Societal Challenges for Seismology

Thomas H. Jordan

Director, Southern California Earthquake Center

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SCEC

an NSF+USGS center

Plan of Talk

- Framework for discussion of societal challenges
- Seismological applications as drivers of basic research
  1. Fluid migration in crustal reservoirs
     - Carbon sequestration at Sleipner field
  2. Nonlinear physics of strong surface motion
     - Extreme ground motions at the Yucca Mt. Nuclear Waste Respository
  3. Scenario building for disaster response
     - The Great Southern California ShakeOut
  4. Physics-based probabilistic seismic hazard analysis (PSHA)
     - CyberShake simulation platform
  5. Mapping strong heterogeneities in the upper crust
     - Full 3D waveform tomography
- Conclusions

Seismology

from the Greek *seismos* (*σεισμός*) = earthquake and *logos* (*λόγος*) = knowledge

- K. Aki & P. G. Richards, *Quantitative Seismology*, p. 1, 1980:

  "Seismology is the scientific study of mechanical vibrations of the Earth."

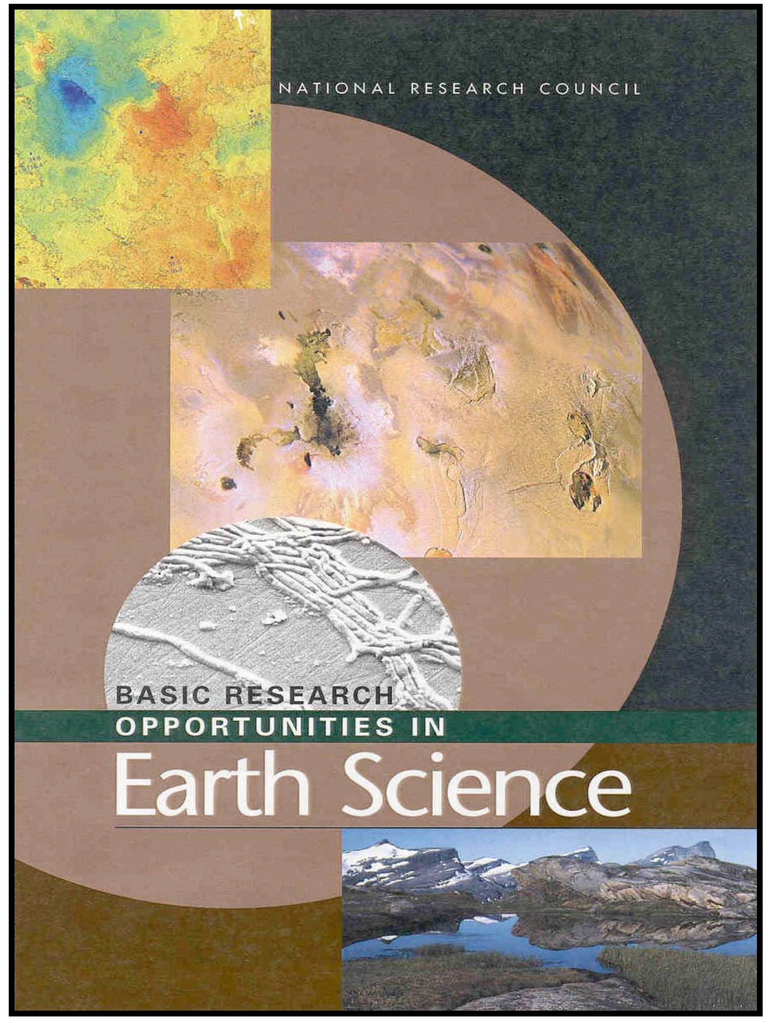
- Wikipedia, 2008:

  "Seismology is the scientific study of earthquakes and the propagation of elastic waves through the Earth. The field also includes studies of earthquake effects, such as tsunamis as well as diverse seismic sources such as volcanic, tectonic, oceanic, atmospheric, and artificial processes (such as explosions). A related field that uses geology to infer information regarding past earthquakes is paleoseismology."

NRC Committee on Basic Research Opportunities in Earth Science (BROES, 2001)

This decadal report lists five main societal challenges for Earth Science:

1. **Discovery, use, and conservation of natural resources**
2. **Characterization and mitigation of natural hazards**
3. **Stewardship of the environment**
4. **Geotechnical support for commercial and infrastructure development**
5. **Terrestrial surveillance for global security and national defense**



http://books.nap.edu/books/030907133X/html/index.html

Seismology contributes tools and knowledge to meet all five of these challenges…

1. **Natural resources**
   – discovery, use, and conservation fossil fuels, minerals, water
2. **Natural hazards**
   – characterization and mitigation of earthquakes, volcanic eruptions, and landslides
3. **Natural environment**
   – environmental protection and remediation of damage
   – monitoring of global change
   – carbon sequestration
4. **Built environment**
   – design of sustainable cities and global infrastructure
   – engineering of resilient communities
5. **Global security**
   – monitoring of nuclear and conventional explosions

Three subfields of seismology; their goals and subjects of study…

A. Source seismology

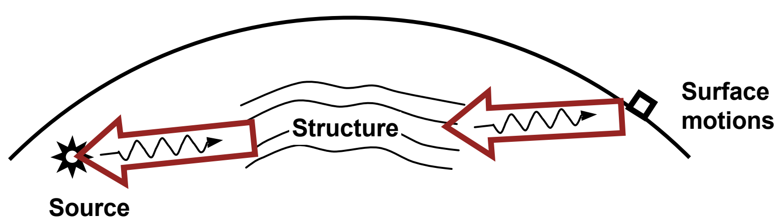
- Detect, characterize, monitor, and predict seismic sources
  - Tectonic fault ruptures
  - Magmatic processes
  - Explosions
  - Induced seismicity
  - Ice ruptures and movements
  - Microseism sources
  - Landslides

B. Structural seismology

- Map earth structure (3D) and its changes through time (4D)
  - Near-surface
  - Crust
  - Mantle
  - Core

C. Surface-motion seismology

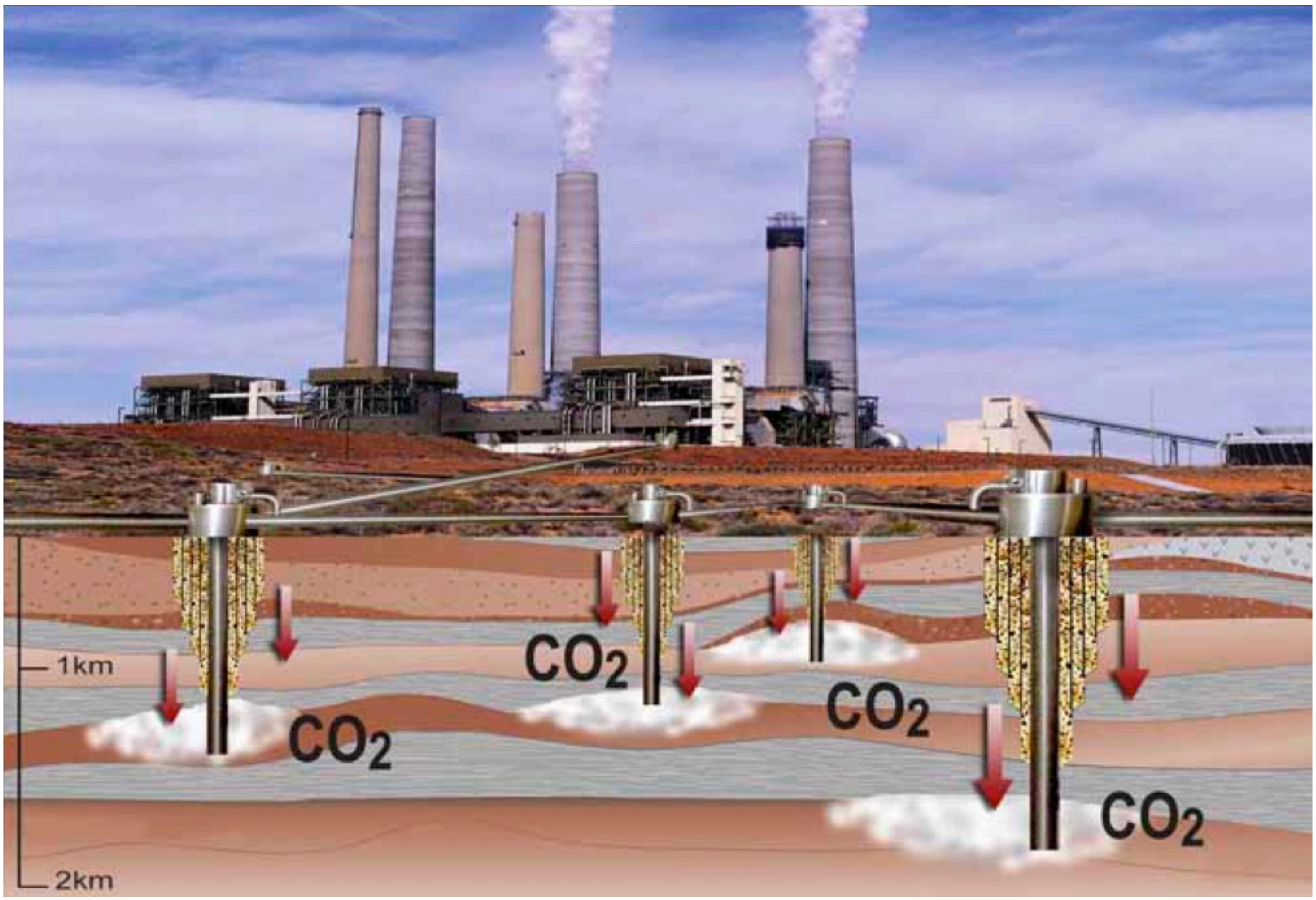
- Detect, characterize, monitor, and predict near-surface seismic motions
  - Faulting
  - Ground motions
  - Tsunami
  - Landslides
  - Liquefaction
  - Fragile geologic structures
  - Seismo-acoustics
  - Seismic noise



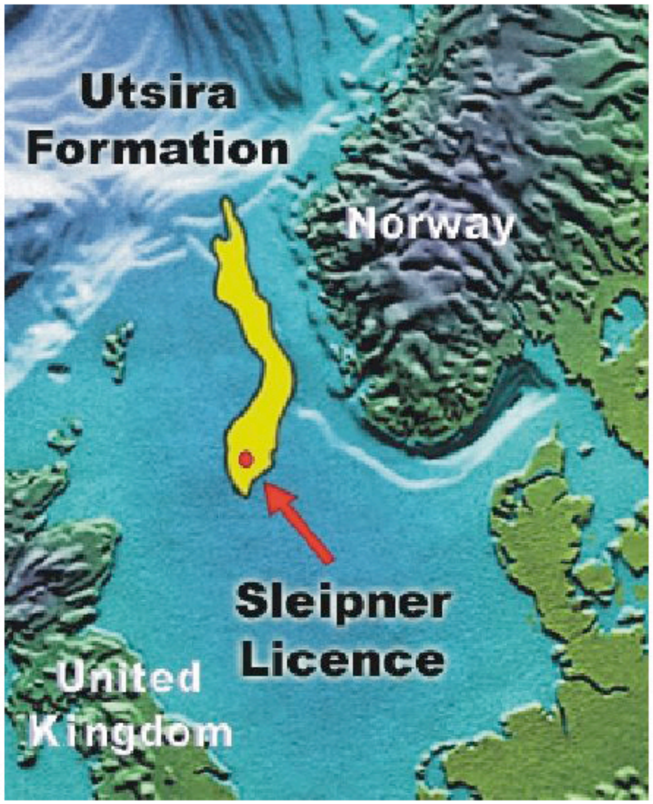
Seismological inverse problems are based on observations of surface motions.

