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"Seventh Workshop on Non-Linear Dynamics and Earthquake Prediction"

29 September - 11 October 2003

What Can We Learn from Catalog Earthquakes?

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What can we learn from a catalog of earthquakes?

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Outline

- What are earthquakes and how to size them?
- How to get information on earthquakes?
- Uncertainties and Catalog errors
- Unified Scaling Law for Earthquakes
- Are earthquakes predictable? “Seismic Roulette”
- Seismic dynamics prior to and after recent earthquakes of magnitude 8.0 or larger

What are earthquakes

Earthquakes are sudden fractures of the Earth’s crust that radiate seismic waves and cause ground shaking.

Although historical records on earthquakes are known from 2100 B.C., most of them before the middle of the 18th century are generally lacking description or are not reliable.

The extreme catastrophic nature of earthquakes is known for centuries due to resulted devastation in many of them.

The abruptness along with apparent irregularity and infrequency of earthquake occurrences facilitate formation of a common perception that earthquakes are random unpredictable phenomena.

The challenging questions remain pressing:

What happens during an earthquake?

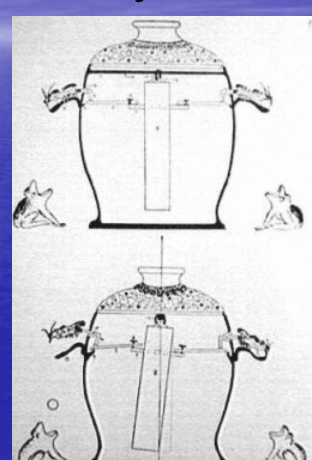
How to size earthquakes?

Why, Where and When do earthquakes occur?

The basic difficulty in answering these questions comes from the fact that no earthquake has been ever observed directly.

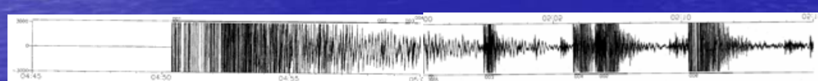
September 25, 2003, HOKKAIDO, JAPAN, Mw=8.3

Chinese scientists created the first earthquake detector 2000 years ago



Recording earthquakes

- In 1870s the English geologist *John Milne* designed a forerunner of modern seismographs.
  A simple pendulum and a needle suspended above a smoked-glass plate allowed to distinguish primary and secondary earthquake waves and, basing on their timing, to derive an accurate statement about location of an earthquake source.
- The modern seismograph was invented in the early 20th century by the Russian Prince *Boris Golitzyn,* who improved similar instruments of the 1890's.
- At present, the classic image of a pen that writes a seismogram has been replaced by enhanced digital systems, but the principle remains the same.



Measuring size of an earthquake

- It was only in the 1930's that *Charles F. Richter*, a California seismologist, introduced the concept of earthquake magnitude.
- His original definition held only for California earthquakes occurring within 600 km of a particular type of seismograph (i.e., the *Woods-Anderson* torsion instrument).
- Richter's original magnitude scale (M_L) was then extended to observations of earthquakes of any distance and of focal depths ranging between 0 and 700 km.

Magnitude scales

- Because earthquakes excite both body waves, which travel into and through the Earth, and surface waves, which are constrained to follow the Earth's uppermost layers, two magnitude scales evolved - the m_b and M_S
- The standard body-wave magnitude formula is

$$m_b = \log_{10}(A/T) + Q(D,h) ,$$

where *A* is the amplitude of ground motion; *T* is the corresponding period; and Q(*D*,*h*) is an empirical function of distance, *D*, between epicenter and station and focal depth, *h*.

- The standard surface-wave formula is

$$M_S = \log_{10}(A/T) + 1.66 \log_{10}(D) + 3.30 .$$

Seismic Moment, M_O

- The seismic moment is related to fundamental parameters of the faulting process.

$$M_O = \mu S\langle d\rangle,$$

where μ is the shear strength of the faulted rock, S is the area of the fault, and ‹d› is the average displacement on the fault.

- These parameters are determined from waveform analysis of the seismograms produced by an earthquake.

Magnitude scale M_W

- This magnitude scale introduced recently is computed from seismic moment as

$$M_W = 2/3 \log_{10}(M_O) - 10.7 .$$

The largest reported moments are 2.5×10^{30} dyn·cm for the 1960 Chile earthquake (M_S8.5; M_W9.6) and 7.5×10^{29} dyn·cm for the 1964 Alaska earthquake (M_S8.3; M_W9.2).

Information on earthquakes

Surfing the Internet for Earthquake Data

(provided by Steve Malone)

- Find the known Internet type connections where original seismic data or seismic research information is available at http://www.geophys.washington.edu/seismosurfing.html
- NOTE:The complete SeismoSurfing index is mirrored for European users by ETH, Zurich at http://seismo.ethz.ch/seismosurf/seismobig.html.

The US GS/NEIC Global Hypocenter Data Base

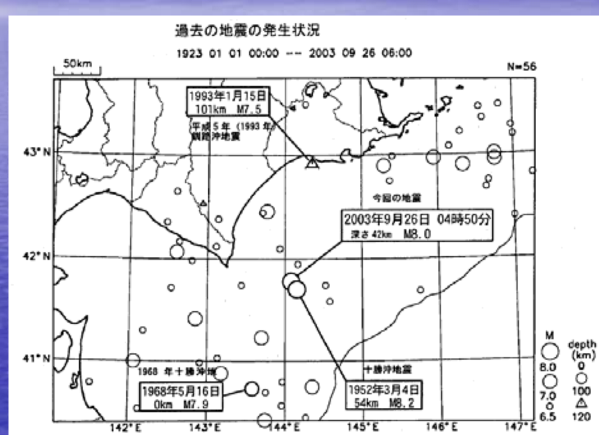
This database available from the US Geological Survey / National Earthquake Information Center at Denver, Colorado. It consists of the data on CD-ROM and its updates with Preliminary Determinations of Epicenters, PDE-monthly and PDE-weekly, and Quick Earthquake Determinations, QED.

P.N. Shebalin, using the original pattern recognition technique merged more than forty source catalogs of the NEIC GHDB into a composite one. We shall use this composite catalog for computer exercises.

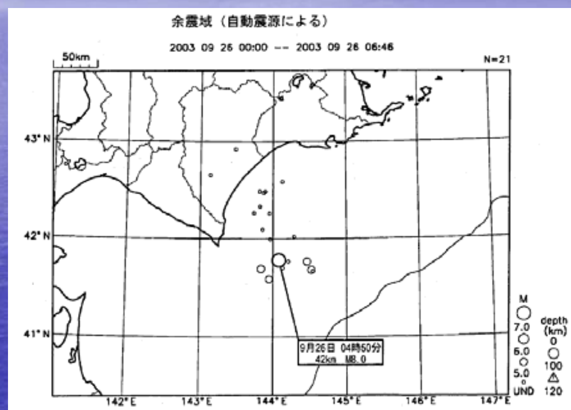
The first determinations by USGS Earthquake Hazards Program: 25 September 2003 HOKKAIDO, JAPAN REGION

The JMA first circular on the 25 September 2003 great earthquake

The JMA second circular compared locations of the 25 September 2003 and other great earthquakes in the past



… and provided distribution of aftershocks in the first two hours after the Big One



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Catalog Errors

All catalogs have errors, which may render invalid conclusions derived in a study based on a catalog of earthquakes.

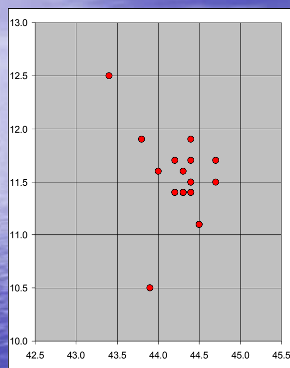
Two ways to avoid the errors –

- Postpone the analysis until the data are refined;
- Use robust methods within the limits of their applicability.

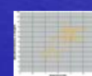
“Undue precision of computations is the first symptom of mathematical illiteracy”

N.Krylov, famous Russian mathematician

Uncertainties and errors



Epicenter distance vs. Station magnitude for the 108 determinations for the 08 September 2002 earthquake NEAR NORTH COAST OF NEW GUINEA, P.N.G.



Fast determinations of the epicenter for the 14 September 2003 earthquake in Northern Italy by different seismological agencies to European-Mediterranean Seismological Centre (EMSC)

The distribution of the difference between average magnitudes in epicenter and antipodal hemispheres

(MCHEDR 1990-2000, all events that have three of more station magnitudes in each hemisphere). The violet curve corresponds to MSZ (4560 differences, Average = -0.147, σ = 0.198), while the blue one - to mb (8175 differences, Average = 0.074, σ = 0.274).

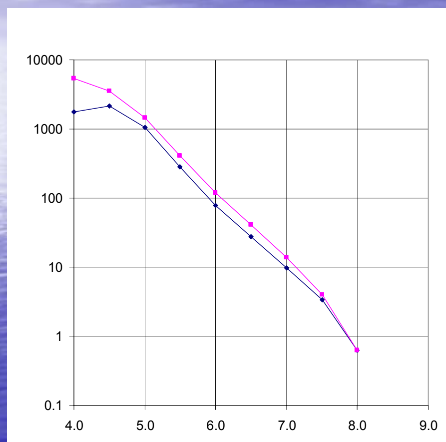
The territorial distribution of the difference between the two averages estimated over the stations from epicenter and antipodal hemispheres (for MSZ magnitudes).

What can we learn from a catalog of earthquakes?

There are two extreme opinions on the subject –

- *Pessimistic*: "… in the case of seismic data, most of the observed variations are, in fact, related to changes in the system for detecting and reporting earthquakes and not to actual changes in the Earth."
- *Optimistic*: Among existing data seismic catalogs remain the most reliable record on distribution of earthquakes in space and time.

