The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization
IAEA
International Atomic Energy Agency

**2060-60**

**Advanced School on Non-linear Dynamics and Earthquake Prediction**

***28 September - 10 October, 2009***

# Practice of Predicting Large Earthquakes on Global and Regional Scales

Vladimir Kossobokov
*International Institute of Earthquake Prediction Theory and Mathematical Geophysics*
*Moscow*
*Russia*
*Institute de Physique du Globe de Paris*
*France*

volodya@mitp.ru/volodya@ipgp.jussieu.fr

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

# Practice of Predicting Large Earthquakes on Global and Regional Scales


Vladimir Kossobokov

International Institute of Earthquake Prediction Theory and Mathematical Geophysics,
Russian Academy of Sciences,
84/32 Profsouznaya Ulitsa, Moscow 117997, Russian Federation

Institute de Physique du Globe de Paris,
4 Place Jussieu, 75252 Paris, Cedex 05, France

*E-mail: volodya@mitp.ru or volodya@ipgp.jussieu.fr*

# Outline

- Earthquake prediction definition
- Intermediate-term middle-range earthquake prediction algorithms M8 and MSc
- First retrospective tests
- Global Test of M8-MSc
- Tests in Italy, Vrancea and Armenia

# What is earthquake prediction?

**The United States National Research Council, Panel on Earthquake Prediction of the Committee on Seismology suggested the following definition (1976, p.7):**

*"An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen with sufficient precision so that the ultimate success or failure of the prediction can readily be judged. Only by careful recording and analysis of failures as well as successes can the eventual success of the total effort be evaluated and future directions charted. Moreover, scientists should also assign a confidence level to each prediction."*

# Stages of earthquake prediction

- Term-less prediction of earthquake-prone areas
- Prediction of time and location of an earthquake of certain magnitude

| Temporal, ***in years*** | | Spatial, ***in source zone size L*** | |
|---|---|---|---|
| Long-term | 10 | Long-range | up to 100 |
| Intermediate-term | 1 | Middle-range | 5-10 |
| Short-term | 0.01-0.1 | Narrow | 2-3 |
| Immediate | 0.001 | Exact | 1 |

- Moreover, the Gutenberg-Richter law suggests limiting magnitude range of prediction to about one unit. Otherwise, the statistics would be essentially related to dominating smallest earthquakes.

(available from *IASPEI Software Library, Vol. 6. Seismol. Soc. Am., El Cerrito, CA, 1997*)

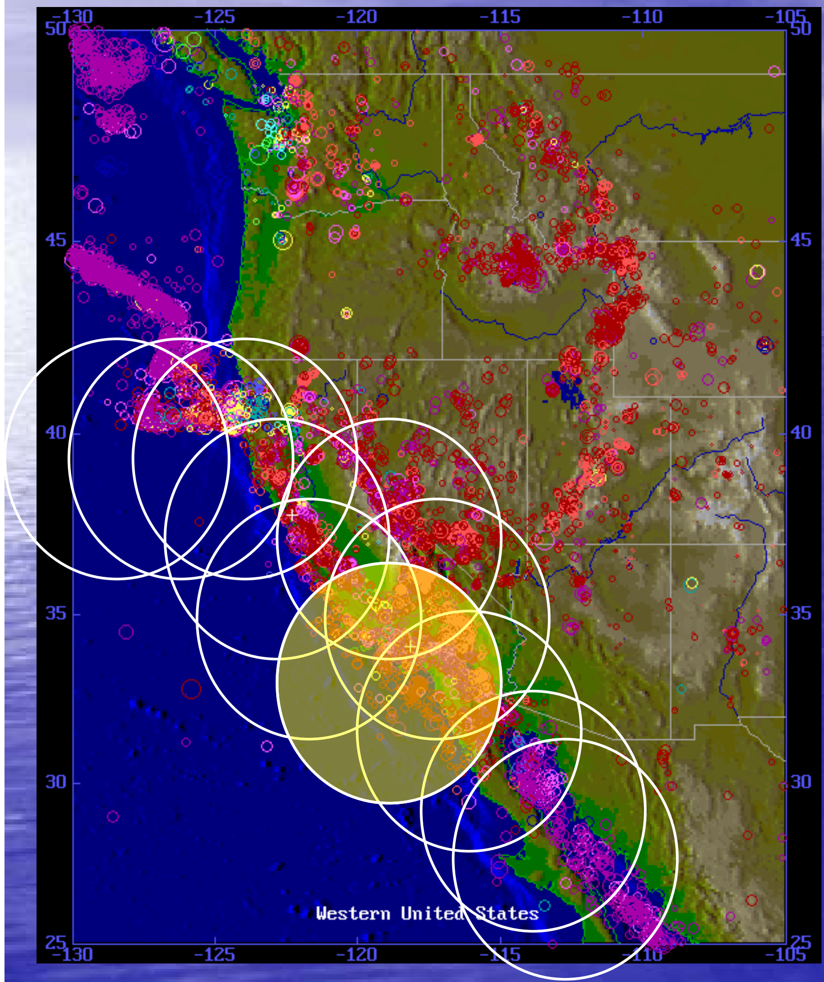
# M8 algorithm

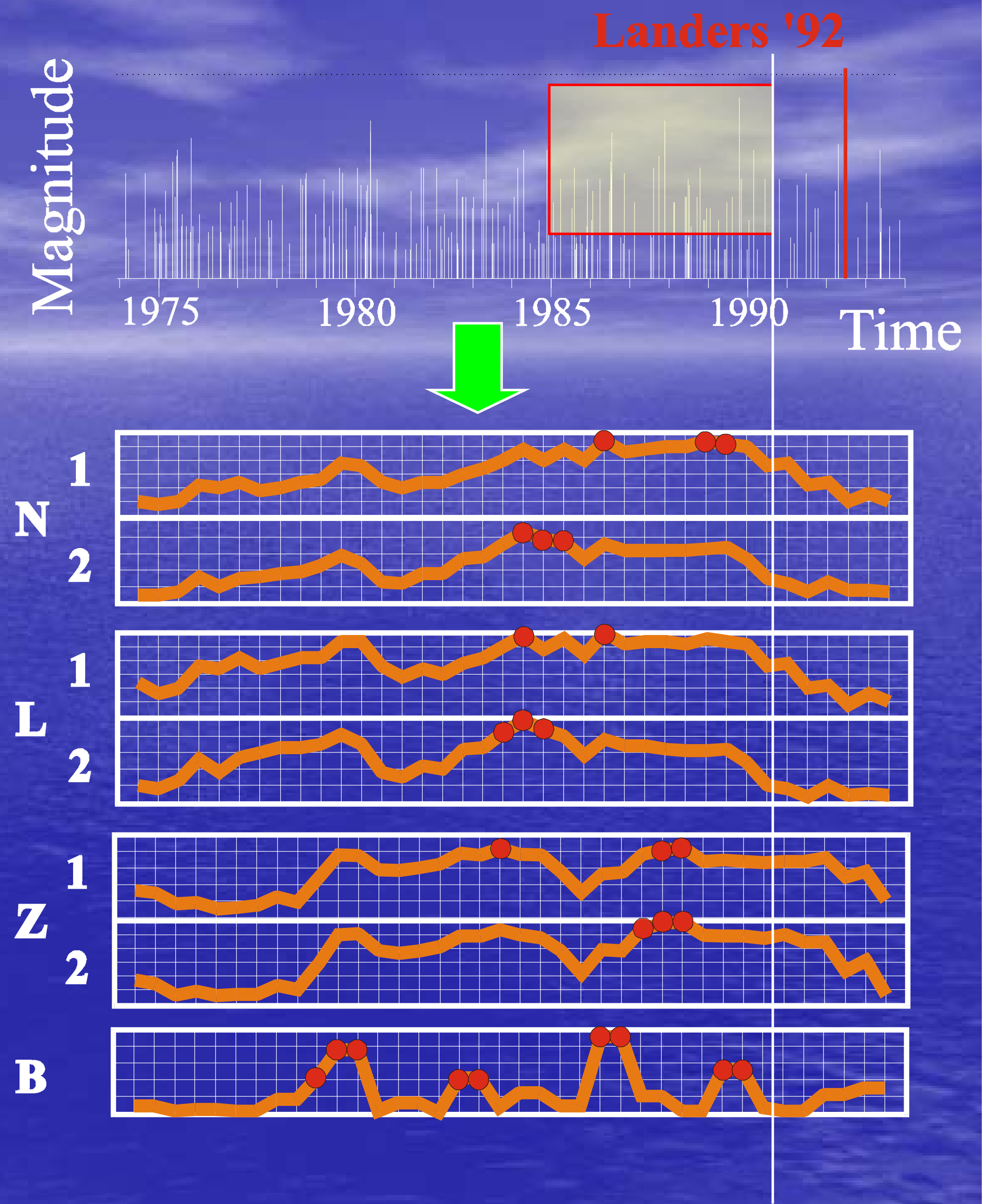
This intermediate-term earthquake prediction method was designed by retroactive analysis of dynamics of seismic activity preceding the greatest, magnitude 8.0 or more, earthquakes worldwide, hence its name.

Its prototype (***Keilis-Borok and Kossobokov, 1984***) and the original version (***Keilis-Borok and Kossobokov, 1987***) were tested retroactively at 143 points, of which 132 are recorded epicenters of earthquakes of magnitude 8.0 or greater from 1857-1983.

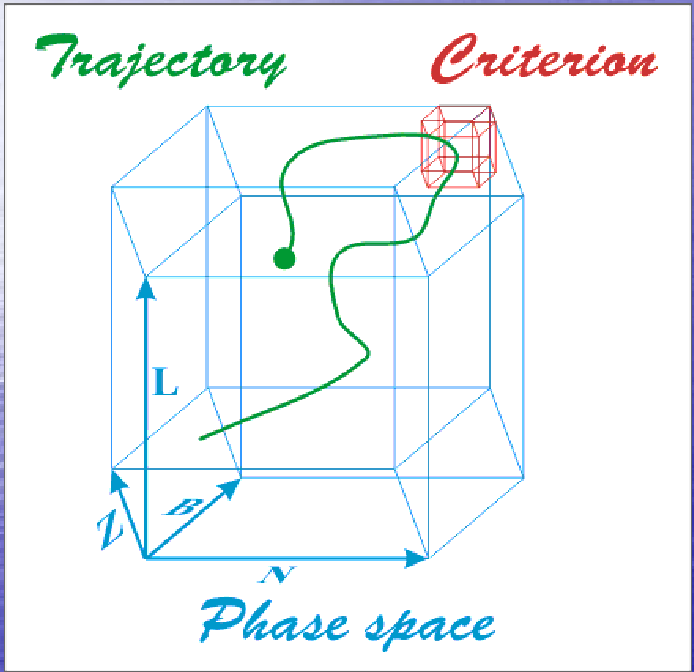
The algorithm is based on a simple physical scheme…

# General scheme



# Criterion in the phase space




- The algorithm M8 uses traditional description of a dynamical system adding to a common phase space of rate (N) and rate differential (L) dimensionless concentration (Z) and a characteristic measure of clustering (B).
- The algorithm recognizes *criterion*, defined by extreme values of the phase space coordinates, as a vicinity of the system singularity. When a trajectory enters the criterion, probability of extreme event increases to the level sufficient for its effective provision.

# Prediction aimed at magnitude $M_0$

- Prediction is aimed at earthquakes of magnitude $M_0$ and larger from the range $M_0+ = [M_0, M_0+\Delta M]$ (where $\Delta M < 1$). Magnitude scale should reflect the size of earthquake sources (accordingly, MS usually taken for larger magnitudes, while mb is used for smaller ones).
- If the data permits, we set different $M_0+$ with a step 0.5.
- Overlapping circles, with the diameter

  $D(M_0) = ( \mathit{exp}(M_0 - 5.6)+1 )^0$ in degrees of the Earth meridian, scan the seismic region under study.

# M8 algorithm performance

- Retrospectively (*Keilis-Borok and Kossobokov, 1990*) the standard version of the algorithm was applied to predict the largest earthquakes (with $M_0$ ranging from 8.0 to 4.9) in 14 regions.

**25 out of 28 predicted in 16% of the space-time considered.**

- Modified versions in 4 regions of lower seismic activity predicted

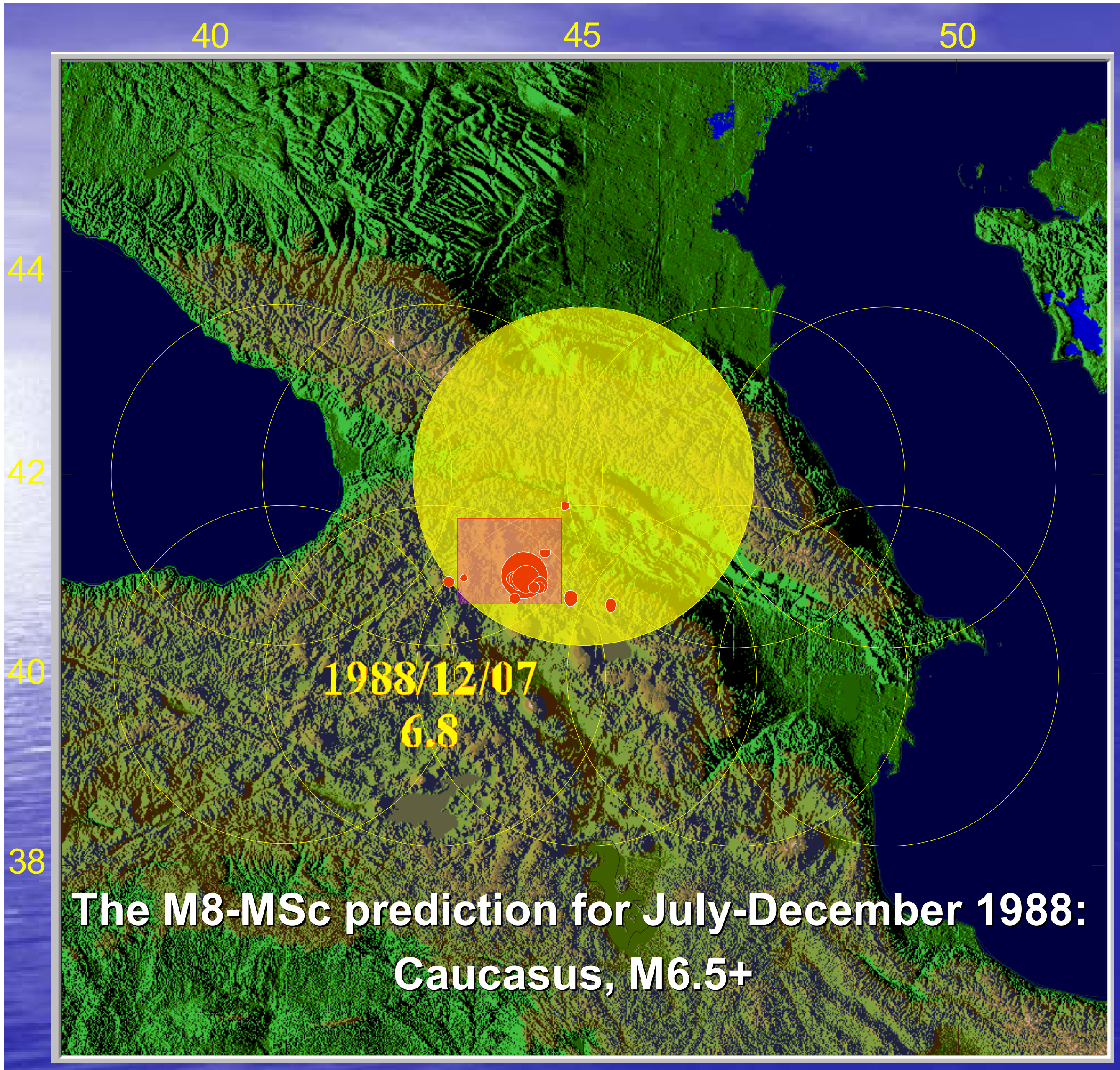
**all the 11 largest earthquakes in 26 % of the space-time considered.**

# Second approximation prediction method

The algorithm for reducing the area of alarm (*Kossobokov, Keilis-Borok, Smith, 1990*) was designed by retroactive analysis of the detailed regional seismic catalog prior to the Eureka earthquake (1980, M=7.2) near Cape Mendocino in California, hence its name abbreviated to MSc.

Qualitatively, the MSc algorithm outlines such an area of the territory of alarm where the activity, from the beginning of seismic inverse cascade recognized by the first approximation prediction algorithm (e.g. by M8), is continuously high and infrequently drops for a short time. Such an alternation of activity must have a sufficient temporal and/or spatial span.

The phenomenon, which is used in the MSc algorithm, might reflect the second (possibly, shorter-term and, definitely, narrow-range) stage of the premonitory rise of seismic activity near the incipient source of main shock.




**The Spitak (Armenia) earthquake was the first tragic confirmation of the high efficiency of the M8-MSc monitoring achieved in the real-time prediction mode.**

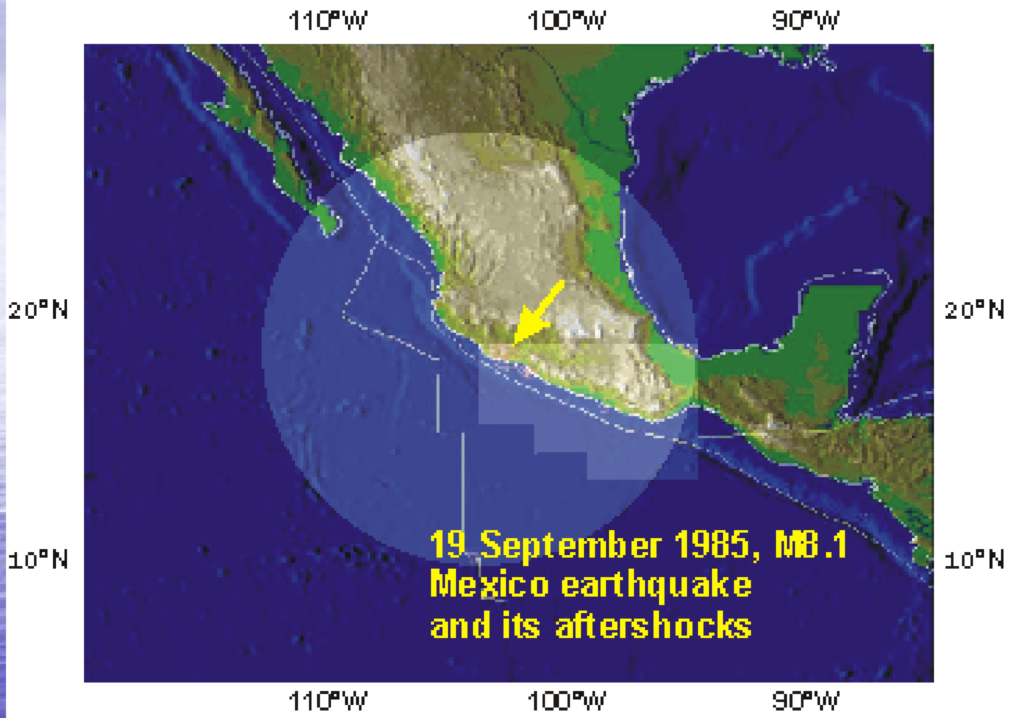
The results of the monitoring of the FSU seismic regions (1986-1990) were encouraging: 6 out of 7 target large earthquakes were predicted with an average probability gain about 7 (at the first approximation,

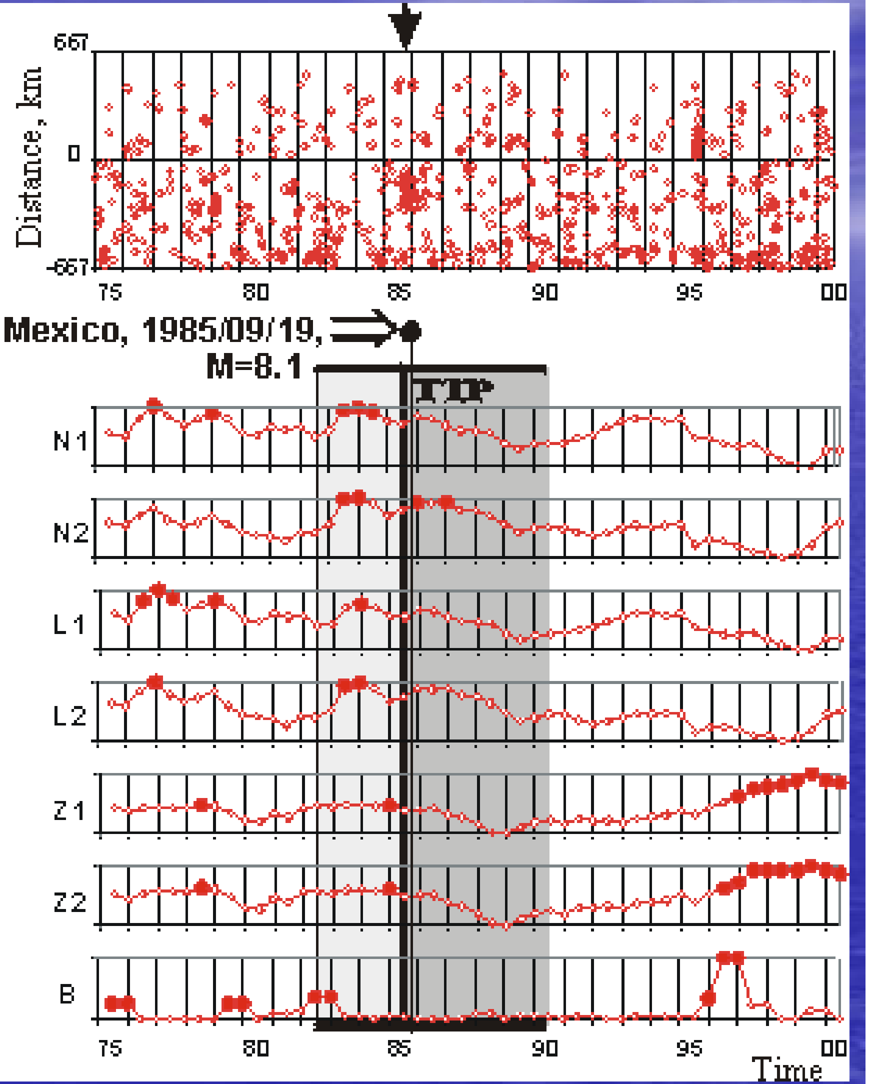
i.e. the M8 stage).

## By 1992 all the components necessary for reproducible real-time prediction, i.e., an unambiguous definition of the algorithms and the data base, were specified in publications

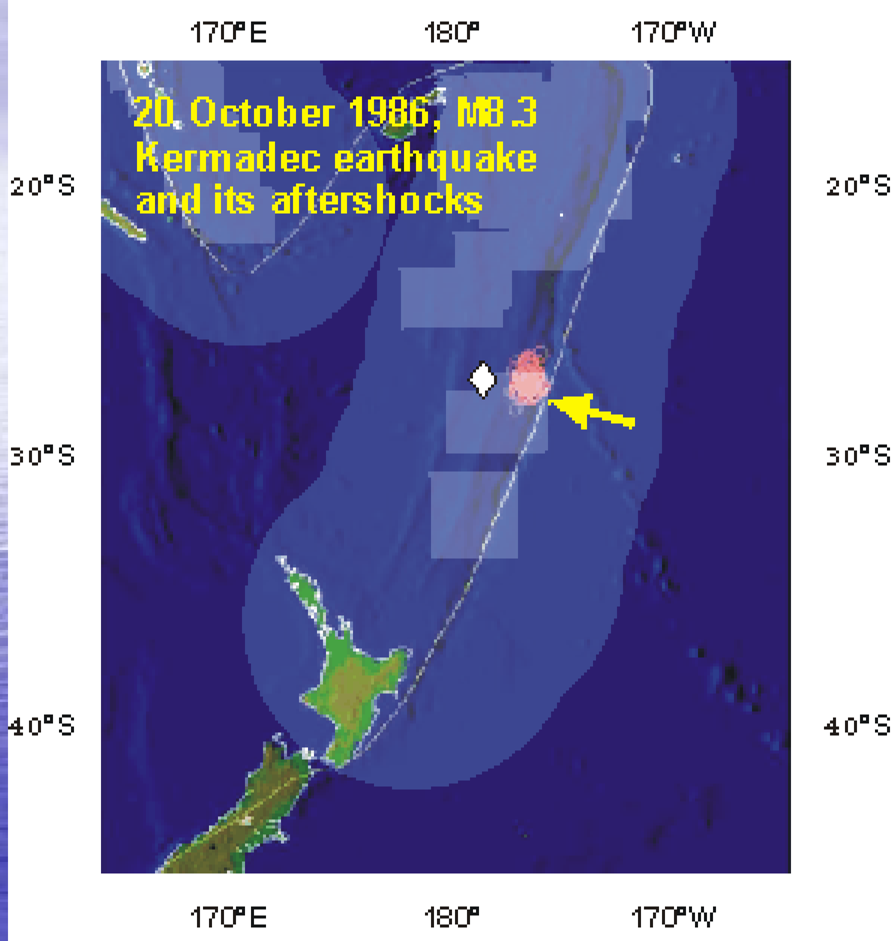
- Algorithm M8 (*Keilis-Borok and Kossobokov, 1984, 1987, 1990*) was designed by retroactive analysis of seismic dynamics preceding the greatest (M≥8) earthquakes worldwide, as well as the MSc algorithm for reducing the area of alarm (*Kossobokov,Keilis-Borok, Smith, 1990*)
- The National Earthquake Information Center Global Hypocenters Data Base (*US GS/NEIC GHDB, 1989*) is sufficiently complete since 1963.
- This allowed a systematic application of M8 and MSc algorithm since 1985.