Problem 1: Fluid migration in crustal reservoirs

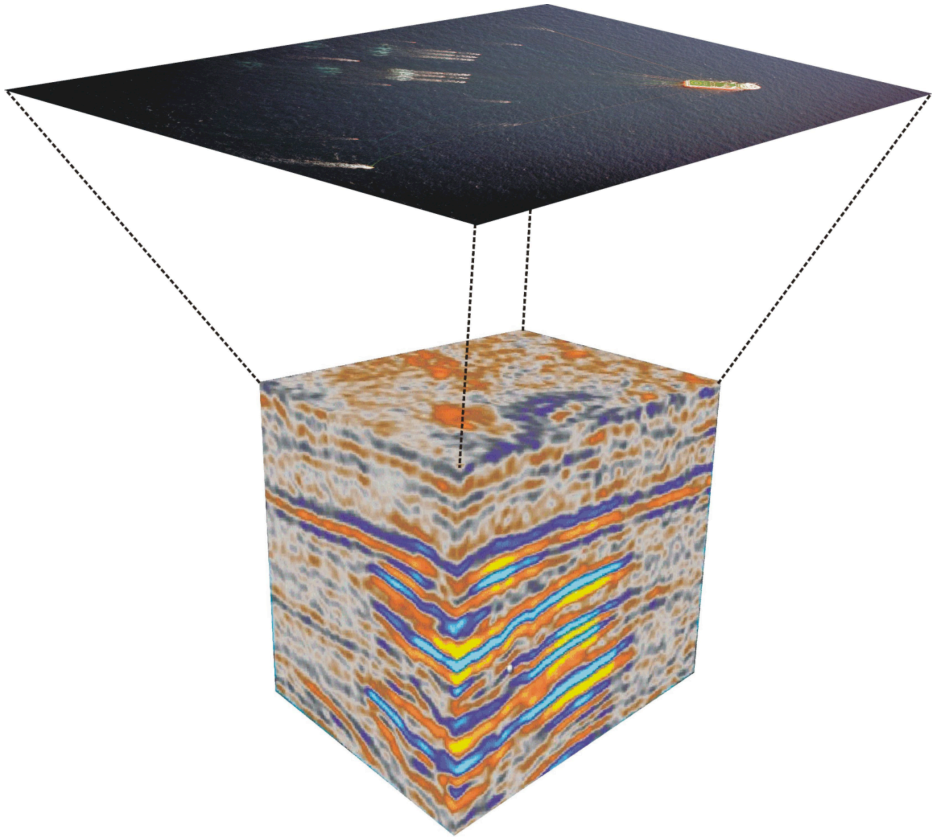
Application: Carbon sequestration



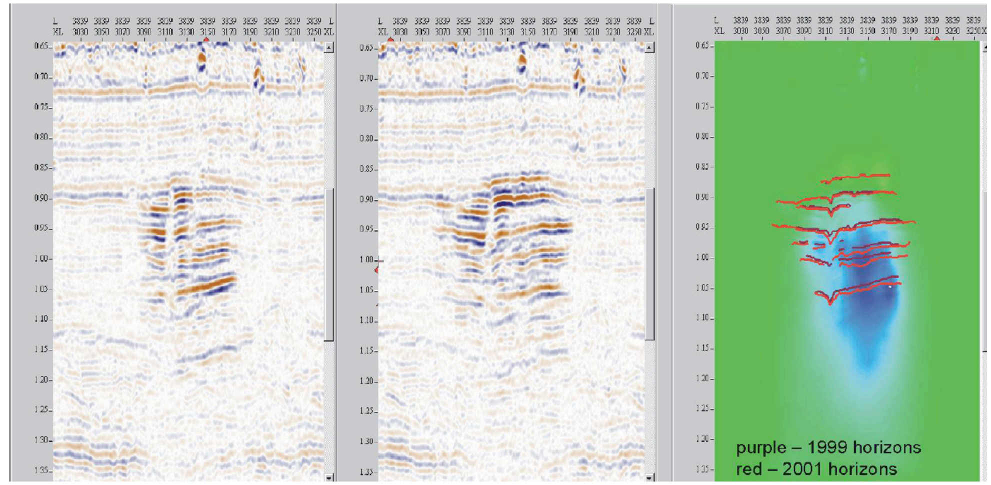
Sleipner CO_2 Reinjection Project



CO_2 injection at Statoil's Sleipner field began in 1996 as the world's first industrial-scale carbon sequestration project designed specifically to mitigate greenhouse gases; by mid-2006, more than 8 Mt of CO_2 had been injected in the reservoir. The injection point lies 3 km from the platform at a depth of 1012 m below sea level.

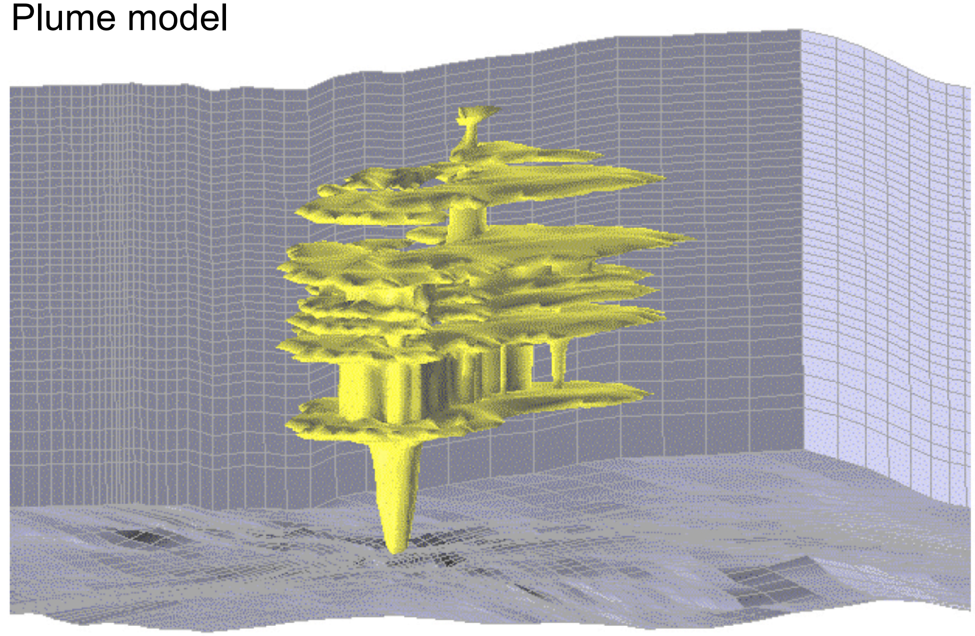


Time dependence



1999 data | 2001 data | 2001_1999 timeshift

Plume model

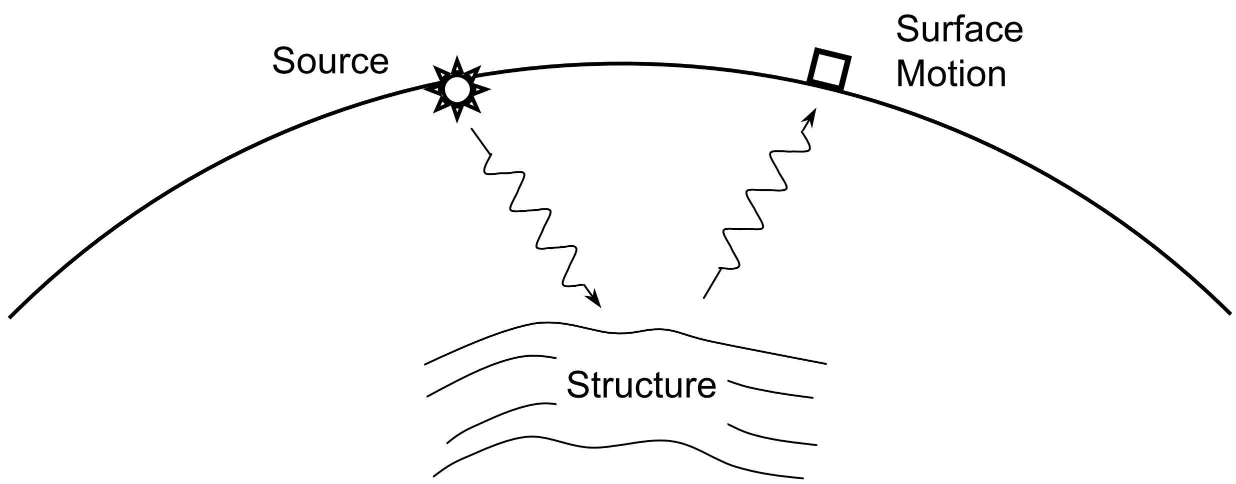


4D Seismic Surveying at Sleipner

(Chadwick et al., 2007)

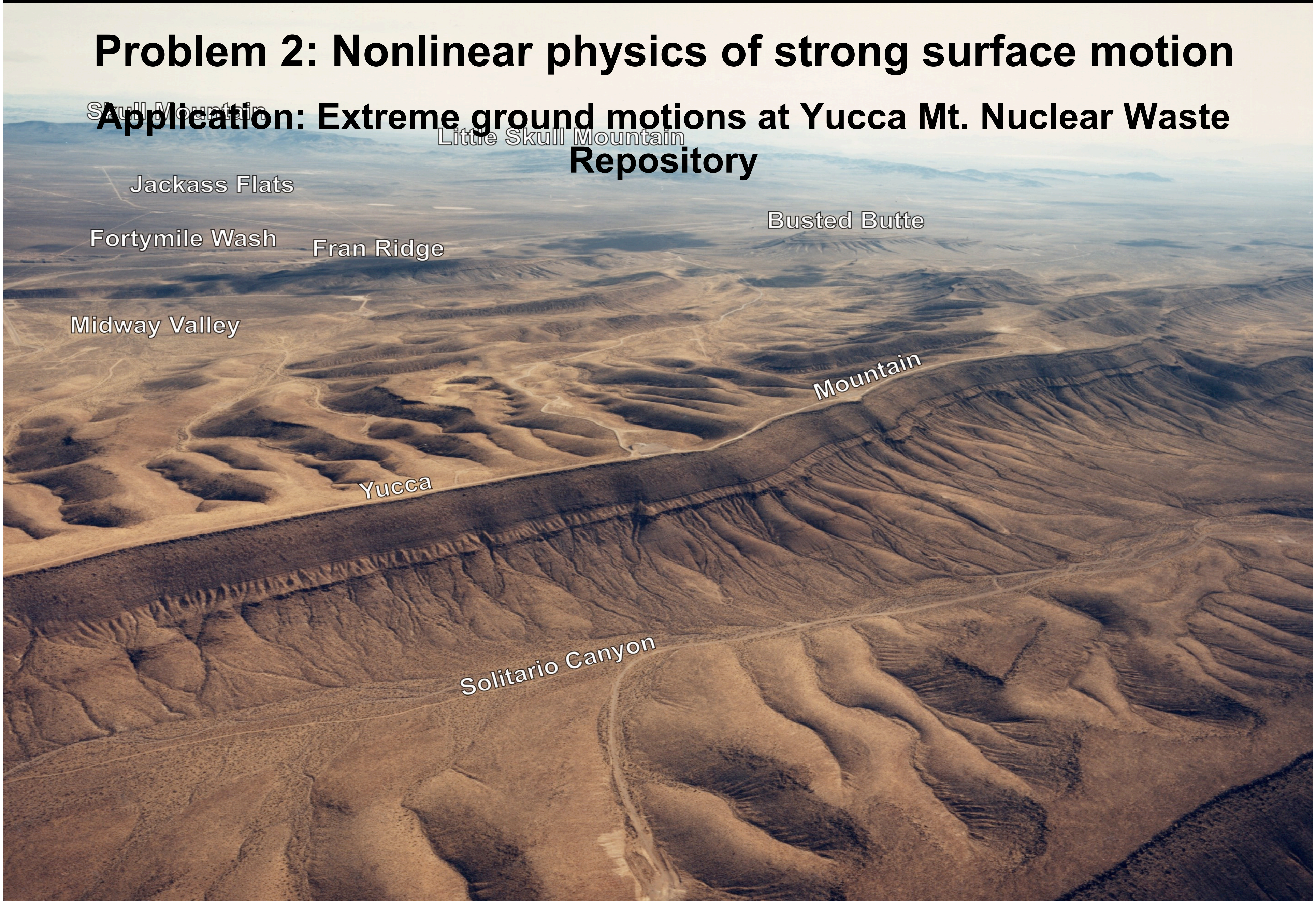
Conclusions

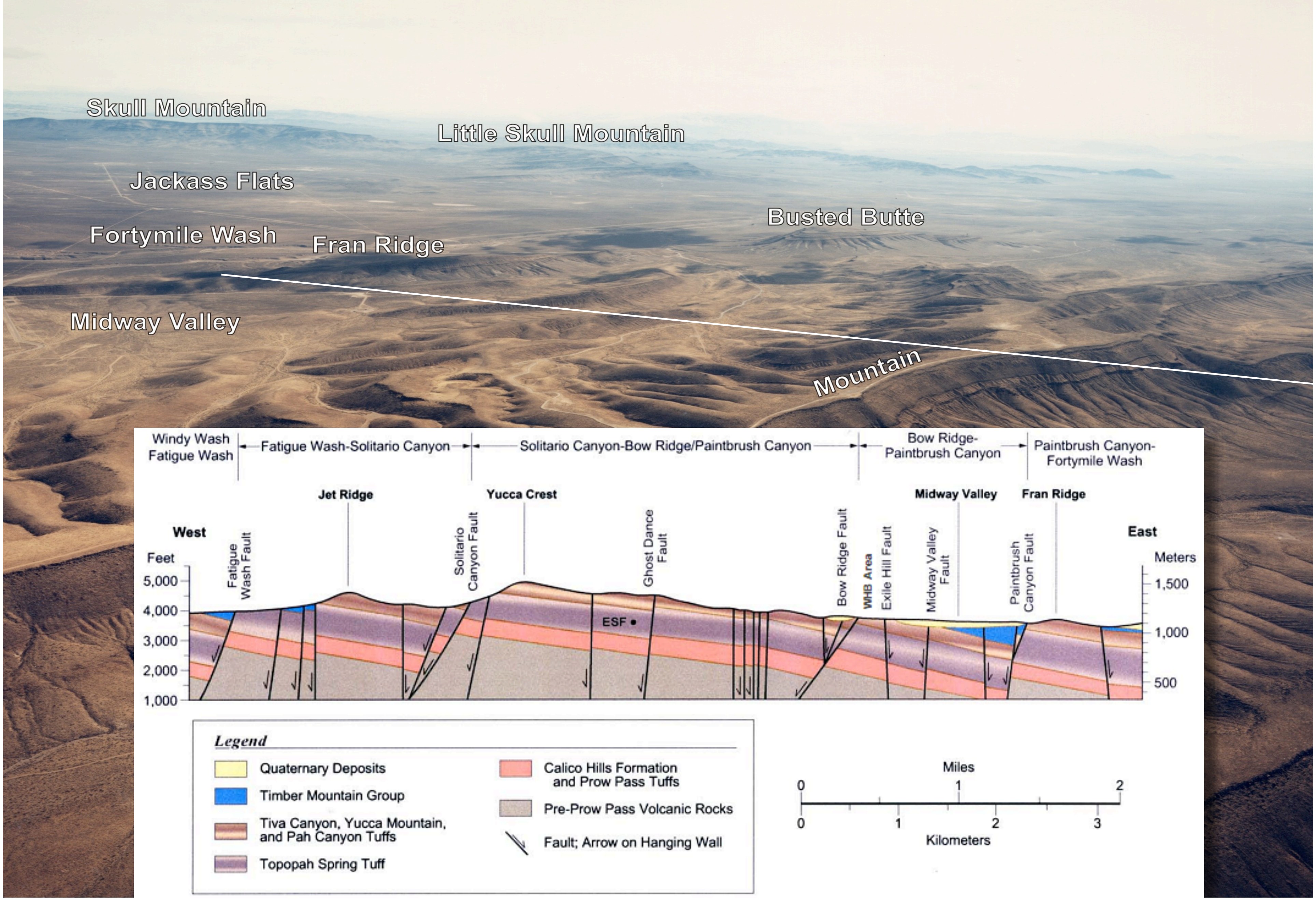
- **4D seismic reflection imaging of fluid reservoirs can resolve changes on a 1 m scale at 1 km depth**
- **Seismic imaging provides ground-truth for dynamic models of reservoir systems**
- **Reservoir system science is a key component of Earth system science**



