Quantitative Earthquake Prediction:
Basics, Implementation, Perspectives

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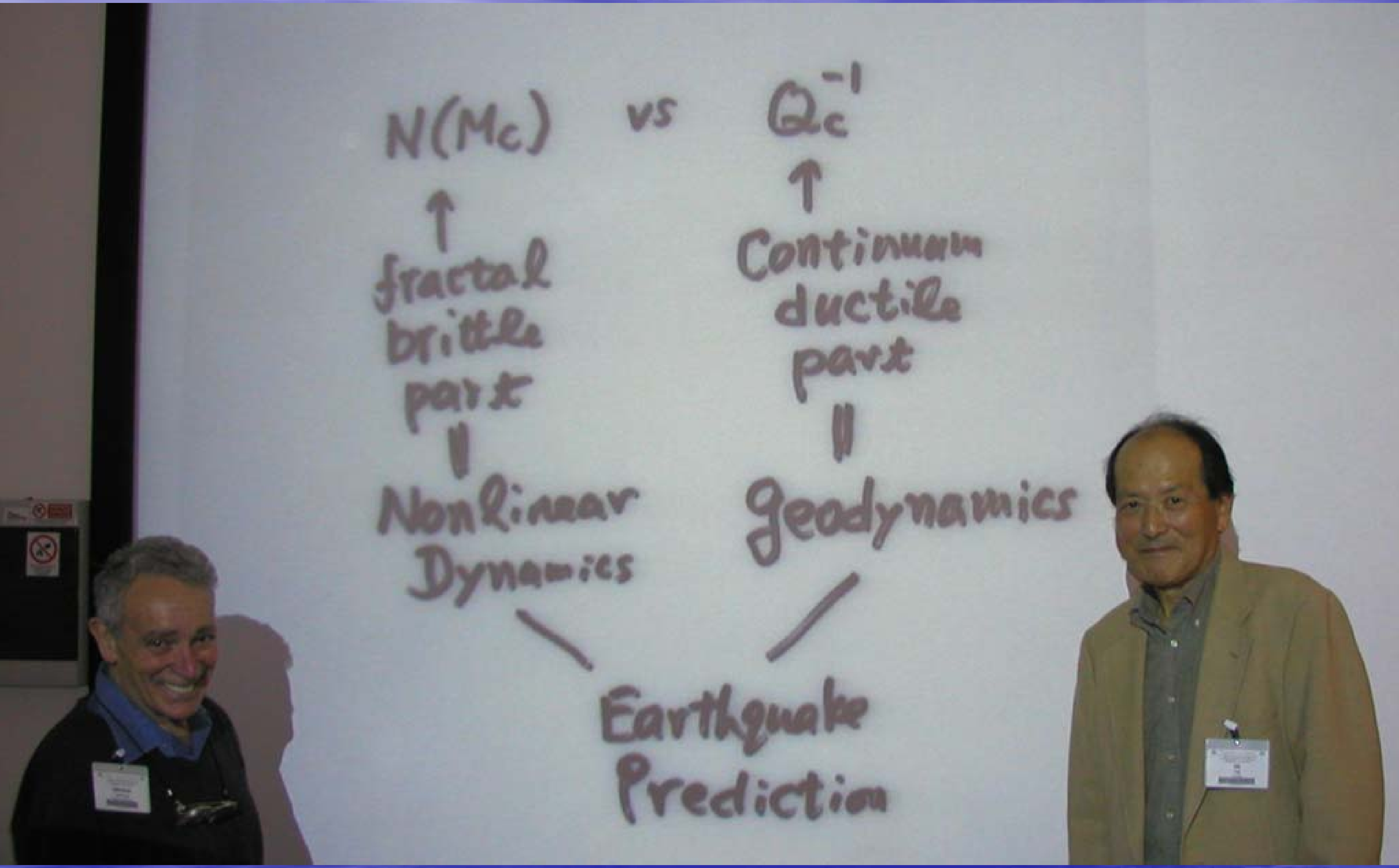
IIEPT

International Conference on Global Warming

Government of Pakistan
National Centre for Physics
Quaid-i-Azam University Campus,Islamabad

13-14 November 2006

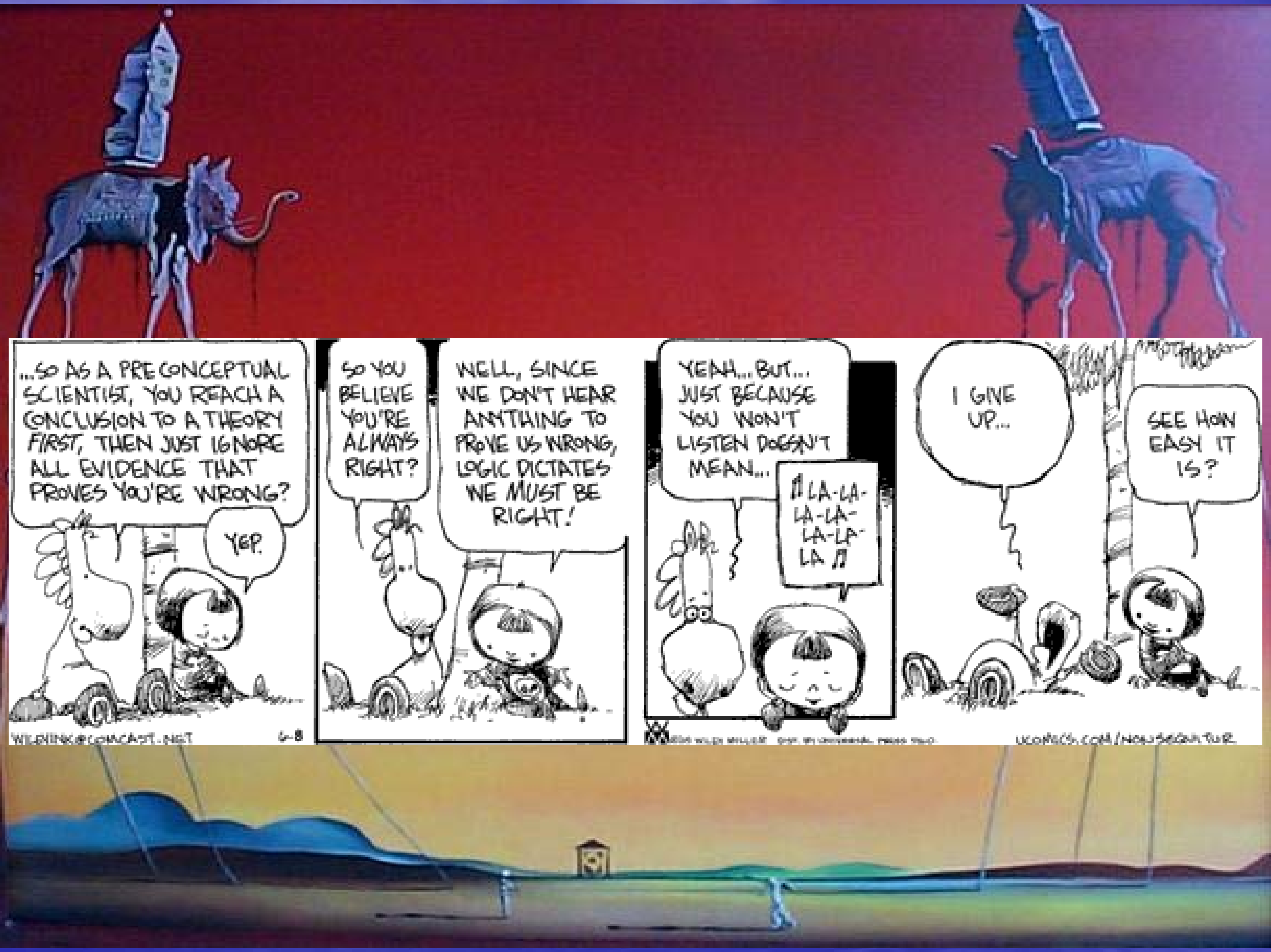

N(Mc) vs Q_c^{-1}
fractal brittle part
Nonlinear Dynamics
Continuum ductile part
Geodynamics
Earthquake Prediction

Usually, forecast/prediction of extreme events is not an easy task.

- By definition, an extreme event is rare one in a series of kindred phenomena. Therefore, it generally implies a delicate application of small sample statistics methodologies to data of different accuracy collected in different environment.
- Many extreme events are clustered (far from independent, e.g., Poisson process) and follow fractal (far from uniform) distribution. Evidently, such an “unusual” situation complicates search and definition of precursory behaviors to be used for forecast/prediction purposes.

- Making forecast/prediction claims quantitatively probabilistic in the frames of the most popular objectivists' viewpoint on probability requires a long series of "yes/no" forecast/prediction outcomes, which cannot be obtained without an extended rigorous test of the candidate method.
- The set of errors ("success/failure" scores and space-time measure of alarms) and other information obtained in such a test supplies us with data necessary to judge the candidate's potential as a forecast/prediction tool and, eventually, to find its improvements.
- This is to be done first in comparison against random guessing, which results confidence (measured in terms of statistical significance).

- Note that an application of the forecast/prediction tools could be very different in cases of different costs and benefits, and, therefore, requires determination of optimal strategies.
- In there turn case specific costs and benefits may suggest an optimal modification of the forecast/prediction tools.

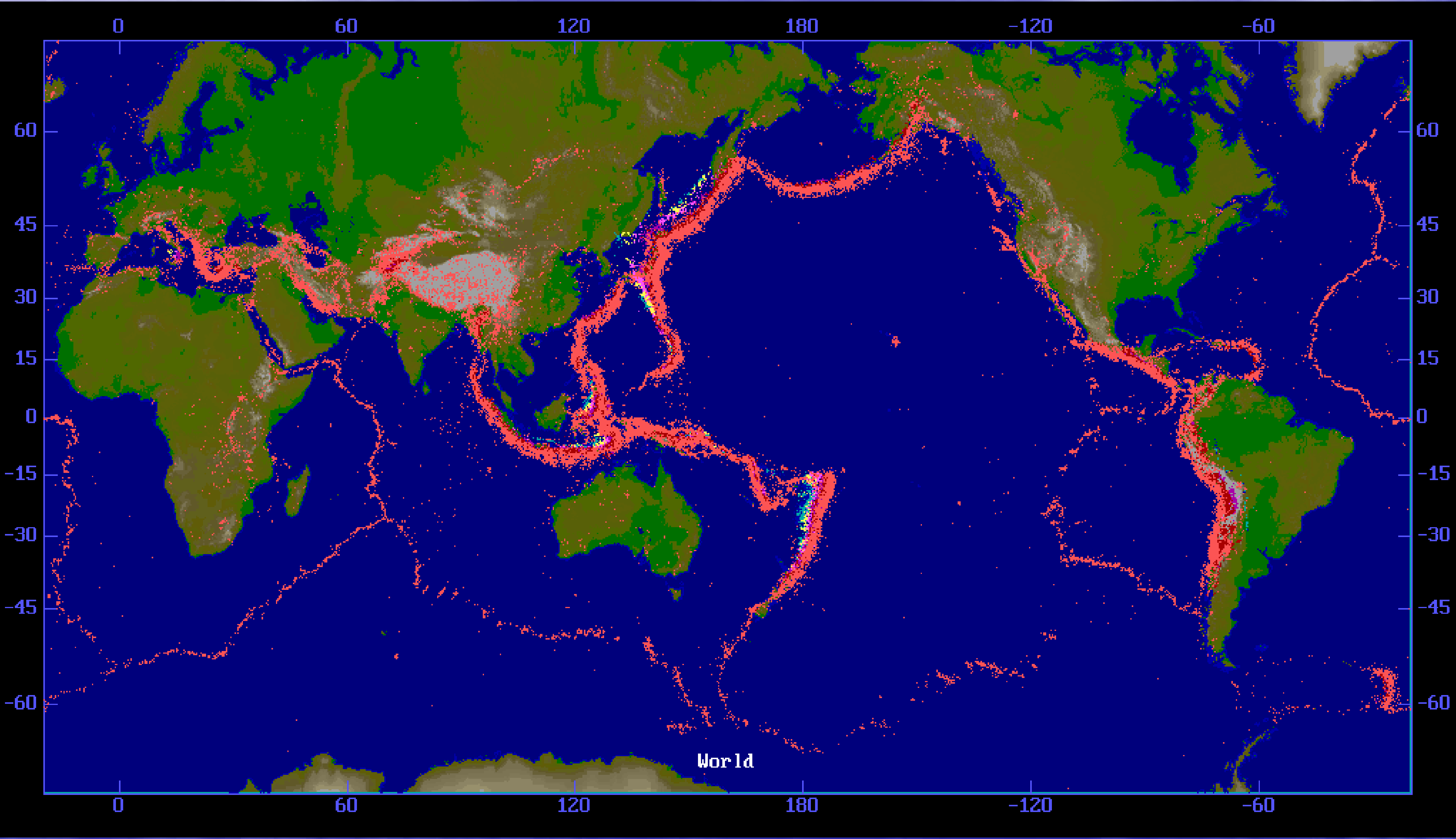


...SO AS A PRECONCEPTUAL SCIENTIST, YOU REACH A CONCLUSION TO A THEORY *FIRST*, THEN JUST IGNORE ALL EVIDENCE THAT PROVES YOU'RE WRONG?
YEP.
SO YOU BELIEVE YOU'RE ALWAYS RIGHT?
WELL, SINCE WE DON'T HEAR ANYTHING TO PROVE US WRONG, LOGIC DICTATES WE *MUST* BE RIGHT!
YEAH... BUT... JUST BECAUSE YOU WON'T LISTEN DOESN'T MEAN...
♫ LA-LA-LA-LA-LA-LA-LA ♫
I GIVE UP...
SEE HOW EASY IT IS?
WILDINK@COMCAST.NET
6-8
UCOMICS.COM/NONSEQUITUR

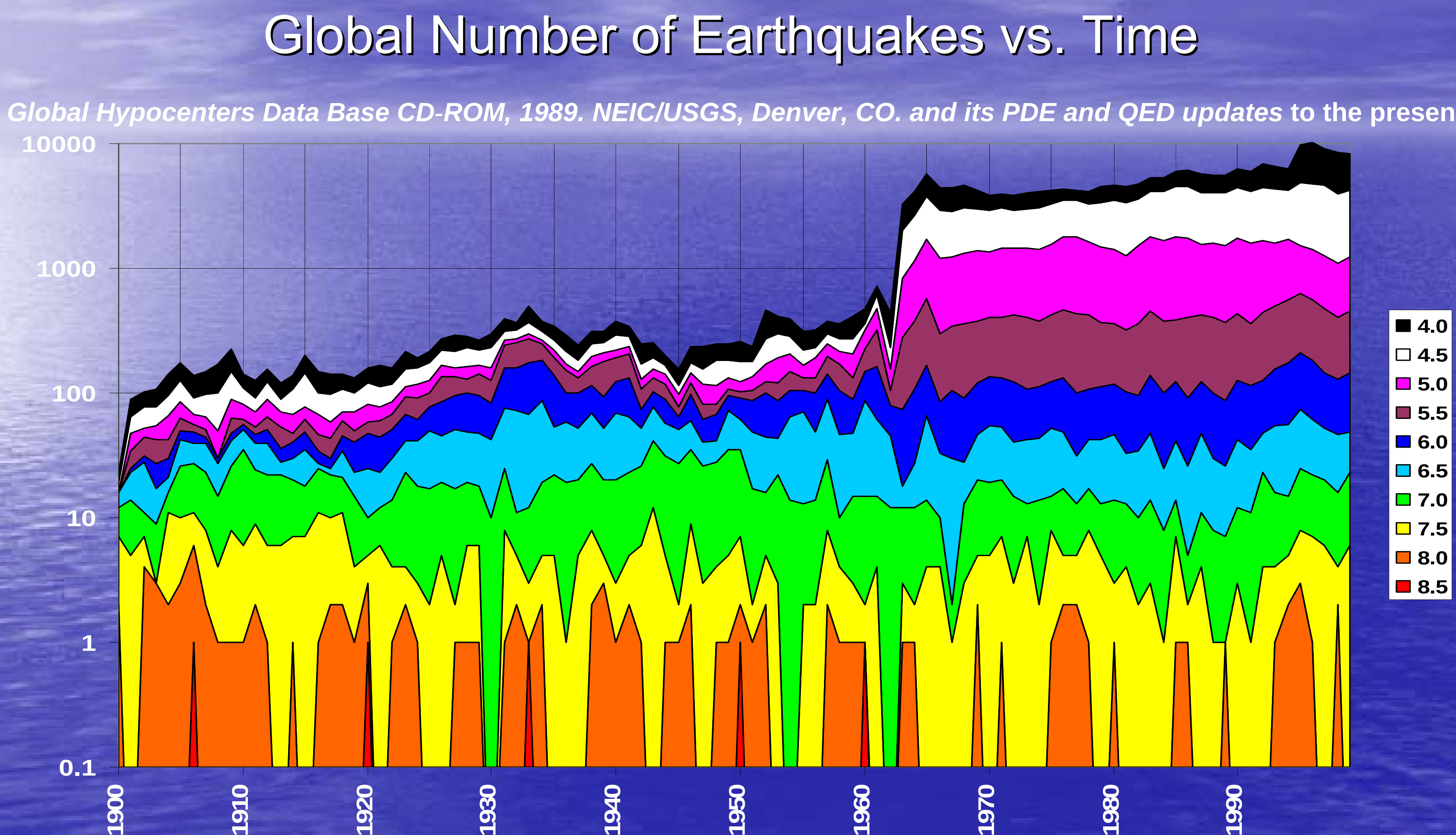
The extreme catastrophic nature of earthquakes is known for centuries due to resulted devastation in many of them.