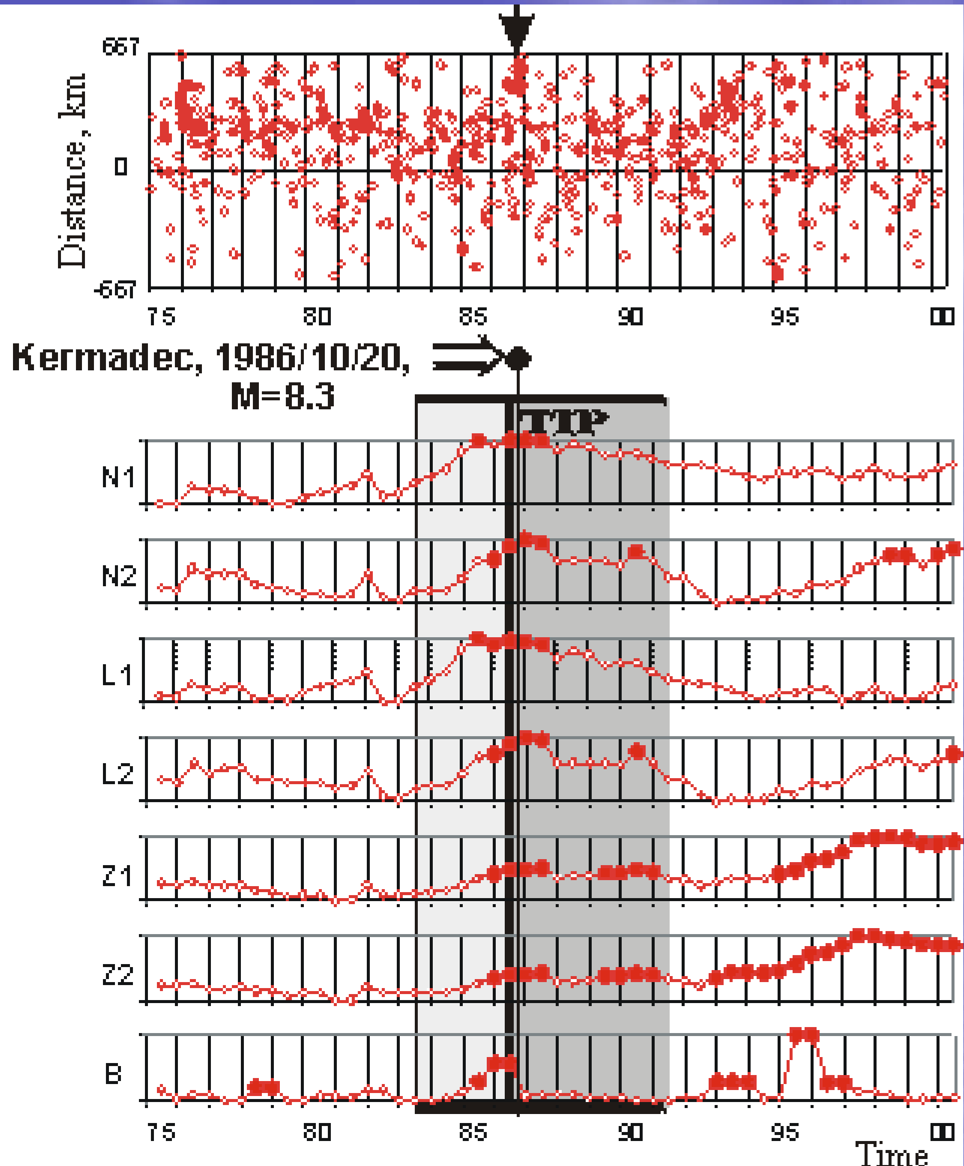
# 19/09/1985 Mexico Earthquake



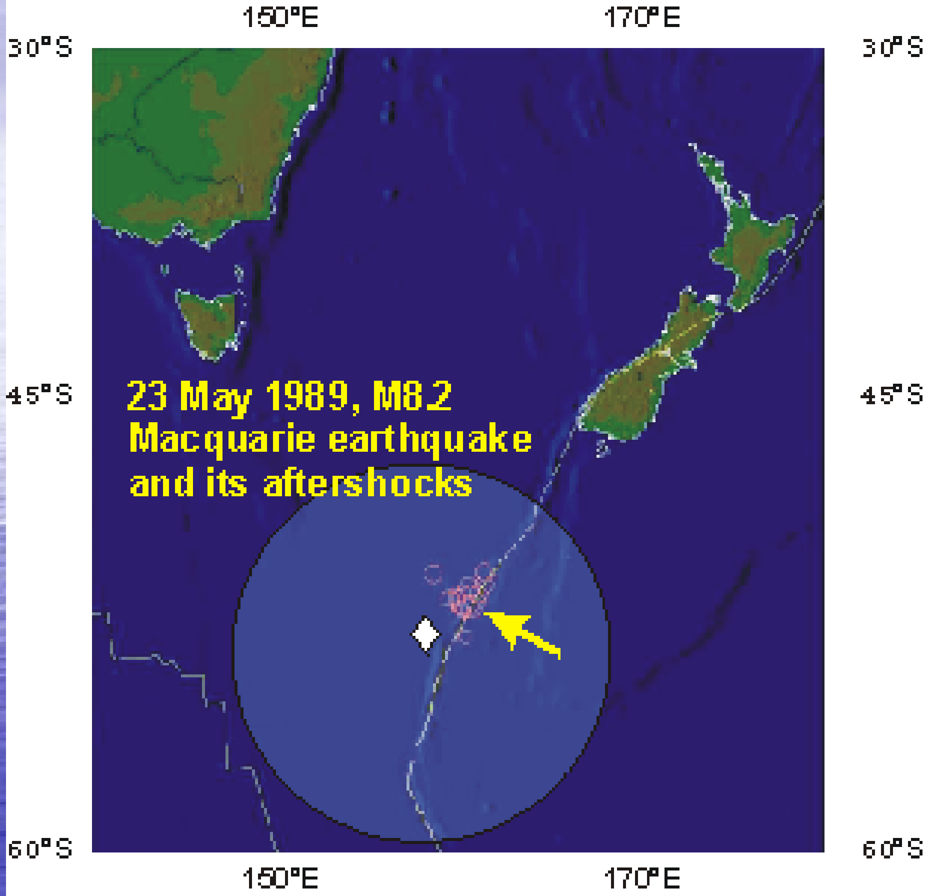
# 20/10/1986 Kermadek Earthquake

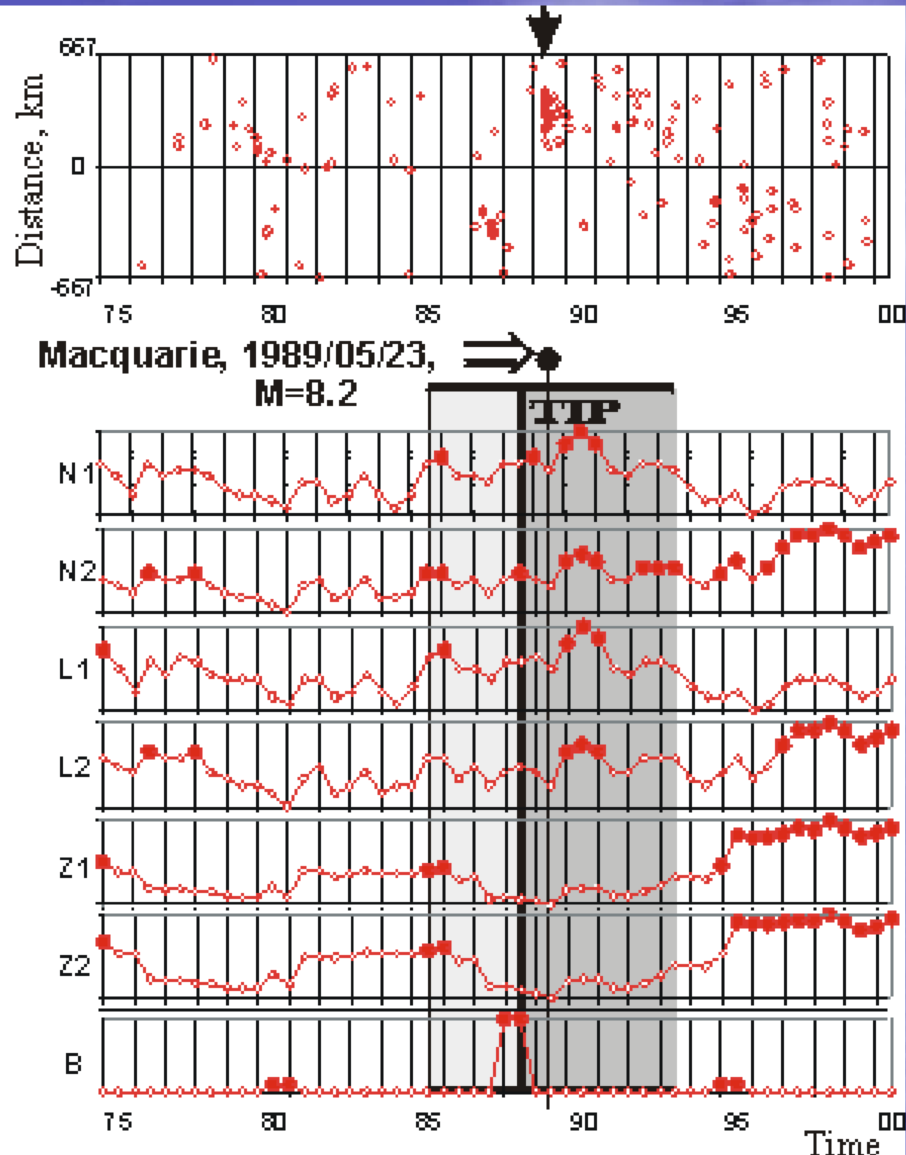


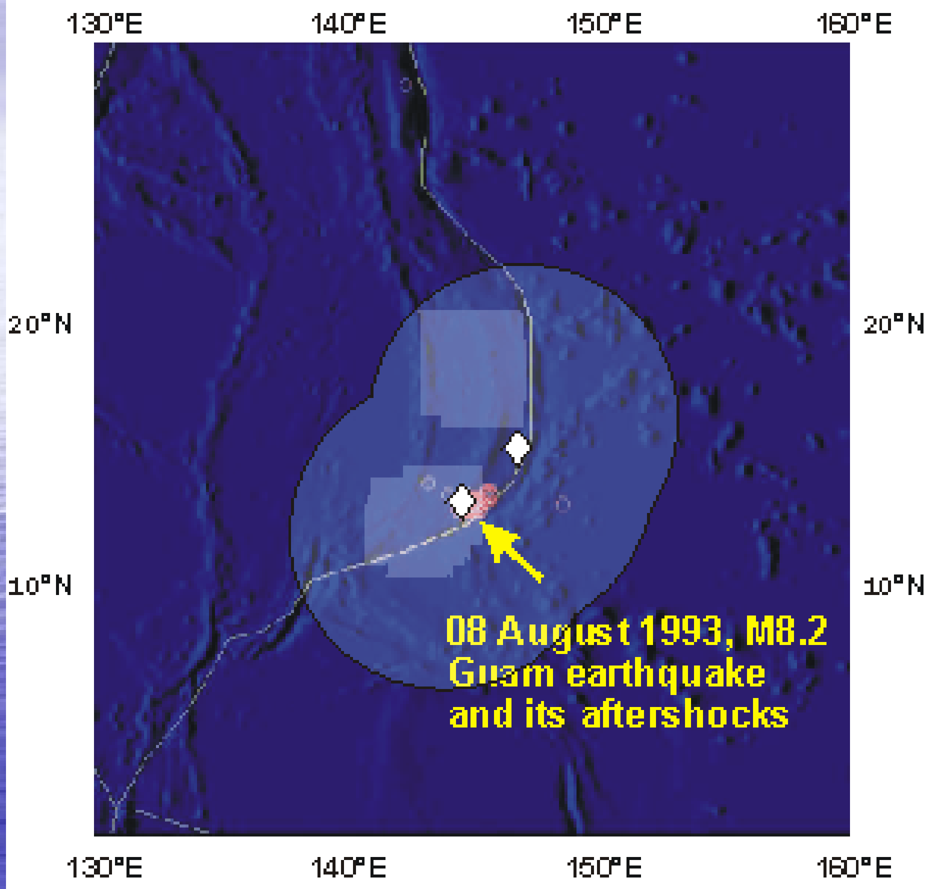
Outside Test Area, NOT COUNTED in the overall statistics

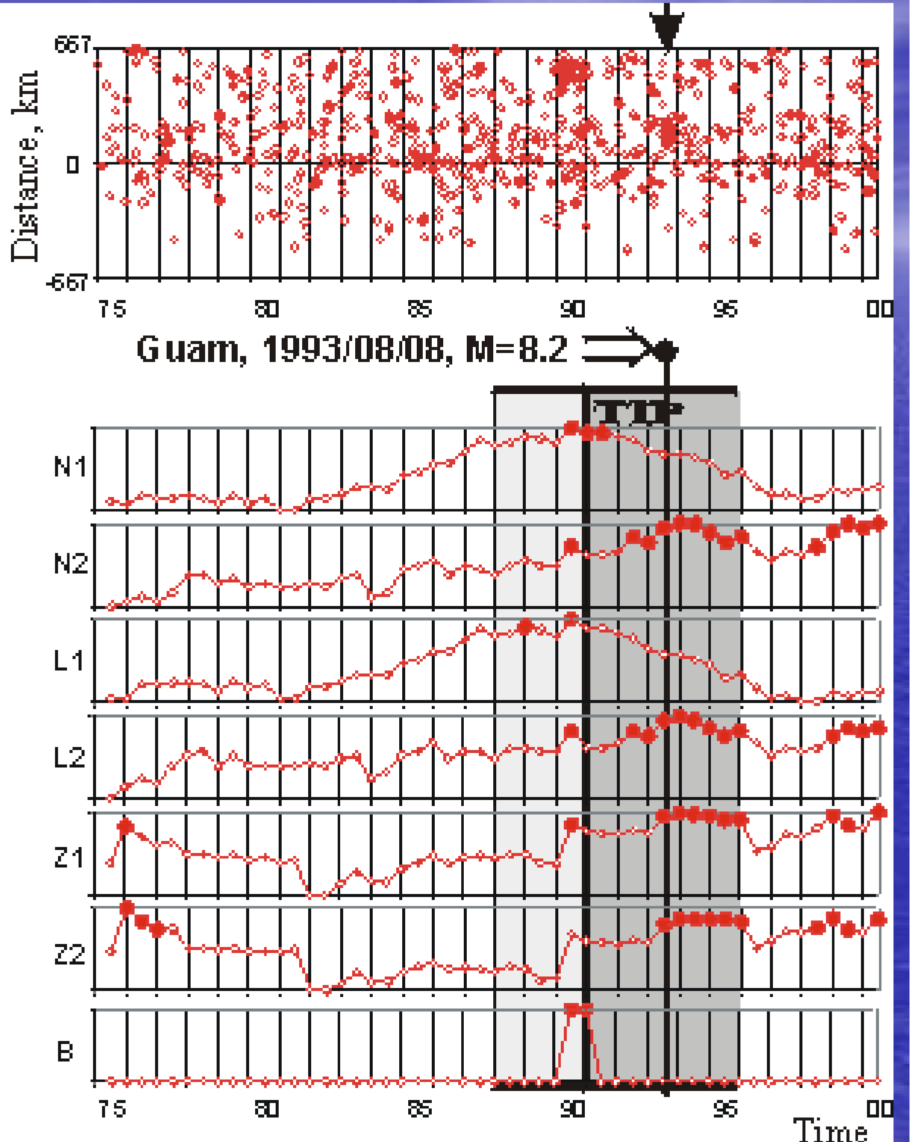
# 23/05/1989 Macquarie Earthquake



# 08/08/1993 Guam Earthquake



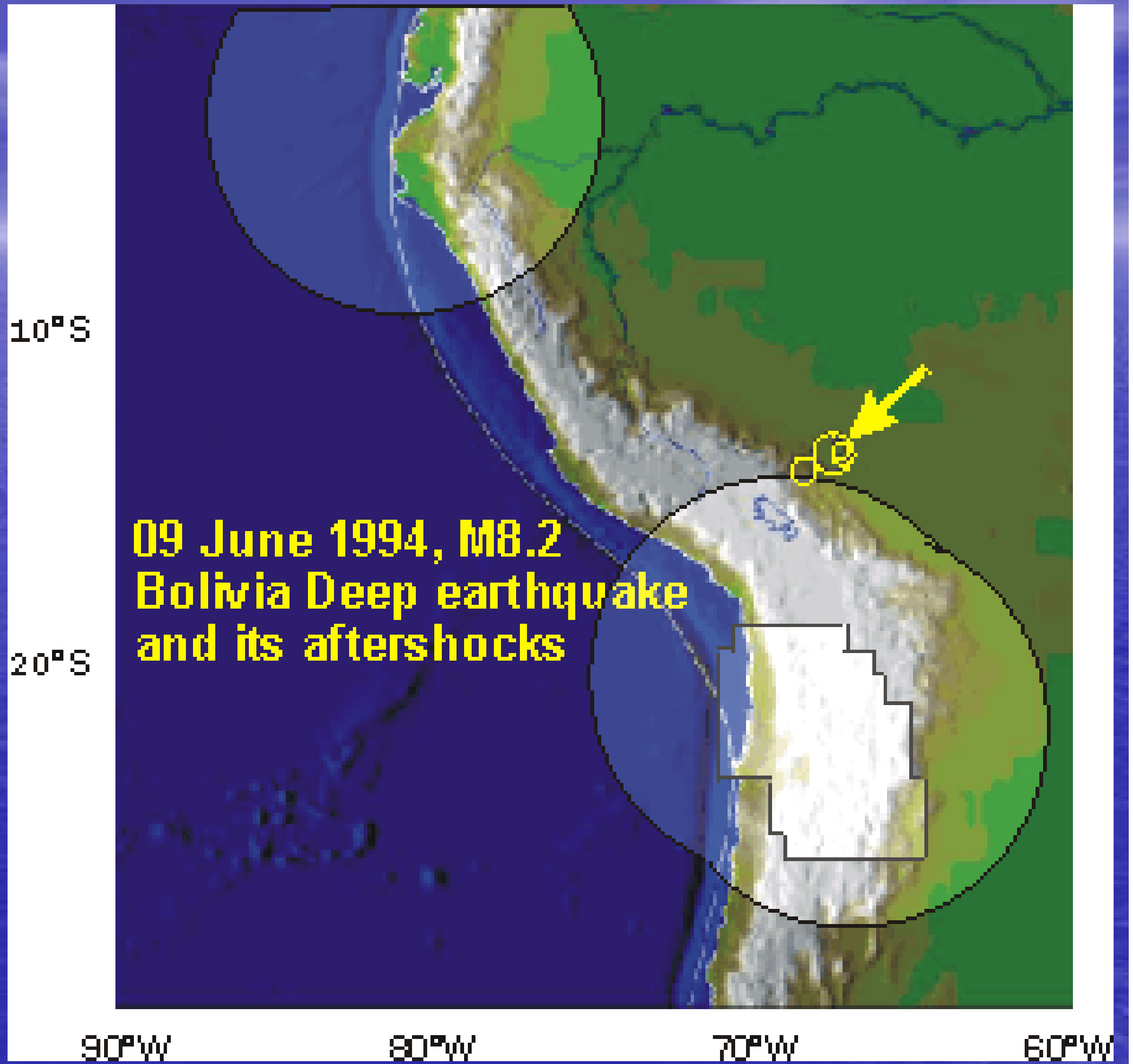



Outside Test Area, NOT COUNTED in the overall statistics

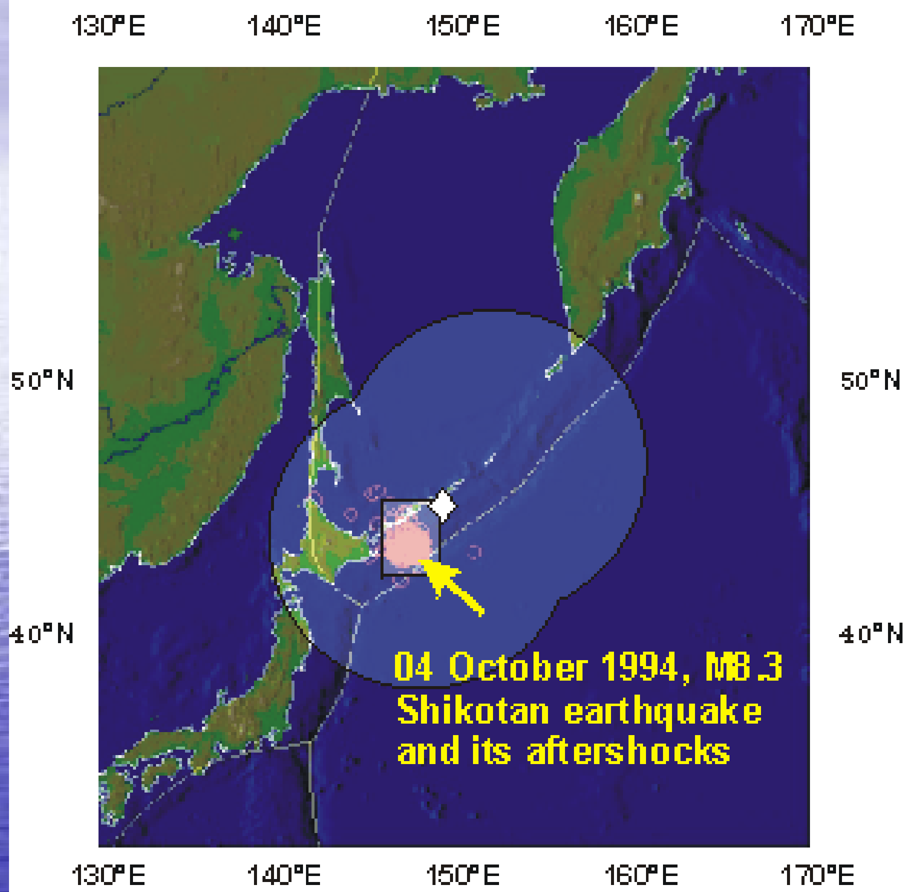
# 09/06/1994 Bolivia Deep Earthquake

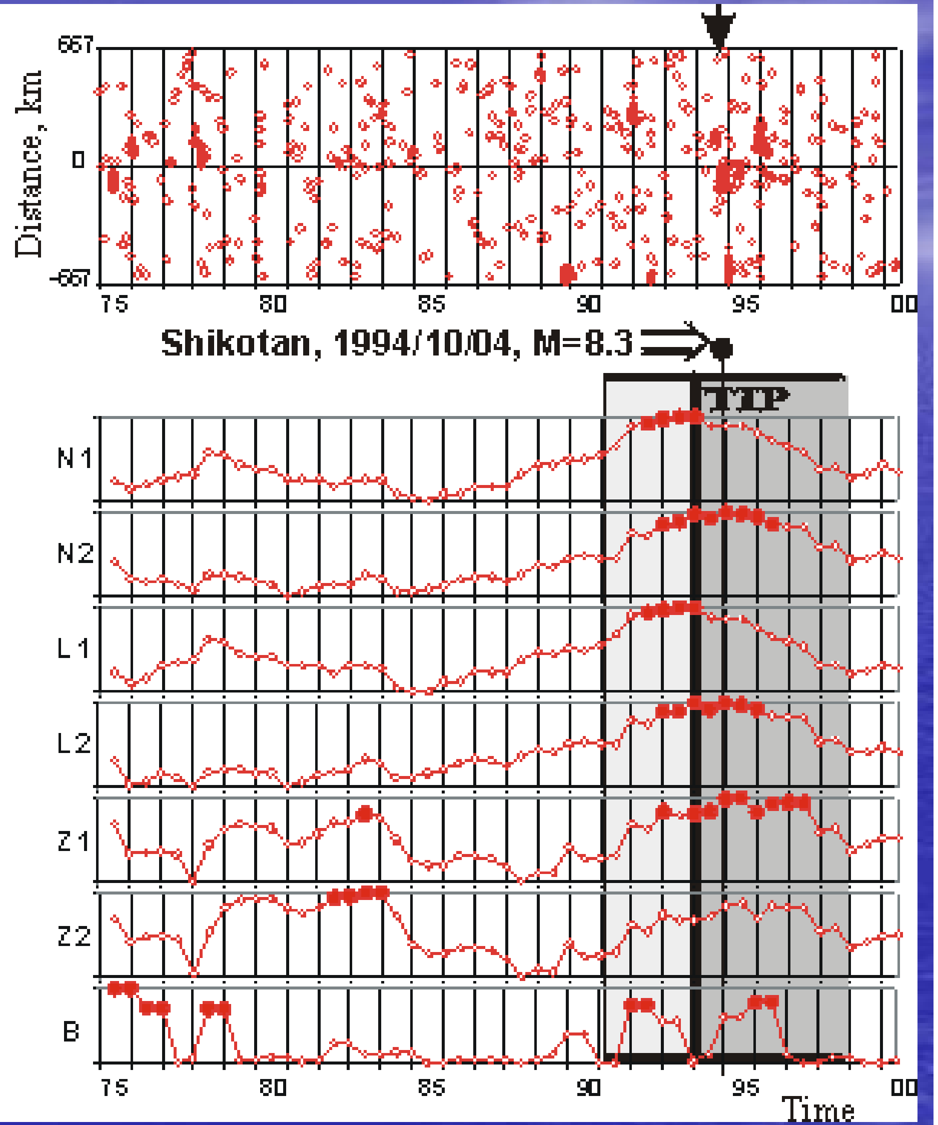
- The Great Deep Bolivia earthquake did occur after the January 10, 1994, magnitude 6.9, depth 595 km earthquake at distance of about 250 km.

The previous earthquake that deep happened here in 1963.

