



Institute for
Catastrophic Loss
Reduction

BENFIELD




Earthquake Forecasting: Advances and Challenges

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Outline

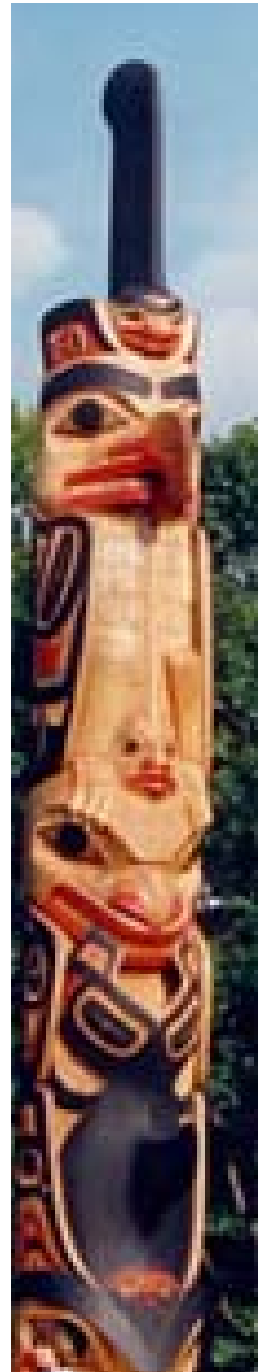
- Introduction
- Patterns and statistics in earthquake systems
- Earthquake forecasting using historic seismicity data
- Improving earthquake forecasting
- Demonstrate a new, interactive program that calculates these forecasts for researchers and, eventually, government agencies
- Examples, including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

Motivation

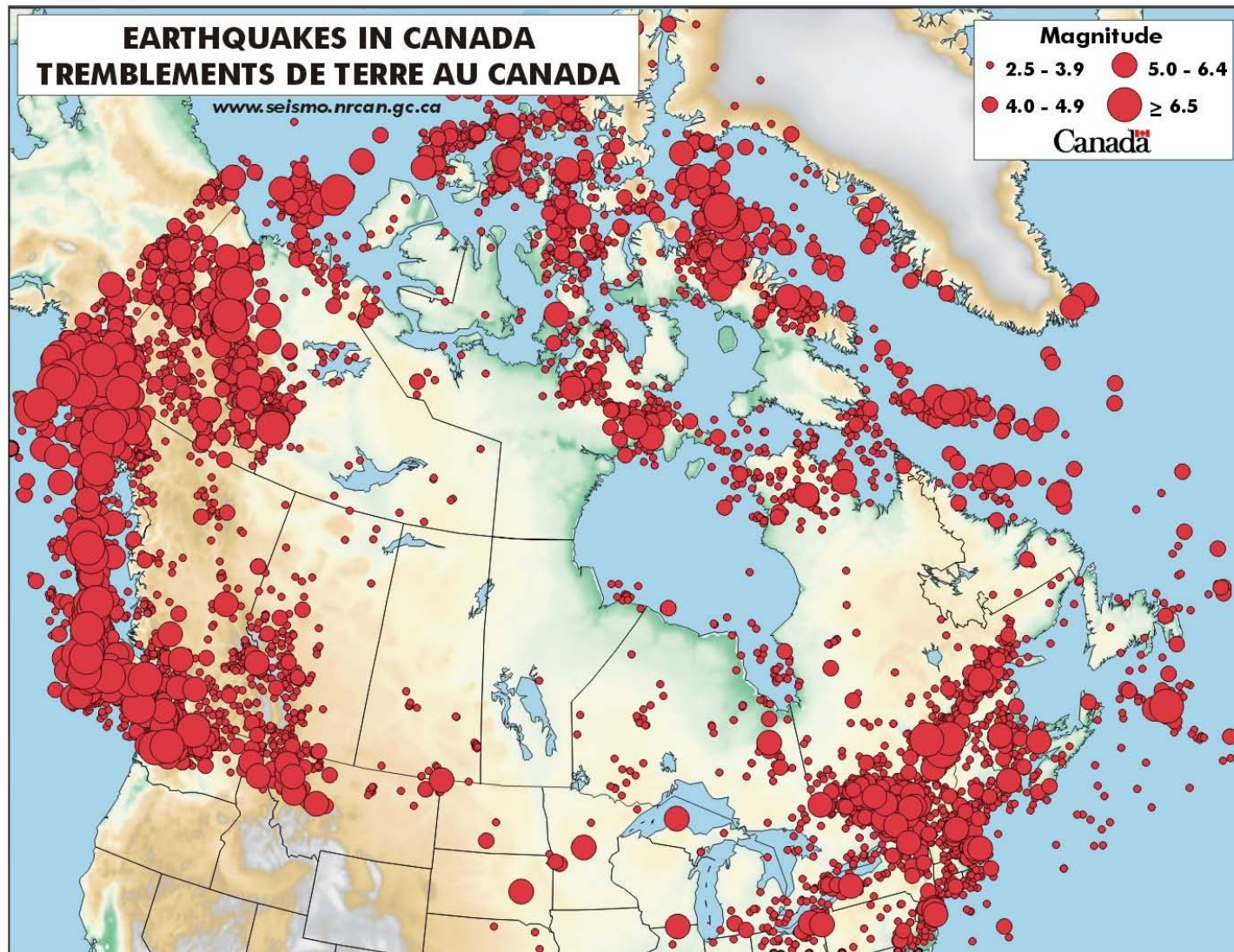
- Earthquakes are generally the most feared of natural hazards because they occur without warning. Hurricanes can be tracked; floods rise in a systematic way; volcanic eruptions are preceded by a variety of phenomena.
- The devastation caused by the Sumatran earthquake, December 2004, and the subsequent 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>



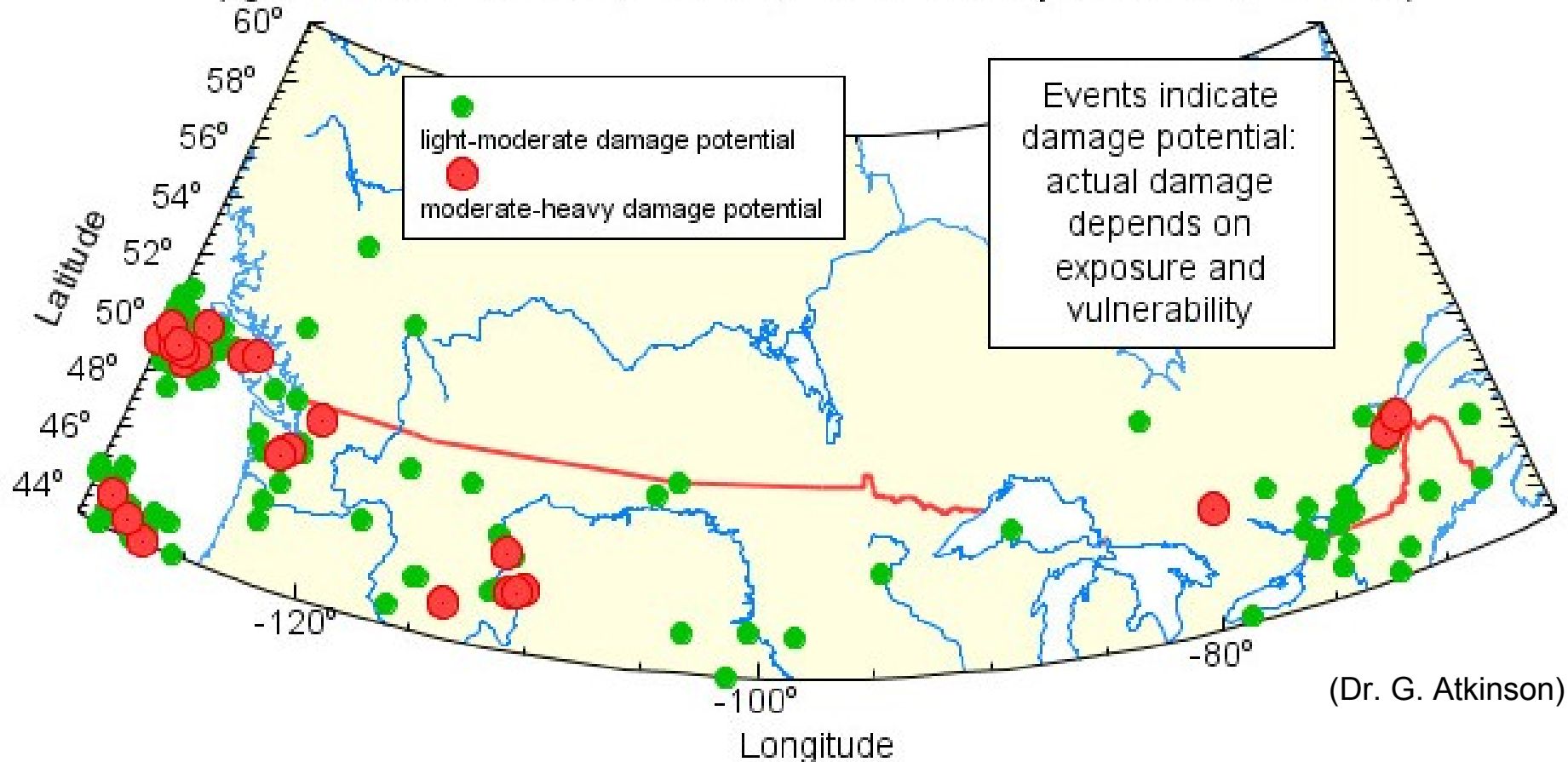
Background: Seismicity of Canada



(Geological Survey of Canada)

Seismicity and damage potential

Historical earthquakes in southern Canada with damage potential (to 2007)
(light-moderate= $M > 5$ east, > 5.5 west; moderate-heavy = $M > 6$ east, > 6.5 west)



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



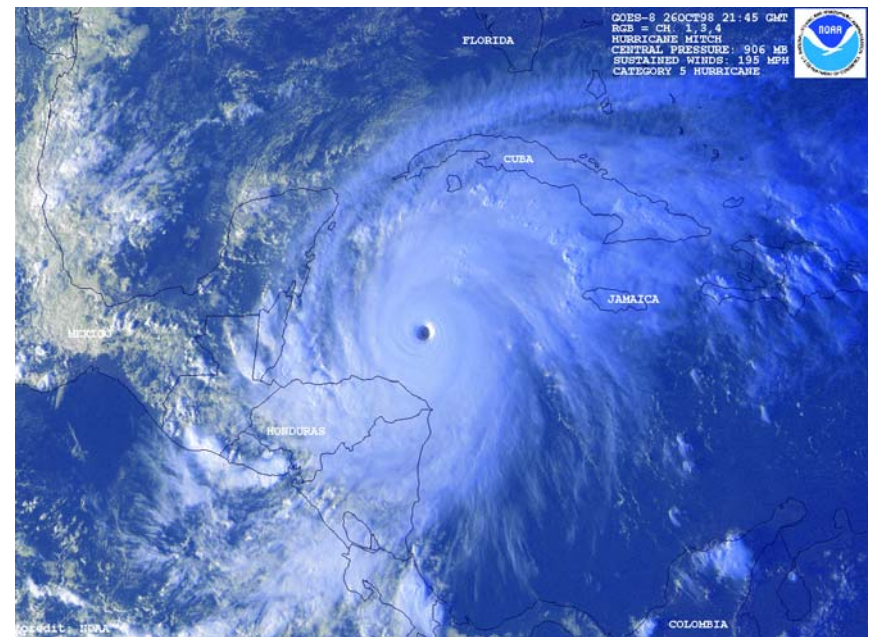
Relative contributions to seismic risk in Canada (source: Geological Survey of Canada)

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
 VOL. 1. NO. 24. FOURTH YEAR. SAN FRANCISCO, WEDNESDAY EVENING, APRIL 18, 1906. INDEPENDENCE. 2ND MONTHLY. 7 CENTS.

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 Corvalli, buried beneath basement floor of burning judge's 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 Whaley 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 San Diego were 100 dead and lying at the Pacific building.
 Mrs. J. M. Smith, wife of Detective Dillon, was confined to death in her home.
 Mrs. A. B. Hill, 755 Howell, killed falling roof.
 Harry Shaw, killed at 7th and Mission.
 Max Wagner and Perry Smith, two police officers with horses on Mission st., were killed by falling bricks at the 18th st.
 Mr. McCann was killed on 3d st.

INJURED
 List of badly injured taken in partial:
 J. Carr, 2421 Hill.
 Do. Simpson, 113 Geary, very bad.
 Ben Stephens, at Sheriff's 6th st., and two children, not fairly.
 T. H. Keane, 1st Leavenworth, legs broken.
 C. C. Perry, Hotel Phillips, 112 6th st.
 Mrs. Johnson and wife, 16th st., crushed badly.
 Mrs. J. Thomas, 381 6th, hurt badly.
 See, Bachwood, Police and 4th.
 Trelawney family at 25 Turk, near, wife and baby killed beside husband, whose head is crushed.
 Miss McHenry, 127 7th.
 Mrs. M. McCann, 140 Ohio st.
 Mrs. McCann killed in ruins United States restaurant, 18th and Market.
 Louisa Thompson, 734 Kearny, badly hurt.
 Mrs. Geo. Greenleaf and Mrs. Howard, 308 Stock, bruised and hurt.

At 108 Langdon, 4 killed; Billy Sheehan, policeman, received 3 injuries.
 Many injured at 137 6th st., Hotel Phillips.
 San Francisco was practically annihilated and totally paralyzed by the earthquake, which commenced 2:11 p. m. on Friday and continued with terrific force for four minutes. From the top of the columns of buildings, from the very tops of the hills, and from the death of Mrs. Pines, broke out a fire storm of the city, which death by fire will exceed to hundreds of millions of dollars.
 The progress of the fire was arrested by a shock from which it will probably take many years to recover.
 Thousands of men, who in the last weekly last night were the morning generally homeless.
 The fear of the number was greater than any that has been known in the history of the city.
 The people are agitated, terror-stricken. Thousands, however, a consequence of the disaster disaster, with results still more dire, are hastening out of the city.
 Many heart-rending scenes have been reported.
 Families are moving their belongings, halar-abeter, and moving wistfully about, hoping in the open.
 The City Hall is a complete wreck. The walls, surrounding the great dome have fallen, leaving only the broken frame, and the top of the dome is gone.
 "Around all sides of the" falling the walls have crumbled, like so many cards. The Receiving Hospital was buried.
 The entrance to Mechanics' Pavilion, which today is a combined hospital and morgue. Dead and dying are brought in by autos, ambulances and even garbage carts.
 Injured patients were taken from the Emergency Hospital to Mechanics' Pavilion. Many of them were hurt. Some broke loose and ran among the dying, adding to their sufferings.
 At 6:15 a second sharp quake occurred, accentuating the horror, and the houses and buildings in the city fell in places, and the earthquake seemed to last later, the whole city could have been later.

At least forty buildings were struck, while ten minutes after the shaking ceased. Among the first to give way were: Powell, 7th, and Stock streets, followed by a general commotion on Greenwich and 10th streets, while the latter street's addition would have been part of the city, were 2d, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100.

THEATER WRECKED
 The Market Theater is shown a house with the roof crashed into the foundation of the building.
 At 1100 California a beam was shaken from its foundation and over the sidewalk.
 The city historical buildings on California and Steiner are badly wrecked. The fronts of the ranges were shaken and the roofs were in danger. The buildings would have been completely a few days.
 The great monument in the city was struck, but that most of the power and light stations are destroyed. All of them, practically, are inoperative for the time being.

BRIEF IDEA OF DISASTER
 Walks near Central Park skating rink are down. Paradise building badly wrecked. The front of the building is down at 119 1/2 st. The main and police walk by side as the fire rages. The 11th, 12th, 13th, 14th, 15th, 16th, 17th, 18th and 19th are down. The 20th and 21st are down. The 22nd and 23rd are down. The 24th and 25th are down. The 26th and 27th are down. The 28th and 29th are down. The 30th and 31st are down. The 32nd and 33rd are down. The 34th and 35th are down. The 36th and 37th are down. The 38th and 39th are down. The 40th and 41st are down. The 42nd and 43rd are down. The 44th and 45th are down. The 46th and 47th are down. The 48th and 49th are down. The 50th and 51st are down. The 52nd and 53rd are down. The 54th and 55th are down. The 56th and 57th are down. The 58th and 59th are down. The 60th and 61st are down. The 62nd and 63rd are down. The 64th and 65th are down. The 66th and 67th are down. The 68th and 69th are down. The 70th and 71st are down. The 72nd and 73rd are down. The 74th and 75th are down. The 76th and 77th are down. The 78th and 79th are down. The 80th and 81st are down. The 82nd and 83rd are down. The 84th and 85th are down. The 86th and 87th are down. The 88th and 89th are down. The 90th and 91st are down. The 92nd and 93rd are down. The 94th and 95th are down. The 96th and 97th are down. The 98th and 99th are down. The 100th and 101st are down.