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

Where earthquakes happen...



How often...



Global Number of Earthquakes vs. Time
Global Hypocenters Data Base CD-ROM, 1989. NEIC/USGS, Denver, CO. and its PDE and QED updates to the present
10000
1000
100
10
1
0.1
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5

Seismic activity is self similar:

Since the pioneering works of Keiiti Aki and M. A. Sadovsky

Okubo, P.G., K. Aki, 1987. Fractal geometry in the San Andreas Fault system. *J. Geophys. Res.*, **92** (B1), 345-356;
Садовский М.А., Болховитинов Л.Г., Писаренко В.Ф., 1982. О свойстве дискретности горных пород. *Изв. АН СССР. Физика Земли*, № 12, 3-18;
Садовский, М.А., Т.В. Голубева, В.Ф. Писаренко, и М.Г. Шнирман, 1984. Характерные размеры горной породы и иерархические свойства сейсмичности. *Известия АН СССР. Физика Земли*, 20: 87–96 .

the understanding of the fractal nature of earthquakes and seismic processes keeps growing.

The Unified Scaling Law for Earthquakes

that generalizes Gutenberg-Richter relation suggests -

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

where N = N(M, L) is the expected annual number of earthquakes with magnitude M in an earthquake-prone 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.

12 KOSOBOKOV AND MAZHKENOV: SIMILARITY IN SPATIAL DISTRIBUTION OF SEISMICITY

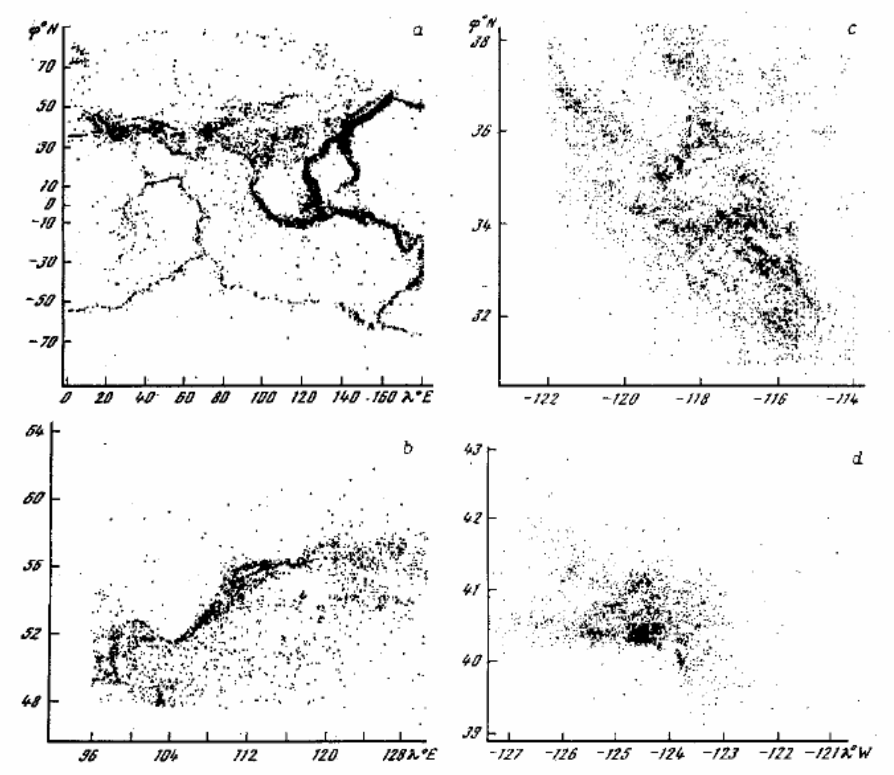


Fig. 2. Examples of spatial distribution of epicenters from catalogs of mainshocks. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

14 KOSOBOKOV AND MAZHKENOV: SIMILARITY IN SPATIAL DISTRIBUTION OF SEISMICITY

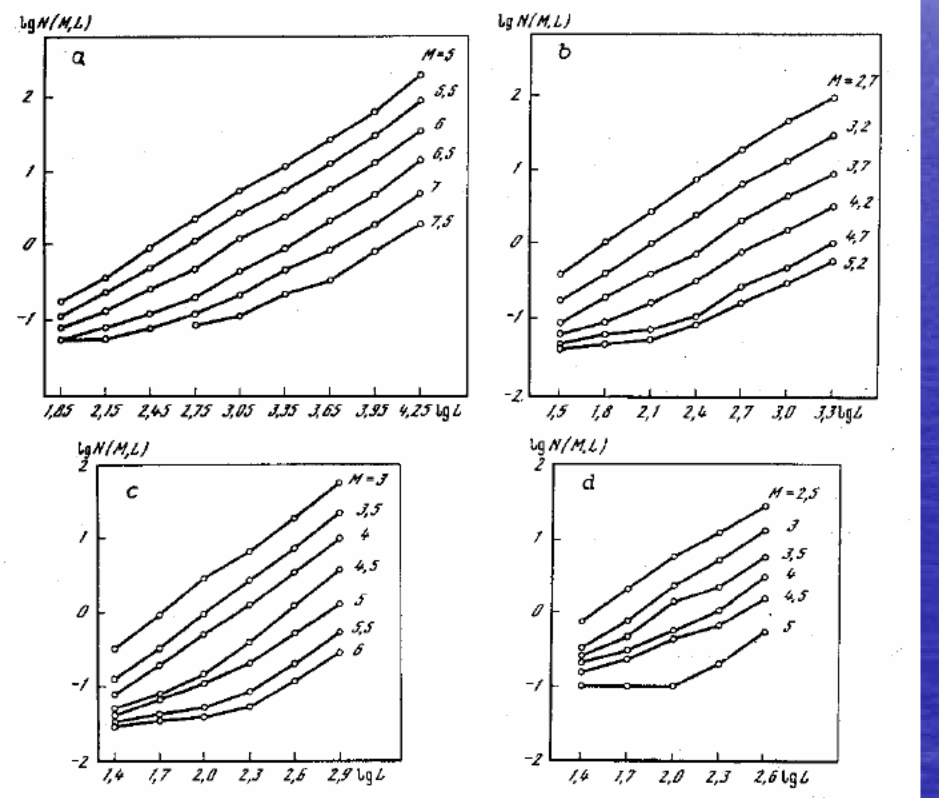
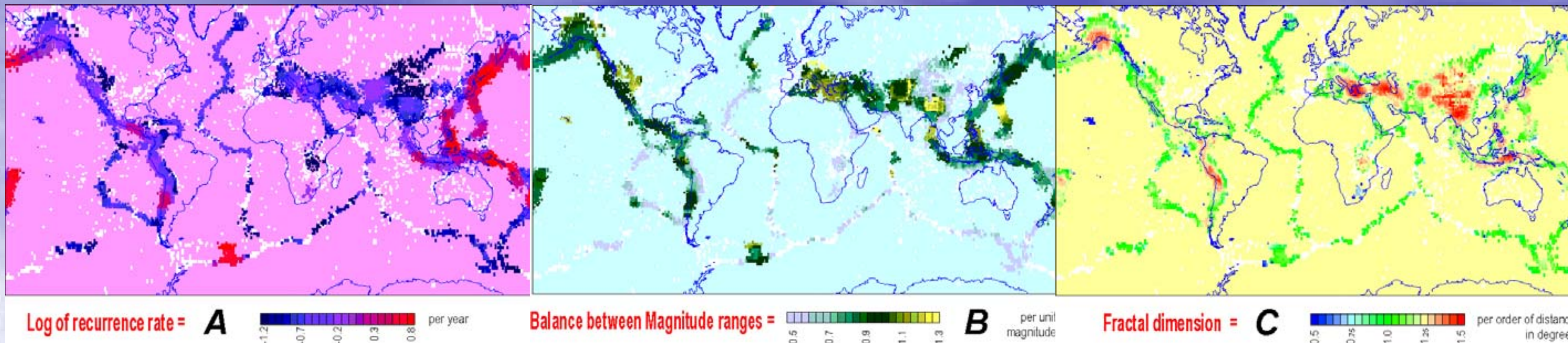


Fig. 3. Examples of log $N(M, L)$ graphs. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

The global map of the USLE coefficients



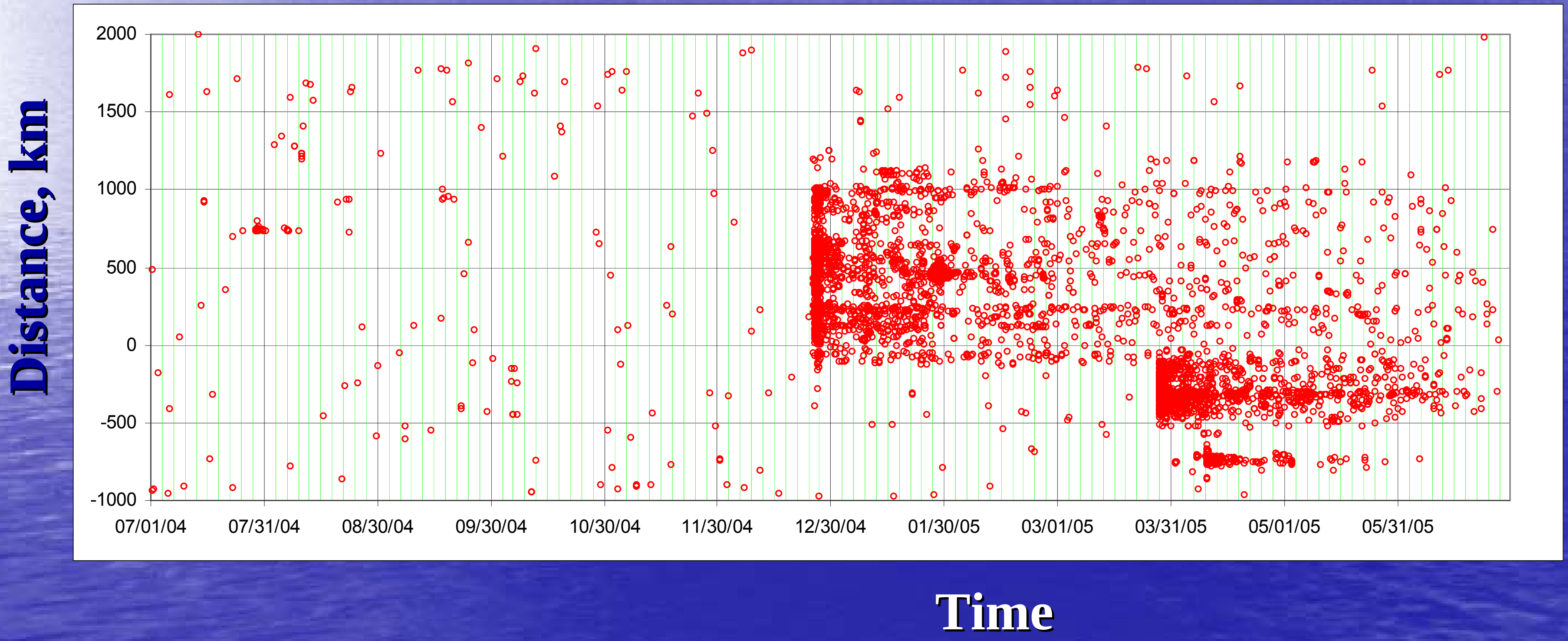
Direct implications for assessing seismic hazard at a given location (e.g., in a mega city)

The estimates for Los Angeles (SCSN data, 1984-2001) -
A = -1.28; B = 0.95; C =1.21 (σ_{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 !**

Scaling for unified application of an earthquake prediction method.

