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

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- 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 that are not properly prepared, such as Haiti.

*http://www.boston.com*

# *Haiti Earthquake*

**M ~ 7, Feb. 27. 2010**

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

*http://www.usgs.com*

# *Maule Earthquake, Chile*

**M ~ 8.8, Feb 2010**

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

*http://www.usgs.com*

# *The Gujarat, India Earthquake*

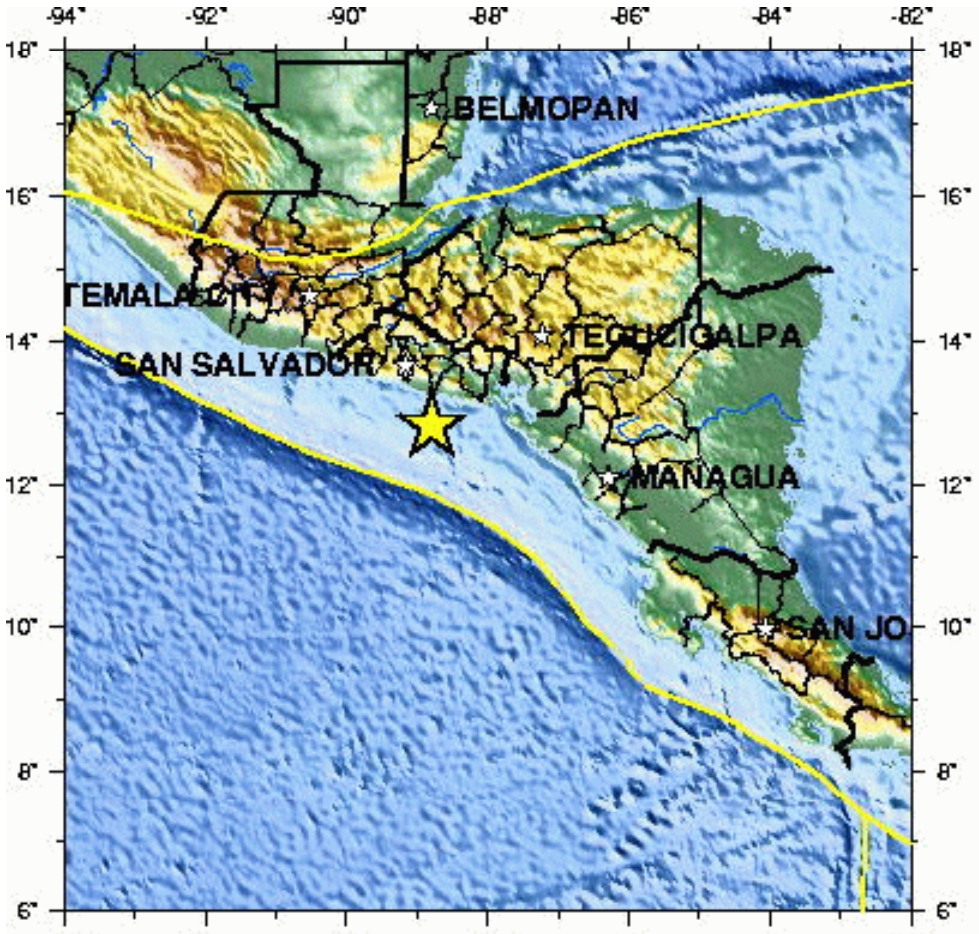
*M ~ 7.9, January 26, 2001*

*More than 30,000 persons died*

*Damages exceeded $10 billion USD*


# The January 13, 2001 El Salvador Earthquake

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




*Courtesy, USGS*

# *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

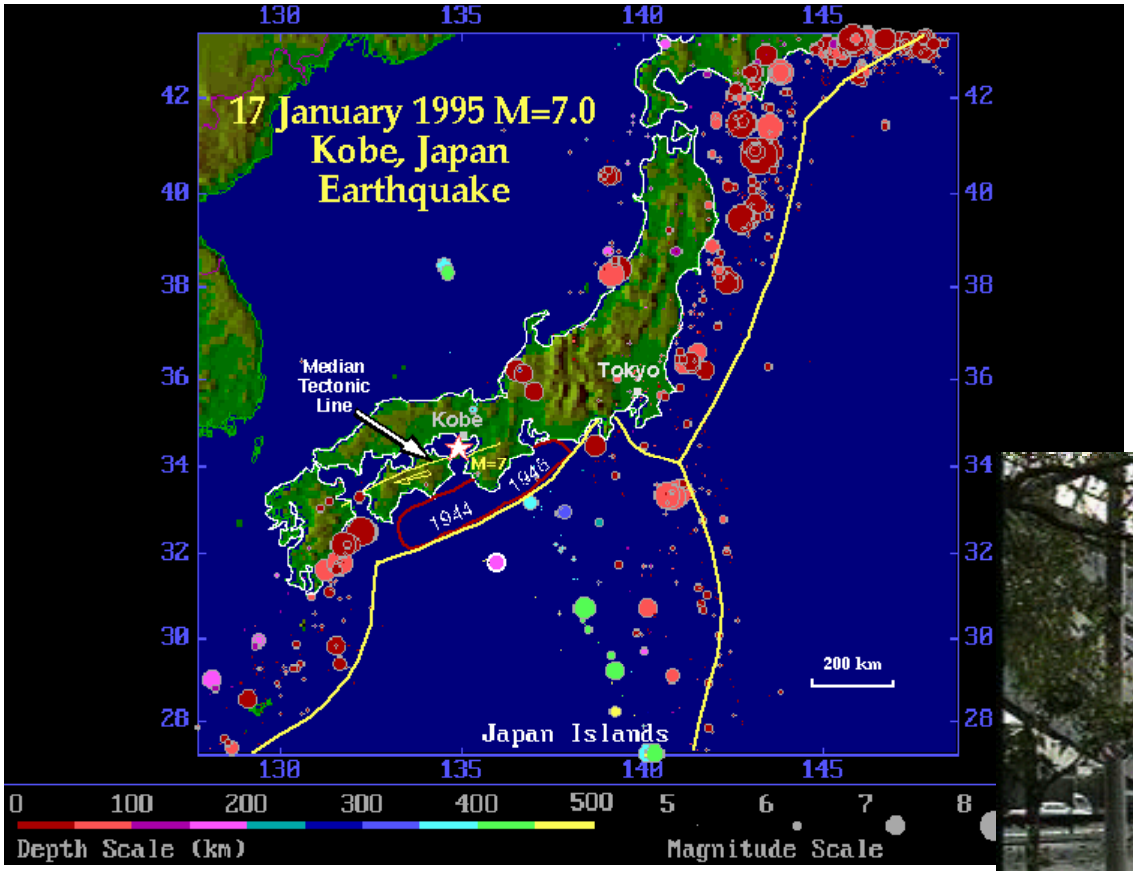


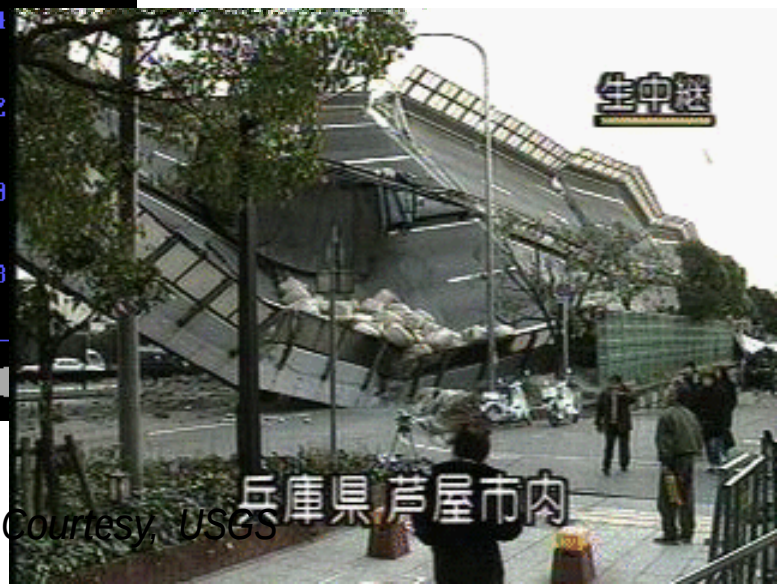
More than 30,000 persons died in the event, and damages exceed $10 Billion

# *The Kobe, Japan Earthquake*

*M ~ 7.0, January 17, 1995*

*$200 Billion in damages and ~ 5000 dead*

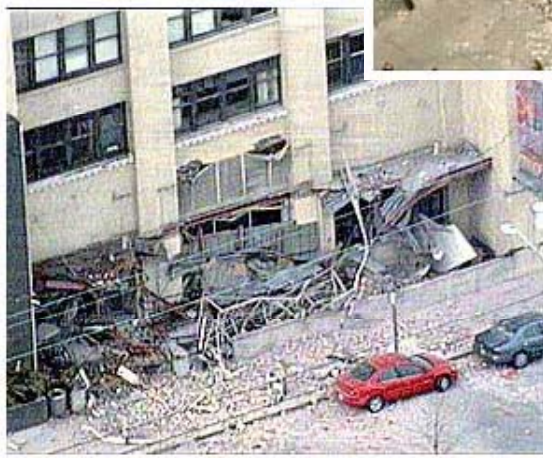



*Courtesy, USGS*

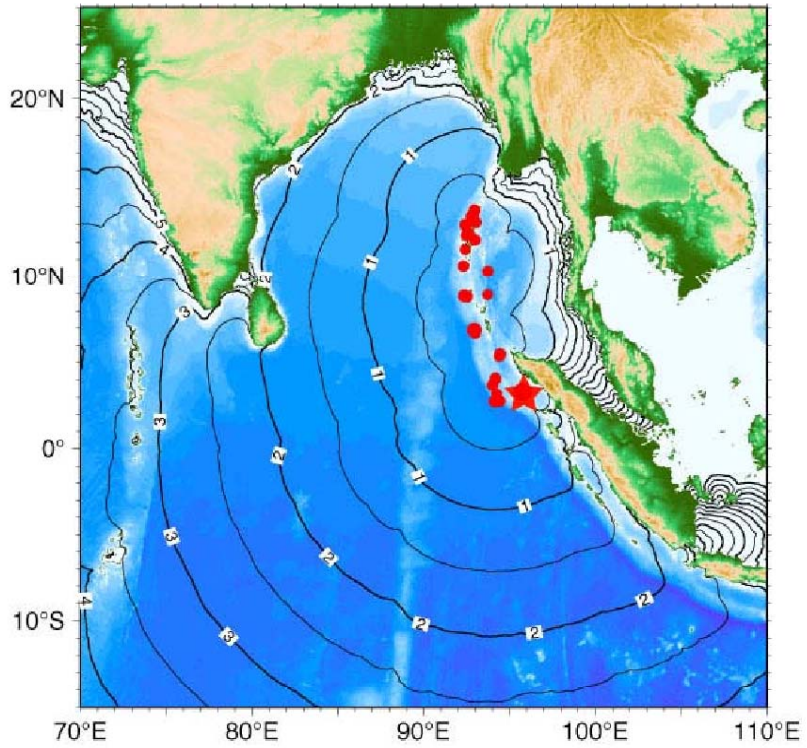
# *The Nisqually, Washington Earthquake*


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

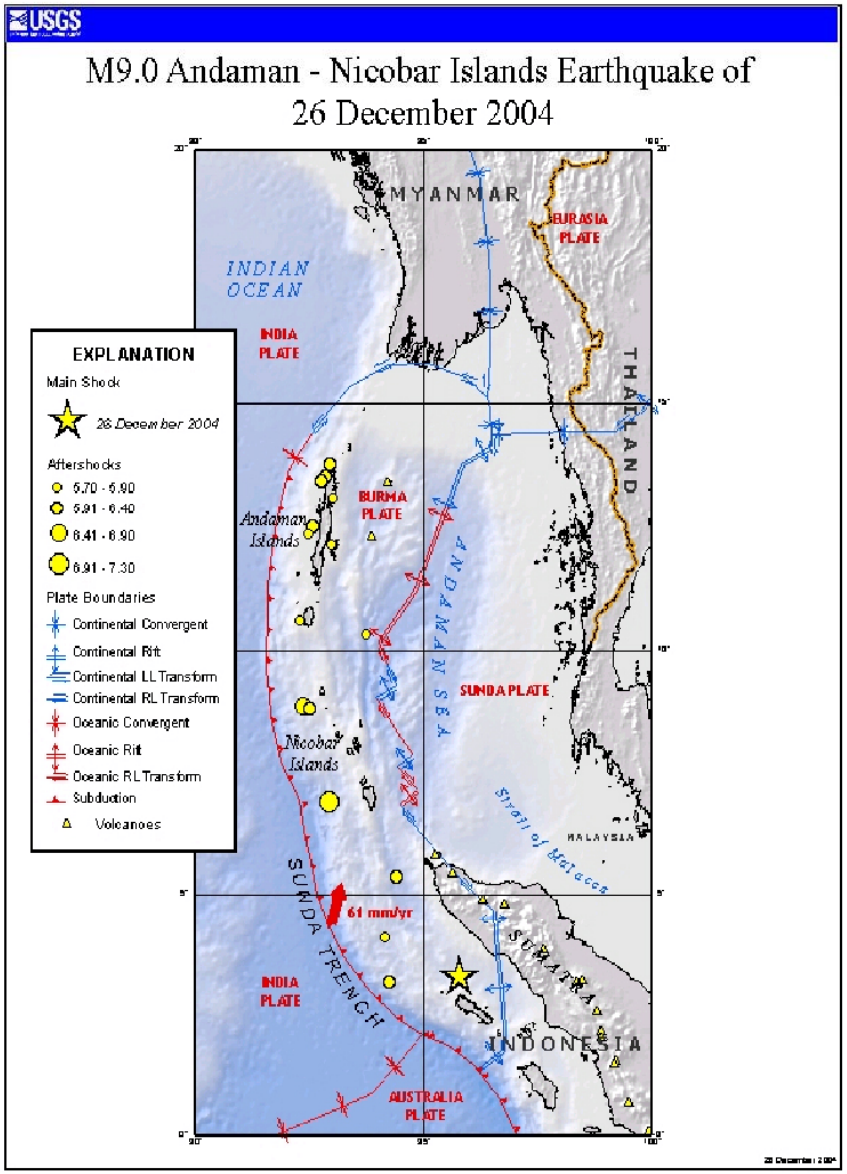


# *The Great Sumatran Earthquake & Tsunami, December 2004*

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 MECHANICS' 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.

