Predictability of seismic extremes: a 20-year test results

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МИТП РАН

IIEPT

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. Generally, it implies investigating a small sample of case-histories with a help of delicate statistical methods and data of different quality, collected in various conditions.
- Many extreme events are clustered (far from independent, e.g., Poisson process) and follow fractal or some other "strange" distribution (far from uniform). 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).

"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.

…

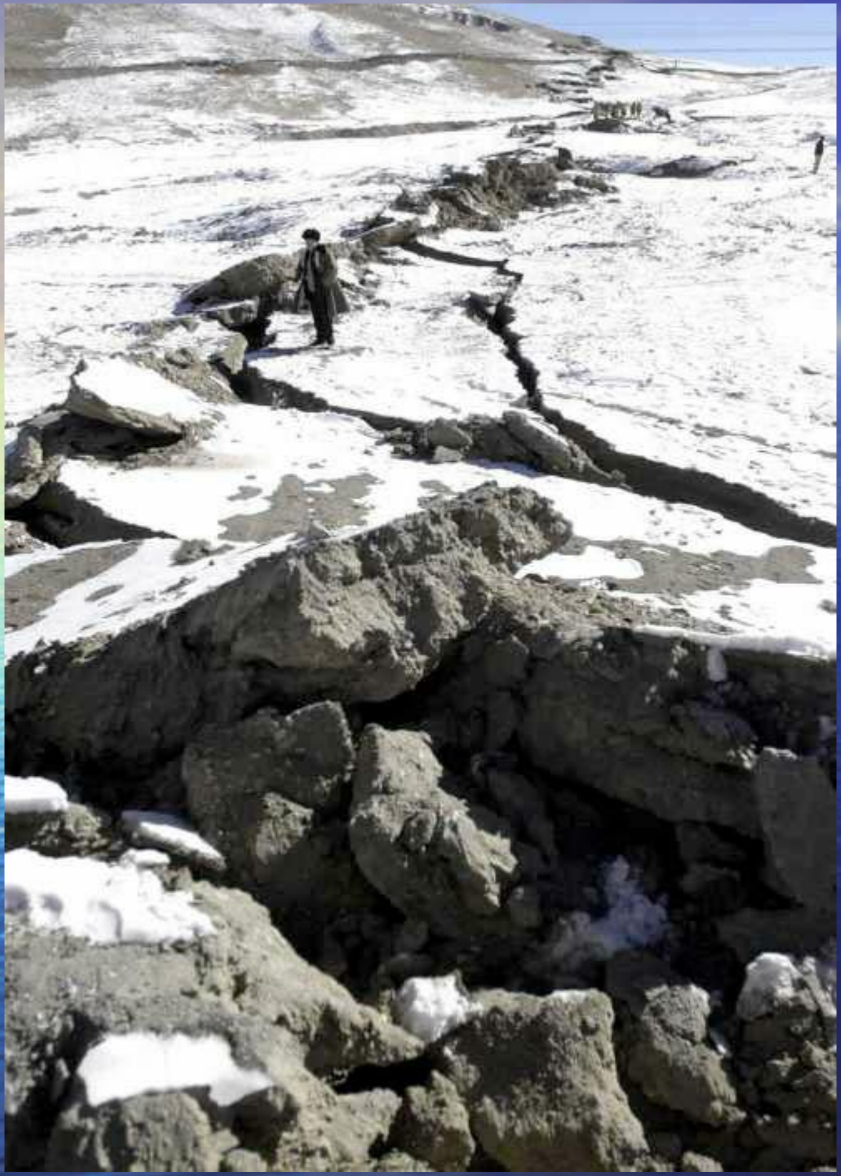
(William H. Press et al., *Numerical Recipes*, p.603)

…

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)

- 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 a modification of the forecast/prediction tools for a more adequate “optimal” application.



Earthquake prediction of seismic extremes.

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.

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.

Seismic Roulette null-hypothesis

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…

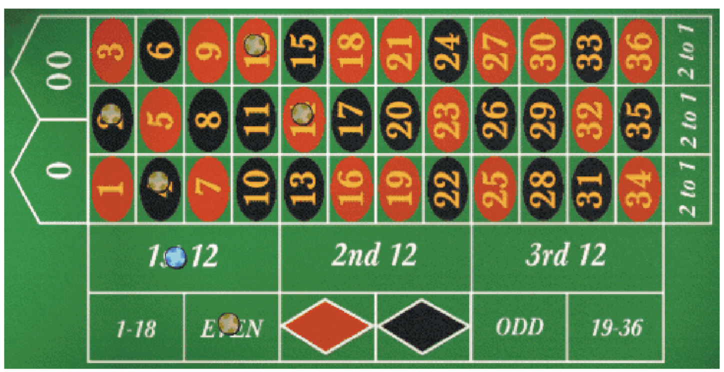
then ***systematically*** you can win! ☺

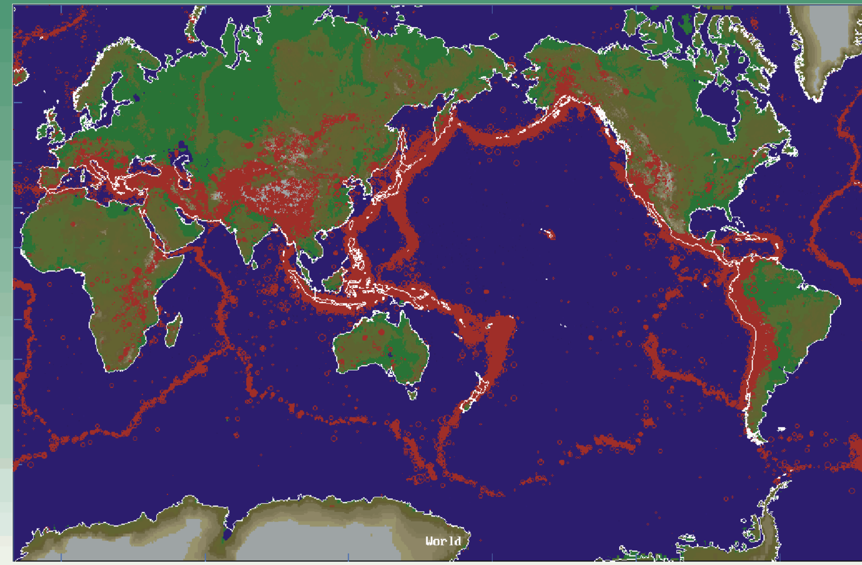
or lose … ☹

If you are smart enough to know "antipodal strategy" (Molchan, 1994; 2003), make the predictions efficient ------

