Southern California Earthquake Center

Forecasting Earthquakes and Predicting Their Hazards

Thomas H. Jordan

Director, Southern California Earthquake Center

Chair, International Commission on Earthquake Forecasting

IUGG Plenary Talk

3 July 2011

Some Destructive Earthquakes Since the 2007 IUGG Meeting

Date	Location	Magnitude	Deaths
2008 05 12	Wenchuan, China	7.9	87,587
2009 04 06	L'Aquila, Italy	6.3	308
2009 09 30	Padang, Indonesia	7.5	1,117
2010 01 12	Port-au-Prince, Haiti	7.0	222,570
2010 02 27	Maule, Chile	8.8	557
2010 04 13	S. Qinghai, China	6.9	2,968
2011 02 22	Christchurch, NZ	6.1	182
2011 03 11	Tohoku, Japan	9.0	28,050

 Science May 31, 2011

Out of the blue. Students at California State University, Northridge, ponder the destruction wrought by a quake on an unrecognized fault.

SEISMOLOGY

Seismic Crystal Ball Proving Mostly Cloudy Around the World

Failing at quake prediction, seismologists tried making fuzzier forecasts, but Japan's megaquake is only the latest reminder of the method's shortcomings

When a devastating megaquake rocked the region north of Tokyo in March, nobody saw such a huge quake coming. "Japanese scientists are among the world's best, and they have the best monitoring networks," notes geophysicist Ross Stein of the U.S. Geological 1960s and '70s, seismologists worked on *prediction*: specifying the precise time, place, and magnitude of a coming quake. To do that, scientists needed to identify reliable signals that a fault was about to fail: a distinctive flurry of small quakes, a whiff of radon gas oozing from the ground, some oddly perturbed wildlife. Unfortunately, no one has yet found a bona fide earthquake precursor. By the time the 2004 magnitude-6.0 Parkfield earthquake—the most closely monitored quake of all time—struck the central San Andreas fault without so much as a hint of a precursor (*Science*, 8 October 2004, p. 206), most researchers had abandoned attempts at precise prediction.

Parkfield did mark an early success of a new strategy: quake *forecasting*. Rather than waiting for a warning sign, forecasters look to the past behavior of a fault to gauge future behavior. They assume that strain on a fault is building steadily and that the same segment of fault that broke in the past will produce a similar break again in the future, once it reaches the same breaking point. Instead of giving the year or range of years when the next quake will strike a particular segment of fault, they express it as a probability.

USGS issued its first official earthquake forecast for the San Andreas in 1988 (*Science*, 22 July 1988, p. 413). Parkfield, which had a long record of similar quakes at roughly 22-year intervals, rated a 99% probability of repeating in the next 30 years. That turned out to be a success for the 1988 forecast. And the southern Santa Cruz Mountains segment, which last slipped in the 1906 San Francisco quake, was given a 30% chance of failing again within 30 years, which it did in 1989.

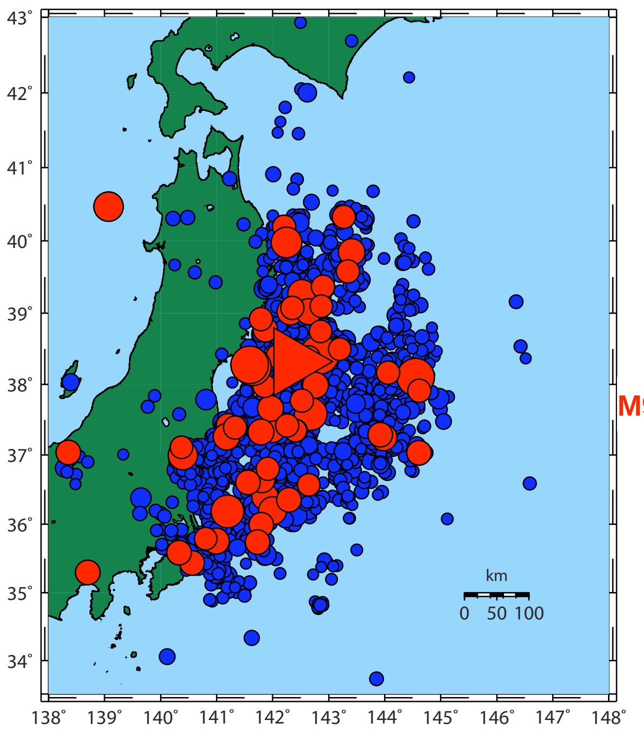
Since then, the 1988 San Andreas forecast

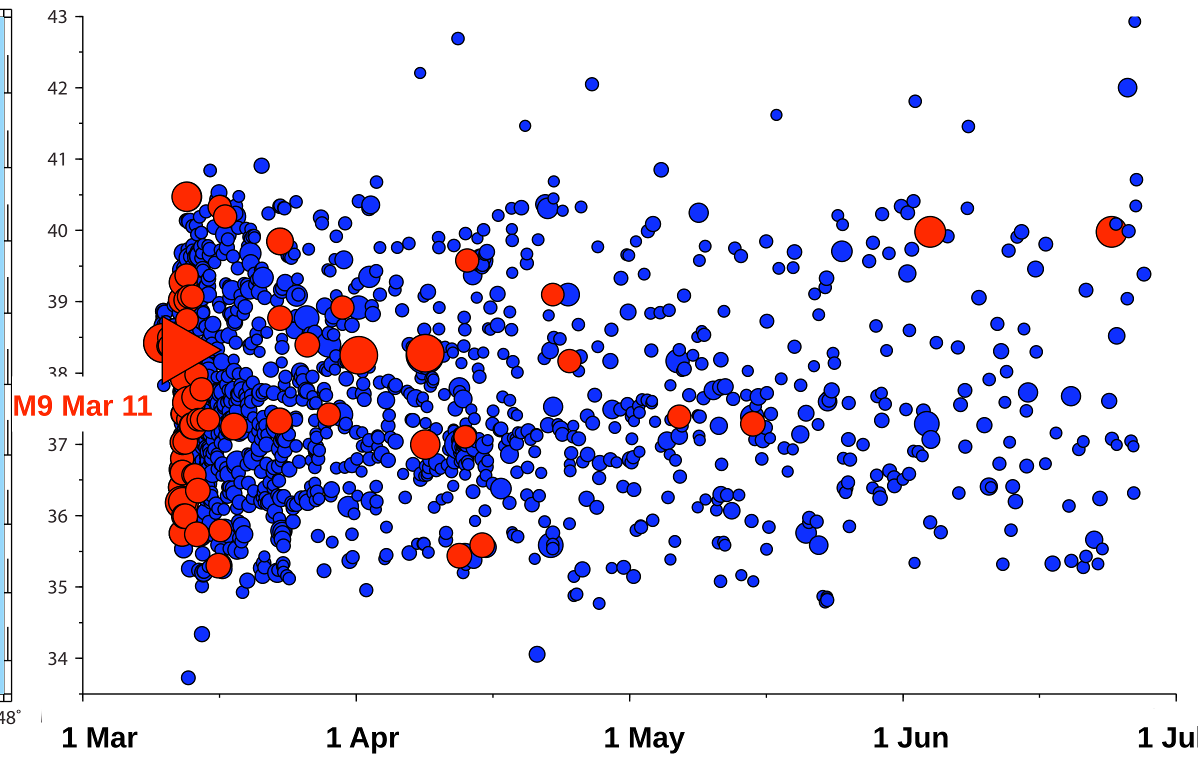
SCEC

Southern California Earthquake Center

Tohoku Sequence

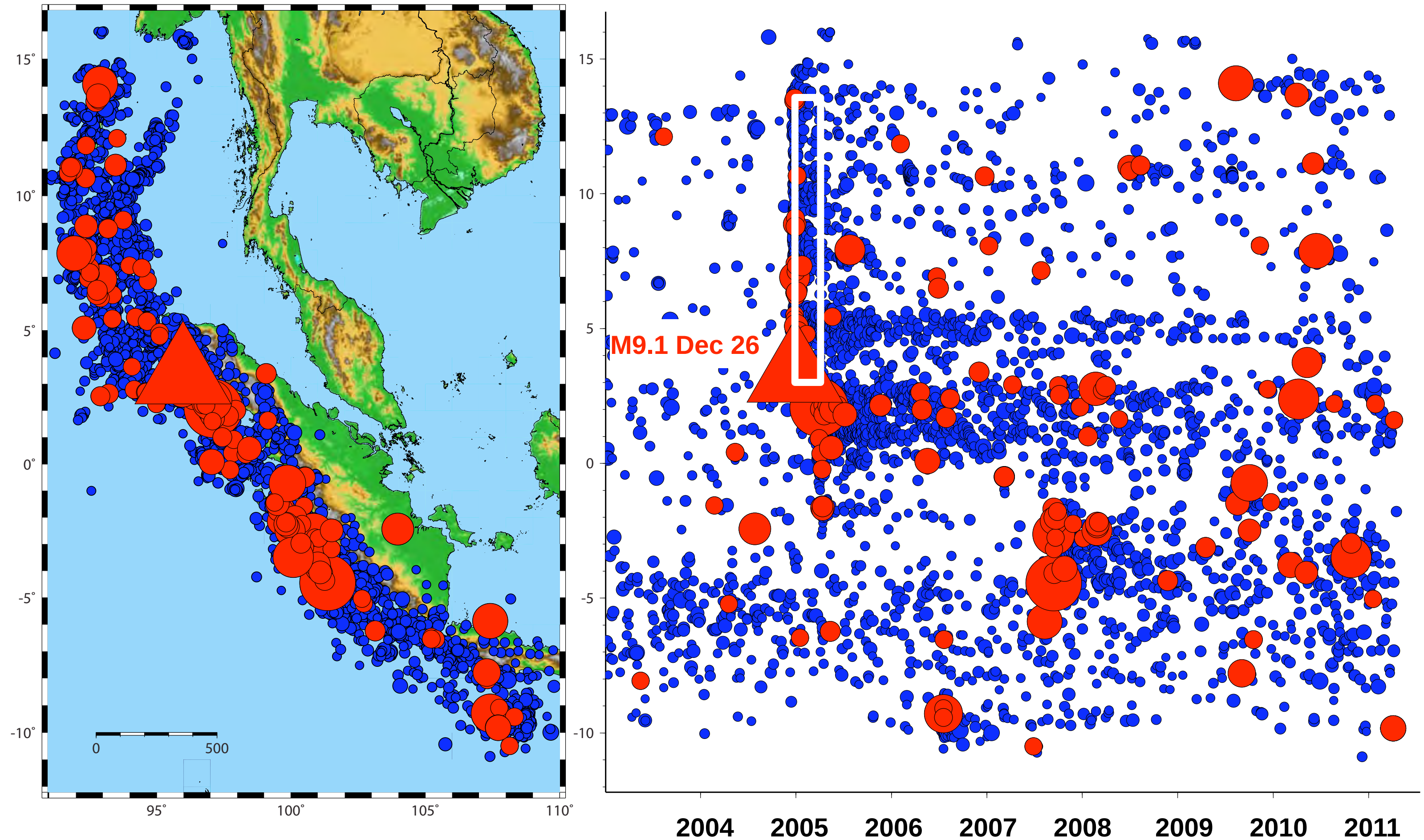
1 Mar – 1 Jul 2011





Epicentral dots scaled by magnitude;
M ≥ 6 in red

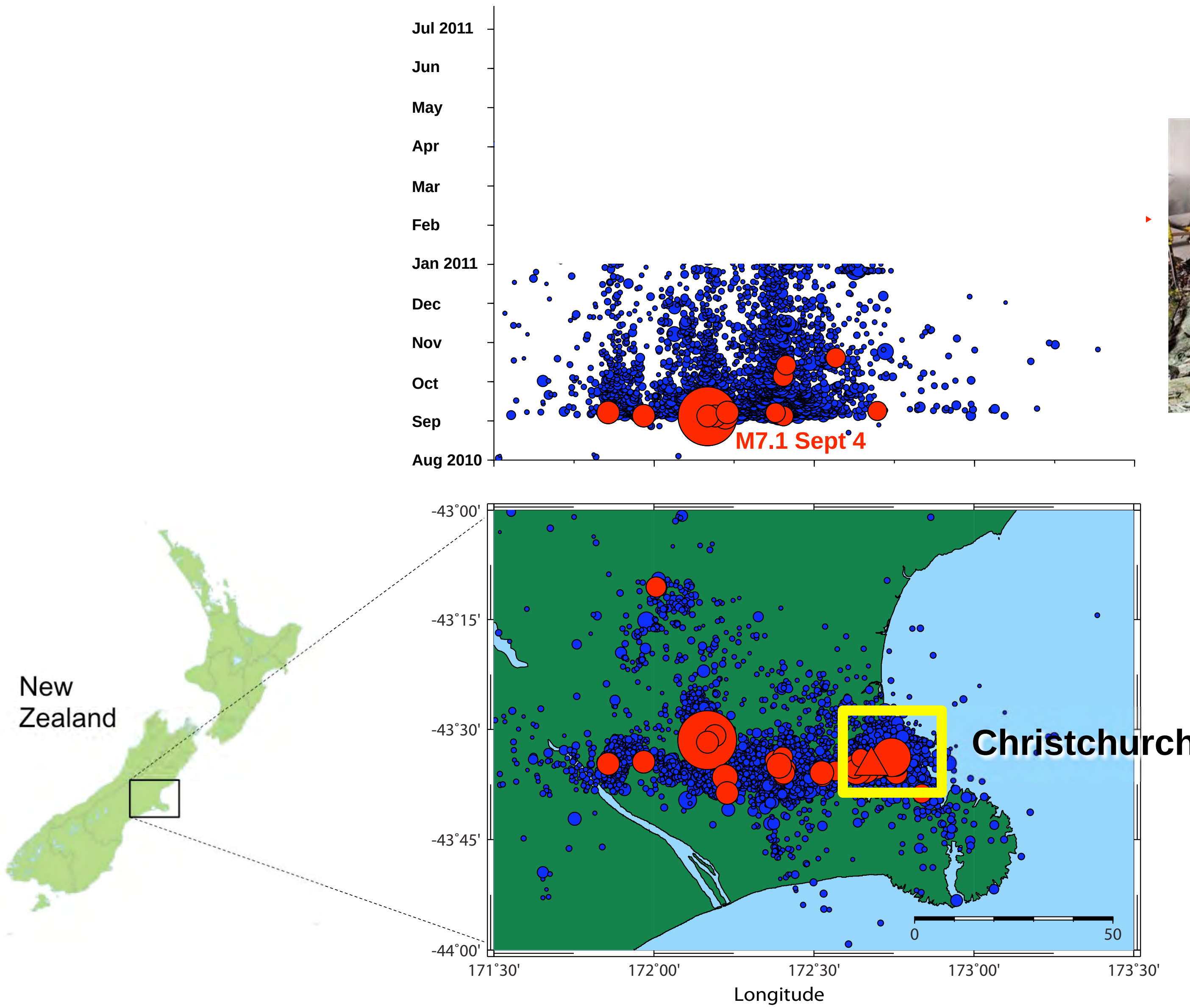
Sumatra-Andaman Island Sequence
2003-2010