Gutenberg-Richter relation



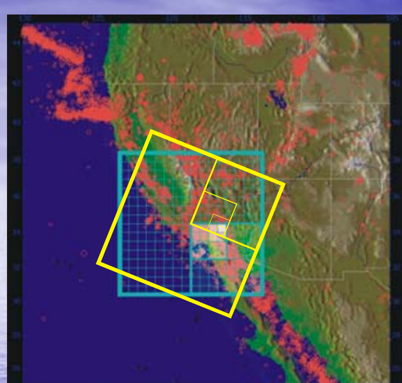
- Averaged over a large territory and time the number of earthquakes equal or above certain magnitude, N(M) scales as

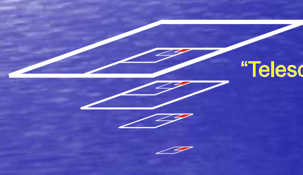
$$\log_{10}N(M) = A + B \times (8 - M)$$

This general law of similarity establishes the scaling of earthquake sizes in a given space time volume …but gives no explanation to the question how the number, N, changes when you zoom the analysis to a smaller size part of this volume.

The answer is not obvious at all.

The scheme for box-counting





The counts in sets of cascading squares, "telescopes", estimate the natural scaling of the spatial distribution of earthquake epicenters and provide evidence for rewriting the G-R recurrence law in the following form -

Generalization of the G-R relation

$$\log_{10}N = A + B\cdot(5 - M) + C\cdot\log_{10}L$$

where N = N(M, L) is the expected annual number of earthquakes with magnitude M in an area of linear dimension L.

The first results *(Kossobokov and Mazhkenov, 1988)*

The method was tested successfully on artificial catalogs with prefixed A, B and C and applied in a dozen of selected seismic regions from the hemispheres of the Earth to a certain intersection of faults.

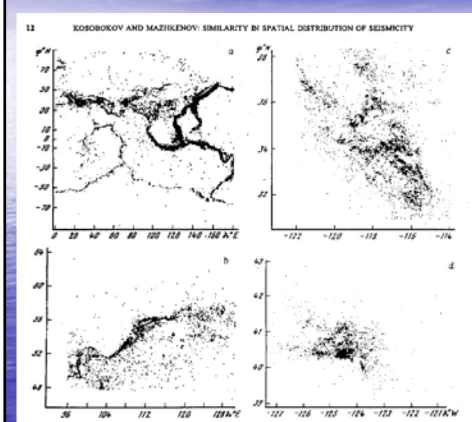


Fig. 2. Examples of spatial distribution of epicenters from catalogs of mainshocks. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

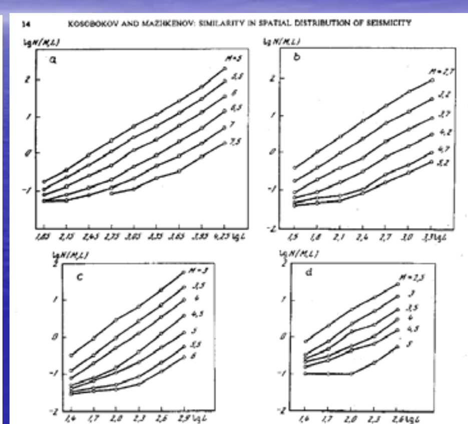
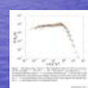


Fig. 3. Examples of log $N(M, L)$ graphs. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

Unified Scaling Law for Earthquakes

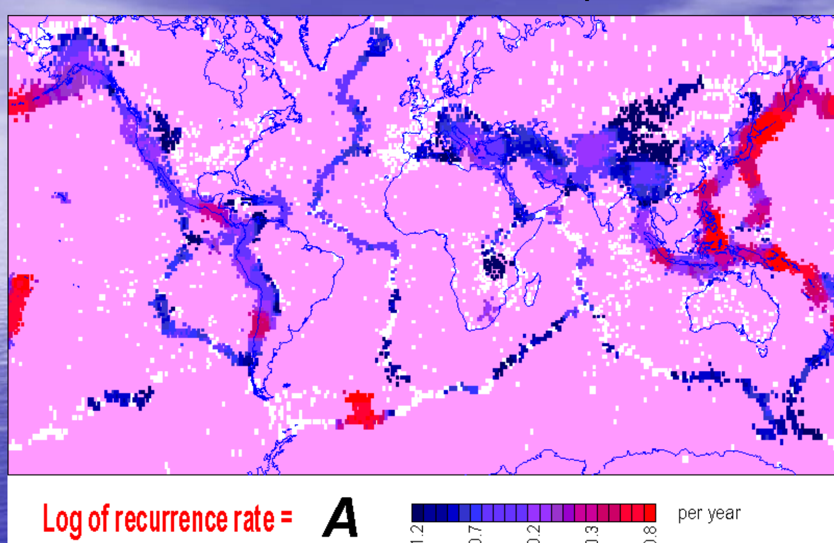


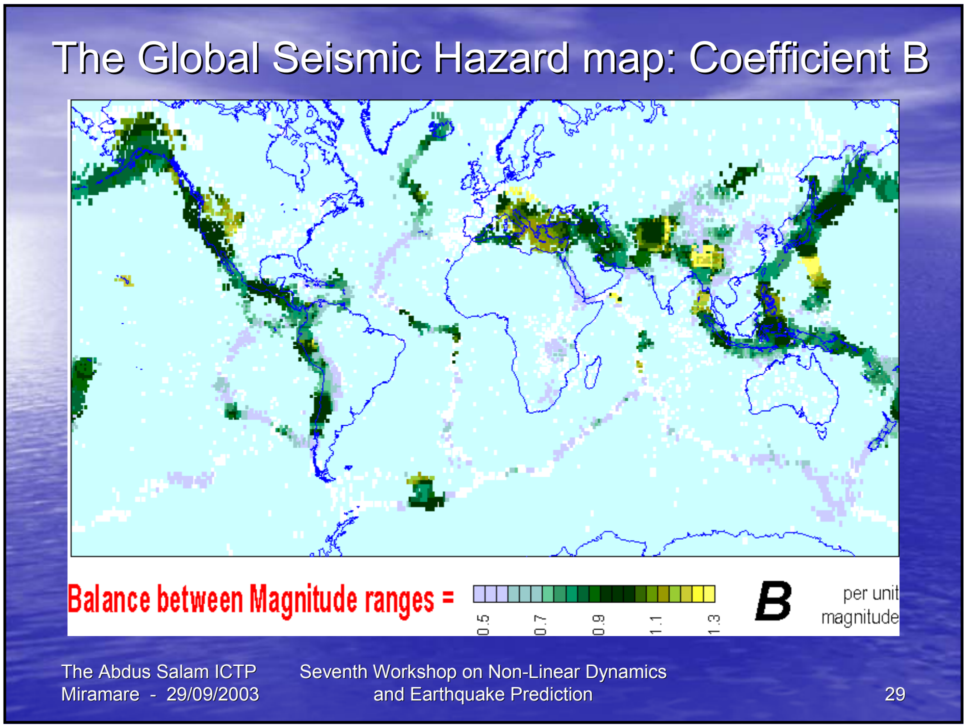
We revisited the problem after Per Back et al. suggested independently a similar generalization in a different formulation (substitutes of 1/N = T, M = Log_{10} S, *b* = B and *df* = C)

"To understand the Unified Law for Earthquakes, it is essential to see what the value of x represents. The quantity $L^{df} \cdot S^{-b}$ in the scaling function represents the average number of earthquakes per unit time, with seismic moment greater than S occurring in the area size L × L. Therefore, x is a measure of the number of earthquakes happening within a time interval T. The Unified Law states that the distribution of waiting times between earthquakes depends only on this value."

Bak, P., K. Christensen, L. Danon, and T. Scanlon, 2002.
Unified Scaling Law for Earthquakes.
Phys. Rev. Lett. 88: 178501-178504

The Global Seismic Hazard map: Coefficient A




The Global Seismic Hazard map: Coefficient B
Balance between Magnitude ranges =
0.5
0.7
0.9
1.1
1.3
B
per unit
magnitude
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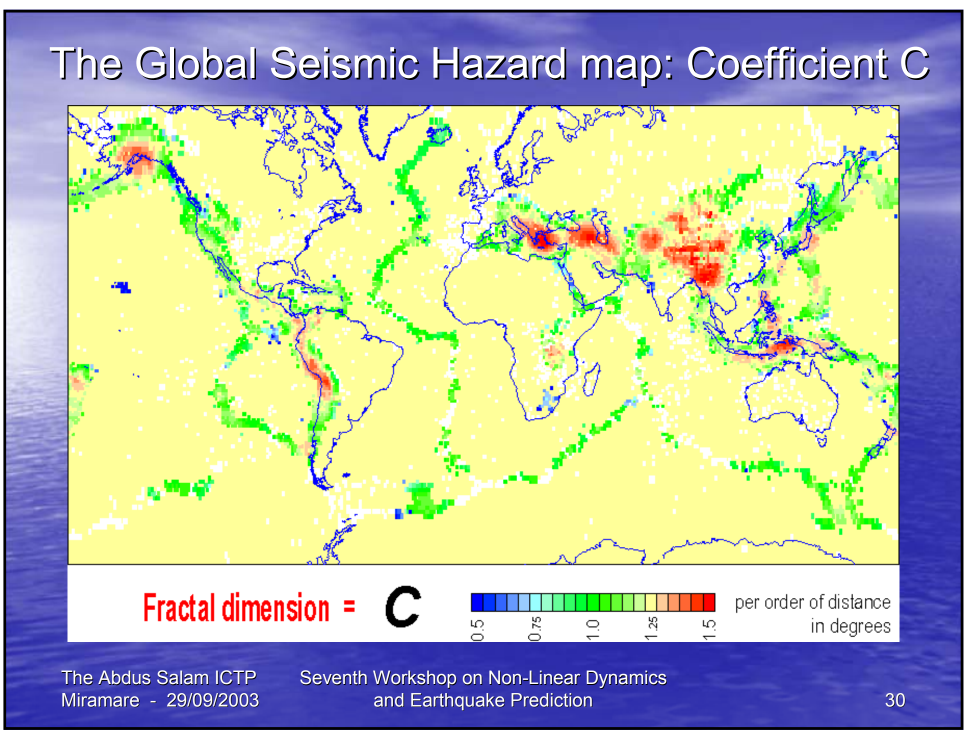
The Global Seismic Hazard map: Coefficient C
Fractal dimension = C
0.5
0.75
1.0
1.25
1.5
per order of distance
in degrees
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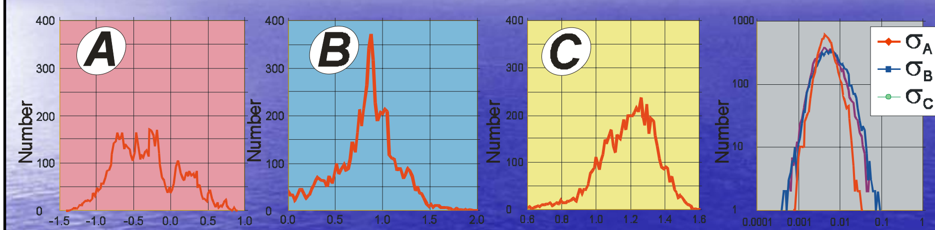
Histograms of A, B, C and σ's



- Note: The histograms of the coefficient value errors, σ's, given in logarithmic scales suggest high degree of overall agreement with the assumption of self-similarity used in computations.

