Earthquake Forecasting and Prediction:

Progress in Model Development and Evaluation

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IASPEI Meeting, Cape Town, South Africa

January 12, 2009

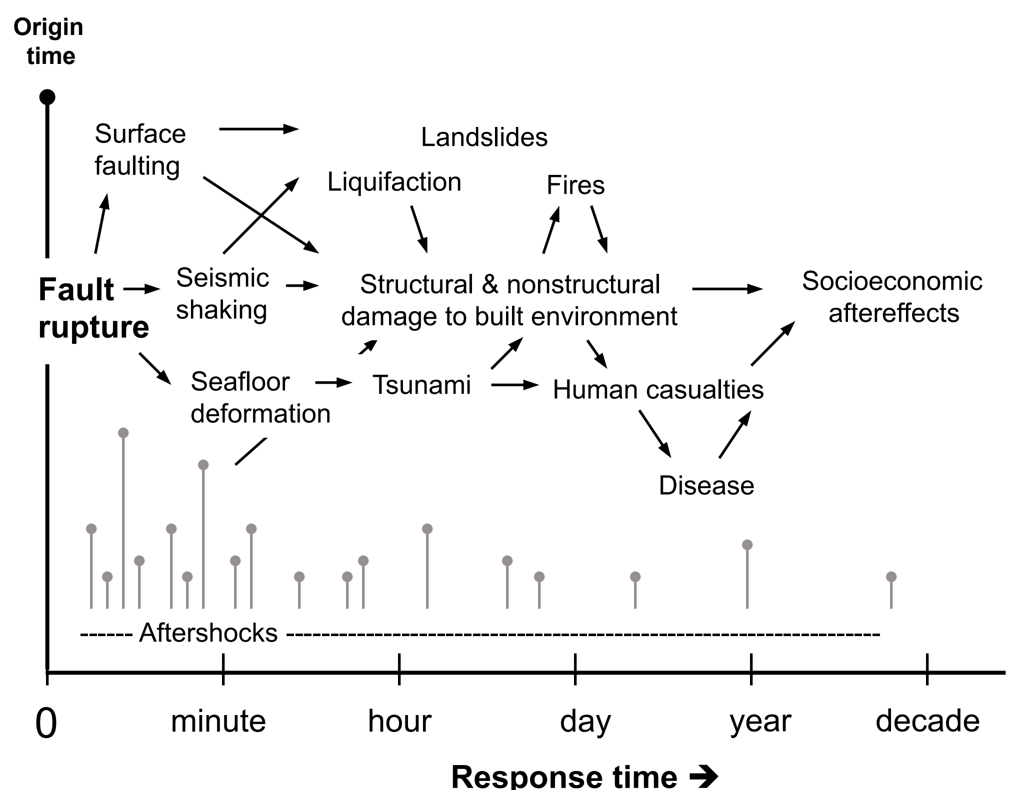
SCEC

an NSF+USGS center

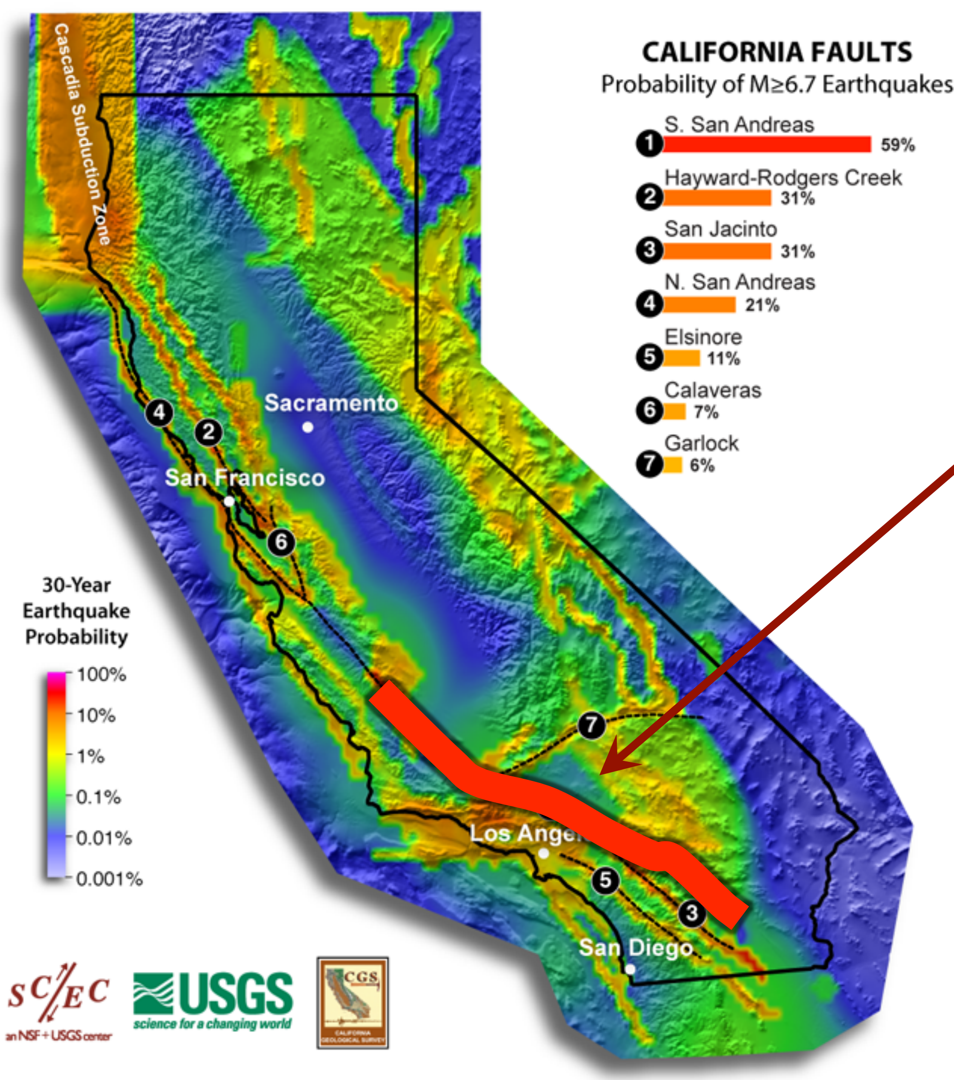
Earthquakes are "system-level" phenomena…

- They emerge from stress-driven interactions within fractal fault networks systems that are complex and opaque
- They cascade as chain reactions through the natural and built environments
- For a specified fault rupture, ***useful predictions*** can be made of the risk to society from the earthquake cascade

  Example: Great Southern California ShakeOut



Uniform California Earthquake Rupture Forecast



Working Group on California Earthquake Probabilities (2007)

Highest probability for a large earthquake rupture is on the Southern San Andreas fault

59% for M ≥ 6.7 in 30 yr

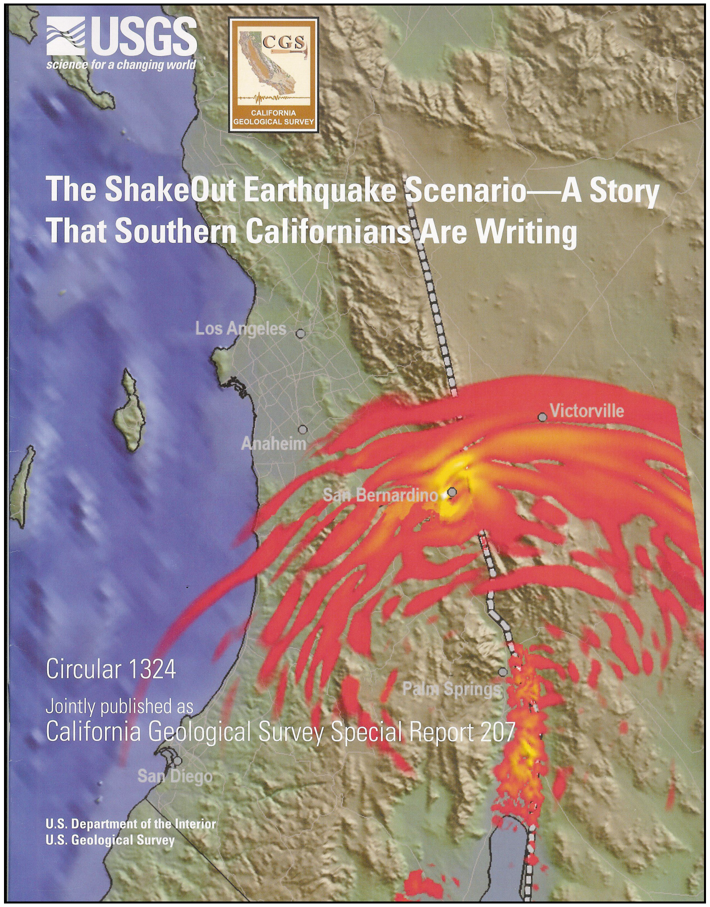
17% for M ≥ 7.8 in 30 yr

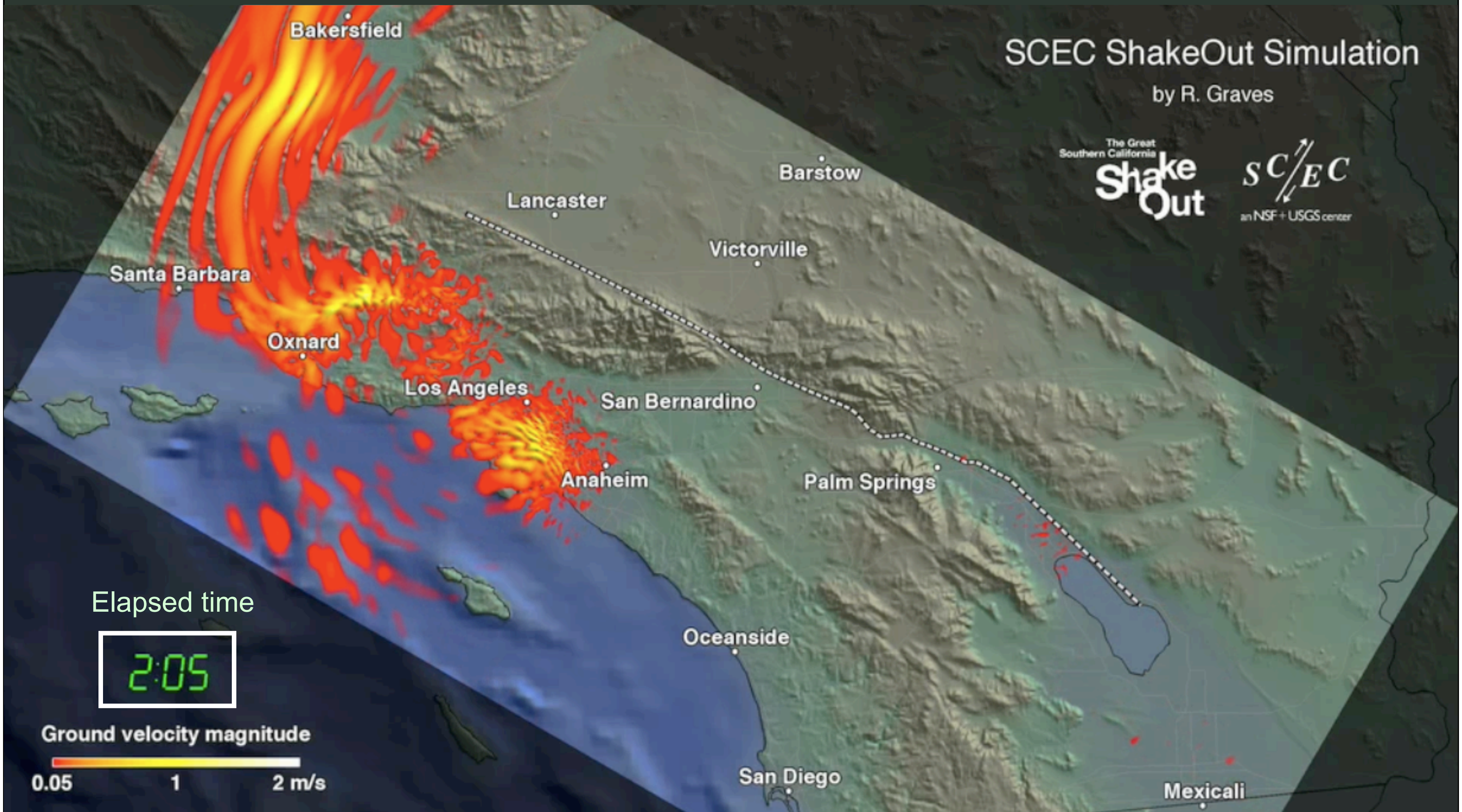
How would Southern California be affected by such an event?

How should we prepare?

Great Southern California ShakeOut
November 13, 2008

- **Exercise to practice response to a major earthquake in Southern California**
  - **Emergency response agencies at all governmental levels**
  - **Communities, schools, and businesses**
- **M7.8 scenario based on realistic simulation of regional ground motions**
  - **Detailed predictions of damage to buildings and infrastructure**
  - **Advance registration of participants encouraged by involvement of traditional and alternative media and social-networking mechanisms**




SCEC ShakeOut Simulation
by R. Graves
The Great Southern California ShakeOut
SCEC
an NSF + USGS center
Bakersfield
Barstow
Lancaster
Victorville
Santa Barbara
Oxnard
Los Angeles
San Bernardino
Anaheim
Palm Springs
Oceanside
San Diego
Mexicali
Elapsed time
2:05
Ground velocity magnitude
0.05
1
2 m/s

