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What do we know about earthquakes and their sequences?

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Outline

- What are earthquakes and how to size them?
- How to get basic information on earthquakes?
- Uncertainties and Catalog errors
- Unified Scaling Law for Earthquakes
- 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 a reliable description.

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?

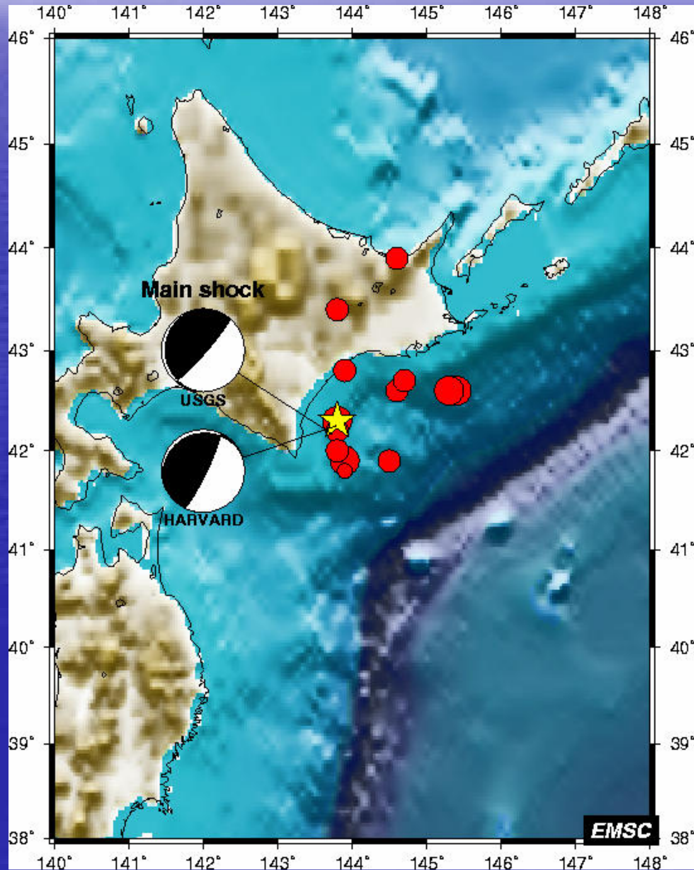
How to size earthquakes?

Why, Where and When do earthquakes occur?

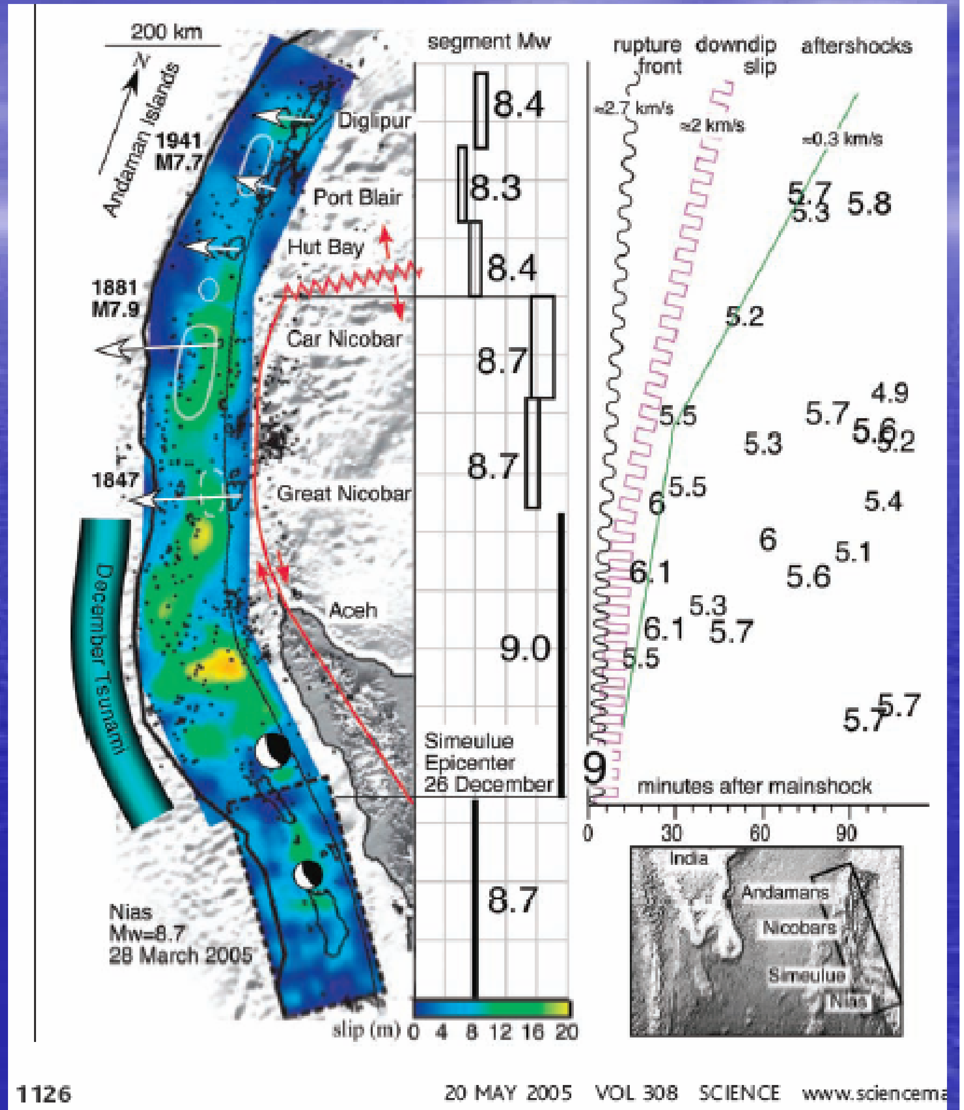
The basic difficulty in answering these questions comes from the fact that no earthquake has been ever observed directly.

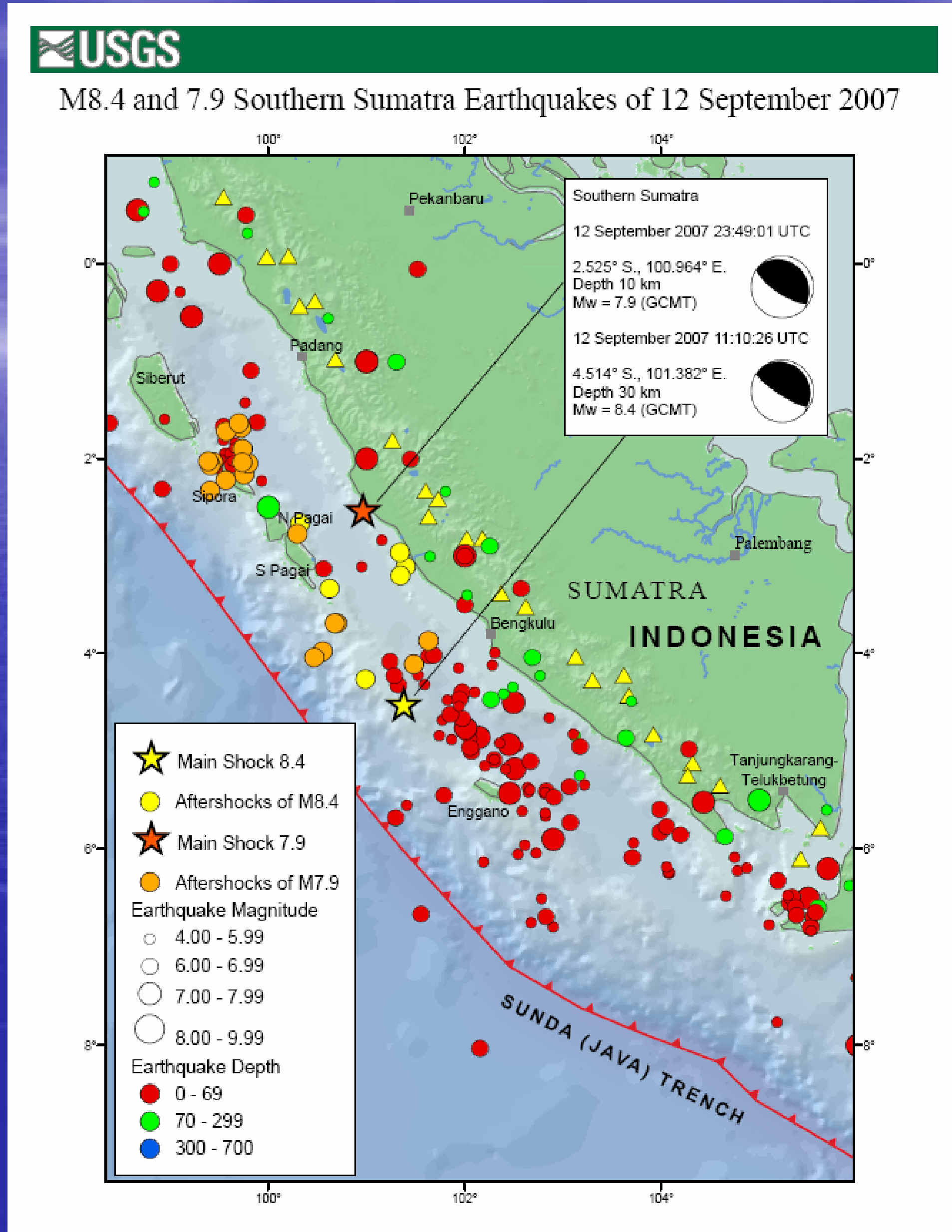
September 25, 2003, HOKKAIDO, JAPAN, Mw=8.3

2003年9月26日　北海道十勝沖地震特集



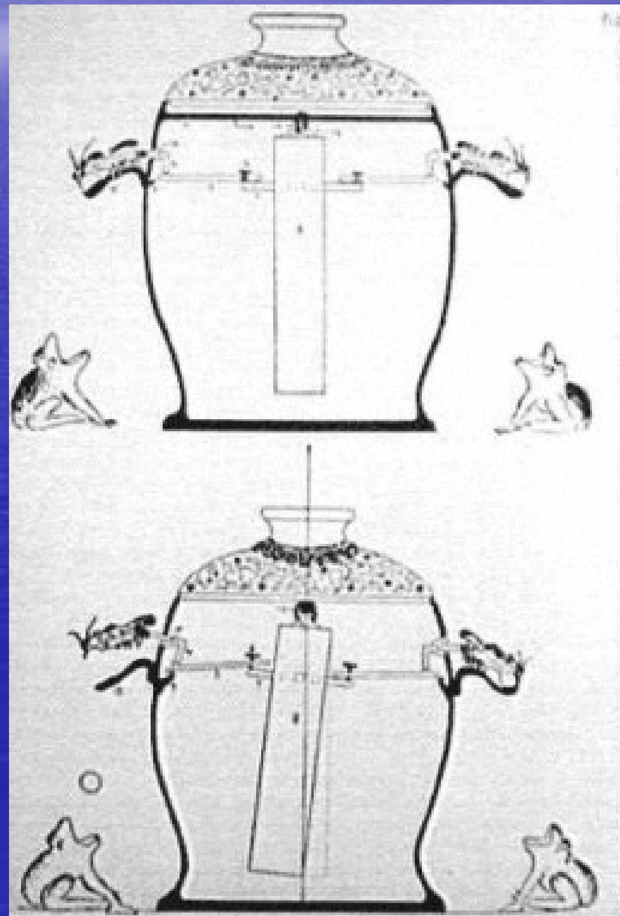
December 26, 2004, Sumatra-Andaman, Mw=9.3




USGS
M8.4 and 7.9 Southern Sumatra Earthquakes of 12 September 2007
Southern Sumatra
12 September 2007 23:49:01 UTC
2.525° S., 100.964° E.
Depth 10 km
Mw = 7.9 (GCMT)
12 September 2007 11:10:26 UTC
4.514° S., 101.382° E.
Depth 30 km
Mw = 8.4 (GCMT)
Pekanbaru
Padang
Siberut
Sipora
N Pagai
S Pagai
Bengkulu
Palembang
SUMATRA
INDONESIA
Enggano
Tanjungkarang-Telukbetung
SUNDA (JAVA) TRENCH
Main Shock 8.4
Aftershocks of M8.4
Main Shock 7.9
Aftershocks of M7.9
Earthquake Magnitude
4.00 - 5.99
6.00 - 6.99
7.00 - 7.99
8.00 - 9.99
Earthquake Depth
0 - 69
70 - 299
300 - 700
100°
102°
104°
0°
2°
4°
6°
8°

How to get info about earthquakes?

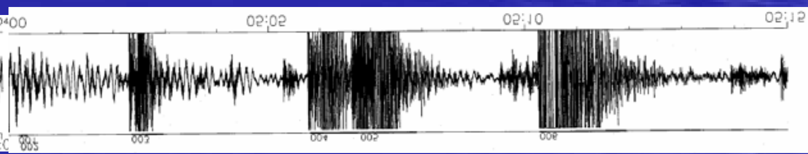
Chinese scientists created the first earthquake detector 2000 years ago



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 $\langle d \rangle$ 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),

1.0×10^{30} dyn·cm for the 2004 Sumatra-Andaman earthquake (M_S8.8; M_W9.3),

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 in 2004)

- Find the known Internet type connections where original seismic data or seismic research information is available at http://www.geophys.washington.edu/seismosurfing.html

The US GS/NEIC Global Hypocenter Data Base

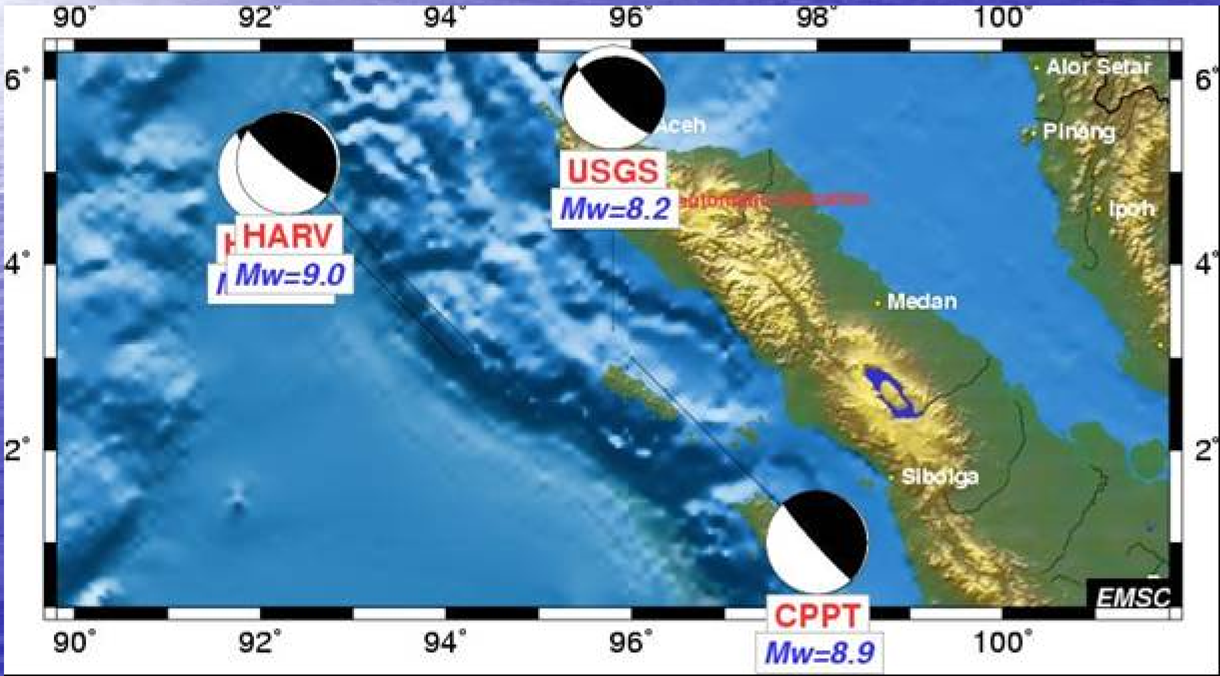
This database available from the US Geological Survey / National Earthquake Information Center at Denver, Colorado. It consists of the data on CD-ROM and its updates with Preliminary Determinations of Epicenters, PDE-monthly and PDE-weekly, and Quick Earthquake Determinations, QED.