Recurrence of earthquakes

The recurrence of earthquakes in a seismic region, for a wide range of magnitudes and sizes, can be characterized with the following law:

$$\text{Log } N(M,L) = A + B\cdot(5 - M) + C\cdot\text{Log } L,$$

where N(M,L) is the expected annual number of main shocks of magnitude M within an area of liner size L.

For a wide range of seismic activity, A, the balance between magnitude ranges, B, varies mainly from 0.6 to 1.1, while the fractal dimension, C, changes from under 1 to above 1.4.

An estimate of earthquake recurrence rate per square km depends on the size of the territory that is used for averaging and may differ from the real one dramatically when rescaled in traditional way to the area of interest.

The Unified Scaling Law for Earthquakes has serious implications for estimation of seismic hazard, for the Global Seismic Risk Assessment, as well as for earthquake prediction.

Implications for assessing seismic hazard at a given location (e.g., in a mega city)

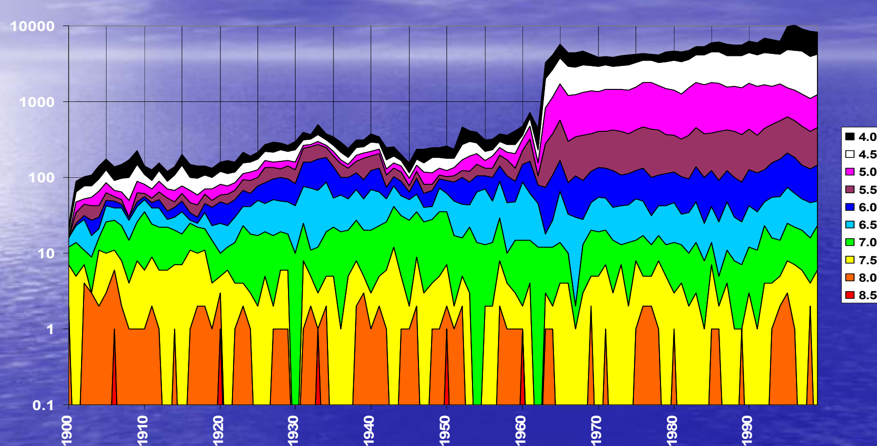
Our estimates for Los Angeles (SCSN data, 1984-2001) -

$A = -1.28; \quad B = 0.95; \quad C = 1.21 \; (\sigma_{total} = 0.035)$

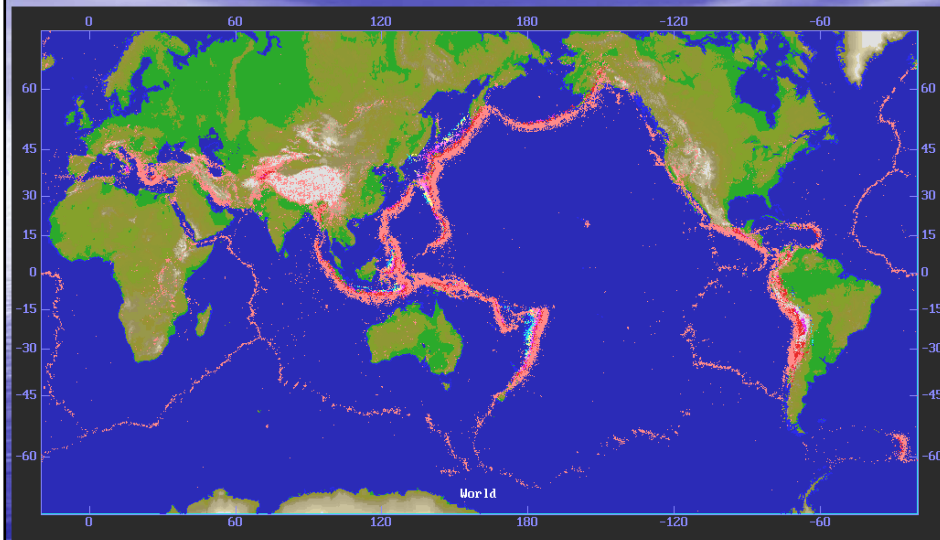
- imply a traditional assessment of recurrence of a large earthquake in Los Angeles, i.e., an area with L about 40 km, from data on the entire southern California, i.e., an area with L about 400 km, being underestimated by a factor of

$$10^2 / 10^{1.21} = 10^{0.79} > 6 \,!$$

Global Number of Earthquakes vs. Time



Where earthquakes occur in Space…



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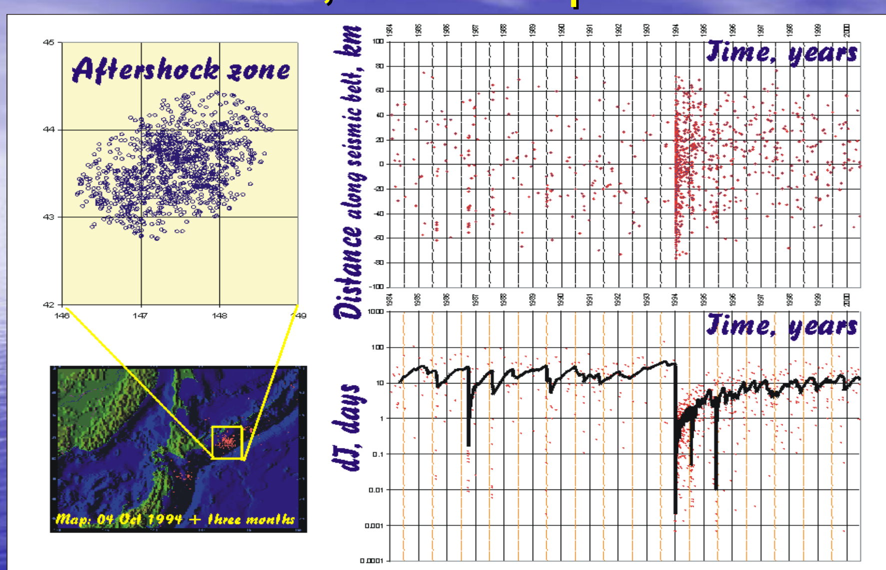
… in Time, and in Space-Time