Problem 2: Nonlinear physics of strong surface motion

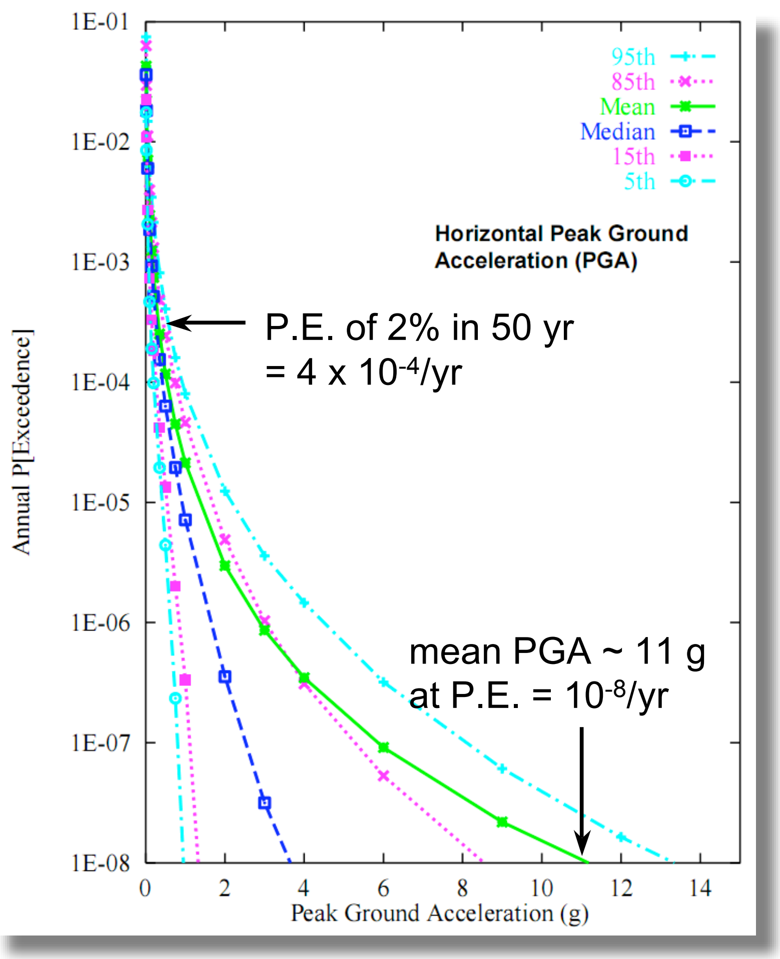
Application: Extreme ground motions at Yucca Mt. Nuclear Waste Repository

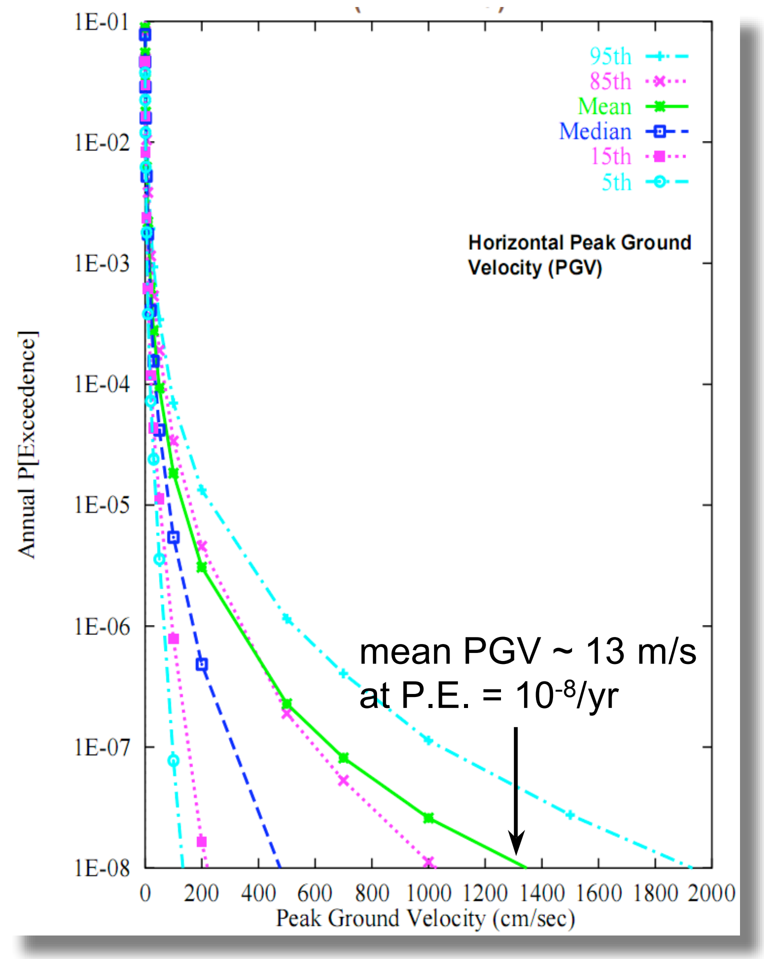



Skull Mountain
Little Skull Mountain
Jackass Flats
Busted Butte
Fortymile Wash
Fran Ridge
Midway Valley
Mountain
Windy Wash
Fatigue Wash
Fatigue Wash-Solitario Canyon
Solitario Canyon-Bow Ridge/Paintbrush Canyon
Bow Ridge-
Paintbrush Canyon
Paintbrush Canyon-
Fortymile Wash
Jet Ridge
Yucca Crest
Midway Valley
Fran Ridge
West
East
Feet
Meters
5,000
4,000
3,000
2,000
1,000
1,500
1,000
500
Fatigue
Wash Fault
Solitario
Canyon Fault
Ghost Dance
Fault
Bow Ridge Fault
WHB Area
Exile Hill Fault
Midway Valley
Fault
Paintbrush
Canyon Fault
ESF
Legend
Quaternary Deposits
Timber Mountain Group
Tiva Canyon, Yucca Mountain,
and Pah Canyon Tuffs
Topopah Spring Tuff
Calico Hills Formation
and Prow Pass Tuffs
Pre-Prow Pass Volcanic Rocks
Fault; Arrow on Hanging Wall
Miles
0
1
2
0
1
2
3
Kilometers

Yucca Mt. PSHA: Extrapolation to low probabilities

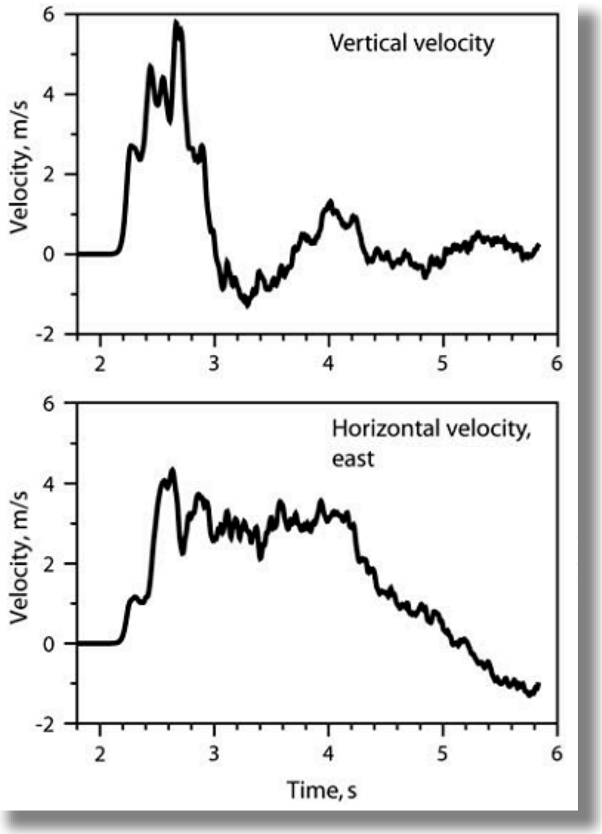
Stepp & Wong (2003)



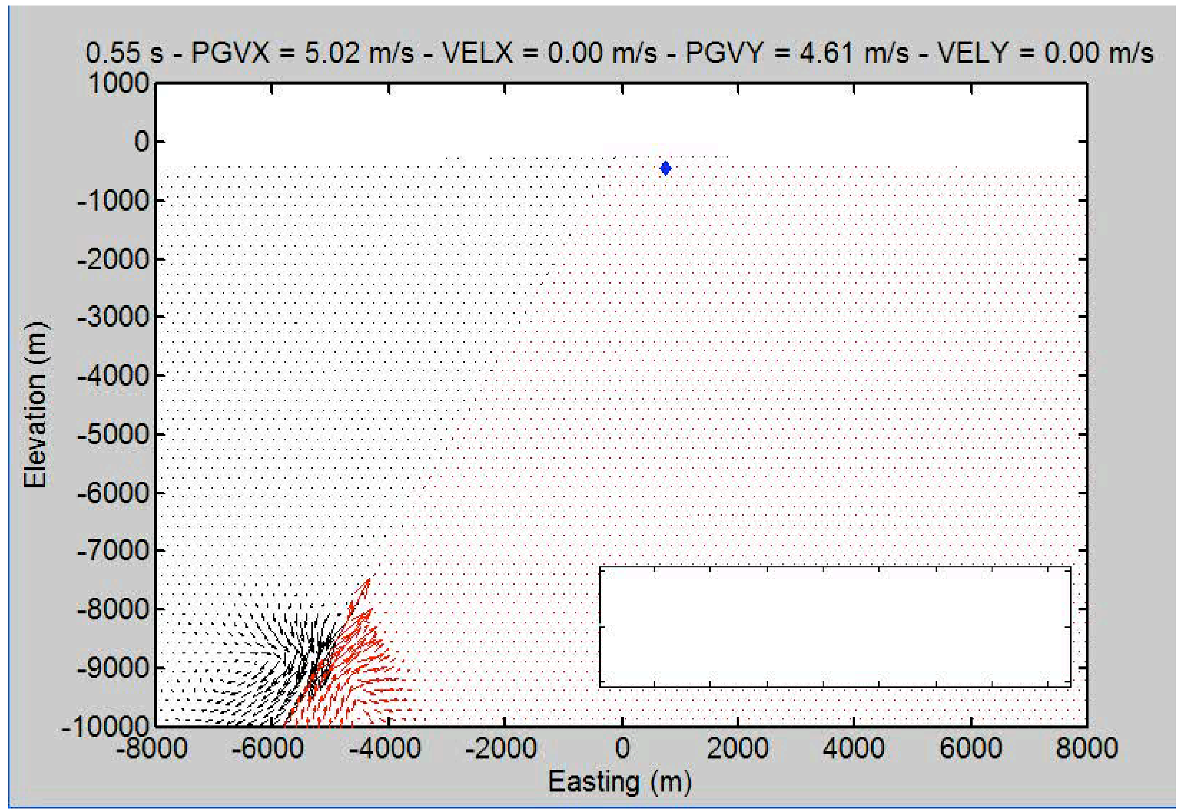


Are such extreme ground motions physically possible?

Simulations of Extreme Event on Solitario Canyon Fault



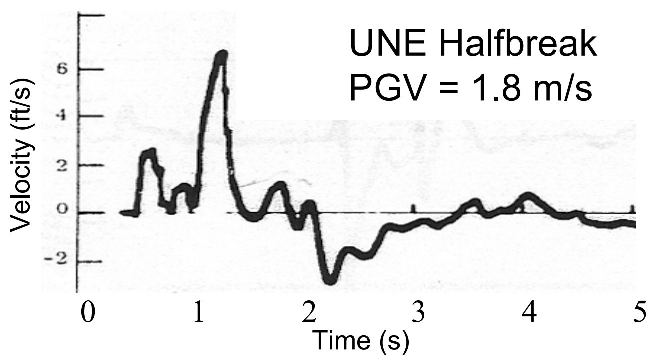
Simulation by Andrews et al. (2007)



Simulation by M. Purvance (2008)

Unexceeded Ground Motions

Underground nuclear explosions at NTS produce megabreccias that are not observed at Yucca Mt.