P.N. Shebalin, using pattern recognition technique merged more than forty source catalogs of the NEIC GHDB into a composite one.

We shall use the updated version of this composite catalog in course the computer exercises of the Workshop.

The first determinations by USGS Earthquake Hazards Program: 26 December 2004 Sumatra-Andaman earthquake

Because of the size (M 9.0) of this earthquake, point-source methods that use only the body-wave portion of the seismogram are inadequate for measuring the true magnitude.




```
04/12/26 00:58:50.76
OFF W COAST OF NORTHERN SUMATRA
Epicenter:   3.298   95.778
MW 8.2

USGS MOMENT TENSOR SOLUTION
Depth   7           No. of sta: 31
Moment Tensor;    Scale 10**21 Nm
  Mrr= 0.91         Mtt=-0.89
  Mff=-0.02         Mrt= 1.78
  Mrf=-1.55         Mtf= 0.47
 Principal axes:
  T  Val=  2.53   Plg=55   Azm= 50
  N        0.09       8       308
  P       -2.61      34       213

Best Double Couple:Mo=2.6*10**21
 NP1:Strike=274 Dip=13 Slip=  55
 NP2:       130     79        98

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            -----------------
          ---#############----
        --####################---
      ##-########################--
     #----########################--
     -------############   ########-
    ---------########### T #########-
    -----------#########   ##########
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    ---------------##################
    ------------------###############
     -------------------############
     --------   -----------#########
      ------- P -------------#####
        -----   ----------------
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```

"This is a REVISED solution for today's earthquake near Sumatra. The solution includes approximately the first 9 hours of data recorded after the earthquake. Owing to the large size of the earthquake, the short-period cutoff for the analysis was set to 300 s. December 26, 2004, OFF W COAST OF NORTHERN SUMATRA, MW=9.0"

(Meredith Nettles, Goran Ekstrom)

```
CENTROID, MOMENT TENSOR SOLUTION
HARVARD EVENT-FILE NAME M122604A
DATA USED: GSN
MANTLE WAVES:    73S,202C, T=300
CENTROID LOCATION:
ORIGIN TIME       01:01: 9.0 0.3
LAT  3.09N 0.04;LON  94.26E 0.03
DEP  28.6 1.3;HALF-DURATION 95.0
MOMENT TENSOR; SCALE 10**29 D-CM
  MRR= 1.04 0.01; MTT=-0.43 0.01
  MPP=-0.61 0.01; MRT= 2.98 0.16
  MRP=-2.40 0.16; MTP= 0.43 0.00
 PRINCIPAL AXES:
 1.(T) VAL=  4.01;PLG=52;AZM= 36
 2.(N)      -0.12;    3;    130
 3.(P)      -3.89;   38;    222
BEST DOUBLE COUPLE:M0=4.0*10**29
 NP1:STRIKE=329;DIP= 8;SLIP= 110
 NP2:STRIKE=129;DIP=83;SLIP=  87

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       #################--
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  -------    ------------########-
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    -----   ------------------
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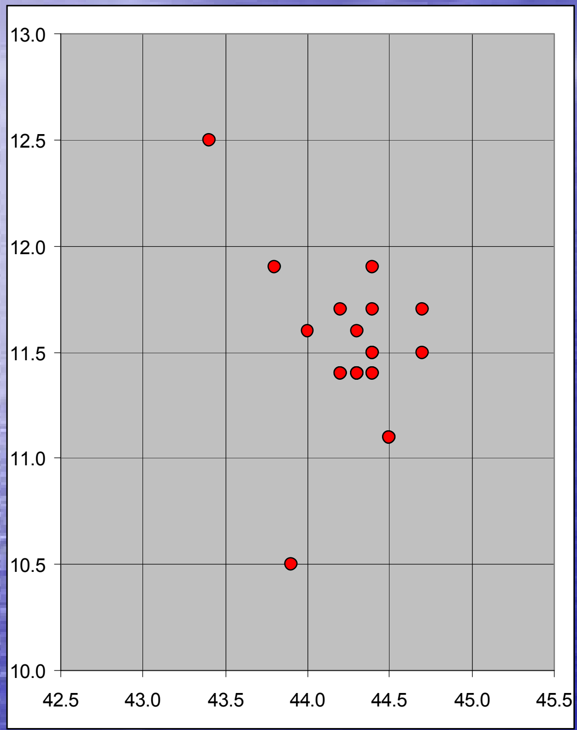
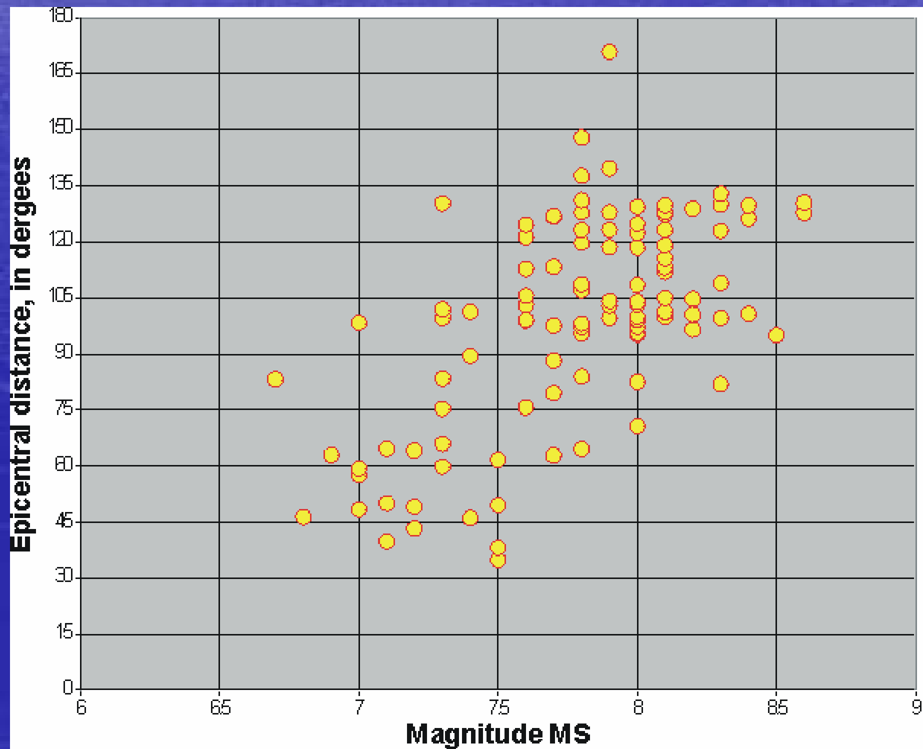
Uncertainties and errors



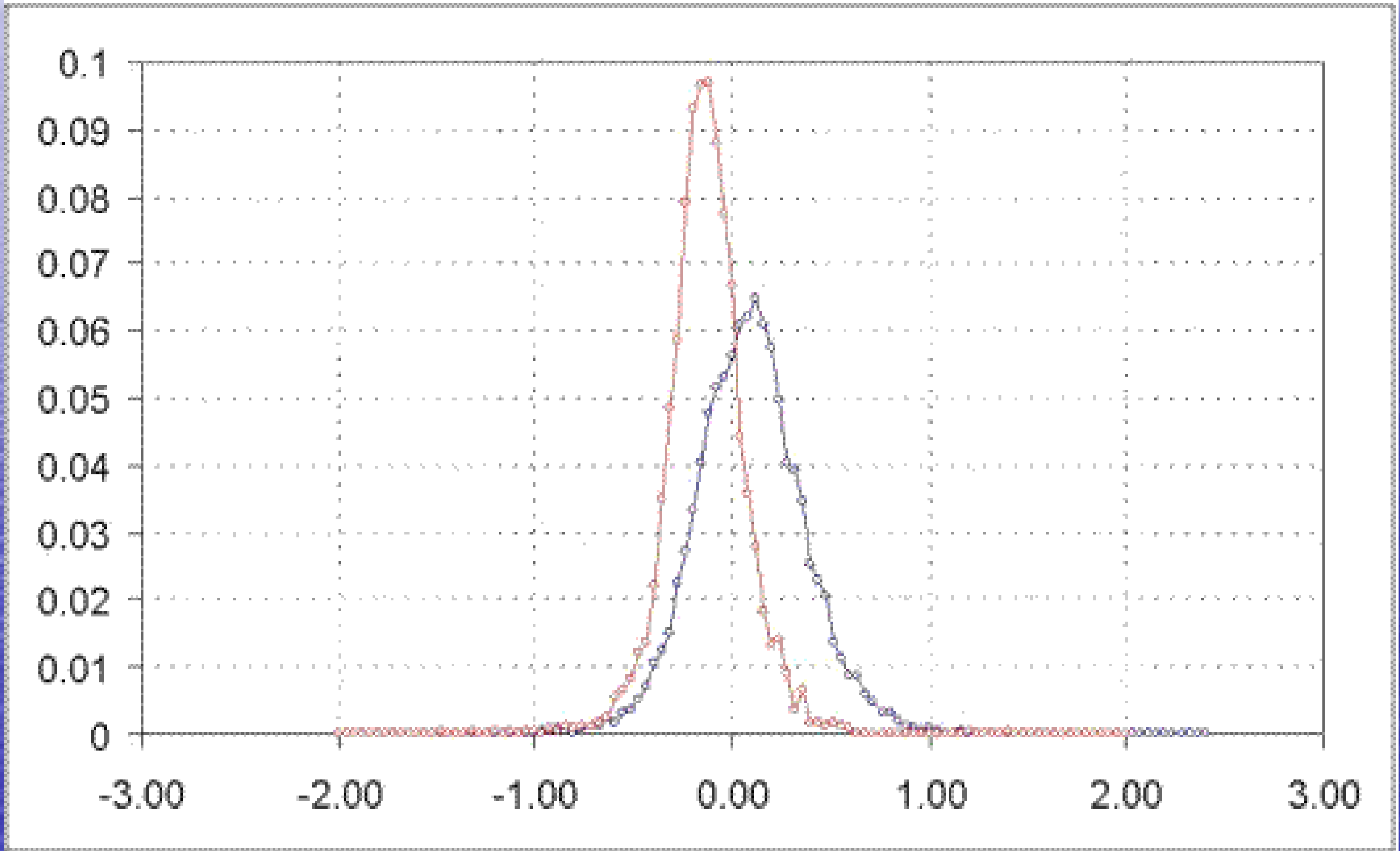
Fast determinations of the epicenter for the 14 September 2003 earthquake in Northern Italy by different seismological agencies to European-Mediterranean Seismological Centre (EMSC)

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

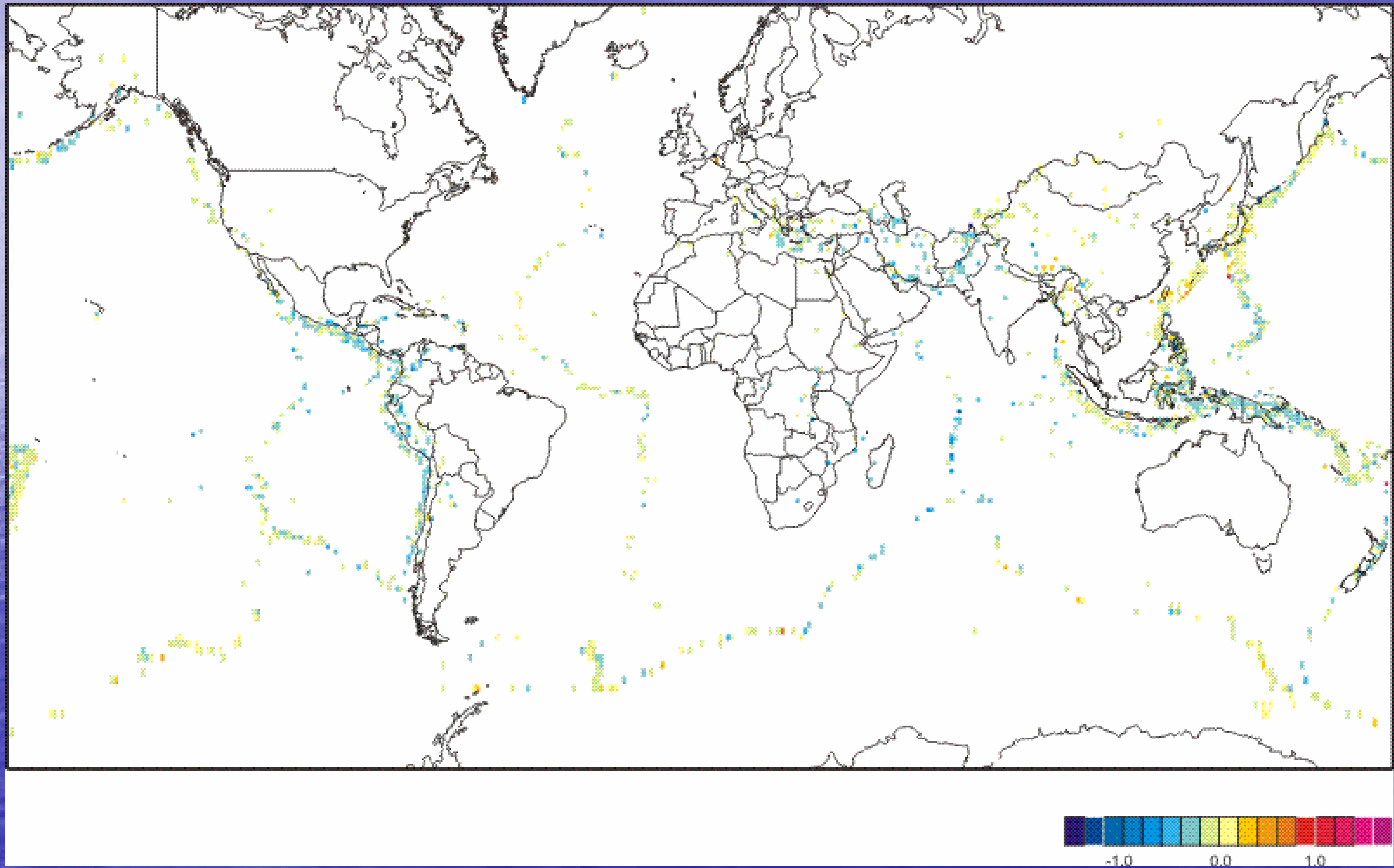


The distribution of the difference between average magnitudes in epicenter and antipodal hemispheres

(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).