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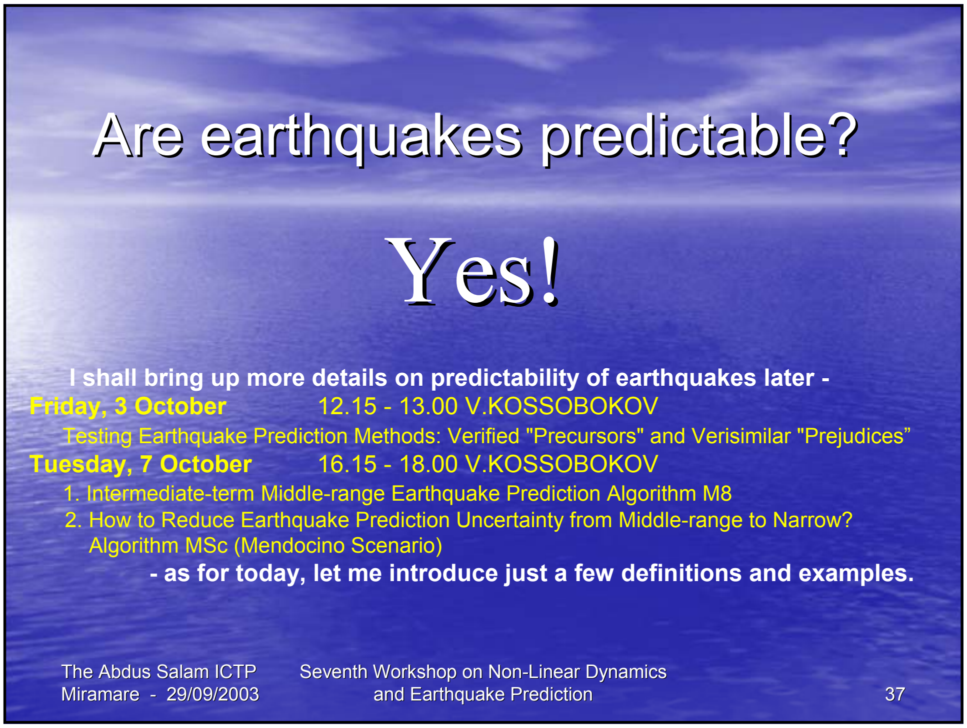
Are earthquakes predictable?
Yes!
I shall bring up more details on predictability of earthquakes later -
Friday, 3 October 12.15 - 13.00 V.KOSSOBOKOV
Testing Earthquake Prediction Methods: Verified "Precursors" and Verisimilar "Prejudices"
Tuesday, 7 October 16.15 - 18.00 V.KOSSOBOKOV
1. Intermediate-term Middle-range Earthquake Prediction Algorithm M8
2. How to Reduce Earthquake Prediction Uncertainty from Middle-range to Narrow? Algorithm MSc (Mendocino Scenario)
- as for today, let me introduce just a few definitions and examples.
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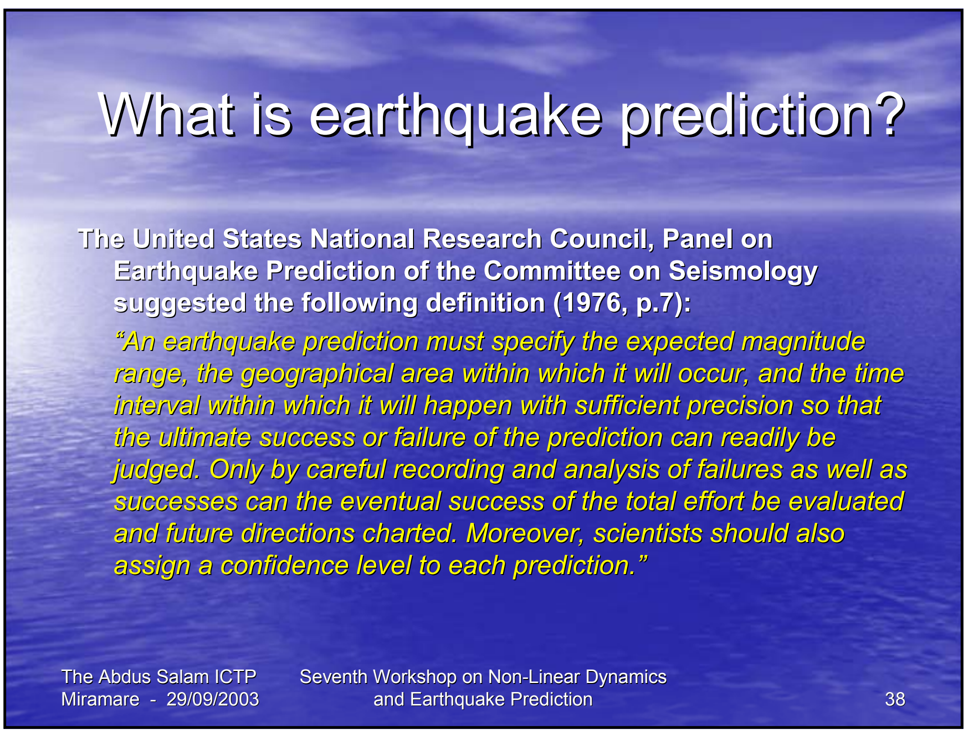
What is earthquake prediction?
The United States National Research Council, Panel on Earthquake Prediction of the Committee on Seismology suggested the following definition (1976, p.7):
"An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, 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."
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PLANETS ALIGN: On Wednesday morning, Sept. 24th, a lovely trio appeared in the eastern sky: Jupiter, the crescent moon and Mercury.

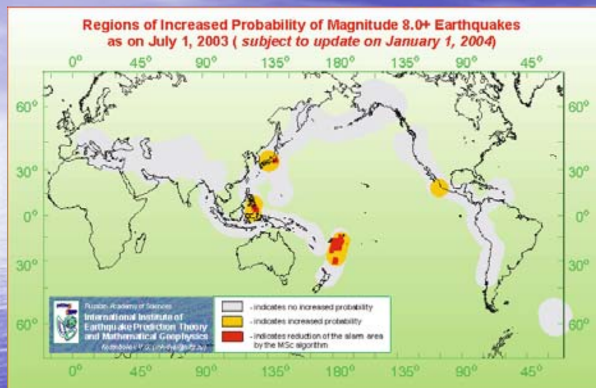
Stages of earthquake prediction

- 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

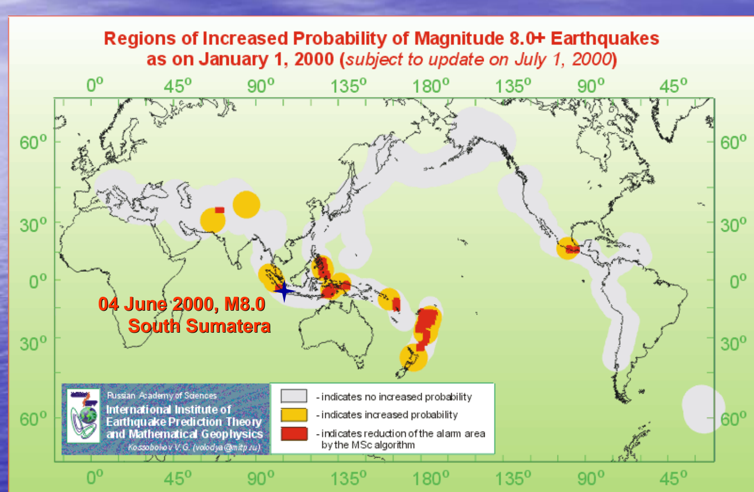
Real-time prediction of the world largest earthquakes

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

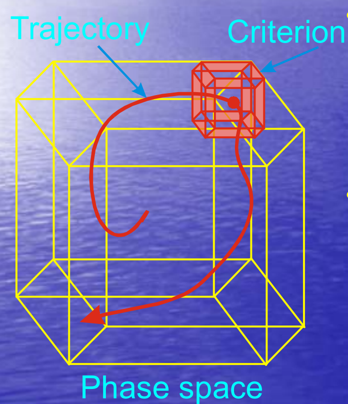


Although the M8-MSc predictions are intermediate-term middle-range and by no means imply any "red alert", some colleagues have expressed a legitimate concern about maintaining necessary confidentiality. Therefore, the up-to-date predictions are not shown here, although available on web-pages of restricted access provided to about 125 members of the Mailing List. /

History, 1985-2002: Prediction Update 2000a



Reproducible intermediate-term earthquake prediction algorithms, M8 and MSc



- 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) to determine middle-range predictions.
- The algorithm MSc reduces the area of alarm outlining such an area where the activity, from the beginning of seismic inverse cascade recognized by M8, is continuously high and infrequently drops for a short time. The phenomenon might reflect the narrow-range intermittence of the seismic premonitory rise near the incipient source of main shock.

Inverse cascading of earthquakes

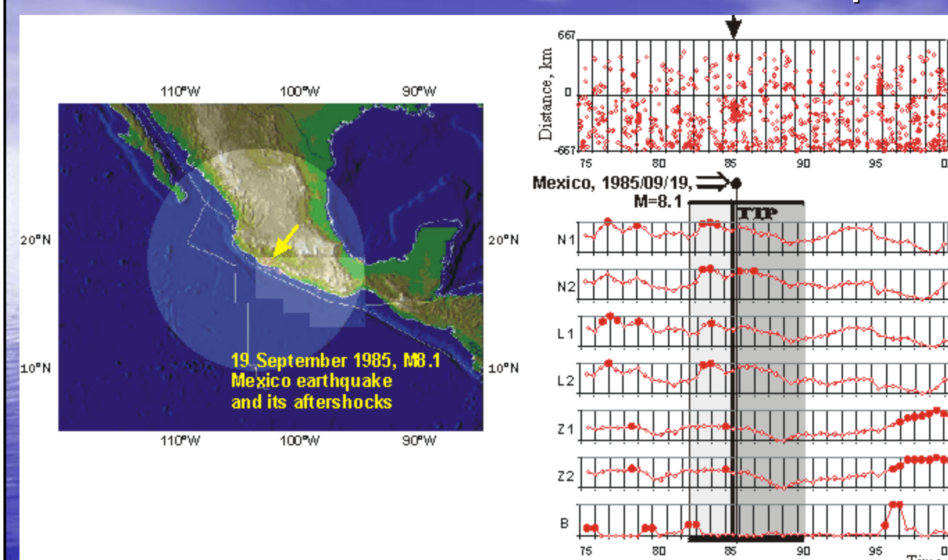
is detectable by reproducible *earthquake prediction methods,* which are scalable to smaller magnitude ranges

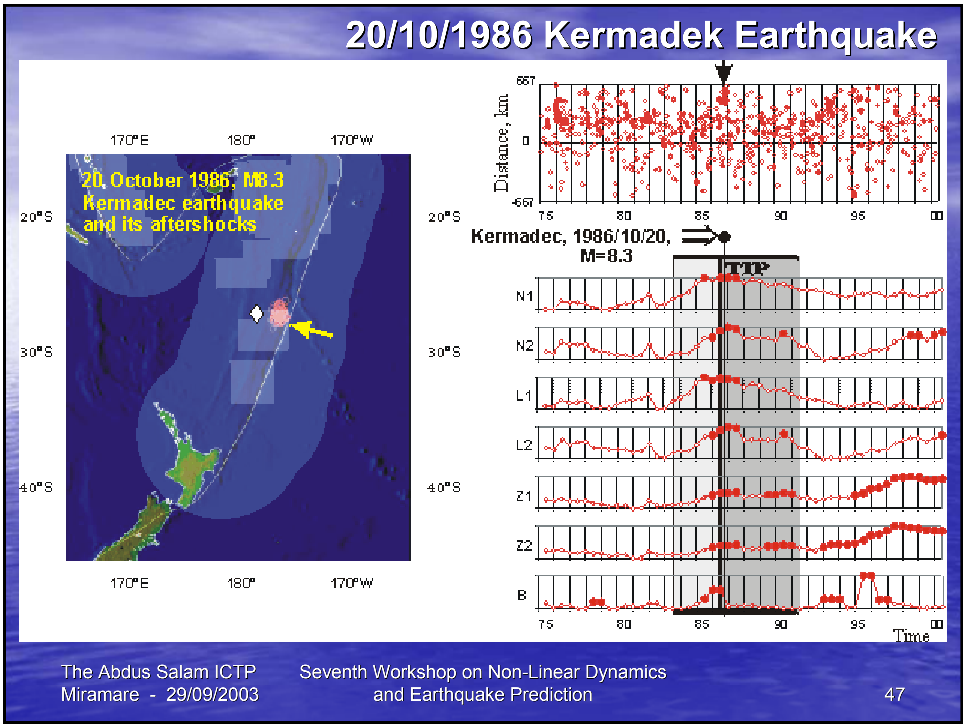
Case histories of the recent earthquakes of magnitude 8 or above prove it and evidence consecutive stages of inverse cascading of seismic activity to the main shock.

