



*Physics-based earthquake forecasting:
Past, present and future*

Dr. Kristy F. Tiampo

*NSERC & Aon Benfield/ICLR Industrial Research Chair
in Earthquake Hazard Assessment*

- Earthquakes are generally the most feared of natural hazards because they occur without warning. Hurricanes can be tracked; floods rise in a systematic way; volcanic eruptions are preceded by a variety of phenomena.



- The devastation caused by the M ~ 9.0 North Sumatra earthquake and subsequent tsunami has once again demonstrated our vulnerability to the effects of a great earthquake.
- Historical records from around the world suggest that, while rare, similar events have occurred elsewhere, including Alaska, Chile, Japan, Iran, and Cascadia.
- The damage from significant, although smaller, earthquakes can cause significant damage in areas that are not properly prepared, such as Haiti.

Haiti Earthquake

M ~ 7, Feb. 27, 2010

200,000 dead, ~ \$14 billion in damages



Maule Earthquake, Chile

M ~ 8.8, Feb 2010

< 1000 dead, \$15 – 30 billion in damages



The Gujarat, India Earthquake

M ~ 7.9, January 26, 2001

More than 30,000 persons died

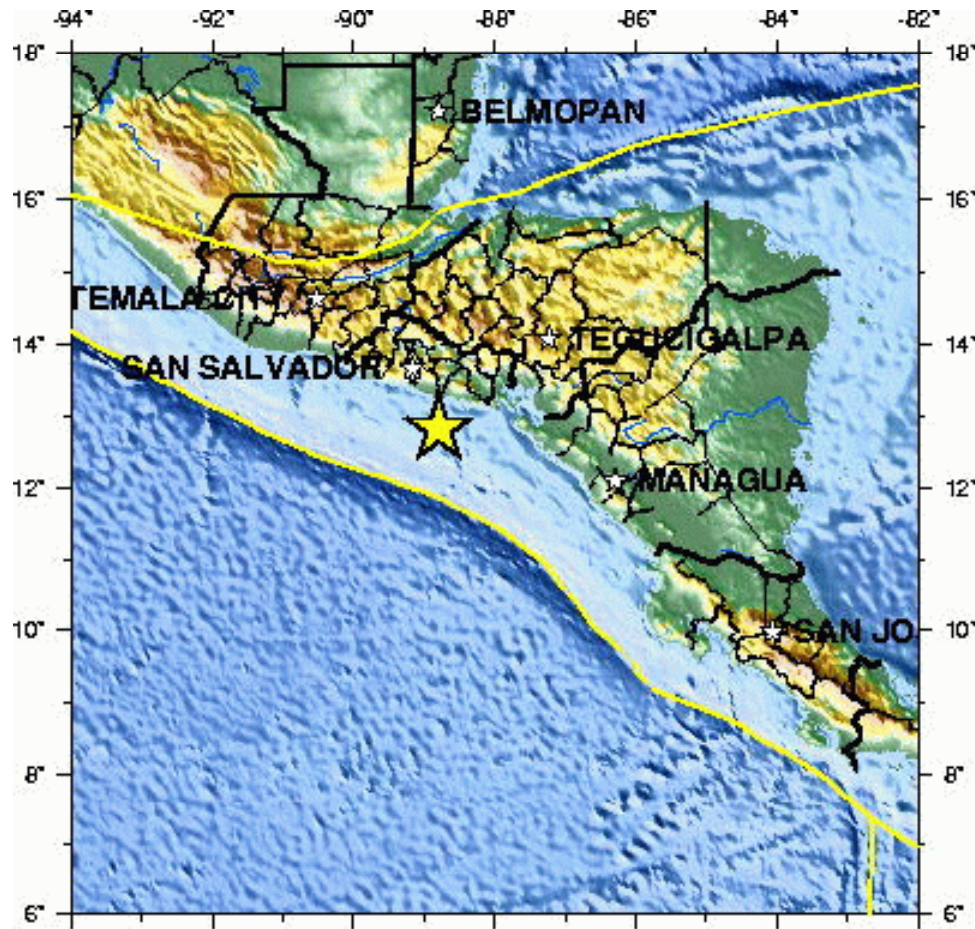
Damages exceeded \$10 billion USD



Reuters

The January 13, 2001 El Salvador Earthquake

~ 2000 dead and more than \$2 Billion USD in damages



Courtesy, USGS



(AP PHOTO)

The Magnitude 7.9 Gujarat, India Earthquake

January 26, 2001 – An intraplate earthquake similar to the New Madrid events of 1811-1812, M ~ 8, in central North America

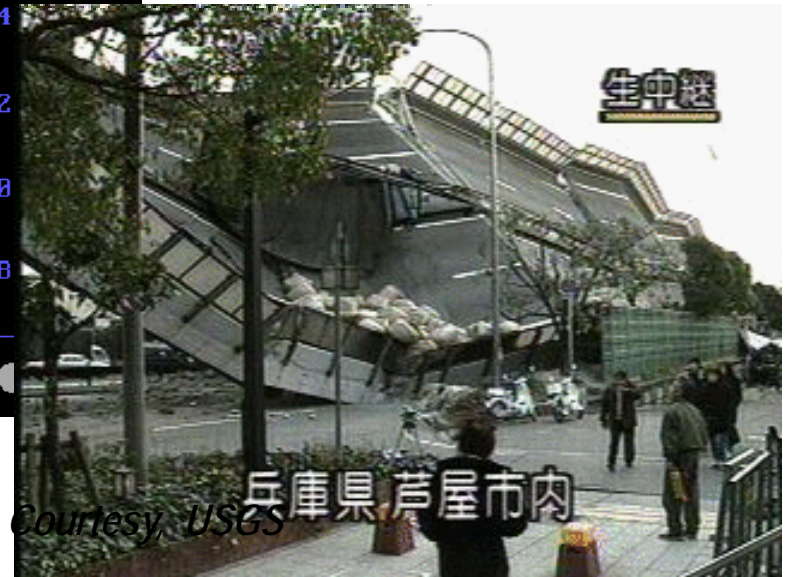
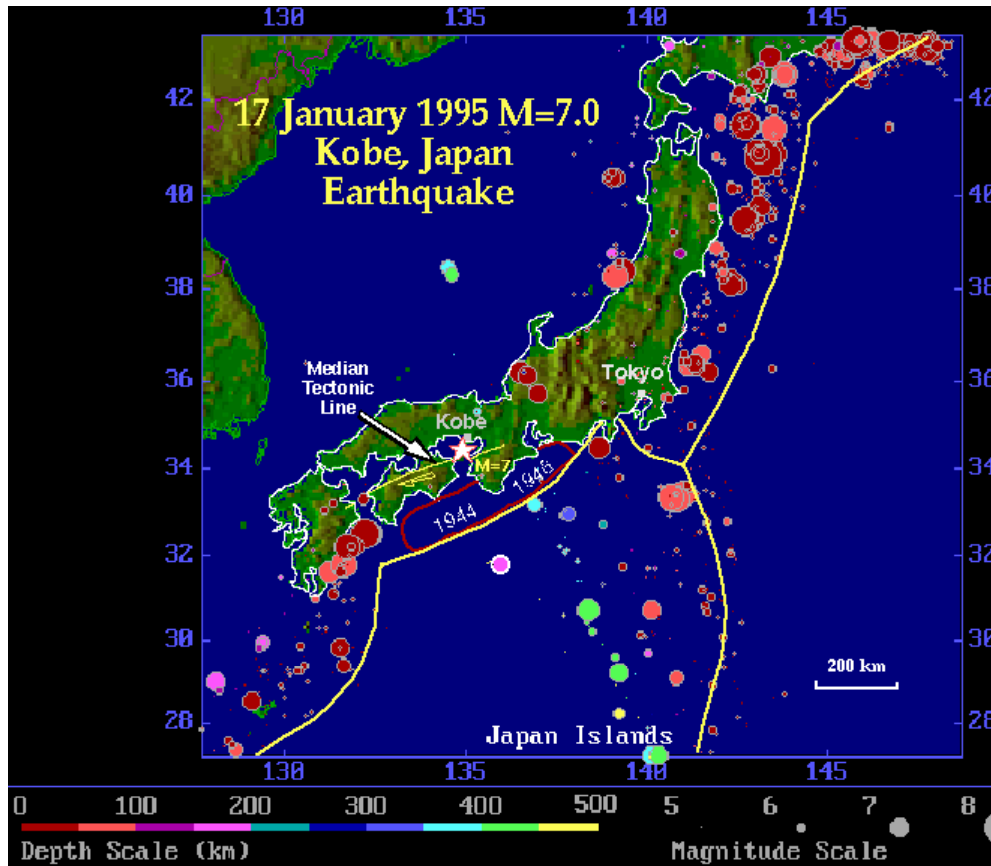


More than 30,000 persons died in the event, and damages exceed \$10 Billion

The Kobe, Japan Earthquake

M ~ 7.0, January 17, 1995

\$200 Billion in damages and ~ 5000 dead



The Nisqually, Washington Earthquake

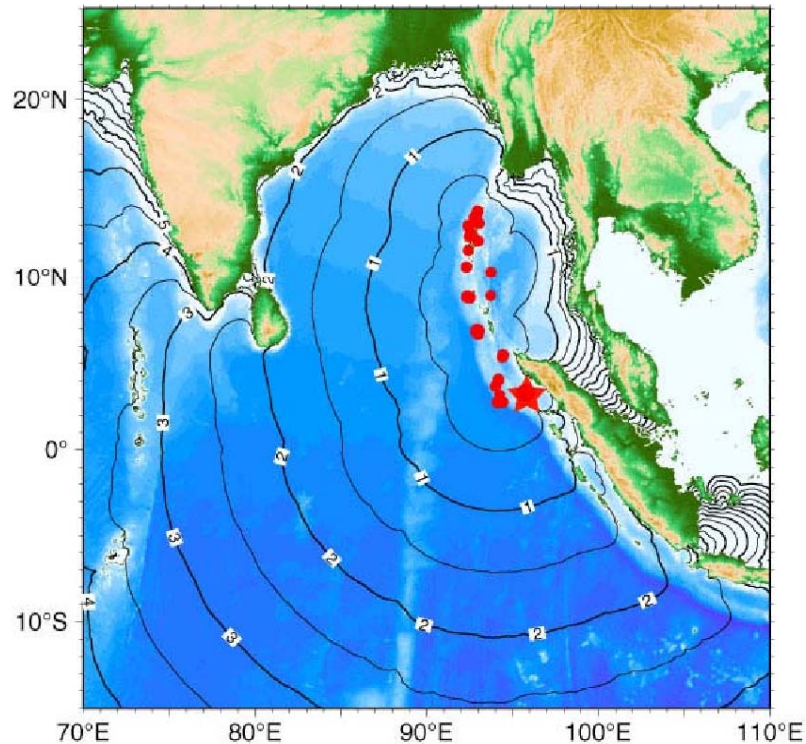


February 2, 2001, a magnitude 6.8 event, it caused more than \$2 billion in damages

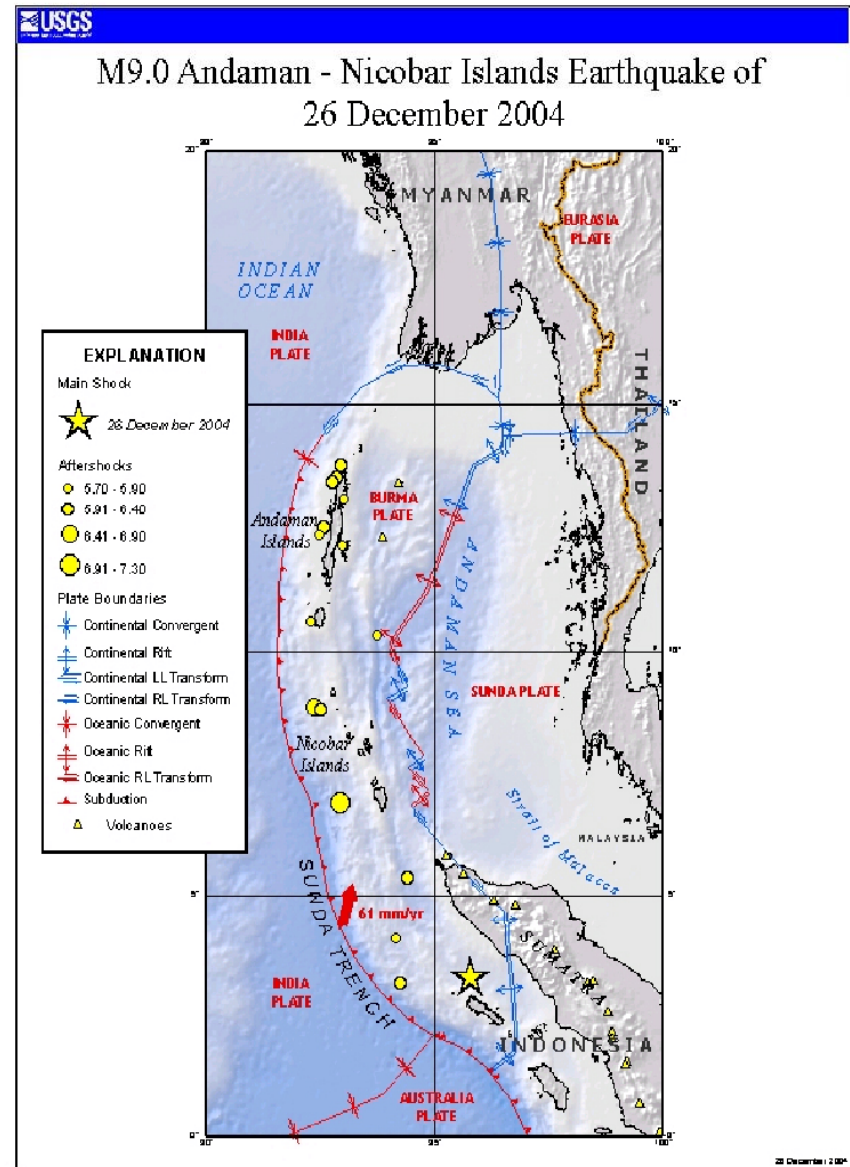


The Great Sumatran Earthquake & Tsunami, December 2004

M ~ 9 Subduction Zone Event



Tsunami travel time model, K. Satake



Courtesy, Benfield Hazard Centre

The San Francisco Earthquake

Destroyed the city in a few tens of seconds, April 18, 1906.

The fire that followed finished what the earthquake started.