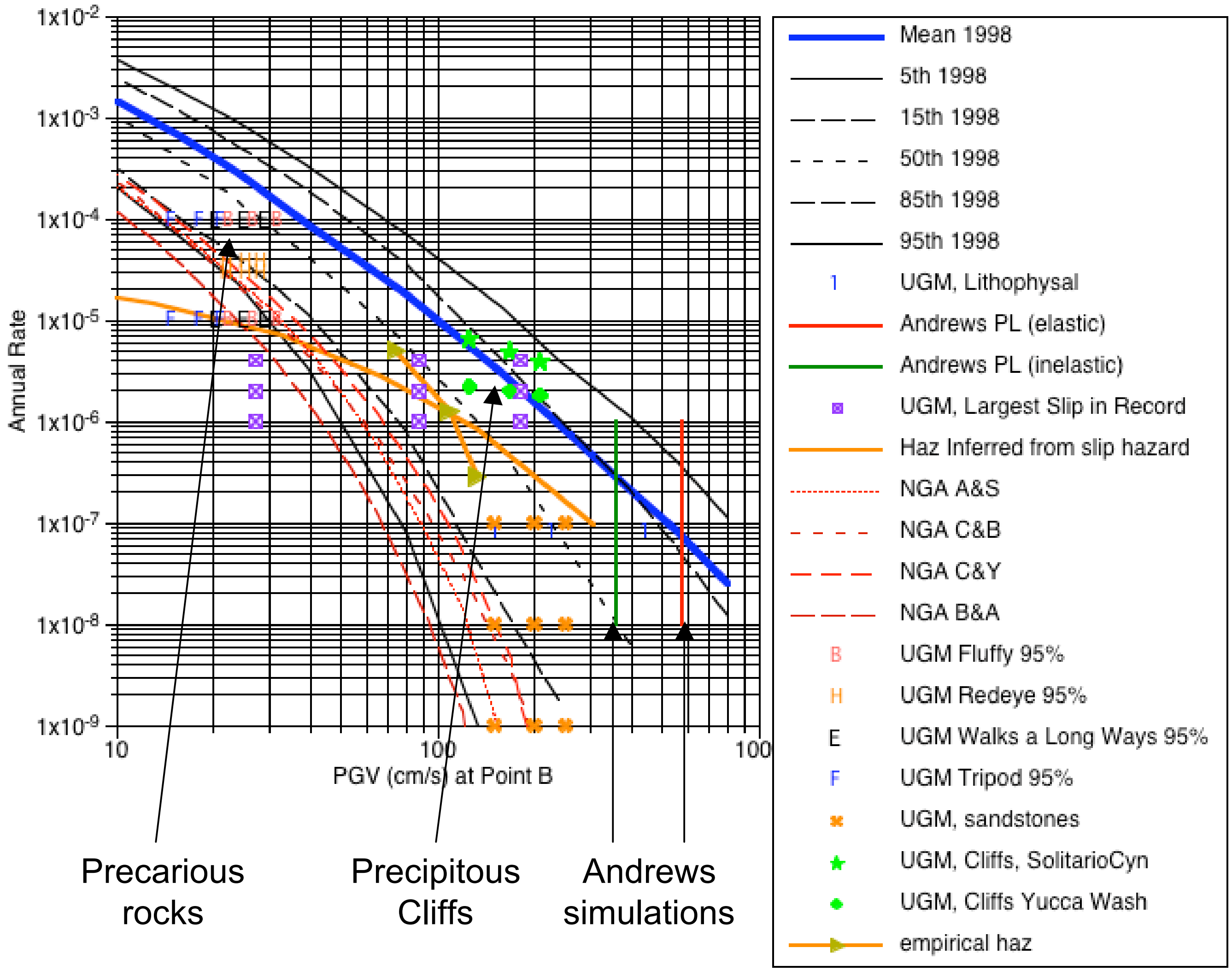
M. Purvance & UNR group (2008)

Precariously balanced rocks

Precipitous cliffs

Existence of old (>100,000 yr) fragile geologic features support the inference that unexceeded ground motions < 2 m/s.

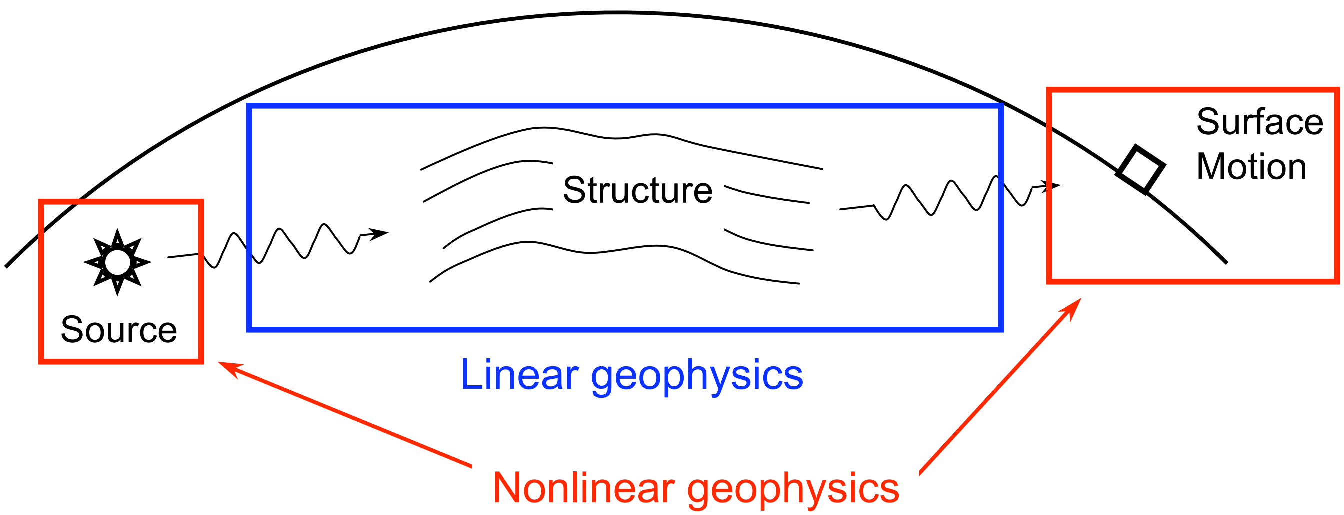
Points in Hazard Space



M. Purvance & UNR group (2008)

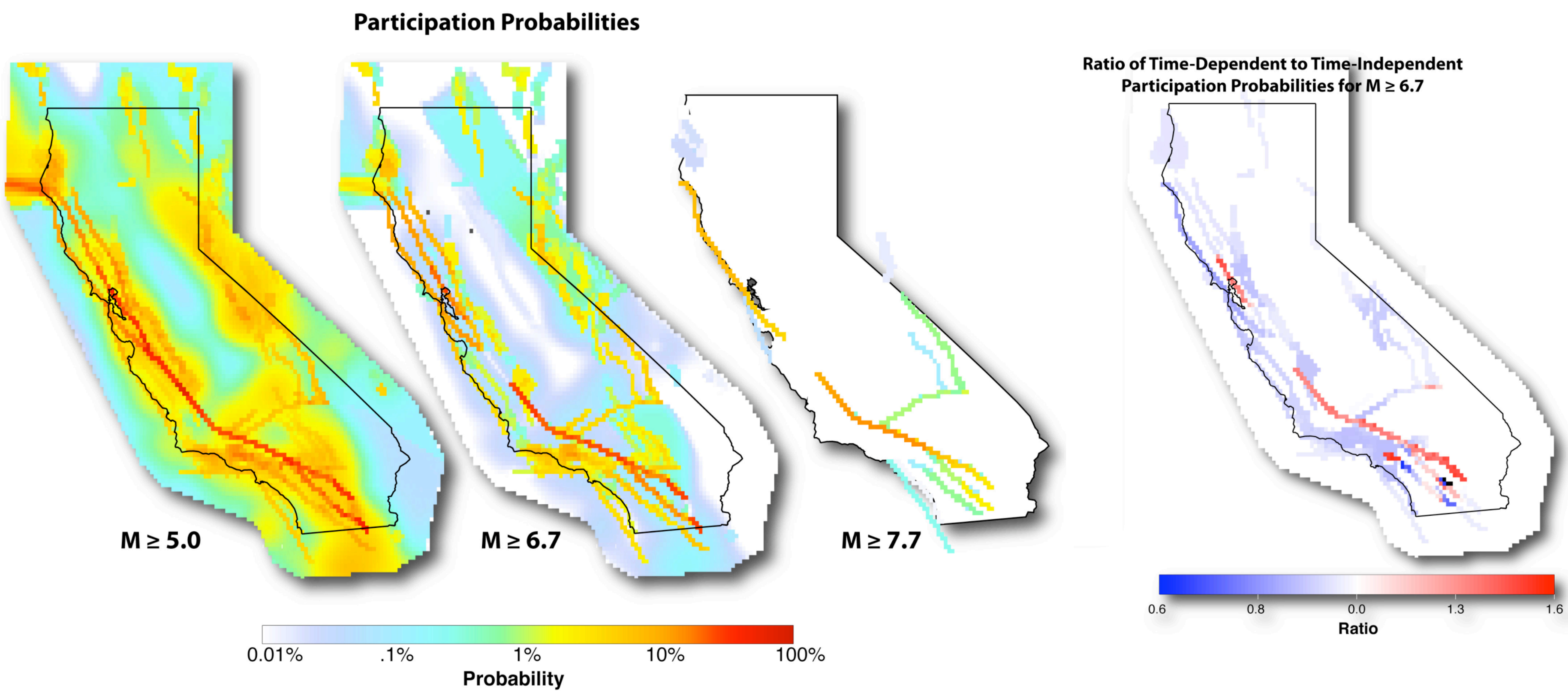
Conclusions

- Placing physical limits on extreme ground motions at critical facilities is a difficult but important problem
- Physics of the seismic source and strong surface motions is nonlinear; many aspects of the nonlinearity are poorly understood
- System-level analysis requires numerical simulations, which must be verified and validated
- Fragile geologic features provide new data for validating PSHA



Problem 3: Scenario building for disaster response

Application: The Great Southern California ShakeOut



Uniform California Earthquake Rupture Forecast (WGCEP, 2007)

Developers of the ShakeOut Scenario

- **USGS Multi-Hazards Demonstration Project (MHDP)**
  - Lucy Jones, Chief Scientist
  - Dale Cox, Project Manager
  - Sue Perry, Staff Scientist
- **10 Section Leaders**
  - Earth and Computer Science
    - Ken Hudnut, USGS
    - Dan Ponti, USGS
    - Mike Reichle, CGS
  - Engineering
    - Keith Porter, EERI
    - Hope Seligson, MMI Engineering
  - Public Health
    - Kim Shoaf, UCLA
  - Disaster Sociology
    - Dennis Mileti, Seismic Safety Commission
    - Jim Goltz, Governor's Office of Emergency Services
  - Disaster Economics
    - Anne Wein, USGS
    - Richard Bernknopf, USGS
- **More than 300 Panelists, Experts, Special Studies**
- **Download reports at urbanearth.usgs.gov**