Epicentral dots scaled by magnitude;
M ≥ 6 in red

Darfield Earthquake Sequence

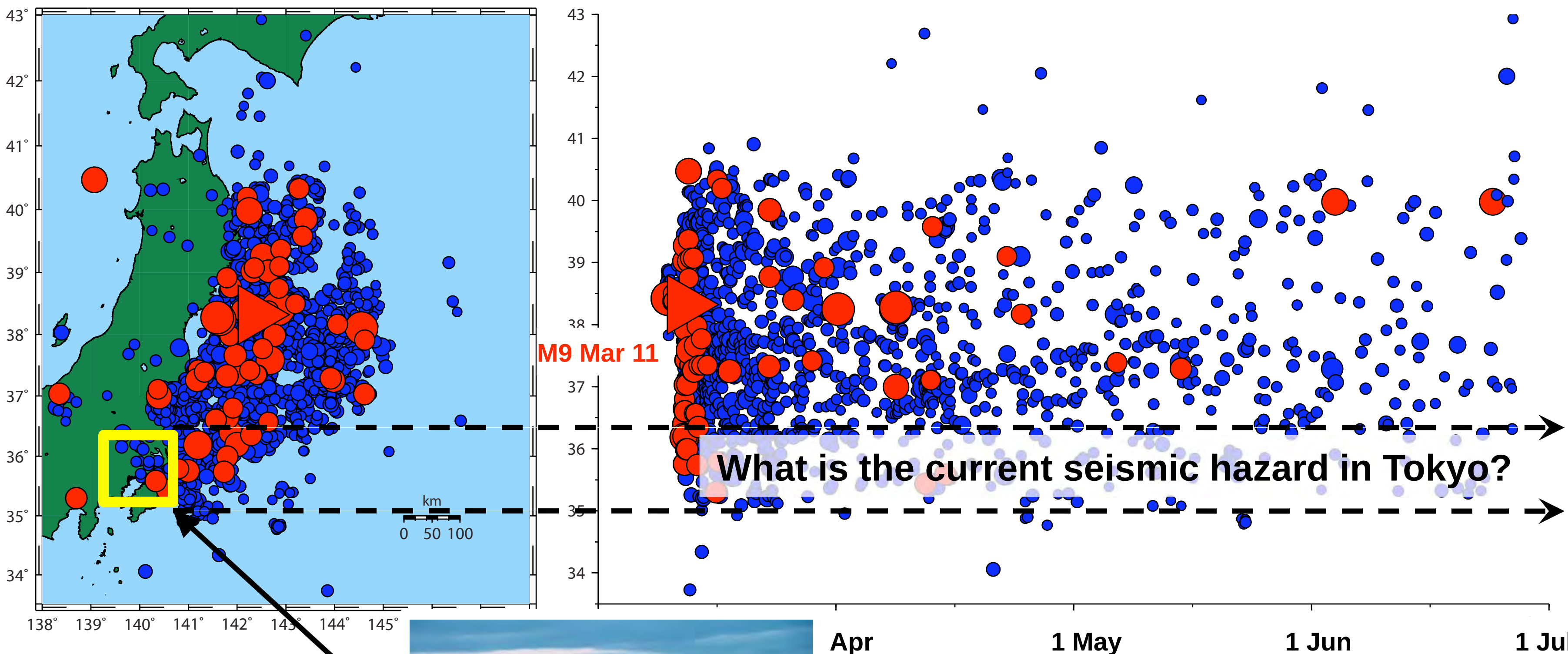
4 Sept 2010 – 1 July 2011



Epicentral dots scaled by magnitude;
$M \geq 5$ in red

Tohoku Sequence

1 March – 1 July 2011



Epicentral dots scaled by magnitude;
M ≥ 6 in red

Operational Earthquake Forecasting

Authoritative information about the time dependence of seismic hazards to help communities prepare for potentially destructive earthquakes.

- **Seismic hazards change with time**
  - **Earthquakes release energy and suddenly alter the tectonic forces that will eventually cause future earthquakes**
- **Statistical models of earthquake interactions capture many of the short-term temporal and spatial features of natural seismicity**
  - **Excitation of aftershocks and other seismic sequences**
- **Models based on regional seismicity can estimate short-term changes in the probabilities of future earthquakes**
  - **Provide the highest validated information gain per earthquake of any known technique**

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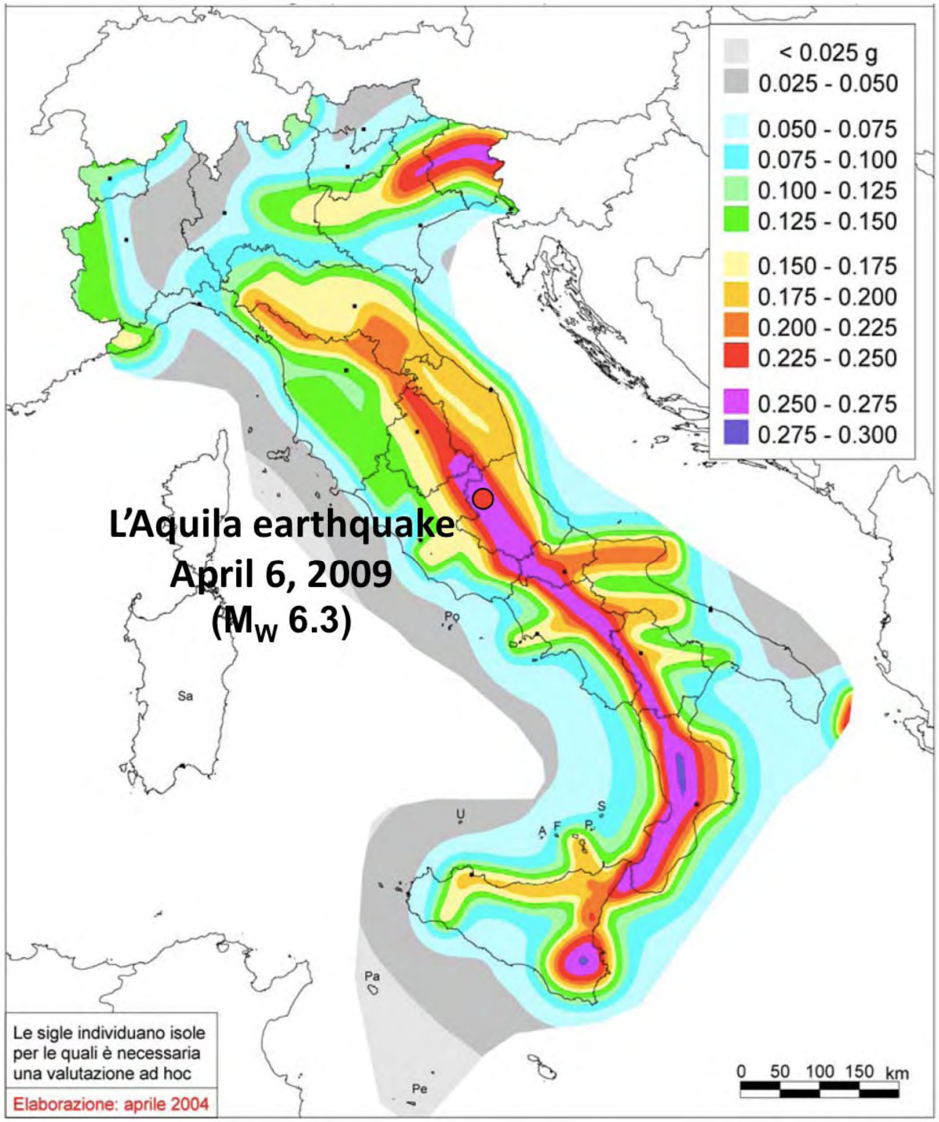
ITALY

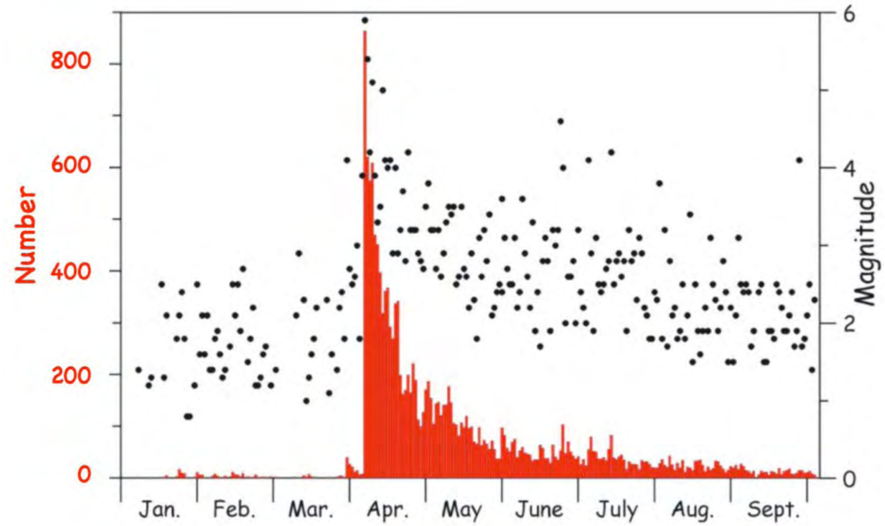
Quake Experts to Be Tried For Manslaughter

Seven scientists and technicians who analyzed seismic activity ahead of the devastating earthquake that struck the Italian town of L'Aquila on 6 April 2009 will indeed face trial for manslaughter, a judge announced says Thomas Jordan, an earth scientist at the University of Southern California in Los Angeles, who chaired an international commission to review earthquake predictions in Italy in the light of the L'Aquila tist at the University of Genoa; and Mauro Dolce, director of the office of seismic risk at the Civil Protection Department.

Central to the prosecutors' case is a meeting held 6 days before the quake in which the risks committee, as well as local politicians and representatives of the Civil Protection Department, discussed a series of recent tremors that had occurred in the province of L'Aquila, including a quake of magnitude 4.0 the previous day. According to the official minutes of the meeting, the seven accused committee members explained that

2009 L'Aquila Earthquake Sequence





L’Aquila Accusations

- Prosecution purports a criminal miscommunication of seismic risk. The seven scientists are charged with:
  - conducting a risk assessment that was “generic and ineffective in relation to the activities and duties of prediction and prevention”
  - providing civil authorities and the public with “incomplete, imprecise, and contradictory information about the nature, causes, and future developments of the seismic hazards in question”
  - characterizing the seismic swarm that affected L'Aquila for about three months before the mainshock as “a normal geological phenomenon”
- In sending the case to trial, the L’Aquila judge agreed with the prosecution that public statements made by the defendants “thwarted the activities designed to protect the public.”

Issues of Operational Earthquake Forecasting

- What are the best available scientific methods for forecasting large earthquakes and their aftershocks?
- Can large earthquakes be forecast with short-term probabilities that are high enough and reliable enough to aid in civil protection?
- How should government authorities use low-probability scientific information to enhance civil protection?
- How should this information be communicated to the public?

International Commission on Earthquake Forecasting (ICEF)

- **Charged by Dipartimento della Protezione Civile (DPC) to:**
    1. **Report on the current state of knowledge of short-term prediction and forecasting of tectonic earthquakes**
    2. **Indicate guidelines for utilization of possible forerunners of large earthquakes to drive civil protection actions**
- **ICEF report: *"Operational Earthquake Forecasting: State of Knowledge and Guidelines for Utilization"***
    - **Findings & recommendations issued on 2 Oct 2009**
    - **Final report accepted by DPC in May 2011 and in press in *Annals of Geophysics***
    - **Proposed for IASPEI endorsement at this meeting**

Members (9 countries):

T. H. Jordan, **Chair, USA**

Y.-T. Chen, **China**

P. Gasparini, **Secretary, Italy**

R. Madariaga, **France**

I. Main, **United Kingdom**

W. Marzocchi, **Italy**

G. Papadopoulos, **Greece**

G. Sobolev, **Russia**

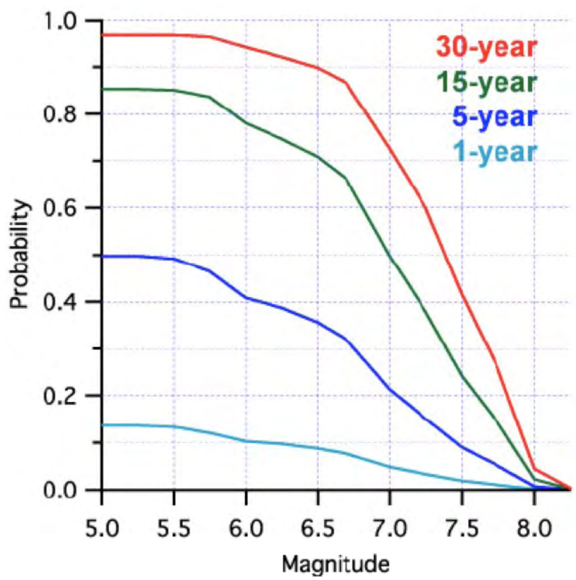
K. Yamaoka, **Japan**

J. Zschau, **Germany**

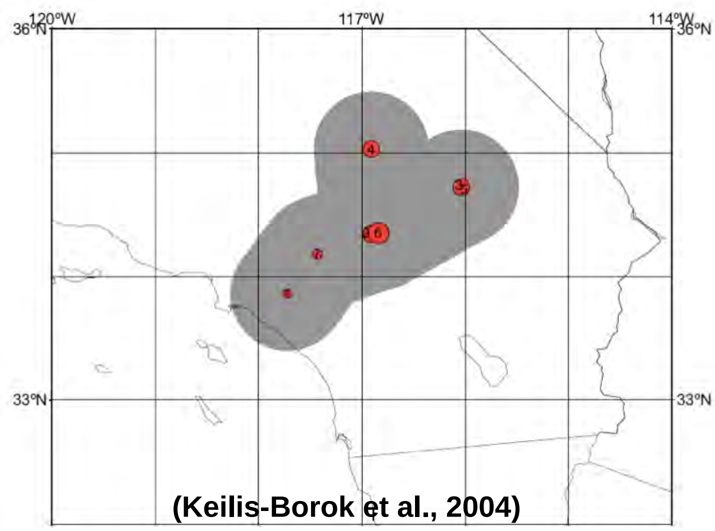
Definition of Prediction vs. Forecasting

