Earthquake Prediction: Basics, Achievements, Perspectives

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ABSTRACT: The recent scientific advances in understanding the hierarchical nature of the lithosphere and its dynamics based on systematic monitoring and evidence of its space-energy similarity at global, regional, and local scales did result the design of reproducible intermediate-term middle-range earthquake prediction technique. The real-time experimental testing aimed at prediction of the largest earthquakes worldwide from 1992 to the present proved statistically a possibility of practical earthquake forecasting although of limited precision. In the first approximation, an accuracy of 1-5 years and 5-10 times the anticipated source dimension is achieved. Further analysis of seismic dynamics allows reducing the spatial uncertainty down to 1-3 source dimensions, although at the cost of additional failures-to-predict. Despite of limited accuracy a considerable damage could be prevented by timely knowledgeable use of the existing predictions and earthquake prediction strategies. The link of theoretical research in modeling earthquake sequences in frames of statistical physics on the one hand and instrumental and algorithm developments on the other hand help developing a new generation of earthquake prediction technique of higher accuracy.

KEYWORDS: Earthquake prediction; dynamical system; hypotheses testing; statistical significance and confidence levels.

1. INTRODUCTION

The extreme catastrophic nature of earthquakes is known for centuries due to resulted devastation in many of them. The vulnerability of the world civilization to disastrous earthquakes keeps increasing rapidly. The direct economic loss in a single event proved surpassing the level of $100,000,000,000. This happened as a result of an earthquake in 1995 Kobe, Japan that was not the largest possible in the region. A repetition of the 1923 Tokyo earthquake is capable of provoking a global economy crisis in addition to unprecedented humanitarian losses. Surely, earthquakes are not the only source of major disasters; however, the six of them (and apparently far from the great ones) are listed among the 20 largest catastrophes of the last decade of the 20th century. That is why earthquake prediction is widely recognized as one of the global challenging problems facing the mankind in the 21st century.

The abruptness along with apparent irregularity and infrequency of earthquake occurrences facilitate formation of a common perception that earthquakes are random unpredictable phenomena. The challenging questions remain pressing: What happens during an earthquake? How to size earthquakes? Why, Where and When do earthquakes occur? The basic difficulty in answering these questions comes from the fact that no earthquake has been ever observed directly. Therefore, the most important tasks in studying earthquakes at present is obtaining observational constrains from systematic analysis of the geologic, geodetic, gravity, heat-flow, petrochemical, geomagnetic, seismic and other data available and linking them together in plausible models and interpretations.

It would be misleading to pretend that the state-of-the-art Physics of earthquakes is a well-developed branch of Science, which deserves including into school programs and textbooks (although a basic knowledge about earthquakes in seismic regions, in particular, help avoiding losses of life and reduce physical damage). To the contrary most of Seismologists clearly understand the pioneering and, therefore, juvenile nature of the present day physical problems related to earthquakes (*Kanamori, Brodsky, 2001*). The mature wisdom of any science is determined by its ability to predict phenomena in study. This paper intends to outline what can be predicted about a "ground shaking" and to discuss the limits of such predictions in advance of a target earthquake.

2. WHAT ARE EARTHQUAKES AND HOW TO SIZE THEM?

Fracturing of the Earth's crust that radiate seismic waves and cause ground shaking produces earthquakes. A ground shaking caused by other than tectonic sources (e.g., by an explosion) is disregarded here as an earthquake although these may be the basis for important studies and experiments providing conclusions about the Earth structure. Some historical records on earthquakes are known from 2100 B.C. However, most of them before the middle of the 18th century are generally lacking description or are not reliable.

There were many earthquakes during the East Han Dynasty (206 BC – 220 AD) in China, so Zhang Heng (AD 78-139), also known as Pingzi, a mathematician and an astronomer who was responsible for observing natural phenomena, managing national documents and editing national history at the imperial court, invented the first machine that was able to detect the direction of earthquakes. The ornamental vessel of cast bronze, consisting of dragons facing outward in a circle, was designed so that any seismic tremor would cause the ball to fall from the jaws of the dragon facing the direction of the tremor. The earthquake detector was earlier than the one made by Europeans by 1700 years.