Two unknown men, brought in autos.

OTHER DEAD

Five killed, 2 injured, in collapse of building at 230 Geary.

Frank Corali, buried, beneath basement floor of burning lodging house 5th and Mission. Heard crying "For God's sake, help me."

Seven firemen killed in collapse of brick power house Valencia and 7th.

John Wheley 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.

THEATER WRECKED

BRIEF IDEA OF DISASTER

IN OAKLAND

THIS EDITION ISSUED FROM 1008 MISSION ST. WHERE 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 Portugese 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*

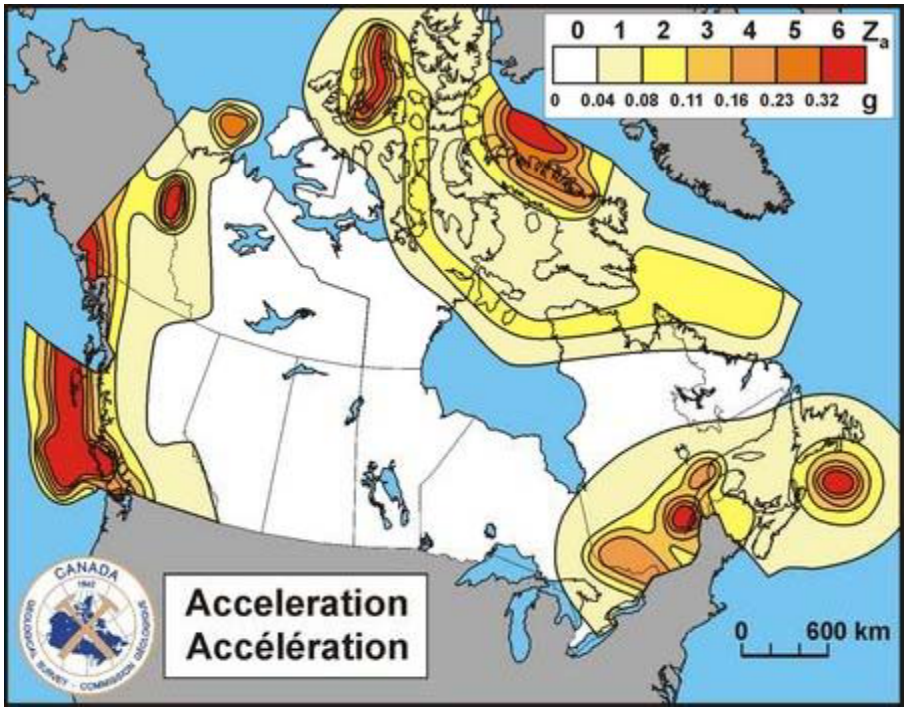
- Hazard maps are widely used to characterize the likelihood of any given region undergoing shaking due to a large earthquake. Hazard maps, however, are not considered earthquake forecasts, but rather a tool for planners, engineers, and emergency managers.
- Forecasts provide a probability of an earthquake 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.

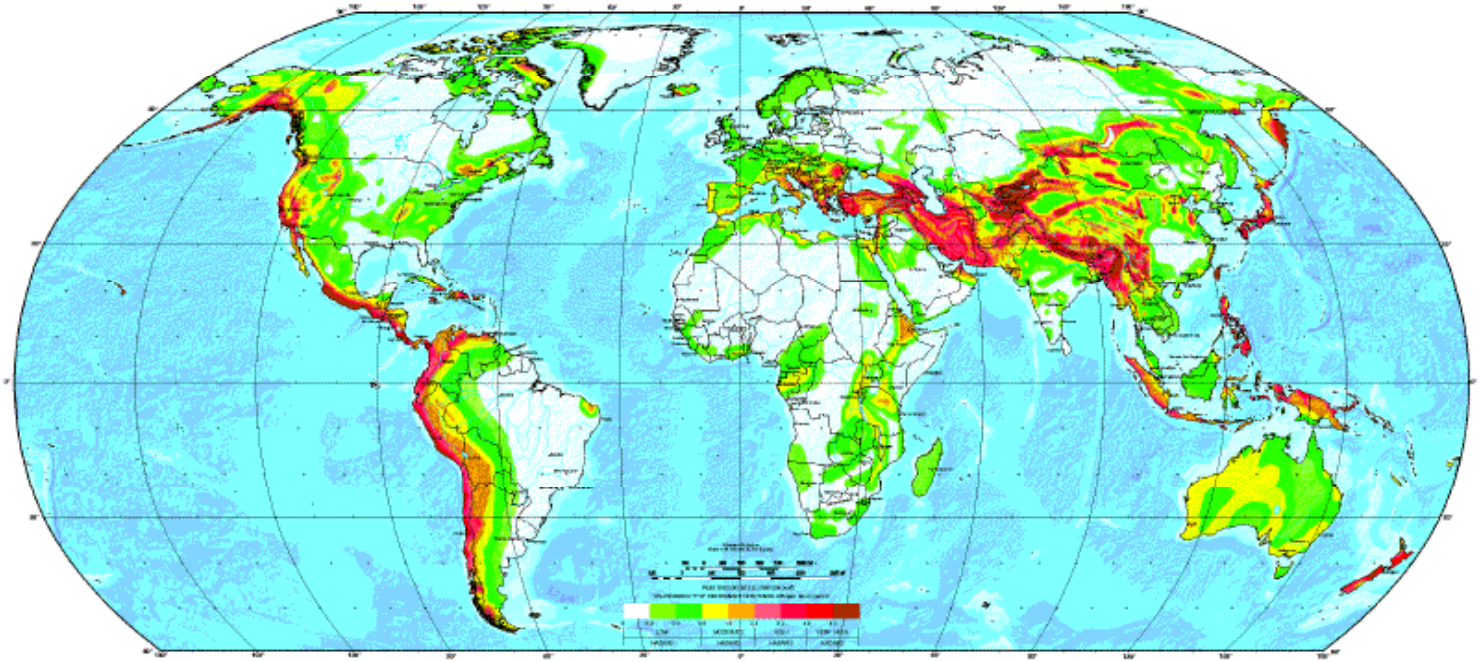
# *Hazard Maps*

Compiled based on historic seismicity records

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

Courtesy NRCAN

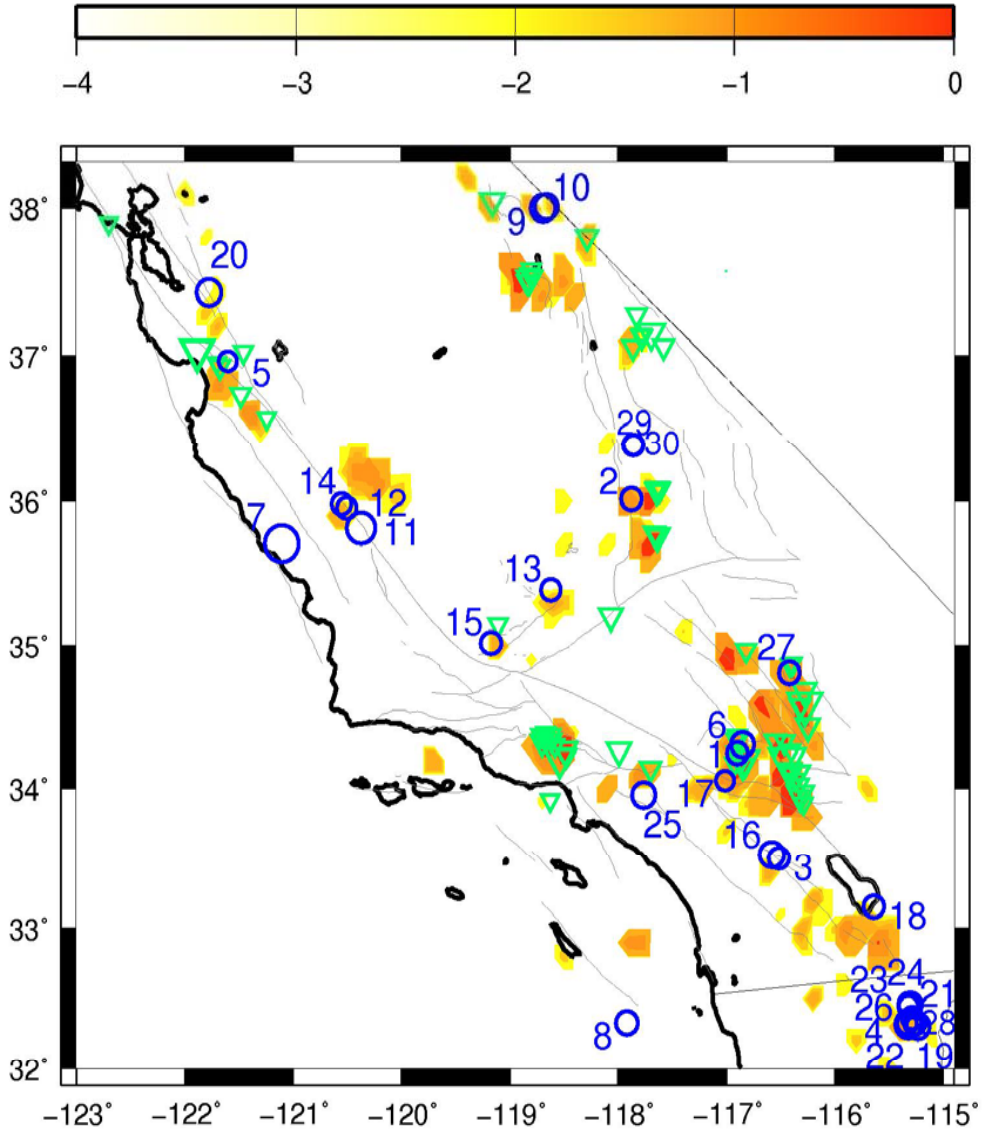


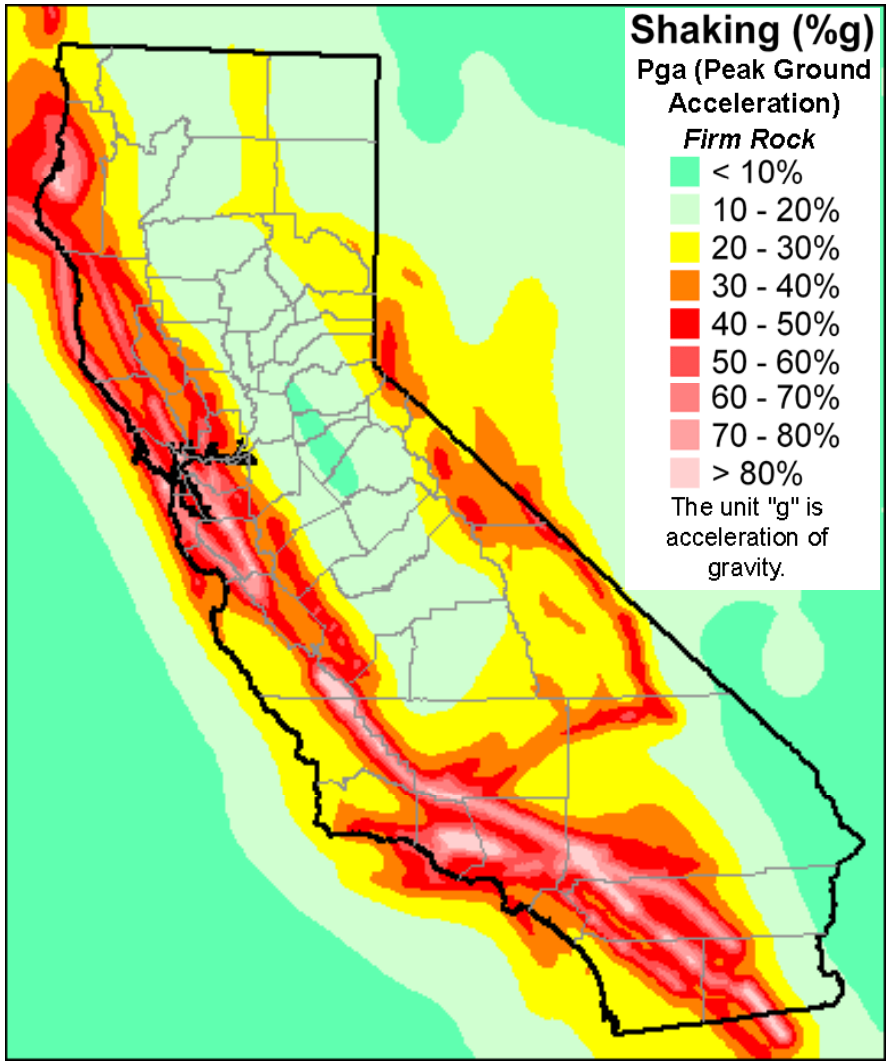
**Left: Seismic Hazard, Low to High, 1999**

