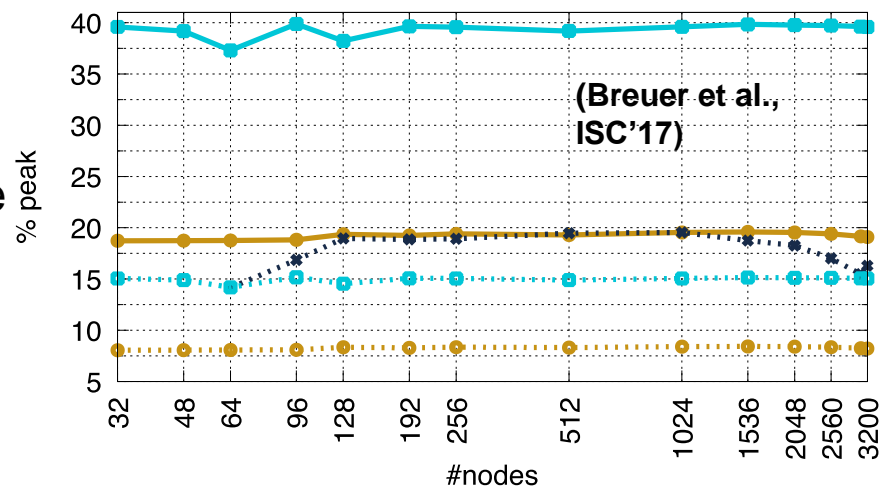
"We congratulate the researchers for their impressive innovations porting our earthquake software code, and in turn for advancing the overall state of seismic research that will have far-reaching benefits around the world," said Yifeng Cui, director of SDSC's High Performance Geocomputing Laboratory, who along with SDSU Geological Sciences Professor Kim Olsen, Professor Emeritus Steven Day and researcher Daniel Roten developed the AWP-ODC code, which stands

EDGE Achieved 10.4 DP-PFLOPs on Cori Phase 2

- **Extreme-scale Discontinuous Galerkin Environment: Seismic wave propagation through DG-FEM**
- **Focus: Problem settings with high geometric complexity**
- **Fused simulations to explore inter-simulation parallelism**
- Tuned for Haswell, Knights Landing, Skylake, and Knights Mill through LIBXSMM library
- Cori Phase 2 weak scaling: **Sustained 10.4 DP-PFLOPs (38% of peak)**
- Theta strong scaling: Sustained 3.4 DP-PFLOPs (40% of peak) for a 100x increase in node count
- Open Source: <http://dial3343.org>
- **Collaboration of SDSC, Intel, and SCEC through Intel PCC program**



Weak scaling study on **Cori-II**. Shown are hardware and non-zero peak efficiencies in flat mode. O denotes the order and C the number of fused simulations.



Strong scaling study on **Theta**. Shown are hardware and non-zero peak efficiencies in flat mode. O denotes the order and C the number of fused simulations.

Takeaways

- Ground motions simulations on HPC are a great learning tool for scientific research
- Simulations are already impacting design, improved hazard will help us to reduce seismic risk
- Continuous development needed
- Collaboration is essential

What's next?

- Replace ERF with earthquake simulator
- Go to up to higher frequencies, extend the range of applications
- Test and implement additional physics
- Formally evaluate uncertainties
- Use simple models as benchmarks in the evaluation of complex models
- Validate, validate, validate...



Partial list of collaborators:

*T. H. Jordan, P. J. Maechling], Y. Cui,
S. Callaghan], K. Olsen, R. Taborda,
J. Bielak, R. Graves, K. Milner, S. Day,
D. Roten,, F. Silva, E. Poyraz, J. Zhou,
A. Chourasia, K. Withers, W. Savran,
Z. Shi, E. Deelman, G. Juve, K. Vahi,
G. Bauer, J. Hill, A. Pope, H. Karaoglu,
Y. Isbilioğlu, D. Restrepo, A. Pitarka,
N. Abrahamson, R. Archuleta,
G. Atkinson, J. Crempien, S.K. Song,
D. Mu, A. Breuer , H. Miyake*