Great Southern California ShakeOut

November 13, 2008

Scenario Results

- 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

Exercise Results

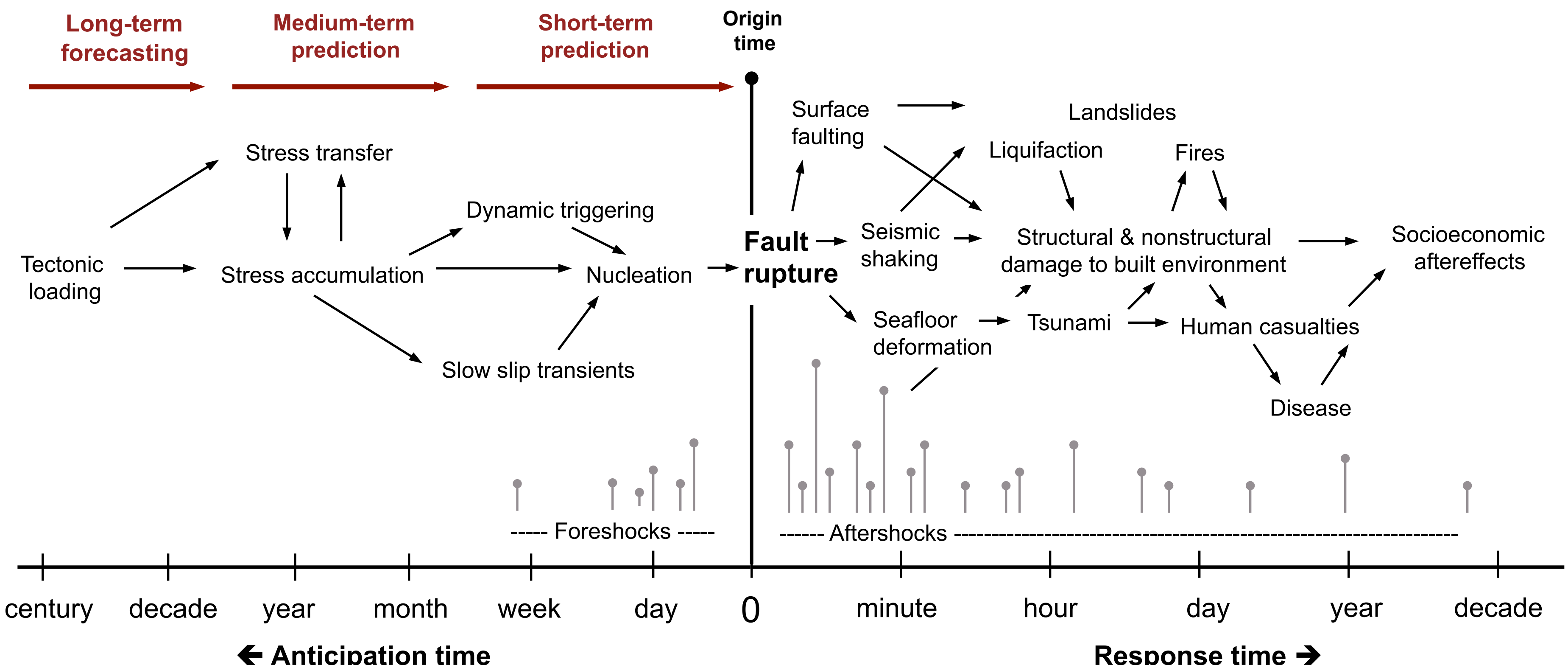
- Largest emergency response exercise in US history
  - 5.3 million registered participants
- Demonstrated that existing disaster plans are inadequate for an event of this scale
  - Has motivated reformulation of emergency response

SHAKING: WEAK STRONG SEVERE

Earthquake rupture prediction is a system-level problem…

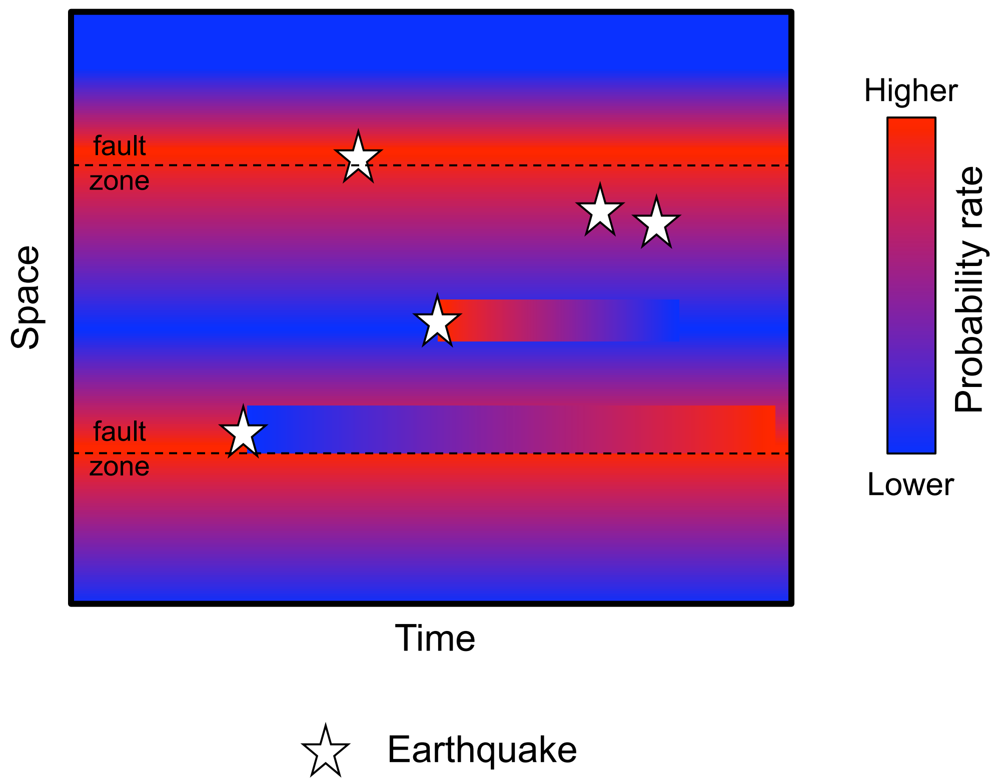
➢ Need to understand static and dynamic processes

- **stress accumulation and transfer**
- **rupture nucleation, propagation, and arrest**
- **static and dynamic triggering**



Earthquake Forecasting

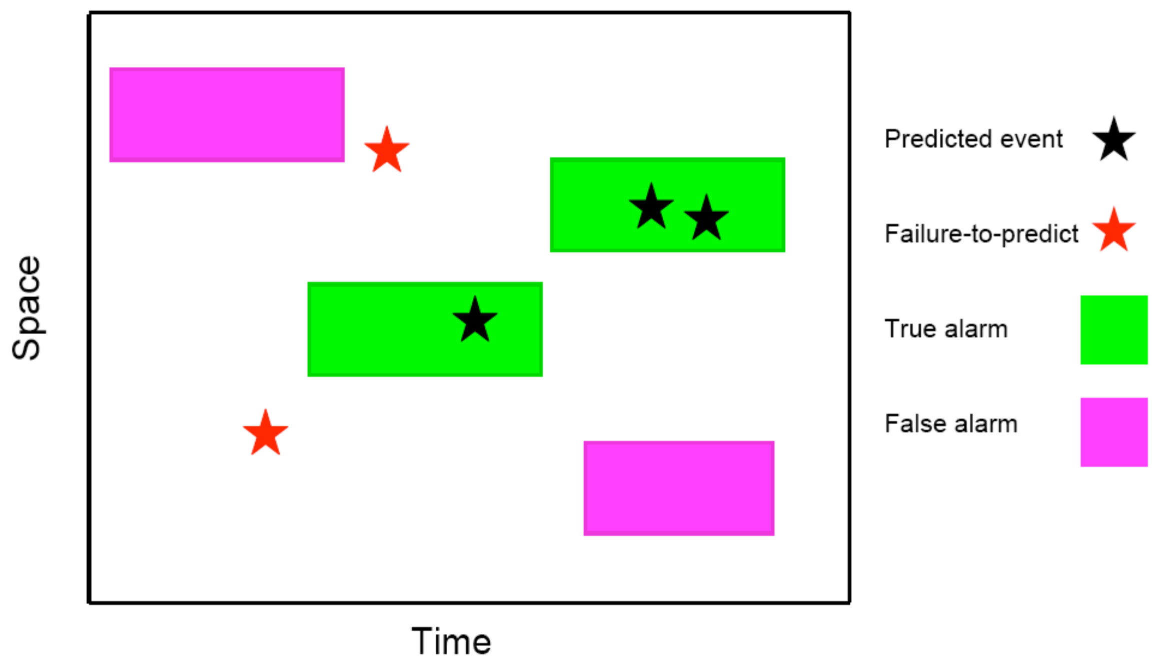
Space-Time Diagram



- **Time-independent models**
  - **Spatially varying model of long-term probability rates**
    - **Assume Poisson behavior**
- **Probability-based forecasts can be evaluated using likelihood methods**
- **Time-dependent models**
  - **Probability rates conditioned on earthquake history**
    - **Long-term stress-renewal models (less clustered than Poisson)**
    - **Short-term triggering models (more clustered than Poisson)**

Earthquake Prediction

Space-Time Diagram



Prediction	Outcome: YES	Outcome: NO
YES	**True alarm (*a*)**	**False alarm (*b*)**
NO	**Failure-to-predict (*c*)**	**True non-alarm (*d*)**

- **A prediction specifies in advance a space-time set of increased probability (alarm) for target earthquakes**
  - **Example: epicenters of events with $M \geq M_0$**
- **Alarm-based predictions can be evaluated using contingency tables**
- **For predictions to be *useful* (to society), they must**
  - **target large events**
  - **have low (and known) error rates**

Three Questions

Q1. **How should scientific earthquake predictions be stated and tested?**

- **How should prediction experiments be conducted and evaluated?**

Q2. **What is the intrinsic predictability of the earthquake rupture process?**

- **What are the coherent space-time structures in the chaotic evolution of active fault systems?**

Q3. **Can knowledge of large-earthquake predictability be deployed as useful predictions?**

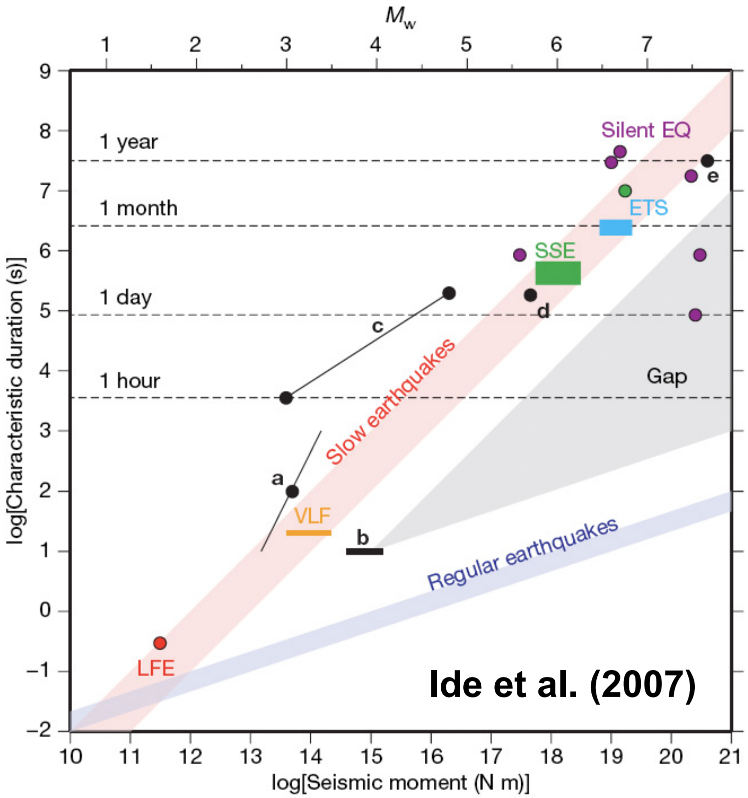
- **Is operational earthquake prediction feasible?**

"Silver Bullet" Approach

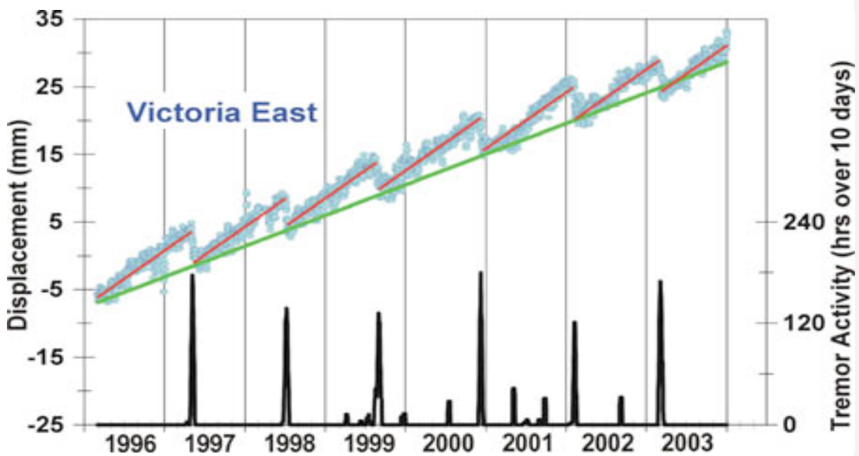
- **Seeks useful, short-term prediction of large earthquakes; i.e., focuses on direct answer to *Q3***
  - "heroic quest" for a simple solution
  - dominated research in the 1970's and 1980's
- **Searches for signals diagnostic of approach to rupture, including:**
  - foreshocks & seismicity patterns
  - strain-rate acceleration
  - seismic velocity changes
  - electromagnetic signals
  - hydrologic changes
  - geochemical signals
  - animal behavior

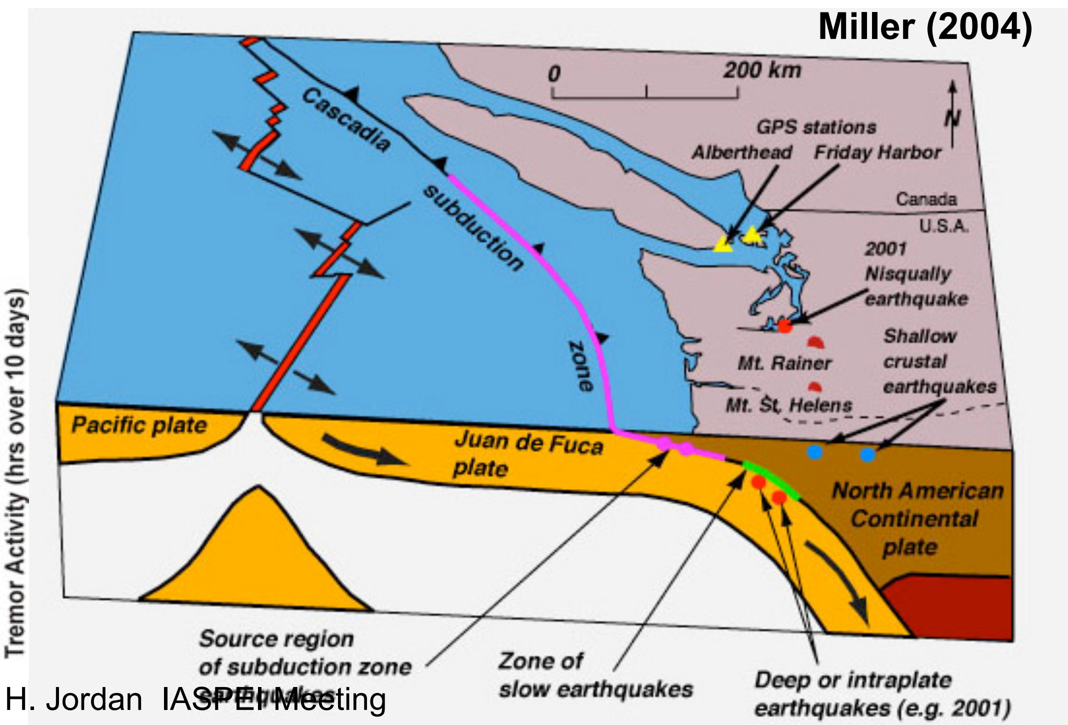
- **Has not thus far led to useful prediction methodologies**

Do slow slip transients in subduction zones trigger fast ruptures?