Courtesy Global Seismic Assessment Program

# Forecast vs. Hazard



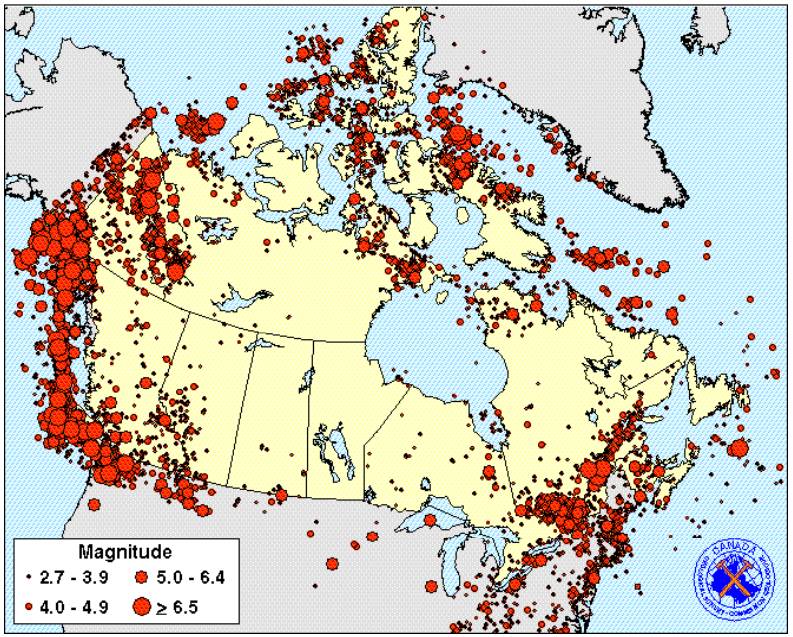

*10-year forecast for earthquakes of M > 5.0, 2000 to 2010*

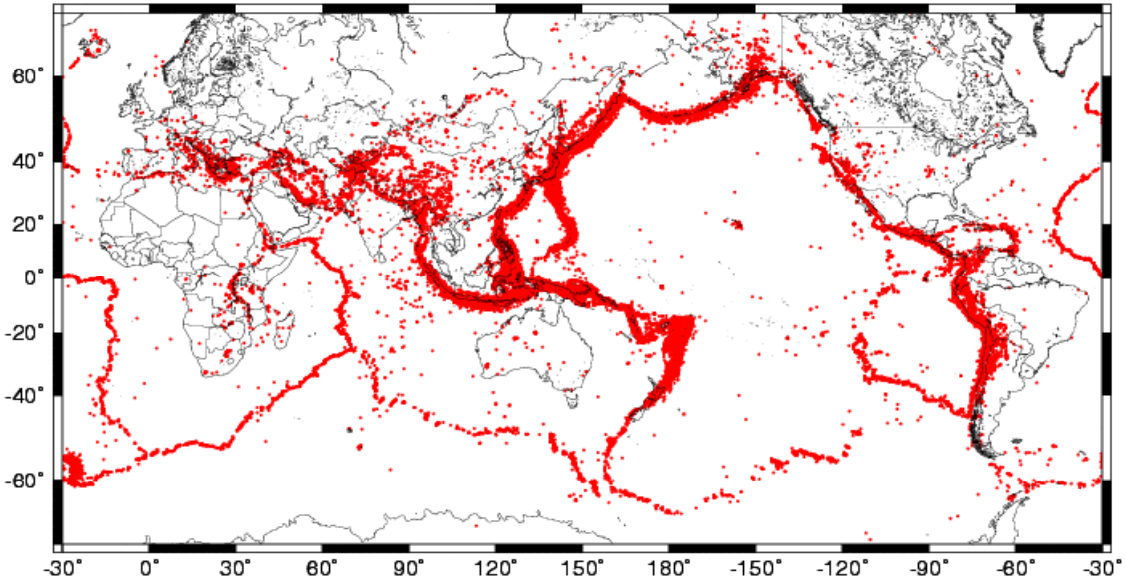



*10% Probability of Exceedance in 50 years.*
*http://www.consrv.ca.gov/CGS/rghm/psha/index.htm*

# *Earthquake Catalogs*

Canadian Seismicity, 20th c.
Courtesy NRCan



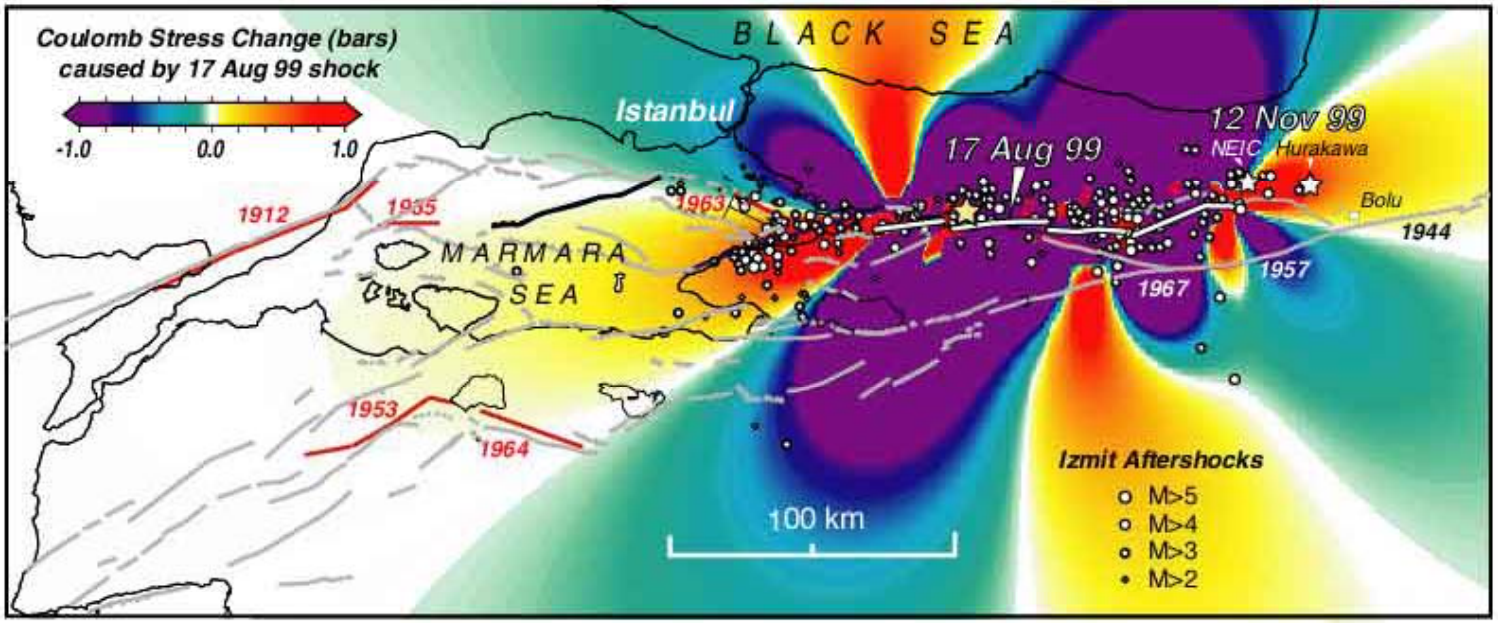

Worldwide Seismicity,
M>5, 1980-2000

# *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 ~ 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.*

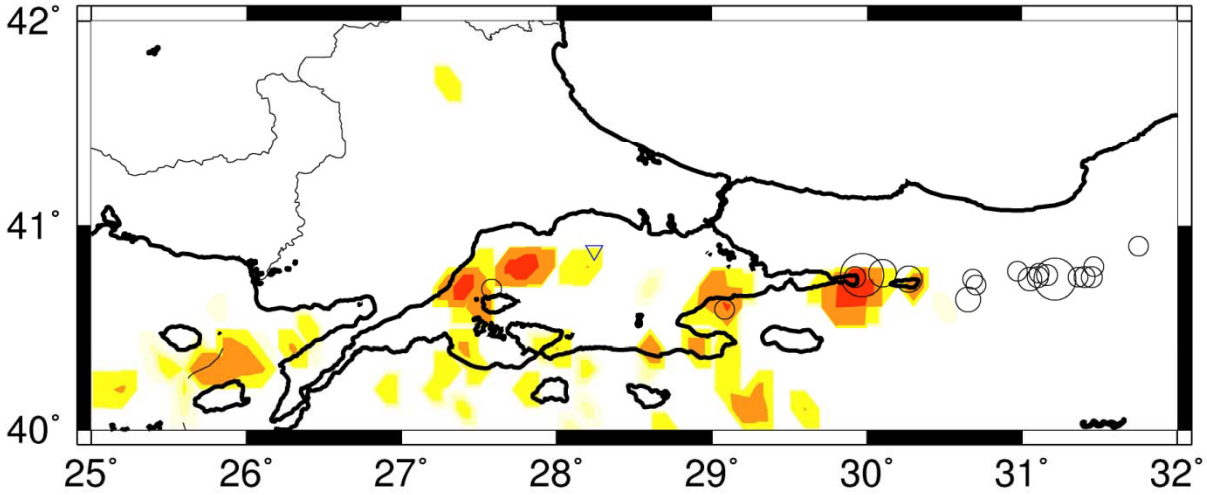



*Calculations by Shinji Toda (ERI), Tom Parsons & Ross Stein (USGS)*

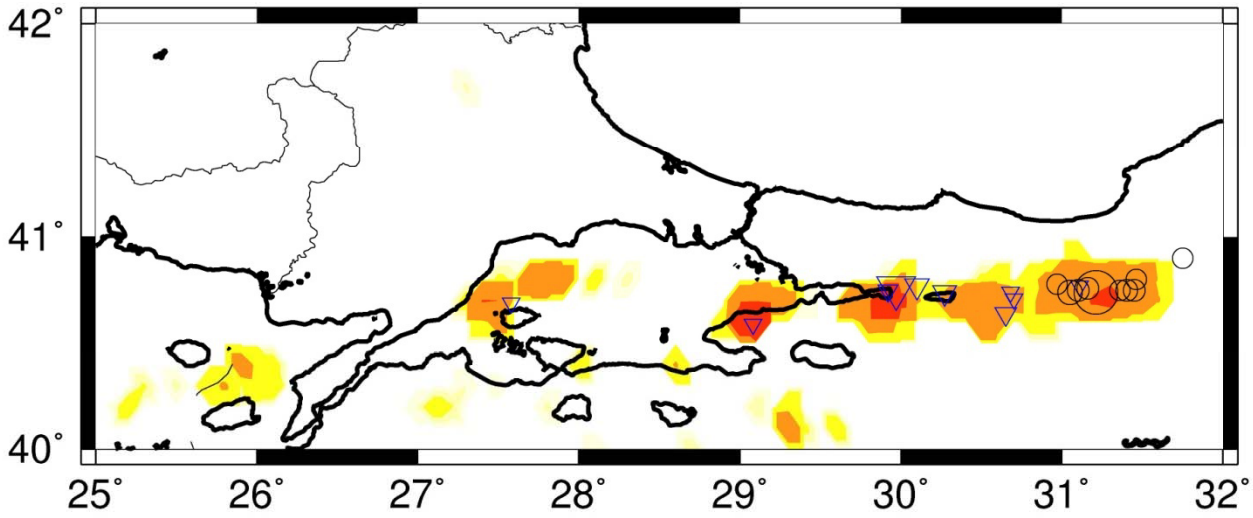
***Izmit & Duzce Earthquakes, Fall 1999***