**Earthquakes – not a
question of if... but
when.**

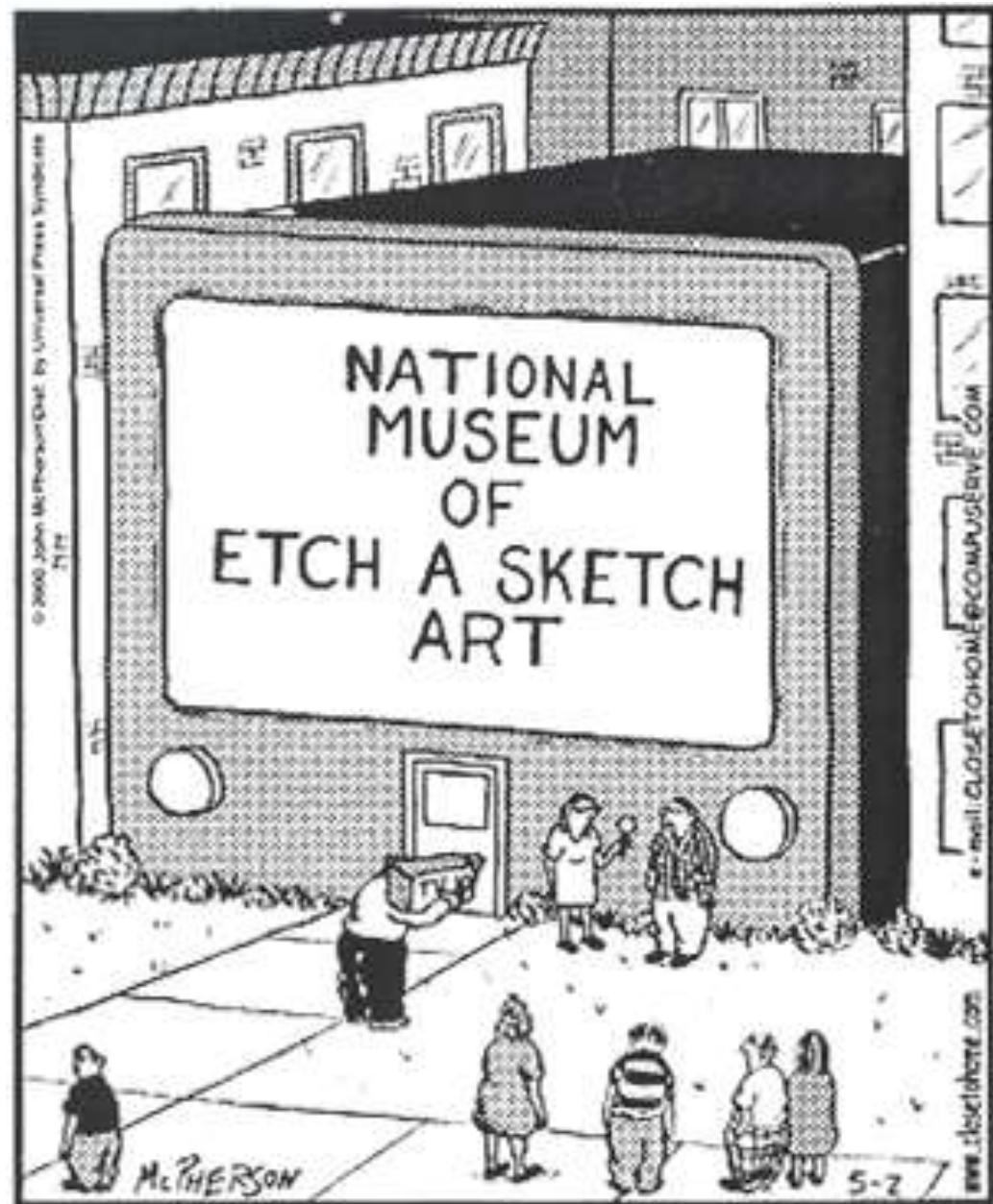
Thank you!

The image features a light green gradient background. At the bottom, there is a dark red silhouette of a city skyline with mountains in the background. The logo for the Southern California Earthquake Center is prominently displayed in the upper left. The logo consists of the letters 'SC' and 'EC' in a large, bold, serif font, with a diagonal slash between them. Below 'SC' is the text 'AN NSF+USGS CENTER'. To the right of the logo, the full name 'Southern California Earthquake Center' is written in a large, bold, italicized serif font.

SC/EC *Southern California*
AN NSF+USGS CENTER *Earthquake Center*

HPC User Forum April 17, 2018

Not all damage is structural...



"Structurally, the building is fine. But sadly, the earthquake destroyed all of our art pieces."

Resilience by Design

Report of the Los Angeles Mayoral Seismic Task Force (Lucy Jones, chair)

Released Dec 8, 2014

“This Report’s approach to evaluating the severity of the risk relies on the ShakeOut Scenario... created by a multidisciplinary team convened by the Multi-Hazards Demonstration Project of the USGS...”

Team included USGS, CGS, FEMA, SCEC, and nearly 200 other partners in government, academia, emergency response, and industry.

