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Seismic Hazard in Asia

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Earthquake Prediction & Unified Scaling Law for Earthquakes

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Quantitative Earthquake Prediction:

Basics, Implementation, Perspectives

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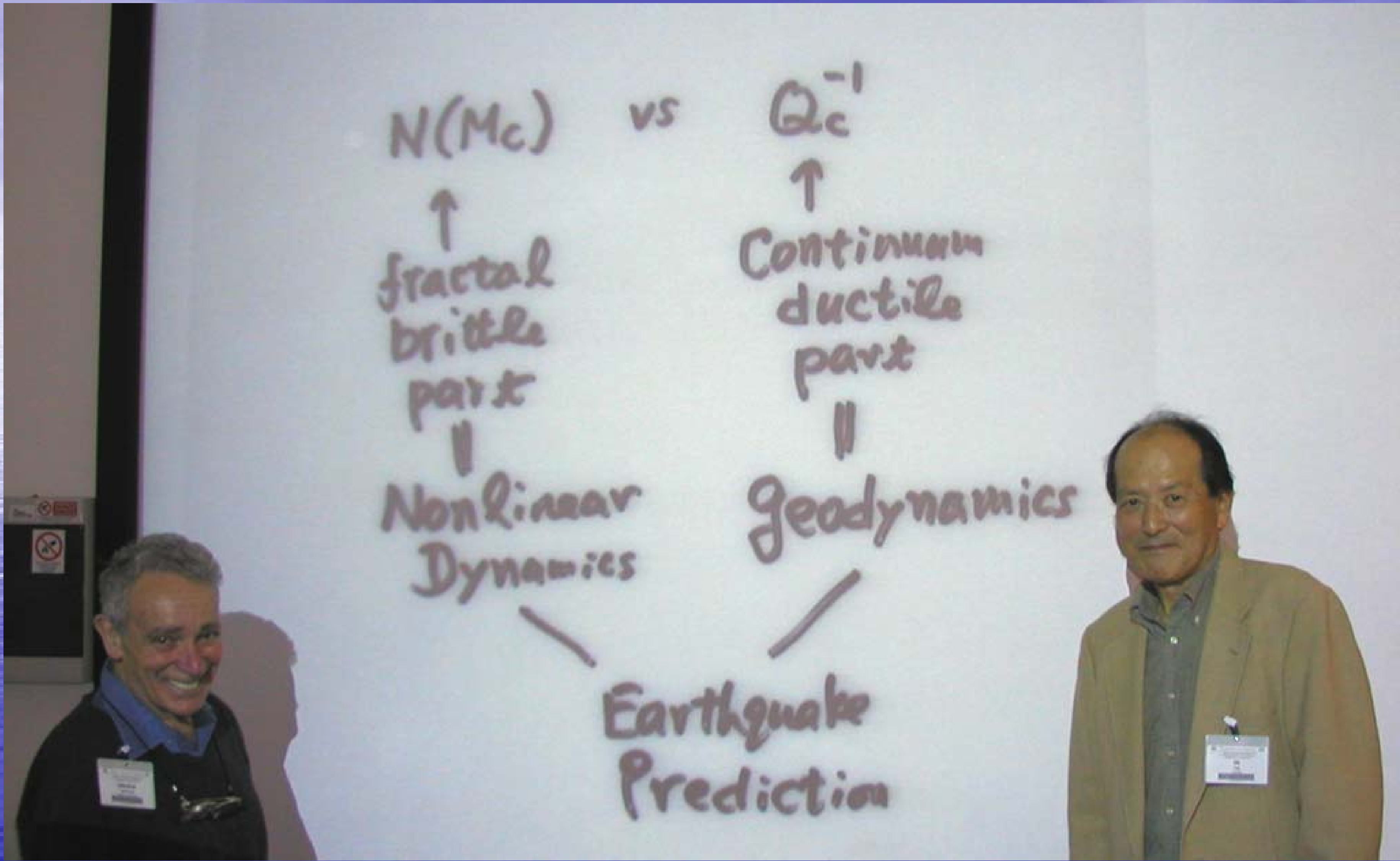

$N(M_c)$ vs Q_c^{-1}
fractal brittle part
Nonlinear Dynamics
Continuum ductile part
Geodynamics
Earthquake Prediction

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).

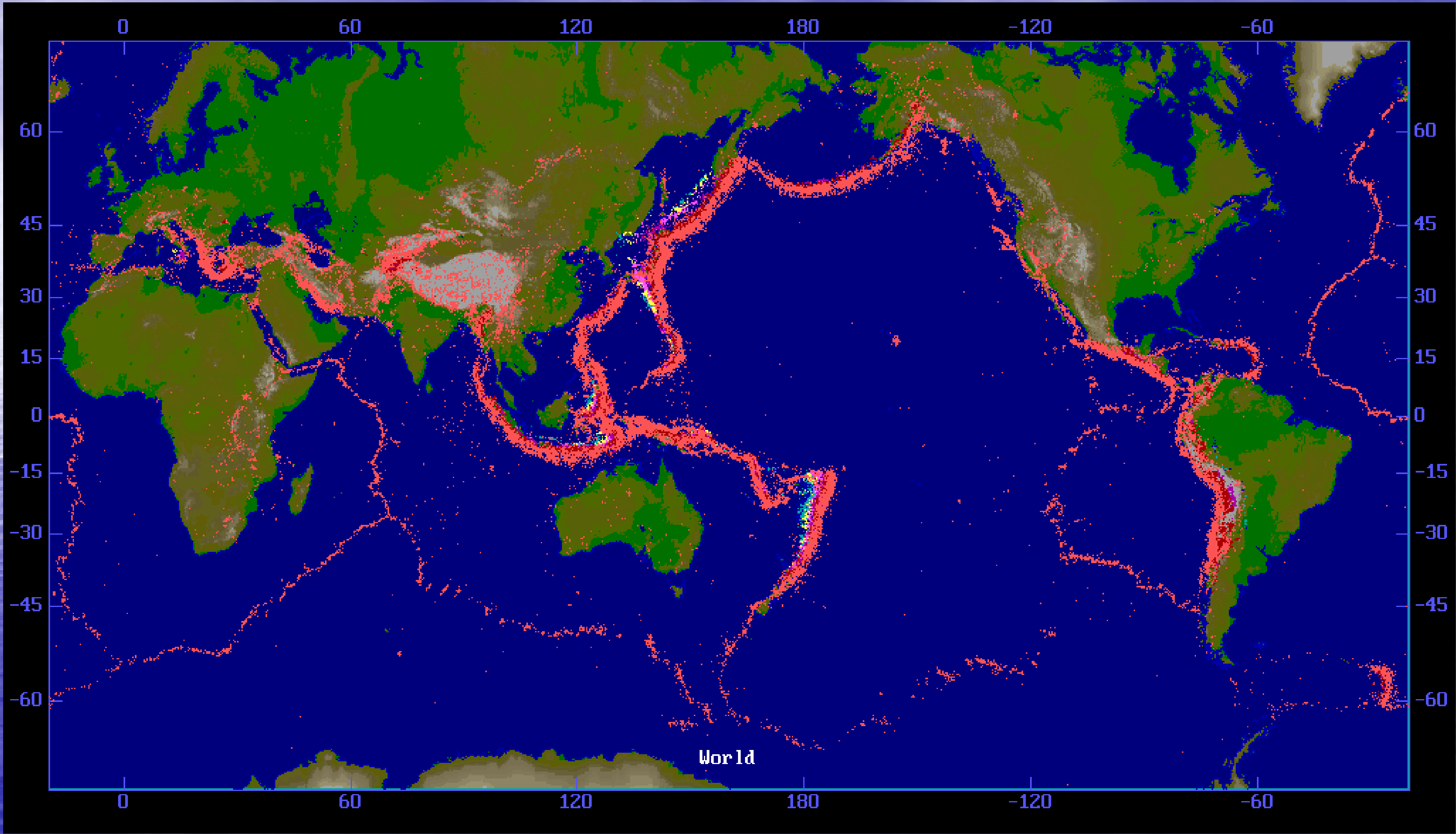
- Note that an application of the forecast/prediction tools could be very different in cases of different costs and benefits, and, therefore, requires determination of optimal strategies.
- In there turn case specific costs and benefits may suggest an optimal modification of the forecast/prediction tools.


...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?
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.

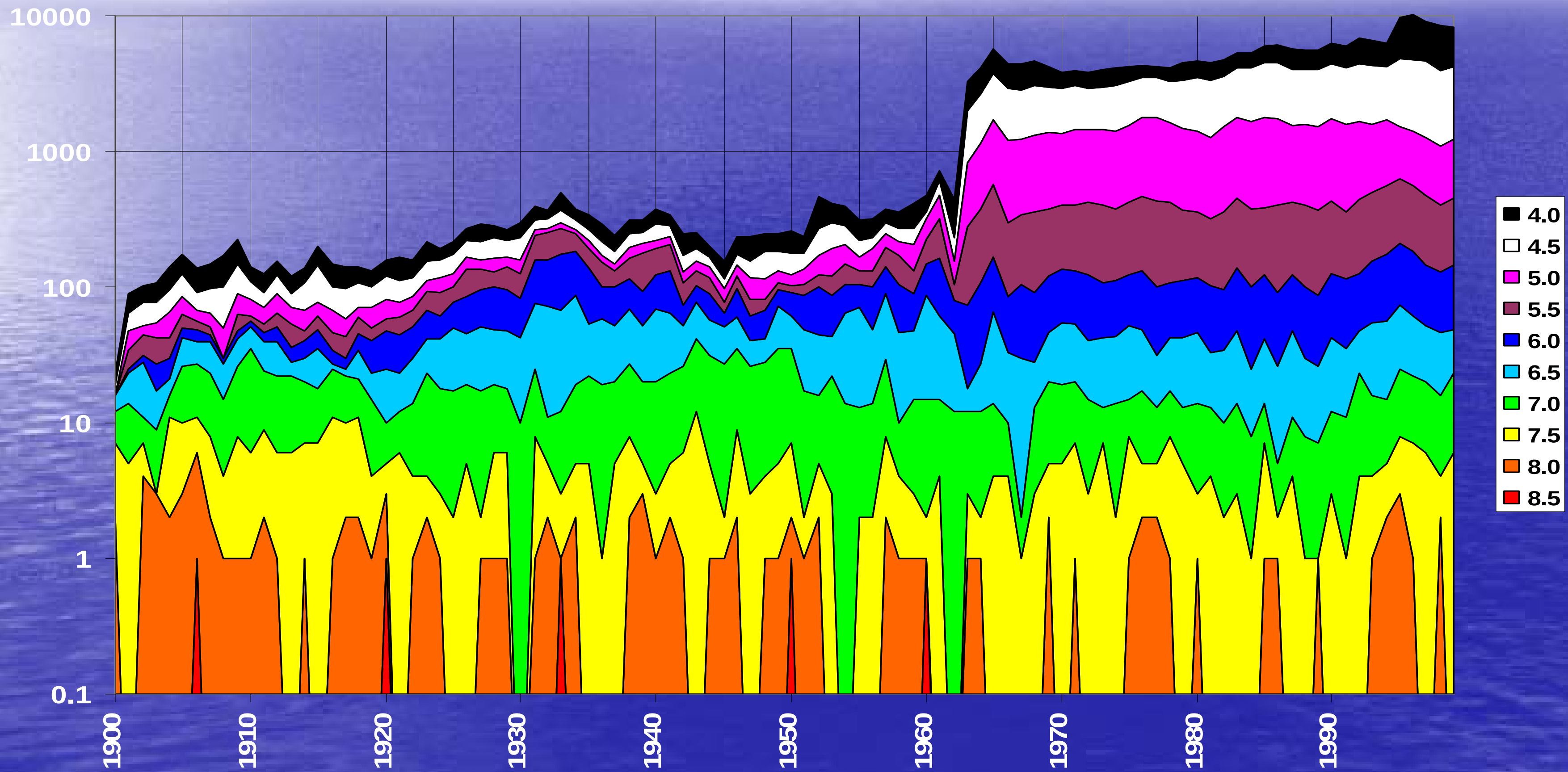
Where earthquakes happen...



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



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

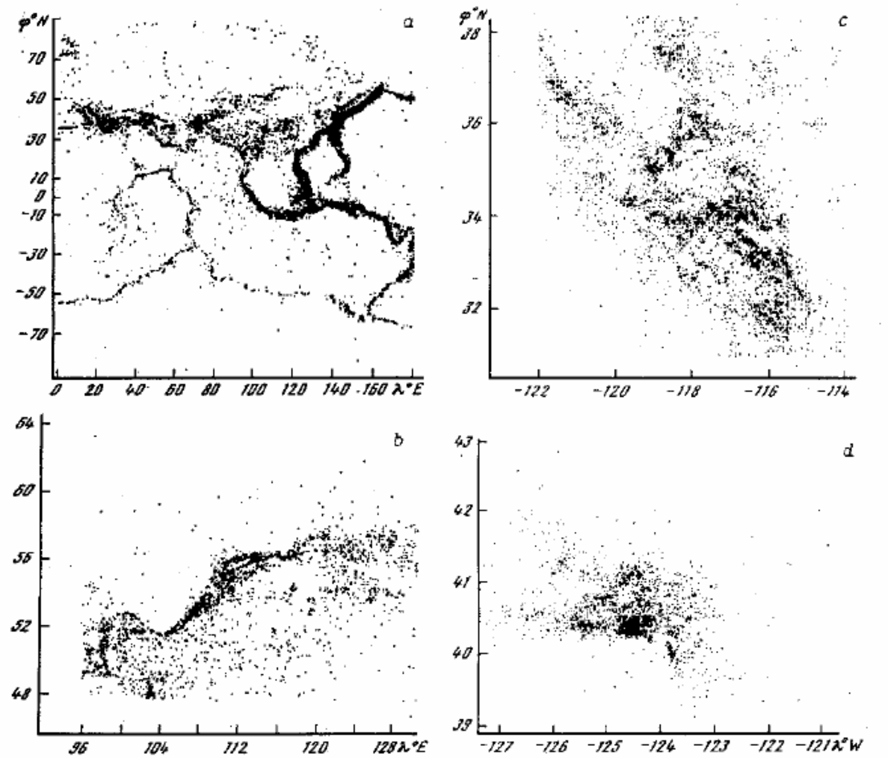


Fig. 2. Examples of spatial distribution of epicenters from catalogs of mainshocks. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

14 KOSOBOKOV AND MAZHKENOV: SIMILARITY IN SPATIAL DISTRIBUTION OF SEISMICITY

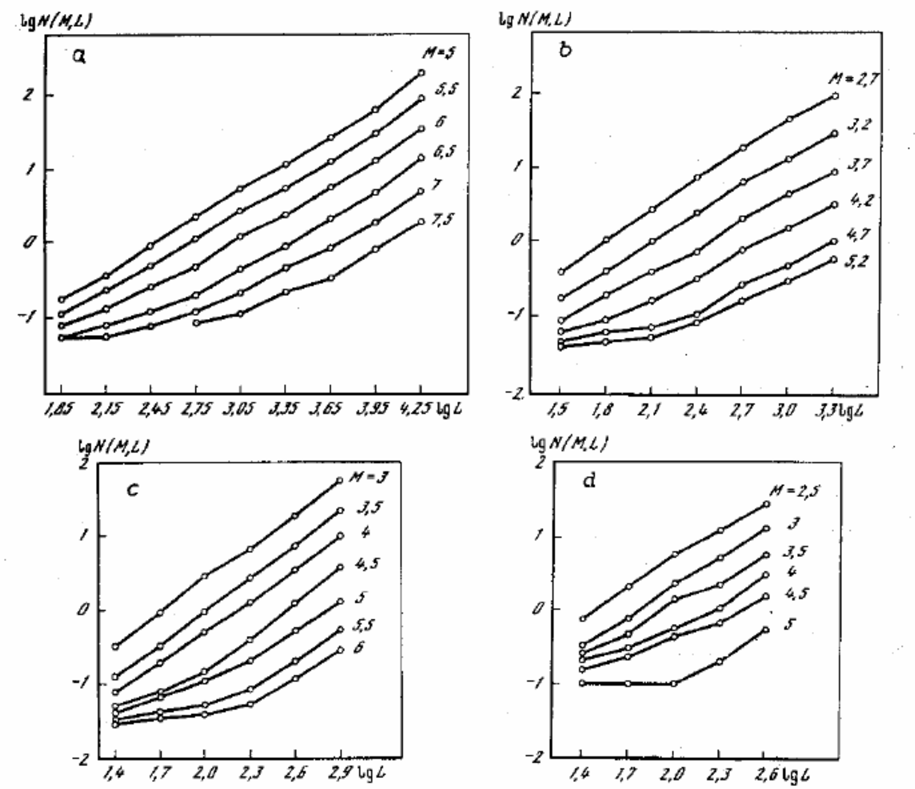
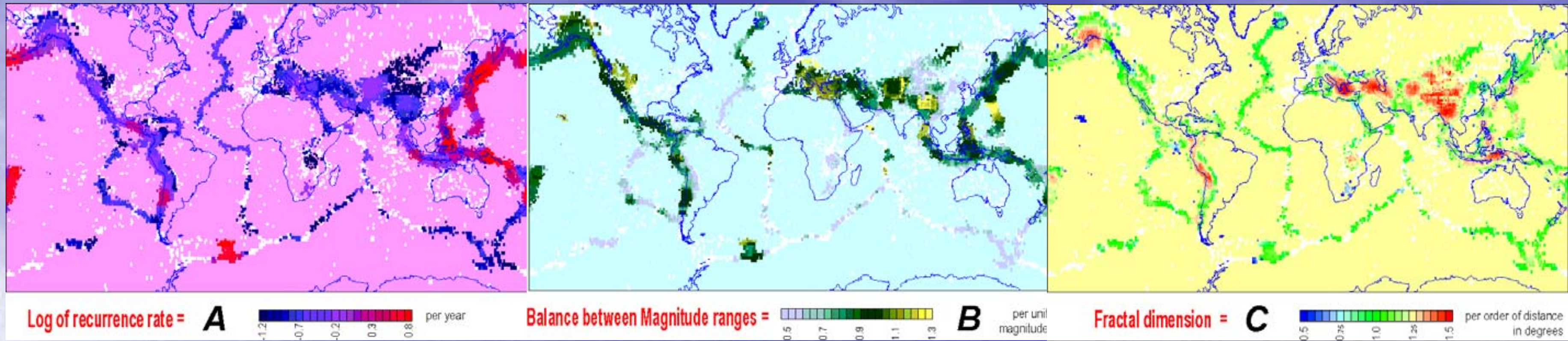


Fig. 3. Examples of log $N(M, L)$ graphs. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

The global map of the USLE coefficients

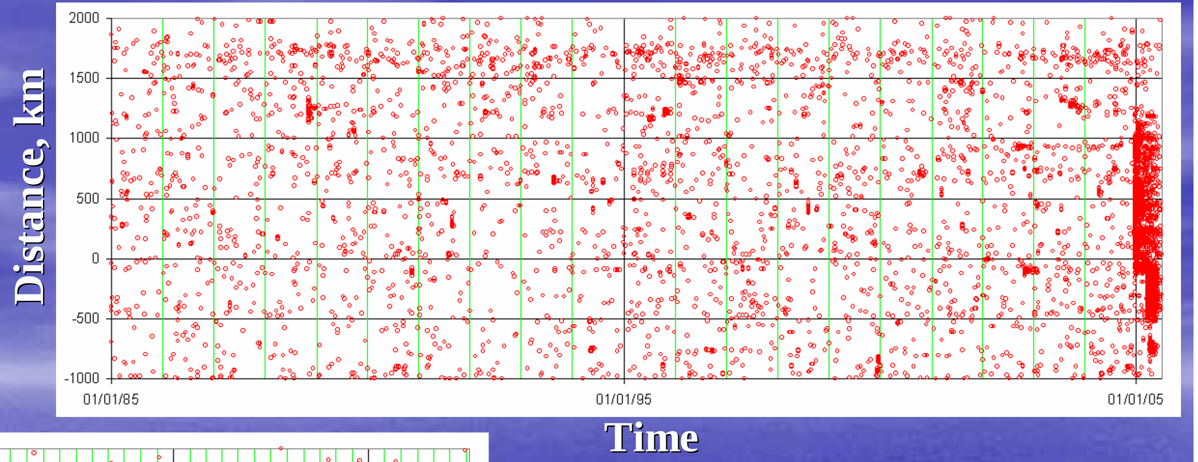


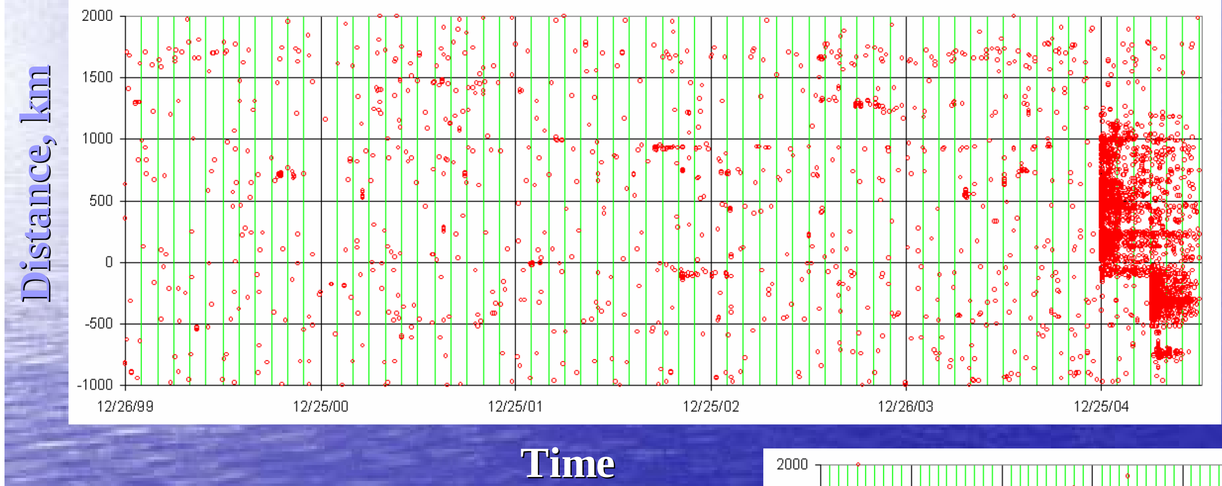
Direct implications for assessing seismic hazard at a given location (e.g., in a mega city)

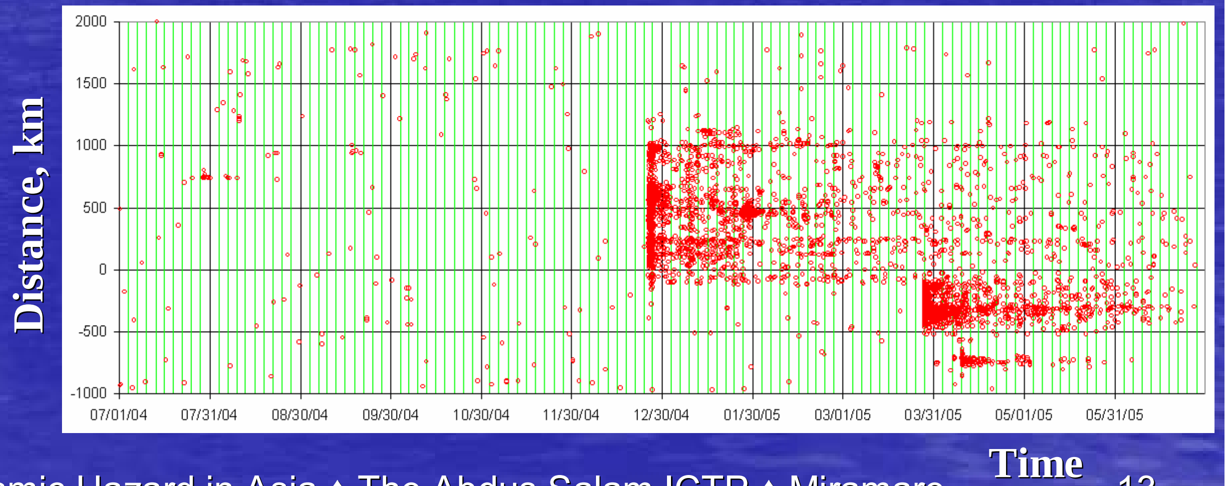
The estimates for Los Angeles (SCSN data, 1984-2001) -
A = -1.28; B = 0.95; C =1.21 (σ_{total} = 0.035)
- imply a traditional assessment of recurrence of a large earthquake in Los Angeles,
i.e., an area with L about 40 km,
from data on the entire southern California, i.e., an area with L about 400 km,
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

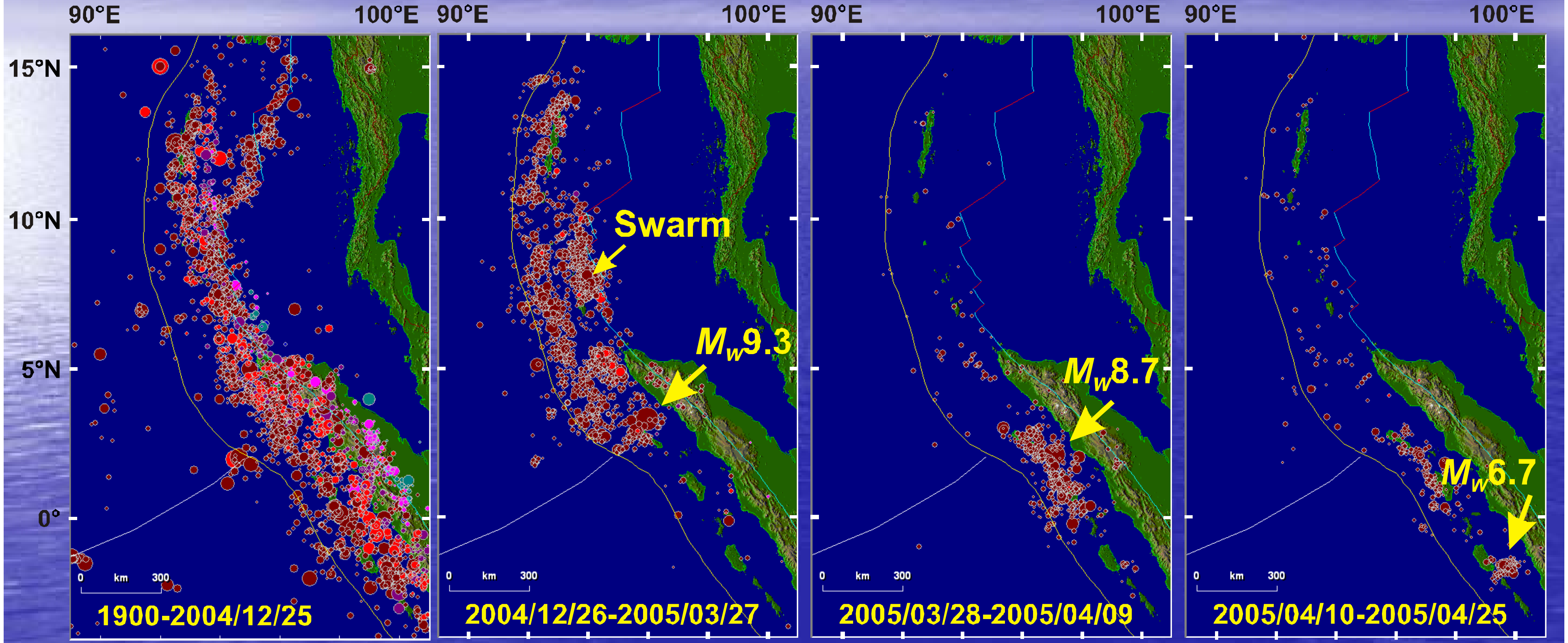






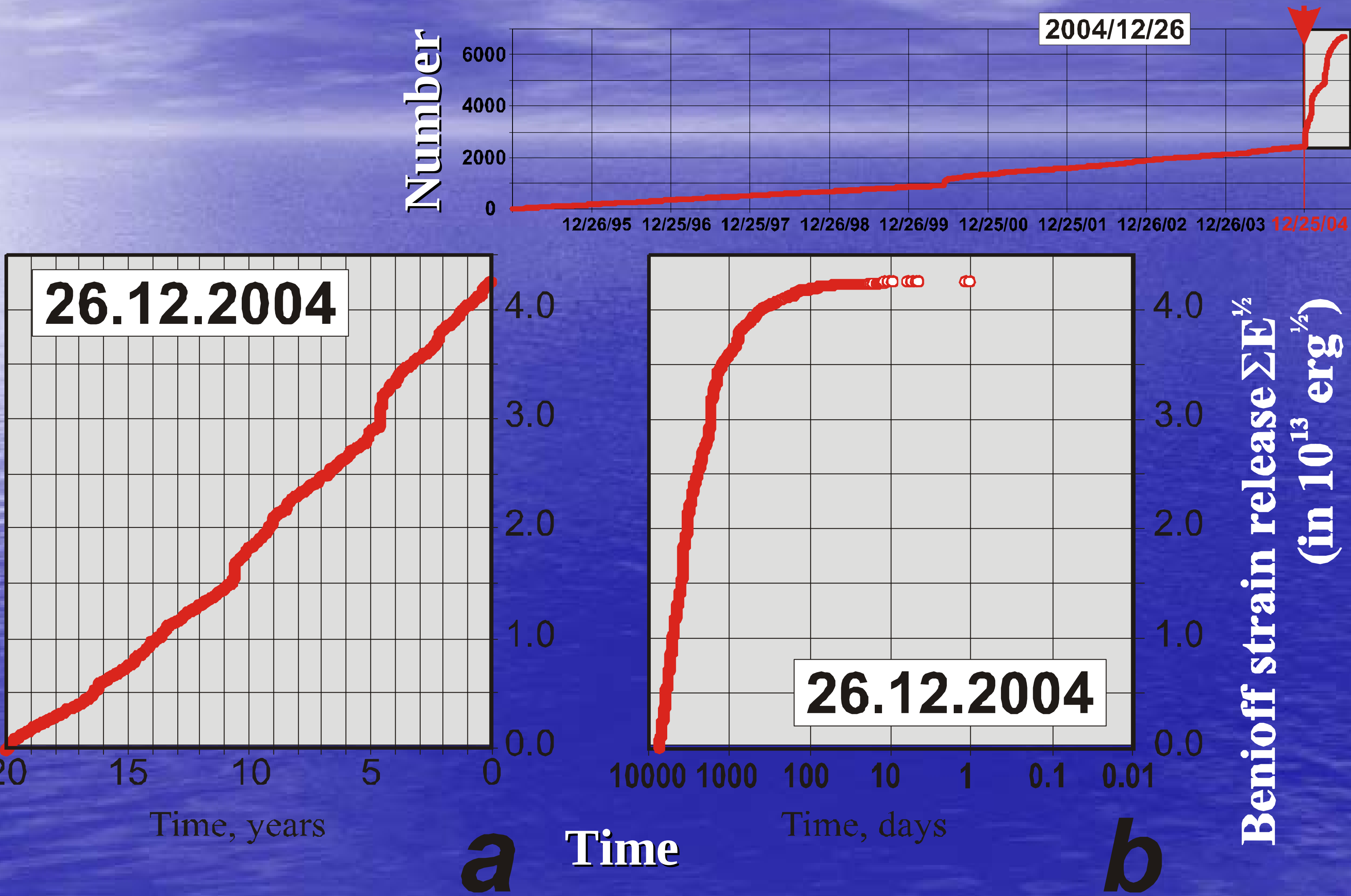
Distribution of earthquakes in Space and Time:

Clustering and cascades



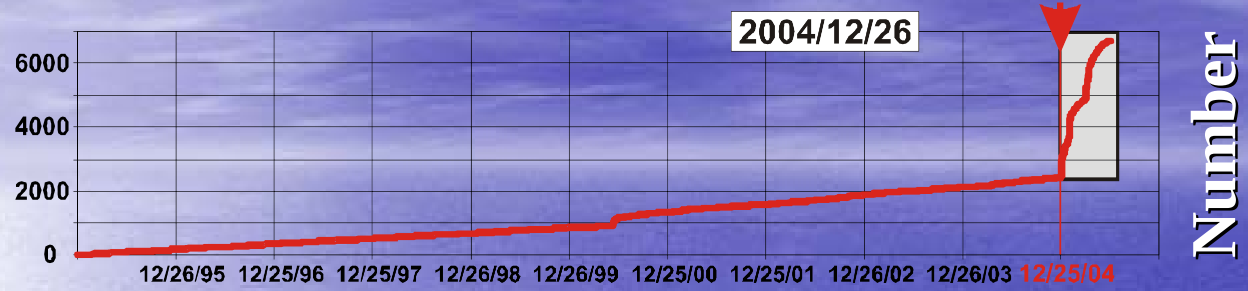
Distribution of earthquakes in Space and Time:

Clustering and cascades

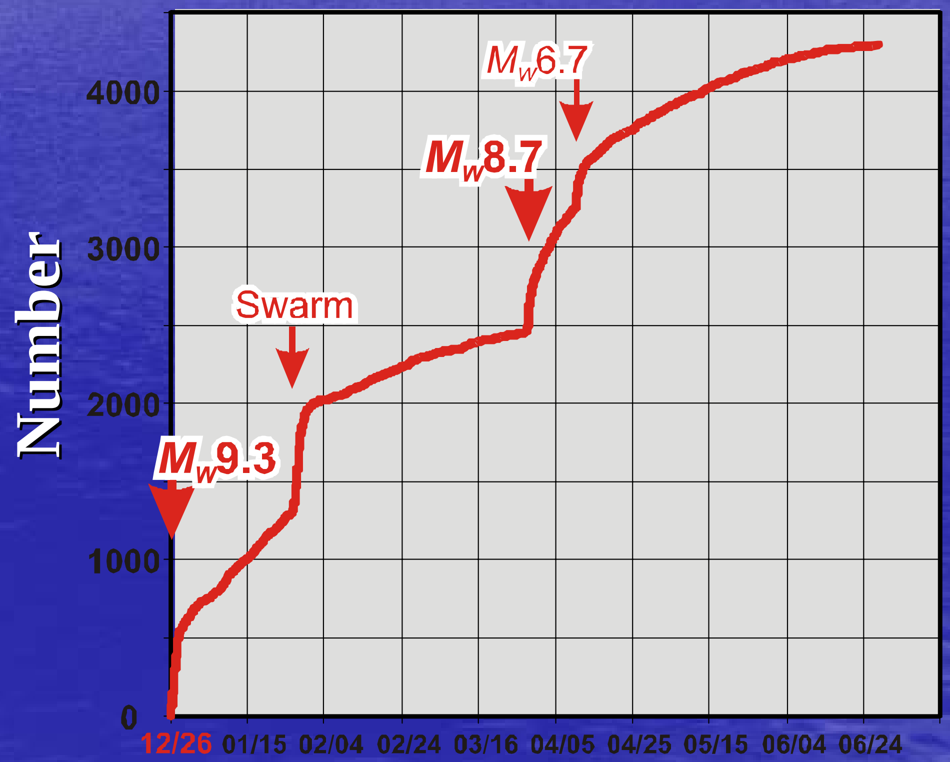


Distribution of earthquakes in Space and Time:

Clustering and cascades

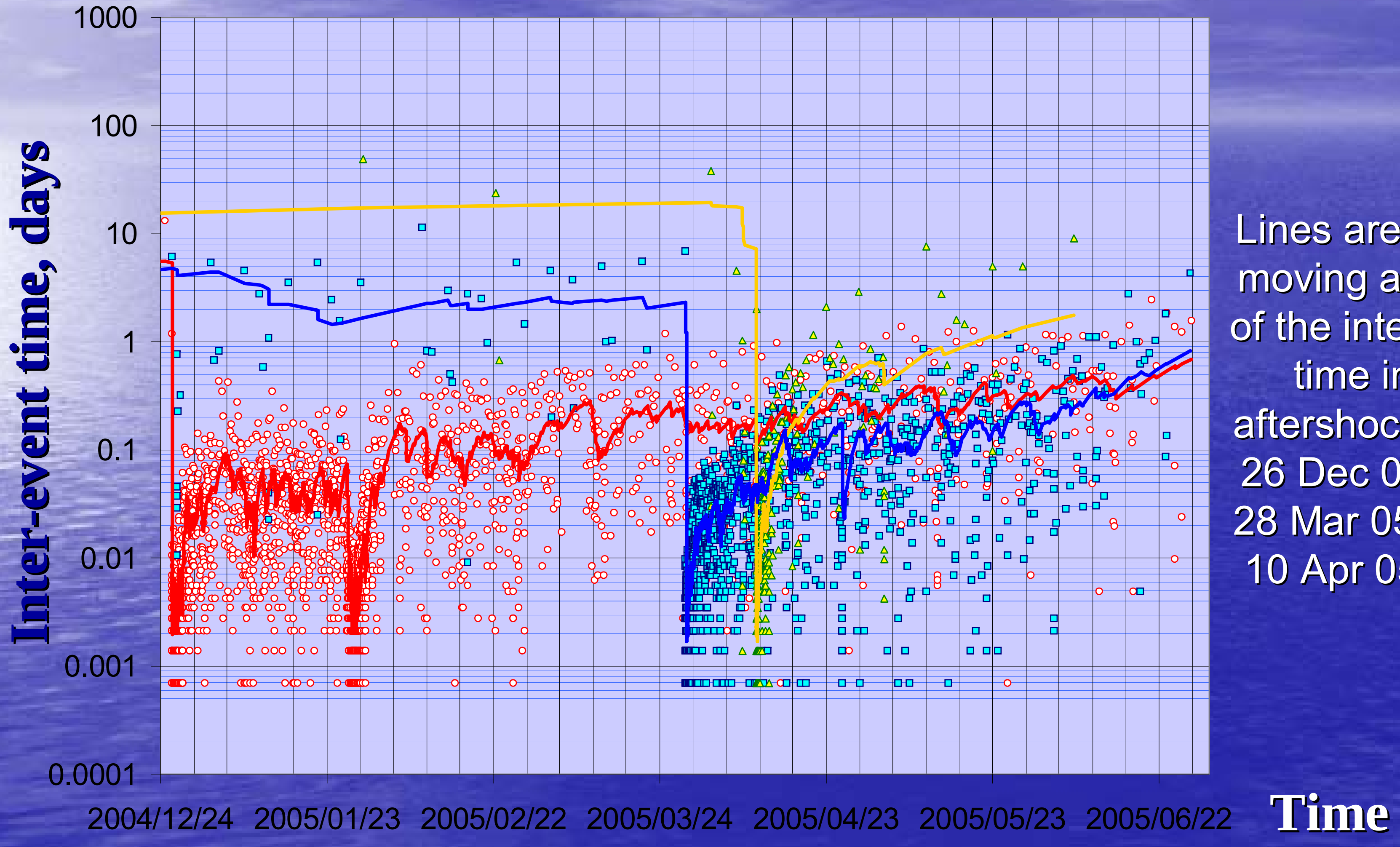


The rate of aftershocks did change in a step-wise manner from 10 (magnitude 4 or larger quakes) per hour to 1.1 per hour until the swarm of 25-27 January, which burst more than 500 events.
Then the rate has drop to about 11 per day during February, then drop again to 6 per day till 28 March 2005 Nias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

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 some main shocks up to magnitude 5.0 (about 10-25% of the total for different magnitudes) and can differ by a factor 10 or more for magnitude 6.0 main shocks (for Whittier Narrows, 1987, M6.2, the number of M2.0+ aftershocks is about one hundred, while for Joshua Tree, 1992, M6.1, it is above 19 hundred). For M7.0+, the recent 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.

Thus, the "old good" Omori's law for aftershocks is hardly a solidly documented fact
(*despite that it is widely used in conceptual models*).

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.*

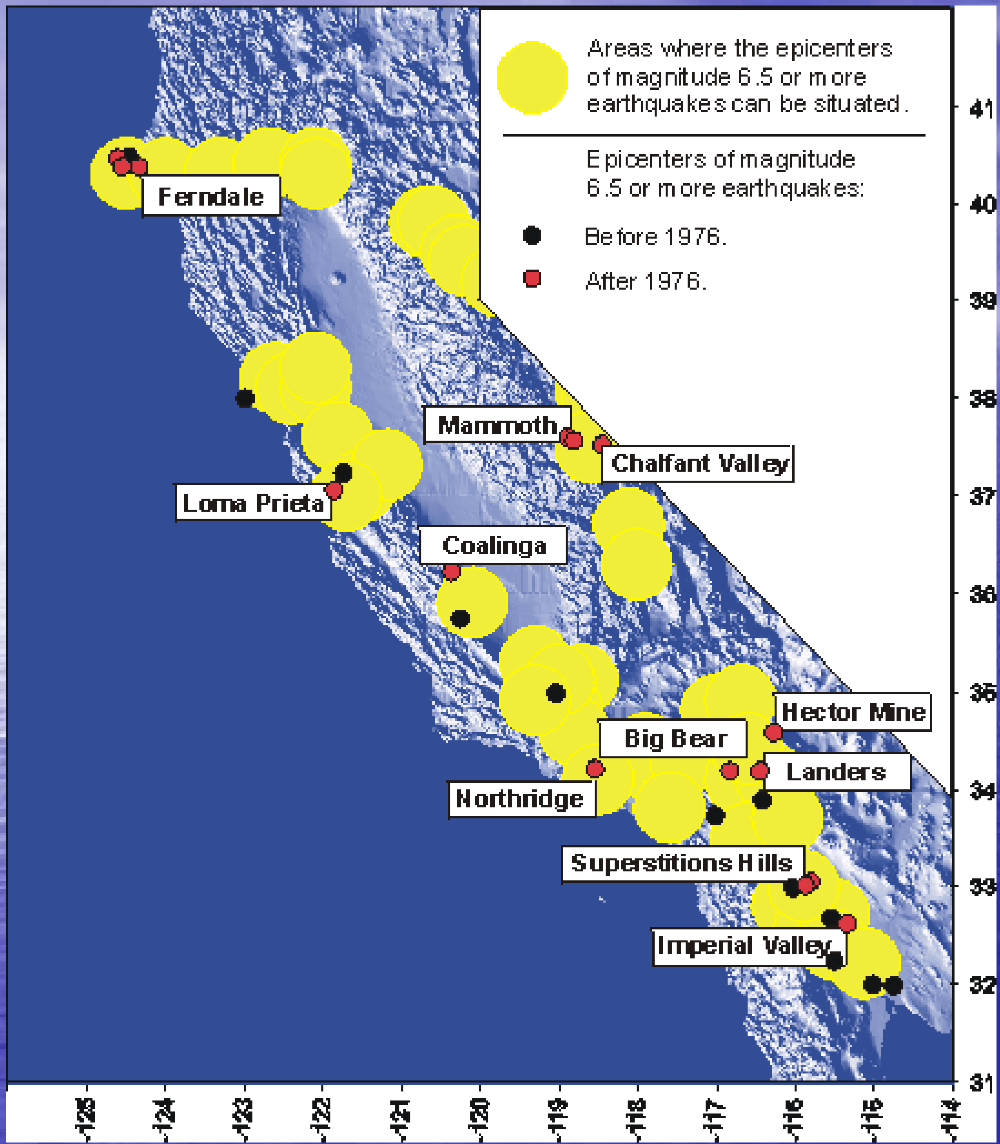
Stages of earthquake prediction

- 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.