- An ***earthquake forecast*** **gives a** **<u>probability</u>** **that a target event will occur within a space-time domain**
- An ***earthquake prediction*** **is a** **<u>deterministic statement</u>** **that a target event will occur within a space-time domain**

Rupture Probability for San Andreas Fault System (WGCEP, 2007)



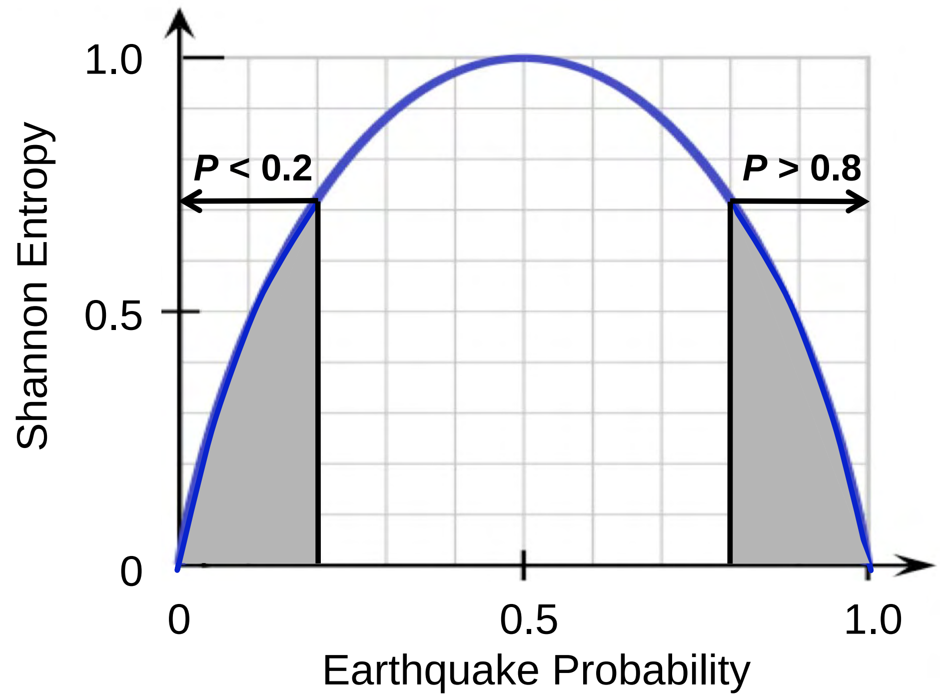
RTP Alarm for California M ≥ 6.4, 15 Nov 2004-14 Aug 2005



Definition of Prediction vs. Forecasting

As tools for helping communities prepare for potential earthquake disasters,

- ***deterministic prediction*** **is only useful in a high-probability environment**
- ***probabilistic forecasting*** **can be useful in a low-probability environment**



ICEF Findings:

- ***For most decision-making purposes, probabilistic forecasting provides a more complete description of prospective earthquake information than deterministic prediction.***
- ***Probabilistic forecasting appropriately separates hazard estimation by scientists from the public protection role of civil authorities.***

Deterministic Earthquake Prediction
(a.k.a. "Silver Bullet Approach")

A precursory change is *diagnostic* if it can predict an impending event's location, time, and magnitude with high probability and low error rates (false alarms and failures-to-predict)

- **Proposed methods include:**
  - **foreshocks & seismicity patterns**
  - **strain-rate acceleration**
  - **seismic velocity changes**
  - **electromagnetic signals**
  - **thermal anomalies**
  - **hydrologic changes**
  - **geochemical signals**
  - **animal behavior**

- **ICEF Finding**: ***Search for diagnostic precursors has not yet produced a successful short-term prediction scheme.***

Search for Diagnostic Precursors

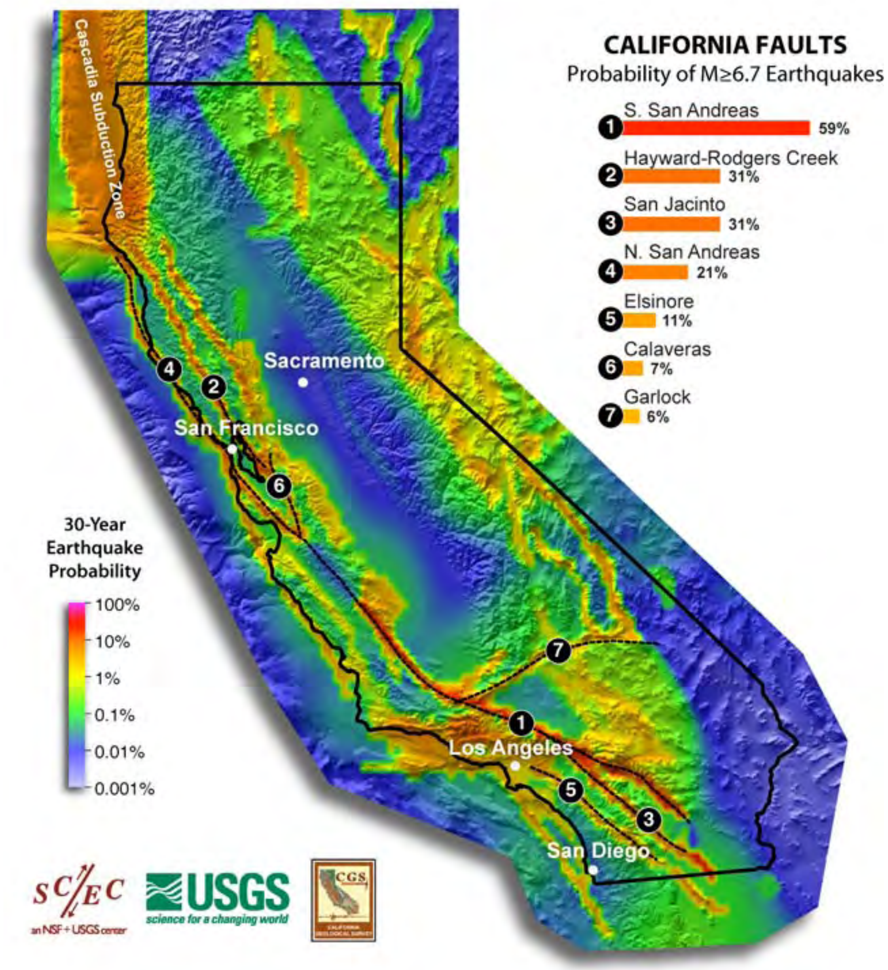
- **The "silver-bullet" strategy for earthquake prediction is predicated on two hypotheses that have not yet been empirically validated:**
  - **Large earthquakes are the culmination of progressive deformation sequences with *diagnostic* precursory changes in the regional stress and strain fields**
  - ***Diagnostic* information about an impending earthquake can be extracted from observations that are sensitive to these precursory stress and strain changes**
- **Statistical analysis of retrospective correlations between proposed precursors and subsequent earthquakes has been inadequate**
  - **Data coverage rarely sufficient to characterize the background noise or evaluate the statistics of false alarms and failures-to-predict**
  - **Prediction success has often been over-estimated by model-tuning during retrospective testing and bias towards selecting positive results**
- **Few prediction schemes have been formulated in a manner that allows rigorous testing**
  - **Prospective testing of formalized models has been infrequent**
  - **Where conducted (e.g., Parkfield), predictions have failed to demonstrate reliability and skill relative to baseline forecasts**

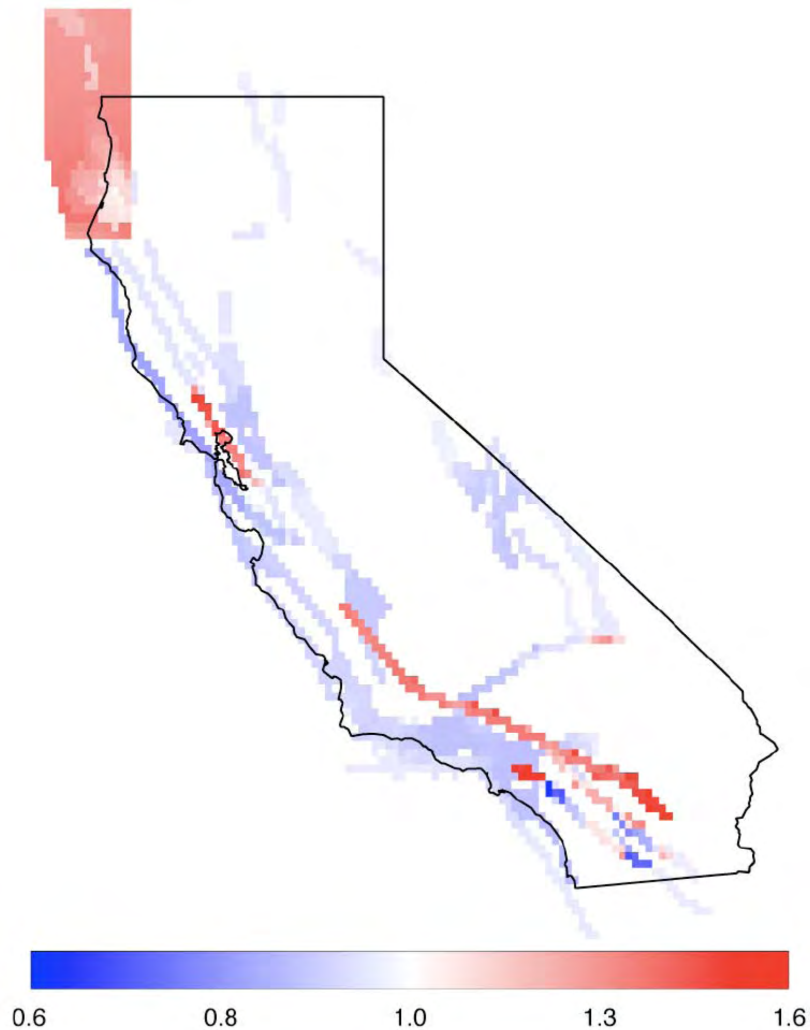
Probabilistic Earthquake Forecasting
(a.k.a. “Brick-by-Brick Approach”)

- System-specific models of earthquake recurrence, stress evolution, clustering, and triggering
  - Long-term (decades to centuries)
  - Intermediate-term (months to years)
  - Short-term (seconds to weeks)
- Sustained effort to understand and improve predictability, even if probability gains are small
- Major issues:
  - What are the performance characteristics of current short-term forecasting methodologies?
  - How should short-term forecasts be integrated with long-term forecasts?
  - How should operational methods be developed, validated, and deployed?
  - How should low-probability, short-term forecasts be used in decision-making related to civil protection?

Working Group on California Earthquake Probabilities (2007)

Uniform California Earthquake Rupture Forecast (UCERF2)



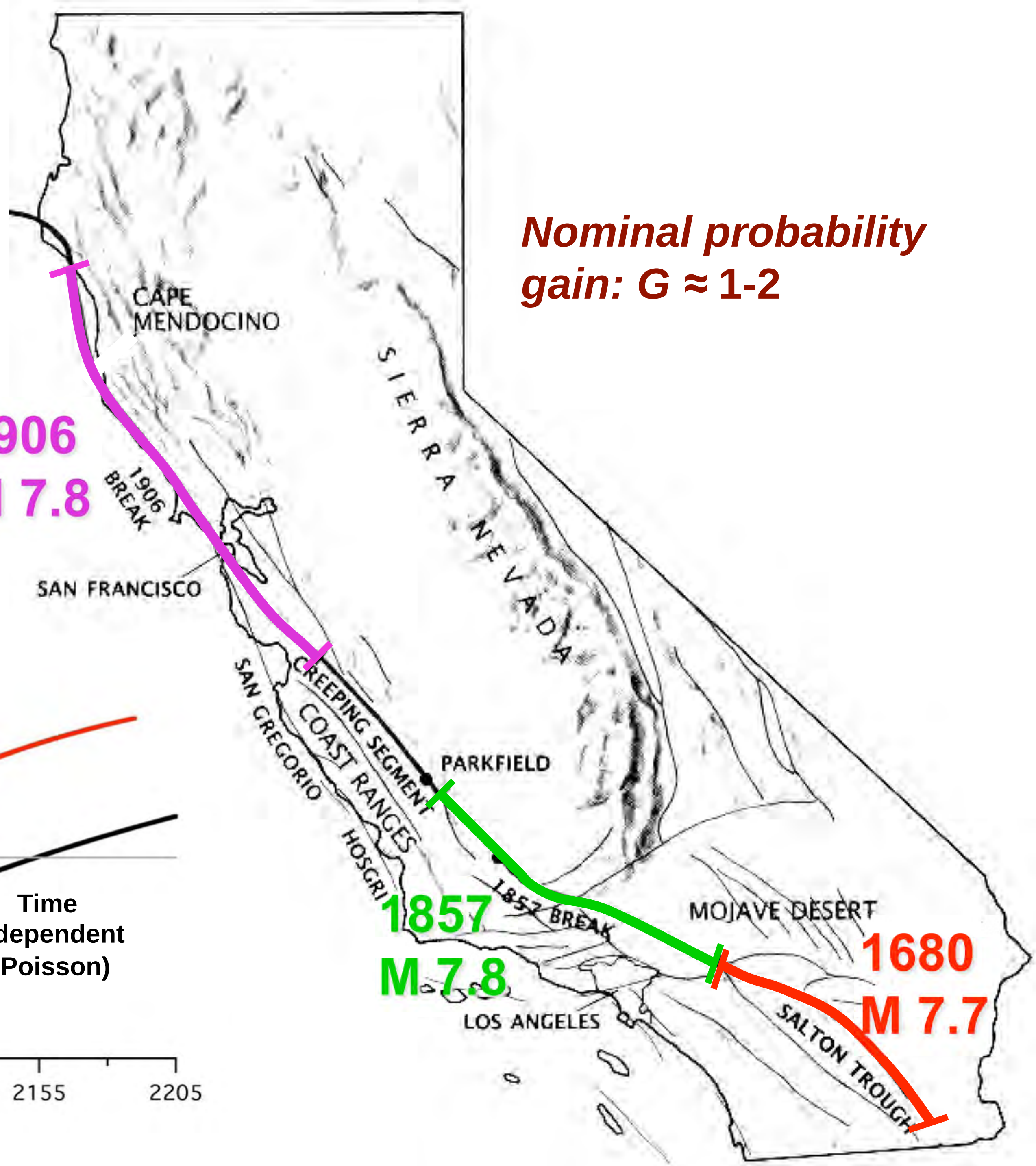


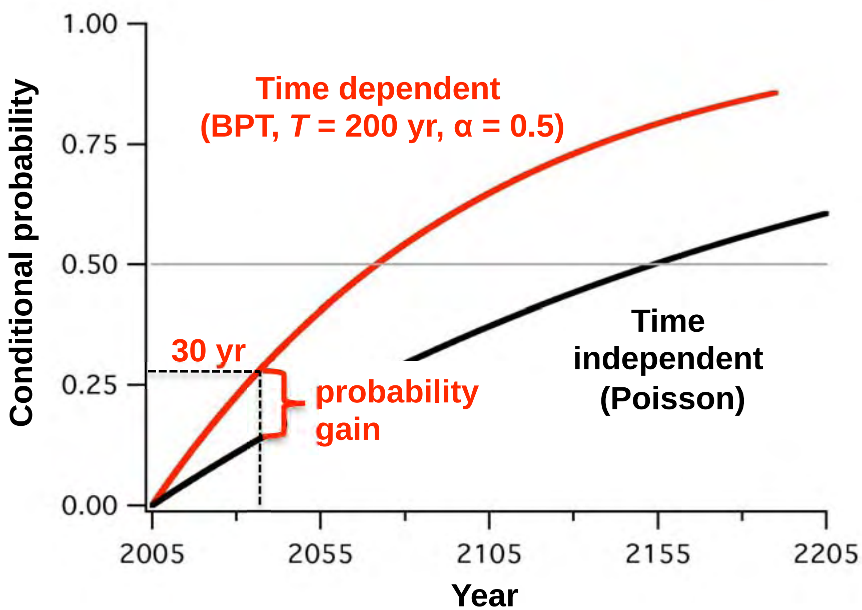
Ratio of time-dependent to time-independent participation probabilities for M ≥ 6.7