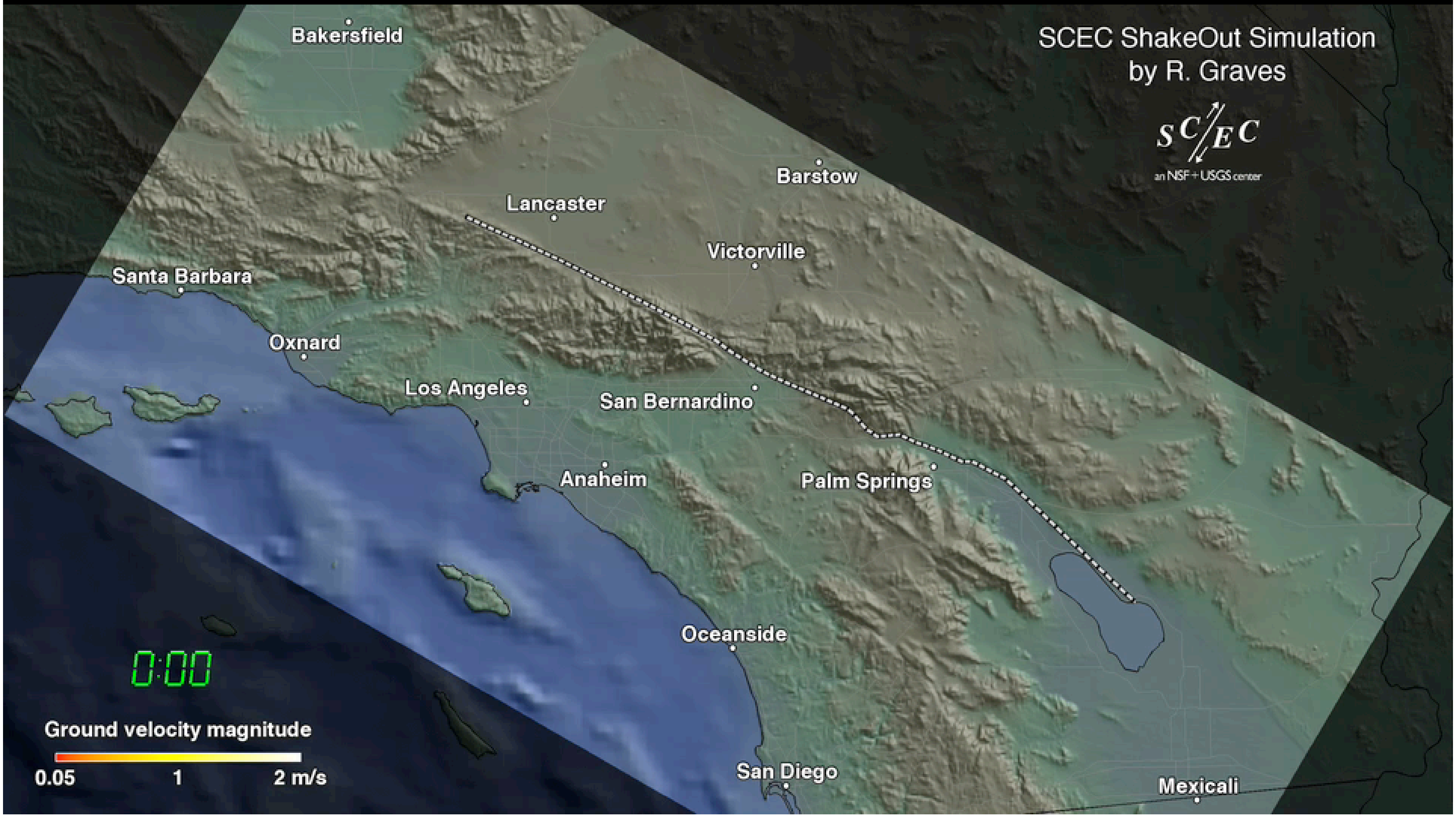
Great Southern California ShakeOut

November 13, 2008

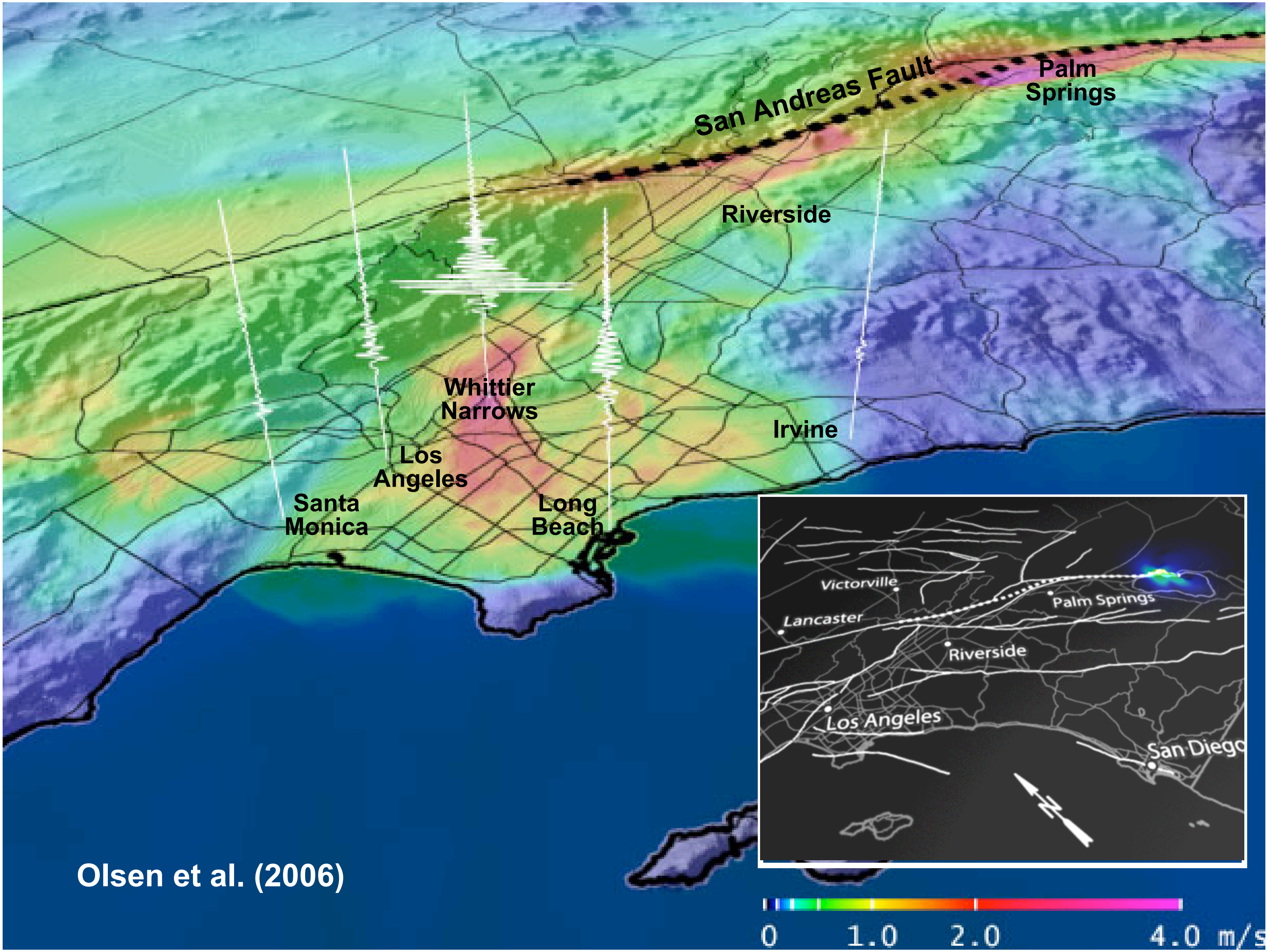
- M7.8 mainshock
- Large aftershocks
  - M7.2, M7.0, M6.0, M5.7…
- 10,000-100,000 landslides
- 1,600 fire ignitions
- 300,000 buildings significantly damaged
- Widespread infrastructure damage
- $213 billion direct economic losses
- 270,000 displaced persons
- 50,000 injuries
- 1,800 deaths
- Long recovery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

SHAKING: WEAK STRONG SEVERE

S O U T H E R N   C A L I F O R N I A   E A R T H Q U A K E   C E N T E R

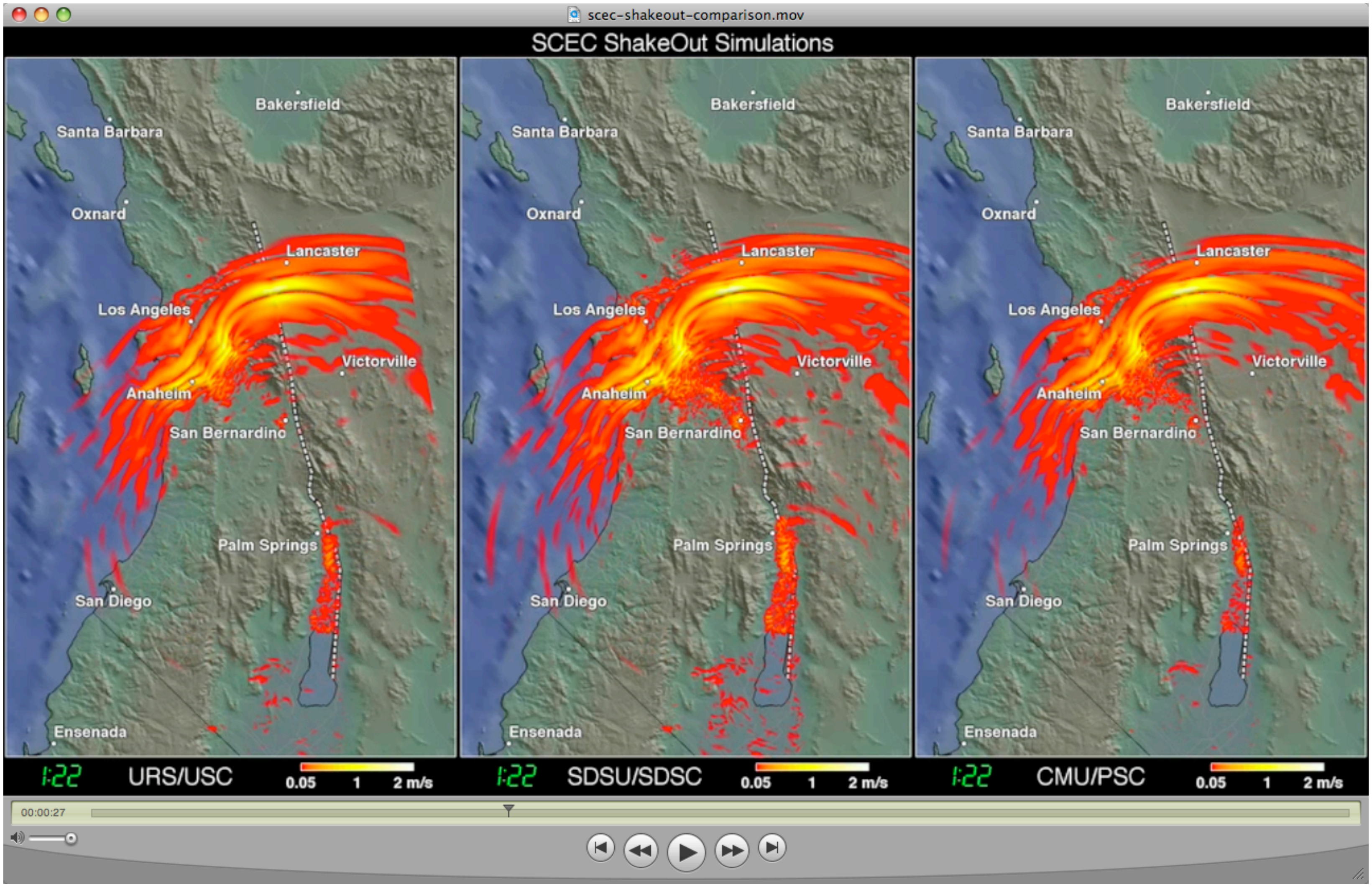


Animation by Geoff Ely



San Andreas Fault
Palm Springs
Riverside
Whittier Narrows
Irvine
Los Angeles
Santa Monica
Long Beach
Olsen et al. (2006)
Victorville
Lancaster
Palm Springs
Riverside
Los Angeles
San Diego
0
1.0
2.0
4.0 m/s

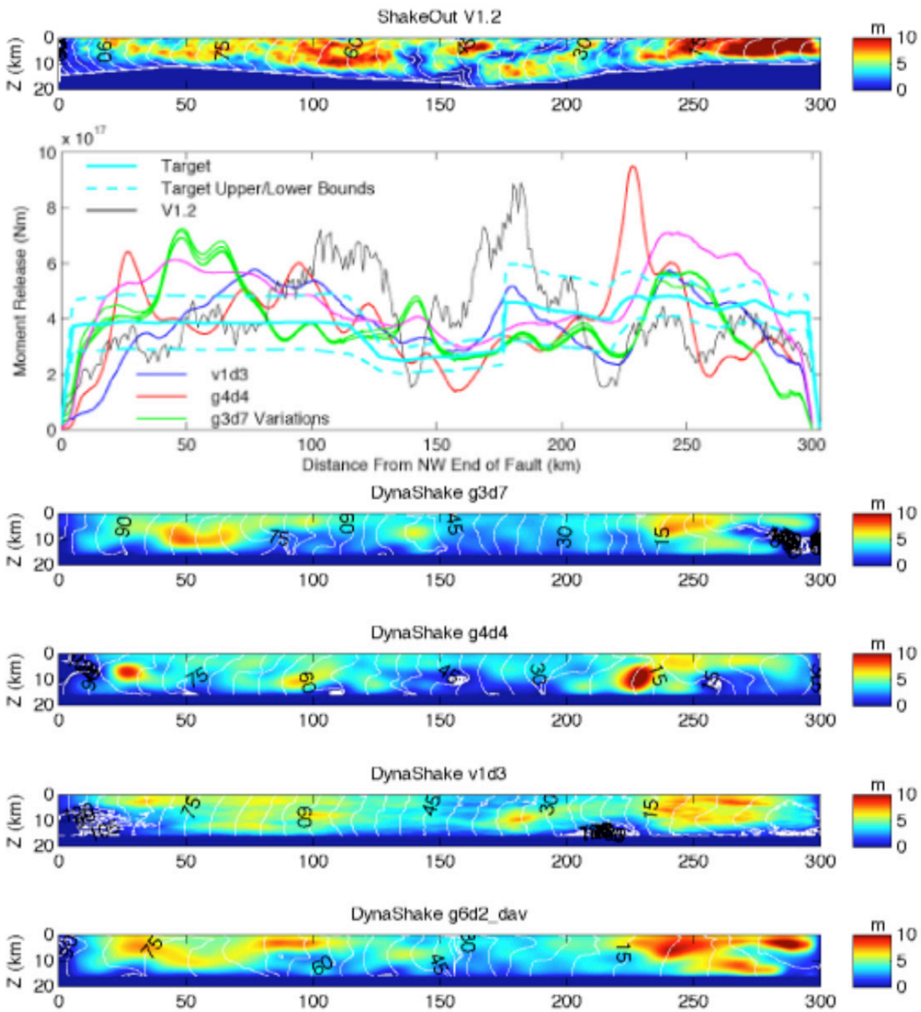
ShakeOut Verification using the TeraShake Platform



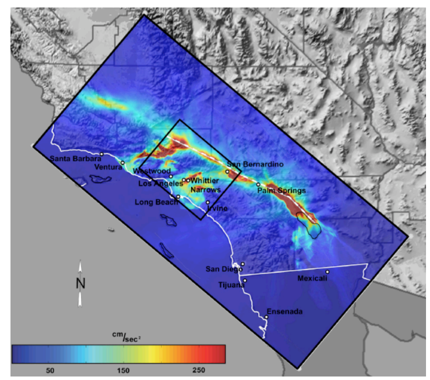
animation by Geoff Ely

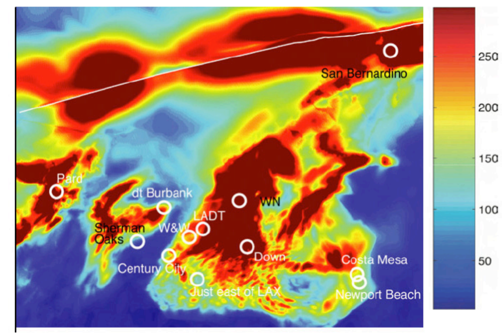
ShakeOut Dynamic Ruptures Using the DynaShake Platform

Olsen et al. (2008)