# *Can we link, or compare, the two techniques?*

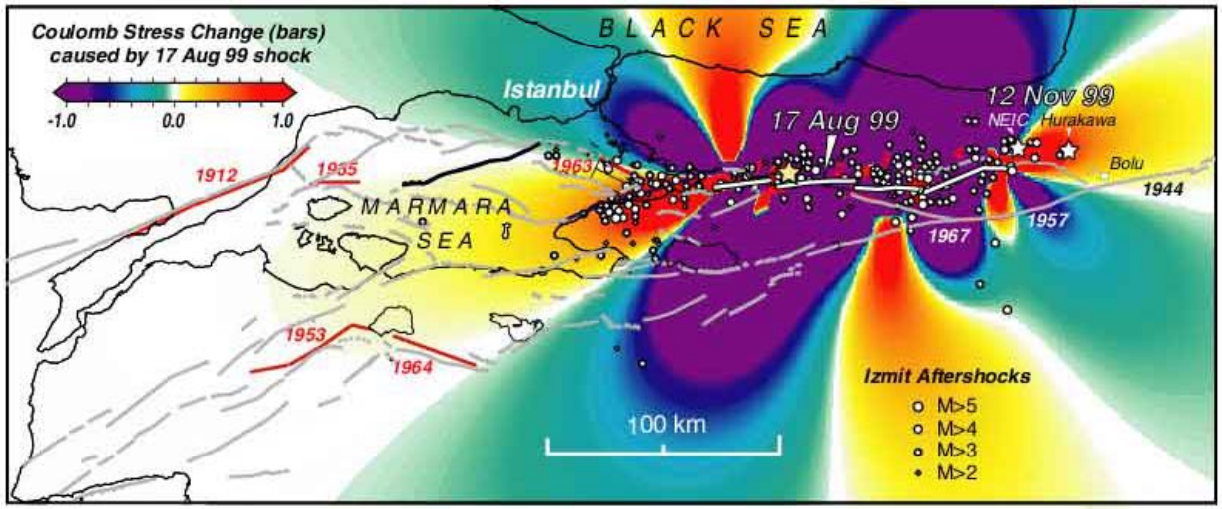
PI: Through December,1998



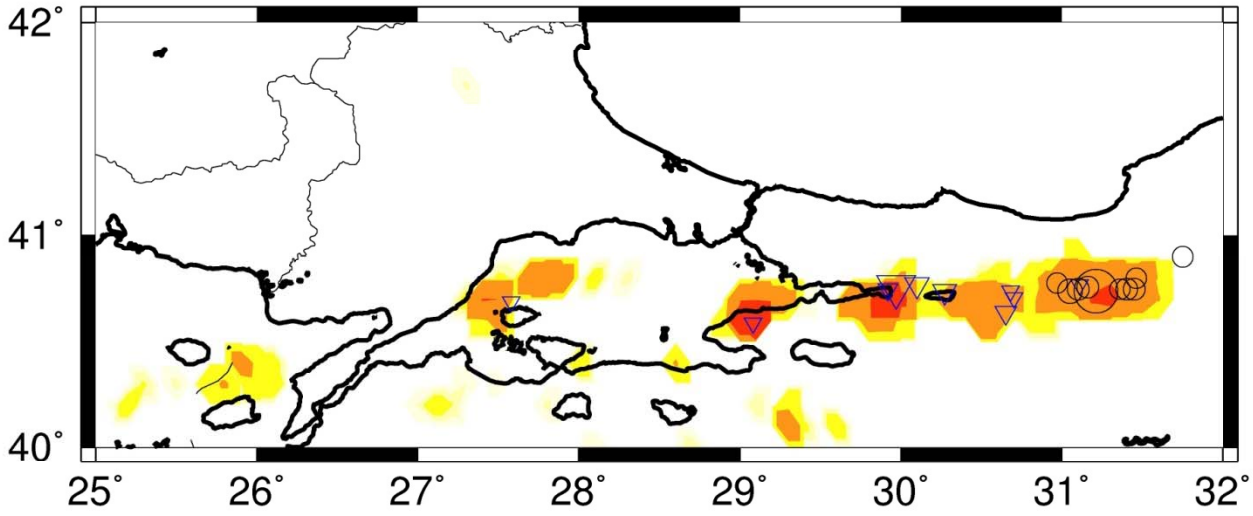

PI : Through October, 1999



# *Can we link, or compare, the two techniques?*




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



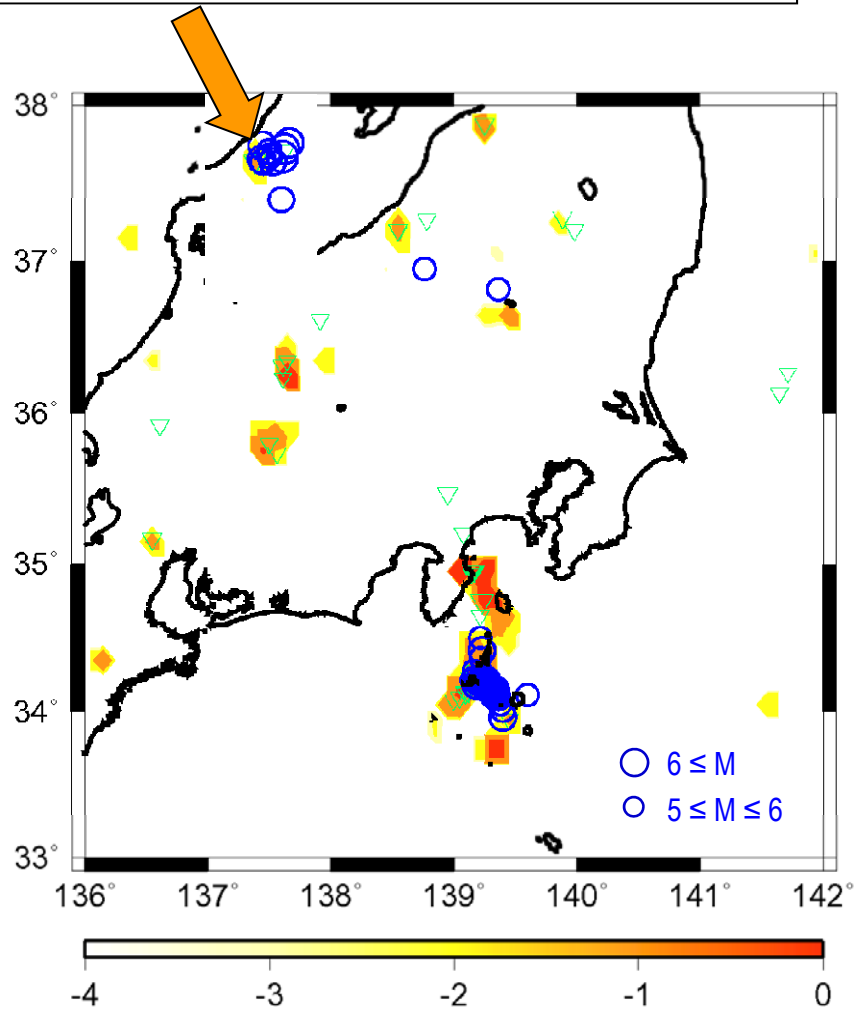

PI : Through October, 1999

# *Japan*

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

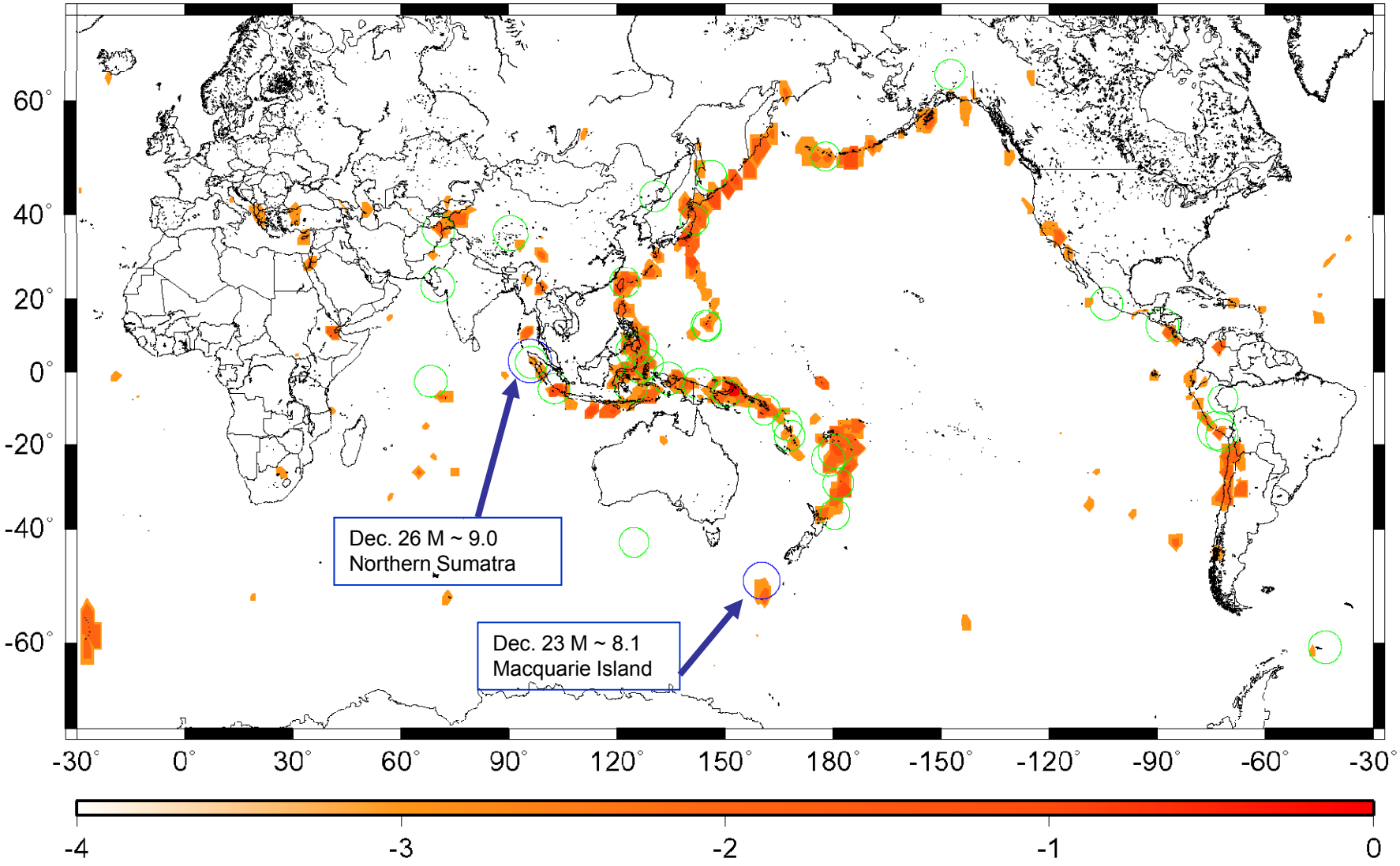
***Forecast for the period: January 1, 2000 ~ December 31, 2010.***

- 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 ≥ 5 are shown (arrow).
- The image at right was shown during lectures in Japan on October 13 & 14, 2004.

