Earthquake Forecasting: Advances and Challenges

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Outline

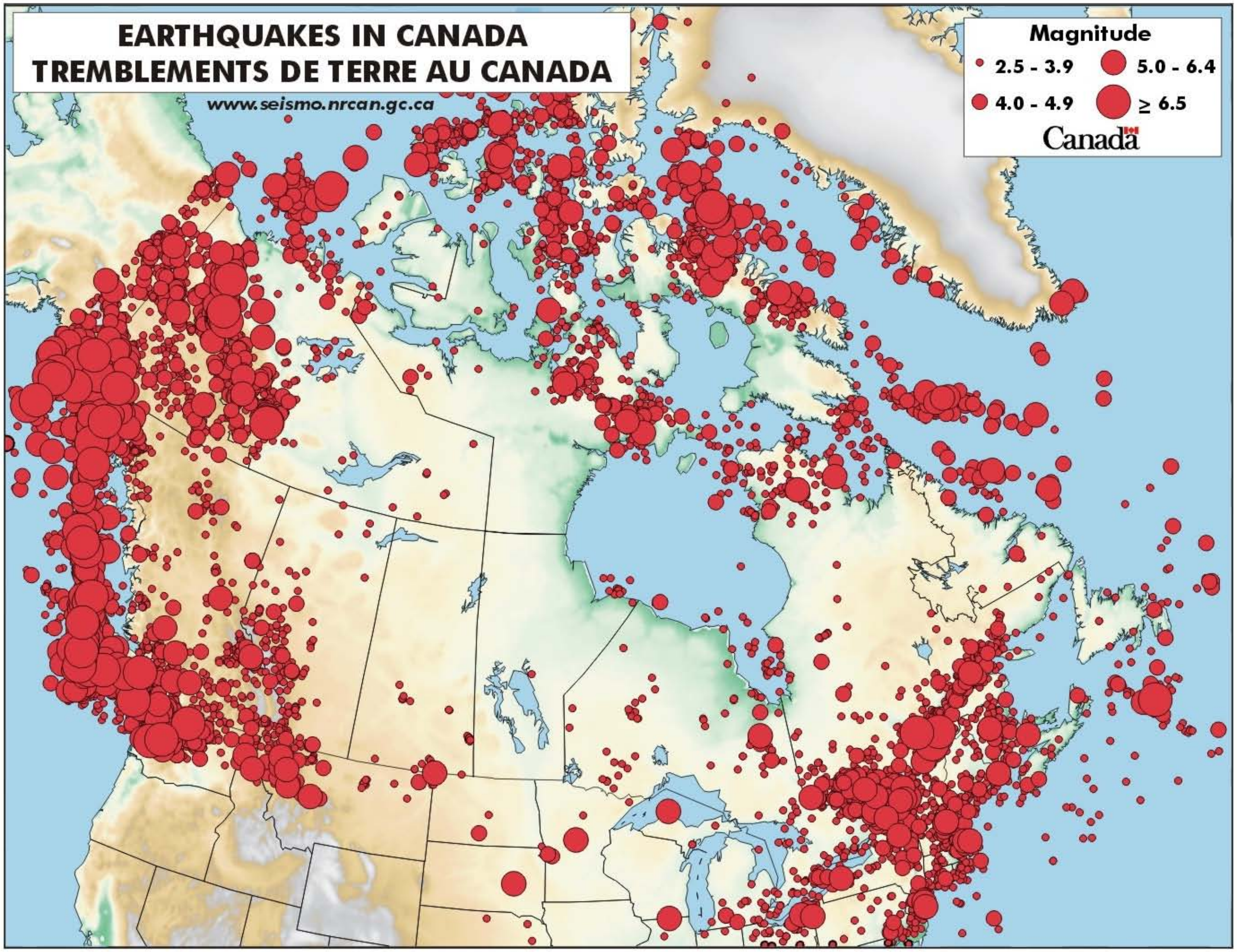
- Introduction
- Patterns and statistics in earthquake systems
- Earthquake forecasting using historic seismicity data
- Improving earthquake forecasting
- Demonstrate a new, interactive program that calculates these forecasts for researchers and, eventually, government agencies
- Examples, including eastern and western Canada

Motivation

- 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 Sumatran earthquake, December 2004, and the subsequent tsunami, once again demonstrated our vulnerability to the effects of a great earthquake.
- Historical records from around the world suggest that, while rare, similar large events ($M \approx 9$) have occurred elsewhere. For example, there is strong evidence that a similar earthquake occurred in the Cascadian subduction zone in 1700.
- Smaller, but also very destructive earthquakes ($M > 6.5$) occur every year, many in populated areas.
- Earthquakes, until very recently, have not been forecast with any significant degree of success.

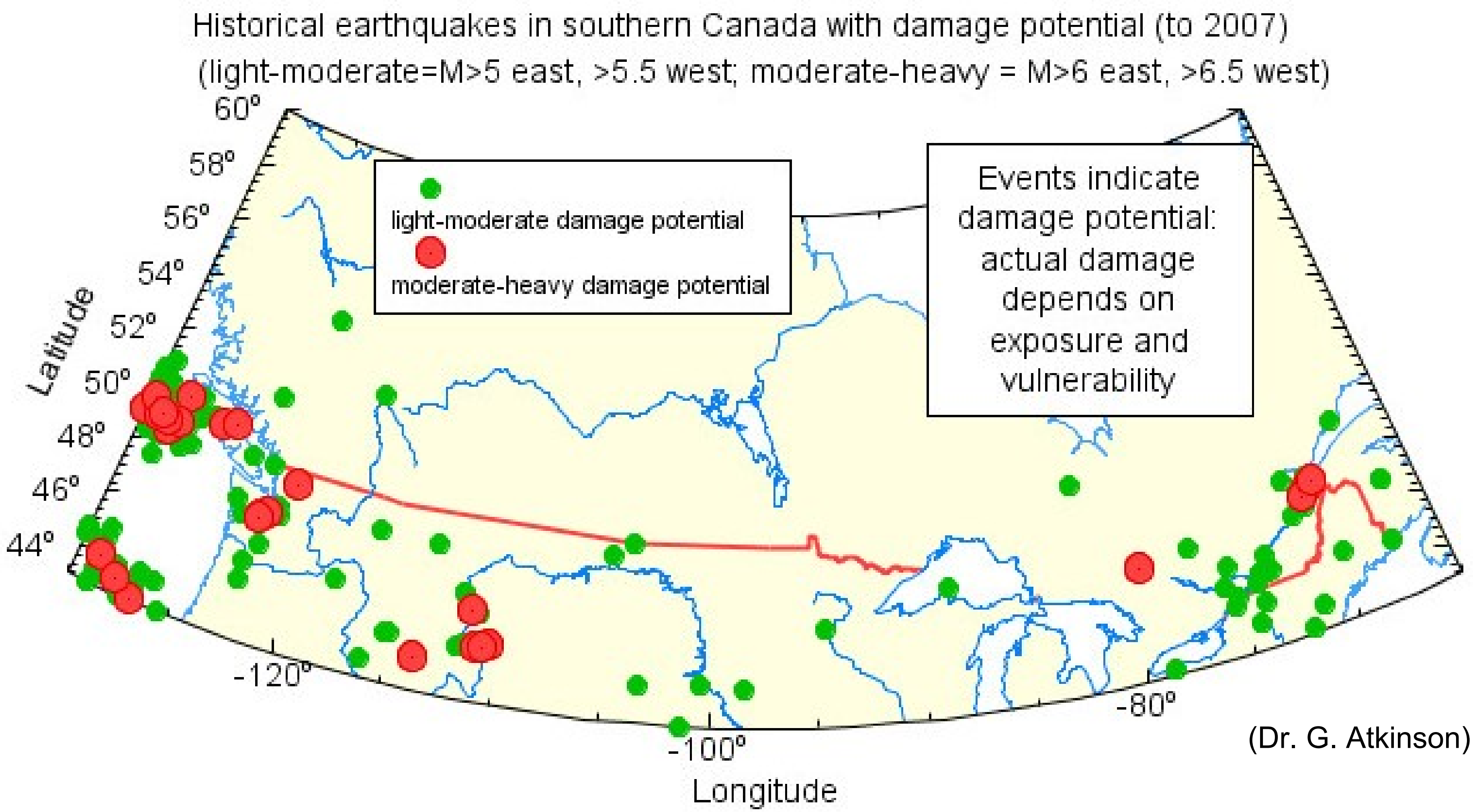
http://www.pnsn.org/ (Ruth Ludwin)
http://www.virtualmuseum.ca

Background: Seismicity of Canada



(Geological Survey of Canada)

Seismicity and damage potential



(Dr. G. Atkinson)

Future earthquakes in Canada are inevitable, and a major urban earthquake is our greatest potential natural disaster (Etkin et al., 2004)

Cities that contribute most to seismic risk in Canada

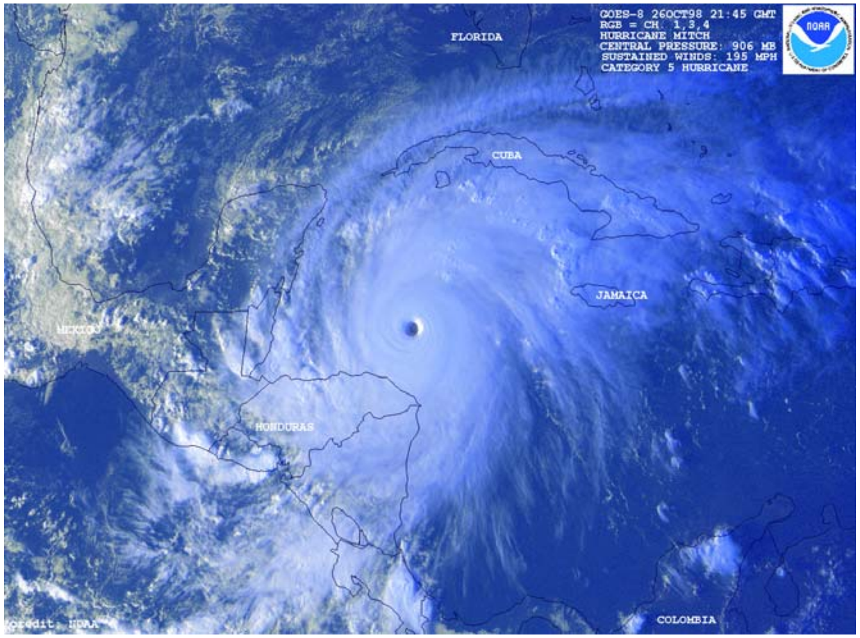
Relative contributions to seismic risk in Canada (source: Geological Survey of Canada)

Background

- In the past, our ability to assess seismic hazard has been largely based on our knowledge of the spatial distribution of large earthquakes.
- However, patterns in seismicity data, both spatial and temporal, have been recognized for as long as we have been keeping records.
- Aftershocks, cascades of smaller events, for example, are recorded after every major event.
- Precursory seismic patterns, either quiescence or activation, have been postulated for more than 40 years, but studies were limited to larger events and local regions.
- Recently, better networks and an interest in stress triggering has led to the collection of higher quality seismic data that includes the very smallest events.
- This enlarged data set has led to the ability to analyze seismicity data, in a statistical sense and to provide insights into the physics of the underlying process.
- One by-product of these statistical studies of earthquake patterns has been a renewed interest in earthquake forecasting, with some promise of success.

Patterns of Extreme Events

- Space-time patterns are observed in many systems in science and engineering.
- Forecasting the future evolution of these space-time patterns can be achieved using time series methods and pattern dynamics analysis.
- Vortices (below) are one type of space-time pattern that emerges from a nonlinear dynamical system. Climate simulations have been remarkably successful over the past 30 years in forecasting its behaviour.
- New approaches from computational physics and nonlinear dynamical systems suggest that the earthquake fault system is a strongly correlated system, coupled across many scales.
- Simulations show that regions of spatially coherent stress are associated with spatially coherent regions of anomalous seismicity (quiescence or activation).



Hurricane Mitch, 1998 (NOAA)

Patterns of Extreme Events: Earthquakes

It is now known that the San Francisco earthquake and fire of April 18, 1906 killed more than 3000 persons. Estimates are that if it were to happen today, damages could total well in excess of $500 billion (USD). (*Damage estimate from T. Wallace testimony to US Congress).*

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 239 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 1308 MISSION ST. WHERE COPIES MAY BE HAD.

Courtesy, Museum of San Francisco

The Nisqually, Washington Earthquake

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

The Magnitude 7.9 Gujarat, India Earthquake

January 26, 2001 – An intraplate earthquake similar to New Madrid, 1811-1812, M ~ 8

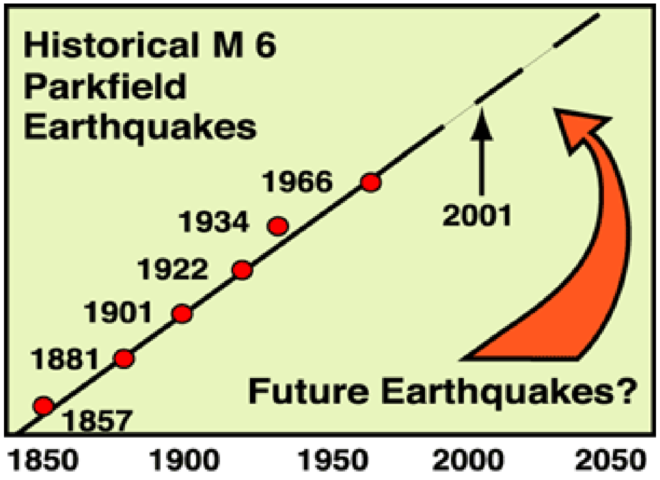
Reuters

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

Seismicity Patterns

- There is increasing evidence that systematic precursory patterns exist in regional seismicity prior to large earthquakes.
- For example, one recurring pattern observed in the data has been coined “characteristic earthquakes”. A characteristic earthquake is one that repeats on a regular basis, in the same location and with the same approximate size every time.
- It was proposed, for example, that the Parkfield earthquake, so named because of its proximity to the town of Parkfield, California, along the San Andreas Fault, was an example of a characteristic earthquake.
- It was observed to repeat regularly every 22 years for more than 100 years.
- Unfortunately, despite a large-scale instrumentation program, the next earthquake in the series, expected in 1988, did not occur until 2004.

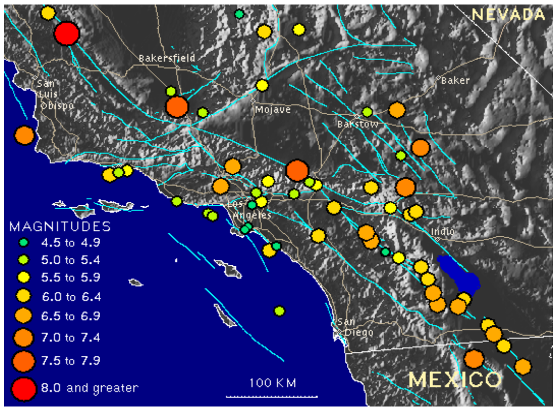
http://quake.wr.usgs.gov



http://www.cisn.org

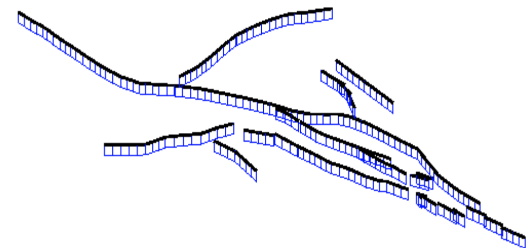
Earthquake Simulations

Virtual California is a Cellular Automata based computational model (PRE, 61, 2000)



Historic Earthquakes: Last 200 Years

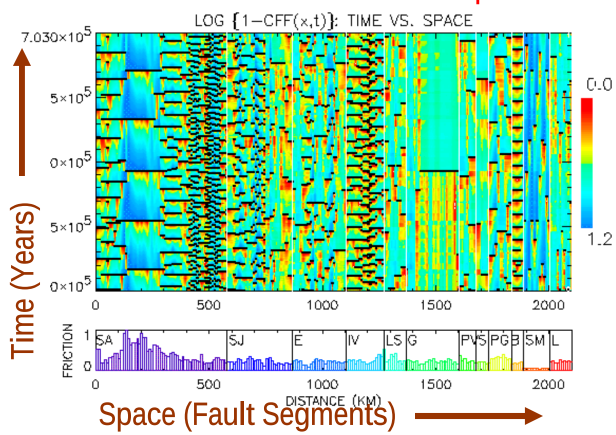
At right is the model fault system used for the simulations.



Fault Network Model for Southern California

The historic record of earthquakes over the last 200 years is shown at left.