IN OAKLAND
 San Francisco and Oakland were both in the city of the disaster. It is thought fully a dozen persons are entombed, dead, dying and injured, in the city of Oakland. Across the bay, from that point a man was seen to rise from the ground. He was what was in other days a portion of the bed of San Francisco Bay.
 A building collapsed at Dolan and Haight streets. No report of loss of life.
 Along Market st., from 3th toward Castro, the sidewalks are literally strewn with wreckage. In many places, the sidewalks have collapsed, falling into the streets.
 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 not 500 persons standing in the city. This means that many more are to be expected, as San Francisco is a city of 500,000 people.
 The West Side Christian Church was shaking on St. Ignace's college, a portion of the building being destroyed.
 A building was struck at the end of California street, in the Richmond.
 Commercial Club, Van Ness Ave., badly damaged. At the Commercial Club, 25th and Mission sts., there was believed to have killed a number of people. The building was nearly destroyed.
 St. Andrew's hospital, near Van Ness, was injured, but not destroyed.
 At 10 the following were at Mechanics' Pavilion: Ray first was dead. Although the injuries of many were reported as fatal.
 Miss Jones, 509 Stevenson, 48 D. W. 234, 244, 254, 264, 274, 284, 294, 304, 314, 324, 334, 344, 354, 364, 374, 384, 394, 404, 414, 424, 434, 444, 454, 464, 474, 484, 494, 504, 514, 524, 534, 544, 554, 564, 574, 584, 594, 604, 614, 624, 634, 644, 654, 664, 674, 684, 694, 704, 714, 724, 734, 744, 754, 764, 774, 784, 794, 804, 814, 824, 834, 844, 854, 864, 874, 884, 894, 904, 914, 924, 934, 944, 954, 964, 974, 984, 994, 1004.
 Dr. Williams, 111 Commercial, 112 Commercial, 113 Commercial, 114 Commercial, 115 Commercial, 116 Commercial, 117 Commercial, 118 Commercial, 119 Commercial, 120 Commercial, 121 Commercial, 122 Commercial, 123 Commercial, 124 Commercial, 125 Commercial, 126 Commercial, 127 Commercial, 128 Commercial, 129 Commercial, 130 Commercial, 131 Commercial, 132 Commercial, 133 Commercial, 134 Commercial, 135 Commercial, 136 Commercial, 137 Commercial, 138 Commercial, 139 Commercial, 140 Commercial, 141 Commercial, 142 Commercial, 143 Commercial, 144 Commercial, 145 Commercial, 146 Commercial, 147 Commercial, 148 Commercial, 149 Commercial, 150 Commercial, 151 Commercial, 152 Commercial, 153 Commercial, 154 Commercial, 155 Commercial, 156 Commercial, 157 Commercial, 158 Commercial, 159 Commercial, 160 Commercial, 161 Commercial, 162 Commercial, 163 Commercial, 164 Commercial, 165 Commercial, 166 Commercial, 167 Commercial, 168 Commercial, 169 Commercial, 170 Commercial, 171 Commercial, 172 Commercial, 173 Commercial, 174 Commercial, 175 Commercial, 176 Commercial, 177 Commercial, 178 Commercial, 179 Commercial, 180 Commercial, 181 Commercial, 182 Commercial, 183 Commercial, 184 Commercial, 185 Commercial, 186 Commercial, 187 Commercial, 188 Commercial, 189 Commercial, 190 Commercial, 191 Commercial, 192 Commercial, 193 Commercial, 194 Commercial, 195 Commercial, 196 Commercial, 197 Commercial, 198 Commercial, 199 Commercial, 200 Commercial.



Courtesy, Museum of San Francisco

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The Nisqually, Washington Earthquake



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

MSNBC



The Magnitude 7.9 Gujarat, India Earthquake

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



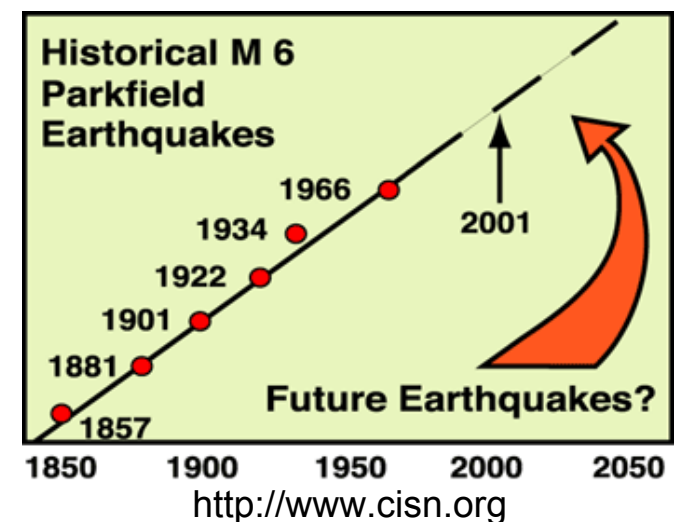
More than 30,000 persons died in the event, and damages exceed \$10 Billion

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.



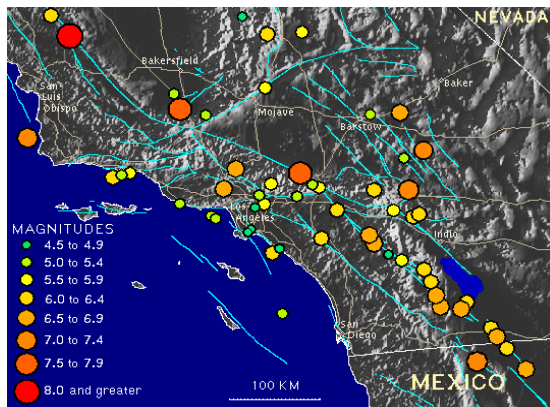
<http://quake.wr.usgs.gov>



<http://www.cisn.org>

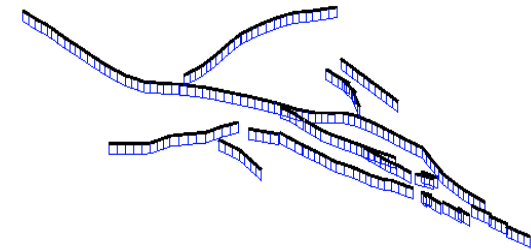
Earthquake Simulations

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.

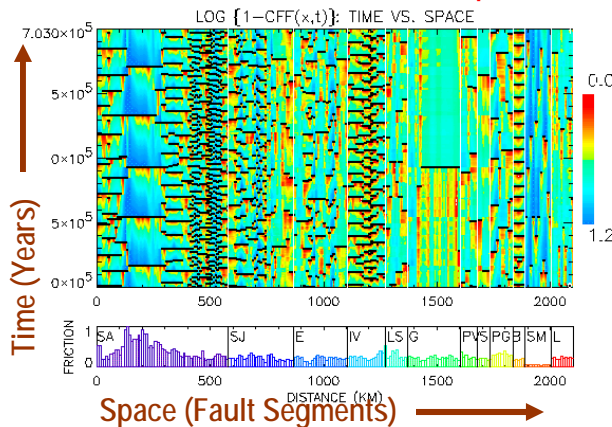


Fault Network Model for Southern California

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



$\sigma = \text{CFF Stress: Time vs. Space}$

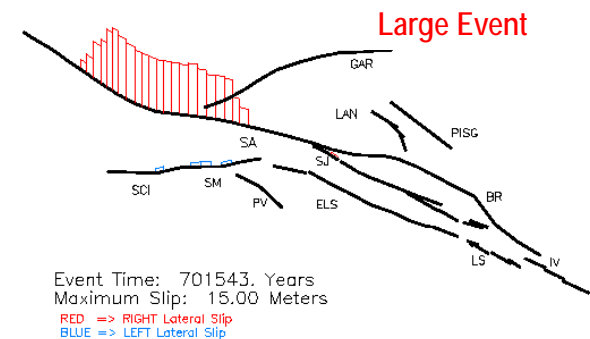


Simulations of earthquake fault systems can be carried out using the Virtual California model. At left is shown the buildup of stress over time and space. Lines = Earthquakes



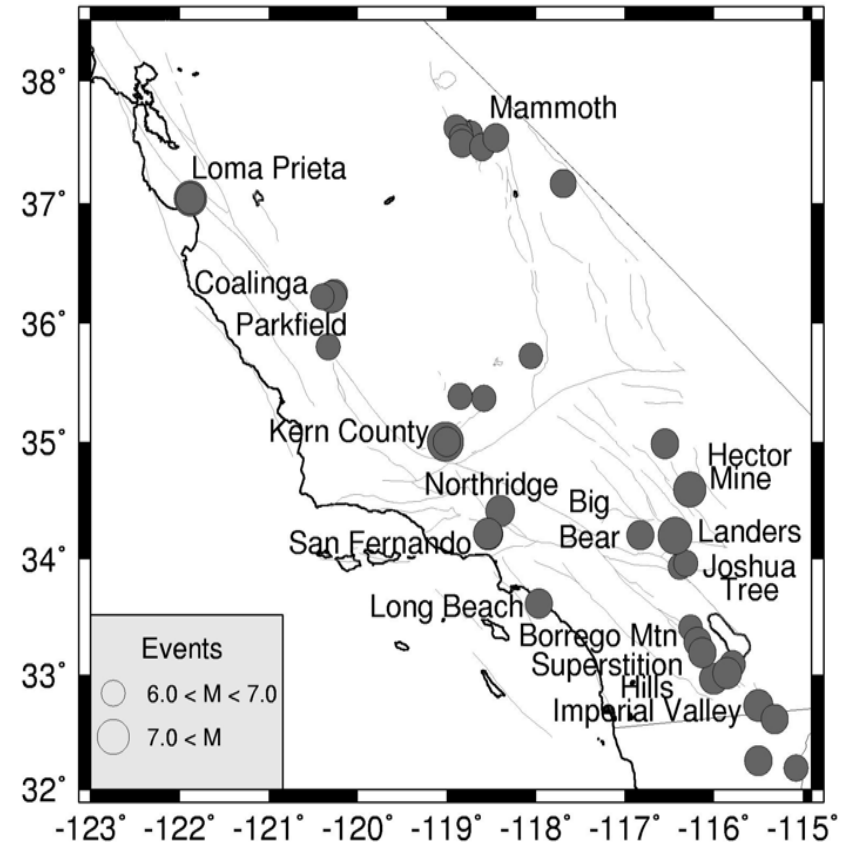
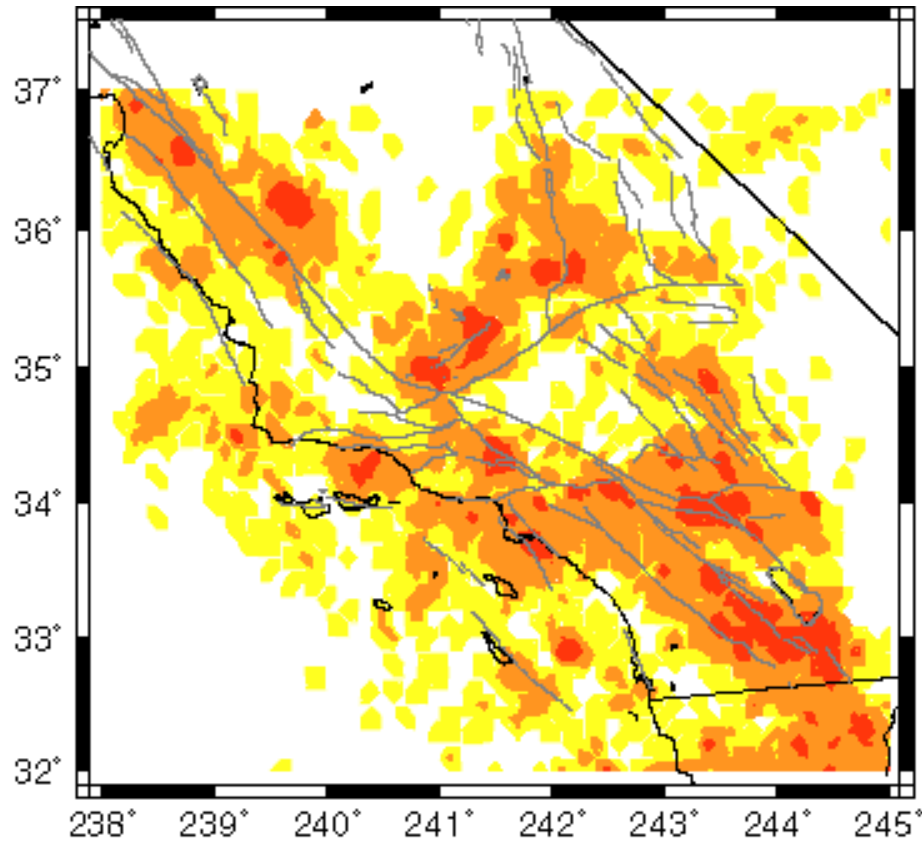
San Andreas Fault

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



Event Time: 701543. Years
Maximum Slip: 15.00 Meters
RED => RIGHT Lateral Slip
BLUE => LEFT Lateral Slip

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.

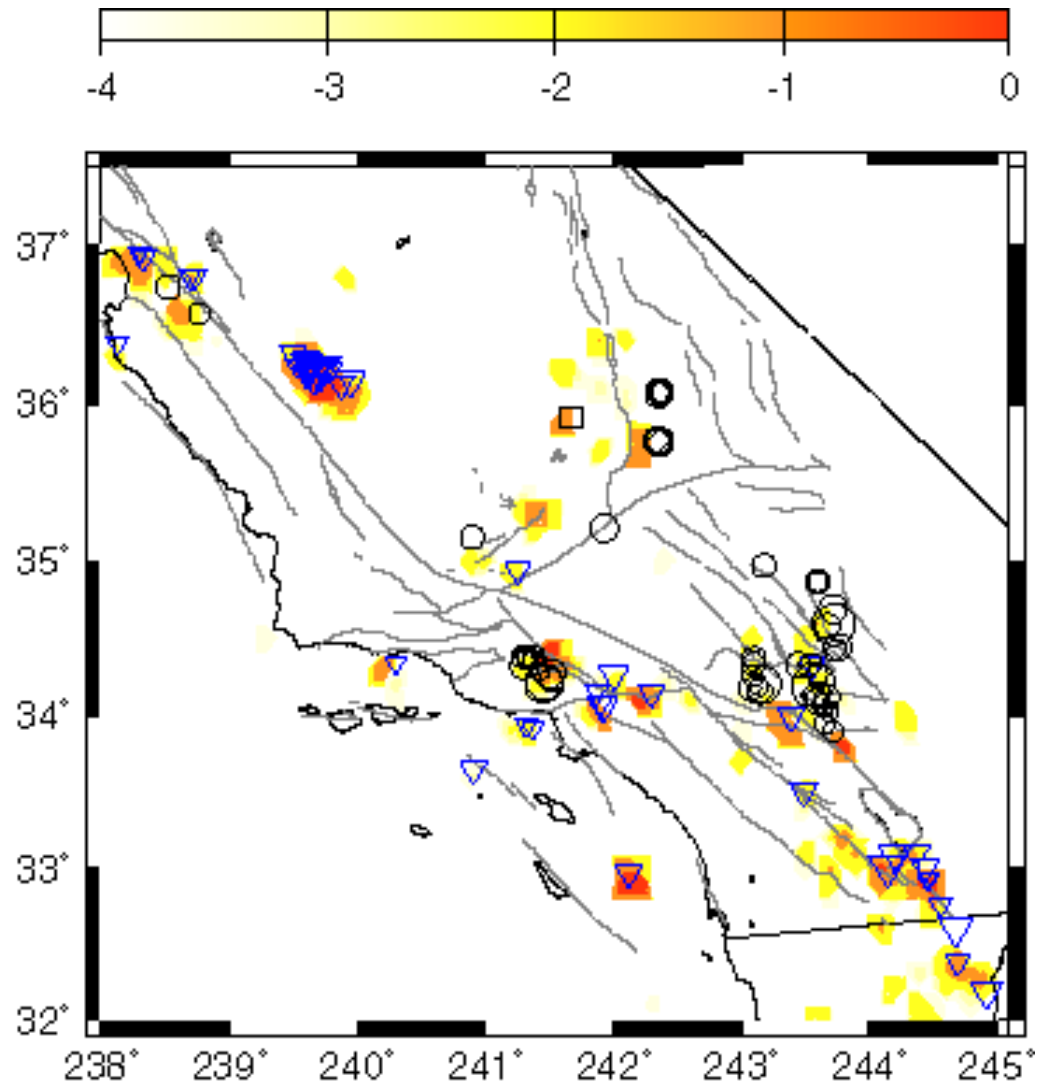
On the right are shown the largest events to occur over the past 70 years.

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 ($M \sim 3$) 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.

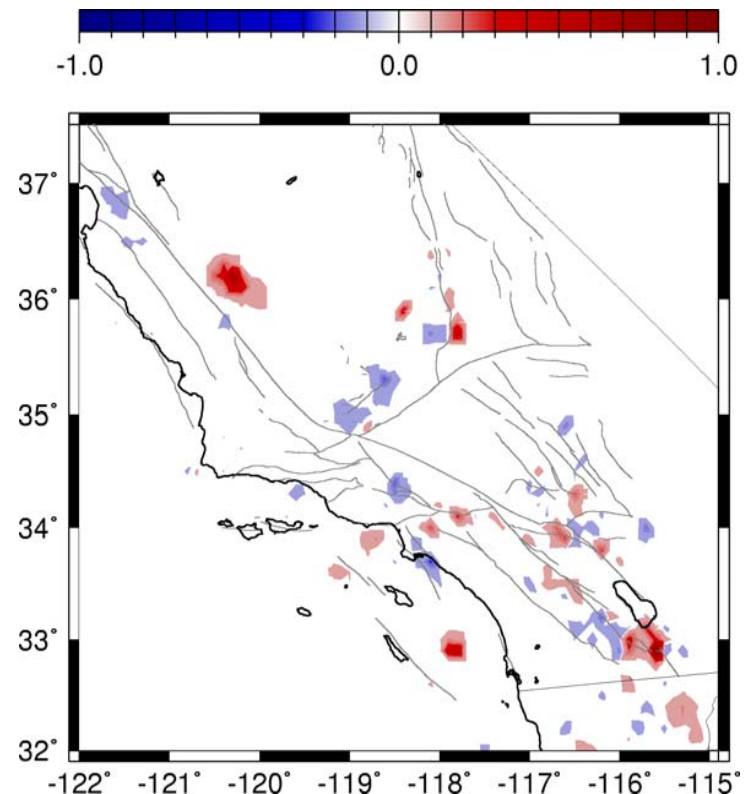
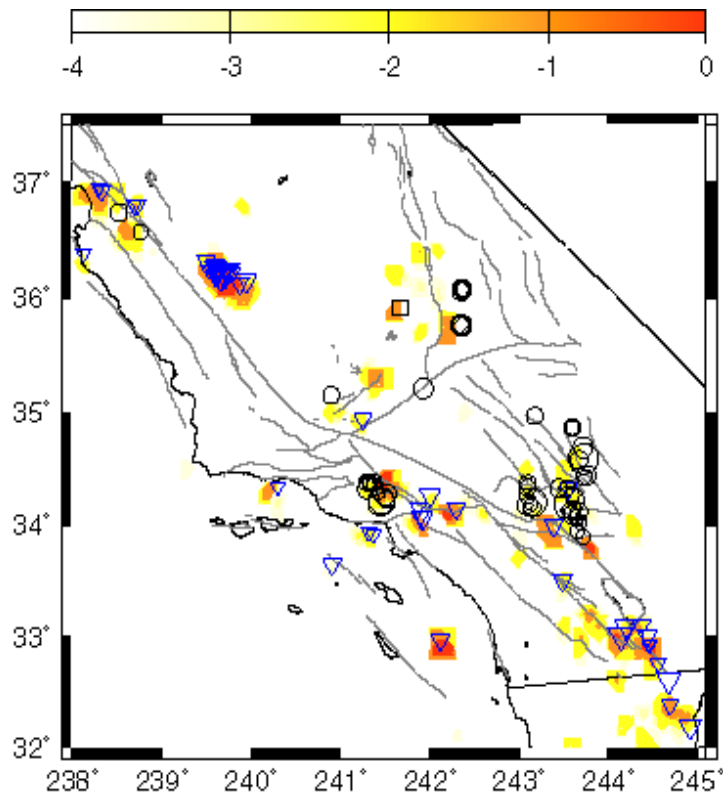
PI Anomalies, S. California, 1978-1991

- Plot of Log_{10} (seismic potential).
- Increase in potential for large earthquakes, $M \geq 5$, 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.