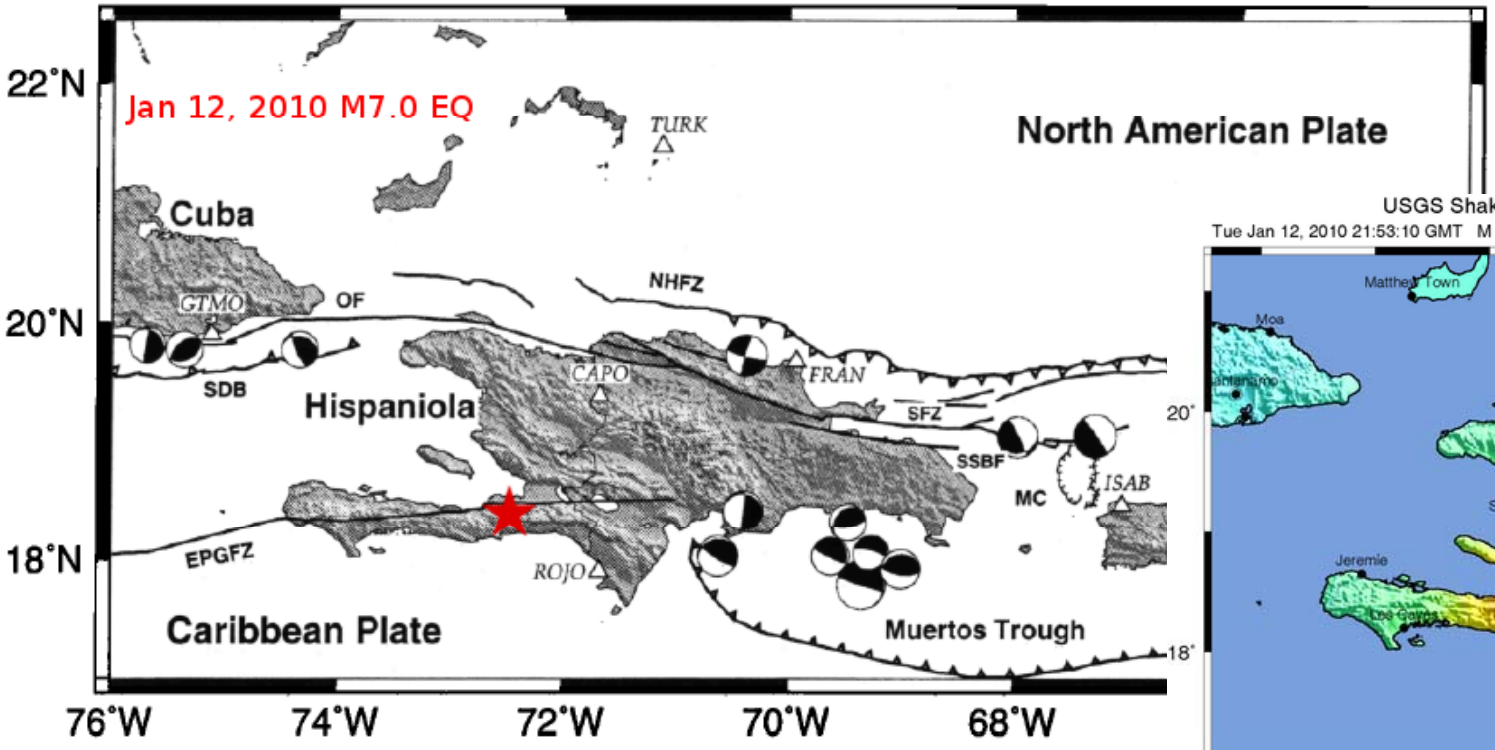


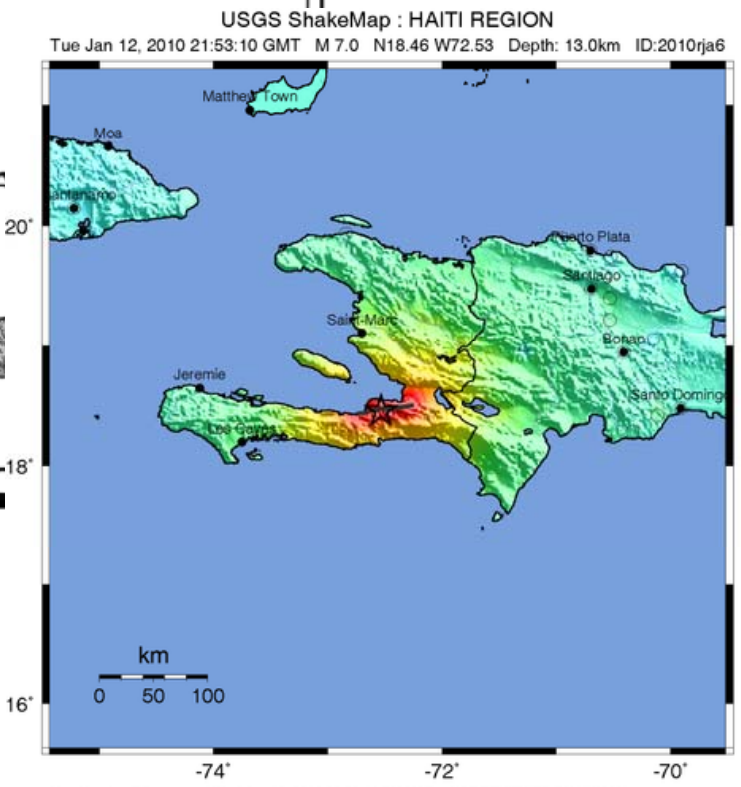
# *World-Wide PI Map for M ≥ 7*
# *2000-2010*

Courtesy J. Holliday, from November 2004



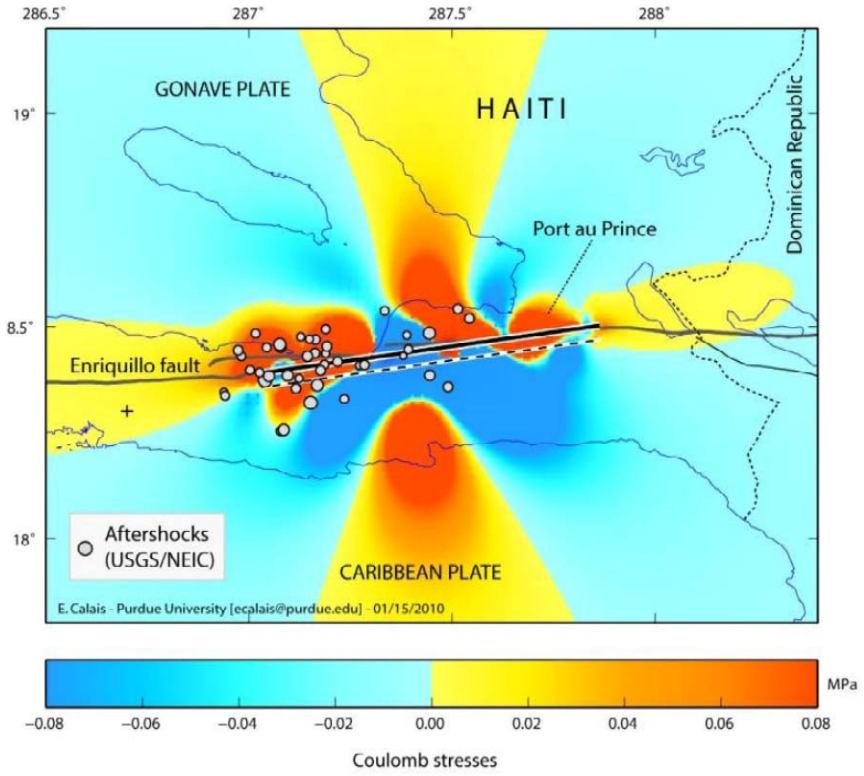
# *Haiti M ~ 7.0 Earthquake, January 12, 2010*

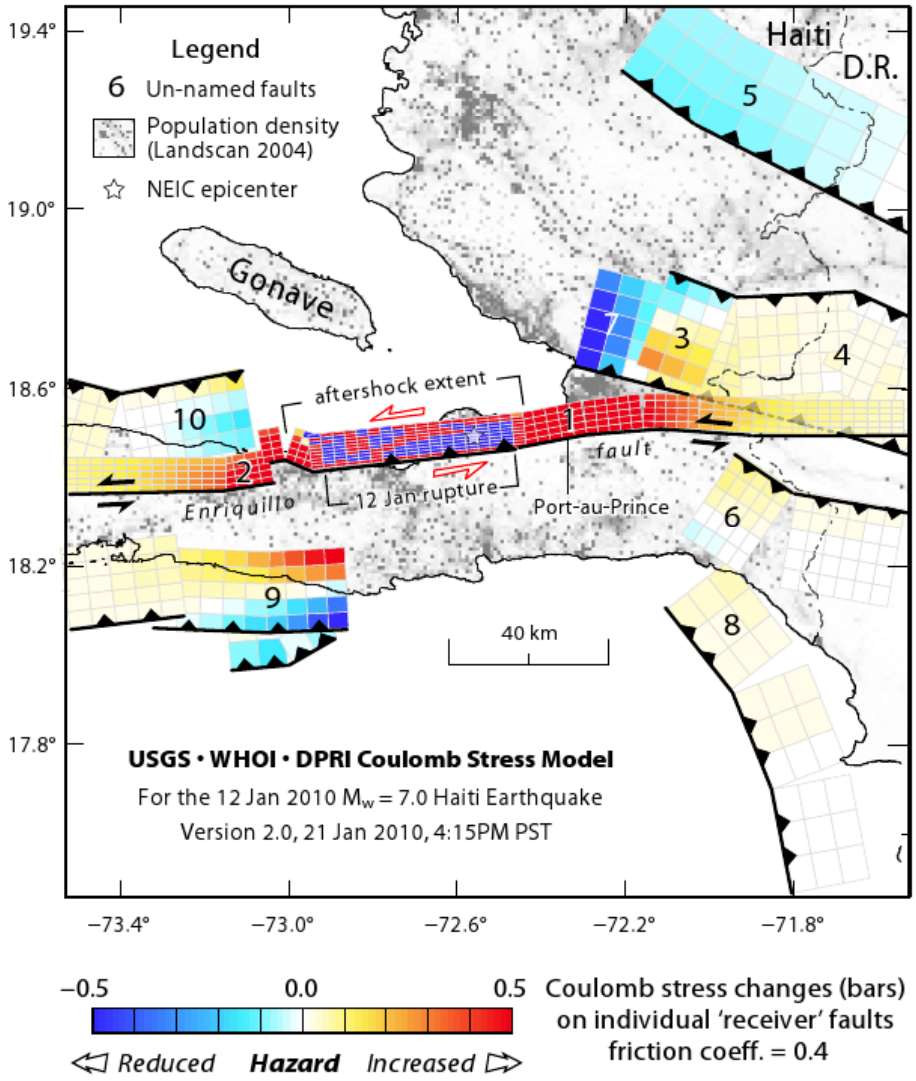



| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | *<.17* | *.17-1.4* | *1.4-3.9* | *3.9-9.2* | *9.2-18* | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(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+ |

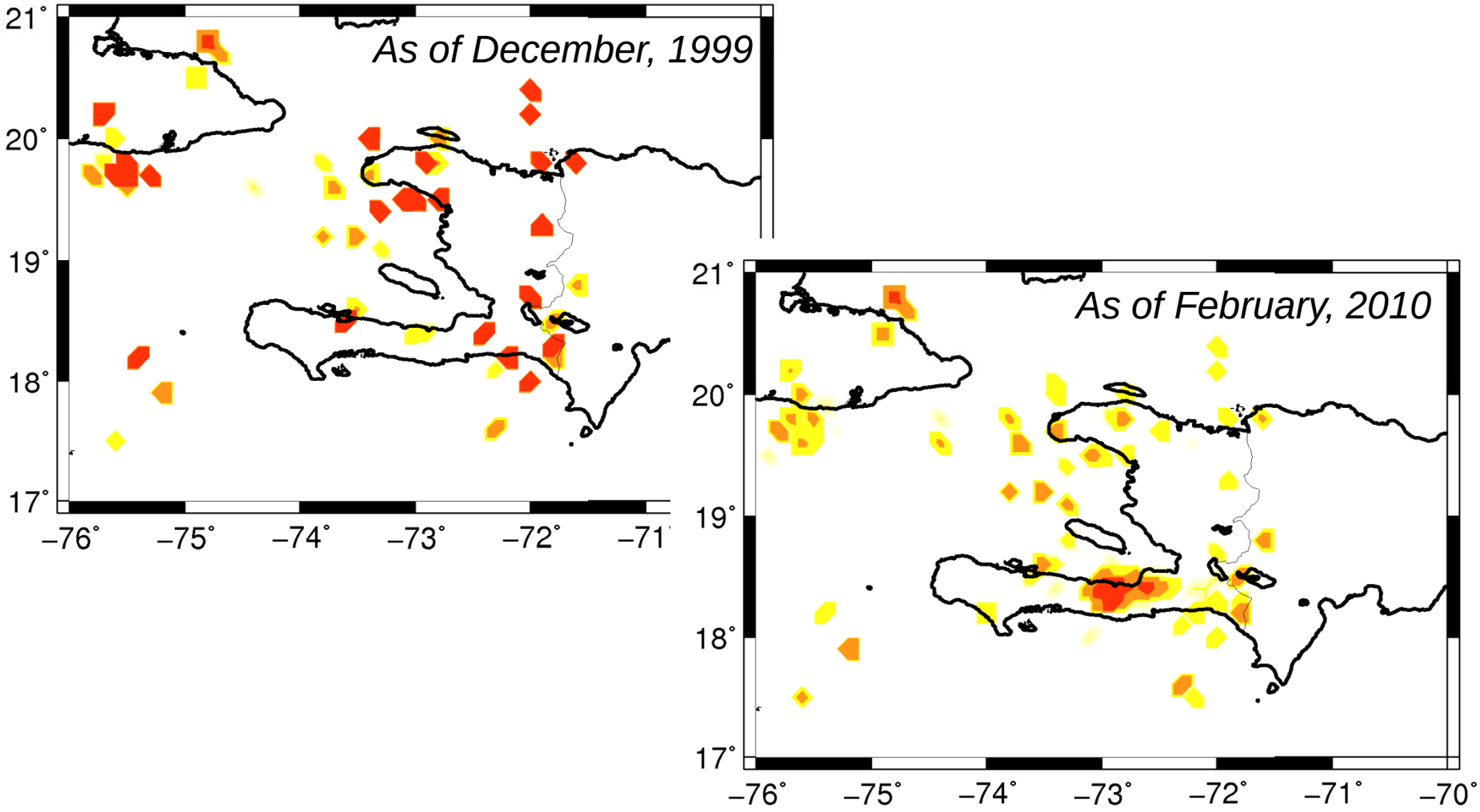
# *Haiti M ~ 7.0 Earthquake, January 12, 2010*