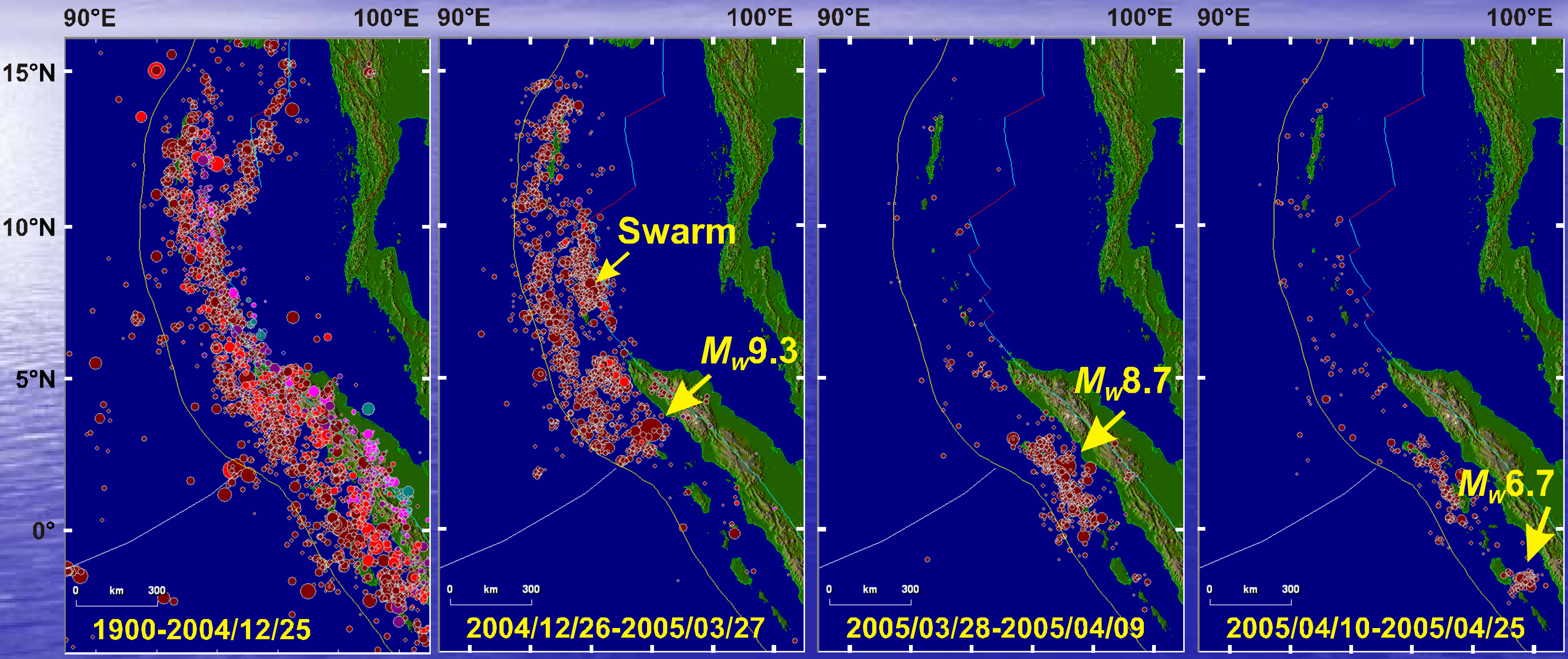
Distribution of earthquakes in Space and Time:

Sumatra-Andaman region



Distribution of earthquakes in Space and Time:

Clustering and cascades



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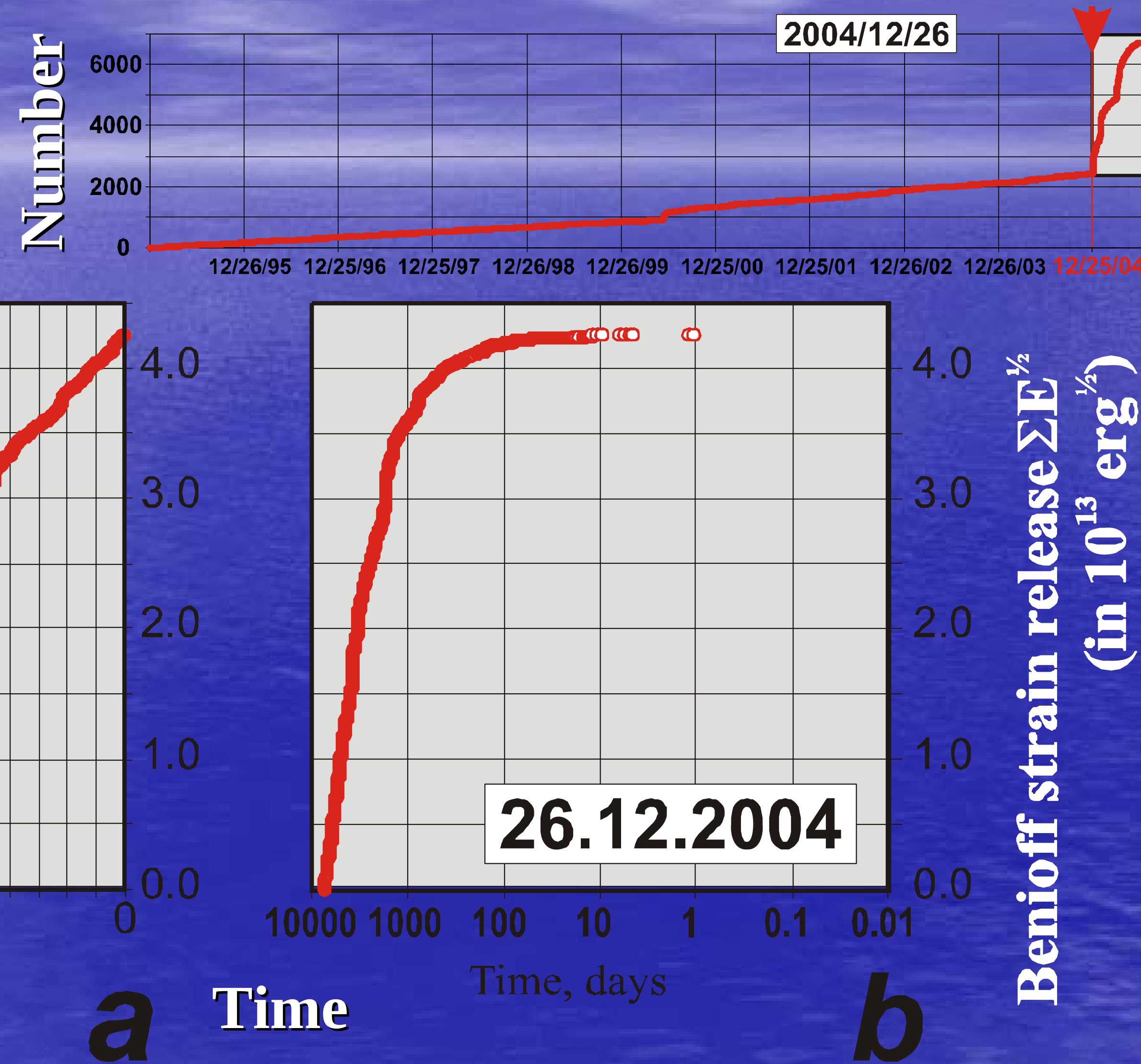
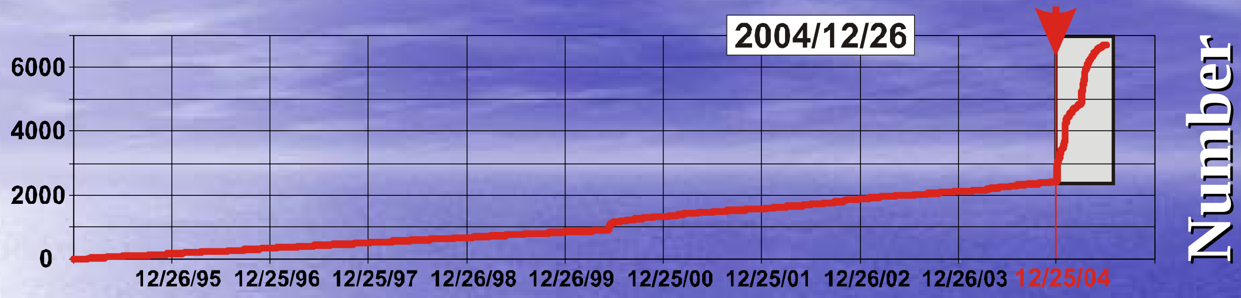
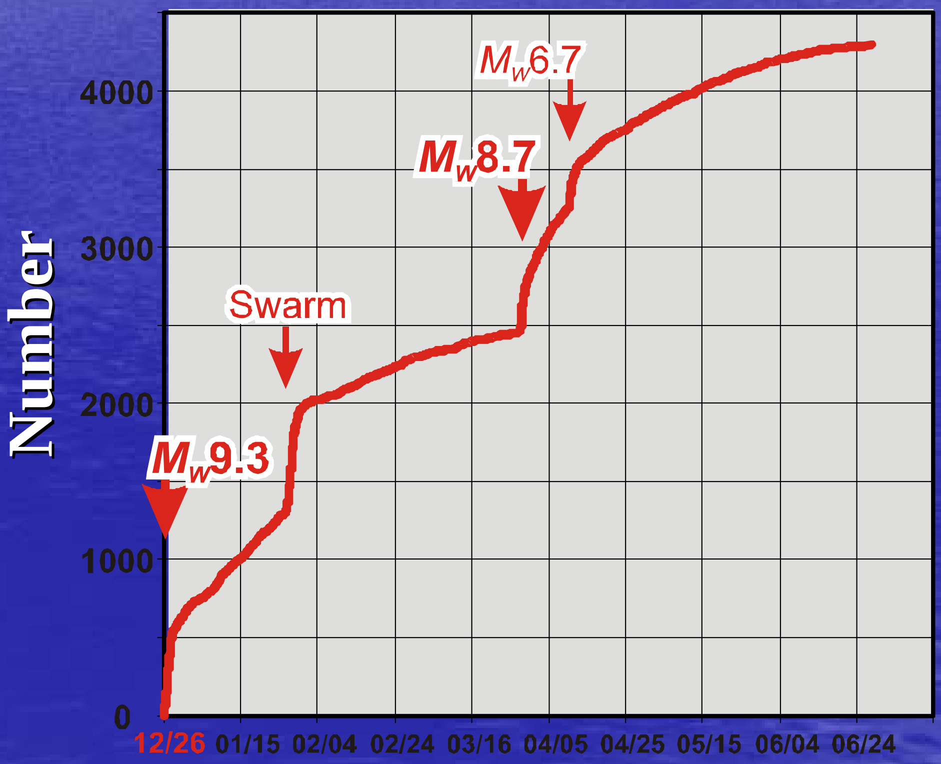


Distribution of earthquakes in Space and Time:

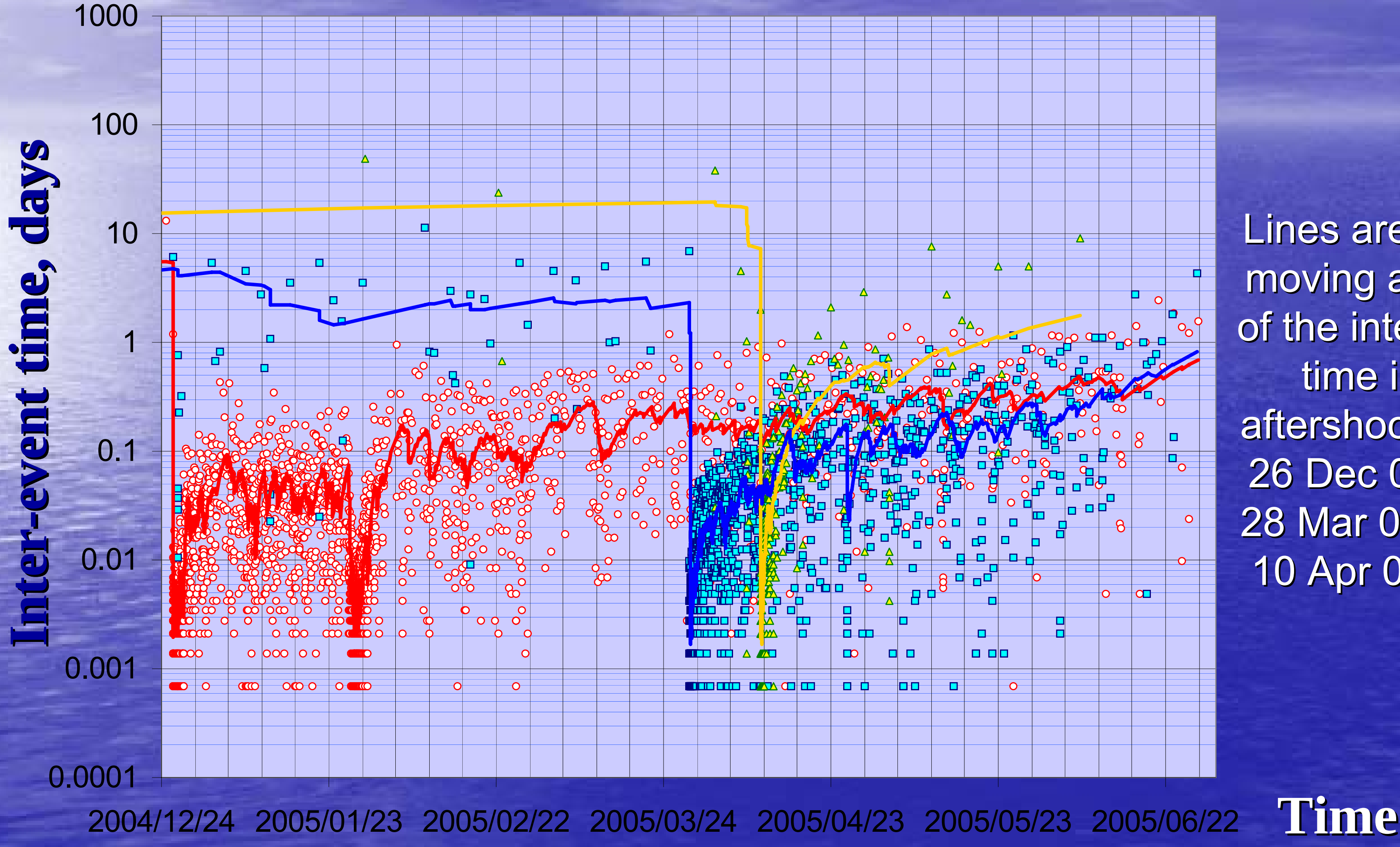
Clustering and cascades



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)

Epoch analysis of aftershocks

(evidence from southern CA)

Aftershock sequences of southern California are extremely different – e.g. the total number of M2.0+ aftershocks in 100 days can be 0 for

Thus, the "old good" Omori's law for aftershocks is hardly a solidly documented fact

(*despite that it is widely used in conceptual models*).

Landers, 1992, M7.3, has about 8.5 thousand, while Hector Mine, 1999, M7.1, has only 4.6 thousand of M2.0+ aftershocks.

Therefore, epoch analysis of the aftershock series is analogous to measuring of the average patients' temperature in a clinic, while "an average behavior of the seismicity" in the region is analogous to crossing the pond through the middle of its waters, which is the average of walking around it, either by turning to the left or to the right.

Consensus definition of 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."

Allen, C.R. (Chaiman), W. Edwards, W.J. Hall, L. Knopoff, C.B. Raleigh, C.H. Savit, M.N. Toksoz, and R.H. Turner, 1976. Predicting earthquakes: A scientific and technical evaluation – with implications for society. *Panel on Earthquake Prediction of the Committee on Seismology, Assembly of Mathematical and Physical Sciences, National Research Council, U.S. National Academy of Sciences, Washington, D.C.*

Stages of earthquake prediction

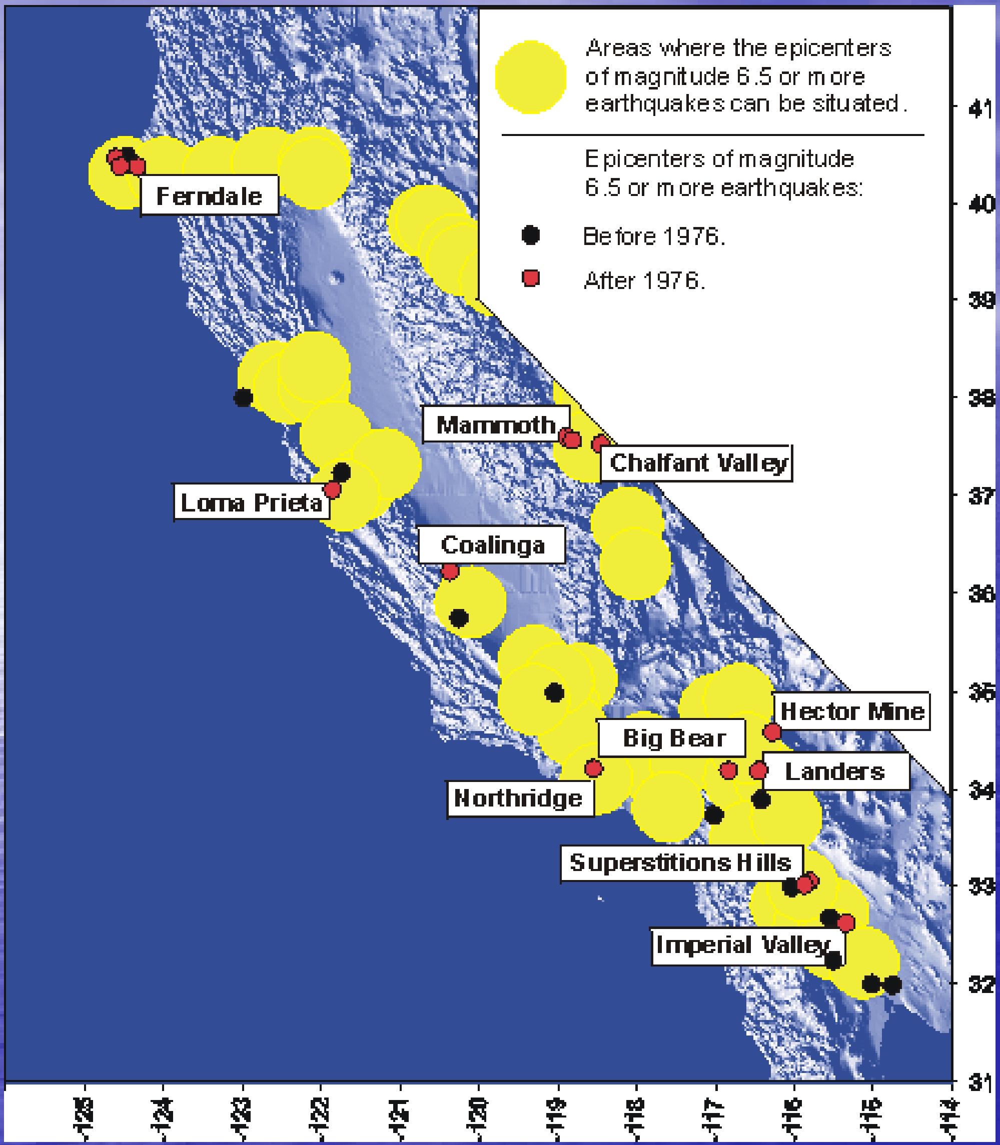
- Term-less prediction of earthquake-prone areas
- Prediction of time and location of an earthquake of certain magnitude

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

- 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.