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

It was only in the 1930's when Charles F. Richter, a California seismologist, introduced the concept of earthquake magnitude. His original definition held only for California earthquakes occurring within 600 km of a particular type of seismograph (the Woods-Anderson torsion instrument). Richter's original magnitude scale (ML) was then extended to observations of earthquakes of any distance and of focal depths ranging between 0 and 700 km (*Lay, Wallace, 1995*). There are many magnitude scales, which are another source of a controversy about earthquakes. Because earthquakes excite both body waves, which travel into and through the Earth, and surface waves, which are constrained to follow the Earth's uppermost layers, two basic magnitude scales evolved - the mb and MS. There is a belief, that a novel extension of the magnitude scale, known as *moment magnitude*, or M_W, is more uniformly applicable and gives, for very large earthquakes the most reliable estimate of earthquake size. Indeed, the seismic moment is related to fundamental parameters of the faulting process

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

where μ is the shear strength of the faulted rock, S is the area of the fault, and $\langle d\rangle$ is the average displacement on the fault. However, these parameters are determined from waveform analysis of seismograms, which parameters have the same uncertainties that are used for determinations of magnitudes from multiple stations. Therefore, the magnitude scale M_W is hardly a universally better estimate of the earthquake size.

3. THE UNIFIED SCALING LAW FOR EARTHQUAKES

Despite multiple uncertainties in determination of earthquake parameters some relations between them are beyond any doubt. One of such is so-called Gutenberg-Richter frequency-magnitude relation (*Gutenberg, Richter, 1954*): Averaged over a large space-time volume the number of earthquakes equal or above certain magnitude, $N(M)$ scales as

$$\log_{10} N(M) = a + b\times(8 - M),$$

where, for M being MS scale magnitude, constant b is generally in the range $0.8 < b < 1.2$ (*Frohlich, Davis, 1993*) but varies from region to region. The constant a is a measure of the regional level of seismic activity. This law seems universal in the realm of multiple fracturing, where it is observed in a broad variety of conditions from laboratory samples of solid materials through geo-technical and engineering constructions to the lithosphere of the Earth (*Barenblatt, 1982, 1996; Turcotte, 1995*) and, perhaps, to extreme energies of "starquakes" (*Kossobokov, Keilis-Borok, Cheng, 2000*). Observations favor also the hypothesis that smaller earthquakes in moderate-sized regions occur at rates that are only weakly dependent on time. Thus, the rate of occurrence of smaller earthquakes can be extrapolated to assess the hazard of larger earthquakes in a region.

Apparently, the Gutenberg-Richter relationship 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. Further investigation of the problem permits to suggest a generalization (*Kossobokov, Mazhkenov, 1988, 1994; Bak et al., 2002; Corral, 2003*) –

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

where $N = N(M, L)$ is the expected annual number of earthquakes with magnitude M in an area of linear dimension L; A and B are similar to a and b, while C estimates fractal dimension of earthquake prone faults. Such a Unified Scaling Law for Earthquakes states that the distribution of rates or waiting times between earthquakes depends only on the local value of the control parameter $10^{-BM}\cdot L^{C}$, which represents the average number of earthquakes per unit time, with magnitude greater than M occurring in the area size $L \times L$.

Thus, for a wide range of seismic activity, A, the balance between magnitude ranges, B, varies mainly from 0.6 to 1.1, while the fractal dimension, C, changes from under 1 to above 1.4 (*Nekrasova, Kossobokov, 2002, 2003*). Apparently an estimate of earthquake recurrence per square km depends on the size of the territory that is used for averaging and may differ from the real one dramatically when rescaled in traditional way to the area of interest. Thus, the Unified Scaling Law for Earthquakes has serious implications for assessment of seismic hazard, risk, and earthquake prediction, in particular.