and your wins will outscore the losses! ☺ ☺ ☹ ☺ ☺ ☺ ☹ ☺ ☺ ☺

Seismic Roulette





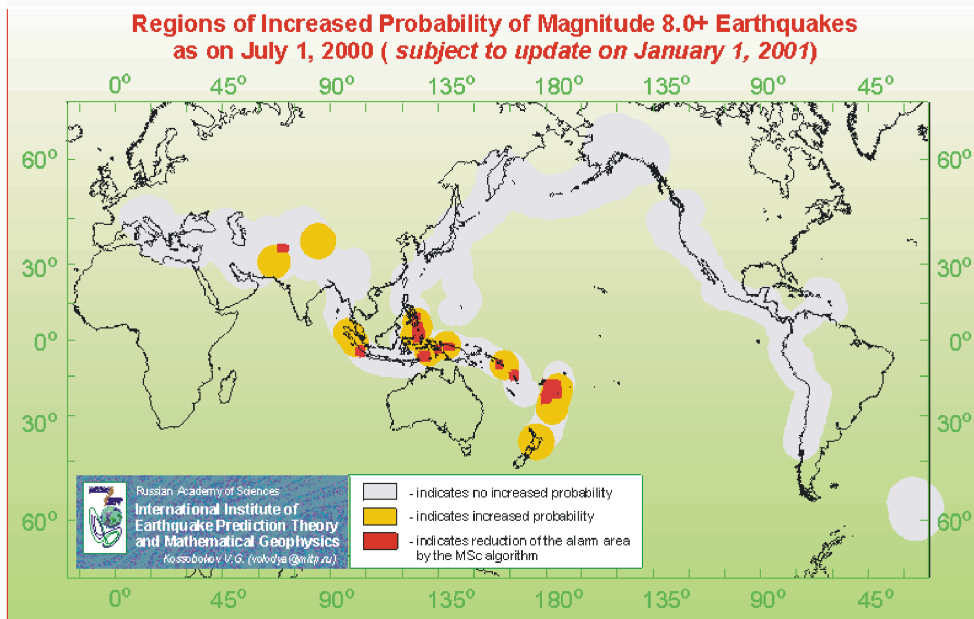
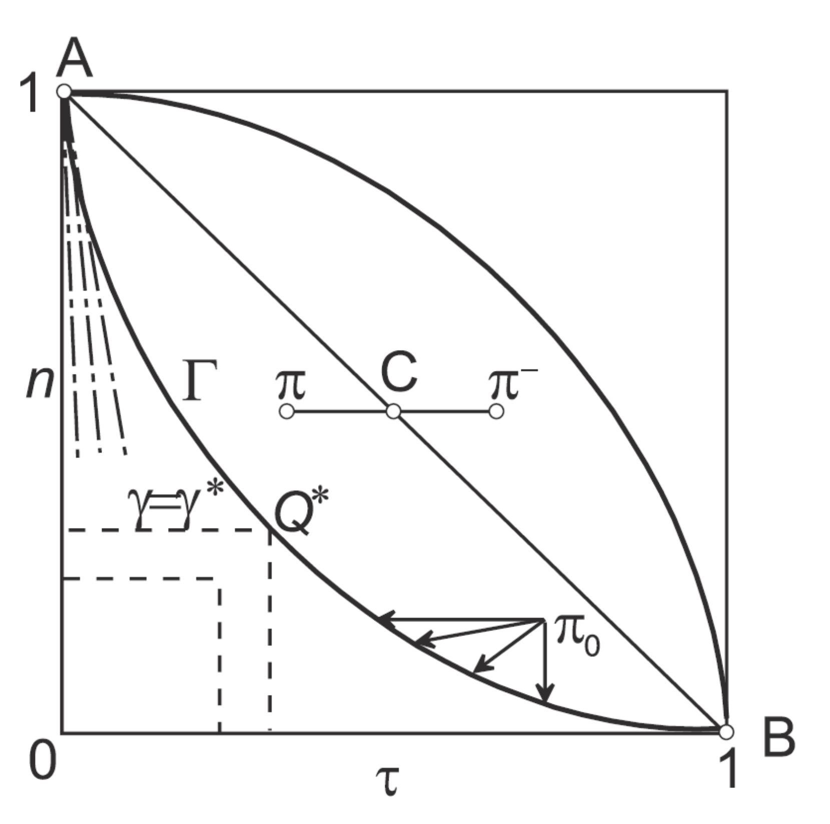


Fig. 5.1. Error set $\mathcal{E}(J)$ for prediction strategies based on a fixed type of information J. Point A corresponds to an optimistic strategy, point B to a pessimistic strategy, and the interval AB corresponds to strategies of random guess. C is the center of symmetry of $\mathcal{E}(J)$. π and π^- are a strategy and its antipodal strategy. Γ is the error diagram of optimal strategies. *Arrows* indicate a better forecast relative to the strategy π_0. *Dashed lines* are contours of the loss function $\gamma = \max(n, \tau)$. Q^* are errors of the minimax strategy, $n = \tau$. *Dash-dotted* lines are contours of the loss function $\gamma = \tau/(1-n)$



Error diagram

Molchan, G.M. , 1997 Earthquake prediction as decision-making problem. *Pure Appl. Geoph*, **149**, 233-247.

Molchan, G.M. , 2003 5. Earthquake prediction strategies: a theoretical analysis. In: Keilis-Borok, V.I., and A.A. Soloviev, (Editors). *Nonlinear Dynamics of the Lithosphere and Earthquake Prediction*. Springer, Heidelberg, 208-237.

Molchan, G.M. & Keilis-Borok, V.I., 2008. Earthquake prediction: probabilistic aspect, *Geophys.J. Int.*, ***173*, *1012–1017.***

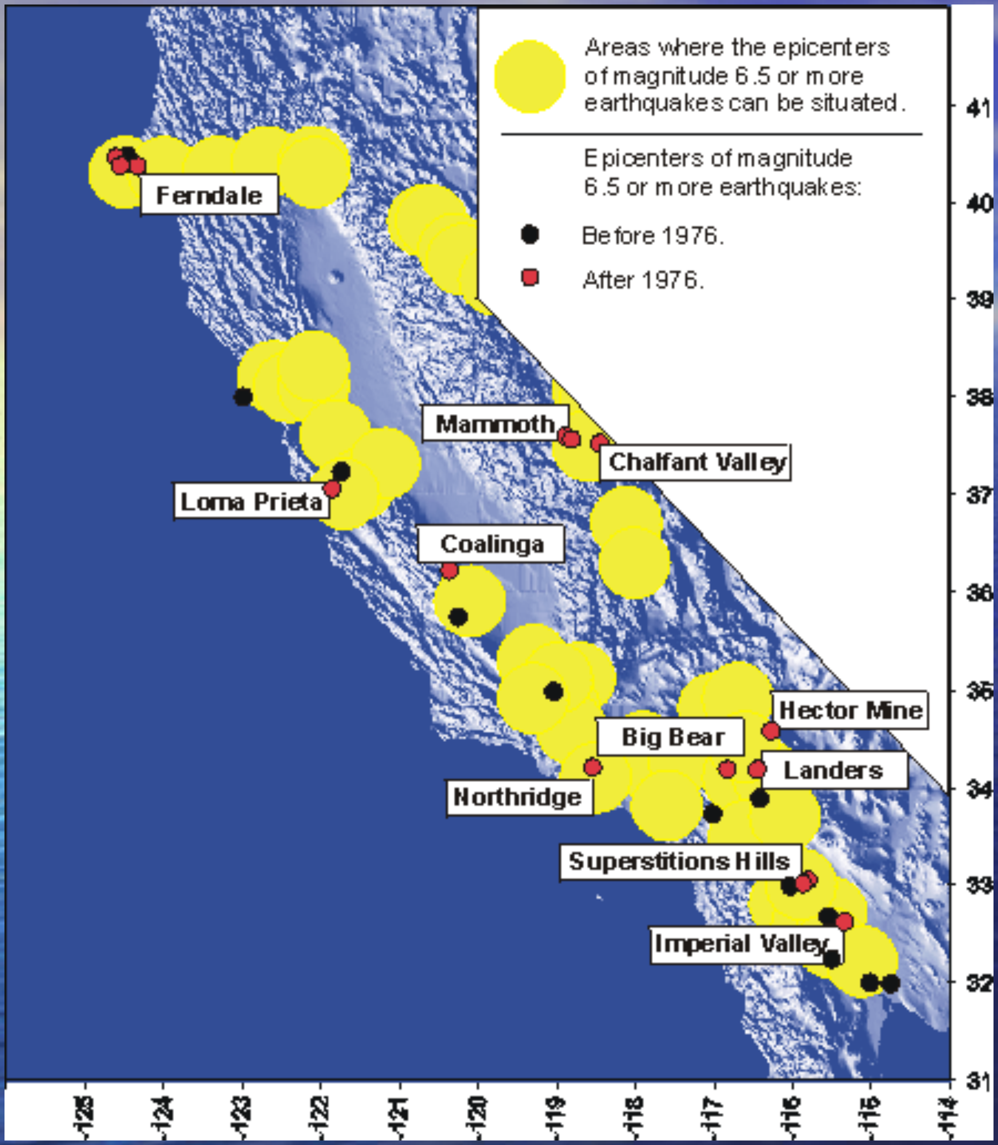
Molchan, G.M., 2010. Space-time earthquake prediction: the error diagrams, *Pure Appl. Geoph.*, ***167(8–9), doi:10.1007/s00024-010-0087-z.***

И.М. Гельфанд
ДВА АРХЕТИПА В ПСИХОЛОГИИ ЧЕЛОВЕЧЕСТВА
1989 Лекция при вручении премии INAMORI FOUNDATION
(Киото, Япония)
Izrail M. Gelfand, Two archetypes in the psychology of Man. Nonlinear Sci. Today 1 (1991), no. 4, 11

"It is frightening that in our technocratic times baseline principles are not subjected to questioning, so that when they built the basis of **trivial or, conversely, delicately-designed model**, it **considered as a full replacement of natural phenomena**. This made the better model, it is worse for its applications – you know that pressure of snatched "baseline principles" brings the model even further beyond its applicability."