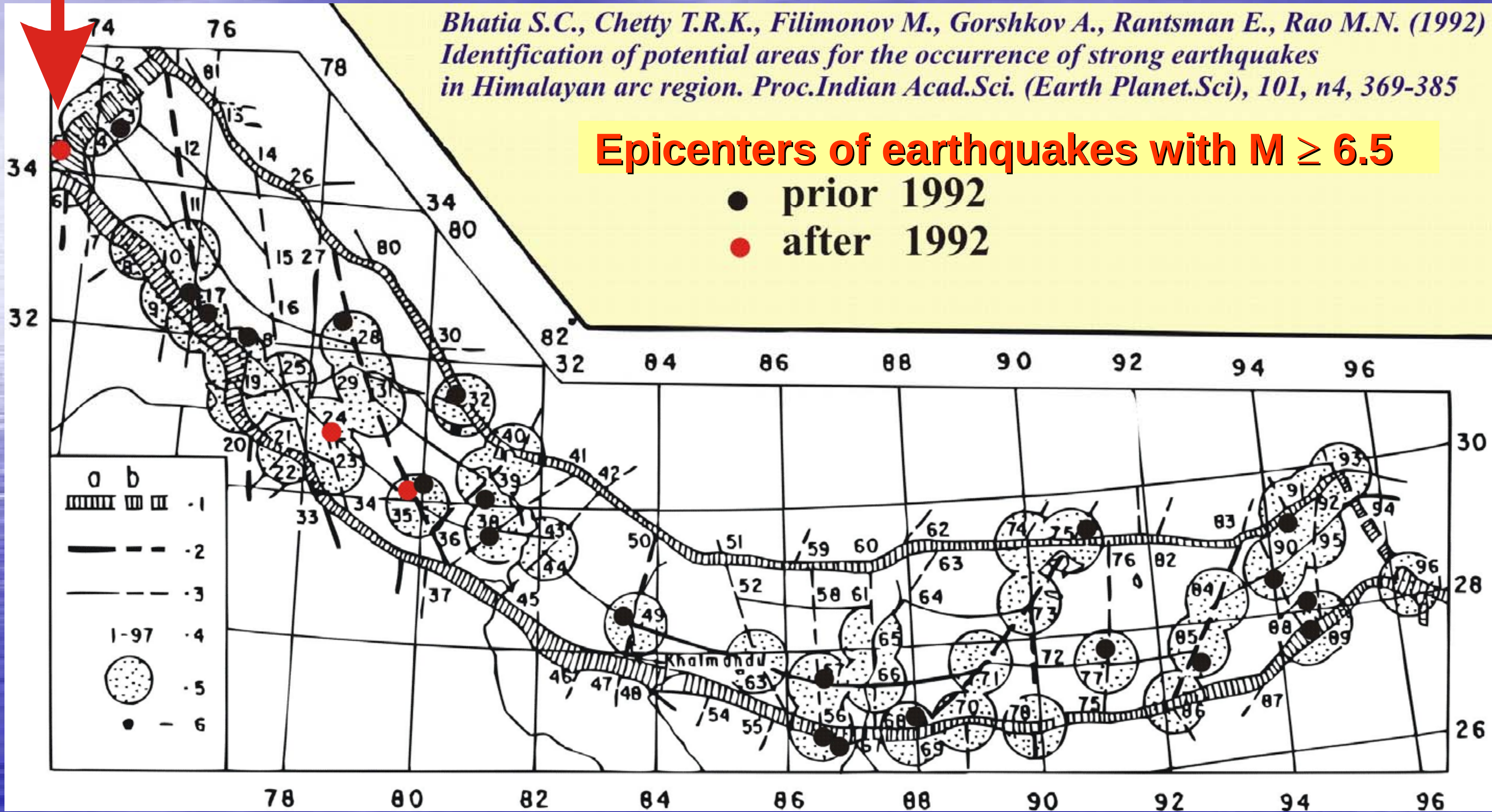


Term-less approximation:

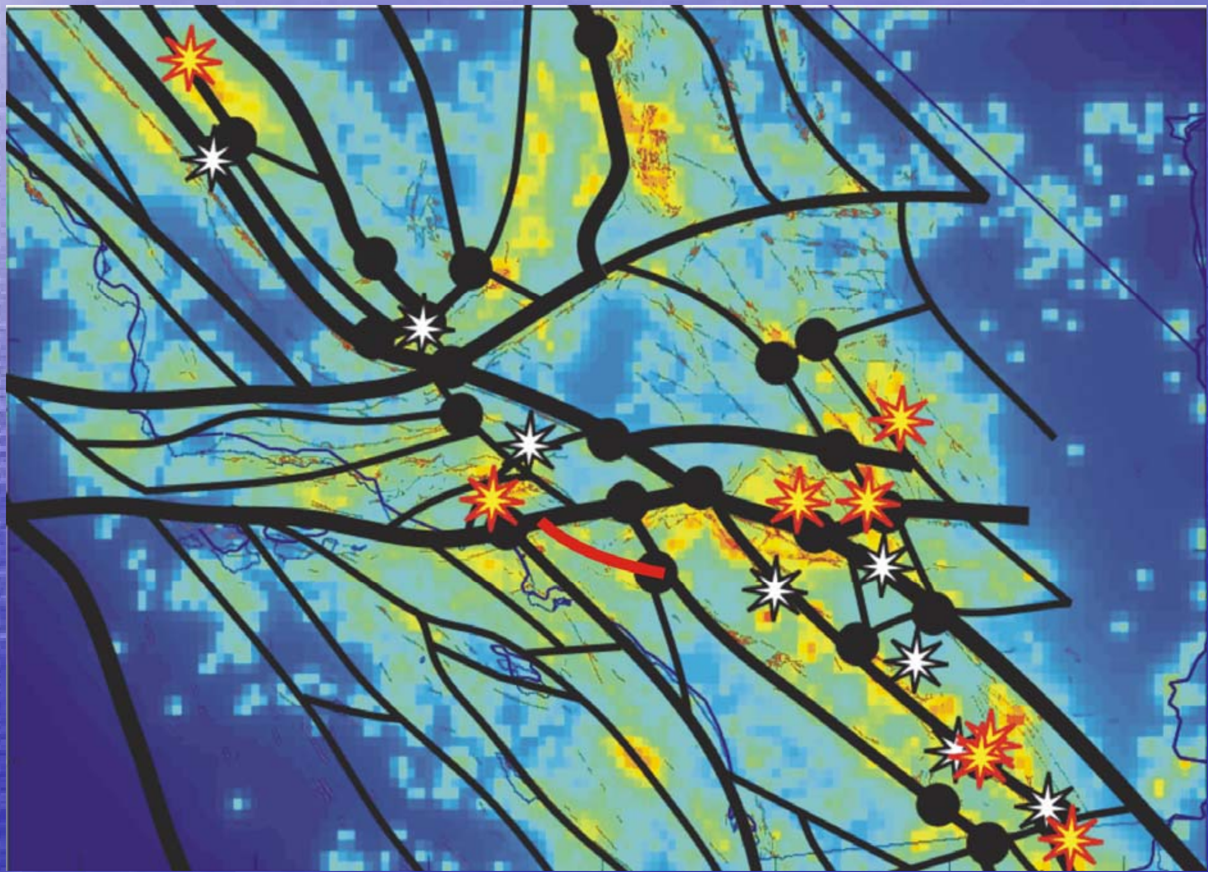
- The 73 D-intersections of morphostructural lineaments in California and Nevada determined by *Gelfand et al.* (1976) as earthquake-prone for magnitude 6.5+ events. Since 1976 fourteen magnitude 6.5+ earthquakes occurred, all in a narrow vicinity of the D-intersections

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.**

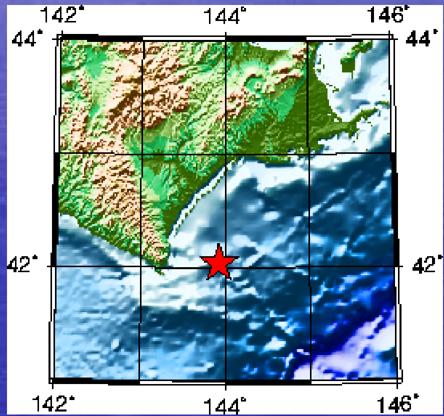


PLANETS ALIGN:
On Wednesday morning, September 24th, 2003 a lovely trio appeared in the eastern sky: **Jupiter, the crescent moon and Mercury…**

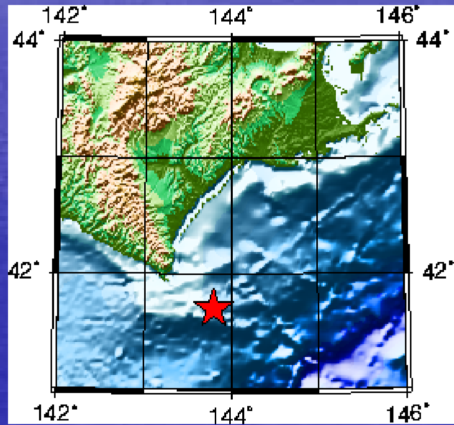
Is it a coincidence or a law?

Two days later …

防災科研**Hi-net**暫定処理による震源位置

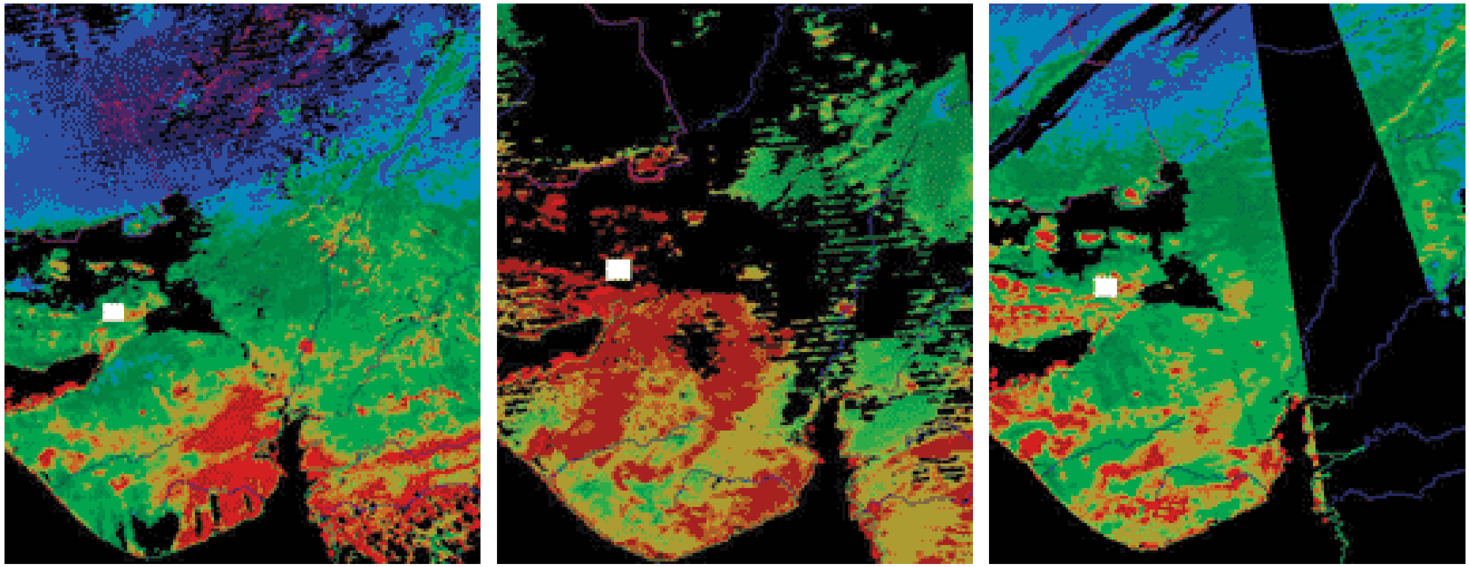


本震
2003年9月26日04時50分11秒
北緯42.0度
東経143.9度
深さ25km
M7.7



最大余震
2003年9月26日06時08分03秒
北緯41.8度
東経143.9度
深さ35km
M7.4

Isn't it a coincidence ?



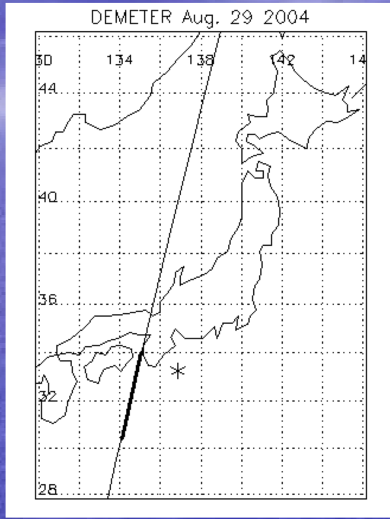
WARM BEFORE THE STORM: An earthquake killed more than 20 000 people on 26 January 2001 in the Indian state of Gujarat. NASA's Terra satellite made infrared maps of the region on 6, 21, and 28 January [left to right]. Five days before the earthquake [middle], the area near the epicenter [white square]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

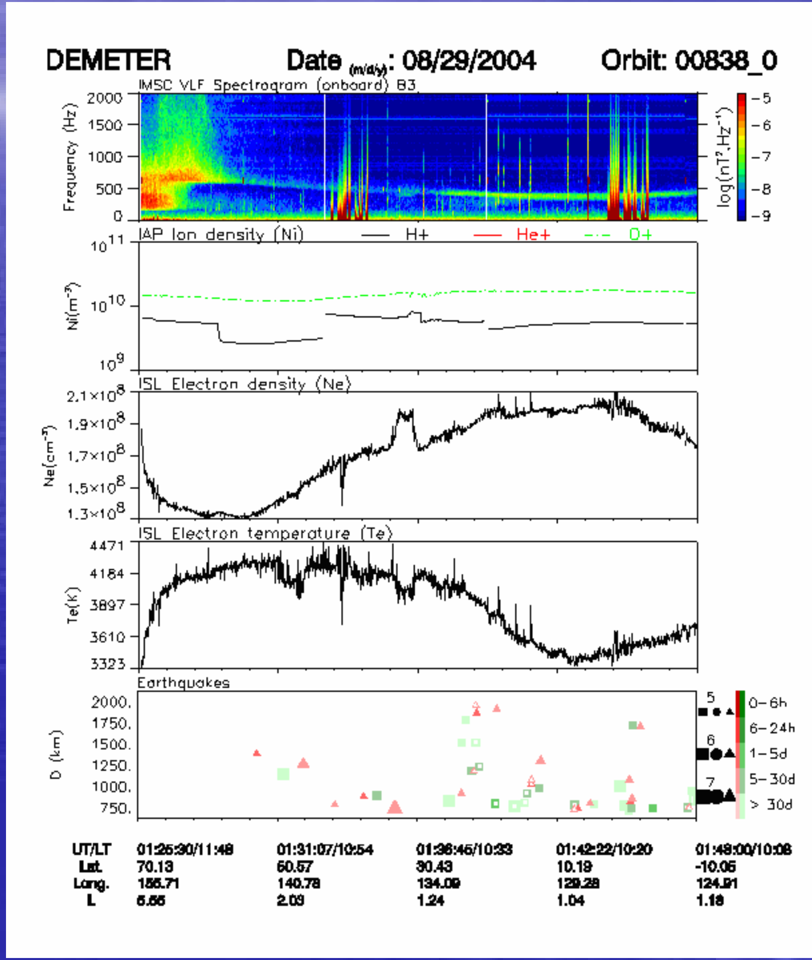
IMAGES: NASA

Isn't it a coincidence ?

"Orbit of DEMETER above Japon on August 29, 2004. The star indicates the epicenter of an earthquake of magnitude 7.1 which will occur on September 5, 2004 in the region of Kii-Peninsula (Lat=33.05N, Long=136.78E).

The thick line on the orbit corresponds to the period where an ionospheric perturbation is observed with DEMETER (next Figure)."





"From the top to the bottom the panels successively show a spectrogram of a magnetic component between 0 and 2 kHz, the ion density given by IAP, the electron density and temperature, and the earthquakes seen by DEMETER along the orbit. In this last panel, the Y-coordinate gives the distance between DEMETER and the earthquake hypocenter. The red color of the symbol which size is proportional to the magnitude shows that DEMETER is flying over the region before the earthquake. A large variation of the ionosphere parameters is observed when the satellite is above the seismic zone (in the top panel, the two bursts of interferences correspond to periods where wheels, which are used for the satellite attitude control, are desaturated)."

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 ?

- 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

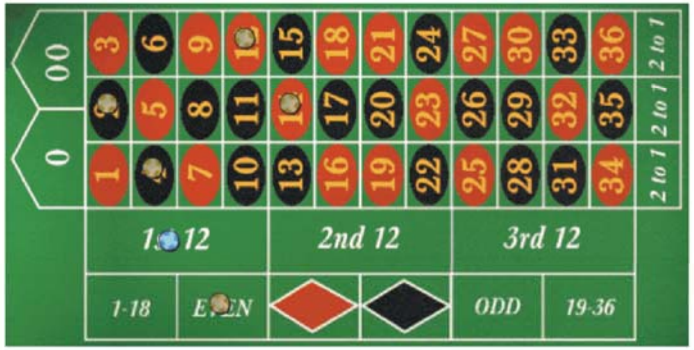
If a statistic falls in a *reasonable* part of the distribution, you must not make the mistake of concluding that the null hypothesis is "verified" or "proved". That is the curse of statistics, that it can never prove things, only disprove them! At best, you can substantiate a hypothesis by ruling out, 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!”

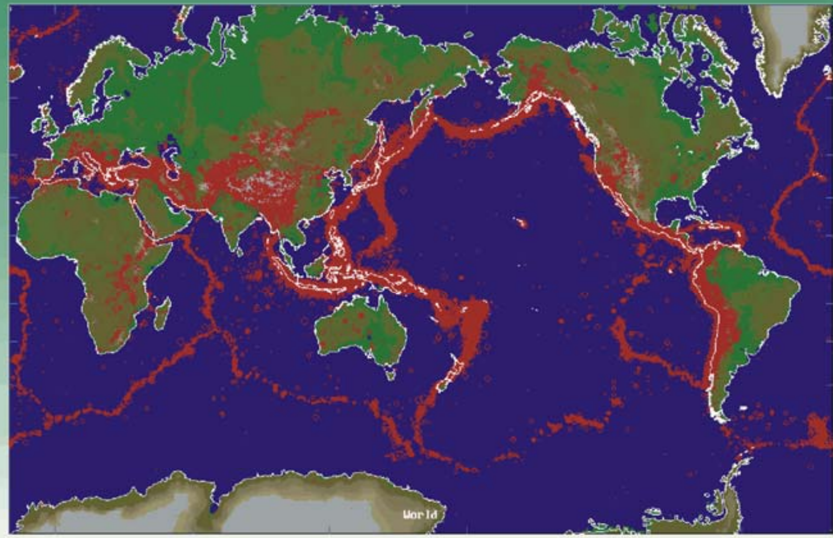
(William H. Press et al., *Numerical Recipes*, p.603)

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

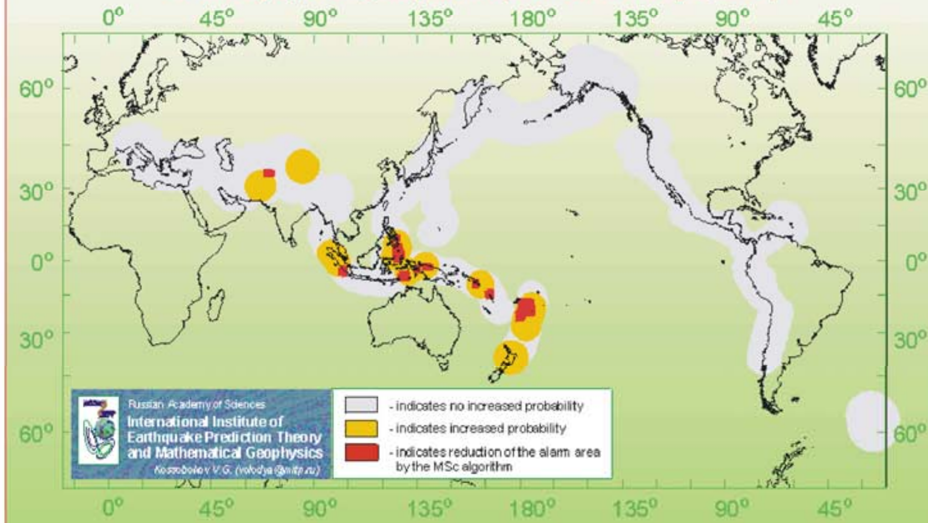
Keiiti Aki (1930-2005)

Seismic Roulette





Regions of Increased Probability of Magnitude 8.0+ Earthquakes
as on July 1, 2000 (*subject to update on January 1, 2001*)



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; τ×μ is a measure on **T**×**S** (we consider here a direct product measure τ×μ 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

$$\boldsymbol{p} = \int_A d(\tau \times \mu) \; / \int_{T \times S} d(\tau \times \mu) \, .$$

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 τ×μ: 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*)

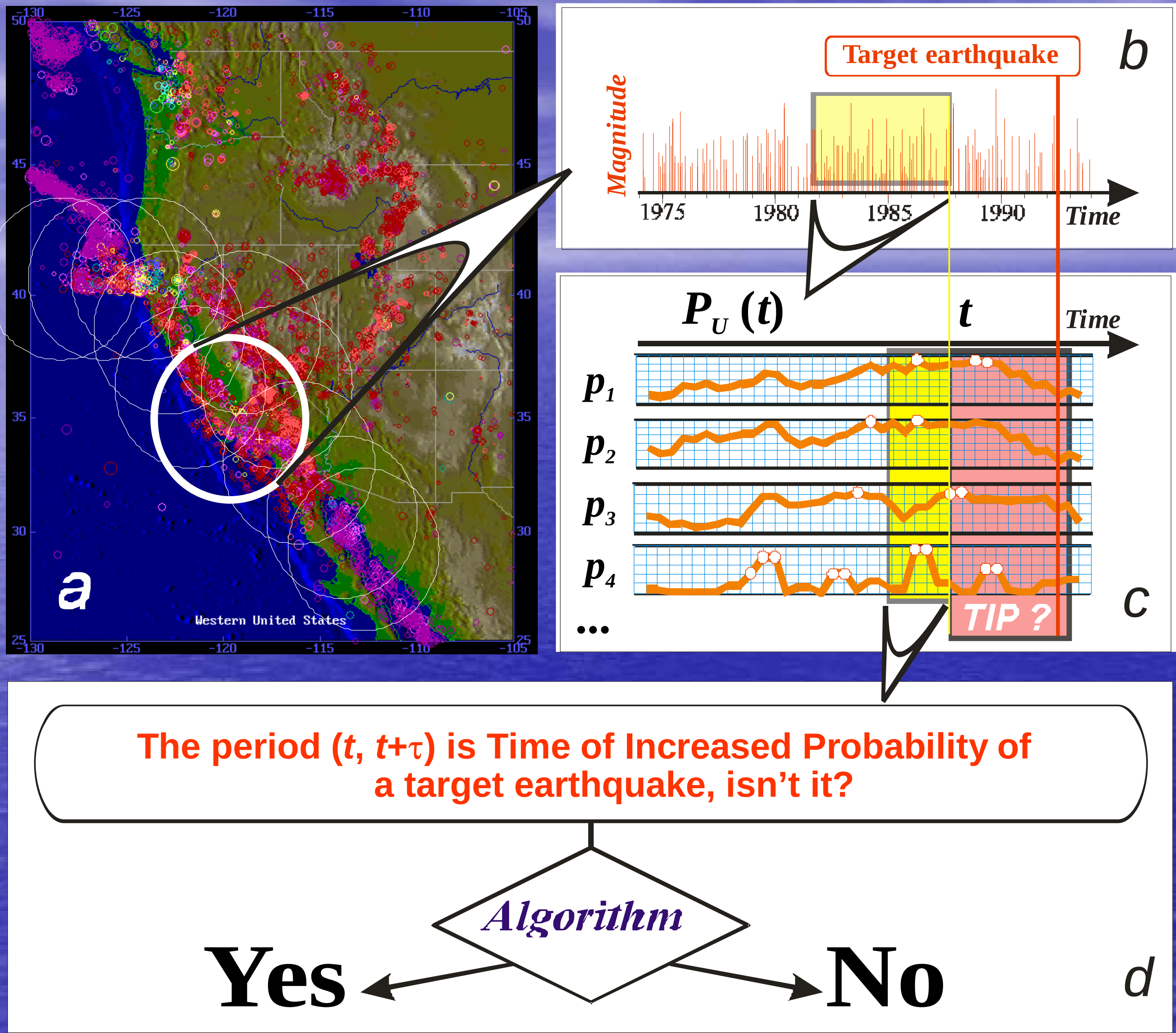
M8 algorithm

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.

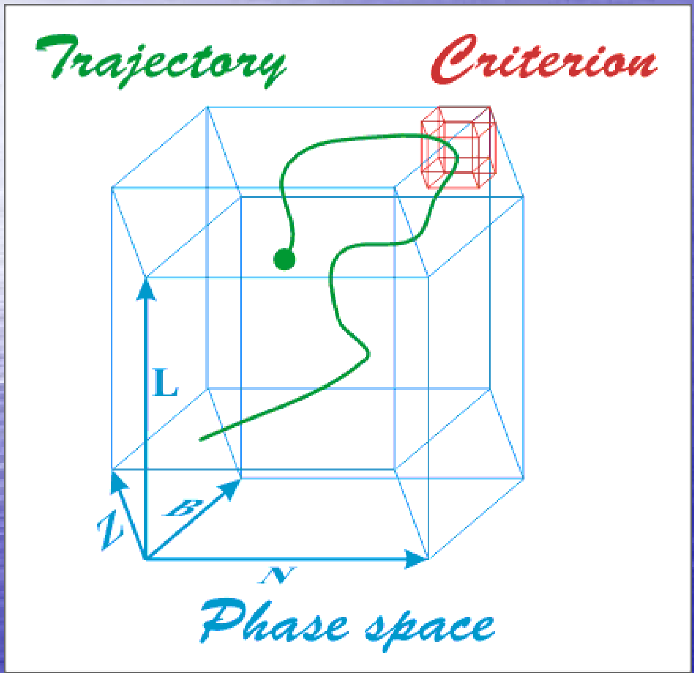
Its prototype (***Keilis-Borok and Kossobokov, 1984***) and the original version (***Keilis-Borok and Kossobokov, 1987***) were tested retroactively. The original version of M8 is subject to the on-going real-time experimental testing. After a decade the results confirm predictability of the great earthquakes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

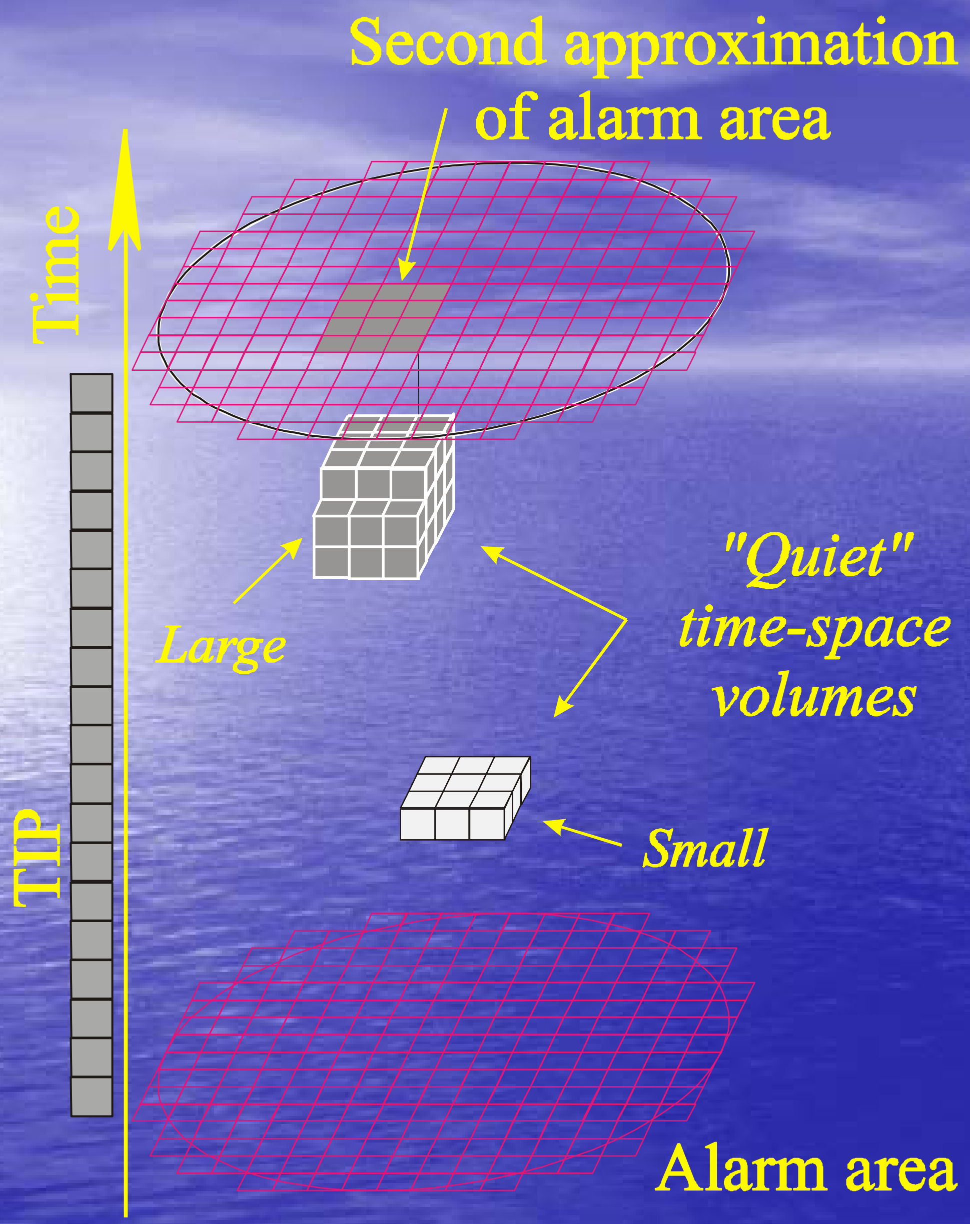
all the 11 largest earthquakes in 26 % of the space-time considered.

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.

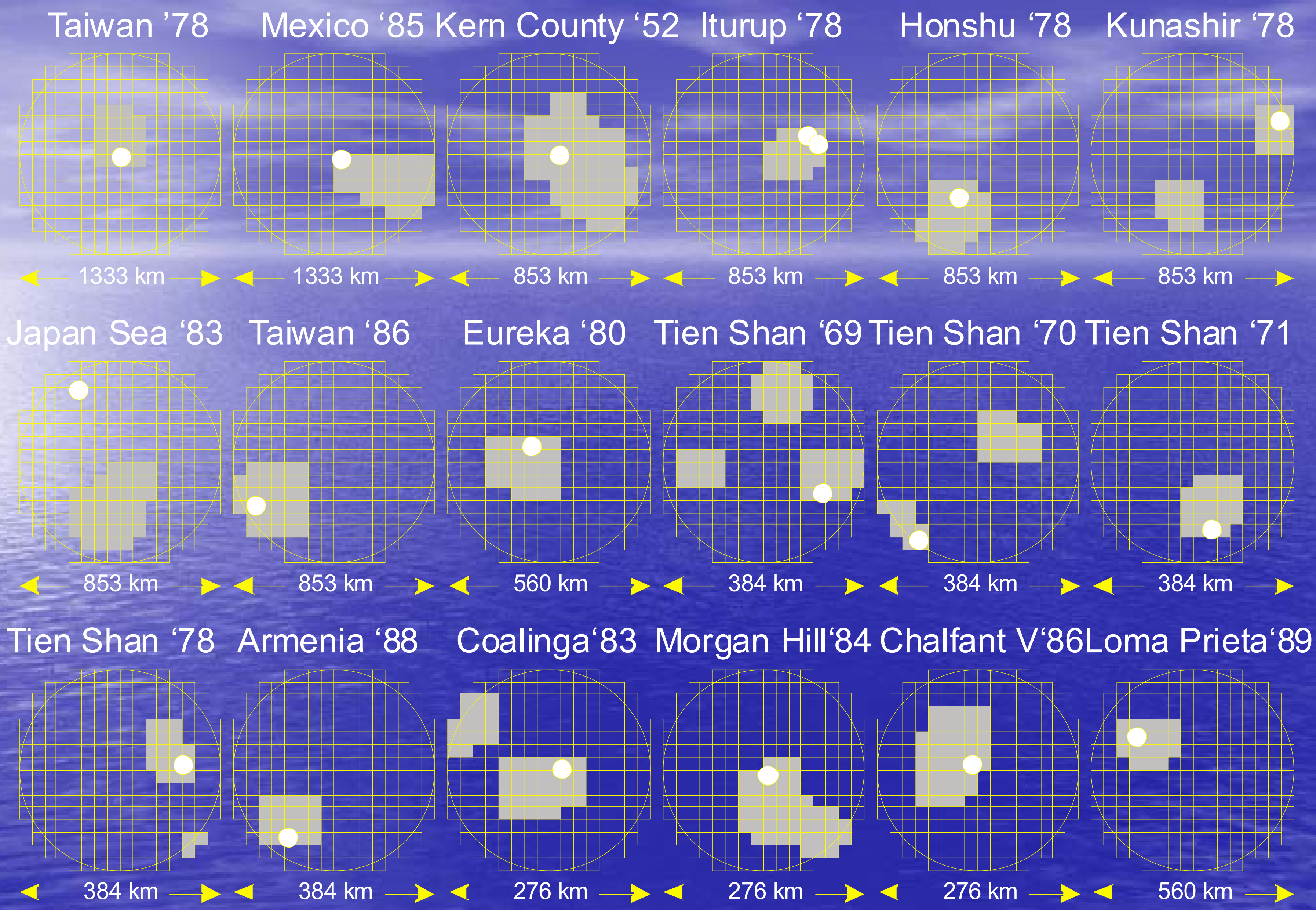
The phenomenon, which is used in the MSc algorithm, might reflect the second (possibly, shorter-term and, definitely, narrow-range) stage of the premonitory rise of seismic activity near the incipient source of main shock.



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.

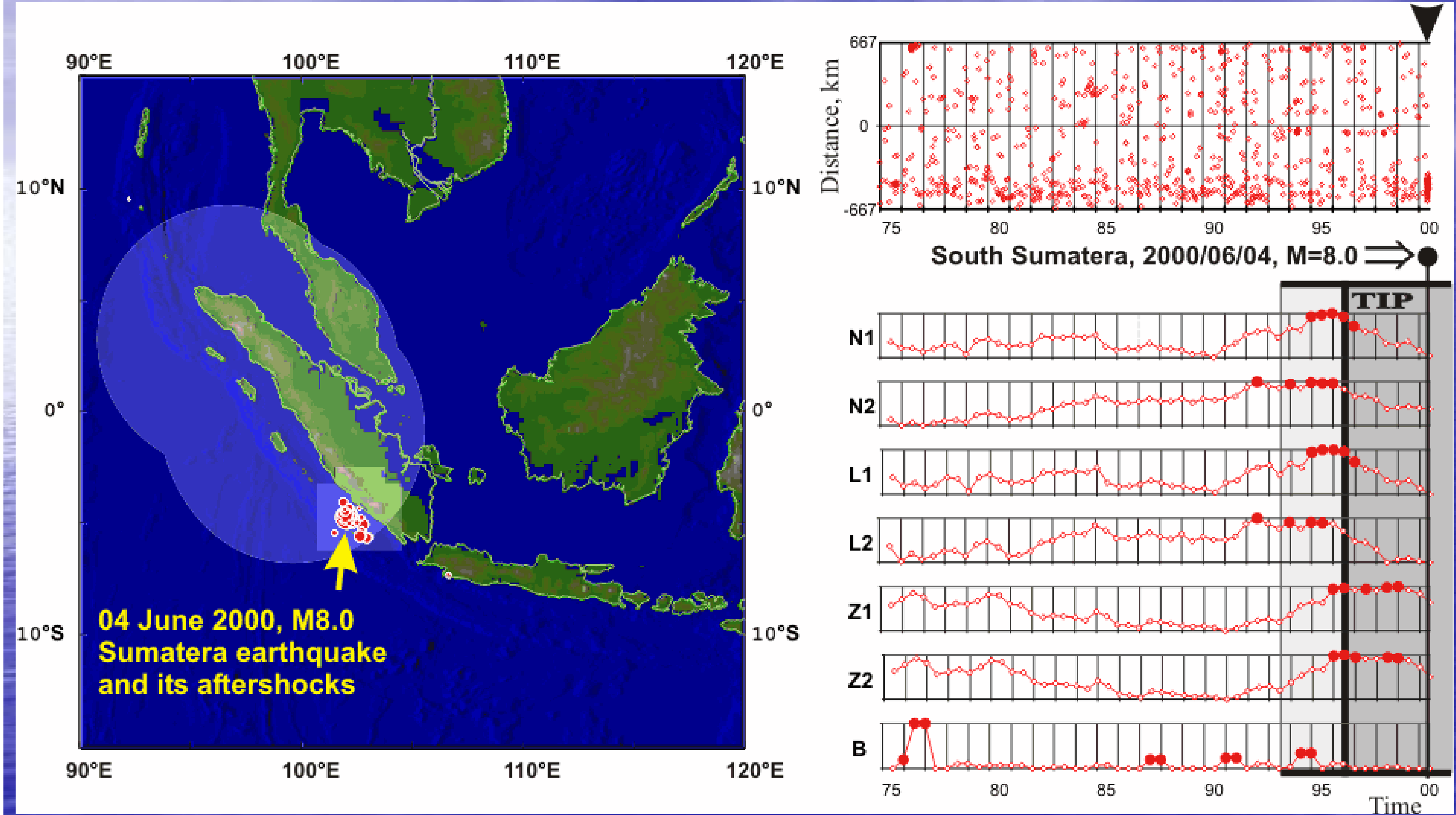


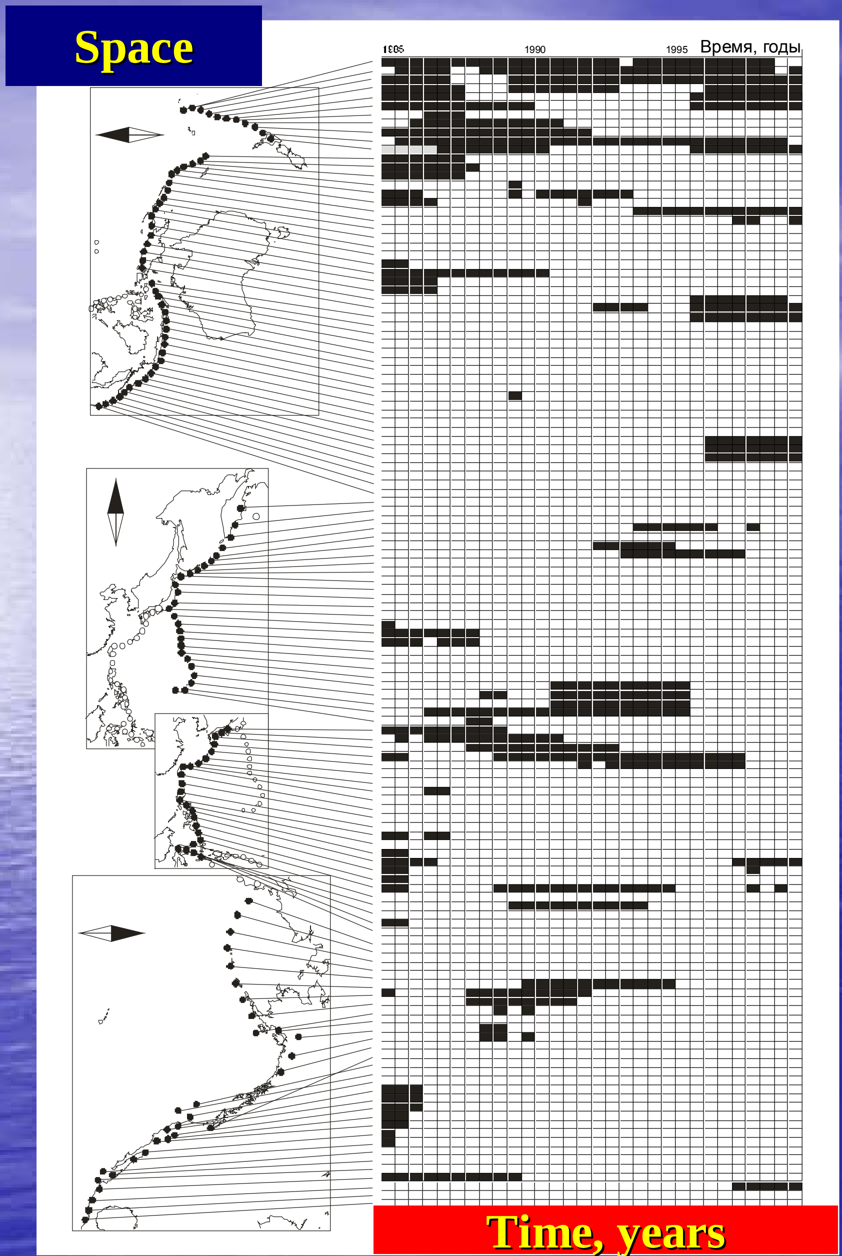
Taiwan '78
Mexico '85
Kern County '52
Iturup '78
Honshu '78
Kunashir '78
1333 km
1333 km
853 km
853 km
853 km
853 km
Japan Sea '83
Taiwan '86
Eureka '80
Tien Shan '69
Tien Shan '70
Tien Shan '71
853 km
853 km
560 km
384 km
384 km
384 km
Tien Shan '78
Armenia '88
Coalinga'83
Morgan Hill'84
Chalfant V'86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

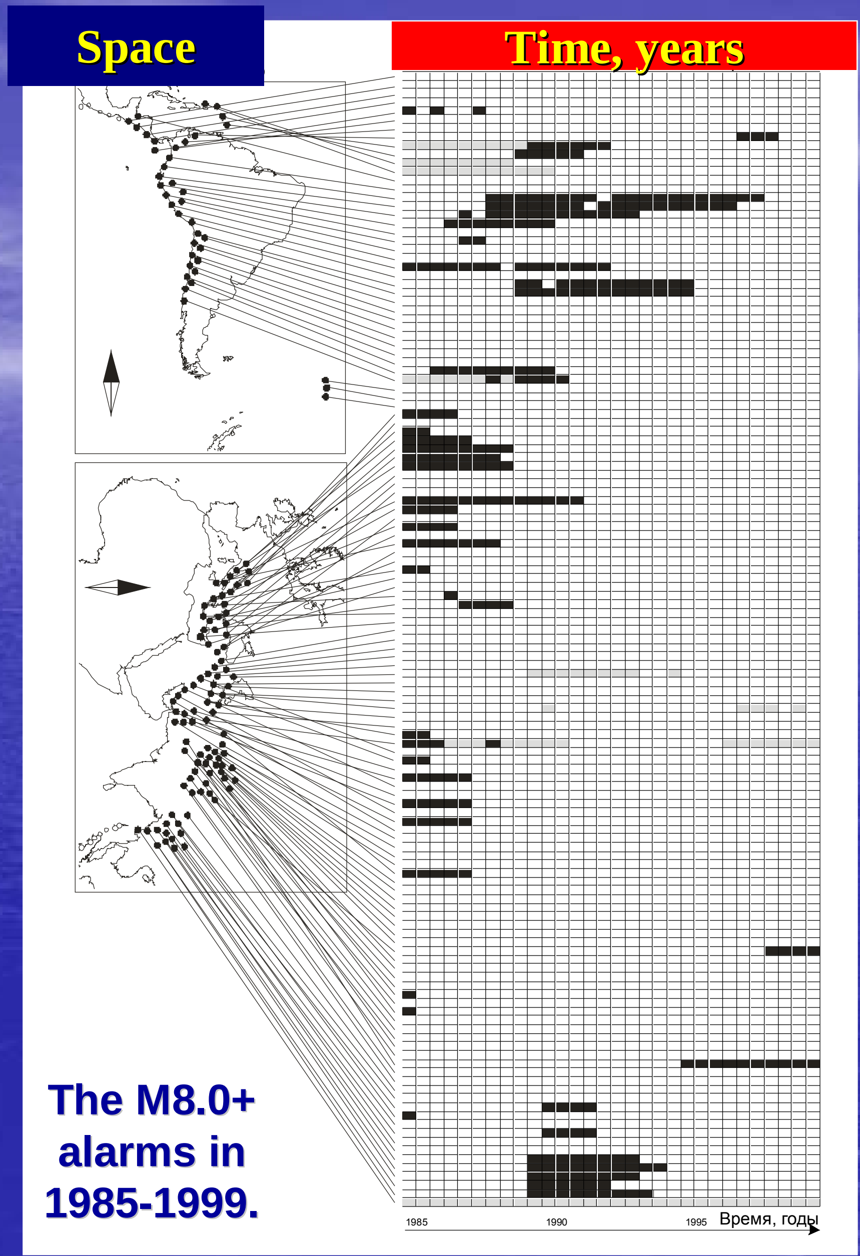
By 1992 all the components necessary for reproducible real-time prediction, i.e., an unambiguous definition of the algorithms and the data base, were specified in publications

- 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



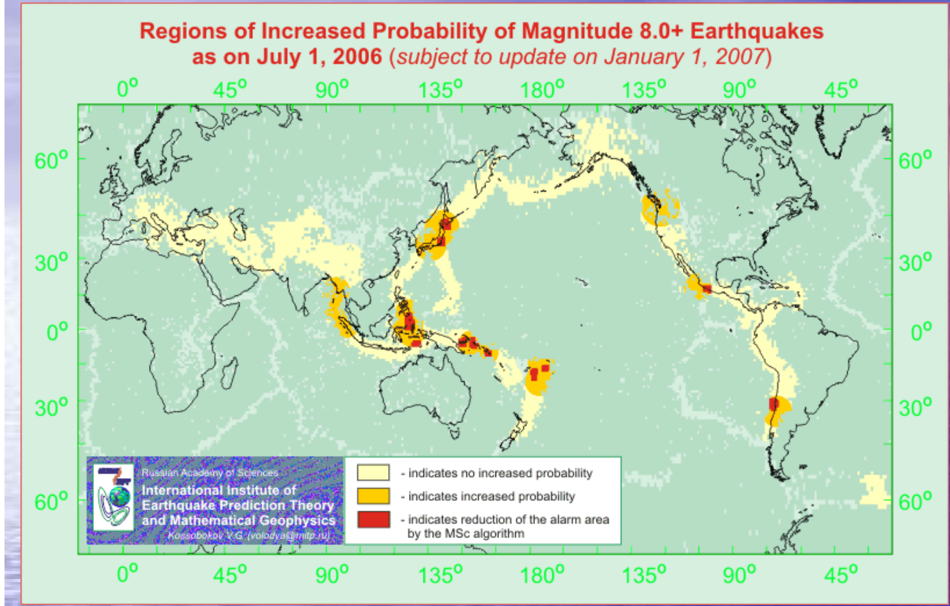




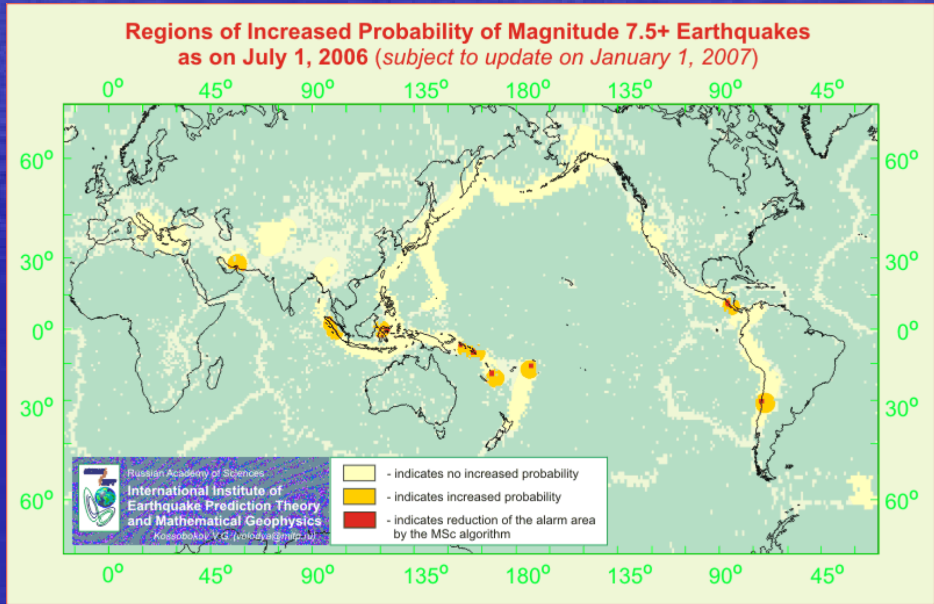
The M8.0+ alarms in 1985-1999.