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"

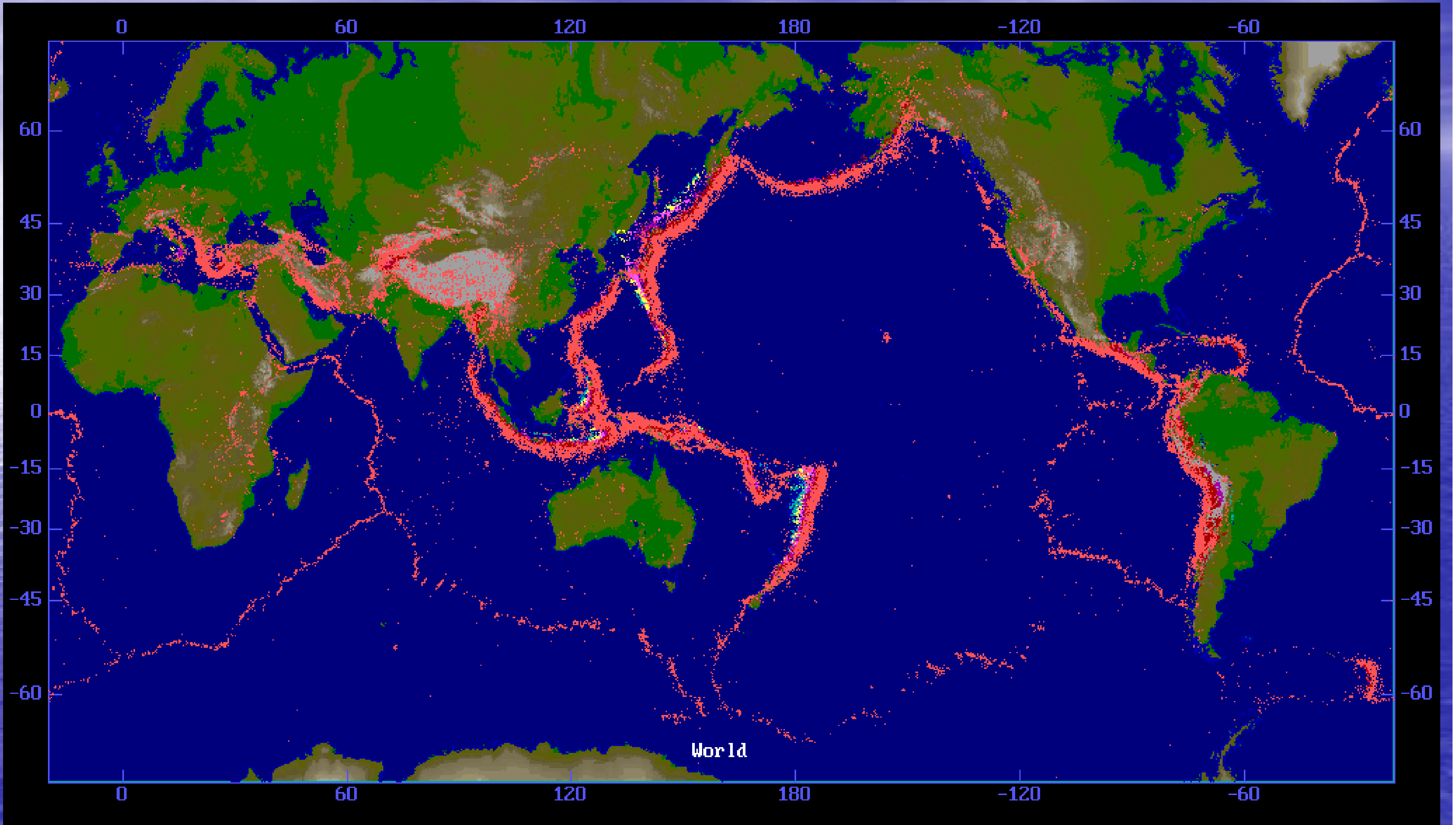
N.Krylov, famous Russian mathematician

What can we learn from a catalog of earthquakes?

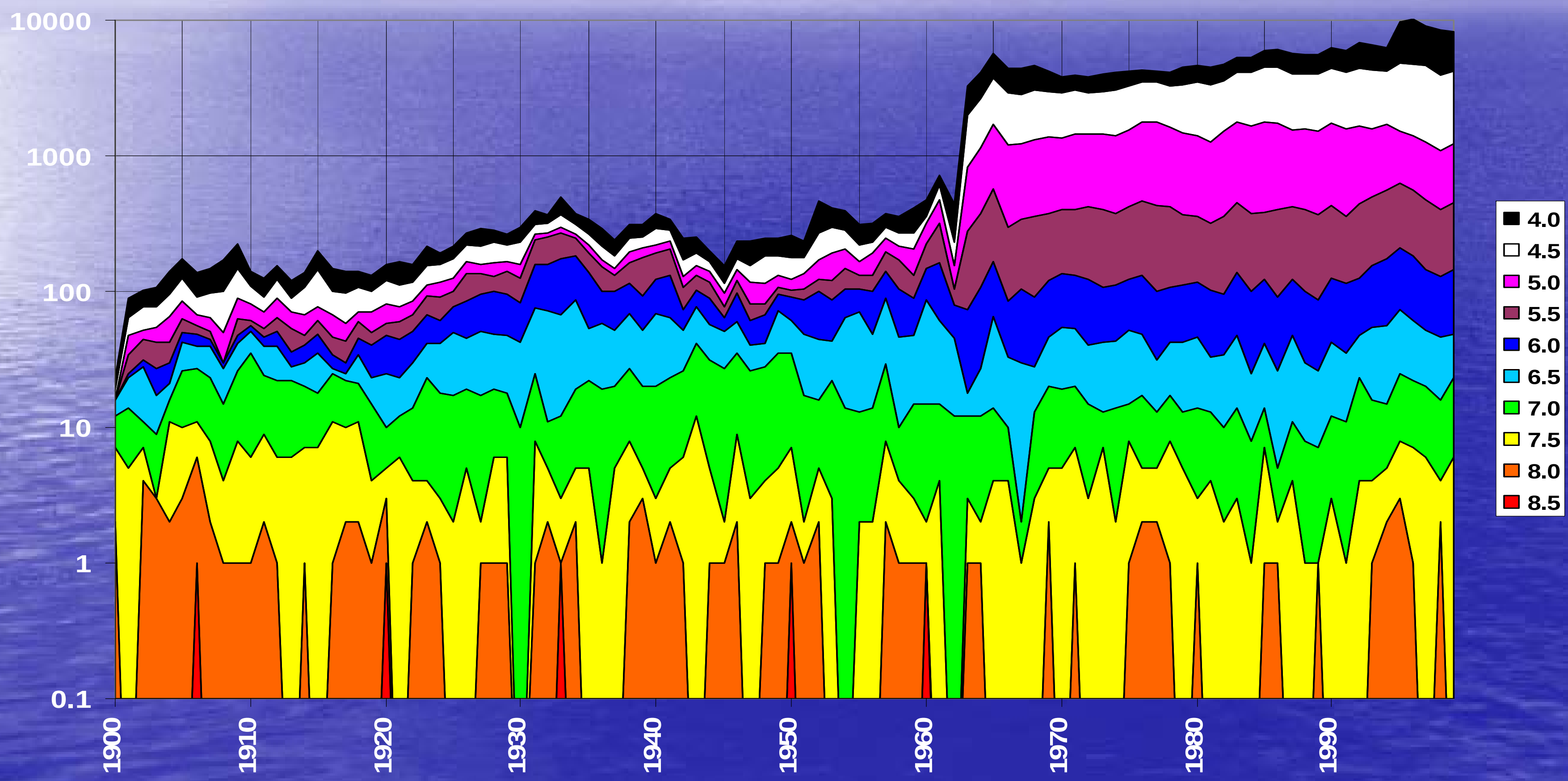
There are two extreme opinions on the subject –

- *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.

Distribution of earthquakes in Space

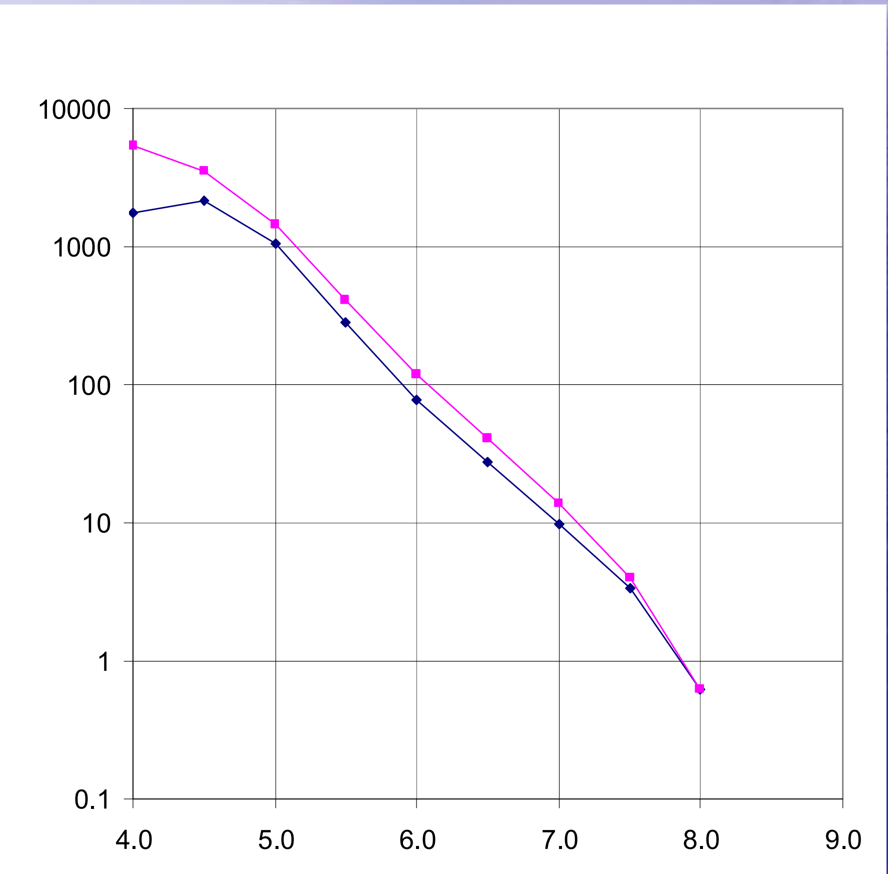


Distribution of earthquakes in Time:
Global Number of Earthquakes vs. Time



Distribution of earthquake size:

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.

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 a seismic prone area of linear dimension L.

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

A simple box counting method tested successfully on artificial catalogs with prefixed A, B, and C, then applied to a dozen of selected seismic regions from the hemispheres of the Earth (*global scale*) down to a certain intersection of seismically active faults (*local scale*).

12 KOSOBOKOV AND MAZHKENOV: SIMILARITY IN SPATIAL DISTRIBUTION OF SEISMICITY

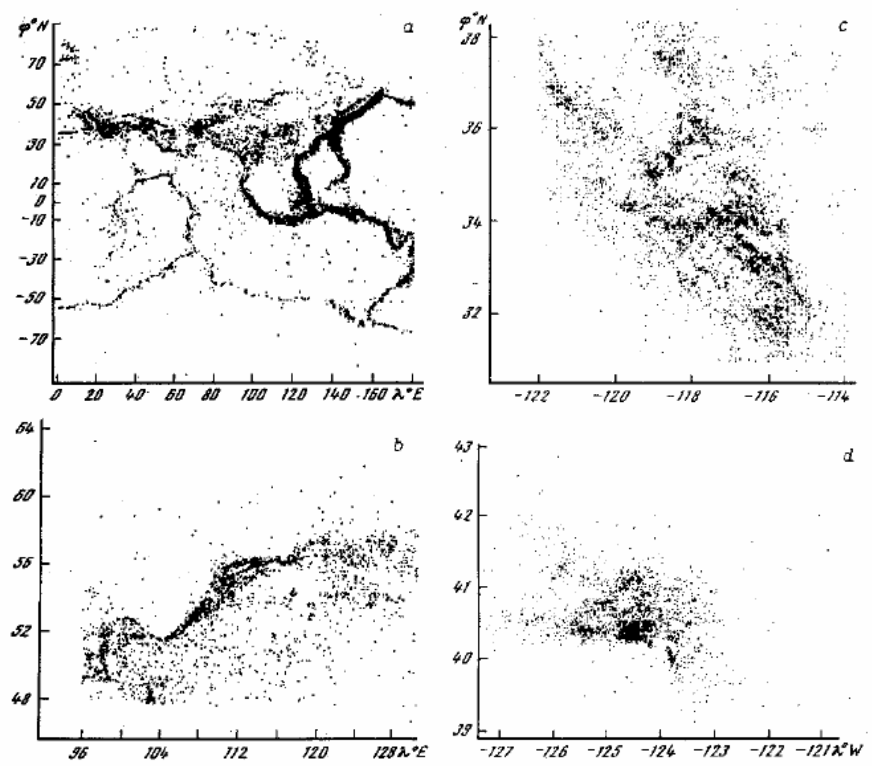


Fig. 2. Examples of spatial distribution of epicenters from catalogs of mainshocks. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