σ = CFF Stress: Time vs. Space

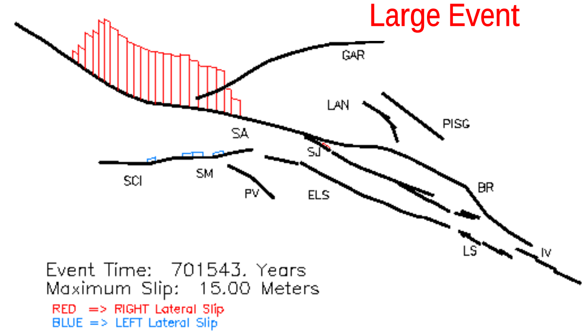


San Andreas Fault

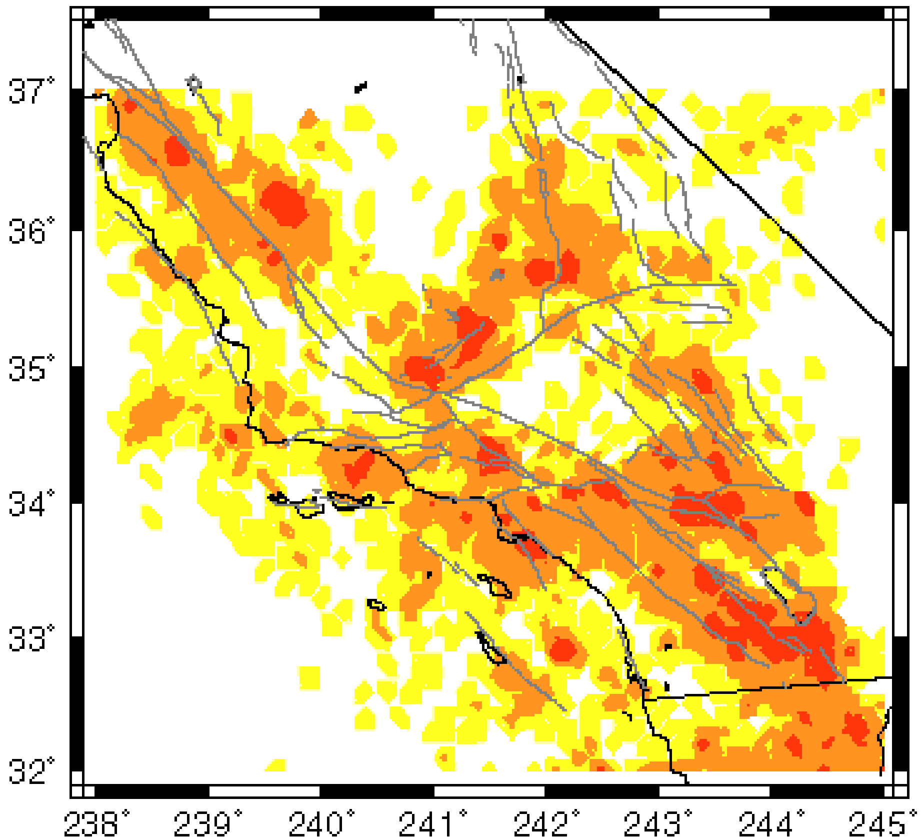
Simulations of earthquake fault systems can be carried out using the Virtual California model. At left is shown the buildup of stress over time and space. Lines = Earthquakes

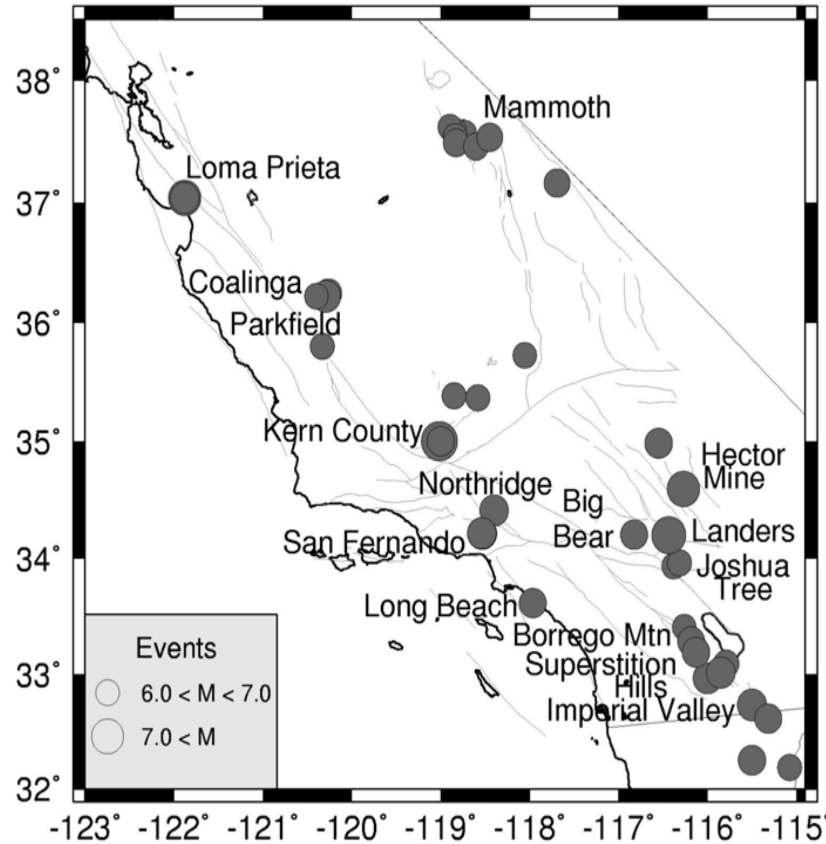
At right is shown an example of one of the large earthquakes that occur during a simulation.

Large Event



Seismicity Data, S. California





The map on the left shows the intensity of seismicity in Southern California during the period 1932-1991, normalized to the maximum value. The most intense red areas are regions of most intense seismic activity. This is called a Relative Intensity (RI) map.

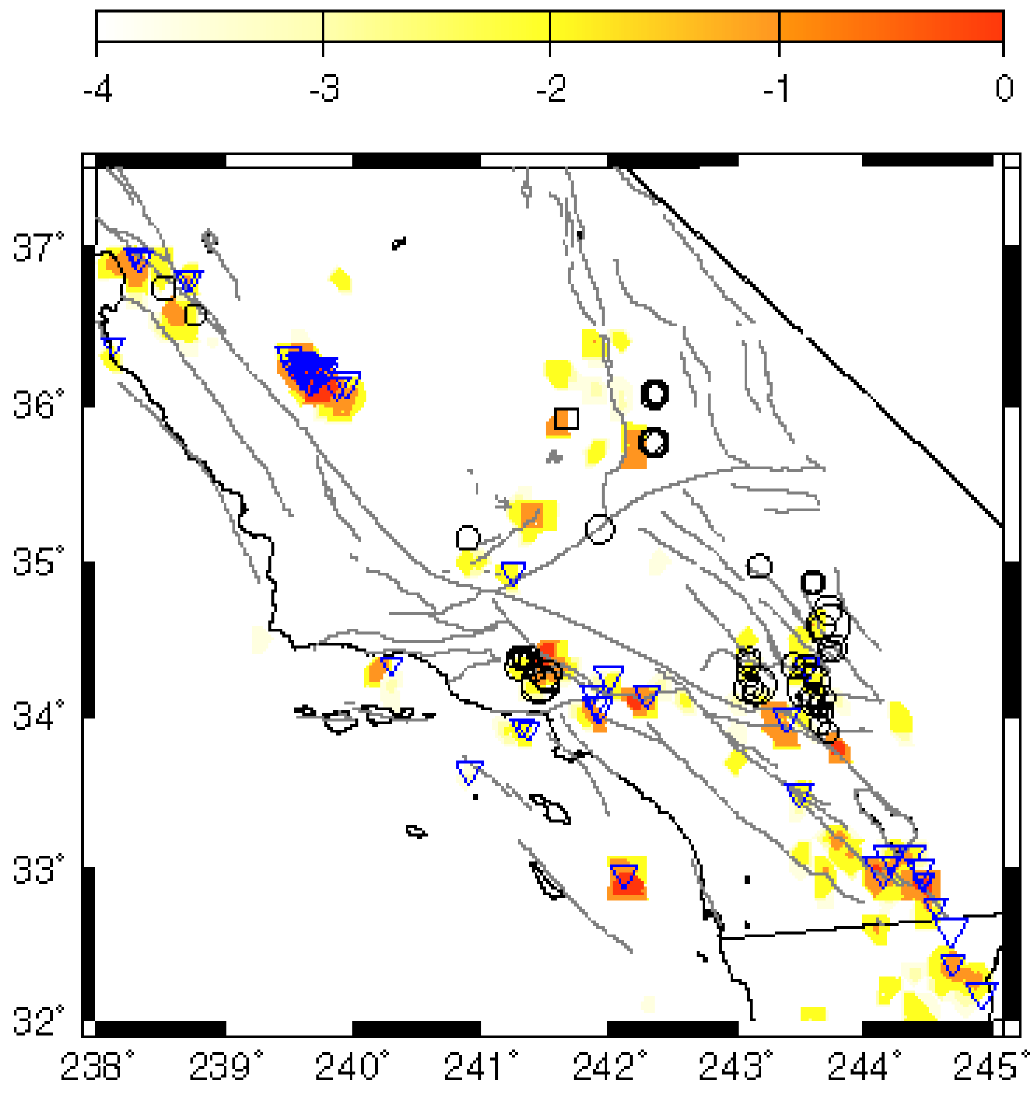
On the right are shown the largest events to occur over the past 70 years.

Pattern Informatics (PI) Index

- A method for analyzing historic catalog data in order to detect changes in observable seismicity prior to major earthquakes, developed from observations and ideas generated by computational simulations.
- It identifies the development over time of spatially coherent regions of seismicity.
- The resulting pattern informatics (PI) index is computed directly from seismicity data.
- Here we use the small earthquakes of magnitude three to act as sensors for the larger earthquakes. The physical idea is that the small earthquakes (M ~ 3) act as a sensor, telling us about changes in the underlying stress level.
- A local coherent structure is measured relative to the long-term regional background rate, and corresponds to the increased probability of an event.
- Note that the actual calculation is calculated using both the long-term mean and variance.

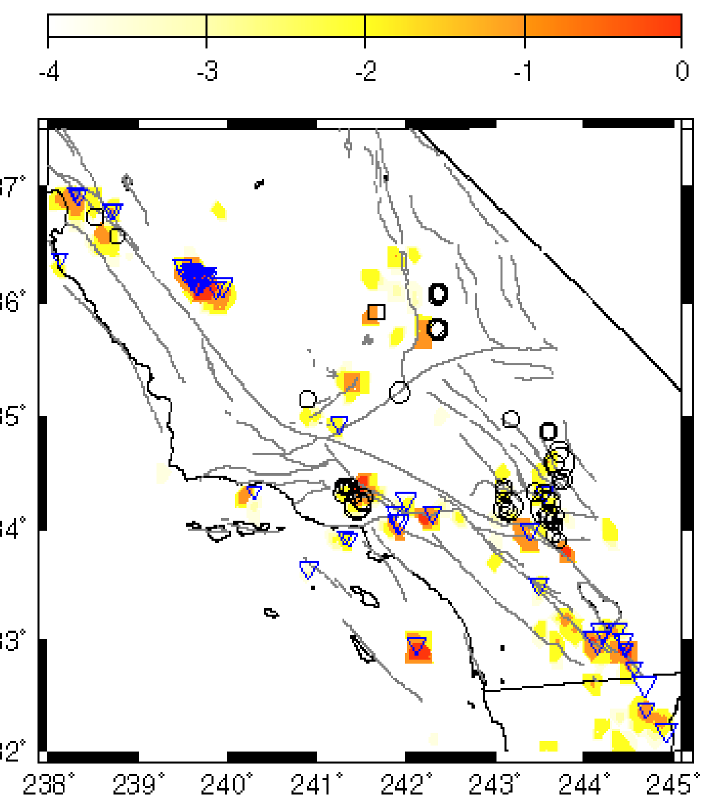
PI Anomalies, S. California, 1978-1991

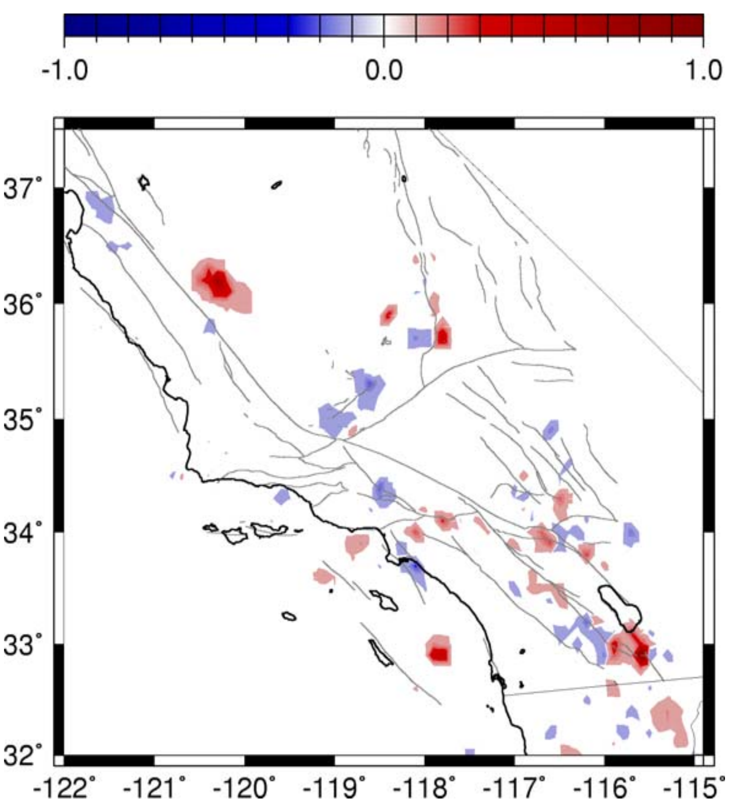
- Plot of Log_{10} (seismic potential).
- Increase in potential for large earthquakes, M ≥ 5, 1991 to 2001.
- Inverted triangles denote those events to occur during the calculation period, 1978-1991.
- Circles denote those events to occur during the forecast period, 1991-2001.



Anomalous Seismic Activity Patterns

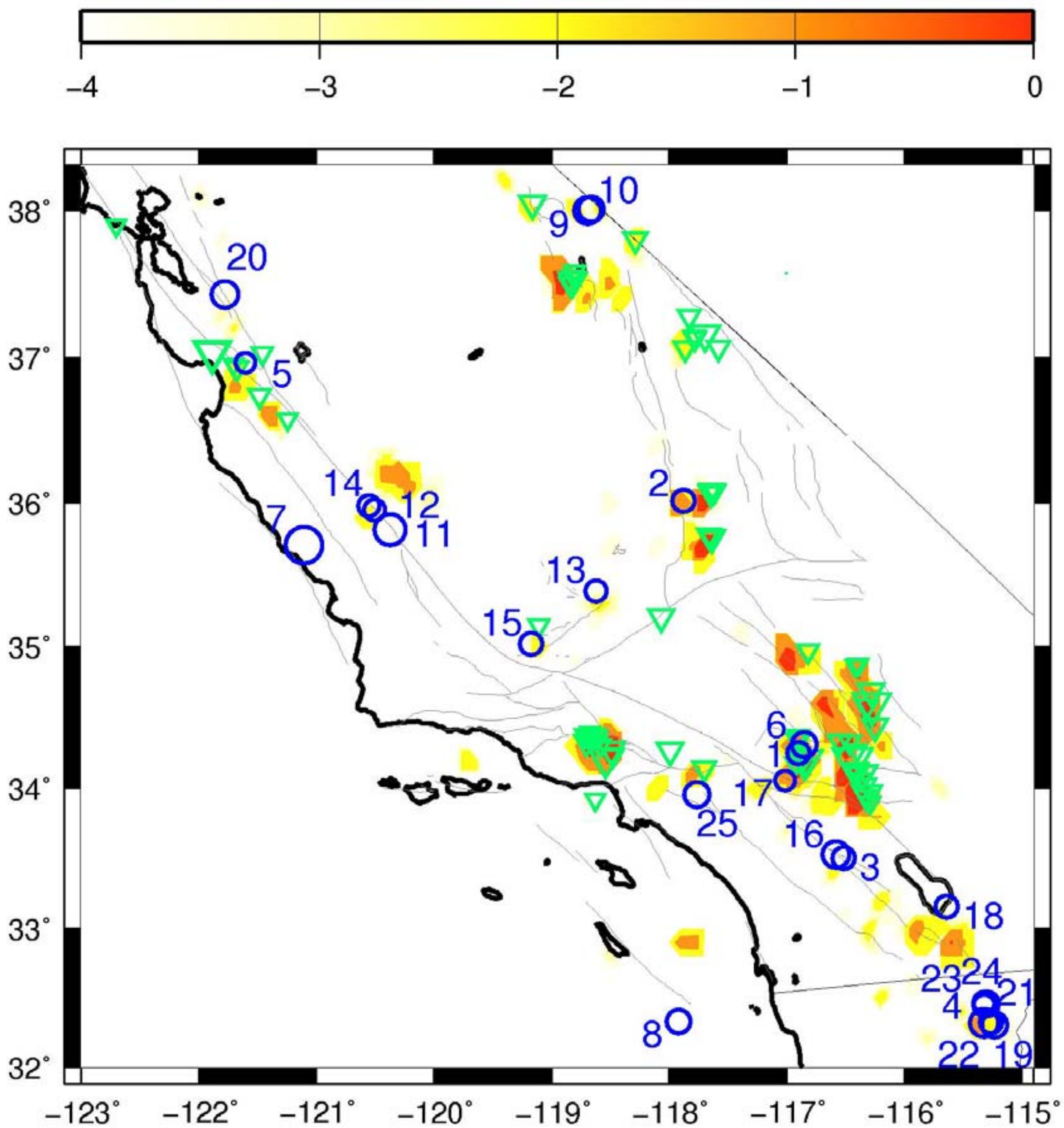
- Does the PI method detect **anomalous activity** or **anomalous quiescence? Both.**
- On the right is shown the corresponding patterns of anomalous activity (red) and anomalous quiescence (blue) during the period 1978 through 1991.