Real-time prediction of the world largest earthquakes

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

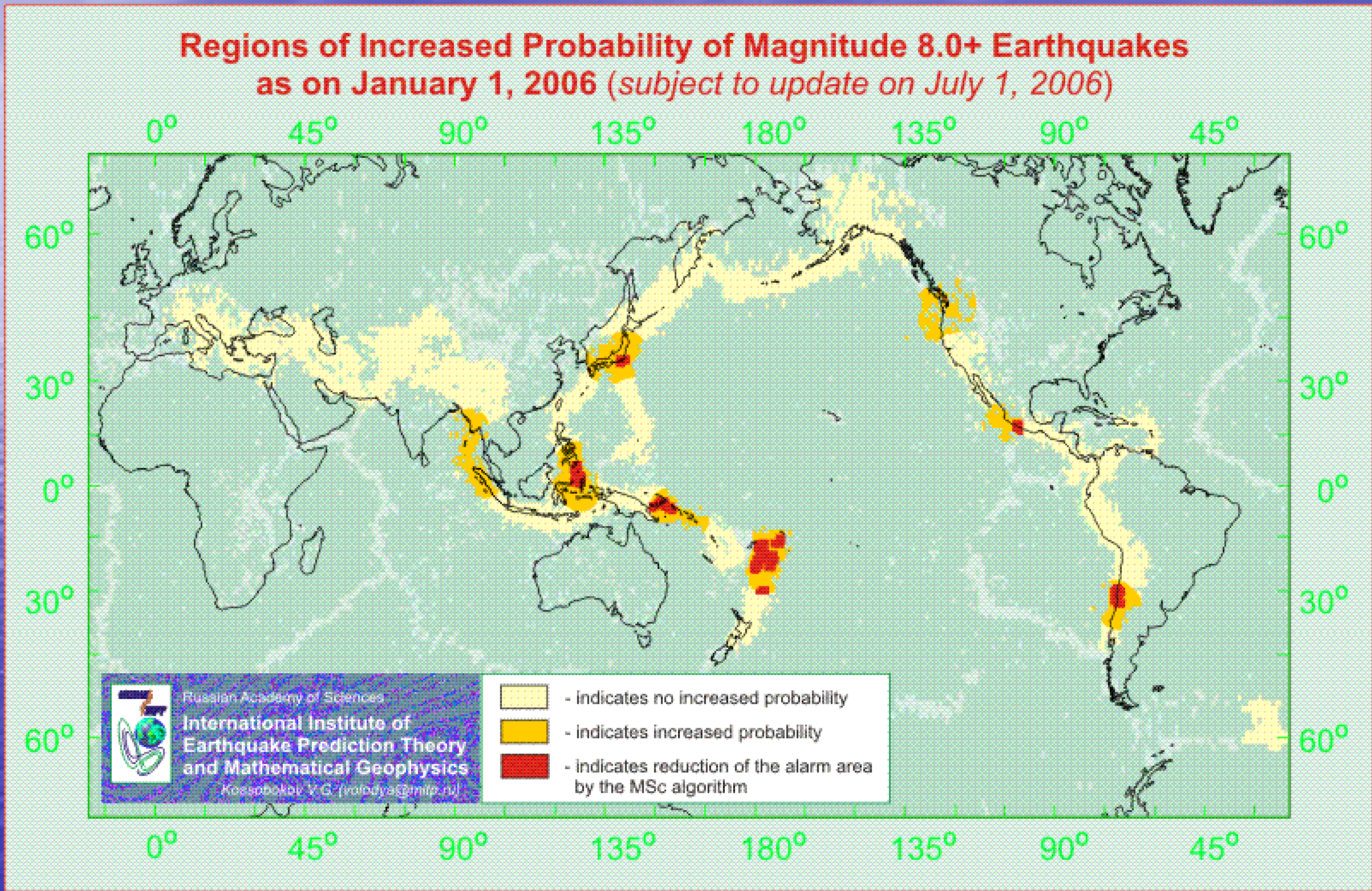


Although the M8-MSc predictions are intermediate-term middle-range and by no means imply any "red alert", some colleagues have expressed a legitimate concern about maintaining necessary confidentiality. Therefore, the up-to-date predictions are not easily accessed, although available on the web-pages of restricted access provided to about 150 members of the Mailing List.



Real-time prediction of the world largest earthquakes

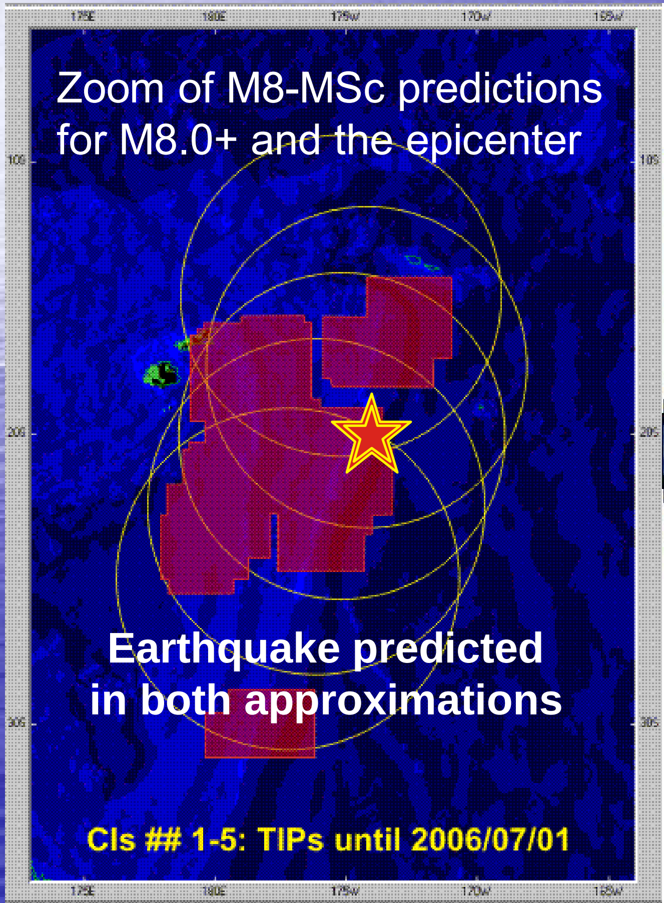
(http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp)

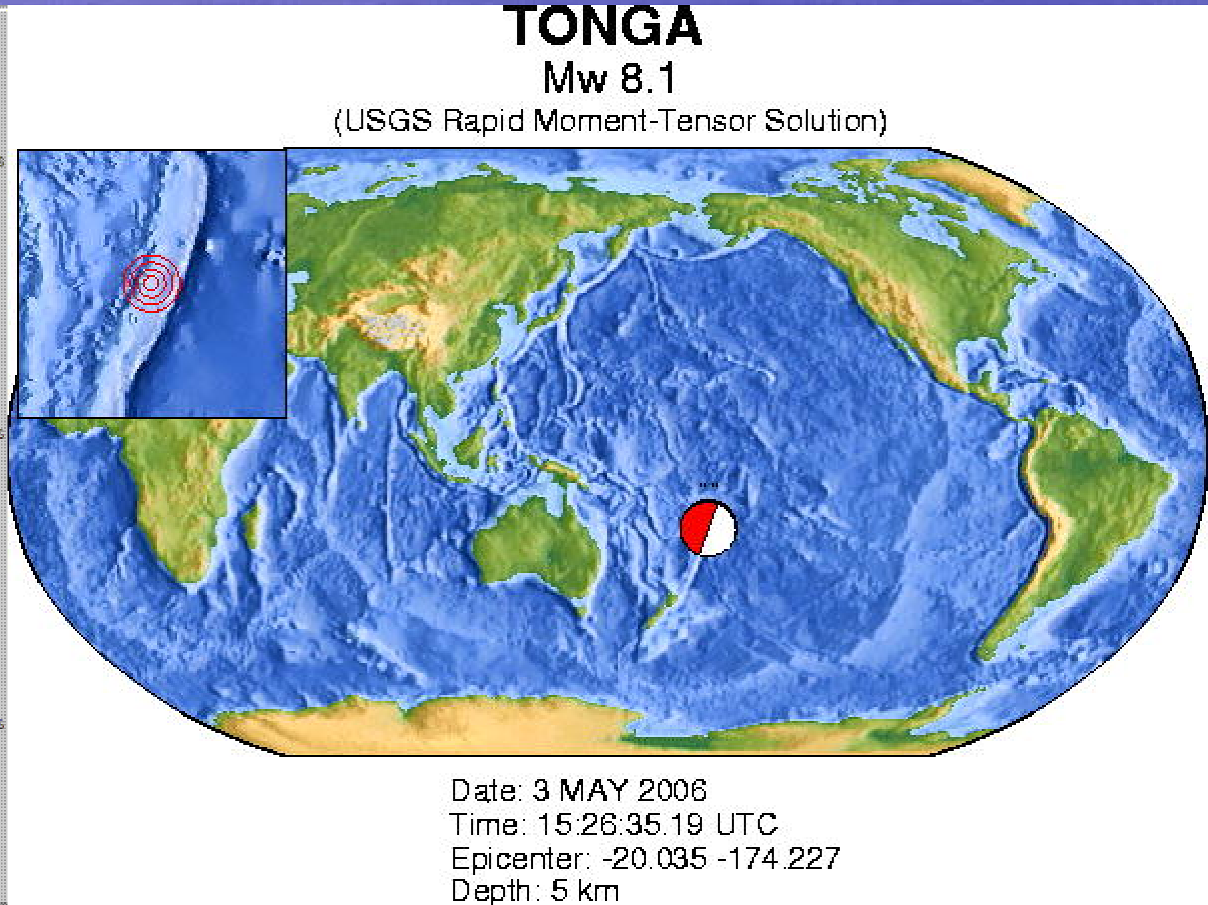


TONGA 06/05/03 15:26:35 UTC: The first automatic determinations

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

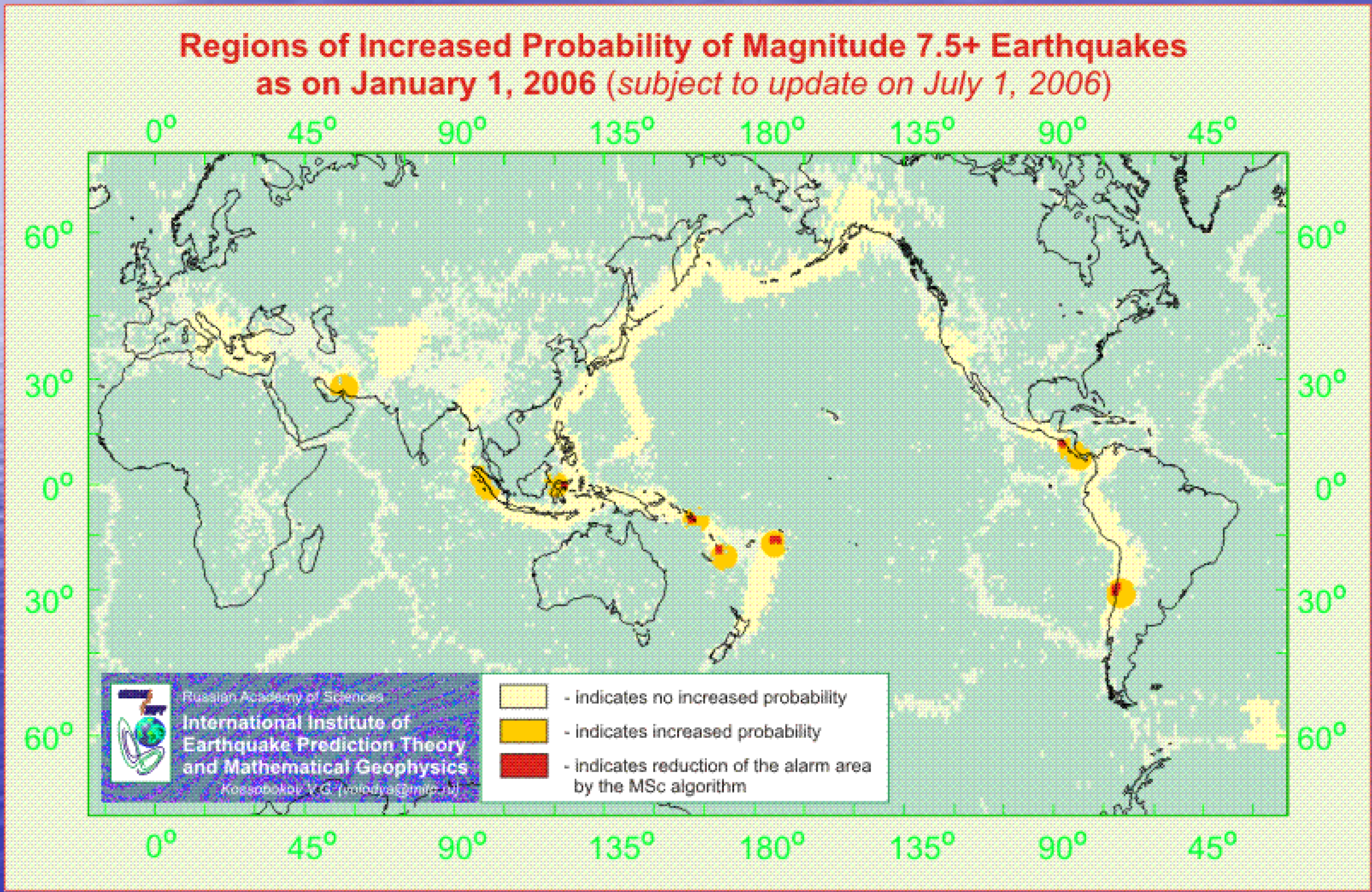
Epicenter: -20.035 -174.227
Depth 5 No. of sta: 44
USGS MOMENT TENSOR SOLUTION
Best Double Couple:Mo=1.8*10**21 Nm
Moment magnitude: MW 8.1





Real-time prediction of the world largest earthquakes

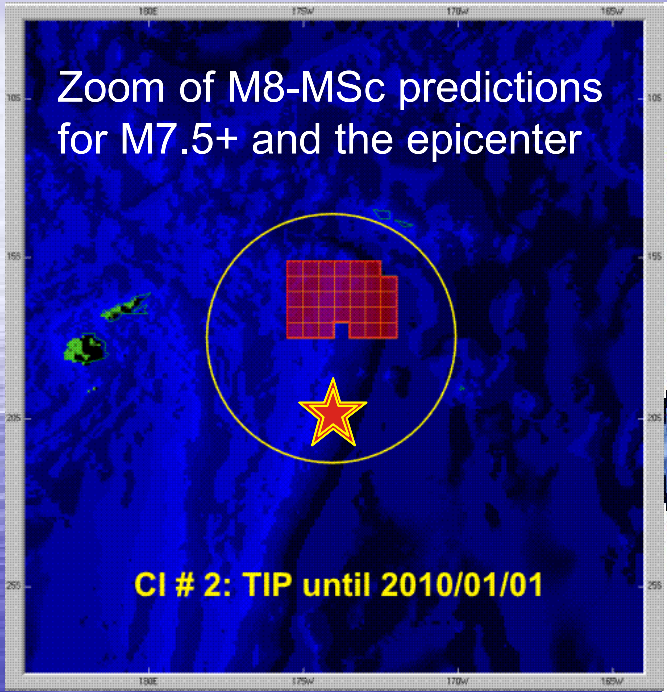
(http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp)



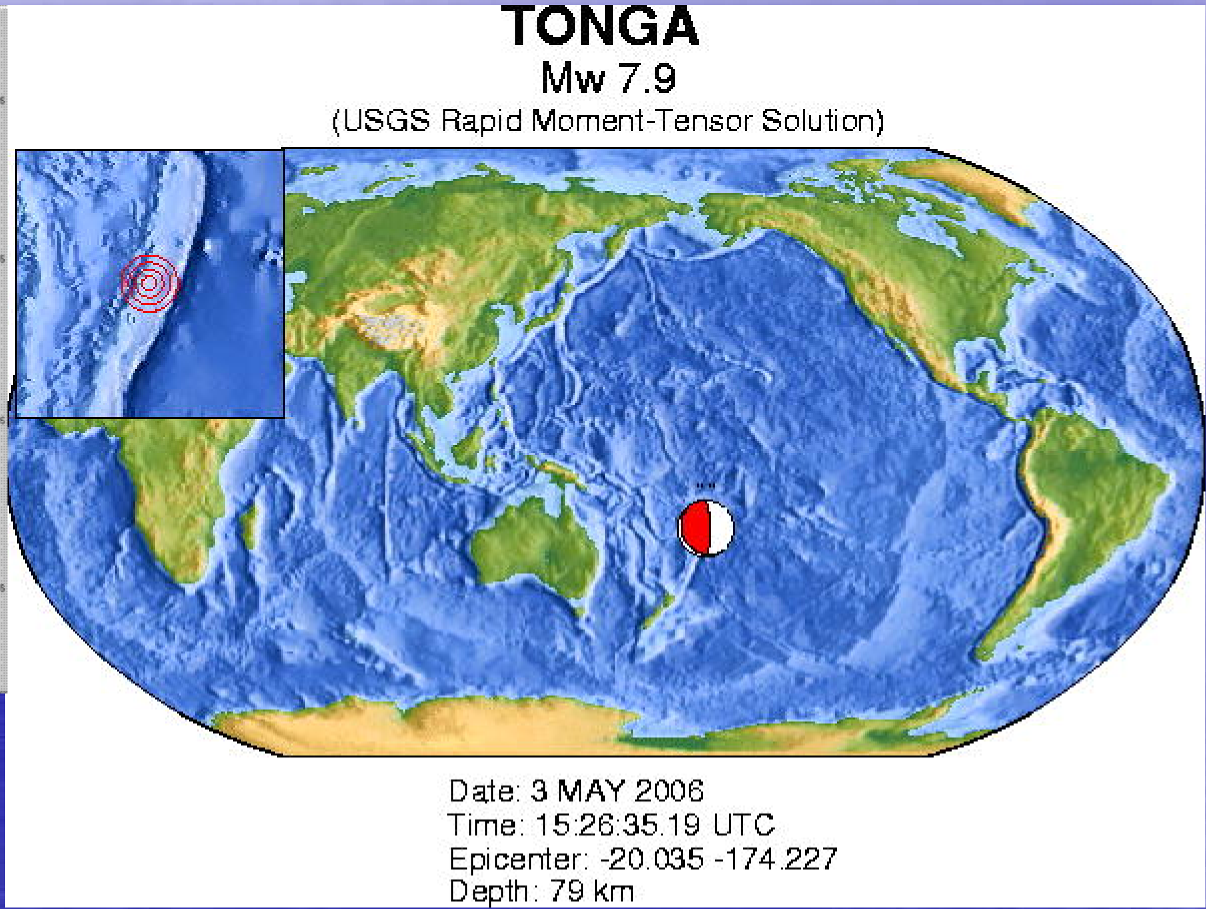
TONGA 06/05/03 15:26:35 UTC: Updated determinations

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			Measure of alarms, %		Confidence level, %	
	Total	Predicted by					
		M8	M8-MSc	M8	M8-MSc	M8	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.

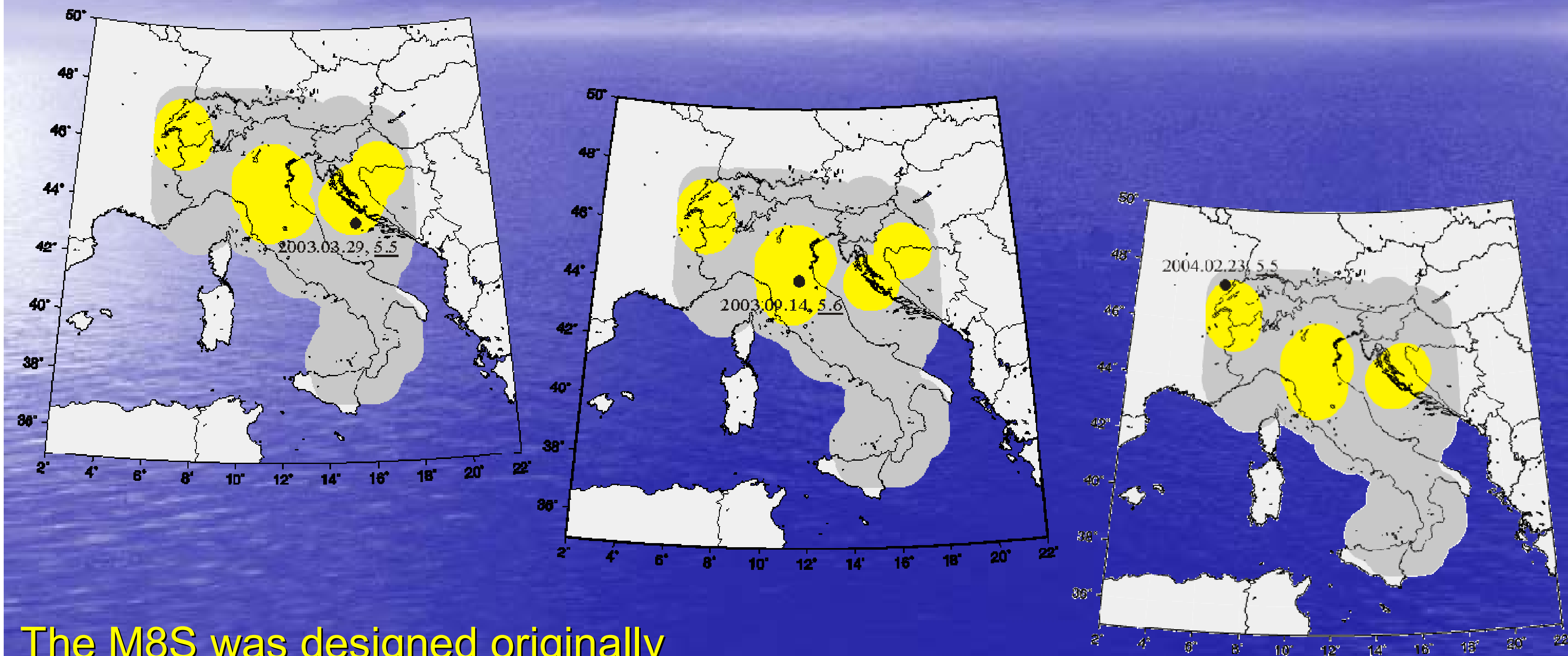
Test period	Large earthquakes Total	Predicted by M8	Predicted by M8-MSc	Measure of alarms, % M8	Measure of alarms, % M8-MSc	Confidence level, % M8	Confidence level, % M8-MSc
1985-present	52	30	16	34.35	11.05	99.95	99.99
1992-present	40	20	10	28.77	10.45	99.34	99.43

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

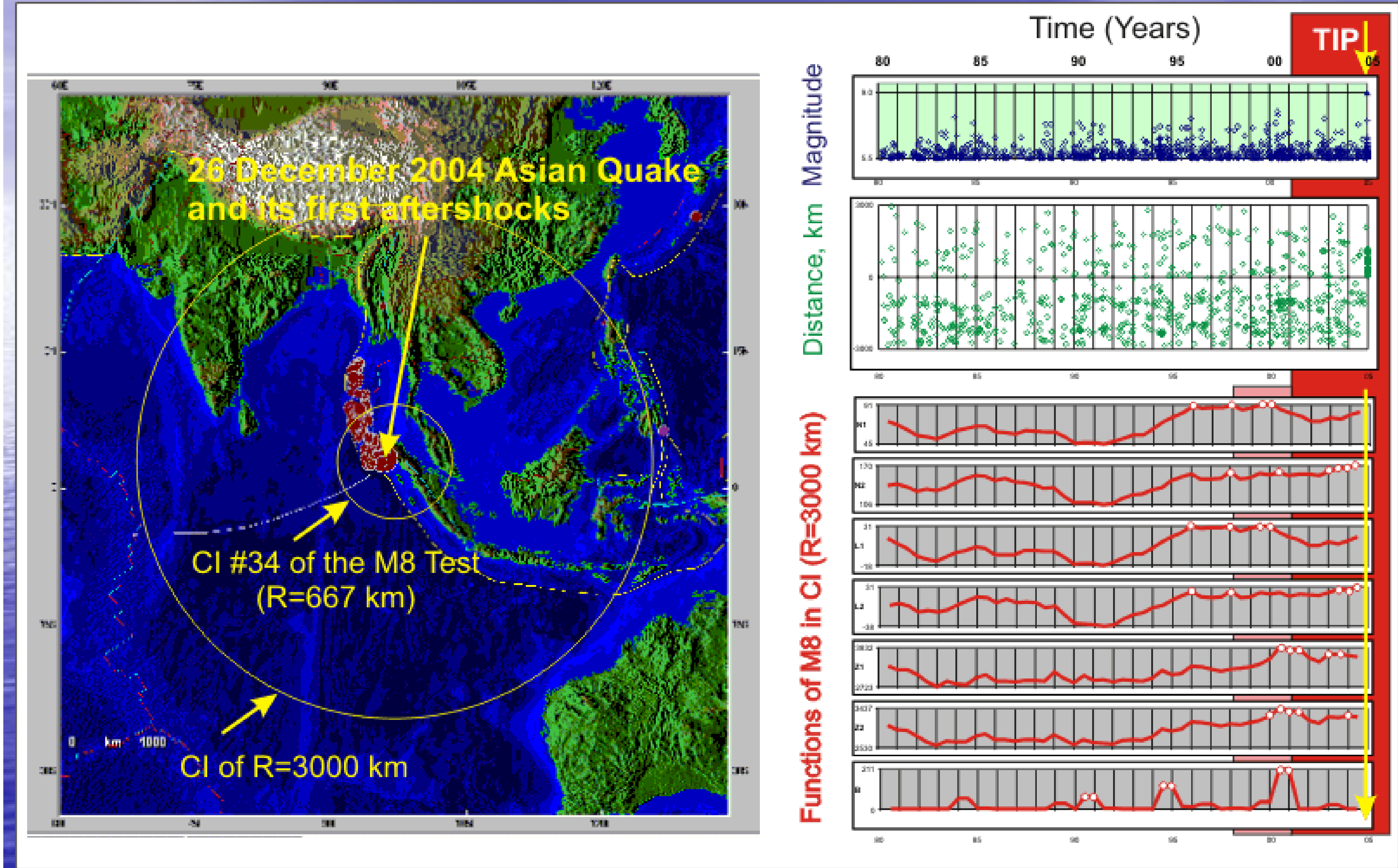
to improve reliability of predictions made by the modified versions of the M8 algorithm applicable in the areas of deficient earthquake data available.

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

Earthquake Forecast/Prediction:
Verification, Accuracy, Limitations

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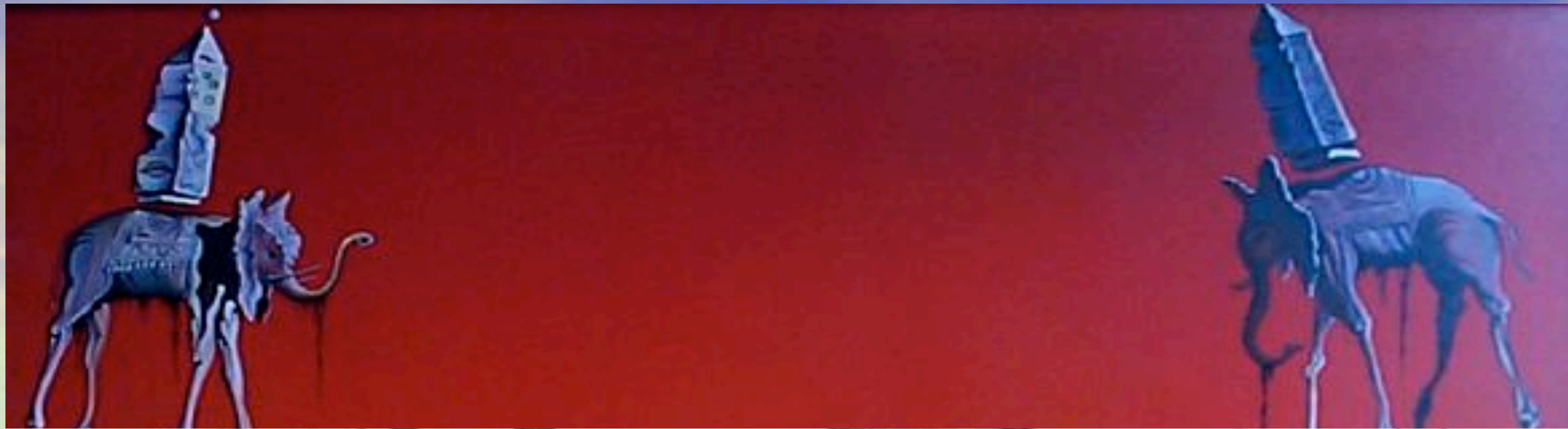
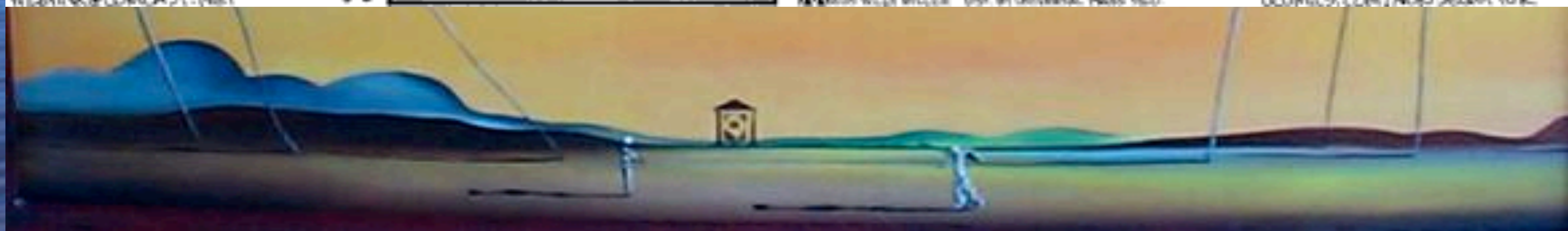
E-mail: volodya@mitp.ru or volodya@ipgp.jussieu.fr




...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-LA-LA ♫
I GIVE UP...
SEE HOW EASY IT IS?
WILEYINK@COMCAST.NET
6-8
UCOMICS.COM/NONSEQUITUR



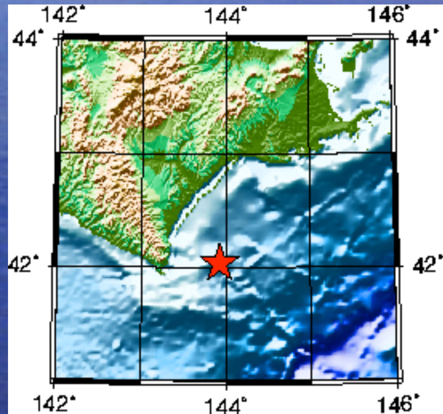
Seismology is juvenile and its appropriate statistical tools to-date may have a "medieval flavor" for those who hurry up to apply a fuzzy language of a highly developed probability theory. To become "quantitatively probabilistic" earthquake forecasts/predictions must be defined with a scientific accuracy. Following the most popular objectivists' viewpoint on probability, we cannot claim "probabilities" adequate without a long series of "yes/no" forecast/prediction outcomes. Without "antiquated binary language" of "yes/no" certainty we cannot judge an outcome ("success/failure"), and, therefore, quantify objectively a forecast/prediction method performance.

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

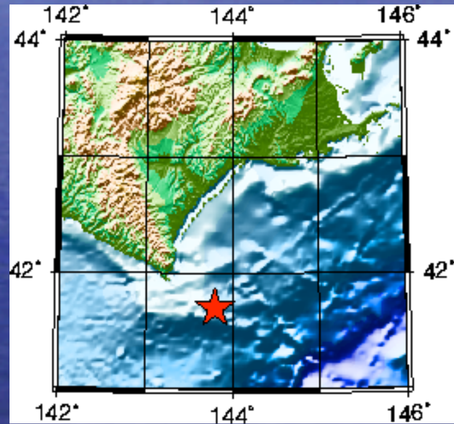
Is it a coincidence or a law?

Two days later …

防災科研Hi-net暫定処理による震源位置

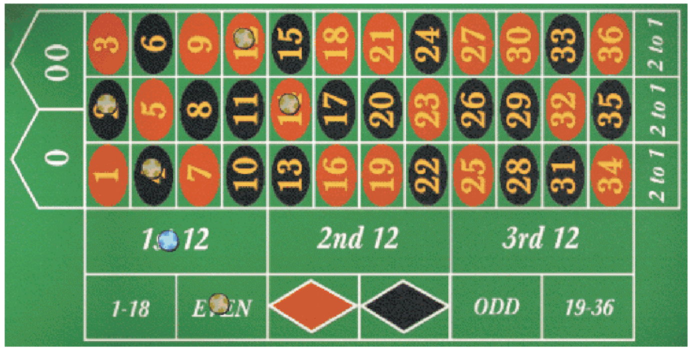


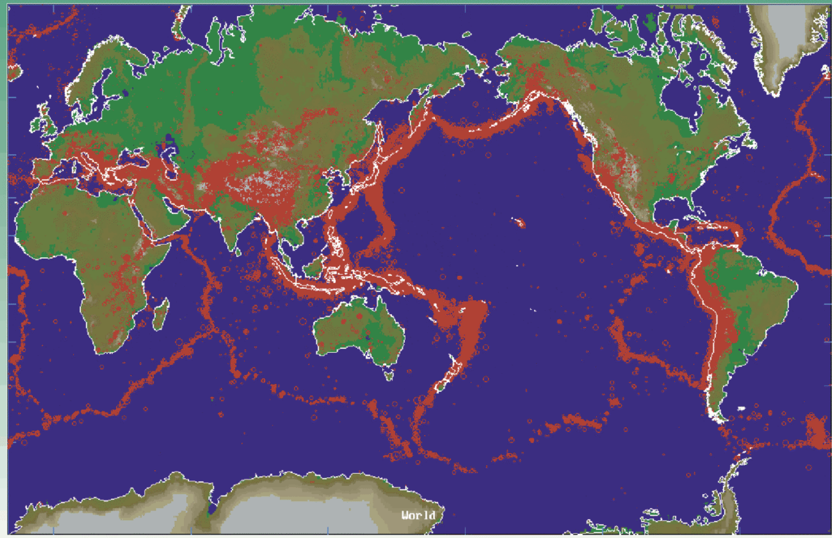
本震
2003年9月26日04時50分11秒
北緯42.0度
東経143.9度
深さ25km
M7.7

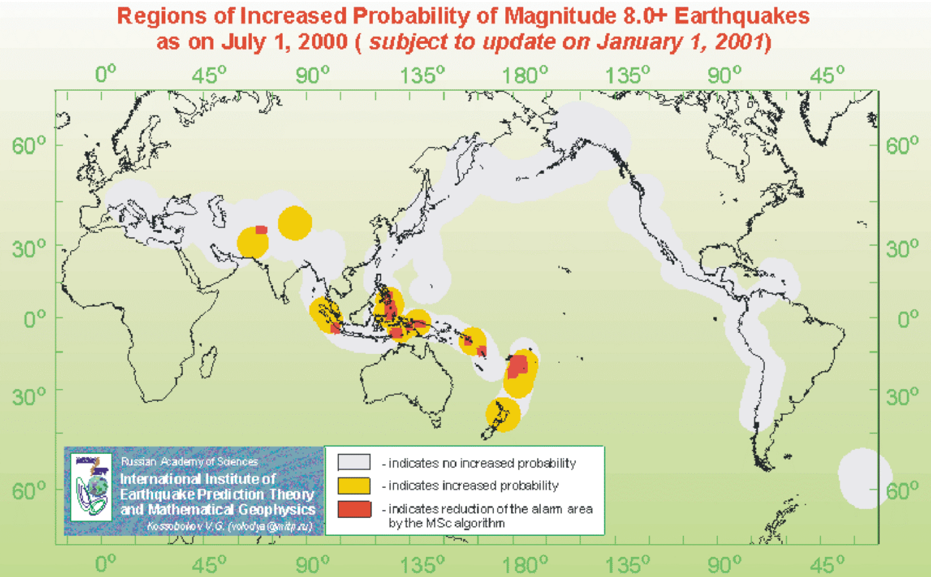


最大余震
2003年9月26日06時08分03秒
北緯41.8度
東経143.9度
深さ35km
M7.4

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…

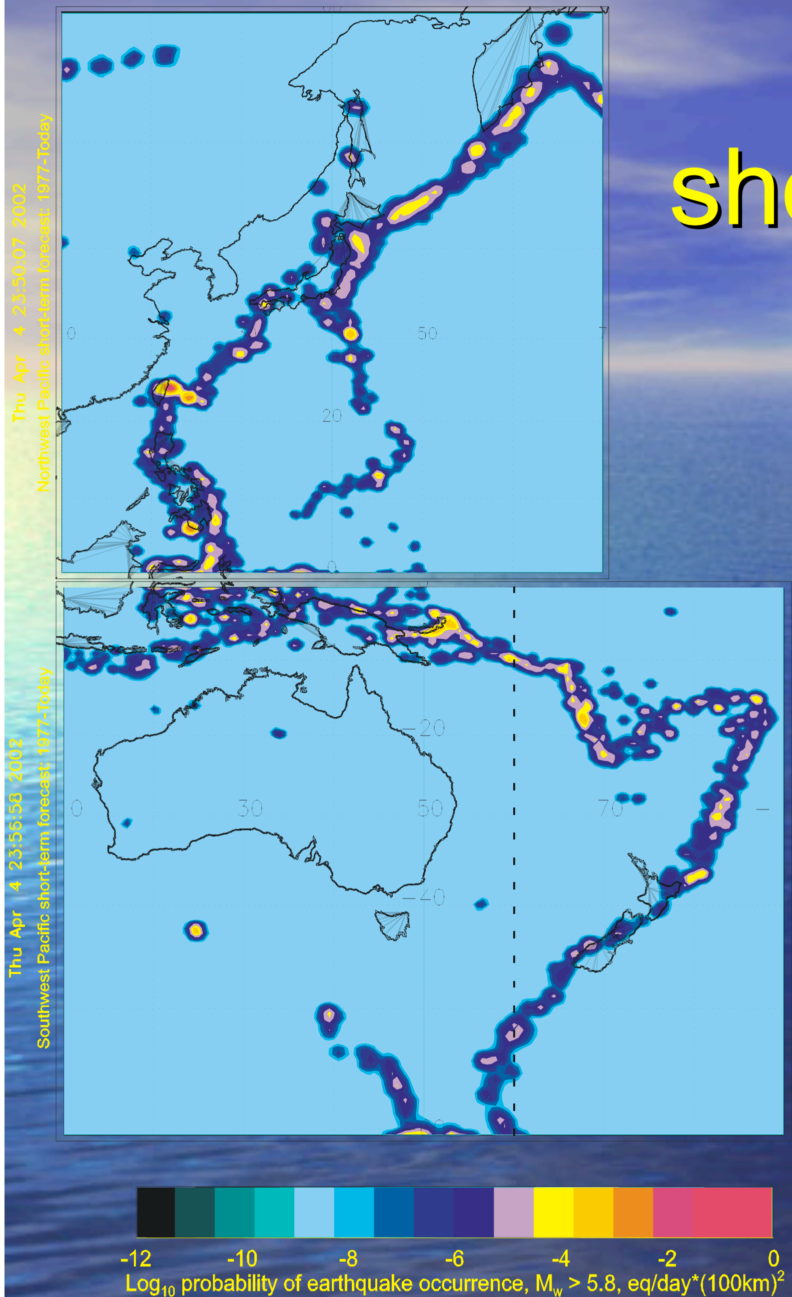
then ***systematically*** you can win! ☺

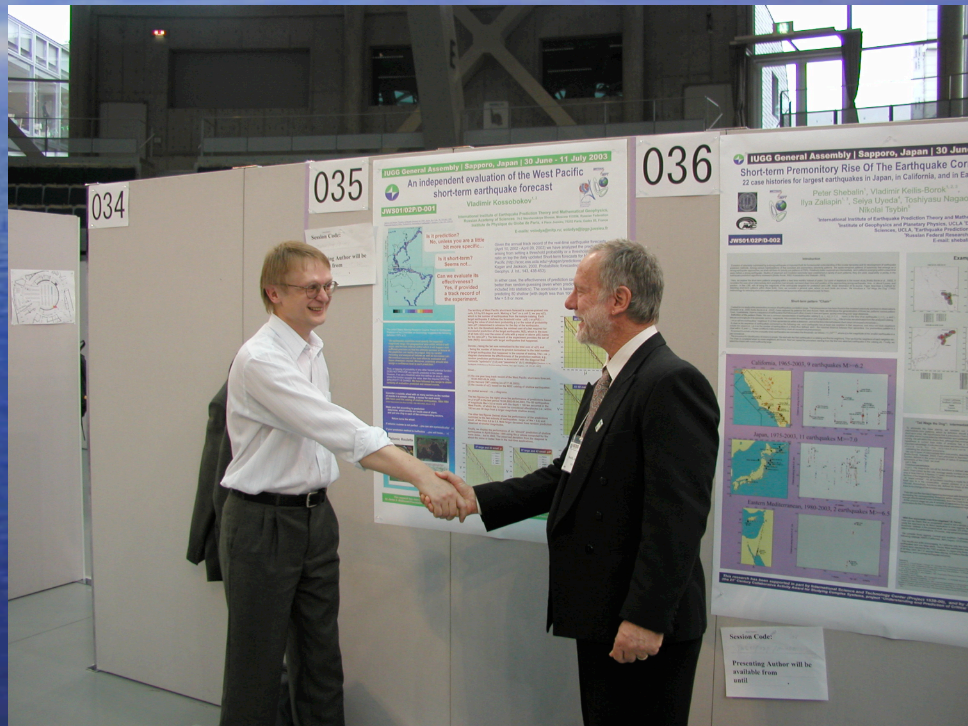
and lose … ☹

If you are smart enough and your predictions are effective ------

the first will outscore the second! ☺ ☺ ☹ ☺ ☺ ☺ ☹ ☺ ☺ ☺

West Pacific short-term forecast





Jackson and Kagan "Testable earthquake forecasts for 1999", Seism. Res. Lett., 70, 393-403, 1999

Kagan and Jackson (2000) "Probabilistic forecasting of earthquakes", Geophys. J. Int., 143, 438-453

We have analyzed the predictions arising from setting a threshold probability or a threshold probability ratio on top the daily updated Short-term forecasts for NW and SW Pacific in April 2002 - September 2004 (*http://scec.ess.ucla.edu/~ykagan/predictions_index.html*; *Kagan and Jackson, 2000. Probabilistic forecasting of earthquakes, Geophys. J. Int., 143, 438-453*) and the catalog of earthquakes for the same period and have come to the following conclusion:

The predictions based on the Yan Y. Kagan and David D. Jackson forecasts are hardly better than random guessing, when main shocks are considered, and could be used for effective prediction of aftershocks only.