Ide et al. (2007)



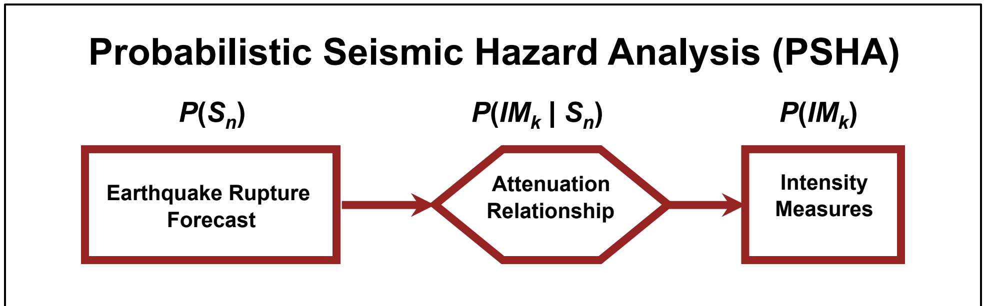


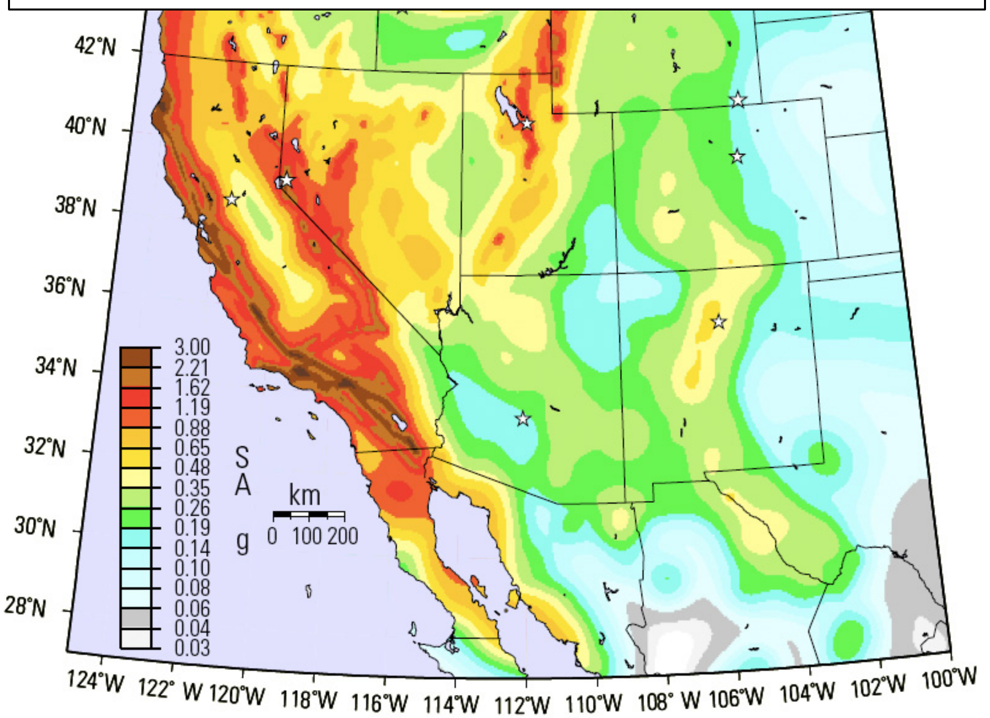
Miller (2004)

"Brick-by-Brick" Approach

- **Focused on experimentation (*Q1*) and predictability (*Q2*), not operational prediction (*Q3*)**
  - **Long-term effort to understand and improve earthquake forecasts, even if probability gains are small**
- **Based on *system-specific, synoptic* models of earthquake recurrence, stress evolution, and triggering**
  - **Statistical approach to stress renewal and triggering, consistent with Probabilistic Seismic Hazard Analysis (PSHA)**
- **Demonstrates predictability by rigorous testing based on *intercomparison* of models**
  - **Requires infrastructure for model experimentation and testing: Collaboratory for the Study of Earthquake Predictability (CSEP)**

NSHMP 2008 Model

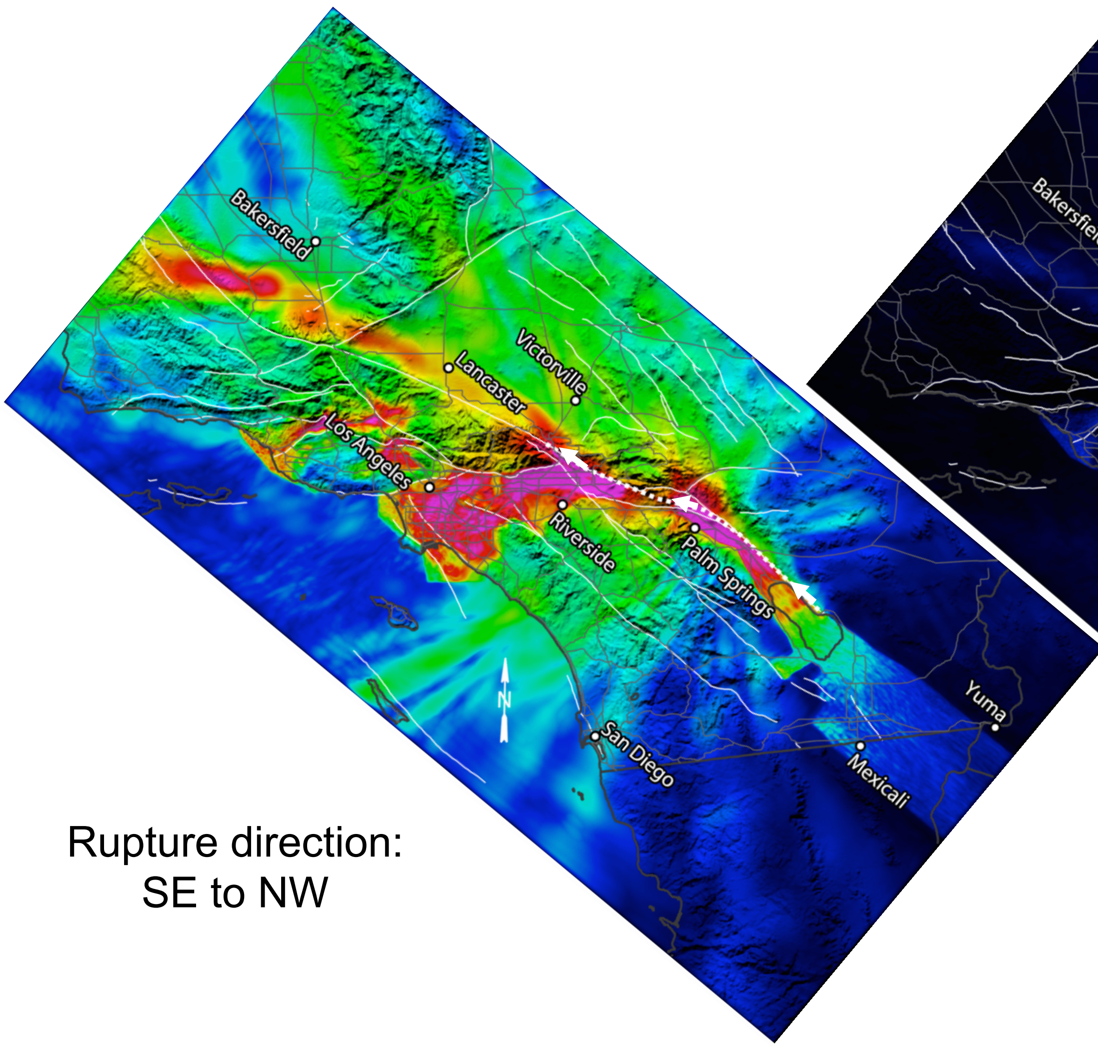




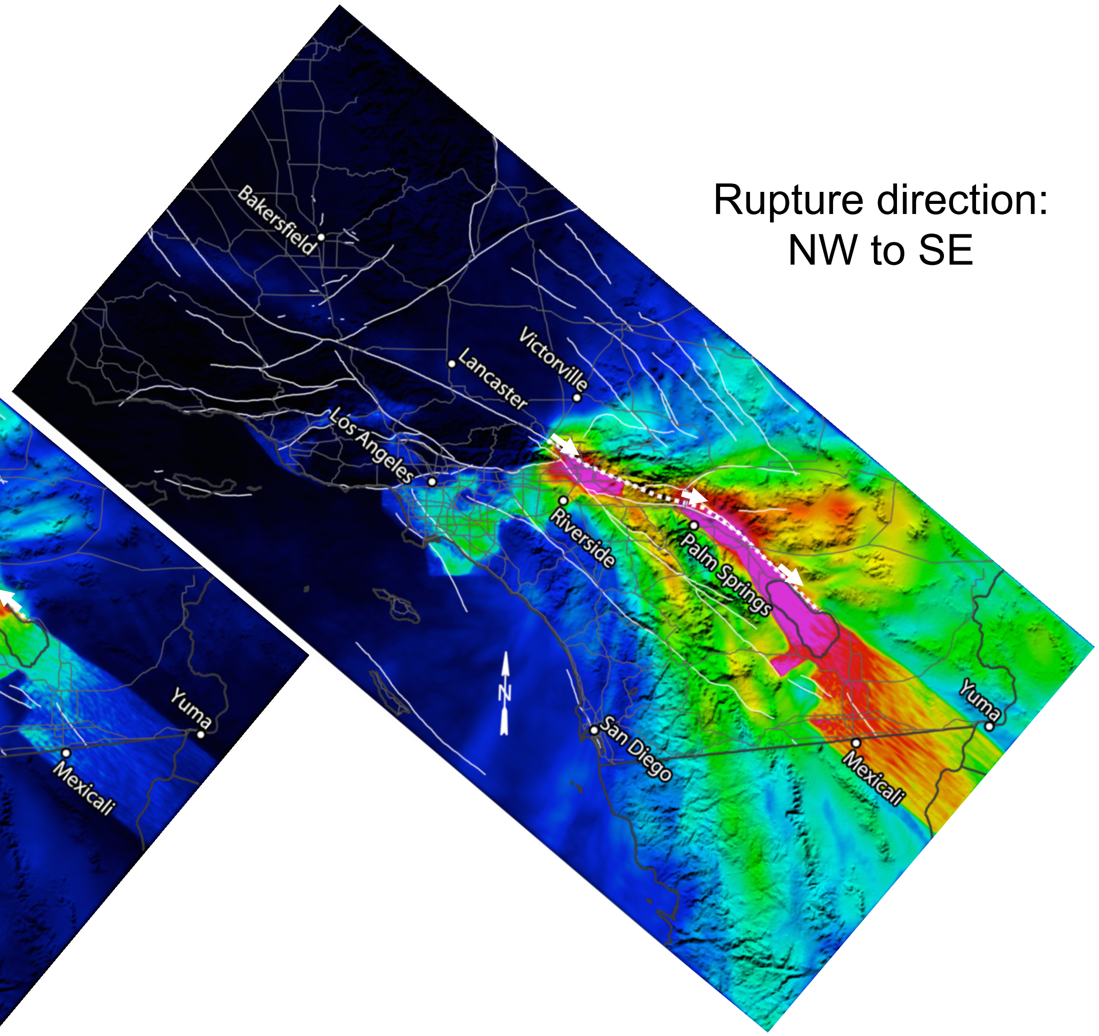
1-s spectral acceleration with 10% exceedance probability in 50 yrs

- **Time-independent earthquake rupture forecast at all U.S. sites from all identified earthquake sources**
  - **Basis for seismic hazard analysis used in building codes and performance-based design**
- **Deficiencies:**
  - **Model represents current fault-system state only through historical seismicity assuming stationary Poisson statistics**
  - **Does not specify rupture directivity or complexity**

Is the rupture direction random, or can it be predicted?



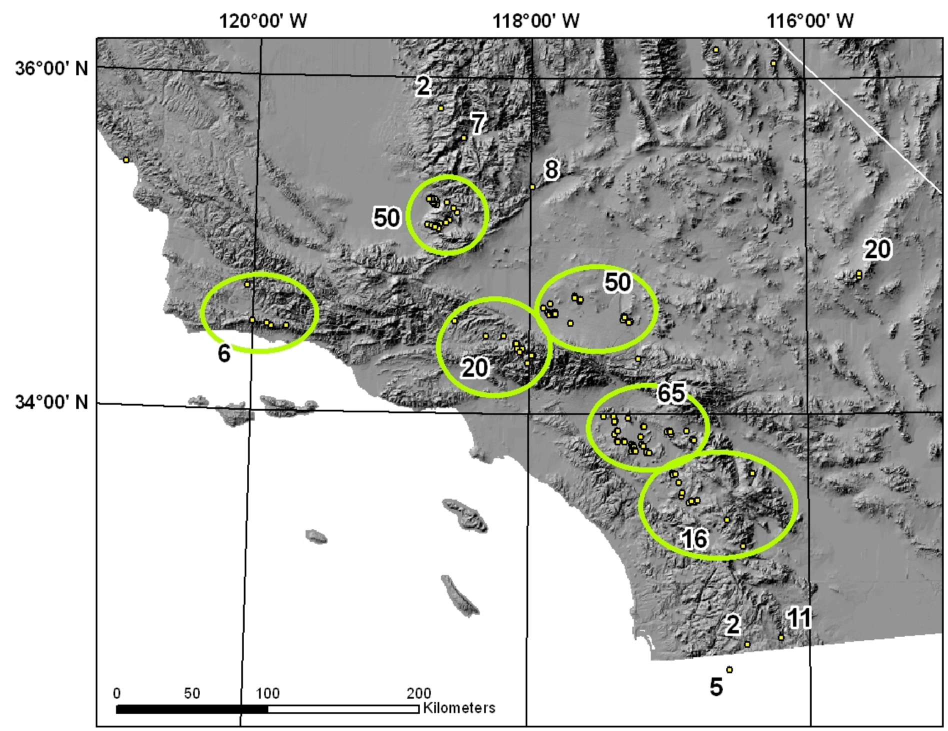
Rupture direction:
SE to NW



Rupture direction:
NW to SE

TeraShake simulations of M7.7 earthquake on Southernmost San Andreas (Olsen et al. 2006)