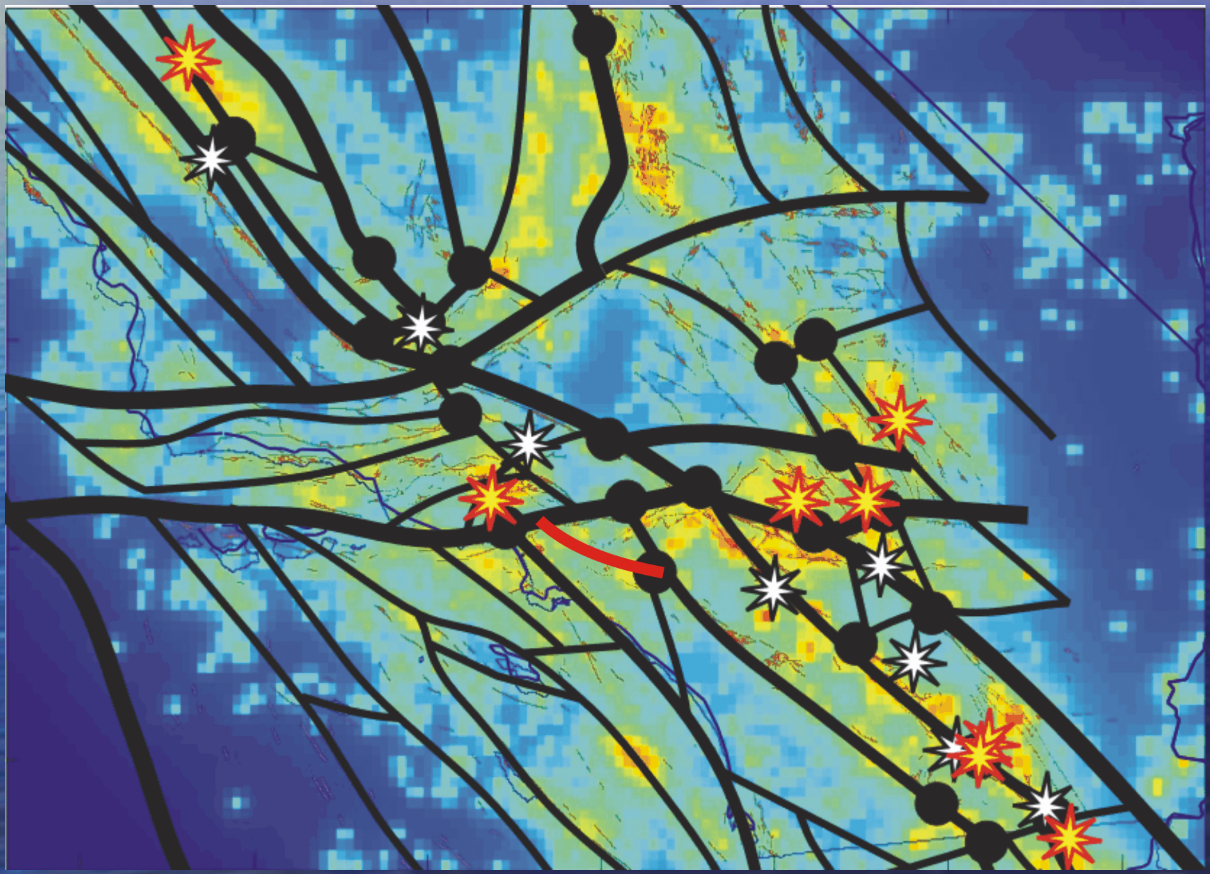
Izrail Moiseevich Gelfand
(1913-2009)

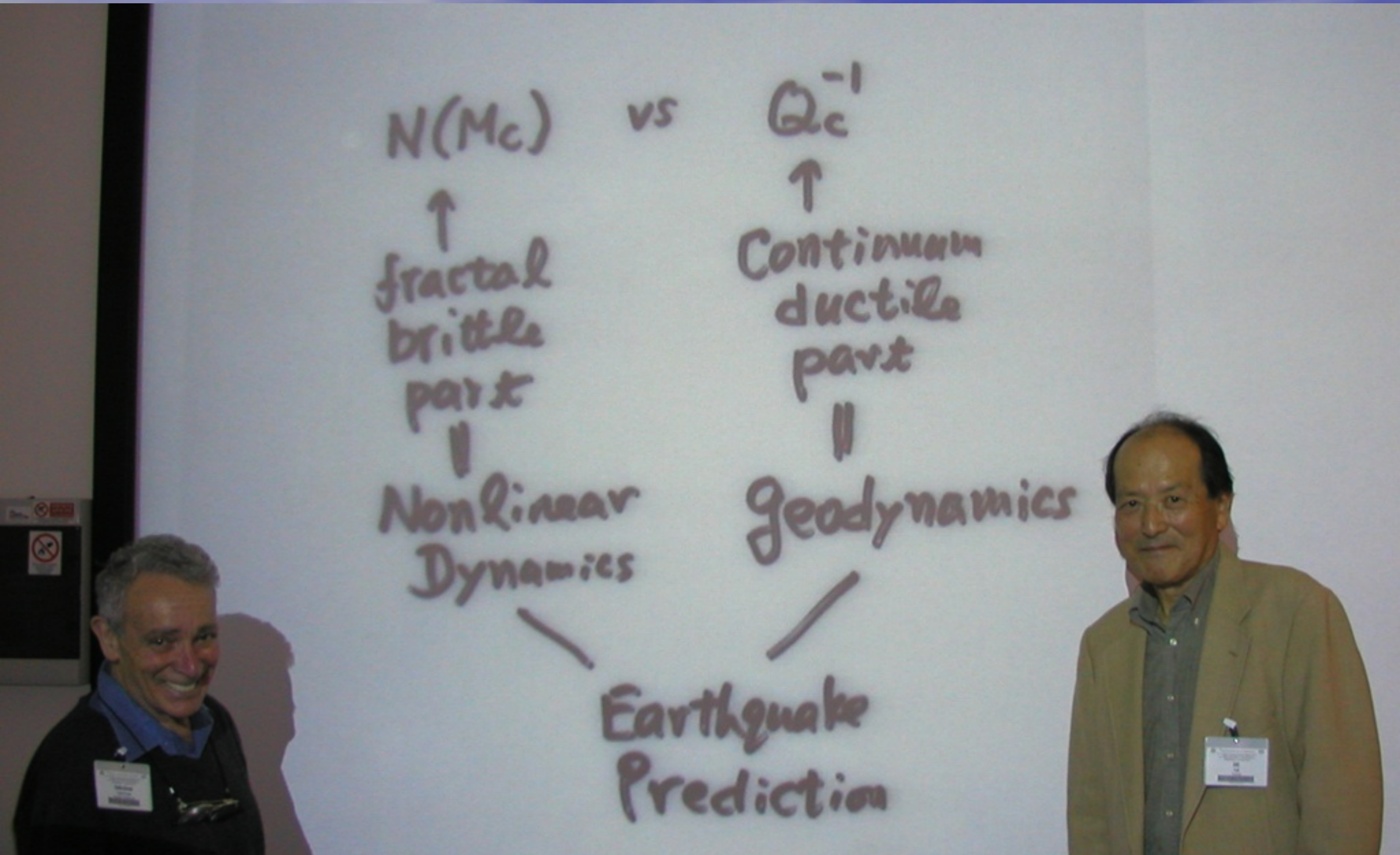
Term-less approximation:



- 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

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.**




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

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

M8 algorithm

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

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

The algorithm 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).

Second approximation prediction method MSc (*Mendocino Scenario*)

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.