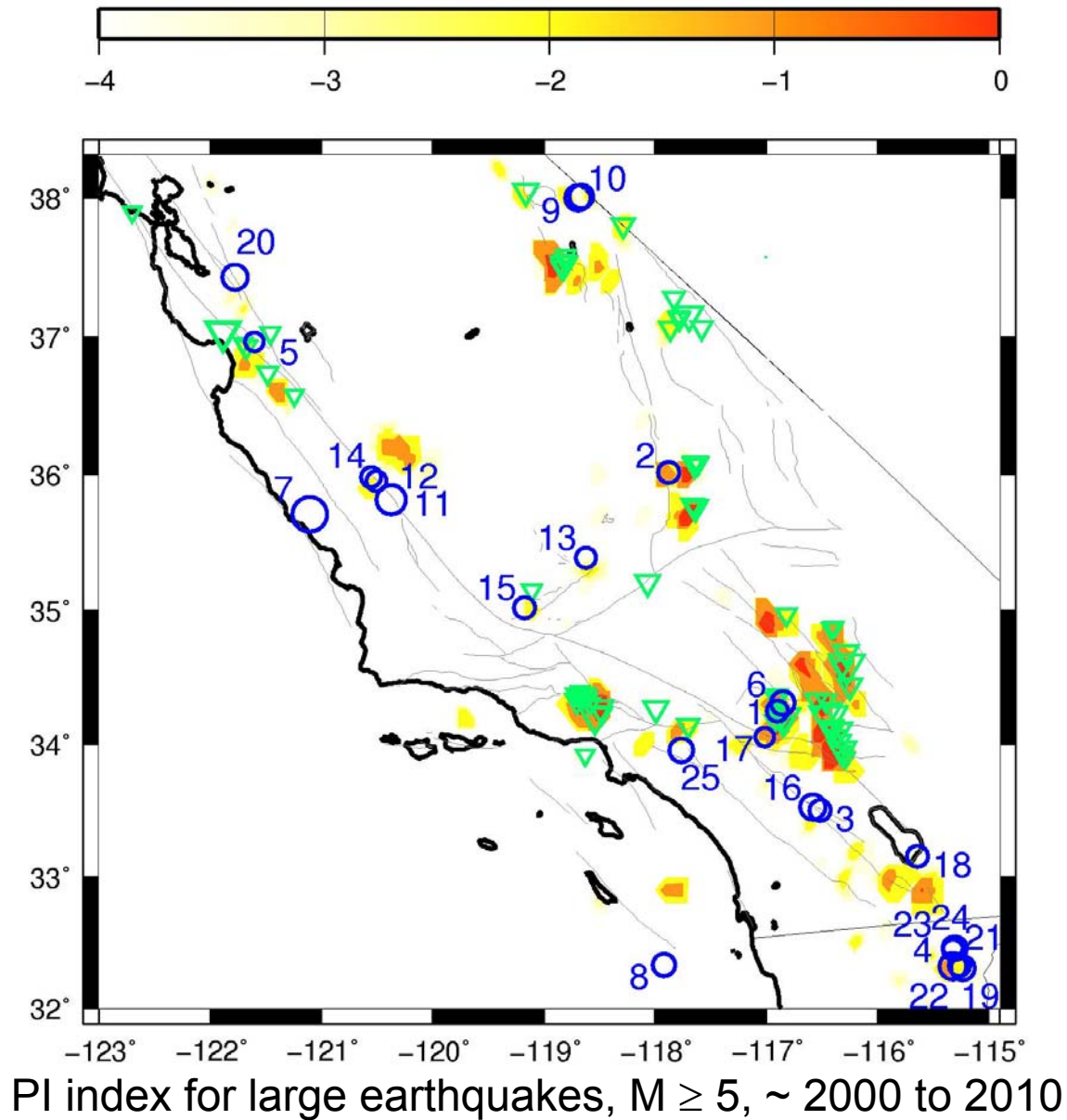
Anomalous Seismic Activity Patterns

- 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

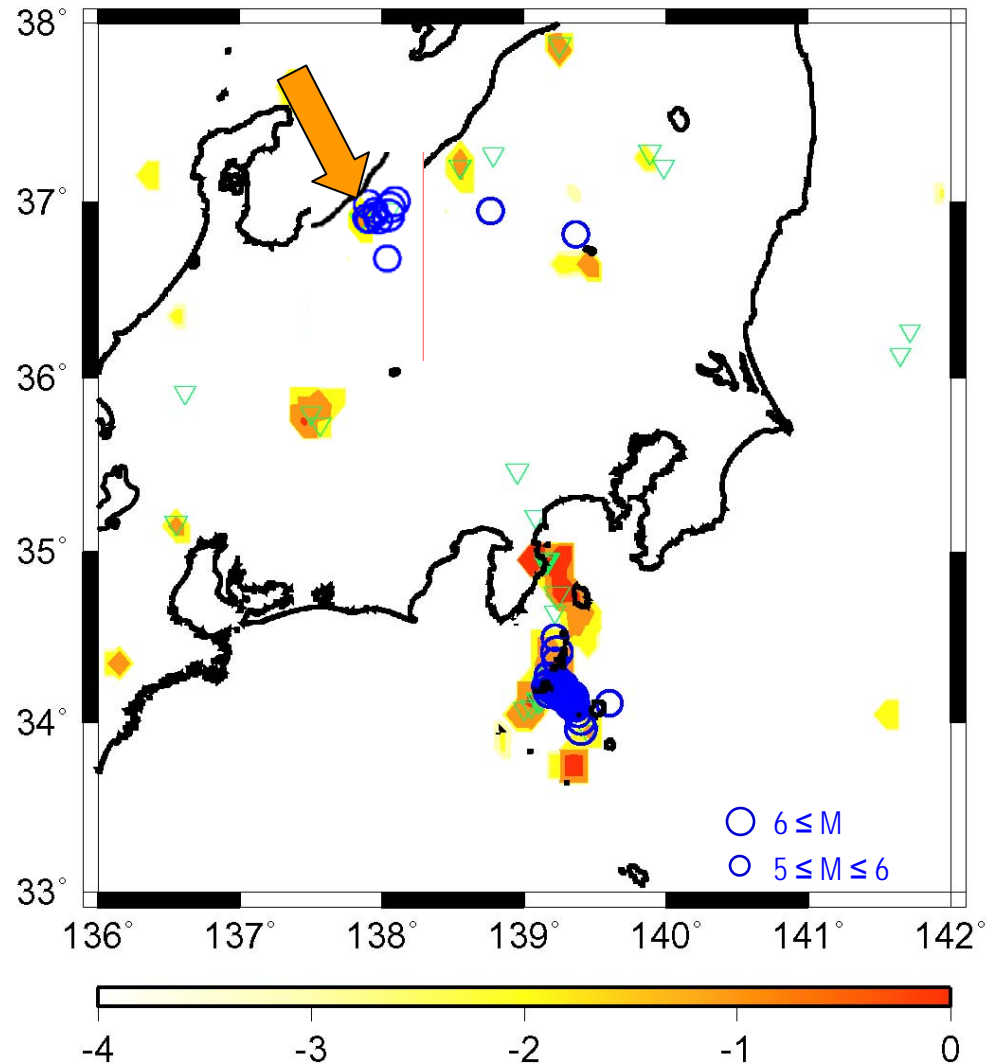
PNAS, 2002



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 $M \geq 5$ are shown (arrow).
- Again, this image was first shown during lectures in Japan on October 13 & 14, 2004.

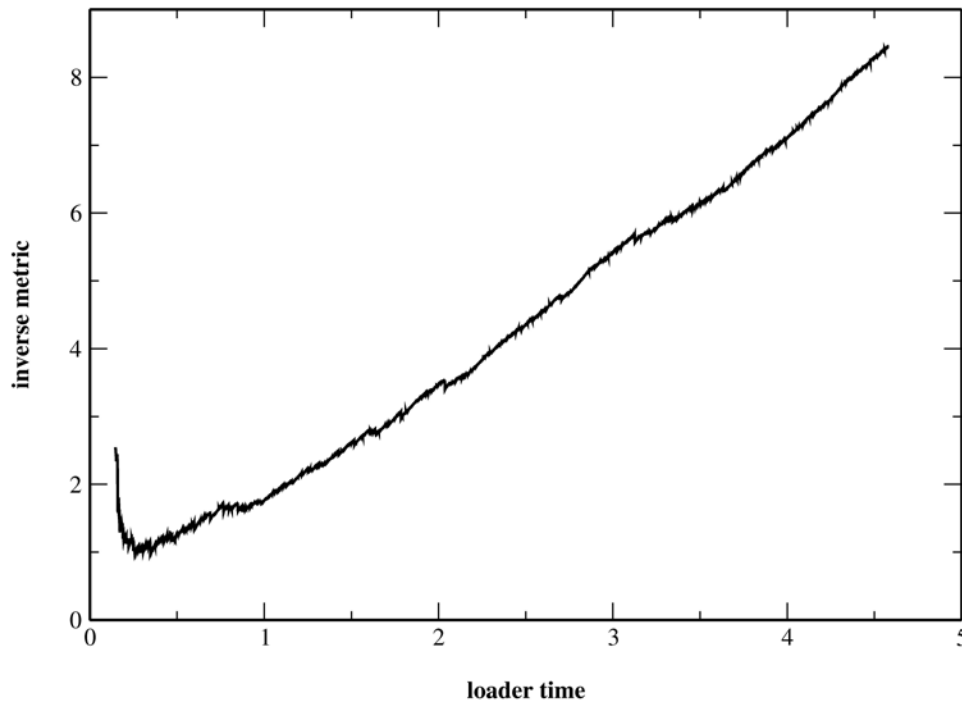


Improving seismicity based forecasts - ergodicity

- 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

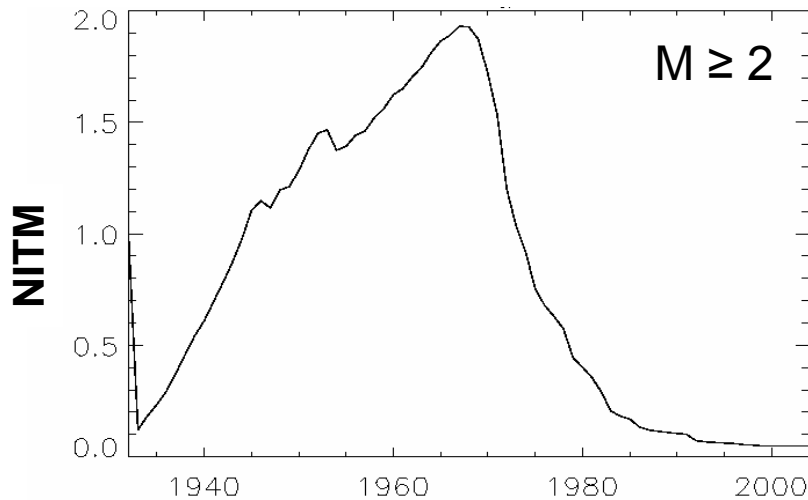
- Seismicity data from the ANSS catalog, for the period 1932-2004 (time period)
- Events are binned into areas 0.1° to a side (spatial discretization)
- Analysis is performed for an area ranging from 32° to 39° latitude, -123° to -115° longitude, or some subset thereof (spatial region). No declustering 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).

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

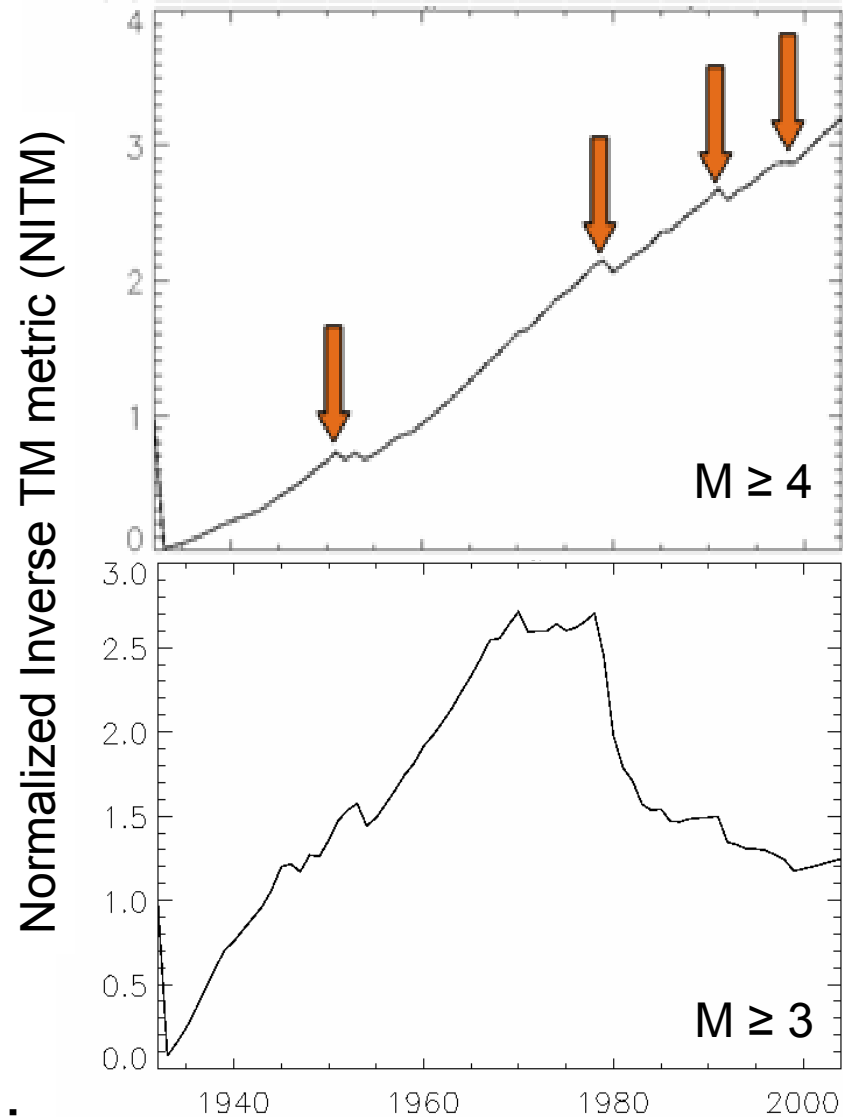
- Study data from several natural catalogs by calculating the TM metric for the number of events, in order to investigate under what conditions (parameters) the system is, or is not, ergodic (Tiampo et al., *PRE*, 2007).