Courtesy, Museum of San Francisco

Damage and Death in 1906

The M - 8 earthquake and fire killed more than 3000 persons. The San Francisco earthquake will happen again. The insurance industry estimates that if it were to happen today, damages would total well in excess of \$1 Trillion USD.

EXTRA THE DAILY NEWS EXTRA

HUNDREDS DEAD!

Fire Follows Earthquake, Laying Downtown Section in Ruins—City Seems Doomed For Lack of Water

KNOWN DEAD AT MECHANICAL PAVILION

Max Fenner, policeman, killed in collapse Essex Hotel.
Niece of Detective Dillon, killed in collapse, 6th and Shipley.
Unidentified woman, killed at 18 7th st.

OTHER DEAD

Five killed, 2 injured, in collapse of building at 230 Geary.
Frank Covall, buried, beneath basement floor of burning building house 6th and Mission. Heard crying "For God's sake, help me."
Seven firemen killed in collapse of brick power house Valencia and 7th.
John Wibley and son, killed in falling house, Steiner and Germania ave.
James Whaley, wife, Nellie Whaley, Marie Whaley, same address. Badly injured.

Unidentified man, buried in remains Valencia-st. Hotel.
At least there were 100 dead and 500 at the Valencia-st. Hotel.

INJURED

J. Carr, 1547 Hill.
D. Simpson, 111 Geary, very bad.

Ben Shipley, of Steiner, 6th str. and two children, not fatally.
J. H. Roman, 184 Leavenworth, legs broken.
C. C. Perry, Hotel Phillips, 117 6th st.
Kate Johnson and wife, Hyde st., crushed badly.
Joe J. Thomas, 381 6th, hurt badly.
Geo. Burdwell, Folsom, and 6th.
Tribunes family at 137 Turk, near, wife and baby killed heads crushed, when head crushed.
Shy family, near 127 Turk, badly hurt.
Miss Murray, and Miss Stewart, 140 Olive st.
Misses boarded in vain United States, restaurant, Nassy and Market.
Louise Burston, 724 Kearny, badly hurt.
Mrs. Geo. Daniels and Leon. Howard, 301 Sixth, bruised and hurt.

At 126 Langton, 4 killed; Billy Sheehan, policeman, crushed 3 people.
Many injured at 117 6th st., Hotel Phillips.
San Francisco was practically obliterated and nearly destroyed by the earthquake, which commenced at 5:12:11 p. m. today and continued with little relief for four minutes.
Great loss of life was caused by the collapse of buildings and many people were killed and mangled by the falling ruins.
The monetary loss caused by the earthquake, the loss which followed it and the depression it caused will reach several hundred millions of dollars.
The program of San Francisco, the municipal and school which it will probably take many years to recover.
Thousands of men who could not be reached last night since the morning promptly tomorrow.
The story of the disaster was greater than any that has been known in the history of the city.

The people are appalled, terrified. Thousands, hundreds of thousands of the greatest disaster, with results with more dire, as happening out of San Francisco.
Many heartrending scenes have been enacted. Families are moving their belongings hither-and-thither, and sweeping wretchedly about, begging for aid.

The City Hall is a complete wreck. The walls are crumbling and several stories have fallen, leaving only the skeleton frame standing and the top of the dome exposed. Around all sides of the building the walls have crumbled, like so many cards. The Receiving Hospital was burned.

The enormous and old Mechanical Pavilion, which today is a combined hospital and morgue. Dead and dying are brought in by auto, ambulance and even garbage carts.
Injured people were taken from the Emergency Hospital to Mechanical Pavilion. Many of them were hurt. Some broke loose and ran among the dying, sending horror to the scene.
At 11:22 a second sharp quake occurred, accentuating the general situation on the peninsula, and was not less than the first. It lasted for the length of about an hour after the first one.

At least forty buildings were struck within ten minutes and the building present among the list, at 60 more the 202 Fourth 5th, and South streets, followed by a general run of panic on Seventh and Eighth streets, while the West.

At 11:22 a second sharp quake occurred, accentuating the general situation on the peninsula, and was not less than the first. It lasted for the length of about an hour after the first one.

All of the city hospitals have been shut down, and within an hour the city was practically a mass of ruins, with the exception of the offices that in the collapse of the main part of the city. The main part of the city was a mass of ruins, with the exception of the offices that in the collapse of the main part of the city.

San Francisco Bay.
A building collapsed at Steiner and Height streets. No report of loss of life.
Along Market st., from 8th toward Center, the sidewalks are literally strewn with wreckage. In many places the sidewalks have collapsed, falling into the basement.
This is true on Market between 5th and 6th, between 6th and 7th, and between 7th and City Hall Square, on the west side.
There are probably as many buildings standing in the city. This number that many were fine are to be repaired. The St. Ignace Church was badly shaken but is intact. Great damage done at St. Ignace's village, a portion of the building being destroyed.

Many people were killed at the end of Calloway street, in the direction of the city.
Concrete Club, Van Ness Ave., badly damaged.
At the Commercial Hotel, Fifth and Mission sts., the building is badly shaken. A number of people, the building was built by the late Gen. Slocum, were injured, but no report.

At 5:30 the following were at Mechanical Pavilion: Miss Jones, 509 Stearnson; M. R. D. Moore, 214 Van Ness; Wm. G. Chas. 607, 410 7th; William Bernard A. Gibson; 139 3rd; Ernest Edward; 1143 Mission; Reg. Kennedy; 171 Howard; Geo. Sullivan, 111 15; D. and Geo. Menworth, 114 4th; Philip Hendon; J. Bode; Wm. Cassman, 112 4th; D. J. Zochak, 172 7th; Geo. Skragone, 24 Polk; Corneil, 529 10 Polk; Wm. Carr, 1547 Hill; Wm. Anderson, 1193 Market; J. Steiner, 127 6th; E. V. Henshaw, 111 Geary; J. Justice, Brunswick House; J. Hart, Los Angeles; J. Young, 1724 Ohio ave; Lora Donald, 2218 Stearnson; Chas. Marshall, 149 Turk; R. M. Peterson, 124 12 Polk; R. M. Lander, 716 and Steiner; Stronach Hotel.

THEATER WRECKED

The Market Theatre is in flames. The roof fell, on the 8th st. side, having fallen on, while the roof came into the building of the building.
At 8:10 California a house was shaken from its foundation and onto the sidewalk.
The St. Ignace Hospital at California and Maple sts. is badly wrecked. The tower, at the west end, was shattered. The hospital would have been completed within a few days.

BRIEF IDEA OF DISASTER

Walls near Central Park shaking risk are down. Foundies and buildings are in flames. The fire department is at 119 6th st. Teams, mules and police work side by side at 8th and Market. The fire department is at 119 6th st. Teams, mules and police work side by side at 8th and Market. The fire department is at 119 6th st. Teams, mules and police work side by side at 8th and Market.

IN OAKLAND

At 11:22 a second sharp quake occurred, accentuating the general situation on the peninsula, and was not less than the first. It lasted for the length of about an hour after the first one.

THIS EDITION ISSUED FROM 1906 MISSION ST. WITH 100 COPIES MAY BE HAD.



Courtesy, Museum of San Francisco

And there was the Lisbon earthquake...

- Magnitude approximately 9.0, the great Lisbon earthquake struck in 1755, with an estimated epicenter off the southwest Iberian peninsula.
- Shaking lasted almost 10 minutes, and was felt as far north as Switzerland.
- The resulting tsunami and fire resulted in the widespread destruction of Lisbon and the Portuguese coast.
- Again, the potential for an earthquake of $M > 8$ must be considered in recurrence probabilities for the Iberian peninsula!



Courtesy, NISEE

Hazard Quantification

- Given that earthquakes are going to happen, what are our biggest concerns?
 - (1) Prevent death
 - (2) Minimize damage
- Ground shaking is what causes death and damage, as structures crack and disintegrate.
- Engineers are concerned with 1 & 2 above.
- Scientists provide engineers with estimates of where the earthquake will occur, and how much shaking they will cause.
- Today, 'shaking' is quantified in terms of peak ground acceleration, PGA, as a percent of gravitational acceleration.

Background

- Today, hazard maps are widely used to characterize the likelihood of any given region undergoing shaking due to a large earthquake. However, hazard maps are not considered earthquake forecasts, but rather a tool for planners, engineers, and emergency managers.
- Time-dependent earthquake forecasts provide the probability of an earthquake occurring at a specific location over a fixed period of time in the future.
- Historically, a wide variety of approaches have been applied to the problem of earthquake forecasting. Generally, these can be divided into three broad categories:
 - (1) Empirical approaches that rely on local observations in the vicinity of the upcoming event,
 - (2) Stress triggering studies and
 - (3) Statistical studies of seismicity patterns.
- While no one approach has proven to be consistently successful for the short-term forecasting of large earthquakes, there has been some recent success in the forecasting of large events on longer, intermediate length time scales.

Forecast vs. Hazard

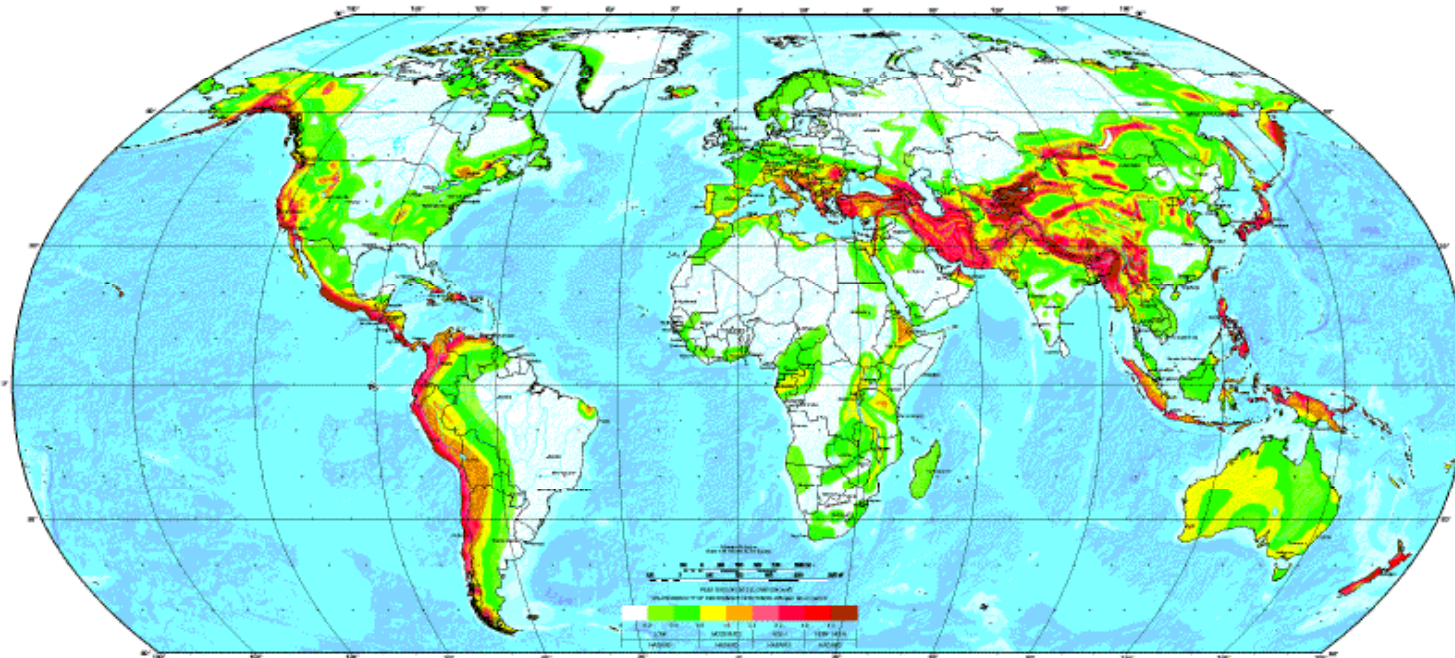
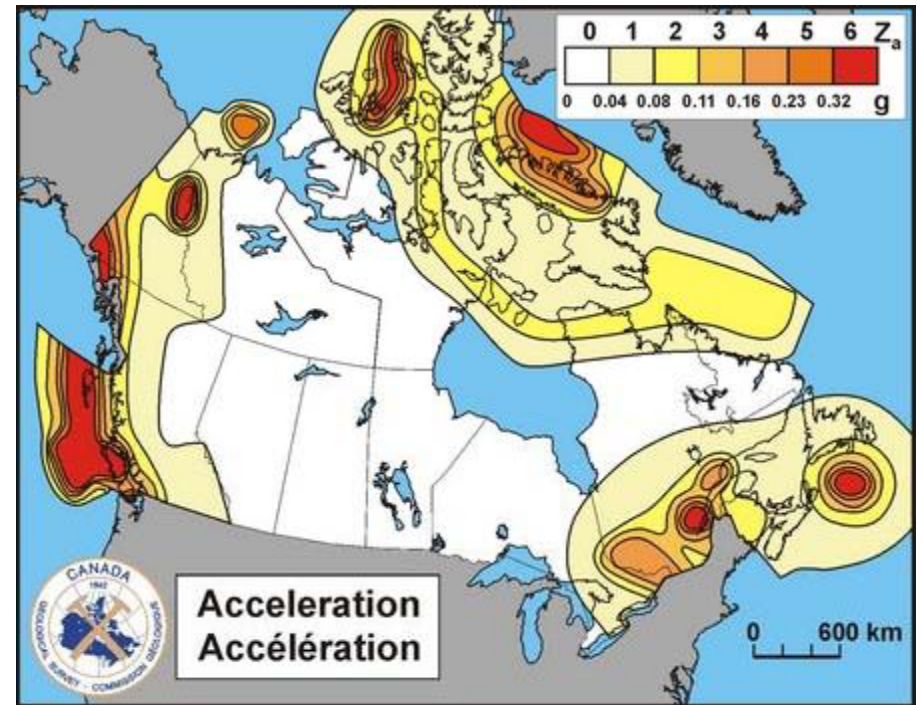
- Hazard maps are widely used to characterize the likelihood of any given region undergoing shaking due to a large earthquake. Hazard maps, however, are not considered earthquake forecasts, but rather a tool for planners, engineers, and emergency managers.
- Forecasts provide a probability of an earthquake occurring at a specific location over a fixed period of time in the future.
- Historically, a wide variety of approaches have been applied to the problem of earthquake forecasting.
- Today, in addition to efforts at intermediate-term forecasting, short-term early warning systems are under development as well. These would post warnings at the very first signs of a significant earthquake and/or tsunami.