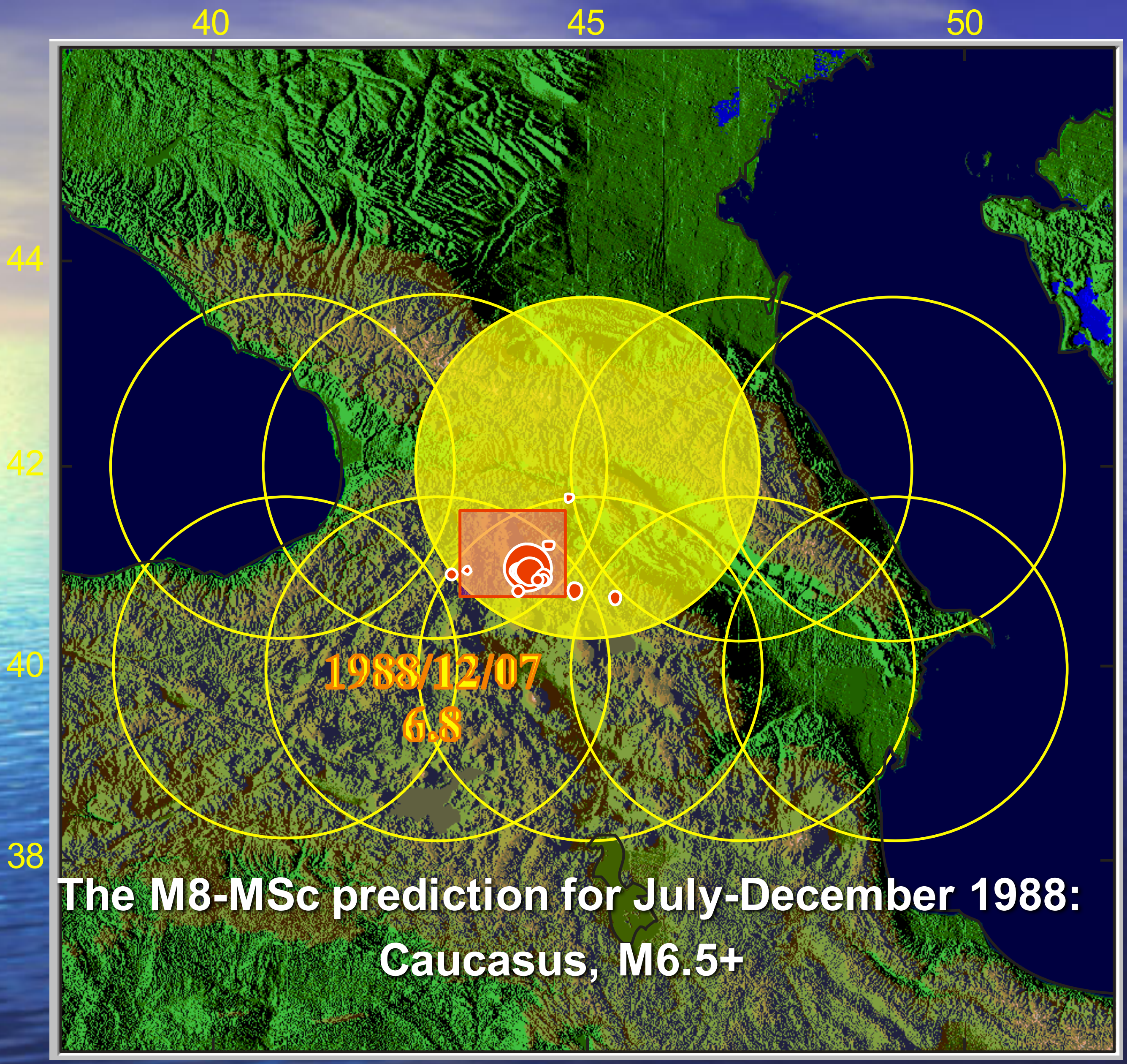
Qualitatively, the MSc algorithm outlines such an area of the territory of alarm where the activity, from the beginning of seismic inverse cascade recognized by the first approximation prediction algorithm (e.g. by M8), is continuously high and infrequently drops for a short time. Such an alternation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

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

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

M8 algorithm is applied first, then, if the data permits, the algorithm MSc provides a reduction of the TIPs' spatial uncertainty (although at the cost of additional failures-to-predict).



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

The results of the monitoring of the FSU seismic regions (1986-1990) were encouraging: 6 out of 7 target large earthquakes were predicted with an average probability gain about 7 (at the M8 approximation).

"As Reagan later recalled for us over lunch, upstairs in his Swiss chateau, Gorbachev's experts gauged a two-thirds chance of an earthquake hitting 7.0 to 7.5 on the Richter scale, and the three fourths chance of a 6.0 to 6.5 earthquake before last November. The first forecast turned out to be more correct."

(San Francisco Chronicle, 26 October 1989)

OPEN FORUM/KEN ADELMAN

Quake Talk At the Summit

CAN YOU BELIEVE that Ronald Reagan and Mikhail Gorbachev discussed, at great length, the probability of a massive California earthquake during their very first encounter?

Well, they did. And somehow Gorbachev got it right. As recounted in "The Great Universal Embrace," my new book about Reagan administration adventures, we thought the topic most peculiar then. It still seems most peculiar now, but also prescient if not downright clairvoyant.

The timing was the end of November 1985. The setting was Geneva. The drama was high. This was the first U.S.-Soviet summit meeting in nearly seven years and the first ever for either Reagan or Gorbachev. President Reagan began his first session alone with the new Soviet leader by, well, just being Reagan. Rather than regurgitate the bureaucracy-furnished "talking points," he opened on a personal note.

The president told Gorbachev how odd life can be. For there they sat, he and Gorbachev, both of humble origins — born in small towns in the middle of nowhere — now, by a quirk of fate, the leaders of the two major world powers.

Gorbachev clearly warmed to the personal, genuine Reagan treatment. He then told how they must strive to overcome differences and build on what they shared. This led into his farsighted talk about the coming quake.

For Gorbachev then turned practical. Americans and Soviets, he told Reagan, could begin developing a better relationship by cooperating on scientific projects like, say, earthquake research. Before heading off to Geneva, in fact, Russian scientists had informed Gorbachev that California would definitely have an earthquake within about three years. That time frame expired only months before the big quake hit San Francisco and environs.

As Reagan later recalled for us over lunch, upstairs in his Swiss chateau, Gorbachev's experts gauged a two-thirds chance of an earthquake hitting 7.0 to 7.5 on the Richter scale, and a three-fourths chance of a 6.0 to 6.5 earthquake, before last November. The first forecast turned out more correct.

Gorbachev then offered to send Soviet scientists here to explain their conclusions and methods to their American counterparts. This kind offer was never accepted.

For at that time, American scientists were less alarmist. They figured only a 60 percent chance of a major earthquake over the next 30 years.

Nonetheless, Gorbachev had hit the right button. Not only did he turn out scientifically correct, but he proved a consummate diplomat by beginning to charm Reagan.

The president repeated for us the elaborate explanation he gave Gorbachev on the 750 mile-long San Andreas Fault. The former actor delivered this seemingly interminable set-piece for us, just as he had done for Gorbachev and for countless audiences before.

I watched Reagan's performance, almost transfixed by its intensity and length. Meanwhile, the whole world was waiting and wondering what momentous issues the two most important individuals on Earth were discussing during their first encounter.

At the time, this seemed a massive diversion. Now, however, it seems more fitting.

Summits are, after all, meant to discuss the world's really big issues.

(Ken Adelman is former director of the Arms Control and Disarmament Agency.)

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 ($M \geq 8$) 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 in retrospection and since 1992 in real-time prediction mode.

Real-time prediction of the world largest earthquakes: An experiment started in 1992 with a publication of

[Healy, J. H., V. G. Kossobokov, and J. W. Dewey. A test to evaluate the earthquake prediction algorithm, M8, *U.S. Geol. Surv. Open-File Report* **92-401**, 23 p. with 6 Appendices, 1992]

is going on.

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.

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

Test period	Target earthquakes: Total	Predicted by M8	Predicted by M8-MSc	Measure of alarms, %: M8	M8-MSc	Confidence level, %: M8	M8-MSc
1985-present	**19**	**14**	**10**	**33.16**	**16.89**	**99.96**	**99.96**
1992-present	**17**	**12**	**8**	**30.09**	**15.04**	**99.93**	**99.82**

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 nine failures-to-predict in a row.