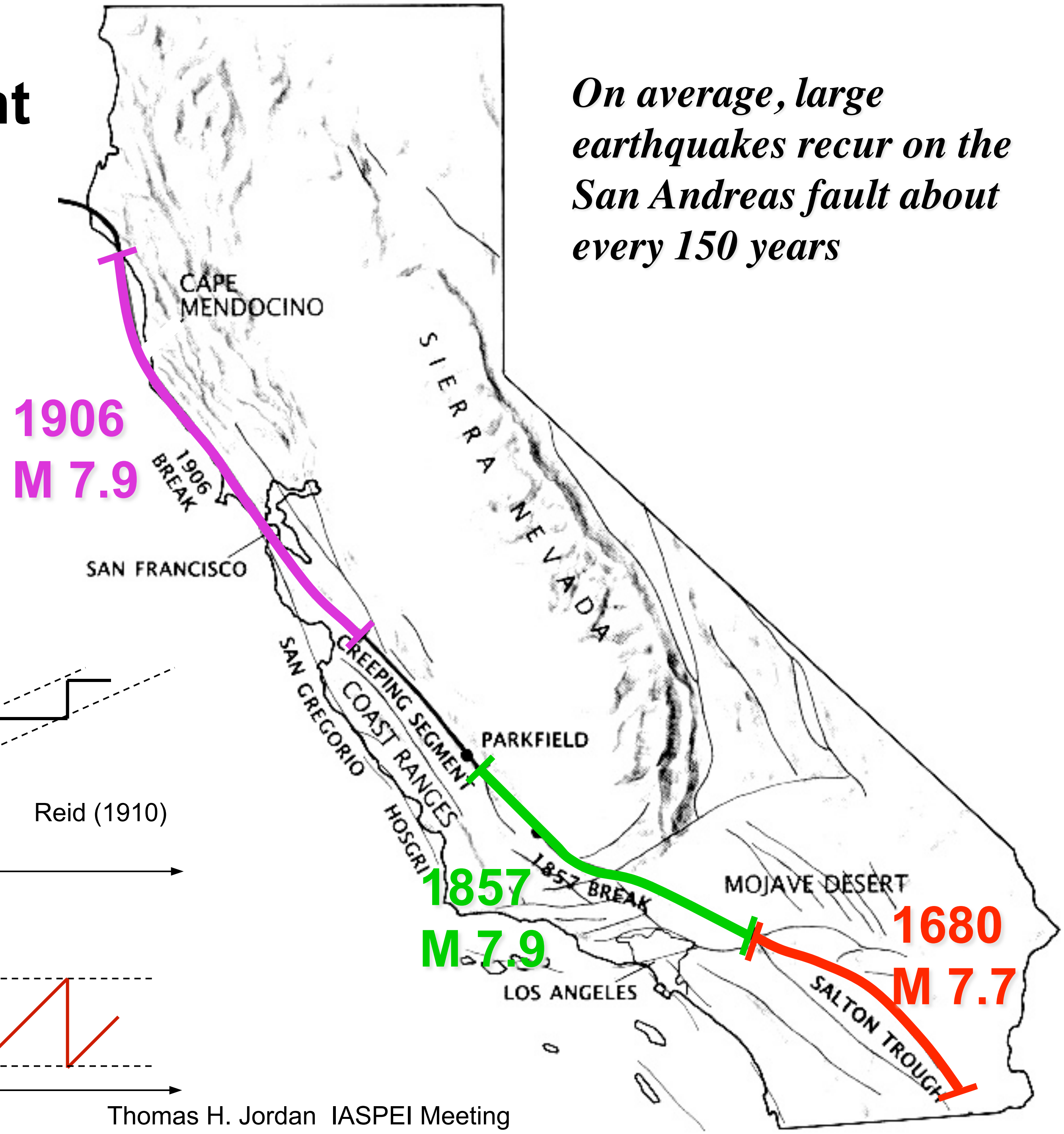
Validation of Simulations Using Precarious Rocks

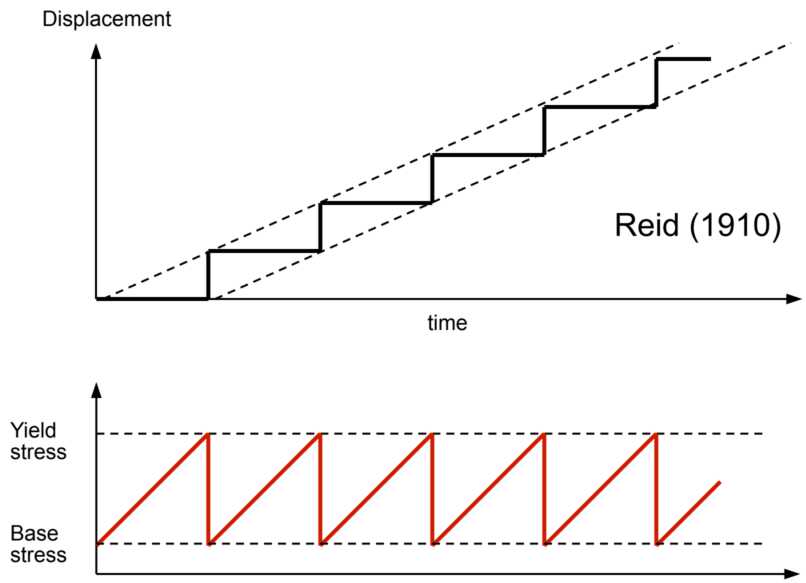


UNR Database
(Brune et al., 2006)

Time-Dependent Forecasting

On average, large earthquakes recur on the San Andreas fault about every 150 years





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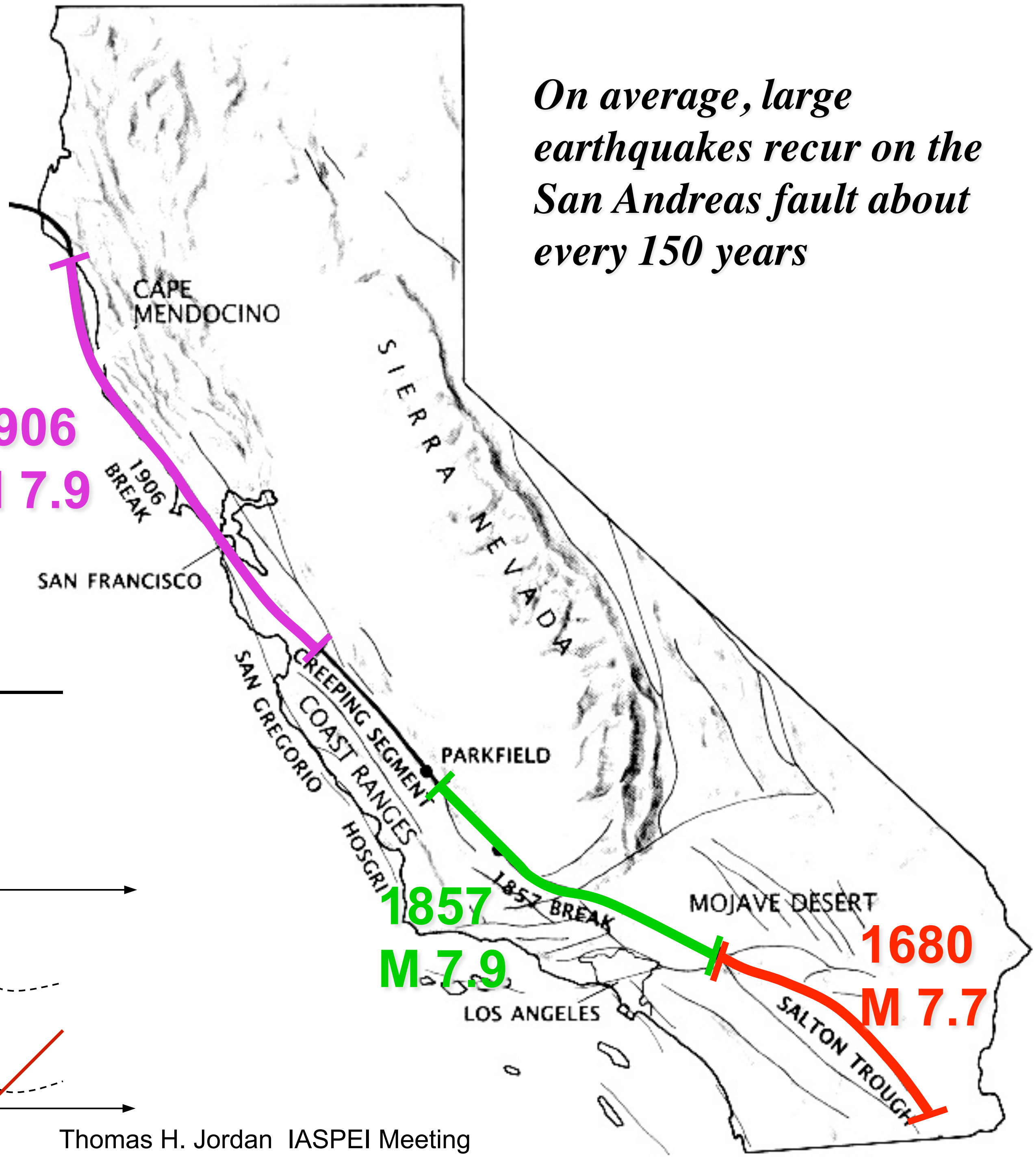

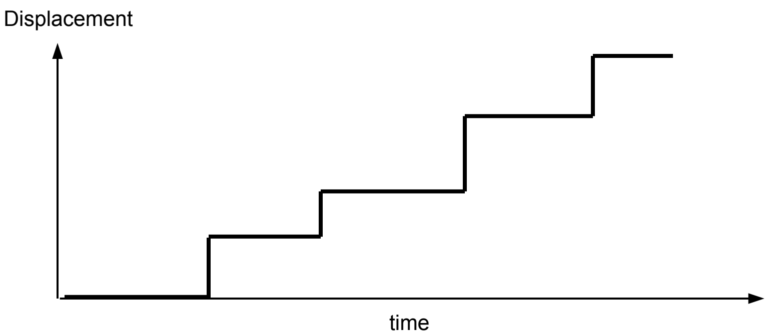

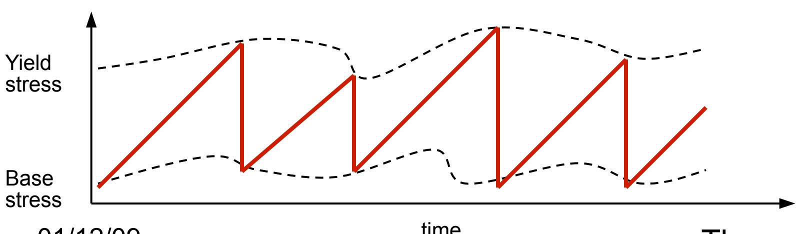

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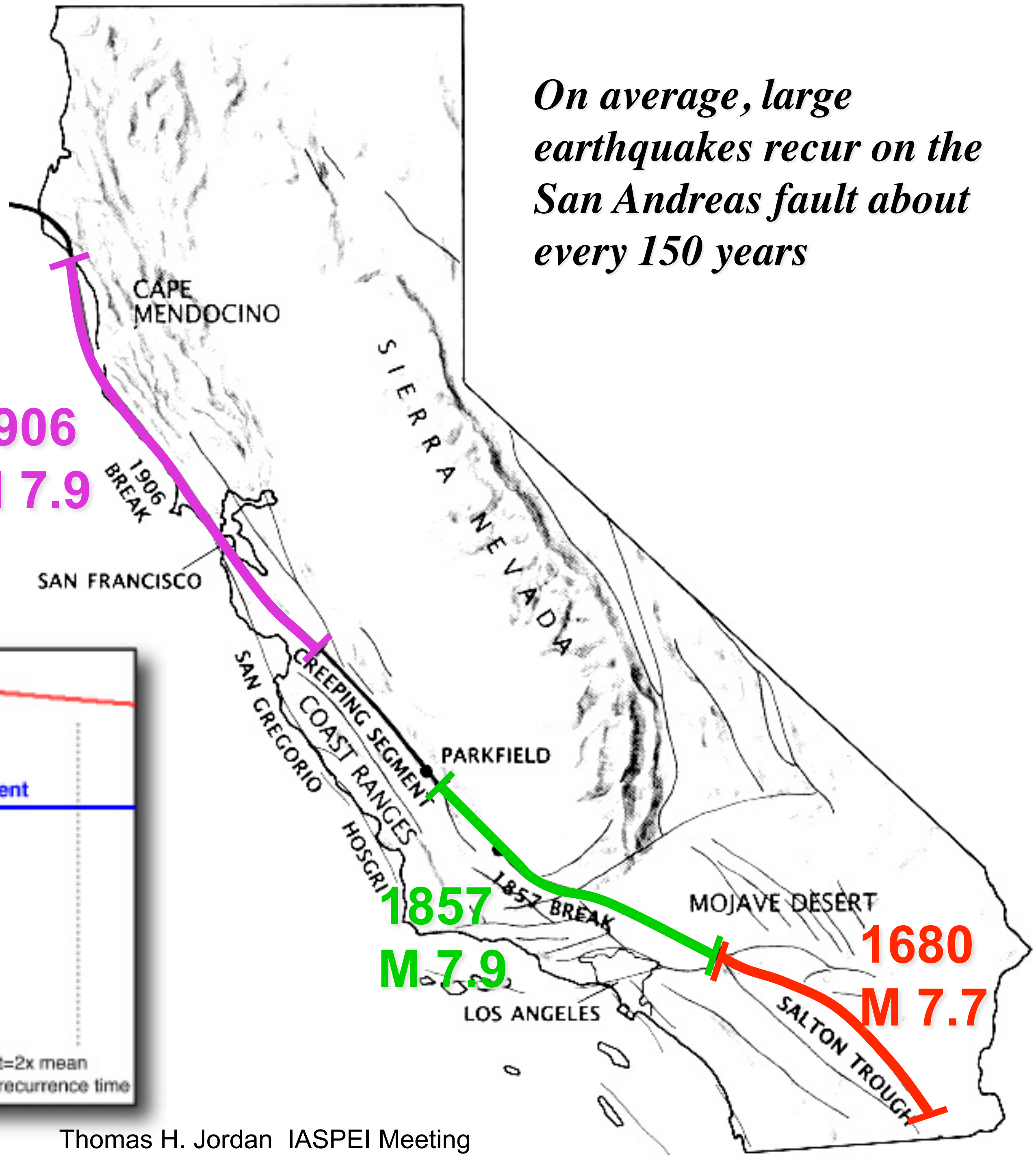