Real-time monitoring (http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp):

Centers of CI's and Great Earthquakes, 1985-2003

19/09/1985 Mexico Earthquake




20/10/1986 Kermadek Earthquake
20 October 1986, M8.3
Kermadec earthquake
and its aftershocks
170°E
180°
170°W
20°S
30°S
40°S
Distance, km
667
0
-667
75
80
85
90
95
00
Kermadec, 1986/10/20,
M=8.3
TIP
N1
N2
L1
L2
Z1
Z2
B
Time
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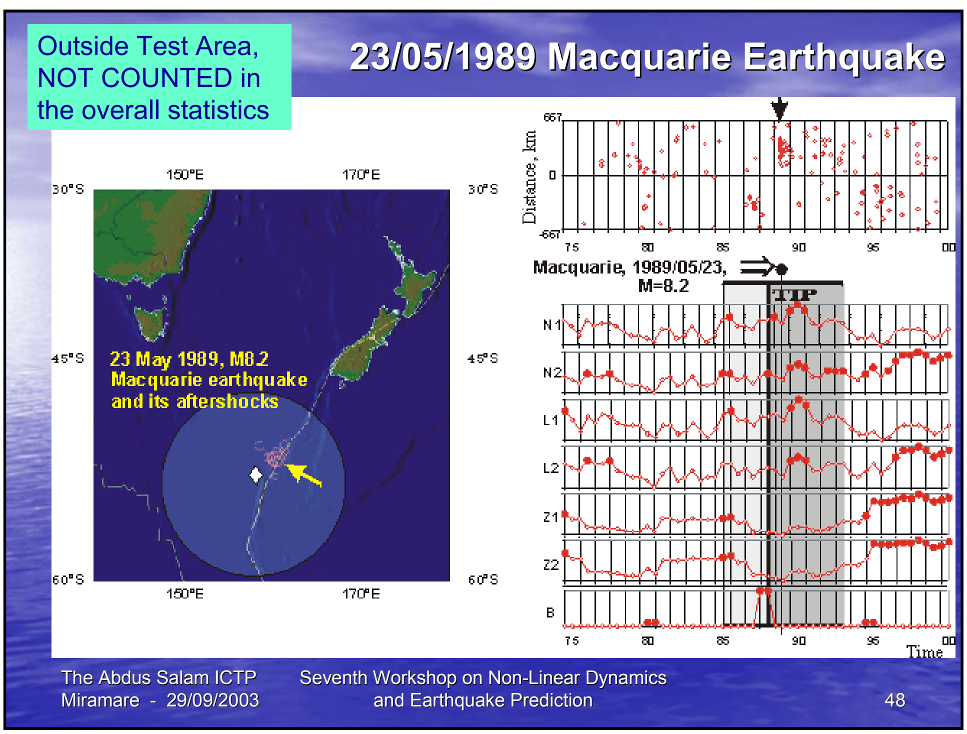
Outside Test Area,
NOT COUNTED in
the overall statistics
23/05/1989 Macquarie Earthquake
23 May 1989, M8.2
Macquarie earthquake
and its aftershocks
150°E
170°E
30°S
45°S
60°S
Distance, km
667
0
-667
75
80
85
90
95
00
Macquarie, 1989/05/23,
M=8.2
TIP
N1
N2
L1
L2
Z1
Z2
B
Time
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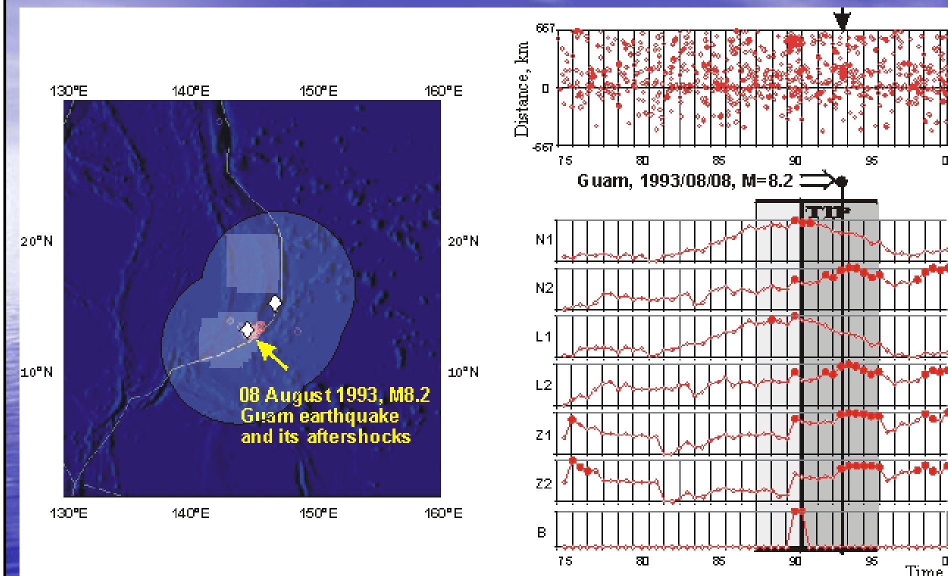
08/08/1993 Guam Earthquake