Ergodicity in Natural Catalogs

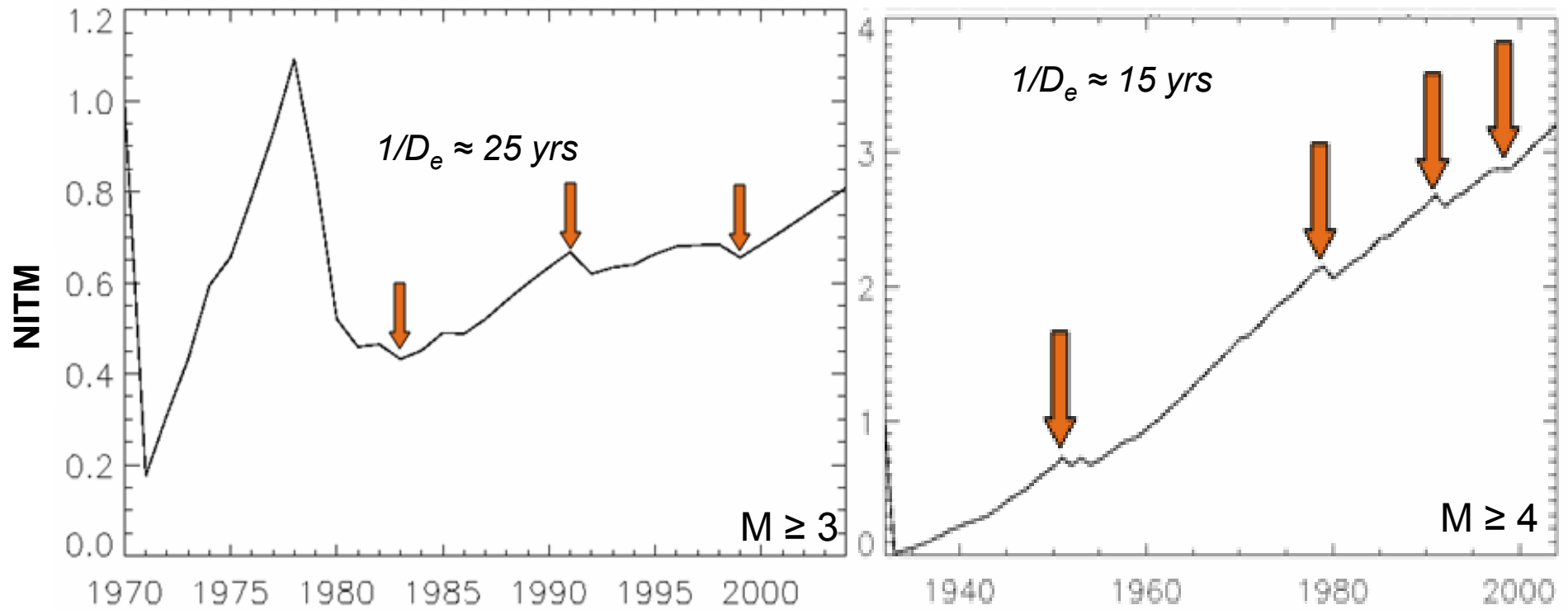
- Again, we bin the California region into a set of locations, and use the numbers of events as our measurable
- Variations in location accuracy, magnitude completeness, and coverage have a significant effect on ergodicity



California



Ergodicity in Natural Catalogs

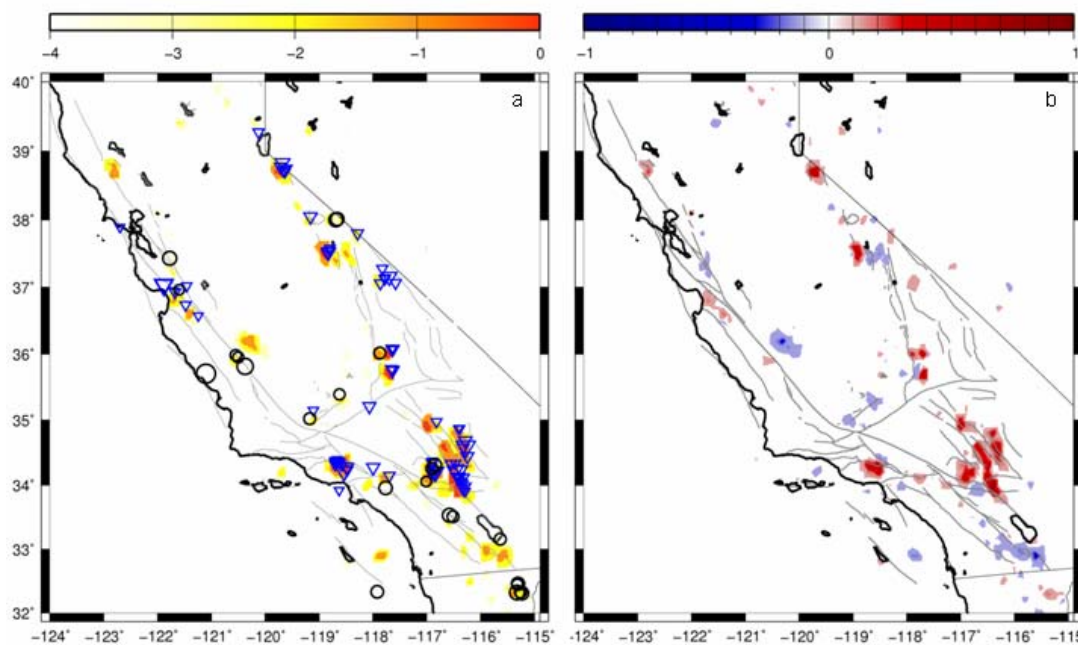


California

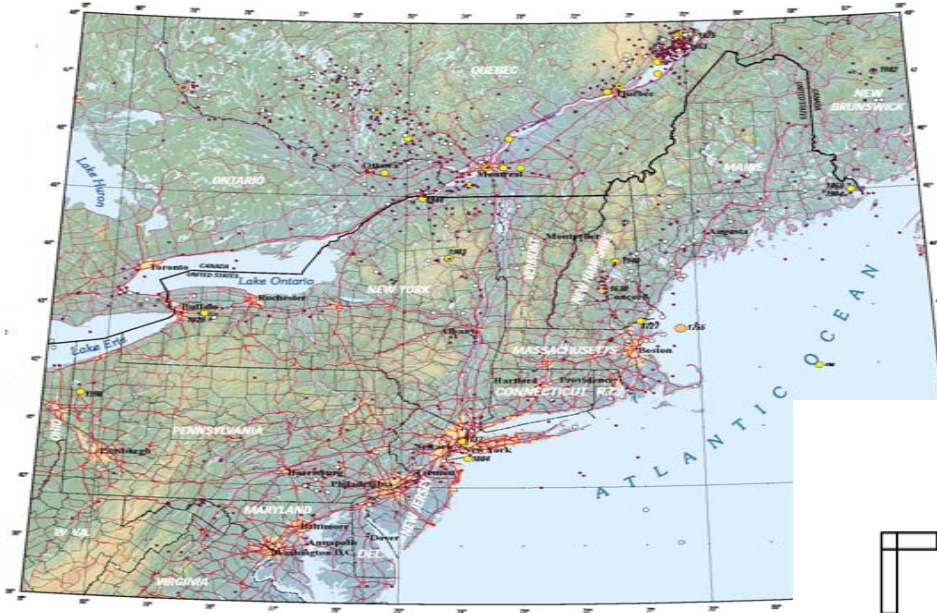
Can these results be used to improve seismicity based earthquake forecasts?

- 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:

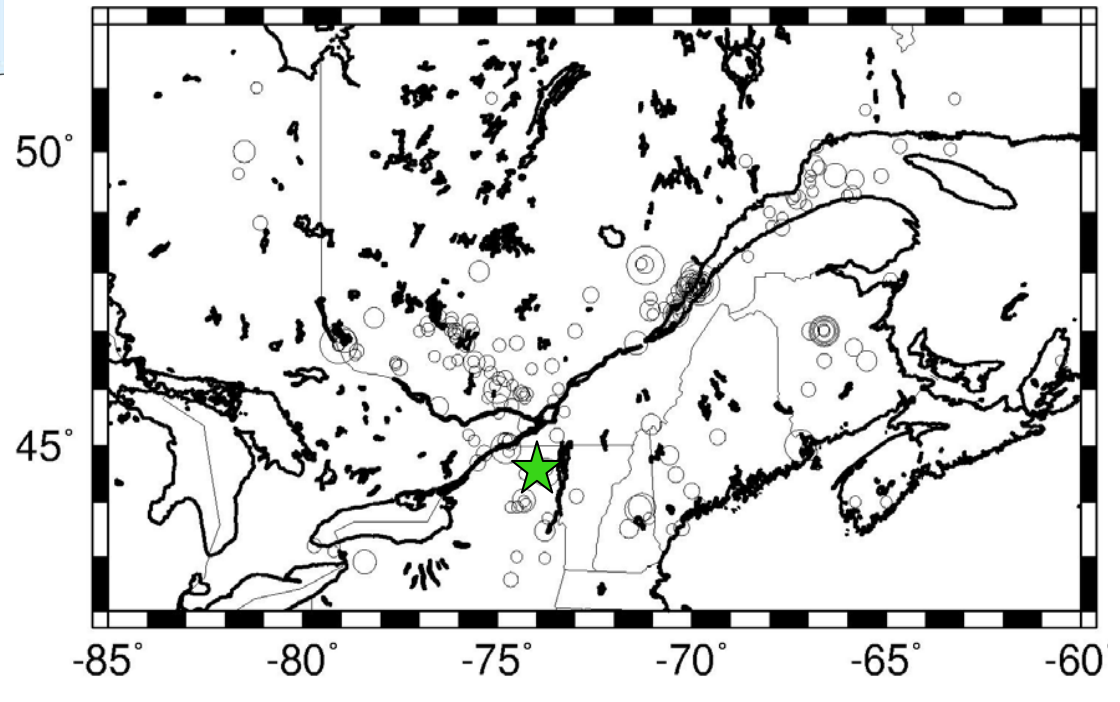
- PI values are directly related to the spatial mean, and inversely related to the standard deviation in the seismicity rate, so it should be directly affected by variations in spatial averages.
- Reductions in noise will improve the false positive rate.
- Optimizing the parameter range of the input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



Eastern North American Seismicity

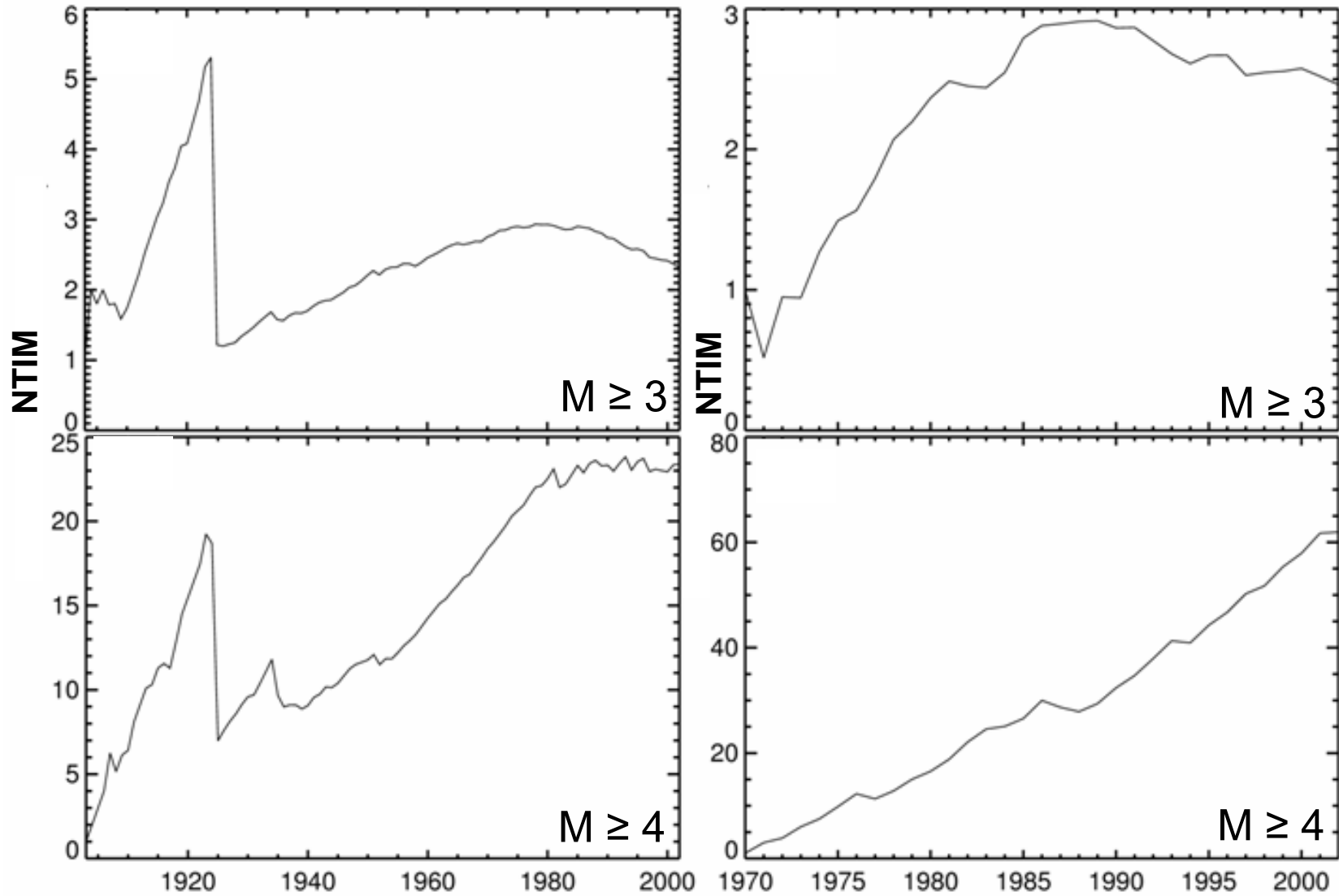


USGS



GSC

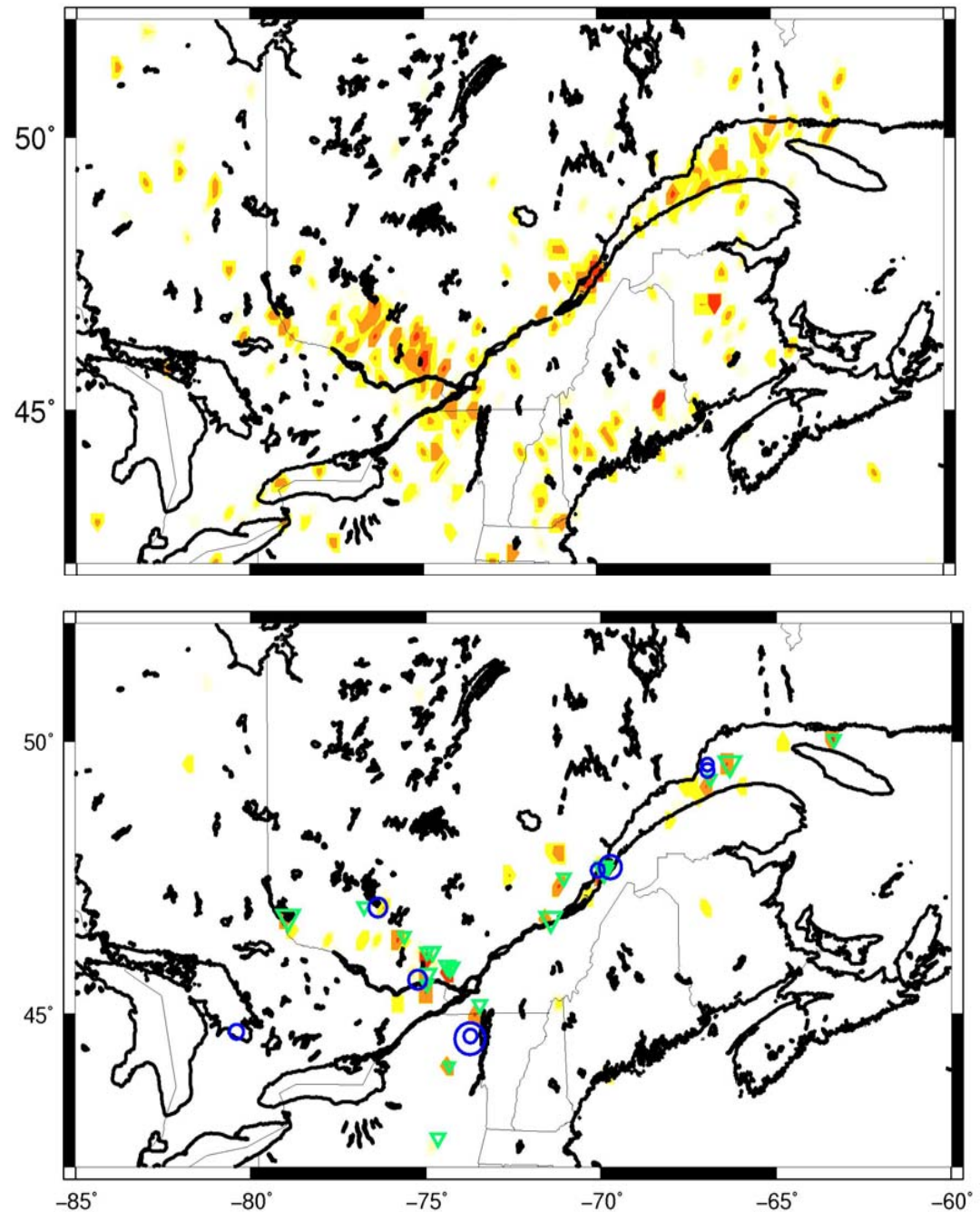
Ergodicity in Natural Catalogs



Boxsize = 0.2

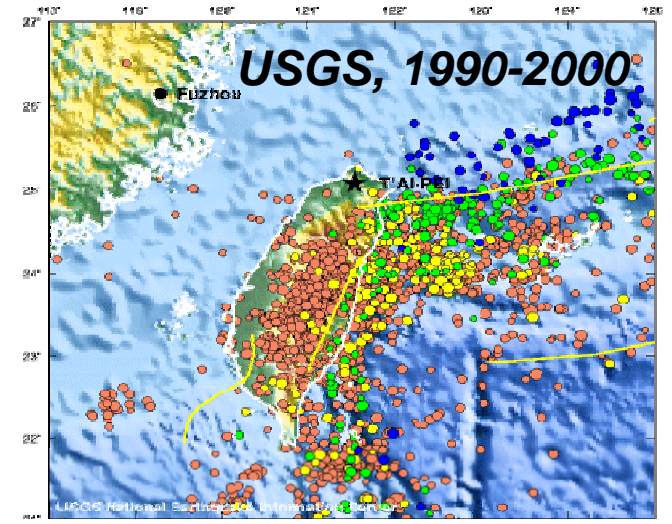
PI Index, eastern Canada

- PI forecast for eastern Canada, 2002-2012. On the top is a forecast for $M \geq 3$, 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.