Long-Term Stress Renewal Models

Working Group on California Earthquake Probabilities (1988, 1989, 1996, 2003, 2007)

Nominal probability gain: G ≈ 1-2





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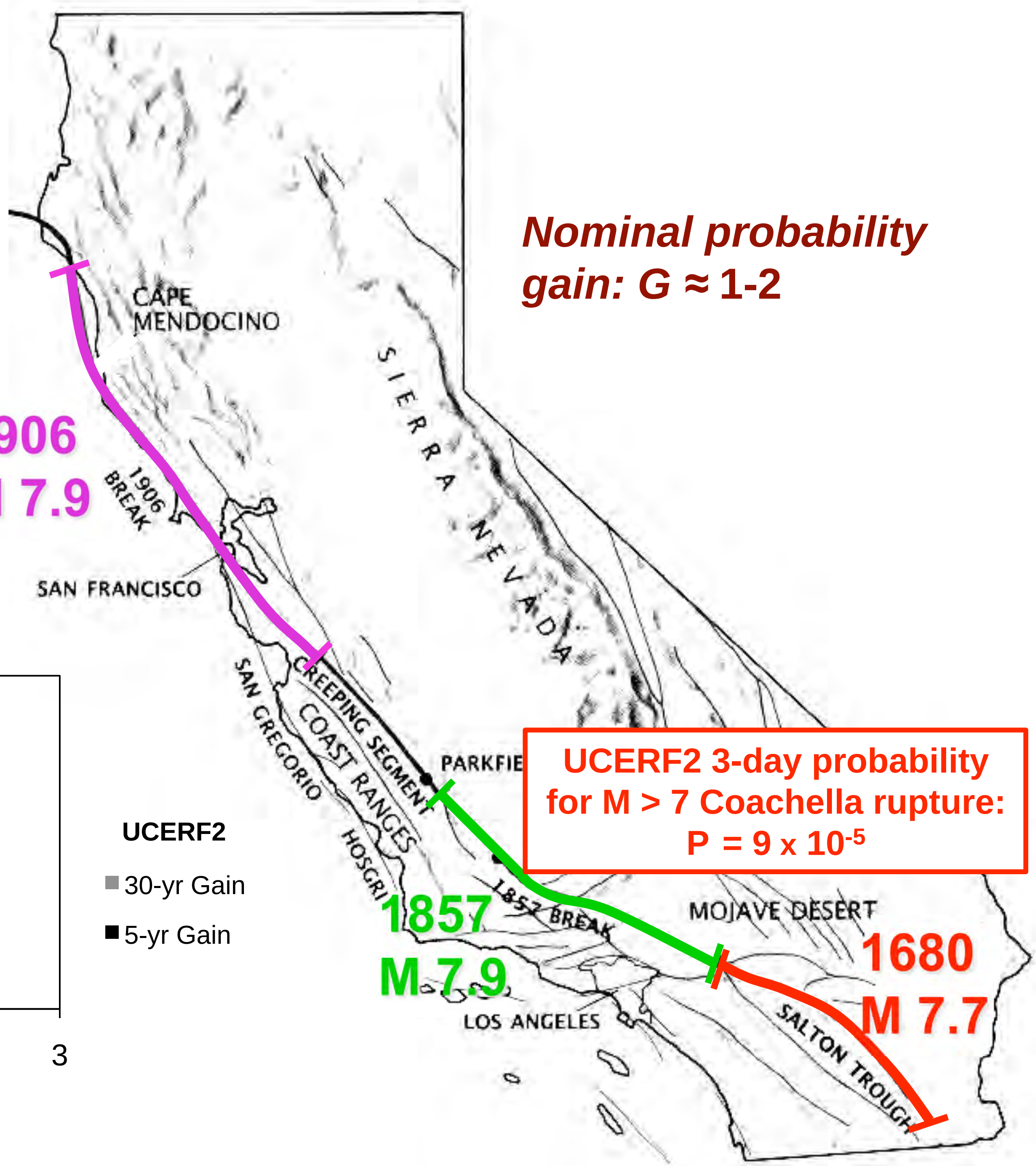
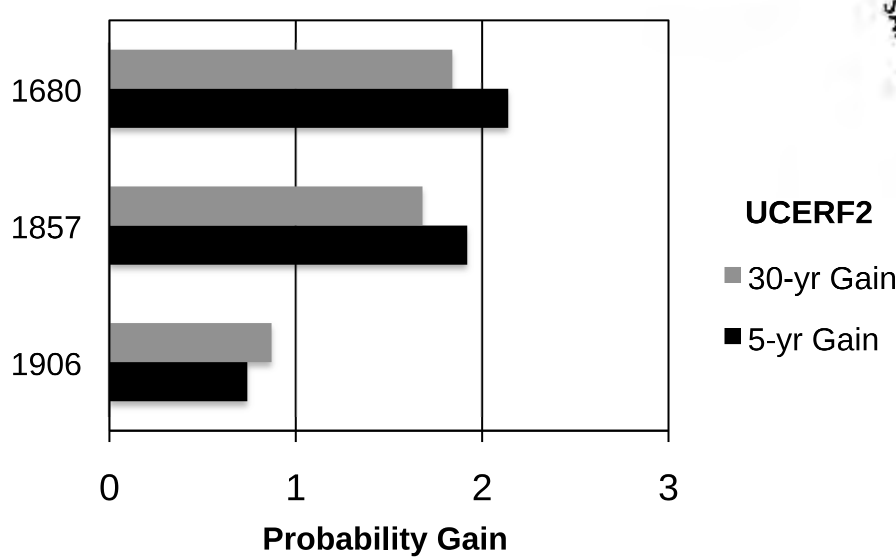
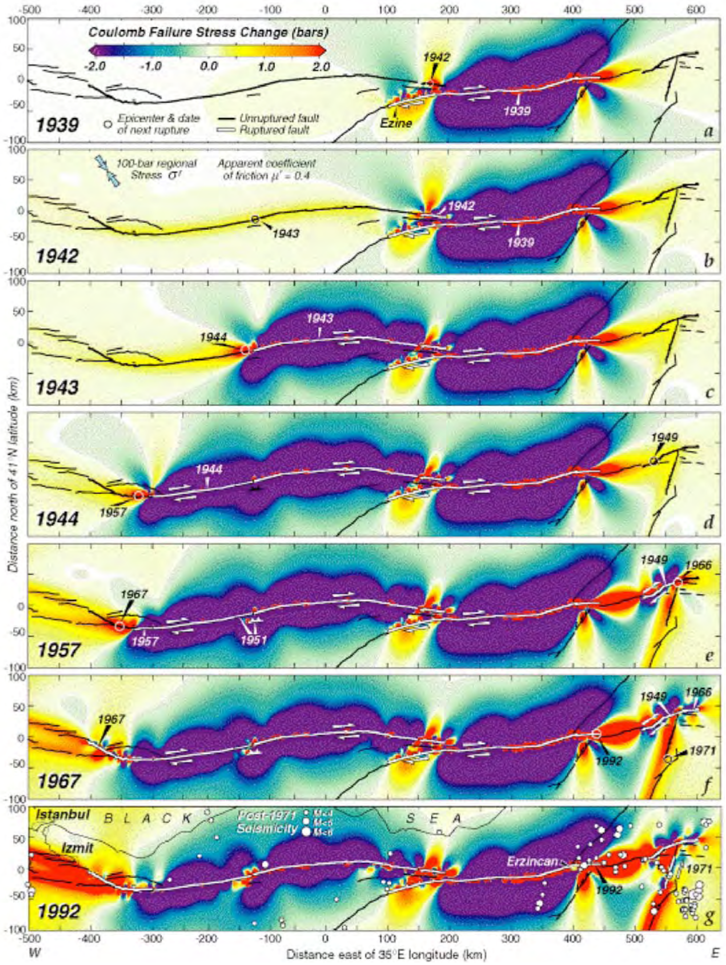


UCERF2 3-day probability for M > 7 Coachella rupture: $P = 9 \times 10^{-5}$

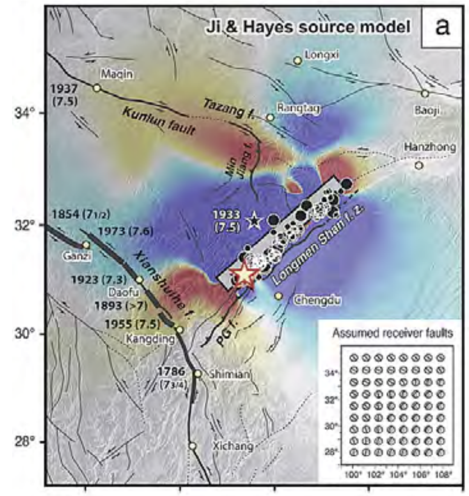


Forecasting Models Based on Stress Changes

Coulomb stress change

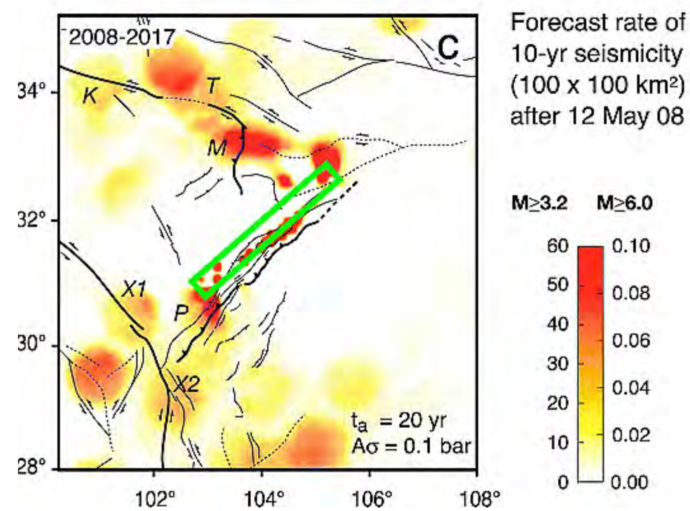


Stress evolution of the North Anatolian fault system (Stein et al., 1997)



Ingredients:

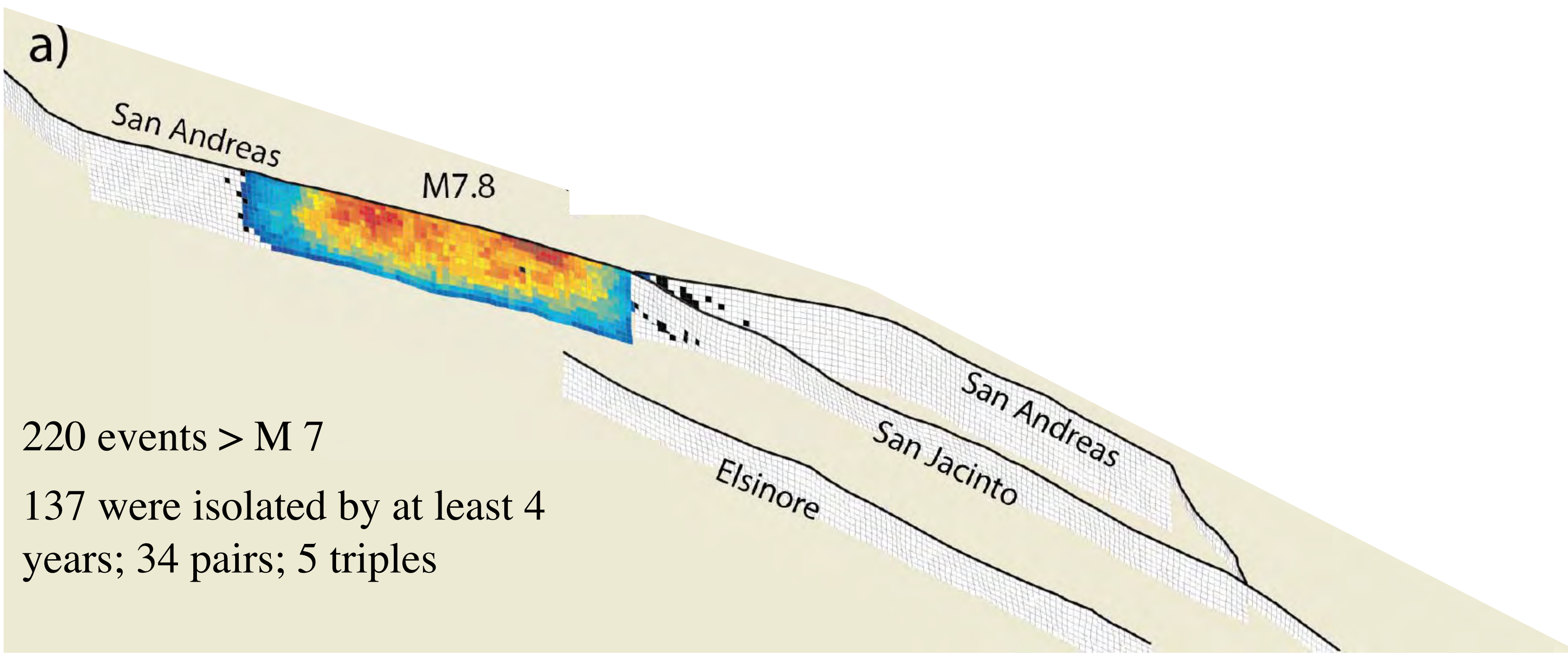
- **Stress changes**
- **Rate/state friction**
- **Background seismicity**