The conclusion is based on the prediction outcome achieved for 218 shallow (with depth less than 70 km) earthquakes of MwHRV = 5.8 or more. According to the definition from (*Keilis-Borok et al., 1980*), there are 67 aftershocks and 151 main shocks.

The territory of West Pacific short-term forecast is coarse-grained into cells, 0.5 by 0.5 degree each. Making a “bet” on a cell C, we pay n(C), which is the number of earthquakes from the sample catalog. Each target earthquake E defines the threshold value - p(E) (or p/P(E)) - being the value of short-term probability p (or the value of probability ratio p/P) determined in advance for the day of the earthquake.
In its turn the threshold defines the minimal cost of a bet required for successful prediction of the target earthquake, N(E), which is the sum of all bets n(C) over the union of cells with p equal or above p(E) (same for the ratio p/P). The track record of the experiment provides the set of bets {N(E)} associated with target earthquakes that happened.

Denote μ being the bet sum normalized to the total sum of n(C) and ν being the number of failures-to-predict normalized to the total number of target earthquakes that happened in the course of testing. The ν vs. μ diagram characterize the effectiveness of the prediction method, e.g., random prediction performance is associated with the diagonal that connects "optimist's" {1,0} and "pessimist's" {0,1} strategies (*Molchan, G. M.. Earthquake Prediction as a Decision-making Problem, Pure Appl. Geophys., 149, 233-247, 1997*).

Given -

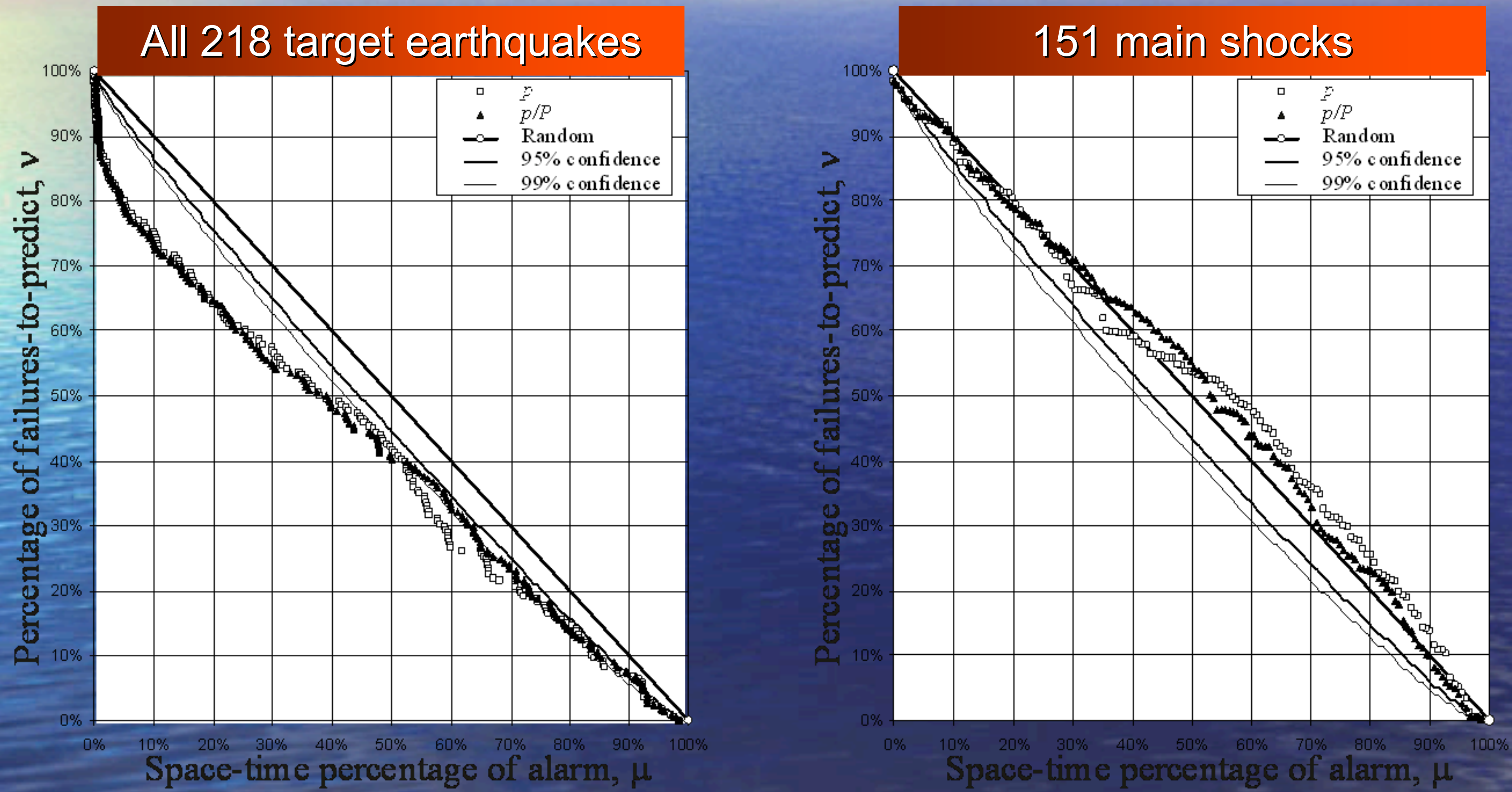
(1) the track record of the West Pacific short-term forecasts in the period from April 10, 2002 to September 13, 2004;

(2) the Harvard CMT catalog for the same period of time;

(3) the counts of n(C) based on the NEIC catalog of shallow earthquakes -

we plotted several ν vs. μ diagrams.

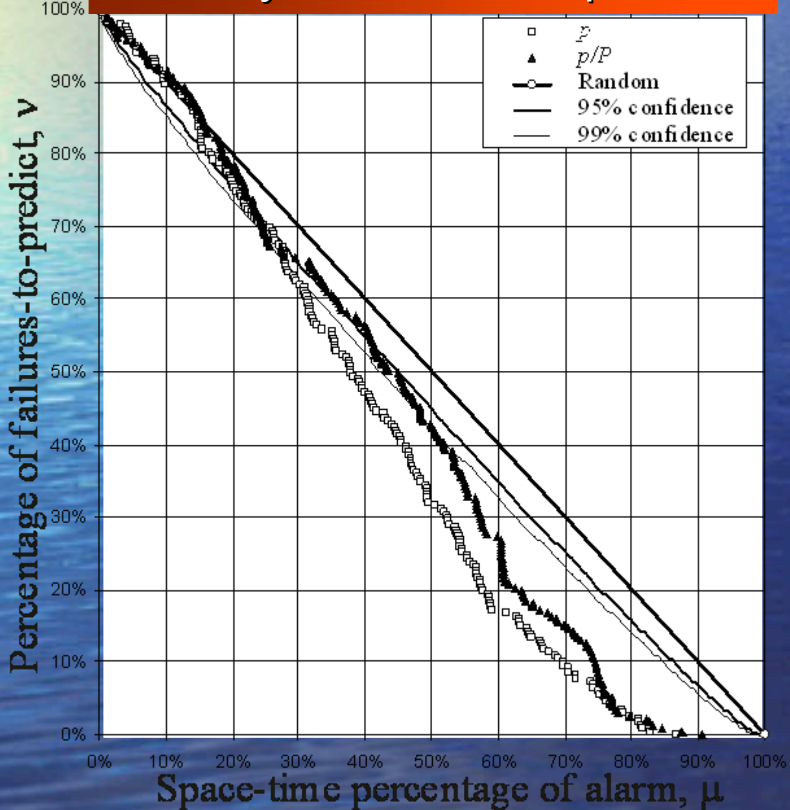
The two figures show the performance of predictions based on p or p/P in the test period from April 10, 2002 to September 13, 2004. The total of 218 earthquakes of magnitude Mw = 5.8 or more with the depth of 70 km or shallower occurred in the West Pacific. According to definition from (*Keilis-Borok et al., 1980*), 67 of them are aftershocks and 151 main shocks.



The outcome of an "absurd" prediction:

The percentage of the failures-to-predict ν versus the percentage of the alerted space-time volume μ: $\{\mu_p(E), \nu_p(E)\}$ and $\{\mu_{p/P}(E), \nu_{p/P}(E)\}$ generated by "prediction" of the 231 earthquakes with magnitude MwHRV ≥ 5.8 and depth ≥ 70 km in April 10, 1992-September 13, 1994 using the *p* and *p/P* maps computed for April 10, 2002-September 13, 2004.

"Delayed" 231 earthquakes



The observed deviation from the diagonal is about the same or larger than in the real-time applications.

Thus, we cannot reject random nature of the Jackson-Kagan "probabilistic" method and may conclude that

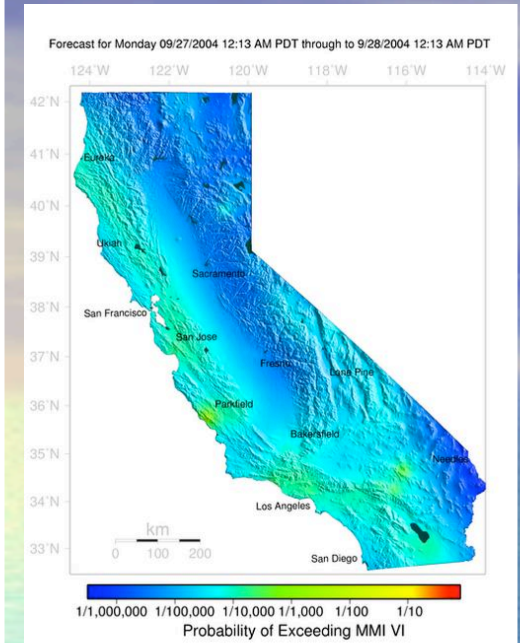
(i) its effectiveness for predicting large earthquakes is doubtful, and

(ii) the applicability of the underlying ETAS model is an ingrained bigotry.

“Hierarchical evidence is a house of cards.
Pull out your primary assumption, and everything gets shaky.”

Regional Earthquake Likelihood Models: A realm on shaky grounds?

Likelihood scoring is one of the delicate tools of Statistics, which could be worthless or even misleading when inappropriate probability models are used. This is a basic loophole for a misuse of likelihood as well as other statistical methods on practice. The flaw could be avoided by an accurate verification of generic probability models on the empirical data. It is not an easy task in the frames of the Regional Earthquake Likelihood Models (RELM) methodology, which neither defines the forecast precision nor allows a means to judge the ultimate success or failure in specific cases. Hopefully, the RELM group realizes the problem and its members do their best to close the hole with an adequate, data supported choice.



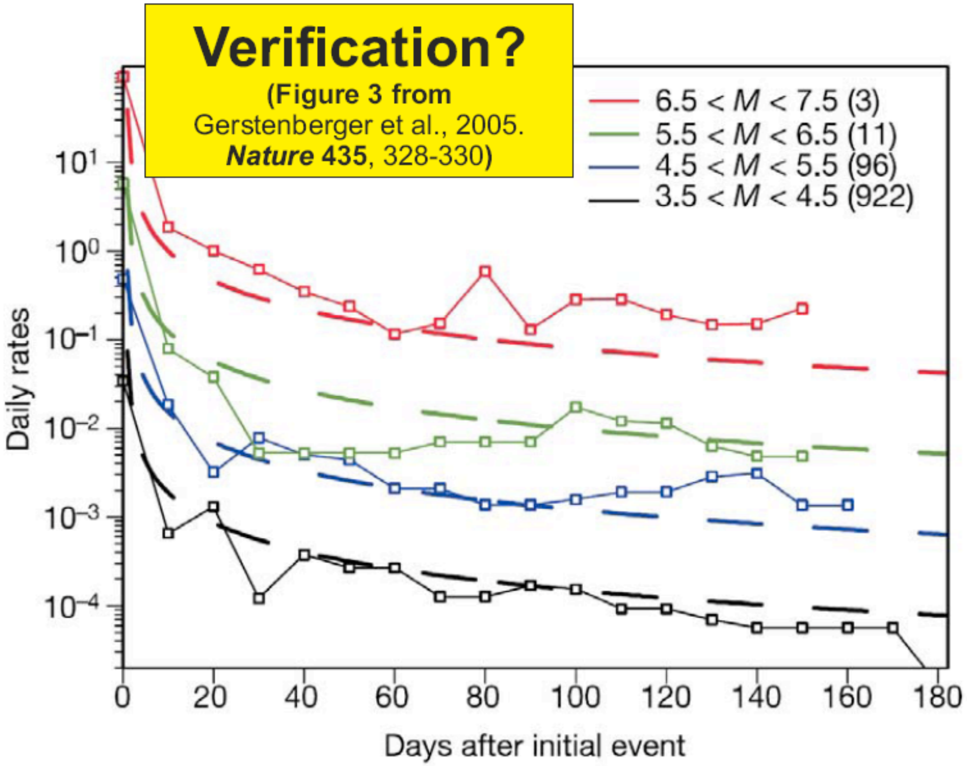
Regretfully, this is not the case with the erroneous choice of Gerstenberger et al., who started the public web site with forecasts of expected ground shaking for `tomorrow' (*Nature* 435, 19 May 2005).

Gerstenberger et al. **HAVE INVERTED THE CRITICAL EVIDENCE OF THEIR STUDY,** i.e., the 15 years of recent seismic record accumulated just in one key figure, which suggests rejecting with confidence above 97% "the generic California clustering model" used in automatic calculations.

Gerstenberger, M. C., Wiemer, S., Jones, L. M. & Reasenberg, P. A. Real-time forecasts of tomorrow's earthquakes in California. *Nature* **435**, 328-331 (19 May 2005)

Schorlemmer, D., Gerstenberger, M., Wiemer, S. & Jackson D. Earthquake Likelihood Model Testing (manuscript in preparation, February 7, 2005)

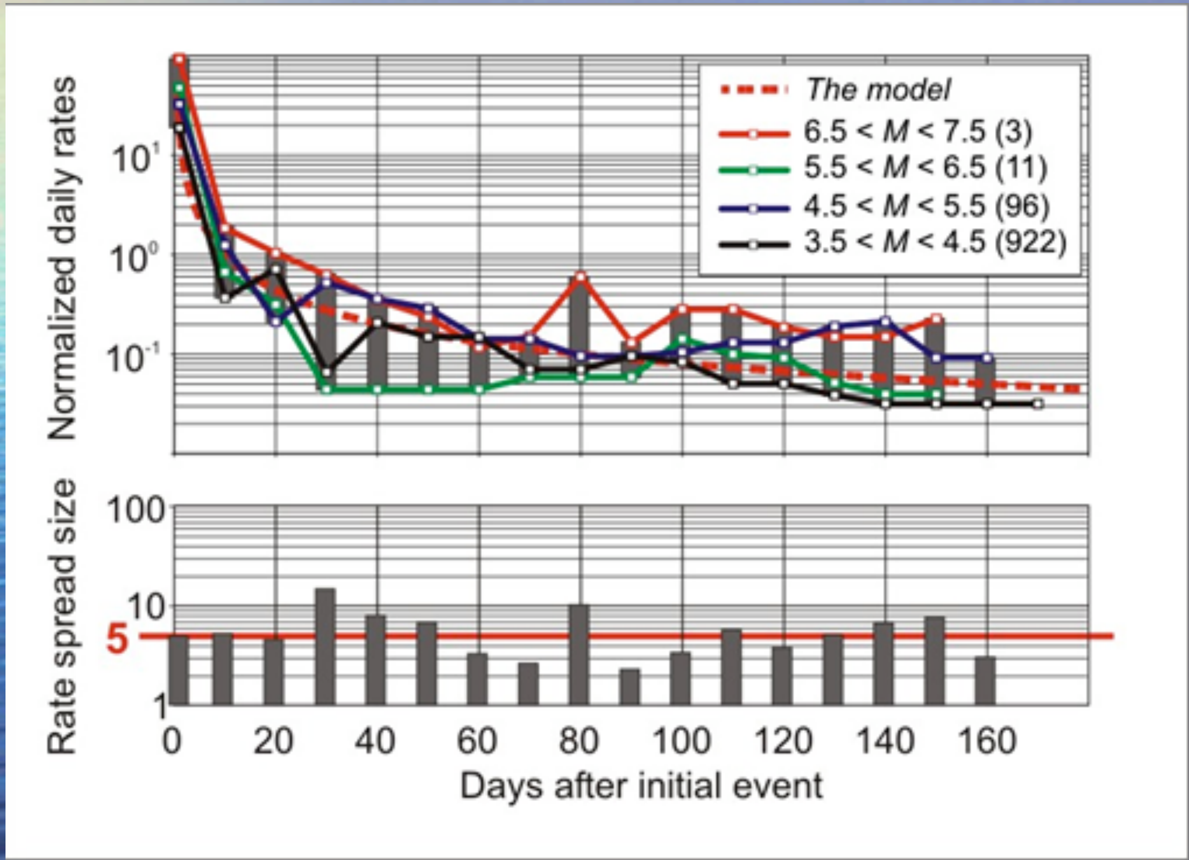
Figure 3 | Calculated and observed rates of events $M \geq 4$ in 24-hour intervals following mainshocks occurring between 1988 and 2002 in southern California. Dashed lines show the rates forecasted by the generic California clustering model (without cascades) for the mainshock magnitude (M) shown. For this test a simple circular aftershock zone implementation (solid lines) gives the observed rates of $M \geq 4.0$ aftershocks following all mainshocks with magnitude within 0.5 units of M. The aftershock zones are defined as the areas within one rupture length of the mainshock epicentre.



Soliciting misuse of Statistics?

"As a first test, we verified that the generic clustering model describes the average clustering activity of California reasonably well. Using data from 1988–2002, after the period used to initially develop the model and thus independent data, we compute the average daily rate of events following an earthquake of a given size (Fig. 3)."

Calculated and observed rates of events $M \geq 4$ in 24-hour intervals following mainshocks occurring between 1988 and 2002 in southern California.



Dashed line shows the rate forecasted by the generic California clustering model for the initial mainshock of magnitude $6.5 < M < 7.5$; solid lines display the observed rates of $M \geq 4$ aftershocks following all mainshocks with magnitude within 0.5 units of M, normalized to the rate of the mainshock of magnitude $6.5 < M < 7.5$. Grey bars stretch from the minimal to the maximal value of the observed rates; their size is about a factor of 5.

Analyzing the figure by means of the well-known Kolmogoroff-Smirnoff criterion, an experimentalist would be led to reject the hypothesis that the random variable "Time after initial event" in different magnitude ranges of the initial event has the same statistical distribution.

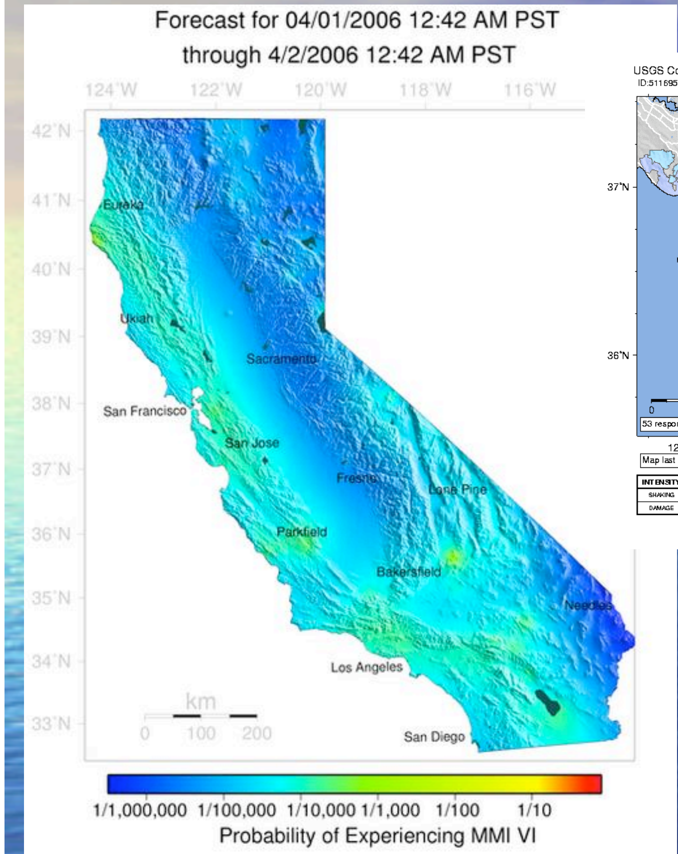
Proof: Normalised by condition that the total integral of the p.d.f. (probability density function) increments equals 1, each of the four plots provides the minimum of positive p.d.f. increments, which are by definition either 1/N or its integer multiple (e.g., 2/N, 3/N, etc.). These are about 0.0012, 0.0008, 0.0025, and 0.0015, which values imply the sample sizes about 846, 1250, 401, and 665 or integer multiples of these values. The probability of a smaller value of the Kolmogoroff-Smirnoff statistic D than that for the two samples used to plot the daily rates after $5.5 < M < 6.5$ (green plot in Figure 3) event and after $3.5 < M < 4.5$ (black plot) event (i.e.,

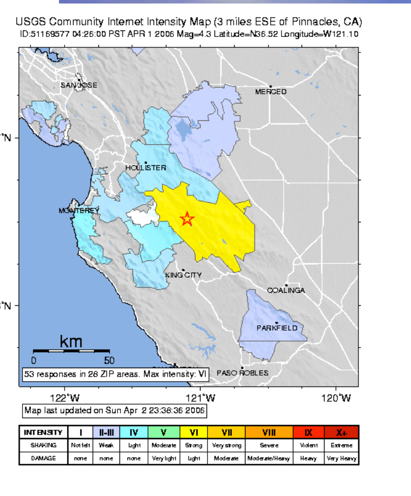
$D = 0.07 \cdot (N_1 N_2/(N_1+N_2))^{1/2} \geq 2.12$) is larger than 97%,

Therefore, the hypothesis that these two samples are drawn from the same distribution can be rejected at significance level of 0.03. ■

(A skilful experimentalist would easily recognize the sample size in the order of a thousand just from the range of the empirical distribution of rates, about three decimal orders, in Figure 3, while a skilful observer would grasp 922 that signifies the number of events about magnitude 4. Moreover, giving a look at Figure 3, he or she, even without any statistical testing, would say that the data does not support the model.)

USGS Web Site May Mislead Californians





Since the time of *Nature* published the work by Gerstenberger *et al* on May 19, 2005 -

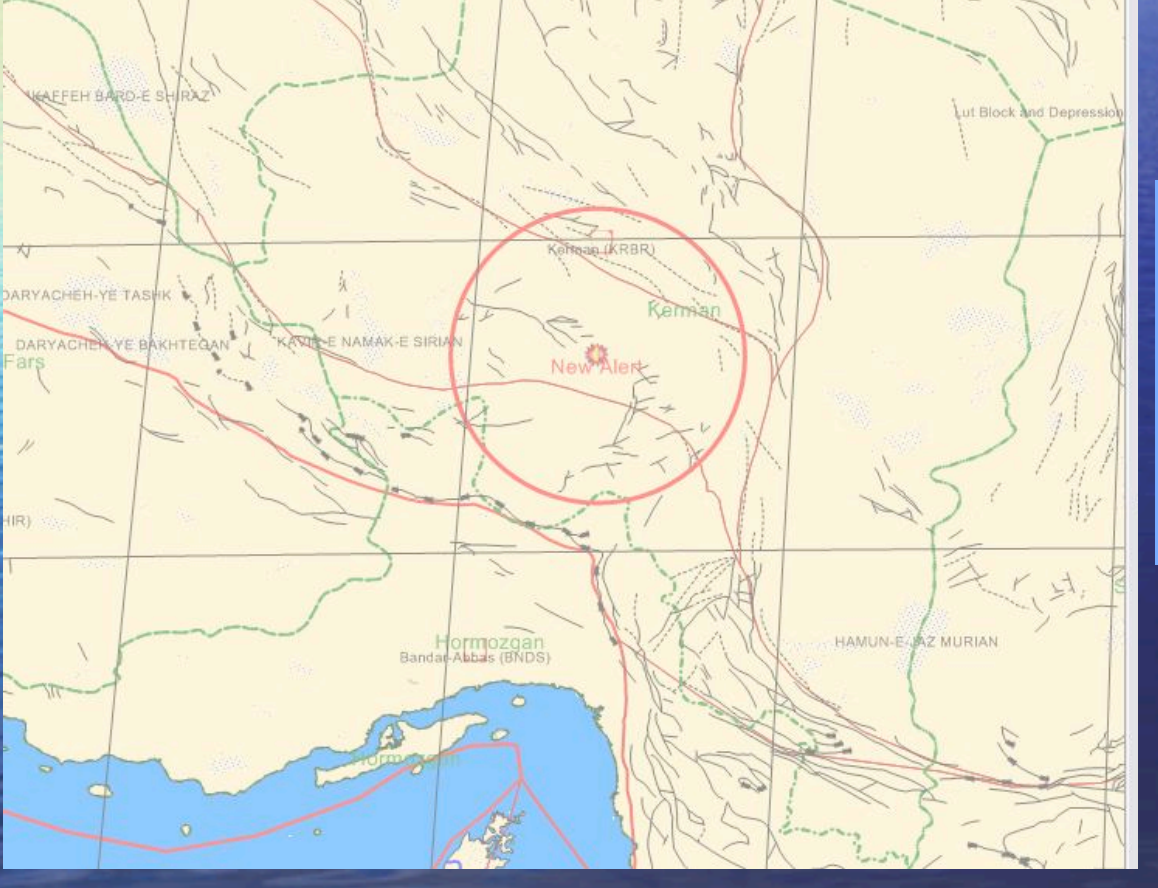
(i) In the 563 days (to Dec 03, 2006) of the real-time forecasting the four earthquakes of Modified Mercalli intensity VI in California have occurred in the "sky blue" areas of the web-site's lowest-risk (about 1/10000 or less). These are the earthquakes on June 12, 2005 near Anza; June 16, 2005 near Yucaipa; April 1, 2006 near Paicines; and August 3, 2006 W of Glen Ellen (pasadena.wr.usgs.gov/shake/ca).

(ii) The extent of the observed areas of intensity VI for these events (i.e., about one hundred for the four areas in total) is by far less than the expected number of cells experiencing VI or greater shaking (i.e., about 451 for the period of 653 days).

As we see, this should not surprise Californians…

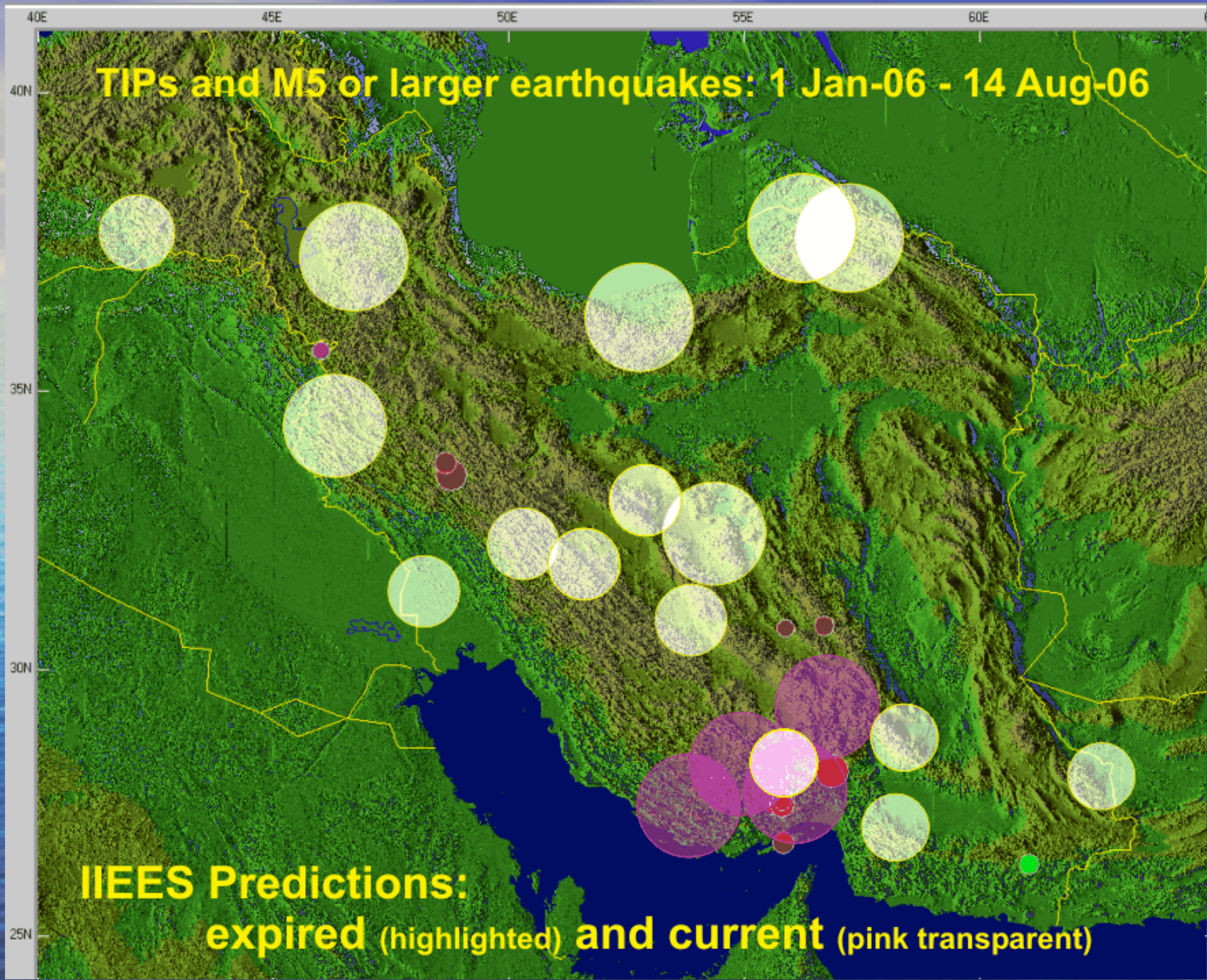
Regretfully, USGS continues delivering to the public, emergency planners and the media, a forecast product, which is based on wrong assumptions, which violates the best-documented earthquake statistics in California, which accuracy was not investigated, and which forecasts were not tested in any rigorous way.

Recently, IIEES did set up a website of restricted access (ftp://www.iiees.ac.ir/eqprediction), which we have a chance to visit systematically since March 8, 2006.

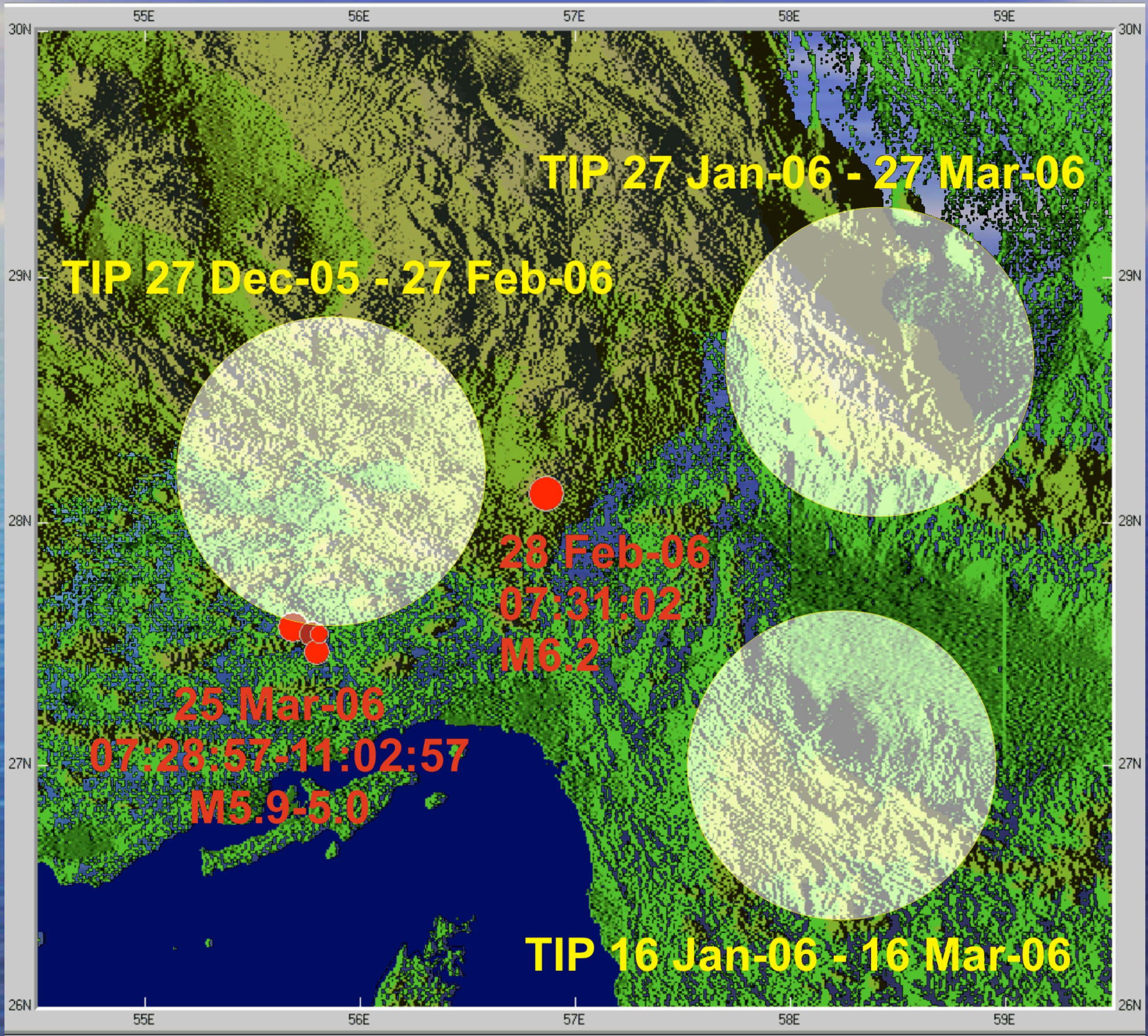


Each prediction reports –

- Location of the alert center;
- The alert radius;
- The alert beginning and end;
- The magnitude of target event;
- Probability (56% in all cases)


TIPs and M5 or larger earthquakes: 1 Jan-06 - 14 Aug-06
IIEES Predictions:
expired (highlighted) and current (pink transparent)
40E
45E
50E
55E
60E
40N
35N
30N
25N

Zoom to alerts and target earthquakes in the South

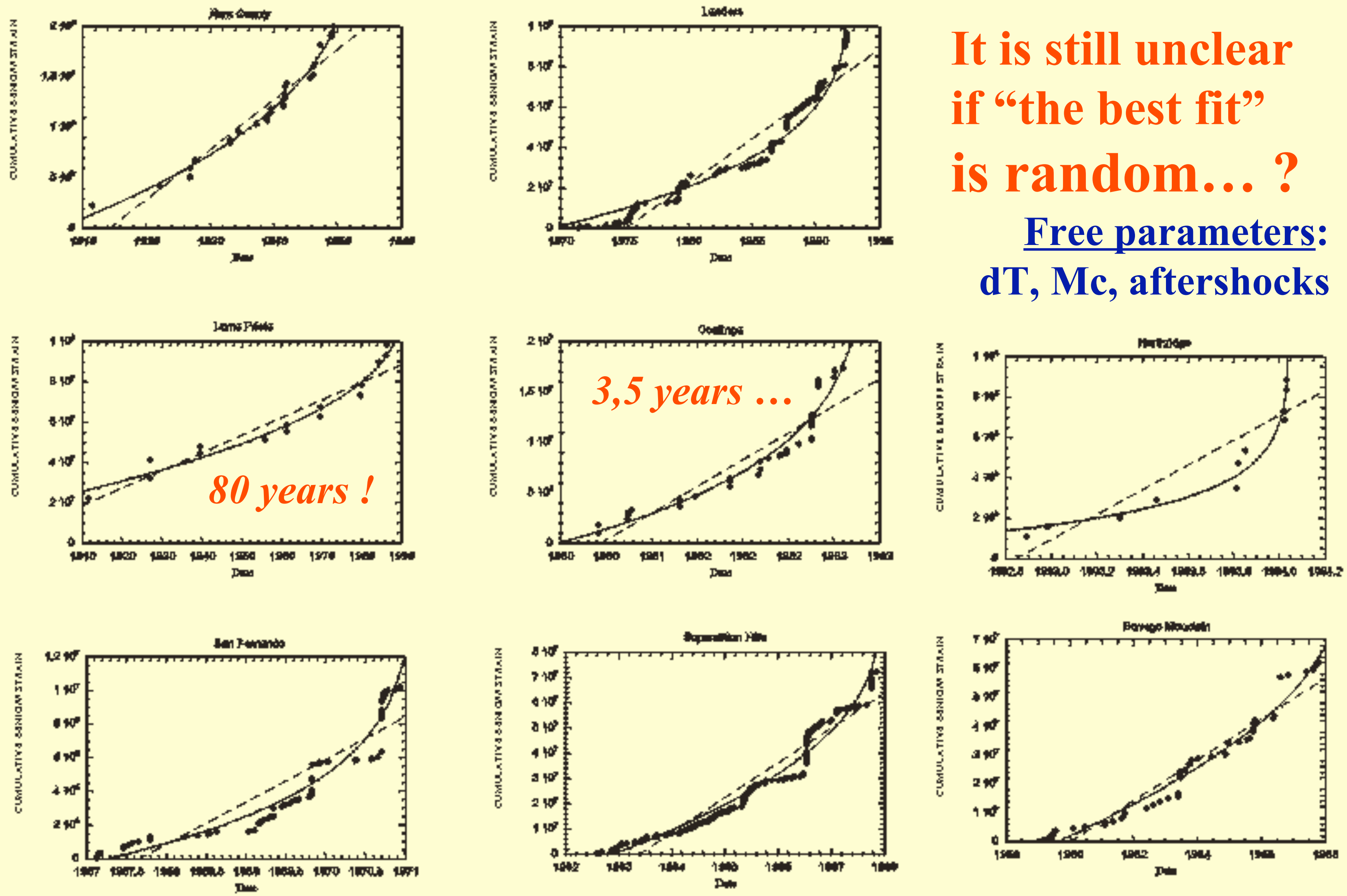


IIEES predictions:

- We continuously observe no success;
- Evidently, this highly contradicts the expected number $P \cdot N = 56\% \cdot 21 = 11.76$ (presumably, P is an estimate of probability of success);
- The IIEES predictions are misleading and their dissemination to the public, emergency planners and the media should not be done;
- The underlying theory is either erroneous or applied in a wrong way.

Other evident cases of misuse of Statistics

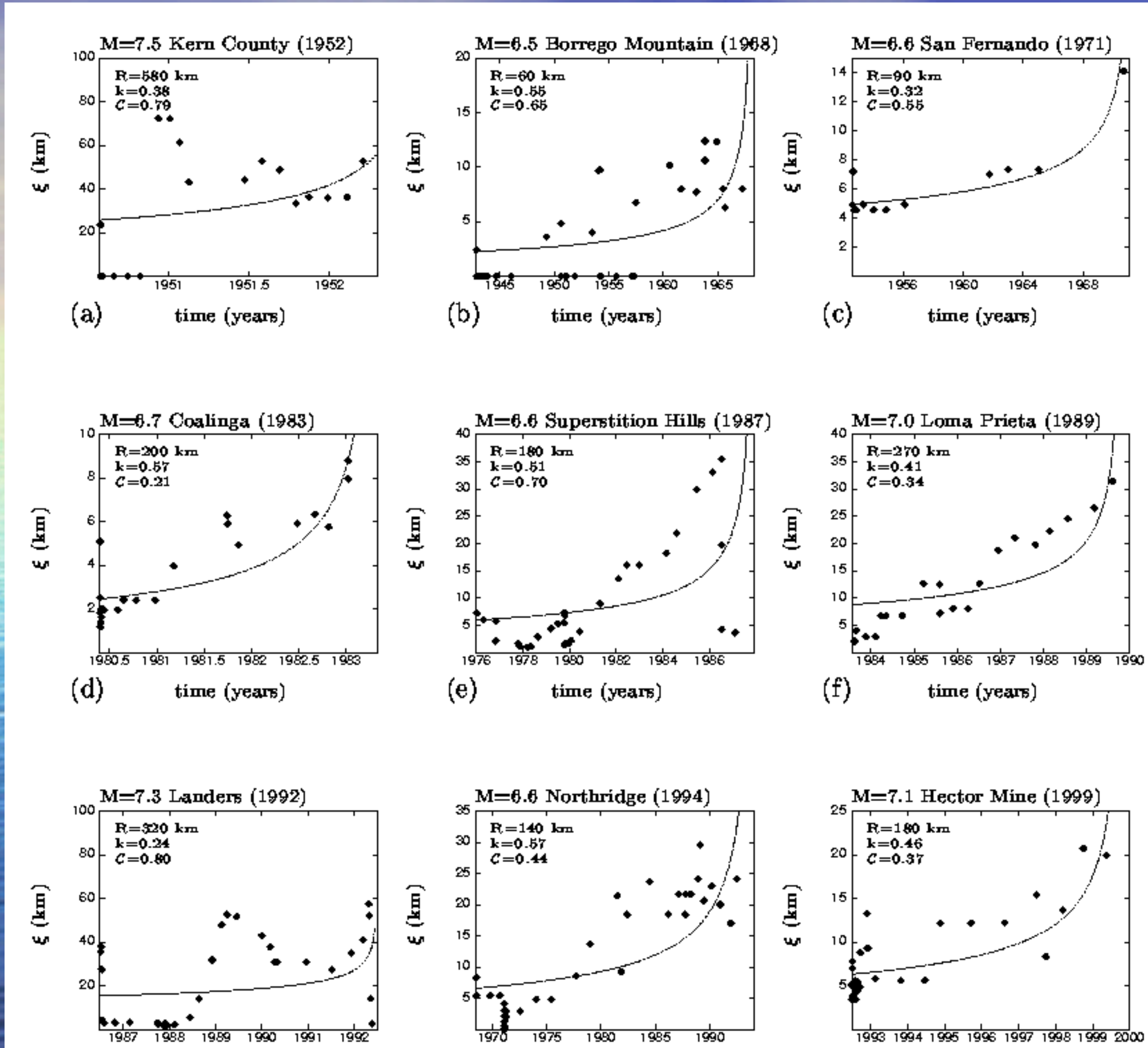
Bowman, Ouillon, Sammis, Sornette, & Sornette, 1998



It is still unclear if "the best fit" is random… ?

Free parameters:

dT, Mc, aftershocks



Zoller, Hainzl & Kurths, 2001

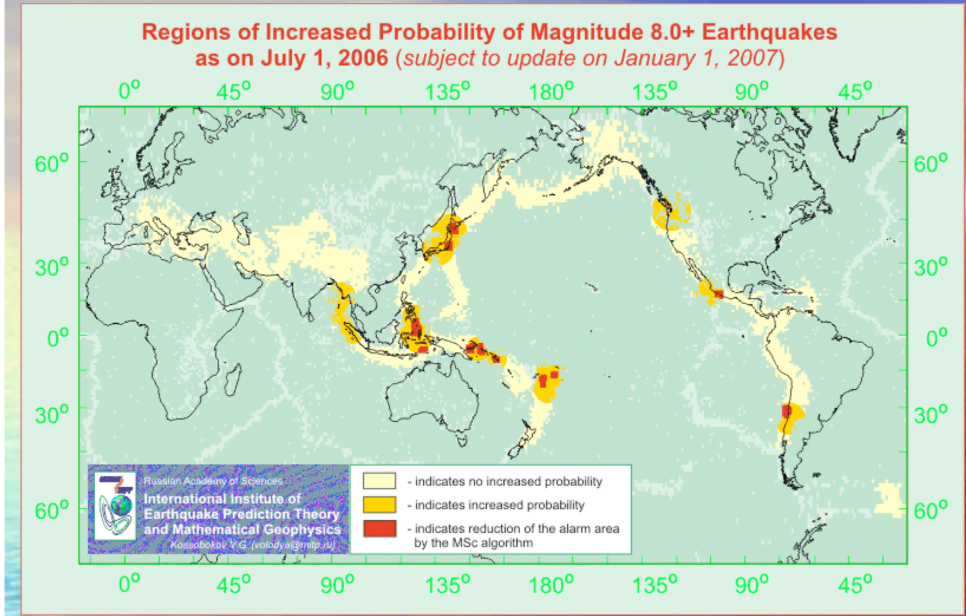
Does "the best fit" fit the data at all ?