4. WHERE EARTHQUAKES OCCUR?

The global distribution of hypocenters displays clearly a high level of the spatial predictability of earthquakes, which show the evident earthquake-prone pattern of the Earth, observed on a global scale. The plate-tectonics hypothesis explains its stability as basic concentration of earthquakes at plate boundaries, although a significant numbers of earthquakes occur within plate interiors. The Earth's crust is extremely complex and faults and earthquakes in a region occur on a wide range of scale. There is considerable evidence that faults and earthquakes interact on a range of scales, from thousands of kilometers to millimeters or less.

The lithosphere of the Earth is structured in a hierarchy of volumes of different size, from about ten major tectonic plates to about 10^{25} grains of rock (*Keilis-Borok, 1990*). The movement of these volumes relative to each other against the forces of friction and cohesion is realized to a large extent through earthquakes. The movement is controlled by a wide variety of processes, concentrated around the fractal mesh of thin boundary zones that separate volumes. In its turn, a boundary zone is a volume that has similar hierarchical structure, consisting of smaller volumes separated boundary zones, etc. Altogether, this hierarchy of movable volumes and processes compose the lithosphere into a large complex non-linear dynamical system. It is evident that prediction of such a system in a sense of extrapolation of the trajectory into the future is not possible due to its complexity, deterministic chaos and strong instabilities in the phase space. However, upon coarse-graining the integral mesoscale, empirical regularities emerge opening possibilities of prediction in a sense of verifiable statement about the phenomenon (e.g., “Undergraduates find *Lorenz* (1963) model predictable” by *Evans et al.* (2003) is a nice illustration of how simple forecasting rules deliver an effective guessing of “Hot” or “Cold” regimes in a classic system with deterministic chaos and strange attractor). This approach led to new paradigms and, on the practical side, created algorithms to predict most of the greatest earthquakes (*Kossobokov et al., 1999*).

5. LONG-TERM SEISMIC STABILITY

Figure 1 shows the annual number of earthquakes from the NEIC Global Hypocenters Data Base and its updates through the 20th century. This frequency-magnitude graph demonstrates temporal variations of the global seismic activity. One can observe several "historic changes" of which the most dramatic reflects deployment of the World Wide Seismic Standard Seismograph Network in 1963. From a statistical viewpoint, since about that time the catalog appears to be surprisingly consistent in reporting magnitude 5.0 and above earthquakes: In logarithmic scale, the magnitude bands have almost the same width in agreement with the Gutenberg-Richter relationship. One can see also that the list of earthquakes above 7.0 in the NEIC GHDB is probably complete from the beginning of the century. Such a remarkable stability of the annual number of earthquakes suggests the global underlying processes rather stationary in the time scale of decades and encourages research aimed at prediction of earthquakes.