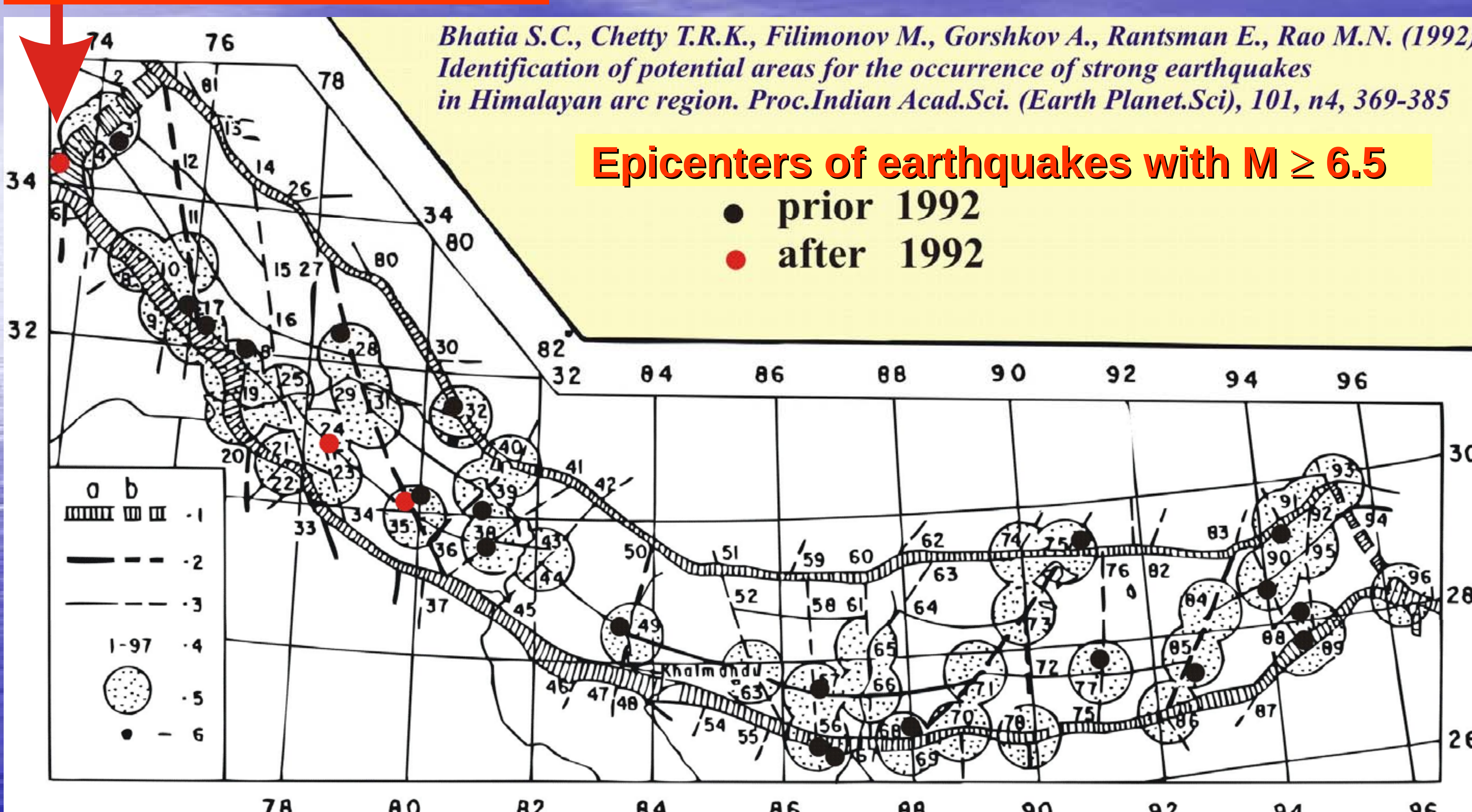
Term-less approximation:



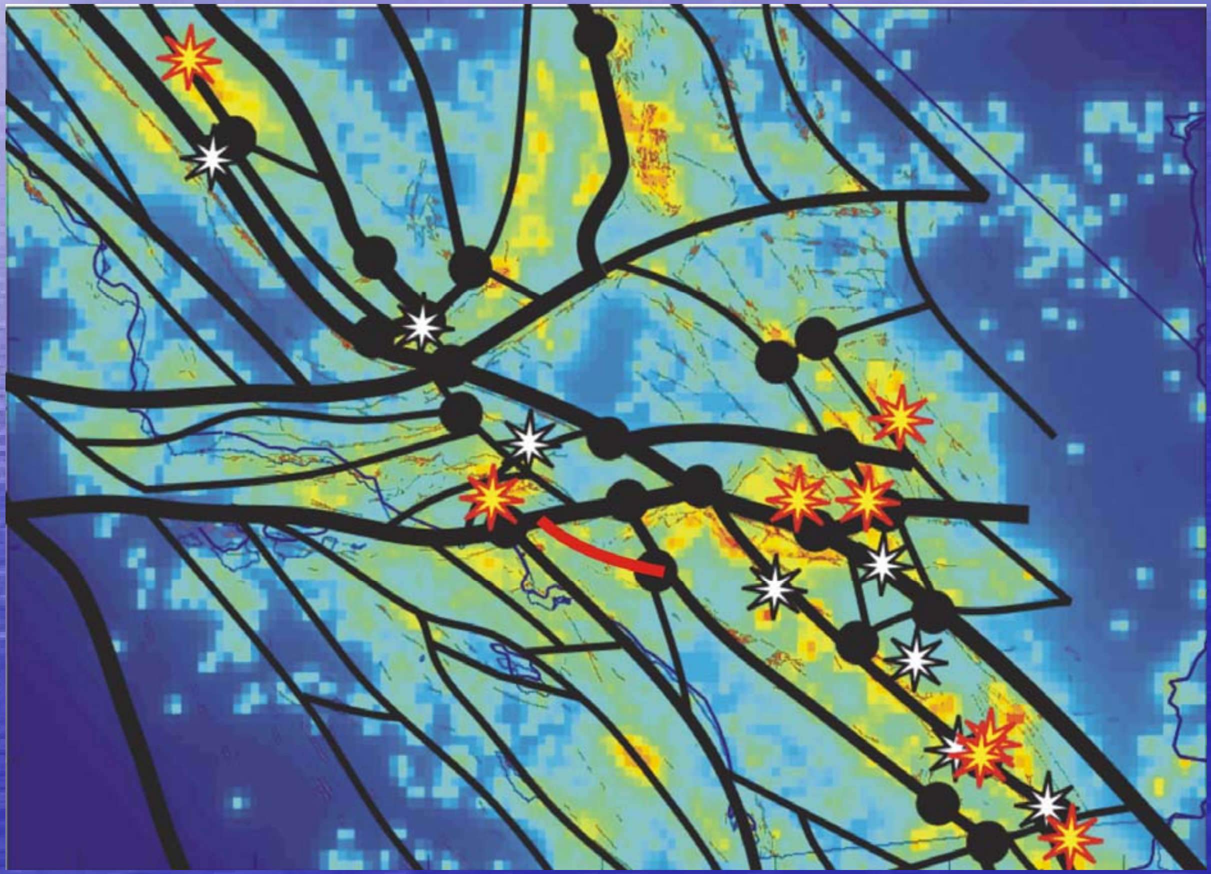
- The 73 D-intersections of morphostructural lineaments in California and Nevada determined by *Gelfand et al.* (1976) as earthquake-prone for magnitude 6.5+ events. Since 1976 fourteen magnitude 6.5+ earthquakes occurred, all in a narrow vicinity of the D-intersections

Region: **PAKISTAN 14 km off Muzaffarabad**
Date Time: **2005/10/08 03:50:36.4 UTC**
Location: **34.47 N ; 73.50 E**
Depth: **10 km**
Magnitude: **7.7**

An example of term-less prediction



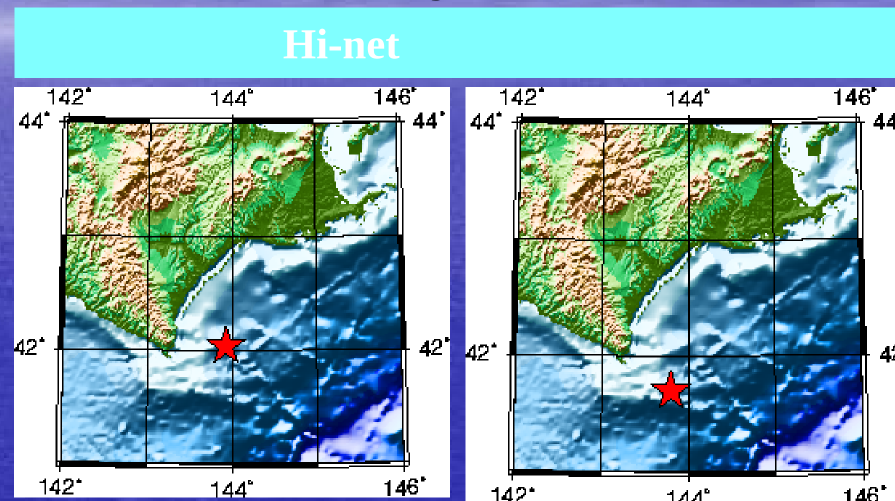
At least one of the newly discovered faults, i.e., the Puente Hills thrust fault (J.H. Shaw and Shearer P.M., 1999. An elusive blind-thrust fault beneath metropolitan Los Angeles. *Science*, **238**, 1516-1518), **coincides exactly with the lineament drawn in 1976.**



PLANETS ALIGN:
On Wednesday morning, September 24th, 2003 a lovely trio appeared in the eastern sky: **Jupiter, the crescent moon and Mercury…**

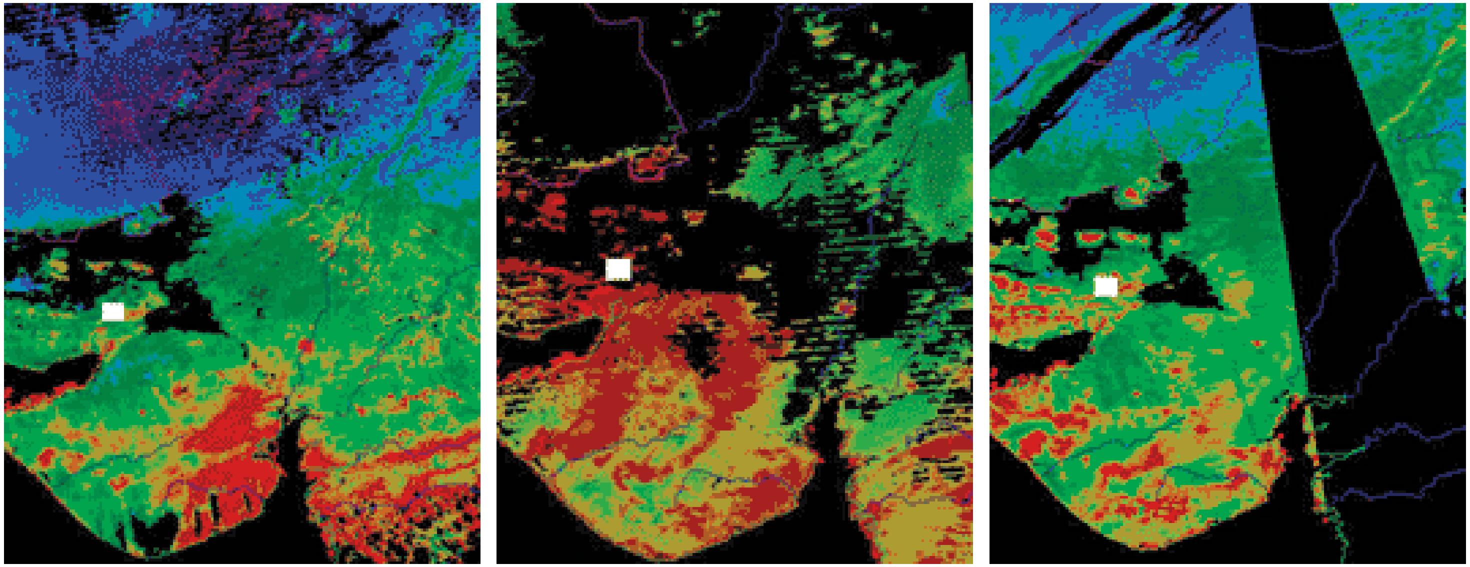
Is it a coincidence or a law?

Two days later …



2003□9□26□04□50□11□	2003□9□26□06□08□03□
□□42.0□	□□41.8□
□□143.9□	□□143.9□
□□25km	□□35km
M7.7	M7.4

Isn’t it a coincidence ?



WARM BEFORE THE STORM: An earthquake killed more than 20 000 people on 26 January 2001 in the Indian state of Gujarat. NASA's Terra satellite made infrared maps of the region on 6, 21, and 28 January [left to right]. Five days before the earthquake [middle], the area near the epicenter [white square] gave off an unusual amount of infrared radiation [red]. Just two days after the quake [right], the radiation was gone.

IMAGES: NASA

“Orbit of DEMETER above Japon on August 29, 2004. The star indicates the epicenter of an earthquake of

Isn’t it a coincidence ?

The explosive eruption of Asama volcano on September 01, which ash-fall covered a narrow elongated area reaching ca 250 km to Pacific Ocean seems a better alternative than the two earthquakes of M7.2 and M7.4 on September 05, 2004 in Japan, doesn’t it ?

are desaturated).”

- One or even a few observations is not enough to claim causality and reject the alternative of coincidence by chance.
- Probability theory helps when a long series of observations permits to suggest a suitable *probability model*.