Verified “Precursors”

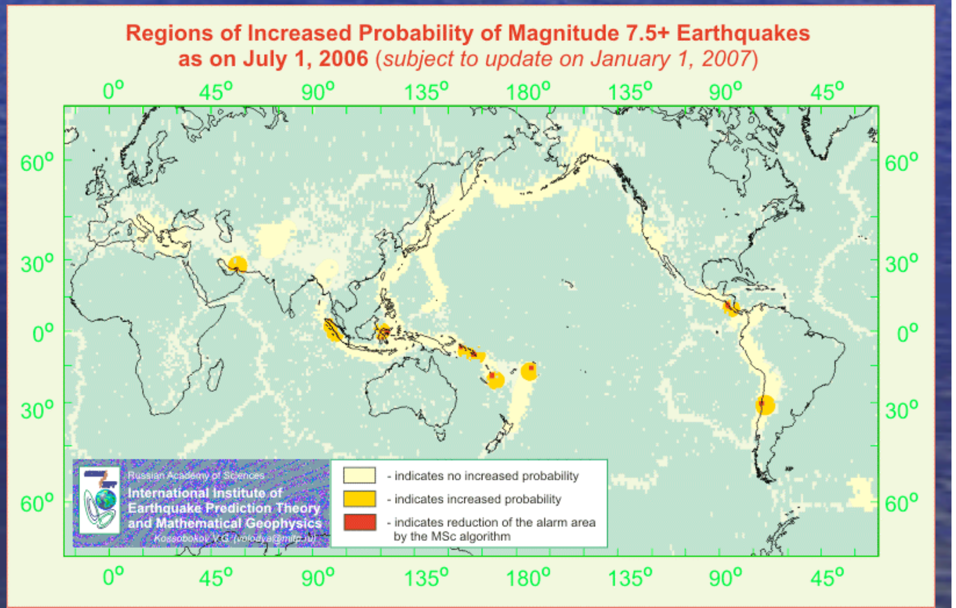
- The simple seismicity patterns – Σ and “burst of aftershocks” – were given unambiguous reproducible definitions and their predictive value was validated by the prospective worldwide tests. **However, it** is not clear yet whether some single simple premonitory pattern may compete in performance with prediction algorithms that combine several traits describing the dynamics of seismic region at the approach of a large earthquake.

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.



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

N.Krylov, famous Russian mathematician

The accuracy of an earthquake prediction method is essentially predefined by the accuracy of the data available, which is far from ideal. The unavoidable natural difficulties in observing seismic events as well as in correlating them with other geophysical phenomena and fields complicates the design and testing of a new generation of earthquake prediction technique.

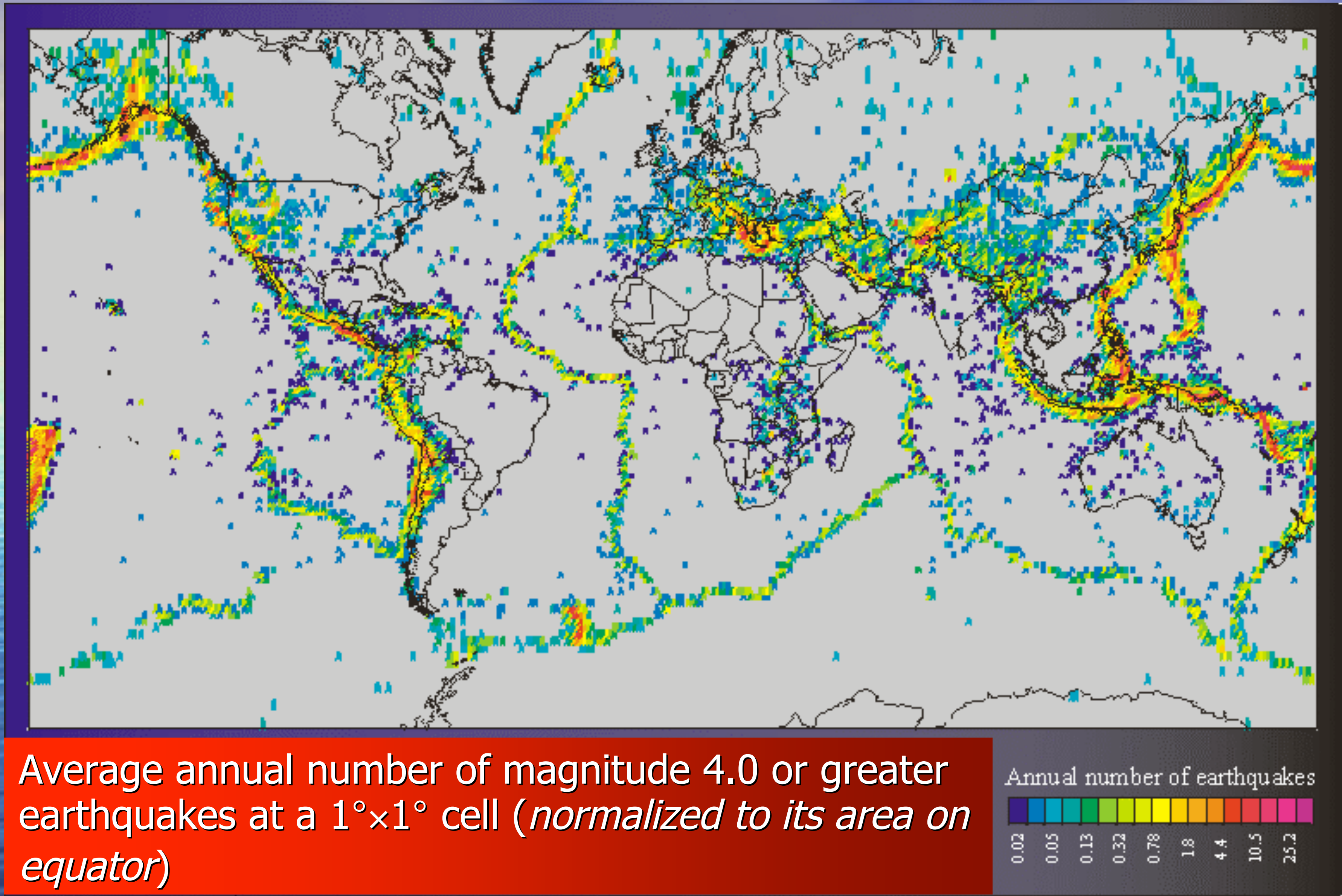
The accumulated case-histories of predicted and not predicted earthquakes provide us unique and so far very limited information that may help understanding the ultimate limits of seismic predictability.

Stages of earthquake prediction

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

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

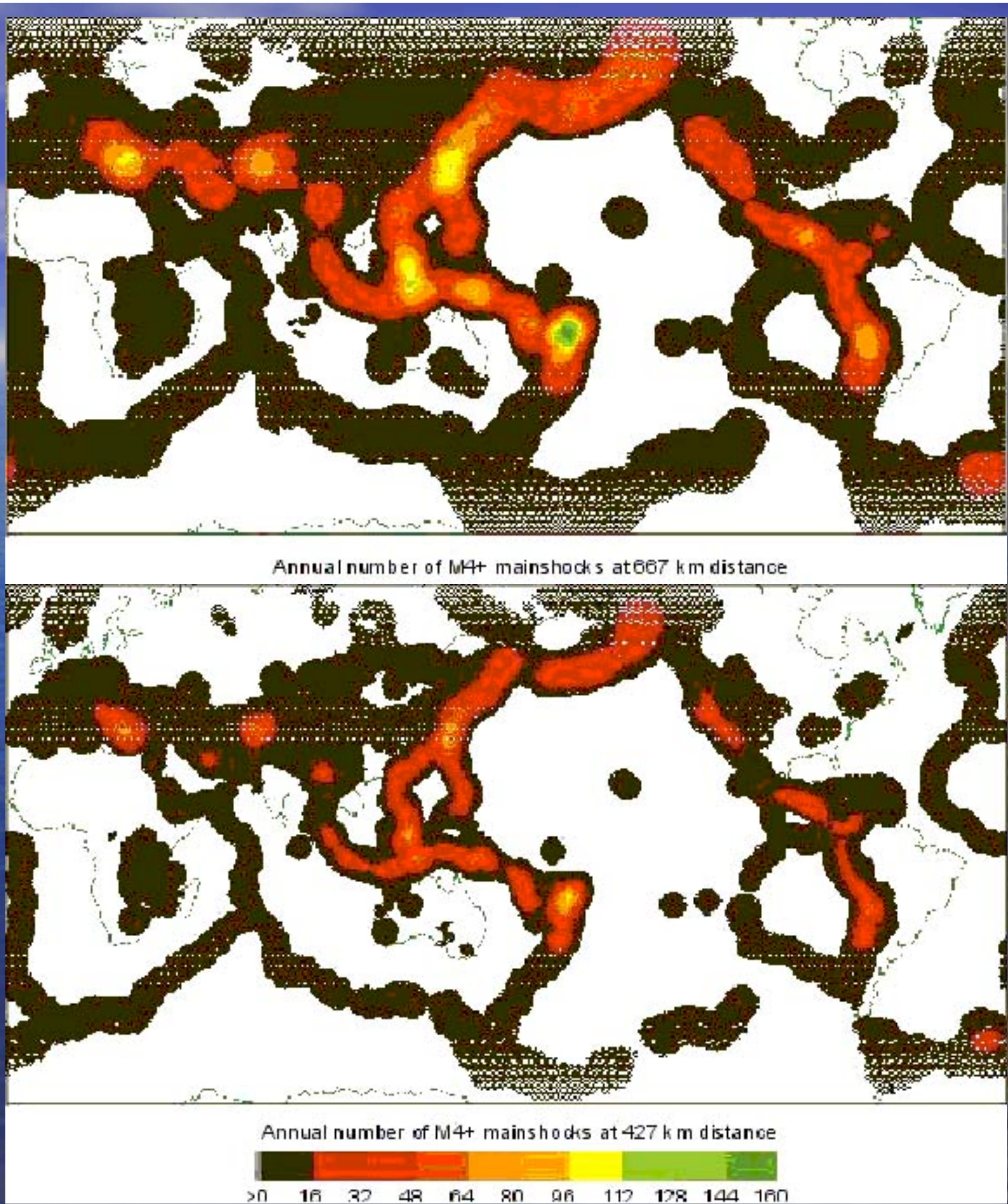
- Moreover, the Gutenberg-Richter law suggests limiting magnitude range of prediction to about one unit. Otherwise, the statistics would be essentially related to dominating smallest earthquakes.



Average annual number of magnitude 4.0 or greater earthquakes at a 1°×1° cell (*normalized to its area on equator*)

Earthquakes are rare events. Therefore, the application of the M8 algorithm is limited to the areas where reported earthquakes are large enough in number.

The color on the maps signifies the annual average number of earthquakes with magnitude 4 or larger in the 667-km (above) and 427-km (below) circles centered at the point.



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	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 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	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.

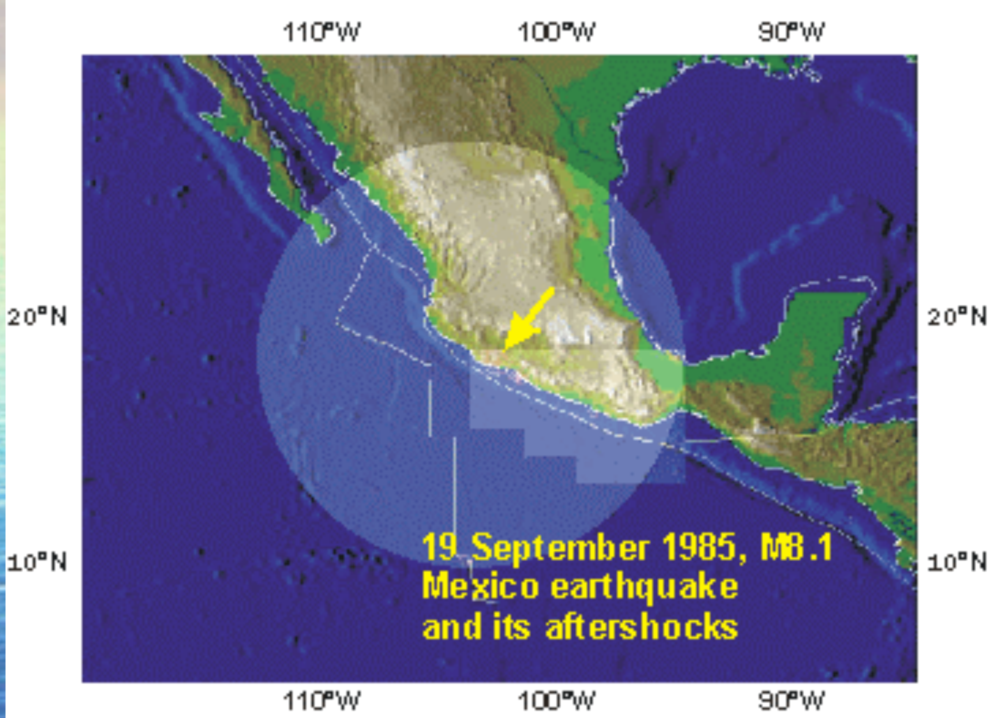
The prediction for M7.5+ is less effective than for M8.0+.

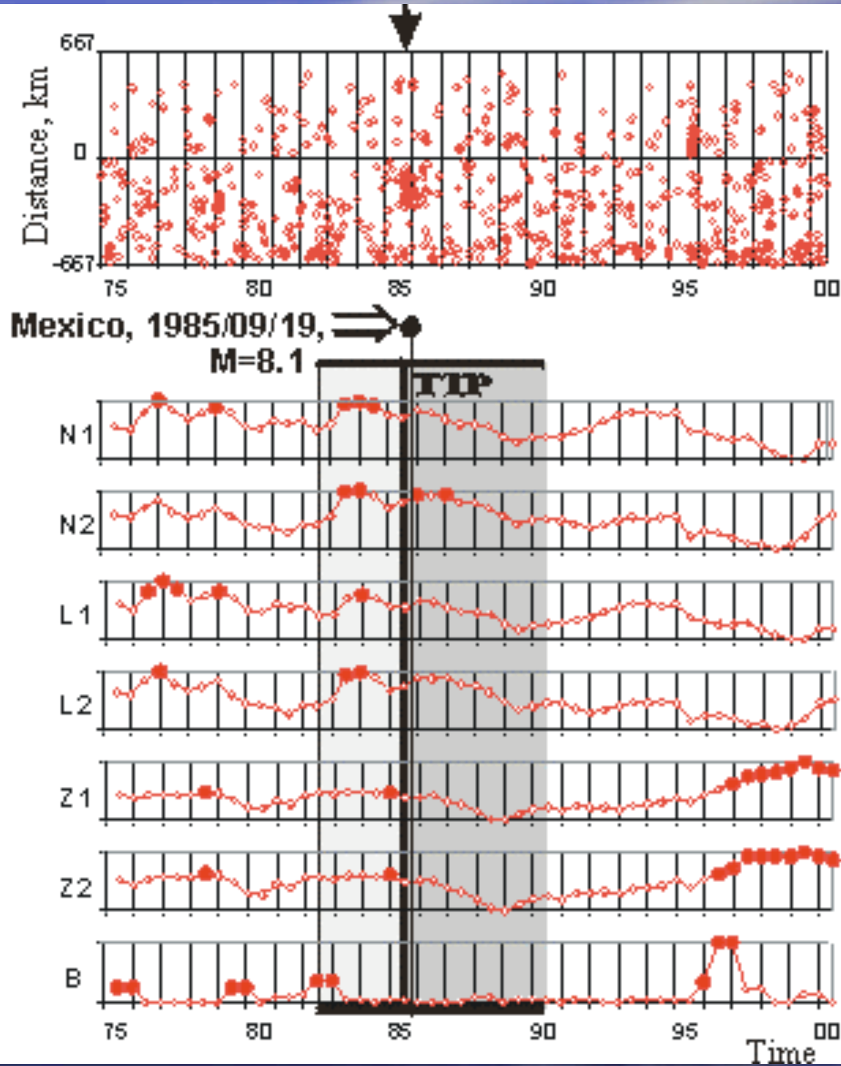
Nevertheless, we continue testing the algorithms for this and smaller magnitude ranges.

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

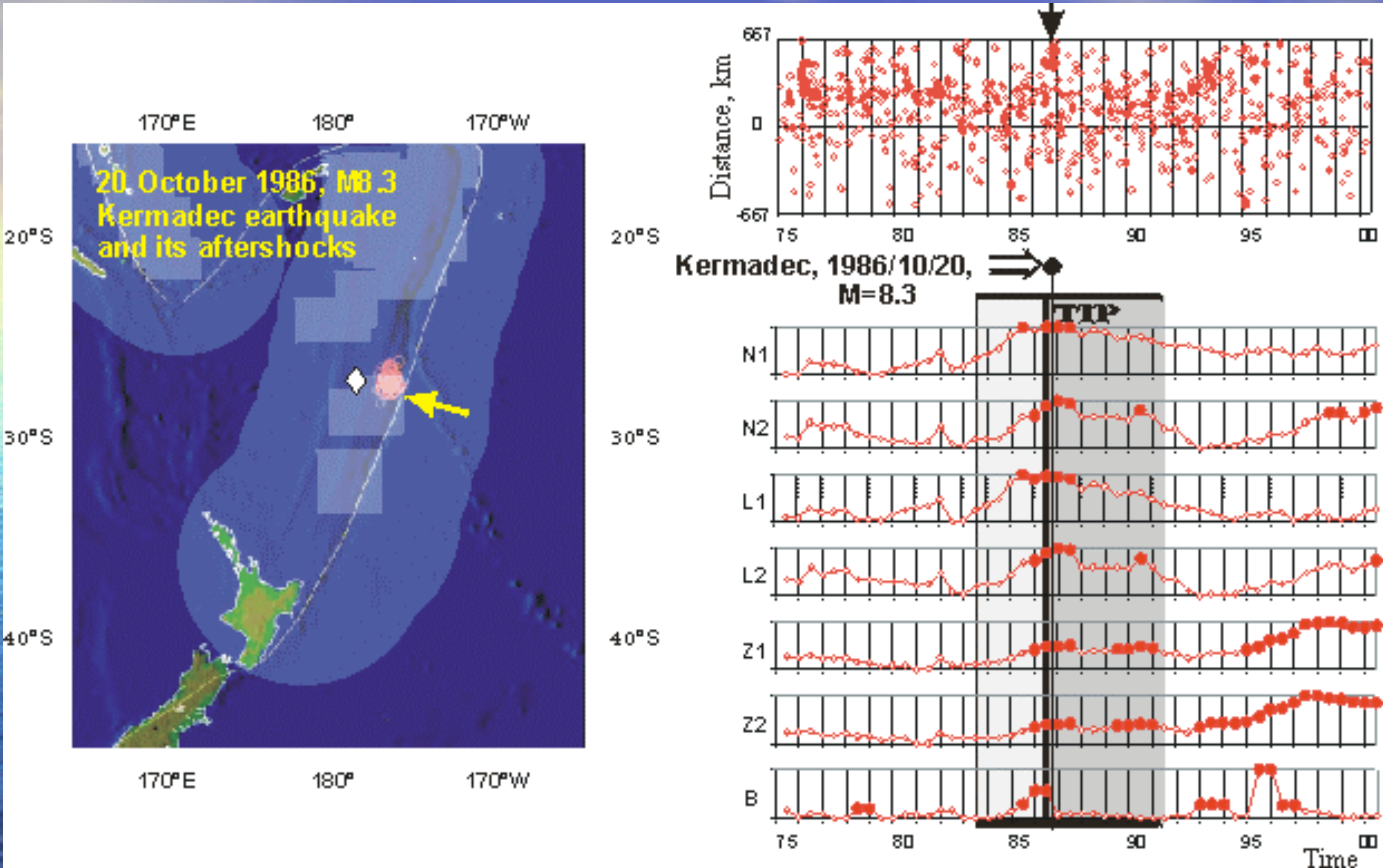
Centers of CI's and Great Earthquakes, 1985-2003

19/09/1985 Mexico Earthquake



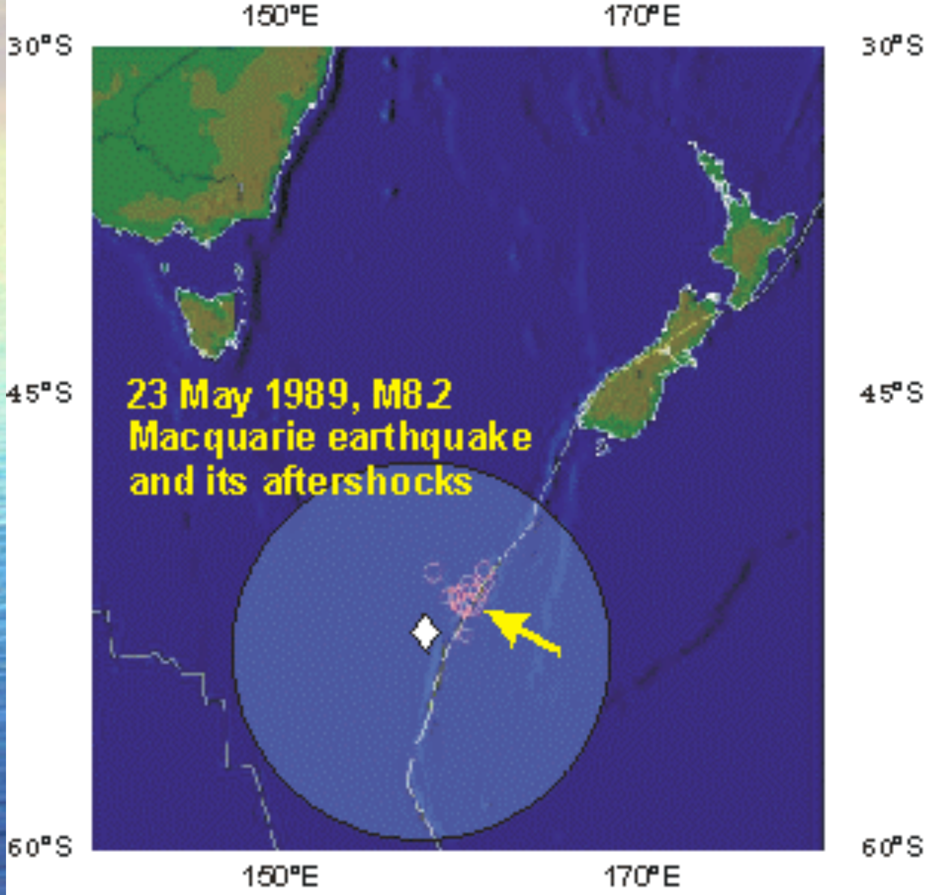


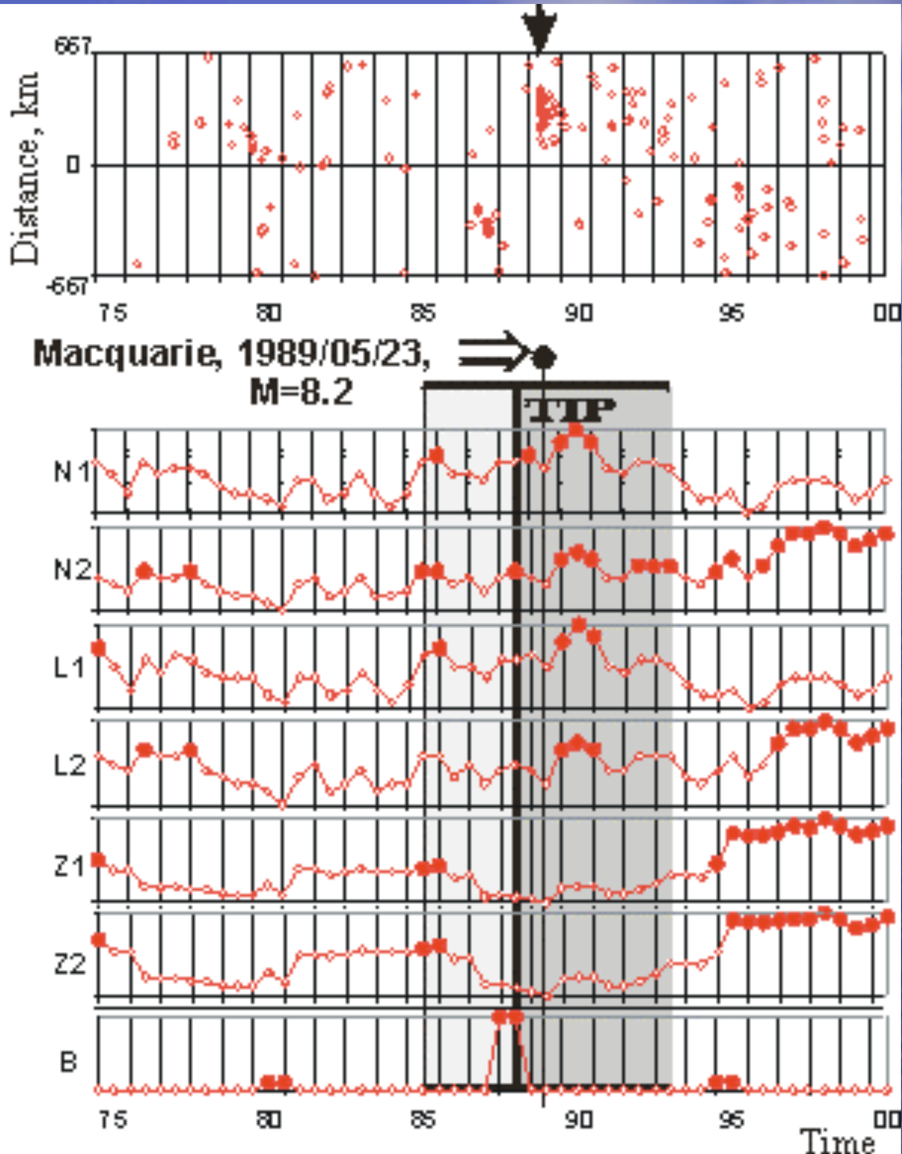
20/10/1986 Kermadek Earthquake



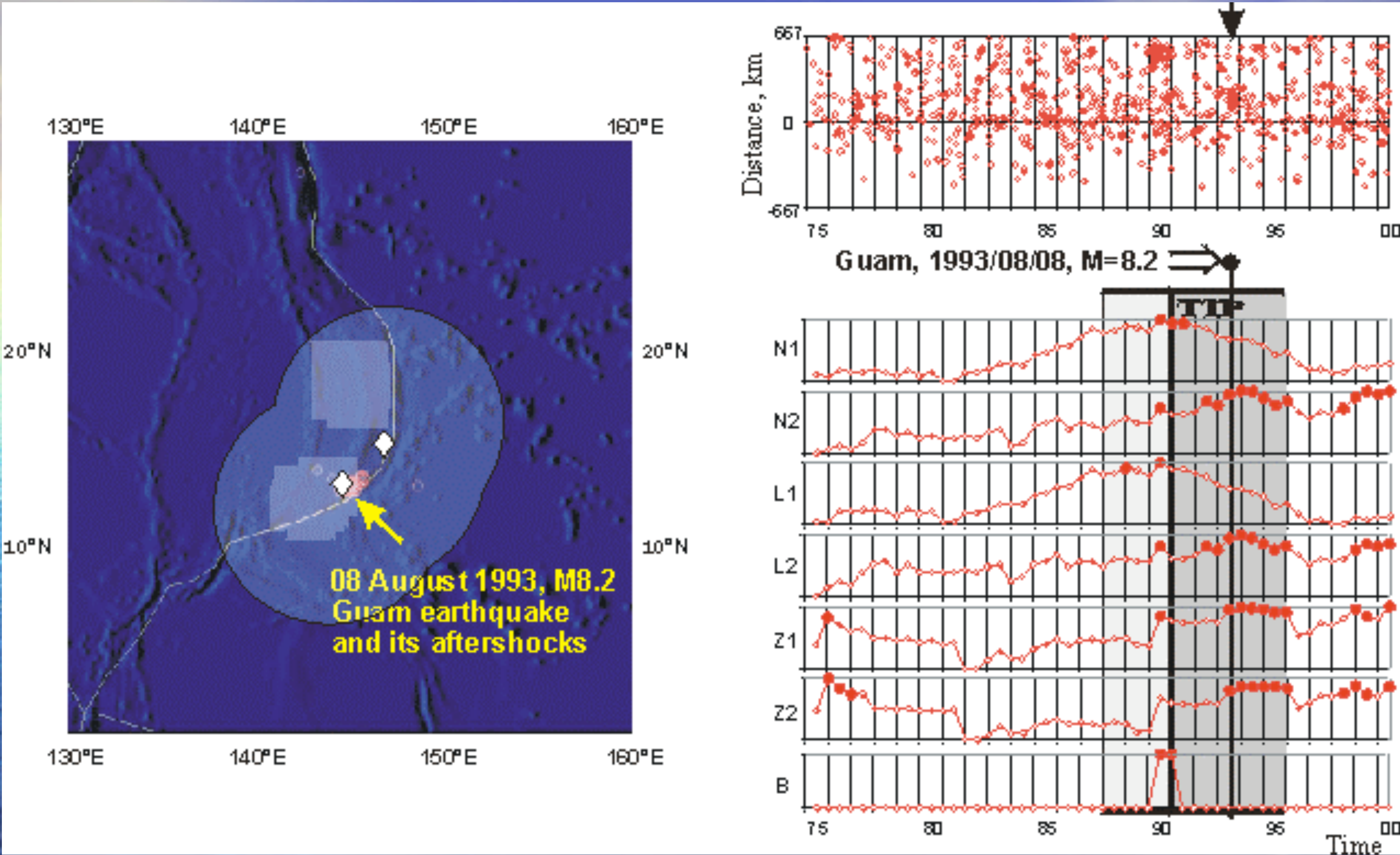
23/05/1989 Macquarie Earthquake

Outside Test Area, NOT COUNTED in the overall statistics





08/08/1993 Guam Earthquake

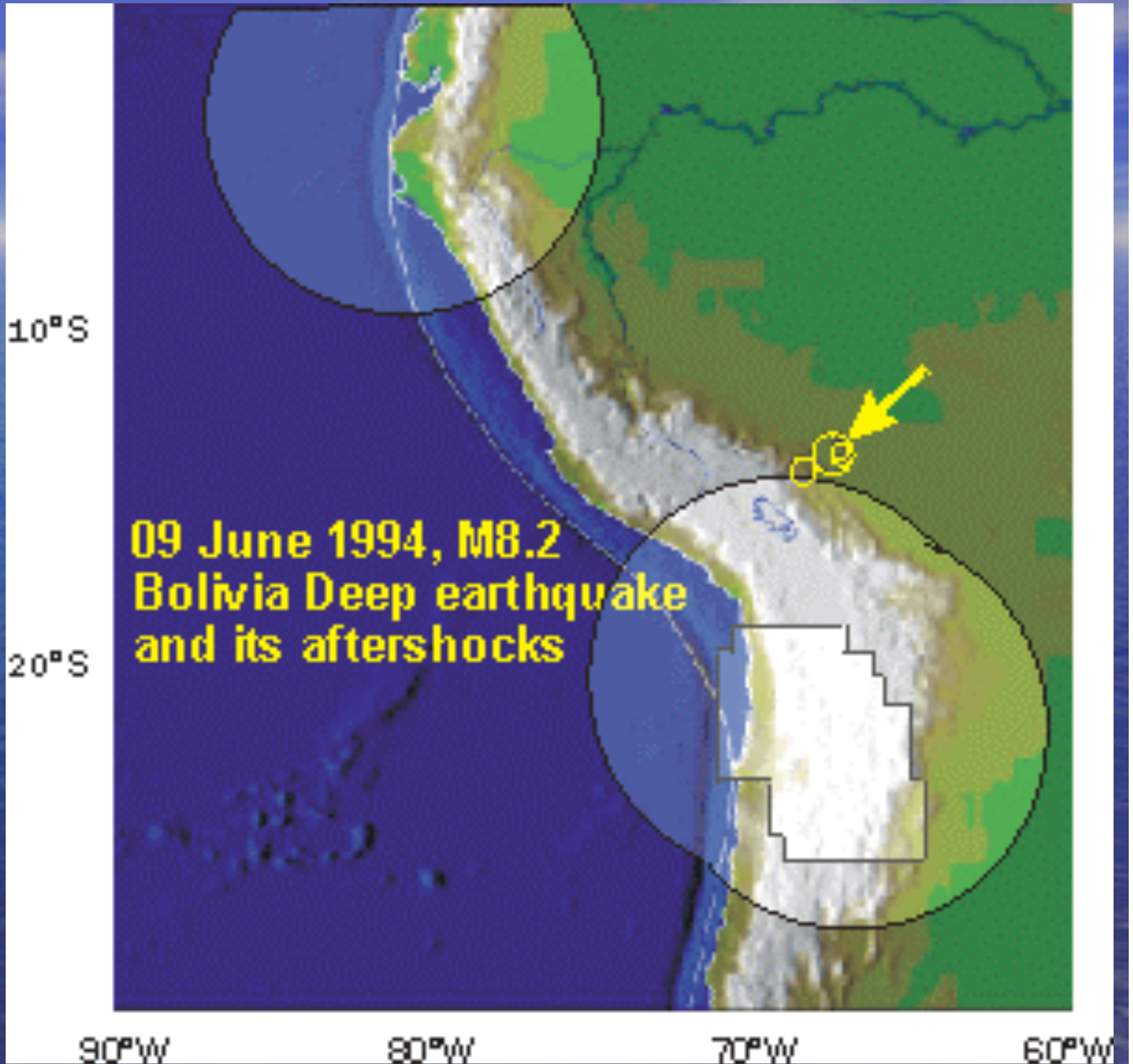


Outside Test Area, NOT COUNTED in the overall statistics

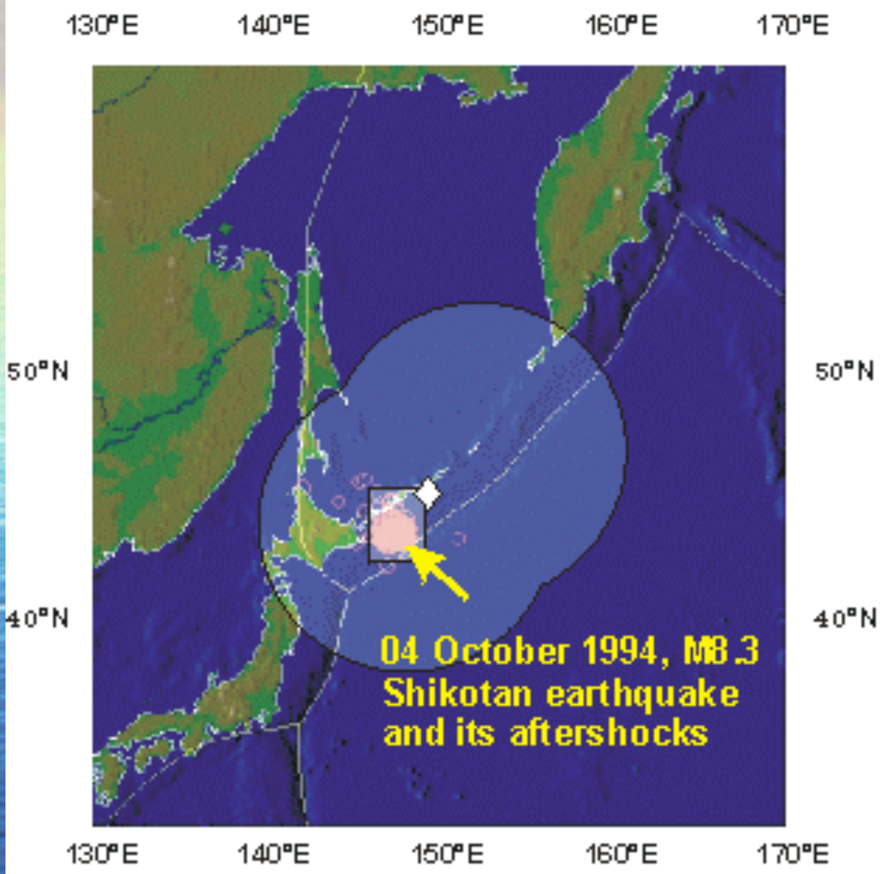
09/06/1994 Bolivia Deep Earthquake

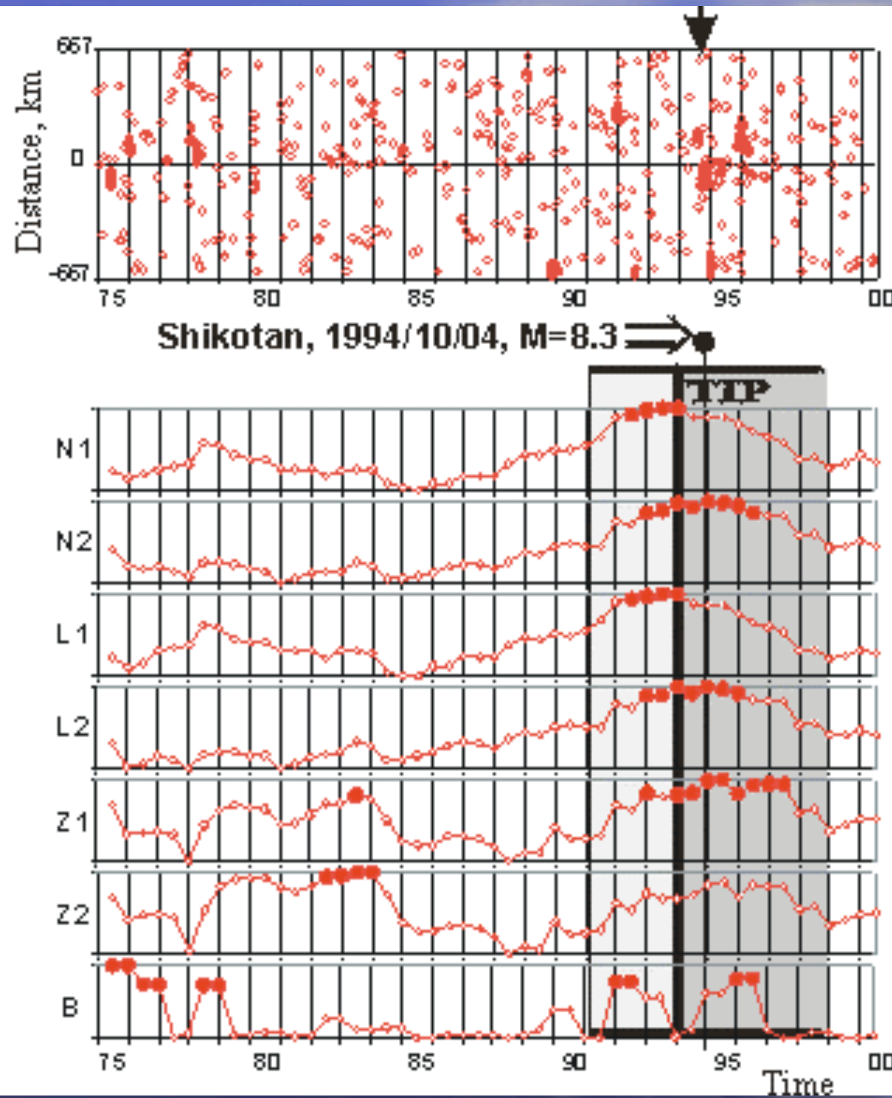
•The Great Deep Bolivia earthquake did occur after the January 10, 1994, magnitude 6.9, depth 595 km earthquake at distance of about 250 km.

The previous earthquake that deep happened here in 1963.