Wenchuan Earthquake Region (Toda et al., 2008)

RSQsim Earthquake Simulator

Southern San Andreas Fault System



220 events > M 7

137 were isolated by at least 4 years; 34 pairs; 5 triples

Dieterich & Richards-Dinger (2010)

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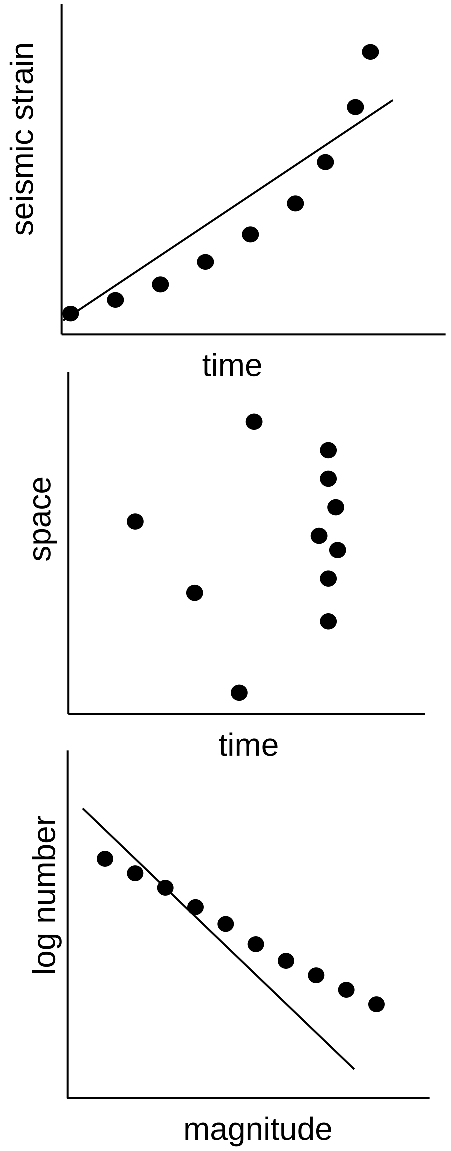
Medium-Term Forecasting Methods Based on Seismic Pattern Recognition



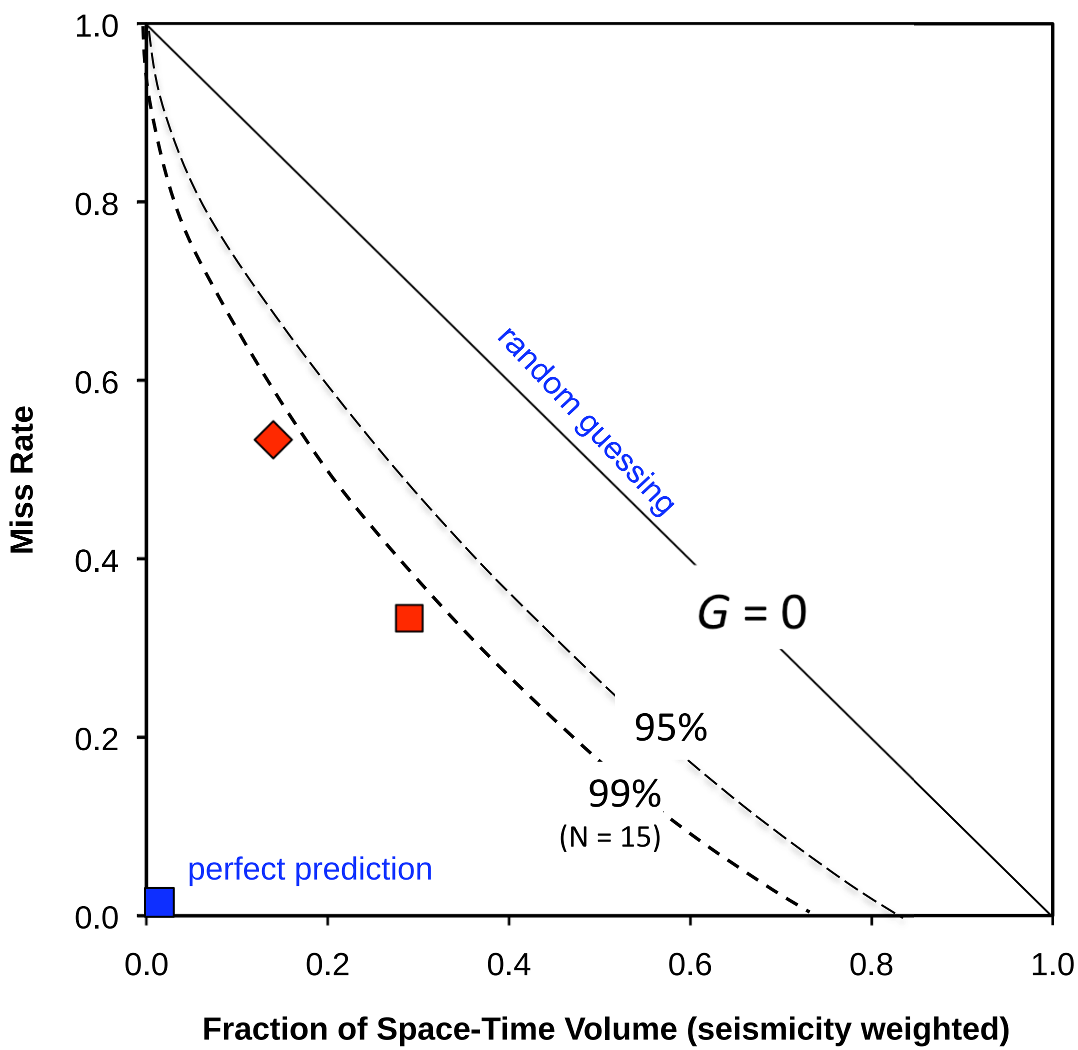
Accelerating Moment Release

Long-Range Correlation

Change in *b*-value

(Keilis-Borok et al.)

Medium-Term Forecasting Methods Based on Seismic Pattern Recognition



Data on Prospective Predictions
(V. Kossobokov, pers.com., 2009)

■ M8 Global (M ≥ 8.0) 1992-2009 (N = 15)

◆ MSc Global (M ≥ 8.0) 1992-2009 (N = 15)

Probability gain:

$P(E \mid F) = [P(F \mid E)/P(F)]\, P(E)$

$= G\, P(E)$

where

$P(F)$ = **probability of alarm**

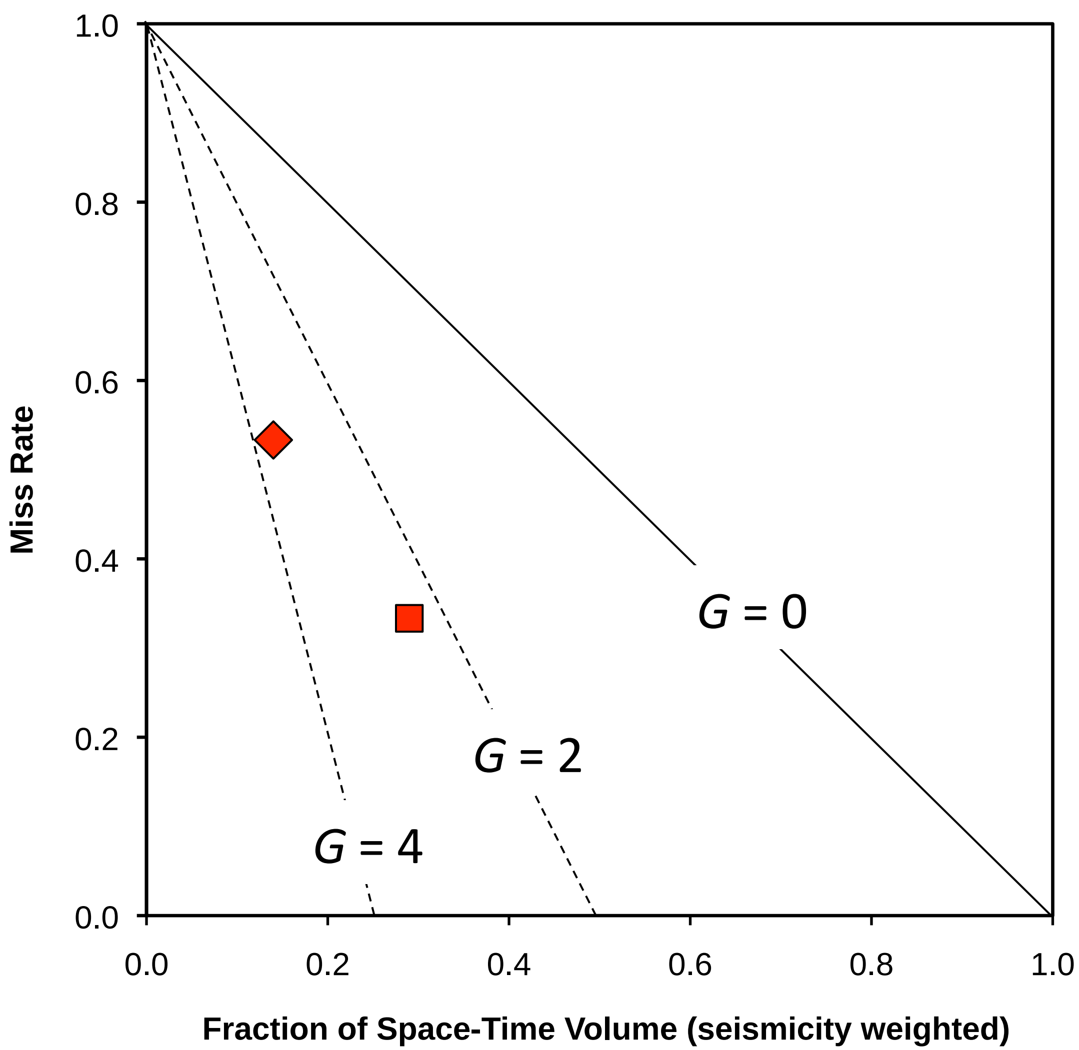
≈ **fraction of space-time in alarm state**

$P(F \mid E)$ = **hit rate**

= **1 – miss rate**

Probability gain is statistically significant…

Medium-Term Forecasting Methods Based on Seismic Pattern Recognition



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where

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≈ fraction of space-time in alarm state

$P(F \mid E)$ = hit rate

= 1 – miss rate

… but the gain factors are modest

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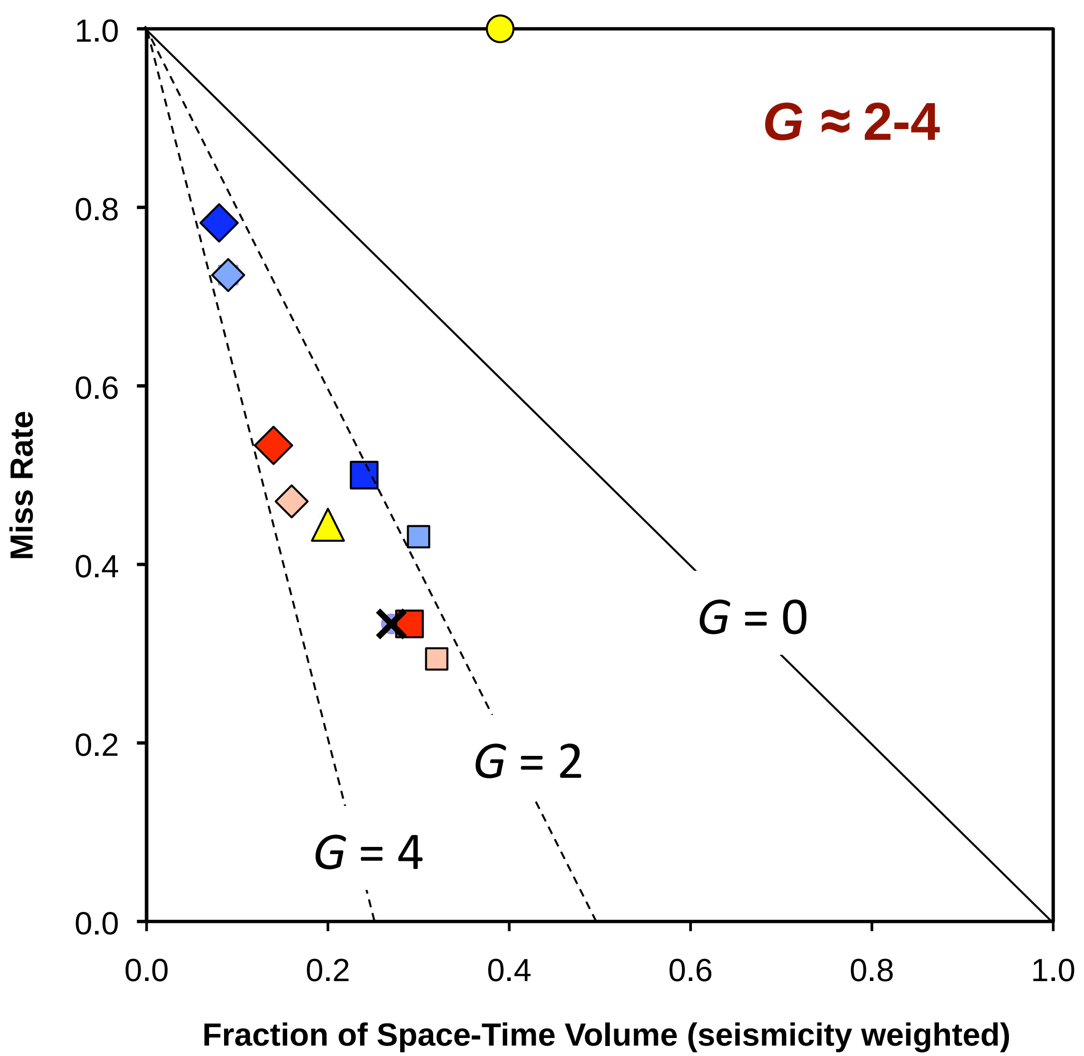
Medium-Term Forecasting Methods Based on Seismic Pattern Recognition