Hazard Maps

Compiled based on historic seismicity records

Right: Probability of Exceedance = 10% in 50 years, 1985.

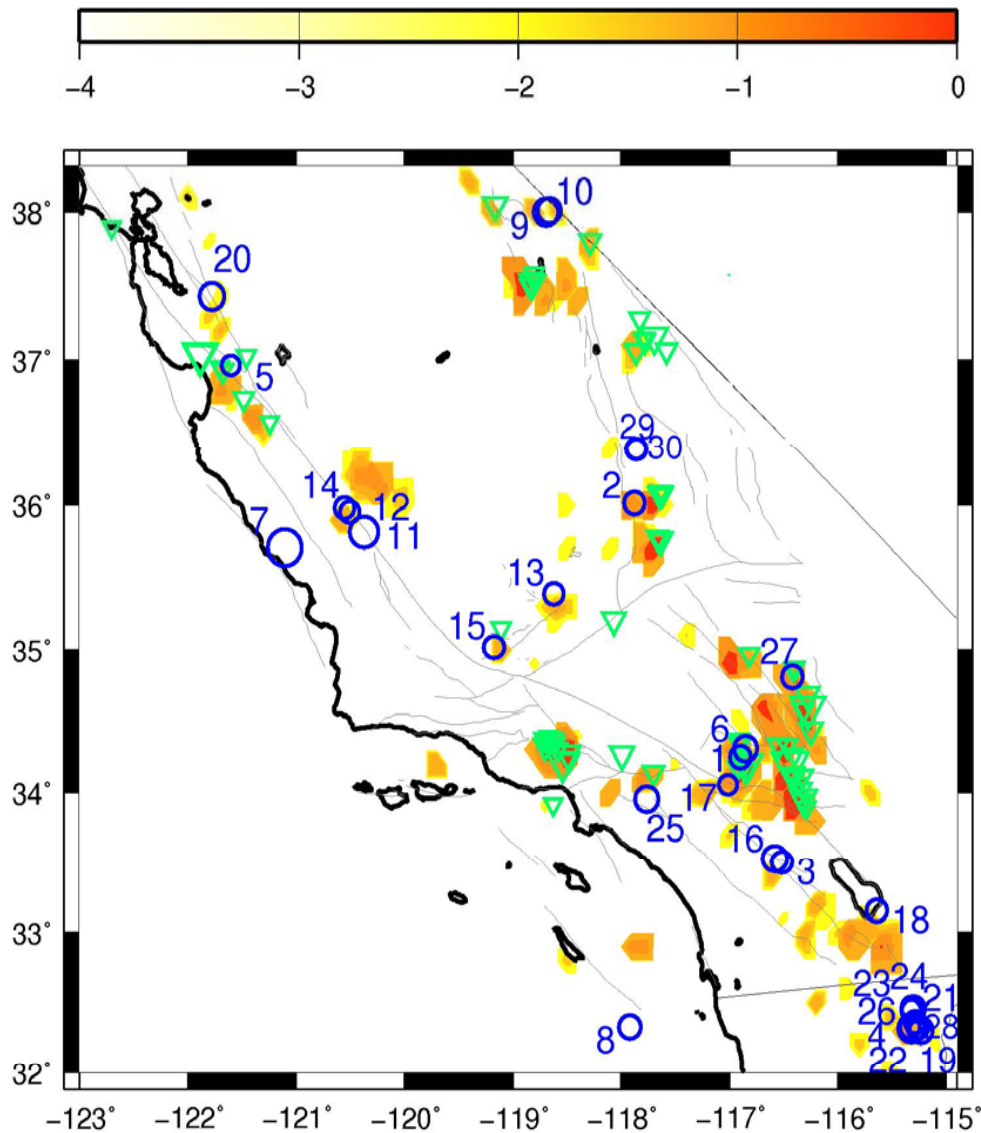
Courtesy NRCAN



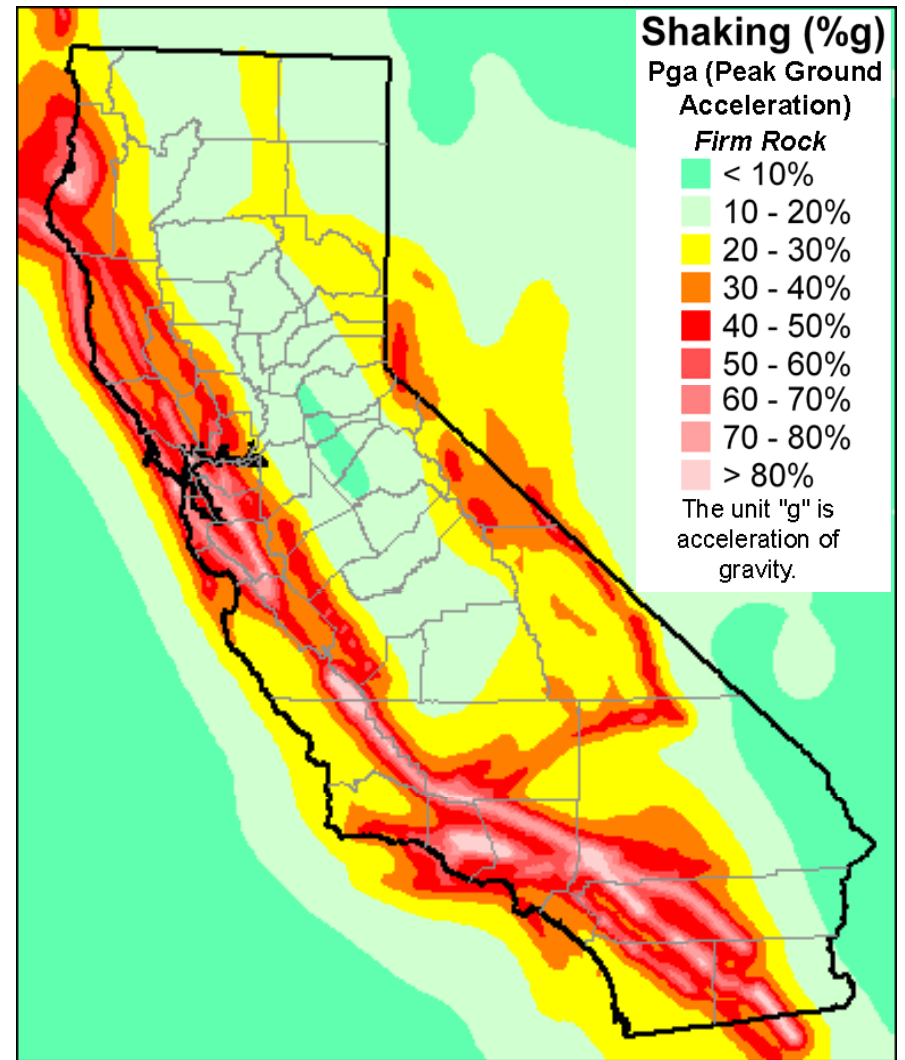
Left: Seismic Hazard, Low to High, 1999

Courtesy Global Seismic Assessment Program

Forecast vs. Hazard



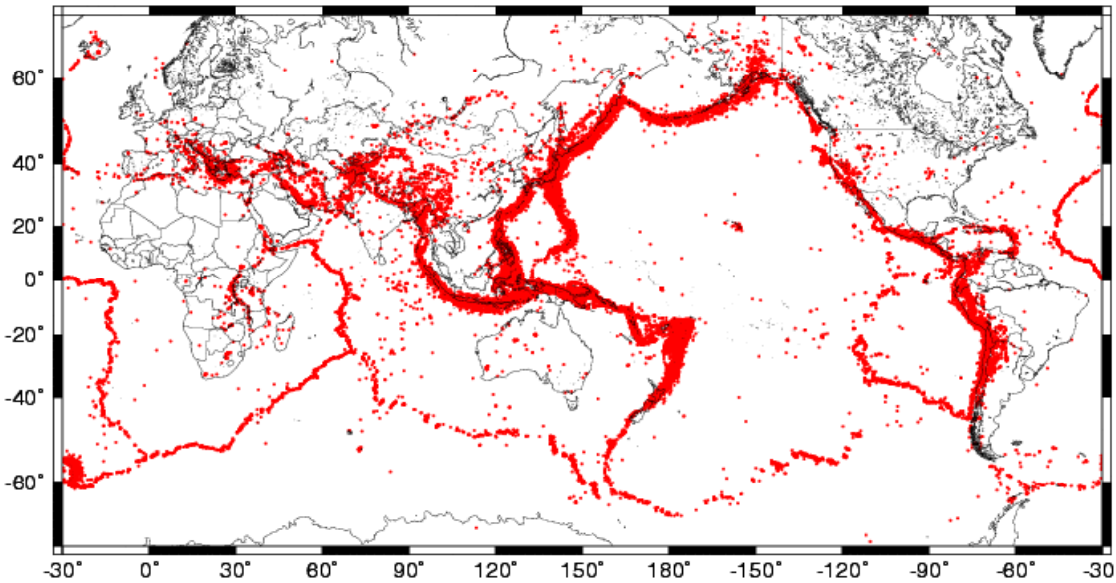
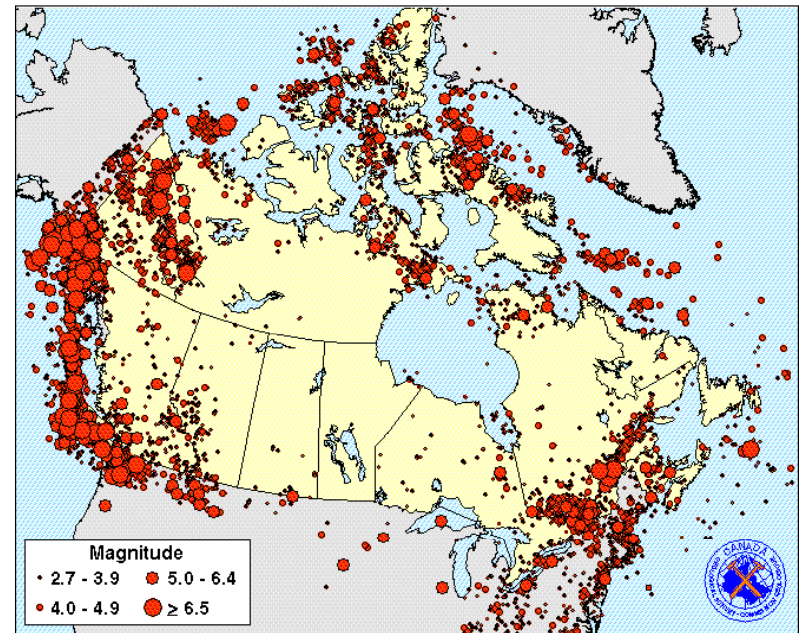
10-year forecast for earthquakes of $M > 5.0$, 2000 to 2010



10% Probability of Exceedance in 50 years.
<http://www.consrv.ca.gov/CGS/rghm/psha/index.htm>

Earthquake Catalogs

Canadian Seismicity, 20th c.
Courtesy NRCCan



Worldwide Seismicity,
M>5, 1980-2000

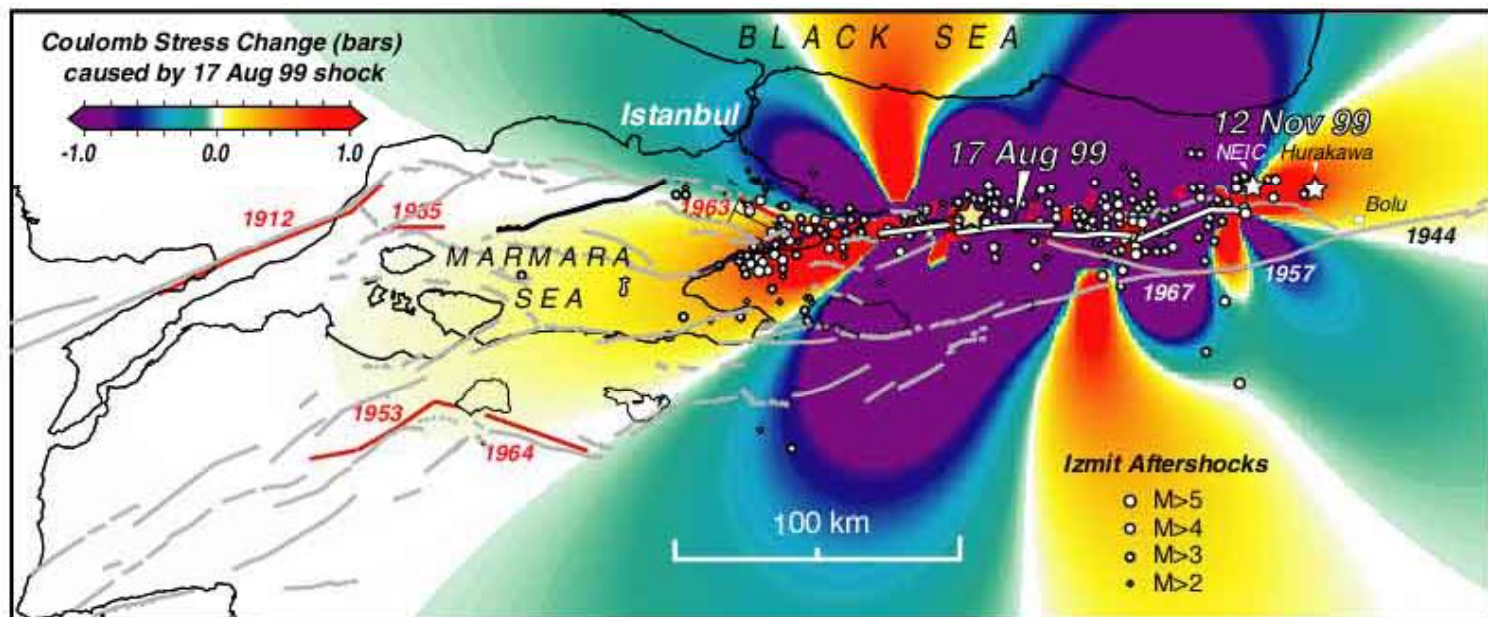
Pattern Informatics (PI) Index

- A method for analyzing historic catalog data in order to detect changes in the small seismicity prior to major earthquakes.
- The resulting PI index is computed directly from seismicity data and identifies the development over time of spatially coherent regions of seismicity.
- Here we use the small earthquakes of magnitude three to act as sensors for the larger earthquakes. The physical idea is that these small earthquakes ($M \sim 3$) are telling us about changes in the underlying stress level.
- *Anomalies are measured relative to the long-term regional background rate, and corresponds to the increased probability of an event.*