An Earthquake Forecasting Experiment

PNAS, 2002

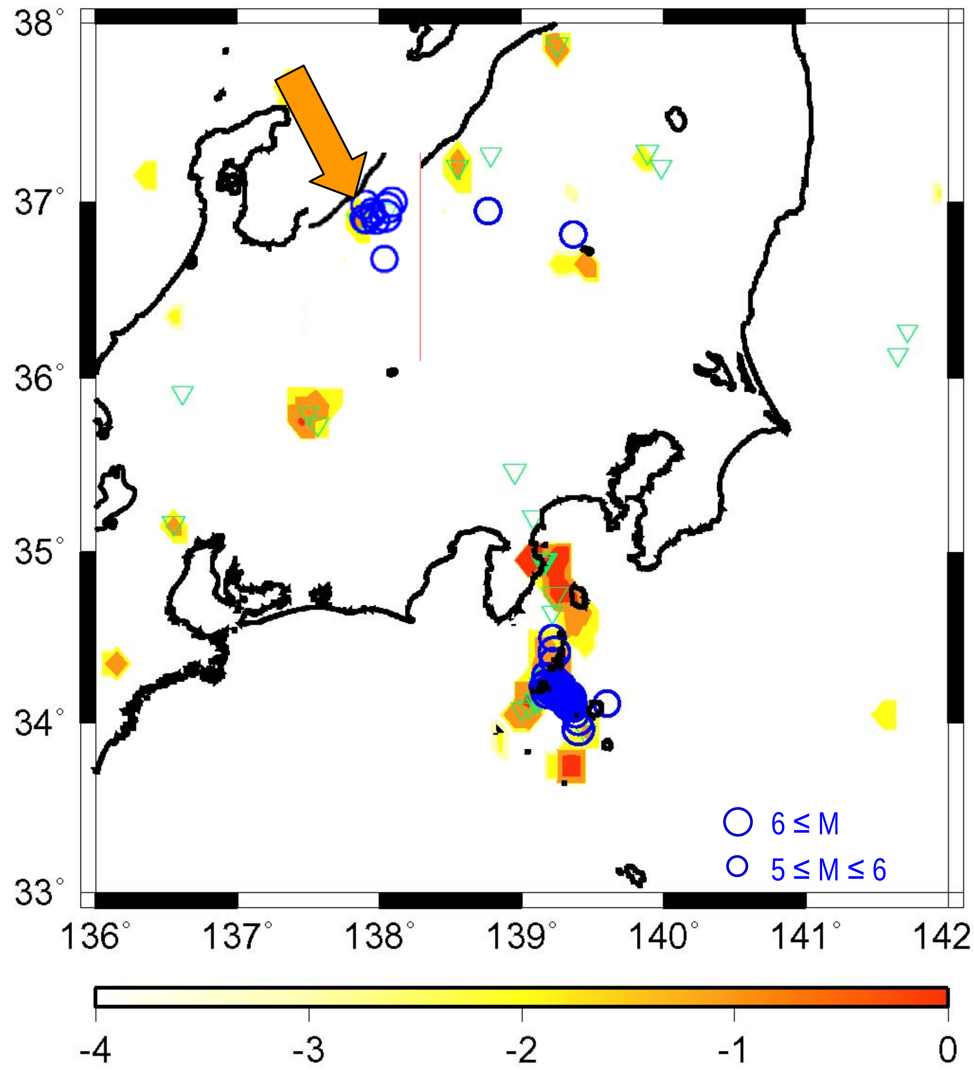


PI index for large earthquakes, M ≥ 5, ~ 2000 to 2010

Forecast of Shallow (<20 km depth) Earthquake Locations

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).
- Again, this image was first shown during lectures in Japan on October 13 & 14, 2004.

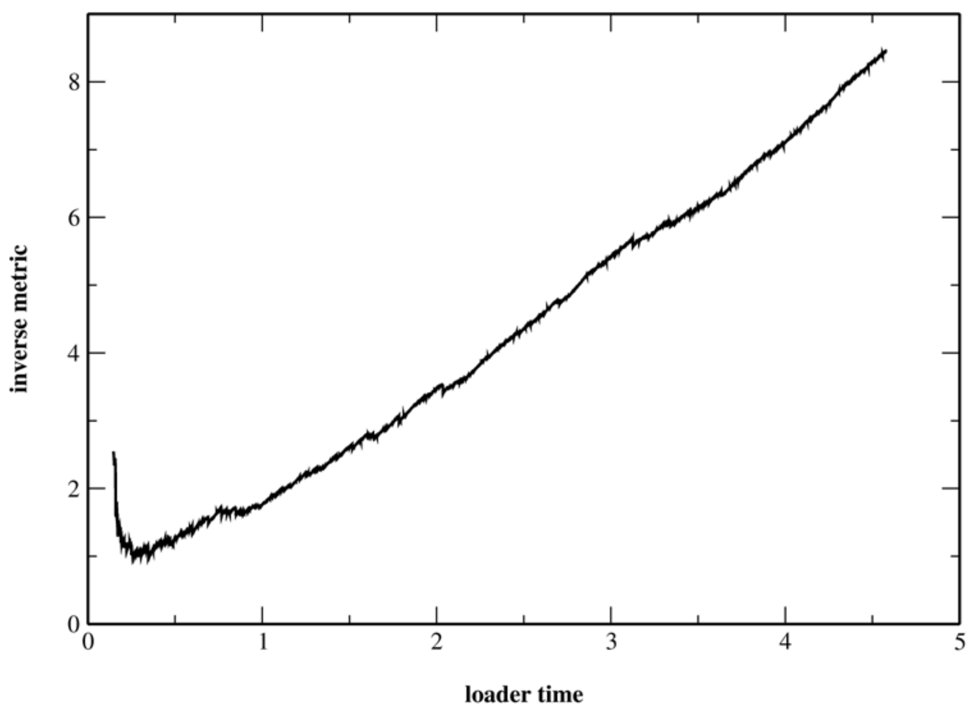


Improving seismicity based forecasts - ergodicity

- In statistical mechanics, a system is determined to be ergodic if it visits every possible state in phase space over the course of time.
- In this application, we are restricted to the very narrowest interpretation: *If a system is ergodic, given enough sampling time, the temporal averages of a particular observable must equal the ensemble average.*
- Why is this useful?
  - One important corollary is that an ergodic system is stationary. If the temporal and spatial mean are approaching the same value, *we can properly estimate the rate of background seismicity*.
  - Because many forecasting algorithms today use variations in seismicity rates to locate anomalous patterns, accurate estimates of the long-term background rates are critical to evaluating and improving these forecasting techniques.
- Here I employ a particular measure of ergodicity, the Thirumalai-Mountain (TM) metric (Thirumalai et al., 1989) developed for studying the behavior of various materials in different thermodynamical phases.

Ergodicity in Fault Models

- We can relate the number of events to the energy of the system. If the system is ergodic, then the inverse TM metric is linear with time.



- At the left is shown the inverse TM metric for *numbers of events*, in a slider block model with precursory slip (Tiampo et al., 2003).
- Note that, while the linear regions here indicate ergodicity, or punctuated ergodicity, there are also certain ranges of parameters, not shown, for which these models, are *not* ergodic.

Typical Analysis - California

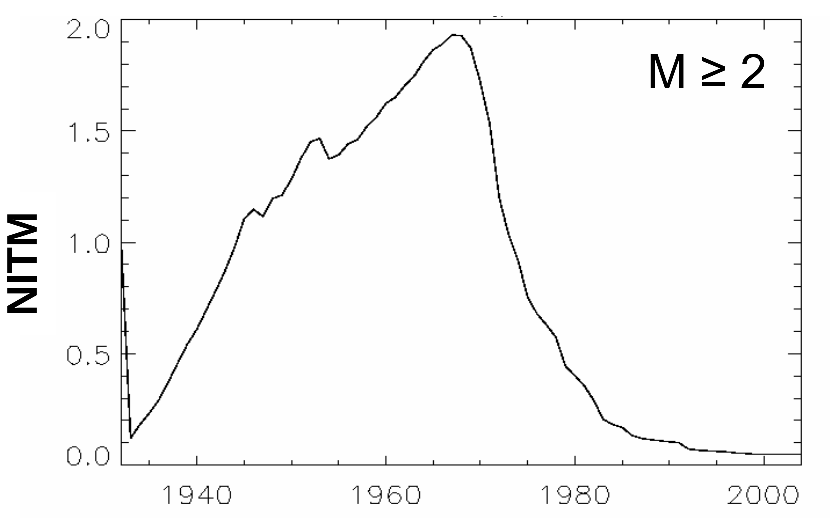
- Seismicity data from the ANSS catalog, for the period 1932-2004 (time period)
- Events are binned into areas 0.1° to a side (spatial discretization)
- Analysis is performed for an area ranging from 32° to 39° latitude, -123° to -115° longitude, or some subset thereof (spatial region). No declustering is performed, except for a particular magnitude cutoff (magnitude cutoff).
- A matrix is created consisting of the seismicity time series (n time steps) for each location (p locations).

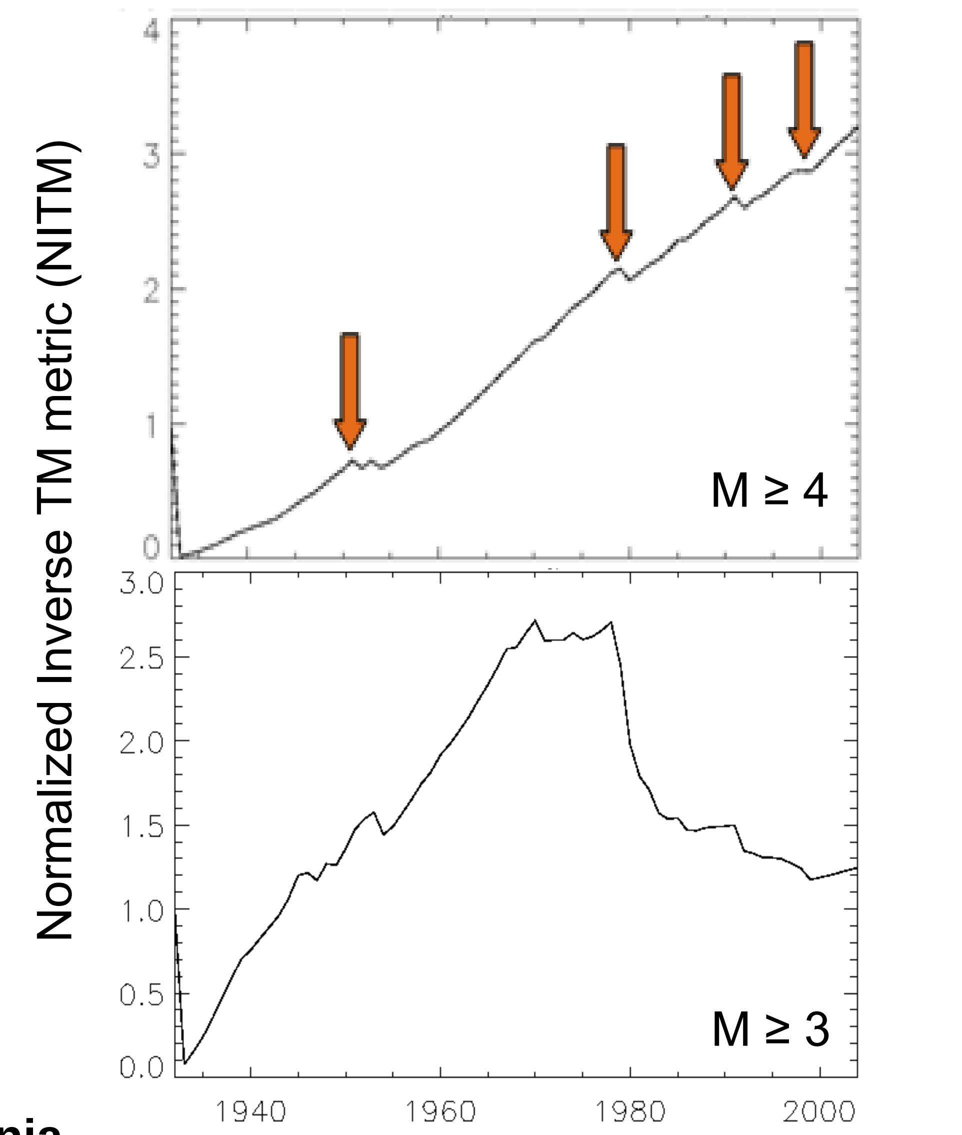
$$T = [\bar{y}_1, \bar{y}_2, \ldots \bar{y}_p] = \begin{bmatrix} y_1^1 & y_1^2 & \cdots & y_1^p \\ y_2^1 & y_2^2 & \cdots & y_2^p \\ \vdots & \vdots & \ddots & \vdots \\ y_n^1 & y_n^2 & \cdots & y_n^p \end{bmatrix}$$

- Study data from several natural catalogs by calculating the TM metric for the number of events, in order to investigate under what conditions (parameters) the system is, or is not, ergodic (Tiampo et al., *PRE*, 2007).

Ergodicity in Natural Catalogs

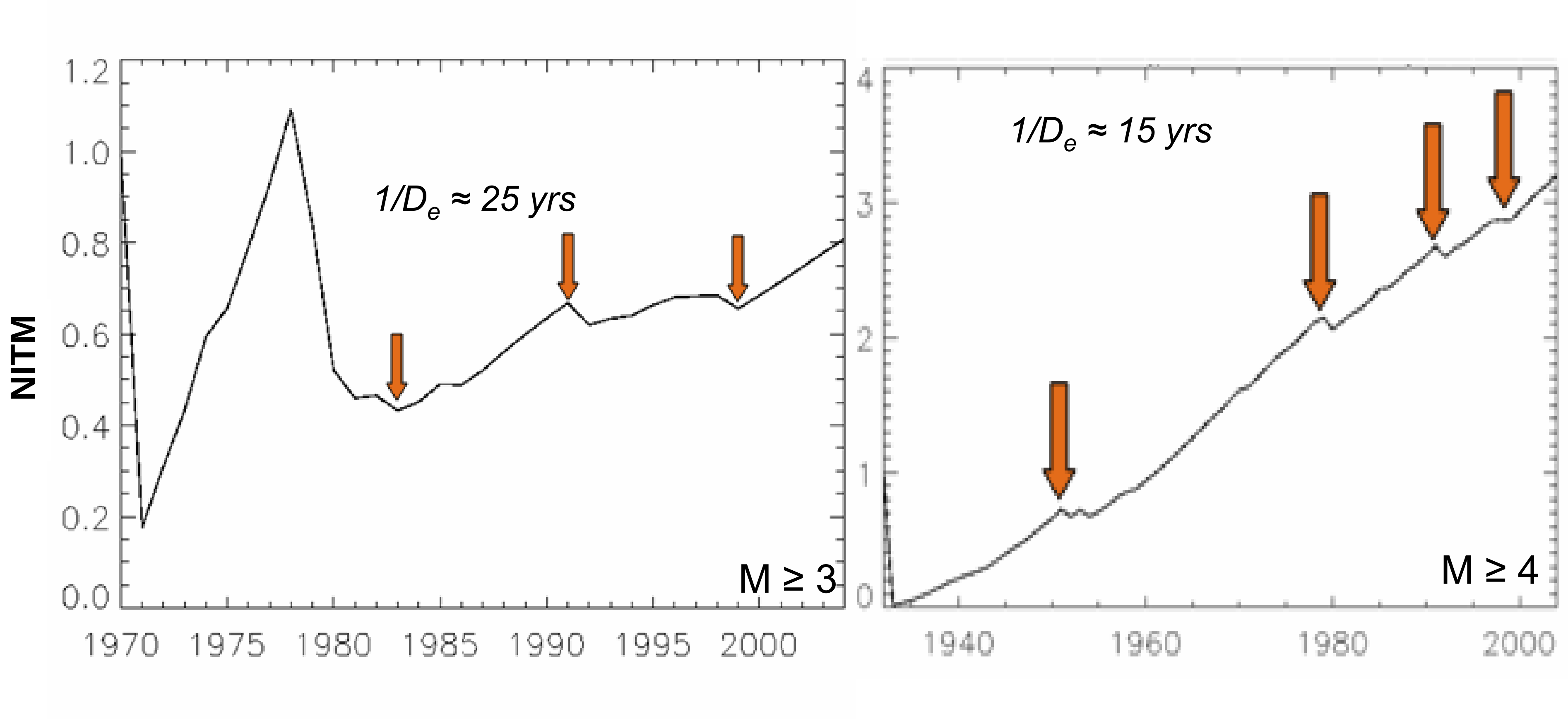
- Again, we bin the California region into a set of locations, and use the numbers of events as our measurable
- Variations in location accuracy, magnitude completeness, and coverage have a significant effect on ergodicity





California

Ergodicity in Natural Catalogs

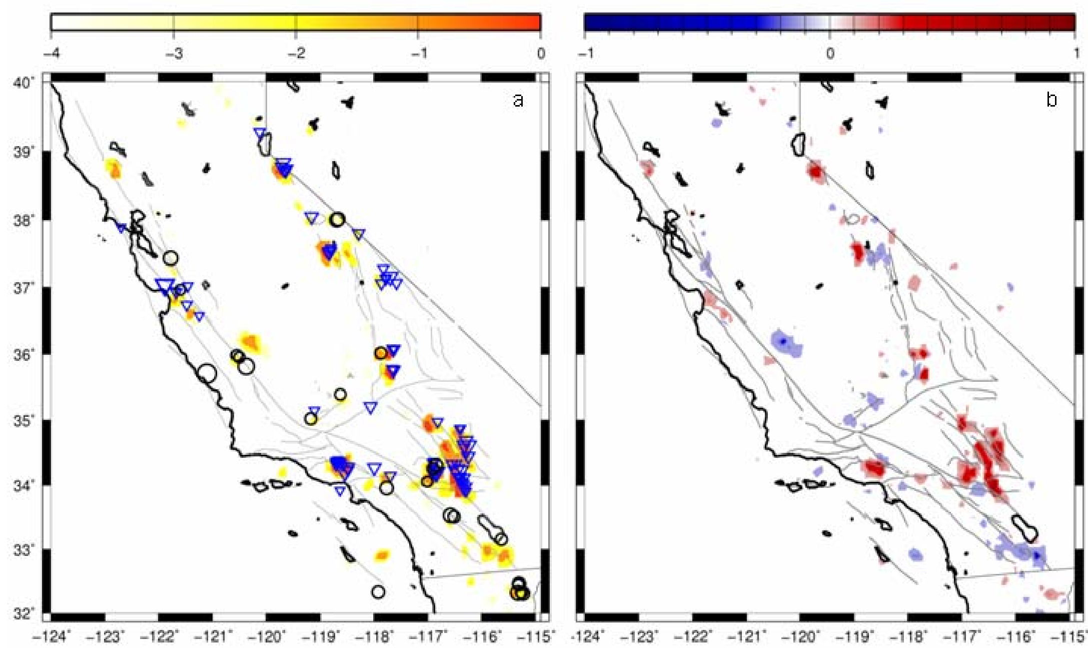


California

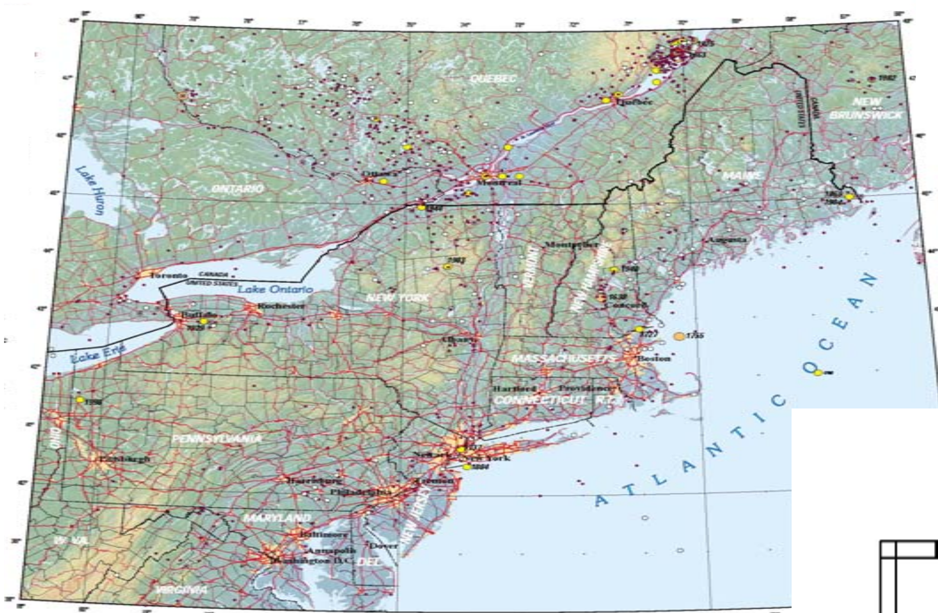
Can these results be used to improve seismicity based earthquake forecasts?