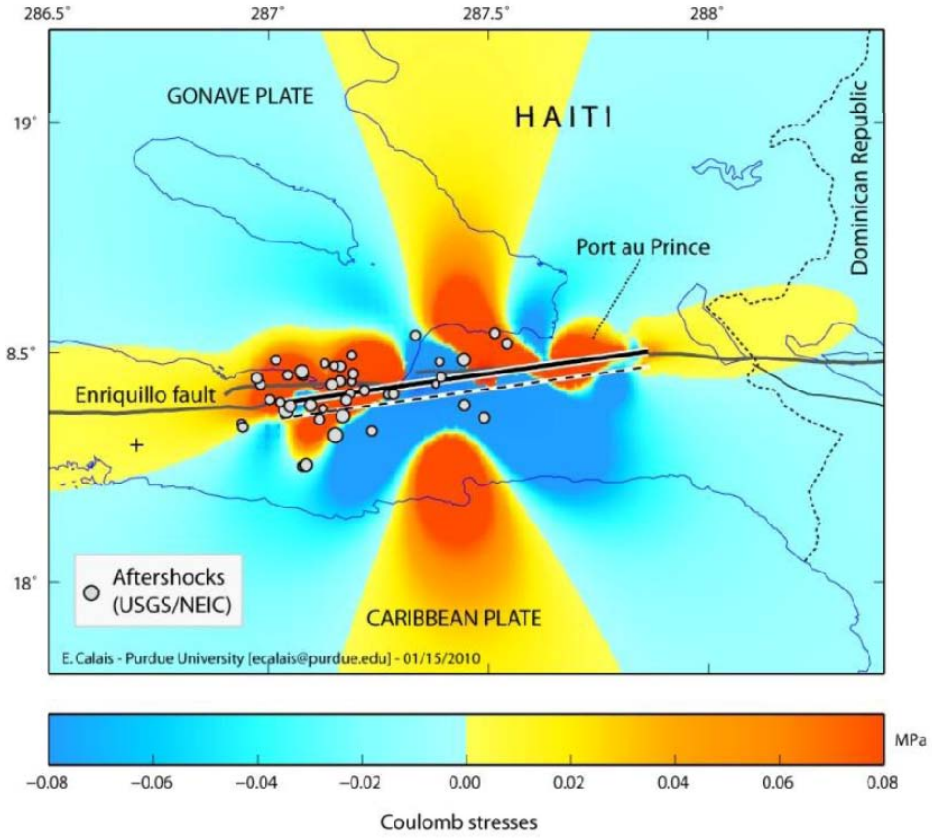



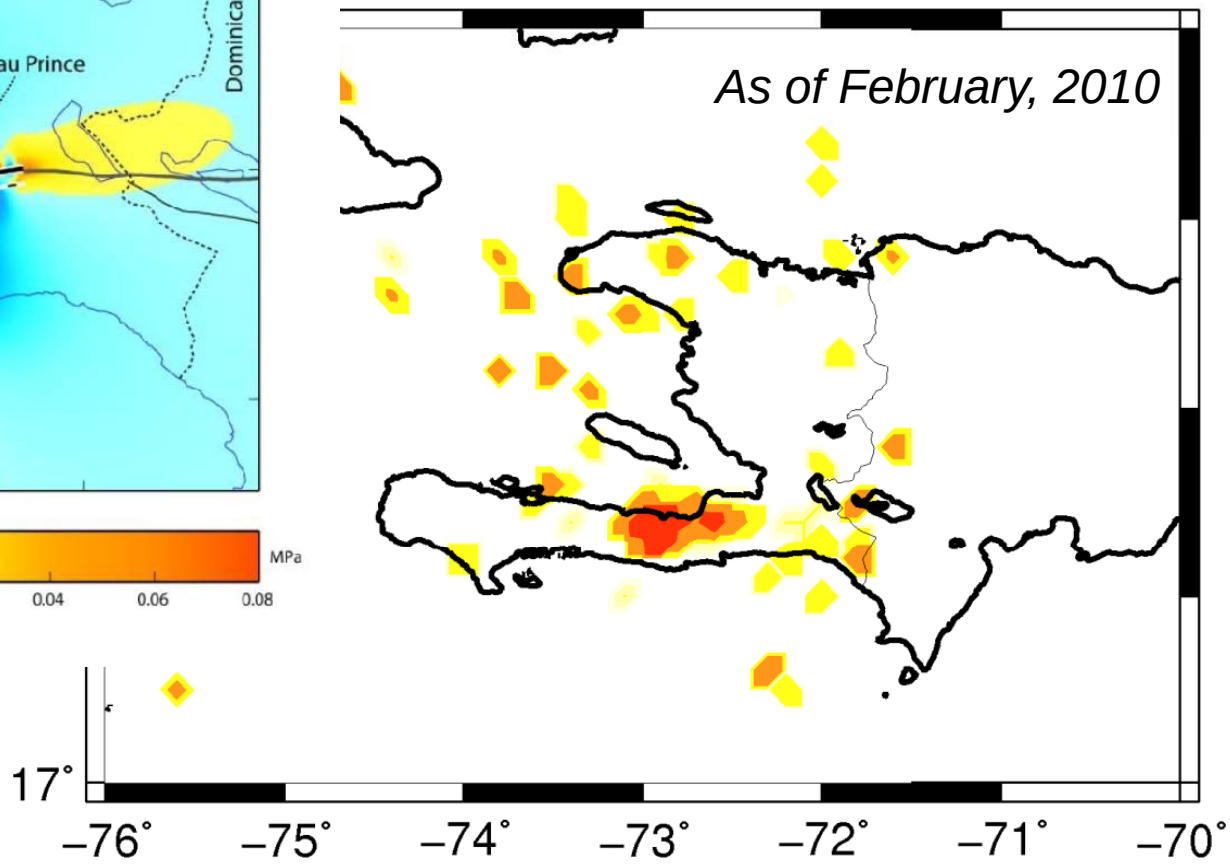

*USGS, 2010*

# PI Forecast, Haiti, 2010

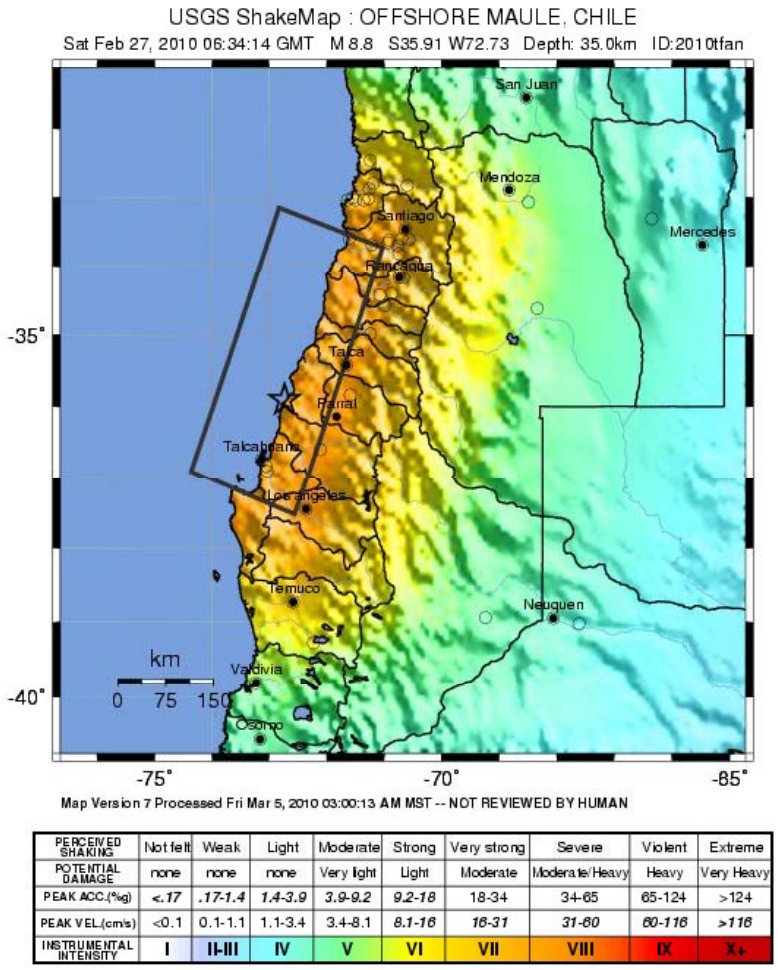


# *Stress Triggering and PI*

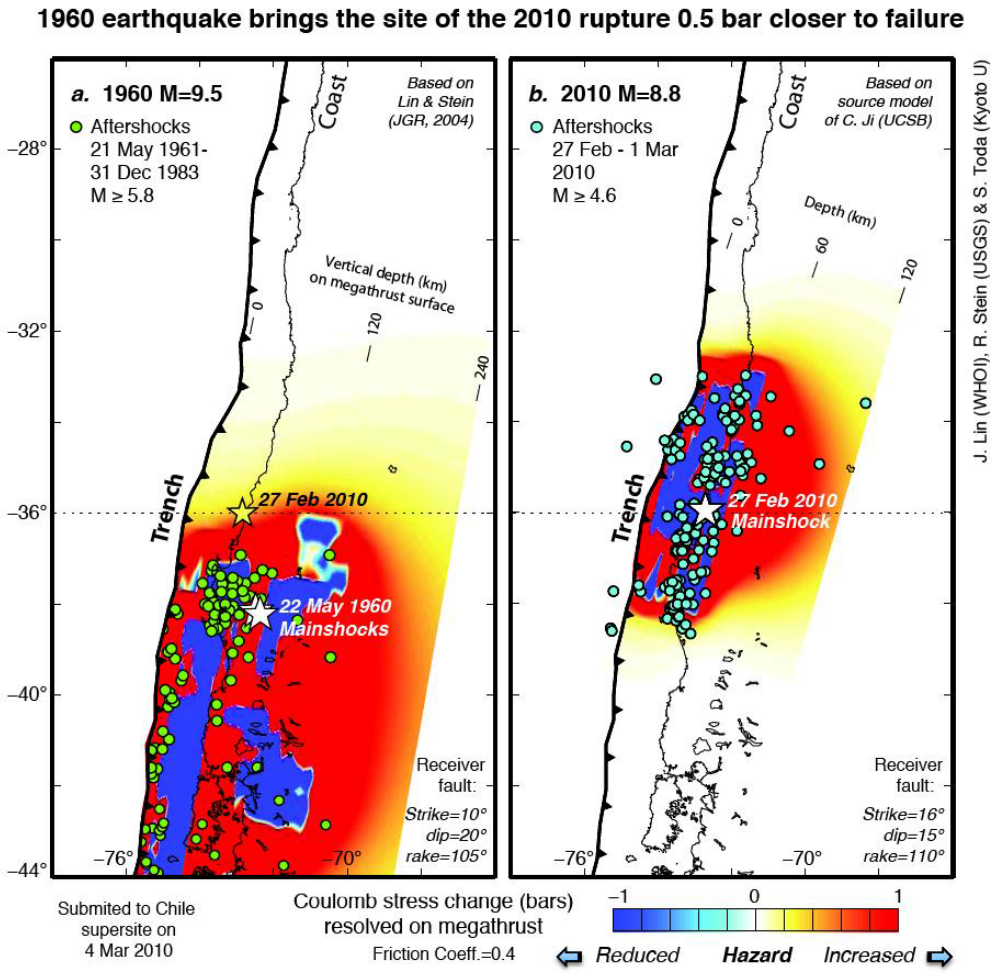


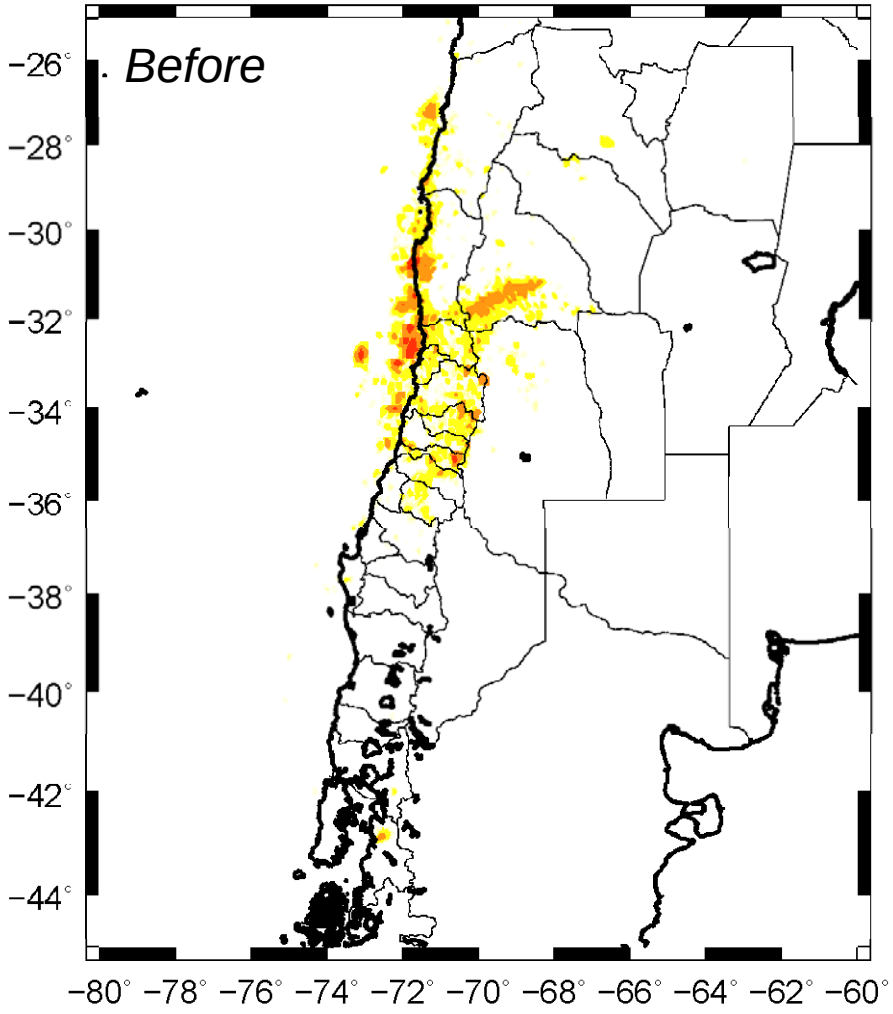
# *Maule Earthquake, Chile, M ~ 8.8*
# *February 27, 2010*