“The analysis of data inevitably involves some trafficking with the field of *statistics*, that gray area which is not quite a branch of mathematics - and just as surely not quite a branch of science. In the following sections, you will repeatedly encounter the following paradigm:

- apply some formula to the data to compute "a statistic"
- compute where the value of that statistic falls in a probability distribution that is computed on the basis of some "null hypothesis"
- if it falls in a very unlikely spot, way out on a tail of the distribution, conclude that the null hypothesis is *false* for your data set

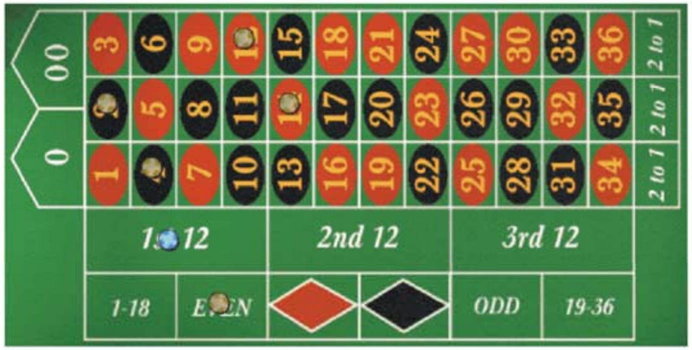
If a statistic falls in a *reasonable* part of the distribution, you must not make the mistake of concluding that the null hypothesis is "verified" or "proved". That is the curse of statistics, that it can never prove things, only disprove them! At best, you can substantiate a hypothesis by ruling out, statistically, a whole long list of competing hypotheses, every one that has ever been proposed. After a while your adversaries and competitors will give up trying to think of alternative hypotheses, or else they will grow old and die, and *then your hypothesis will become accepted*. Sounds crazy, we know, but that's how science works!”

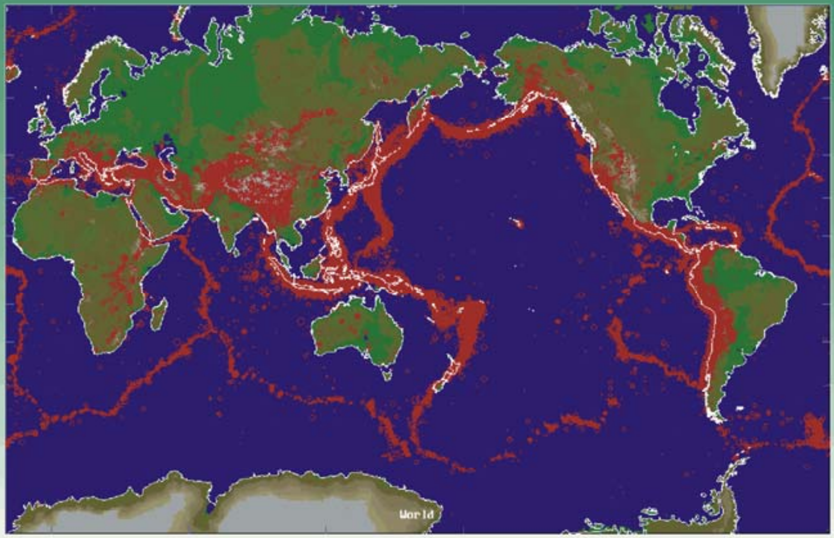
(William H. Press et al., *Numerical Recipes*, p.603)

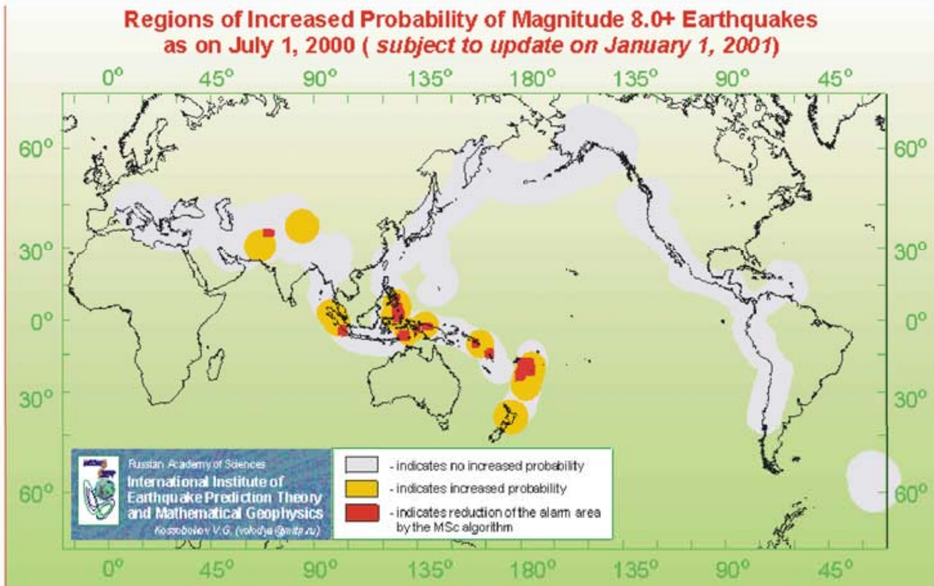
"Earthquakes are so complicated that we must apply some Statistics."

Keiiti Aki (1930-2005)

Seismic Roulette







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! ☺ ☺ ☹ ☺ ☺ ☺ ☹ ☺ ☺ ☺

Statistical significance and effectiveness of predictions

A statistical conclusion about the effectiveness and reliability of an earthquake prediction algorithm could be attributed in the following way.

Let **T** and **S** be the total time and territory considered; A_t is the territory covered by the alarms at time t; $\tau\times\mu$ is a measure on **T**×**S** (we consider here a direct product measure $\tau\times\mu$ reserving a general case of a time-space dependent measure ν for future more sophisticated null-hypotheses); **N** counts the total number of large earthquakes with $M \geq M_0$ within **T**×**S** and **n** counts how many of them are predicted. The time-space occupied by alarms, $\mathbf{A} = \bigcup_{T} A_t$, in percentage to the total space-time considered equals

$$\boldsymbol{p} = \int_{A} \mathrm{d}(\tau \times \mu) \Big/ \int_{T\times S} \mathrm{d}(\tau \times \mu) .$$

The statistical significance level of the prediction results equals

$$1 - B(\mathbf{n-1}, \mathbf{N}, \boldsymbol{p}),$$

where B is the cumulative binomial distribution function.

Measure $\tau\times\mu$: For time we assume the uniform measure τ, which corresponds to the Poisson, random recurrence of earthquakes. For space we assume the measure μ proportional to spatial density of epicenters. Specifically, the measure μ of an area is proportional to the number of epicenters of earthquakes from a sample catalog.

This simple comparison with random guessing apply to any prediction method

- GAP theory
- Quiescence hypothesis
- the VAN method
- the Jackson-Kagan forecast probability maps
- the Kushida method
- etc

Surprisingly, most of the authors seem avoiding real-time testing, evaluation and verification...

How earthquake prediction methods work?

"Predicting earthquakes is as easy as one-two-three.

- Step 1: Deploy your precursor detection instruments at the site of the coming earthquake.

Routine seismological data bases, e.g. US GS/NEIC

- Step 2: Detect and recognize the precursors.

Reproducible intermediate-term algorithms, e.g. M8

- Step 3: Get all your colleagues to agree and then publicly predict the earthquake through approved channels."

Number of earthquakes have been predicted

Scholz, C.H., 1997. Whatever happened to earthquake prediction. *Geotimes*, 42(3), 16-19

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

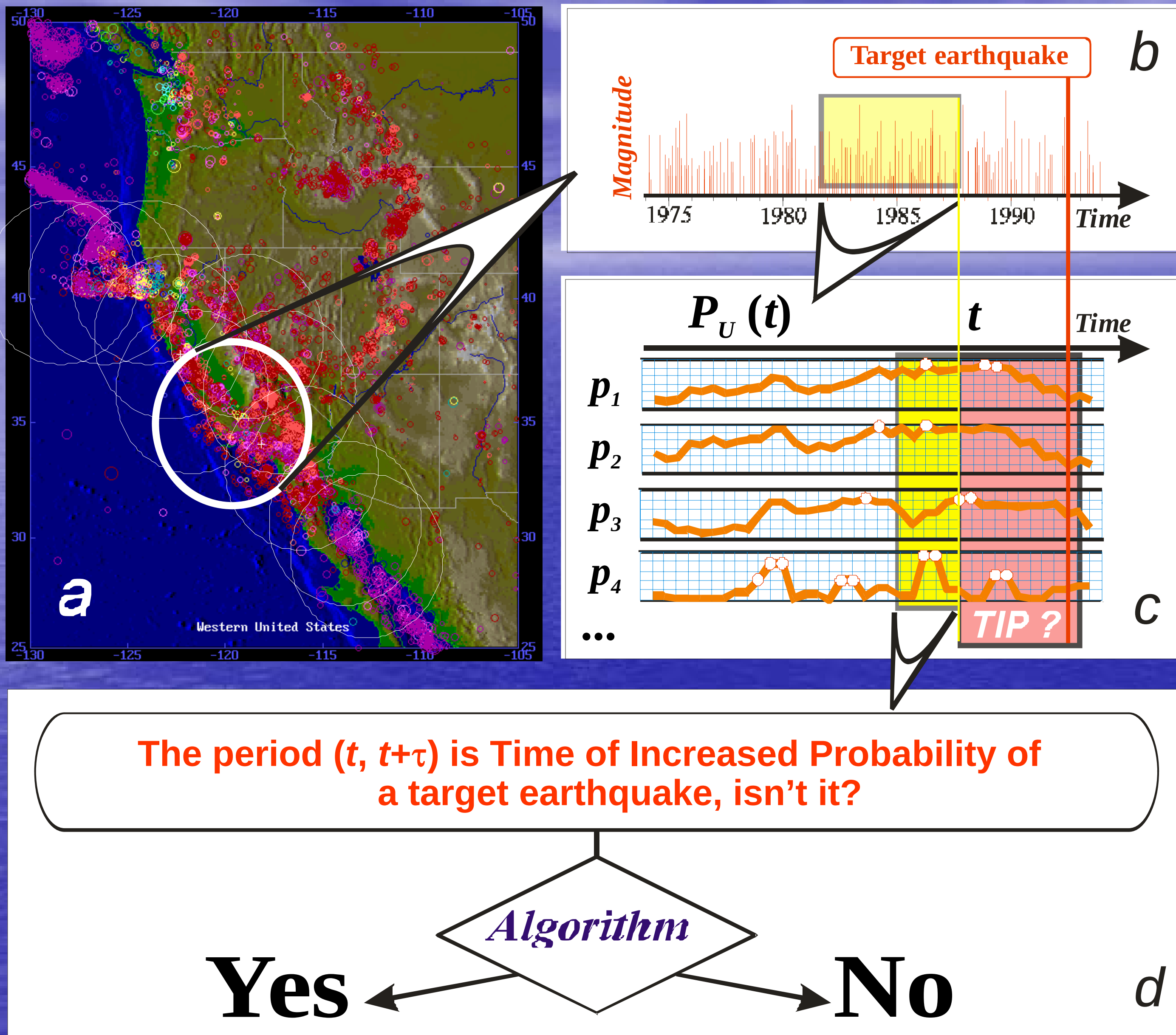
M8 algorithm

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.

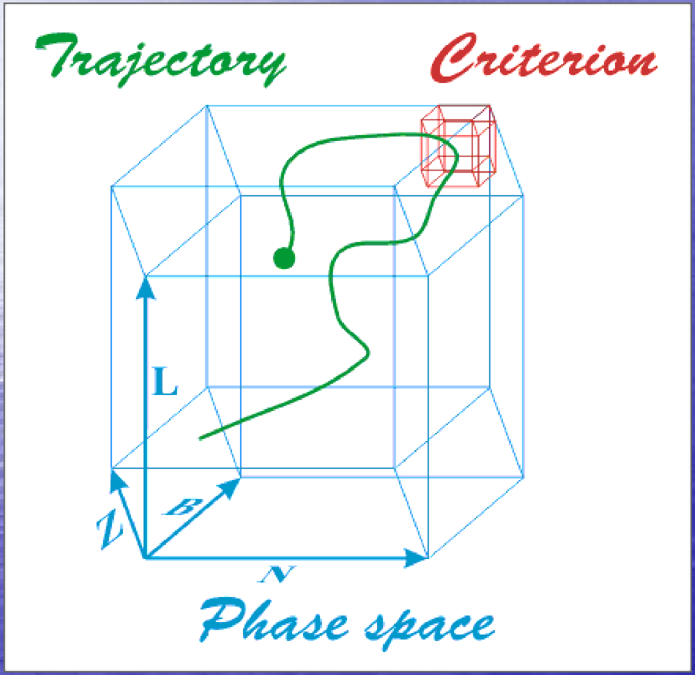
Its prototype (***Keilis-Borok and Kossobokov, 1984***) and the original version (***Keilis-Borok and Kossobokov, 1987***) were tested retroactively. The original version of M8 is subject to the on-going real-time experimental testing. After a decade the results confirm predictability of the great earthquakes beyond any reasonable doubt.

The algorithm is based on a simple physical scheme…

General scheme of prediction



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.

M8 algorithm performance

(in the retrospect applications)

- 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.

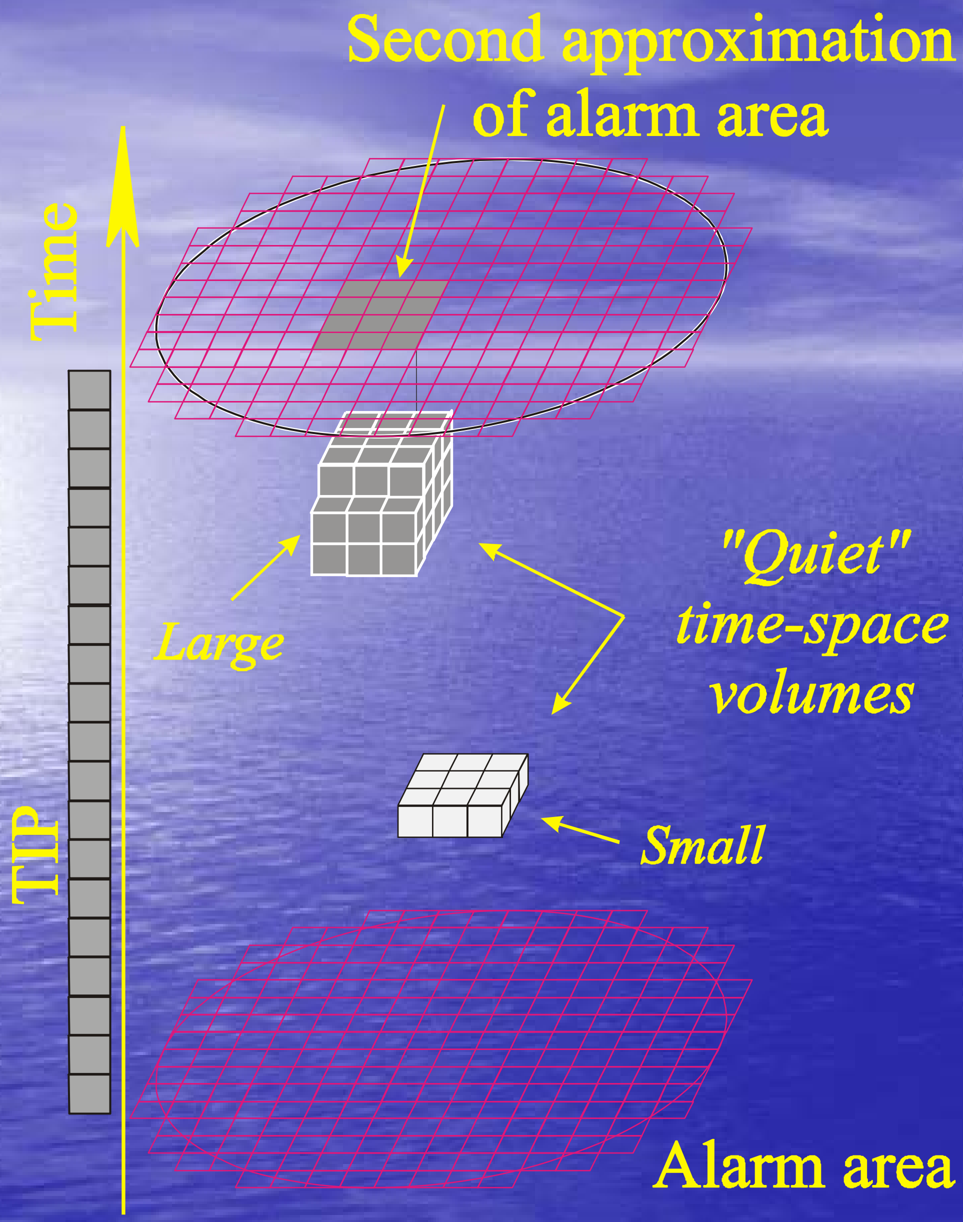
Second approximation prediction method

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.