An ambitious plan to

- strengthen buildings
- fortify water supply and distribution system
- enhance reliable telecommunications

<http://www.lamayor.org/earthquake>

“Los Angeles will have the nation’s toughest earthquake safety rules” – *LA Times*

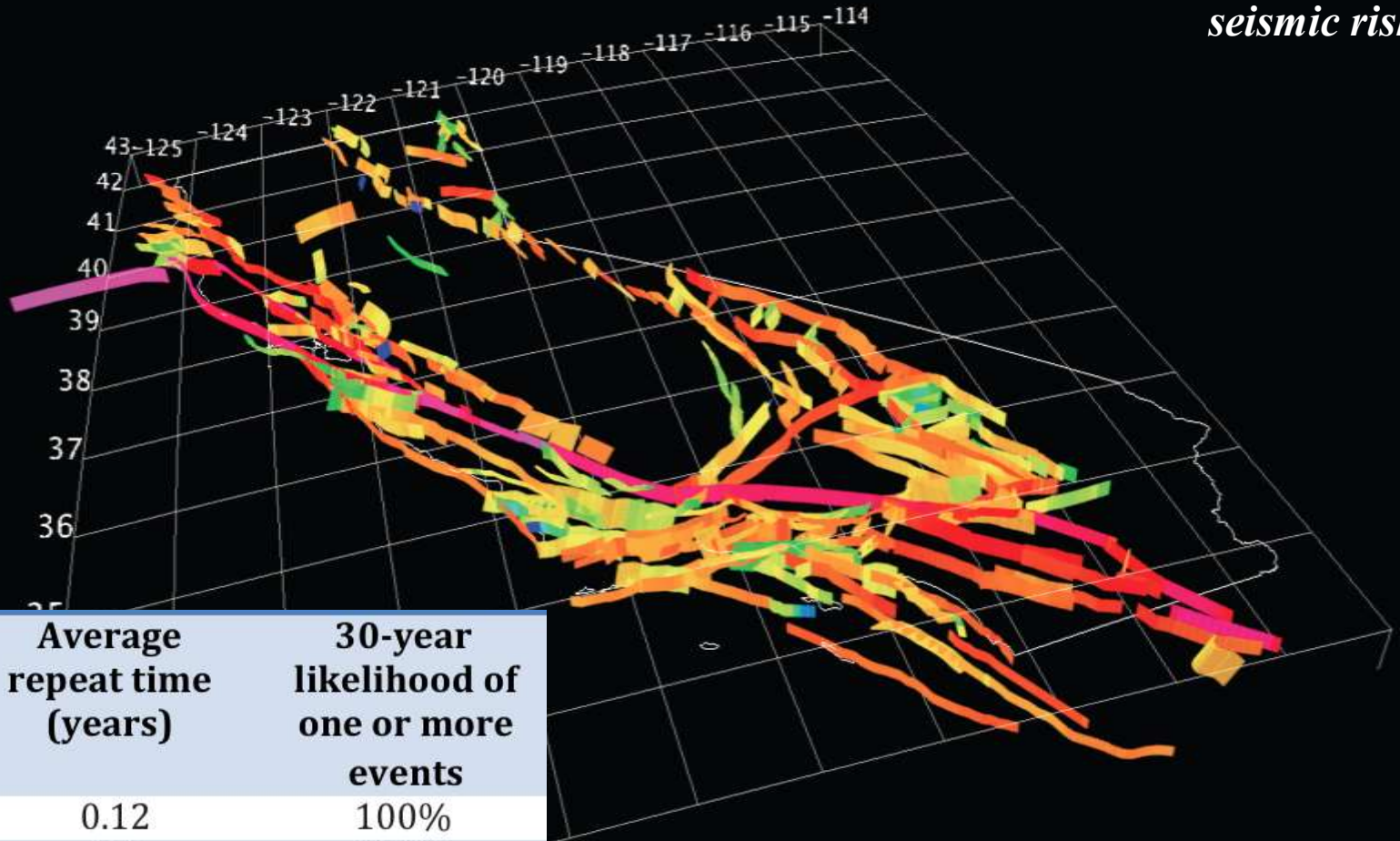


Resilience by Design



Not a question of “if”...

Future earthquakes in California constitute ~ 66% of the long-term national seismic risk



Magnitude (greater than or equal to)	Average repeat time (years)	30-year likelihood of one or more events
5	0.12	100%
6	1.2	100%
6.7	6.3	>99%
7	13	93%
7.5	52	48%
SCE8	494	7%