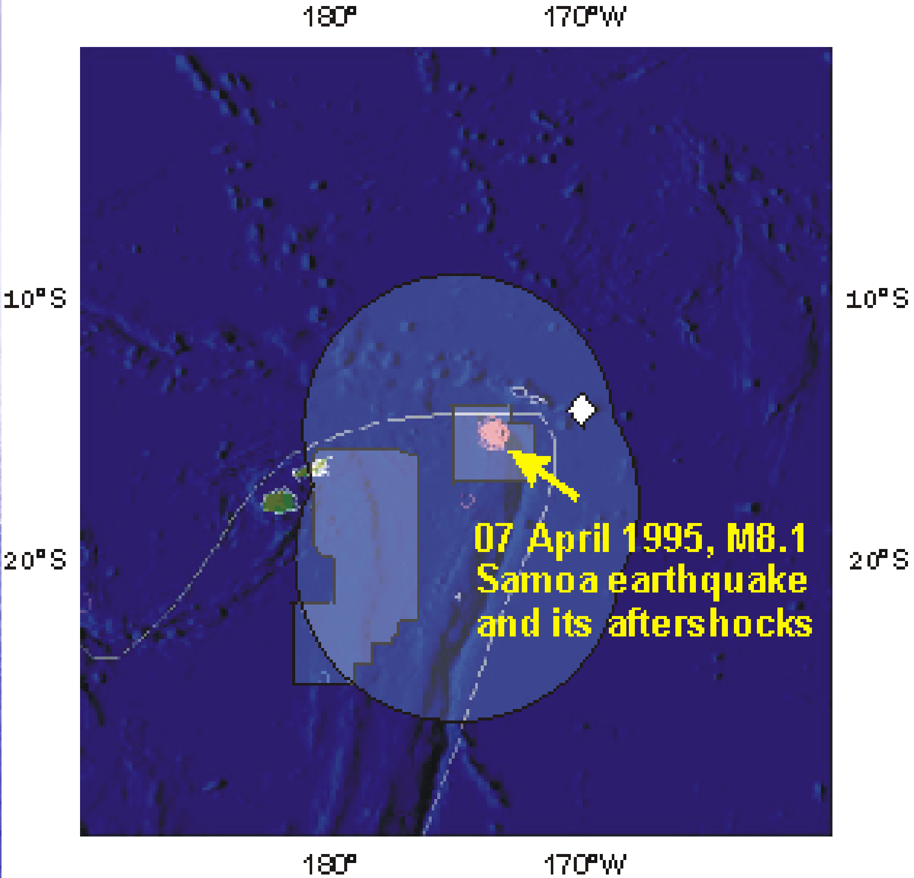


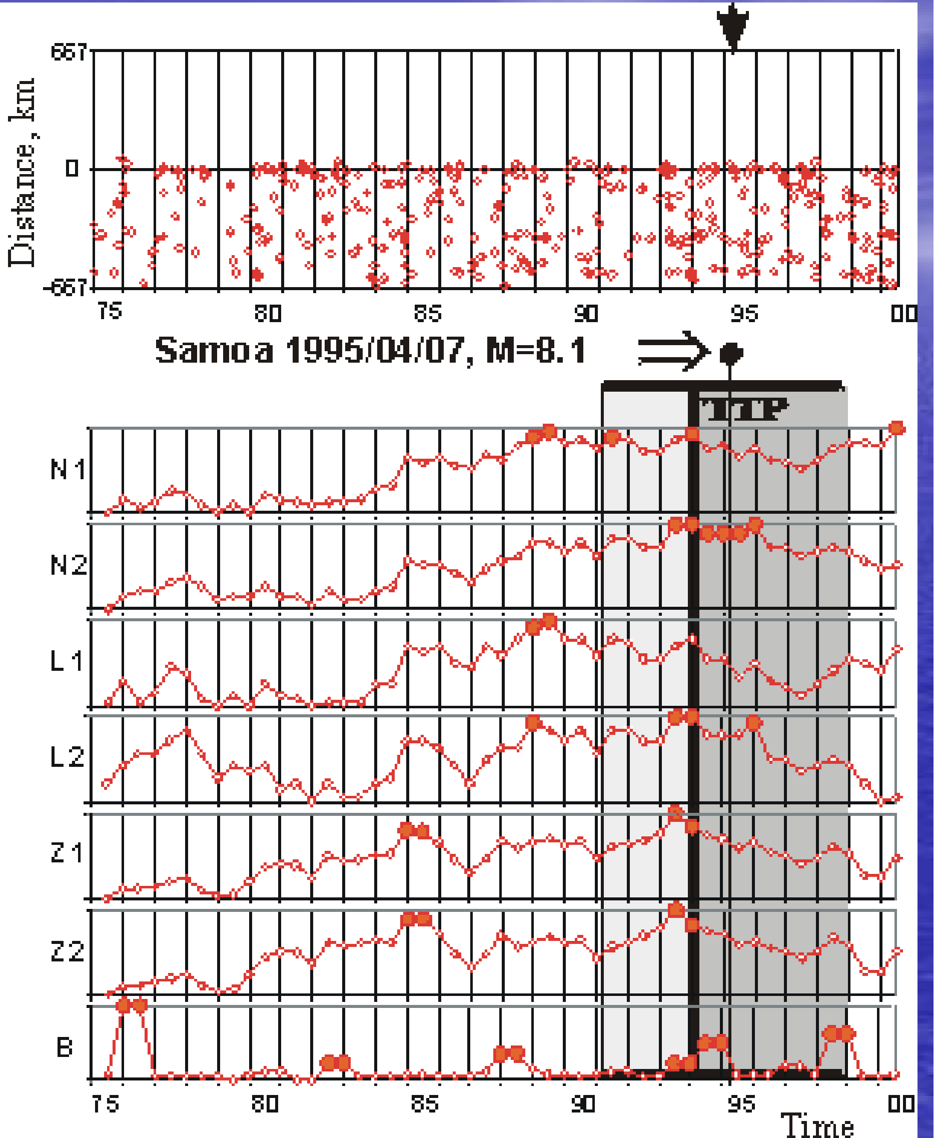
# 04/10/1994 Shikotan Earthquake



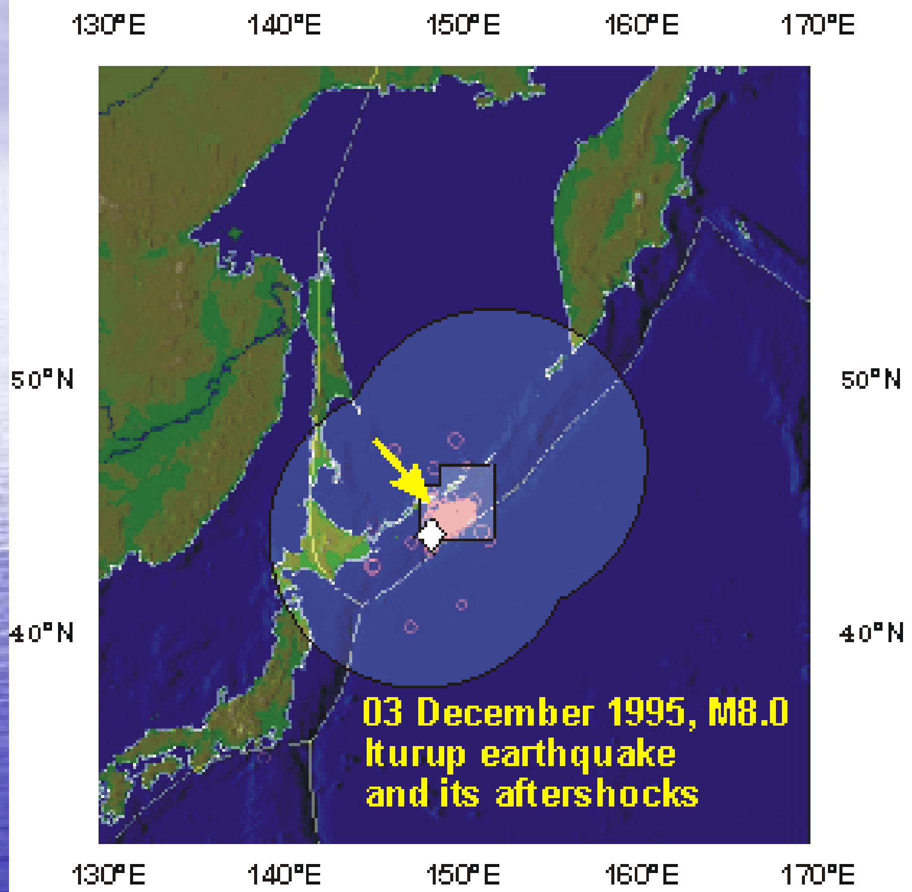



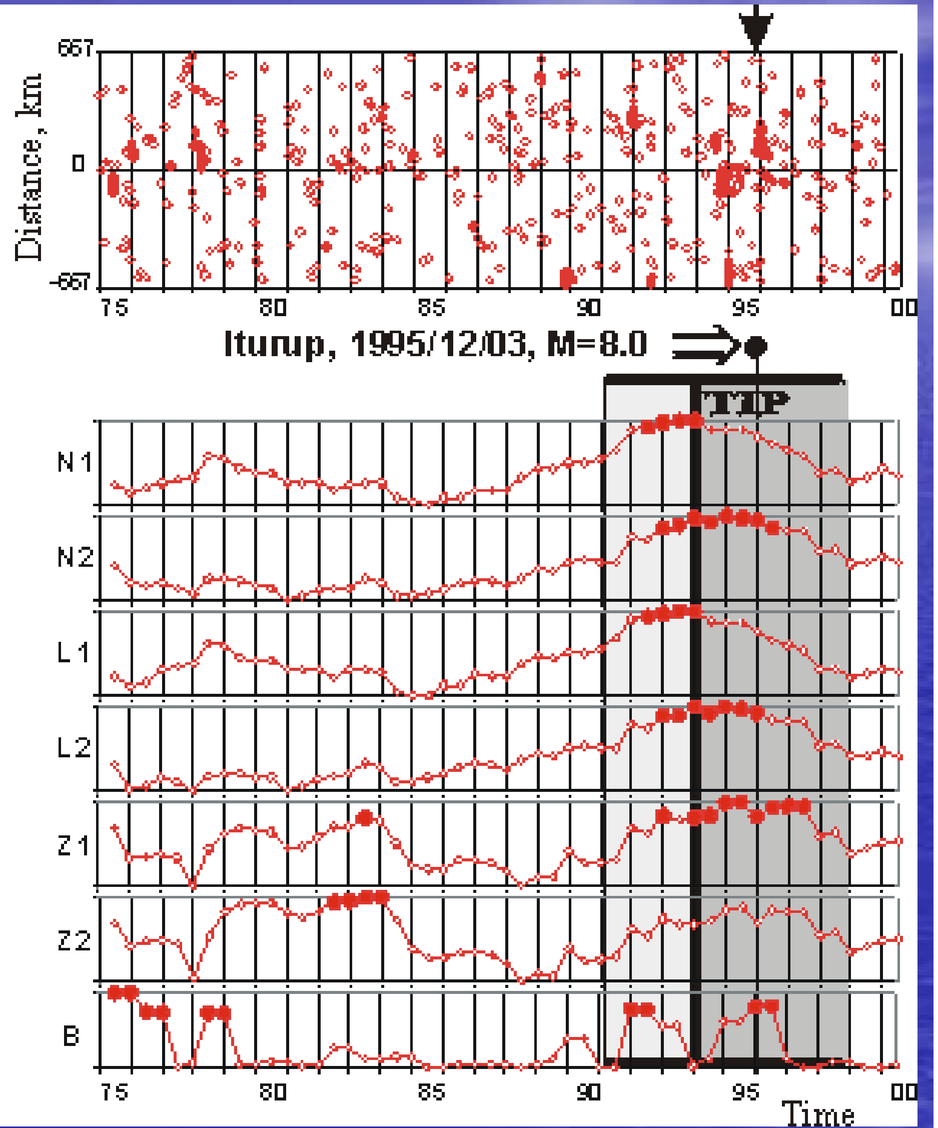
# 07/04/1995 Samoa Earthquake



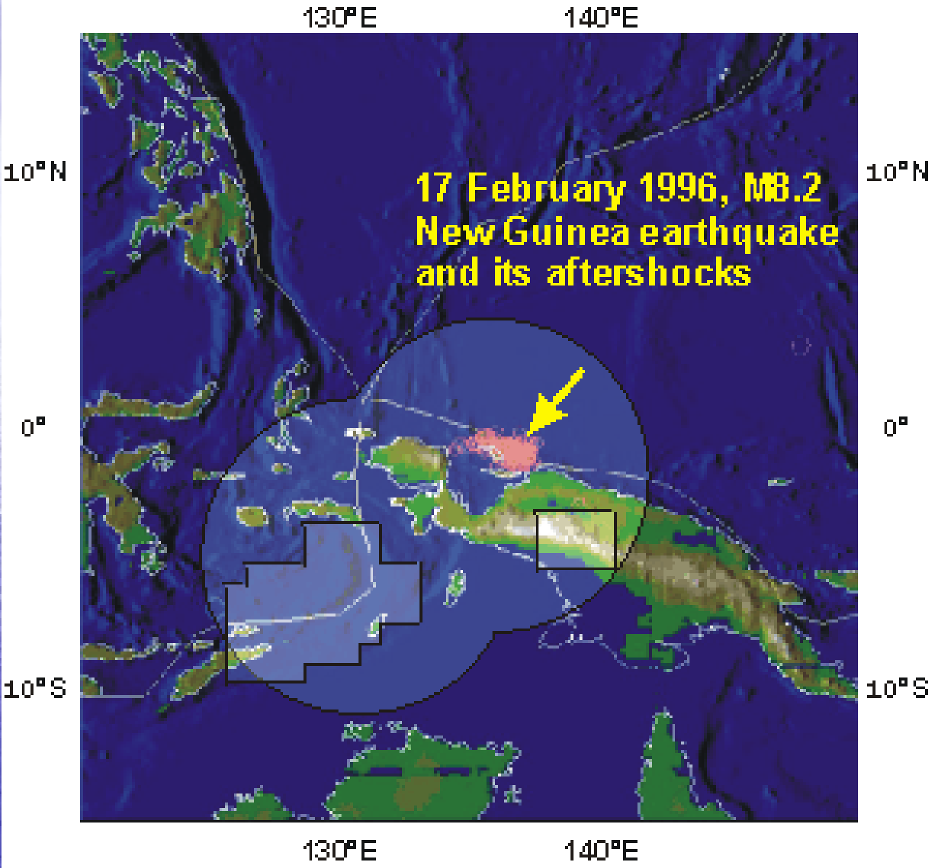



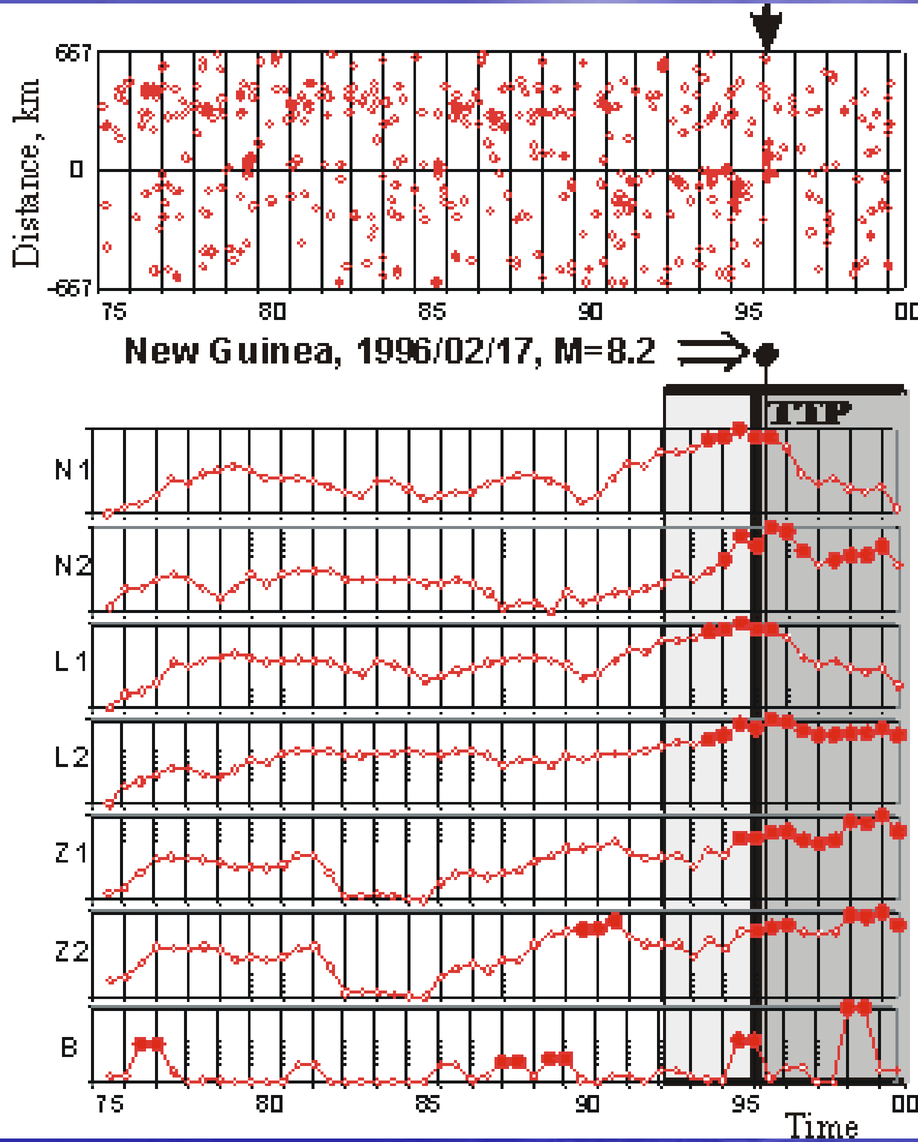
# 03/12/1995 Iturup Earthquake



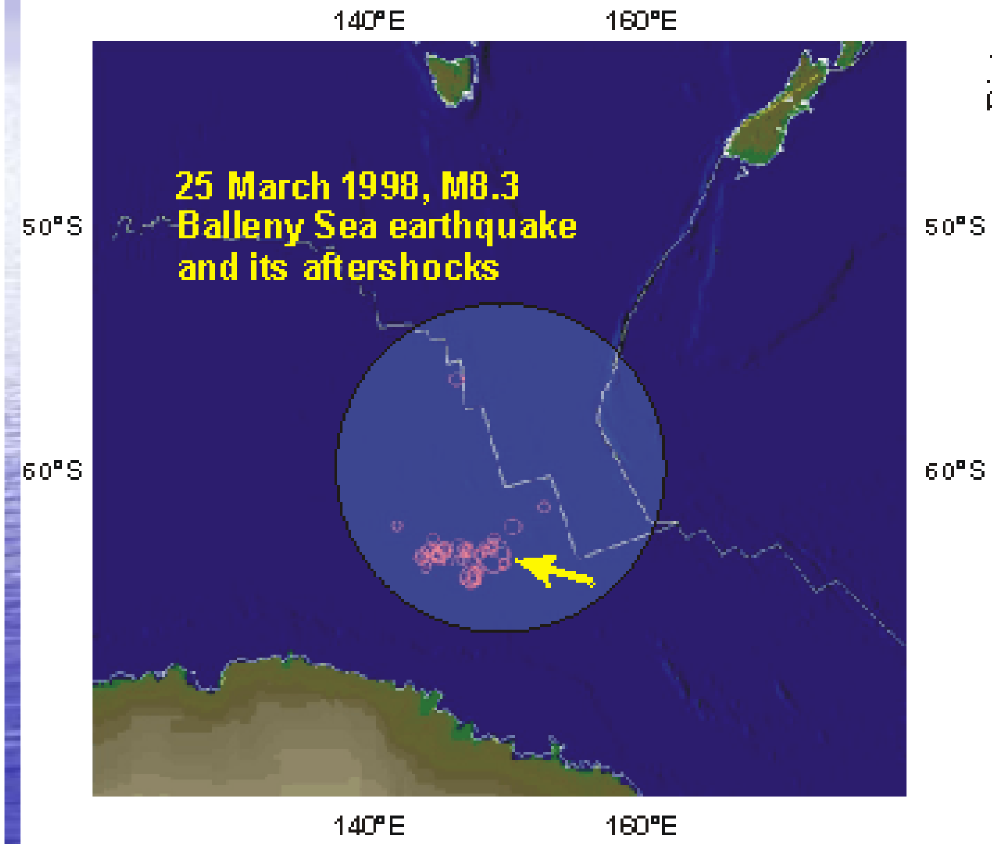
# 17/02/1996 New Guinea Earthquake

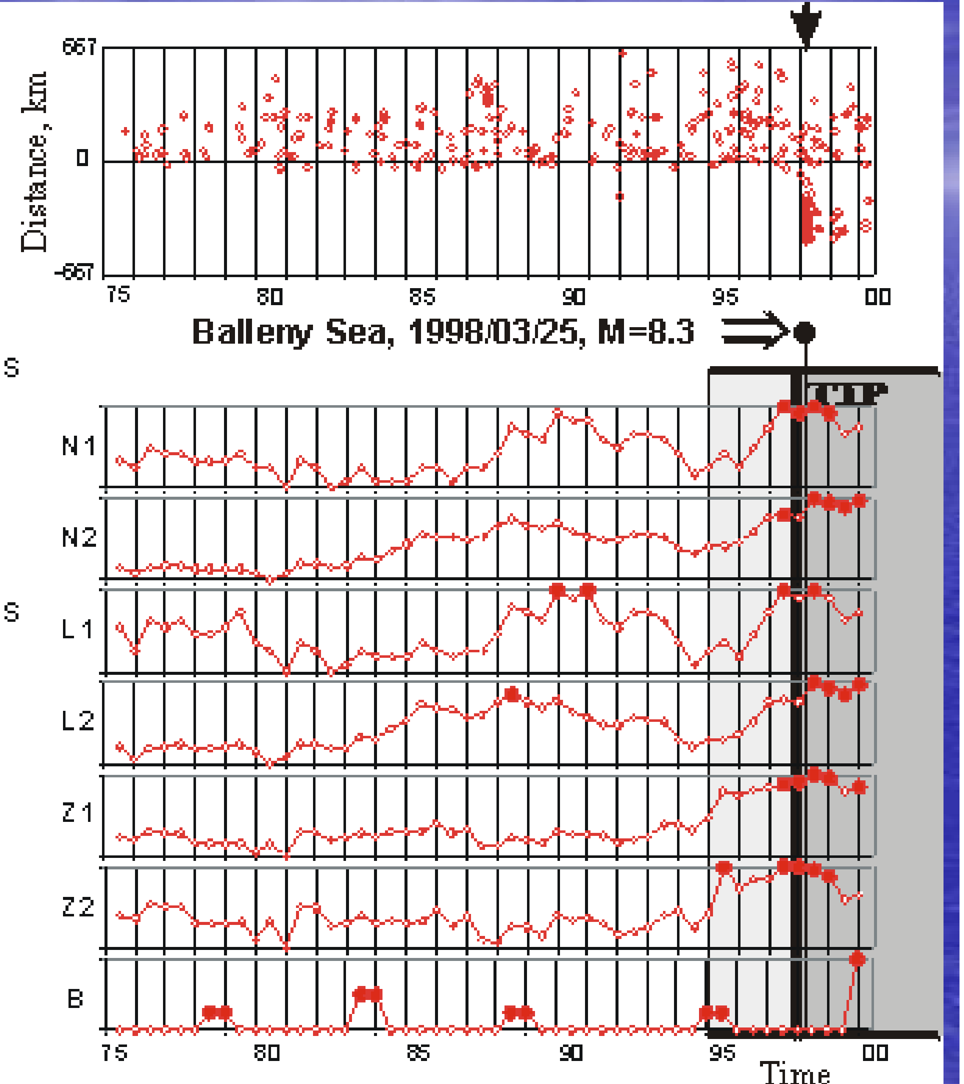


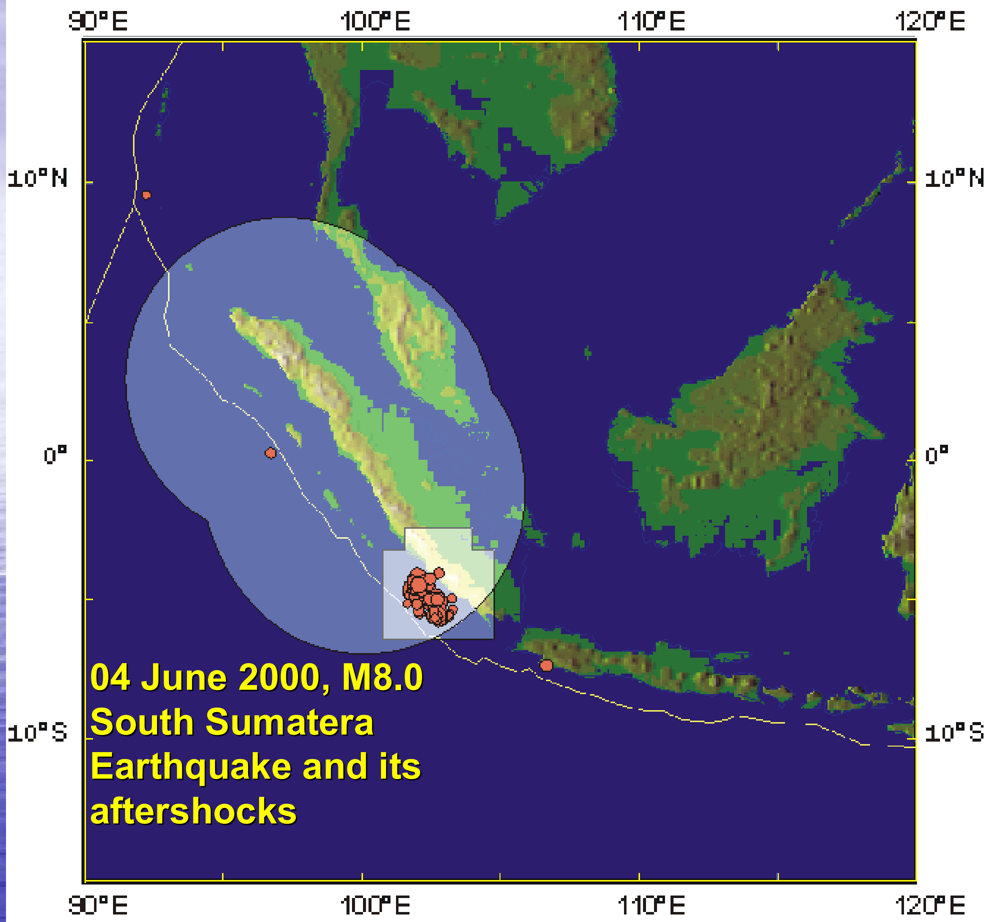
Outside Test Area, NOT COUNTED in the overall statistics