Stress Triggering Studies

- The idea here is that, every time an earthquake occurs it changes the loading on nearby earthquake faults.
- If we could know the current levels of stress on all these faults, i.e. how close they were to failure, we could predict whether or not one earthquake was going to trigger another.
- **The drawback:** *Our lack of detailed knowledge of the current state of Earth's interior.*

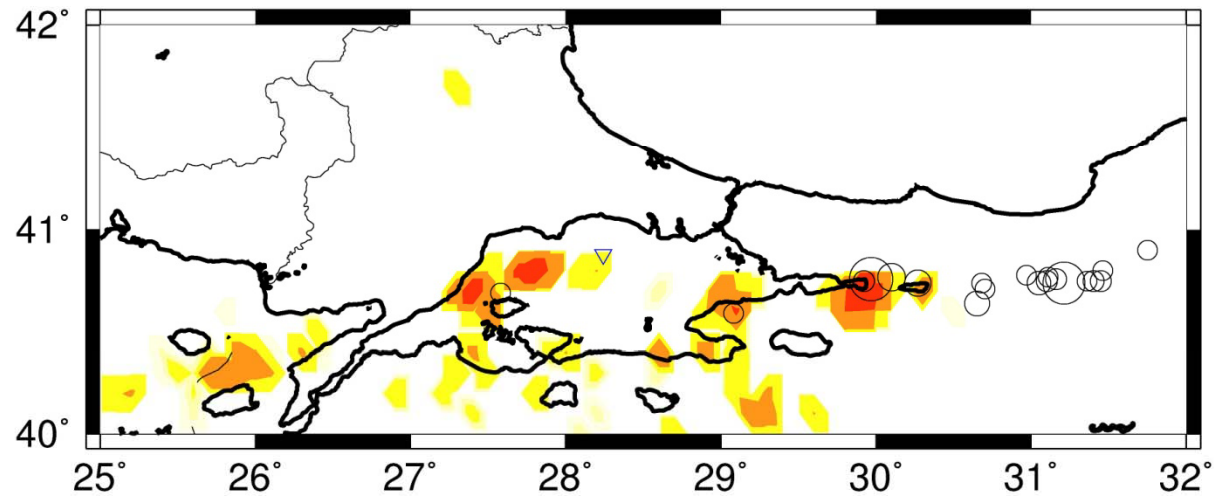


Calculations by Shinji Toda (ERI), Tom Parsons & Ross Stein (USGS)

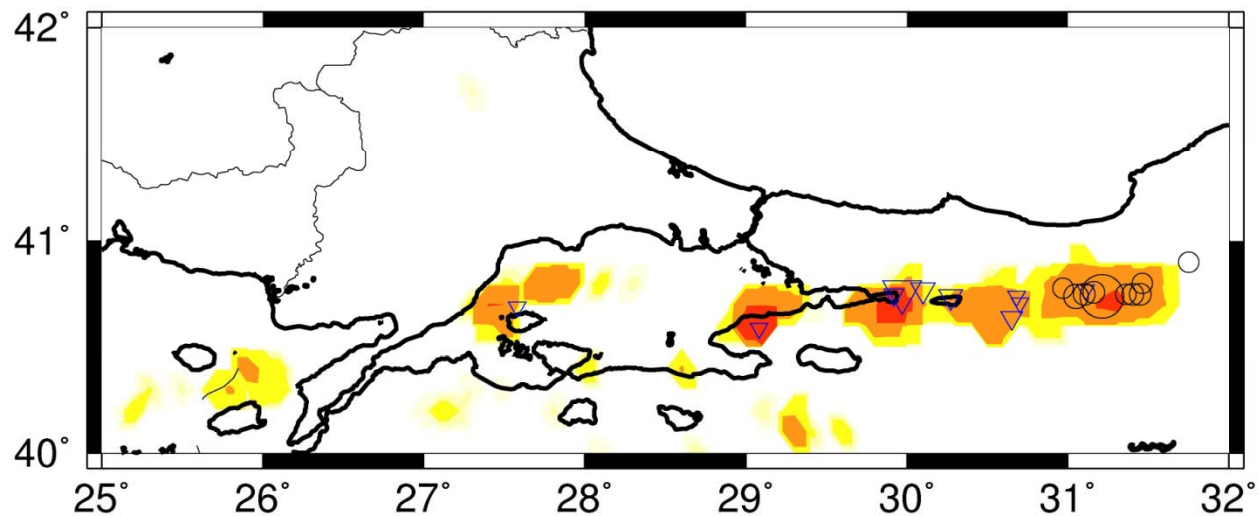
Izmit & Duzce Earthquakes, Fall 1999

Can we link, or compare, the two techniques?

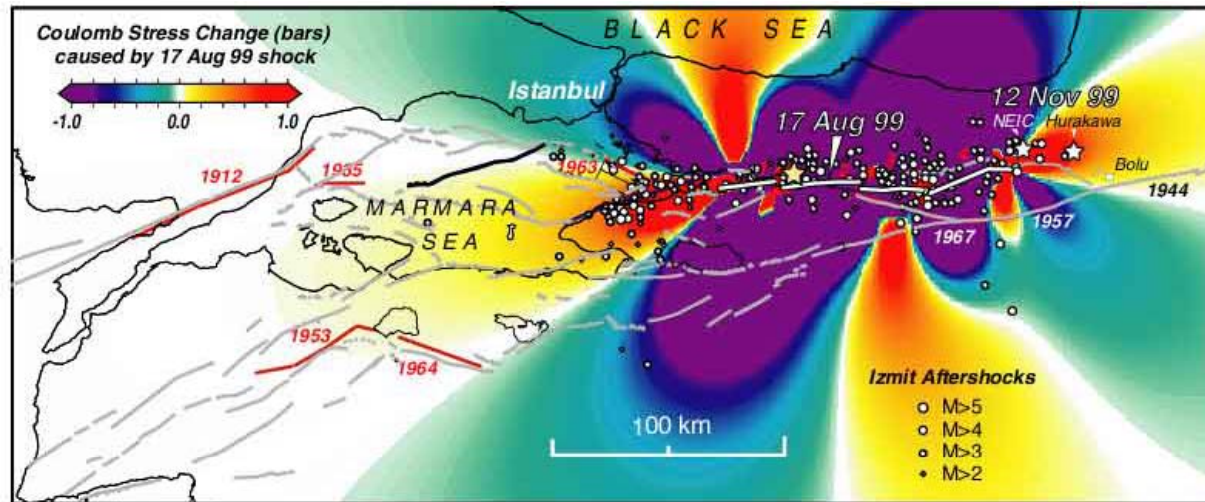
PI: Through December, 1998



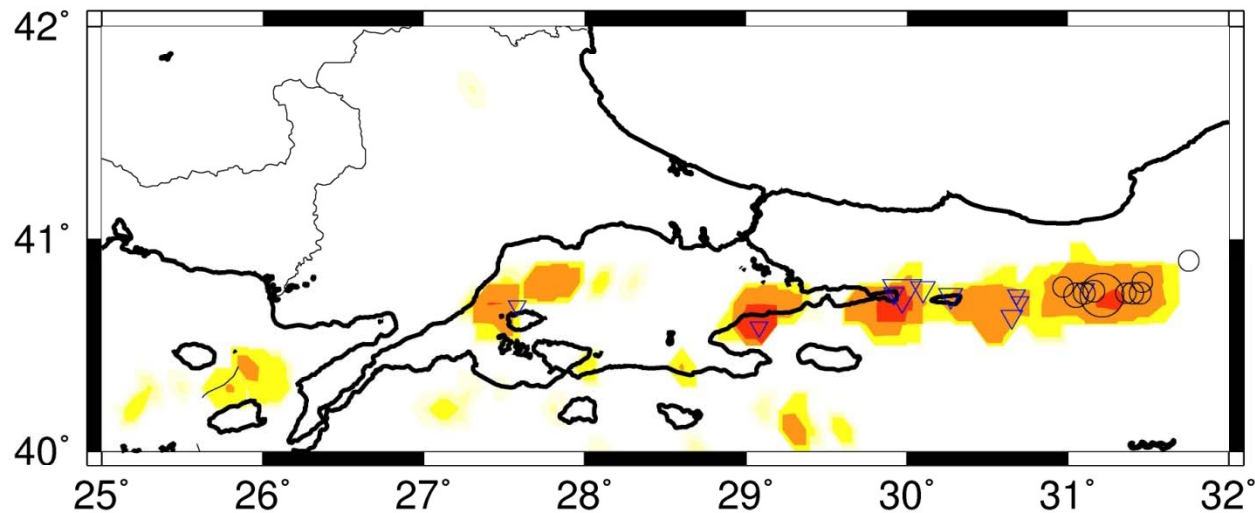
PI : Through October, 1999



Can we link, or compare, the two techniques?



Calculations by Shinji Toda (ERI), Tom Parsons & Ross Stein (USGS)



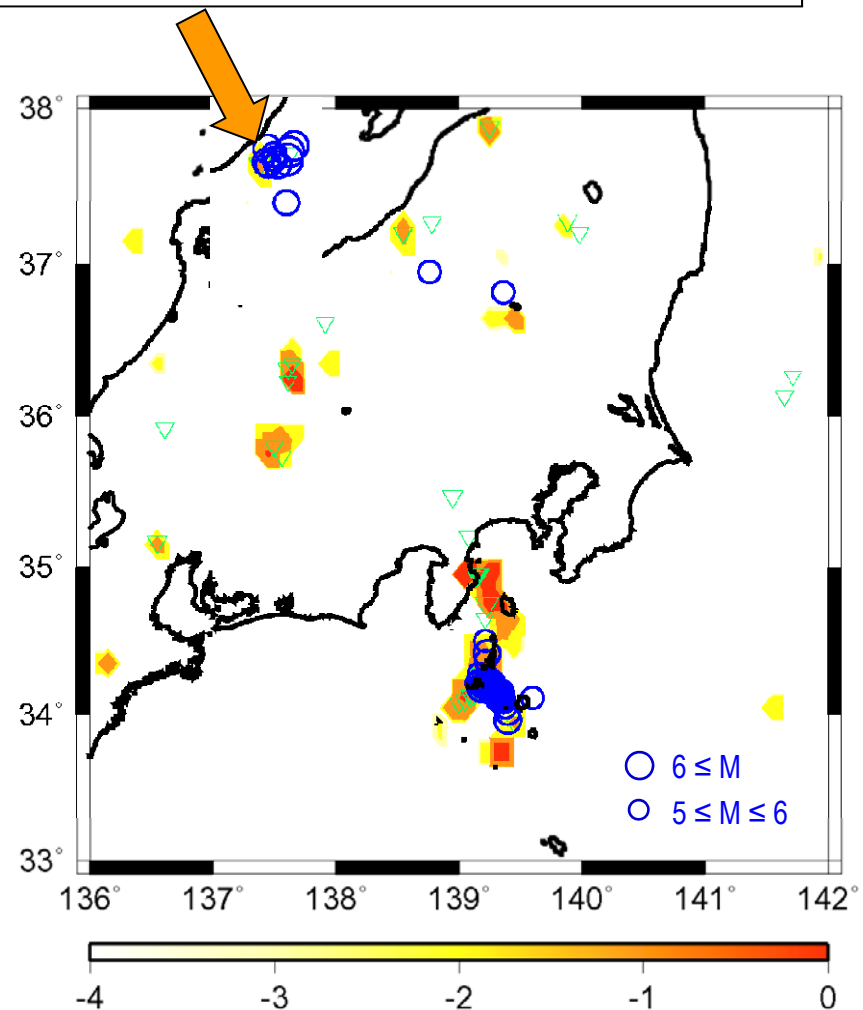
PI : Through October, 1999

Japan

Tokyo Area, Japan (Courtesy K. Nanjo, et al., 2004).

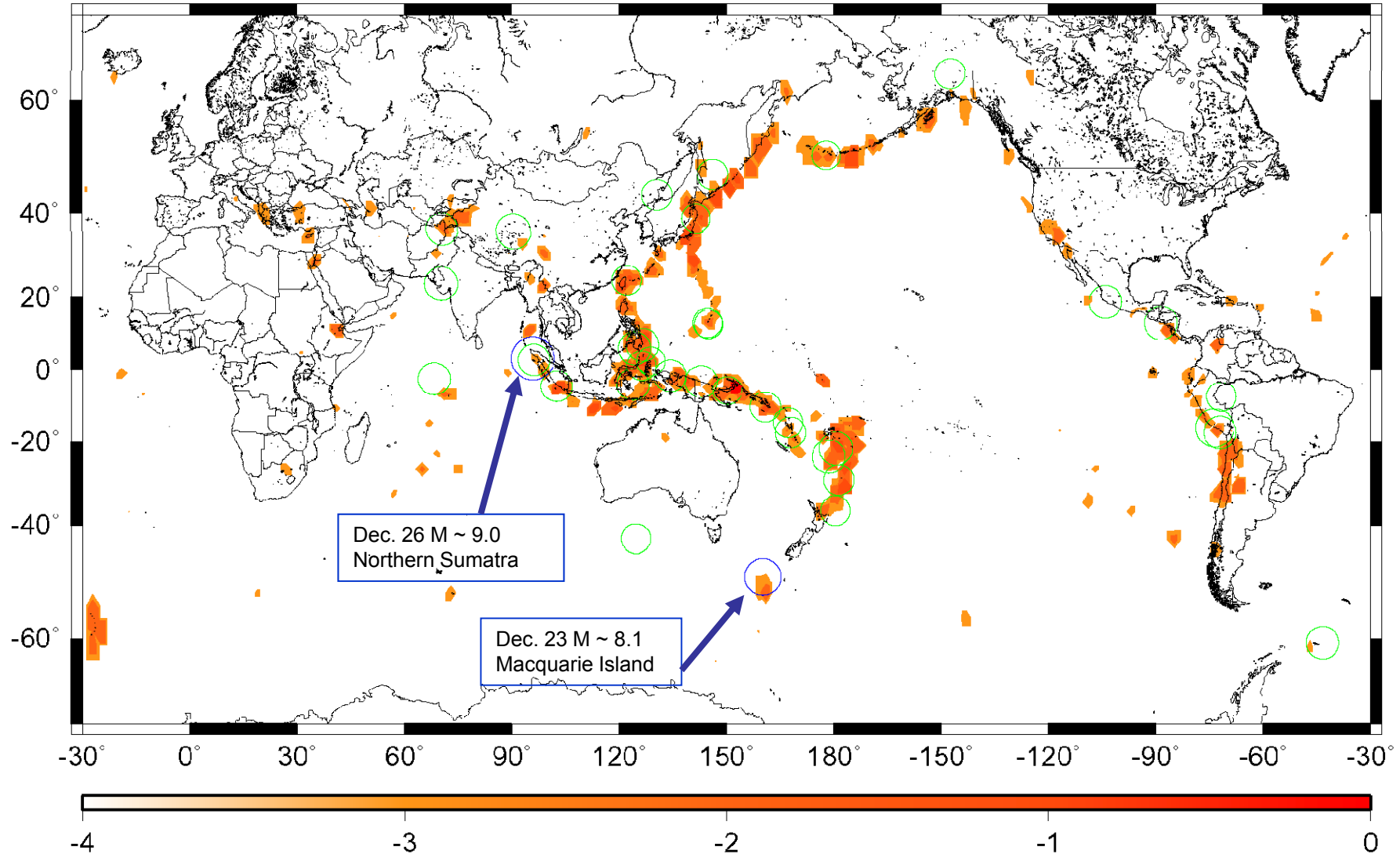
Forecast for the period: January 1, 2000 ~ December 31, 2010.