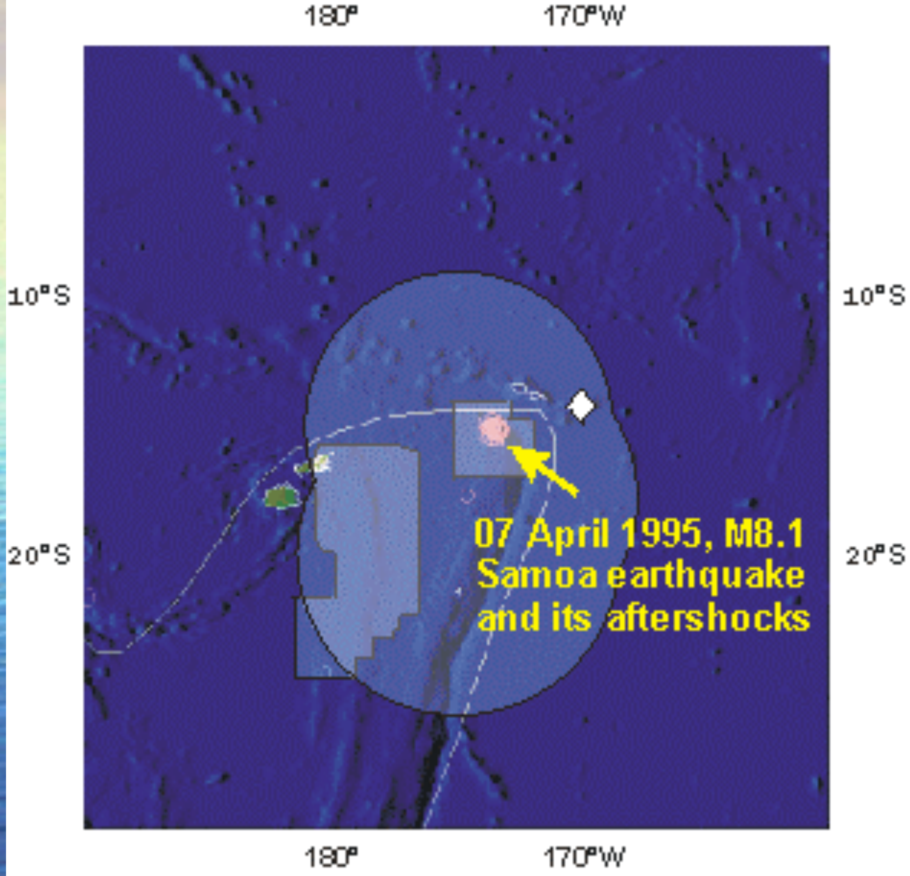


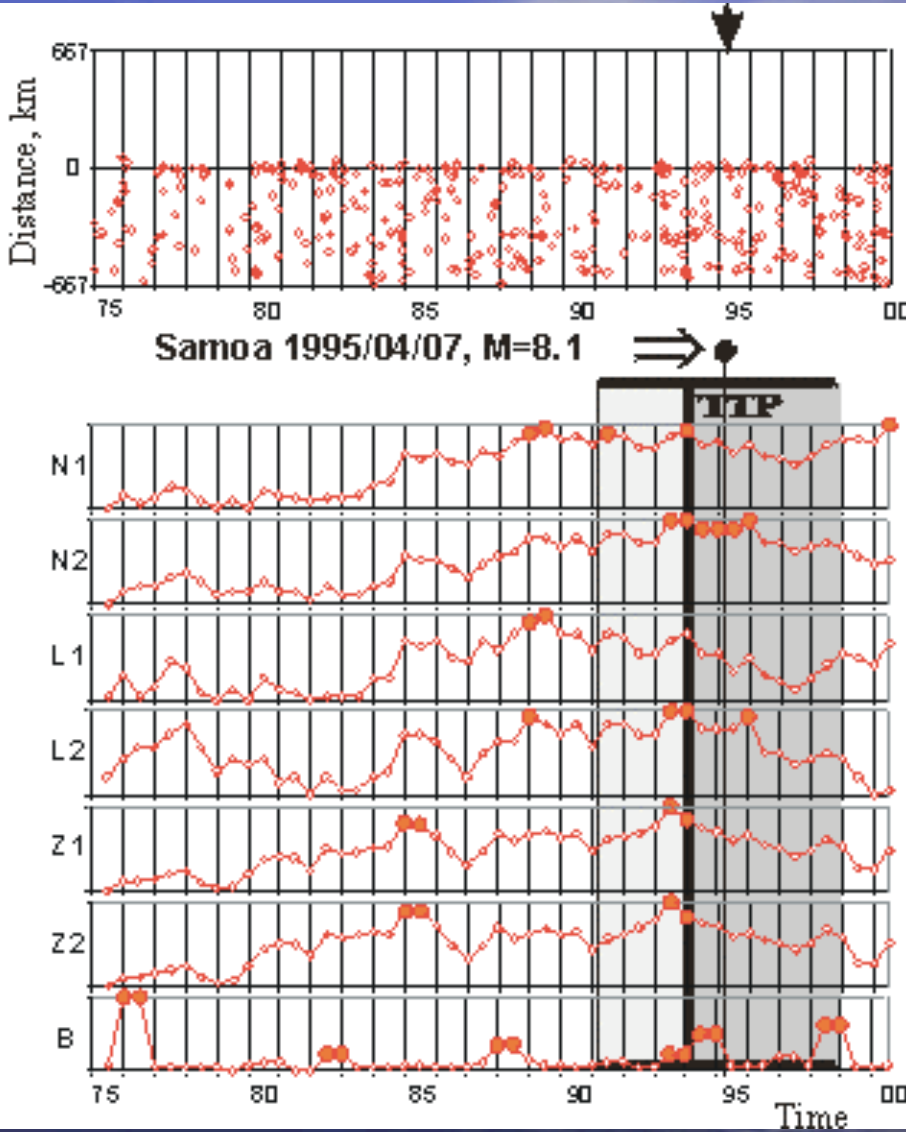
04/10/1994 Shikotan Earthquake



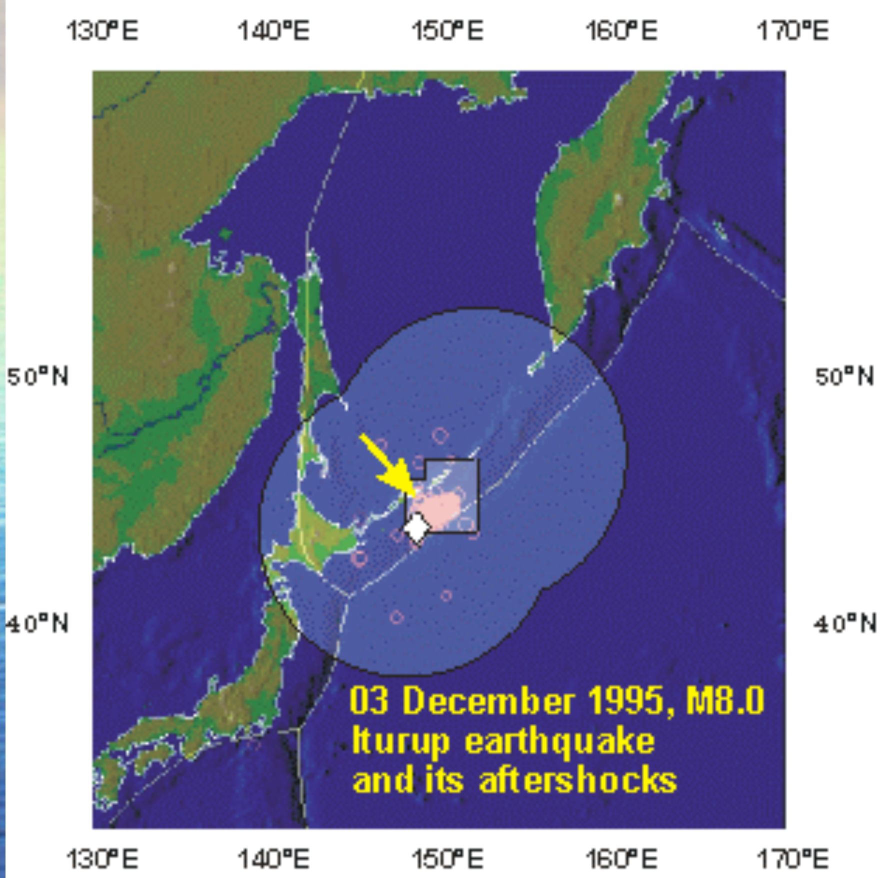


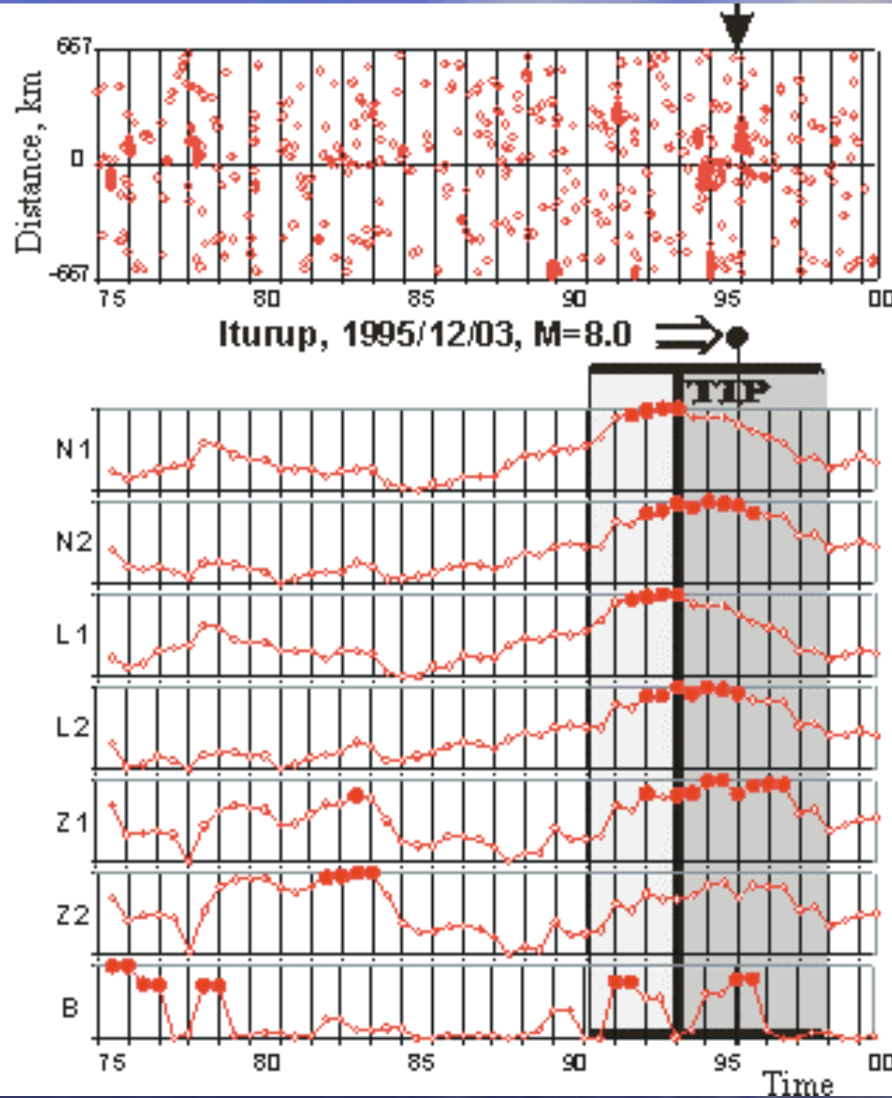
07/04/1995 Samoa Earthquake



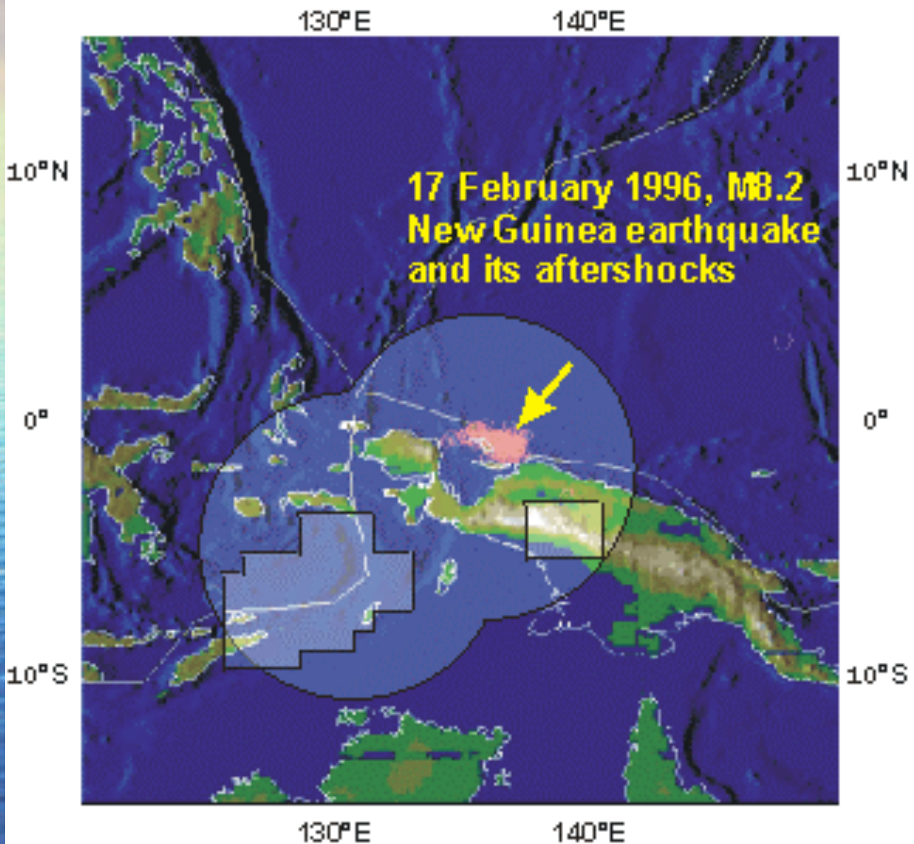


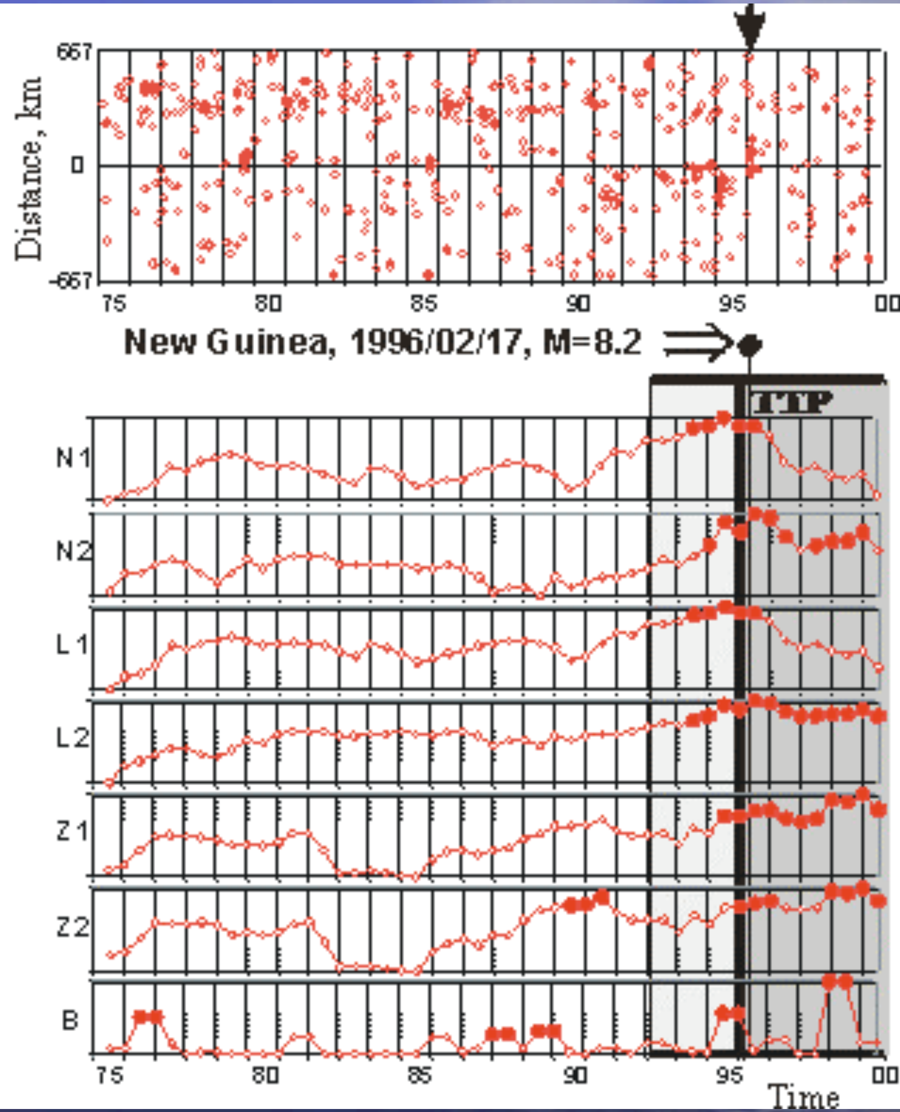
03/12/1995 Iturup Earthquake





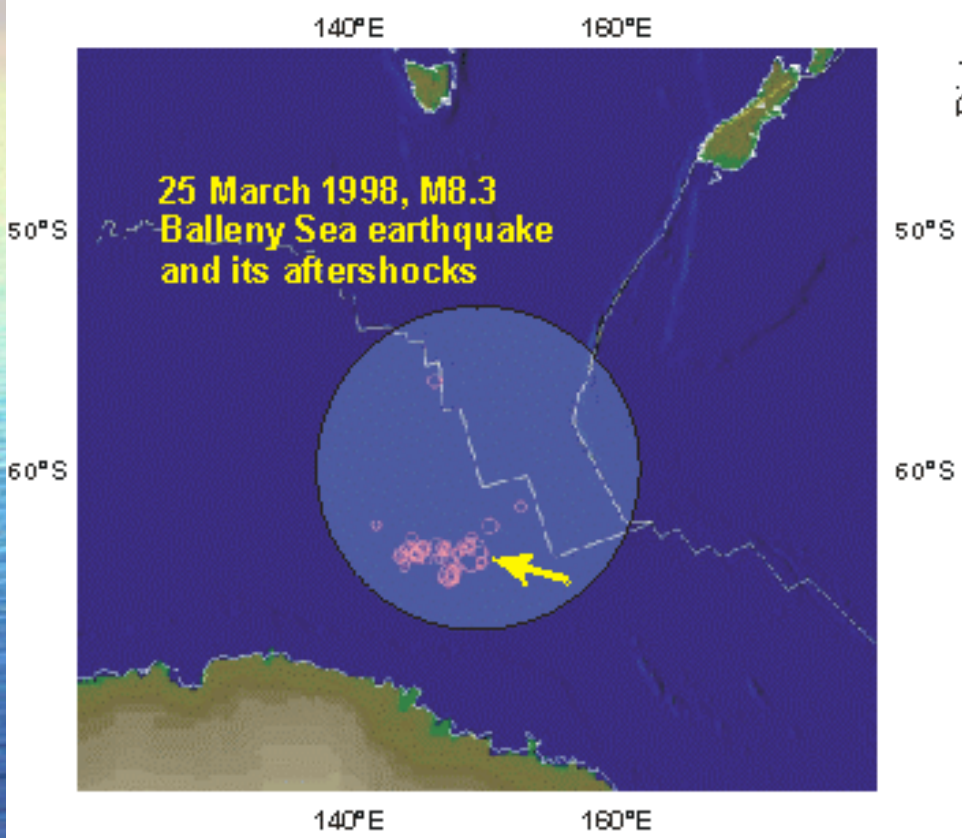
17/02/1996 New Guinea Earthquake

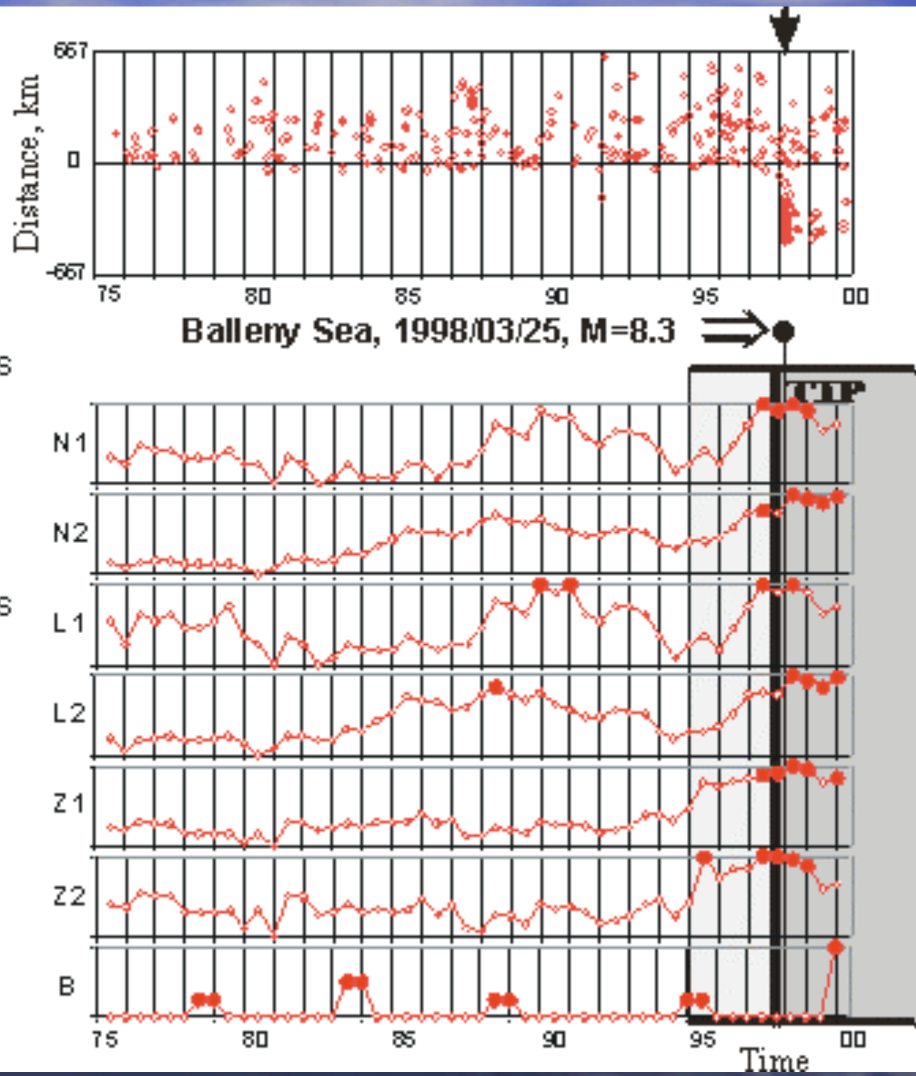




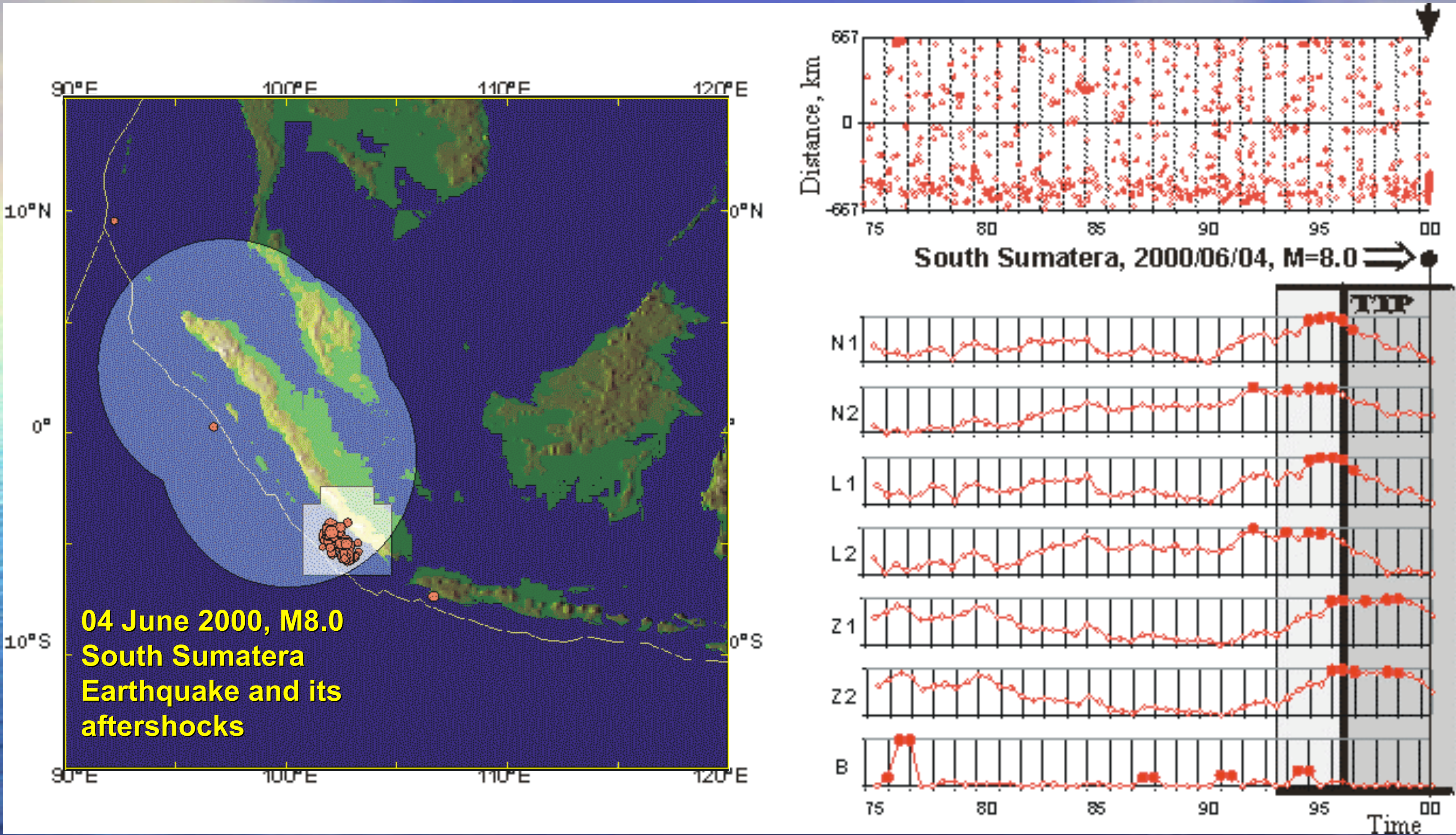
25/03/1998 Balleny Sea Earthquake

Outside Test Area, NOT COUNTED in the overall statistics

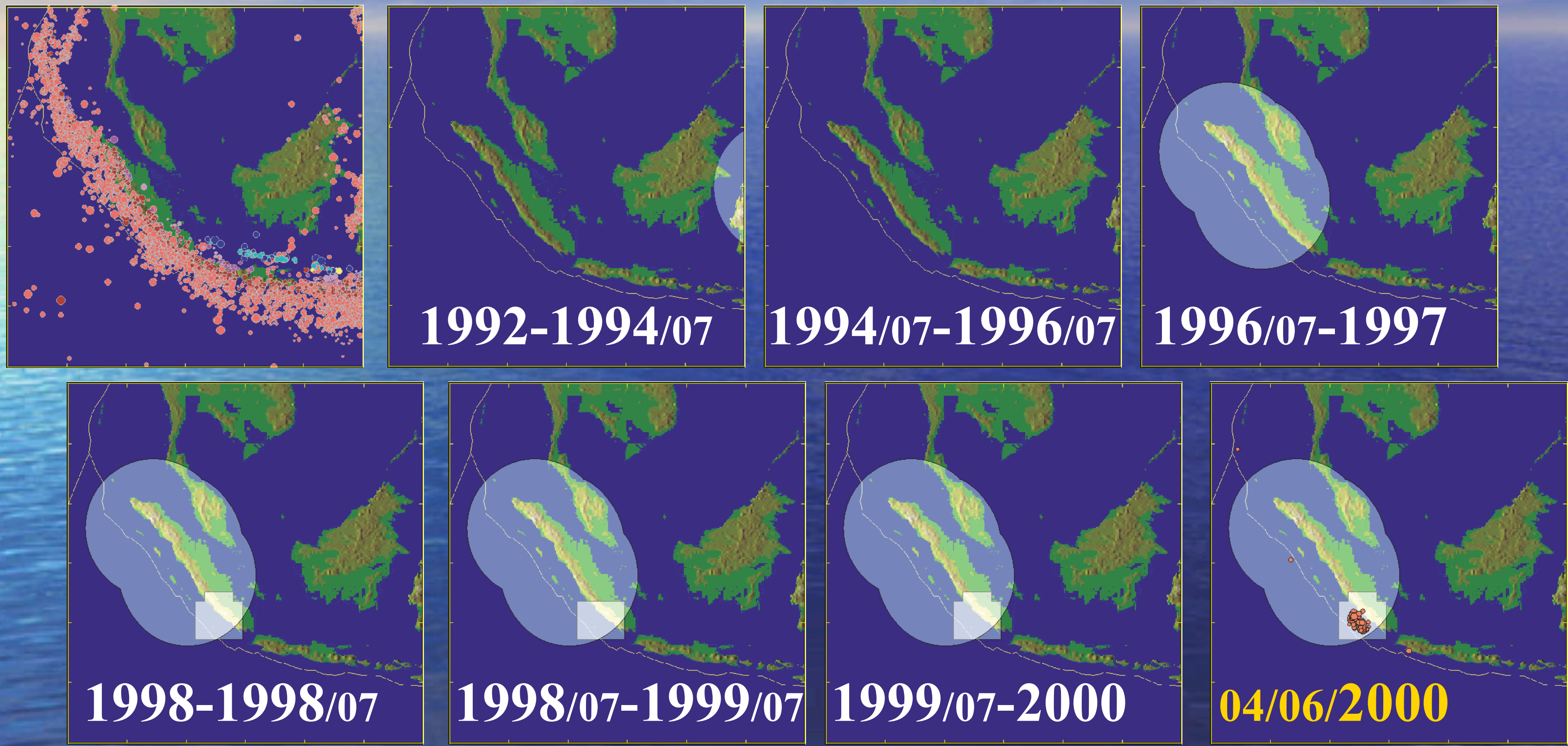




04/06/2000 South Sumatera Earthquake



Case history of the South Sumatera Earthquake

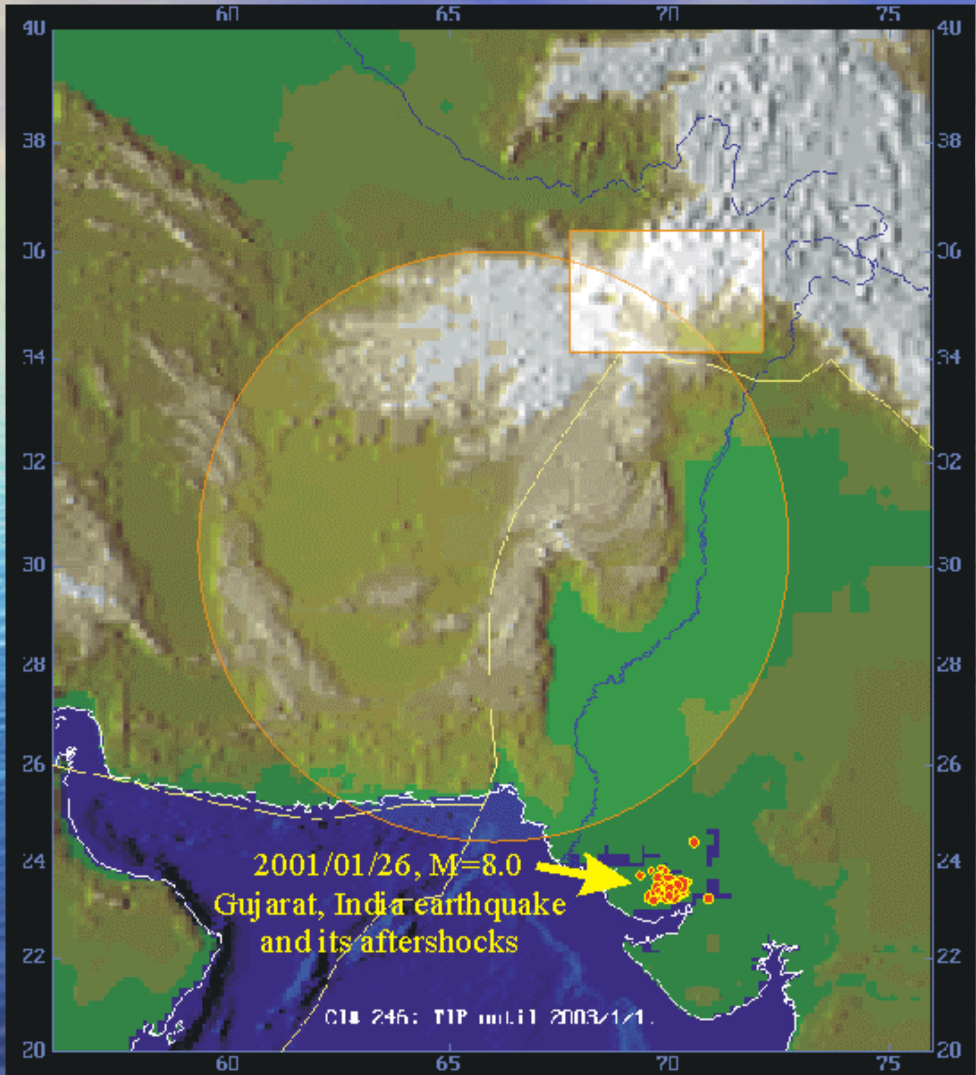


Seismic events that big were reported in the Indian Ocean subduction zones only twice in the 20th century: These are the 1941 Andaman, Ms8.1 and the 1977 Sumbawa, Ms8.0 earthquakes.

This implies local probability gain of more than 20

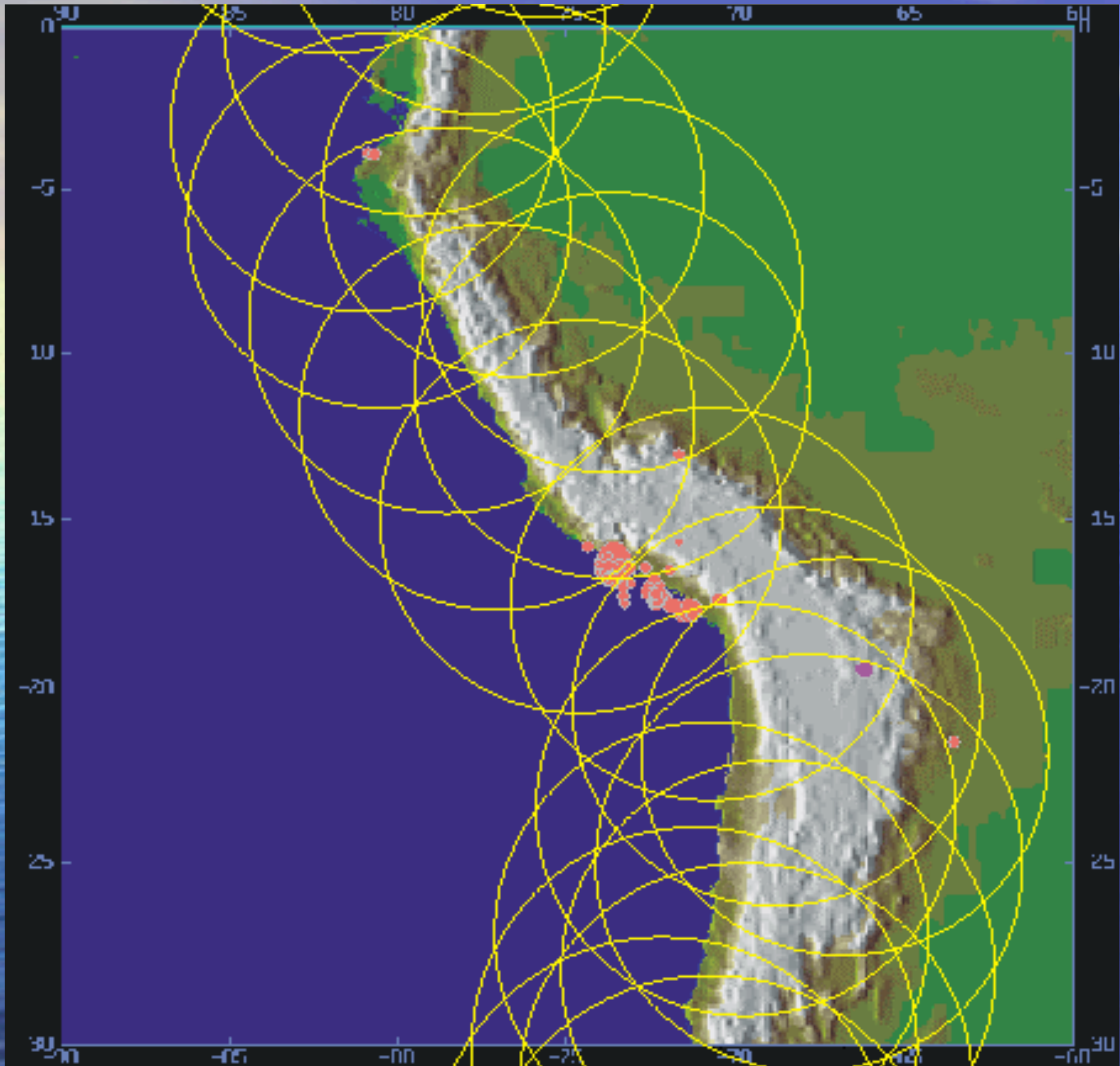
Outside Test Area, NOT COUNTED in the overall statistics

26/01/2001 Gujarat, India earthquake



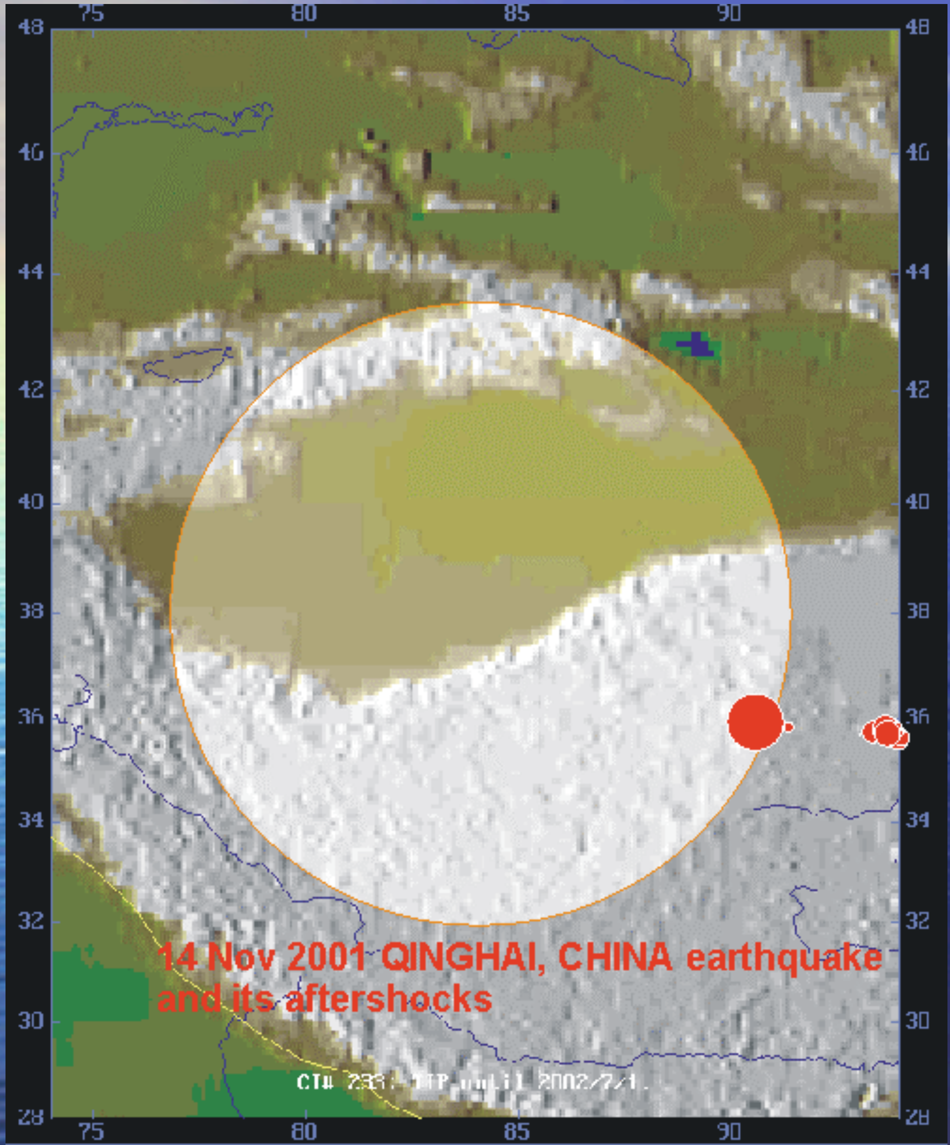
The 26 Jan 2001 Gujarat, India earthquake is just outside the area, where the NEIC data permits to run the original version of the M8 algorithm. Note that one of the circles, nearest to the epicenter of the 2001 Gujarat earthquake was in state of alarm, although the MSc predicts an opposite side of it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

23/06/2001 earthquake NEAR COAST OF PERU



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

14/11/2001 QINGHAI, CHINA earthquake



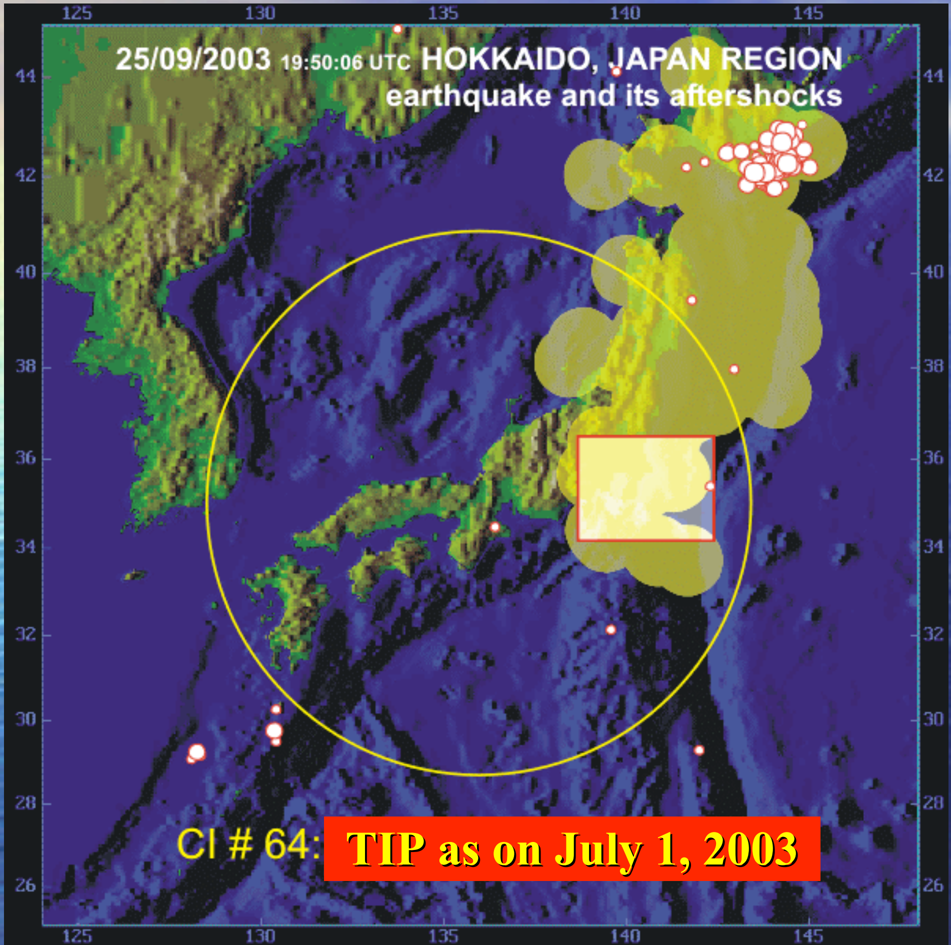
No earthquake of such magnitude had been ever reported inside CI#233 before the 2001 Qinghai earthquake.

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

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

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

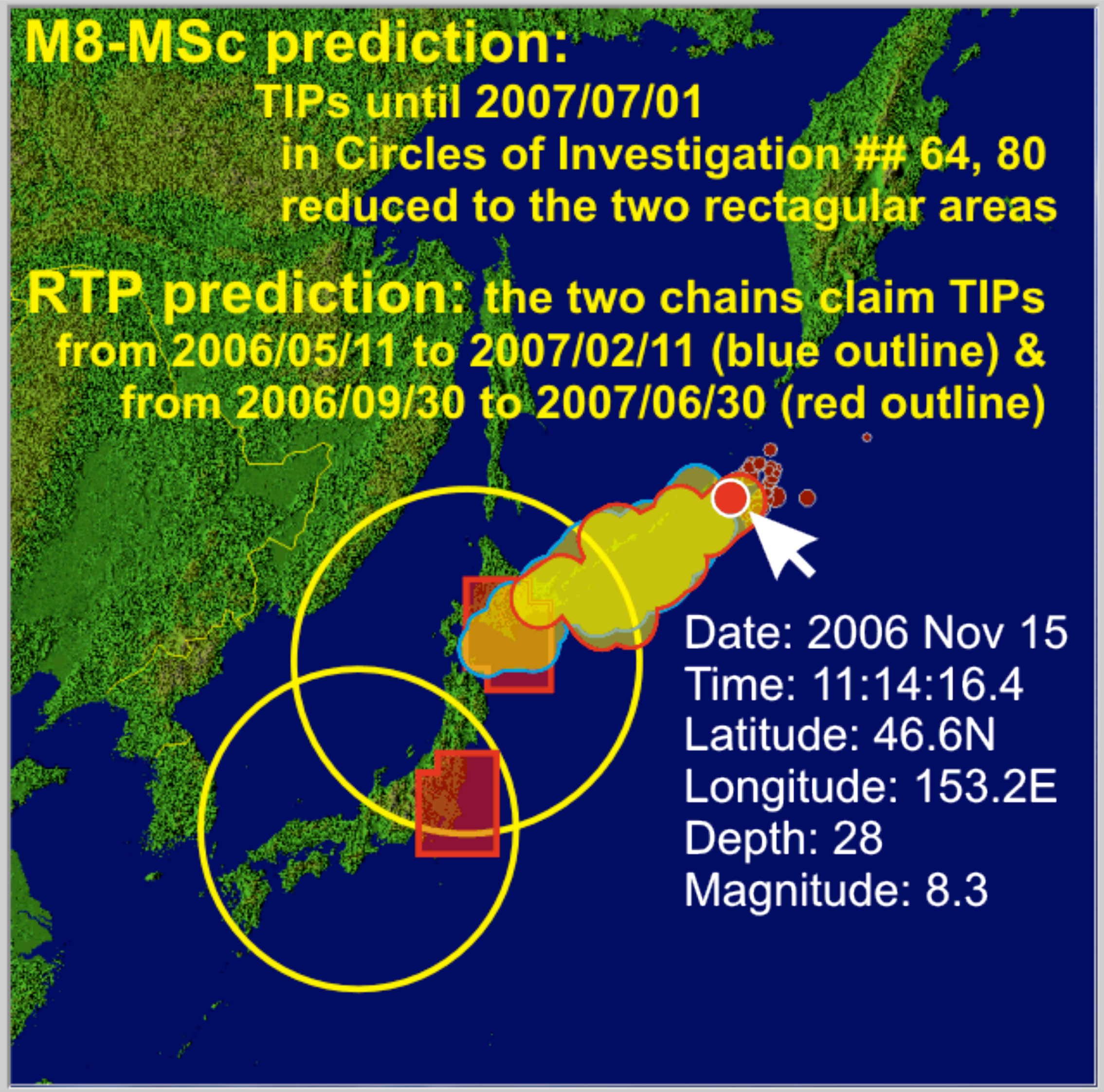
25/09/2003 19:50:06 UTC HOKKAIDO, JAPAN REGION earthquake



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

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

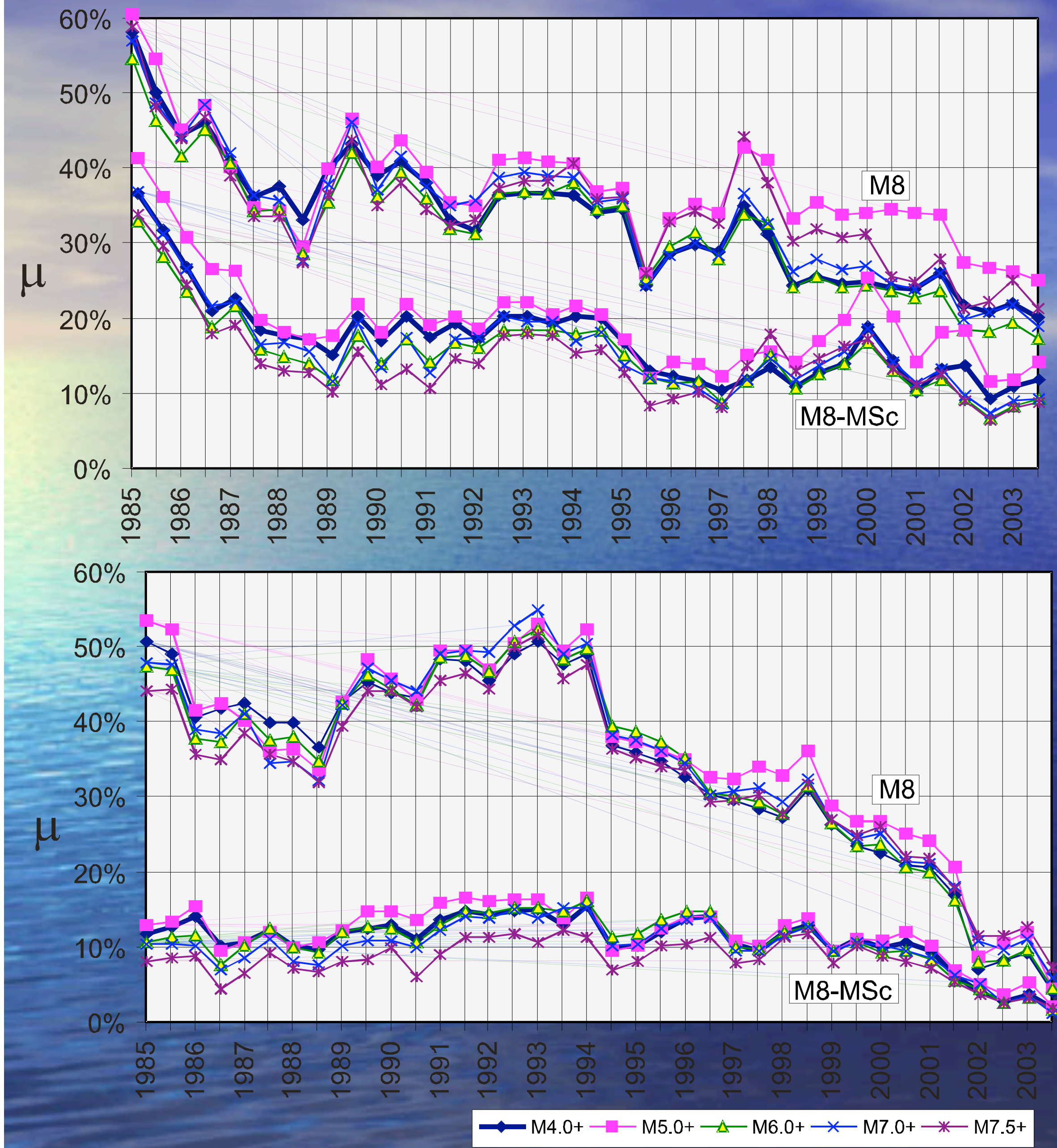
15/11/2006 11:14:16 UTC KURIL ISLANDS earthquake



This is the third failure-to-predict in course the M8-MSc Global Test. Its similarity with the second one (25/09/2003 19:50:06 UTC, MwHRV=8.3, HOKKAIDO, JAPAN REGION earthquake) **is evident:**

Same as in case of the 2003 Hokkaido earthquake the M8-MSc alarm for M8.0+ switched on in July 2006 is about 500 km off the epicenter, while the independent shorter term RTP analysis of the regional JMA catalog of earthquakes performed by V.I. Keilis-Borok and P.N. Shebalin has indicated in advance the two chains of correlated quakes connecting the M8-MSc prediction to the epicenter of the anticipated great shock

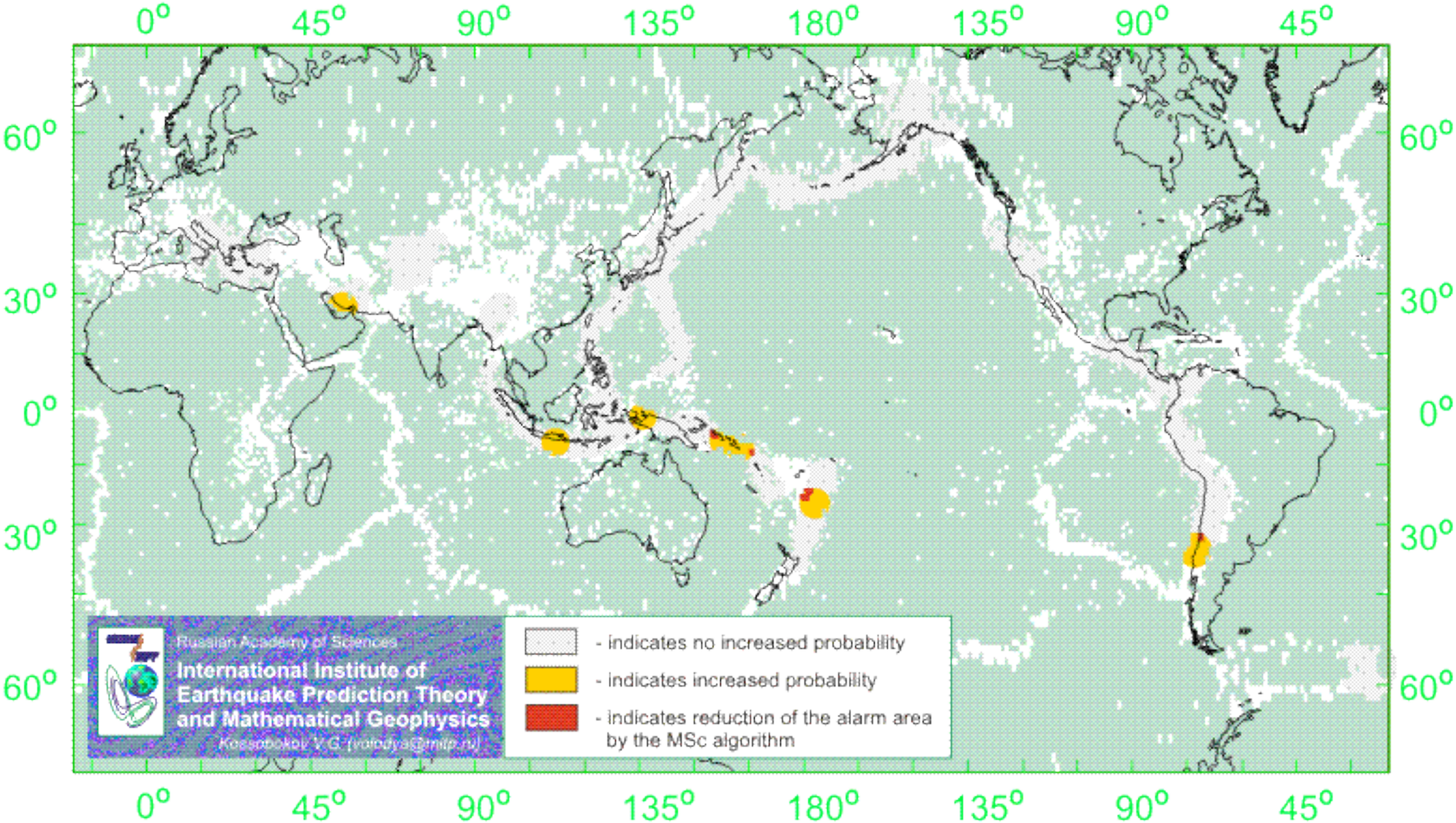
(see "Experiment in prospective earthquake prediction using RTP" at *http://www.igpp.ucla.edu/prediction/rtp/RTP10a_confirmed.pdf*).