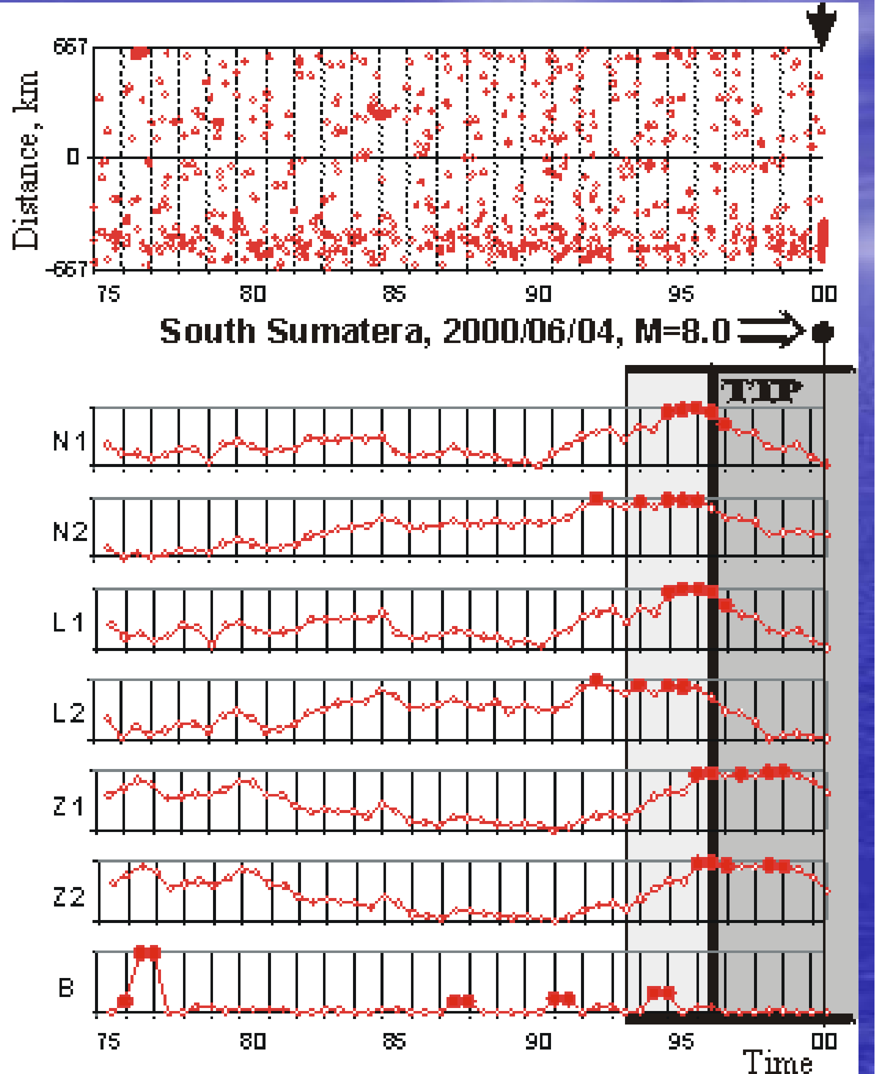
# 25/03/1998 Balleny Sea Earthquake



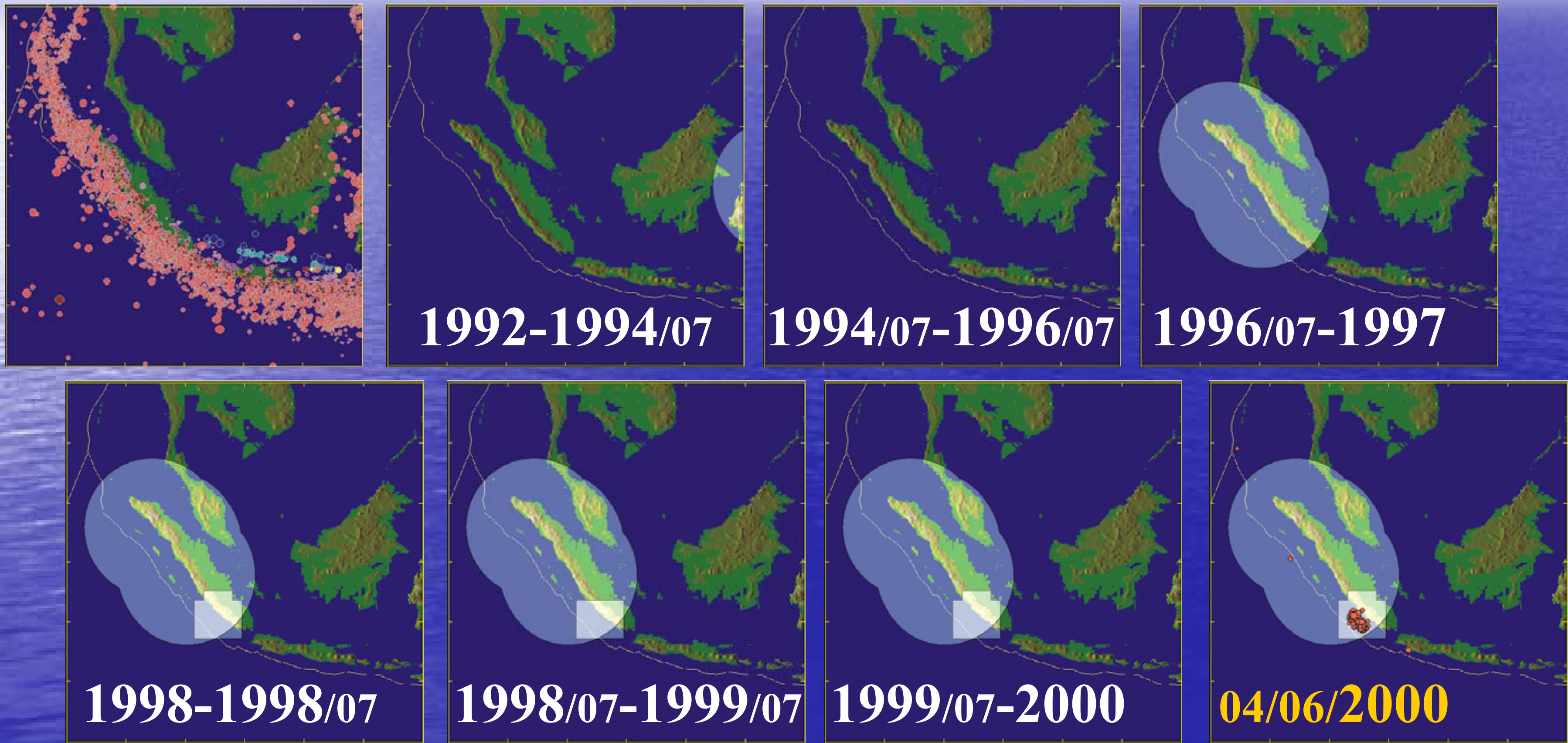



# 04/06/2000 South Sumatera Earthquake



# Case history of the South Sumatera Earthquake

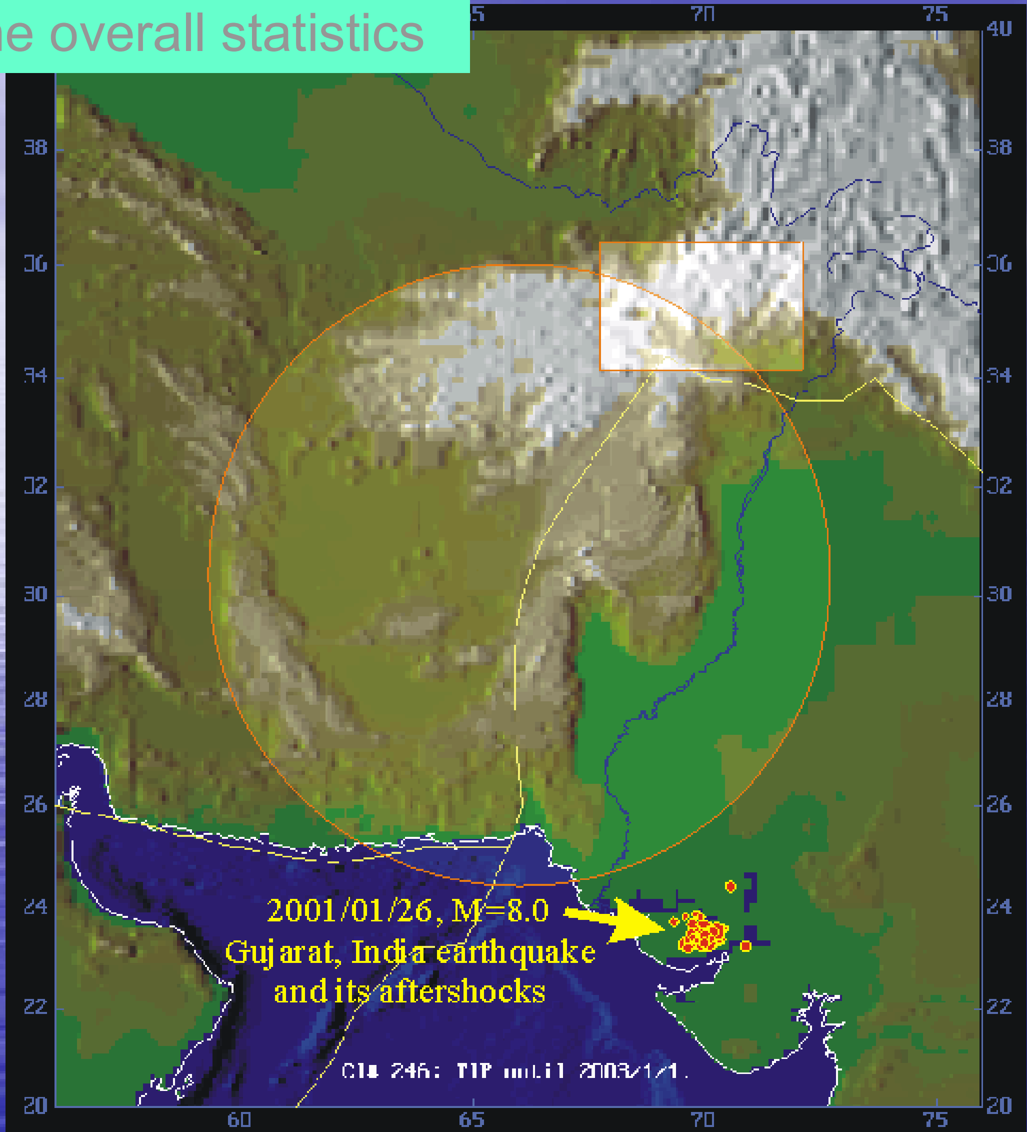


Seismic events that big were reported in the Indian Ocean subduction zones only twice in the 20th century:
These are
the 1941 Andaman, Ms8.1 and
the 1977 Sumbawa, Ms8.0 earthquakes.

This implies local probability gain of more than 20

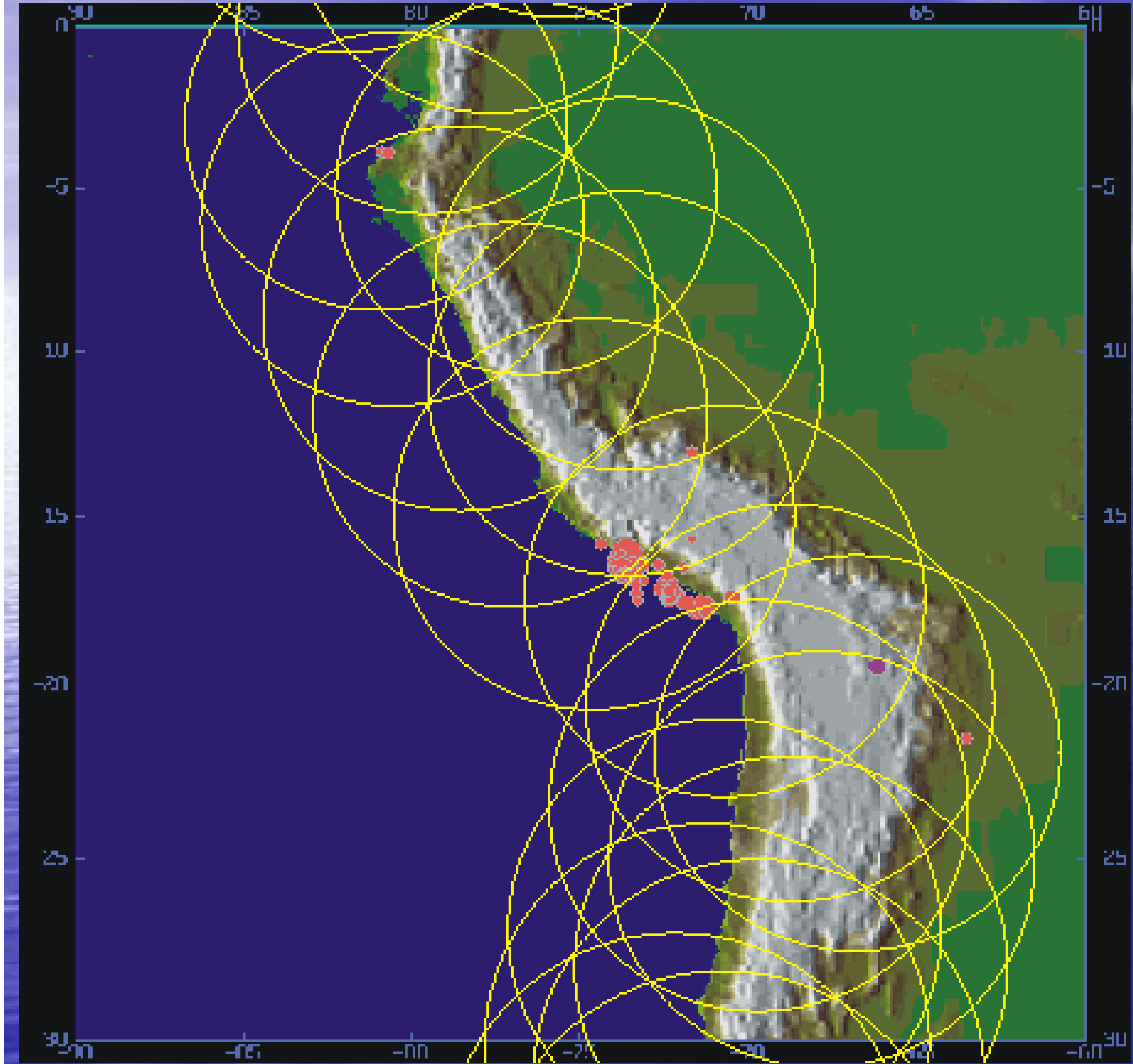
Outside Test Area, NOT COUNTED in the overall statistics

# 26/01/2001 Gujarat, India earthquake



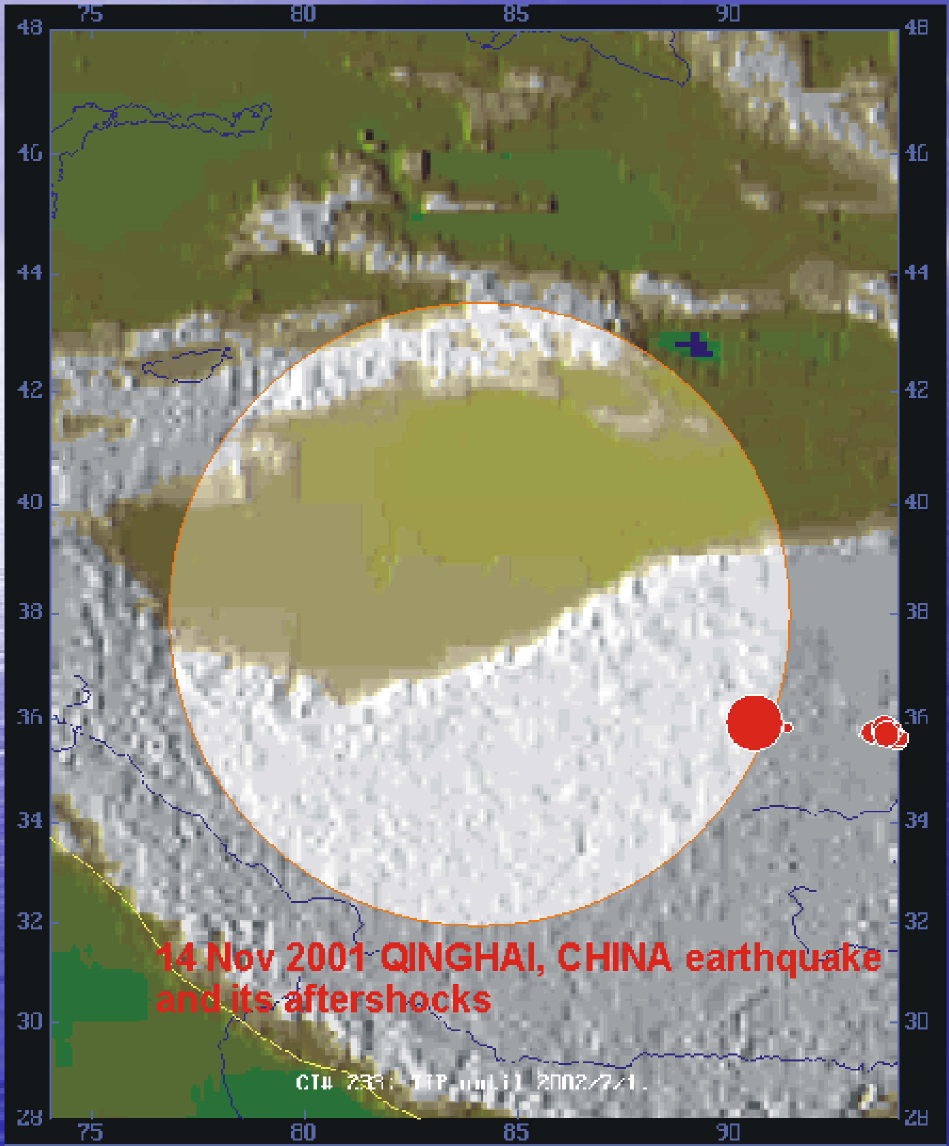

The 26 Jan 2001 Gujarat, India earthquake is just outside the area, where the NEIC data permits to run the original version of the M8 algorithm. Note that one of the circles, nearest to the epicenter of the 2001 Gujarat earthquake was in state of alarm, although the MSc predicts an opposite side of it as the most dangerous area.

# 23/06/2001 earthquake NEAR COAST OF PERU



**This earthquake is the first failure-to-predict in M8-MSc testing aimed at magnitude 8.0+.**

# 14/11/2001 QINGHAI, CHINA earthquake

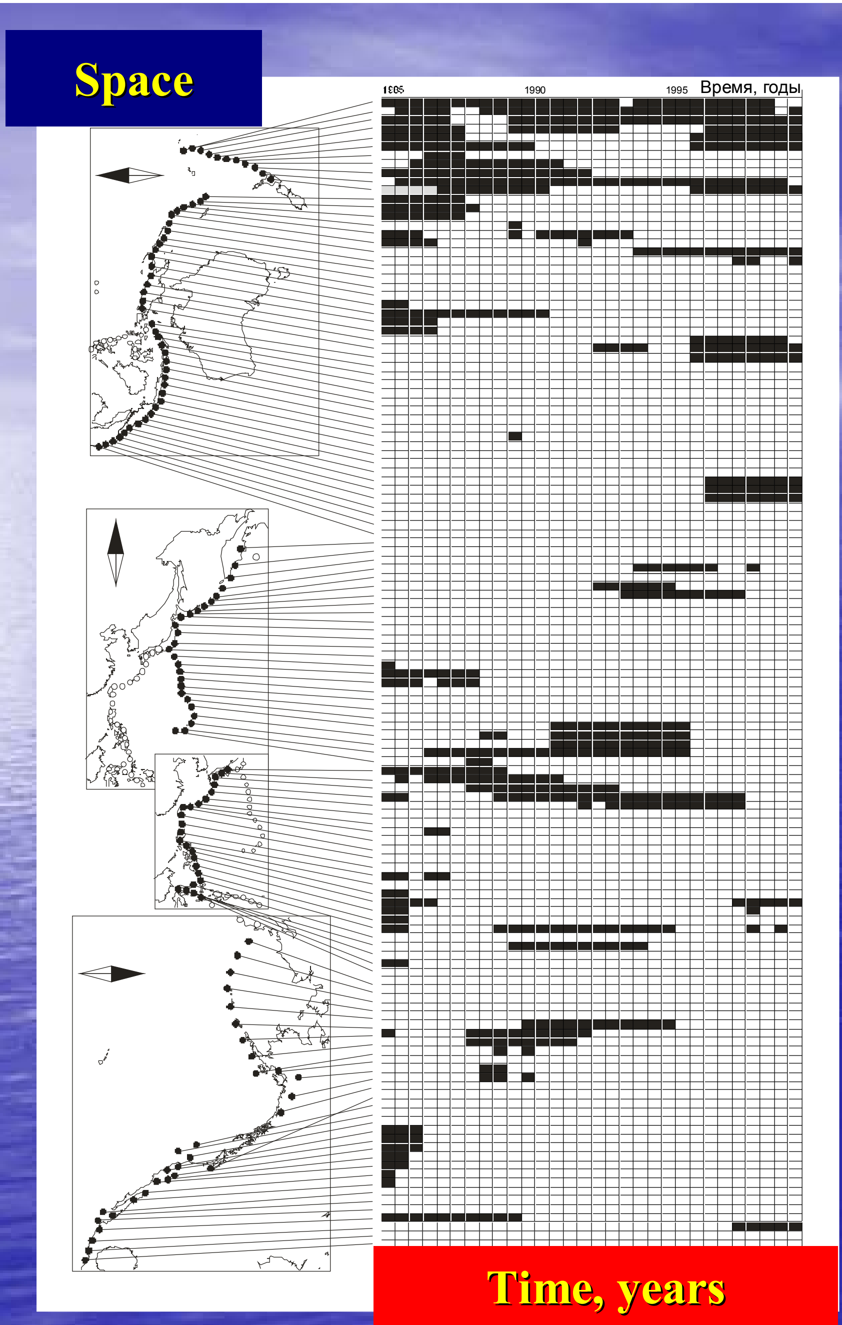


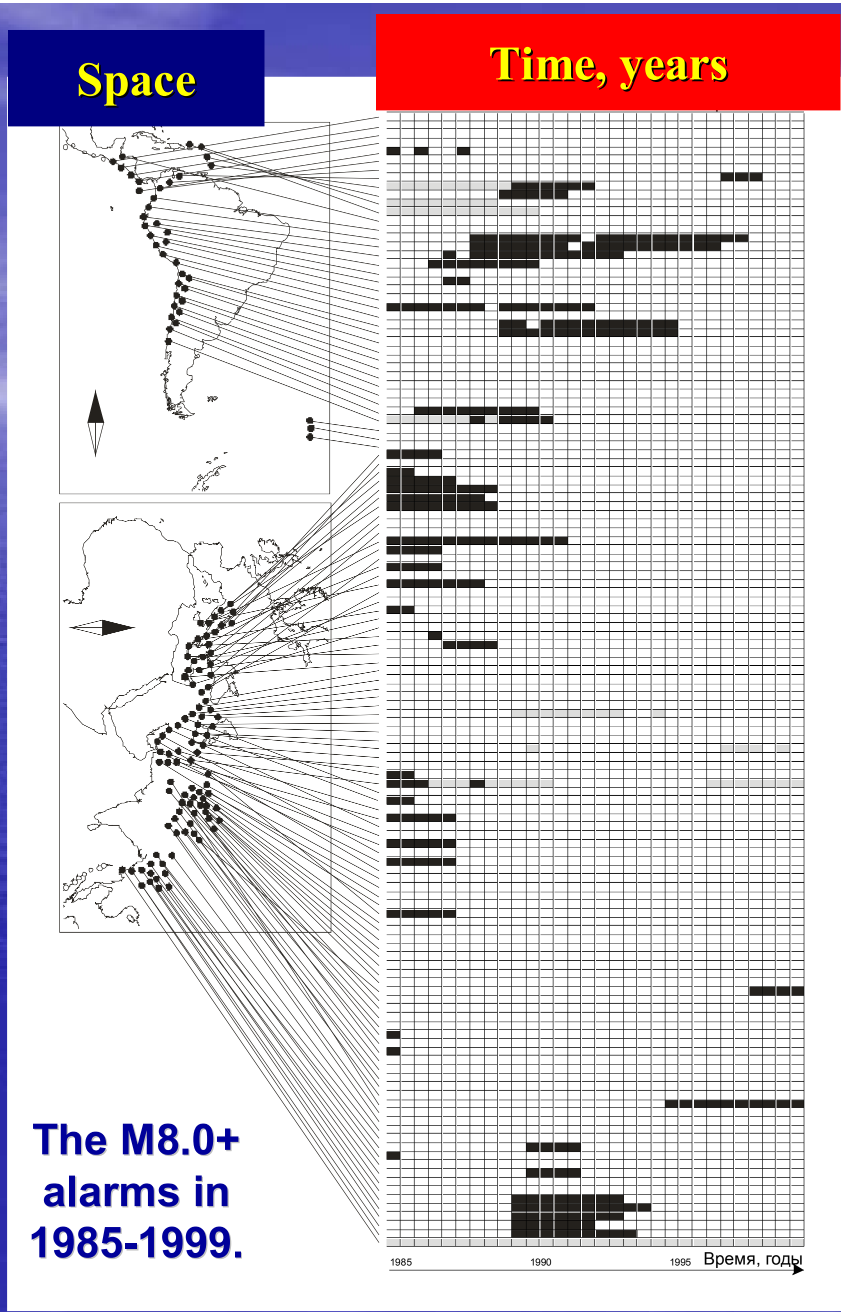

No earthquake of such magnitude had been ever reported inside CI#233 before the 2001 Qinghai earthquake.