- The PI index measures anomalous seismicity rate, both positive (activation) and negative (quiescence), relative to the long-term background rate. These anomalous regions are then interpreted as a proxy for a forecast of an upcoming event.
- There tend to be very few false negatives (misses) if the historic data is of good quality, but more false positives.
- It is a good candidate to test potential improvements for ergodic regions because:

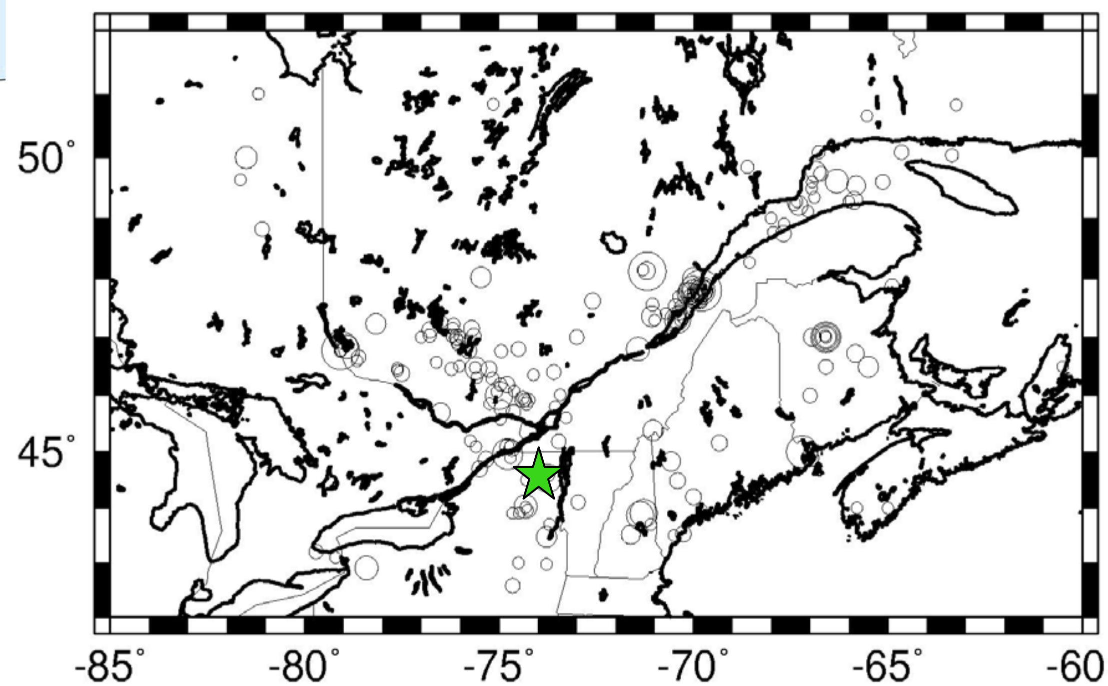
  - PI values are directly related to the spatial mean, and inversely related to the standard deviation in the seismicity rate, so it should be directly affected by variations in spatial averages.
  - Reductions in noise will improve the false positive rate.
  - Optimizing the parameter range of the input data for ergodic regions should increase the accuracy of the resulting forecasts.



Eastern North American Seismicity

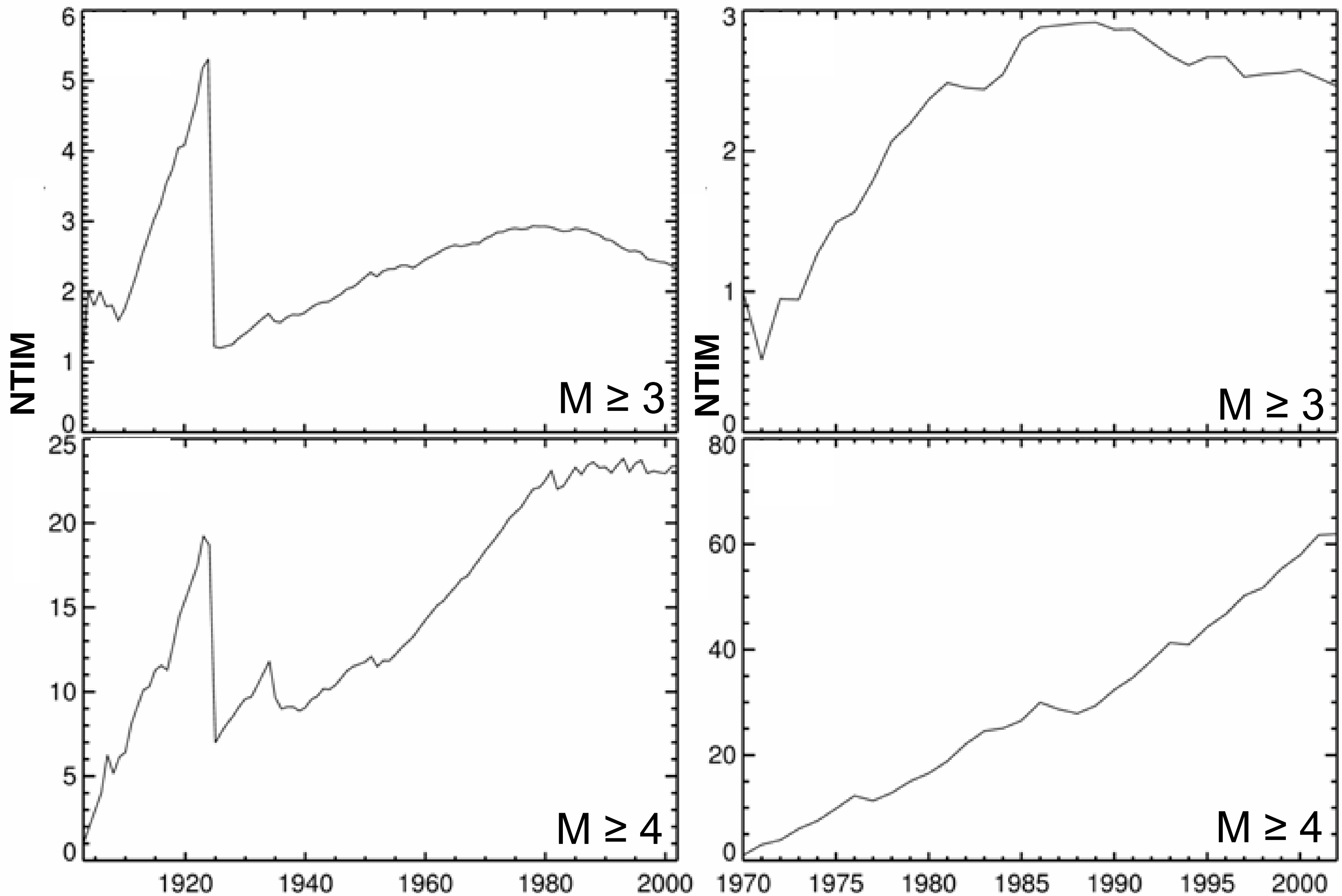


USGS



GSC

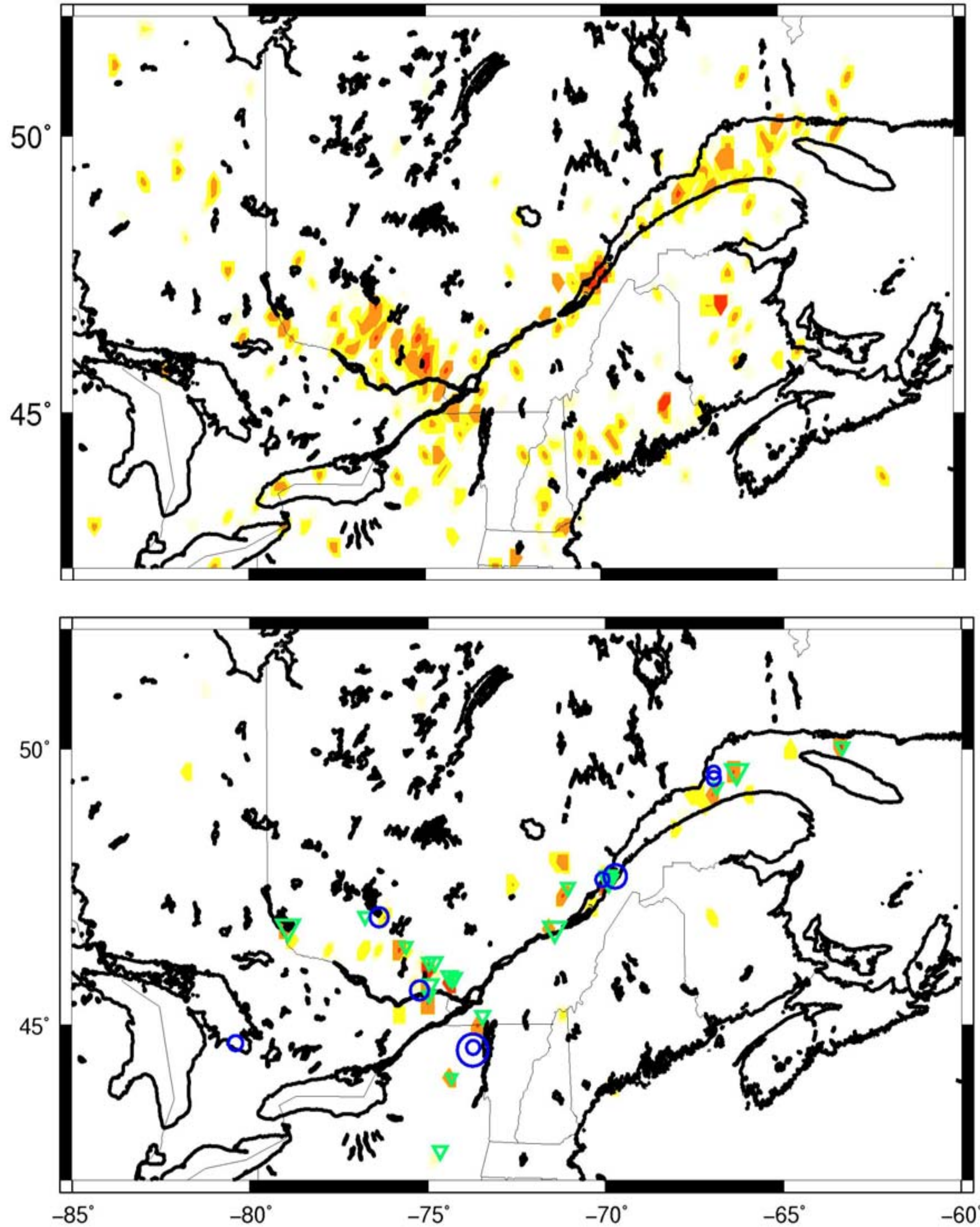
Ergodicity in Natural Catalogs



Boxsize = 0.2

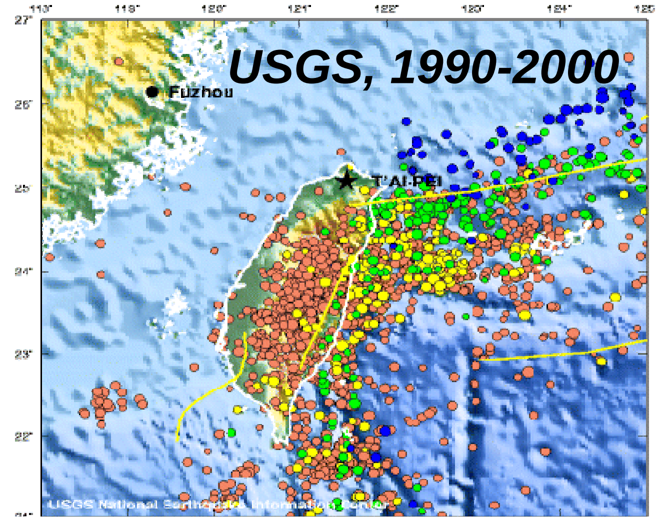
PI Index, eastern Canada

- 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.



Ergodicity in Natural Catalogs

Taiwan, M ≥ 3, 1973-2005



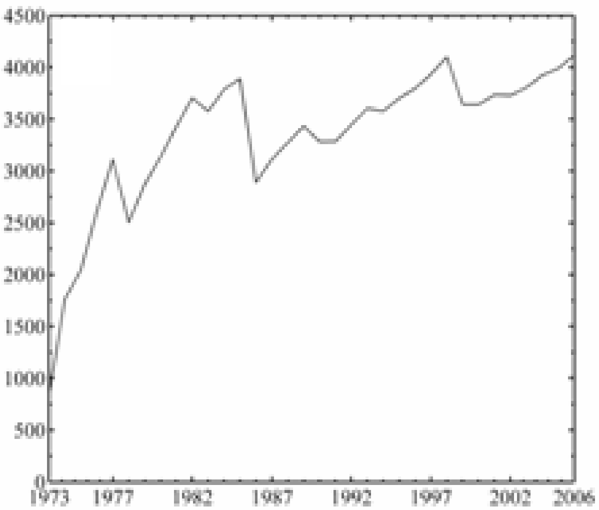
2D analysis, boxsize = 0.1

3D analysis, discretization of 0.1°×0.1°×1 km

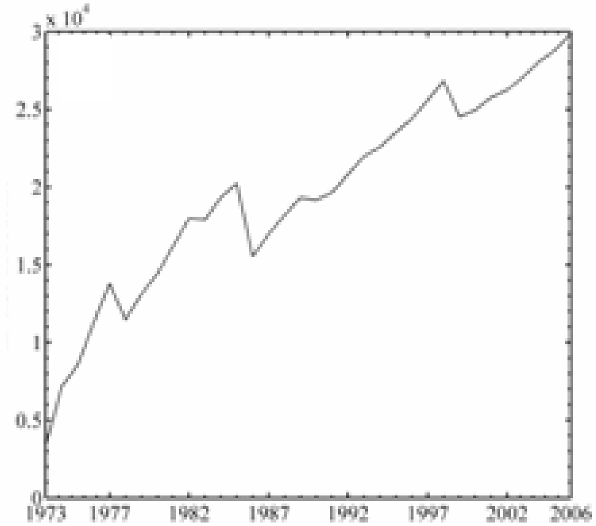
3D analysis, discretization of 0.1°×0.1°×0.25 km

Ergodicity in Natural Catalogs

2D analysis,
boxsize = 0.02°



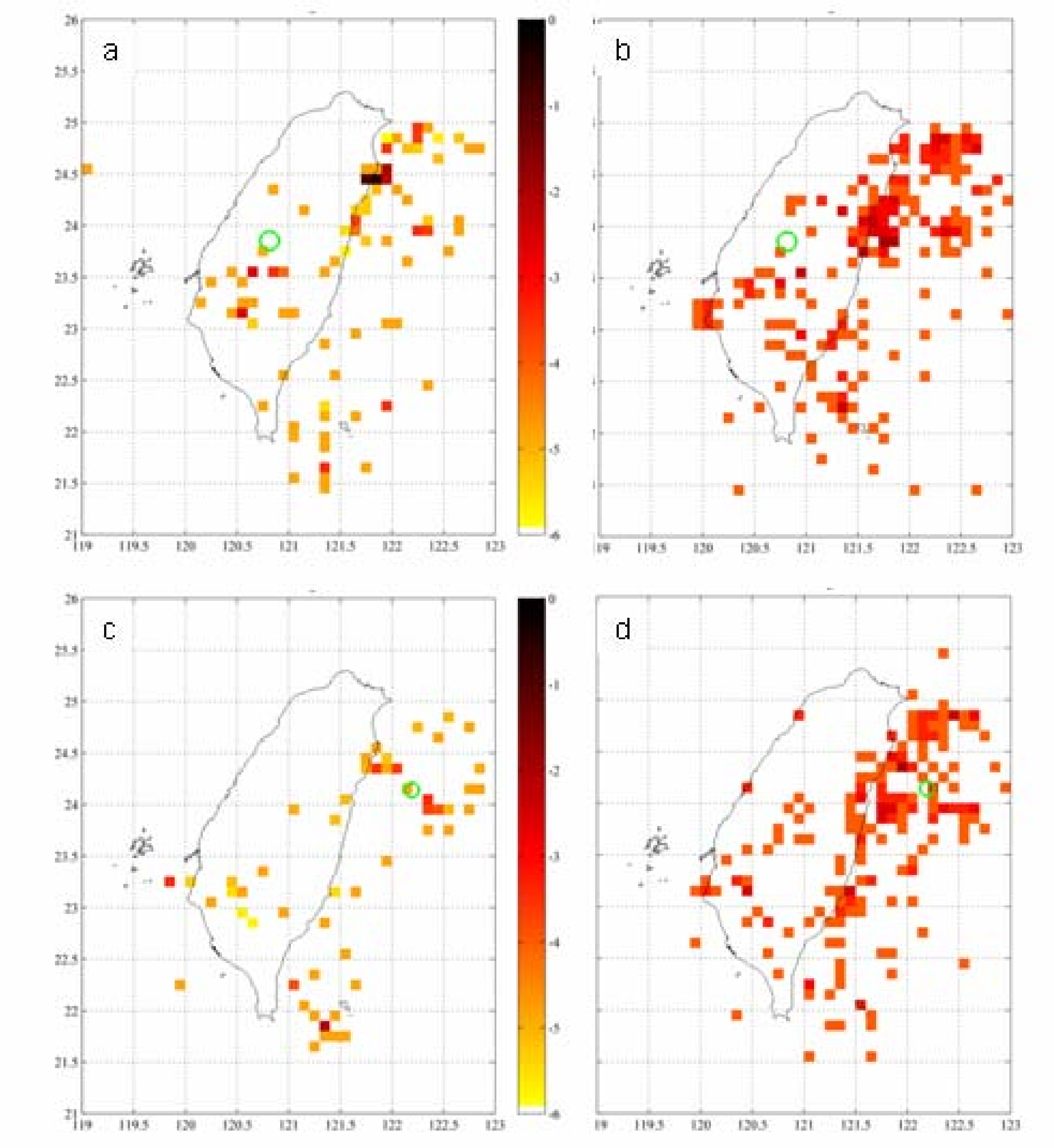
3D analysis,
discretization of
0.1°×0.1°×1 km