- The October 23, 2004, $M = 6.8$ Niigata, Japan earthquake killed at least 37 people and injured thousands. Its main shock and principal aftershocks with $M \geq 5$ are shown (arrow).
- The image at right was shown during lectures in Japan on October 13 & 14, 2004.

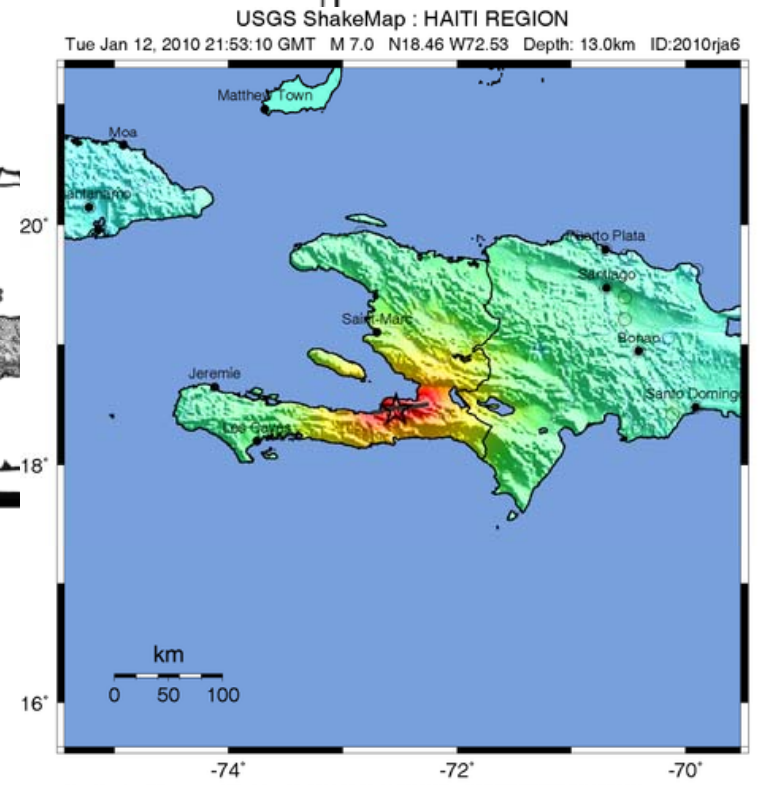
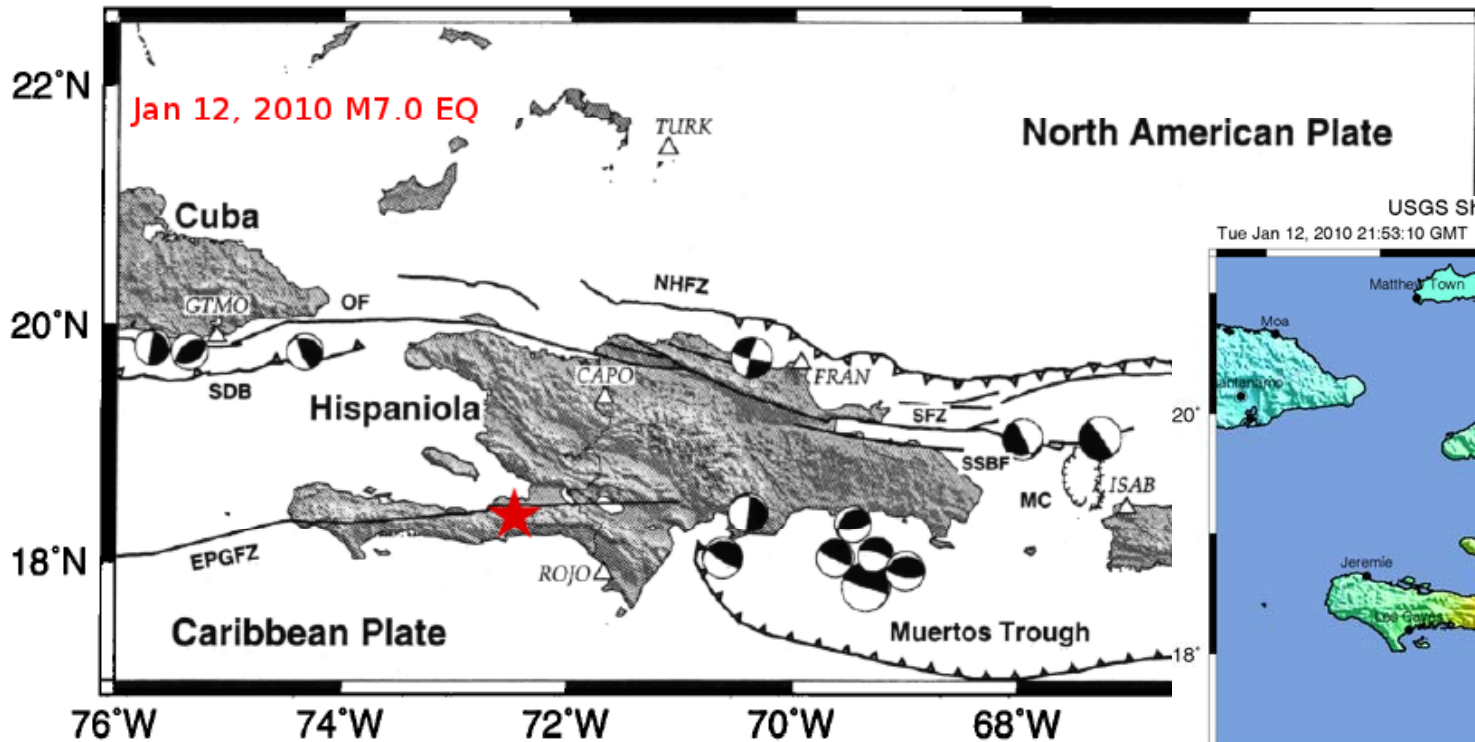


World-Wide PI Map for $M \geq 7$ 2000-2010

Courtesy J. Holliday, from November 2004

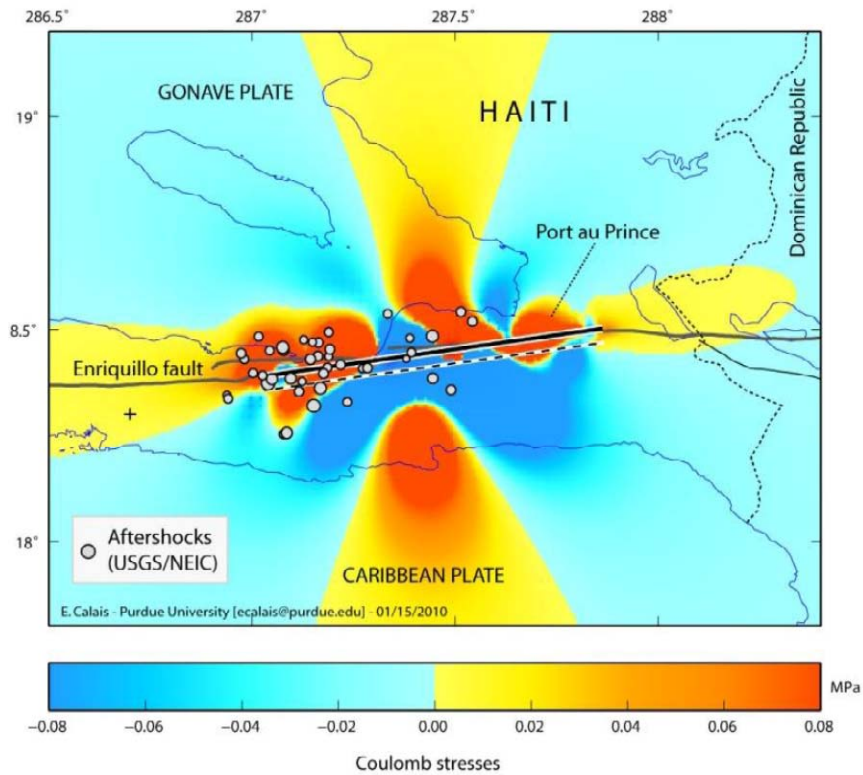


Haiti M ~ 7.0 Earthquake, January 12, 2010

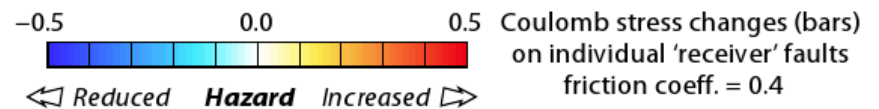
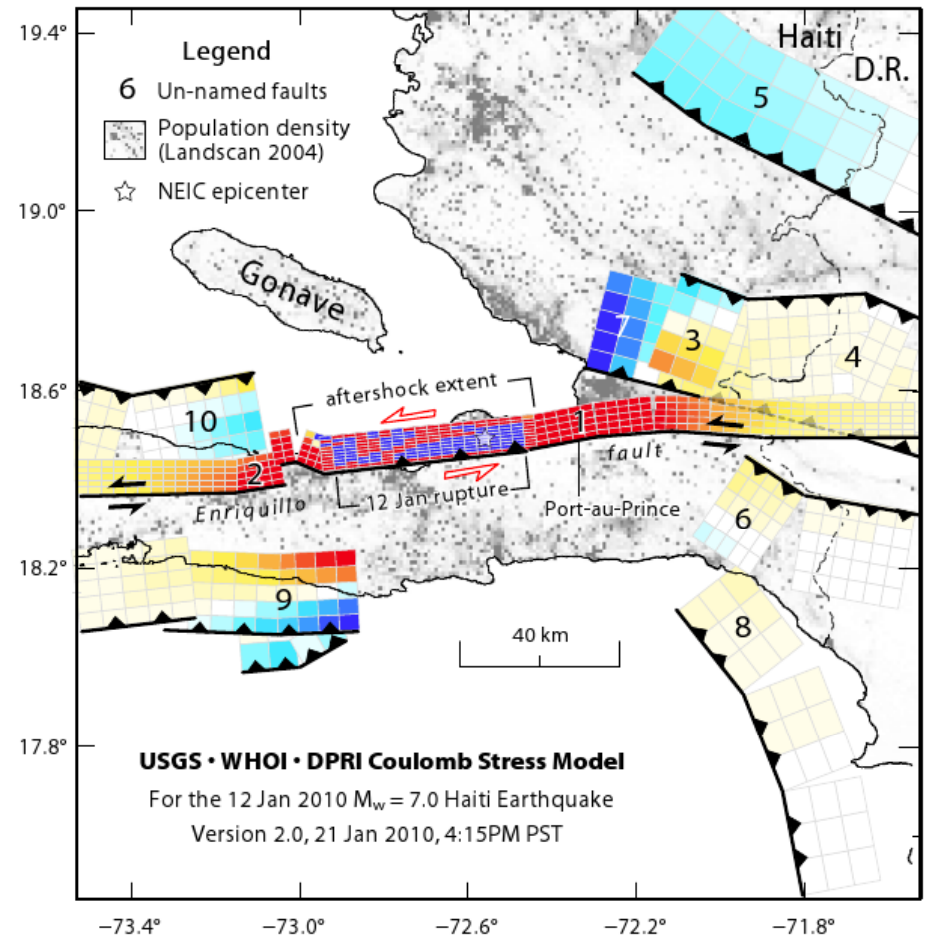


PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cms)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