The largest one in the 20th century has magnitude MS= 7.9 and happened on November 08, 1997 four months after declaration of the M8 alarm in our Test. (The next largest magnitude is 7.3.)

A conservative estimation of probability gain is about 20, so that the prediction is not trivial indeed.

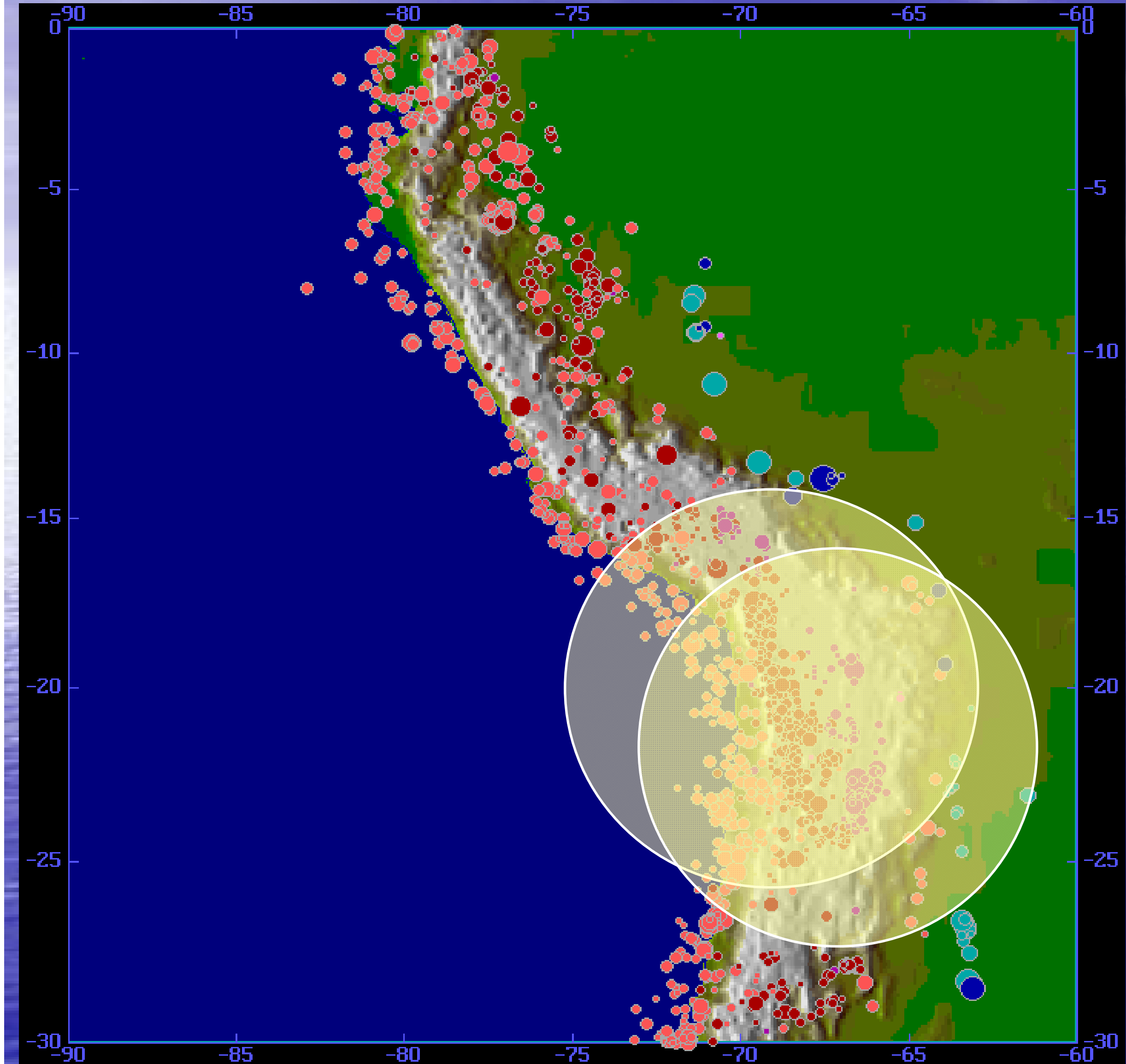
The nearest magnitude 8.0+ earthquake happened on November 18, 1951 near Lhasa, Xizang (Tibet) 375 miles (600 km) south of the November 14, 2001 epicenter.




**The M8.0+ alarms in 1985-1999.**

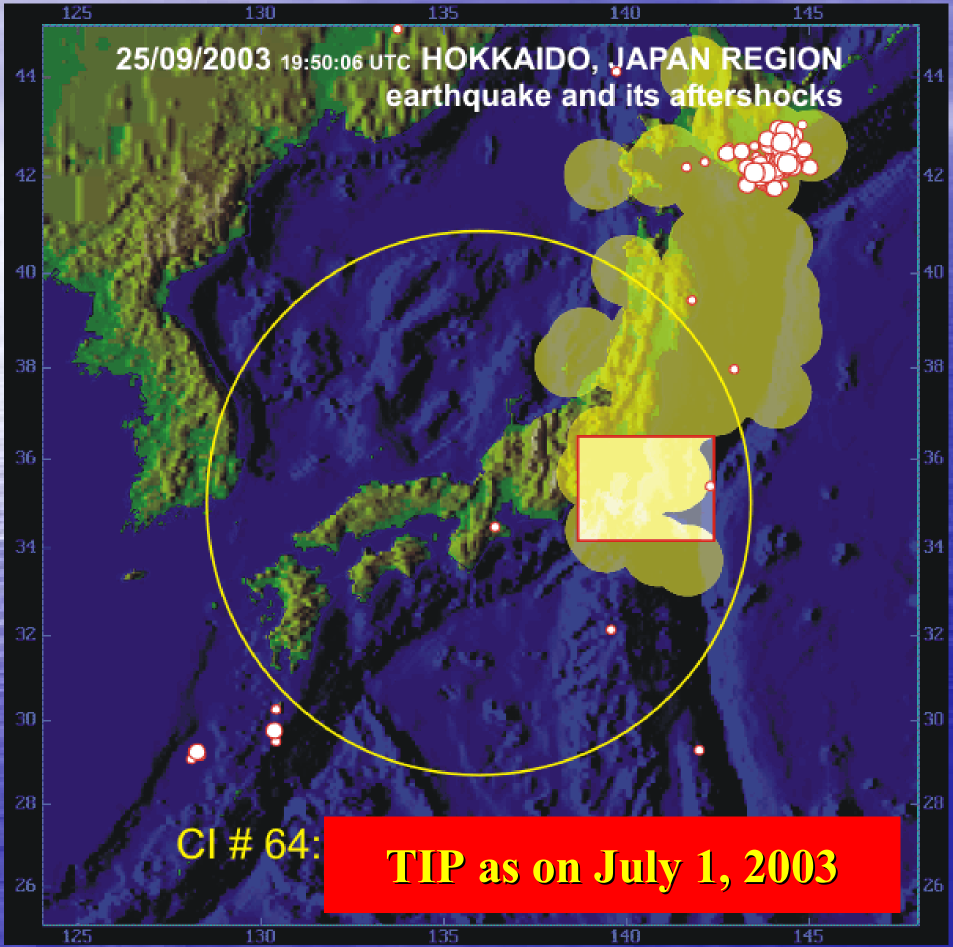
# An example of false alarm in CI's ## 156-157




The TIP in these Circles of Investigation lasted for 6.5 years from 1989 to the middle of 1995.

No magnitude 8.0 or larger earthquake occurred.

# 25/09/2003 19:50:06 UTC HOKKAIDO, JAPAN REGION earthquake

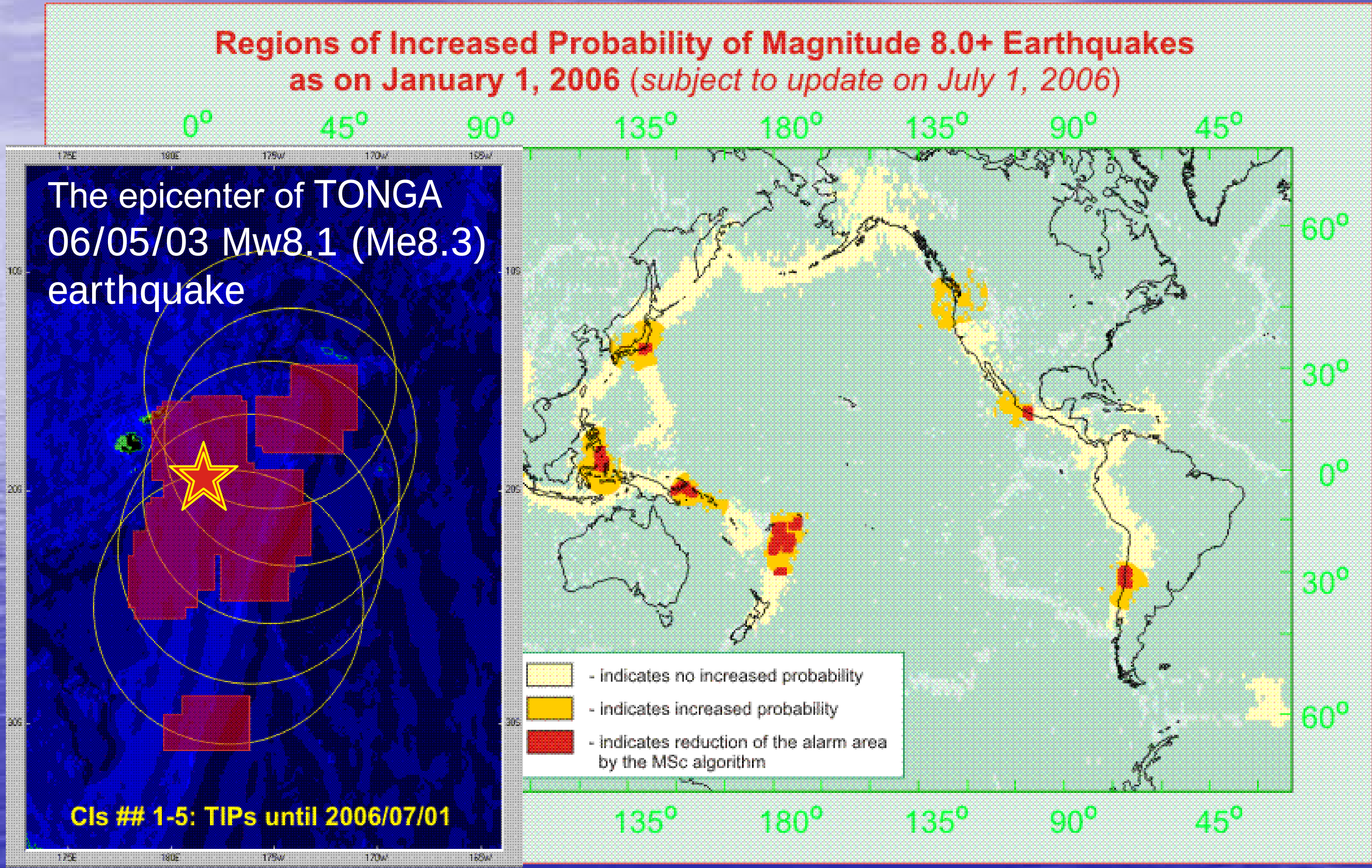



**This is the second failure-to-predict the world largest earthquakes in course the Global real-time prediction experiment aimed at M8.0+ events.**

**Can we exclude a possibility that the *Time of Increases Probability*, TIP, in CI#64 is related to the occurrence of 25 September 2003 great quake? The analysis at a shorter-term lower-magnitude scales [***Shebalin, Keilis-Borok, Zaliapin, Uyeda, Nagao, Tsybin, 2003. Short-term Premonitory Rise of the Earthquake Correlation Range. In IUGG2003, June 30 – July 11, 2003*** **] suggests that, perhaps, we can not.**

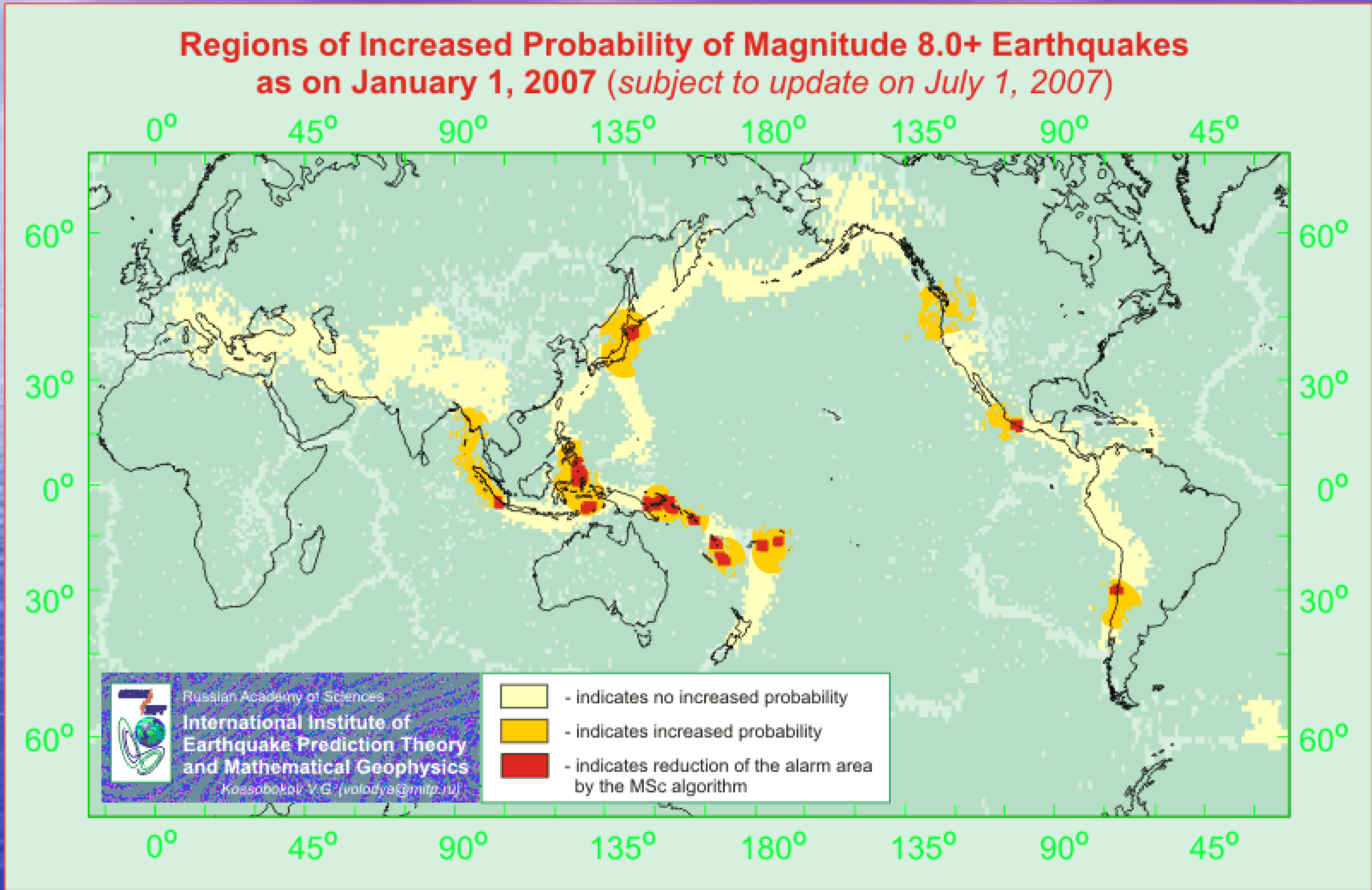
# Real-time prediction of the world largest earthquakes

( http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp )



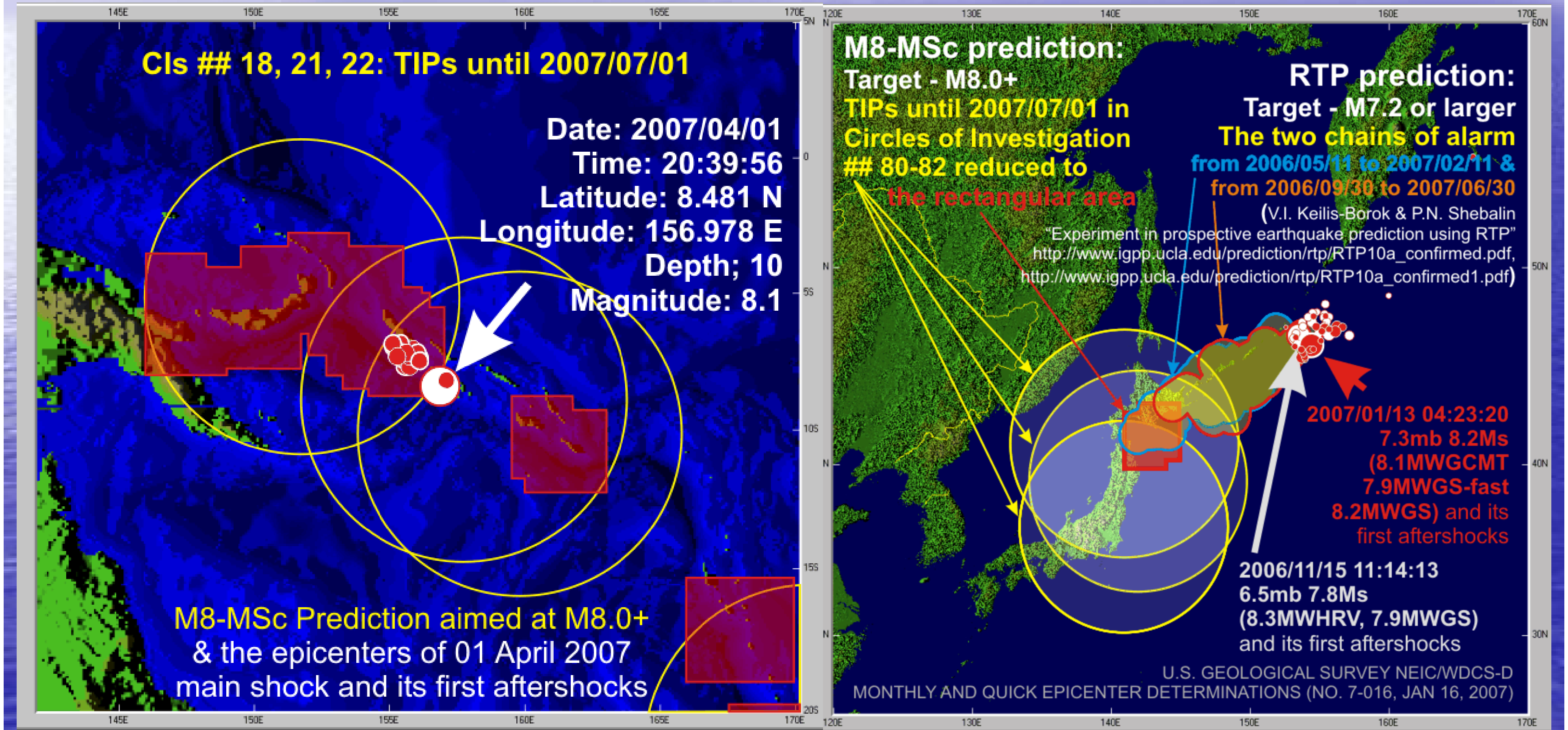
# Real-time prediction of the world largest earthquakes

( http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp )



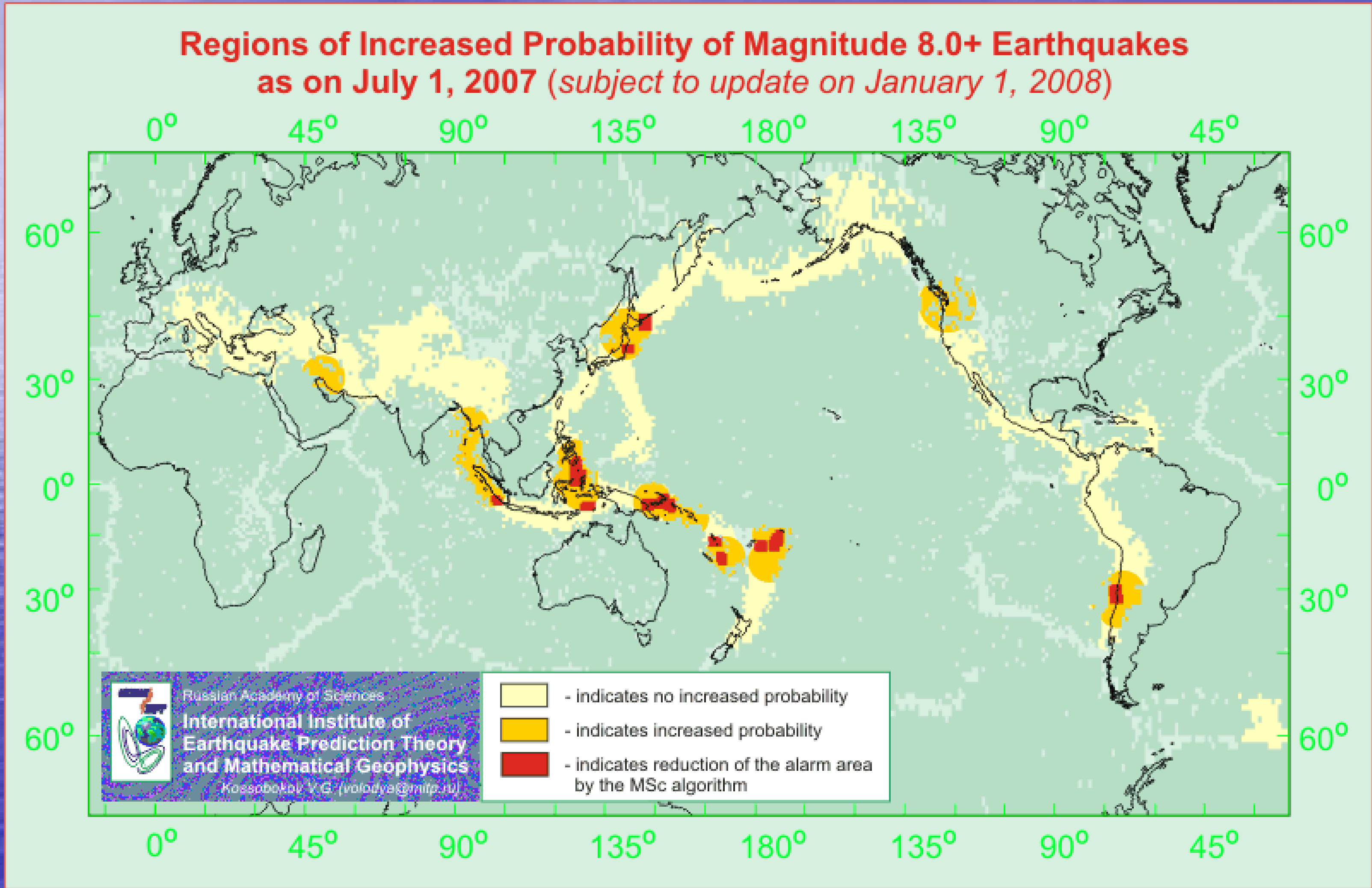
# Real-time prediction of the world largest earthquakes

( http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp )



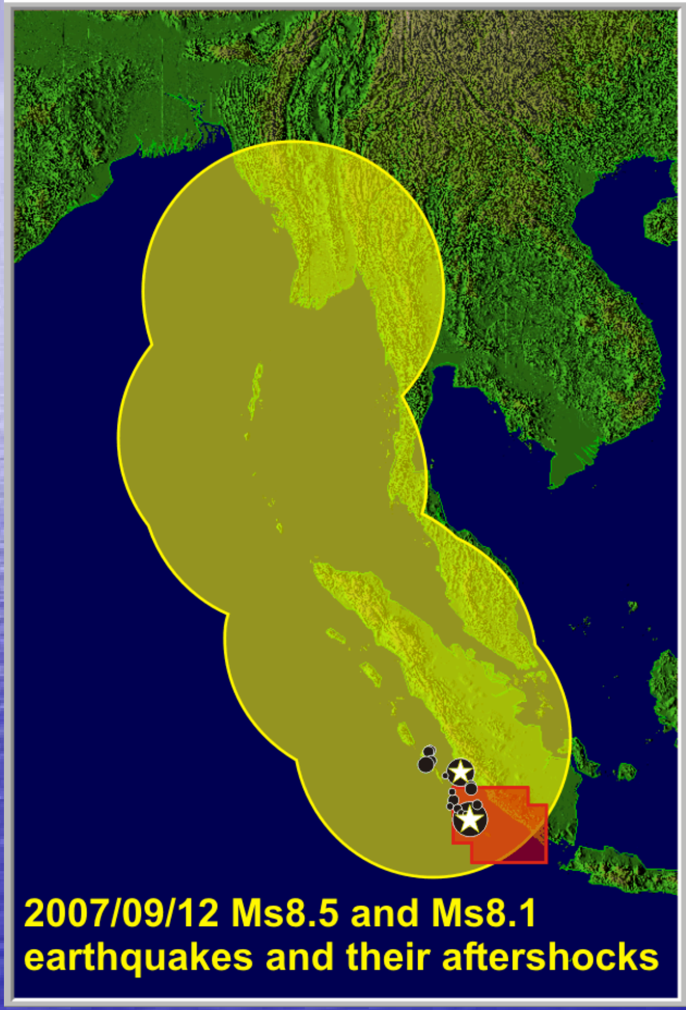
# Real-time prediction of the world largest earthquakes