Ergodicity in Natural Catalogs

Taiwan, $M \geq 3$, 1973-2005



2D analysis,
boxsize = 0.1



3D analysis,
discretization of
 $0.1^\circ \times 0.1^\circ \times 1$ km

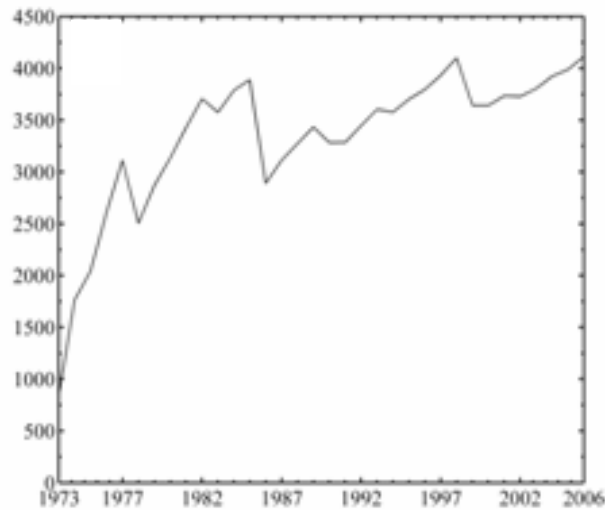


3D analysis,
discretization of
 $0.1^\circ \times 0.1^\circ \times 0.25$ km

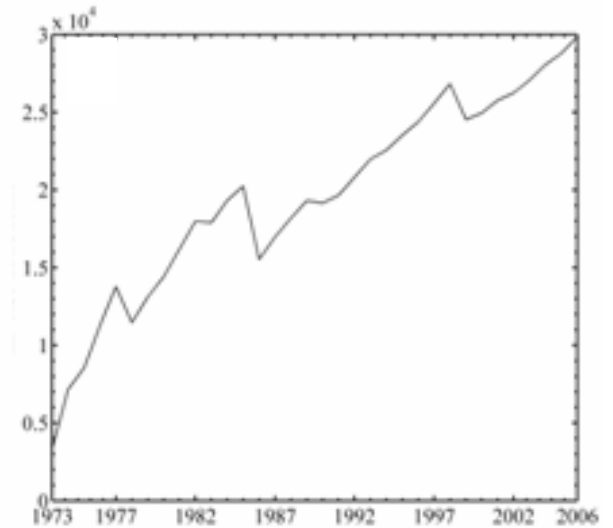
Ergodicity in Natural Catalogs



*2D analysis,
boxsize = 0.02°*



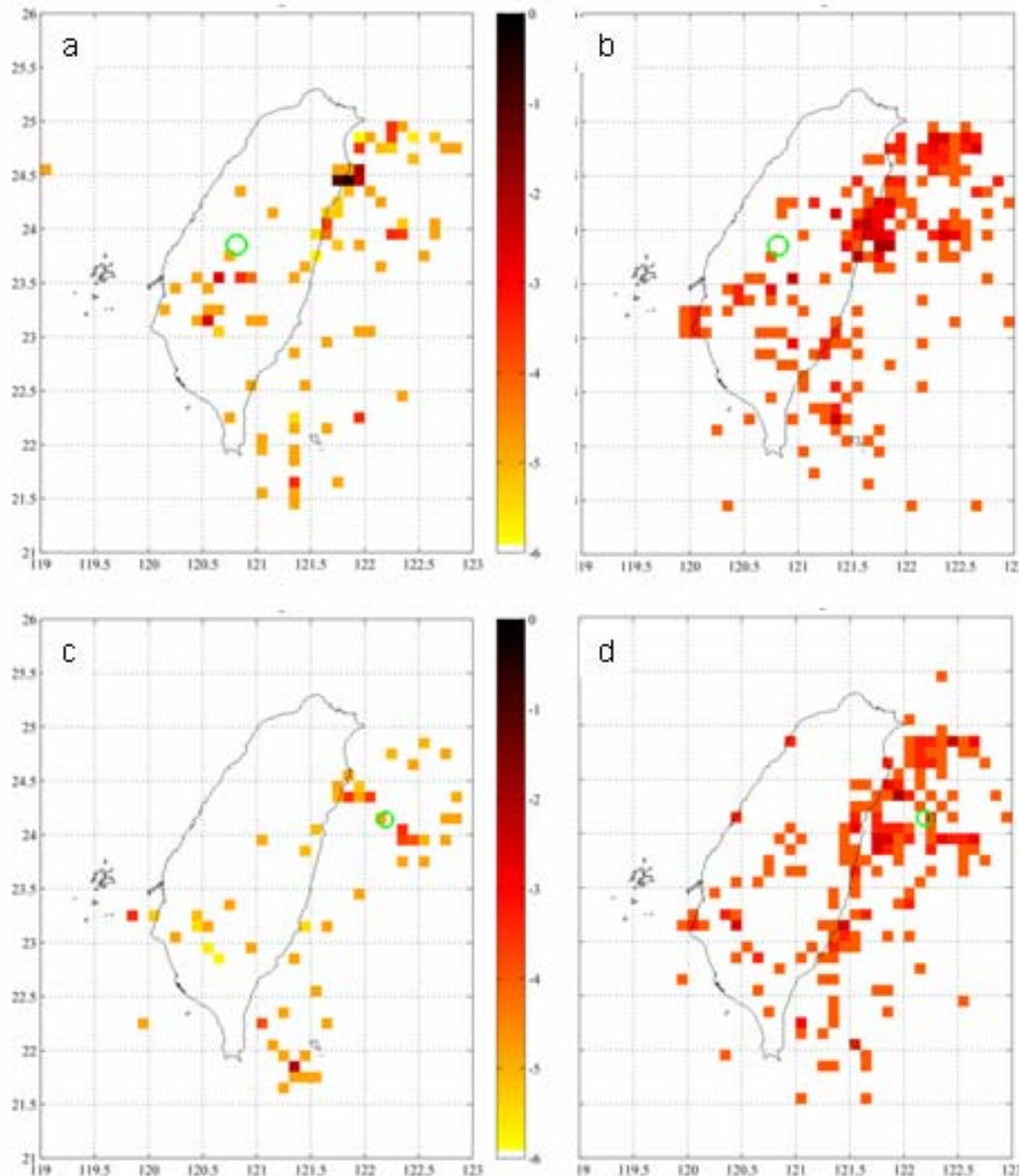
*3D analysis,
discretization of
 $0.1^\circ \times 0.1^\circ \times 1 \text{ km}$*



*3D analysis,
discretization of
 $0.1^\circ \times 0.1^\circ \times 0.25 \text{ km}$.*

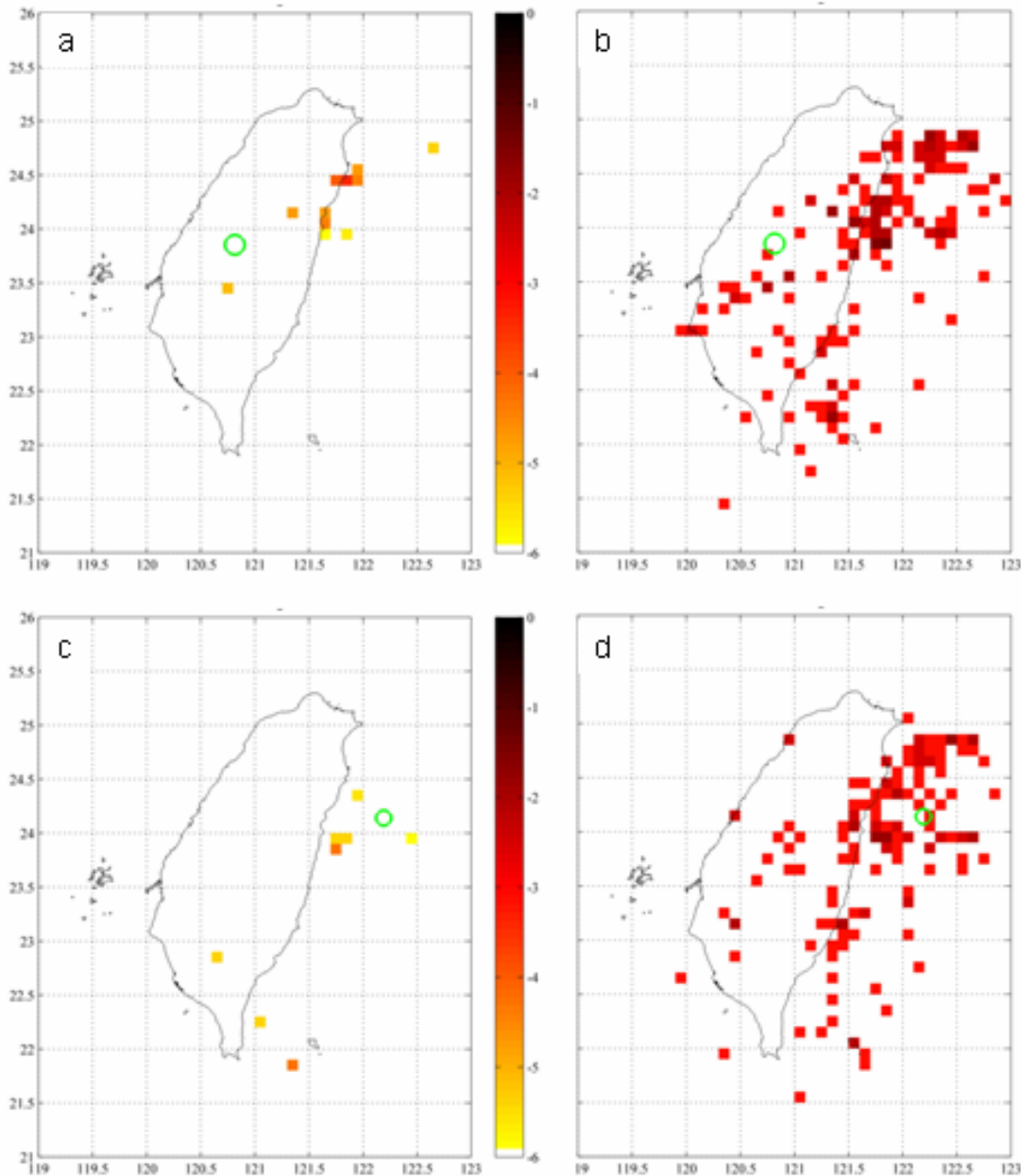
Taiwan, $M \geq 4$, 1973-2005

Ergodicity in Natural Catalogs



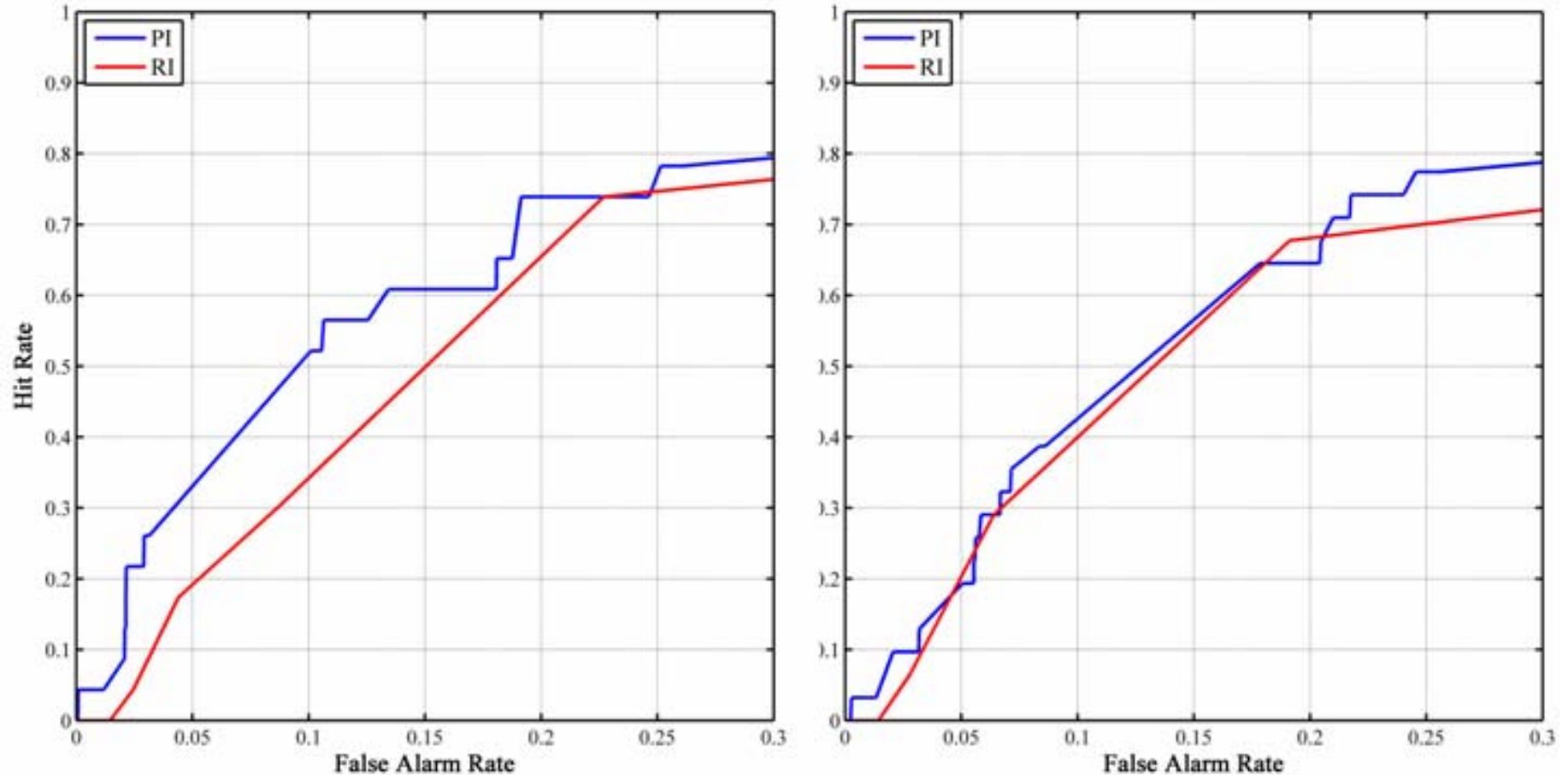
Plots of 3D PI and RI maps the Taiwanese subduction zone for $M \geq 3$, a time step of 1 year, and a discretization of $0.1^\circ \times 0.1^\circ \times 0.25$ km, calculated for 1994-1998. Green circles indicate the large events of $M \geq 6$ that occur in the period 1999-2003. Depth ranges of a) and 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



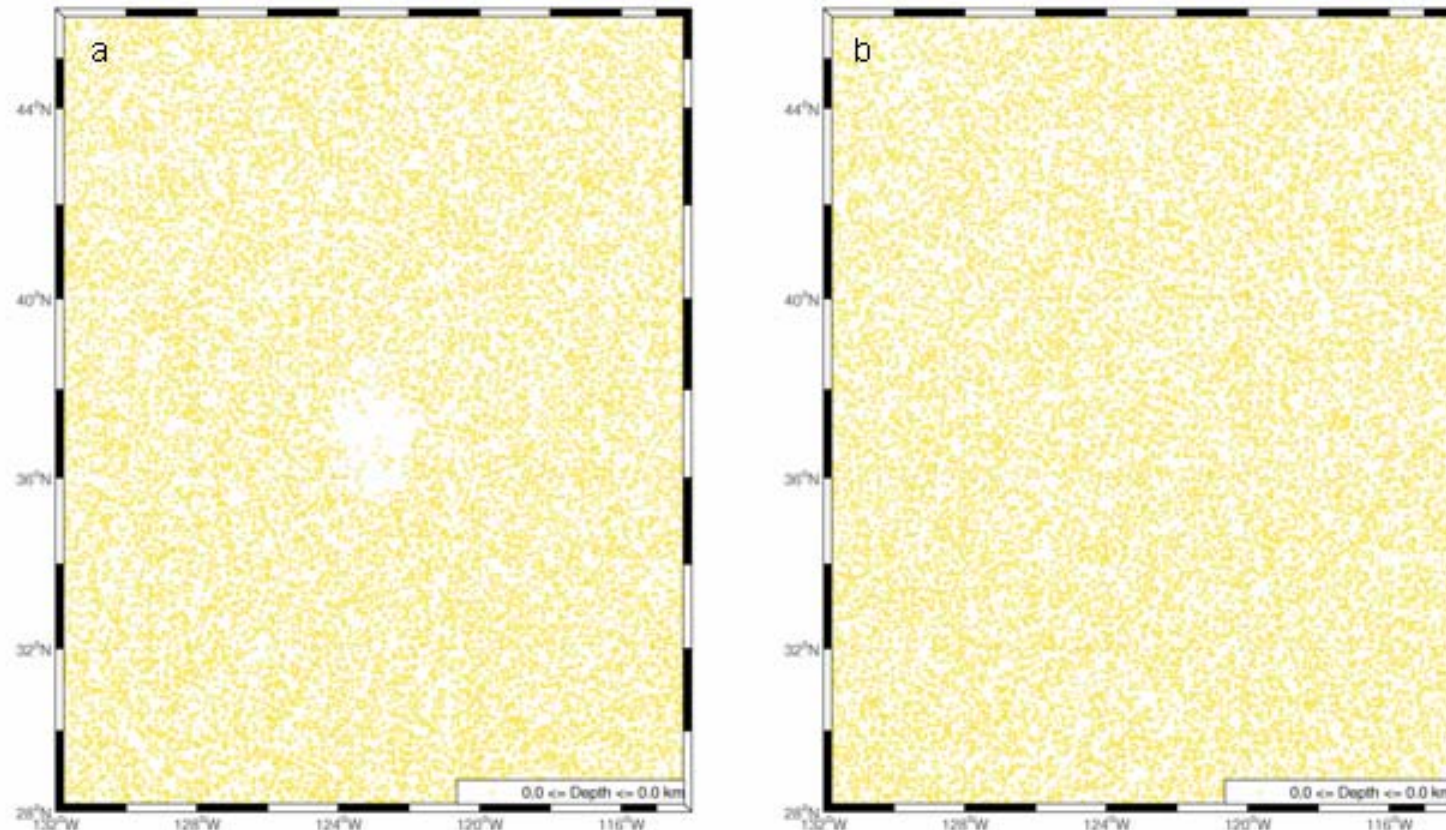
Plots of 3D PI and RI maps with parameters as shown previously, but for the calculation period of 1988-1997. Depth ranges again are for a) and b) 7.75 to 8.00 km, c) and d) 13.75 to 14.00 km.