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

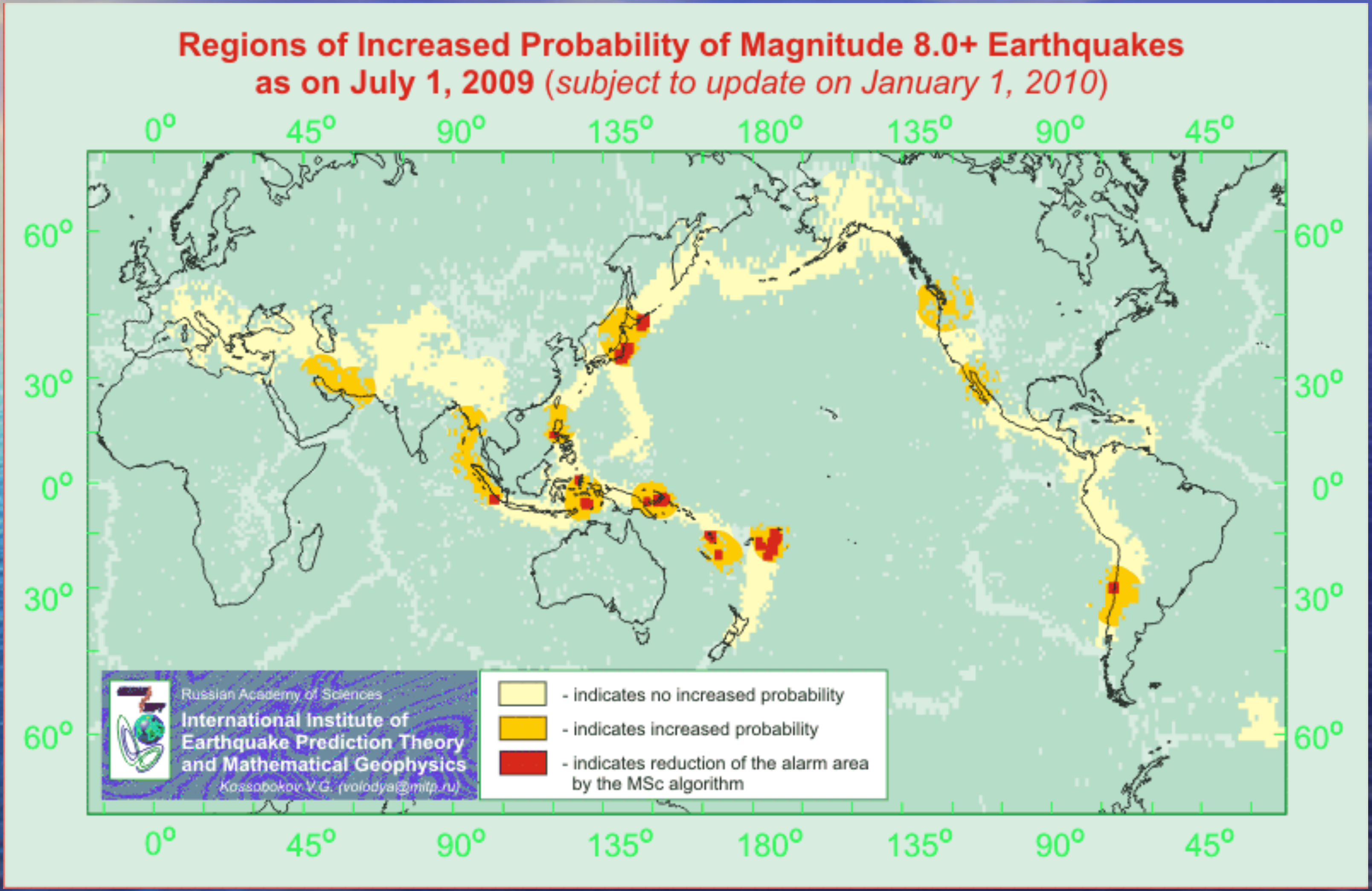
Test period	Target earthquakes Total	Predicted by M8	Predicted by M8-MSc	Measure of alarms, % M8	Measure of alarms, % M8-MSc	Confidence level, % M8	Confidence level, % M8-MSc
1985-present	65	38	16	28.73	9.32	99.99	99.98
1992-present	53	28	10	23.14	8.31	99.99	98.89

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 15(!) failures-to-predict in a row.

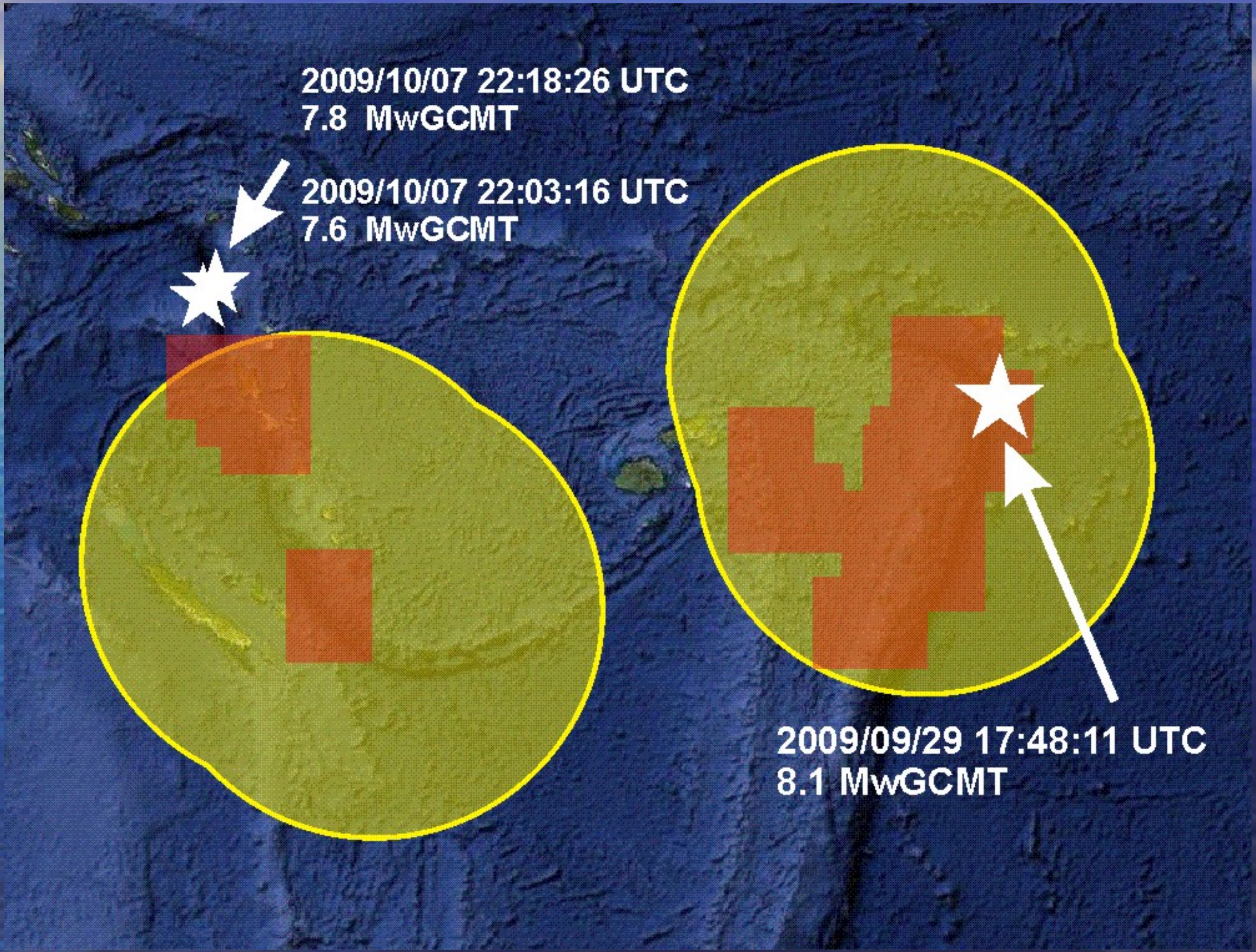
Real-time prediction of the world largest earthquakes

(http://www.mitp.ru)