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- M8 Global (M ≥ 7.5) 1985-2009 (N = 58)
- M8 Global (M ≥ 7.5) 1992-2009 (N = 46)
- MSc Global (M ≥ 8.0) 1985-2009 (N =17)
- MSc Global (M ≥ 8.0) 1992-2009 (N = 15)
- MSc Global (M ≥ 7.5) 1985-2009 (N = 58)
- MSc Global (M ≥ 8.0) 1992-2009 (N = 46)
- M8S Italy (M ≥ 6.0) 2002-2009 (N = 1)
- M8S Italy (M ≥ 5.5) 2002-2009 (N = 9)
- CN Italy (M ≥ 5.4-5.6) 2002-2009 (N = 6)

Short-Term ETAS Model

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

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

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

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

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

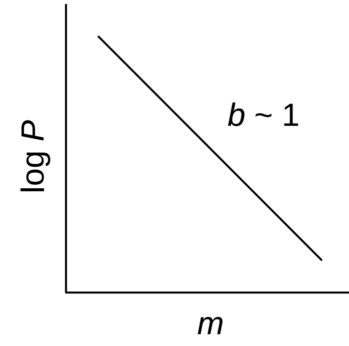
$$\rho(m) = k\ 10^{\alpha(m-m_0)}$$

4. decrease with distance from the mother event,

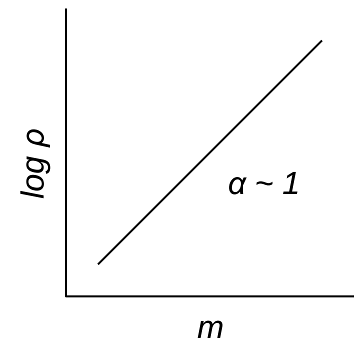
$$\phi(r) \sim (d+r)^{-q}$$

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

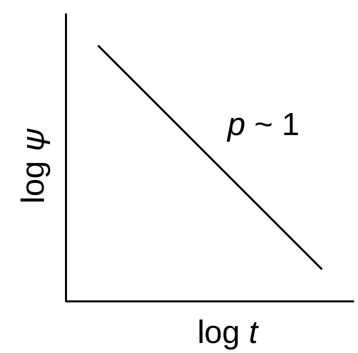
$$\psi(t) \sim (c+t)^{-p}$$



Gutenberg-Richter scaling

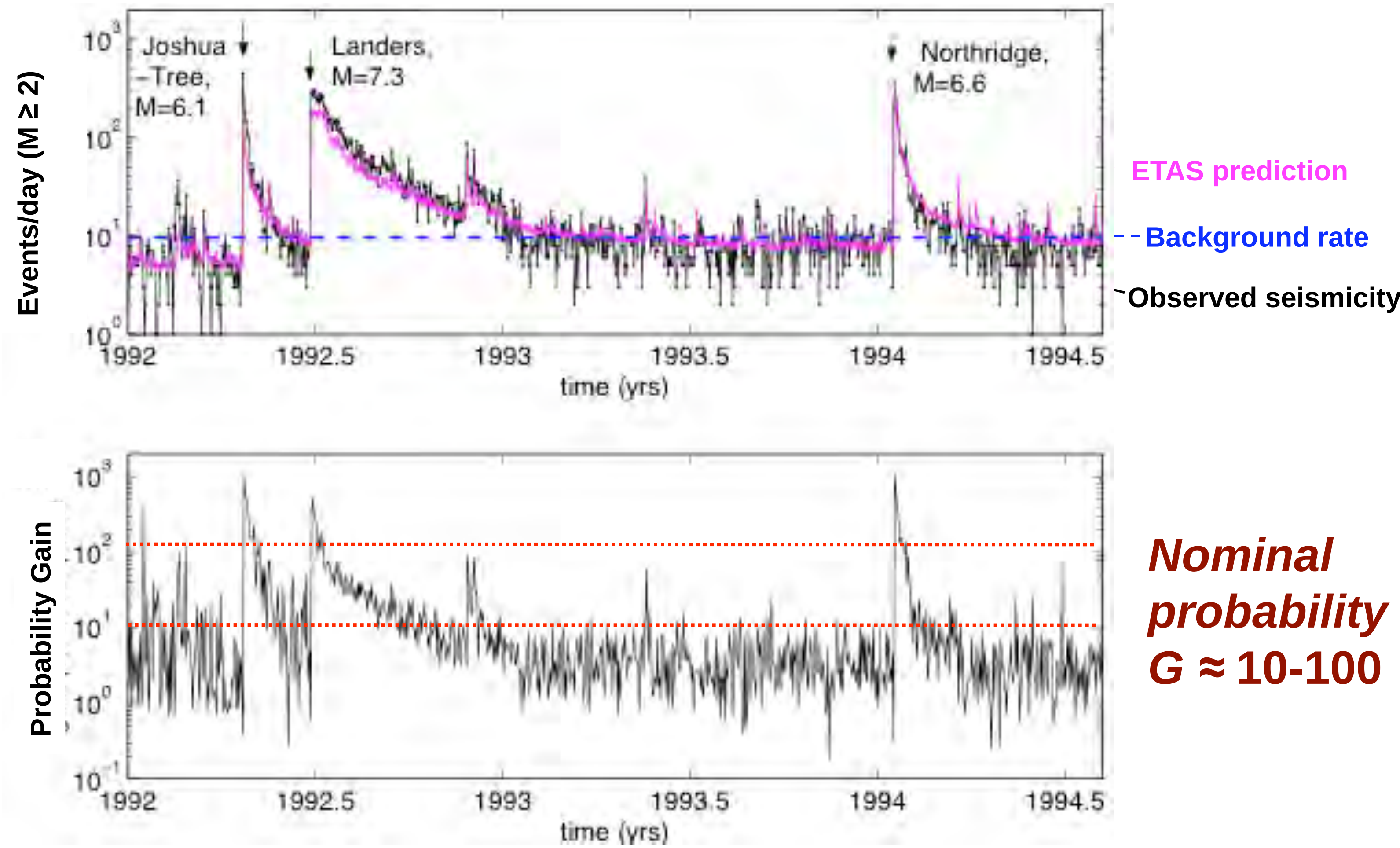


Utsu scaling



Omori scaling

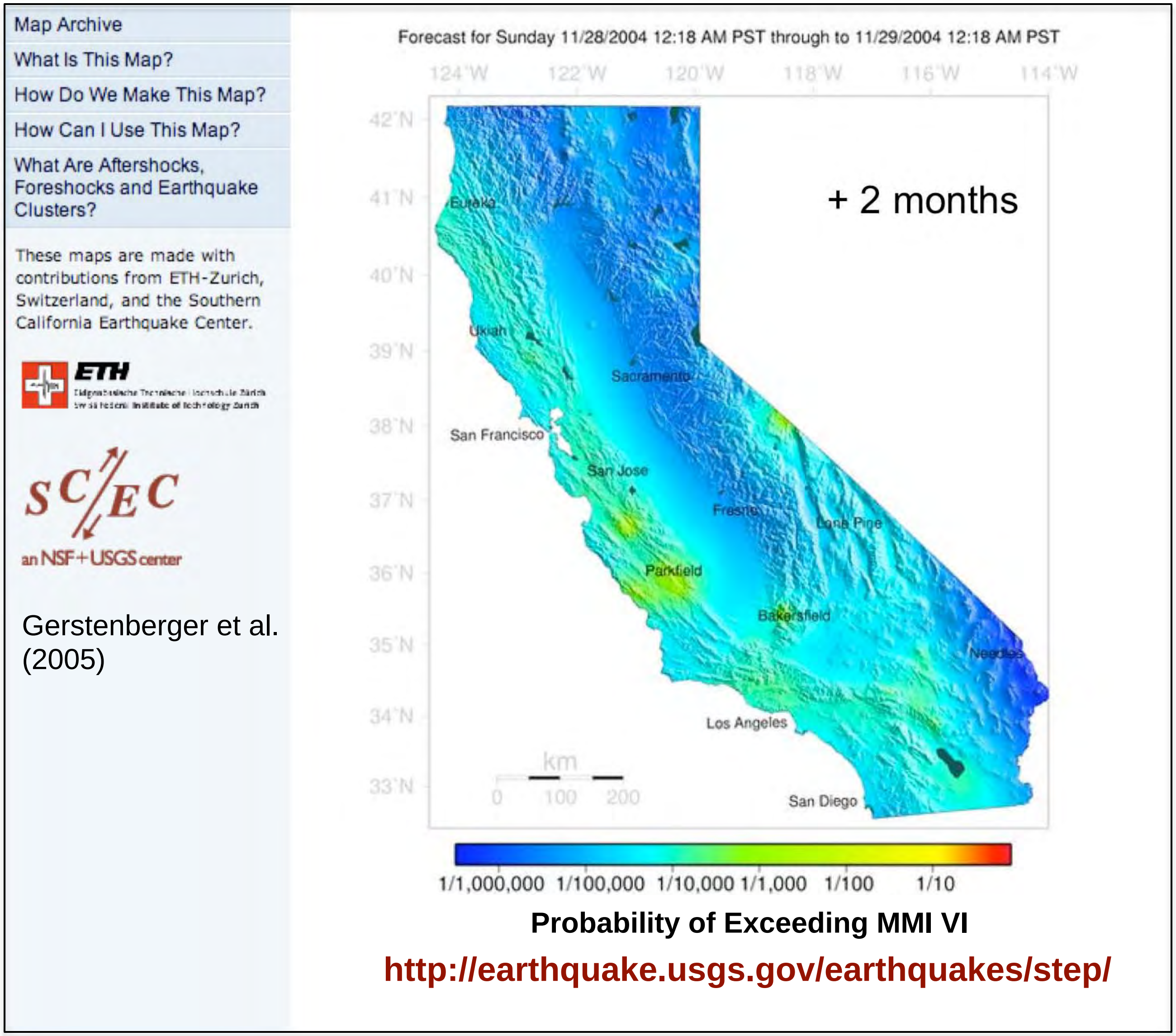
Short-Term ETAS Model



Nominal probability gain:
G ≈ 10-100

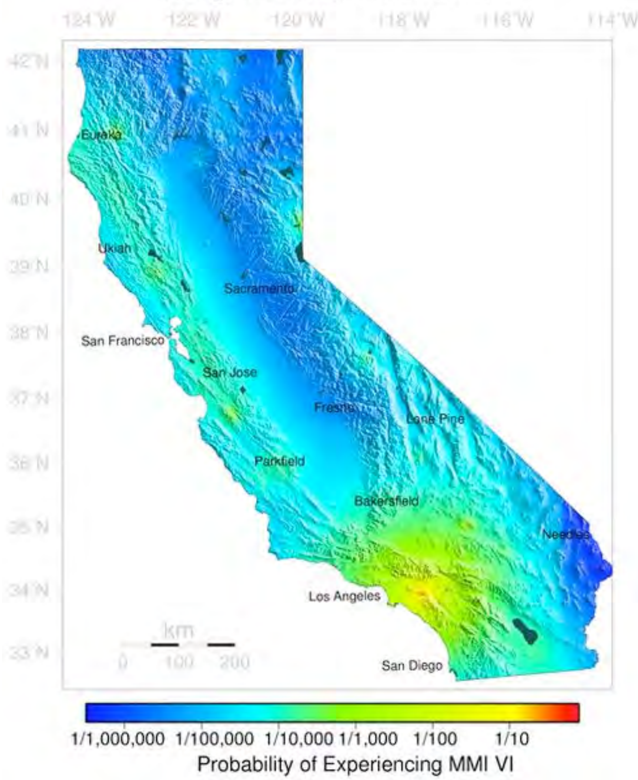
Retrospective daily ETAS predictions of Southern California seismicity (Helmstetter et al., 2006)

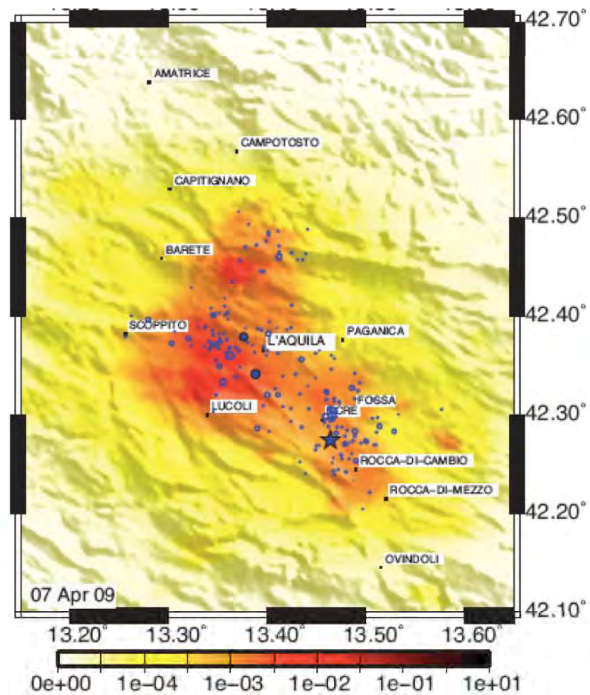
Short-Term Earthquake Probability (STEP) Model

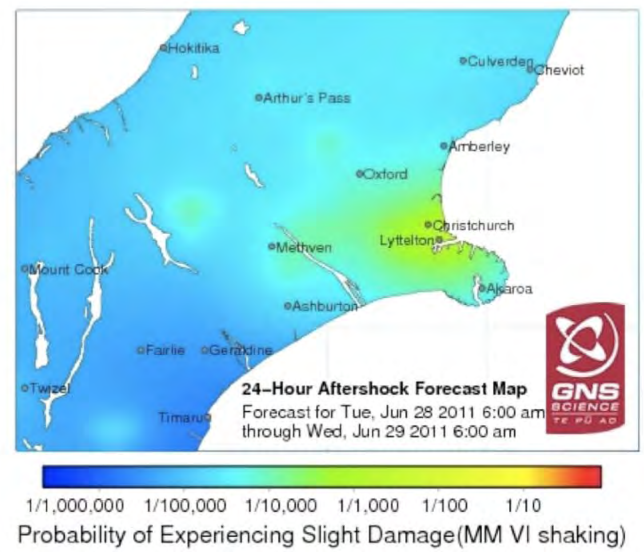


2004 Parkfield Earthquake

24-hr Aftershock Forecast Maps







California
29 July 2008
(Gerstenberger et al., 2005)

Italy
7 April 2009
(Marzocchi & Lombardi, 2009)

New Zealand
28 June 2011
(Gerstenberger, 2011)

Validation of Forecasting Methods

Criteria for operational fitness:

- **Quality validated by retrospective and prospective testing**
- **Consistency across temporal and spatial scales**
- **Value to users**