Ergodicity in Natural Catalogs



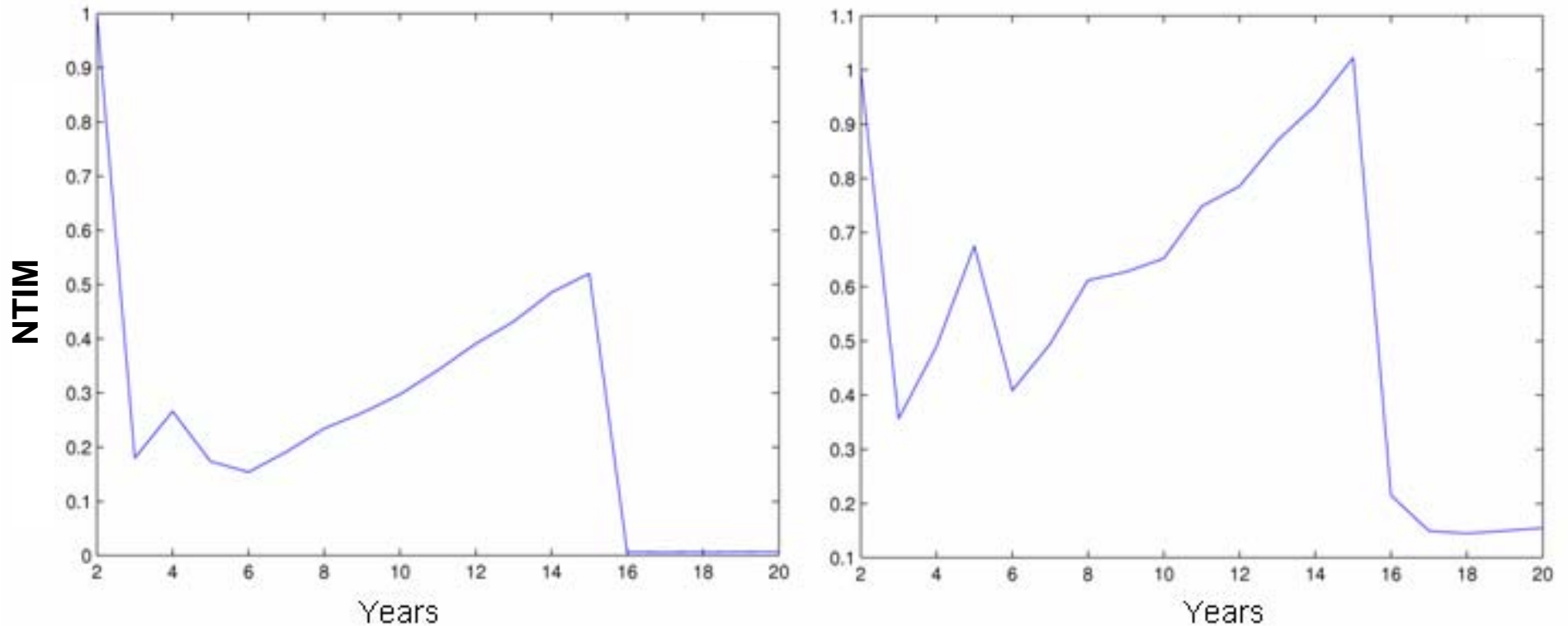
ROC diagrams comparing the PI and RI maps for the previous forecasts. Again, on the left is shown the results for a forecast using the effectively ergodic period, 1994-1998, while on the right is shown the same forecast using a non-ergodic period, 1988-1997.

Ergodicity in Synthetic Catalogs



Left: Synthetic catalog with a reverse fault ($L = 200$ km, $W = 10$ km, $dip = 45^\circ$, expected magnitude $M \sim 7.3$) 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.

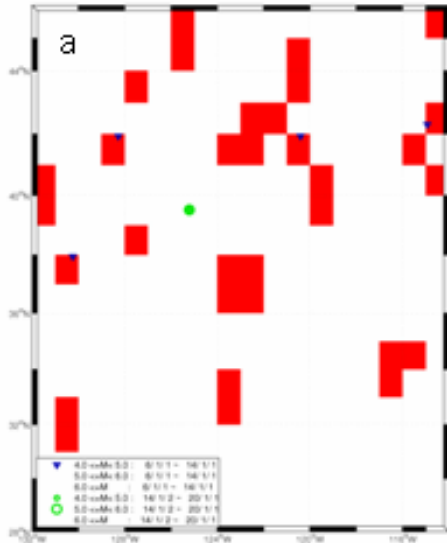
Ergodicity in Synthetic Catalogs



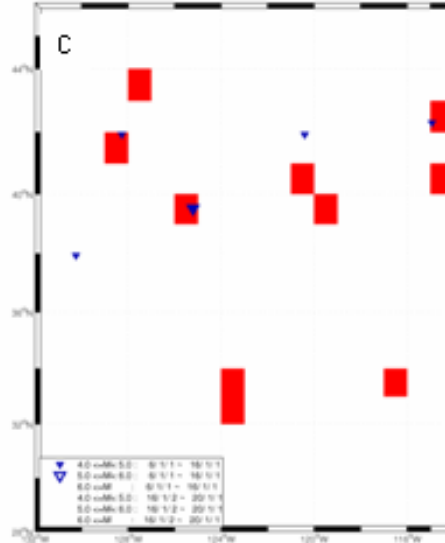
Left: Inverse TM metric, for the synthetic catalog with quiescence;
Right: Inverse TM metric for the random catalog.

Ergodicity in Synthetic Catalogs

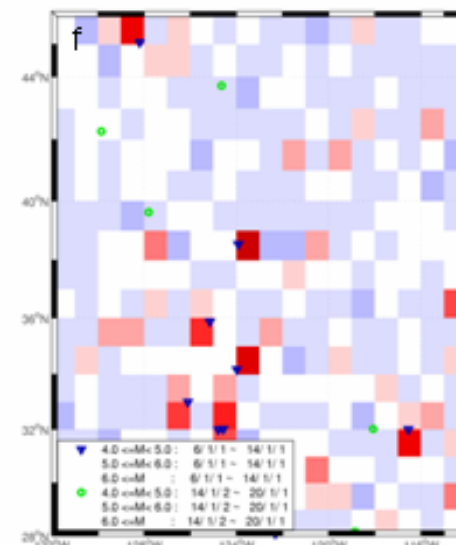
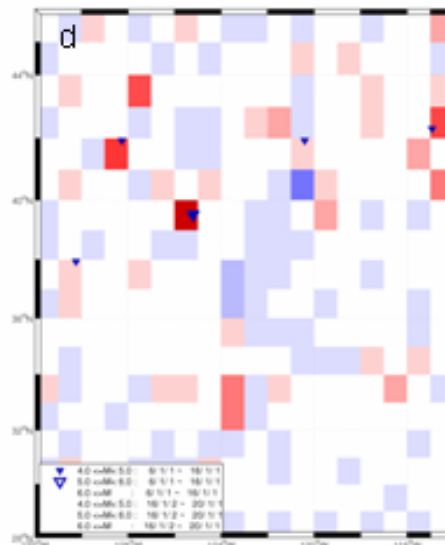
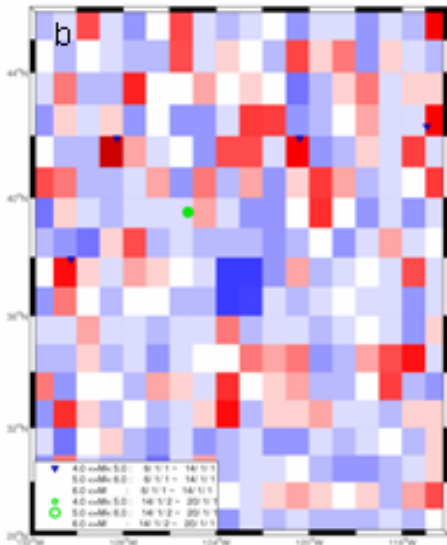
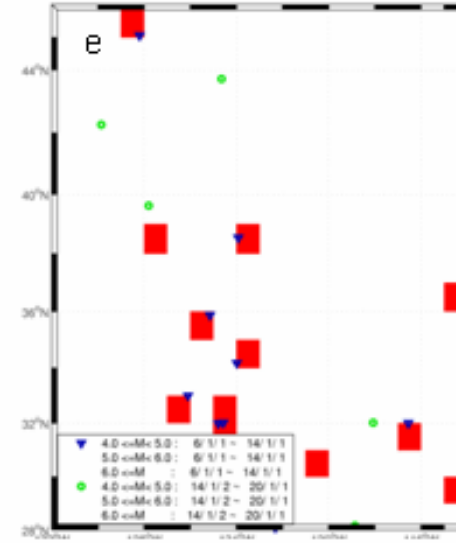
Year 14 – 6



Year 16 – 6



Year 14 – 6

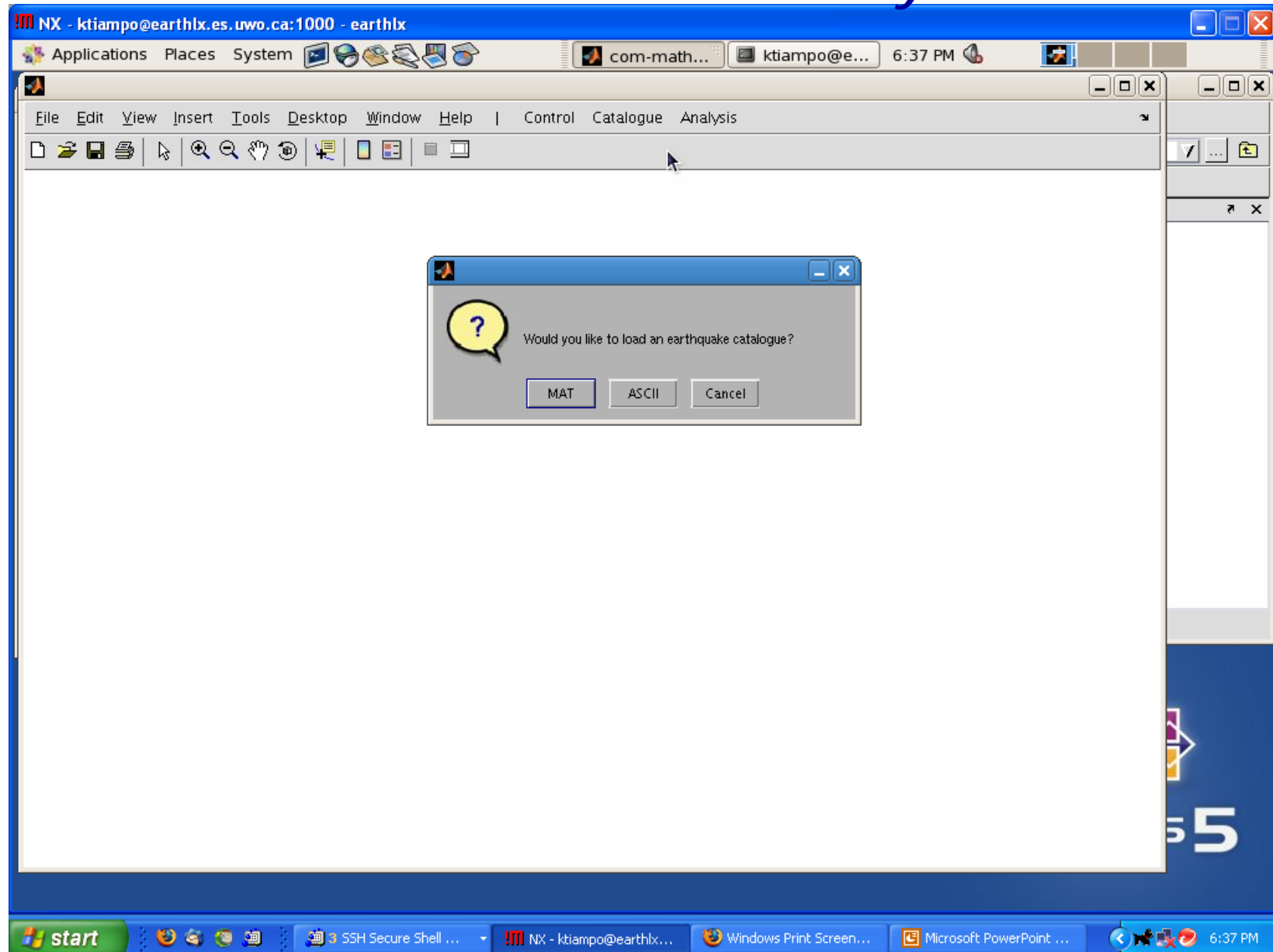


Non-Critical PAST

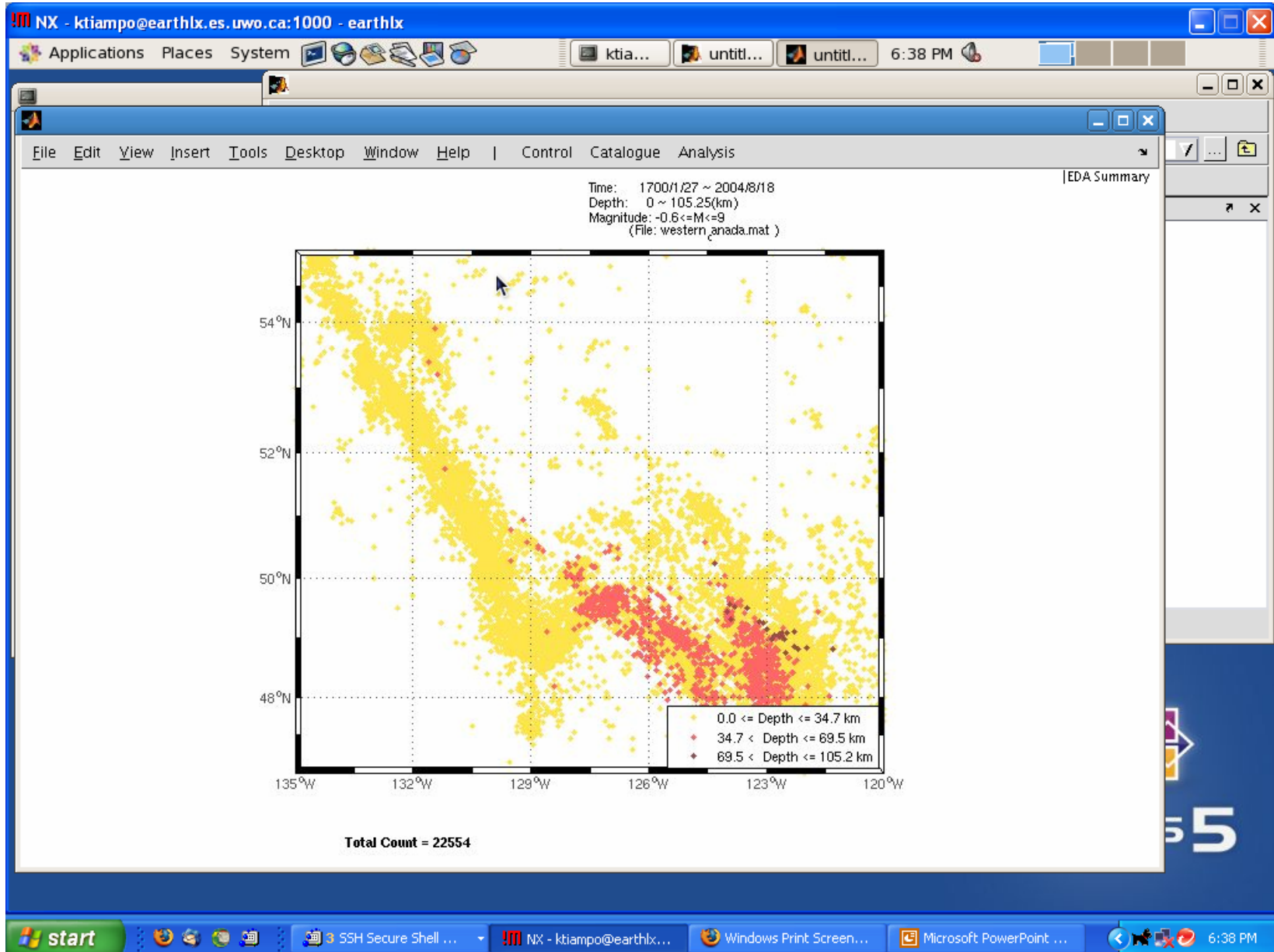
Non-Critical PAST

Random

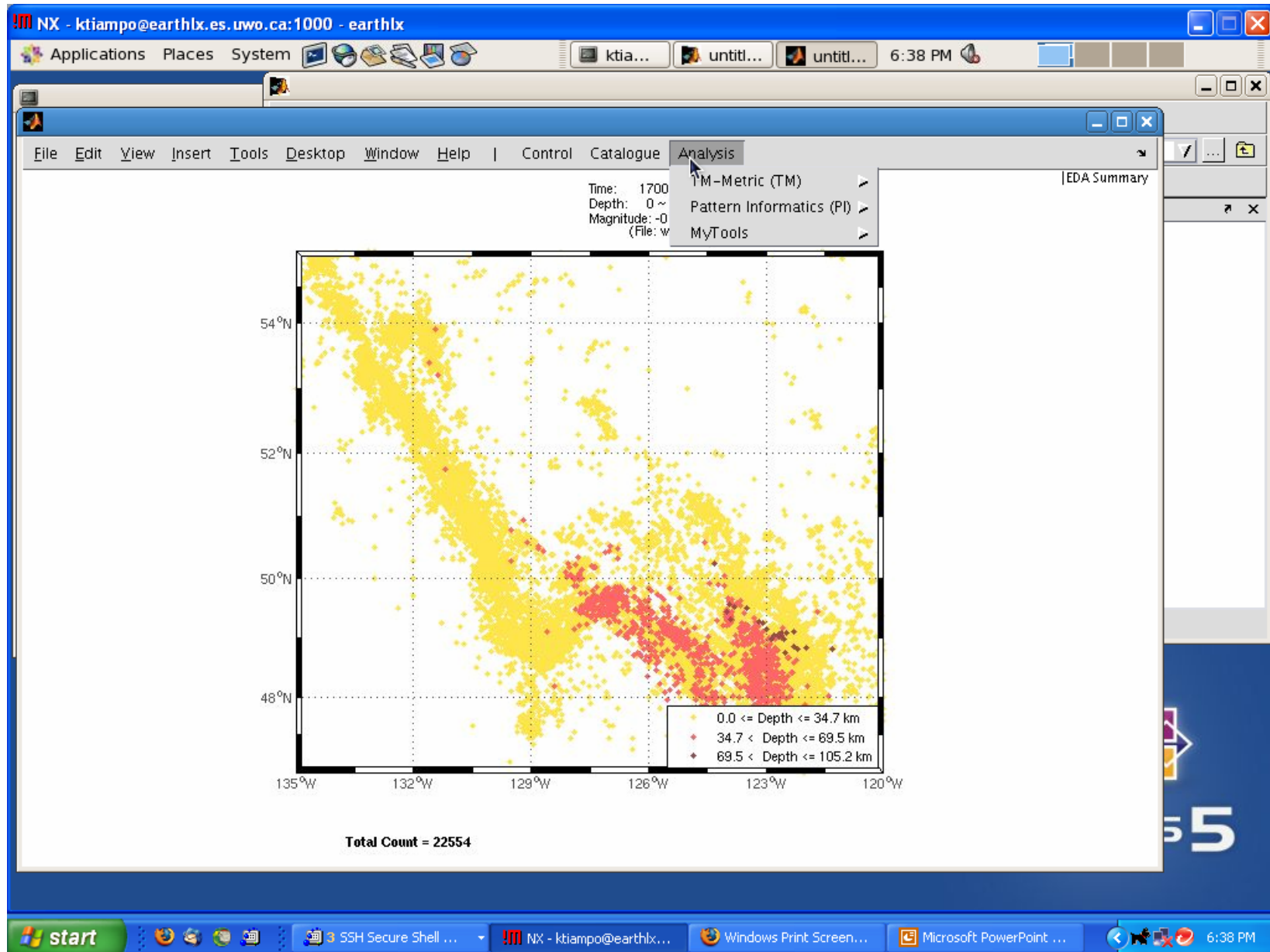
MAPI – A software tool to implement and test these methods interactively