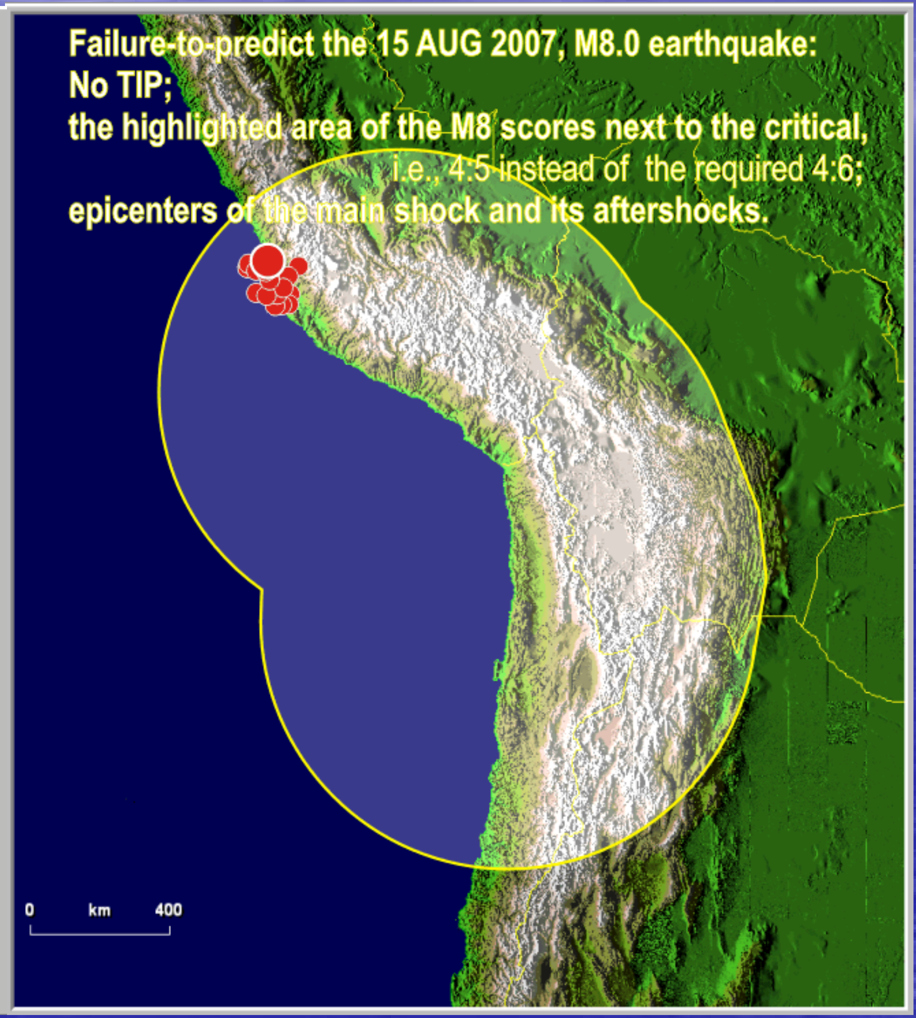
( http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp )



# Real-time prediction of the world largest earthquakes

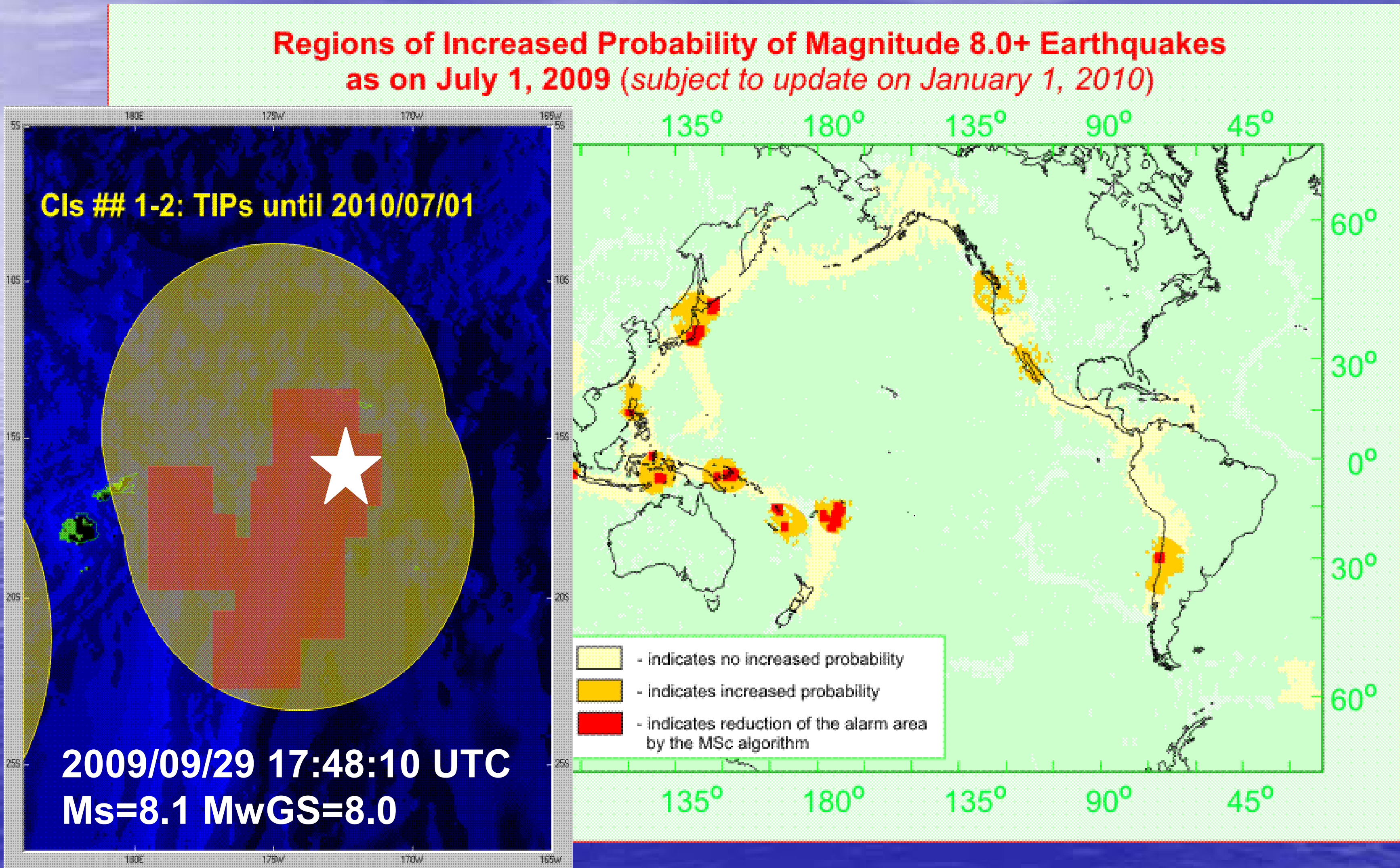
( http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp )



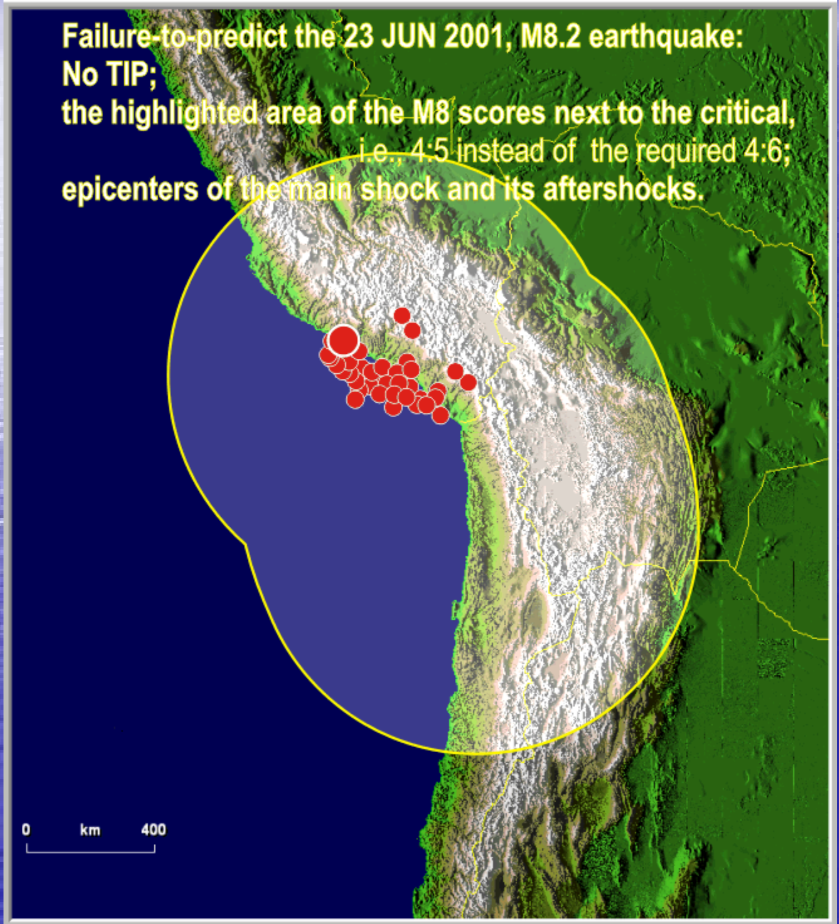
# Real-time prediction of the world largest earthquakes

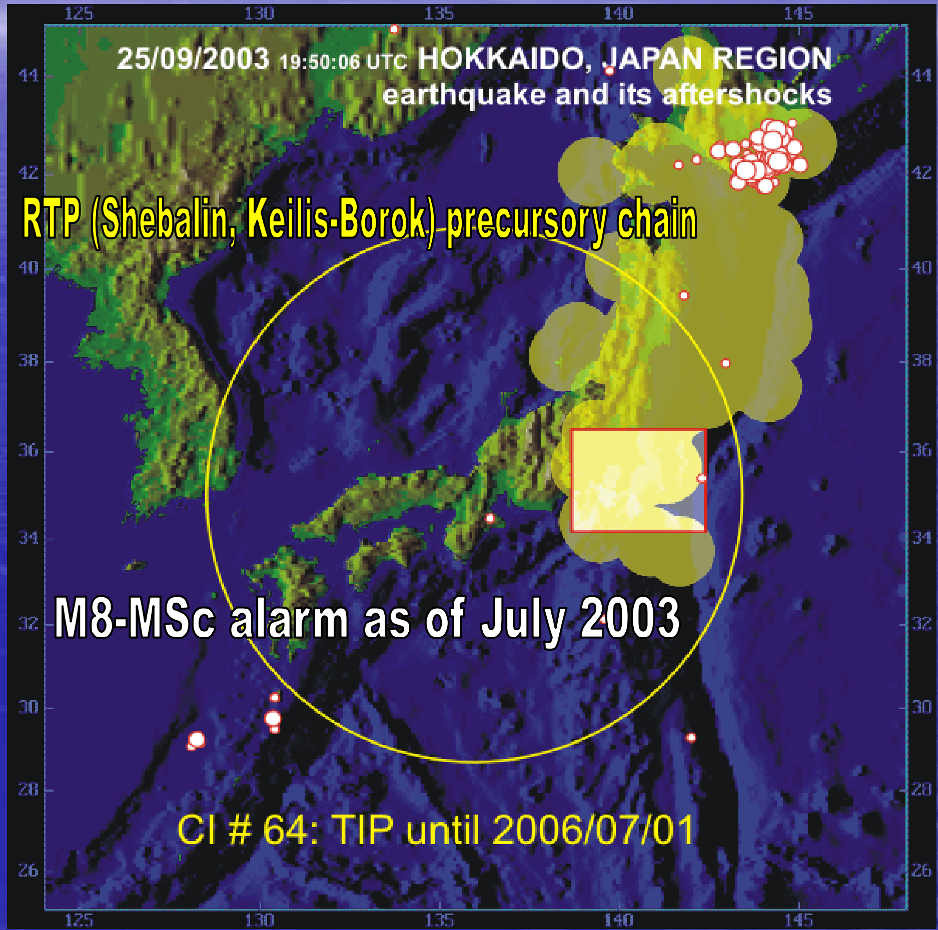
( http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp )



# The emerging two types of failures-to-predict

**All the five M8.0+ earthquakes that were not predicted in course the Global Test are either in the area of the scoring next-to-critical or in the chain of correlated earthquakes connected with M8-MSc prediction.**



# Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 8.0+.

| Test period | Large earthquakes Total | Predicted by M8 | Predicted by M8-MSc | Measure of alarms, % M8 | Measure of alarms, % M8-MSc | Confidence level, % M8 | Confidence level, % M8-MSc |
|---|---|---|---|---|---|---|---|
| 1985-present | 18 | 13 | 10 | 32.93 | 16.78 | 99.93 | 99.98 |
| 1992-present | 16 | 11 | 8 | 29.17 | 14.54 | 99.88 | 99.91 |

The significance level estimates use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters.

To drive the achieved confidence level below 95%, the Test should encounter eight failures-to-predict in a row.

*Romashkova, L.L., Kossobokov, V.G., Peresan, A., and Panza, G.F., 2001. Stabilizing intermediate-term medium-range earthquake predictions, Preprint, IC/2001/168, The Abdus Salam Iternational Centre for Theoretical Physics. ICTP, Trieste, Italy, 20 p.*

*Kossobokov, V.G., L.L. Romashkova, G.F. Panza, and A. Peresan. Stabilizing intermediate-term medium-range earthquake predictions. J. Seismology Earthquake Engineering, 2002, 4, 2&3: 11-19*

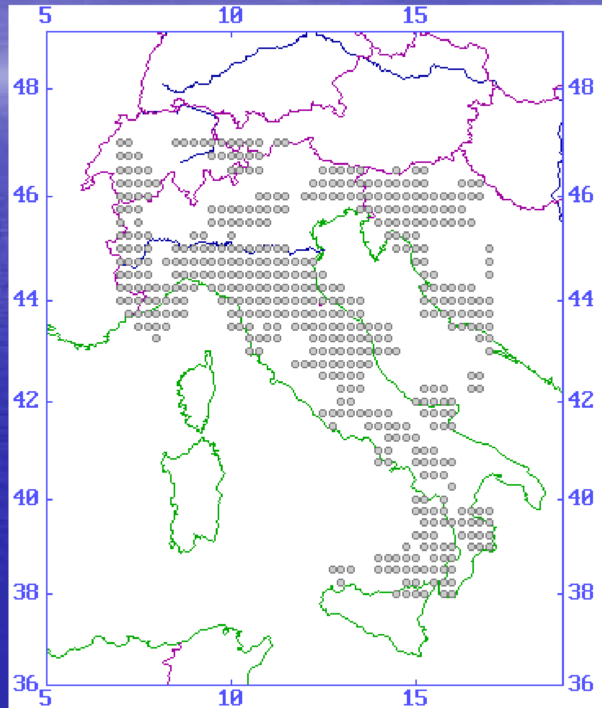
# M8S algorithm

***The scheme for the spatial stabilization of the M8 prediction makes use of the natural heterogeneity of earthquake distribution and eliminates subjectivity in the positioning areas of investigation.***

***In addition to that M8S guaranties stability of diagnosis, hence its name.***

# A simplified description of the M8S algorithm is as follows:

Consider the territory covered by data from a given catalogue and exclude the band of about 0.5R-1.0R near its boundary, where R is the radius of circles of investigation.

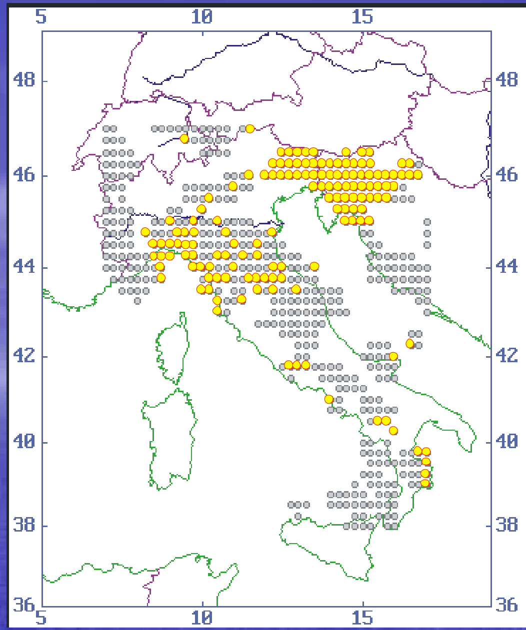


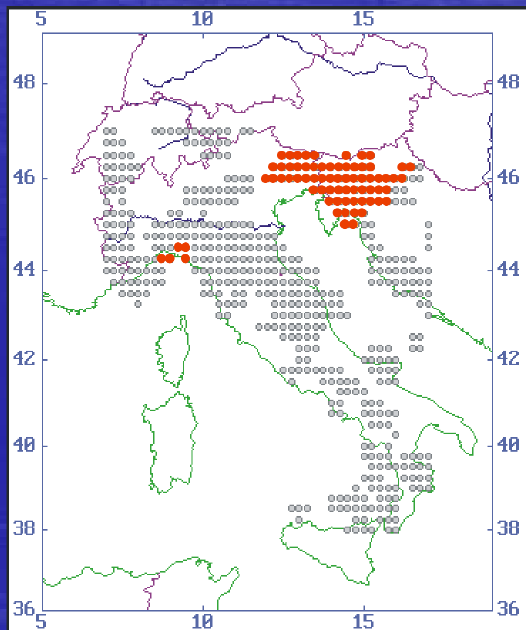

- Scan the territory with smaller circles distributed over a fine grid and find all local seismically active places, keeping the grid points with the average annual rate of seismic activity, in the small circle, above a certain threshold.
- Exclude the grid points, where the data is insufficient for application of M8 algorithm in the circles of investigation centered on them. Then remove isolated grid points and pairs of points.

- Apply M8 algorithm using the circles of investigation centered on each of the remaining grid points.
- Remove the circles in state of alarm centered on the grid points that do not satisfy the following clustering condition:

*The overwhelming majority of the circles of investigation, centered on the neighboring grid points that remain in the analysis, are in state of alarm.*

(The overwhelming majority is defined by 75% of the remaining neighboring grid points from a 3×3-grid square.)



# The adjustable parameters of the M8S algorithm

•*Fine grid size:* ***Set to the linear dimension of the target earthquake source length.***

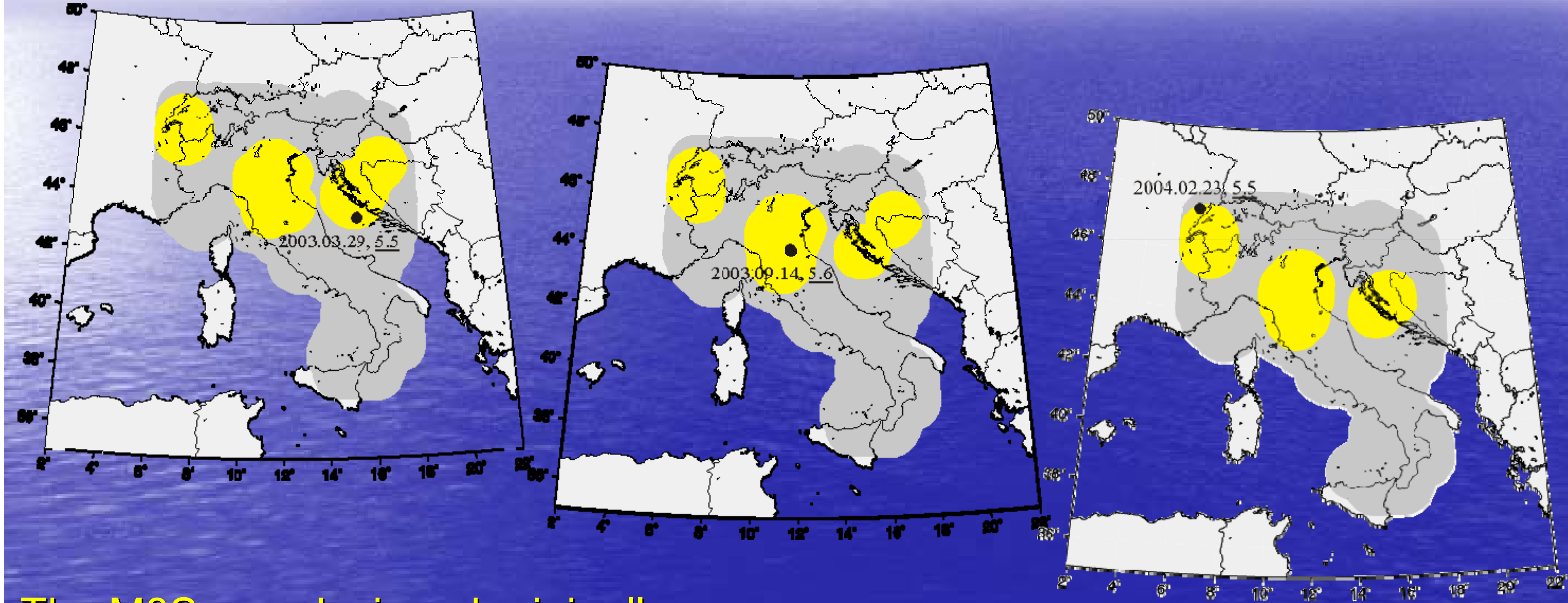
***Radius of smaller circles:*** ***Set to 28 km*** (may differ from region to region depending on the earthquake catalog coverage and completeness).

***Magnitude threshold for background activity count:*** ***Depends on a catalog available.***

***The "overwhelming majority" threshold:*** ***Set to 75%.***

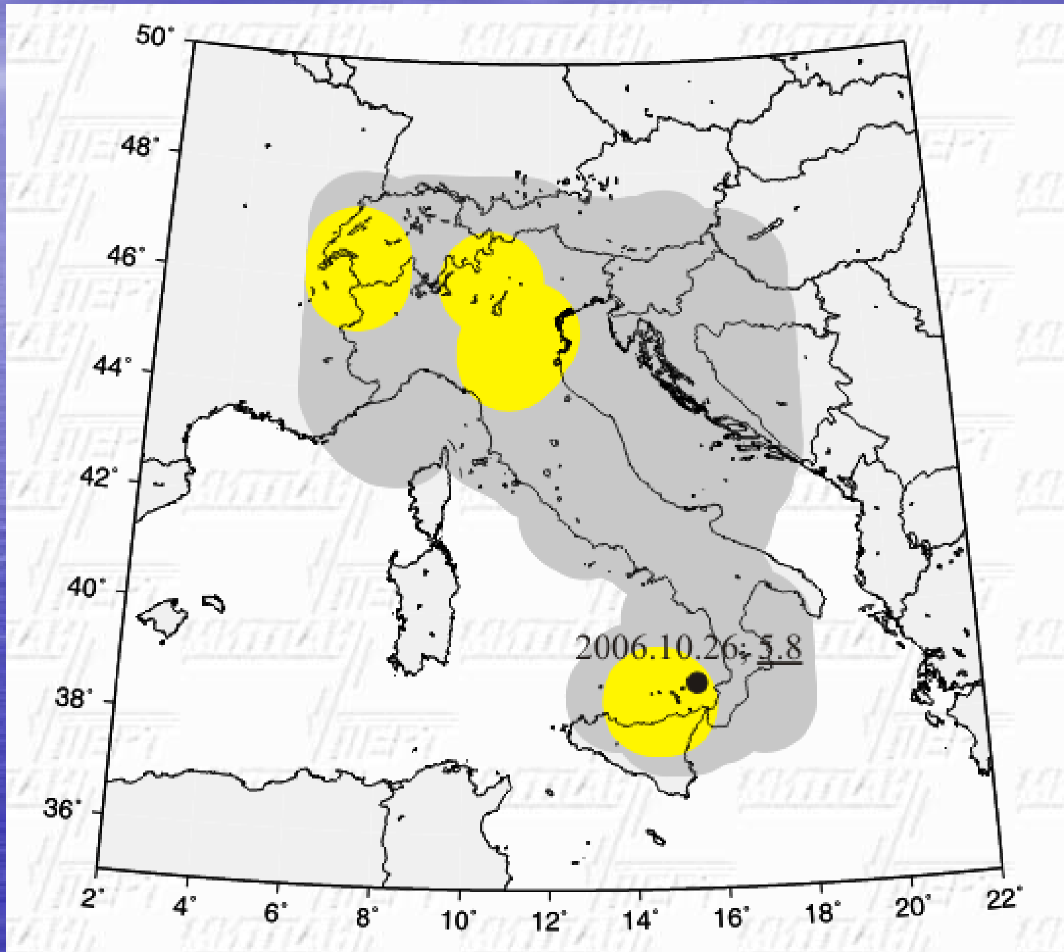
***The variation of the diagnosis observed when adjustable parameters change for up to 35% of their values remains within a few percent.***

The targeting smaller magnitude earthquakes at regional scales may require application of a recently proposed scheme for the spatial stabilization of the intermediate-term middle-range predictions. The scheme guarantees a more objective and reliable diagnosis of times of increased probability and is less restrictive to input seismic data.