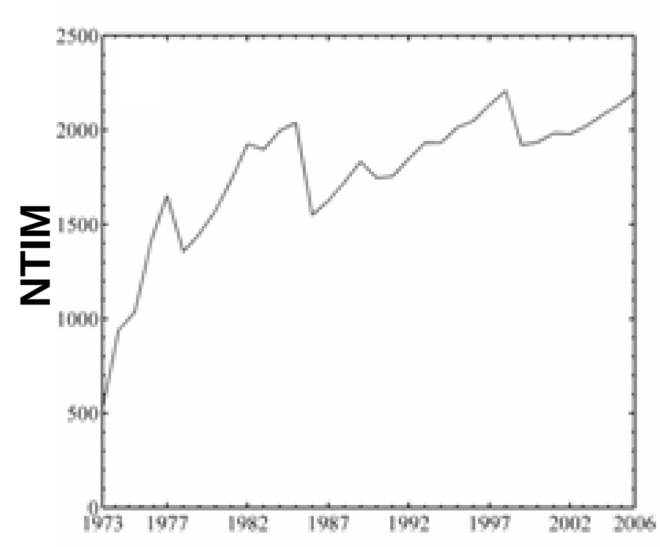


3D analysis,
discretization of
0.1°×0.1°×0.25 km.

Taiwan, M ≥ 4, 1973-2005

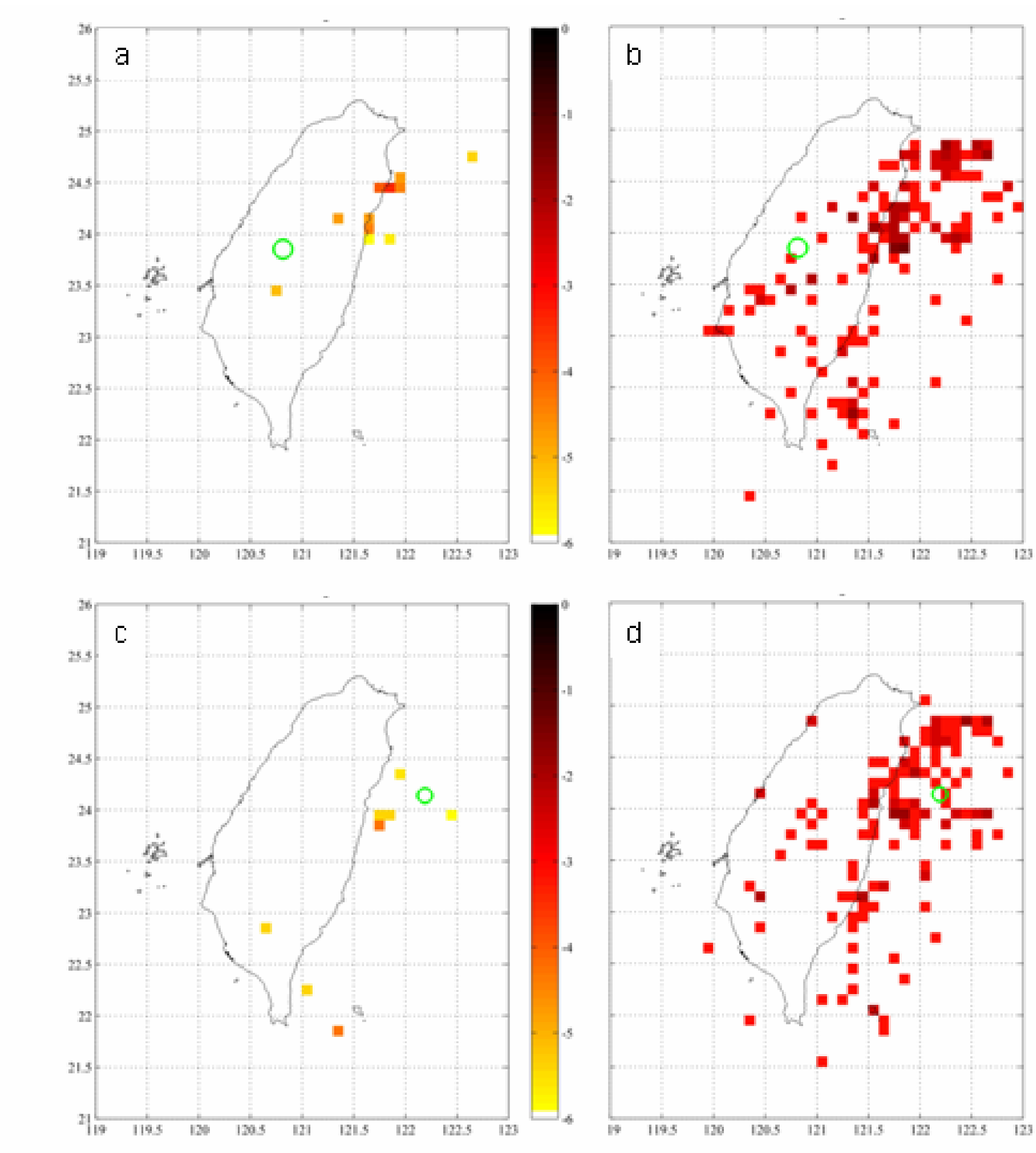
Ergodicity in Natural Catalogs

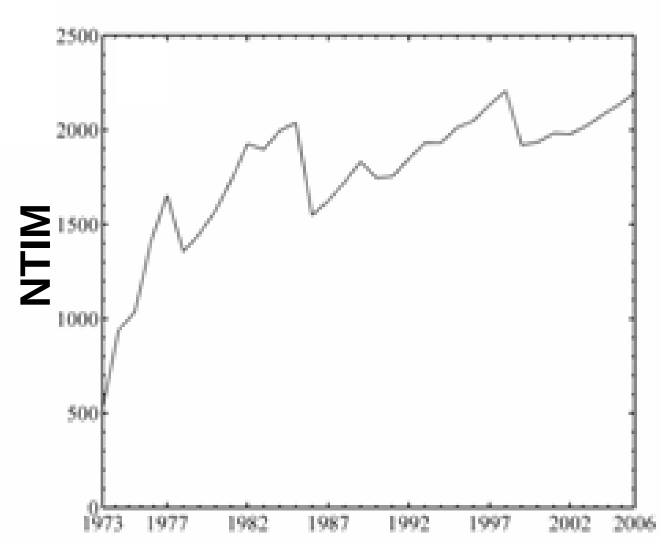




Plots of 3D PI and RI maps the Taiwanese subduction zone for $M \geq 3$, a time step of 1 year, and a discretization of 0.1°×0.1°×0.25 km, calculated for 1994-1998. Green circles indicate the large events of $M \geq 6$ that occur in the period 1999-2003. Depth ranges of a) and b) 7.75 to 8.00 km, c) and d) 13.75 to 14.00 km. The color scale is logarithmic.

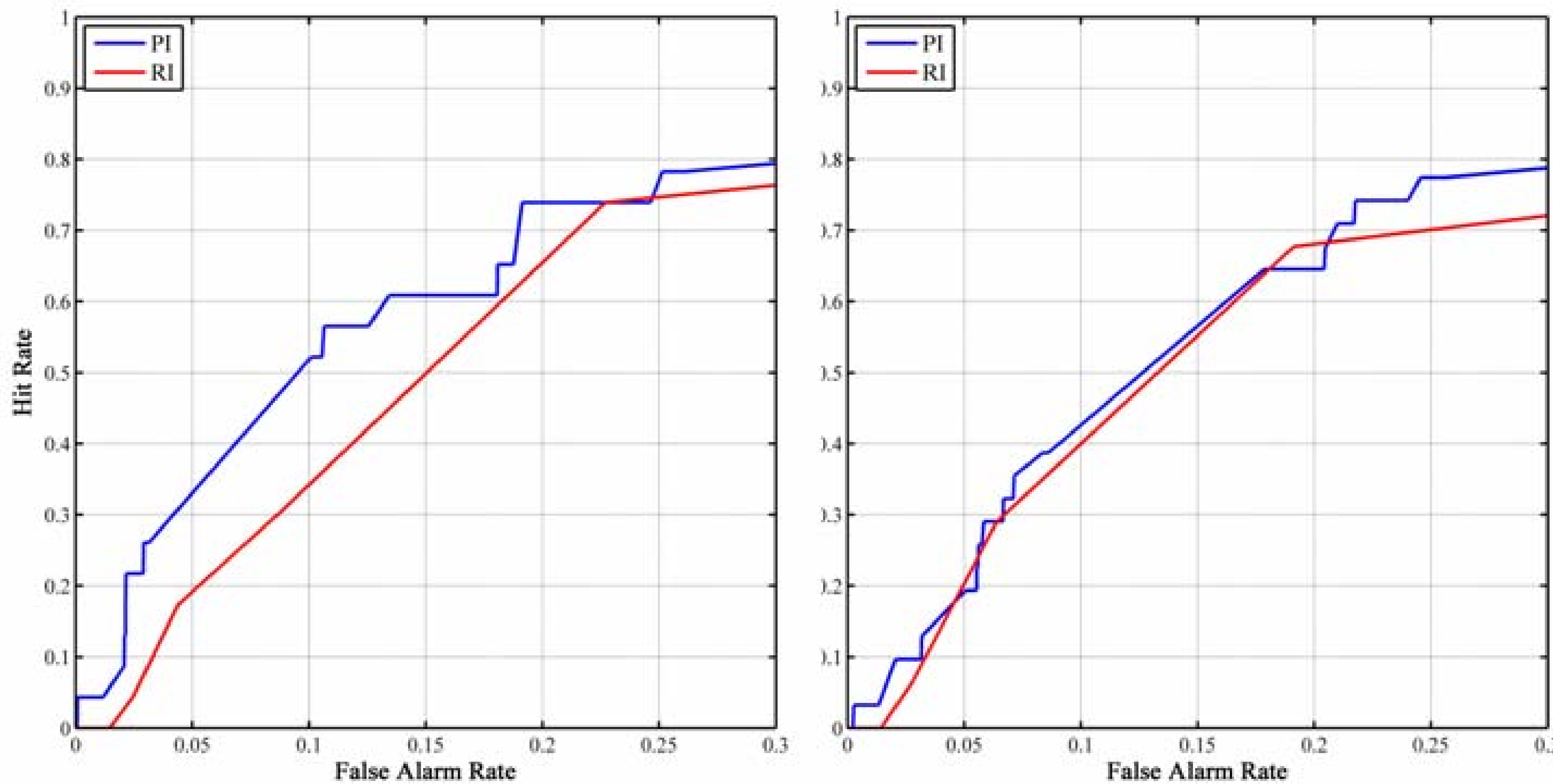
Ergodicity in Natural Catalogs





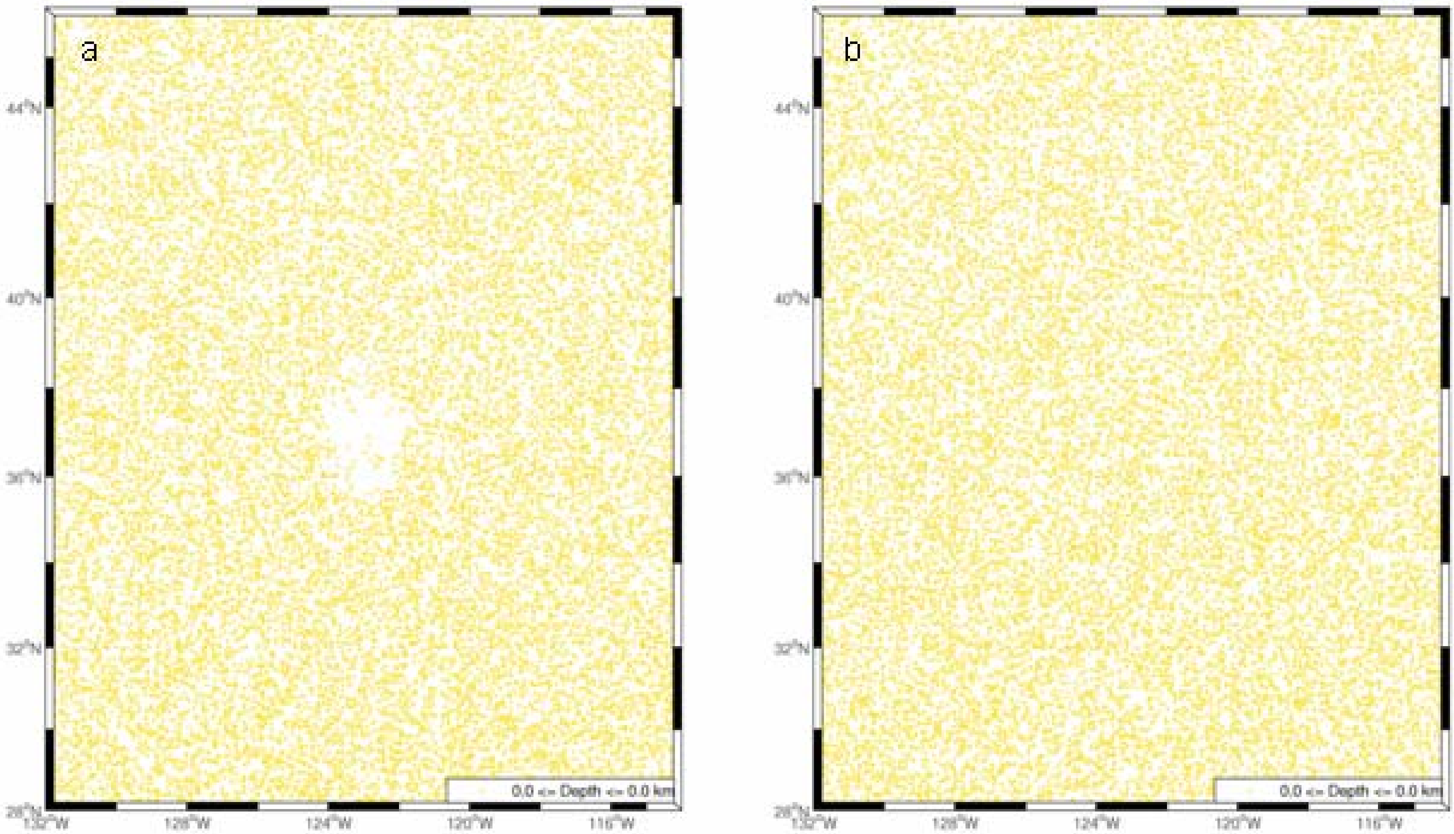
Plots of 3D PI and RI maps with parameters as shown previously, but for the calculation period of 1988-1997. Depth ranges again are for a) and b) 7.75 to 8.00 km, c) and d) 13.75 to 14.00 km.

Ergodicity in Natural Catalogs



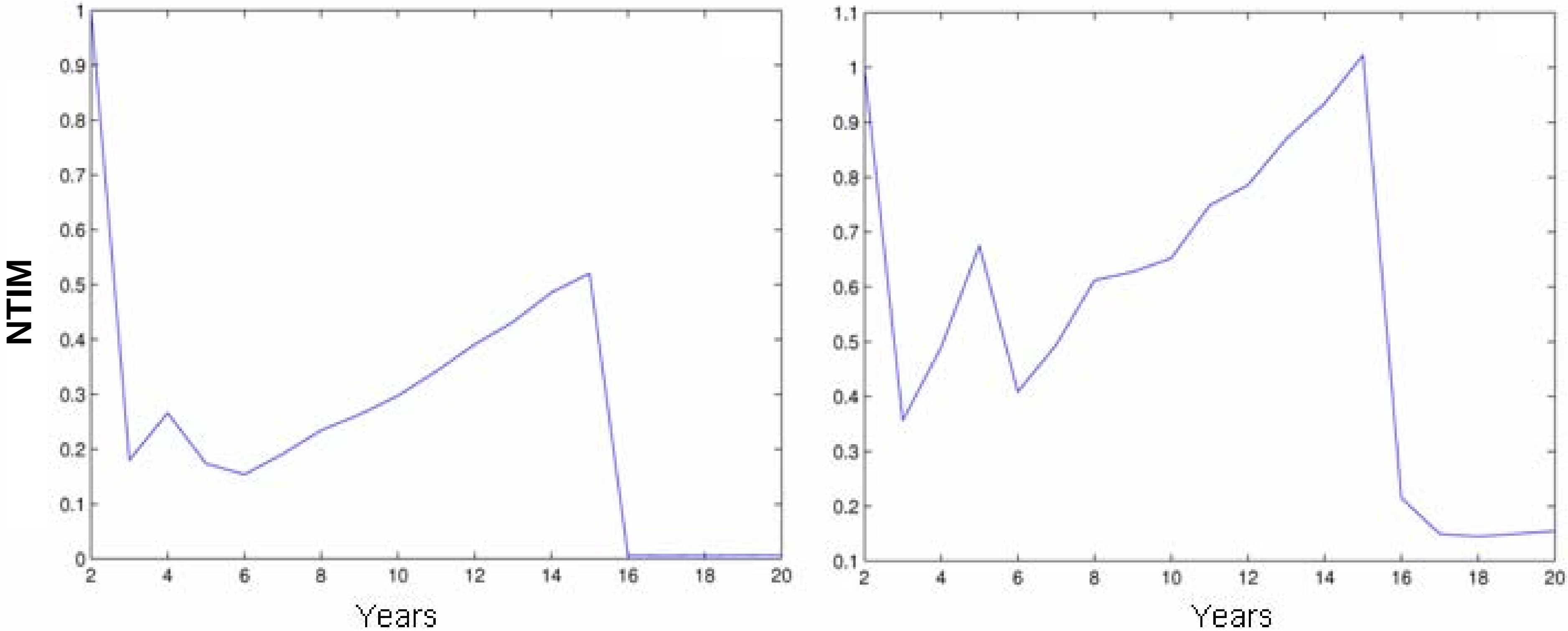
ROC diagrams comparing the PI and RI maps for the previous forecasts. Again, on the left is shown the results for a forecast using the effectively ergodic period, 1994-1998, while on the right is shown the same forecast using a non-ergodic period, 1988-1997.