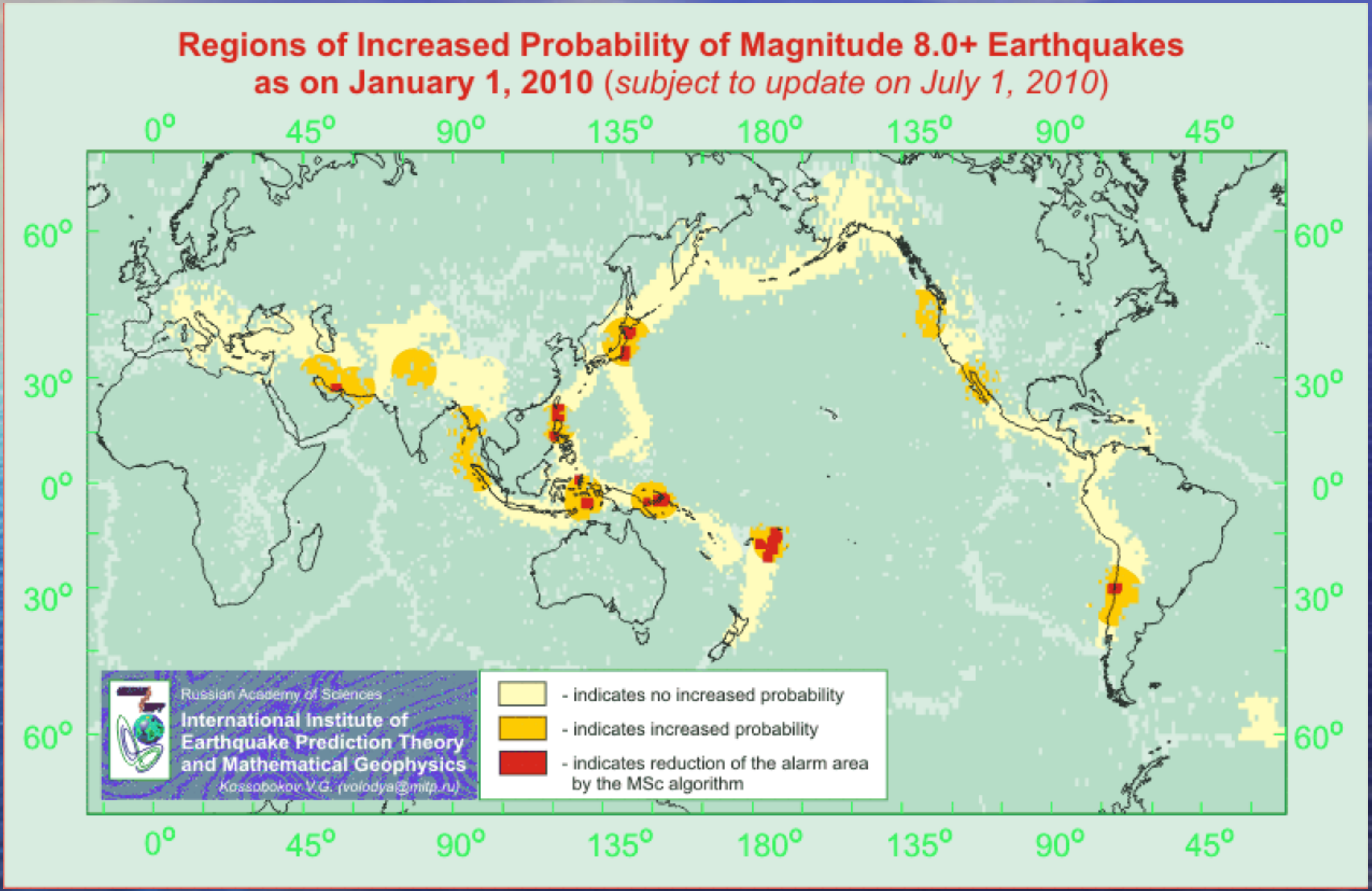


Real-time prediction of the world largest earthquakes

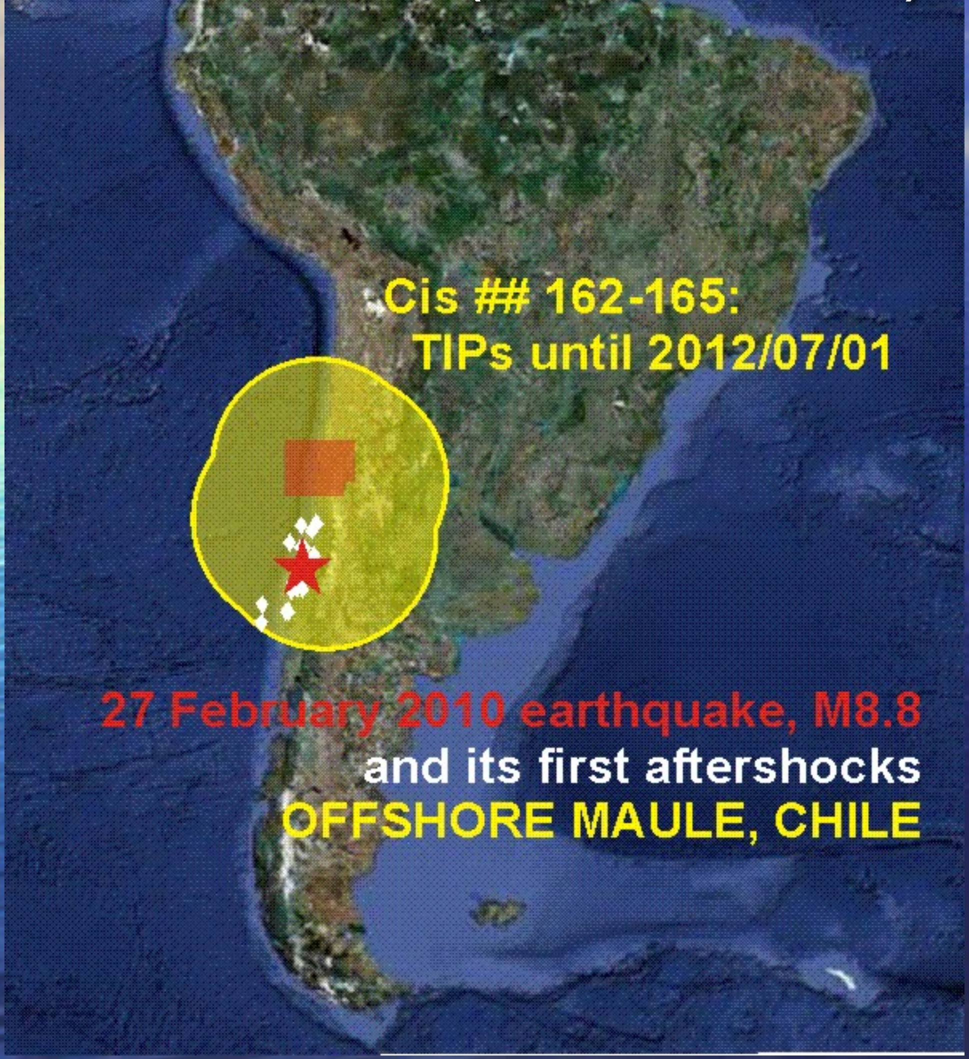
(http://www.mitp.ru)



Real-time prediction of the world largest earthquakes
(http://www.mitp.ru)



Real-time prediction of the world largest earthquakes (http://www.mitp.ru): Magnitude 8.0+.