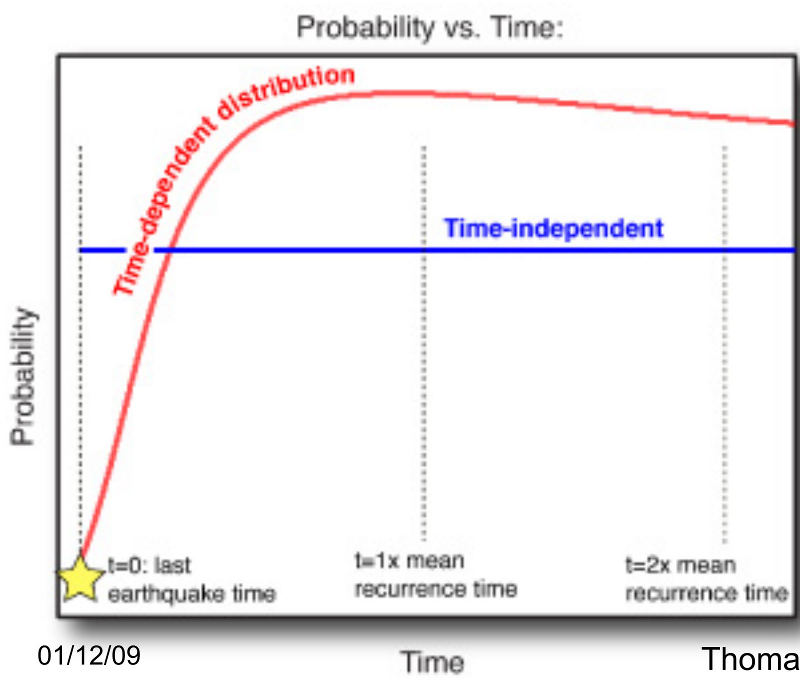

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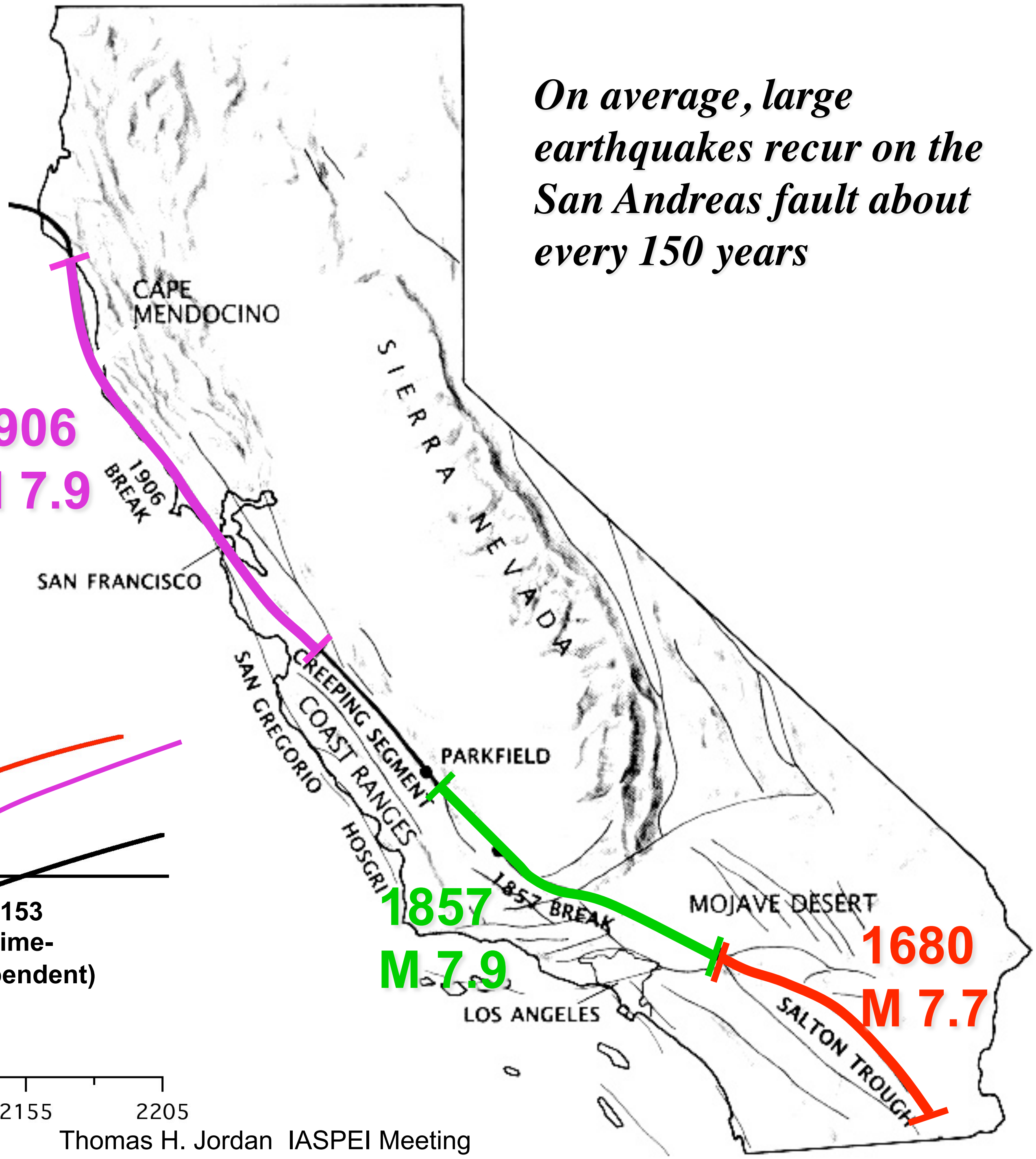
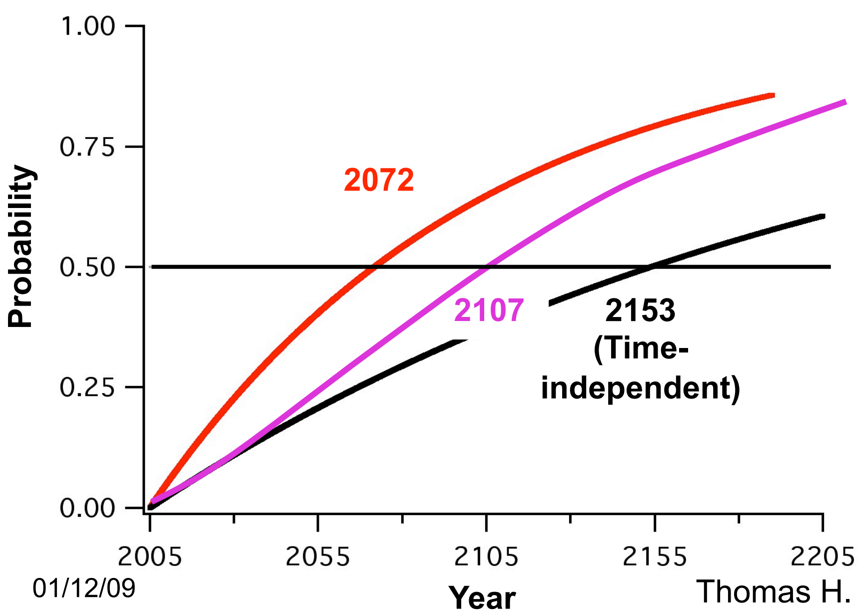
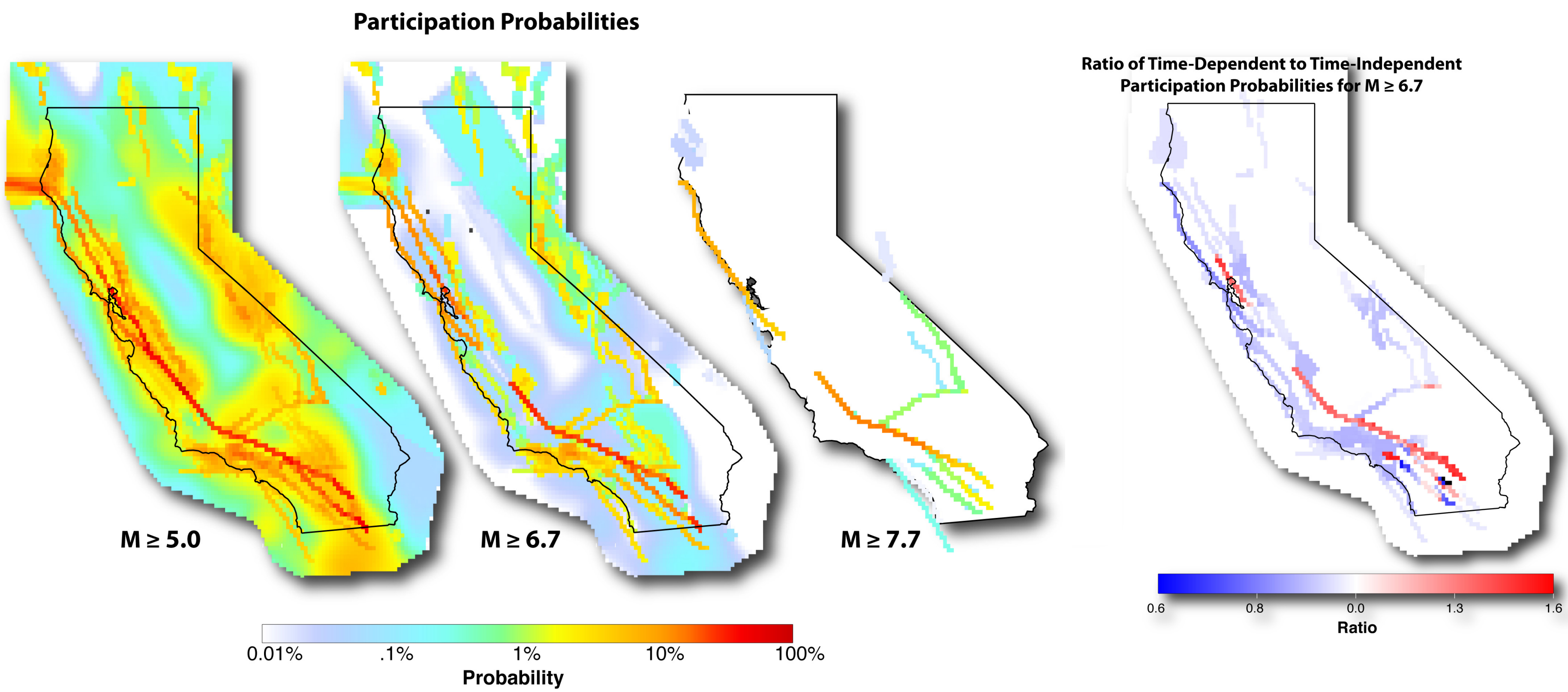




SCEC-USGS-CGS Working Group on California Earthquake Probabilities (2007)

Uniform California Earthquake Rupture Forecast



Uniform California Earthquake Rupture Forecast (WGCEP, 2007)

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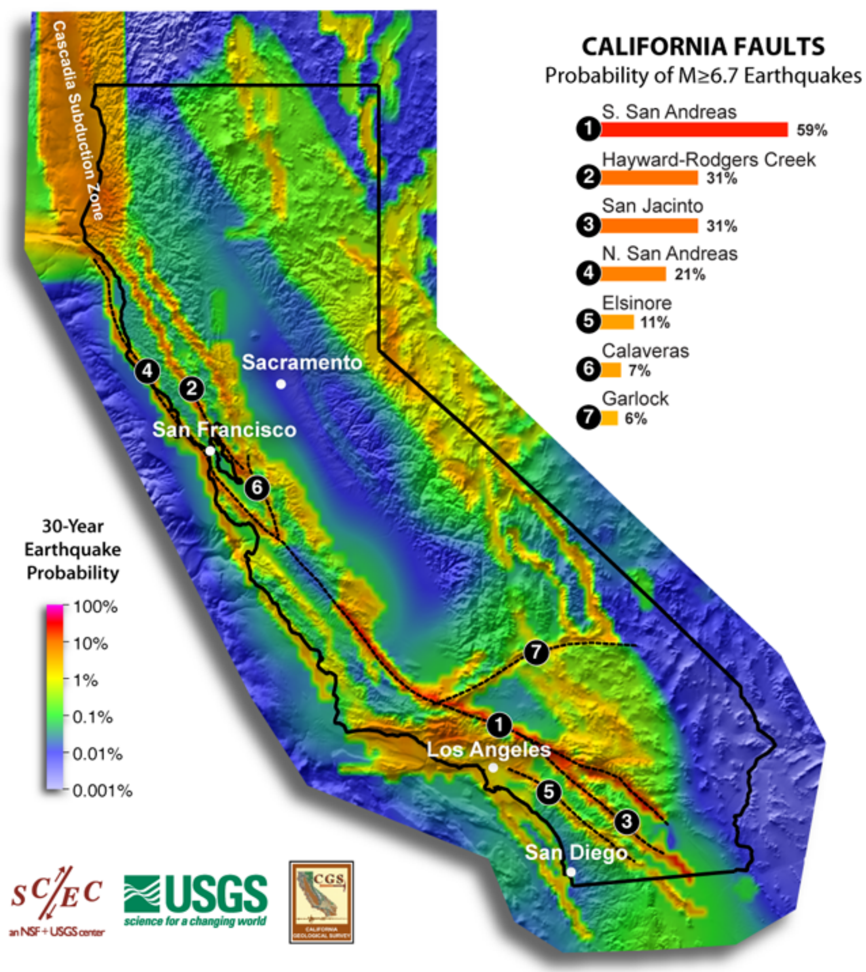
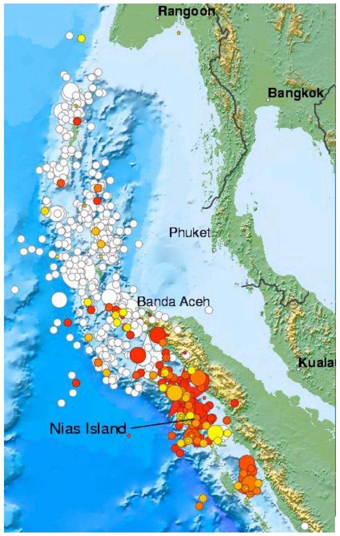
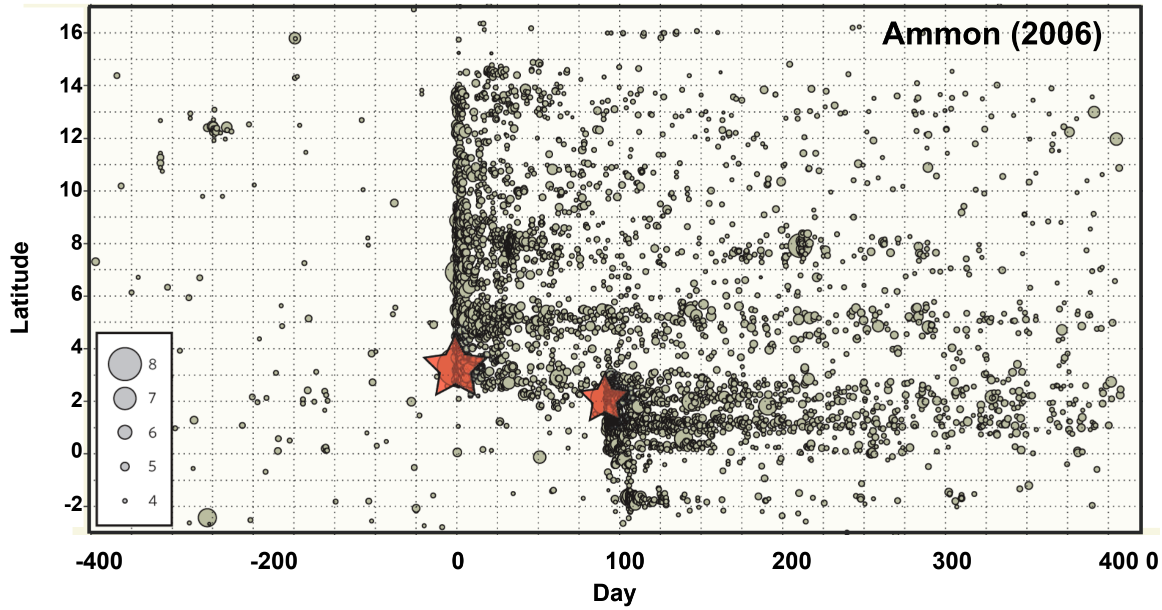


- **Time-dependent earthquake rupture forecast for California**
  - **Basis for seismic hazard analysis used in building codes and performance-based design**
- **Deficiencies:**
  - **Model represents current fault-system state only through date of last major earthquake on Type-A faults**
  - **Does not include short-term clustering, triggering, and stress-transfer effects**

Aftershocks, Stress Transfer, and Triggering



After 28 Mar 2005



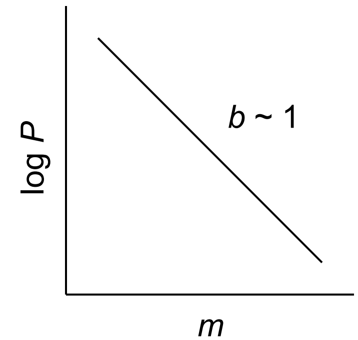
Sumatra-Andaman Earthquake Sequence

- **Approaches:**
  - **Coulomb stress changes**
  - **Statistical triggering models**
    - **Epidemic-Type Aftershock Sequence (ETAS) models**