Ergodicity in Synthetic Catalogs



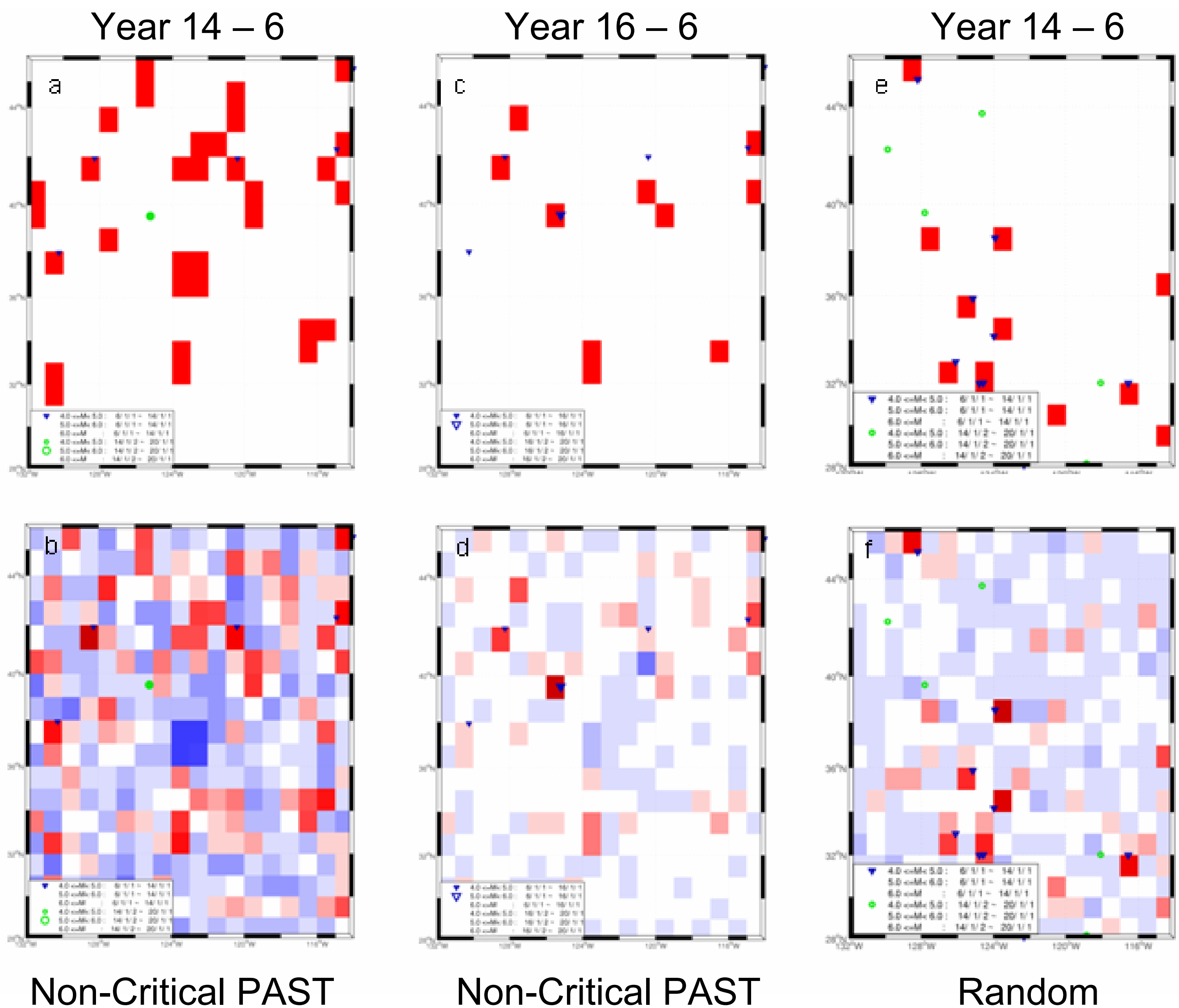
Left: Synthetic catalog with a reverse fault (*L* = 200 km, *W* = 10 km, *dip* = 45°, expected magnitude *M* ~ 7.3) is located in the centre of an 18 degree square region. A stress shadow (quiescence) is created at *t*=0 and decreases in size through time, until t_f = 20 yrs. Background events produce aftershocks which can also produce their own aftershocks. Right: Synthetic seismicity catalog, background seismicity only.

Ergodicity in Synthetic Catalogs

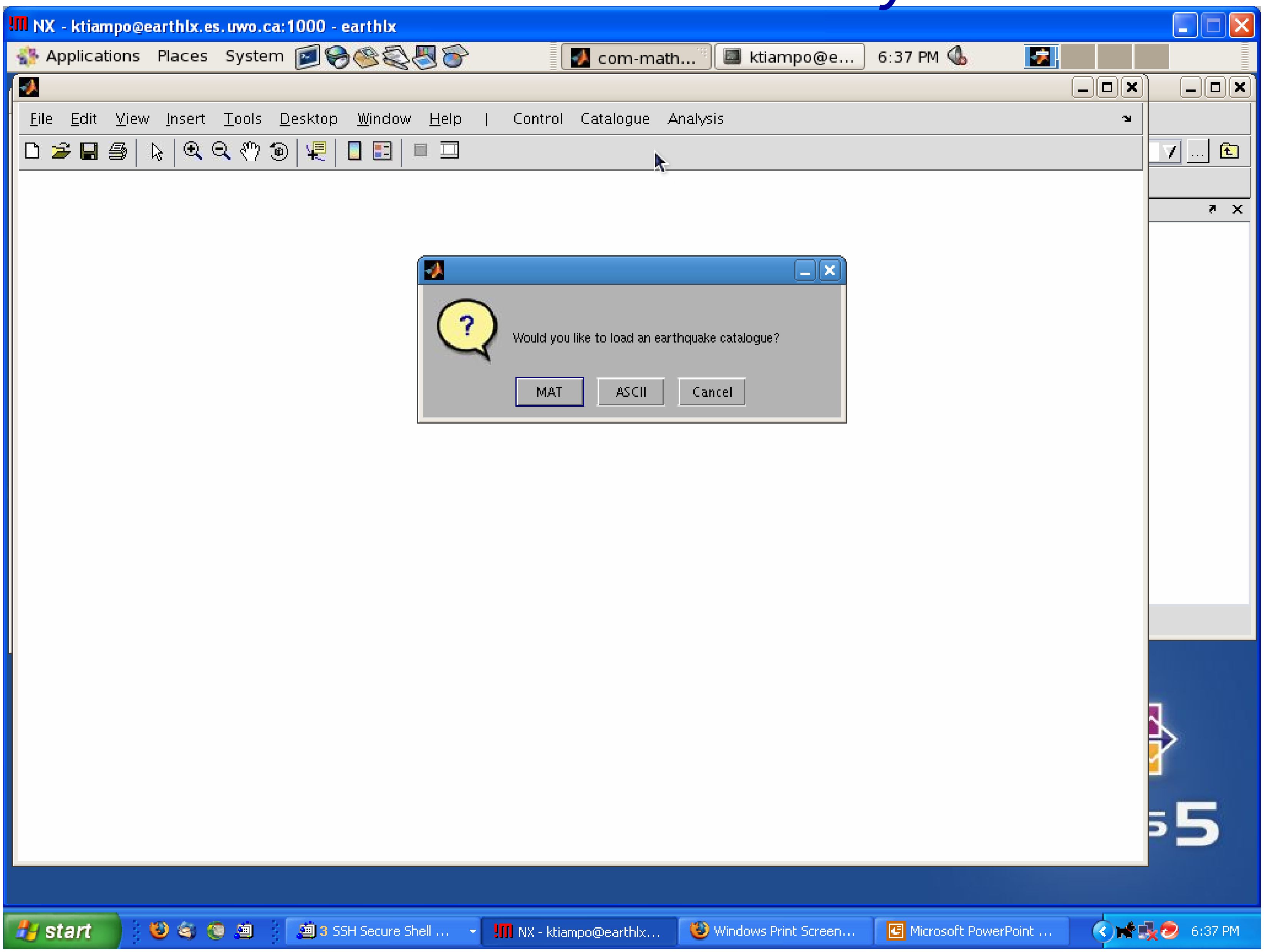


Left: Inverse TM metric, for the synthetic catalog with quiescence;
Right: Inverse TM metric for the random catalog.

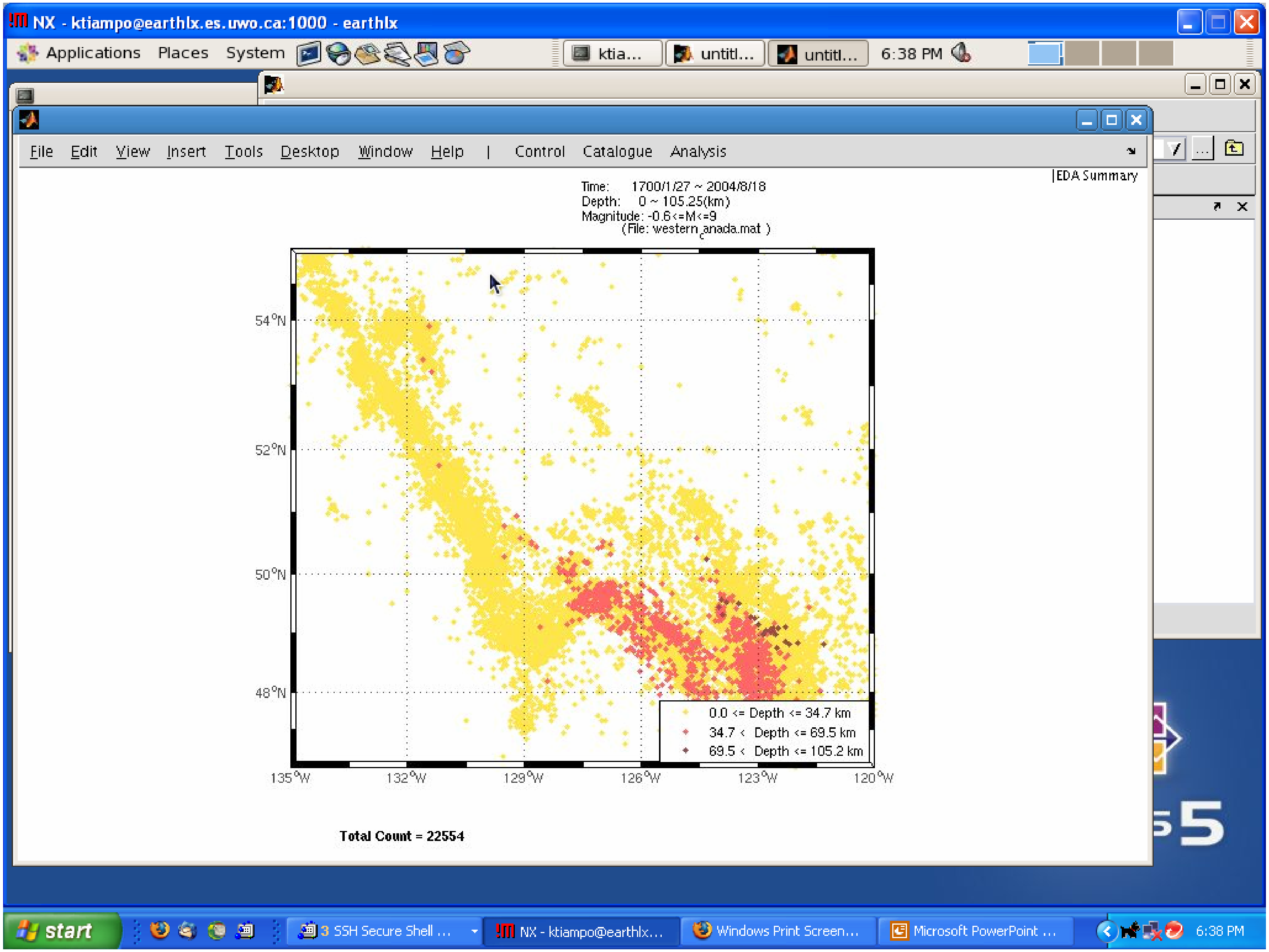
Ergodicity in Synthetic Catalogs



MAPI – A software tool to implement and test these methods interactively

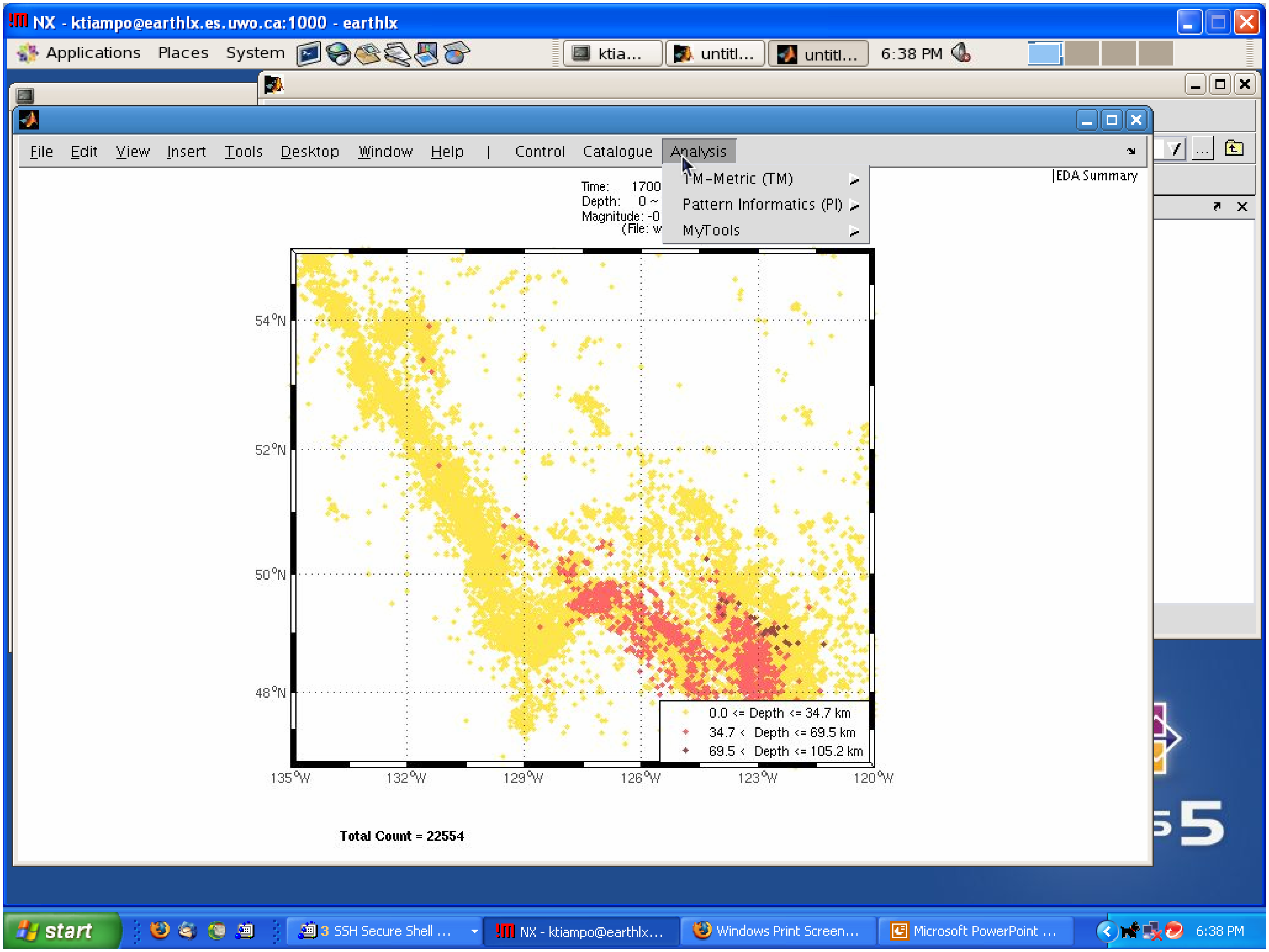


MAPI



NX - ktiampo@earthlx.es.uwo.ca:1000 - earthlx
Applications Places System
File Edit View Insert Tools Desktop Window Help | Control Catalogue Analysis
EDA Summary
Time: 1700/1/27 ~ 2004/8/18
Depth: 0 ~ 105.25(km)
Magnitude: -0.6<=M<=9
(File: western_canada.mat)
54°N
52°N
50°N
48°N
135°W
132°W
129°W
126°W
123°W
120°W
0.0 <= Depth <= 34.7 km
34.7 < Depth <= 69.5 km
69.5 < Depth <= 105.2 km
Total Count = 22554
start