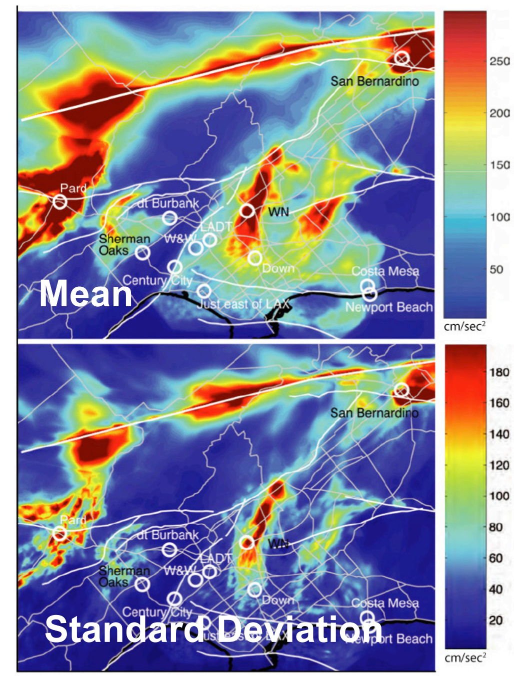


ShakeOut V1.2 (kinematic)



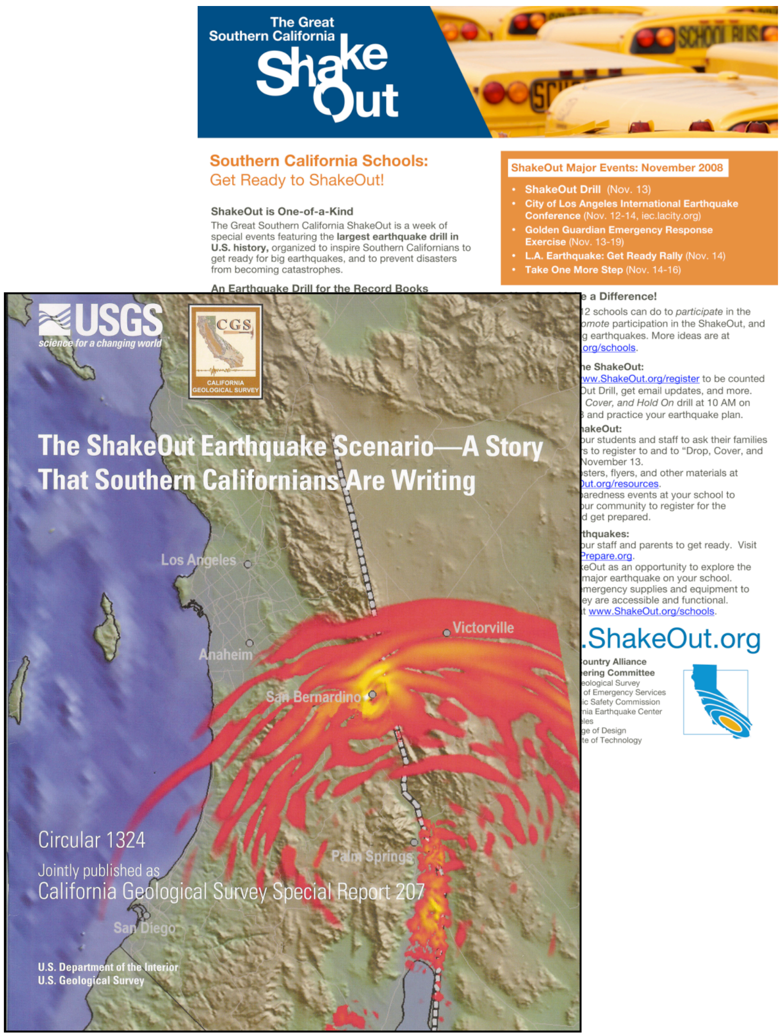


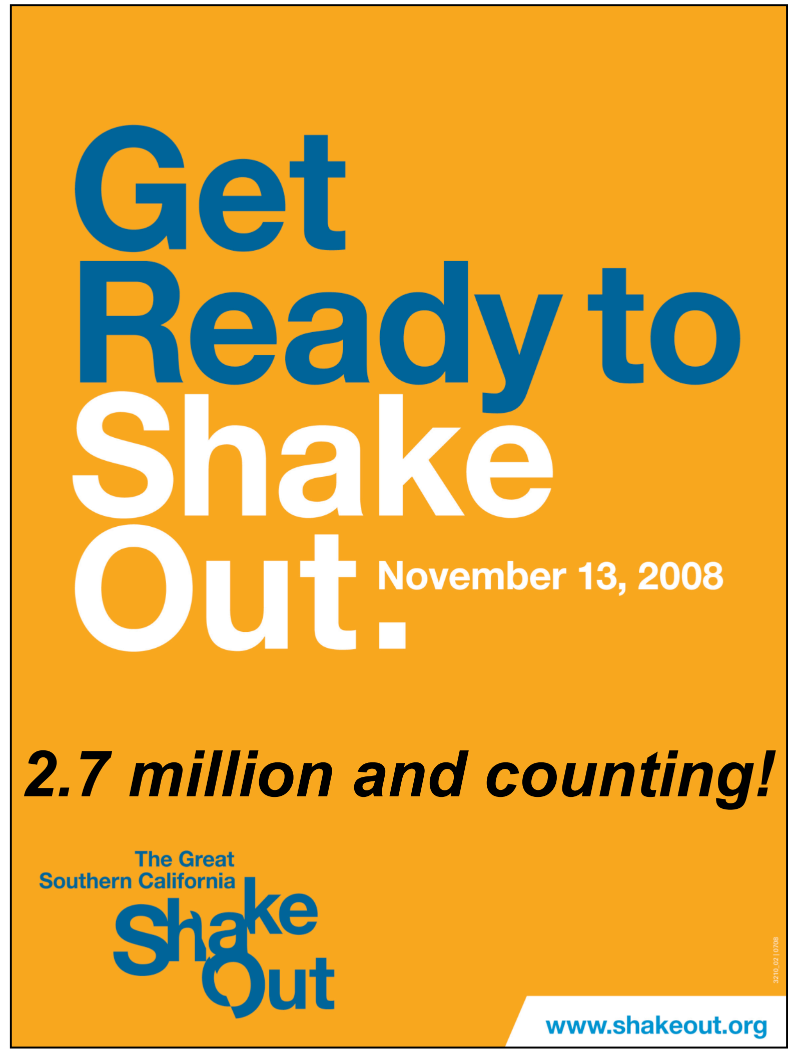
DynaShake sources (dynamic)



Great Southern California ShakeOut

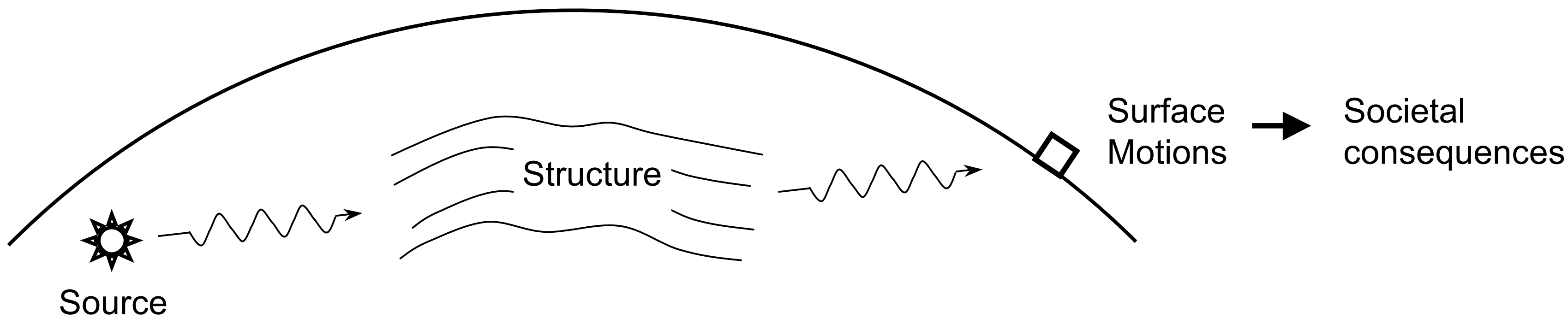
November 13, 2008





Conclusions

- Disaster scenarios provide the basis for thinking through how society can cope with extreme events that can potentially "break the system"
- Scenario development requires end-to-end simulation and thus interdisciplinary, multi-institutional collaborations
- The ShakeOut scenario has raised important scientific issues for earthquake rupture forecasting and ground motion prediction
- The public responds enthusiastically to well-organized preparatory exercises

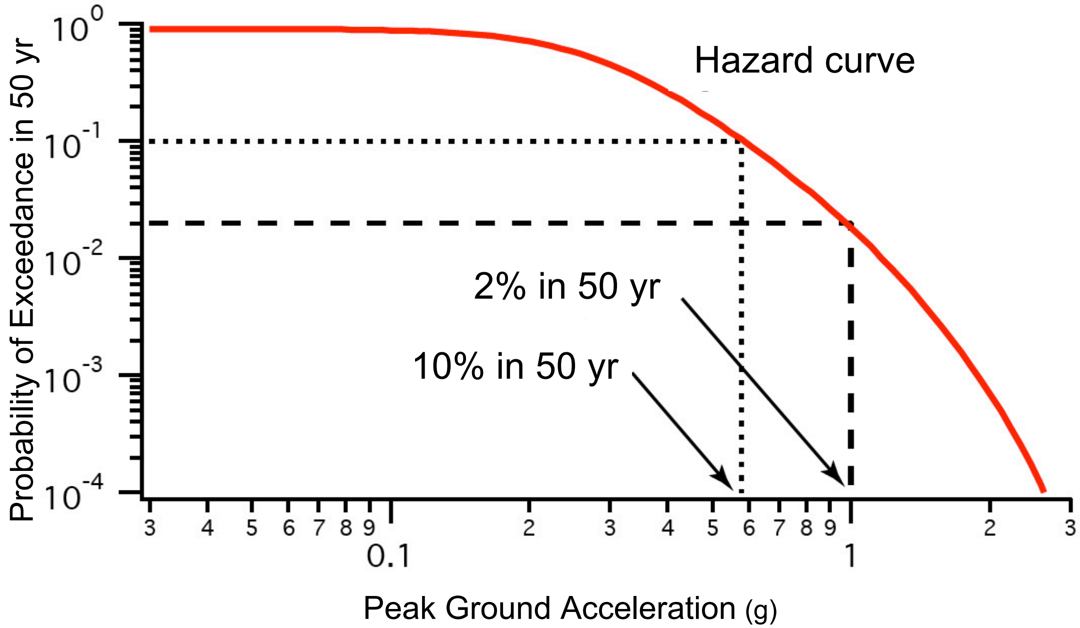


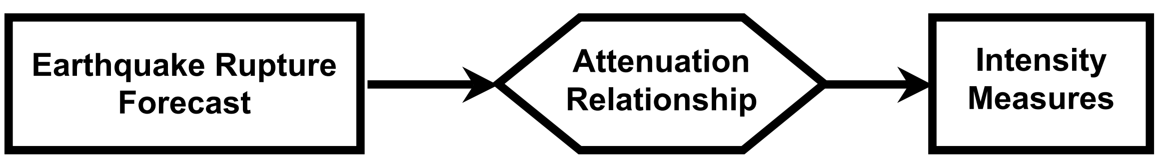
Problem 4: Physics-based PSHA

Application: CyberShake simulation platform

Hazard Curve:

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

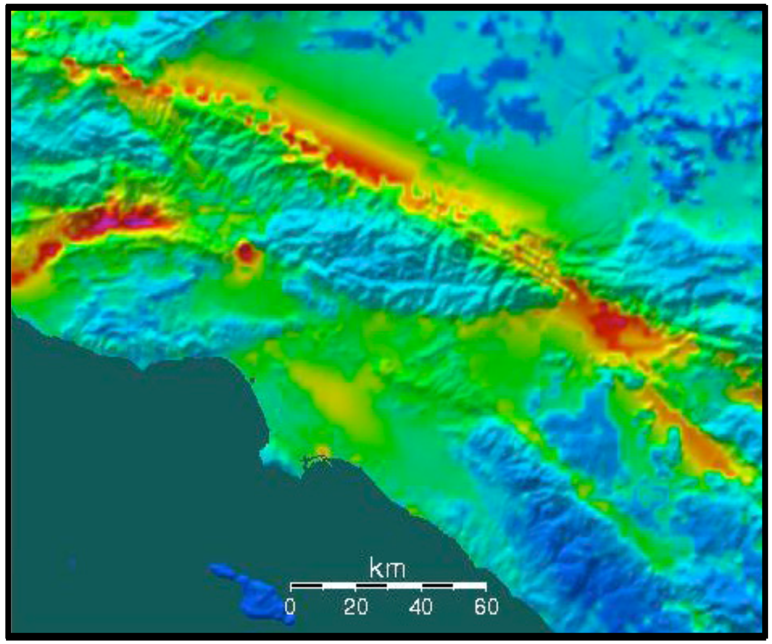




$P(S_n)$ $\quad$ $P(IM_k \mid S_n)$ $\quad$ $P(IM_k)$

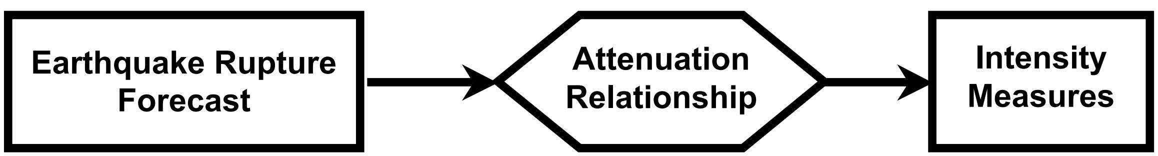
Problem 4: Physics-based PSHA

Application: CyberShake simulation platform



Hazard Map:

- **Shaking intensity : Peak Ground Acceleration (PGA)**
- **Interval: 50 years**
- **Probability of exceedance: 2%**