ICEF Recommendations:

- ***To be qualified for operational use, forecasting methods should be scientifically tested against the available data for reliability and skill, both retrospectively and prospectively.***
- ***All operational models should be under continuous prospective testing.***

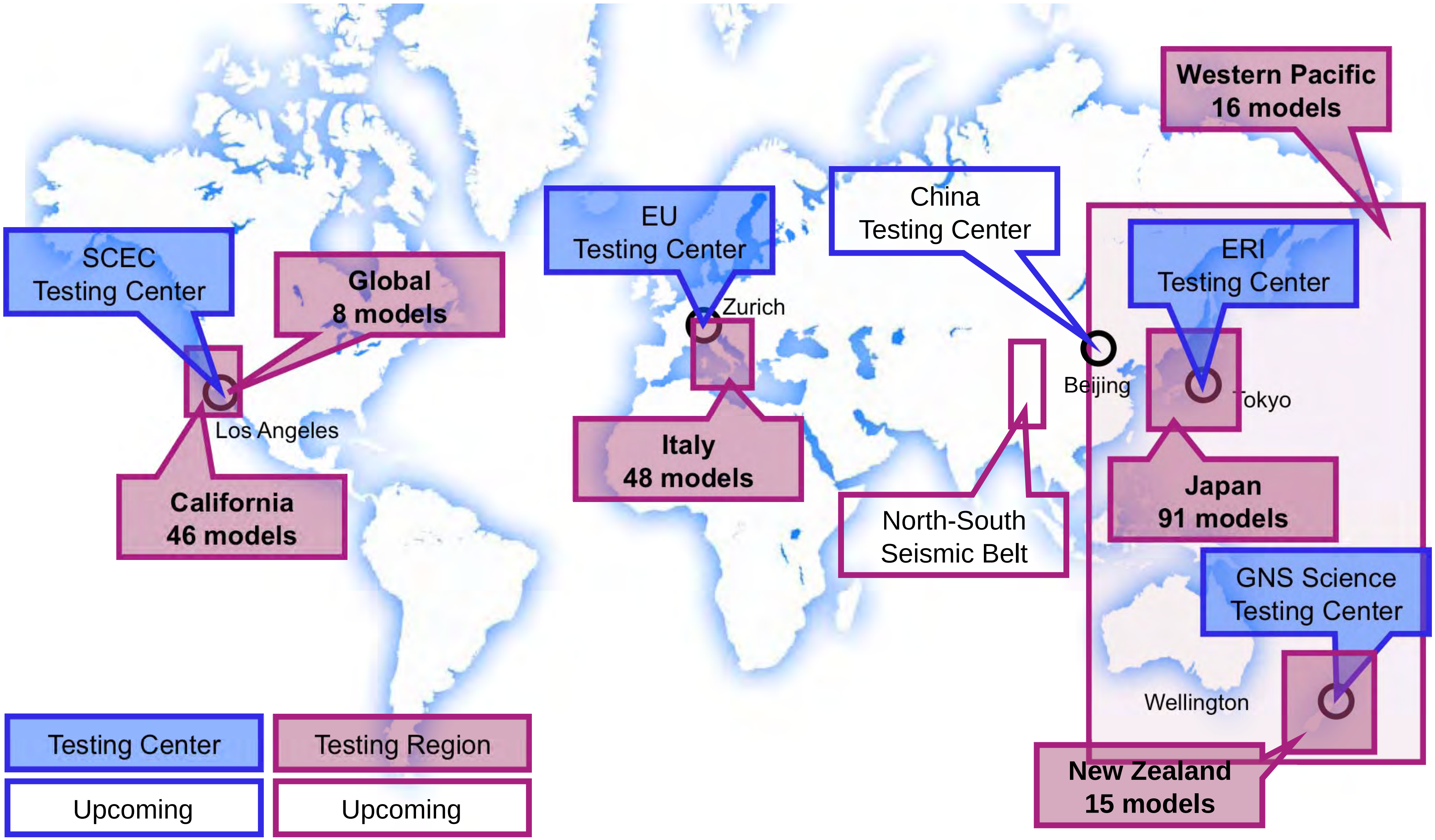
Collaboratory for the Study of Earthquake Predictability

- **CSEP goal is rigorous testing of predictability hypotheses and forecasting models**
  - **Automate blind, prospective testing in a standardized, controlled environment**
  - **Establish experiments in a variety of tectonic environments and on a global scale**

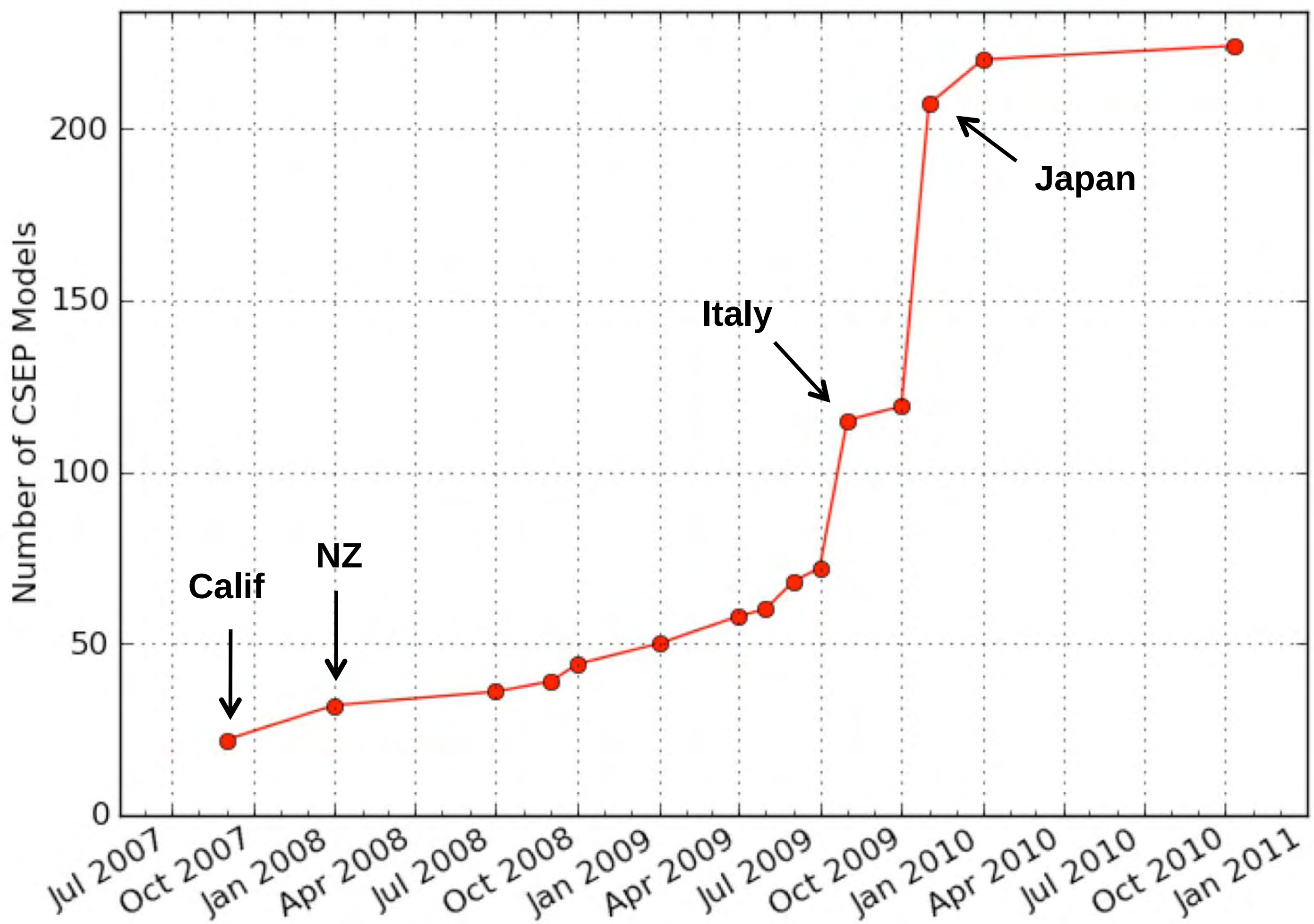
- **CSEP components:**
  - ***Natural laboratories* comprising active fault systems with adequate, authorized data sources for conducting forecasting experiments**
  - ***Testing centers* with validated procedures for registering and evaluating prediction experiments**
  - ***Model classes* with common target events, forecasting regions, and forecast updating intervals**