A simple ETAS model …

1. All earthquake magnitudes above a lower cutoff m_0 are independent samples of the Gutenberg-Richter probability distribution,

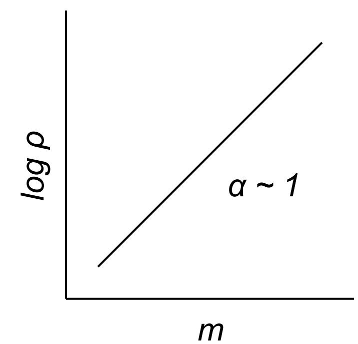
$$P(m) = 10^{-b(m-m_0)}$$



G-R law

2. All earthquakes give birth to daughter events at an average rate

$$R(m,x,t) \;=\; \rho(m)\phi(x)\psi(t)$$



triggering relation

3. The triggering rate is assumed to increase exponentially with magnitude,

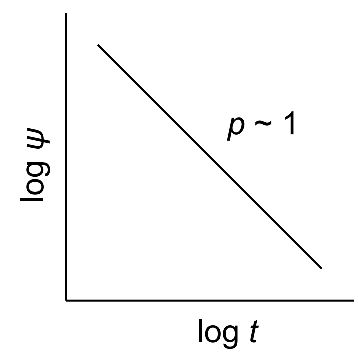
$$\rho(m) = k\,10^{\alpha(m-m_0)}$$

4. decrease with distance from the mother event,

$$\phi(r) \;\sim\; (d+r)^{-q}$$

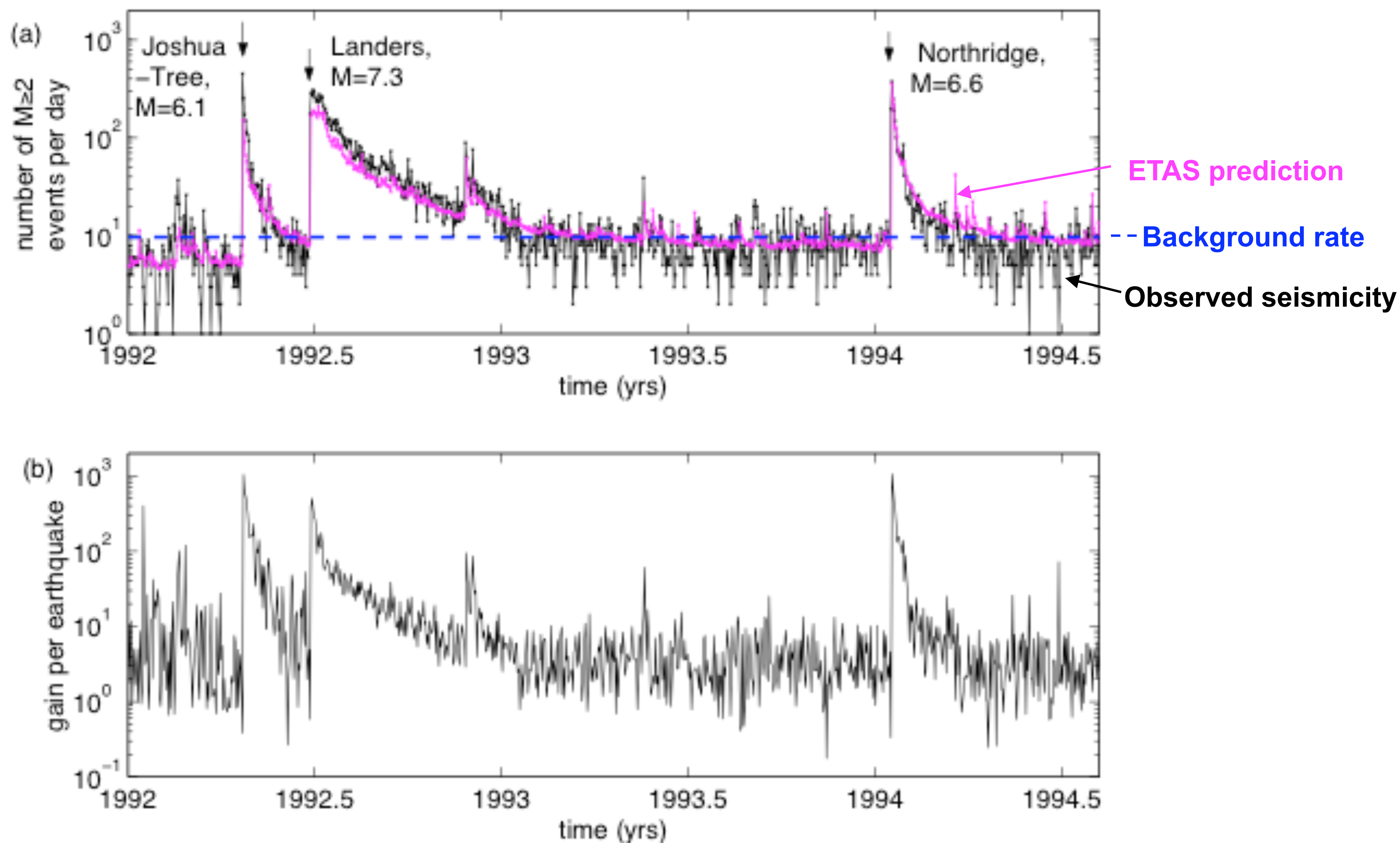
5. and decay with time according to the modified Omori law,

$$\psi(t) \;\sim\; (c+t)^{-p}$$



modified Omori law

ETAS Prediction of Short-Term Seismicity



Retrospective daily ETAS predictions of Southern California seismicity by Helmstetter et al. (2006)

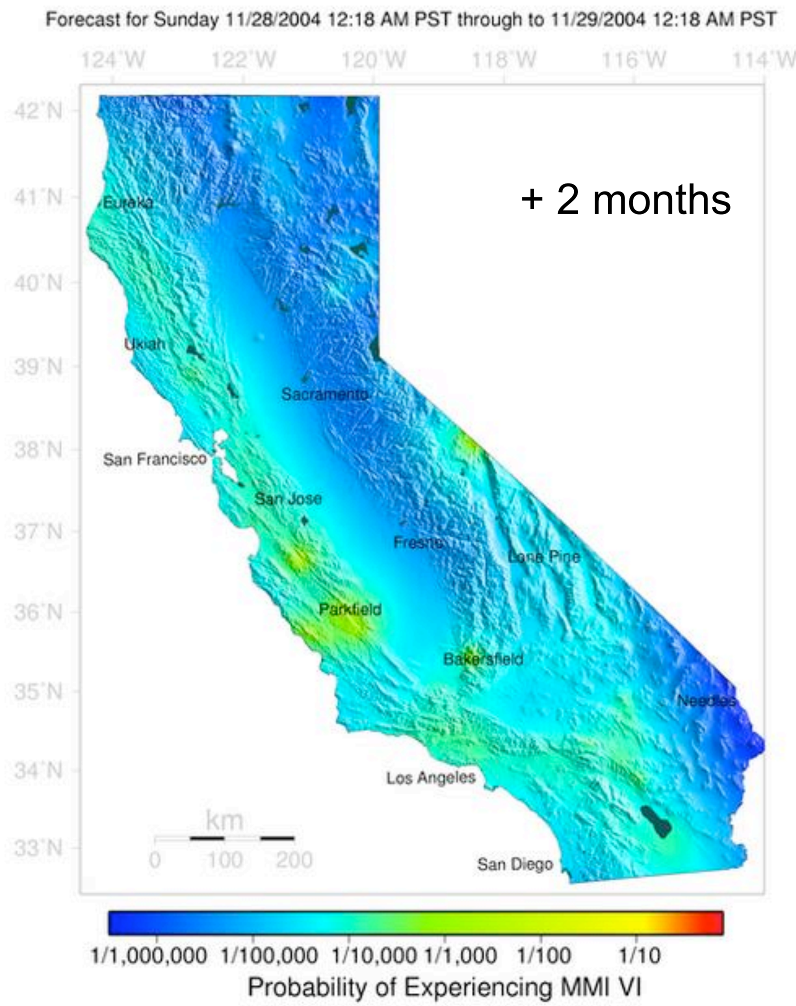
Short-Term Earthquake Probability (STEP) Map

- Map Archive
- What Is This Map?
- How Do We Make This Map?
- How Can I Use This Map?
- What Are Aftershocks, Foreshocks and Earthquake Clusters?

These maps are made with contributions from ETH-Zurich, Switzerland, and the Southern California Earthquake Center.

ETH

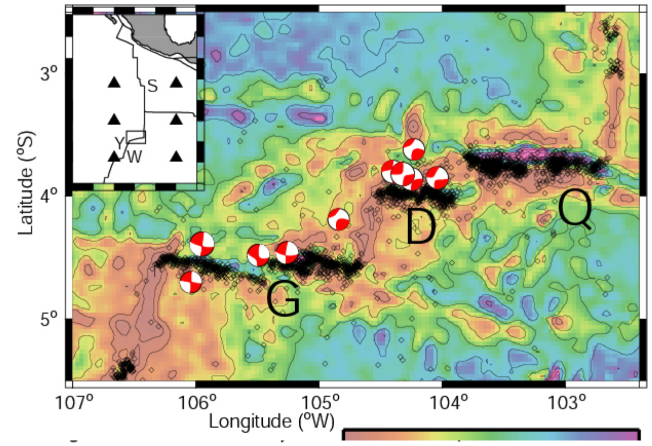
SCEC
an NSF+USGS center

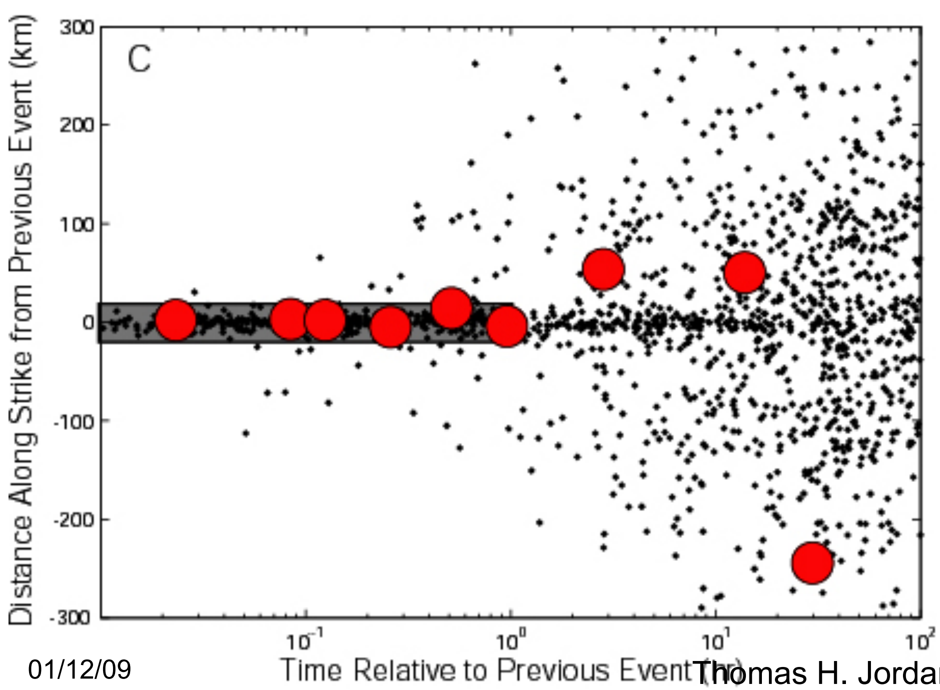


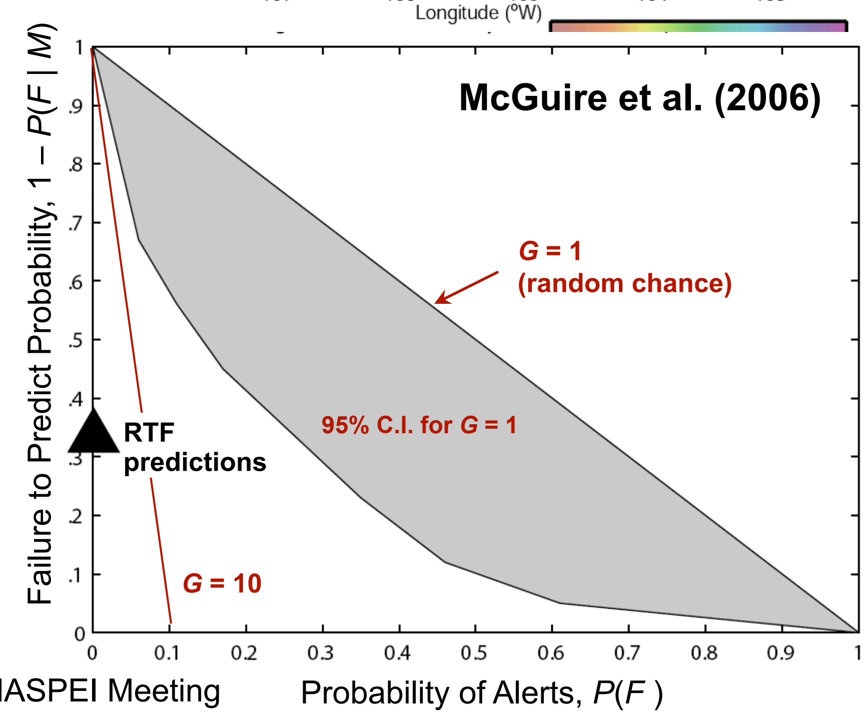
http://pasadena.wr.usgs.gov/step

Enhanced Short-Term Predictability

- **Foreshocks of large earthquakes on ridge transform faults provide more predictability than expected from ETAS models**
  - **Slow precursors have been observed**