14 KOSOBOKOV AND MAZHKENOV: SIMILARITY IN SPATIAL DISTRIBUTION OF SEISMICITY

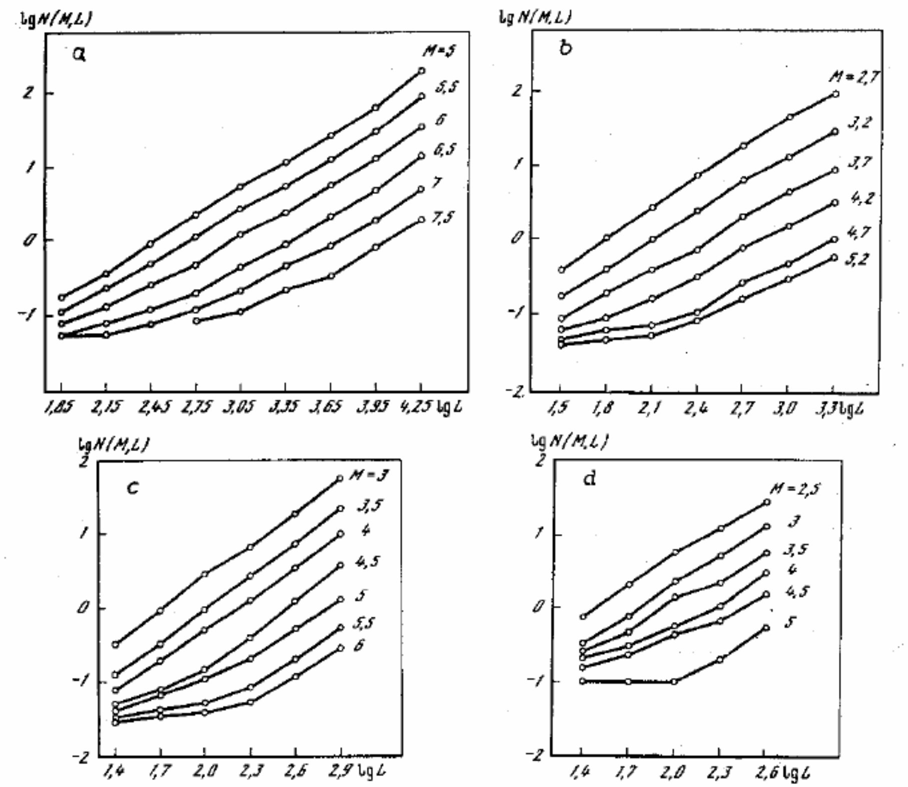
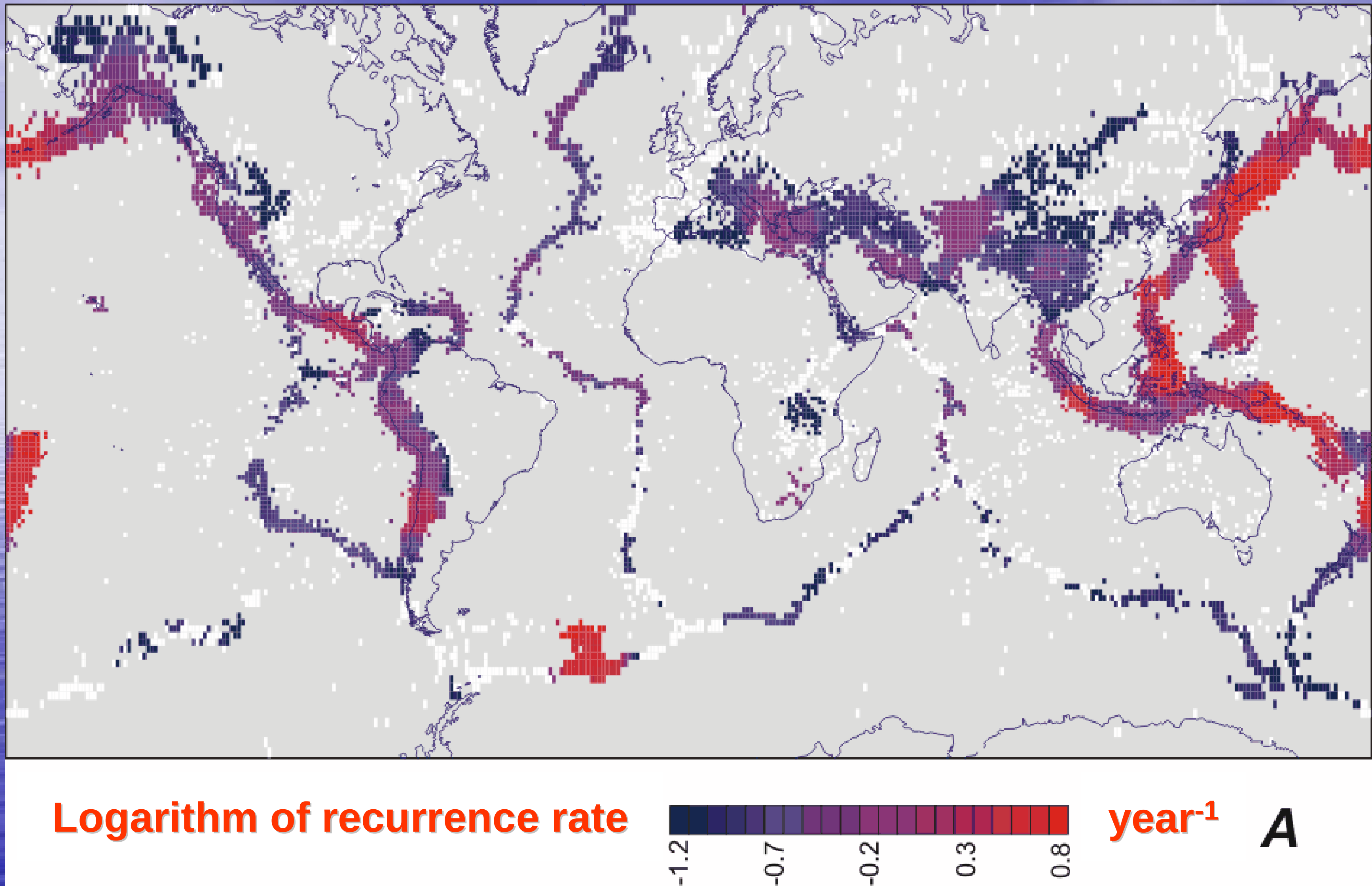
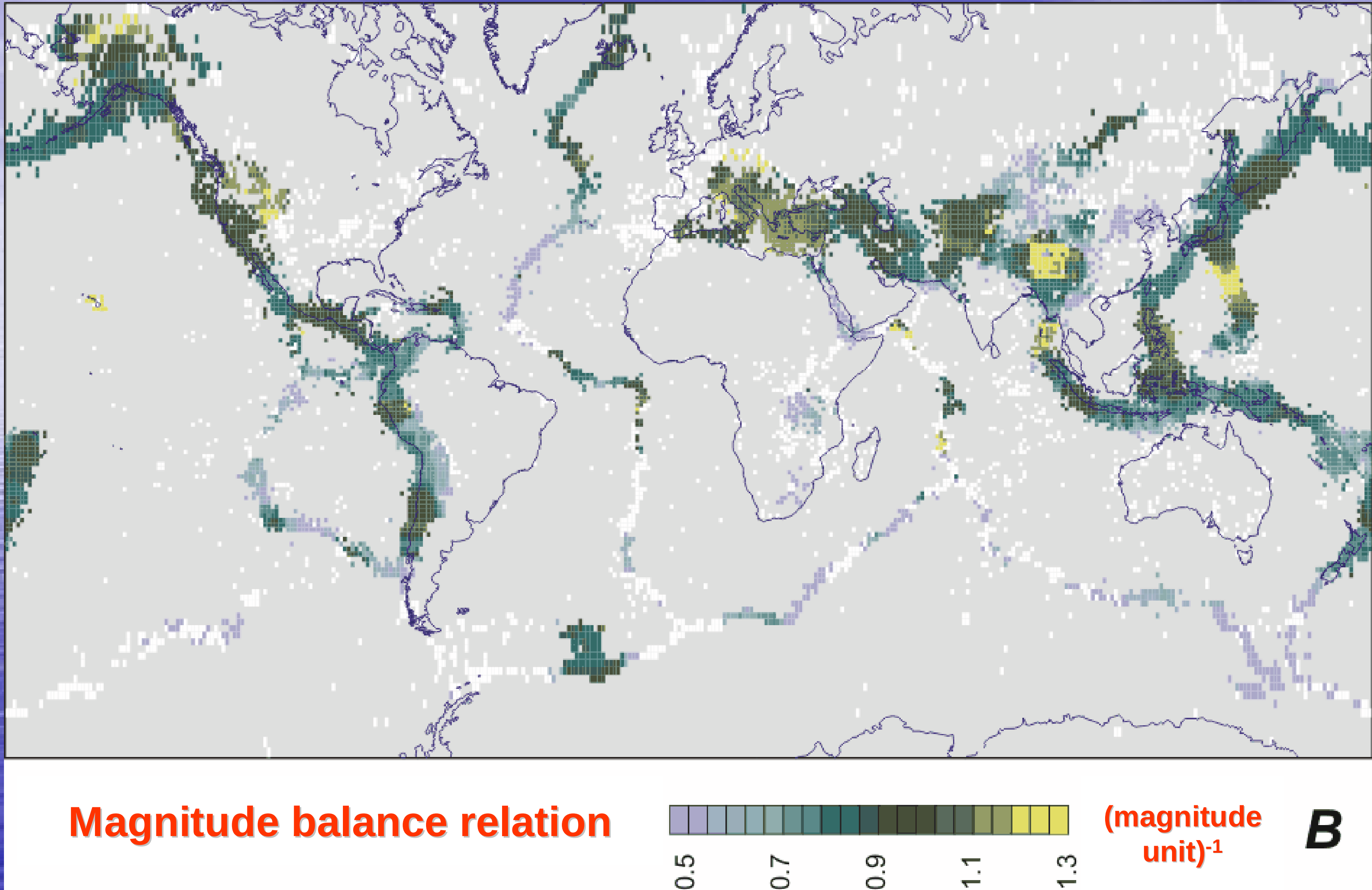


Fig. 3. Examples of log $N(M, L)$ graphs. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

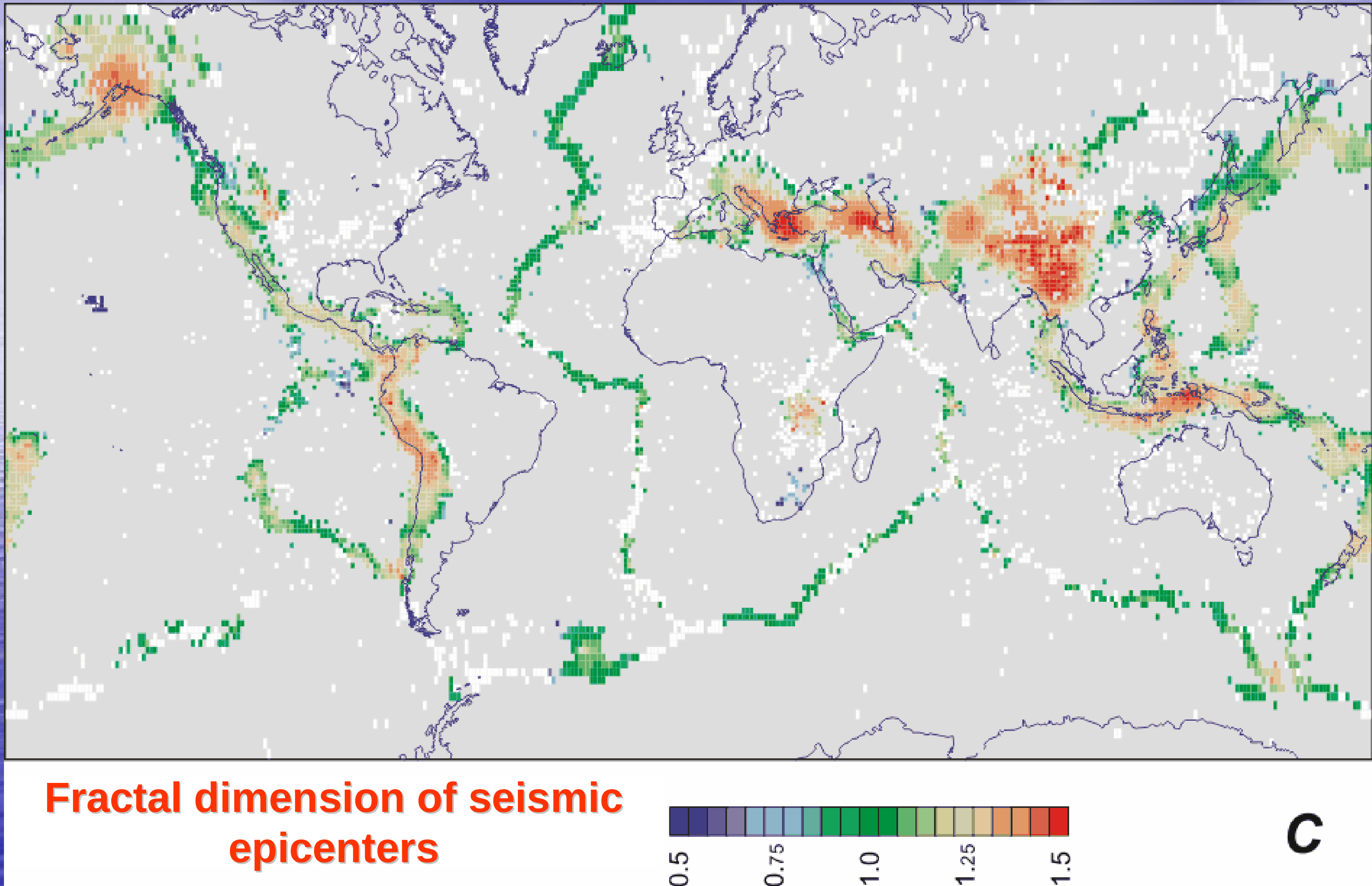
The Global Seismic Hazard map: Coefficient A



The Global Seismic Hazard map: Coefficient B

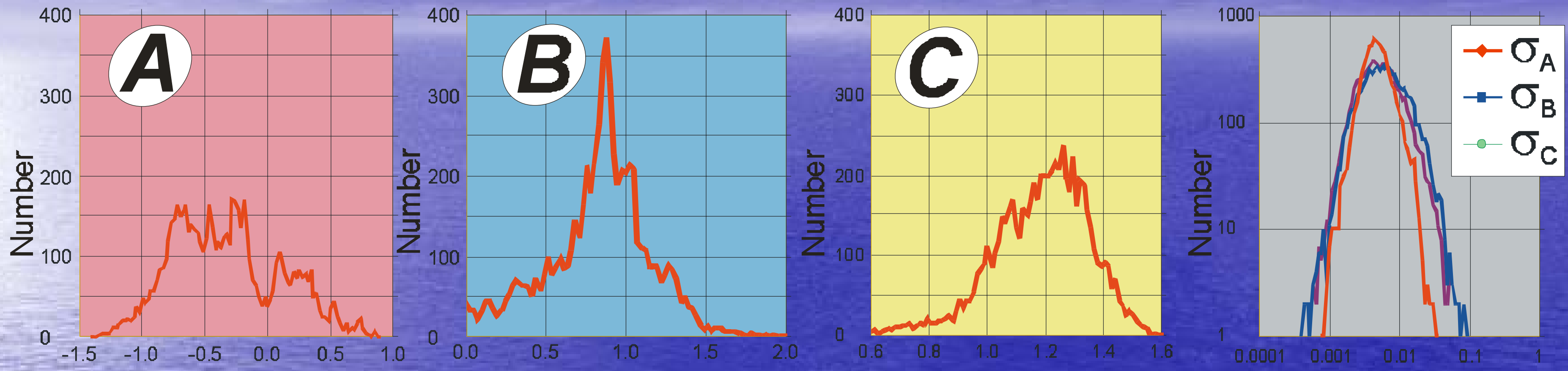


The Global Seismic Hazard map: Coefficient C



Fractal dimension of seismic epicenters

Histograms of A, B, C and σ's



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

Thus, confirming the Unified Scaling Law for earthquakes.

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.