The M8S was designed originally

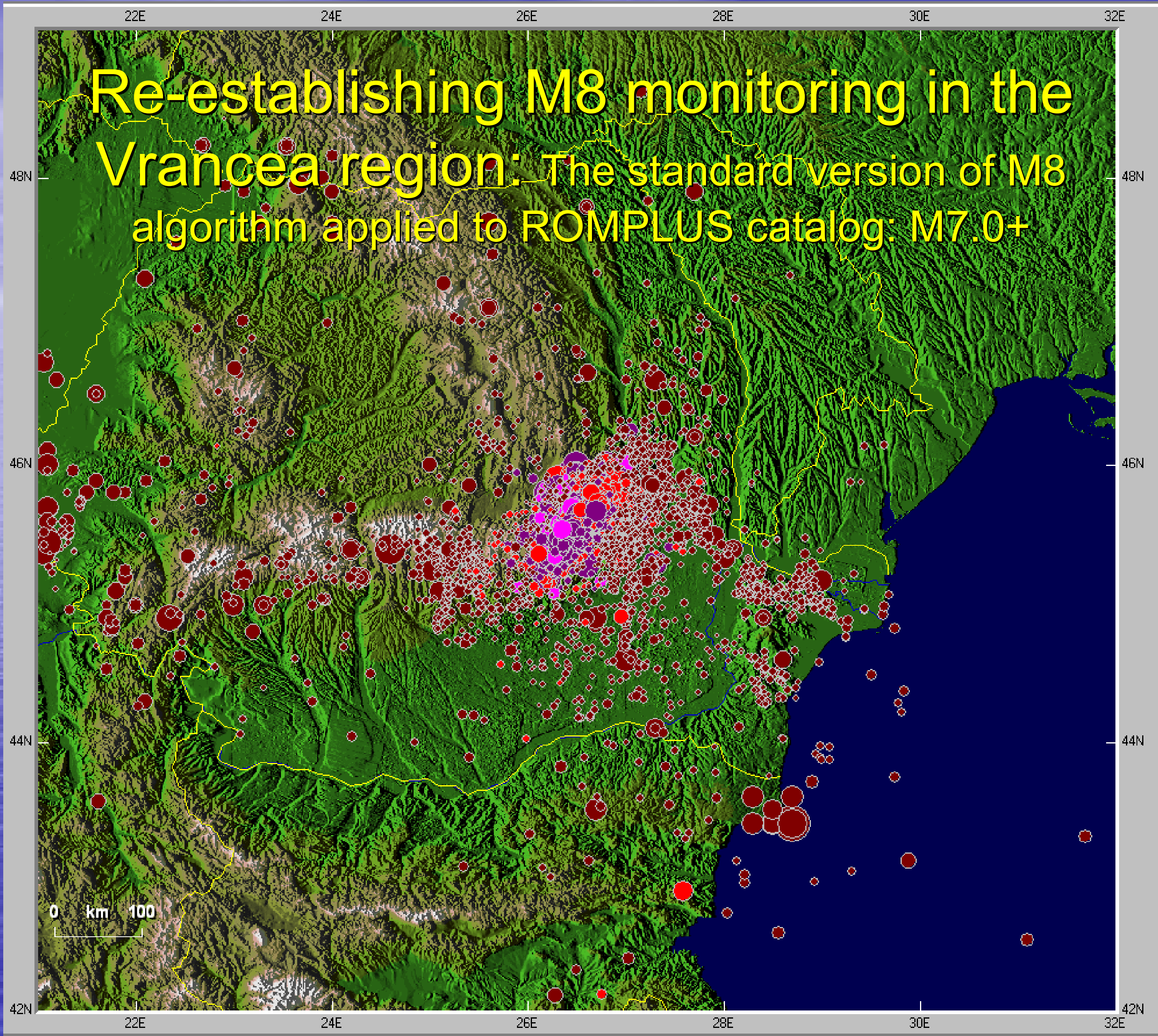
to improve reliability of predictions made by the modified versions of the M8 algorithm applicable in the areas of deficient earthquake data available.

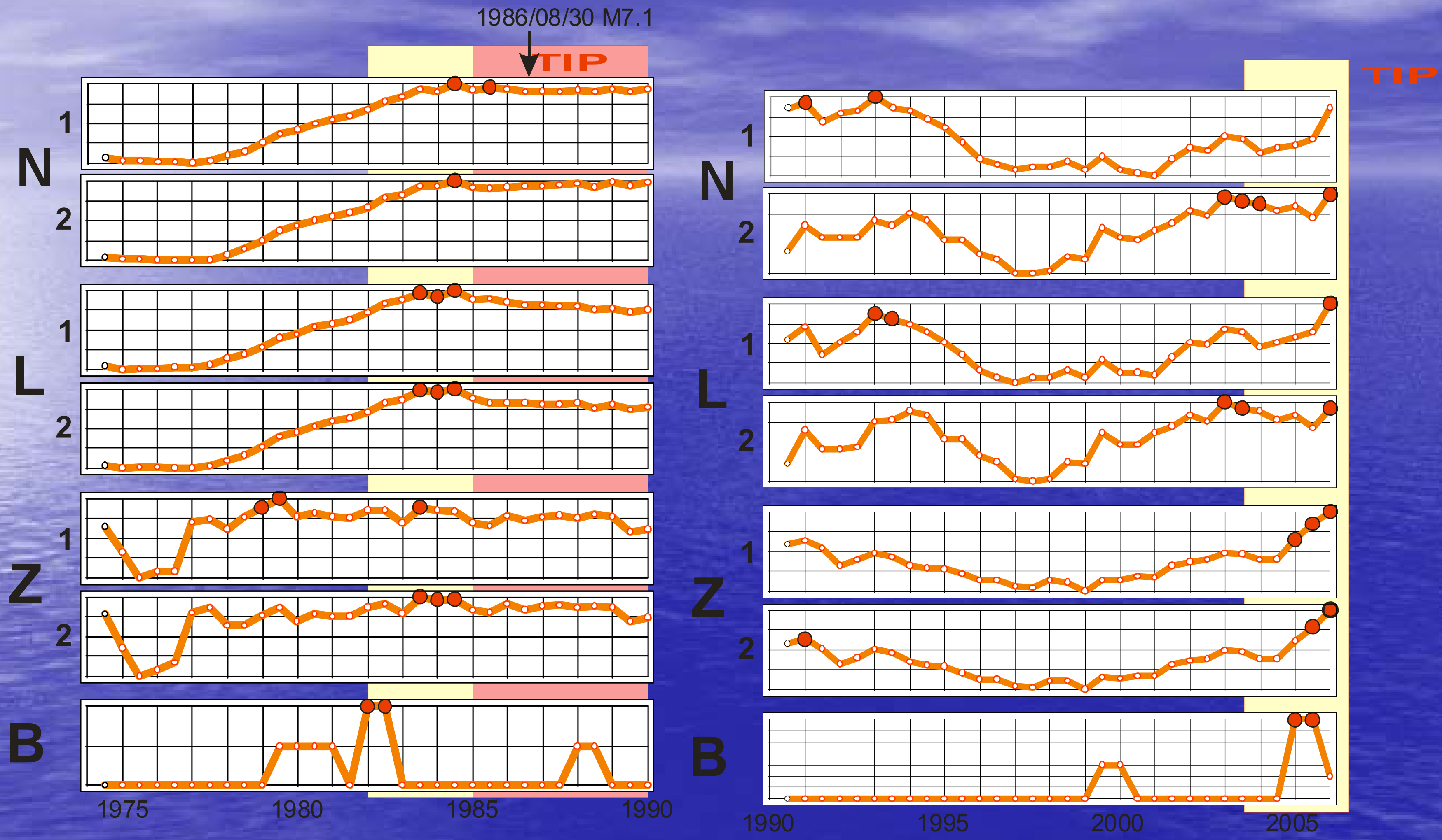

50°
48°
46°
44°
42°
40°
38°
36°
2006.10.26; 5.8
2°
4°
6°
8°
10°
12°
14°
16°
18°
20°
22°

# M8 vs. M8S scores in Circum Pacific, 1985-2003.

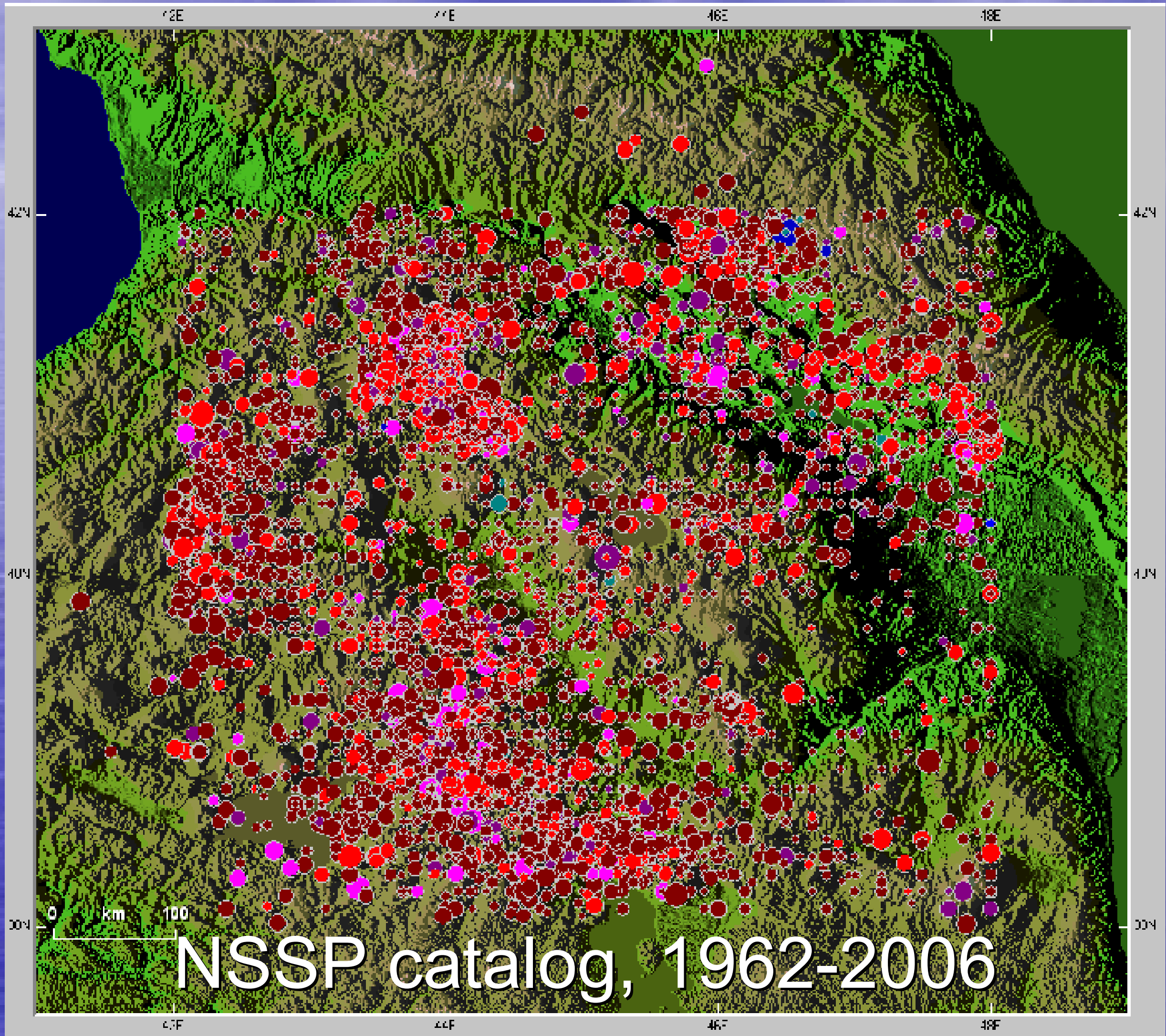
| Region | Total | Predicted M8/M8S | Alarm, % | | Reduction factor |
|---|---|---|---|---|---|
| | | | M8 | M8S | |
| Tonga - New Zealand | 2 | 2 | 90 | 75 | 1.2 |
| Southeastern Asia | 3 | 2 | 39 | 22 | 1.8 |
| Kamchatka – Japan – Bonnin Isls | 3 | 2 | 38 | 29 | 1.3 |
| Aleutians - Alaska | 1 | 0 | 14 | 7 | 2.0 |
| Western U.S. | 0 | 0 | 6 | 4 | 1.5 |
| Central America | 1 | 1/0 | 14 | 4 | 3.5 |
| Southern America | 1 | 0 | 29 | 6 | 4.8 |
| **Total score:** | **11** | **7/6** | **38** | **25** | **1.5** |

# Re-establishing M8 monitoring in the Vrancea region: The standard version of M8 algorithm applied to ROMPLUS catalog: M7.0+



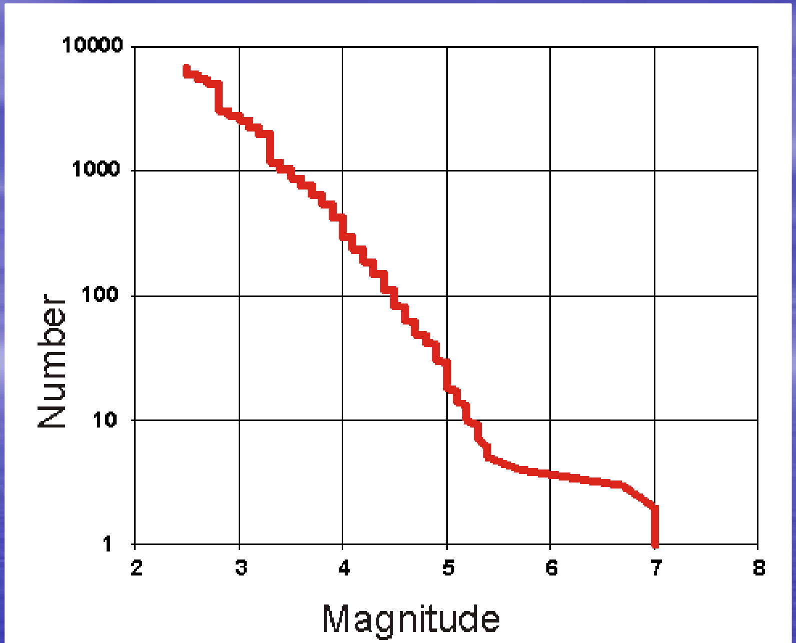

1986/08/30 M7.1
TIP
N
L
Z
B
1
2
1975
1980
1985
1990
1990
1995
2000
2005
TIP

# Re-establishing M8 monitoring in Armenia and adjacent areas

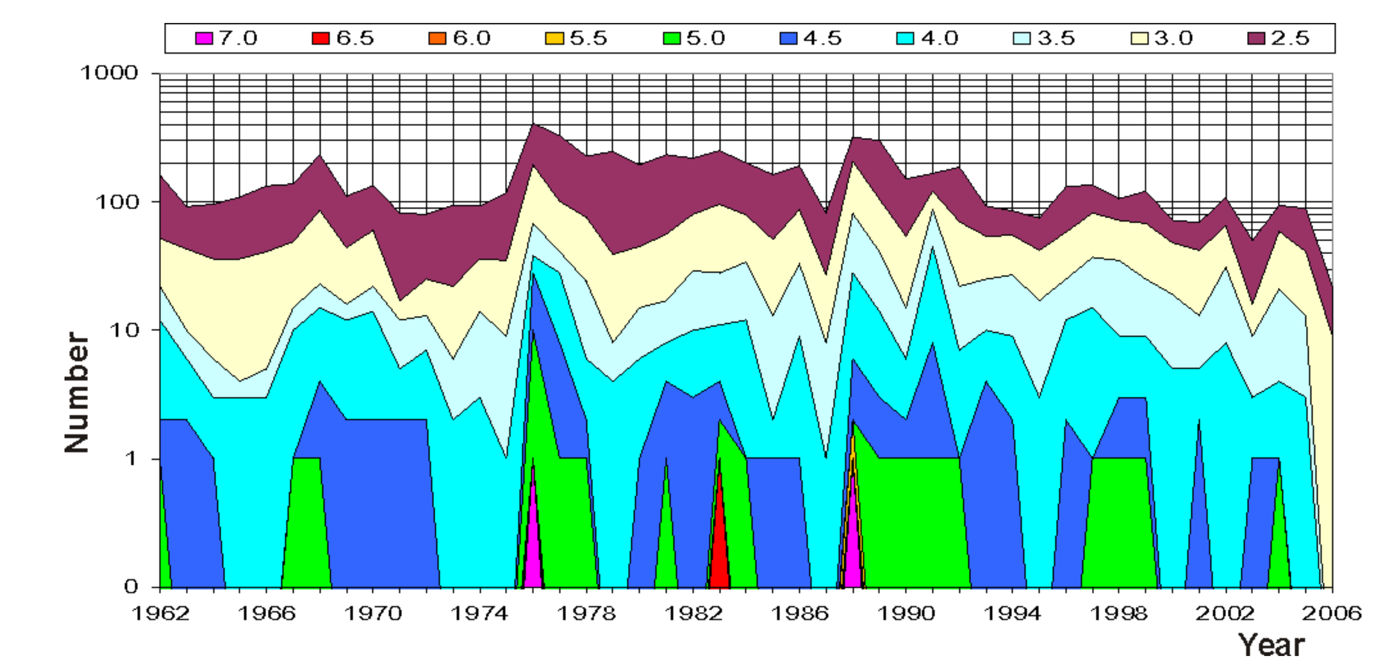


# NSSP catalog, 1962-2006:

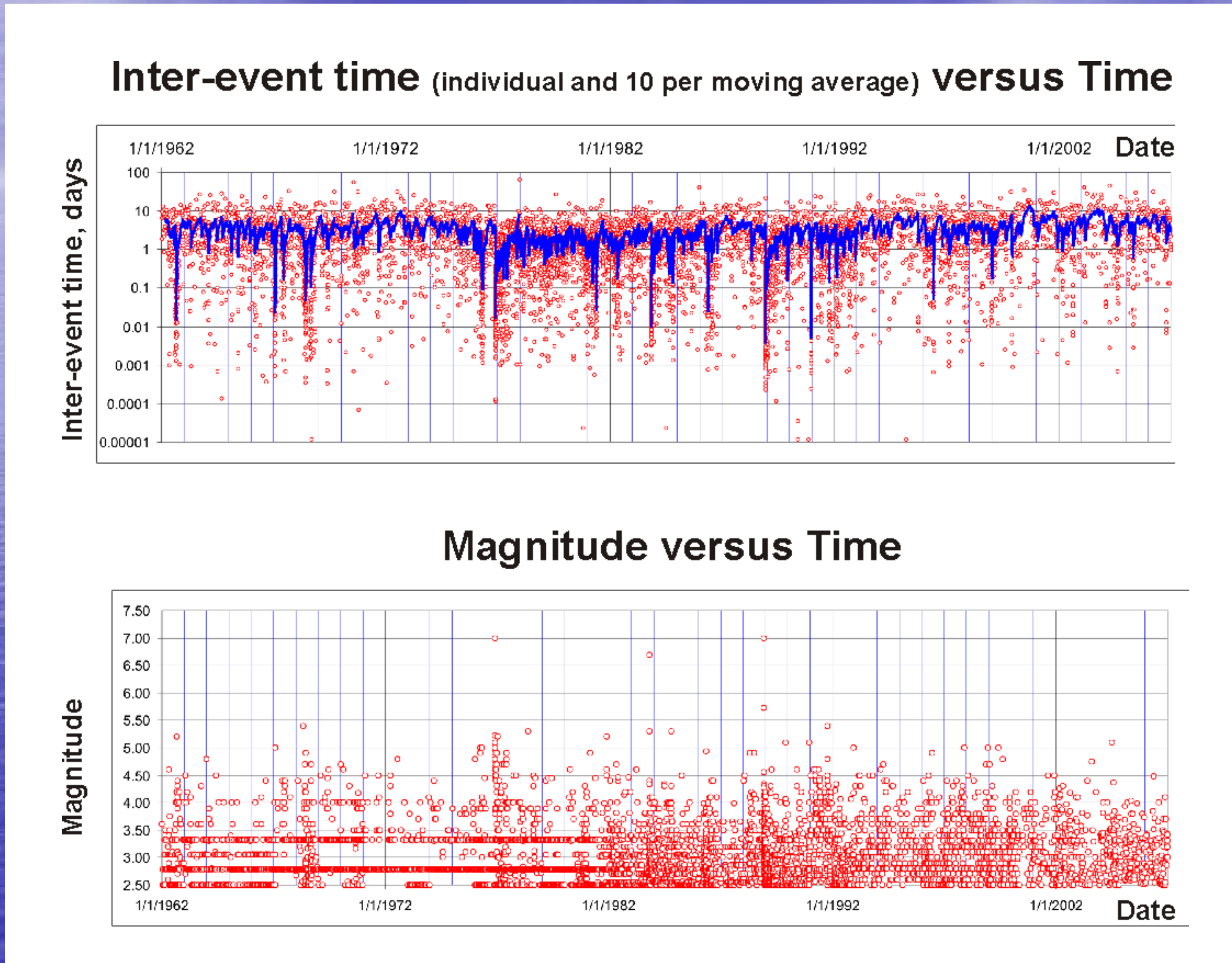
Gutenberg-Richter plot




Frequency Magnitude vs Time diagram



# NSSP catalog, 1962-2006:

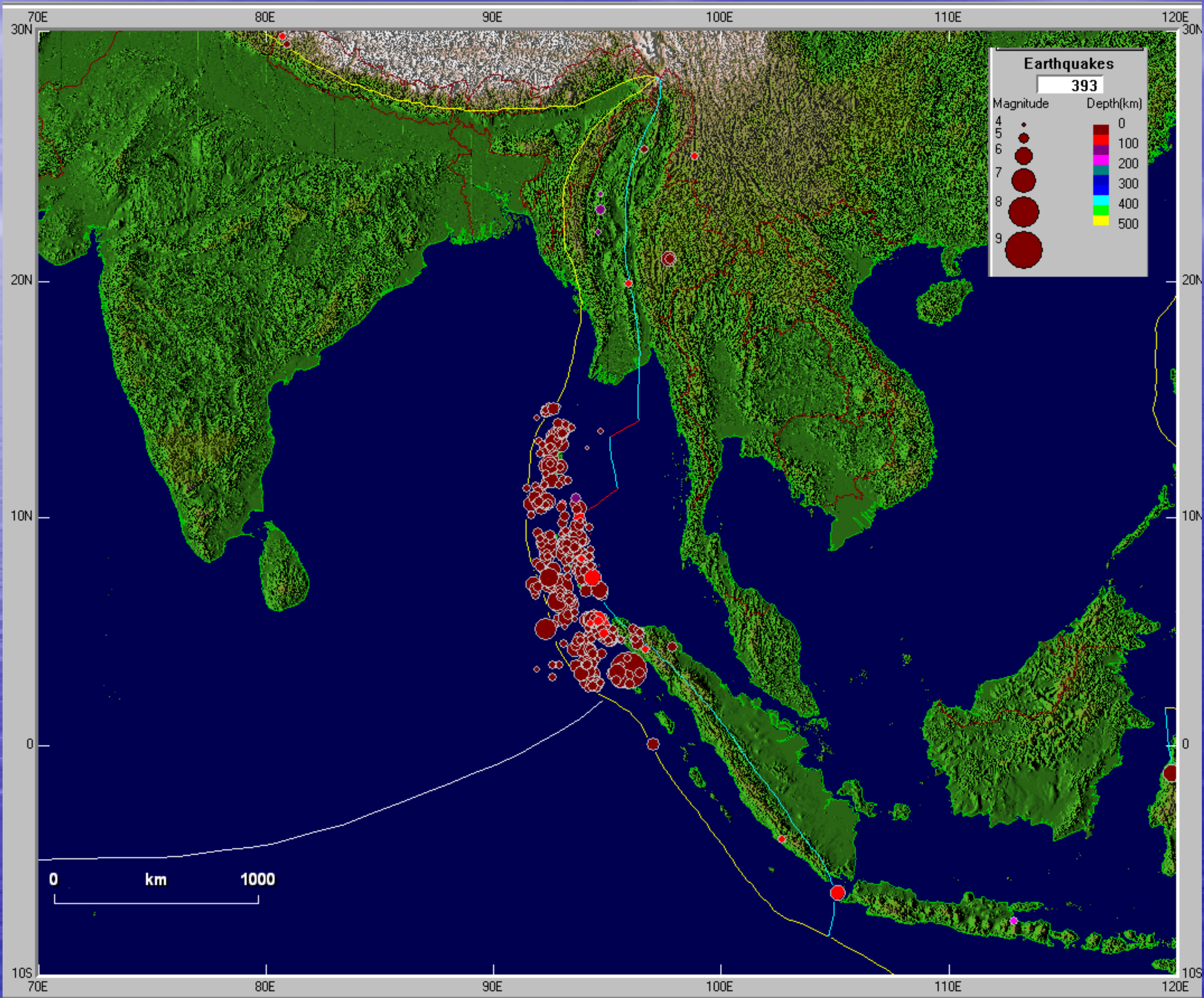


# NSSP catalog, 1962-2006:

Unlike the decline of seismic observations in other former Soviet Republics, the regional seismic network of Armenia has managed to overcome the hardships keeping reliable reports on every magnitude 3 earthquake in the region. A comprehensive analysis of the earthquake catalogs available from Armenia and neighboring countries results a conclusion on feasibility to re-establish monitoring intermediate-term middle-range precursory changes of seismic activity at least inside the territory between 42-48°N and 38-42°E. The data available is suitable for monitoring the times of increased probability of strong (magnitude 6.0-6.9) and major (magnitude 7.0-7.9) earthquakes in the region by means of the intermediate-term earthquake prediction algorithm M8.

The experiment did start anew from January 2007.