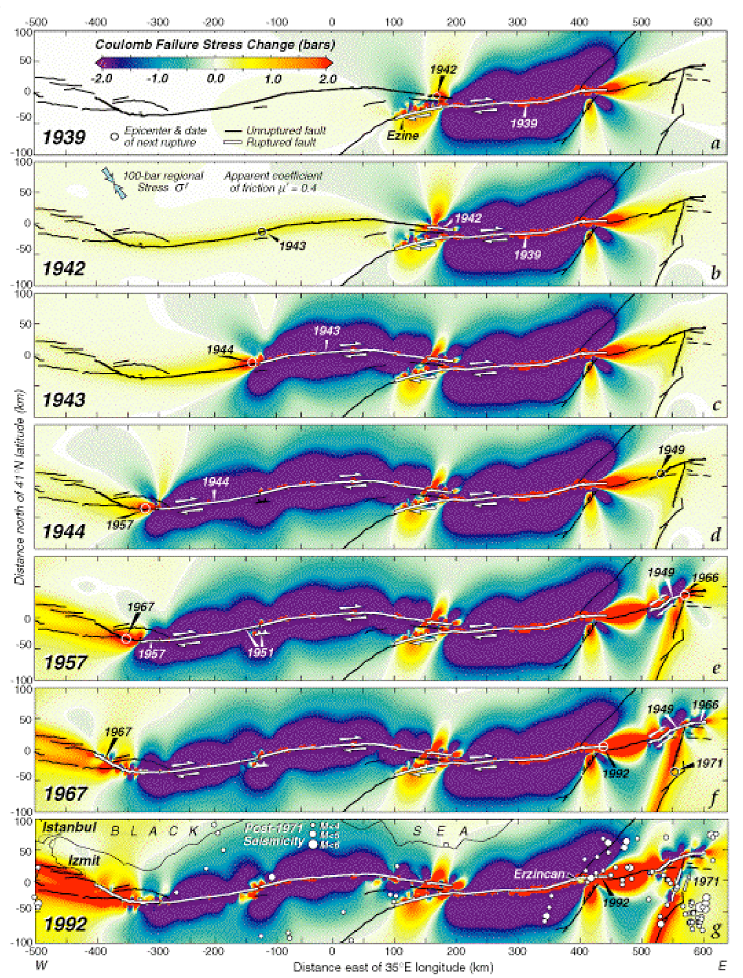






Unification Across Scales

- **Earthquake systems have significant predictability across a range of scales**
  - **Large-scale, long-term: fault-based models, e.g. UCERF**
  - **Small-scale, short-term: at least as good as STEP**
- **Unification across scales requires a focus on *medium-term predictability***
  - **Physical basis in stress evolution, transfer, and triggering**



Stress evolution of the North Anatolian fault system (Stein et al., 1997)

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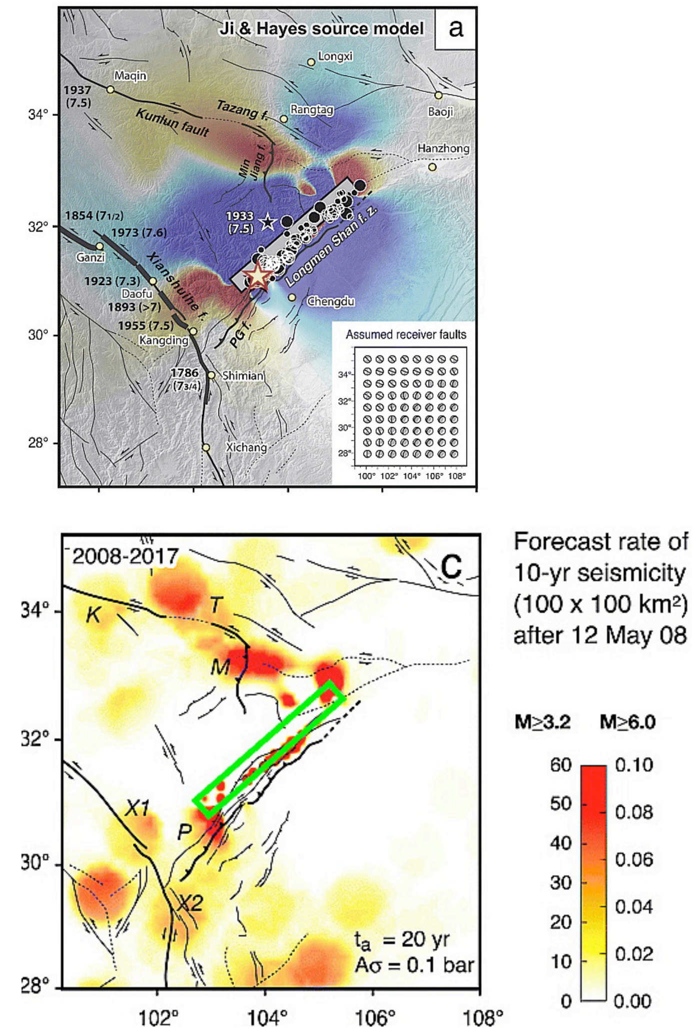

Wenchuan Earthquake Region (Toda et al., 2008)

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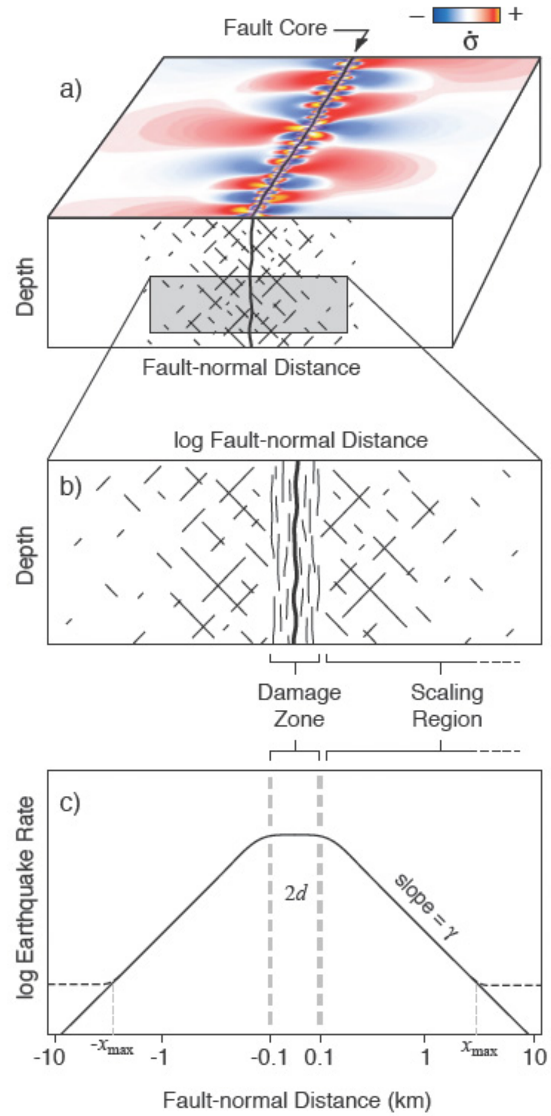

Powers & Jordan (2009)

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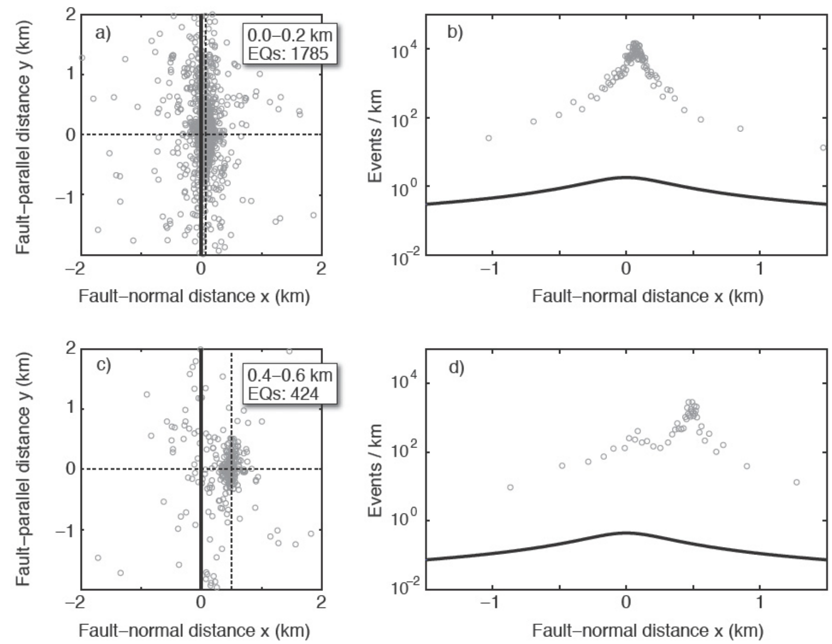

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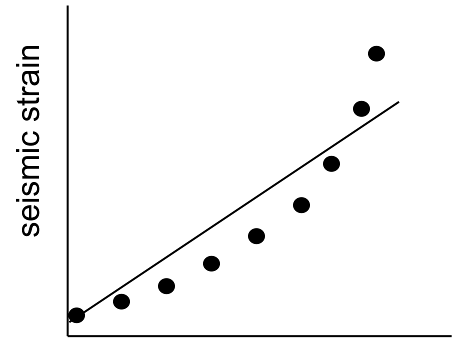
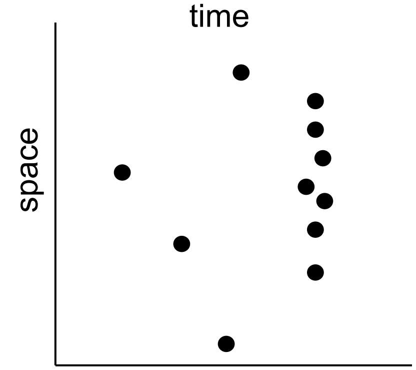
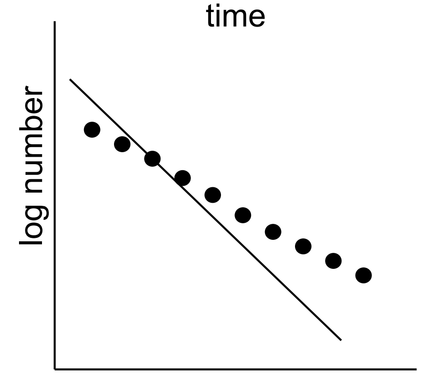
Accelerating Moment Release



Long-Range Correlation



Change in *b*-value



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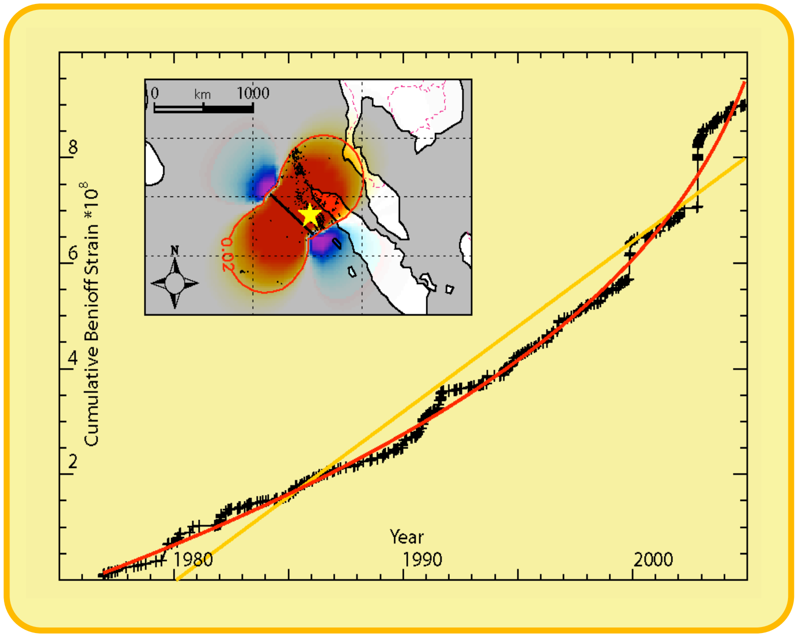
Accelerating Seismicity Before the 2004 M9.1 Sumatra-Andaman Islands Earthquake (retrospective analysis)



Mignan, Bowman & King (2005)

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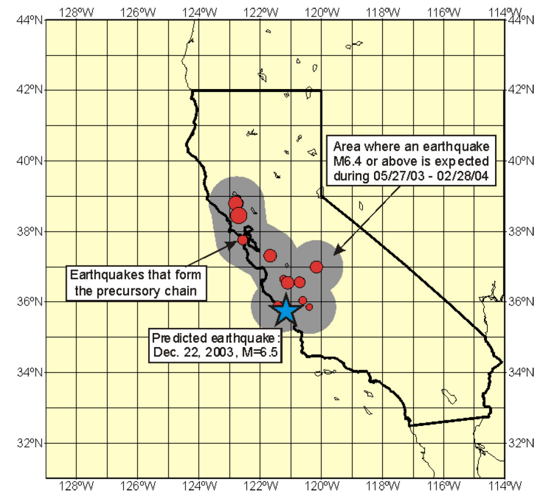
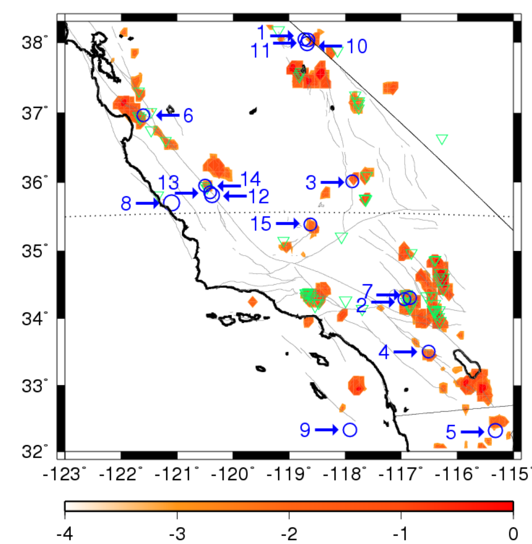
RTP Method of Keilis-Borok et al. (2003)

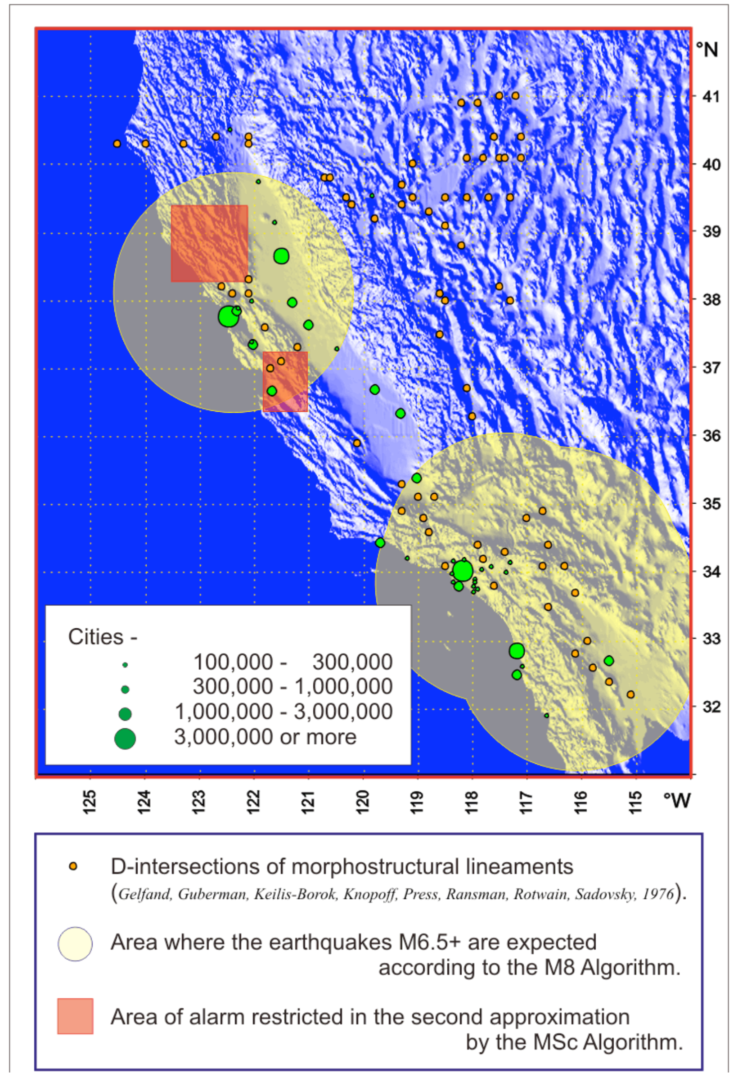


PI Method of Rundle et al. (2002)