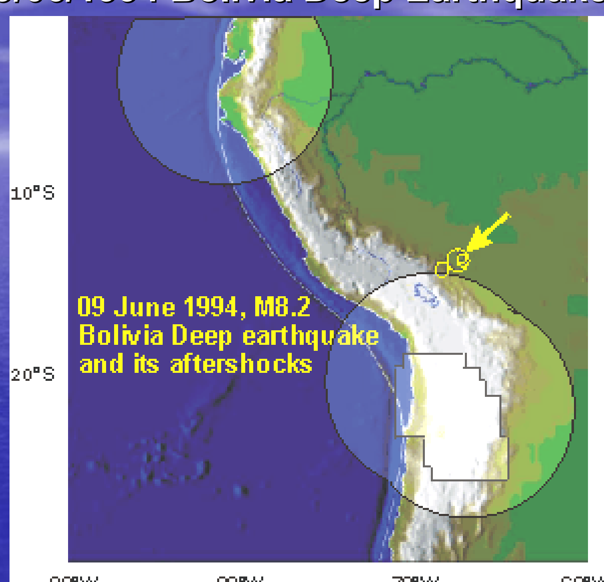


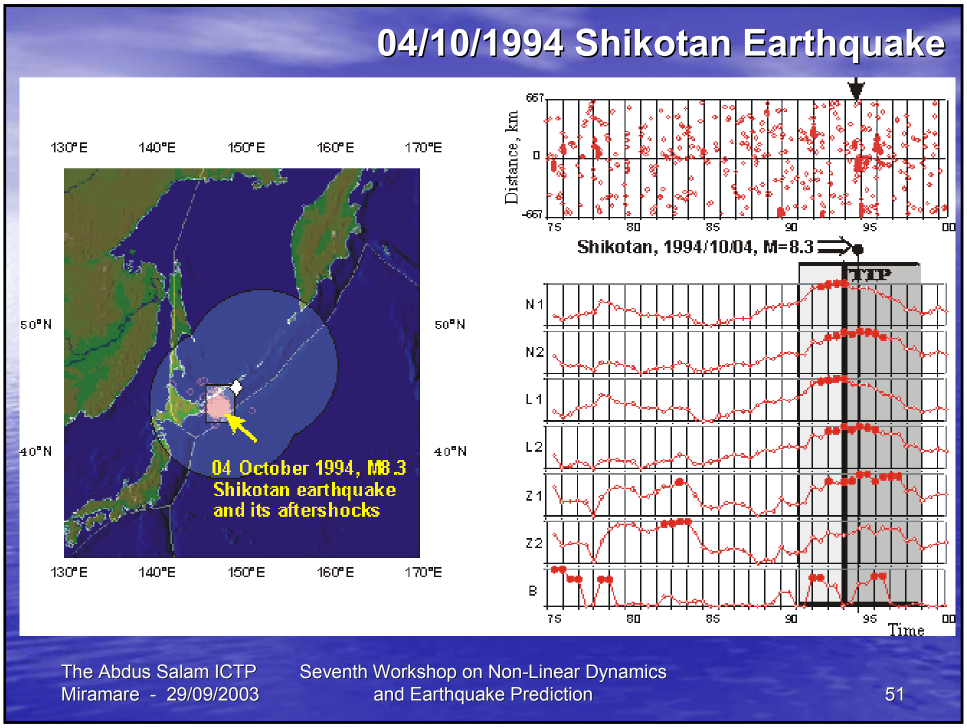
09/06/1994 Bolivia Deep Earthquake

Outside Test Area, NOT COUNTED in the overall statistics

- 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
130°E
140°E
150°E
160°E
170°E
50°N
40°N
04 October 1994, M8.3
Shikotan earthquake
and its aftershocks
Distance, km
667
0
-667
75
80
85
90
95
00
Shikotan, 1994/10/04, M=8.3
TIP
N1
N2
L1
L2
Z1
Z2
B
Time
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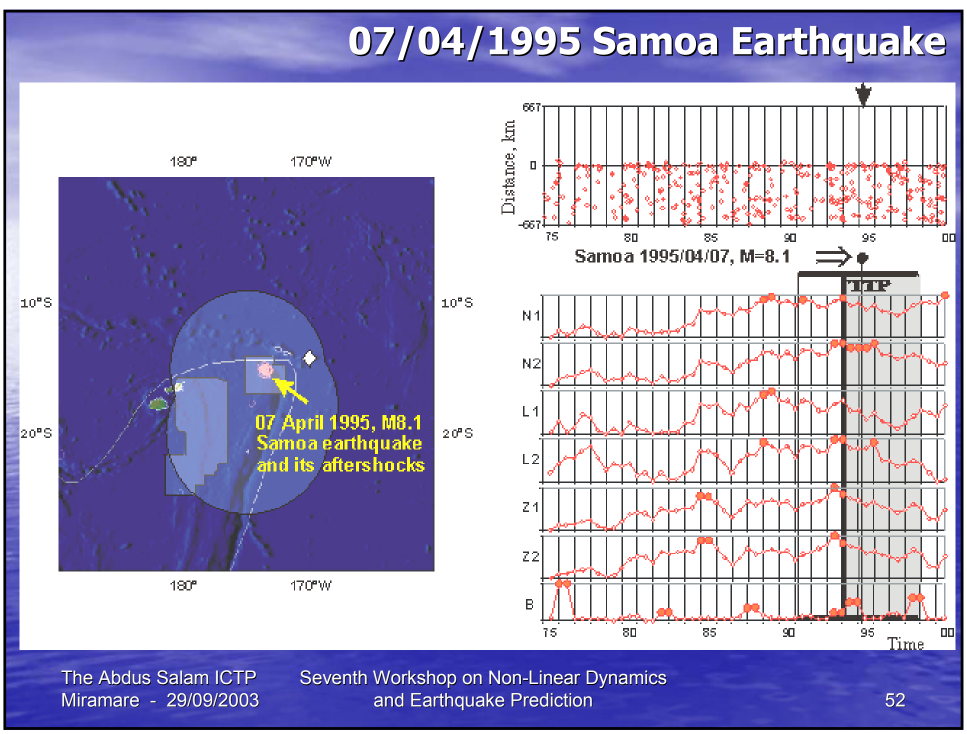
07/04/1995 Samoa Earthquake
180°
170°W
10°S
20°S
07 April 1995, M8.1
Samoa earthquake
and its aftershocks
Distance, km
667
0
-667
75
80
85
90
95
00
Samoa 1995/04/07, M=8.1
TIP
N1
N2
L1
L2
Z1
Z2
B
Time
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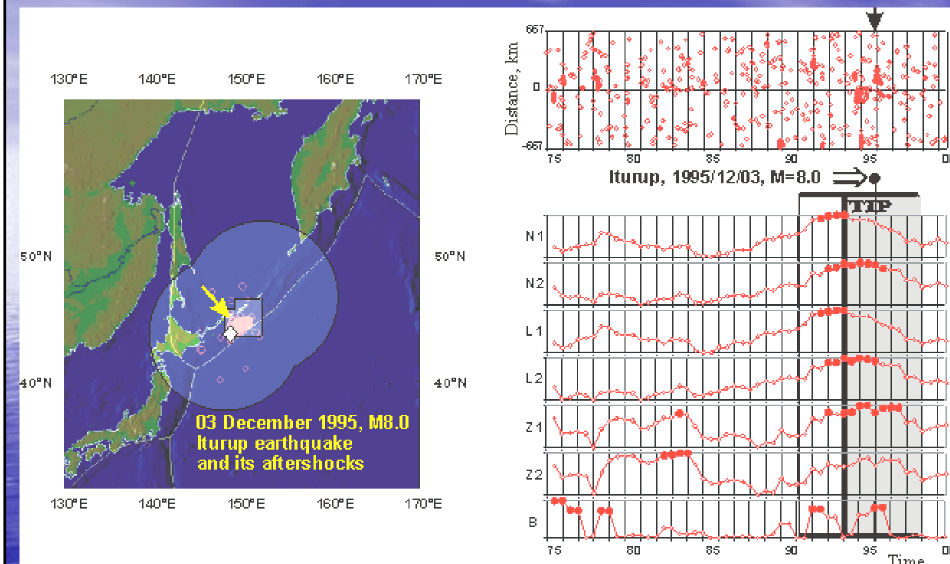
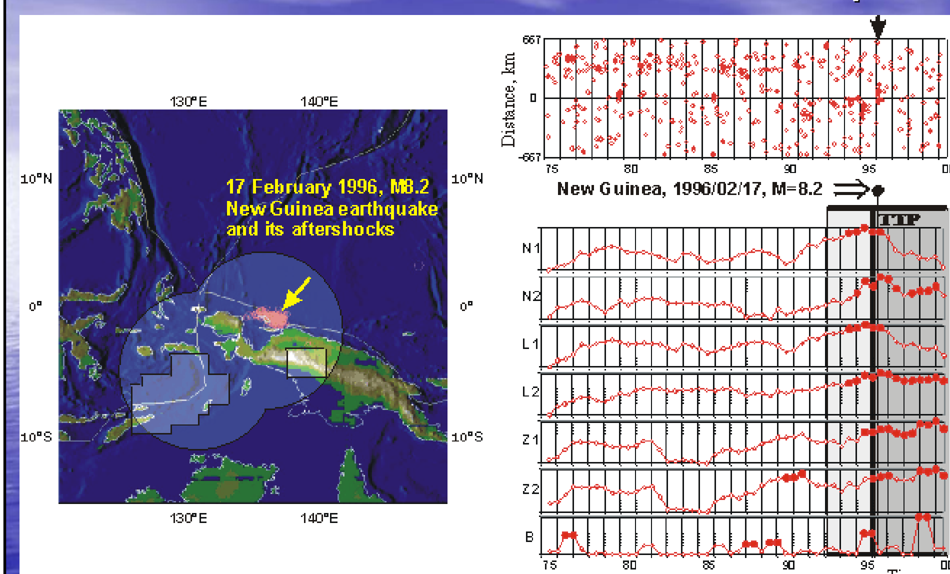
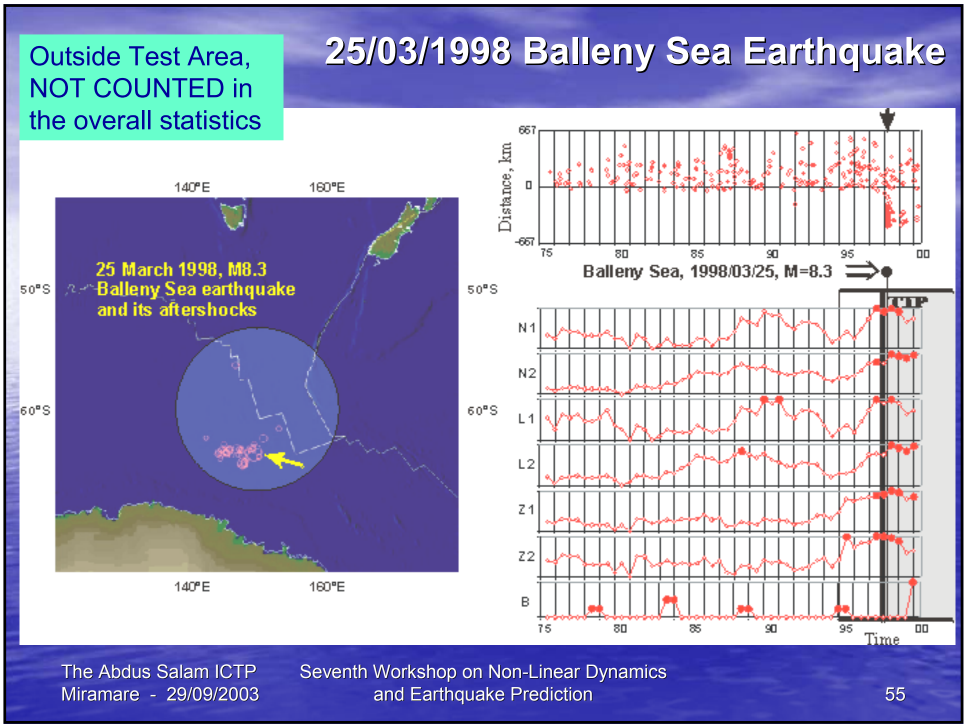
03/12/1995 Iturup Earthquake