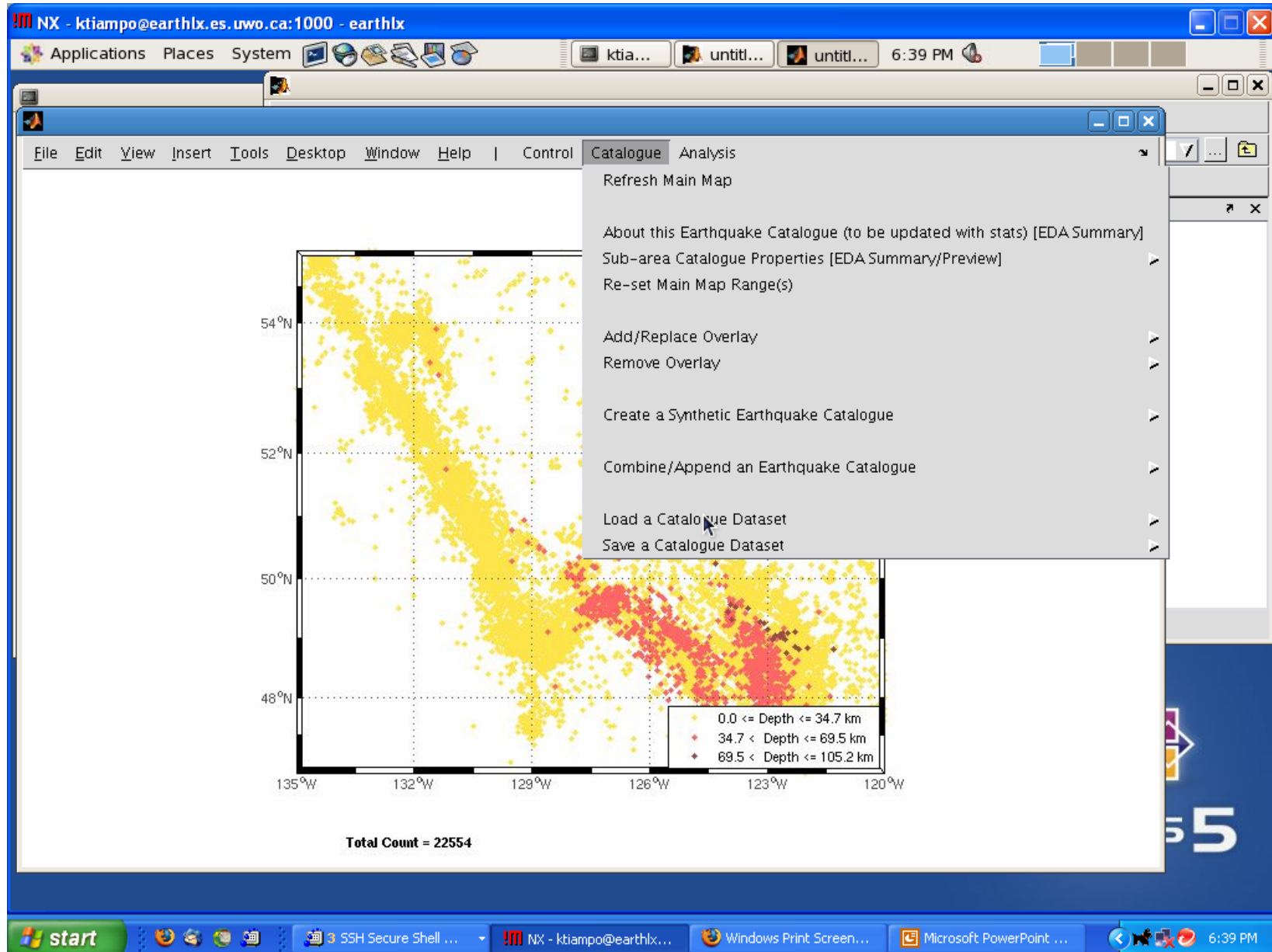
MAPI



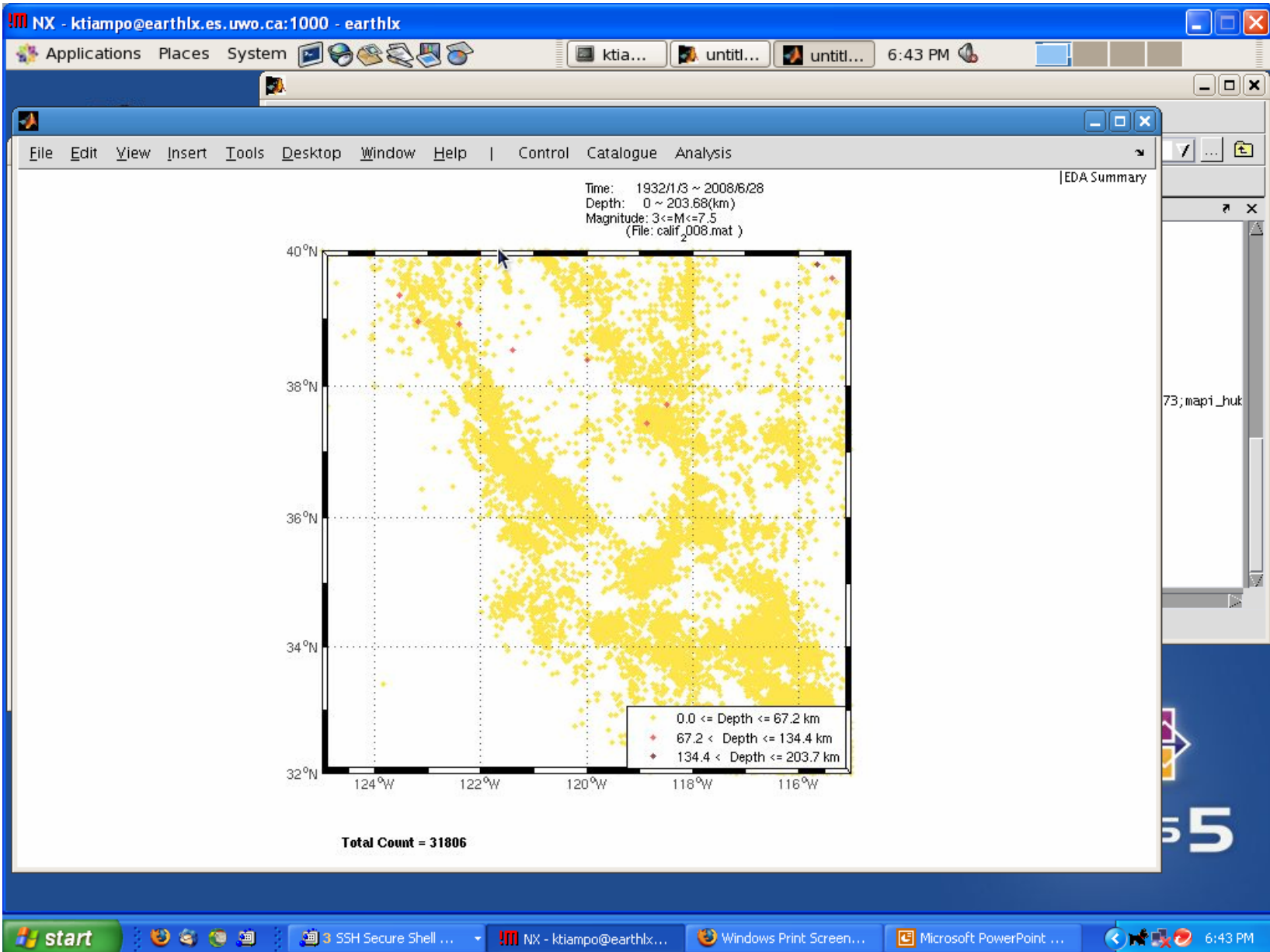
MAPI



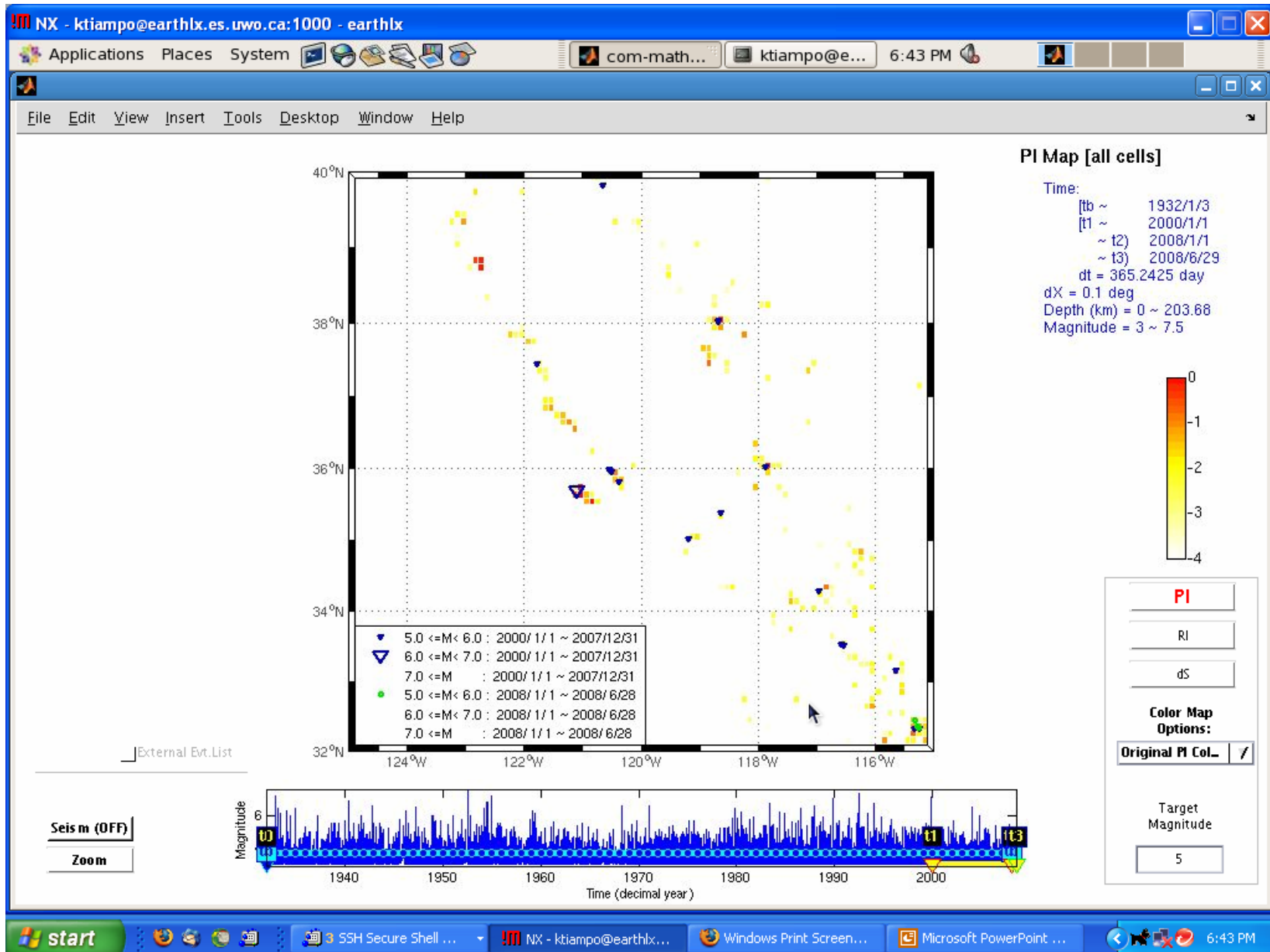
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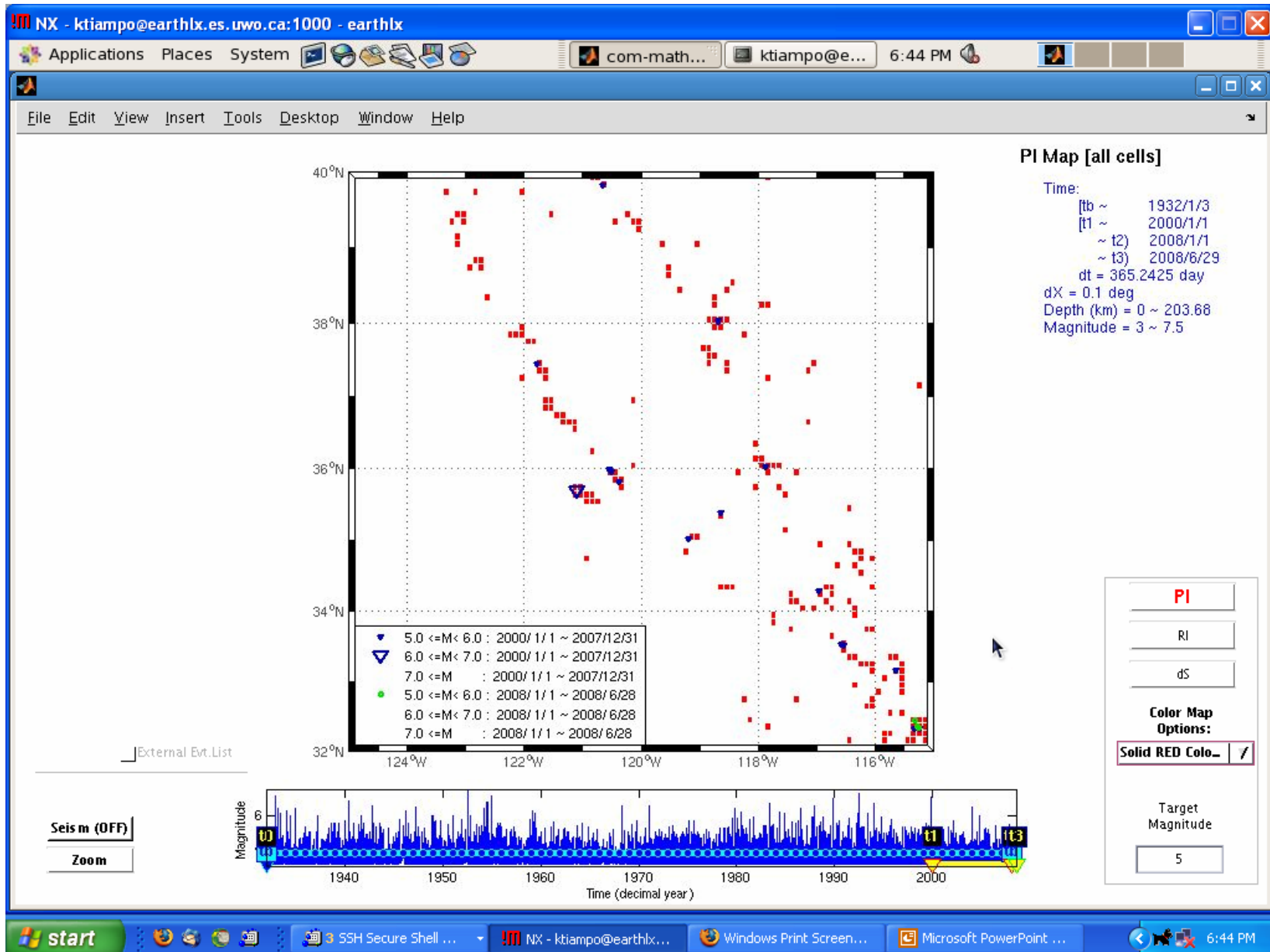
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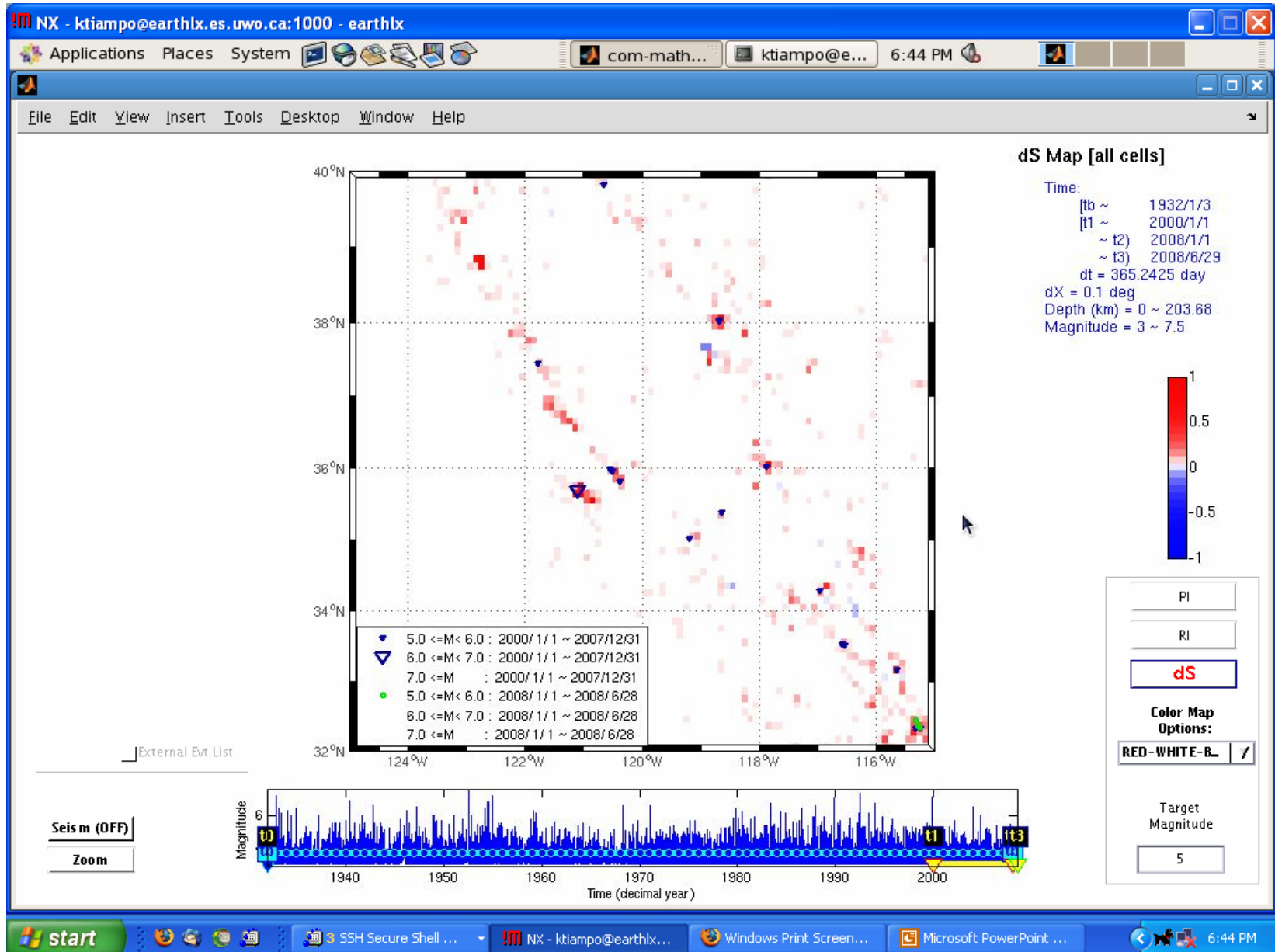
MAPI