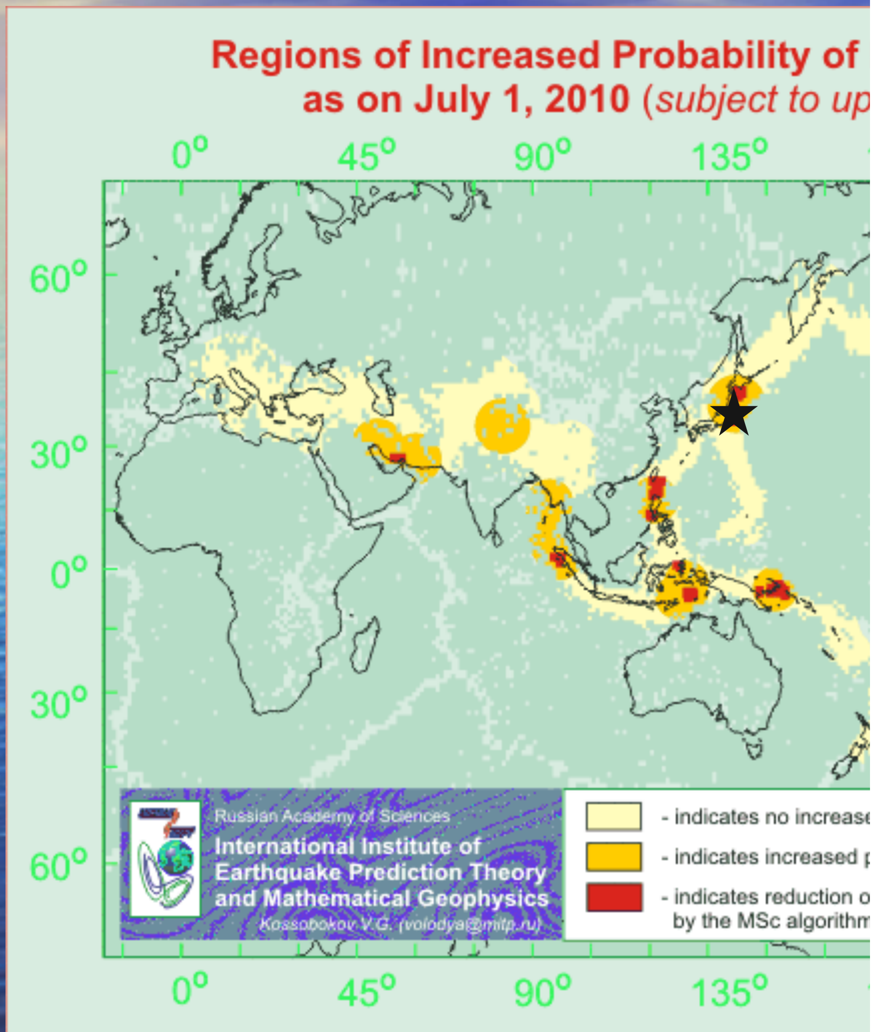


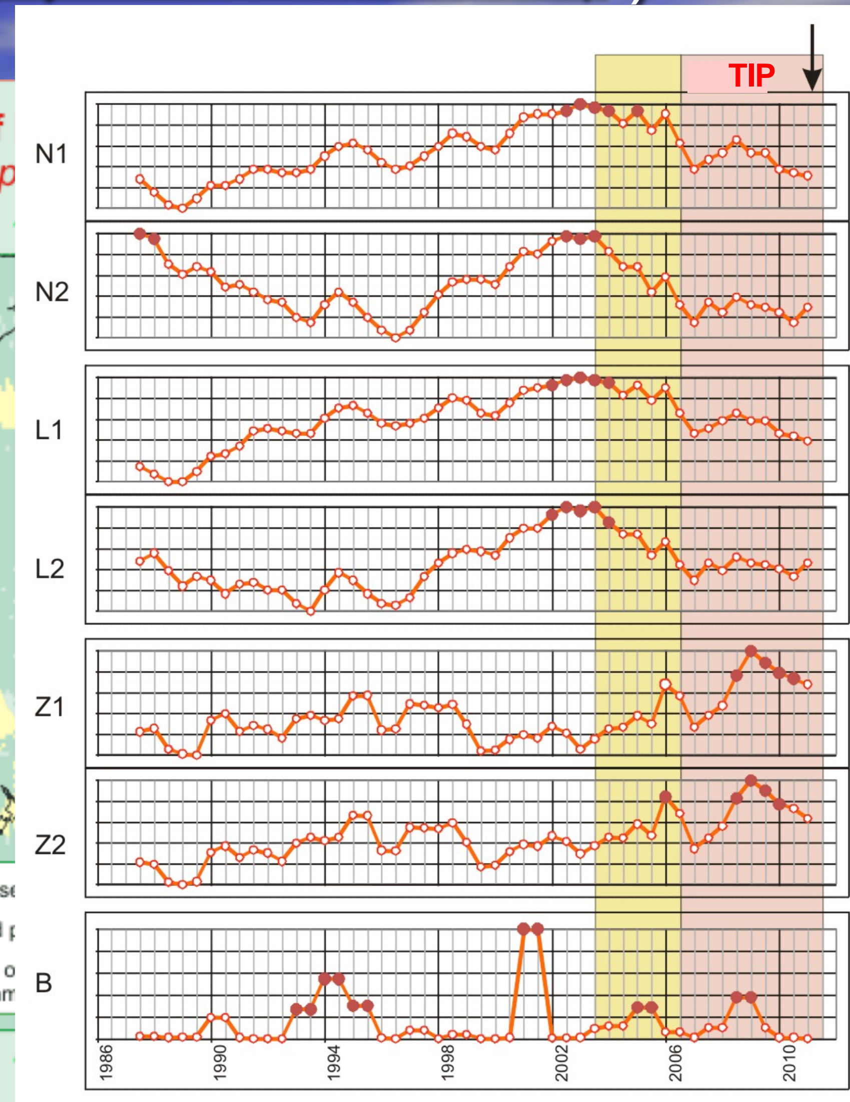
The 27 February 2010 mega-earthquake OFFSHORE MAULE, CHILE has ruptured the 600-km portion of the South American subduction zone, which was recognized (yellow outline) as capable of producing a magnitude M8.0+ event before mid-2012 in the regular 2010a Update. The earthquake epicenter missed the reduced area of alarm (red outline) diagnosed in the second approximation by algorithm MSc.

The failure of MSc algorithm is somewhat natural, taking into account the linear extent of the event, which is about a half of the area alerted in the first approximation.

Real-time prediction of the world largest earthquakes

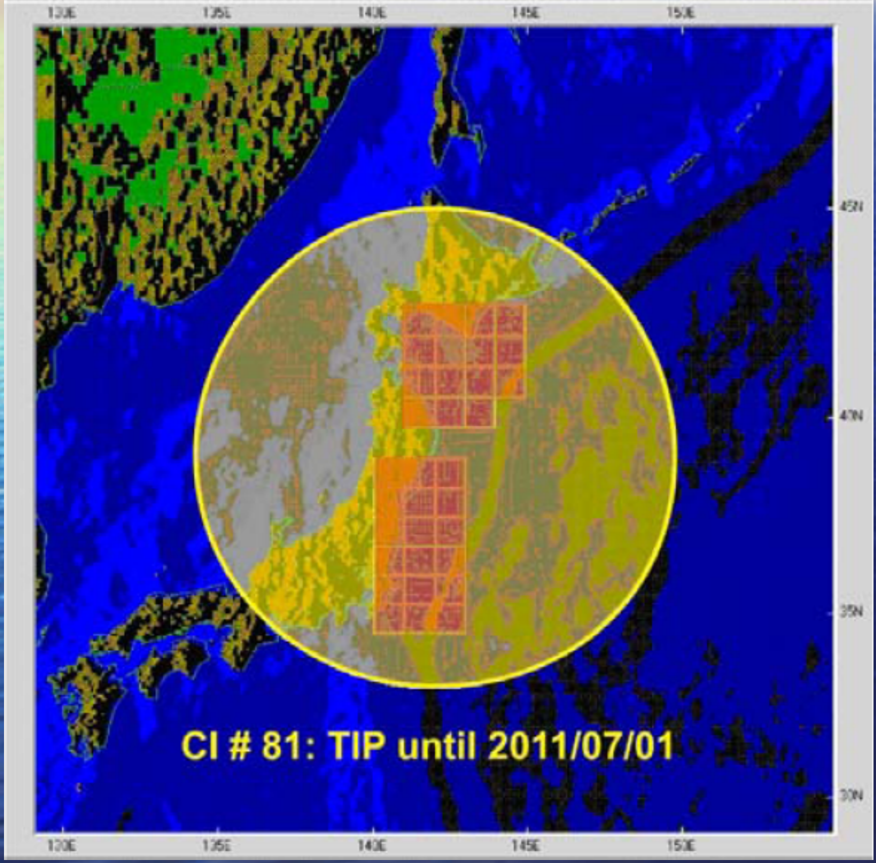
(http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp)