17/02/1996 New Guinea Earthquake




Outside Test Area, NOT COUNTED in the overall statistics
25/03/1998 Balleny Sea Earthquake
25 March 1998, M8.3
Balleny Sea earthquake
and its aftershocks
Distance, km
Balleny Sea, 1998/03/25, M=8.3
TIP
N1
N2
L1
L2
Z1
Z2
B
Time
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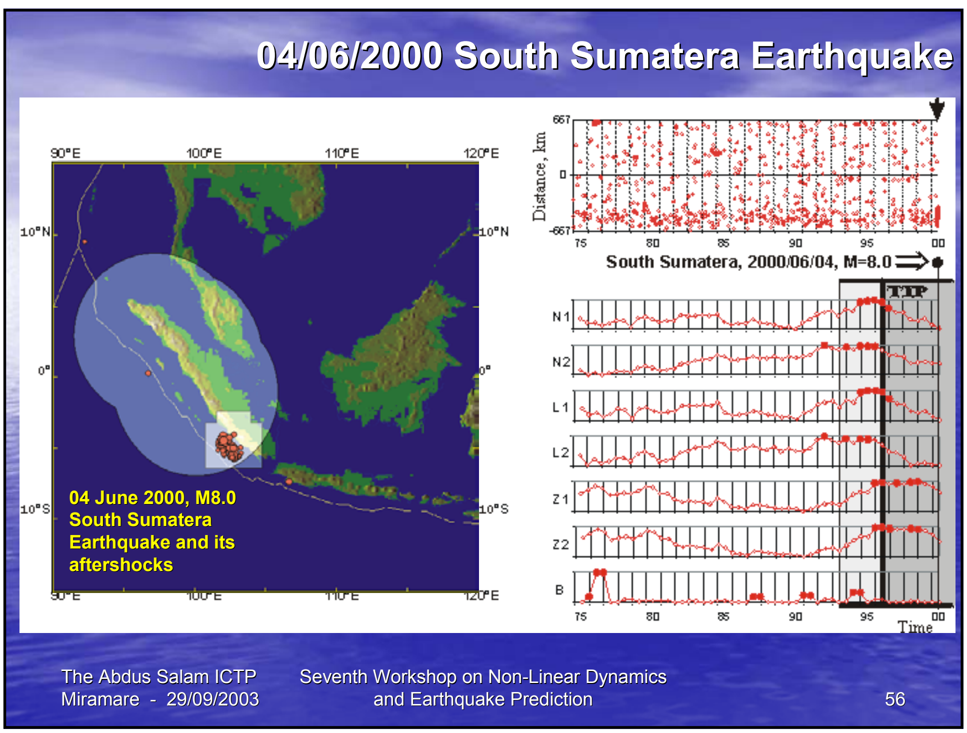
04/06/2000 South Sumatera Earthquake
04 June 2000, M8.0
South Sumatera
Earthquake and its
aftershocks
Distance, km
South Sumatera, 2000/06/04, M=8.0
TIP
N1
N2
L1
L2
Z1
Z2
B
Time
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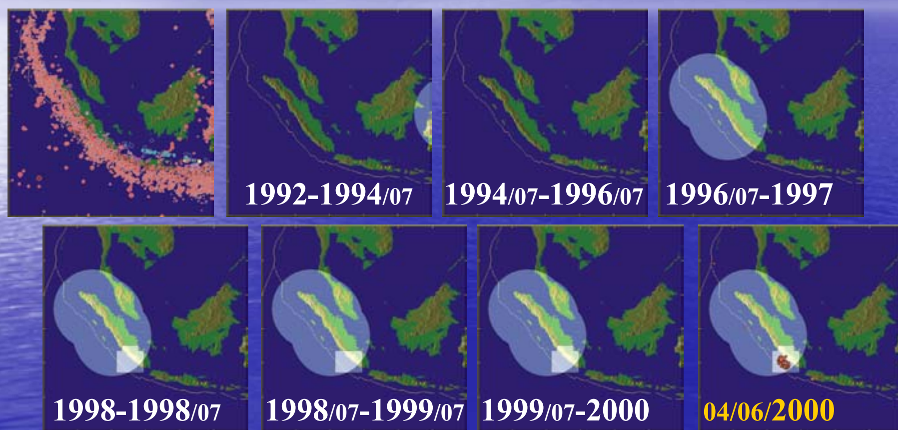
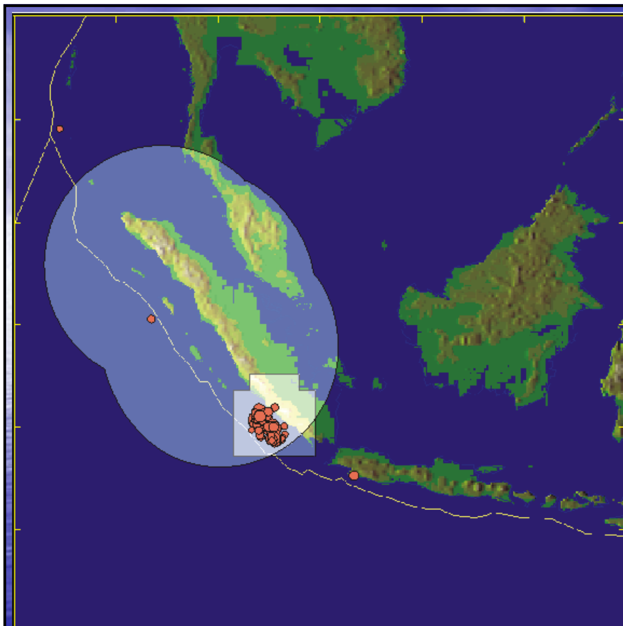
Case history of the South Sumatera Earthquake



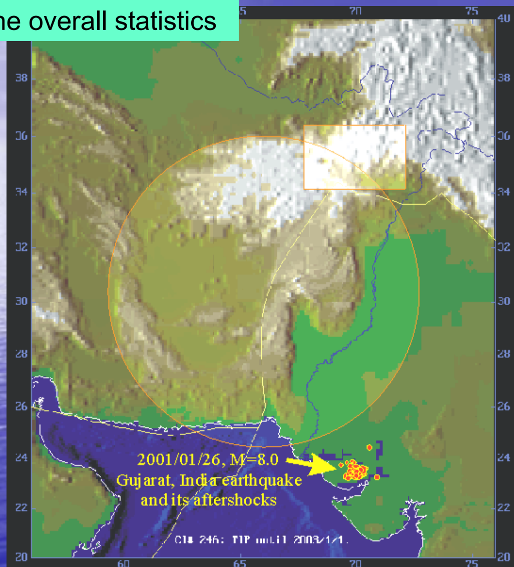


Seismic events that big were reported in the Indian Ocean subduction zones only twice in the 20th century: These are the 1941 Andaman, Ms8.1 and the 1977 Sumbawa, Ms8.0 earthquakes.

This implies local probability gain of more than 20

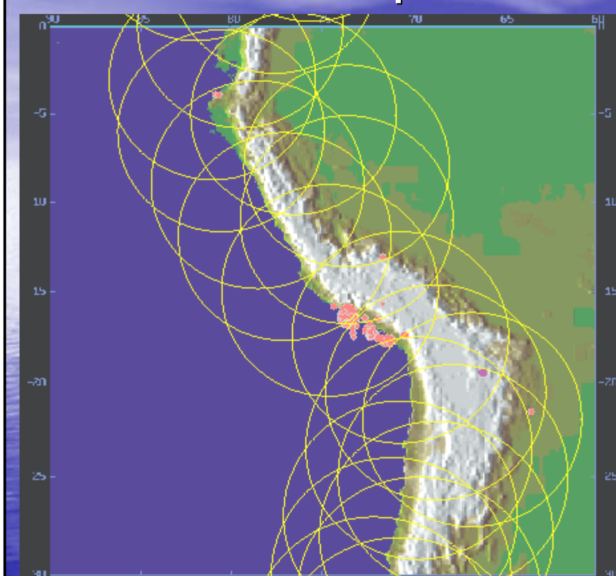
Outside Test Area, NOT COUNTED in the overall statistics

01/2001 Gujarat, India earthquake



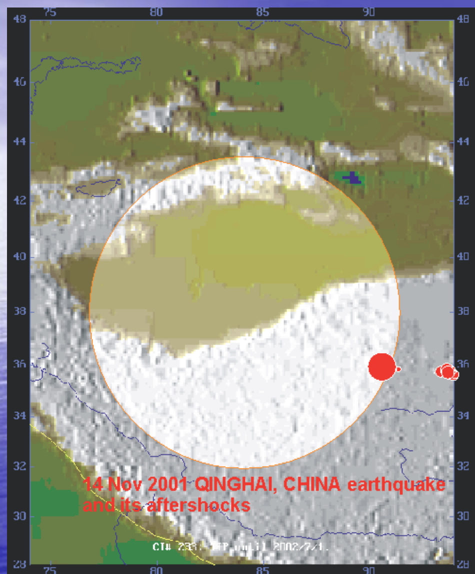
The 26 Jan 2001 Gujarat, India earthquake is just outside the area, where the NEIC data permits to run the original version of the M8 algorithm. Note that one of the circles, nearest to the epicenter of the 2001 Gujarat earthquake was in state of alarm, although the MSc predicts an opposite side of it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

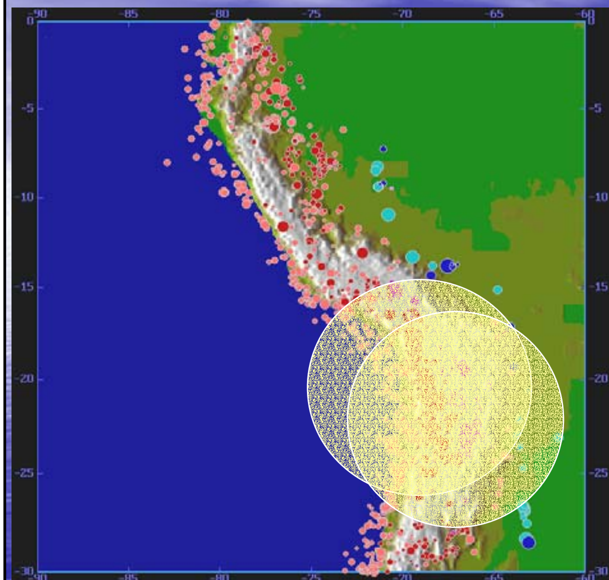
The nearest magnitude 8.0+ earthquake happened on November 18, 1951 near Lhasa, Xizang (Tibet) 375 miles (600 km) south of the November 14, 2001 epicenter.

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

Although the M8-MSc predictions are intermediate-term middle-range and by no means imply any "red alert", some colleagues have expressed a legitimate concern about maintaining necessary confidentiality. Therefore, the up-to-date predictions are not shown here, although available on web-pages of restricted access provided to about 125 members of the Mailing List.

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

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.

How to estimate the effectiveness of predictions?

The simple recipe has a nice analogy that justifies using statistical tools available for centuries, since *Blaise Pascal* (1623-1662).

Seismic Roulette

Consider a roulette wheel with as many sectors as the number of events in a sample catalog, a sector per each event.

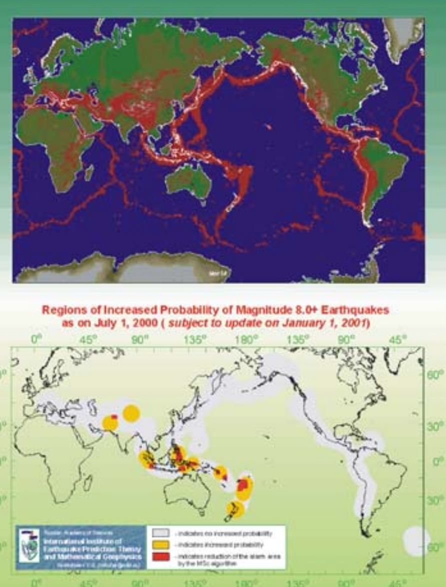
- Make your bet according to prediction: determine, which events are inside area of alarm, and put one chip in each of the corresponding sectors.
- Nature turns the wheel.
- If seismic roulette is not perfect…

then ***systematically*** you can win! ☺

and lose … ☹

If you are smart enough and your predictions are effective ------ the first will outscore the second! ☺ ☺ ☹ ☺ ☺ ☺ ☹ ☺ ☺ ☺

Seismic Roulette



Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 8.0 or more.