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

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

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

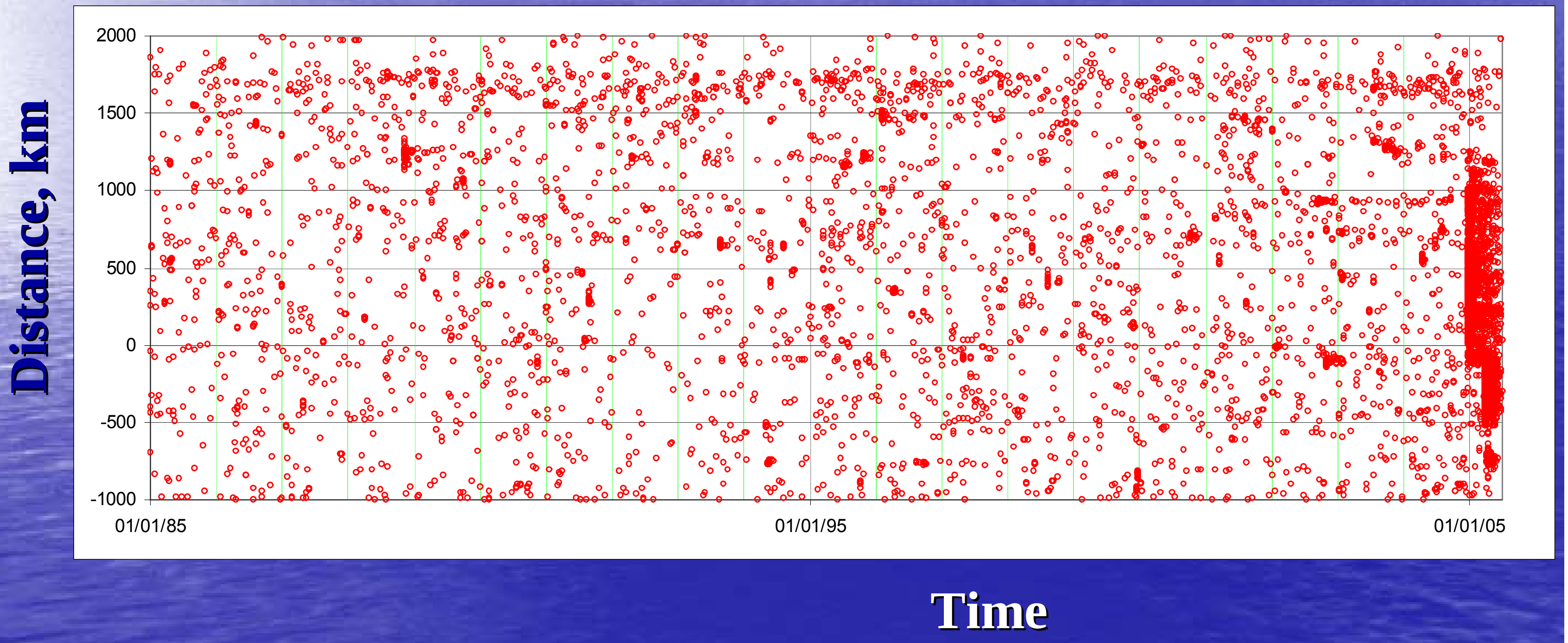
- imply a traditional assessment of recurrence of a large earthquake in Los Angeles, i.e., an area with L about 40 km, from data on the entire southern California, i.e., an area with L about 400 km, being underestimated by a factor of

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

Similarly, underestimation is about a factor of 8 for Petropavlovsk (Kamchatka; A = 0.12, B = 0.86, C =1.26, σ_{total} = 0.04), about a factor of 10 for Irkutsk (Lake Baikal; A = -1.51, B = 0.88, C =1.38, σ_{total} = 0.03), etc.

Distribution of earthquakes in Space and Time:

Sumatra-Andaman region



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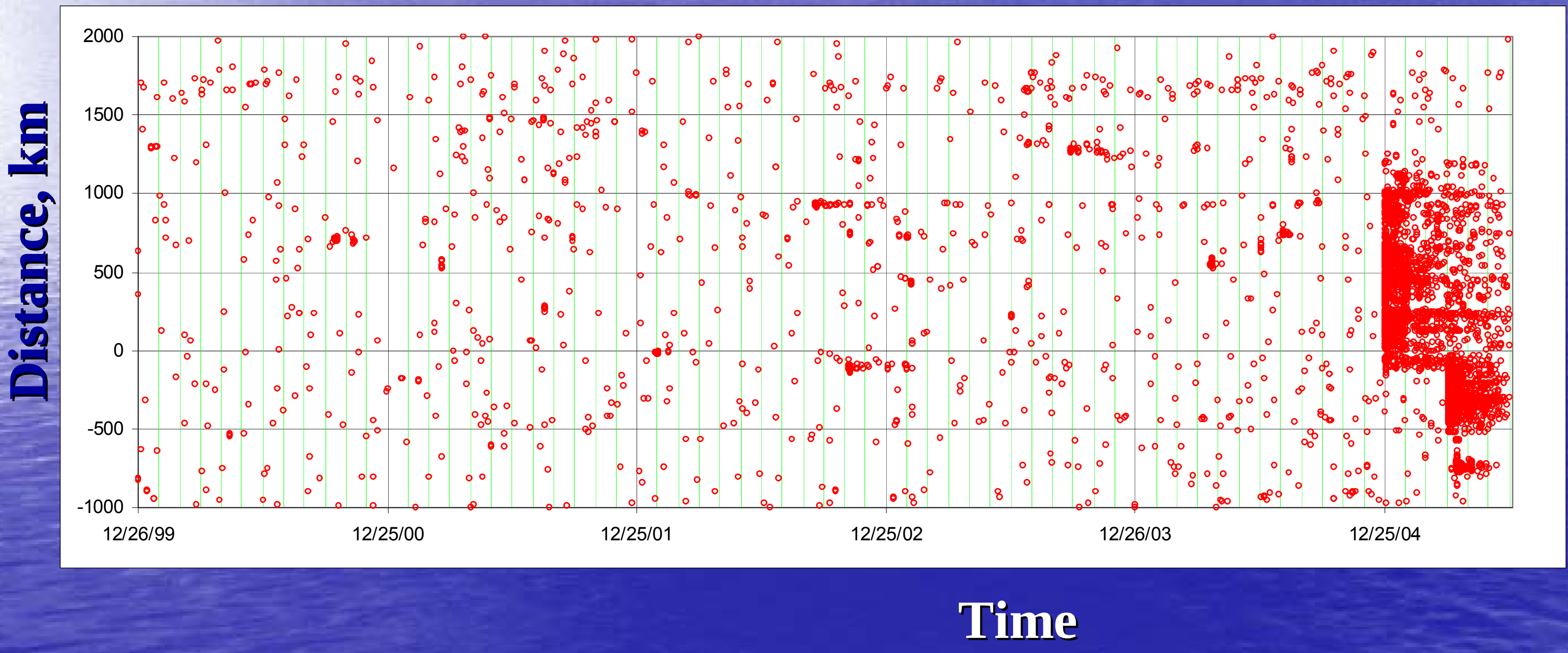

Distribution of earthquakes in Space and Time:

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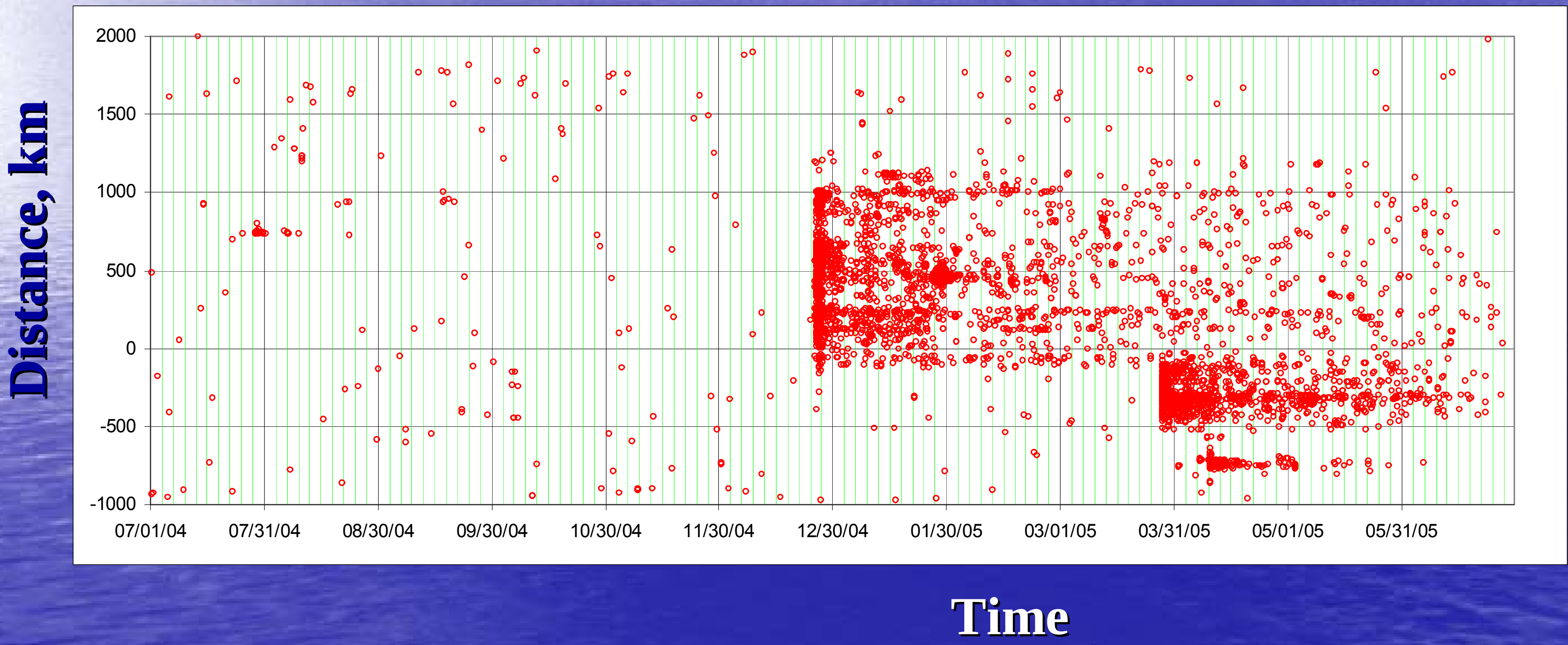
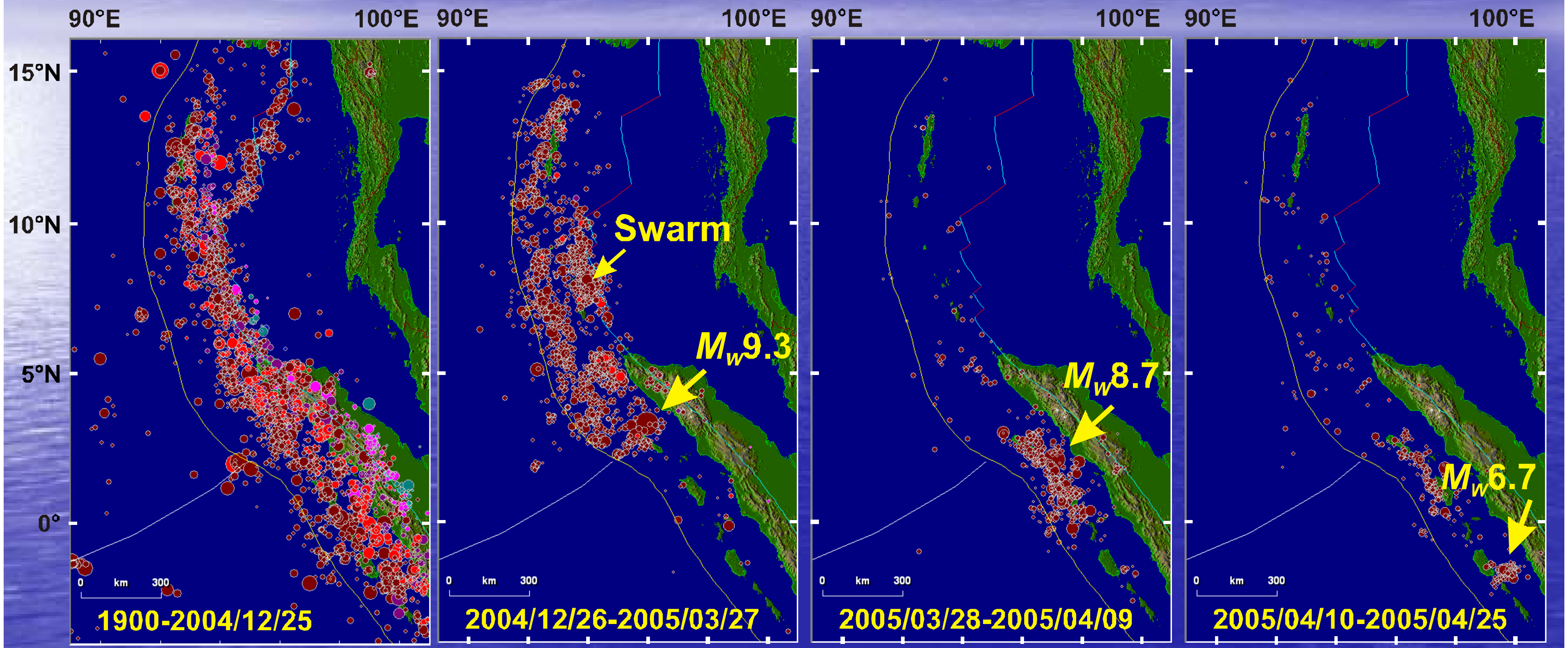


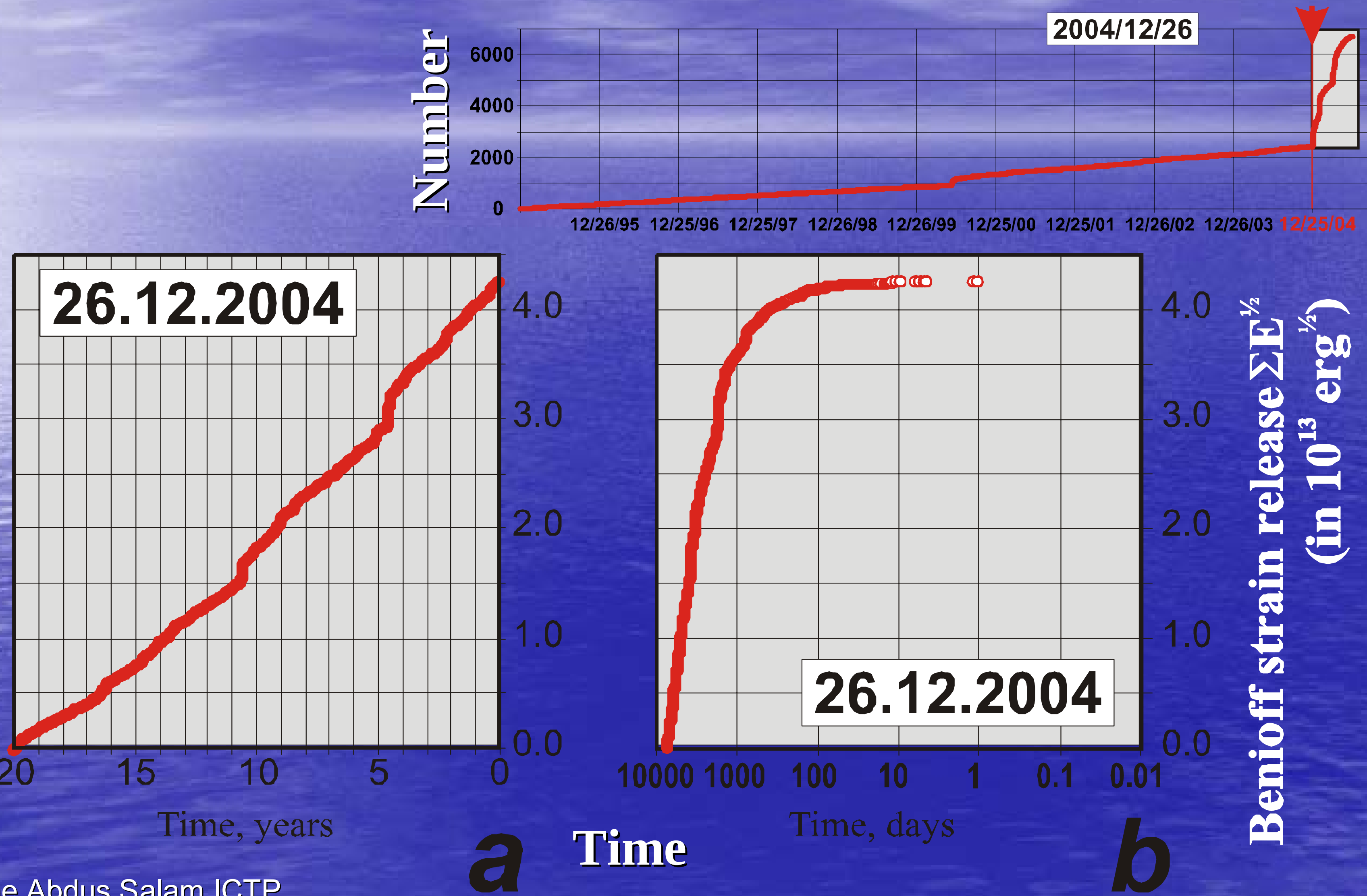
Distribution of earthquakes in Space and Time:

Clustering and cascades



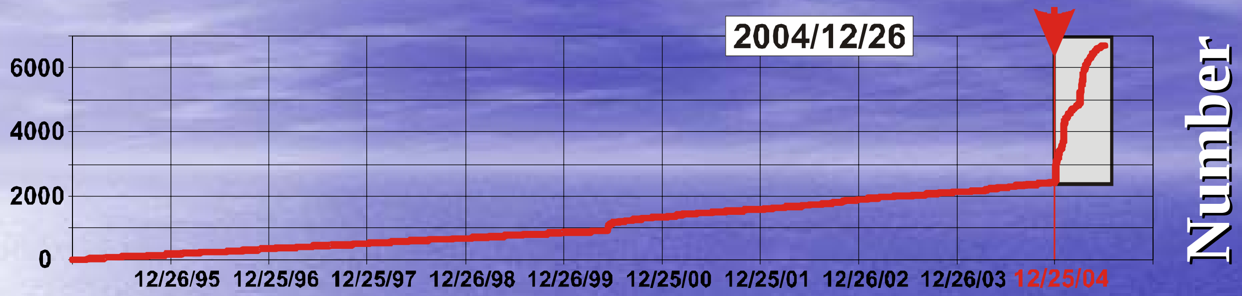
Distribution of earthquakes in Space and Time:

Clustering and cascades

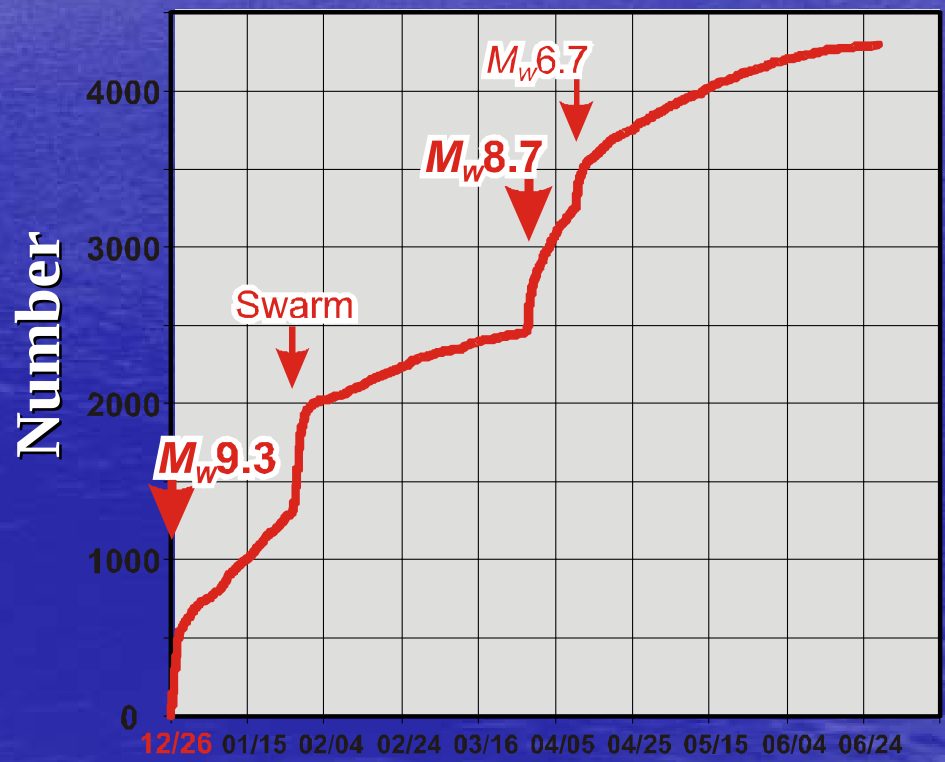


Distribution of earthquakes in Space and Time:

Clustering and cascades

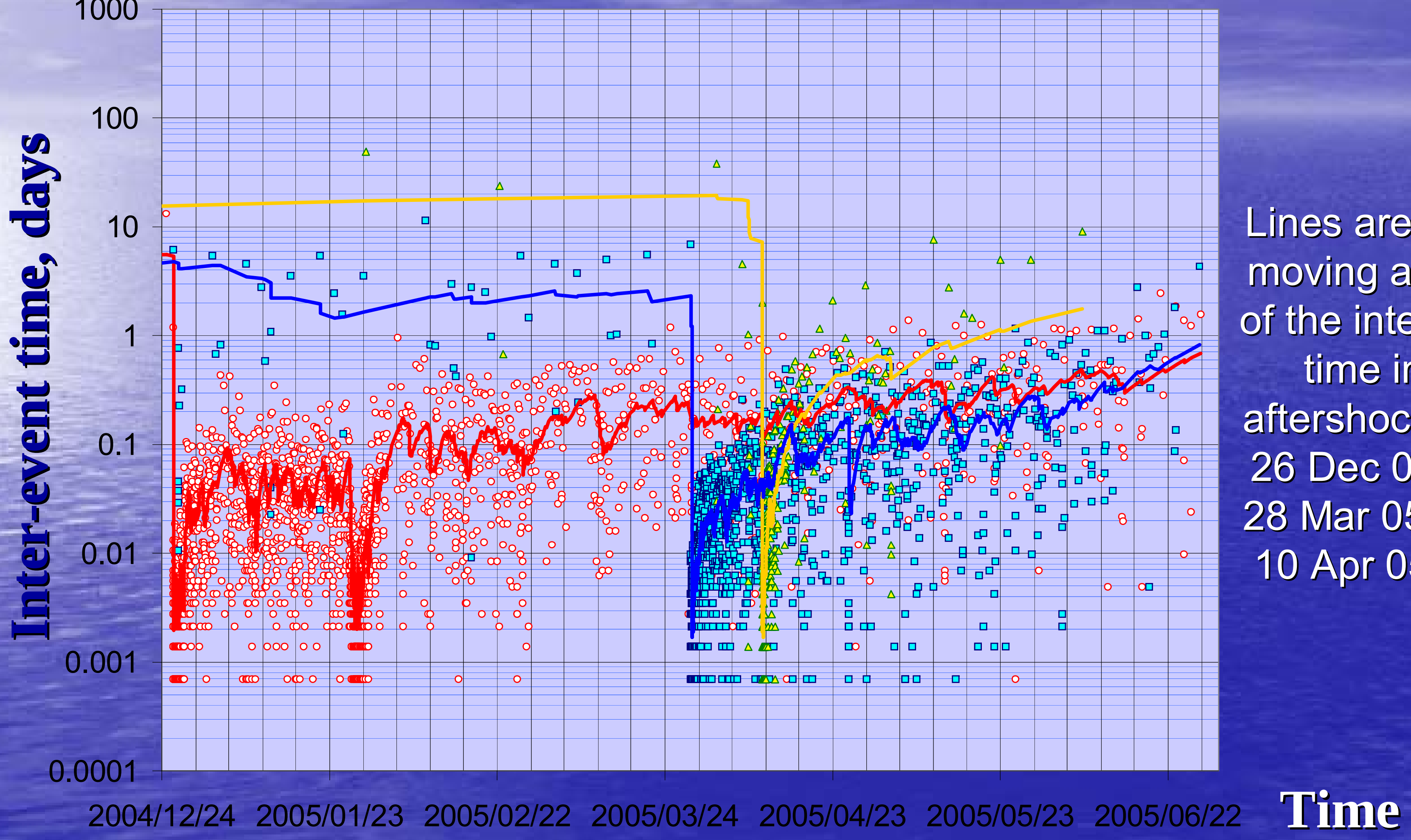


The rate of aftershocks did change in a step-wise manner from 10 (magnitude 4 or larger quakes) per hour to 1.1 per hour until the swarm of 25-27 January, which burst more than 500 events.
Then the rate has drop to about 11 per day during February, then drop again to 6 per day till 28 March 2005 Nias Mw8.7 earthquake.



Distribution of earthquakes in Space and Time:

Clustering and cascades

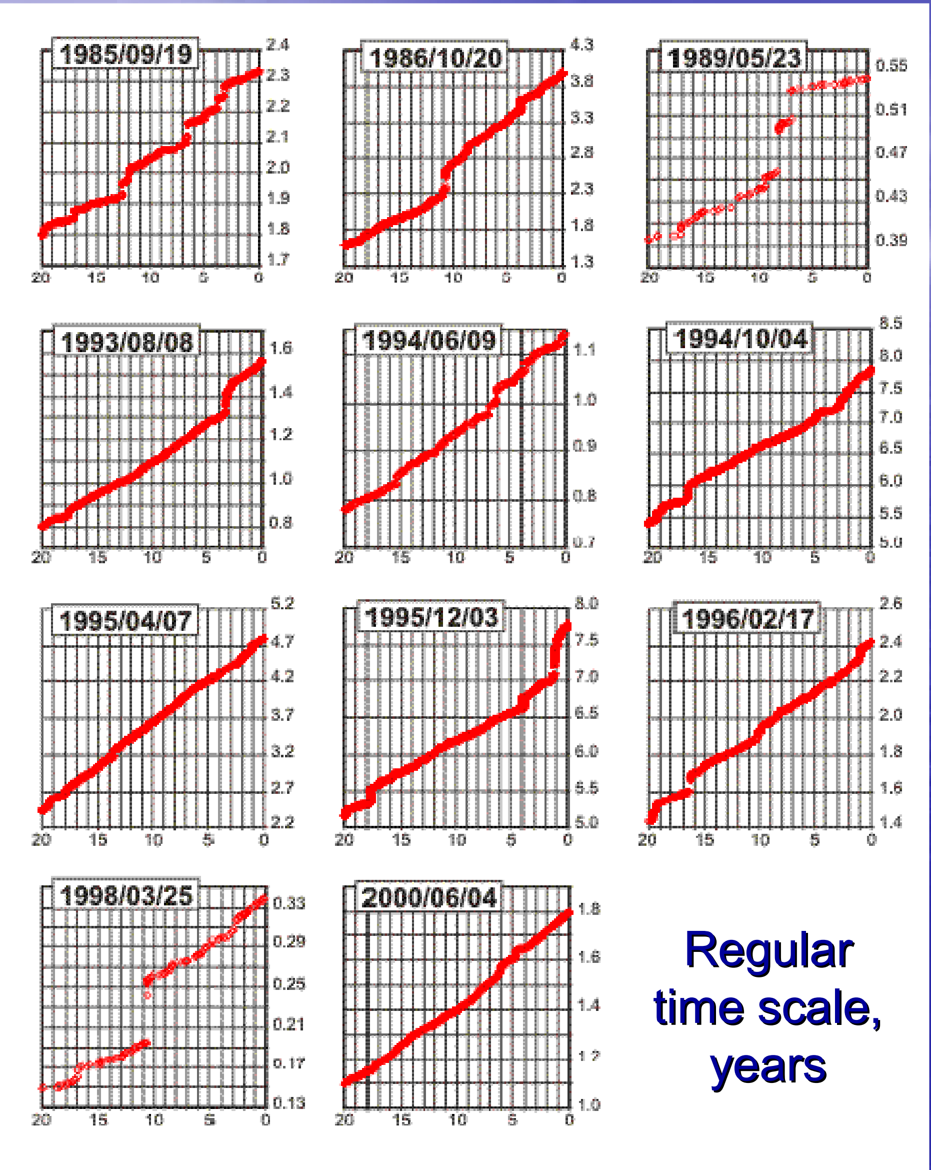


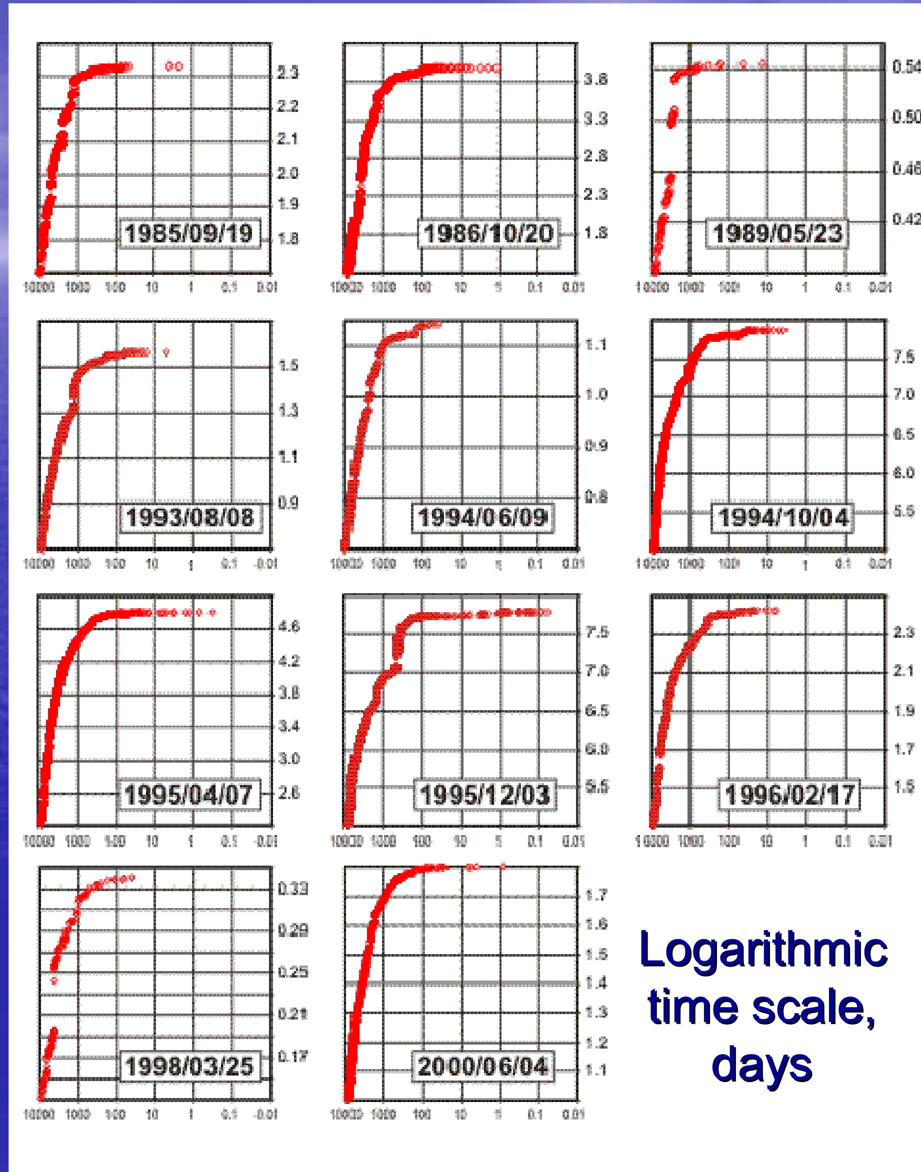
Lines are 20 per moving average of the inter-event time in an aftershock zone:
26 Dec 04 (red)
28 Mar 05 (blue)
10 Apr 05 (yellow)