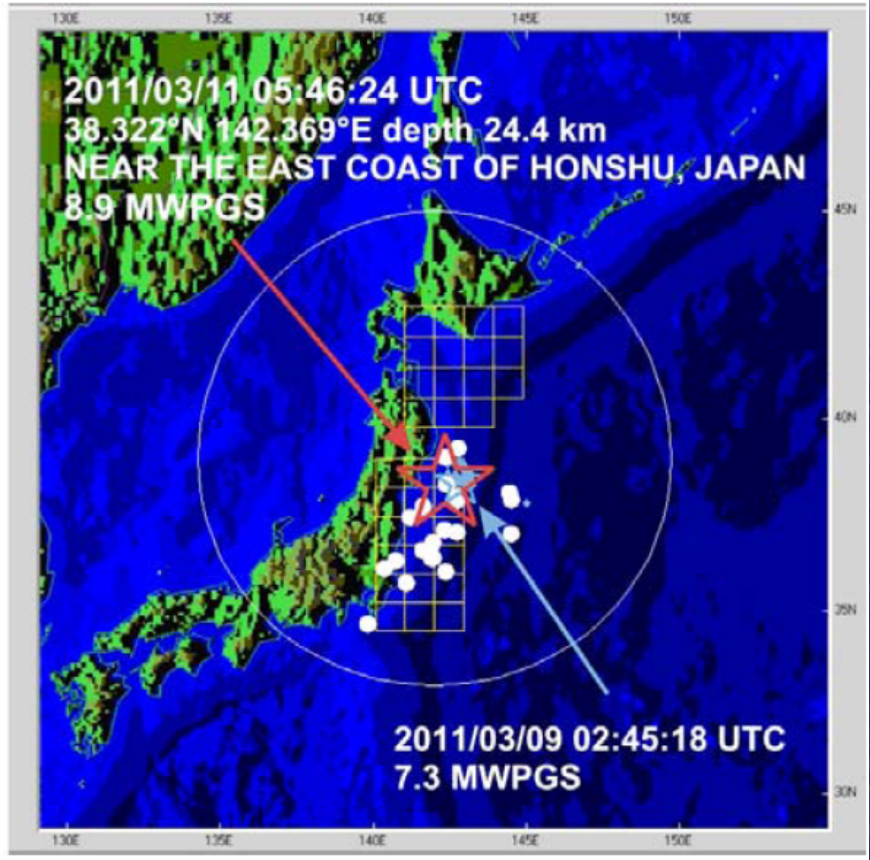




Real-time prediction of the world largest earthquakes
(http://www.mitp.ru)

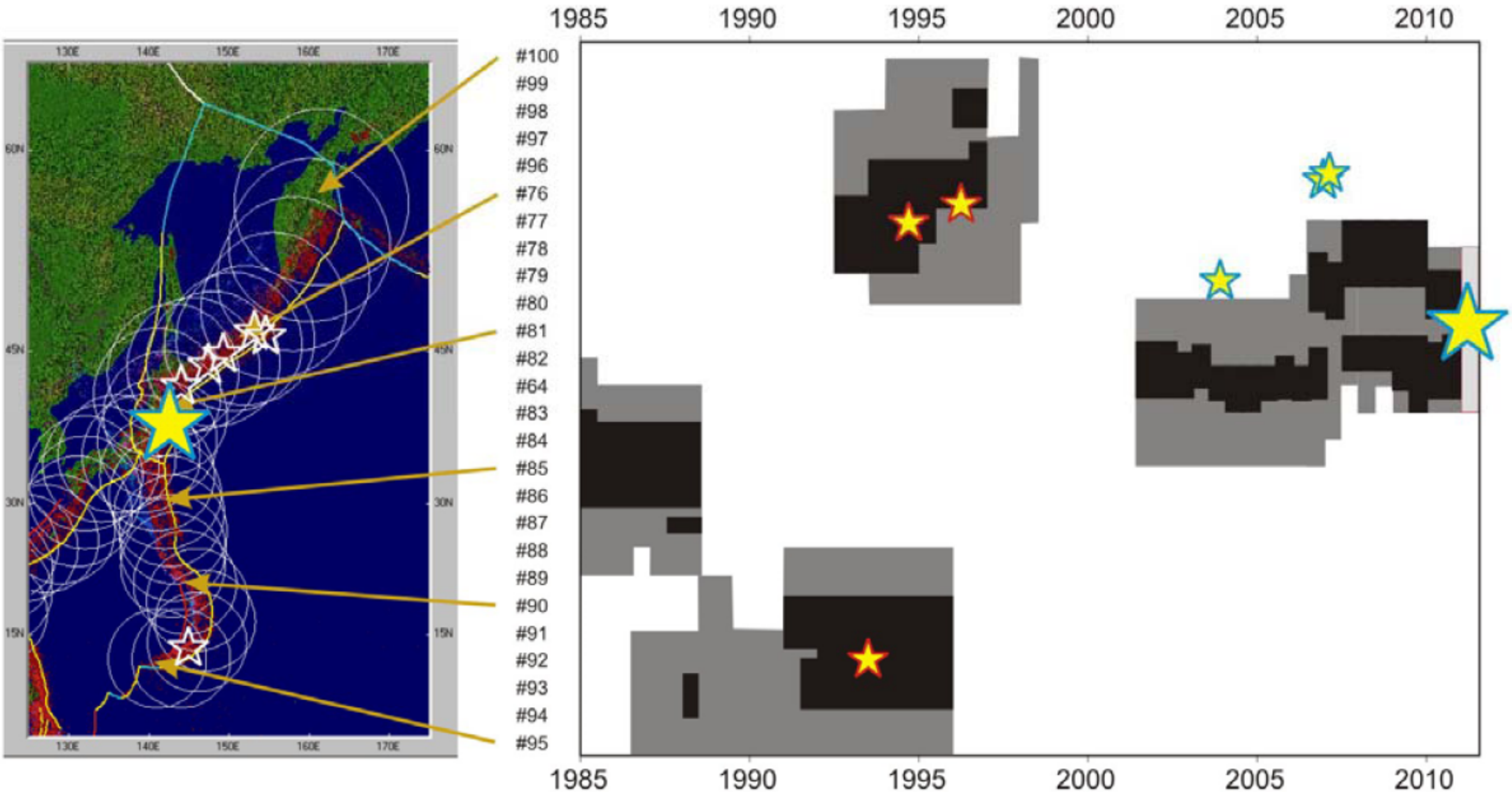
The 11 March 2011 MwGCMT 9.0 Tōhoku mega-thrust – the 2011 Great East Japan Earthquake





Space-time history of M8-MSc predictions in West Pacific

Space Time



ГЕОФИЗИЧЕСКИЕ ПРОЦЕССЫ И БИОСФЕРА, 2011, Т. 10, № 2, с. 5–21

ARE MEGA EARTHQUAKES PREDICTABLE?

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Abstract. In the course of the ongoing since 1992 Global Test of the intermediate-term middle-range earthquake forecast/predictions by the algorithms M8 and MSc place and time of each of the mega-earthquakes of 27 February 2010 in Chile and 11 March 2011 in Japan were recognized as in state of increased probability of such events in advance their occurrences. In conjunction with a retrospective analysis of seismic activity preceding the first of a series of mega earthquakes of the 21st century, i.e. 26 December 2004 in the Indian Ocean, these evidences give grounds for assuming that the algorithms of proven validated effectiveness in magnitude ranges *M*7.5+ and *M*8.0+ can be applied to predict the mega-earthquakes as well.

Keywords: earthquake, mega earthquake, forecast, prediction, algorithm, statistical hypothesis testing, random guessing, confidence level.

First conclusions on predictability of mega-earthquakes reported in 2005:

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

Kossobokov, V.G., 2005. 26 December 2004 Greatest Asian Quake: When to expect the next one? *Statement at Special Session on the Indian Ocean Disaster: risk reduction for a safer future*. UN World Conference on Disaster Reduction, 18-22 January 2005, Kobe, Hyogo, JAPAN.

Further confirmations expected…

Conclusions – The Four Paradigms

Statistical validity of predictions demonstrated in two decades of rigorous testing 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

(Keilis-Borok, Gabrielov, and Soloviev, 2009;
Keilis-Borok,Soloviev, and Lichtman, 2009).

Conclusions – Seismic Roulette is not perfect

- The accuracy of the M8-MSc predictions 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.

General Conclusions

Based on the recent, enormous progress in real-time retrieval and monitoring of distributed multitude of geophysical data -

- Contemporary Science can do a better job in disclosing Natural **Hazards**, assessing **Risks**, and delivering such info in advance catastrophic events.
- Geoscientists must initiate shifting the minds of community from pessimistic disbelieve to optimistic challenging issues of **Hazard Predictability**

Thank you!