Unification Across Scales

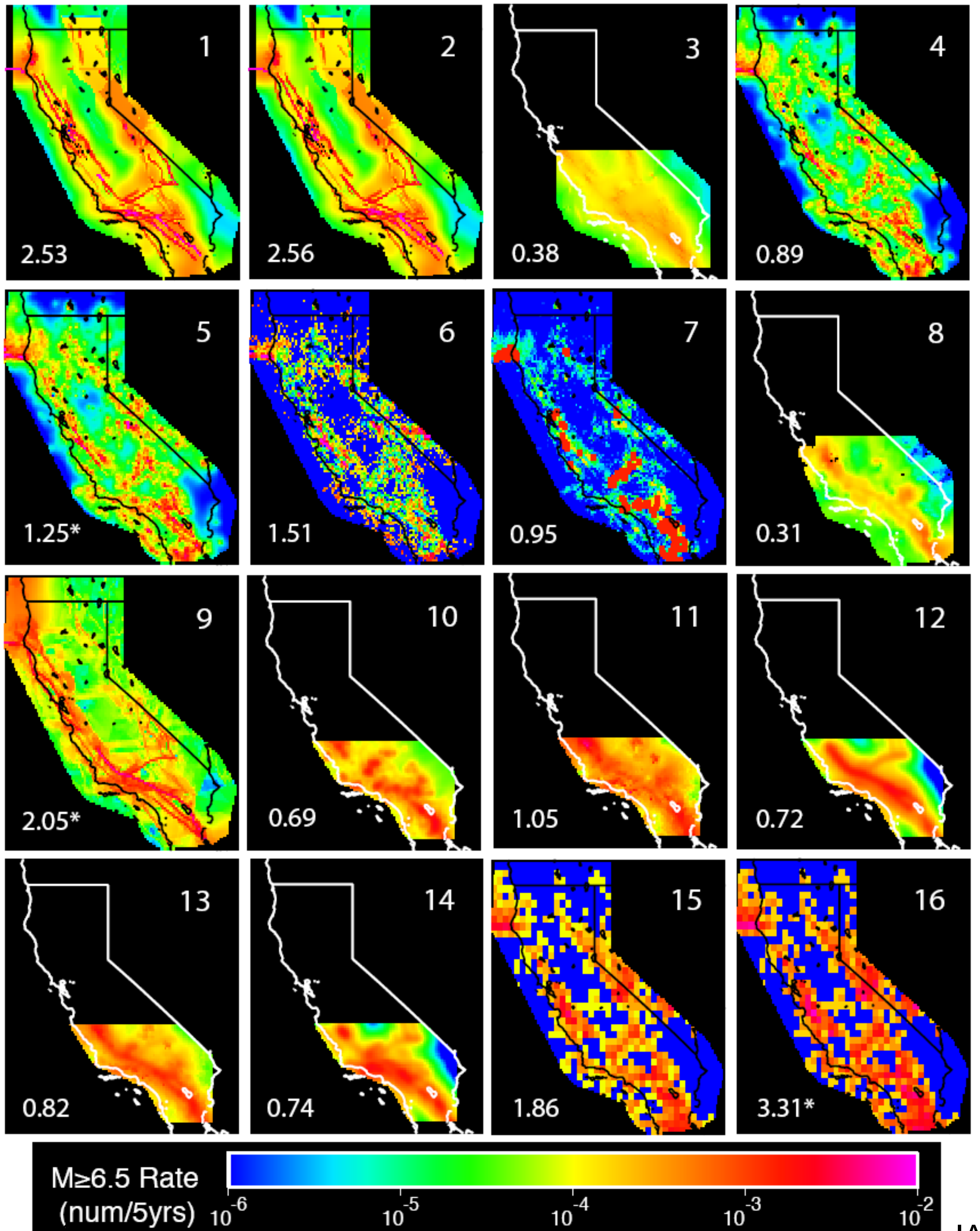
- **Earthquake systems have significant predictability across a range of scales**
  - **Large-scale, long-term: fault-based models, e.g. UCERF**
  - **Small-scale, short-term: at least as good as STEP**
- **Unification across scales requires a focus on *medium-term predictability***
  - **Physical basis in stress evolution, transfer, and triggering**
  - **Integration into fault-system models**
  - **Statistical basis in seismicity patterns**



Current M8 & MSc Alarms in California (Kossobokov, Jan 2008)

Problems in Assessing Earthquake Prediction Experiments

- **Scientists are over-optimistic about their own results**
- **Scientific publications provide insufficient information for independent evaluation**
- **Active researchers are constantly tweaking their procedures, which become moving targets**
- **Standards are lacking for testing predictions against reference forecasts**
- **Data to evaluate prediction experiments are often improperly specified**
- **Infrastructure for conducting and evaluating long-term prediction experiments has not existed**



SCEC/USGS Working Group on

Regional Earthquake Likelihood Models (RELM)

Intermediate-term experiments underway in the California Natural Laboratory

Papers describing 19 RELMs have appeared in a special issue of *SRL*, February, 2007

http://www.relm.org

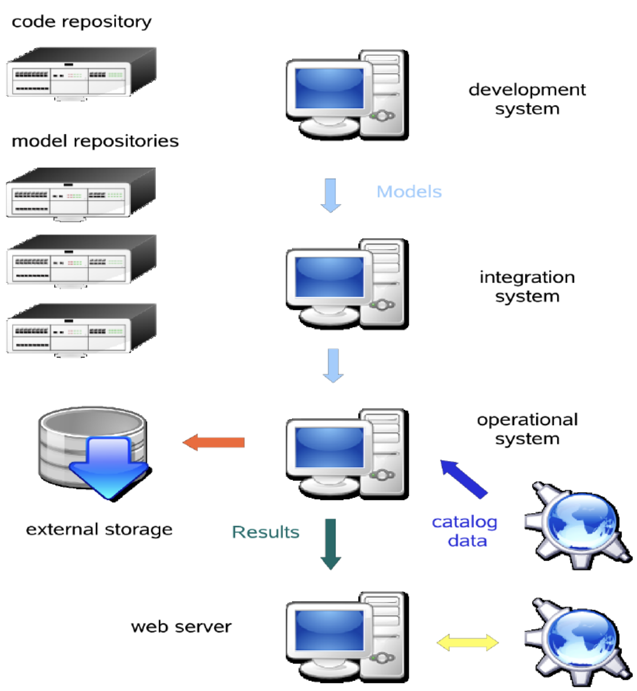
Collaboratory for the Study of Earthquake Predictability (CSEP)

- **Motivation**
  - **Earthquake prediction research is hampered by inadequate infrastructure for conducting scientific prediction experiments**
- **Primary goal**
  - **Rigorous *comparative* testing of scientific prediction experiments spanning a variety of fault systems to study the physical basis for earthquake predictability**
- **CSEP is building on RELM and similar efforts**
  - **International partnerships are establishing natural laboratories for scientific earthquake prediction experiments**

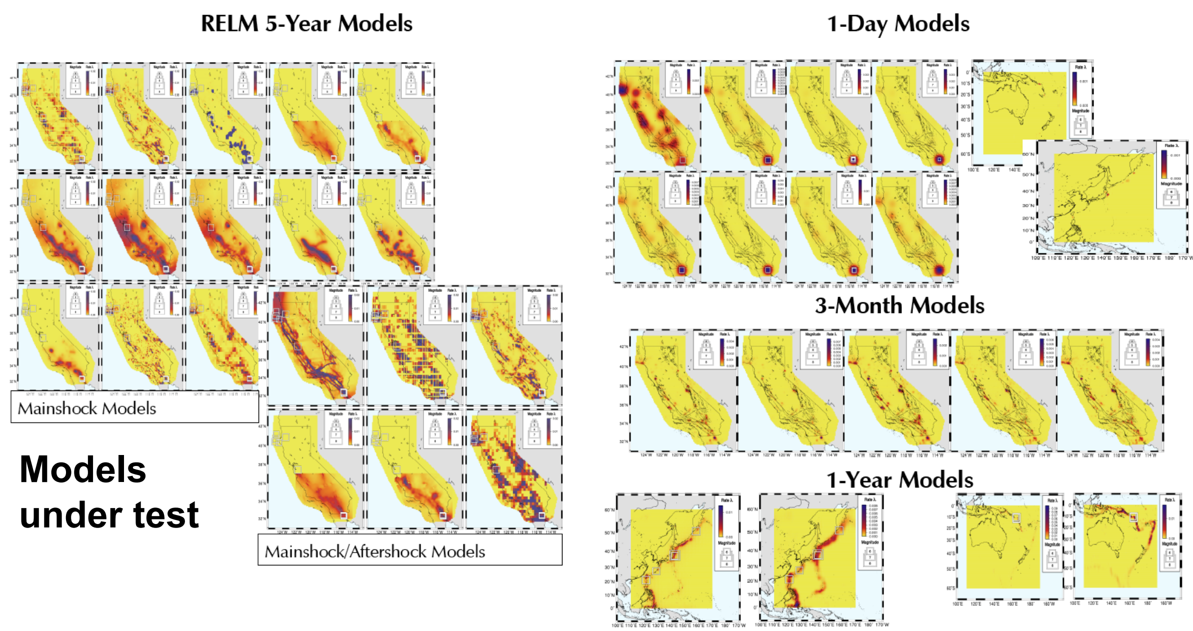
Four CSEP Components

1. ***Testing regions***: **natural laboratories comprising active fault systems with adequate, authorized data sources for conducting prediction experiments**
2. ***Community standards***: **rules for the registration and evaluation of scientific prediction experiments**
3. ***Testing centers***: **facilities with validated procedures for conducting and evaluating prediction experiments**
4. ***Communication protocols***: **procedures for conveying scientific results and their significance**
    - **the scientific community, including professional societies**
    - **government agencies responsible for risk management**
    - **the general public and other end-users**

SCEC Testing Center

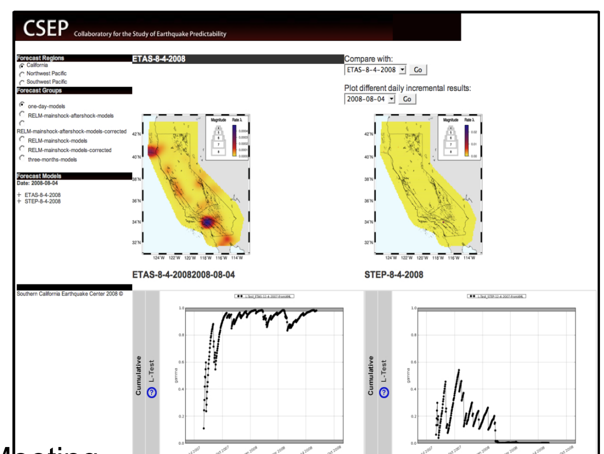


Computational system



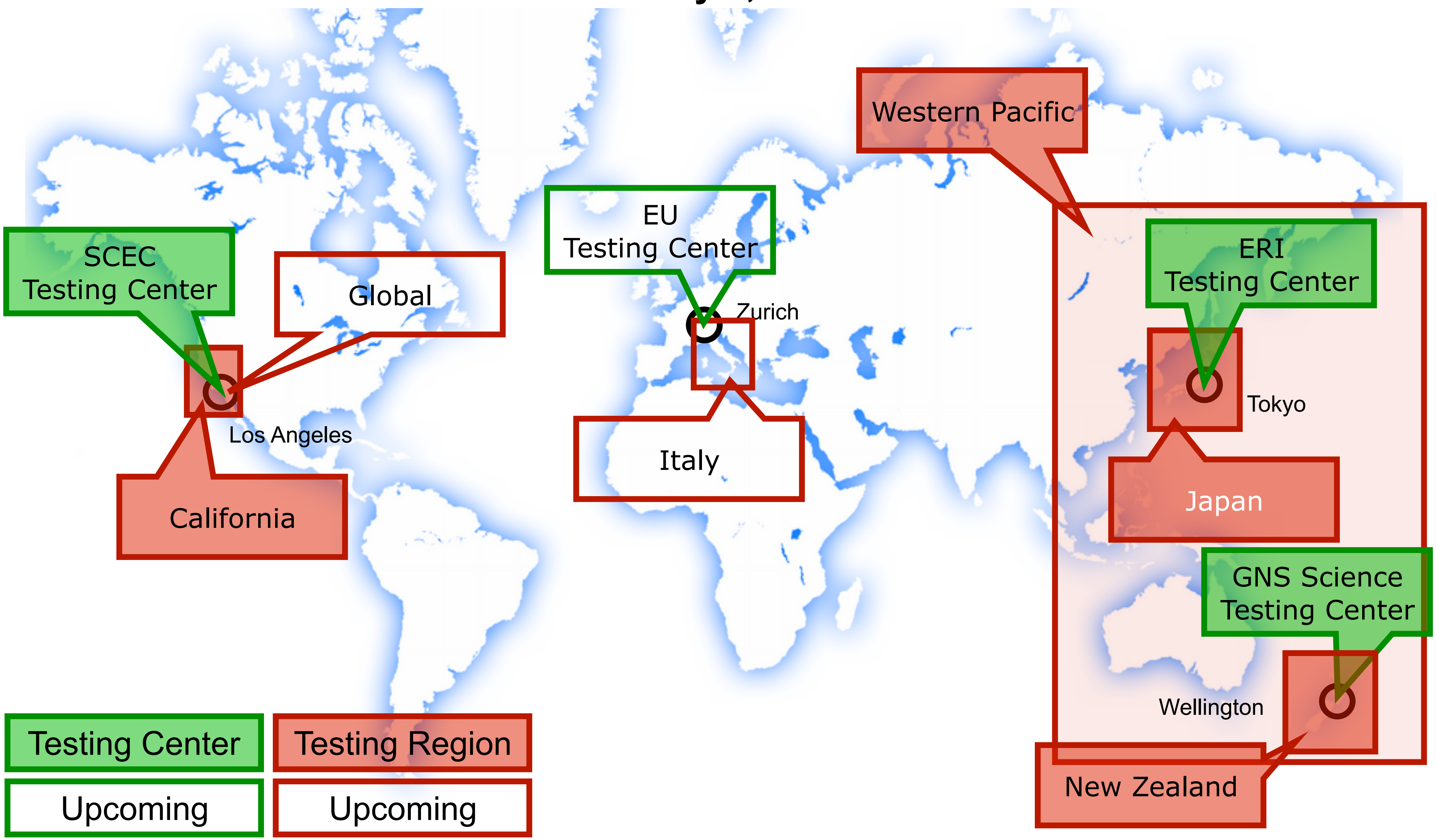
Models under test

Testing results



CSEP Testing Regions & Testing Centers

January 1, 2009



CSEP Goals

1. **Reduce the controversy surrounding earthquake prediction through a collaboratory infrastructure to support a wide range of scientific prediction experiments**

2. **Promote rigorous research on earthquake predictability through global partnerships**

3. **Help the responsible government agencies assess the feasibility of earthquake prediction and the performance of proposed prediction algorithms**

End