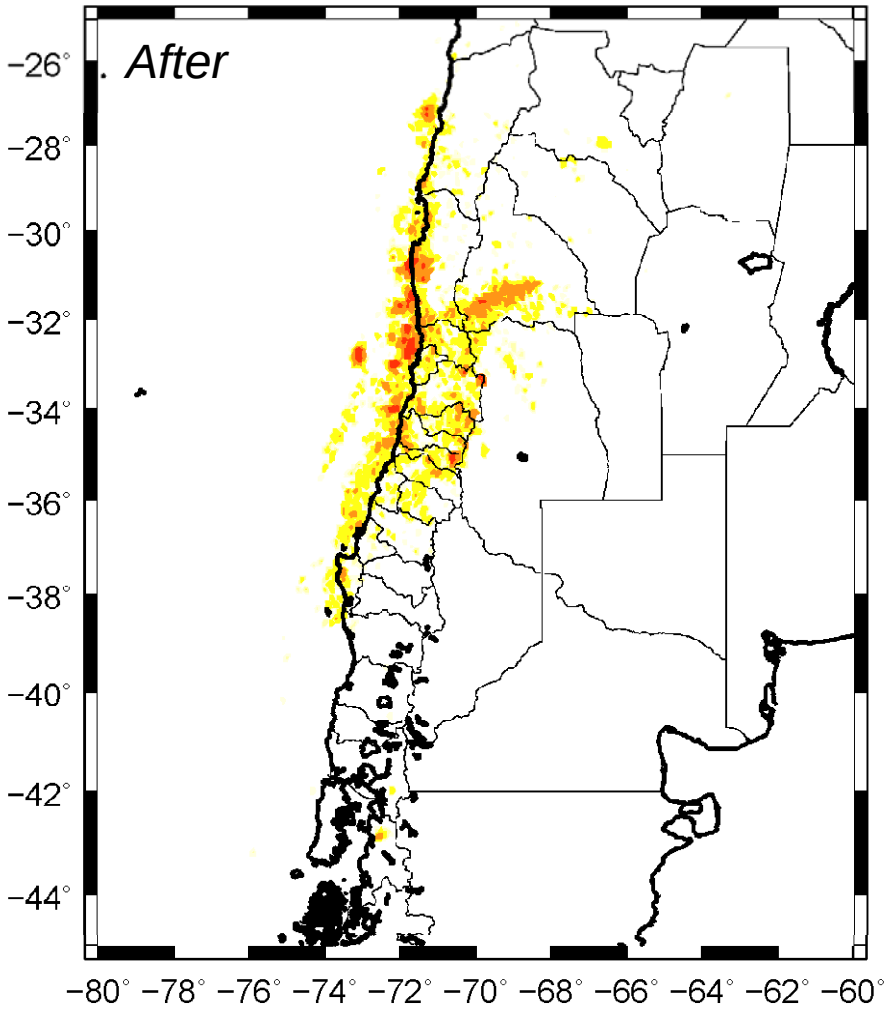



| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | <.17 | .17-1.4 | 1.4-3.9 | 3.9-9.2 | 9.2-18 | 18-34 | 34-65 | 65-124 | >124 |
| PEAK VEL.(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+ |