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	11	9	7	34.9	18.0	99.80	99.90
1992-present	9	7	5	30.2	15.3	99.55	99.39

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 four failures-to-predict in a row.

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Catalogs make possible to study systematically seismic cascades

- Earthquakes evidently cascade into aftershocks that re-adjust the hierarchical system of blocks-and-faults in the locality of the main shock rupture.
- Systematic analysis shows less evident inverse cascade in seismic activity prior to the recent greatest earthquakes.

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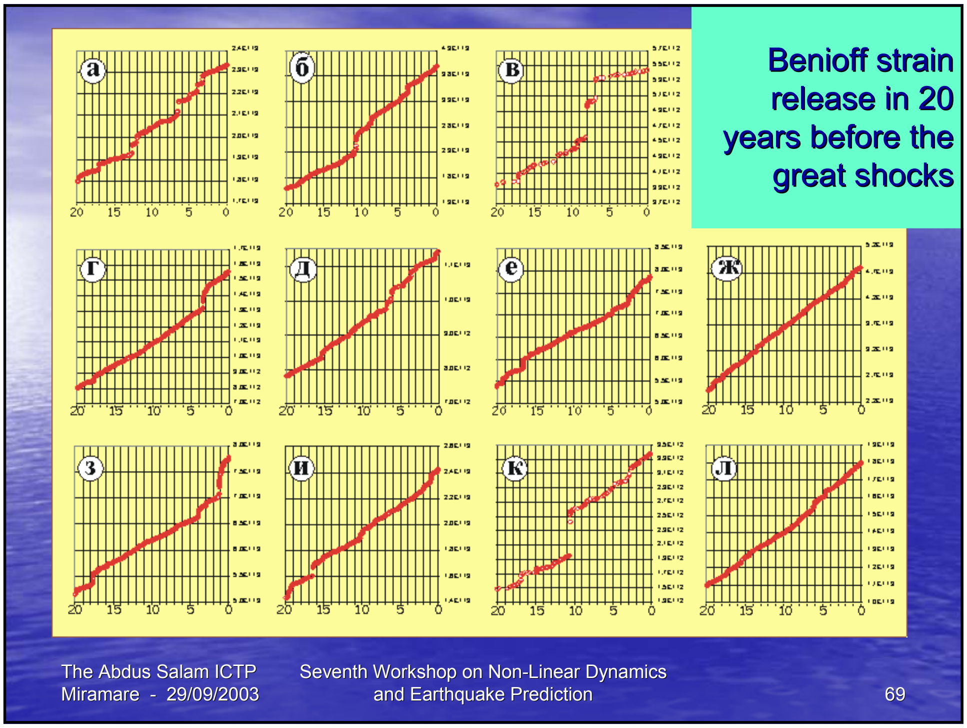
Benioff strain release in 20 years before the great shocks
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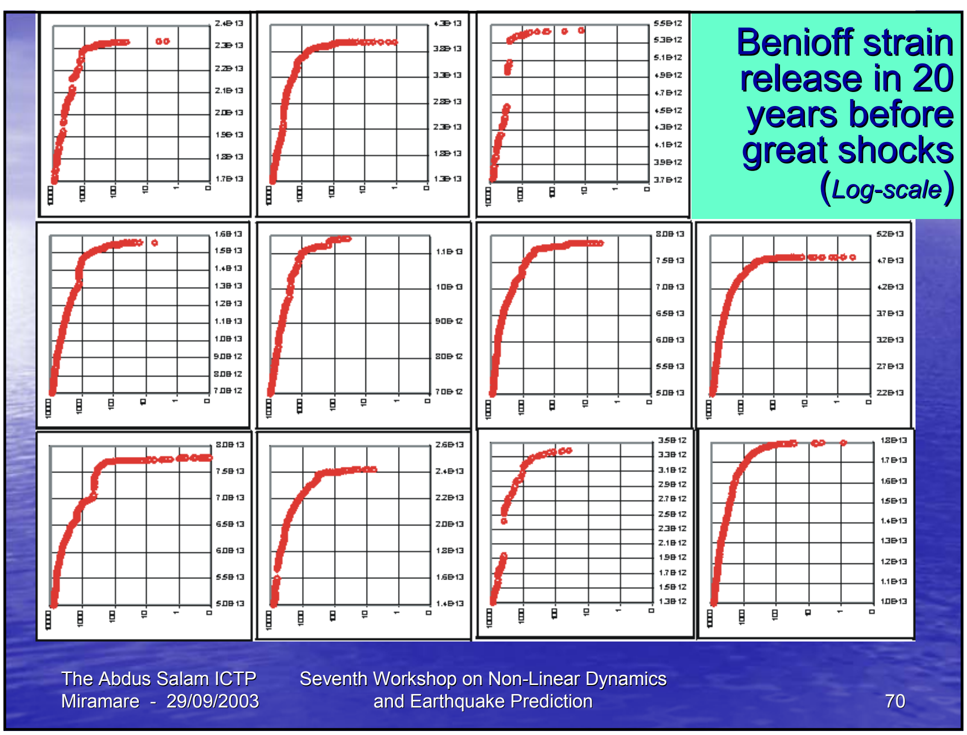
Benioff strain release in 20 years before great shocks
(Log-scale)
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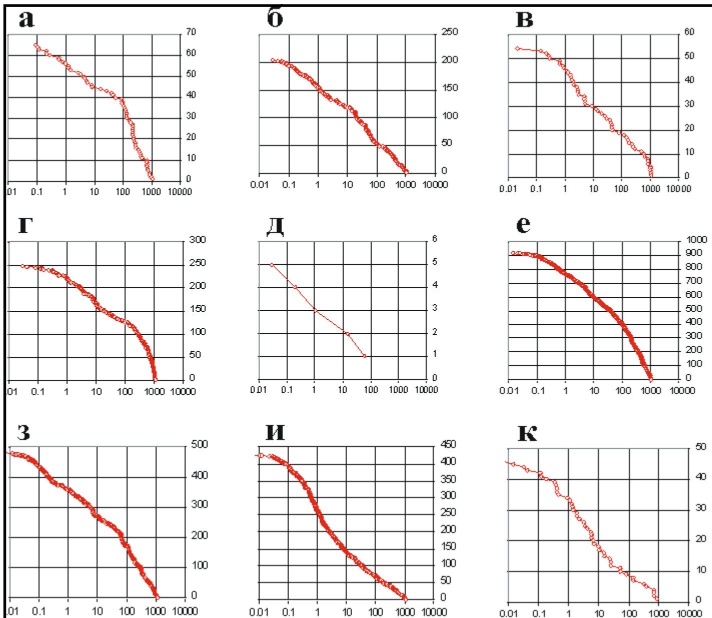
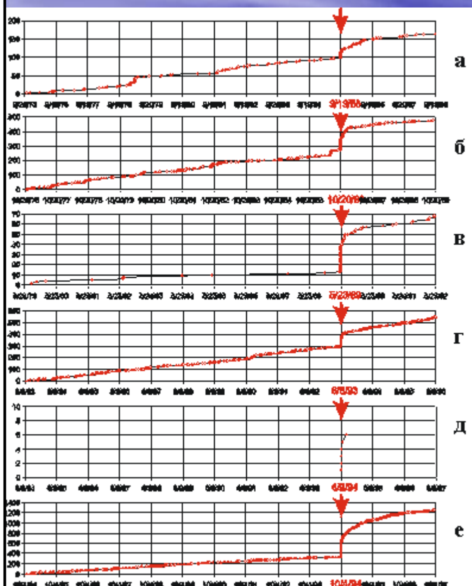
Aftershock sequences of the great shocks

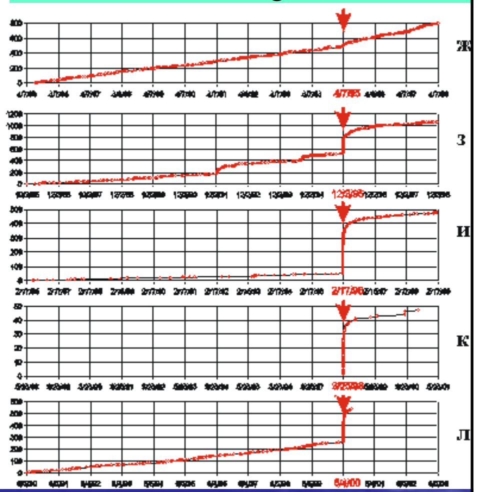


Combination of inverse and direct seismic cascades

- Apparently display phase transition of the system of blocks-and-faults from one steady stable seismic regime to another one.

Activity in 10 years before + 3 years after the great shocks





Aftershock sequences of the great shocks (*summary*)

Date	Number 100 days	Number 3 years	Aftershocks decay 100 d	Aftershocks decay 3 y	Relaxation time, years
1985/09/19	29	65	Omori Law	Modified OL 3	284 days
1986/10/20	151	205	Modified OL 3	Modified OL 3	100 days, =1.5
1989/05/23	36	54	Omori Law	Modified OL 2	1.3 years, >3
1993/08/08	121	247	Modified OL 2	Modified OL 3	65 days, >1.5
1994/06/09	5	5	Modified OL 2	-	-
1994/10/04	515	919	Modified OL 2	Modified OL 3	2 years, >2.5
1995/04/07	52	302	Modified OL 2	Modified OL 2	14 days, >2
1995/12/03	311	483	Modified OL 2	Modified OL 3	1 year
1996/02/17	357	427	Modified OL 2	Modified OL 2	2 years, >2.5
1998/03/25	38	46*	Omori Law	Modified OL 2	140 days
2000/06/04	278	278*	Modified OL 2	*	*

Conclusions

- We have no luxury of postponing usage of the existing earthquake catalogs to the benefit of population living in seismic regions.
- Catalogs evidence consecutive stages of inverse cascading of earthquakes to main shock and direct cascading of aftershocks.
- The first may reflect coalescence of instabilities at the approach, while the second may indicate readjustment of a complex system of blocks-and-faults in a new state after a catastrophe.

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