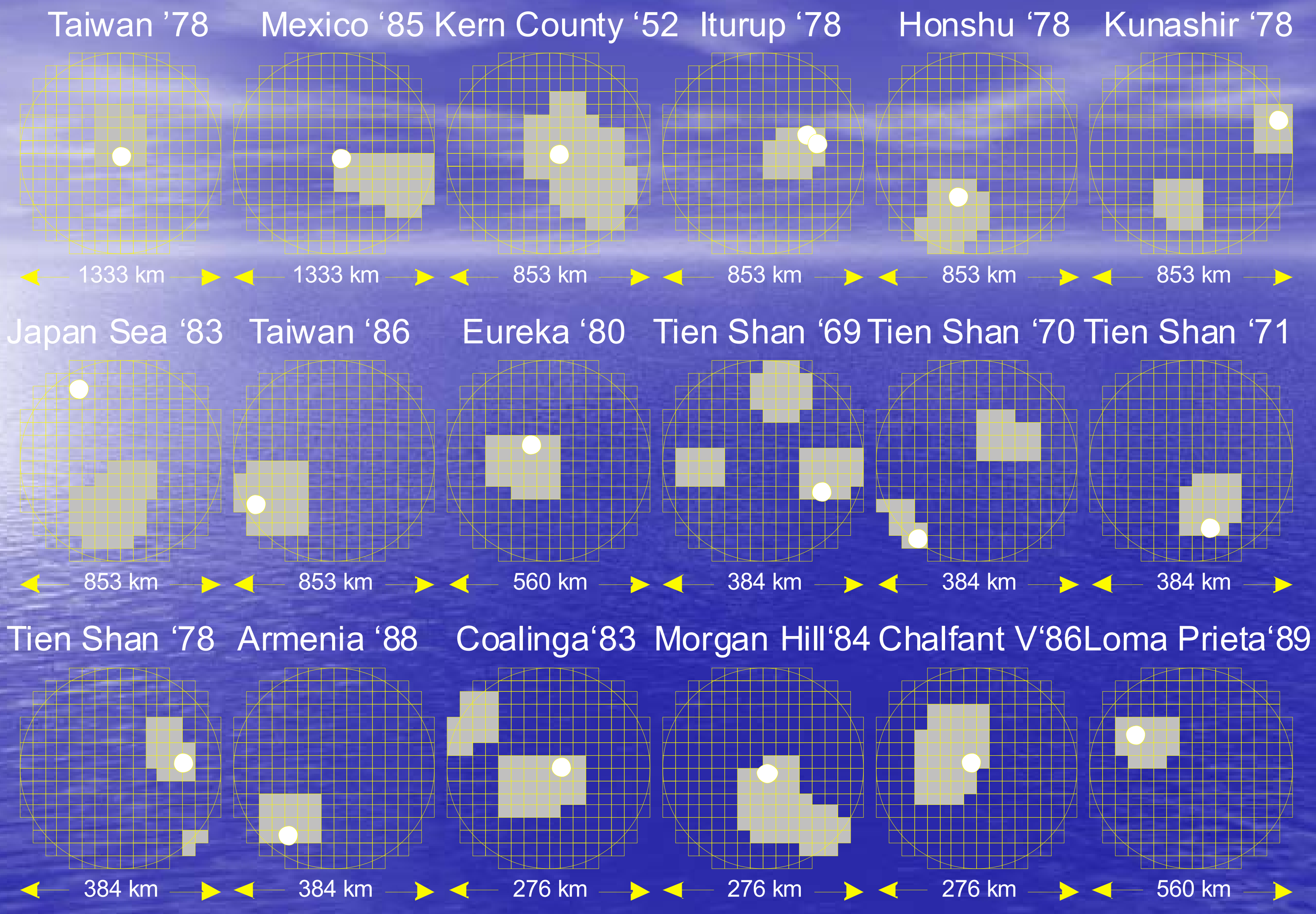
The phenomenon, which is used in the MSc algorithm, might reflect the second (possibly, shorter-term and, definitely, narrow-range) stage of the premonitory rise of seismic activity near the incipient source of main shock.

The MSc Algorithm



The prediction is localized to a spatial projection of all recent "sufficiently large" clusters of squares being in state of "anomalous quiescence".

"Anomalous quiescence" suggests high level of seismic activity during formation of a TIP and after its declaration. "Sufficiently large" size of clusters suggests large scale correlations in the recent times.

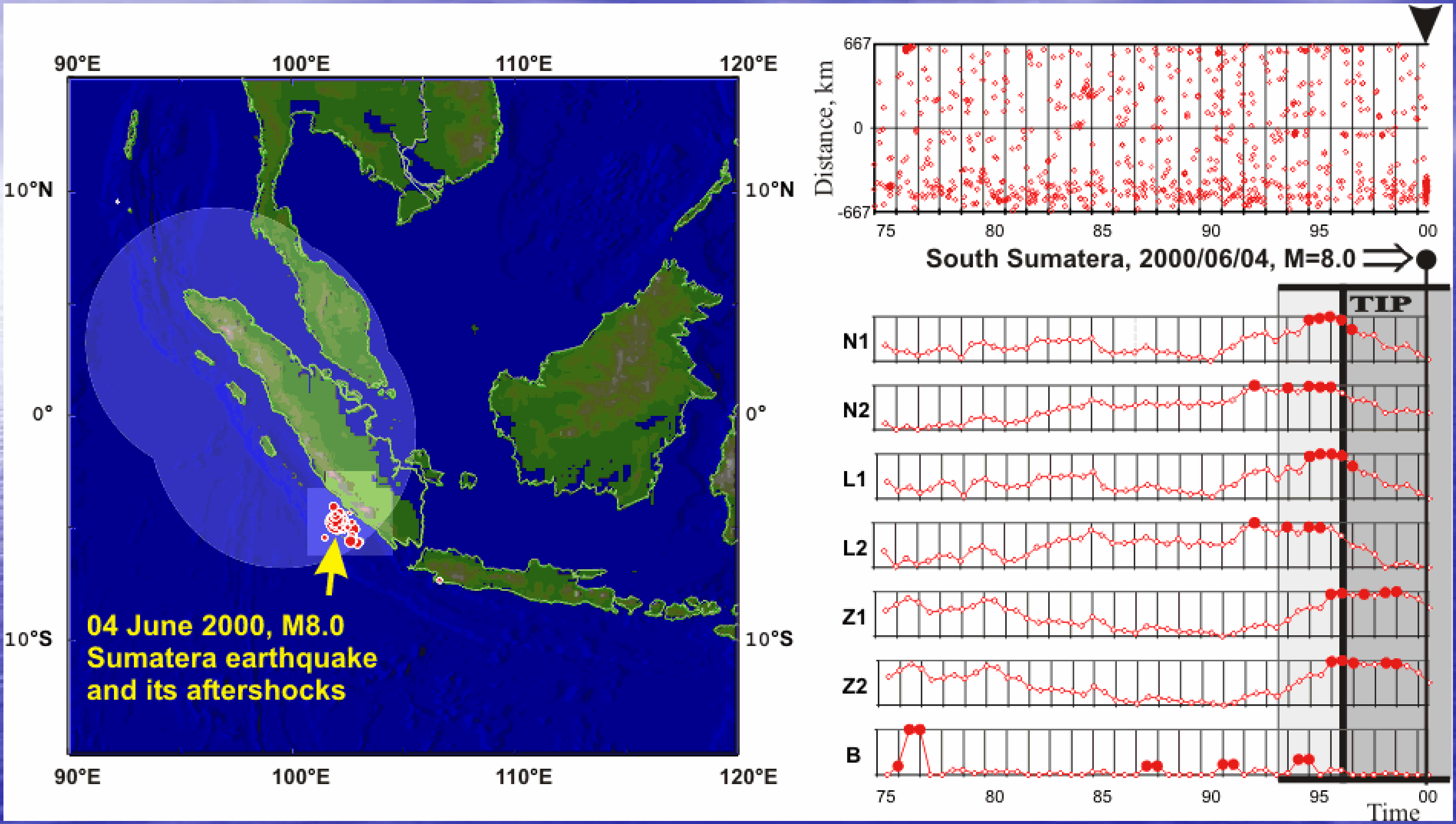


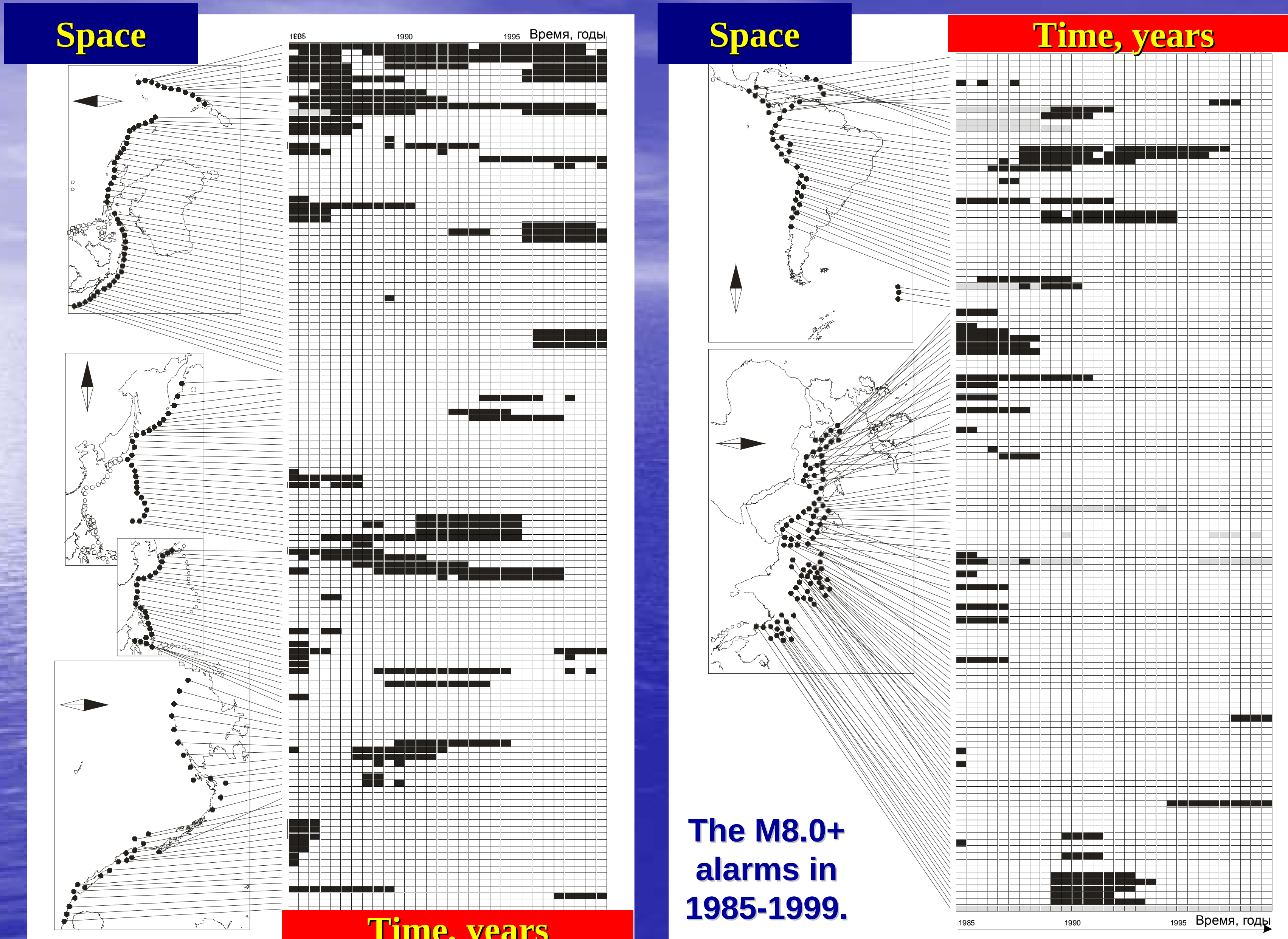
Taiwan '78
Mexico '85
Kern County '52
Iturup '78
Honshu '78
Kunashir '78
1333 km
1333 km
853 km
853 km
853 km
853 km
Japan Sea '83
Taiwan '86
Eureka '80
Tien Shan '69
Tien Shan '70
Tien Shan '71
853 km
853 km
560 km
384 km
384 km
384 km
Tien Shan '78
Armenia '88
Coalinga'83
Morgan Hill'84
Chalfant V'86
Loma Prieta'89
384 km
384 km
276 km
276 km
276 km
560 km

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.

Case history of the 04/06/2000 South Sumatera Earthquake

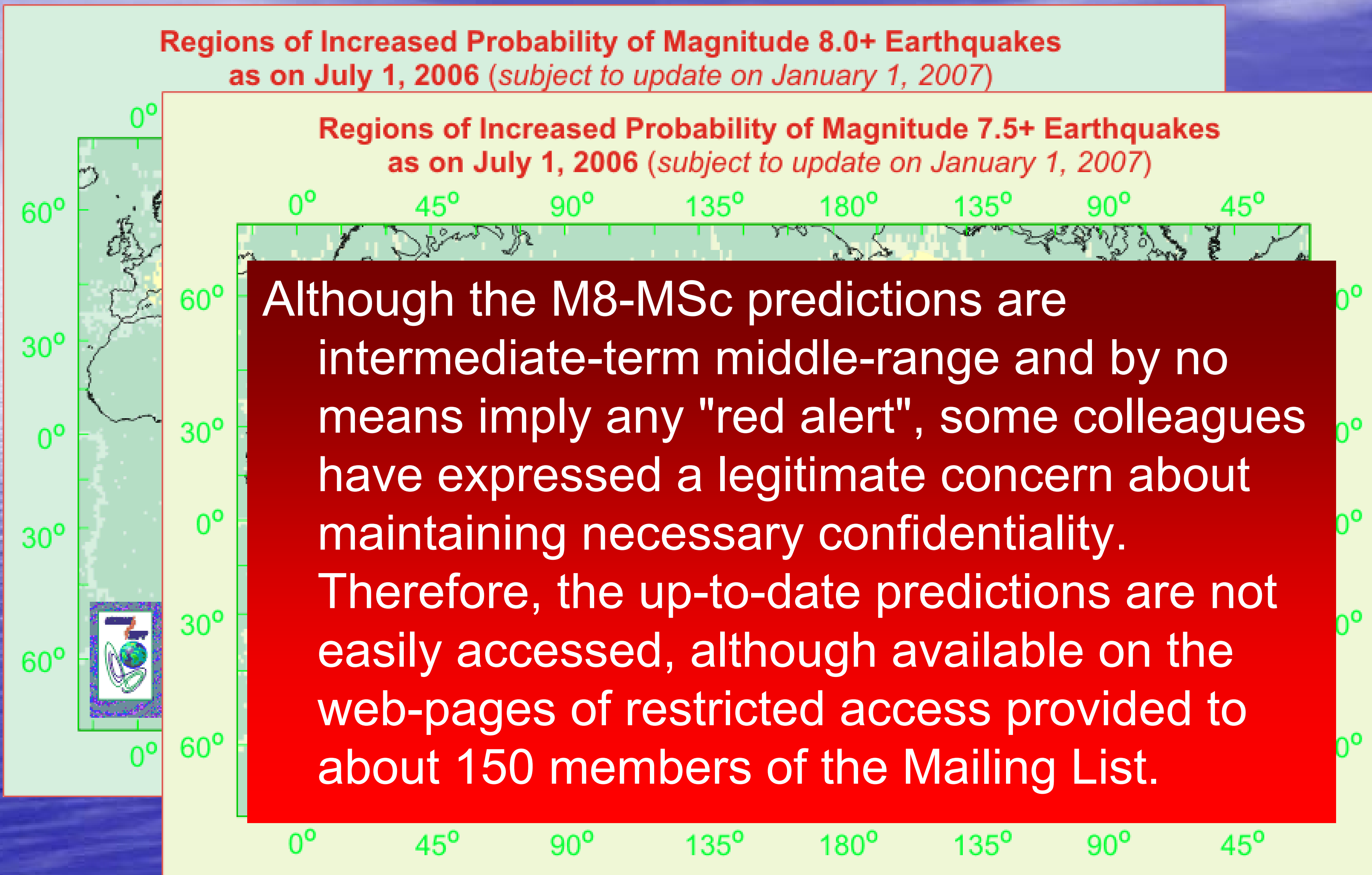




The M8.0+ alarms in 1985-1999.