MAPI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54°N
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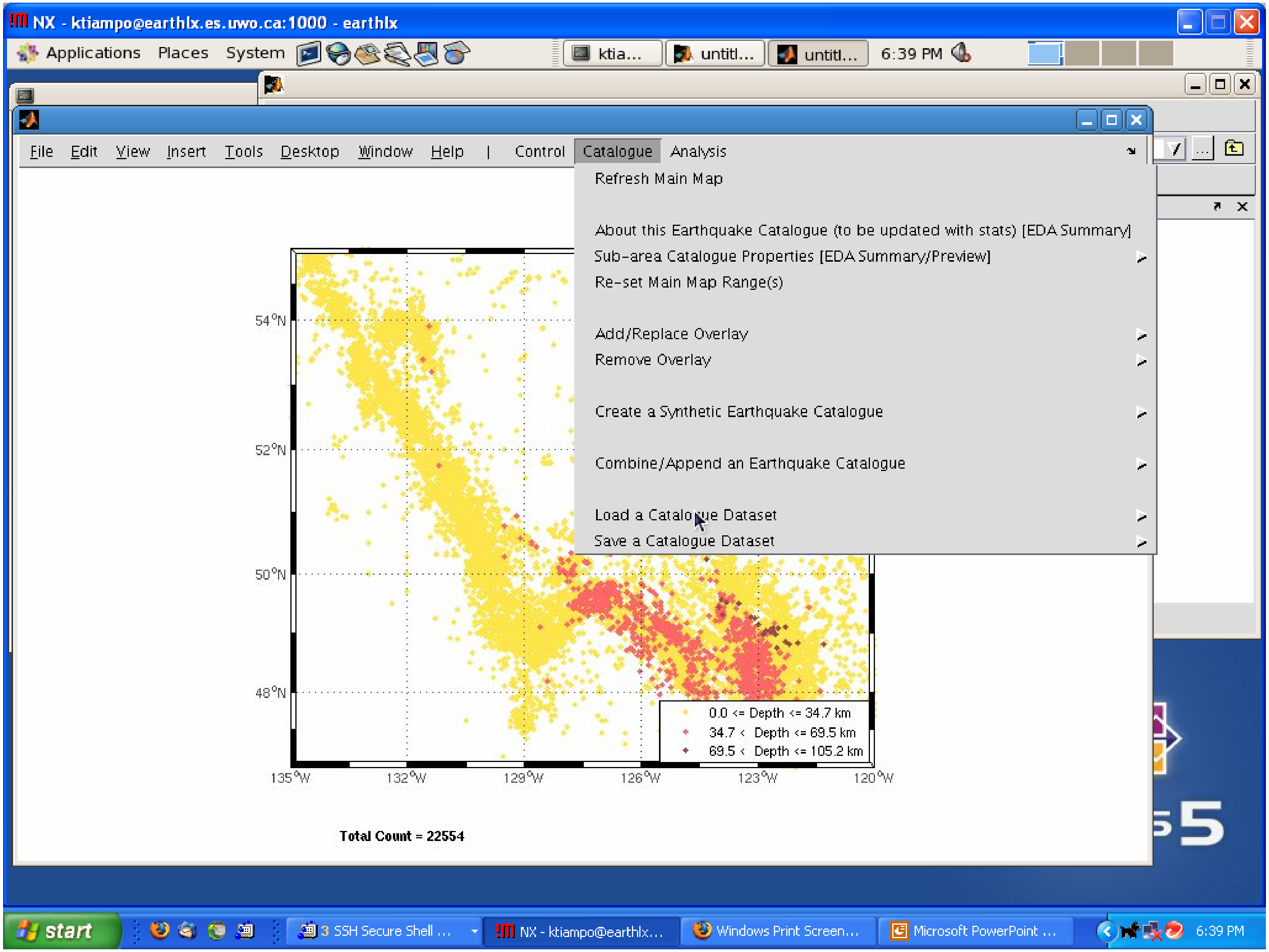
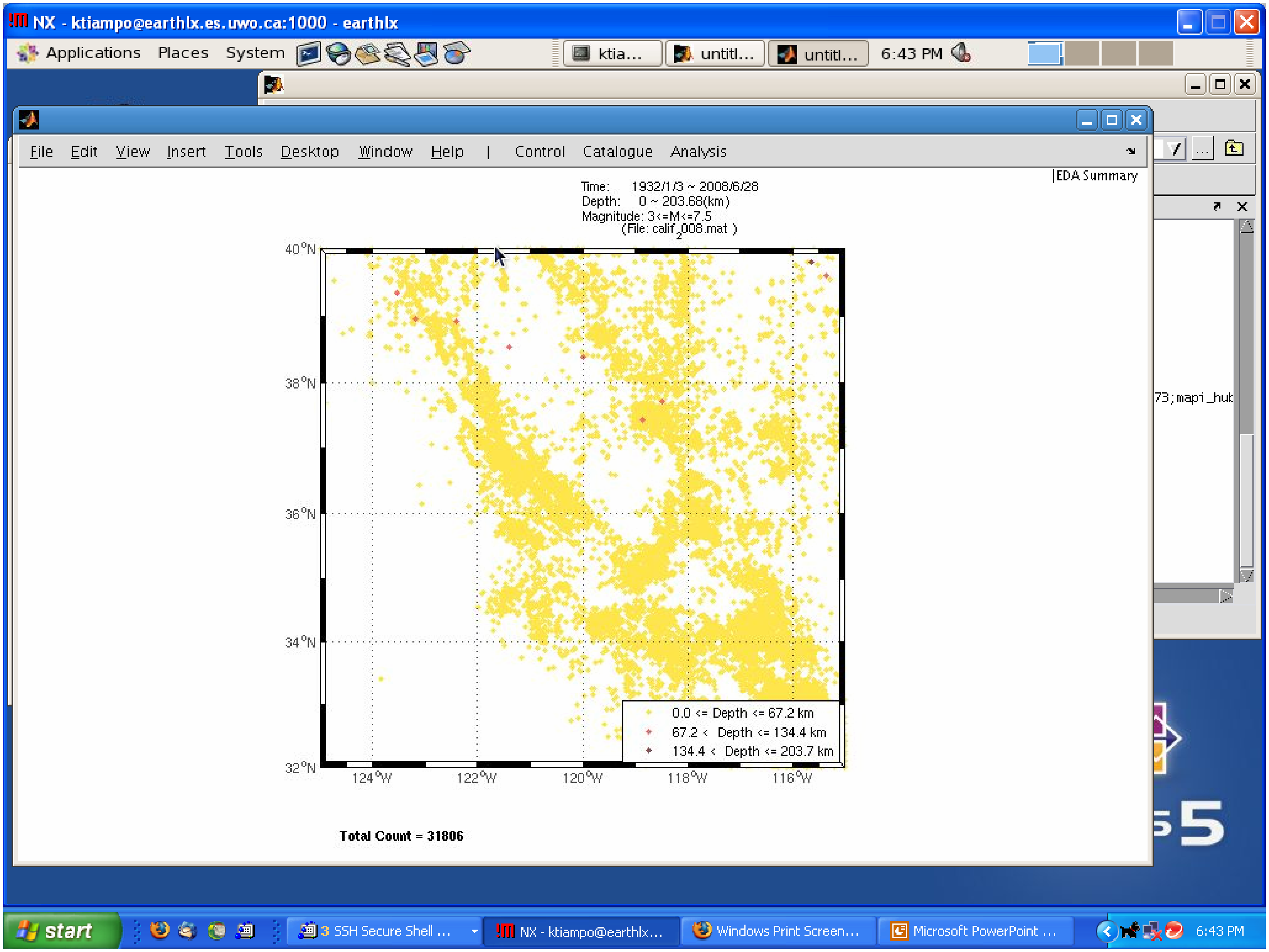
0.0 <= Depth <= 34.7 km
34.7 < Depth <= 69.5 km
69.5 < Depth <= 105.2 km
Total Count = 22554
start
3 SSH Secure Shell ...
NX - ktiampo@earthlx...
Windows Print Screen...
Microsoft PowerPoint ...
6:38 PM

MAPI



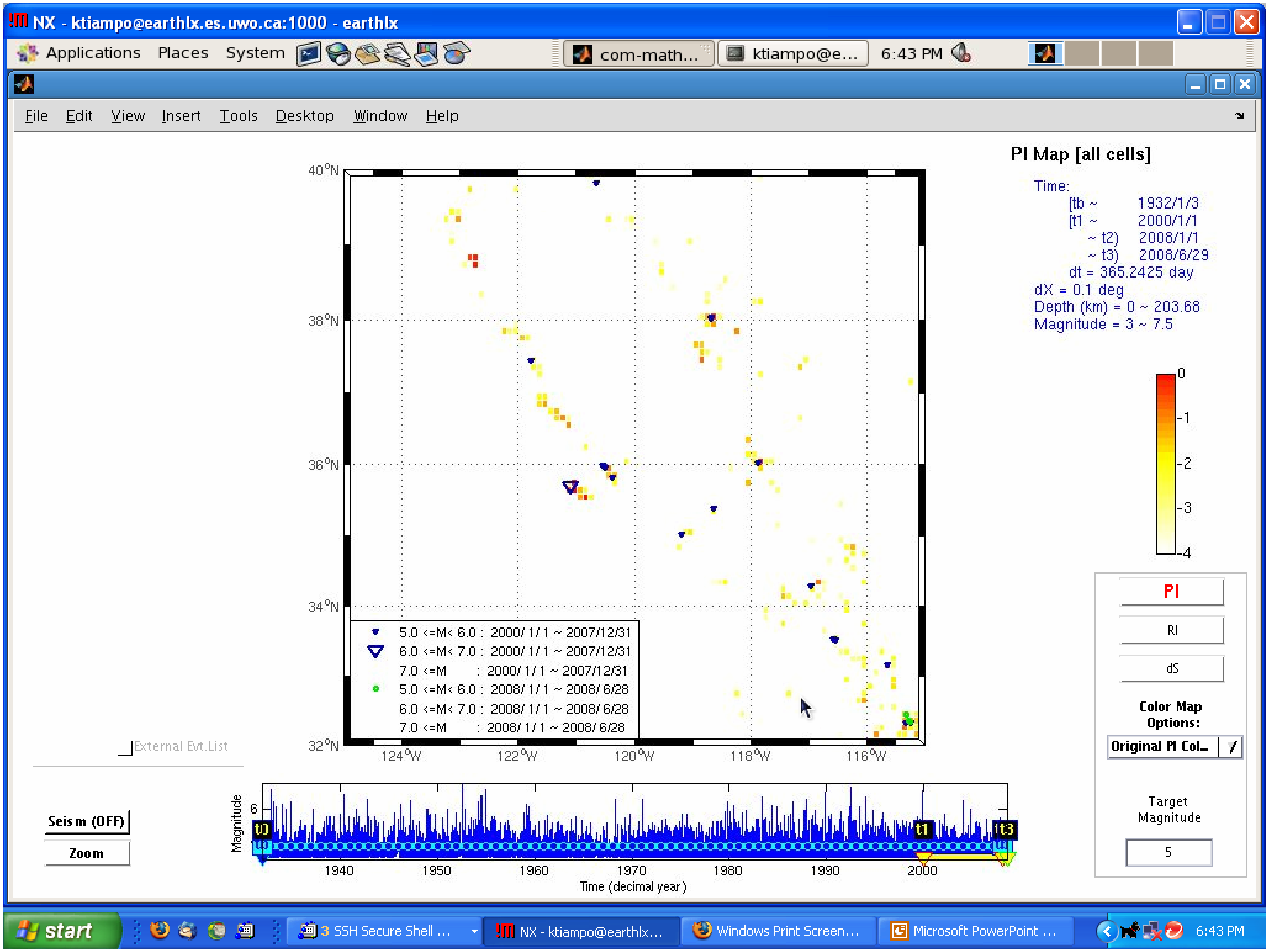
NX - ktiampo@earthlx.es.uwo.ca:1000 - earthlx
Applications Places System
6:39 PM
File Edit View Insert Tools Desktop Window Help | Control Catalogue Analysis
Refresh Main Map
About this Earthquake Catalogue (to be updated with stats) [EDA Summary]
Sub-area Catalogue Properties [EDA Summary/Preview]
Re-set Main Map Range(s)
Add/Replace Overlay
Remove Overlay
Create a Synthetic Earthquake Catalogue
Combine/Append an Earthquake Catalogue
Load a Catalogue Dataset
Save a Catalogue Dataset
54°N
52°N
50°N
48°N
135°W
132°W
129°W
126°W
123°W
120°W
0.0 <= Depth <= 34.7 km
34.7 < Depth <= 69.5 km
69.5 < Depth <= 105.2 km
Total Count = 22554
start
3 SSH Secure Shell ...
NX - ktiampo@earthlx...
Windows Print Screen...
Microsoft PowerPoint ...
6:39 PM

MAPI



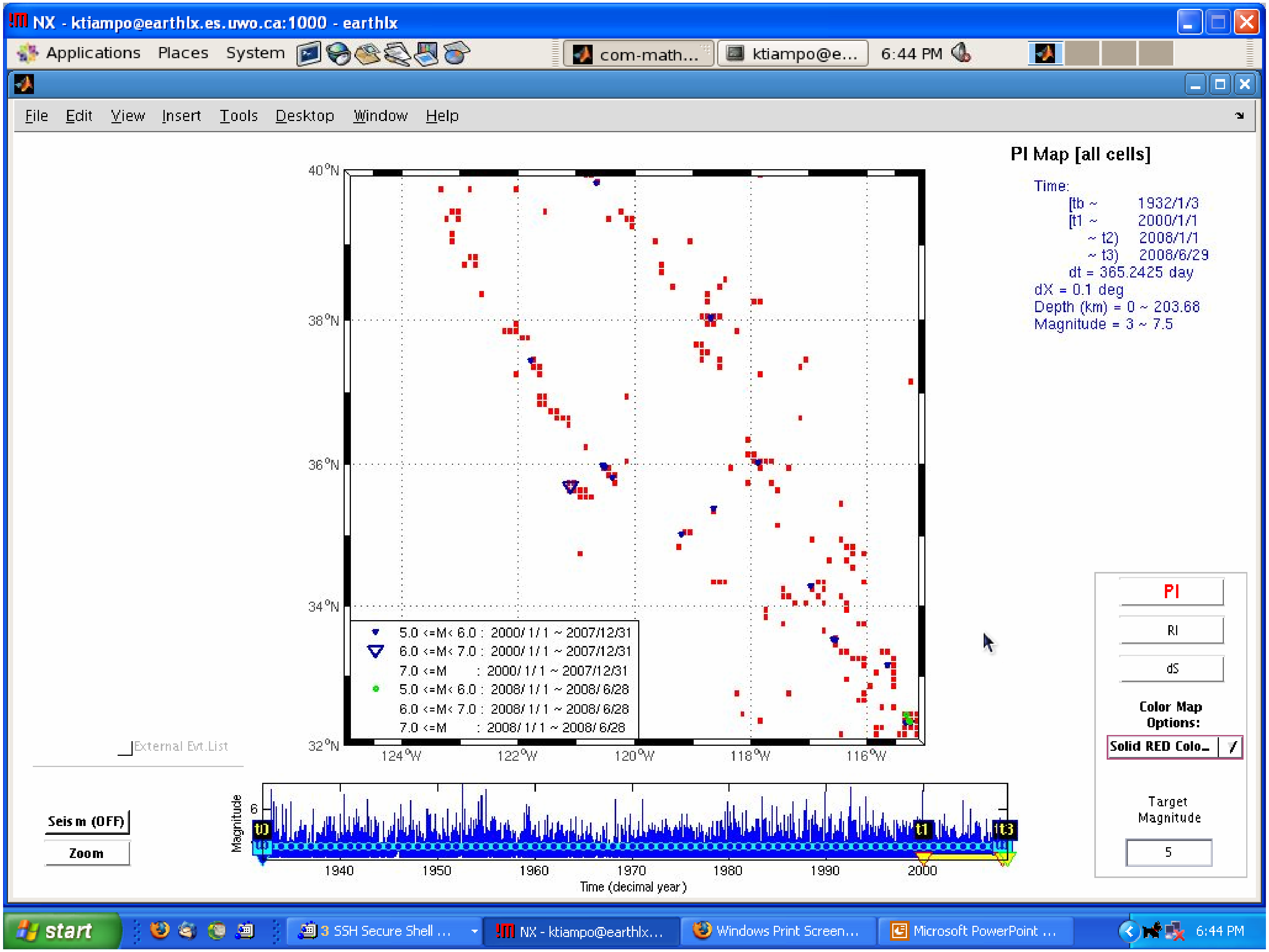
NX - ktiampo@earthlx.es.uwo.ca:1000 - earthlx
Applications Places System
6:43 PM
File Edit View Insert Tools Desktop Window Help | Control Catalogue Analysis
EDA Summary
Time: 1932/1/3 ~ 2008/6/28
Depth: 0 ~ 203.68(km)
Magnitude: 3<=M<=7.5
(File: calif_2008.mat)
40°N
38°N
36°N
34°N
32°N
124°W
122°W
120°W
118°W
116°W
0.0 <= Depth <= 67.2 km
67.2 < Depth <= 134.4 km
134.4 < Depth <= 203.7 km
Total Count = 31806
start
3 SSH Secure Shell ...
NX - ktiampo@earthlx...
Windows Print Screen...
Microsoft PowerPoint ...
6:43 PM