The percentage of alerted area as a function of time for M8.0+ (above) and M7.5+ (below).

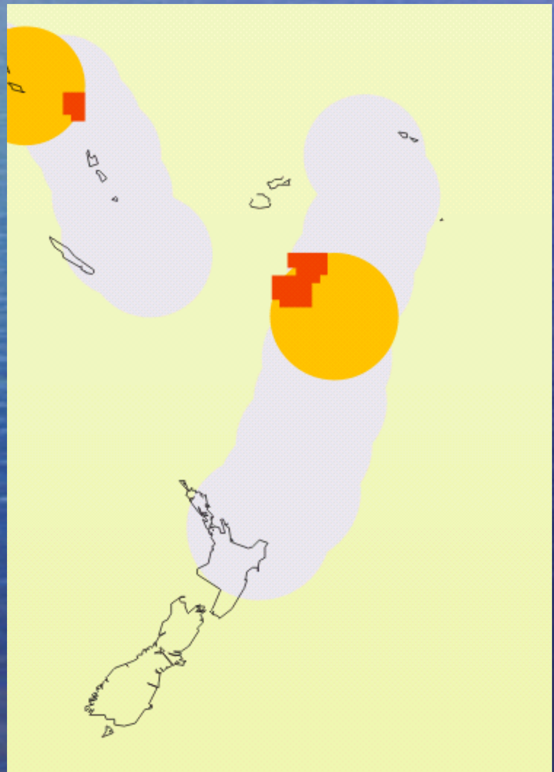
The obtained estimates are based on the counts of magnitude 4 or more and 5 or more earthquakes in the period from 1964 through 1984, while the counts of magnitude above 6.0, 7.0, and 7.5 in 1900-1984

Regions of Increased Probability of Magnitude 7.5+ Earthquakes as on July 1, 2002 (*subject to update on January 1, 2003*)



Sent on Monday, July 15, 2002 (Subject: The 2002b Update of the M8-MSc predictions) along with the updated predictions of major earthquakes worldwide.

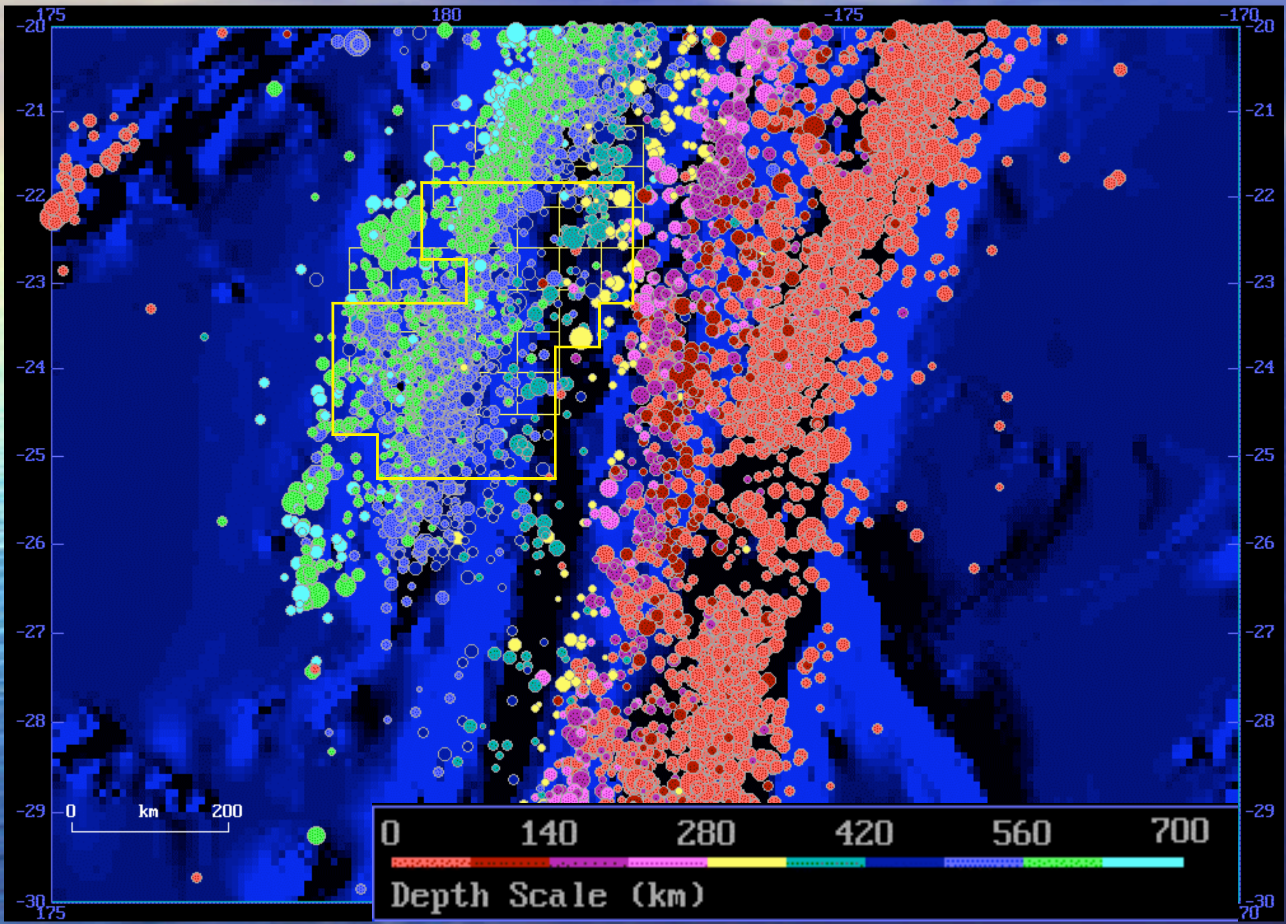
What was predicted…



- Earthquake(s) with magnitude 7.5 or more will occur in CI #5 (yellow) during the time period from July 2002 through July 2003.
- In the second approximation the MSc algorithm has identified the area (red) that stretch between

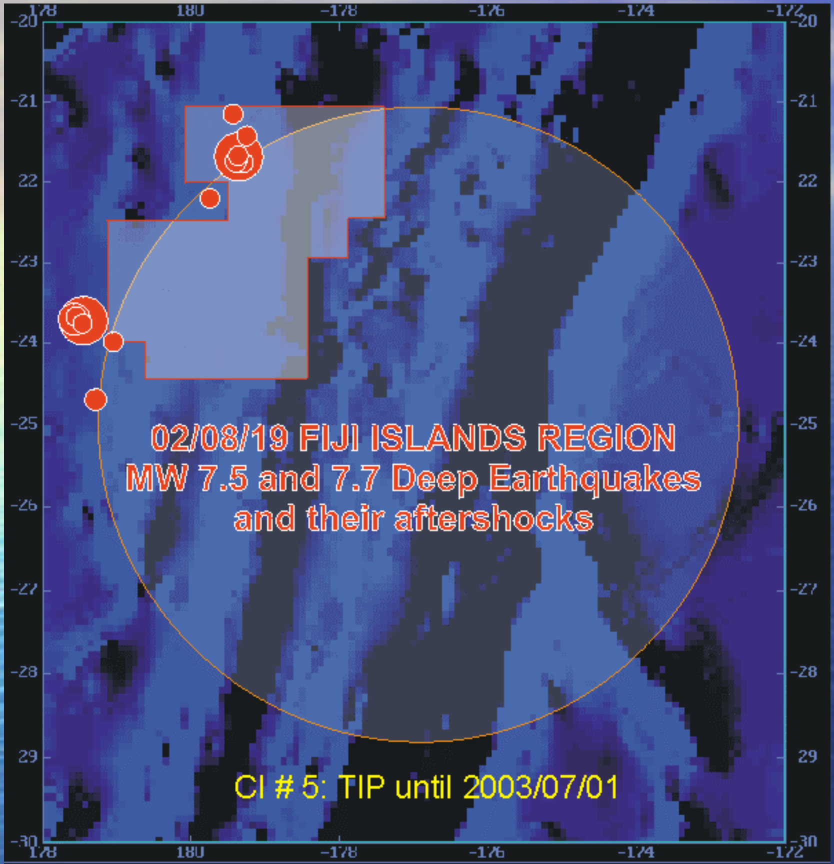
  24.52S - 21.16S and 178.76E - 177.53W.

What was predicted…



- The position of the M8-MSc alarm that narrow down substantially the prediction area suggested the occurrence of the great deep earthquakes (**depth of about 240-700 km**).

What happened…



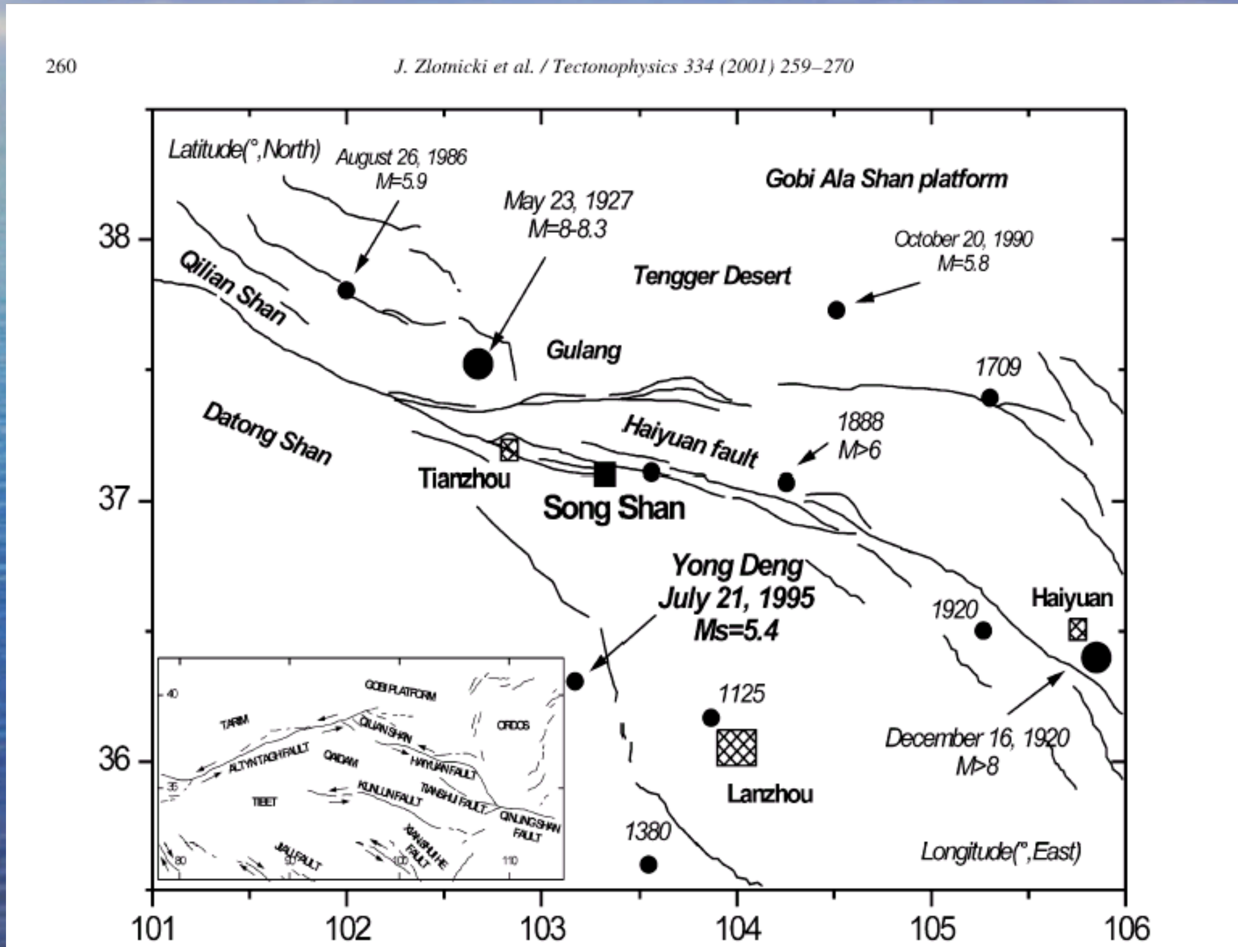
- EARTHQUAKES:
  Origin times -
  2002/08/19 11:01:01
  2002/08/19 11:08:25
  ;
  Coordinates –
  21.80S 179.49W
  23.85S 178.41E;
  Depths - 586.8 and 693.7 km;
  Magnitudes –
  MwGS (MeGS)
  7.5 and 7.7 (7.7 and 7.4);
  F-E Regions –
  FIJI ISLANDS REGION and
  SOUTH OF FIJI ISLANDS.

The two August 19 main shocks mark both northern and southern edges of the prediction area. Does it mean that sometimes exact prediction is not possible? This reduction of the uncertainty provides probability gain of more than 25.

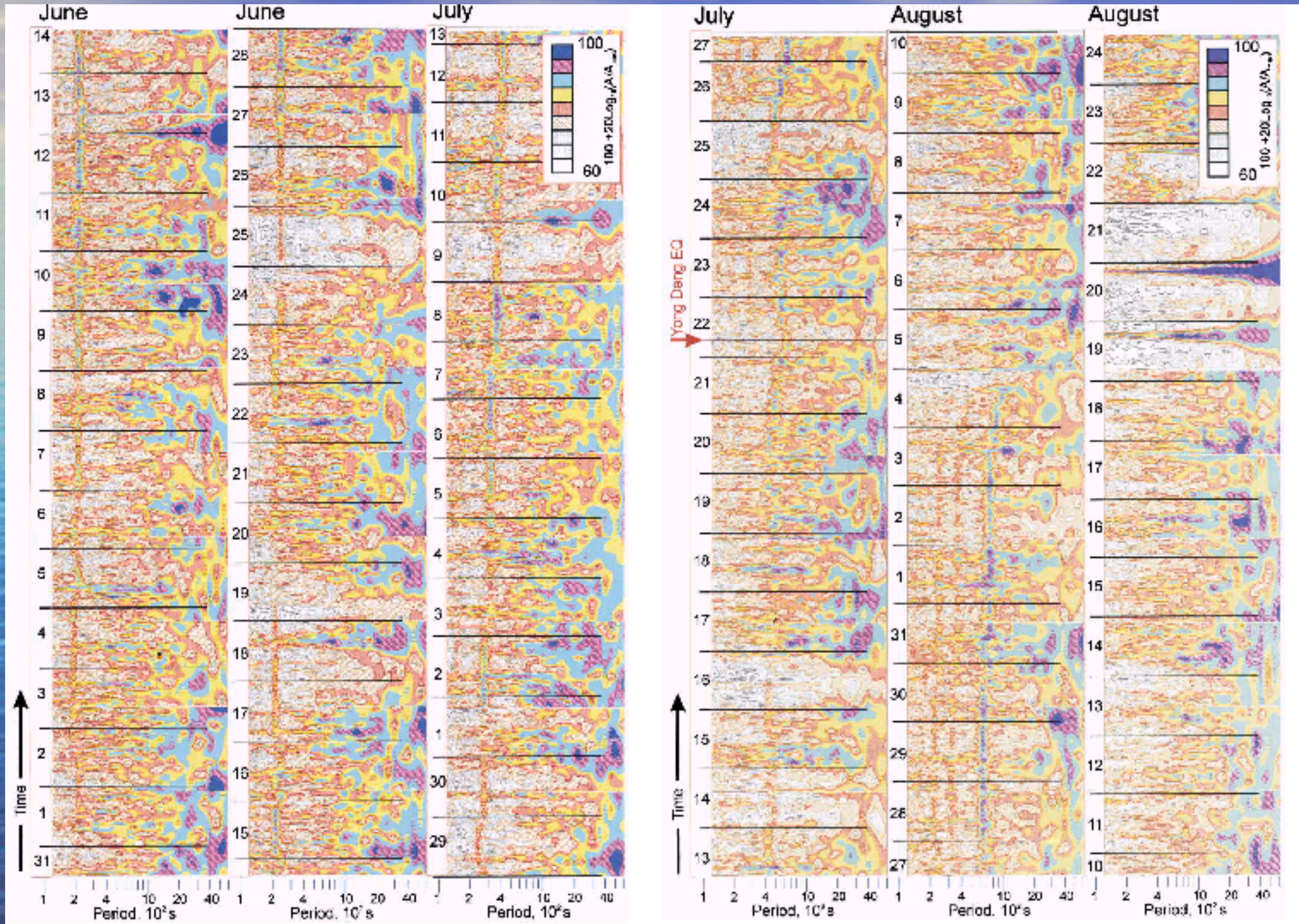
Thus, the accuracy achieved by M8 and MSc algorithms in the on-going Global testing is intermediate in time domain and varies from middle to exact in space domain.

In some cases, the accuracy could be improved by making use of additional short-term monitoring of seismic activity and, perhaps, other geophysical fields in the alerted area of investigation.

One case-study of electromagnetic record about the site of 21 July 1995, M5.7 Yong Deng, China, earthquake in Tibet



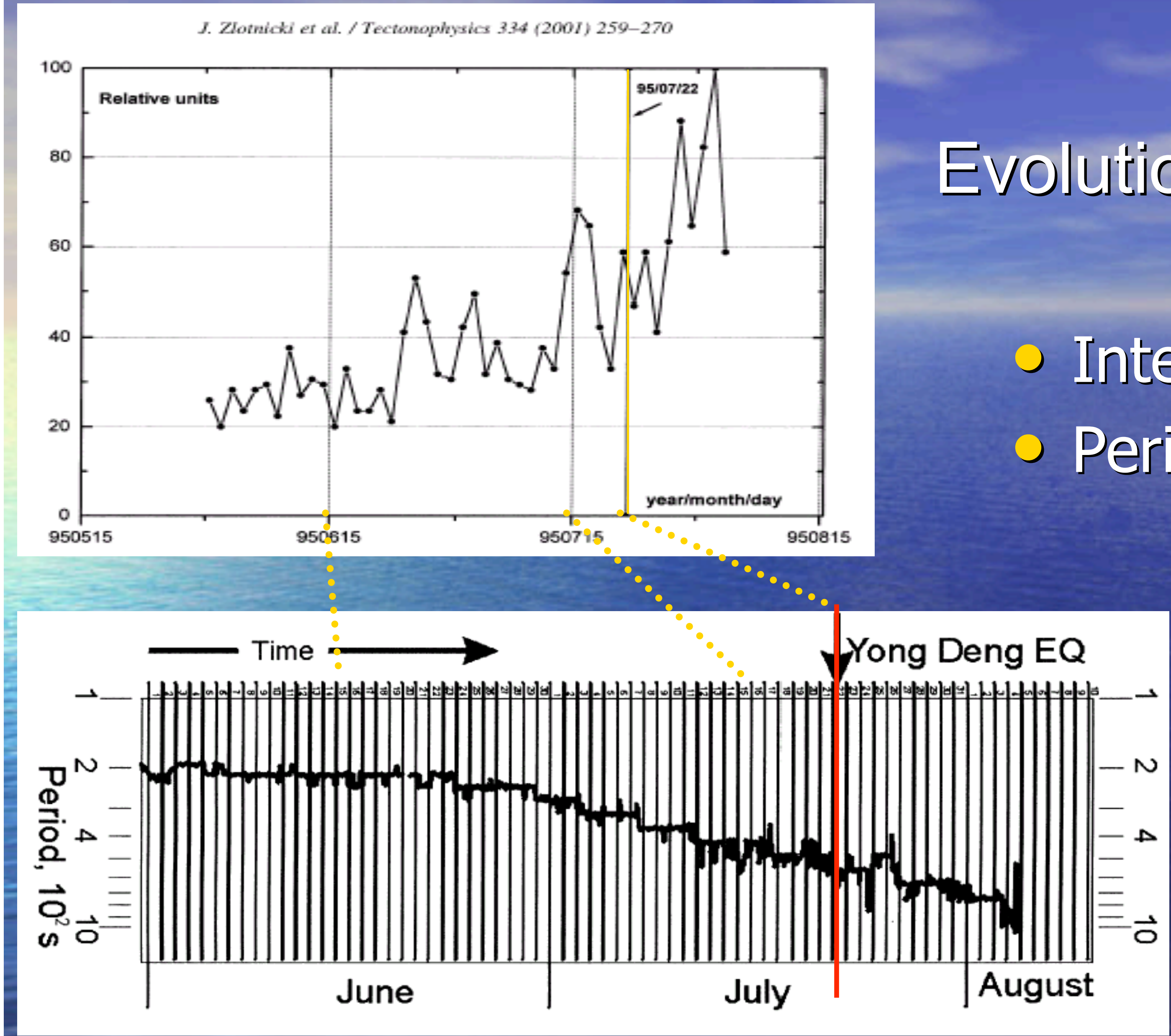
FTAN diagram of the resistance observed on NS 250-m line

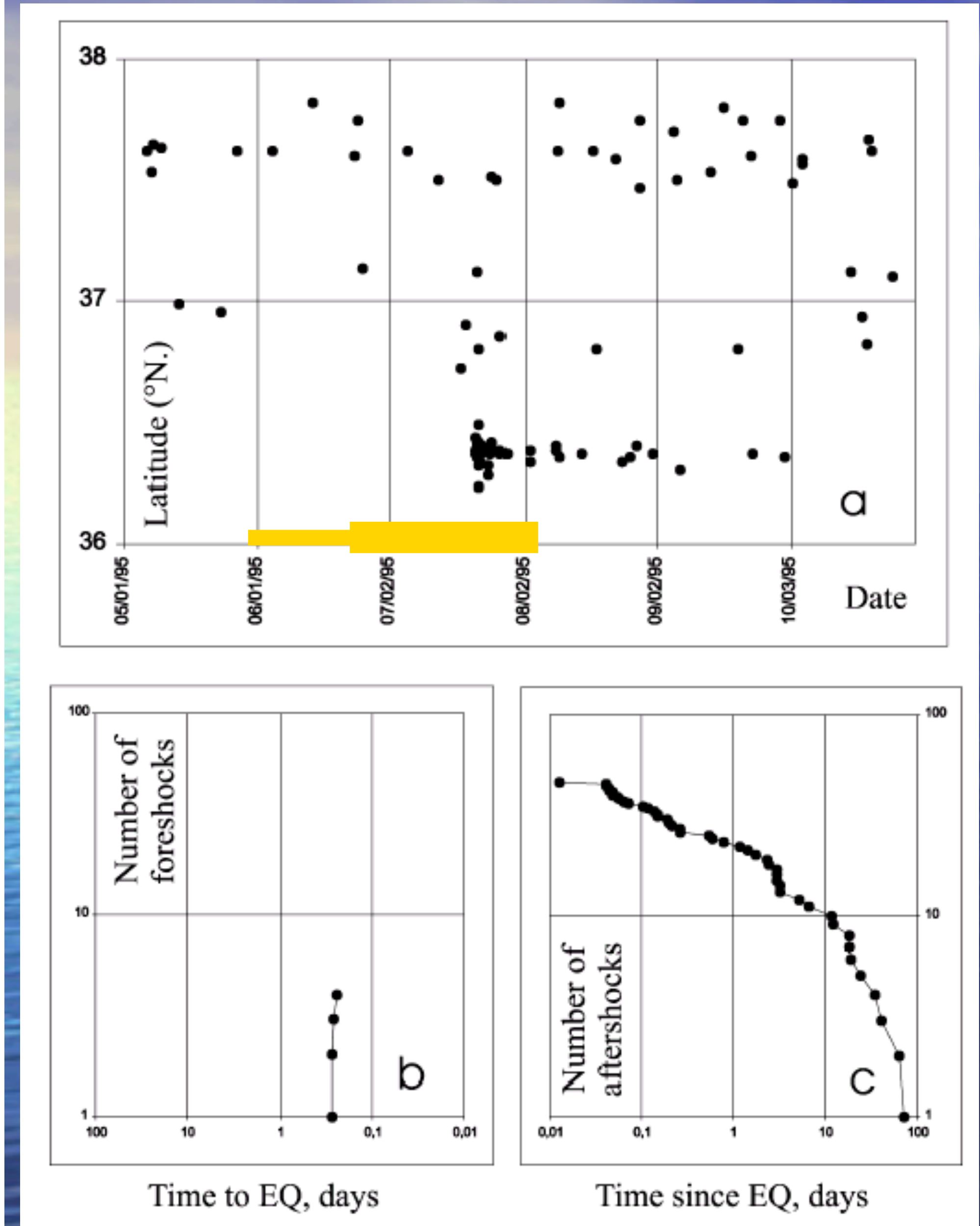


Evolution of the ULF signal

- Intensity and
- Period

GROW





Evolution of the ULF signal

- The 1995 Yong Deng earthquake occurred in less than 100 km from the instrument at the time of characteristic ULF and/or its power decay on component directed at the epicenter.
- The appearance of the ULF signal accompanied with a rise of seismic activity on adjusting segment of Haiyuan fault system.
- The characteristic ULF collapsed just before aftershocks fast disappeared (exponentially).

Thank you

Unified Scaling Law for Earthquakes and Seismic Hazard Assessment

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МИТПАН
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The evident heterogeneity of patterns of seismic distribution and dynamics are apparently scalable according to the generalized Gutenberg-Richter recurrence law that accounts for the fractal nature of faulting. The results of our global and regional analyses imply

(i) the recurrence of earthquakes in a seismic region, for a wide range of magnitudes and sizes, can be characterized with the following law: $\log N(M,L) = A + B \cdot (5 - M) + C \cdot \log L$,

where N(M,L) is the expected annual number of main shocks of magnitude M within a seismic locus of liner size L

(ii) for a wide range of seismic activity, A, the balance between magnitude ranges, B, varies from 0.6 to 1.4, while the fractal dimension, C, changes from under 1 to 1.6

(iii) an estimate of earthquake recurrence rate depends on the size of the territory that is used for averaging and may differ dramatically when rescaled in traditional way to the area of interest.

The confirmed multiplicative scaling of earthquakes changes the traditional view on their recurrence, and has serious implications for estimation of seismic hazard, for the Seismic Risk Assessment, as well as for earthquake prediction.

Outline

- What is lacking in the Gutenberg-Richter relation, log N = A + B·(8 - M) ? Space.
- The Unified Scaling Law for Earthquakes:

  The first results and conclusions
- Revisiting the ABC problem on a global scale:

  The Global Seismic Hazard maps that display at 100-km scale the A, B, and C's for the recurrence of earthquakes
- Implications for assessing seismic hazard and risks at a given location, e.g., in megacities

What is lacking in the Gutenberg-Richter relation, $\log_{10}N = A + B\cdot(8 - M)$?

- Being a general law of similarity the GR relation establishes the scaling distribution 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.

Seismic activity is self similar:

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

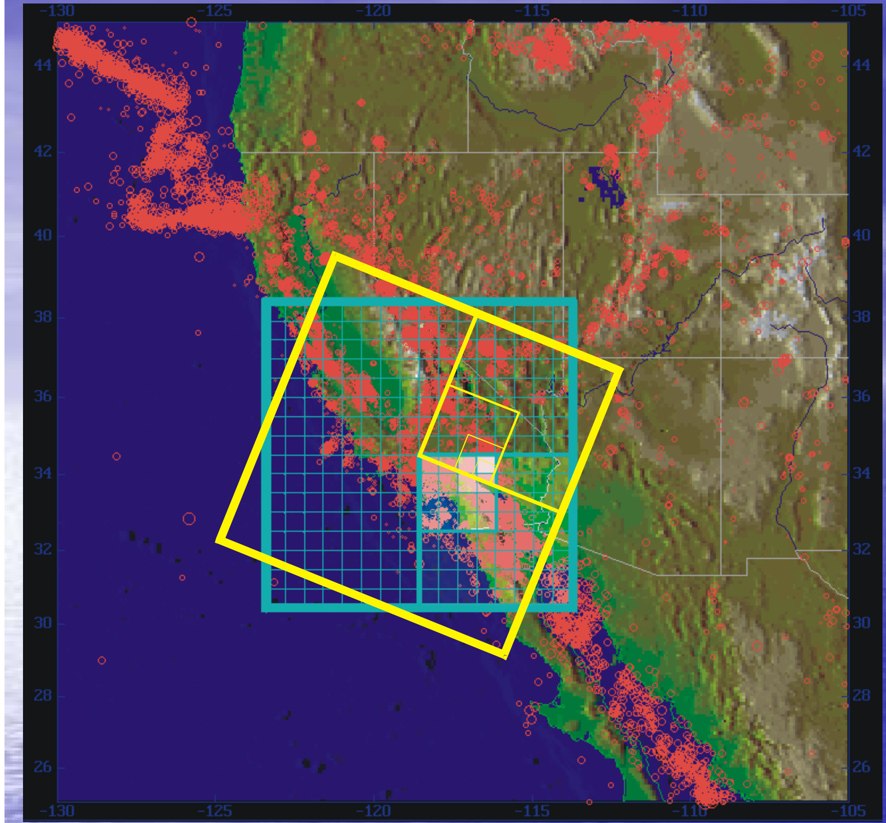
Okubo, P.G., K. Aki, 1987. Fractal geometry in the San Andreas Fault system. *J. Geophys. Res.*, **92** (B1), 345-356;
Садовский М.А., Болховитинов Л.Г., Писаренко В.Ф., 1982. О свойстве дискретности горных пород. *Изв. АН СССР. Физика Земли*, № 12, 3-18;
Садовский, М.А., Т.В. Голубева, В.Ф. Писаренко, 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 scheme for box-counting

The counts in a set of cascading squares, **"telescope"**, estimate the natural scaling of the spatial distribution of earthquake epicenters and provide evidence for rewriting the G-R recurrence law.

The box-counting algorithm
(*Kossobokov and Mazhkenov, 1988*)

For each out of m magnitude ranges and for each out of h levels of hierarchy the following numbers $N_{j,i}$ are found:

$$N_{j,i} = \sum n_i (Q_i)^2 / N_j ,$$

where i = 0,1….h-1, j = 1,2….m, $n_j(Q_i)$ is the number of events from a magnitude range M_j in an area Q_i of linear size L_i; N_j is the total number of events from a magnitude range M_j.

The A, B, C's are derived by the least-squares method from the system

$$\mathbf{log_{10}} N_{j,i} = A + B \cdot (5 - M_j) + \mathbf{Clog_{10}} L_i .$$

An interpretation of the box-counting

Number N_{ji} can be considered as the empirical mean recurrence rate of events in the magnitude range M_j, calculated over their locus in an area at the i-th level of spatial hierarchy.

Specifically, if we denote a “telescope” a set of h+1 embedded squares $W = \{w_0, w_1, \ldots , w_h\}$, so that each w_i belongs to the I-th level of hierarchy. Note that each “telescope” grows uniquely from the lowest level. Assume that the M_j epicenter set is defined by a sample catalog of earthquakes $X_j = \{x_1, \ldots , x_{Nj}\}$. Each earthquake x_k defines the “telescope” $W(_{xk})$ that grows from $w_h(x_k)$, to which x_k belongs. Consider the set of “telescopes” $\{W(x_k) \}$that corresponds to the catalog X_j. Denote $n_j(w_i)$ as the number of events from X_j that fall within w_i.

Then, the mean number of events in an area of i-th level of hierarchy over X_j is $N_{ji} = \Sigma_{\{k=1,\ldots,Nj\}} n_j(w_i(x_k)) / N_j$.

Substituting summation over X_j by summation over the areas $w_i(x_k)$ from the i-th level, we obtain the formula.

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

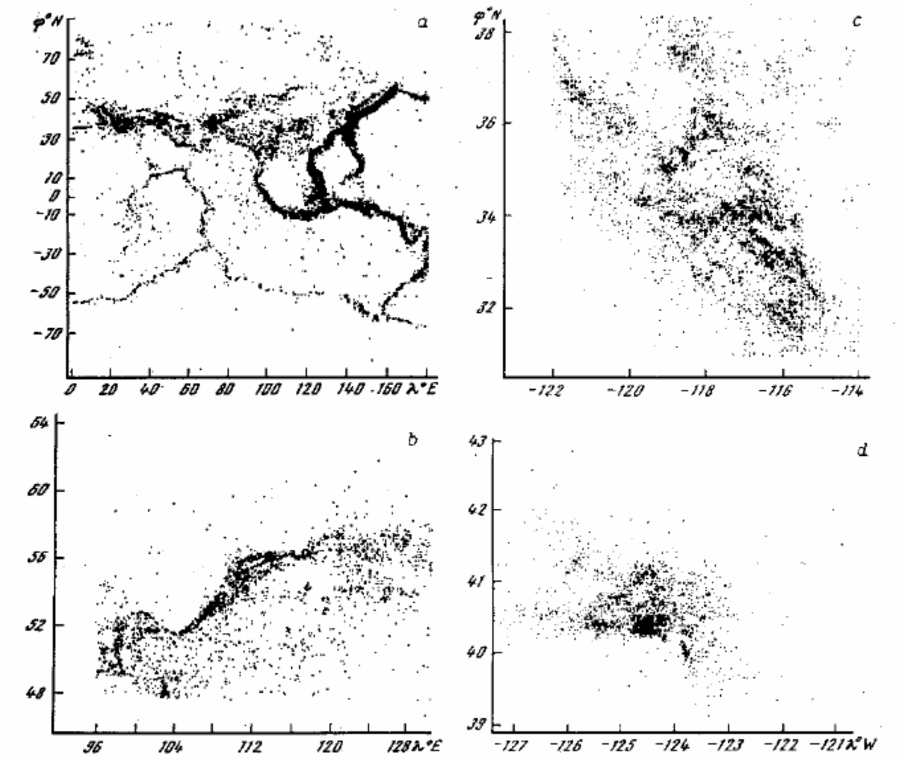


Fig. 2. Examples of spatial distribution of epicenters from catalogs of mainshocks. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

14 KOSOBOKOV AND MAZHKENOV: SIMILARITY IN SPATIAL DISTRIBUTION OF SEISMICITY

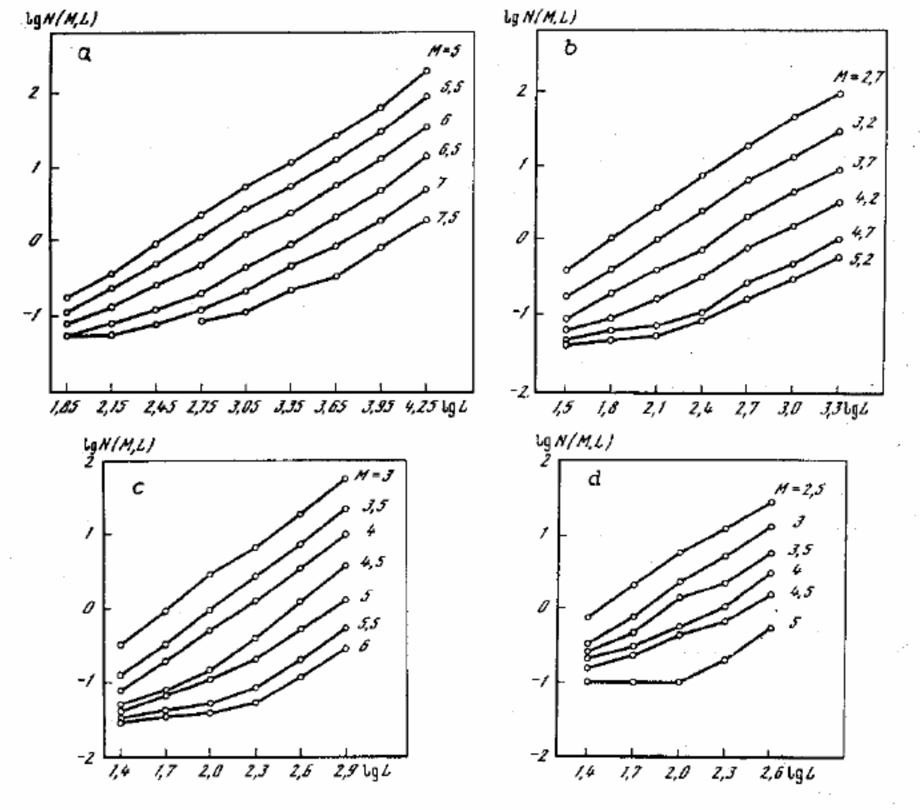


Fig. 3. Examples of log $N(M, L)$ graphs. (a) Eastern Hemisphere. (b) Lake Baikal area. (c) Southern California. (d) The Cape Mendocino vicinity.

The Unified Scaling Law for Earthquakes

We revisited the problem after Per Back et al. suggested the Unified Scaling Law for Earthquakes in a different formulation (with substitutes of 1/N = T and M = $\mathbf{Log_{10}}$ S),

"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

What Per Bak et al. (2002) done?...

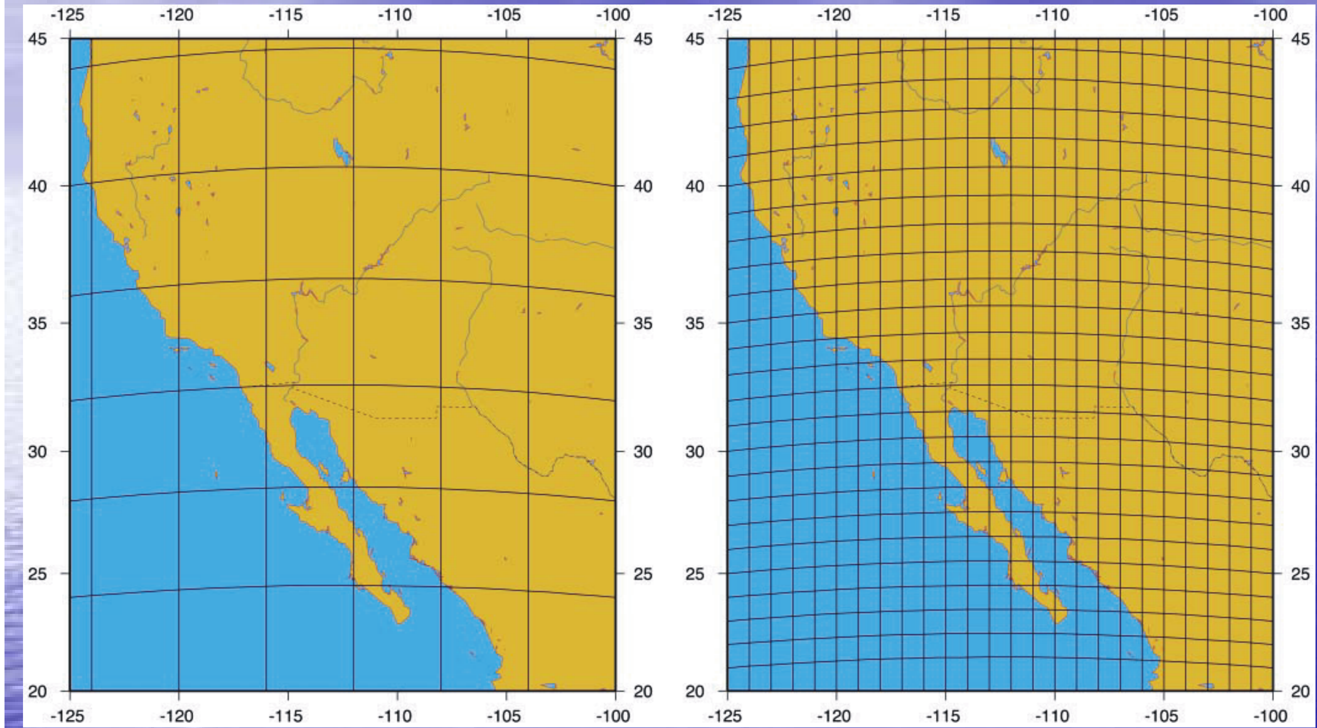


Fig. 1. Southern California seismic region covered by a grid of cells of 4° × 4° (*Left*) and cells of 1° × 1° (≈ 111 × 111 km²) (*Right*).