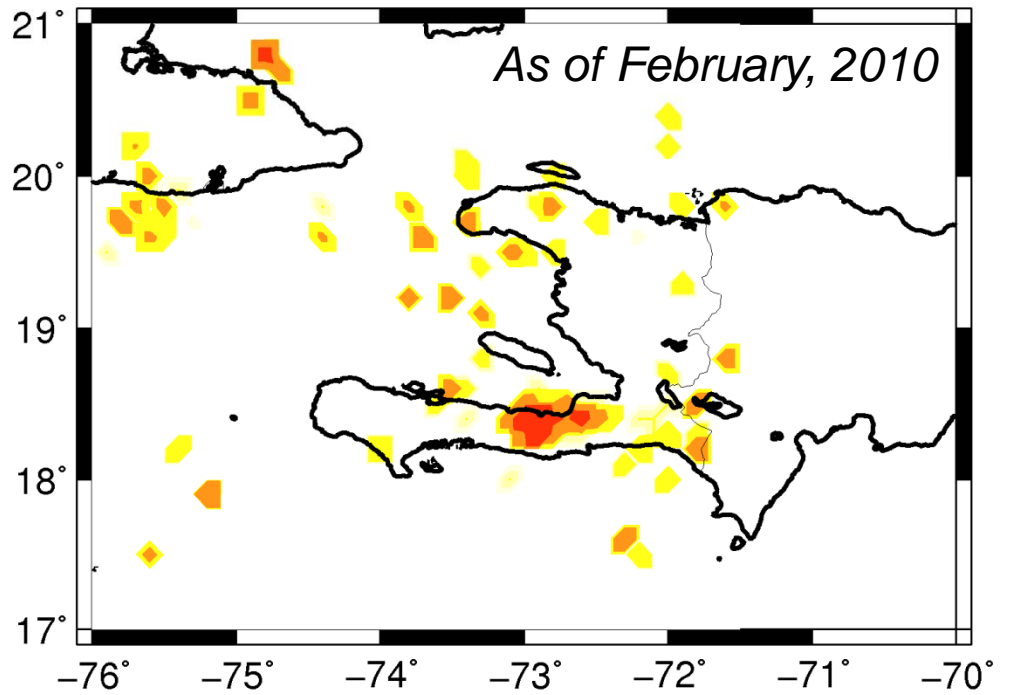
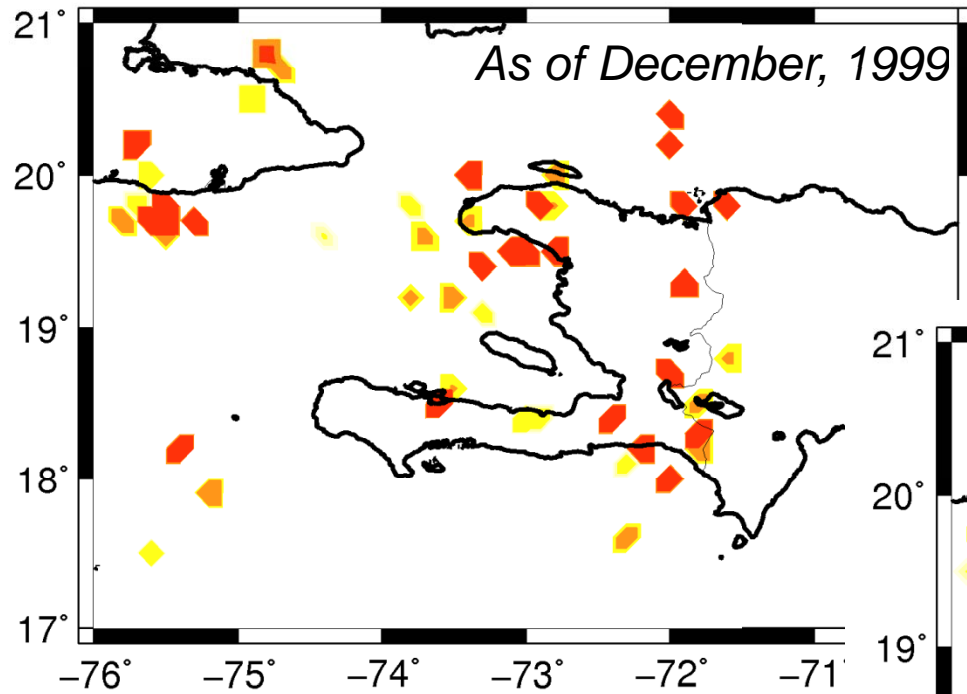
Haiti M ~ 7.0 Earthquake, January 12, 2010



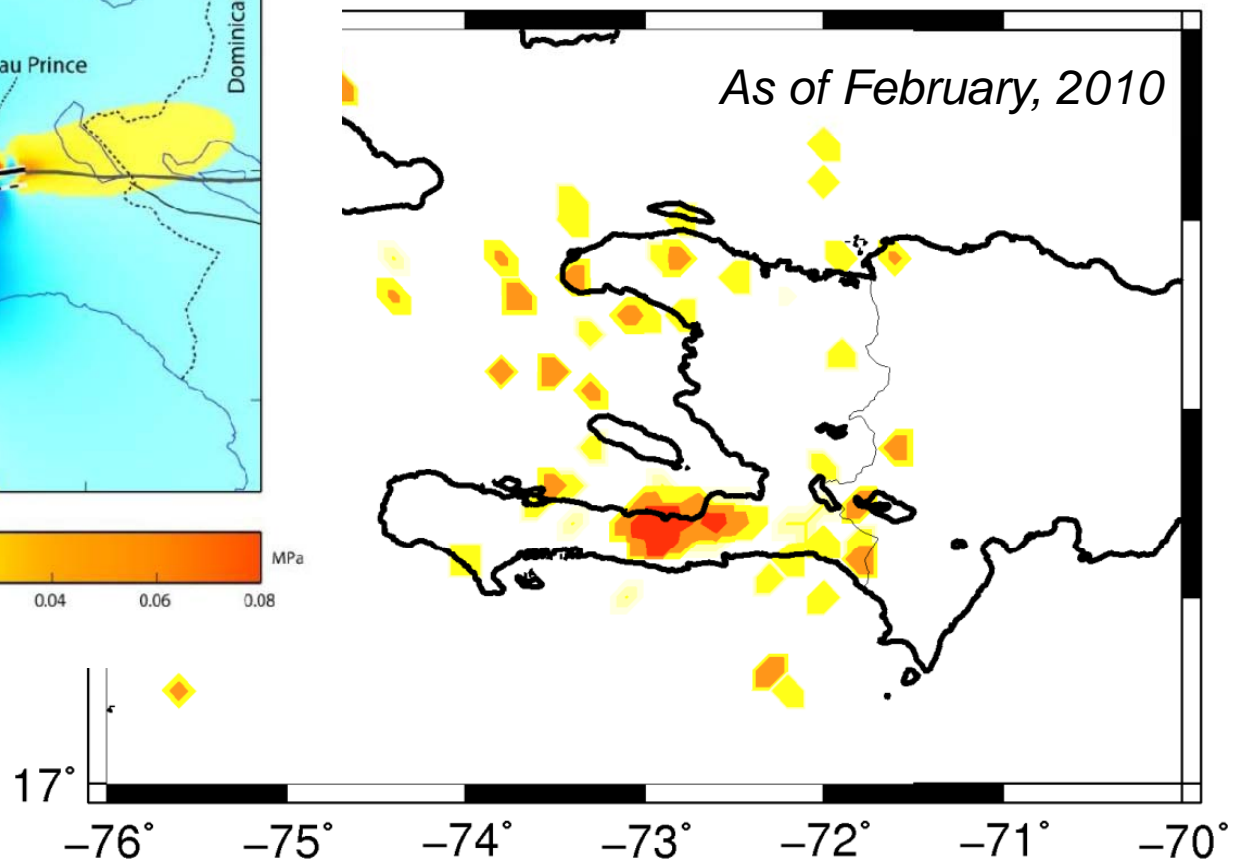
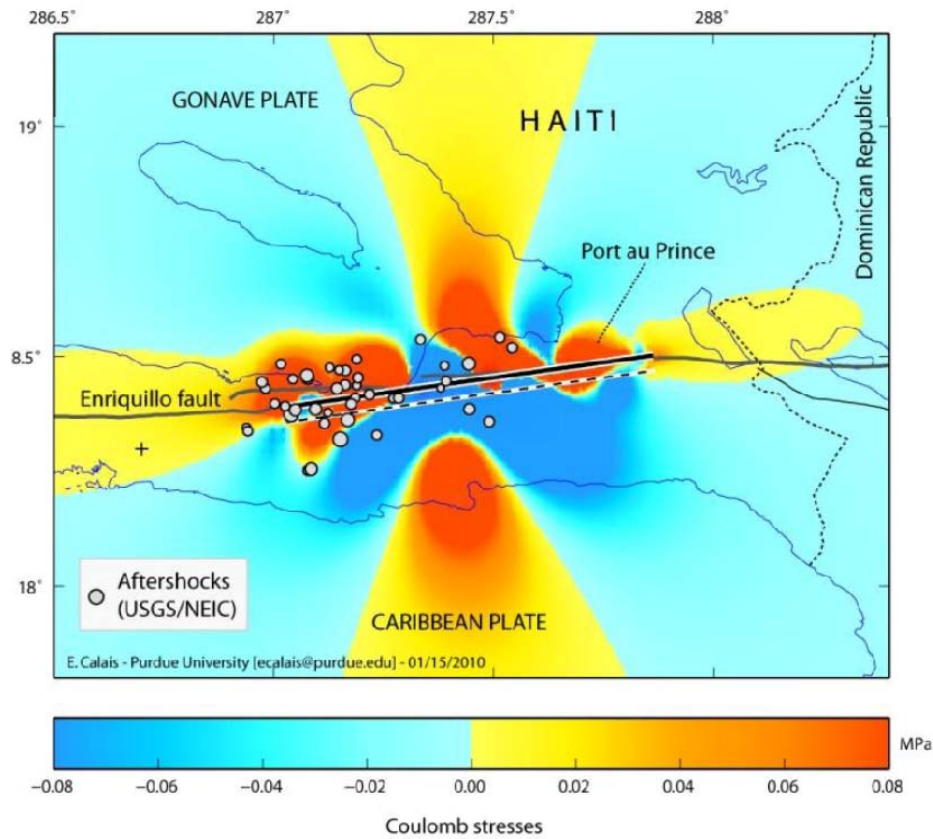
USGS, 2010