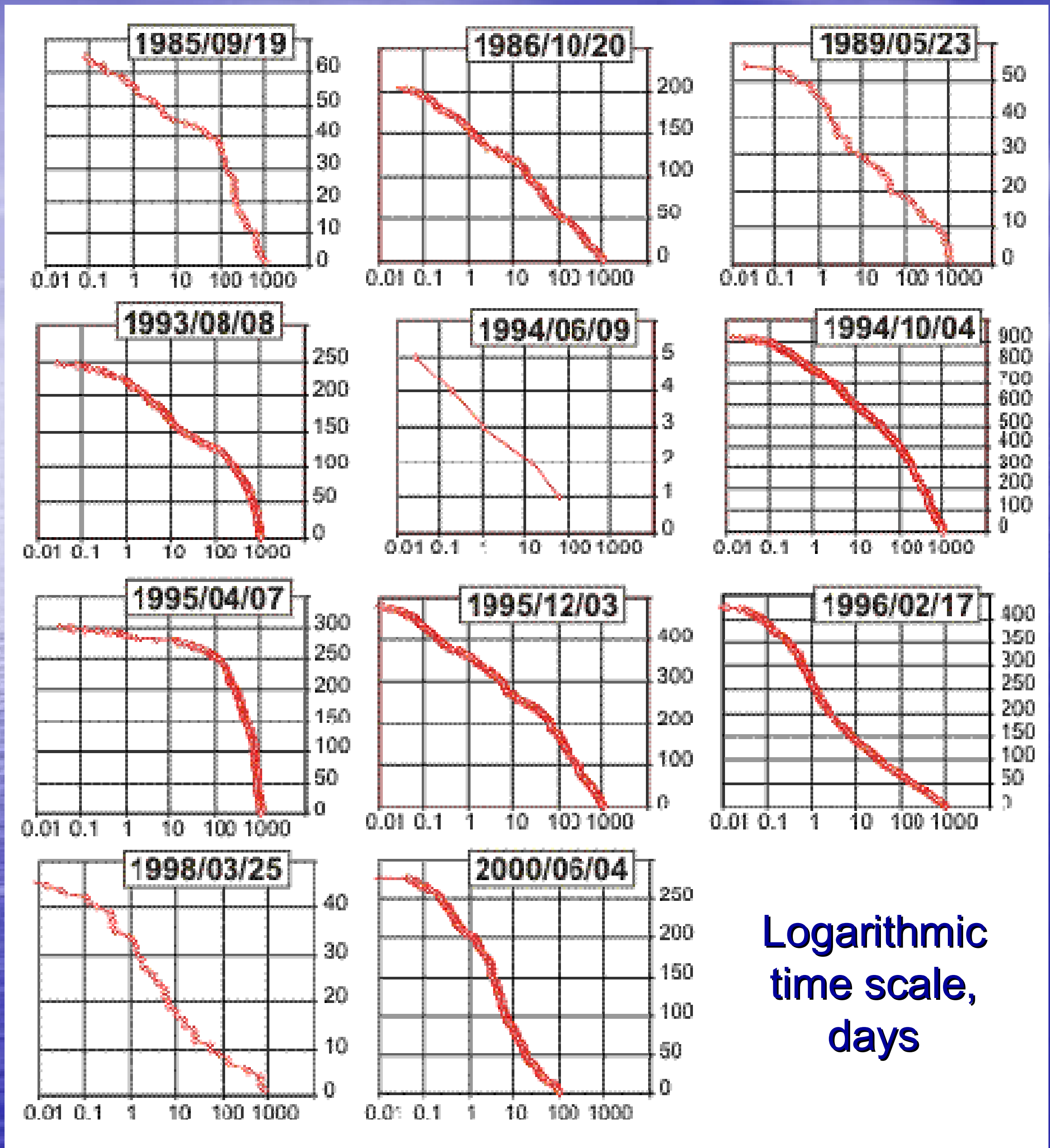
Catalogs of earthquakes make possible to study systematically seismic variability in space and time

- 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.

Benioff strain release $\Sigma E^{1/2}$ (10^{12} erg$^{1/2}$) 20 years before the great shocks

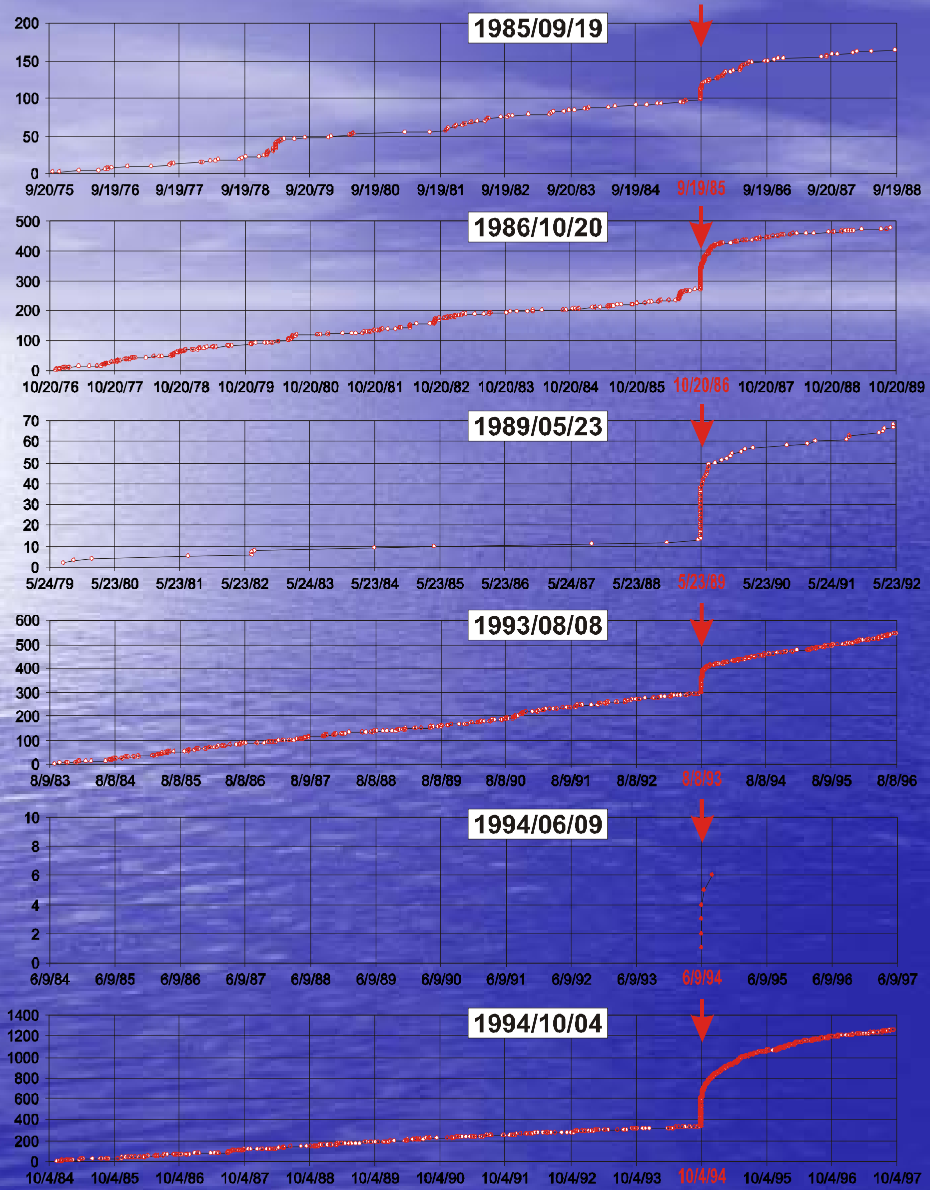


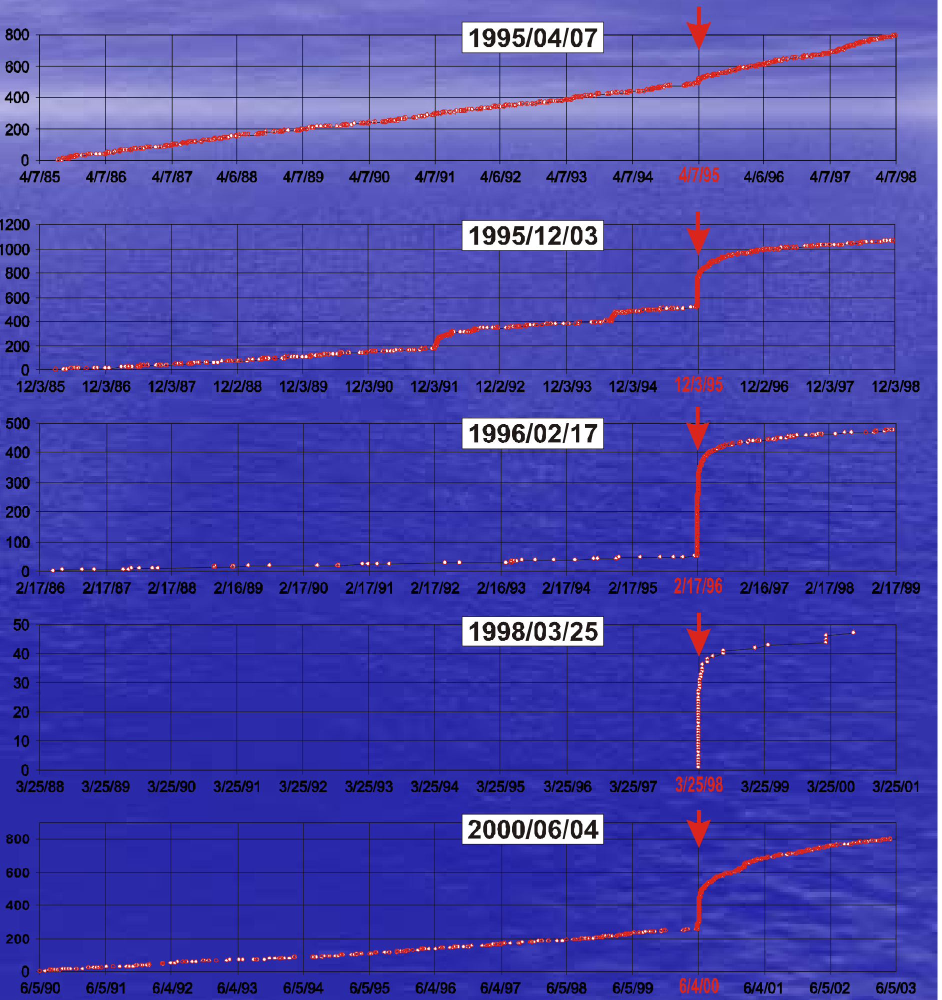




The number of aftershocks in the period from time τ to 3 years after the great shock

Activity in 10 years before and 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	47	Omori Law	Modified OL 2	140 days
2000/06/04	278	799	Modified OL 2	Modified OL 2	2 years, >1.7

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.

Conclusions

- Catalogs evidence clear patterns in space-time-energy distribution of earthquakes, as well as consecutive stages of their inverse cascading to main shocks 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.
- Despite evident difficulties of compilation in the real time, seismologists have no luxury of postponing usage of the existing earthquake catalogs to the benefit of population living in seismic regions.

Are earthquakes predictable?

Yes!

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

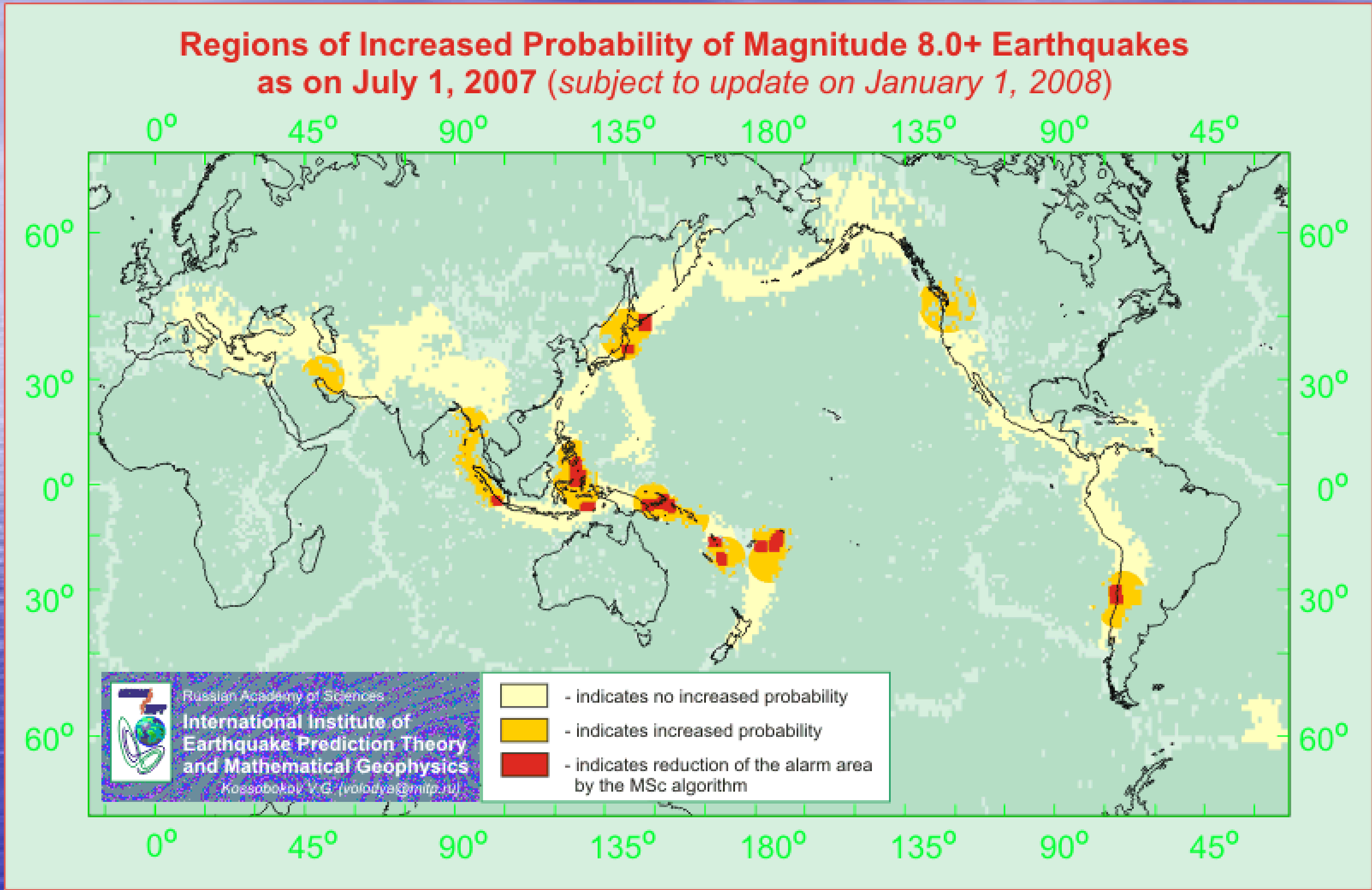
Test period	Large earthquakes Total	Predicted by M8	Predicted by M8-MSc	Measure of alarms, % M8	Measure of alarms, % M8-MSc	Confidence level, % M8	Confidence level, % M8-MSc
1985-present	**17**	**12**	**9**	**32.93**	**16.78**	**99.83**	**99.93**
1992-present	**15**	**10**	**7**	**29.17**	**14.54**	**99.71**	**99.70**

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 six failures-to-predict in a row.