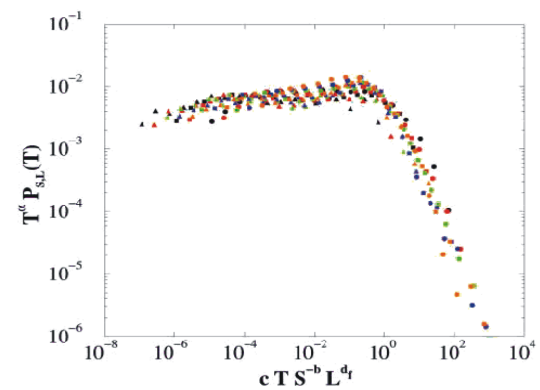
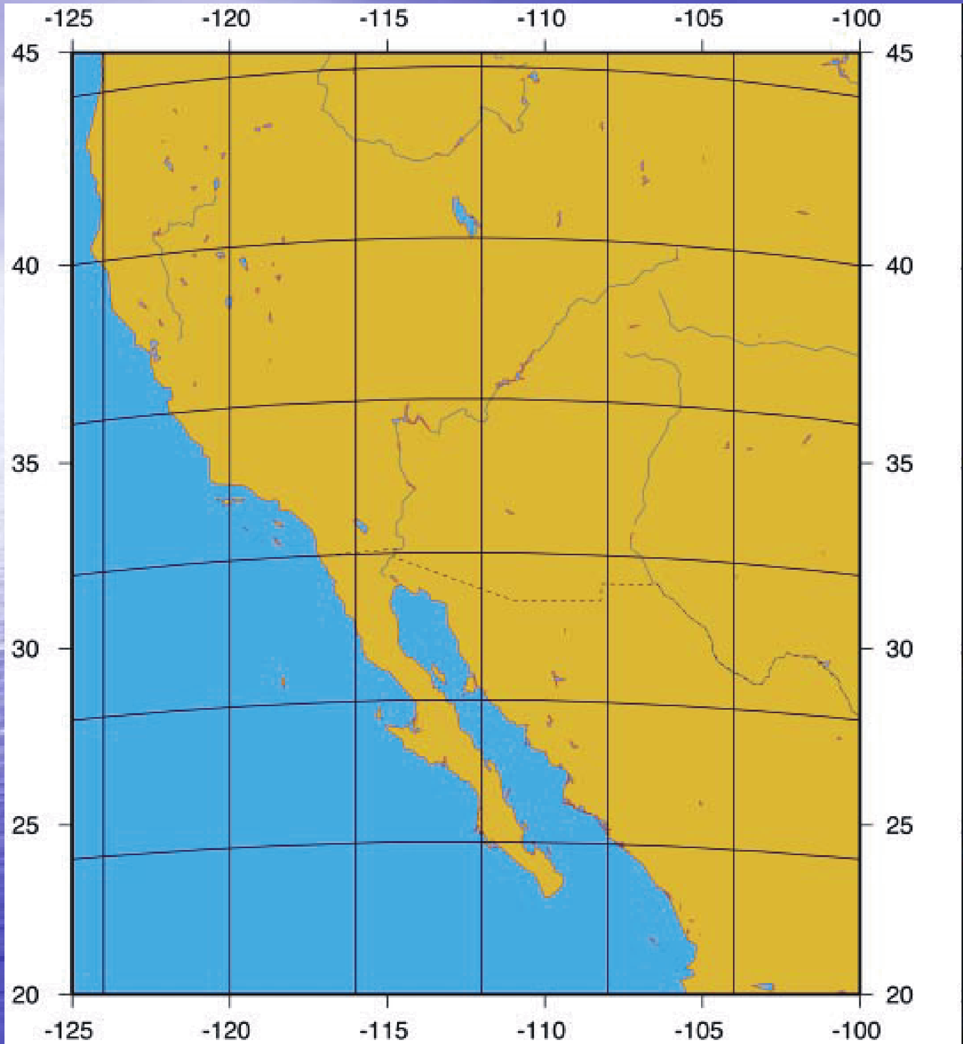


Fig. 6. The data in Fig. 3 with $T > 38$ s replotted with $T^{\alpha}P_{S,L}(T)$ as a function of the variable $x = cTS^{-b}L^{d_f}$, $c = 10^{-4}$. The Omori Law exponent $\alpha \approx 1$, Gutenberg–Richter value $b \approx 1$, and fractal dimension $d_f \approx 1.2$ have been used to collapse all of the data onto a single, unique curve $f(x)$. The curve is constant for $x < 1$, corresponding to the correlated, Omori Law regime but decays fast for $x > 1$, associated with uncorrelated events.

Christensen *et al.*

... and what they overlooked.



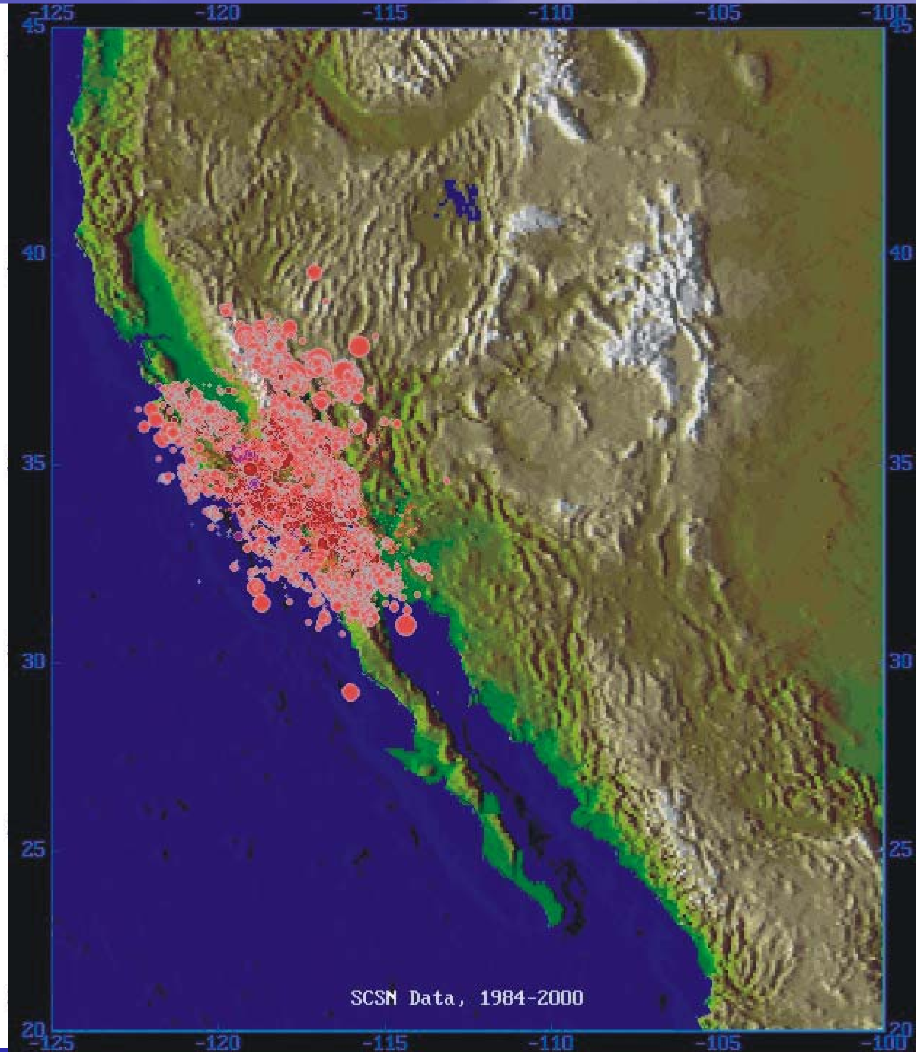


Fig. 1. Southern California seismic region covered by a grid of cells of 4° × 4° (*Left*) and cells of 1° × 1° (≈ 111 × 111 km^2) (*Right*).

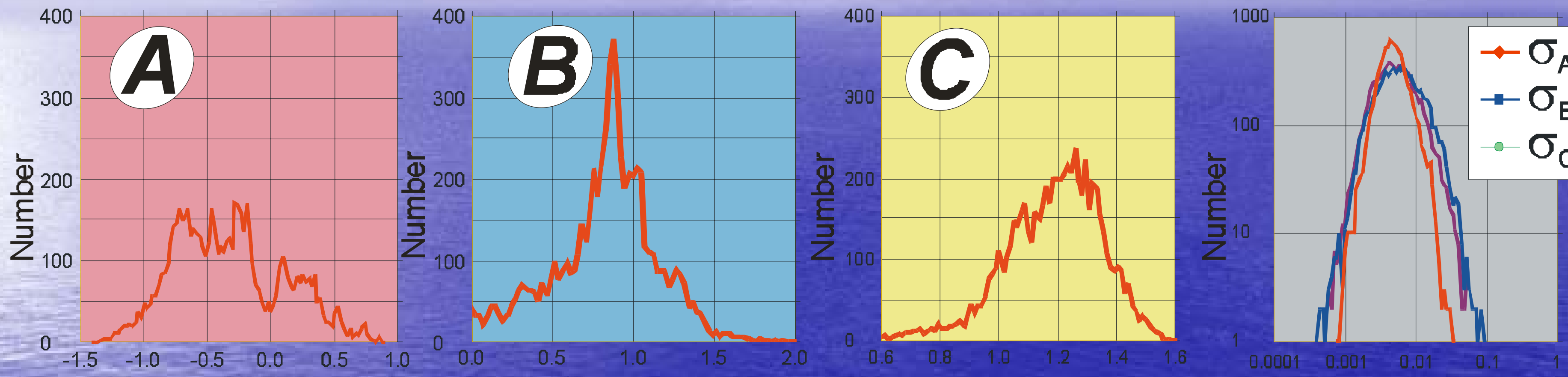
Revisiting the ABC problem on a global scale: **The Global Seismic Hazard maps display the A, B, and C's for earthquakes**

The data from the US GS/NEIC hypocenter data base permitted us to investigate systematically regions from a wide range of seismic activity, A (that differ by a factor up to 30 or more).
We found, for earthquakes with hypocenters above 100 km –

- **the balance between magnitude ranges, B, varies mainly from 0.6 to 1.1 with a sharp maximum of density at 0.9, while**

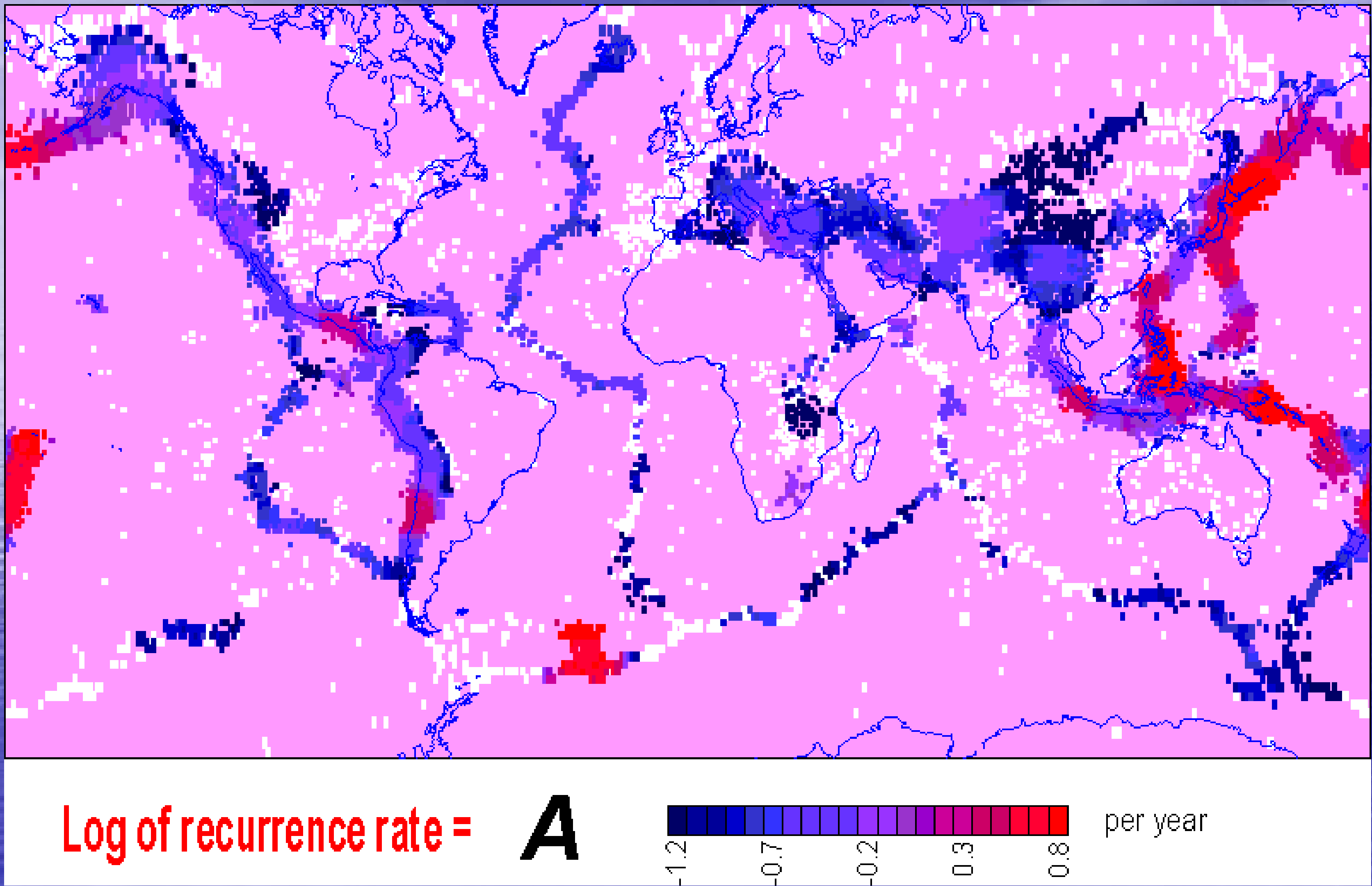
- **the fractal dimension, C, changes from under 1 to 1.6 with a maximal density within 1.2-1.3.**

Histograms of A, B, C and σ's

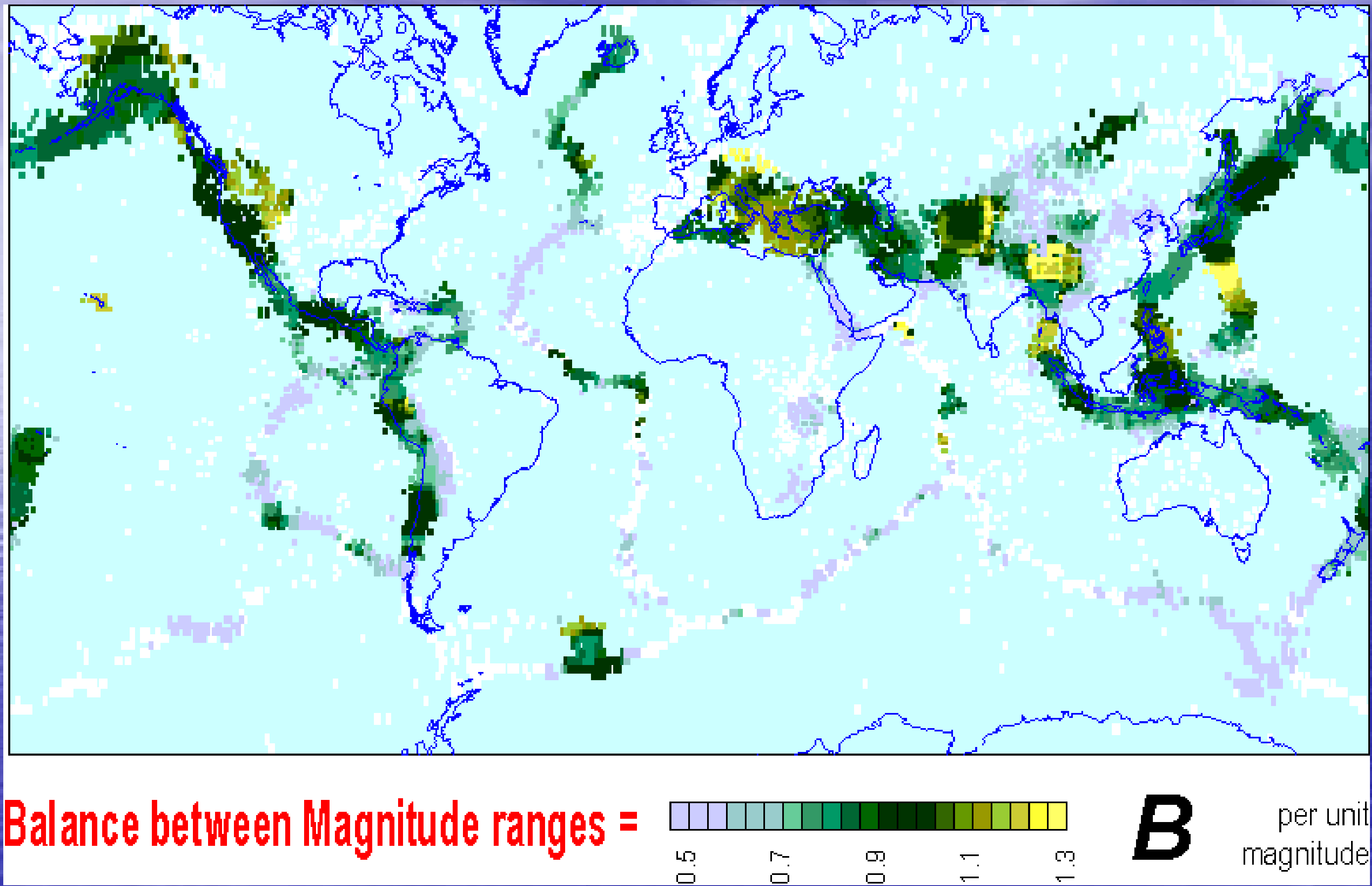


Note: The histogram of the coefficients' value errors, σ's, given in logarithmic scales. It suggests high degree of overall agreement with the assumption of self-similarity used in computations.

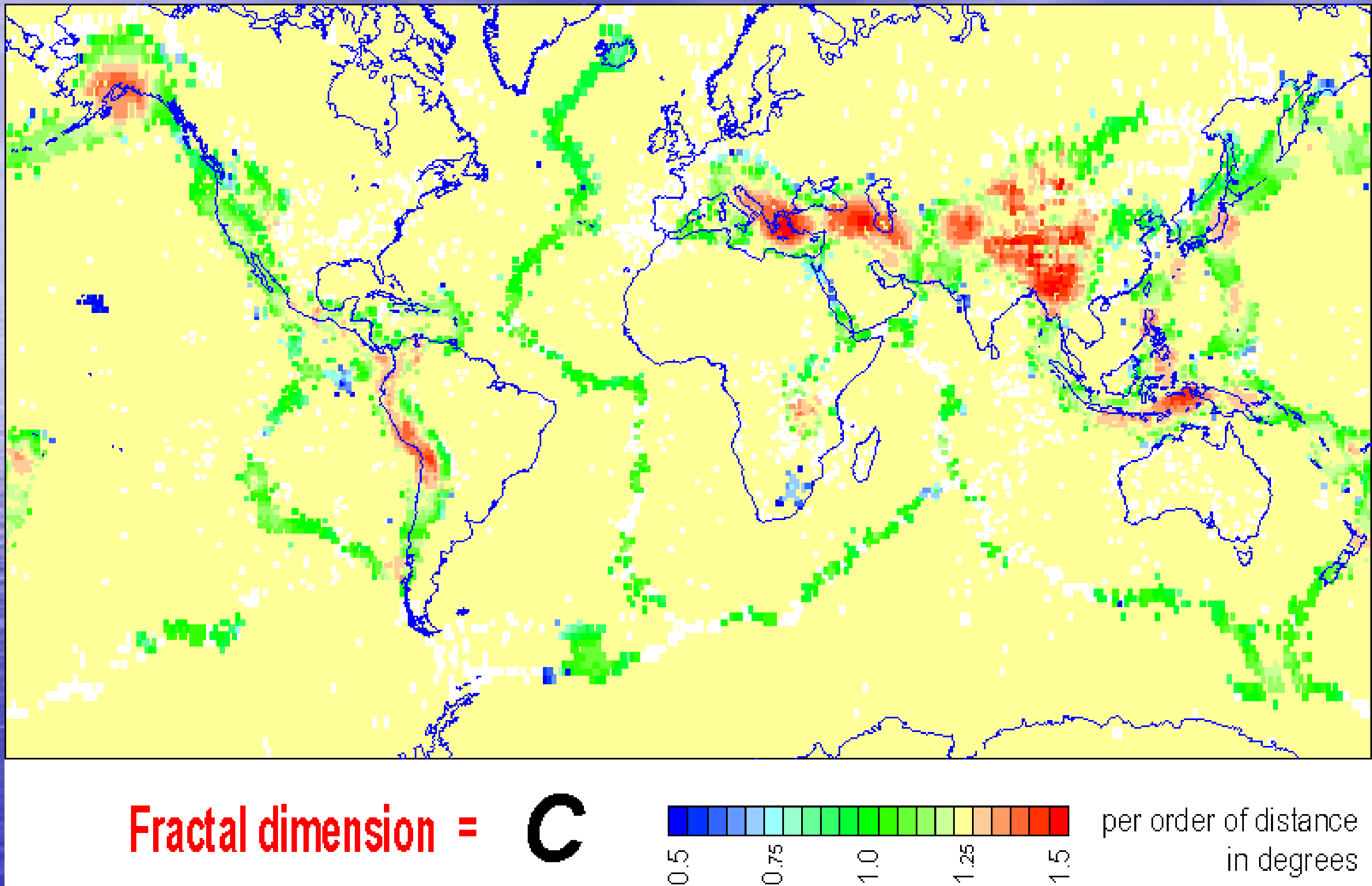
The Global Seismic Hazard map: Coefficient A



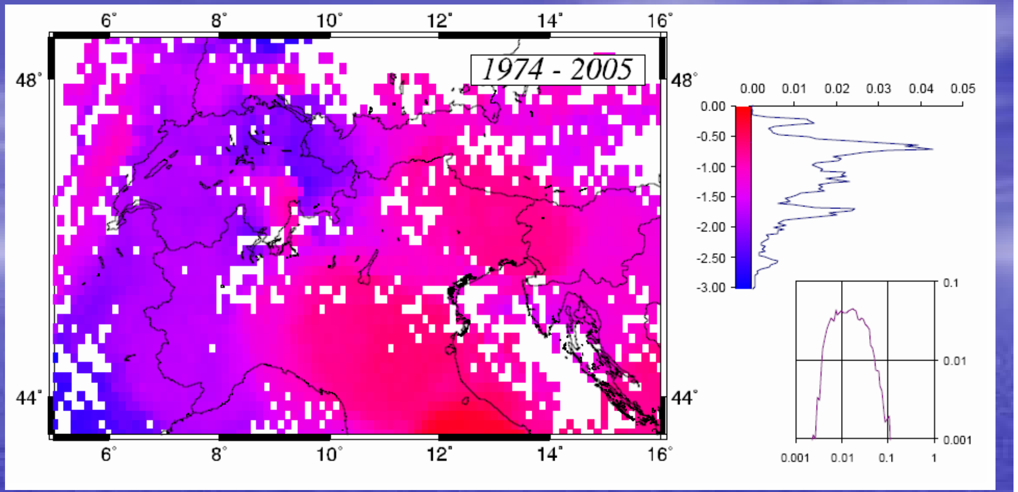
The Global Seismic Hazard map: Coefficient B

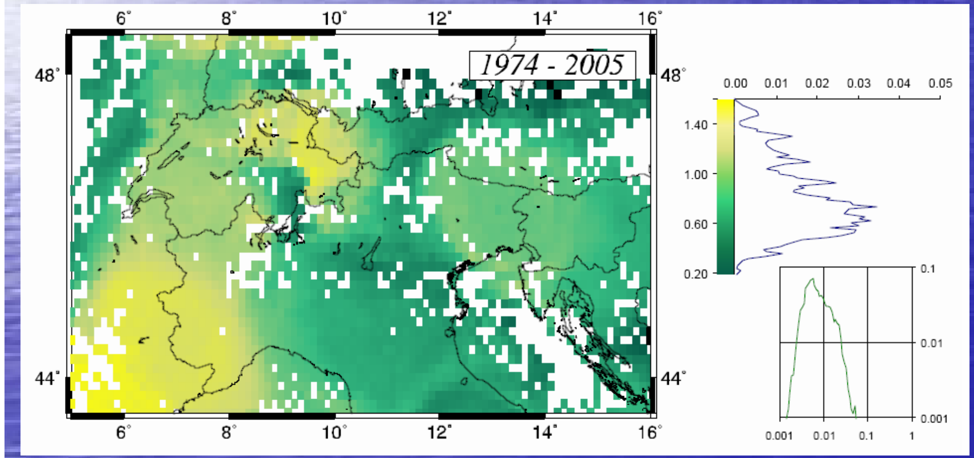


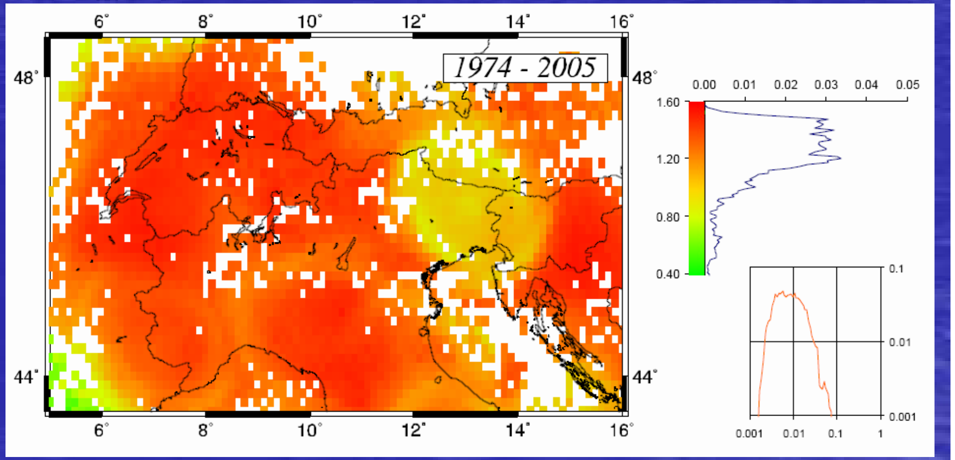
The Global Seismic Hazard map: Coefficient C

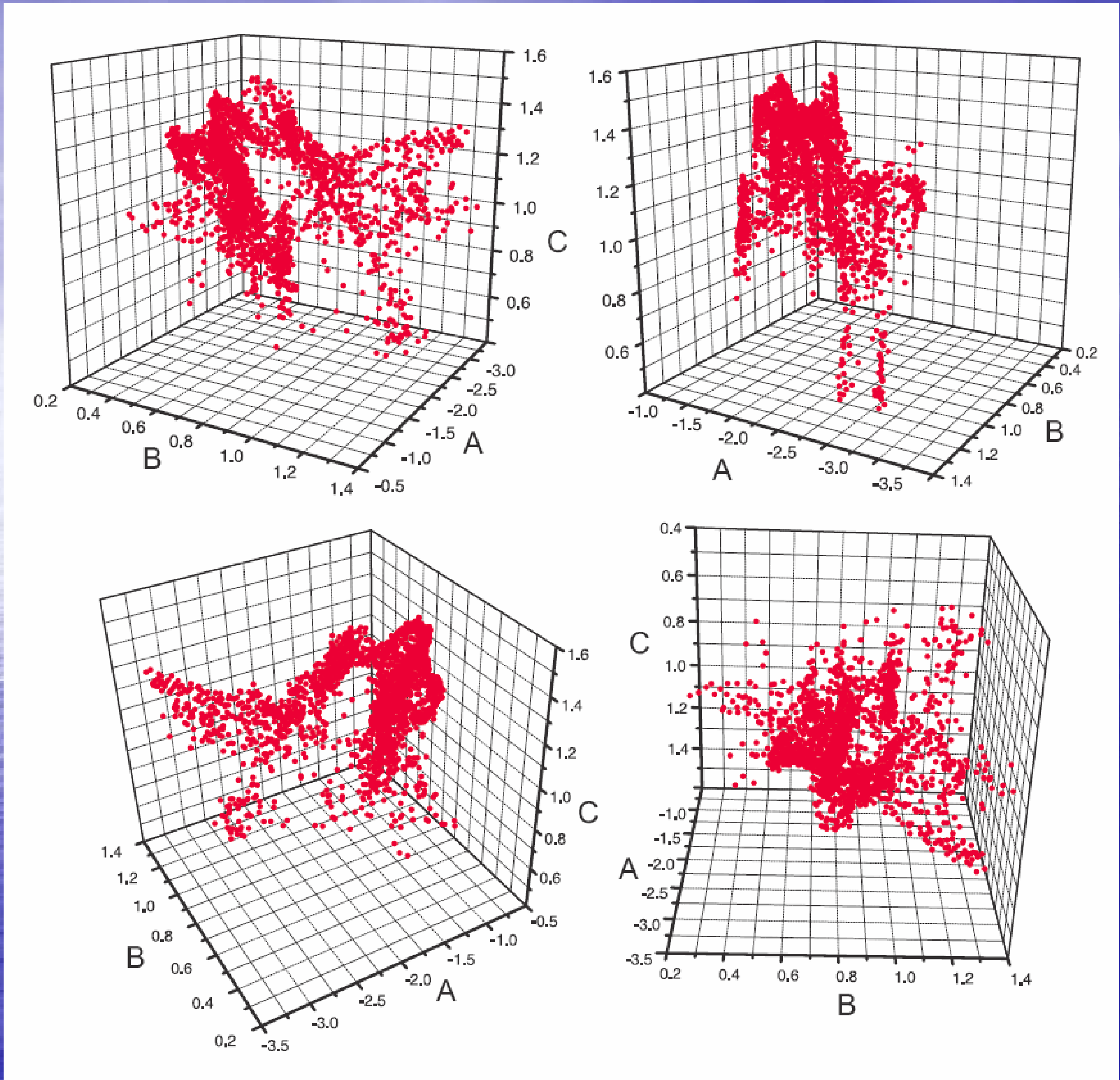


The Regional Seismic Hazard Map: Northern Italy









Sample 3-D views of the 2352 combinations of *A*, *B*, *C* coefficients in Italy and surroundings, 1870-2005.

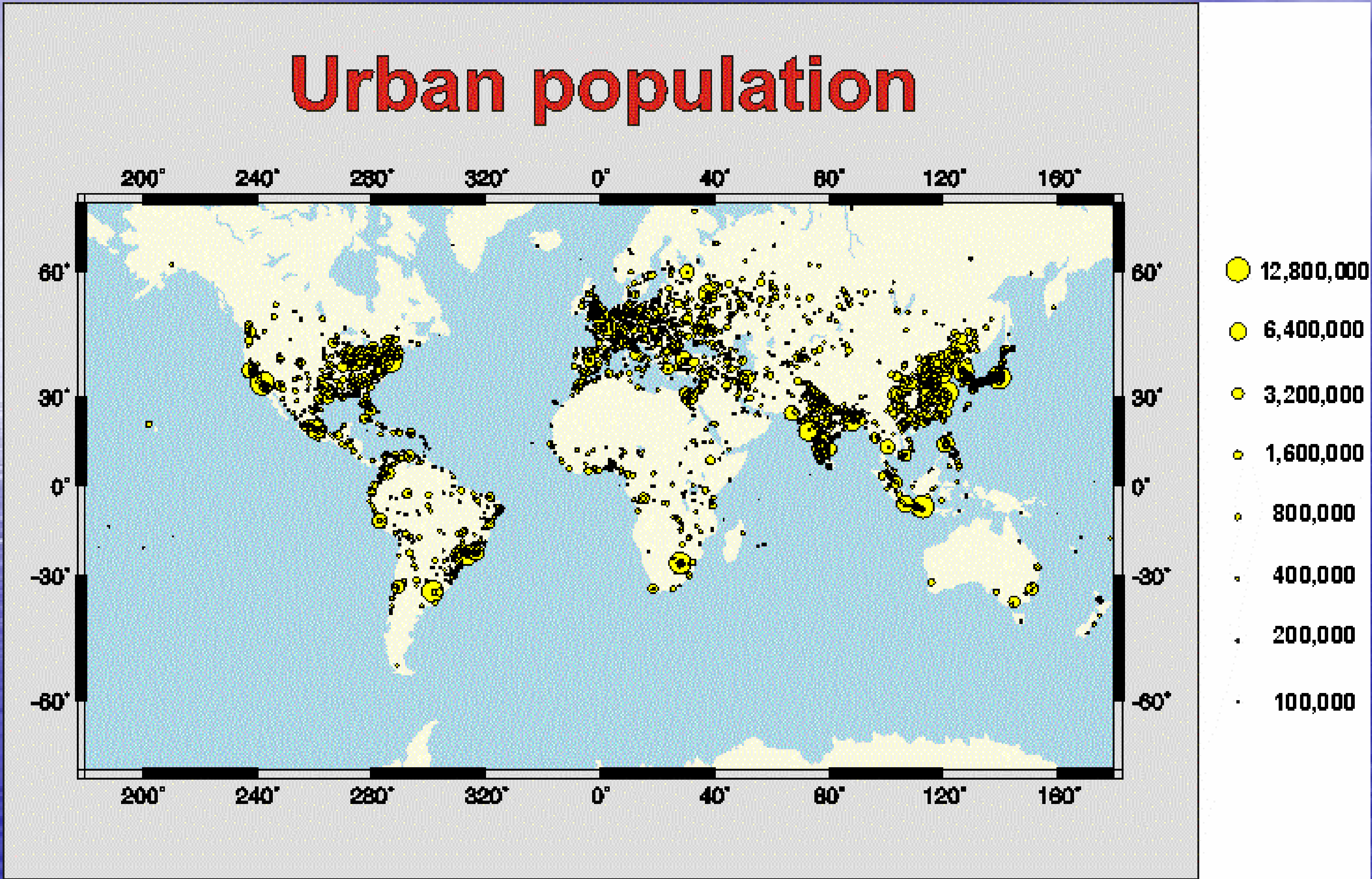
Direct implications for assessing seismic hazard at a given location (e.g., in a mega city)

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 !**

Similarly, the underestimation is about a factor of
6.4 for San Francisco (A = -0.38, B = 0.93, C = 1.20, σ_{total}=0.07),
4.6 for Tokyo (A = 0.14, B = 0.94, C = 1.34, σ_{total}=0.05),
8 for Petropavlovsk-Kamchatsky (A = -0.01, B = 0.83, C = 1.22, σ_{total}=0.05),
10 for Irkutsk (A = -1.12, B = 0.80, C = 1.05, σ_{total}=0.03),
etc.

Scaling for unified application of an earthquake prediction method.

Convolving Seismic Hazard with Object of Risk and its Vulnerability provides an estimation of Seismic Risk

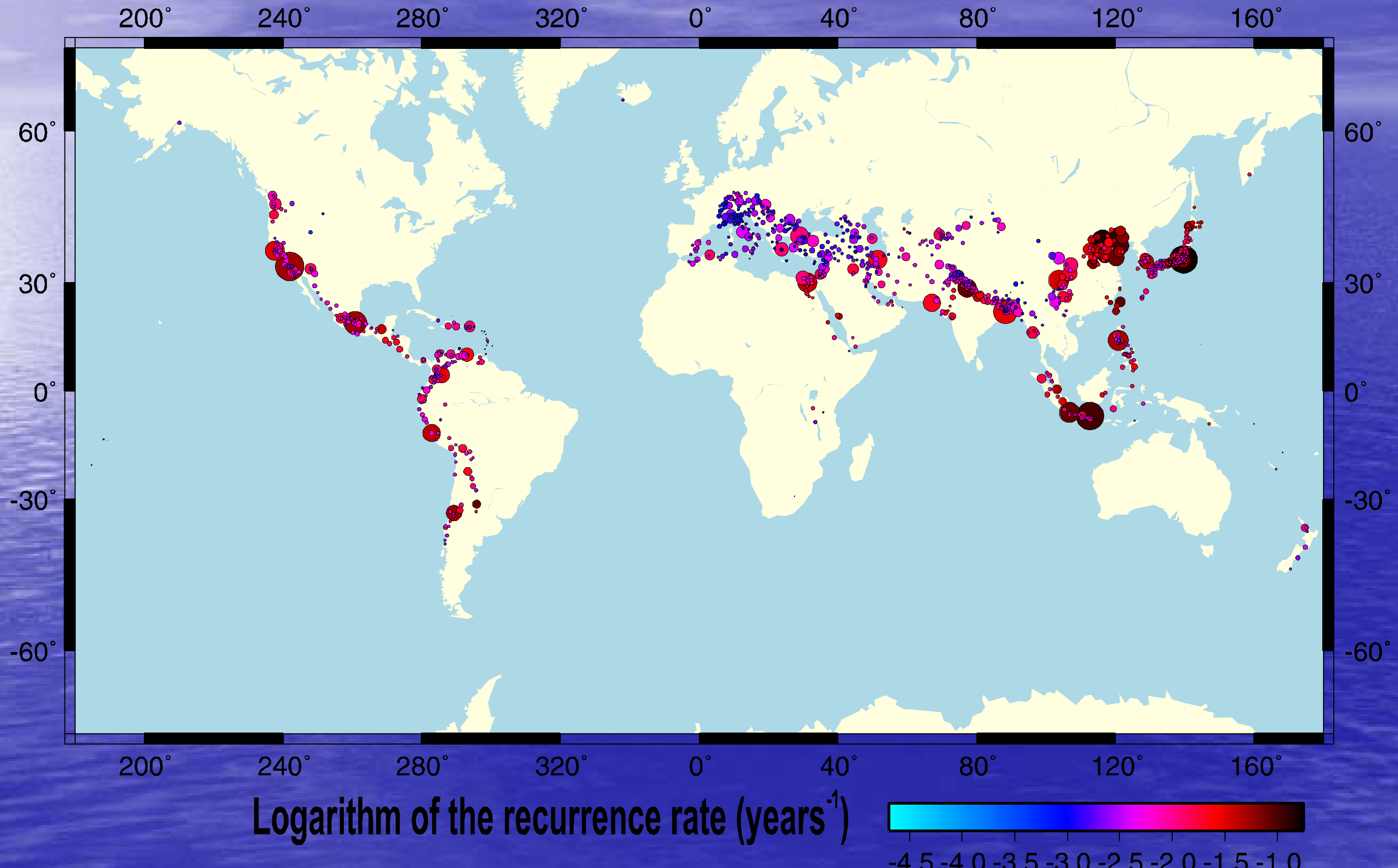


Recurrence rates

$10^{A} \times 10^{B\times(5-M)} \times (\text{City Area})^{C/2}$

City Area = 0.001×Population/(1°×1°)

Strong, magnitude 6, earthquakes.



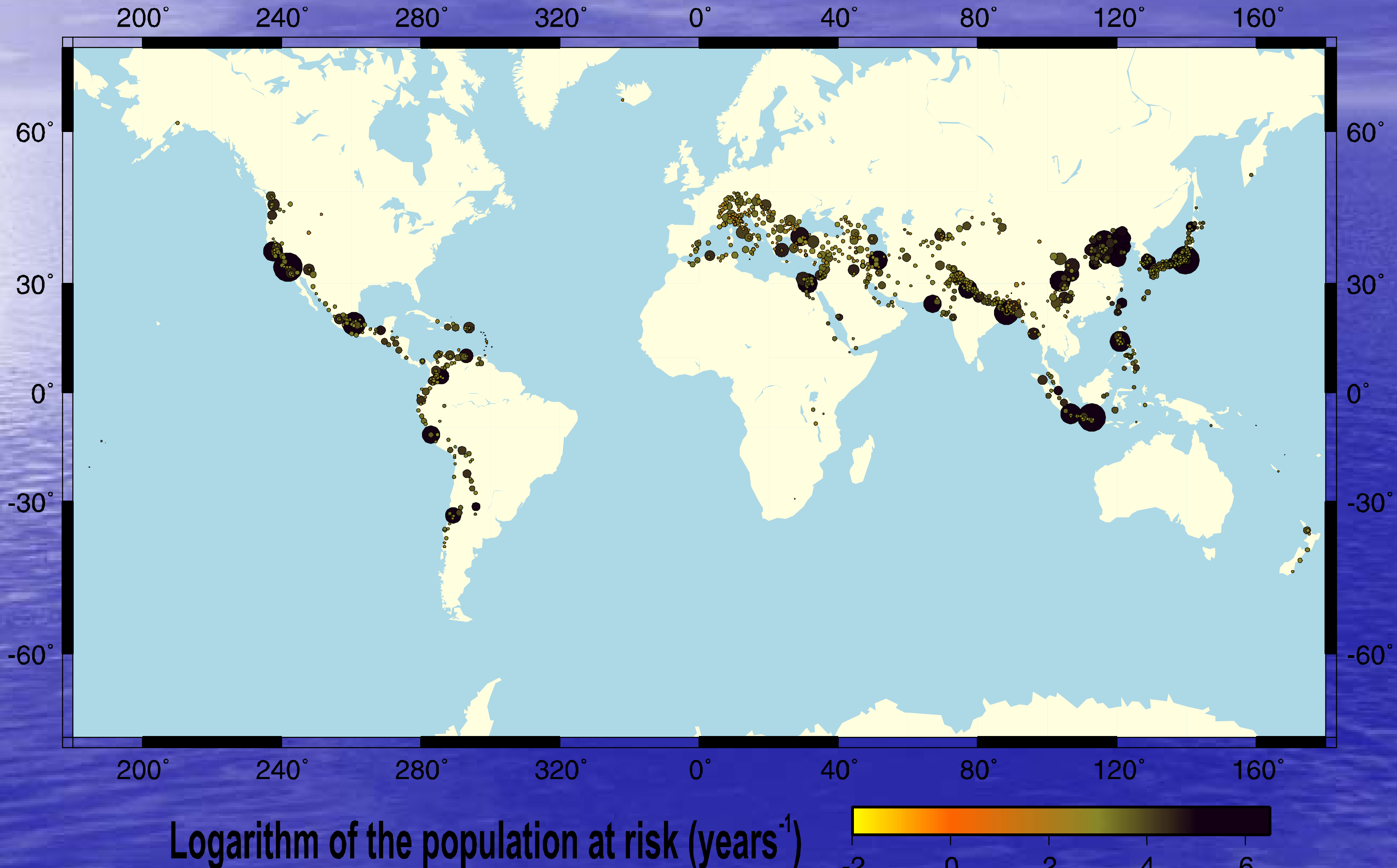
Top ten* recurrence rates for strong (M6+) earthquakes

City	Country	Population	A	B	C	Recurrence rate, years^{-1}
Tokyo	Japan	11,906,331	0.14	0.94	1.34	0.15663
Taipei	China	1,769,568	0.22	0.80	1.15	0.08580
Jakarta	Indonesia	6,503,449	0.15	1.06	1.23	0.08349
Kobe	Japan	1,422,922	0.17	0.90	0.84	0.07368
Yokohama	Japan	3,049,782	0.15	0.95	1.32	0.06258
Kyoto	Japan	1,480,355	0.16	0.93	0.96	0.06177
Santiago	Chile	4,099,714	0.08	1.05	1.21	0.05579
Quanzhou	China	403,180	0.39	0.95	0.96	0.05310
Los Angeles	US	13,074,800	-0.34	0.95	1.19	0.05267
Gaoxiong	China	828,191	0.21	0.80	1.18	0.05165

Urban population at risk

Recurrence rate×Population

Strong, M6, earthquakes.



Top ten* of the population at risk for strong (M6+) earthquakes

City	Country	Population	A	B	C	Population at risk, year^{-1}
Tokyo	Japan	11,906,331	0.14	0.94	1.34	1,864,928
Los Angeles	US	13,074,800	-0.34	0.95	1.19	688,671
Jakarta	Indonesia	6,503,449	0.15	1.06	1.23	543,000
Mexico	Mexico	8,831,079	-0.16	1.05	1.24	444,839
Manila	Philippines	6,720,050	0.03	1.16	1.35	325,408
Santiago	Chile	4,099,714	0.08	1.05	1.21	228,741
Lima	Peru	5,008,400	-0.26	0.86	1.36	204,522
Yokohama	Japan	3,049,782	0.15	0.95	1.32	190,865
San Francisco	US	5,877,800	-0.38	0.93	1.20	183,198
Taipei	China	1,769,568	0.22	0.80	1.15	151,830

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

$$\log N(M,L) = A + B\cdot(5 - M) + C\cdot\log L,$$

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

(ii) for a wide range of seismic activity, A, the balance between magnitude ranges, B, varies from 0.6 to 1.4, while the fractal dimension, C, changes from under 1 to 1.6

(iii) an estimate of earthquake recurrence rate depends on the size of the territory that is used for averaging and may differ dramatically when rescaled in traditional way to the area of interest.

The confirmed multiplicative scaling of earthquakes changes the traditional view on their recurrence, the catastrophic ones in particular, and has serious implications for estimation of seismic hazard, for the Seismic Risk Assessment, as well as for earthquake prediction.

Thank you