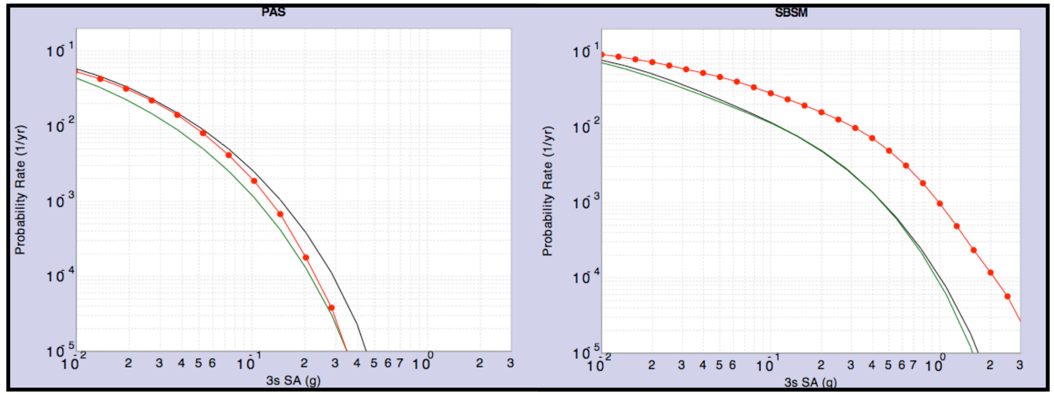
$P(S_n)$ $P(IM_k \mid S_n)$ $P(IM_k)$

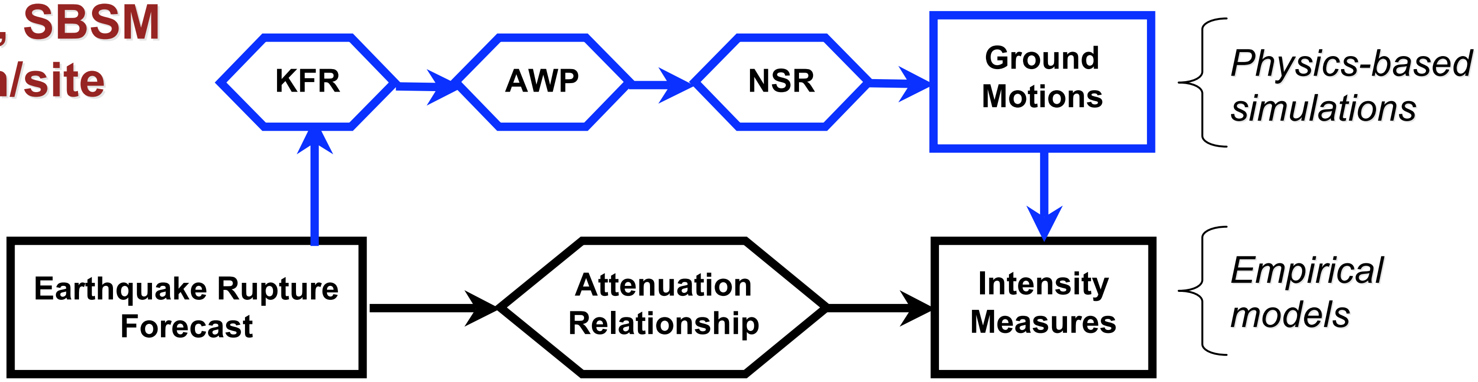
Problem 4: Physics-based PSHA

Application: CyberShake simulation platform

CyberShake Hazard Curves:

- **Shaking intensity:** **Peak Ground Acceleration (PGA)**
- **Interval:** **50 years**
- **Sites:** **PAS, SBSM** **400,000 sim/site**



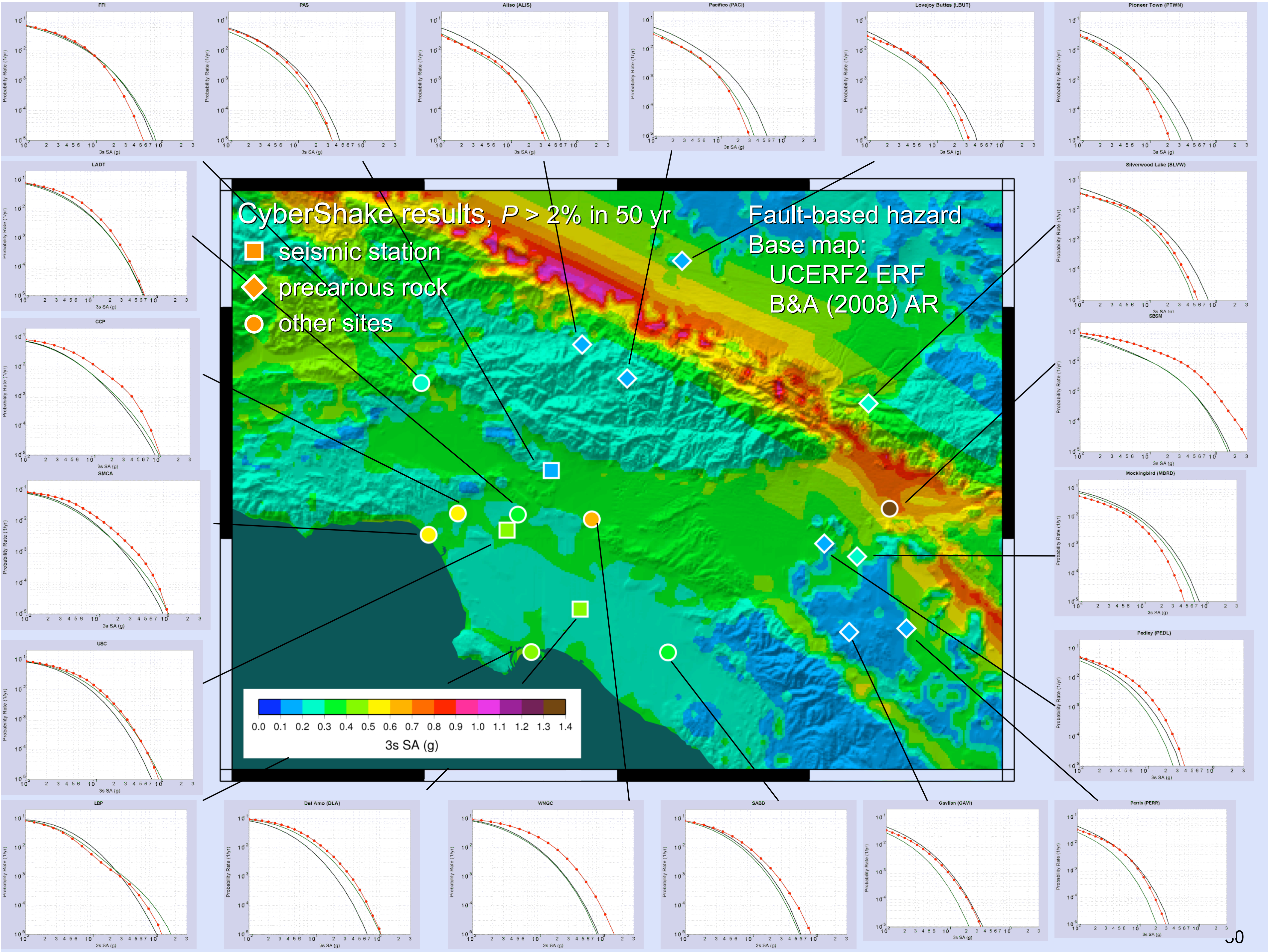


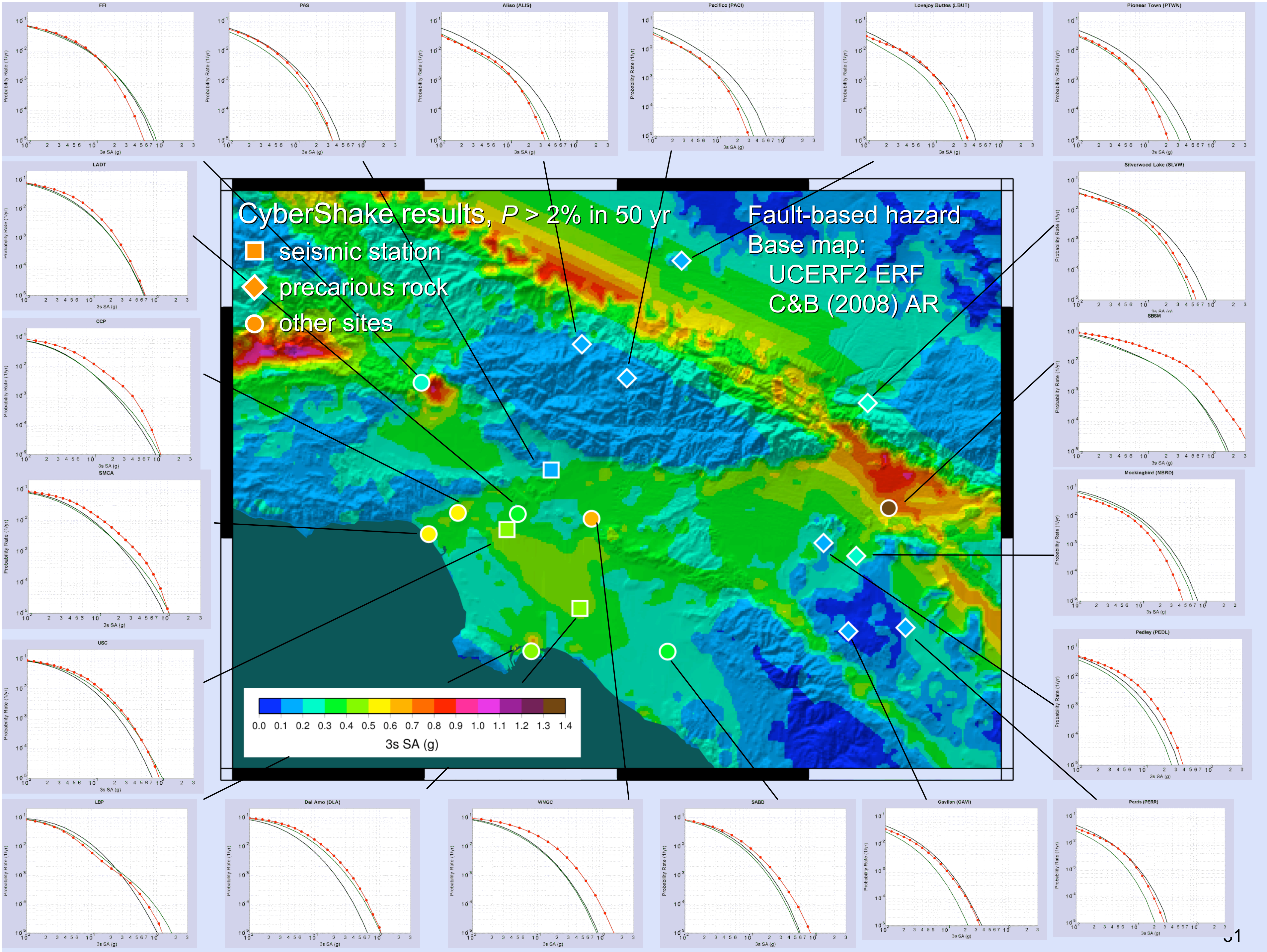
KFR = Kinematic Fault Rupture

DFR = Dynamic Fault Rupture

AWP = Anelastic Wave Propagation

NSR = Nonlinear Site Response


CyberShake results, P > 2% in 50 yr
seismic station
precarious rock
other sites
Fault-based hazard
Base map:
UCERF2 ERF
B&A (2008) AR
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
3s SA (g)
FFI
PAS
Aliso (ALIS)
Pacifico (PACI)
Lovejoy Buttes (LBUT)
Pioneer Town (PTWN)
LADT
Silverwood Lake (SLVW)
CCP
SBSM
SMCA
Mockingbird (MBRD)
USC
Pedley (PEDL)
LBP
Del Amo (DLA)
WNGC
SABD
Gavilan (GAVI)
Perris (PERR)
Probability Rate (1/yr)
3s SA (g)