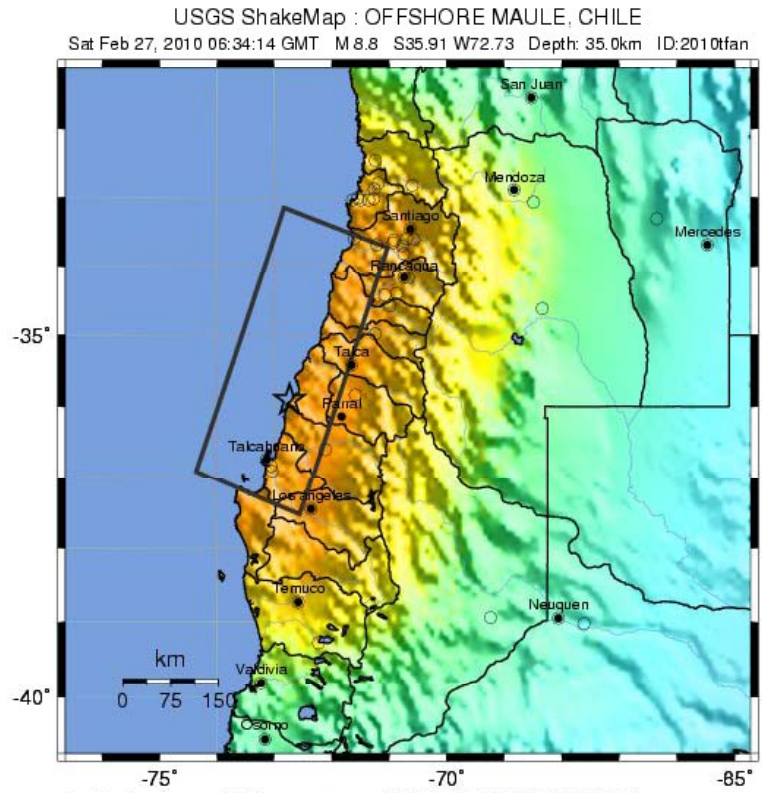
PI Forecast, Haiti, 2010



Stress Triggering and P_f

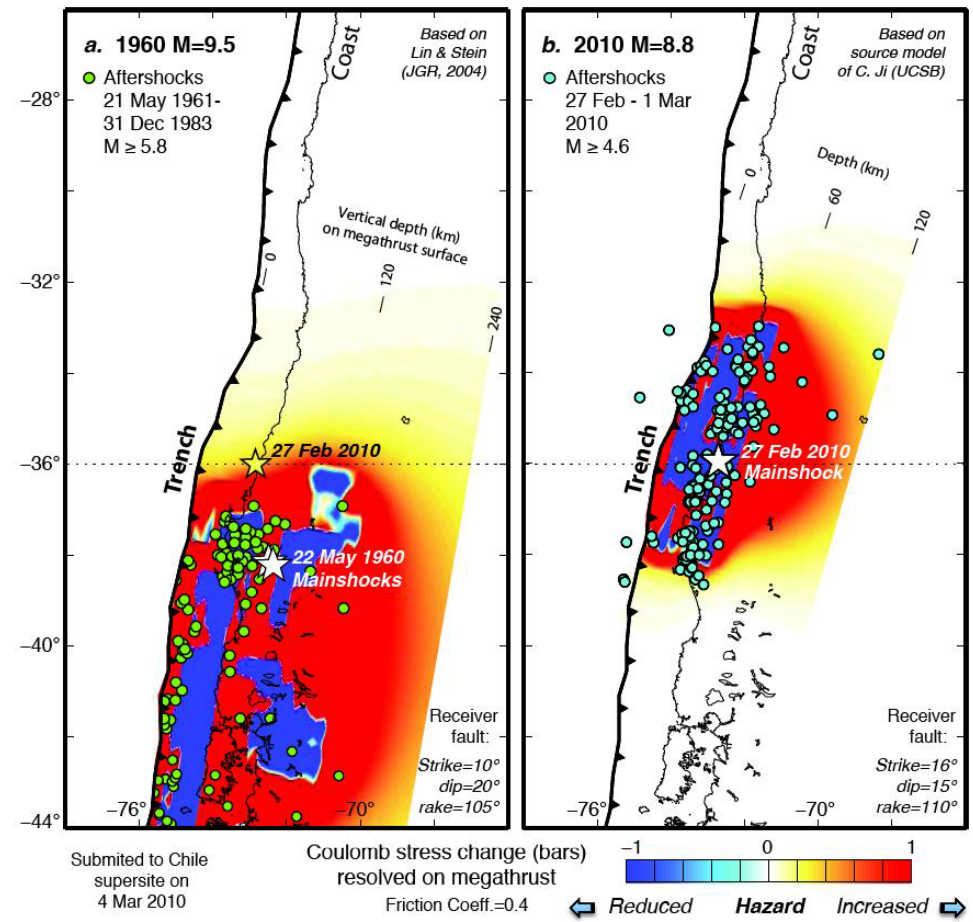


Maule Earthquake, Chile, $M \sim 8.8$ February 27, 2010



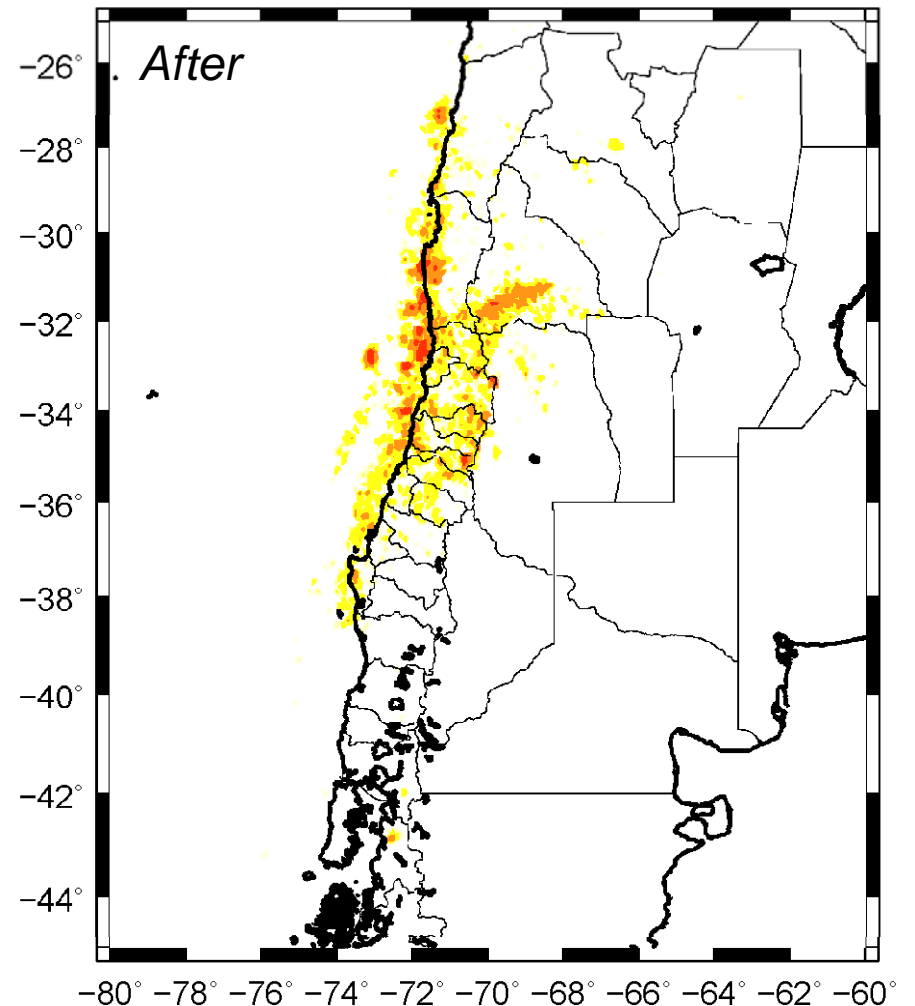
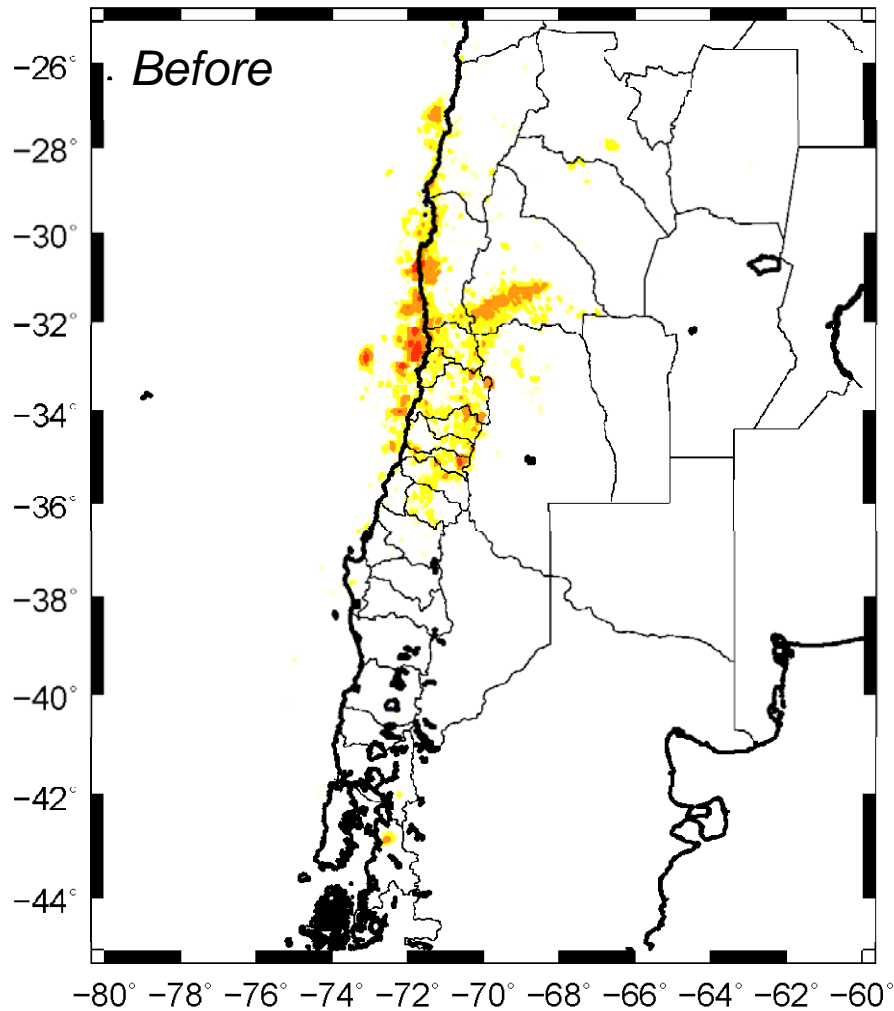
PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy	
PEAK ACC.(%)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

1960 earthquake brings the site of the 2010 rupture 0.5 bar closer to failure

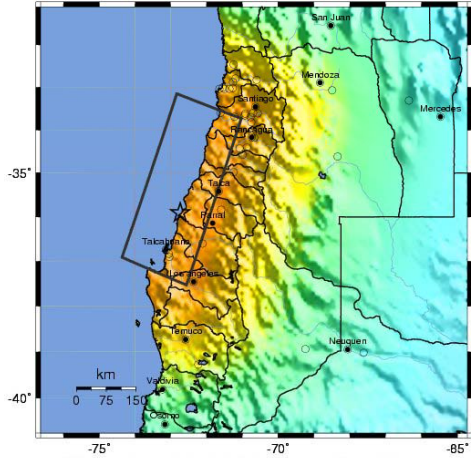


J. Lin (WHOI), R. Stein (USGS) & S. Toda (Kyoto U)

PI Analysis, Maule Earthquake, Chile

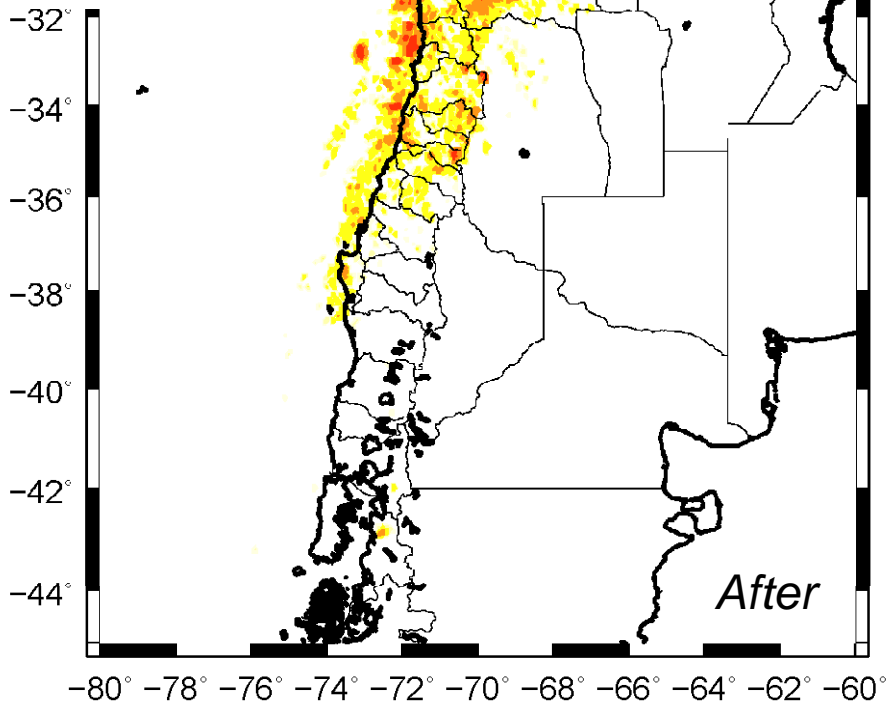


USGS ShakeMap : OFFSHORE MAULE, CHILE
 Sat Feb 27, 2010 06:34:14 GMT M 8.8 S39.91 W72.73 Depth: 35.0km ID:2010ftan

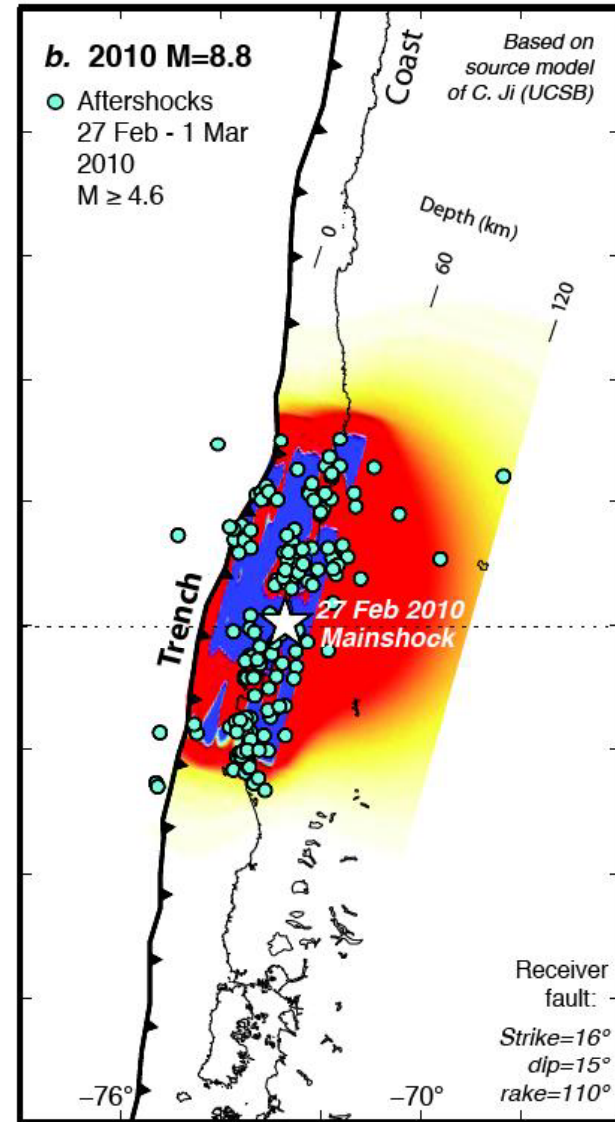


Map Version 7 Processed Fri Mar 5, 2010 03:00:13 AM MST -- NOT REVIEWED BY HUMAN

PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy	>124
PEAK ACC.(g)	<.17	.17-1.4	1.4-2.0	2.0-2.8	2.8-3.4	3.4-6.1	6.1-16	16-31	>31
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-18	18-31	31-60	60-118	>118
INSTRUMENTAL DAMAGE	I	II-III	IV	V	VI	VII	VIII	IX	X+



Stress Triggering and PI Analysis

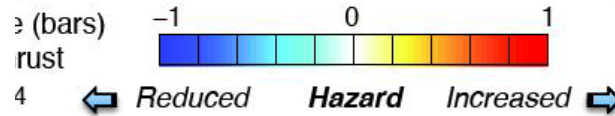


b. 2010 M=8.8

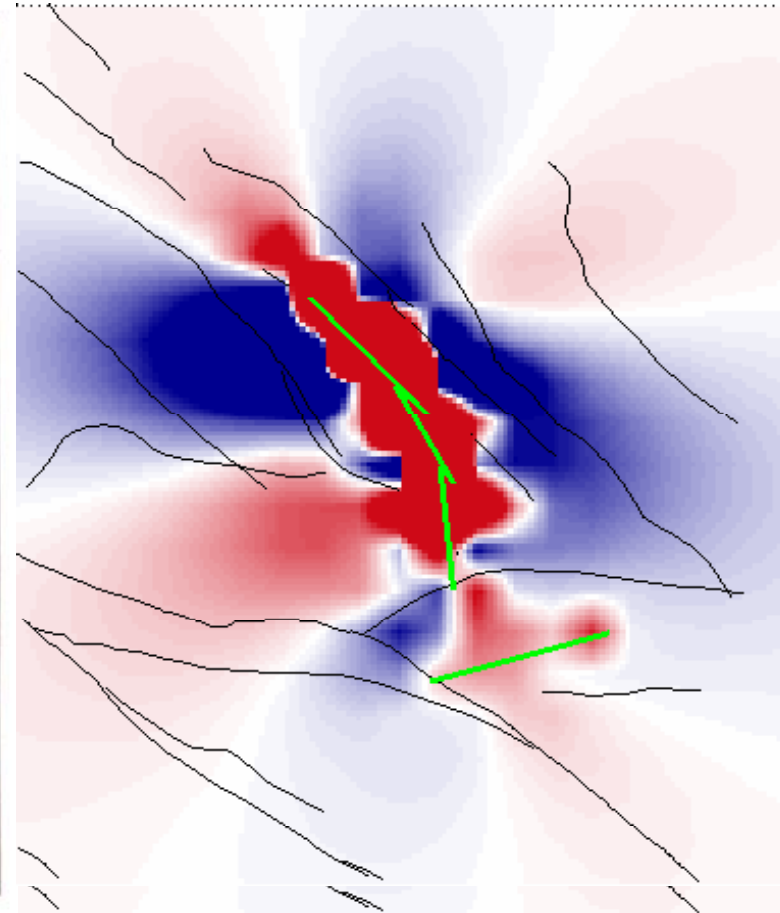
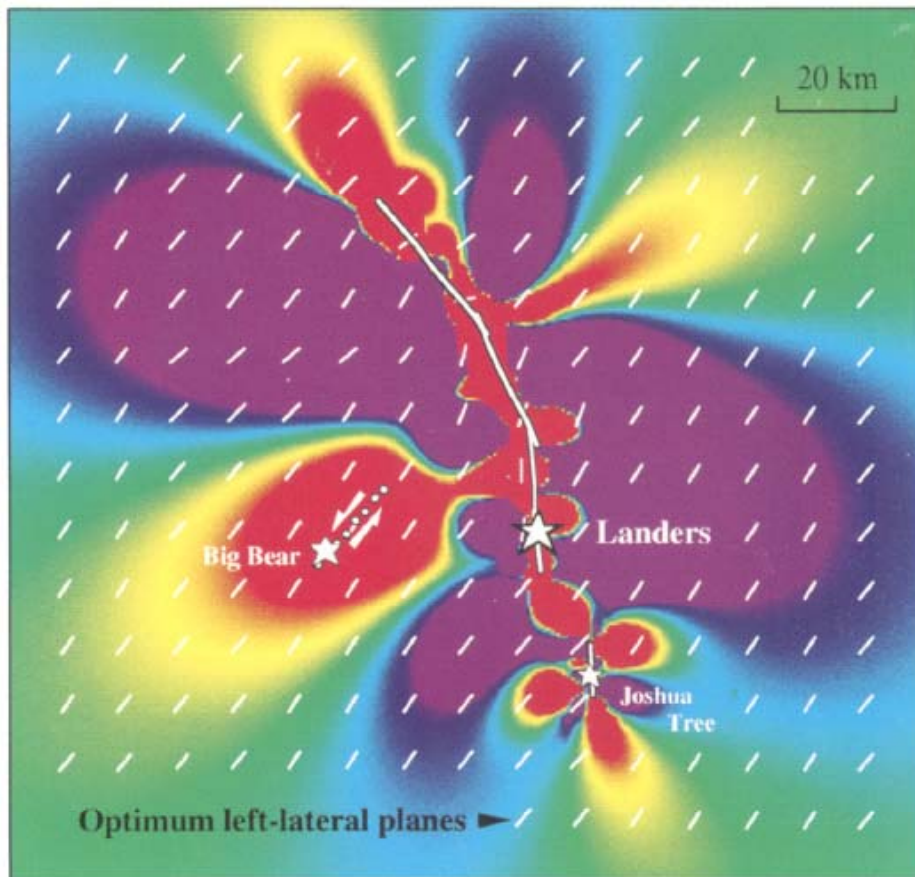
● Aftershocks
 27 Feb - 1 Mar
 2010
 M ≥ 4.6