Real-time prediction of the world largest earthquakes

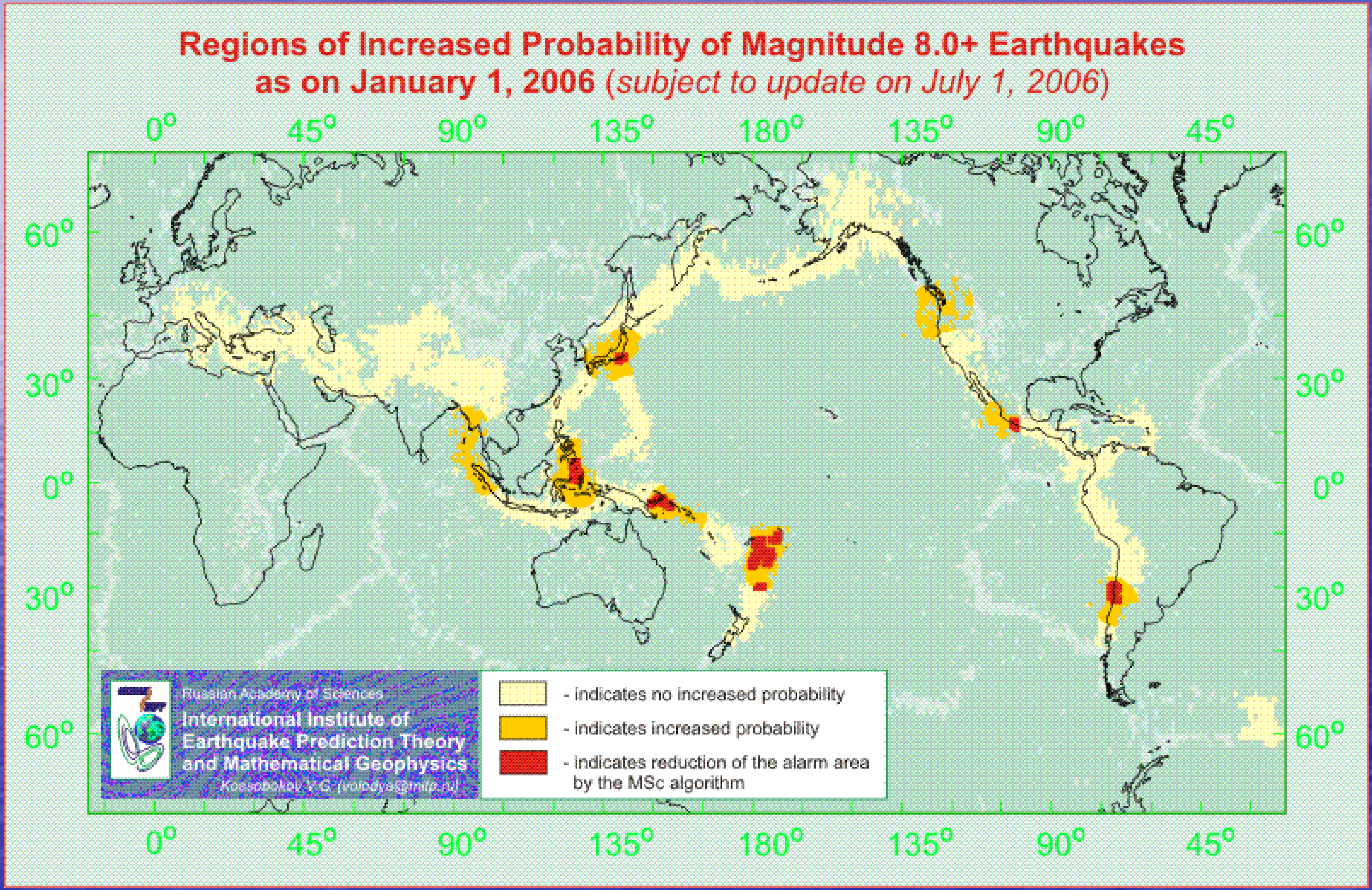
(http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp)



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)



TONGA 06/05/03 15:26:35 UTC: The first automatic determinations

Epicenter 20.03S 174.23W

BROADBAND SOURCE PARAMETERS

Energy Magnitude: Me 8.3

Radiated Energy: Es 6.3*10**16 Nm

No. of sta: 12 Focal mech. F

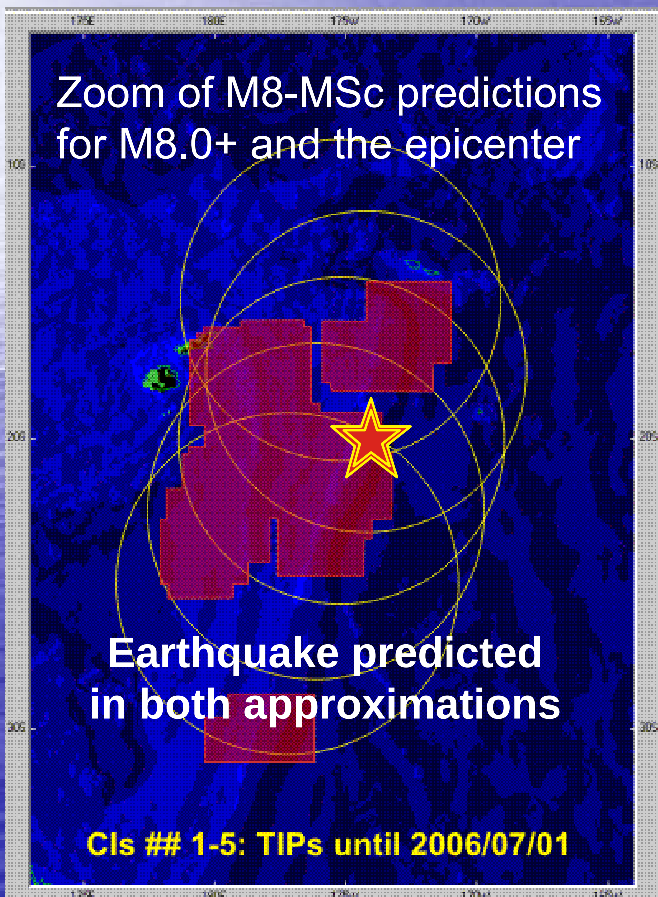
Epicenter: -20.035 -174.227

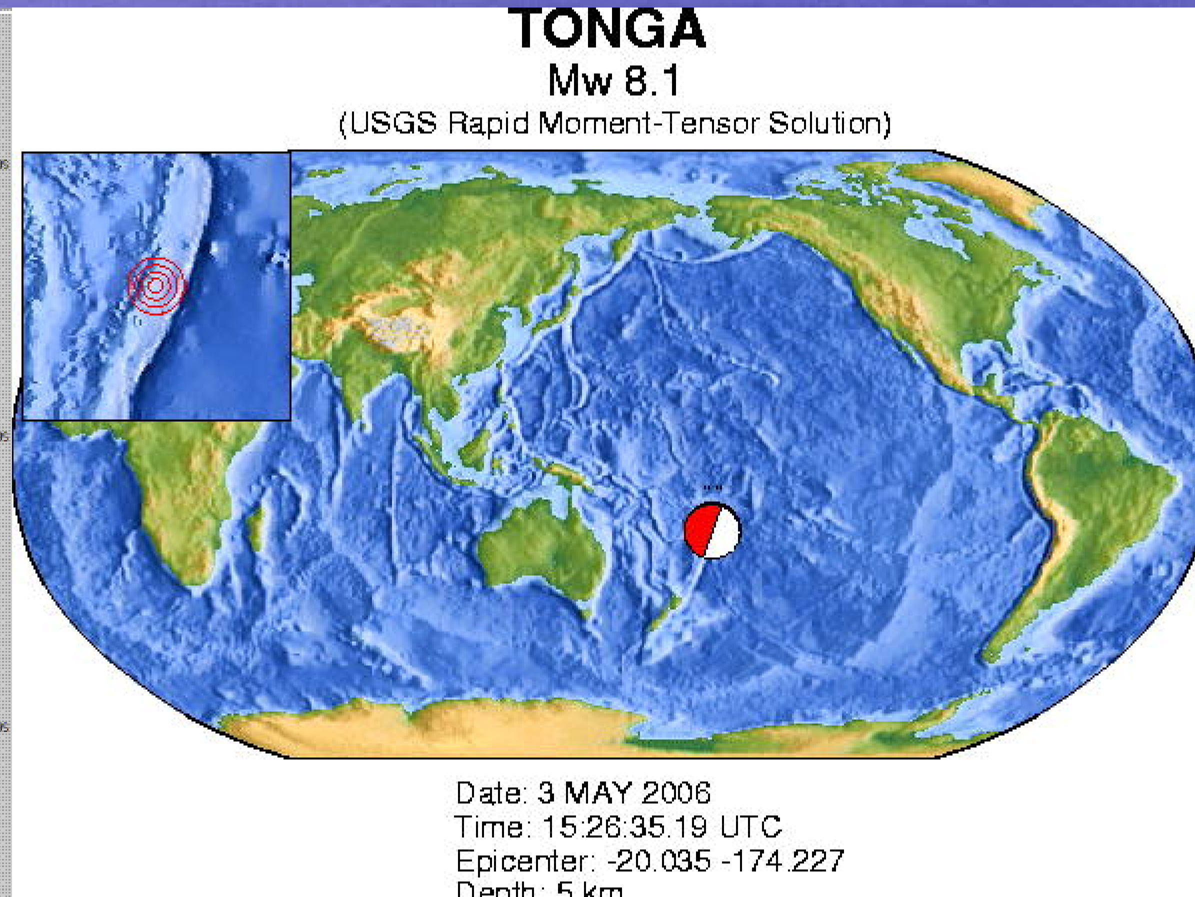
Depth 5 No. of sta: 44

USGS MOMENT TENSOR SOLUTION

Best Double Couple:Mo=1.8*10**21 Nm

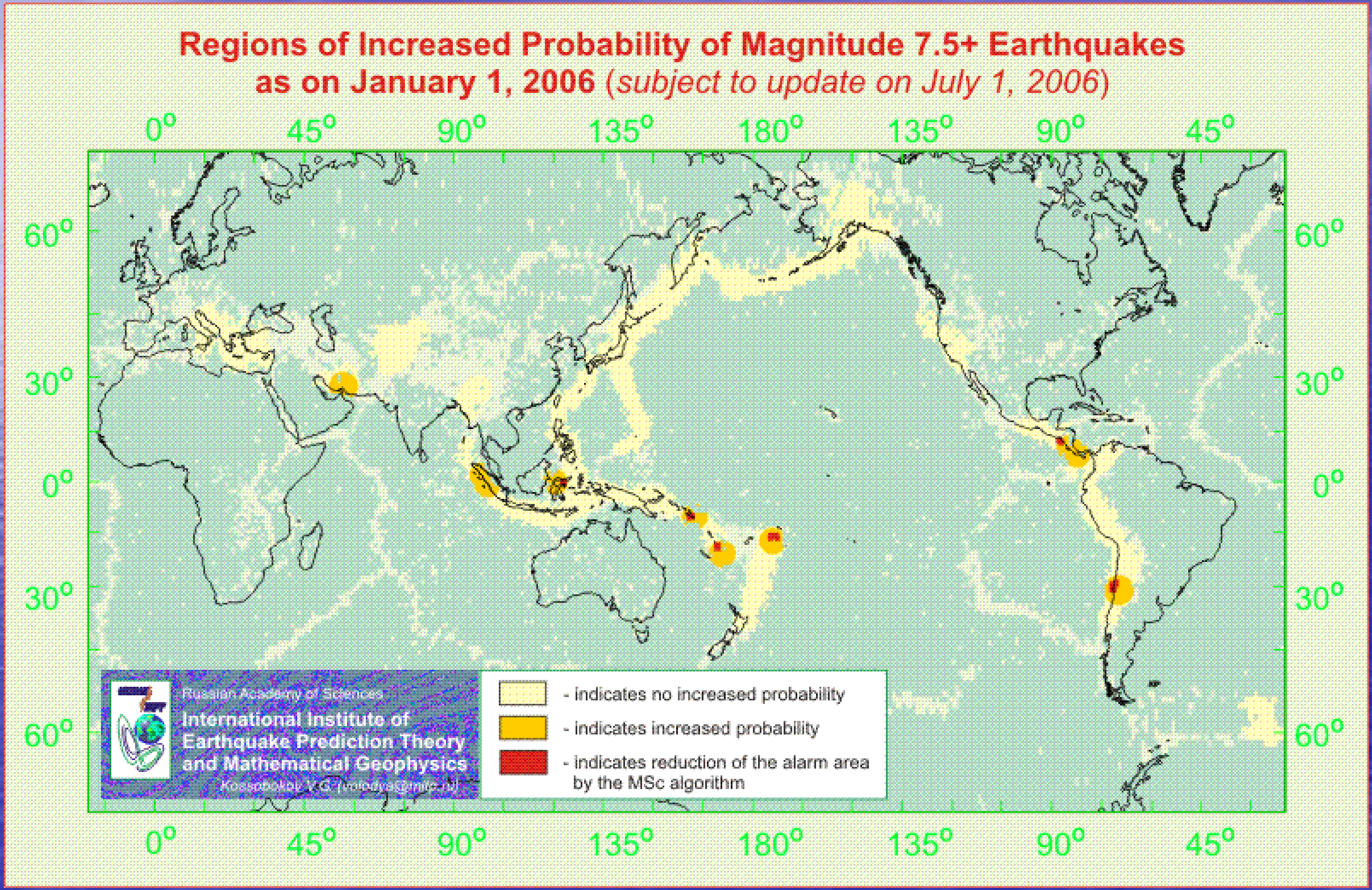
Moment magnitude: MW 8.1





Real-time prediction of the world largest earthquakes

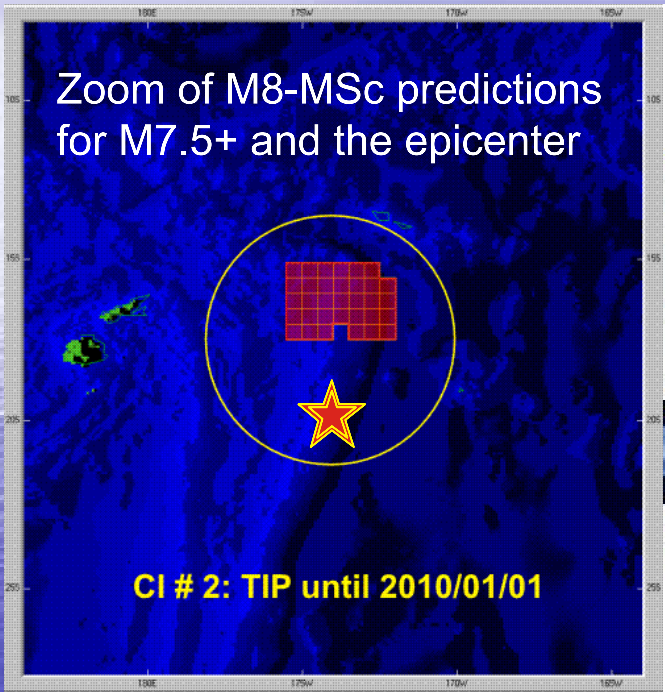
(http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp)