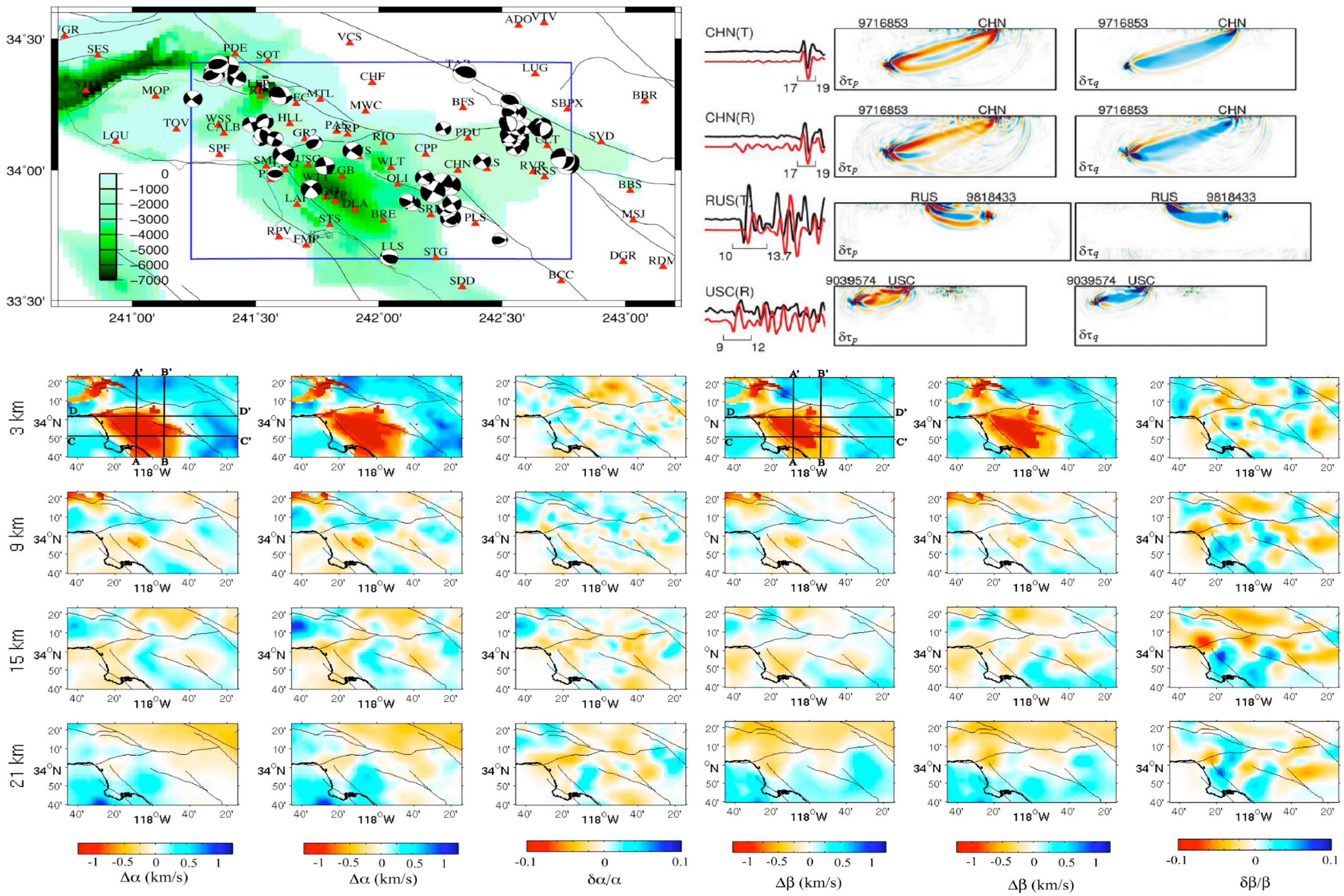

CyberShake results, P > 2% in 50 yr
seismic station
precarious rock
other sites
Fault-based hazard
Base map:
UCERF2 ERF
C&B (2008) AR
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1 1.2 1.3 1.4
3s SA (g)
FFI
PAS
Aliso (ALIS)
Pacifico (PACI)
Lovejoy Buttes (LBUT)
Pioneer Town (PTWN)
LADT
Silverwood Lake (SLVW)
CCP
SBSM
SMCA
Mockingbird (MBRD)
USC
Pedley (PEDL)
LBP
Del Amo (DLA)
WNGC
SABD
Gavilan (GAVI)
Perris (PERR)
Probability Rate (1/yr)
3s SA (g)

Conclusions

- **Standard seismic hazard analysis does not properly capture important controls on strong ground motions**
  - Near-source effects
  - Source directivity
  - Basin excitation
  - Wavefield complexity
- **Transforming PSHA into physics-based science requires**
  - Extending earthquake rupture forecasts to include full source descriptions
  - Augmenting empirical attenuation relations with wavefield simulations that account for source and structural complexity
- **Physics-based PSHA is a major driver for**
  - Basic research in earthquake system science
  - High-performance computing and communication
  - Collaboration between seismologists and engineers

Problem 5: Mapping strong crustal heterogeneities

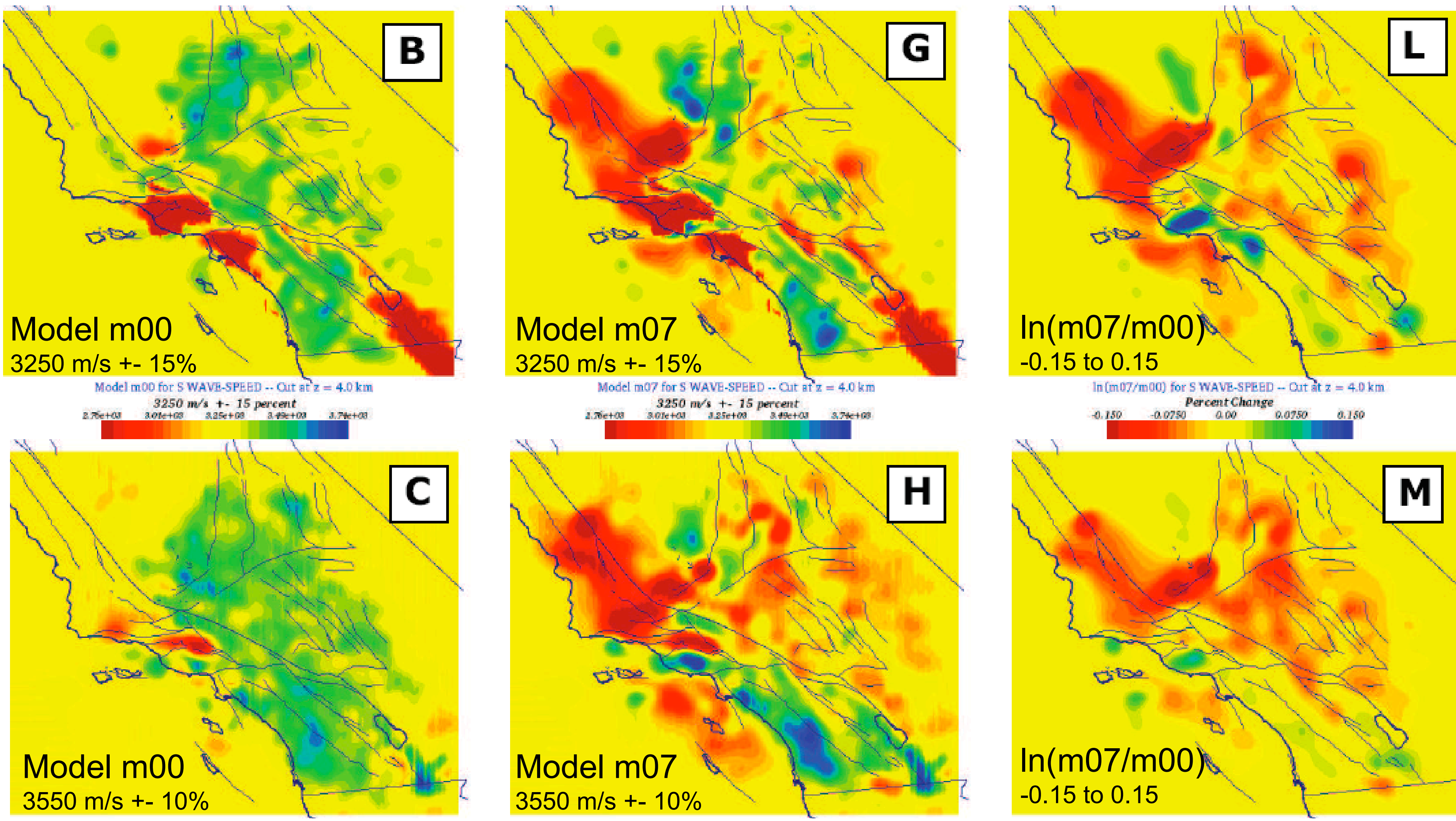
Application: Full 3D waveform tomography



Scattering integral method (Chen et al., 2007)

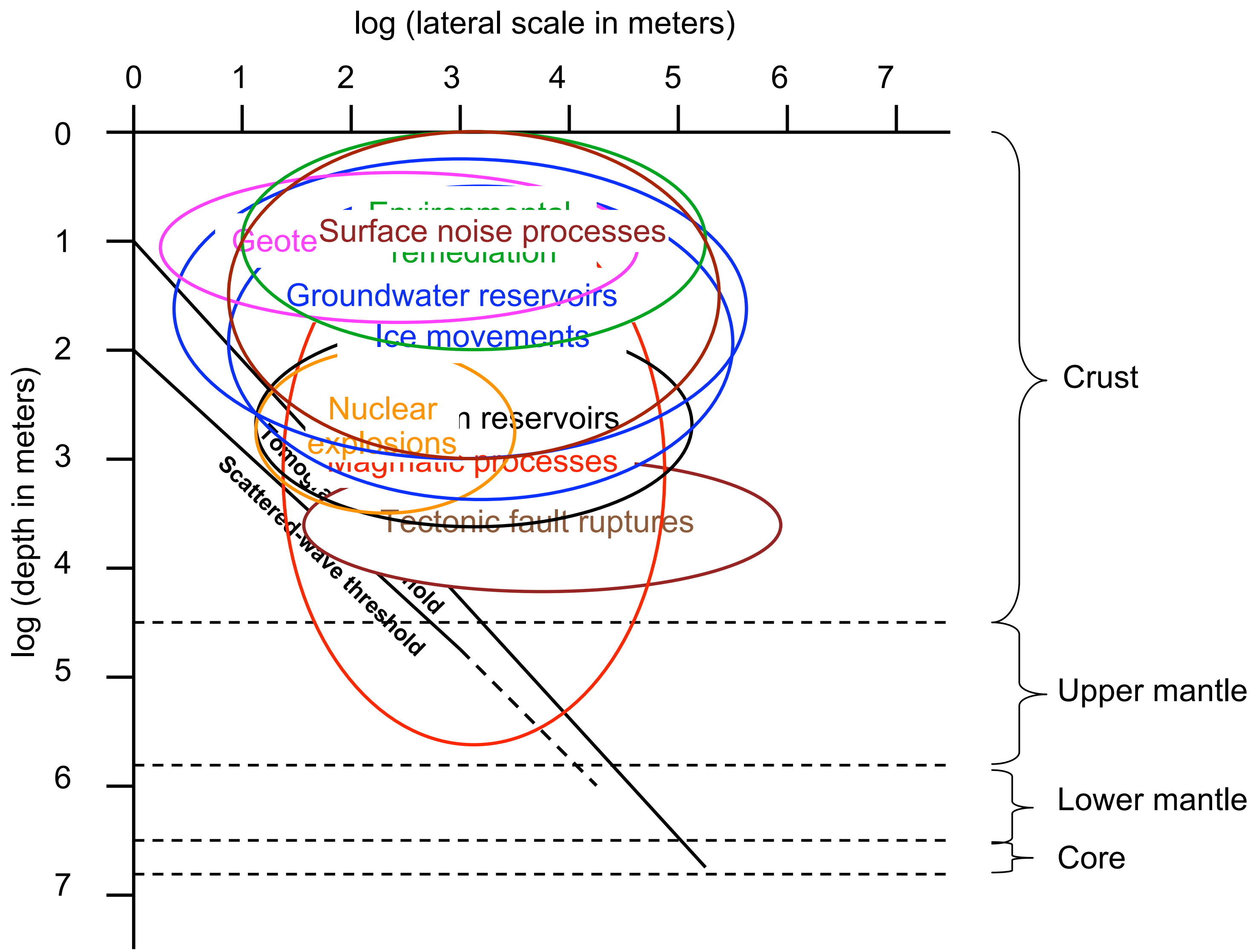
Problem 5: Mapping strong crustal heterogeneities

Application: Full 3D waveform tomography



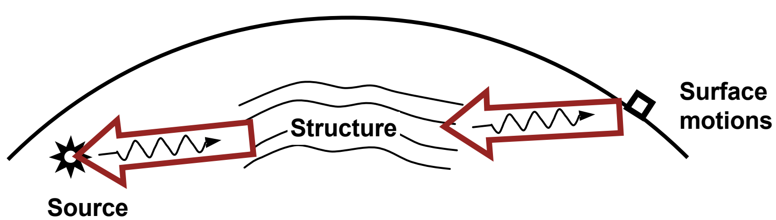
Adjoint wavefield method (Tape et al., 2008)

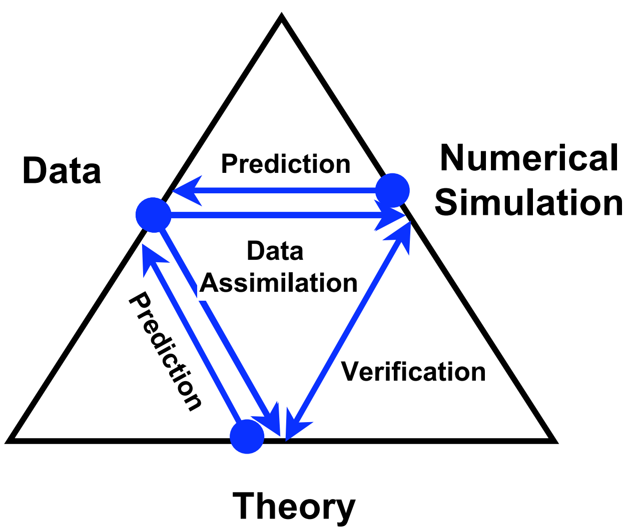
Societal challenges for seismology are concentrated in the near-surface environment…



Conclusions

- The upper crust is Earth's most heterogeneous region
  - Imaging this heterogeneity is critical to addressing many societal challenges
- Full 3D waveform tomography plus scattered-wave imaging can provide high-resolution models on regional scales
  - e.g. method for assimilating earthquake data into ground motion prediction models
- Full 3D waveform tomography is a major HPCC driver





General Conclusions

- Seismology provides the tools and knowledge to address critical societal challenges
  - Many challenges involve predictions of surface motions, which are system-level problems
- Practical applications are vigorous drivers of basic research in seismology
  - The most relevant geosystem science concerns the near-surface environment
- Assimilation of seismological constraints into dynamic system models requires strong interdisciplinary collaboration

End