# 26/12/2004 Mw9.3 Great Asian mega earthquake



# Was it predicted?

In fact, it was. The manuscript GJI-04-0498 - **Temporal changes in the cumulative piece-wise gradient of a variant of the Gutenberg-Richter relationship, and the imminence of extreme events** - by J. Latchman, F.D. Morgan, and W. Aspinall was submitted to Geophysical Journal International three weeks in advance the 26 December 2004 Indian Ocean Disaster concluding the imminence of a mega-earthquake from the global data analysis…

Latchman et al., 2007, Earth Science Reviews /
http://dx.doi.org/10.1016/j.earscirev.2007.11.001

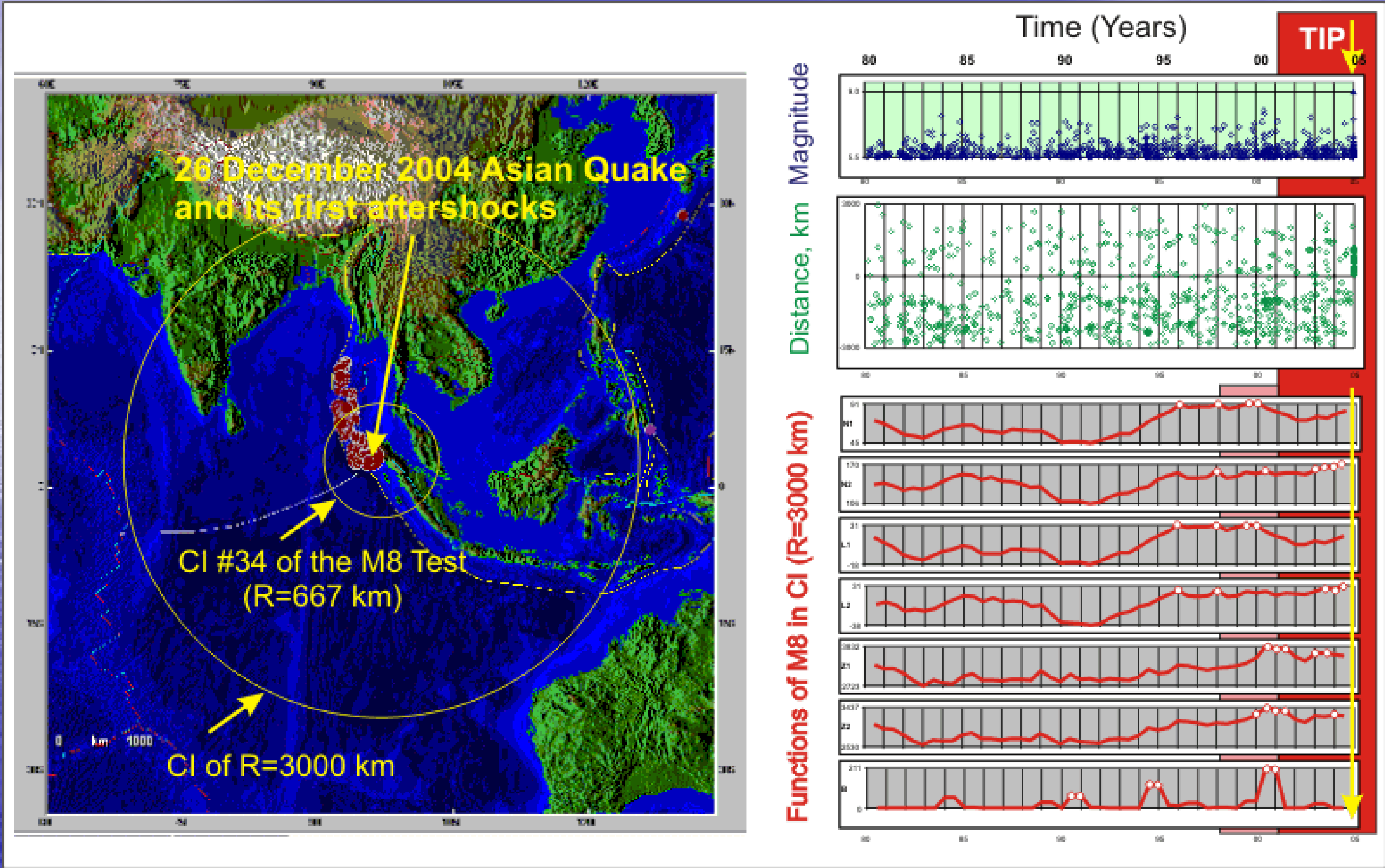
The manuscript - **Does the Earth show up an impending mega-earthquake?** – by L.L. Romashkova
http://ru.arxiv.org/ftp/physics/papers/0703/0703241.pdf

confirms the conclusion and enhances the description of global activation of seismic activity in advance 26 December 2004 at the level of statistical perfection of the arguments.

# Was it predicted in the Test of M8? No, however...

- If on July 1, 2004 someone had been sufficiently ambitious to extend application of the M8 algorithm into the uncalibrated magnitude range targeting M9.0+ earthquakes, he or she would have diagnosed Time of Increased Probability in advance of the 2004 Great Asian Quake.
- In the on-going Global Testing of M8-MSc predictions aimed at M8.0+ events, it was a case of one not being able to see the forest for the trees.

# 26/12/2004 Mw9.3 Great Asian mega-thrust earthquake



# First conclusions:

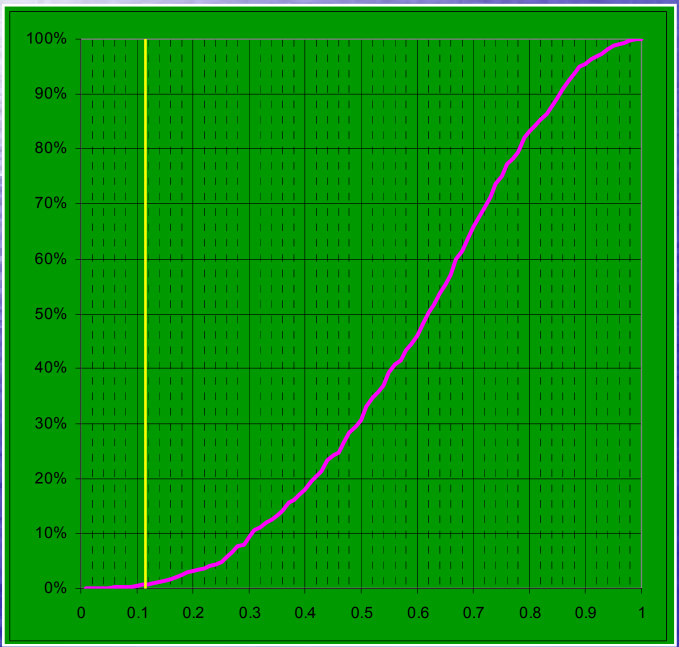
**UN World Conference on Disaster Reduction, Special Session on the Indian Ocean Disaster, 20 January 2005, Kobe (JAPAN)**

- The December 26 event happened to be the first indication that the algorithm, designed for prediction of M8.0+ earthquakes can be rescaled for prediction of mega-earthquakes of M9.0+.

  (The algorithm efficiency in prediction of smaller magnitude earthquakes, e.g., M7.5+ worldwide, M5.5+ in Italy has been proved by growing statistics of the on-going real-time experimental testing.)
- The event is not full verification, but it is very important for general understanding of our methodology (*Keilis-Borok, V.I., and A.A. Soloviev (Editors). Nonlinear Dynamics of the Lithosphere and Earthquake Prediction. Springer, Heidelberg, 2003* ) and the Problem of Earthquake Prediction.

| Location | Date UTC | Magnitude | Latitude | Longitude |
|---|---|---|---|---|
| 5.Kamchatka | 4-Nov-1952 | 9.0 | 52.76 N | 160.06 E |
| 4.Andreanof Islands, Alaska | 9-Mar-1957 | 9.1 | 51.56 N | 175.39 W |
| 1.Chile | 22-May-1960 | 9.5 | 38.24 S | 73.05 W |
| 3.Prince William Sound, Alaska | 28-Mar-1964 | 9.2 | 61.02 N | 147.65 W |
| 2.Off the West Coast of Northern Sumatra | 26-Dec-2004 | 9.3 | 3.30 N | 95.78 E |

# The relevant observation:




**All four mega-earthquakes of the 20th century happened within a narrow interval of time. Such a cluster is unlikely with a 99% confidence for uniformly distributed independent events.**

# First conclusions:

**Kossobokov, 2005. 26 December 2004 Greatest Asian Quake: When to expect the next one ?**
**UN World Conference on Disaster Reduction, Special Session on the Indian Ocean Disaster, 20 January 2005, Kobe (JAPAN)**

- **Since good evidence suggests that mega-earthquakes as other seismic events cluster, it is likely that we shall evidence further confirmations of the prediction within 5-10 years.**

The extent of the M9.0+ alerts in space and time is thought provoking: There was one cluster of them in 1984-1989 around western Mediterranean (compact union of eight out of the 262 CI's) and another one in 1994-1999 around the Cascadia subduction zone (compact union of the five CI's off coast of the western U.S.).

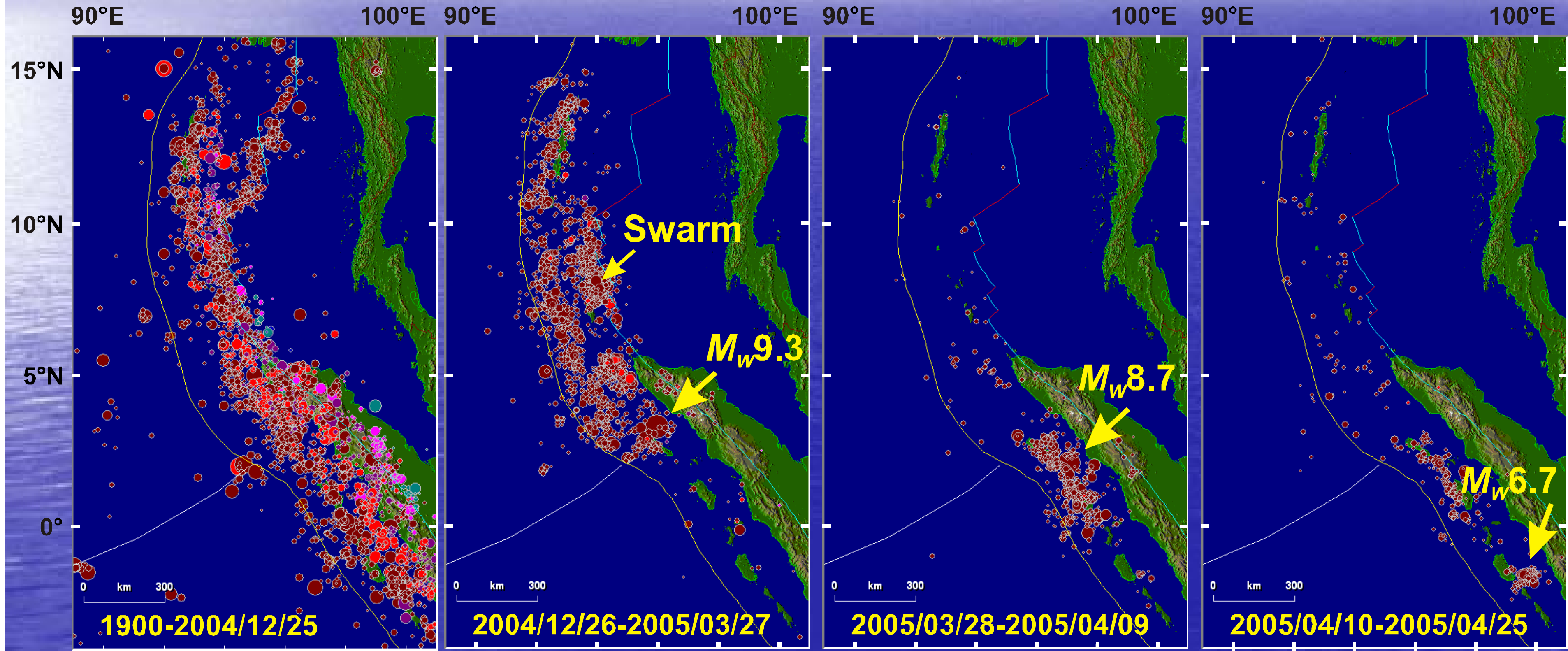
Neither of these produced an M9.0+ event.

**The extent of precursory seismic mega-activation remains widespread globally, although it has decreased**

**from 126 CI's in 2004 to 47 CI's today.**

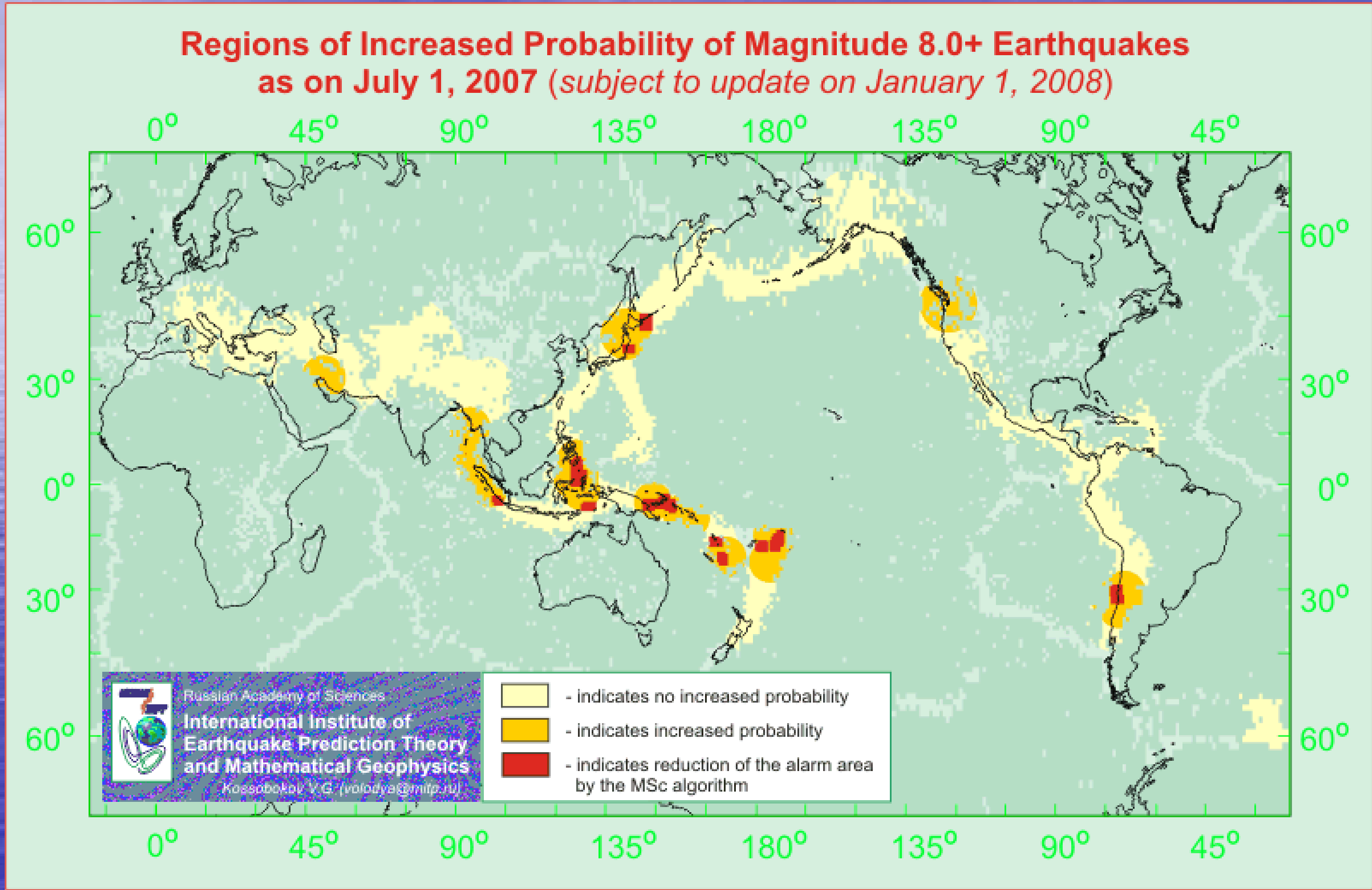
# First confirmation:

## 28 March 2005 Nias, M8.7 earthquake



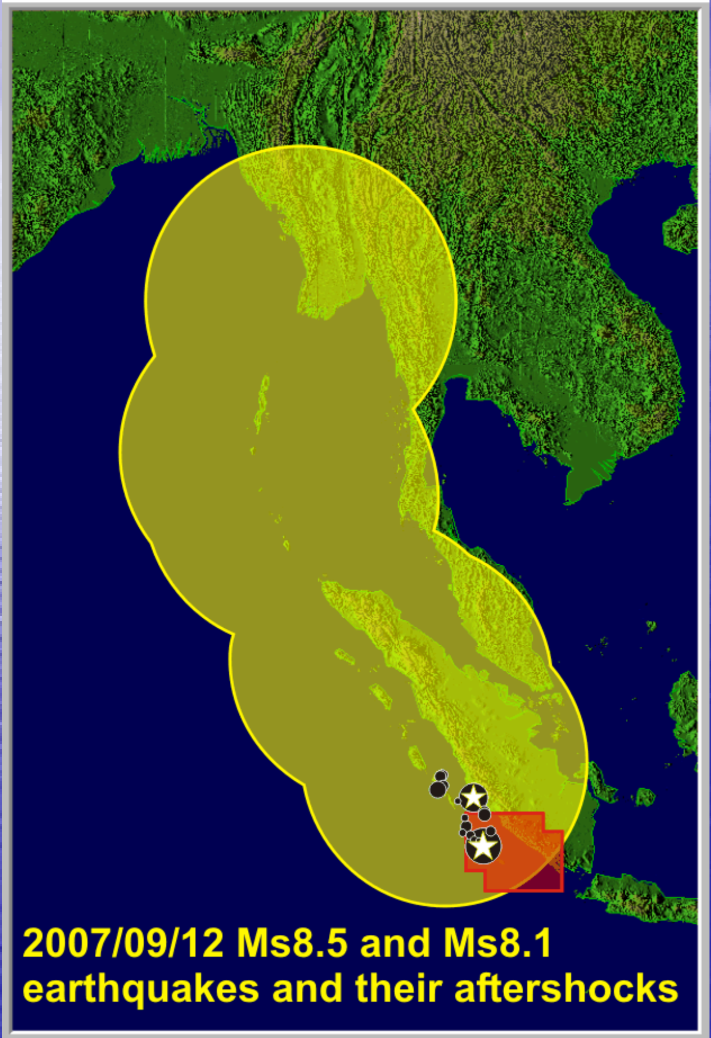
# Further confirmations expected:

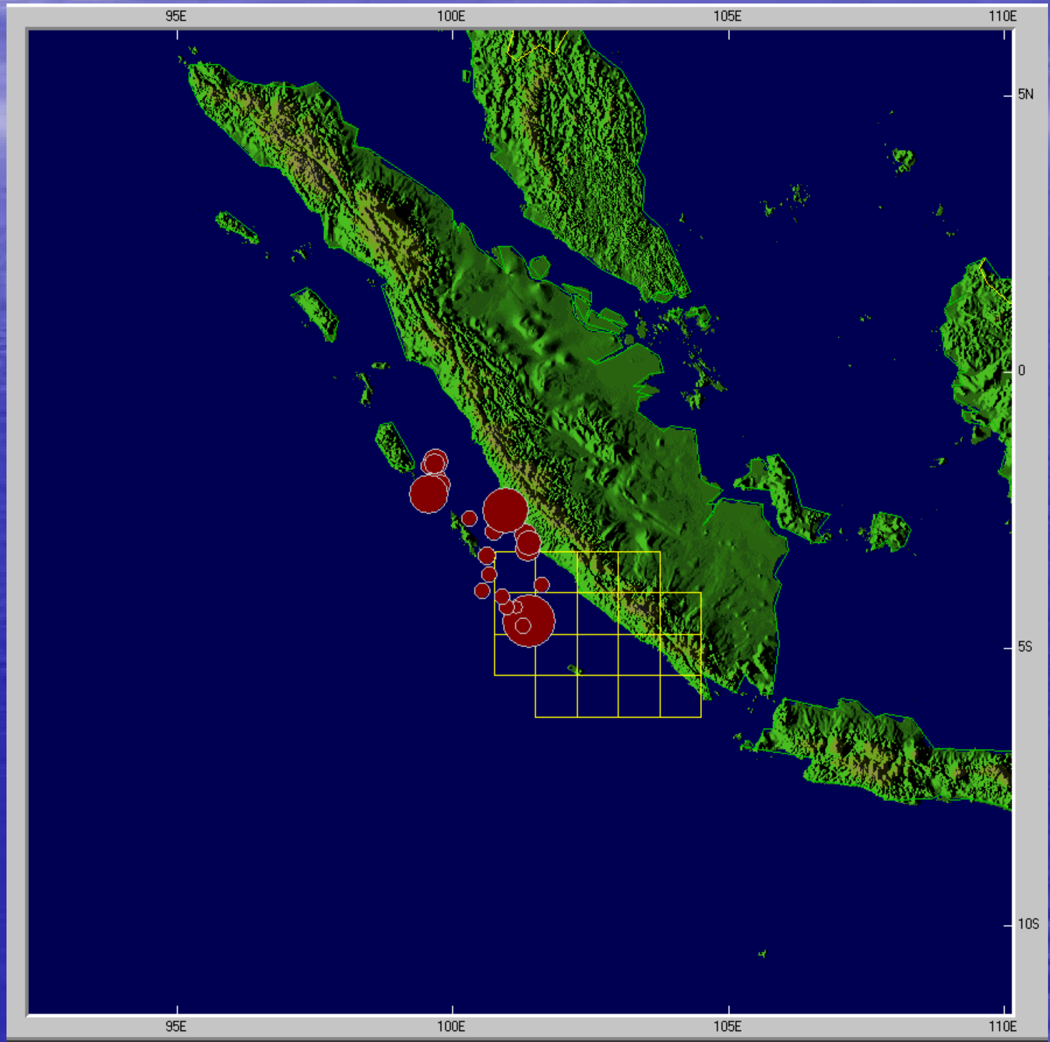
12 September 2007, M8.5 earthquake



# Further confirmations expected:

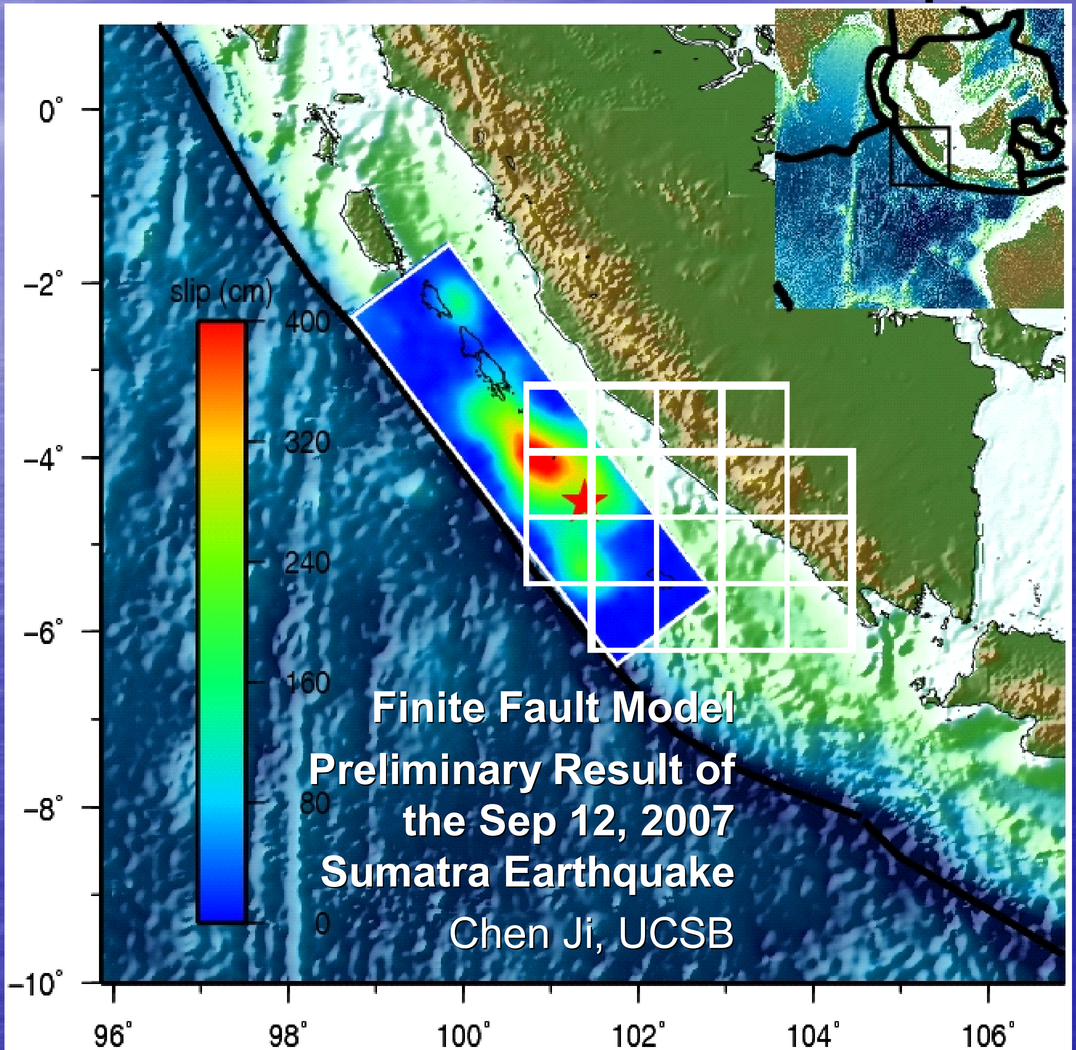
12 September 2007, M8.5 earthquake



# Further confirmations expected:

12 September 2007, M8.5 earthquake



# Conclusions – The Four Paradigms

Statistical validity of predictions confirms the underlying paradigms:

- Seismic premonitory patterns exist;
- Formation of earthquake precursors at scale of years involves large size fault system;
- The phenomena are similar in a wide range of tectonic environment...
- ... and in other complex non-linear systems.

# Opinion:

## of the IUGG GeoRisk Commission member

Losses from natural disasters continue to increase mainly due to the lack of knowledge and poor understanding by scientific community, as well as by decision makers and people, the three components of Risk, i.e.,

**Hazard, Exposure, and Vulnerability**.

Contemporary Science (Geophysics and Seismology, in particular) is responsible for not coping with the challenging changes of Exposures and their Vulnerability inflicted by growing population, its concentration, etc., which result in the observed steady increase of social Losses due to Natural Hazards. Scientists owe to the Society for lack of knowledge, education, and communication...