CSEP Testing Regions & Testing Centers

224 models under test in June, 2011

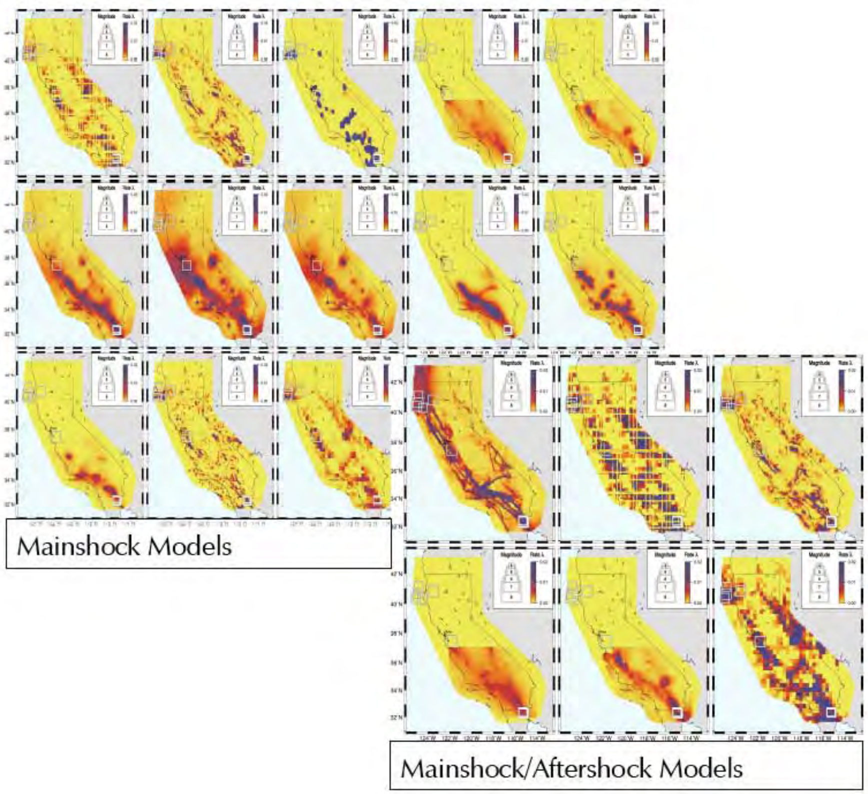


CSEP Models Under Test

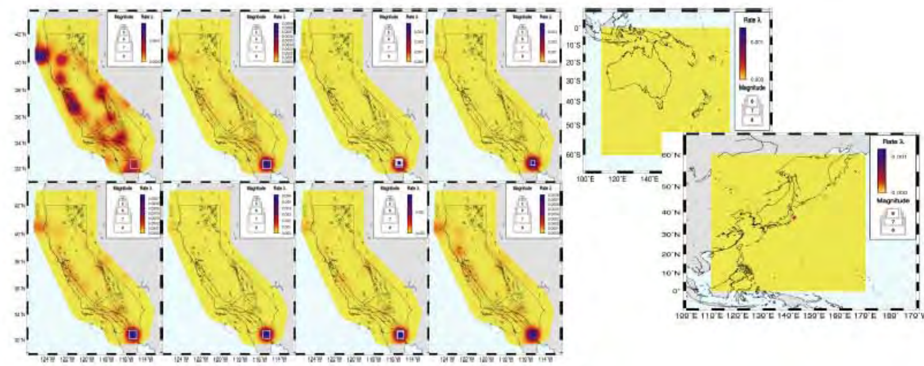


Examples of Forecasting Models Currently Under CSEP Testing in California

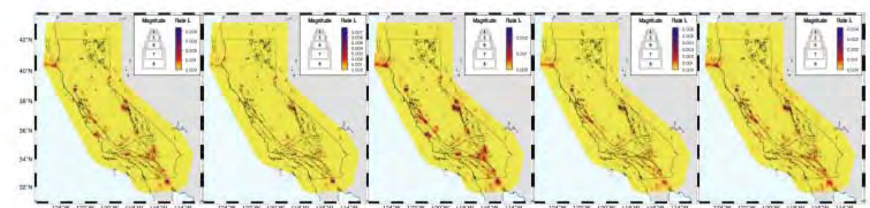
RELM 5-Year Models



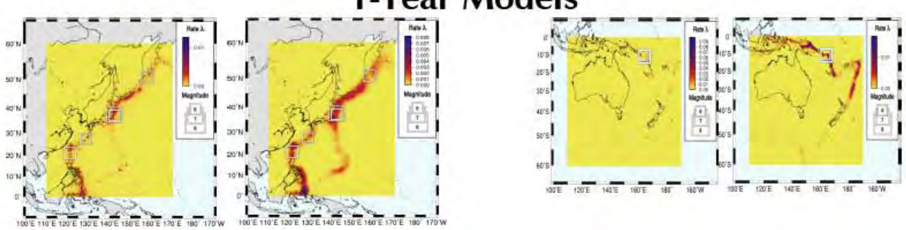
1-Day Models



3-Month Models



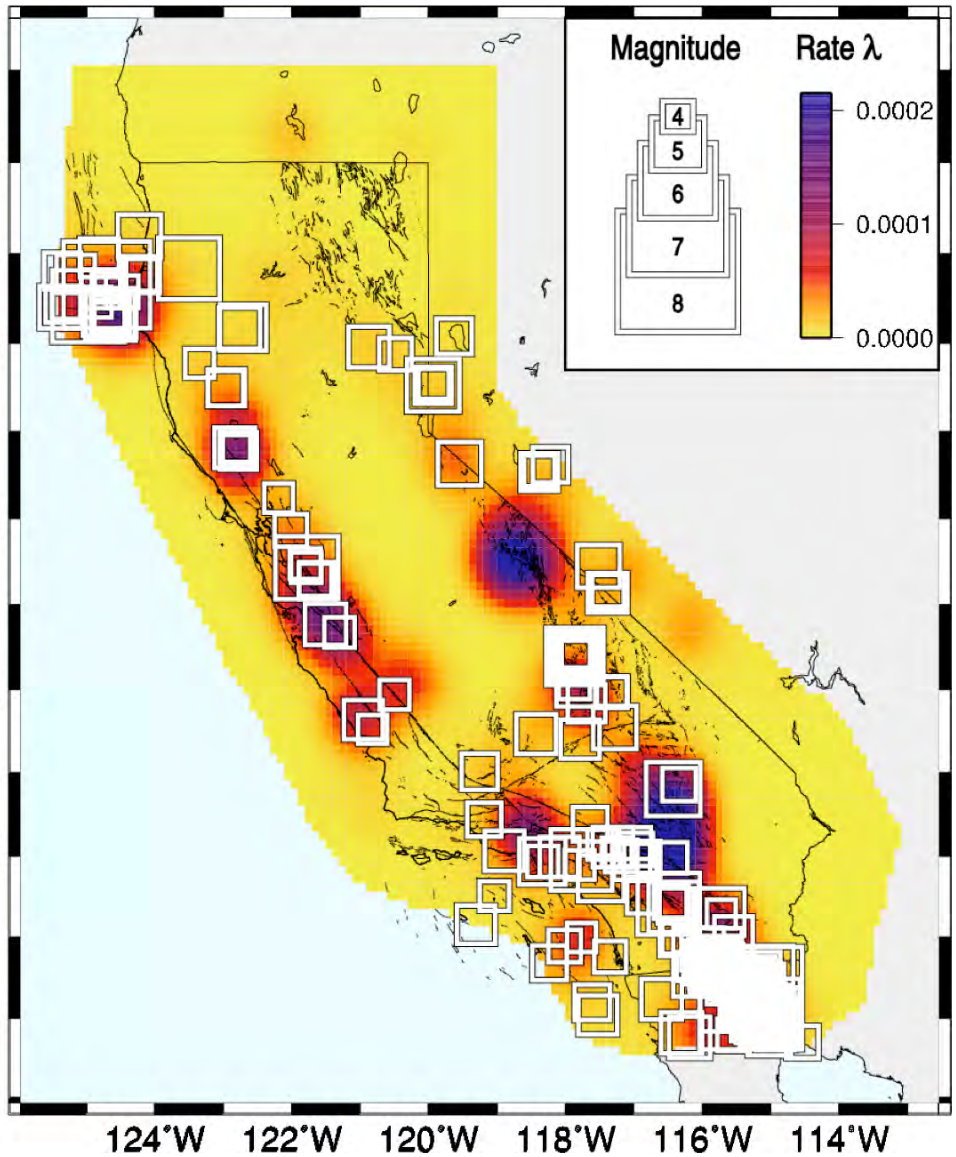
1-Year Models



Examples of Forecasting Models Currently Under CSEP Testing in California

Testing region: California
Forecast model: TripleS

Testing period: 2008-2010
Target events: M ≥ 3.95 (301)

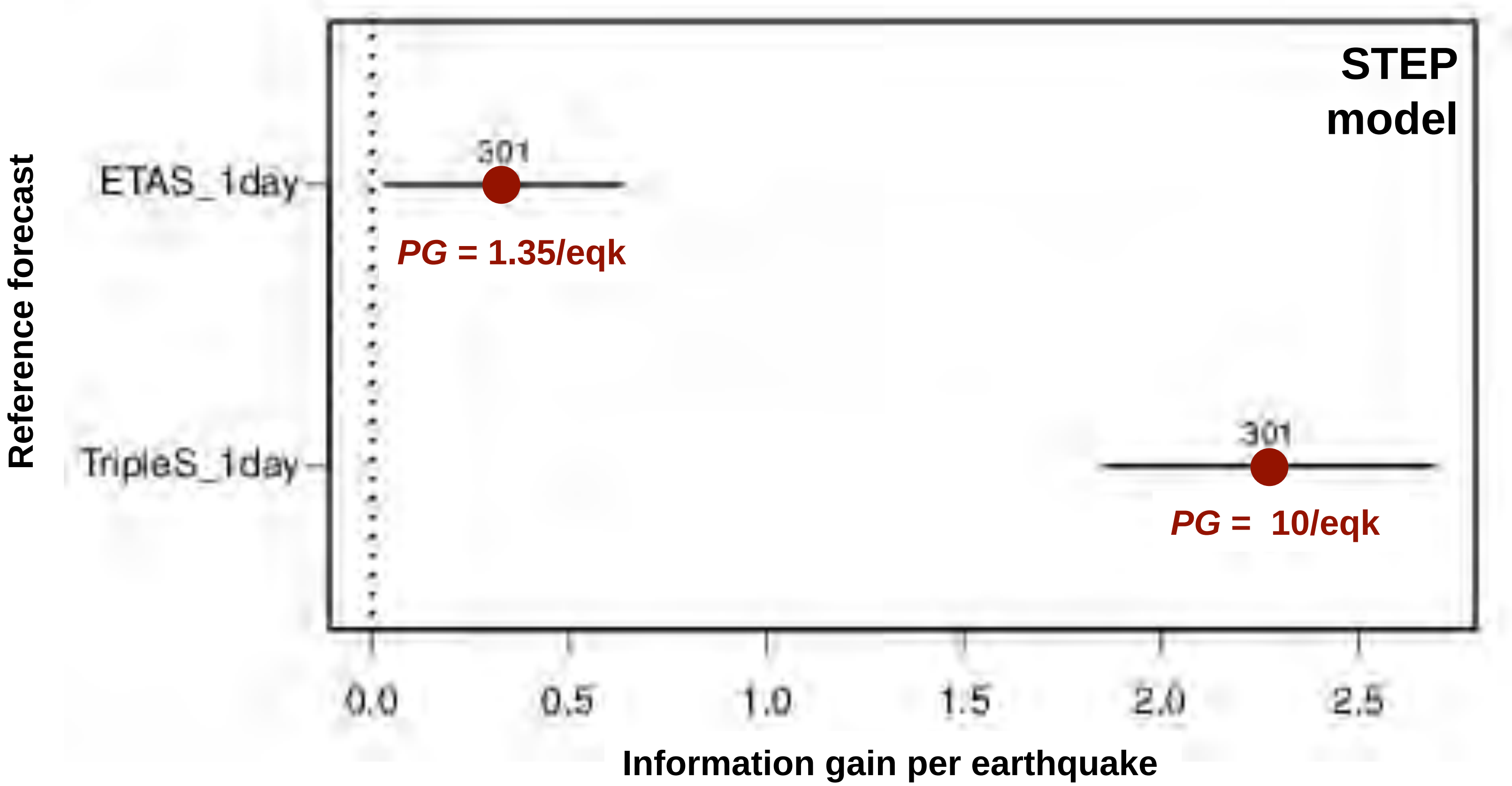


Triggering Models vs. Smoothed Seismicity

Testing region: California
Target events: M ≥ 3.95
Testing period: 2008-2010
Testing method: T-test

PG = probability gain
= P / P_0

IG = information gain
= $\log_e(PG)$



Japan and NZ Testing Regions

Testing region	Model class				
	1 day	3 month	1 year	3 year	Total
All Japan	5	9	12	9	35
Mainland	2	9	11	7	29
Kanto	4	7	8	8	27
Total	11	25	31	24	91

	1 day	3 month	6 month	5 year	Total
New Zealand	2	8	1	4	15

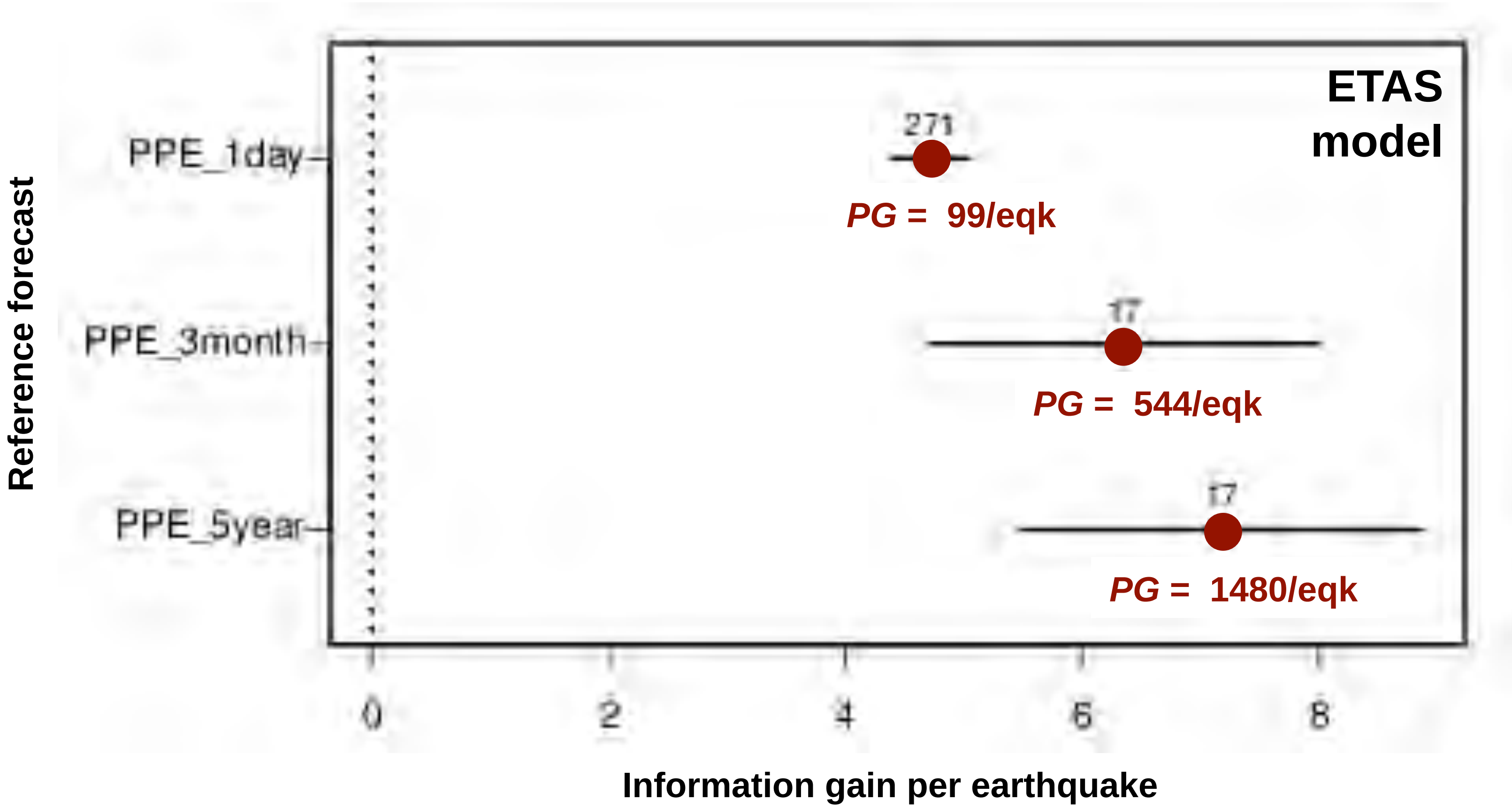
Darfield Aftershock Forecasting
(Gerstenberger & Rhoades)

Testing region: New Zealand

Target events: M ≥ 4 (PPE-1d), M ≥ 5 (PPE-3m, PPE-5y)

Testing period: 4 Sept 2010 - 8 Mar 2011

Testing method: T-test



Summary of Probability Gains

Method	Gain Factor	P_{max}(3 day) SAF-Coachella	Prospectively validated?
Long-term renewal	1-2	1×10^{-4}	
Medium-term seismicity patterns	2-4	2×10^{-4}	✔
Short-term STEP/ETAS	10-100	3×10^{-3}	✔
Short-term empirical foreshock probability	100-1000	3×10^{-2}	

ICEF Finding: ***The probability gains of short-term, seismicity-based forecasts can be high (> 100 relative to long-term forecasts), but the absolute probabilities of large, potentially destructive earthquakes typically remain low (< 1% per day).***

ICEF Findings & Recommendations

- **Utilization of Earthquake Forecasts**
  - **An outstanding challenge is short-term decision-making in a "low-probability environment."**

    Recommendation: ***Quantitative and transparent protocols should be established, including mitigation actions to be implemented if certain thresholds in earthquake probability are exceeded.***

  - **Providing probabilistic forecasts to the public is an important operational capability.**

    Recommendation: ***Agencies should continuously inform the public about the seismic situation based on probabilistic forecasting, in accordance with social-science principles for effective public communication.***

Survey of Operational Earthquake Forecasting

- **Six countries surveyed: China, Greece, Italy, Japan, Russia, United States**
  - **Long-term time-independent earthquake forecasting models are the basis for seismic hazard mapping in all six countries**
  - **In most countries, assessments are provided by scientific advisory groups with access to continuous data from earthquake monitoring networks**
- **Operational earthquake forecasting has not been fully implemented (i.e., regularly updated and on a national scale) in surveyed countries**
  - **Short-term forecasting of aftershocks is practiced in several**
  - **Research on probabilistic forecasting and operational applications is being supported in all**
- **In a few seismically active regions (e.g., California), routine use is made of operational earthquake forecasting**
  - **Forecasts are based on the statistical evaluation of seismicity**
  - **Forecasters typically operate in a low-probability environment**
  - **Use of formalized models is limited, and public dissemination of forecasting information is sporadic**

Implementation of Operational Earthquake Forecasting

- **Utilization of earthquake forecasts for risk mitigation and earthquake preparedness should comprise two basic components**
  - Scientific advisories expressed in terms of probabilities of threatening events
  - Protocols that establish how probabilities can be translated into mitigation actions and preparedness
- **Public sources of information on short-term probabilities should be authoritative, scientific, open, and timely**
  - Authoritative forecasts, even when the absolute probability is low, can provide a psychological benefit to the public by filling information vacuums that can lead to informal predictions and misinformation
  - Should continuously inform the public about the seismic situation, in accordance with social-science principles for effective public communication of warnings
  - Need to convey the epistemic uncertainties in the operational forecasts
- **Alert procedures should be standardized to facilitate decisions at different levels of government and among the public, based in part on objective analysis of costs and benefits**
  - Should also account for less tangible aspects of value-of-information, such as gains in psychological preparedness and resilience

Conclusions

- **Statistical models of earthquake clustering capture many of the short-term features of natural seismicity**
  - **Provide short-term forecasts with the highest validated information gain**
- **Implementation of operational earthquake forecasting systems is required to meet rising public expectations about transparency of scientific information**
  - **Should deliver scientific, authoritative, consistent, and timely information about short-term earthquake probabilities, including epistemic uncertainties**
- **Authoritative statements the time-dependence of seismic hazard can benefit the public by filling information vacuums that lead to informal predictions and misinformation**
  - **Increases awareness of long-term risk**
- **Current policies need to be adapted to low-probability forecasting**
  - **High-probability predictions are not yet (and may never be) possible**

End