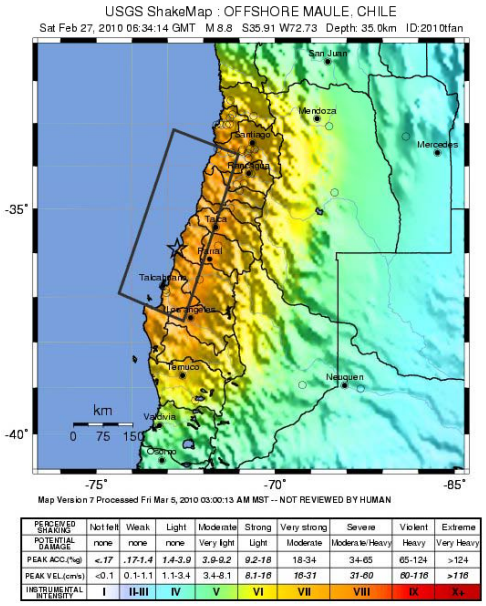


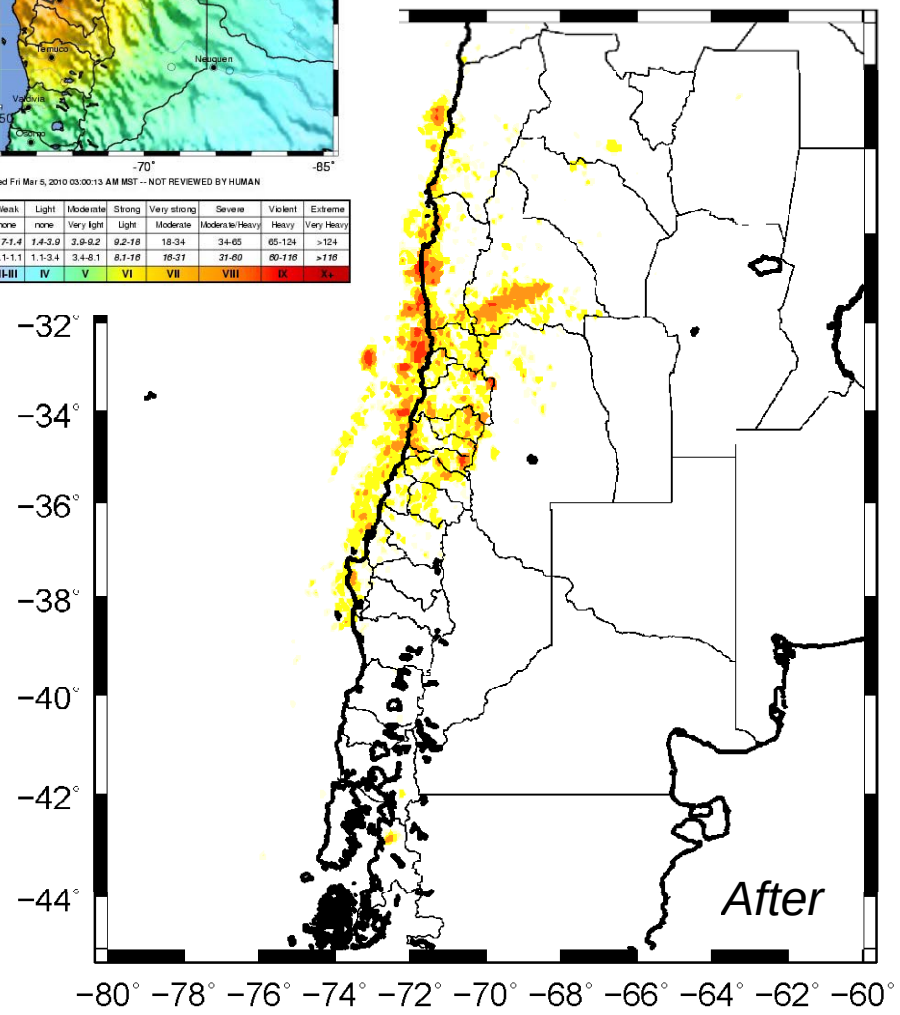
# PI Analysis, Maule Earthquake, Chile

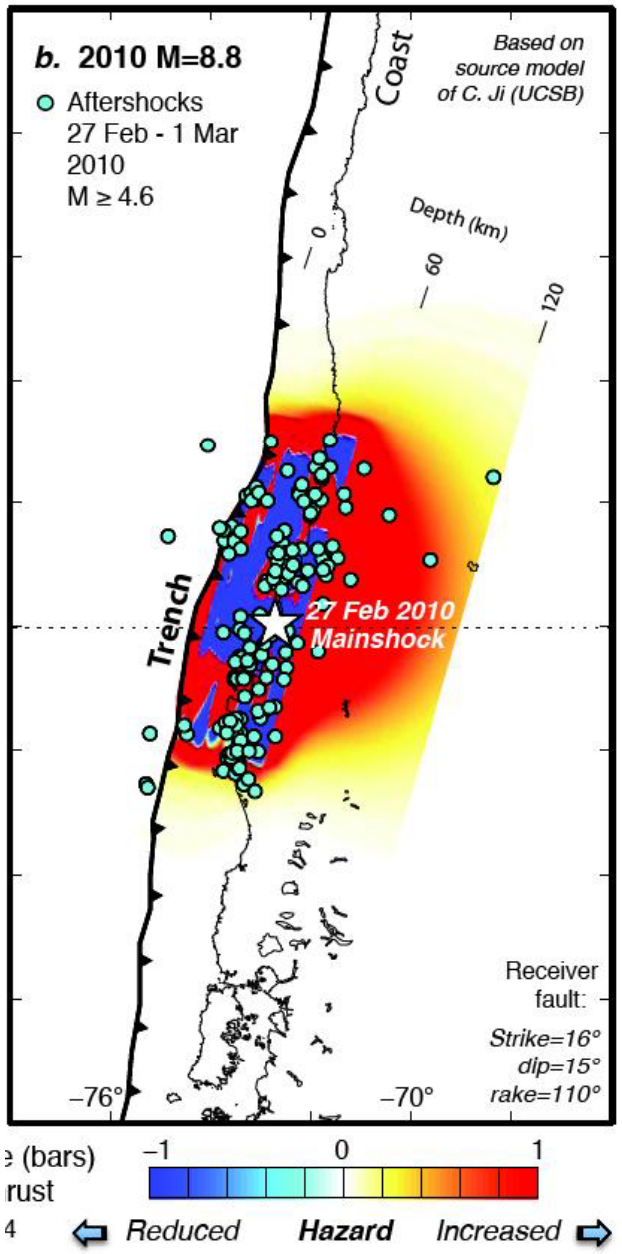


# Stress Triggering and PI Analysis

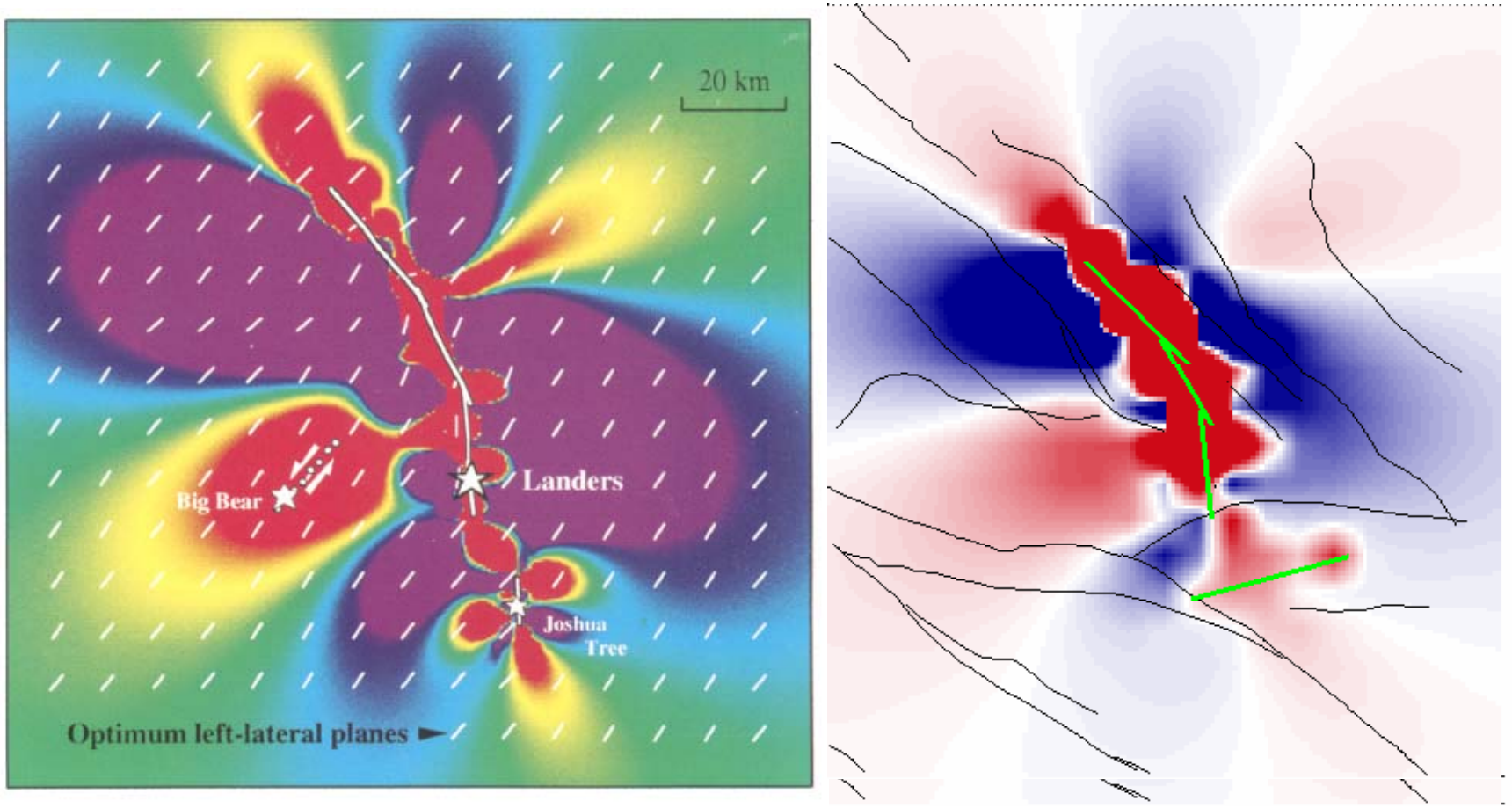



J. Lin (WHOI), R. Stein (USGS) & S. Toda (Kyoto U)

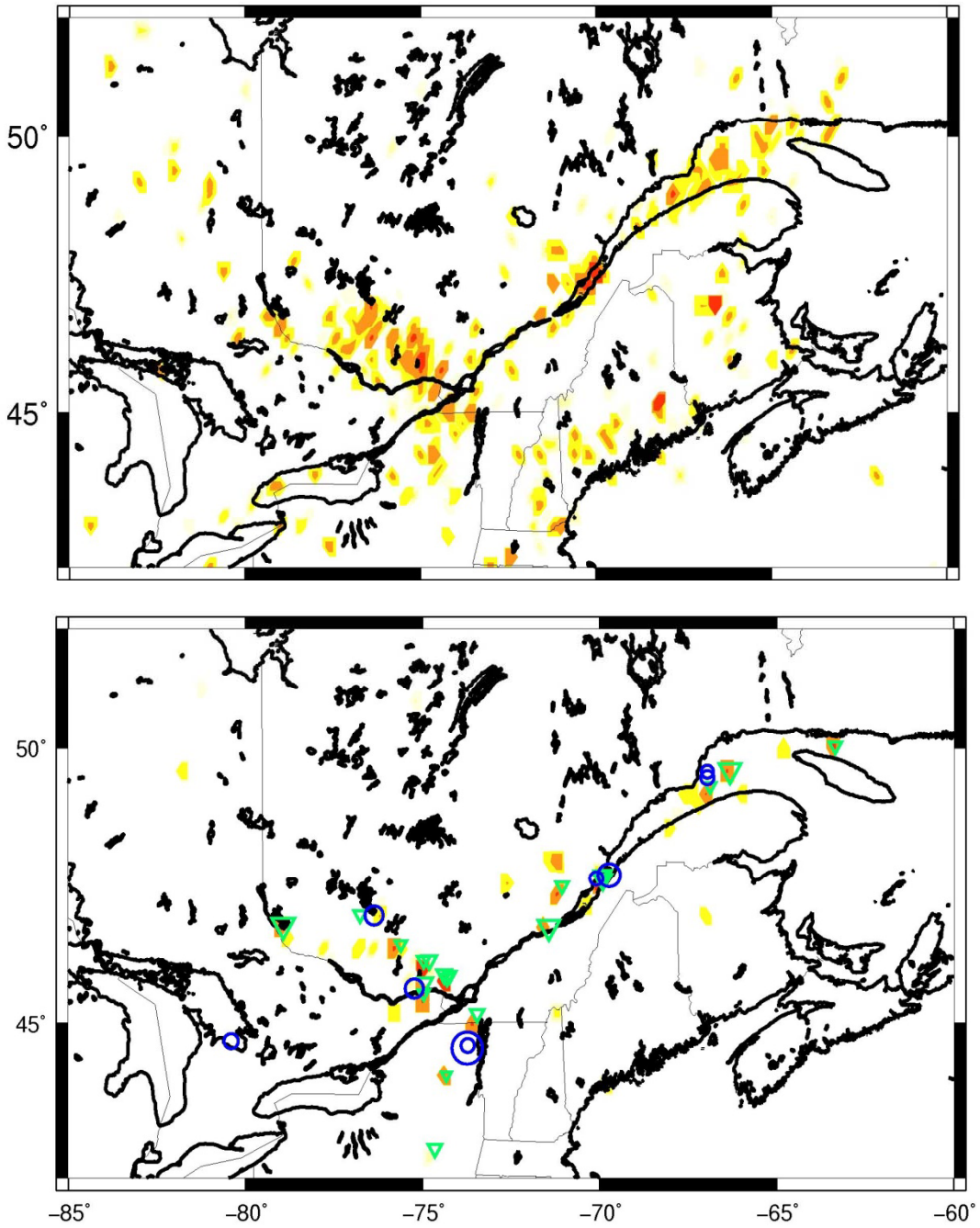
# *Detailed Aftershock Studies Using PI Analysis*




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)

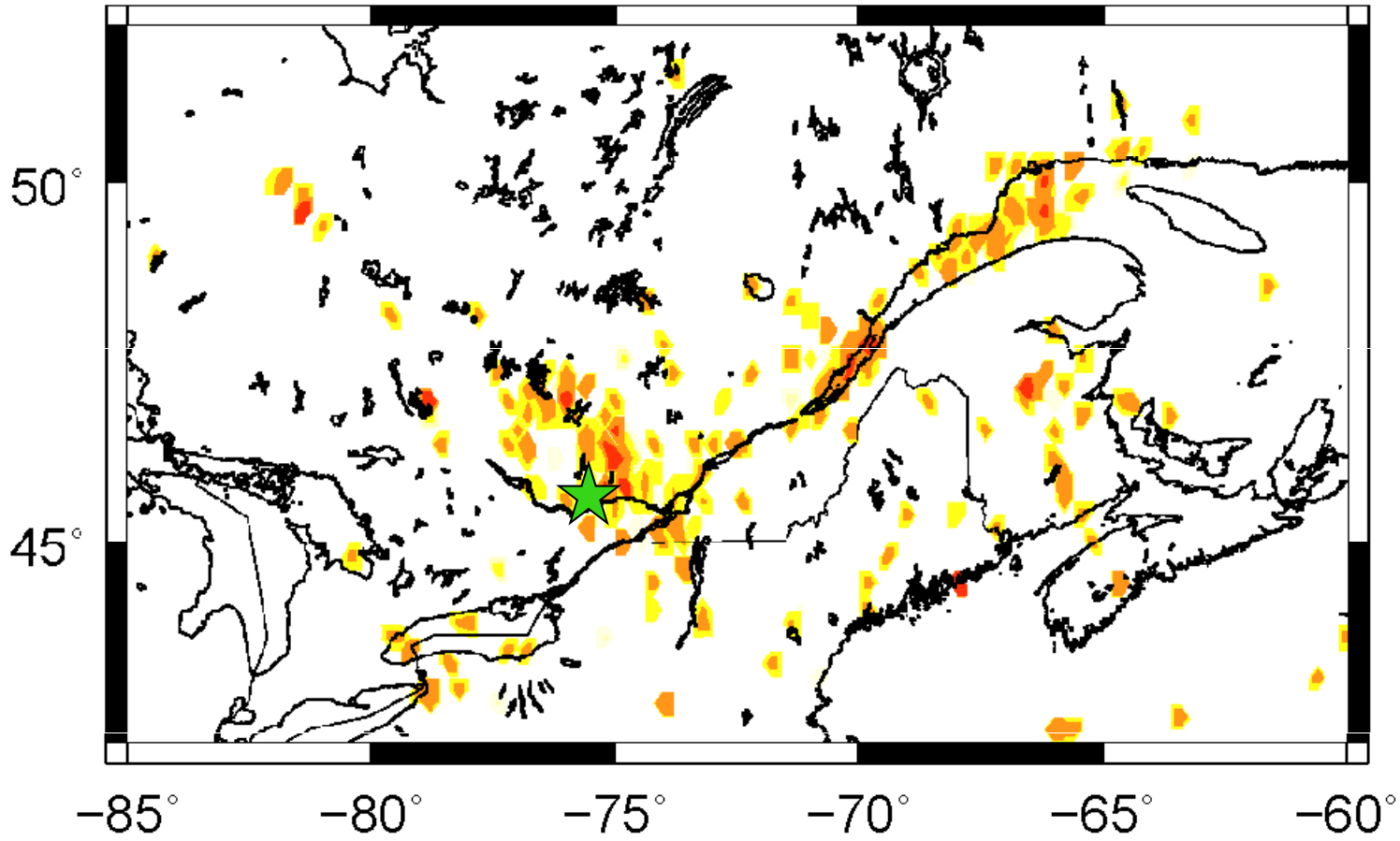
# *PI Index Eastern Canada*

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

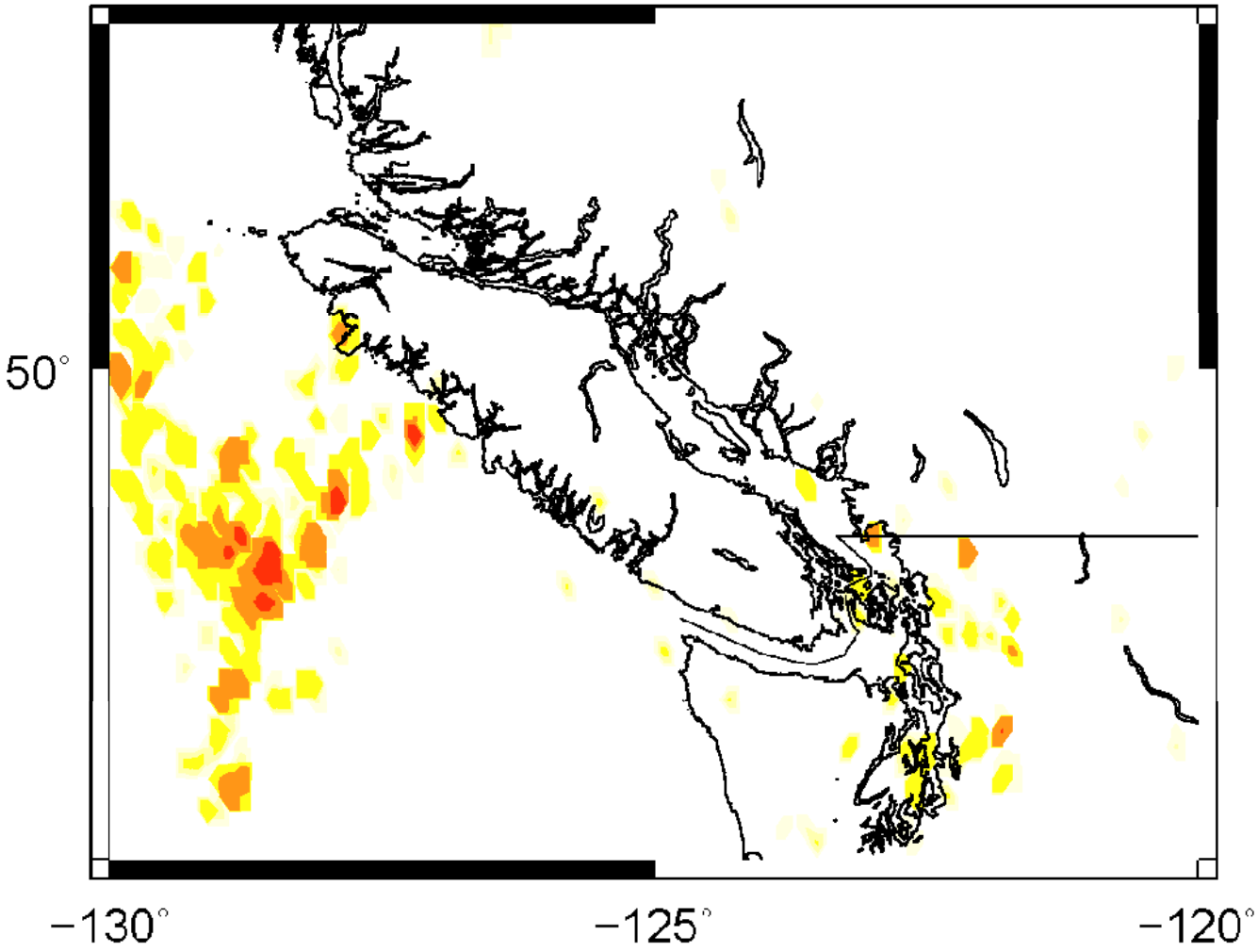


# *Ottawa Earthquake, June 2010, M ~ 5.0*

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 an 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.