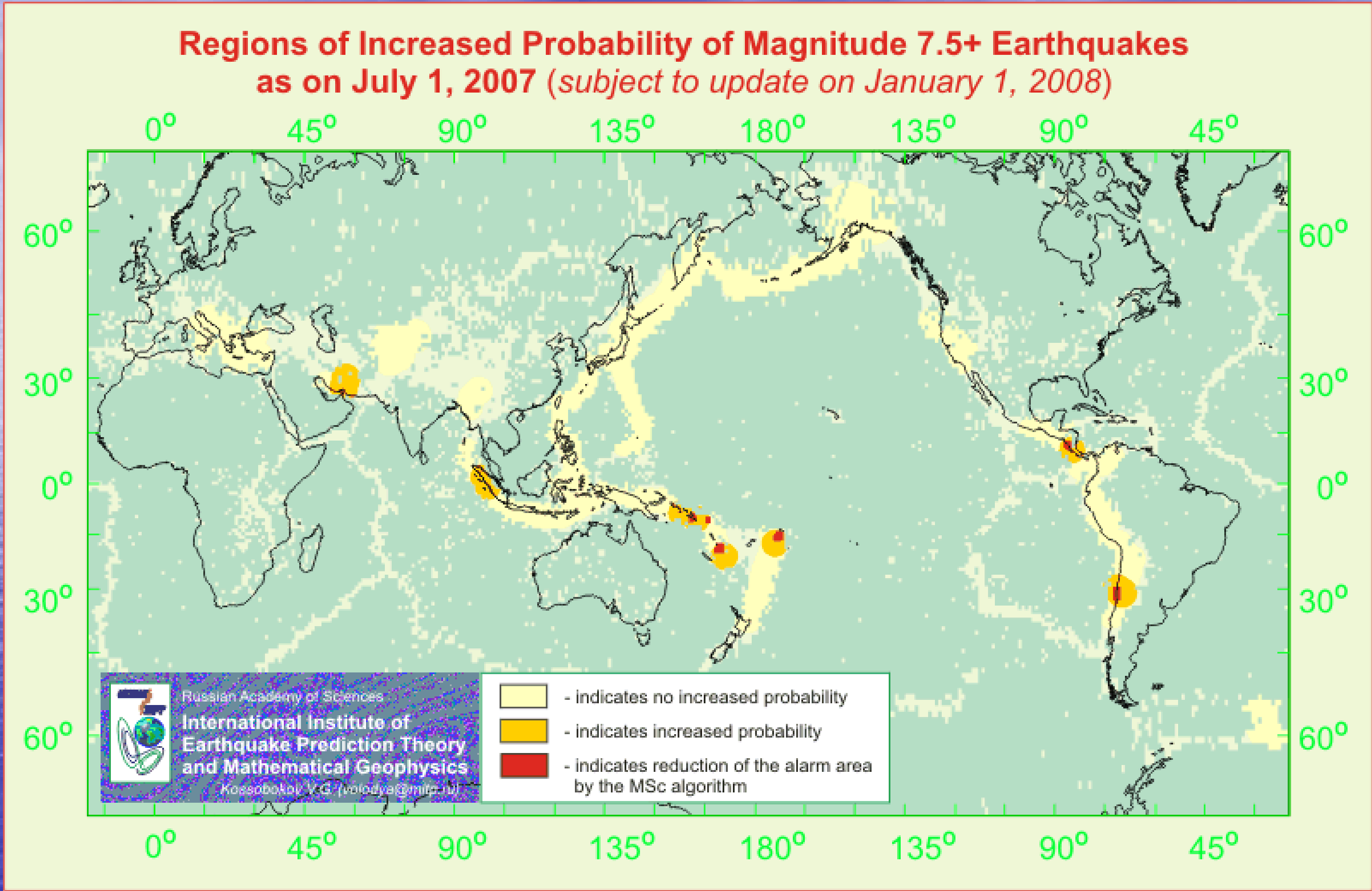
Real-time prediction of the world largest earthquakes

(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)



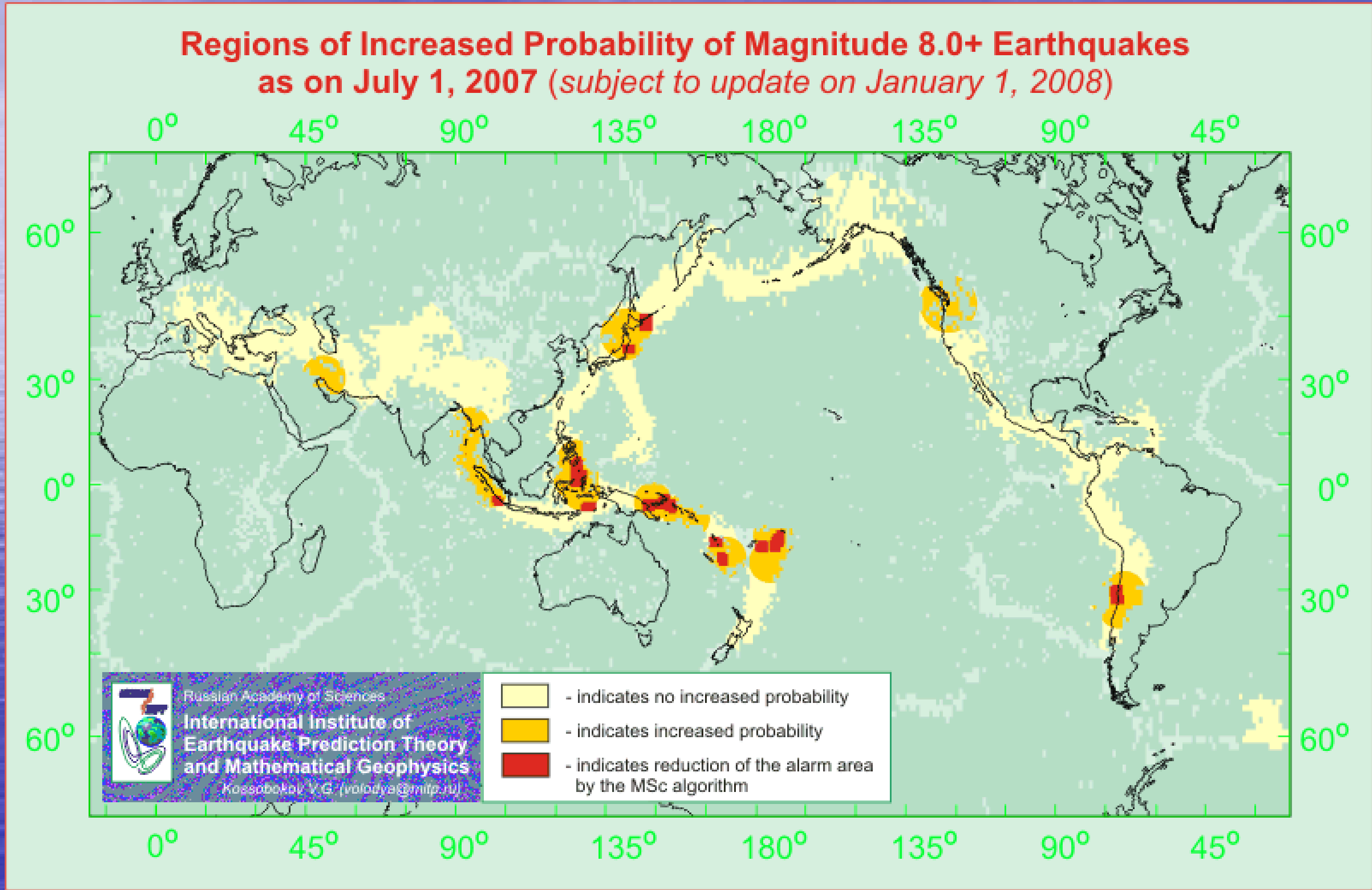
Real-time prediction of the world largest earthquakes

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

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 easily accessed, although available on the web-pages of restricted access provided to about 150 members of the Mailing List.

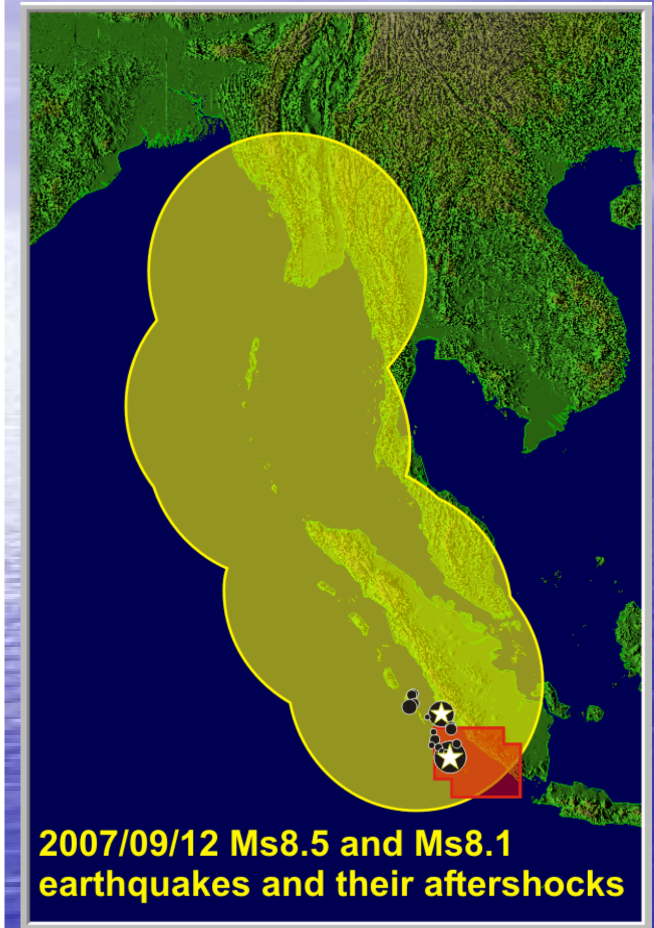
Real-time prediction of the world largest earthquakes

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

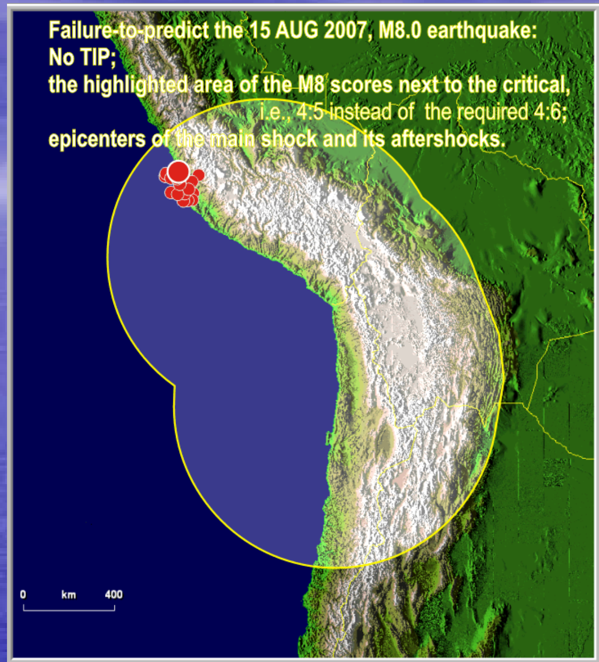


Real-time prediction of the world largest earthquakes

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



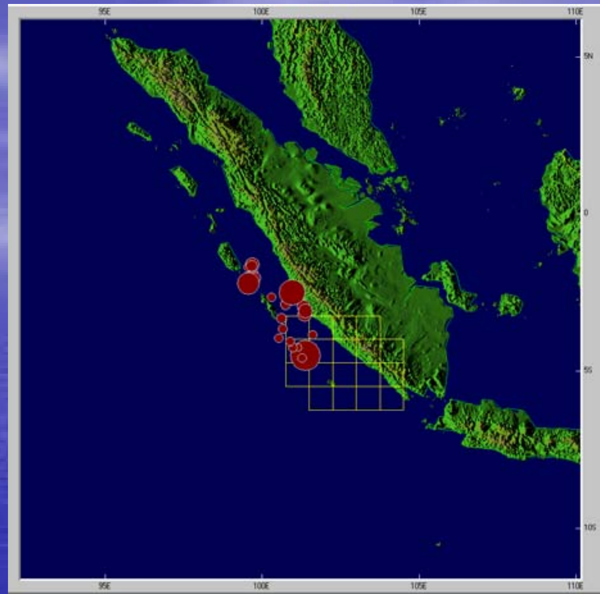
2007/09/12 Ms8.5 and Ms8.1 quakes and their aftershocks

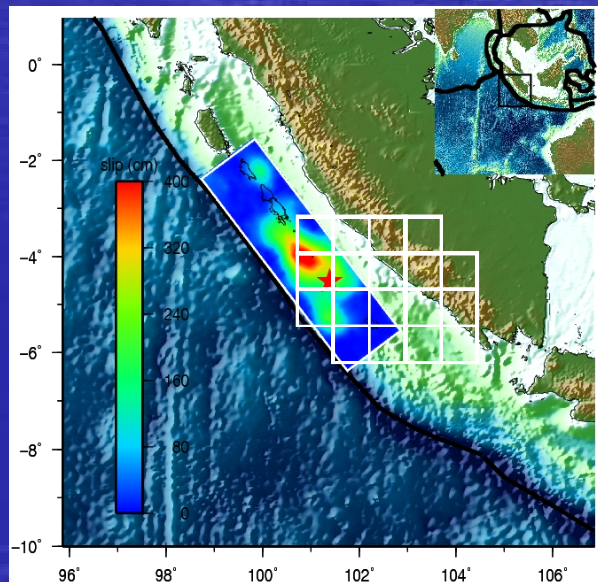


Finite Fault Model

Preliminary Result of the Sep 12, 2007 Sumatra Earthquake

Chen Ji, UCSB





After we learn together a bit more about

Measuring Variability of an Earthquake Sequence

Tuesday, October 2 11.10 - 12.00

I shall talk next week on predictability of earthquakes -

1. Earthquake prediction: Problem and Practical Solutions

   Monday, October 8 13.30 - 14.15

2. Practice of Predicting Large Earthquakes on global and Regional Scales

   Wednesday, October 10 13.30 - 14.15

3. Earthquake forecast/prediction: Problem of Verification

   Thursday, October 11 14.25 - 15.10

4. Earthquake forecast/prediction: Accuracy and Limitations

   Thursday, October 11 15.20 - 16.05

as well as on -

Unified Scaling Law for Earthquakes and Seismic Hazard Assessment

Friday, October 12 14.25 - 15.10

Similarity and Differences in Sequences of Earthquakes, Solar Flares, and Starquakes

Friday, October 12 15.20 - 16.05

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