Based on
 source model
 of C. Ji (UCSB)

J. Lin (WHOI), R. Stein (USGS) & S. Toda (Kyoto U)



Detailed Aftershock Studies Using PI Analysis

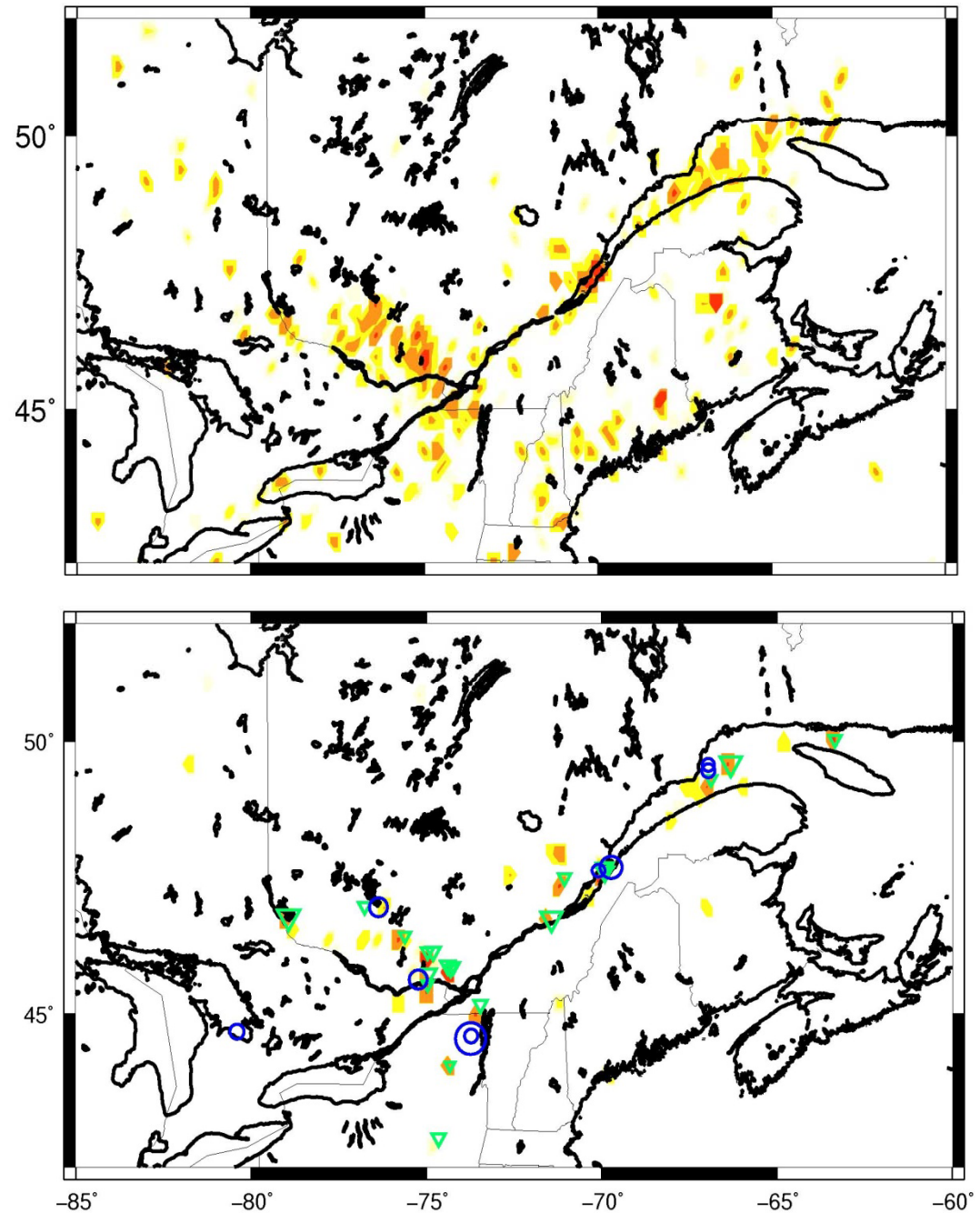


On the left are shown Coulomb stress changes for the 1992 Joshua Tree and Landers earthquakes from King et al. (1994).

On the right are shown Coulomb stress changes after an inversion of PI results calculated for 0-20 days after the event (C. Latimer)

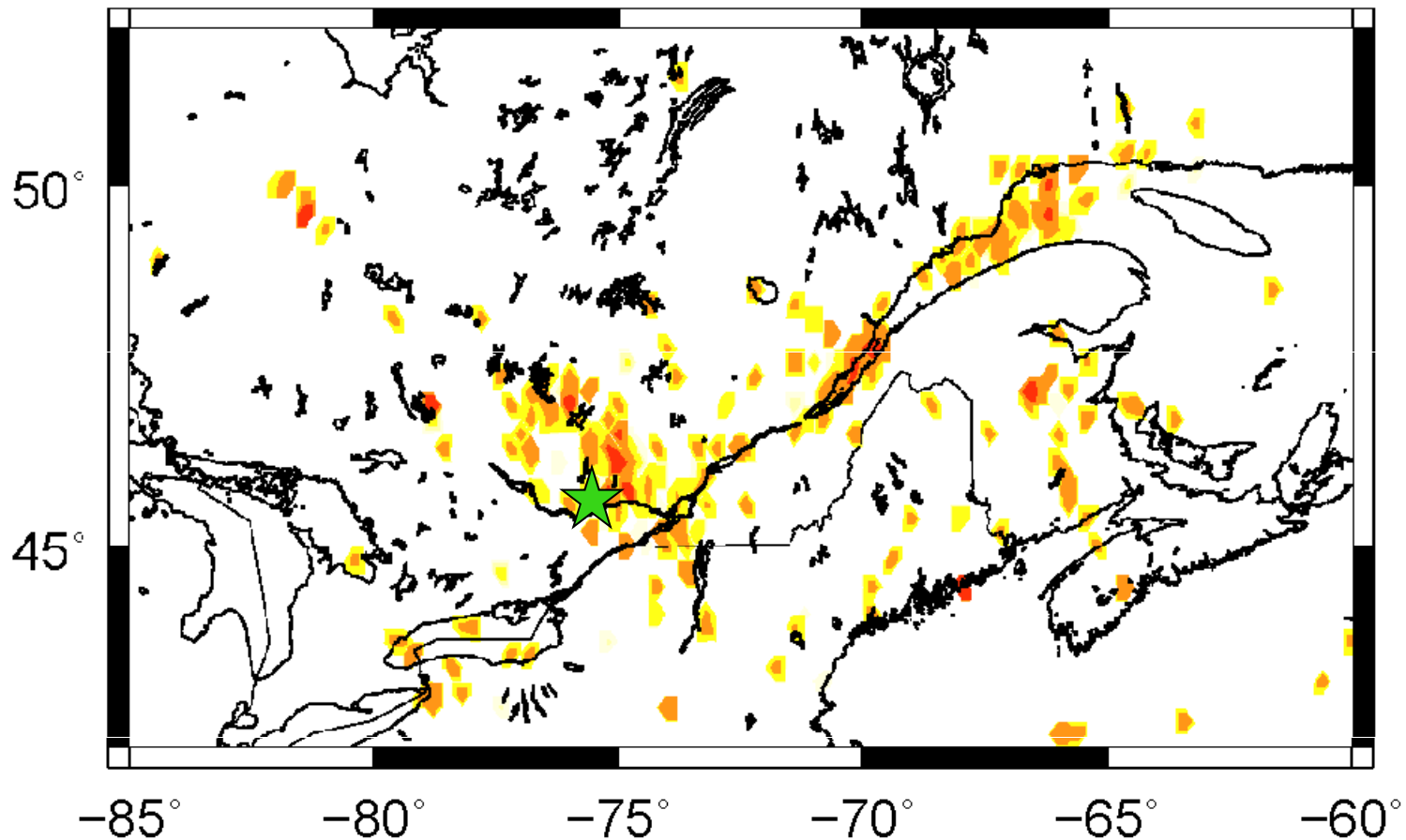
PI Index Eastern Canada

- PI forecast for eastern Canada, 2002-2012. On the top is a forecast for $M \geq 3$, at the bottom is shown the same forecast for $M \geq 4$.
- Note that we have significantly decreased the false positive rate shown at the top.

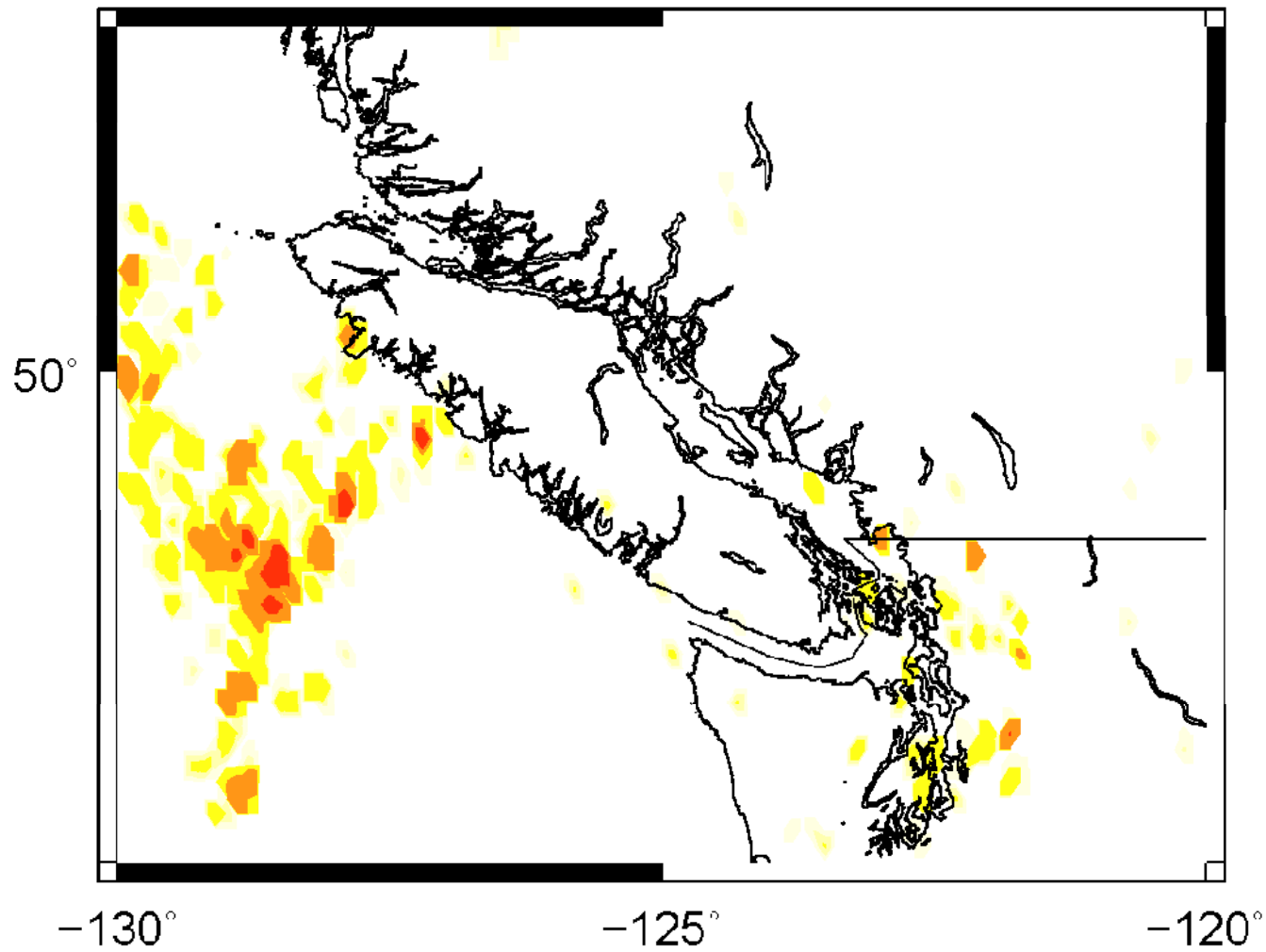


Ottawa Earthquake, June 2010, $M \sim 5.0$

PI forecast for eastern Canada, 2009-2014. The location of the Ottawa earthquake is shown with a star.



PI Forecast, Western Canada 2009-2018



Summary

- The important contributions of those who worked in the fields of statistical seismology, earthquake forecasting, and pattern recognition led to the PI method, the first small magnitude seismicity method to quantify time-dependent earthquake hazard.
- The outgrowth of additional seismicity-based forecasting methods after the publication of the prospective earthquake forecast in 2002 has resulted in a new and significant investment in forecasting assessment methodologies, including the Collaboratory for the Study of Earthquake Predictability (CSEP).
- Ongoing studies support the hypothesis that small magnitude seismicity is a proxy for underlying stress change and can be interpreted as a precursor to larger events, in many cases.
- The PI index can provide additional information over and above standard stress triggering studies in order to provide a better understanding of the short and long-term hazard following a significant earthquake.