MAPI



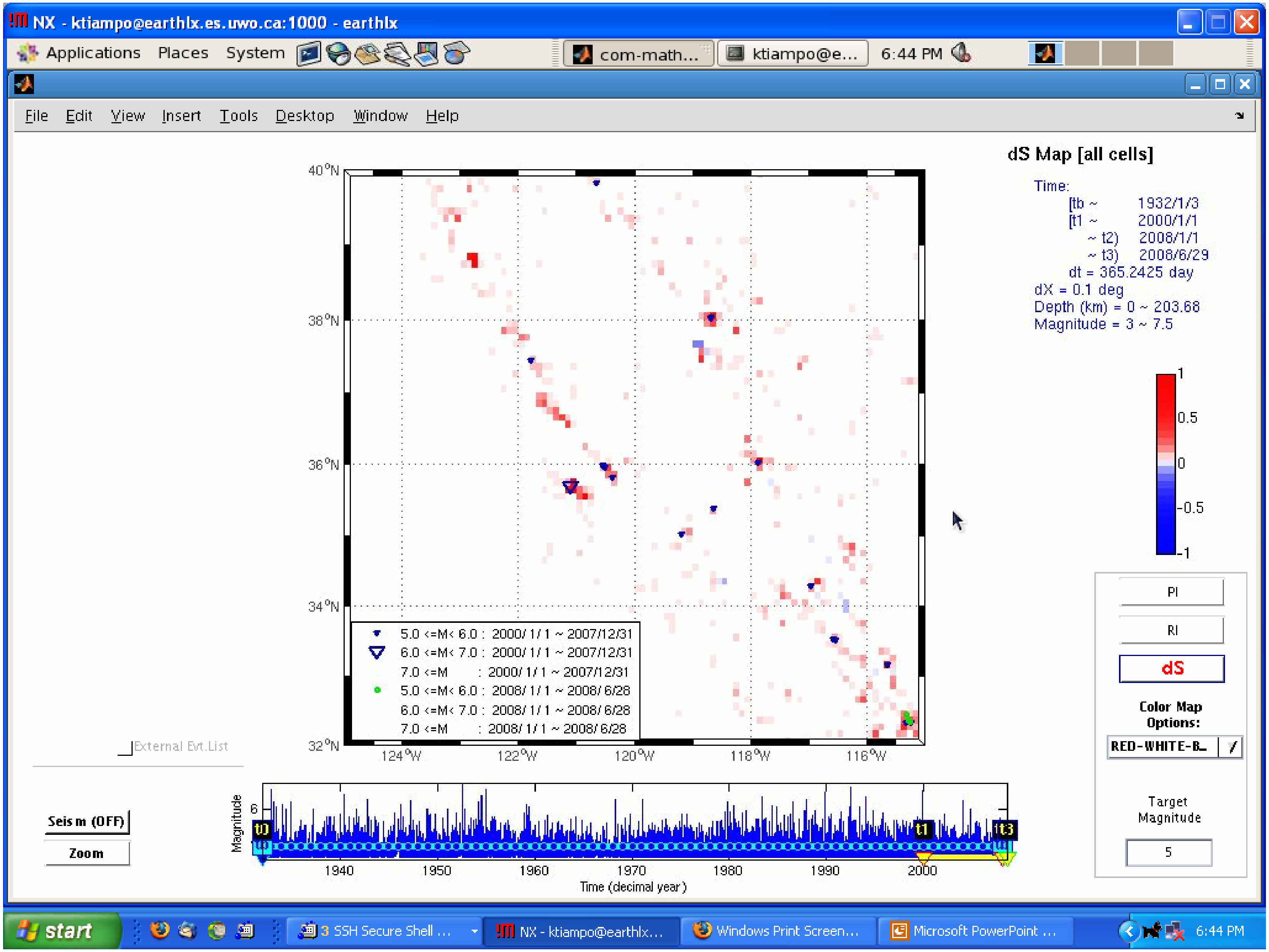
NX - ktiampo@earthlx.es.uwo.ca:1000 - earthlx
Applications Places System
com-math...
ktiampo@e...
6:43 PM
File Edit View Insert Tools Desktop Window Help
PI Map [all cells]
Time:
[tb ~ 1932/1/3
[t1 ~ 2000/1/1
~ t2) 2008/1/1
~ t3) 2008/6/29
dt = 365.2425 day
dX = 0.1 deg
Depth (km) = 0 ~ 203.68
Magnitude = 3 ~ 7.5
0
-1
-2
-3
-4
40°N
38°N
36°N
34°N
32°N
124°W
122°W
120°W
118°W
116°W
5.0 <=M< 6.0 : 2000/1/1 ~ 2007/12/31
6.0 <=M< 7.0 : 2000/1/1 ~ 2007/12/31
7.0 <=M : 2000/1/1 ~ 2007/12/31
5.0 <=M< 6.0 : 2008/1/1 ~ 2008/6/28
6.0 <=M< 7.0 : 2008/1/1 ~ 2008/6/28
7.0 <=M : 2008/1/1 ~ 2008/6/28
PI
RI
dS
Color Map Options:
Original PI Col...
Target Magnitude
5
External Evt.List
Seism (OFF)
Zoom
Magnitude
6
t0
t1
t3
1940
1950
1960
1970
1980
1990
2000
Time (decimal year)
start
3 SSH Secure Shell ...
NX - ktiampo@earthlx...
Windows Print Screen...
Microsoft PowerPoint ...
6:43 PM

MAPI

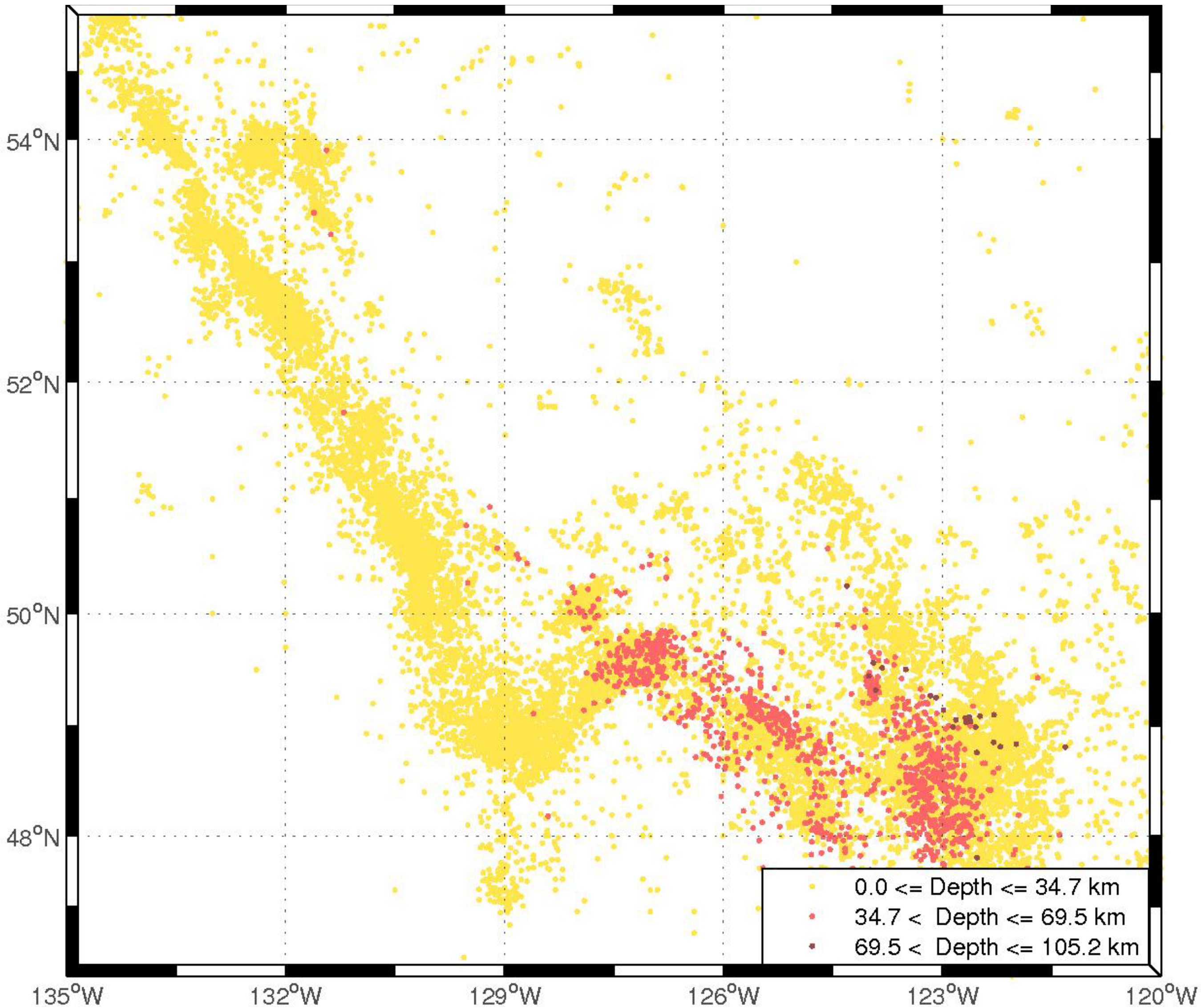


NX - ktiampo@earthlx.es.uwo.ca:1000 - earthlx
Applications Places System
com-math...
ktiampo@e...
6:44 PM
File Edit View Insert Tools Desktop Window Help
PI Map [all cells]
Time:
[tb ~ 1932/1/3
[t1 ~ 2000/1/1
~ t2) 2008/1/1
~ t3) 2008/6/29
dt = 365.2425 day
dX = 0.1 deg
Depth (km) = 0 ~ 203.68
Magnitude = 3 ~ 7.5
5.0 <=M< 6.0 : 2000/1/1 ~ 2007/12/31
6.0 <=M< 7.0 : 2000/1/1 ~ 2007/12/31
7.0 <=M : 2000/1/1 ~ 2007/12/31
5.0 <=M< 6.0 : 2008/1/1 ~ 2008/6/28
6.0 <=M< 7.0 : 2008/1/1 ~ 2008/6/28
7.0 <=M : 2008/1/1 ~ 2008/6/28
40°N
38°N
36°N
34°N
32°N
124°W
122°W
120°W
118°W
116°W
External Evt.List
PI
RI
dS
Color Map Options:
Solid RED Colo...
Target Magnitude
5
Seism (OFF)
Zoom
Magnitude
6
t0
t1
t3
1940
1950
1960
1970
1980
1990
2000
Time (decimal year)
start
3 SSH Secure Shell ...
NX - ktiampo@earthlx...
Windows Print Screen...
Microsoft PowerPoint ...
6:44 PM

MAPI

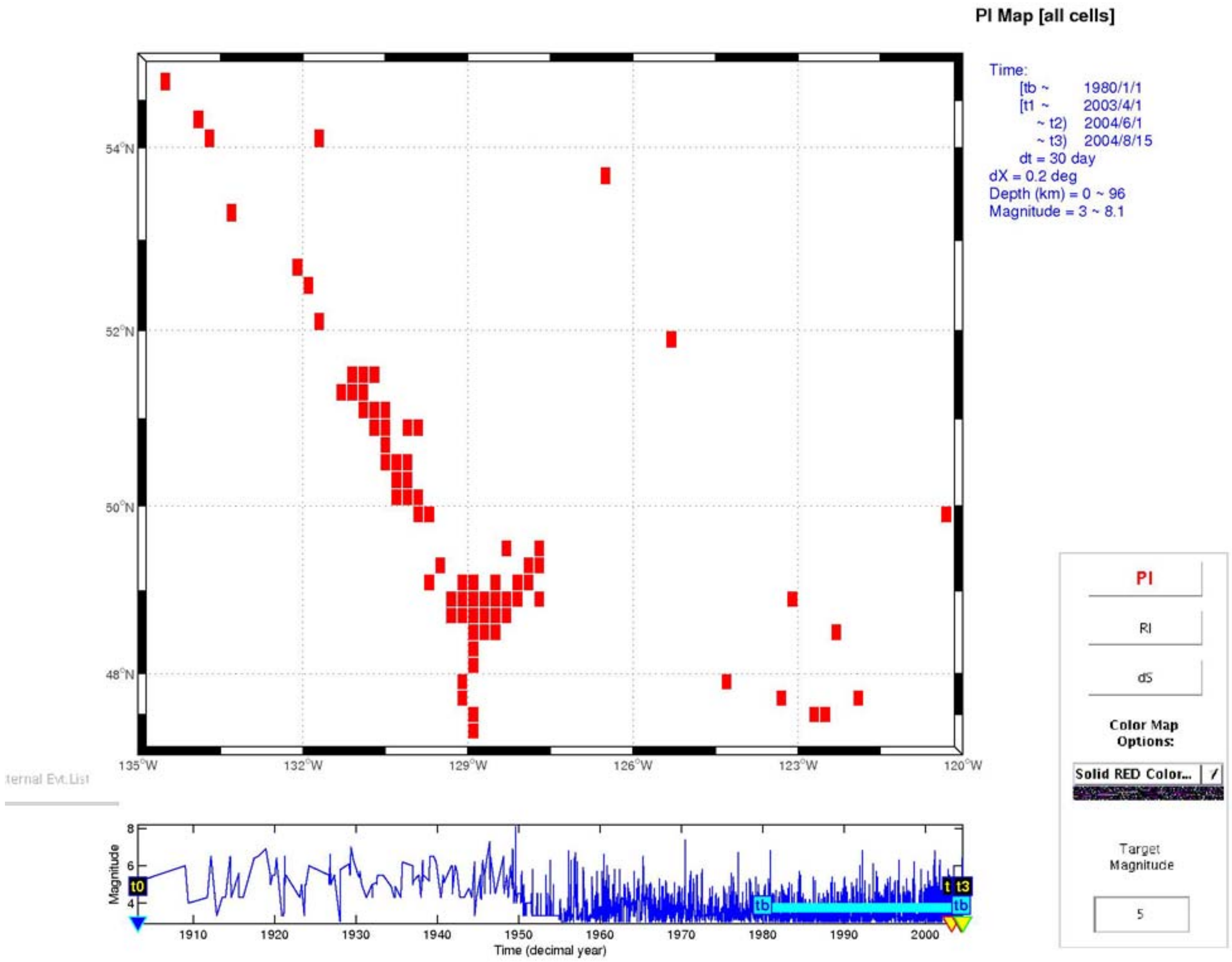

NX - ktiampo@earthlx.es.uwo.ca:1000 - earthlx
Applications Places System
File Edit View Insert Tools Desktop Window Help
dS Map [all cells]
Time:
[tb ~ 1932/1/3
[t1 ~ 2000/1/1
~ t2) 2008/1/1
~ t3) 2008/6/29
dt = 365.2425 day
dX = 0.1 deg
Depth (km) = 0 ~ 203.68
Magnitude = 3 ~ 7.5
5.0 <=M< 6.0 : 2000/ 1/ 1 ~ 2007/12/31
6.0 <=M< 7.0 : 2000/ 1/ 1 ~ 2007/12/31
7.0 <=M : 2000/ 1/ 1 ~ 2007/12/31
5.0 <=M< 6.0 : 2008/ 1/ 1 ~ 2008/ 6/28
6.0 <=M< 7.0 : 2008/ 1/ 1 ~ 2008/ 6/28
7.0 <=M : 2008/ 1/ 1 ~ 2008/ 6/28
40°N
38°N
36°N
34°N
32°N
124°W
122°W
120°W
118°W
116°W
PI
RI
dS
Color Map Options:
RED-WHITE-B
Target Magnitude
5
Seism (OFF)
Zoom
External Evt.List
Magnitude
Time (decimal year)
1940
1950
1960
1970
1980
1990
2000
start
3 SSH Secure Shell ...
NX - ktiampo@earthlx...
Windows Print Screen...
Microsoft PowerPoint ...
6:44 PM

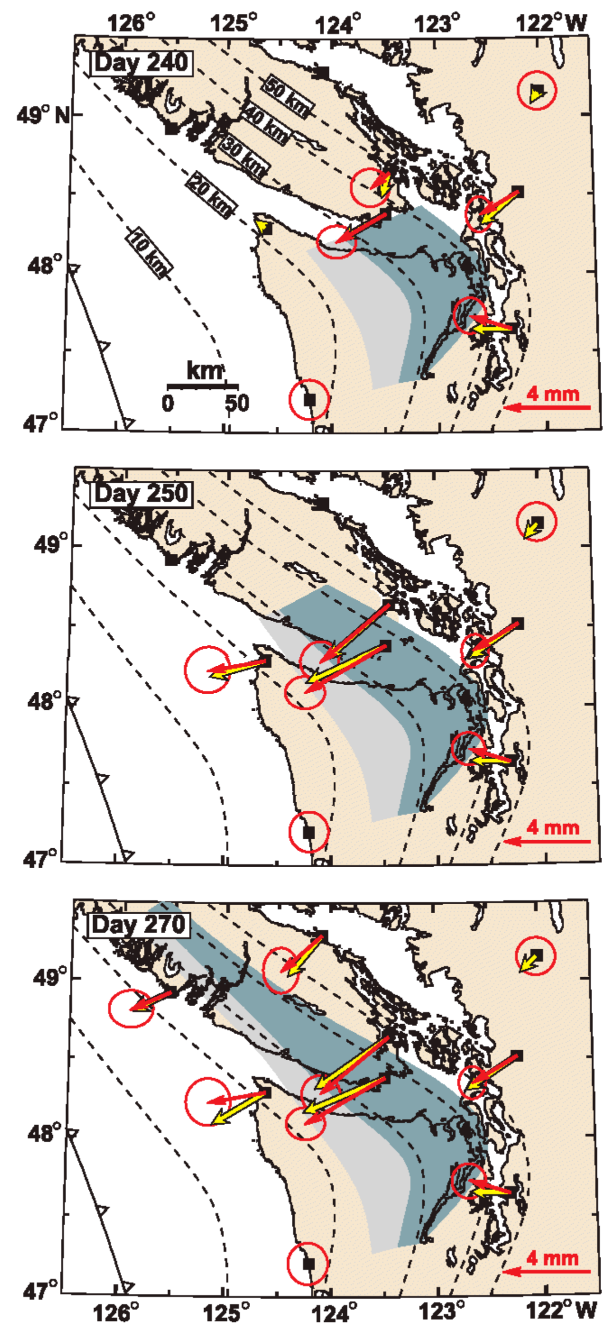
Western Canada



Western Canada

Episodic Tremor & Slip (ETS), 2004





gsc.nrcan.gc.ca/geodyn/silentslip2_e.php

Western Canada

PI: 2003-1993