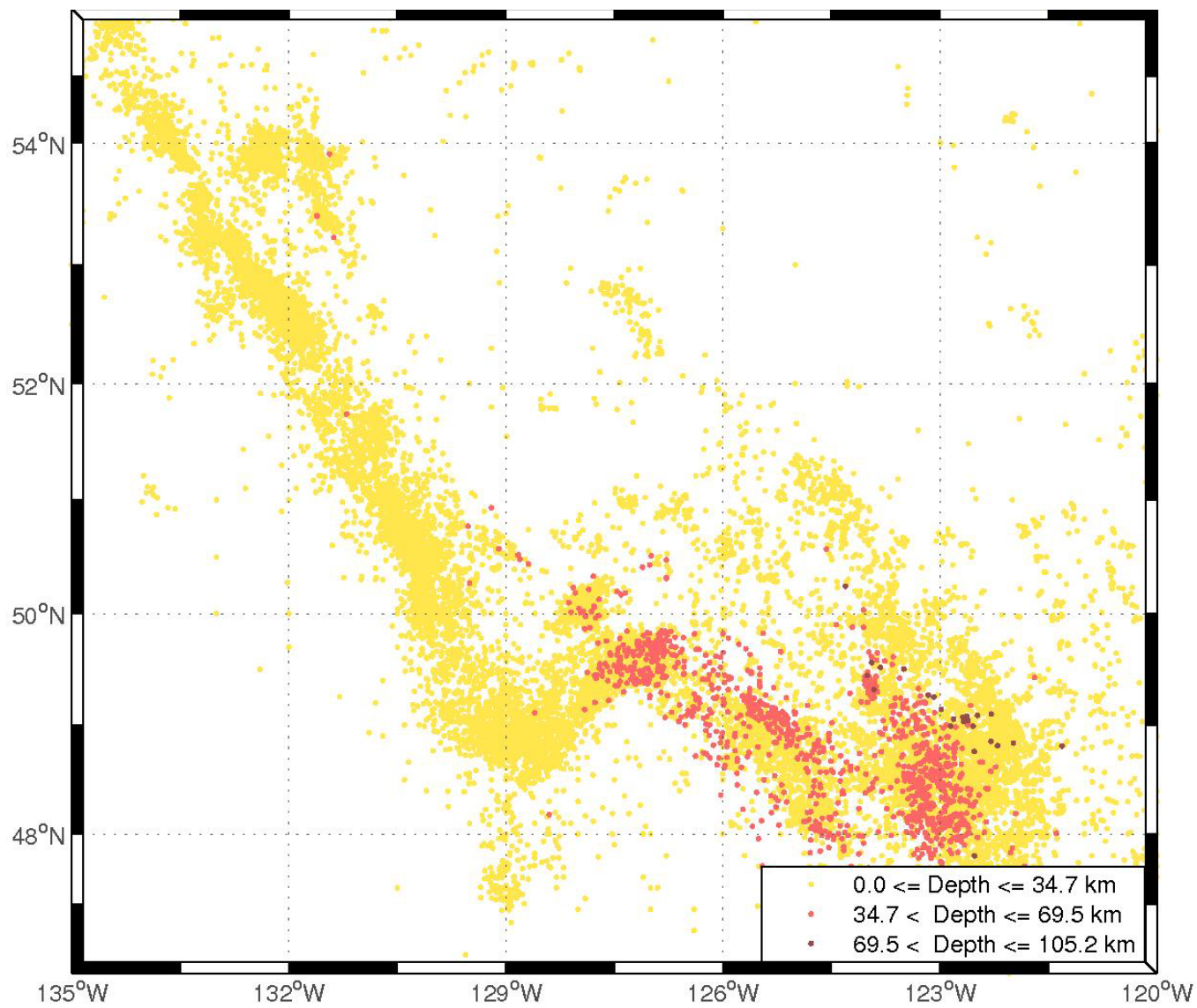
MAPI



MAPI

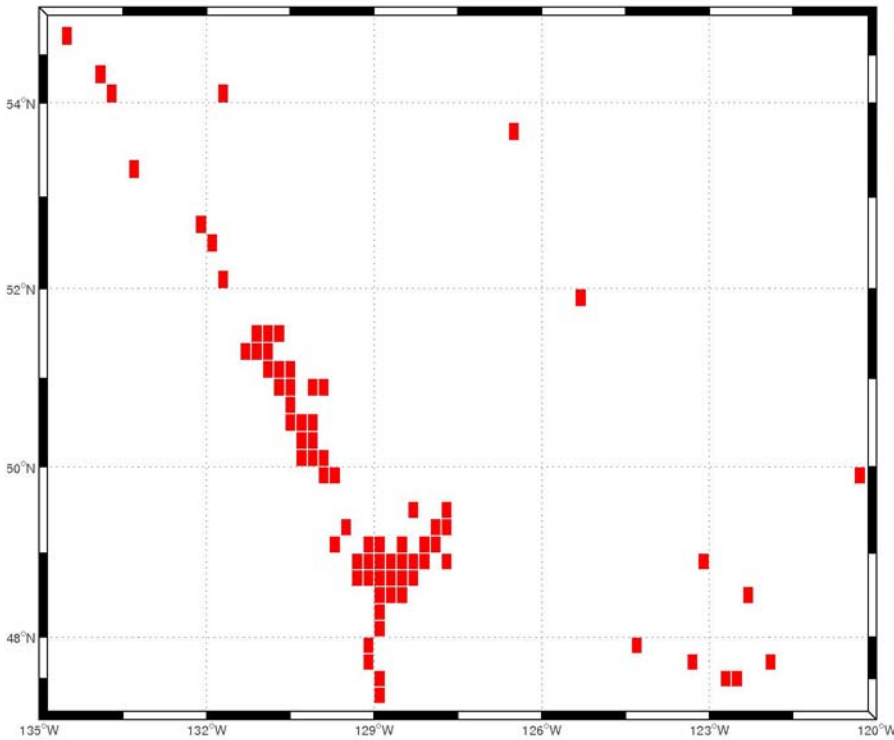


Western Canada

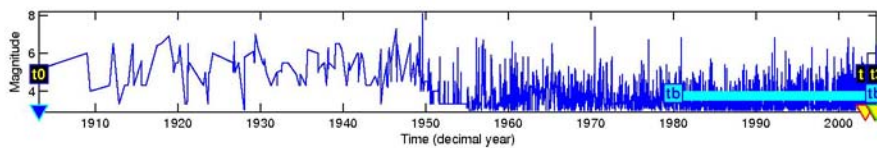


Western Canada

Episodic Tremor & Slip (ETS), 2004



ternal Ext.List



PI Map [all cells]

Time:
 [tb ~ 1980/1/1
 [t1 ~ 2003/4/1
 ~ t2) 2004/6/1
 ~ t3) 2004/8/15
 dt = 30 day
 dX = 0.2 deg
 Depth (km) = 0 ~ 96
 Magnitude = 3 ~ 8.1

PI

RI

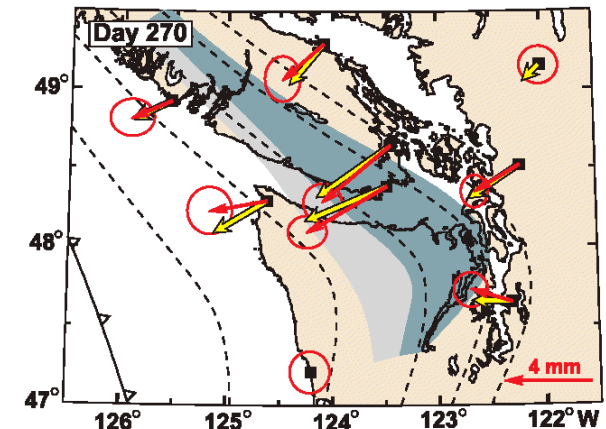
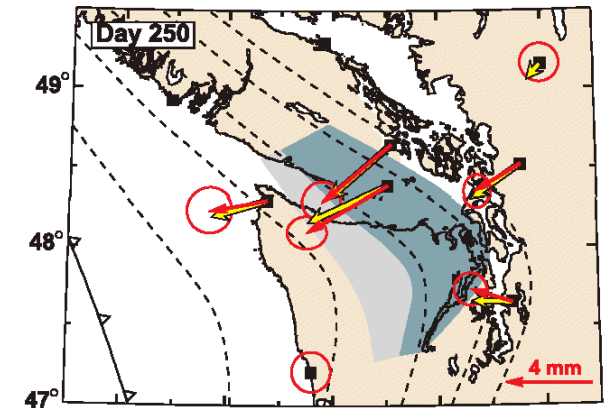
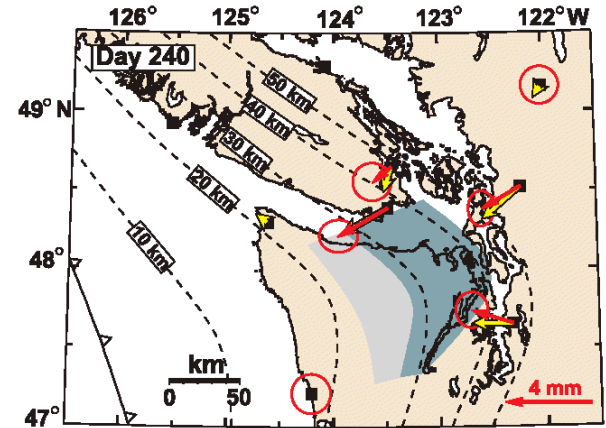
dS

Color Map Options:

Solid RED Color... /

Target Magnitude

5

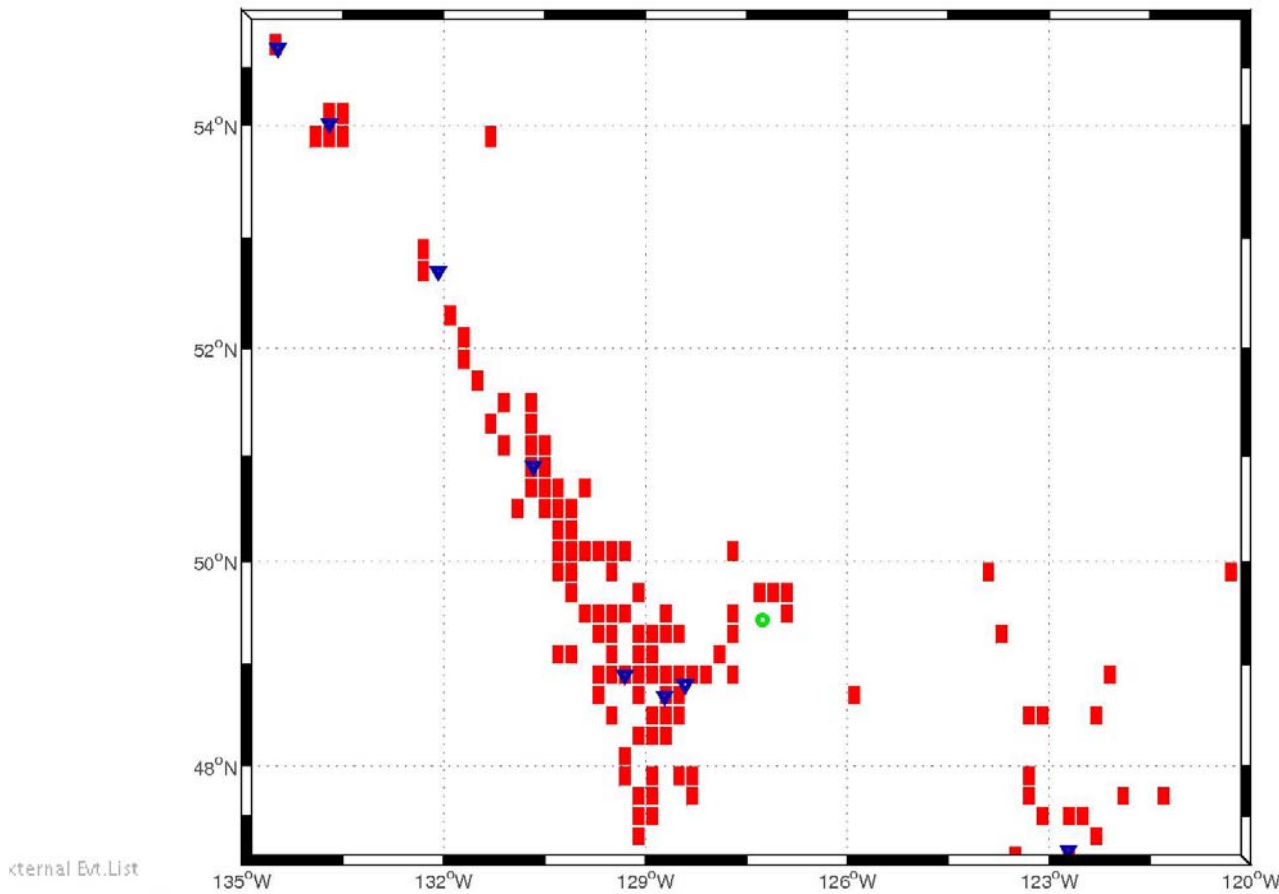


Western Canada

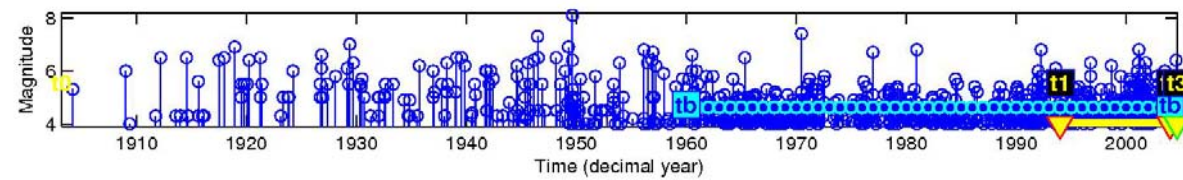
PI: 2003-1993

PI Map [all cells]

Time:
[tb ~ 1960/1/1
[t1 ~ 1994/1/1
~ t2) 2004/1/1
~ t3) 2004/8/15
dt = 365.2425 day
dX = 0.2 deg
Depth (km) = 0 ~ 96
Magnitude = 4 ~ 8.1



External Evt. List



PI

RI

dS

Color Map Options:

Solid RED Colo_ /

Target Magnitude

6