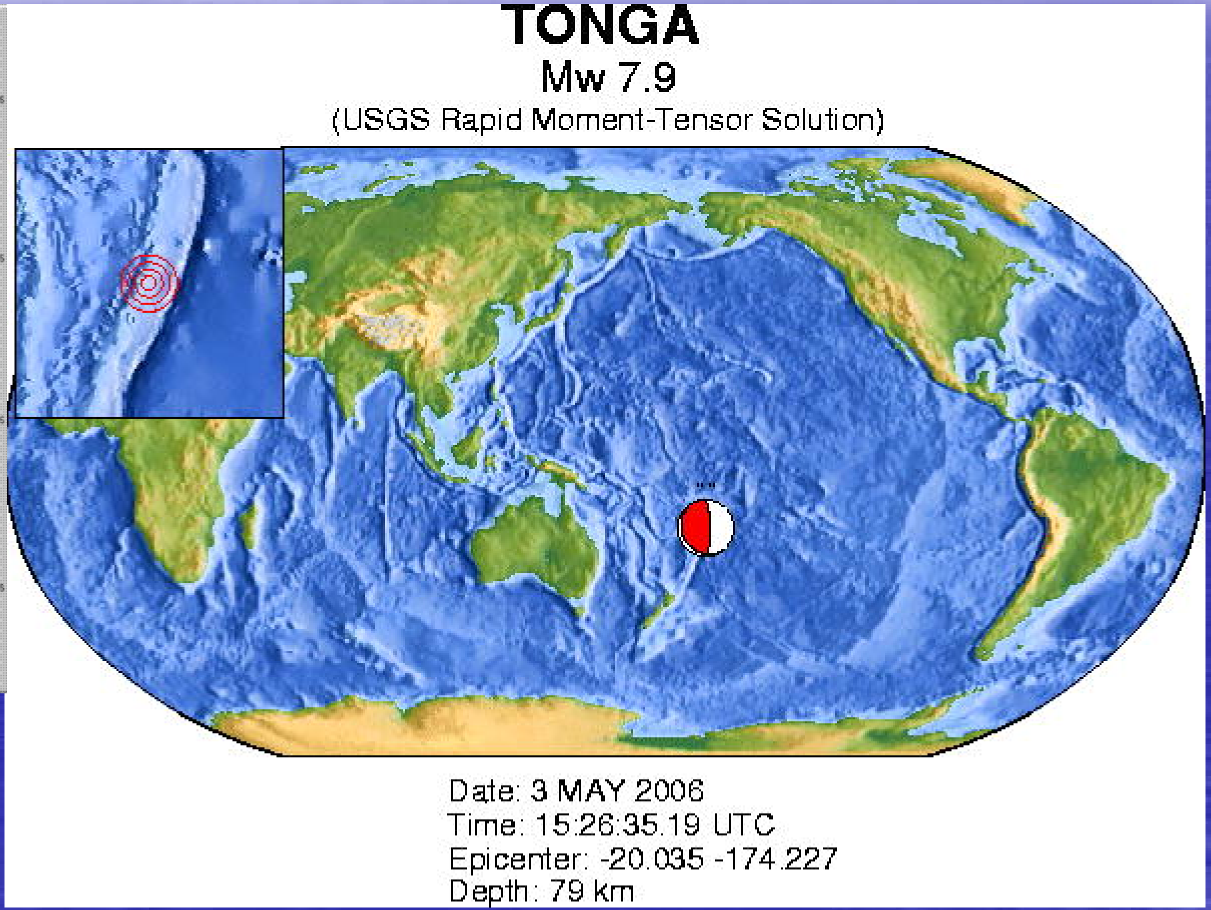
TONGA 06/05/03 15:26:35 UTC: Updated determinations

The magnitude and location may be revised when additional data and further analysis results are available.

Epicenter: -20.035 -174.227
Depth 79 No. of sta: 13
USGS MOMENT TENSOR SOLUTION
Best Double Couple:Mo=8.5*10**20 Nm
Moment magnitude: MW 7.9



Earthquake predicted in the M8 approximation and missed by MSc



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

Test period	Large earthquakes: Total	Large earthquakes: Predicted by M8	Large earthquakes: 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	33.24	17.14	99.87	99.92
1992-present	9	7	5	28.42	14.37	99.69	99.54

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.

Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 7.5 or more.

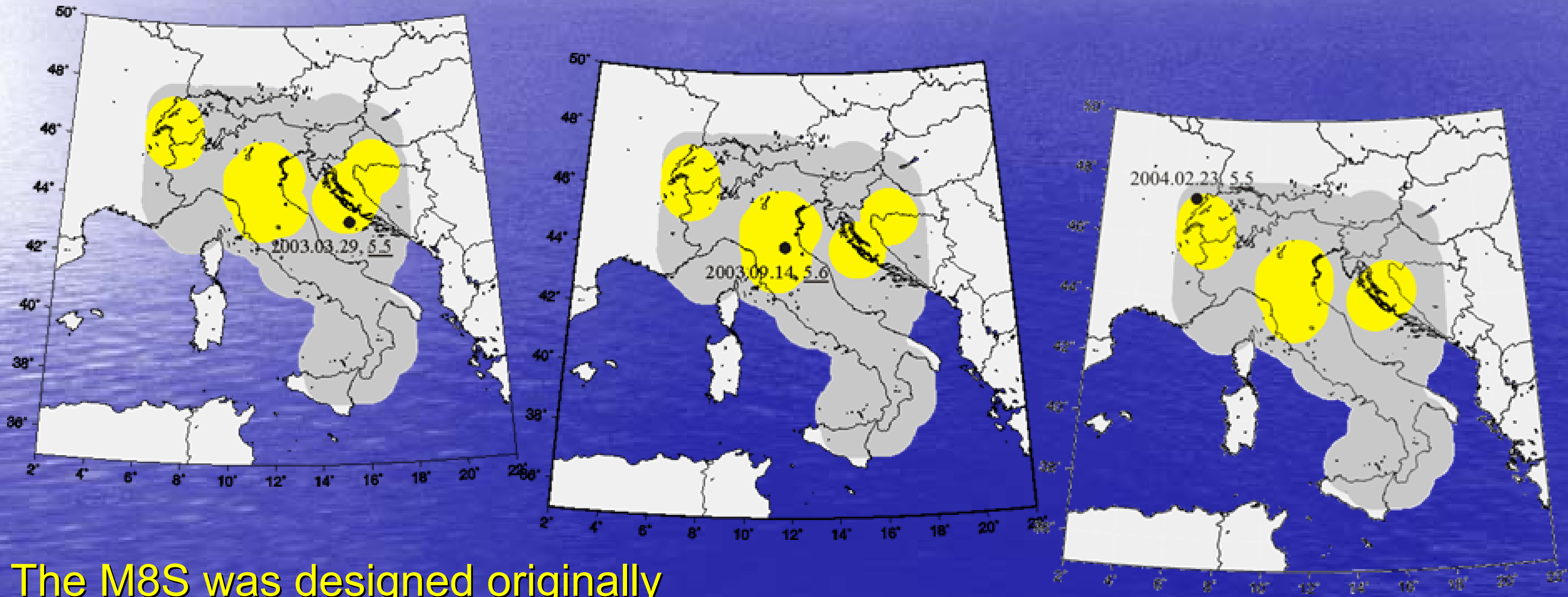
Test period	Large earthquakes			Measure of alarms, %		Confidence level, %	
	Total	Predicted by					
		M8	M8-MSc	M8	M8-MSc	M8	M8-MSc
1985-present	52	30	16	34.35	11.05	99.95	99.99
1992-present	40	20	10	28.77	10.45	99.34	99.43

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

The prediction for M7.5+ is less effective than for M8.0+.

Nevertheless, we continue testing the algorithms for this and smaller magnitude ranges.

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.



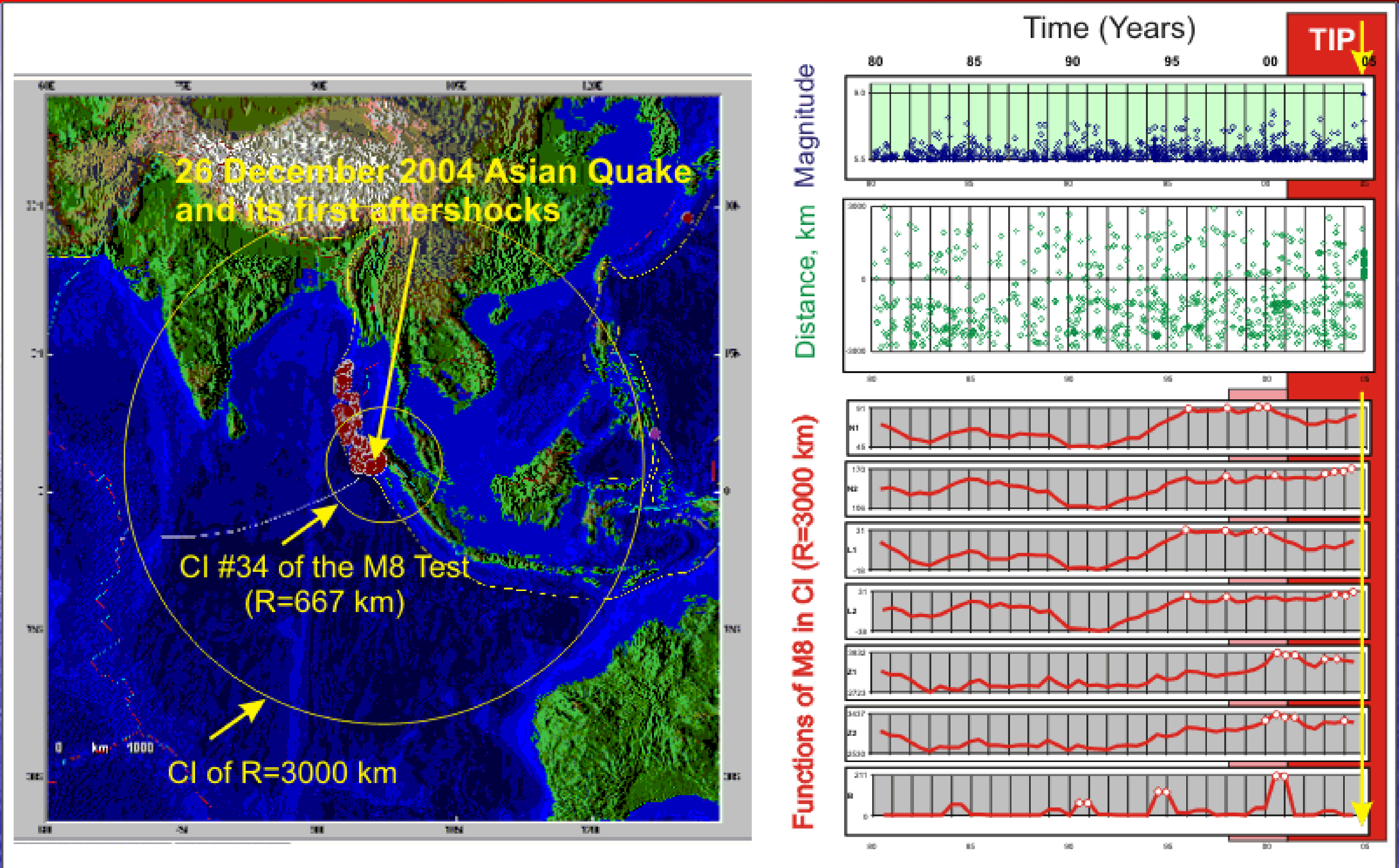
The M8S was designed originally to improve reliability of predictions made by the modified versions of the M8 algorithm applicable in the areas of deficient earthquake data available.

The recent disaster in Indian Ocean

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. Unfortunately, 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.

The December 26 event seems to be the first indication that the algorithm, designed for prediction of M8.0+ earthquakes can be rescaled for prediction of both smaller magnitude earthquakes (e.g., down to M5.5+ in Italy http://www.mitp.ru/m8s/M8s_italy.html) and for mega-earthquakes of M9.0+. The event is not full verification, but very important for general understanding of our methodology (*Nonlinear Dynamics of the Lithosphere and Earthquake Prediction. Keilis-Borok, V.I., & A.A. Soloviev (Eds). Springer, Heidelberg, 2003*) and the Problem of Earthquake Prediction.

26/12/2004 Mw9.0 Great Asian mega-thrust earthquake



The relevant observation:

- All the largest four mega-earthquakes of the 20th century (*Kamchatka, 1952/11/04, Mw9.0; Andreanoff Islands, 1957/03/09, Mw9.1; Chile, 1960/05/22, Mw9.5; Alaska, 1964/03/28, Mw9.2*) happened within a narrow interval of time. Such a cluster is unlikely with a 99% confidence for uniformly distributed independent events.
- **Since good evidence suggests that seismic events including mega-earthquakes cluster, it is possible that we will have further confirmation of the prediction within 5-10 years in other regions.**
- The 28 March 2005 Nias Mw8.7 mega-earthquake seems to be the first confirmation.

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.

Conclusions – *Seismic Roulette is not perfect*

Are these predictions useful?

- Yes, if used in a knowledgeable way.
- Their accuracy is already enough for undertaking earthquake preparedness measures, which would prevent a considerable part of damage and human loss, although far from the total.
- The methodology linking prediction with disaster management strategies does exist (*Molchan, 1997*).

Kofi Annan:

Introduction to Secretary-General's Annual Report on the Work of the Organization of United Nations, 1999 - A/54/1

"More effective prevention strategies would save not only tens of billions of dollars, but save tens of thousands of lives. Funds currently spent on intervention and relief could be devoted to enhancing equitable and sustainable development instead, which would further reduce the risk for war and disaster. Building a culture of prevention is not easy. While the costs of prevention have to be paid in the present, its benefits lie in a distant future. Moreover, the benefits are not tangible; they are the disasters that did NOT happen."

We have no luxury of postponing usage of the existing data on earthquakes to the benefit of population living in seismic regions.

Conclusions – *Implications for Physics*

- The predictions provide reliable empirical constrains for modeling earthquakes and earthquake sequences.
- Evidence that distributed seismic activity is a problem in statistical physics.
- Favor the hypothesis that earthquakes follow a general hierarchical process that proceeds via a sequence of inverse cascades to produce self-similar scaling (*intermediate asymptotic*), which then truncates at the largest scales bursting into direct cascades (*Gabrielov, Newman, Turcotte, 1999*).

What are the Next Steps?

- The algorithms are neither optimal nor unique (CN, SSE, Vere-Jones "probabilistic" version of M8, RTP, R.E.L.M., E.T.A.S., "hot spots", etc.). Their non-randomness could be checked and their accuracy could be improved by a systematic monitoring of the alarm areas and by designing a new generation of earthquake prediction technique.

... and an obvious general one -

- More data should be analyzed systematically to establish reliable correlations between the occurrence of extreme events and observable phenomena.

Thank you