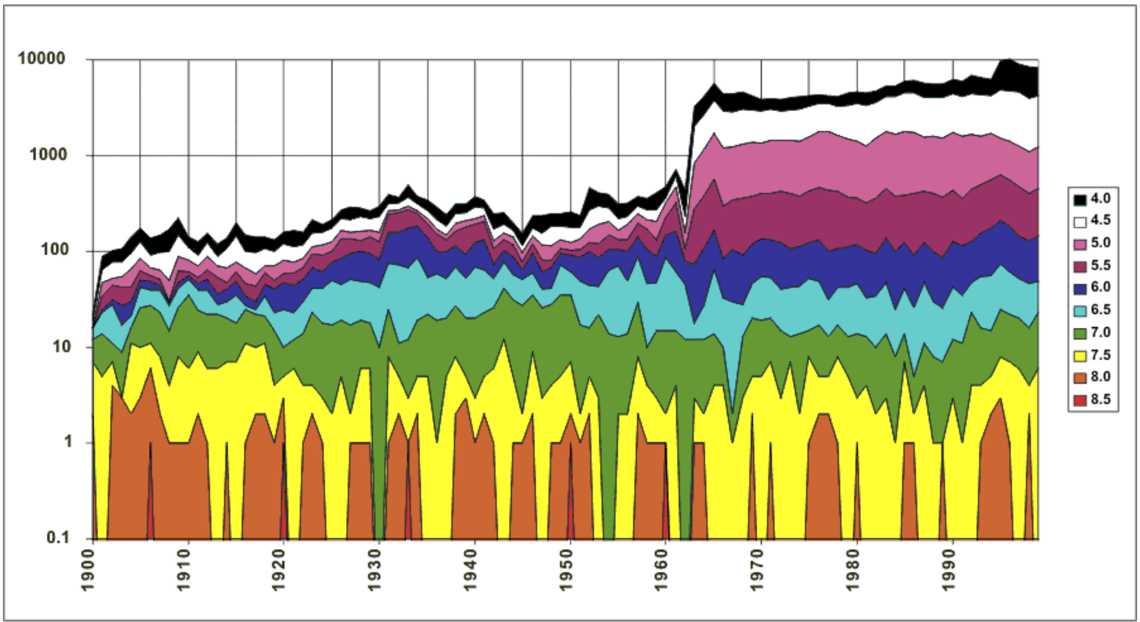

Figure 1. Annual number of earthquakes recorded in the 20th century (according to the NEIC/US GS Global Hypocenter Data Base)

While Figure 1 predicts the annual number of magnitude 6 or larger earthquakes in the range from 90 to 200, the global map of epicenters displays clearly a high level of the spatial self-organization of earthquakes. Together with the global distributions of the A, B and C of the Unified Scaling Law they provide simple tools to produce global maps of seismic hazard. However, when looking into a single seismic location we observe high variability of rates and intermittent switching from steady state recurrence to bursting activity. Such intermittence is usually attributed to the occurrence of larger earthquakes, but in some cases it is observed also in the absence of one dominating event, e.g., during seismic swarms. The local variability of seismic sequences is the key to the gates of earthquake prediction. Case histories of the most recent great earthquakes evidence consecutive stages of inverse cascading of seismic activity, within long-, intermediate-, and short-term scales at distances of up to 10 or more times larger than their sources dimension (*Romashkova, Kossobokov, 2001*). Presumably a blurry inverse cascading reflects coalescence of instabilities at the approach of a catastrophe, whereas a clear direct cascading of aftershocks indicates complex stage of readjustments in the system within the area affected by a great earthquake (*Gabrielov, Newman, Turcotte, 1999*).

6. ARE EARTHQUAKES PREDICTABLE?

The temporal predictability of large earthquake occurrences requires a special comment on the recently revived discussions (*Geller et al., 1997; Wyss, 1997a; Nature, 1999*). No current theory of dynamics of seismic activity can answer this question. Inevitably, a negative statement that asserts a non-trivial limitation on predictability is merely a conjecture. On the other hand, forward testing of a reproducible prediction method and, so far, in no other way, can unequivocally establish a certain degree of predictability of earthquakes. The results of the on-going real-time monitoring of the global seismic activity aimed at intermediate-term middle-range prediction of the largest earthquakes (http://www.mitp.ru) has proved (*Kossobokov et al., 1999; Kossobokov, Shebalin, 2003*) the high statistical significance of the two methods, algorithms M8 (*Keilis-Borok, Kossobokov, 1990*) and MSc (*Kossobokov, Keilis-Borok, Smith, 1990*), described below, did confirm a positive statement on predictability of earthquakes (despite dramatic changes both in seismicity and in compilation of the earthquake catalog during the test period). Furthermore, it appears that inverse cascading of seismic activity to a catastrophe evolves through long-, intermediate-, short-, immediate-term and even nucleation (*Ellsworth, Beroza, 1995*) phases.

Let us clarify *what is earthquake prediction*? The United States National Research Council, Panel on Earthquake Prediction of the Committee on Seismology suggested the following consensus definition (*Allen et al., 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."

It is notable that most of so-called precursors that flourish in the realm of publications on earthquake forecasting do not qualify as predictions (*Wyss, 1991, 1997b*). For example, according to this definition one the most developed and daily updated Short-term forecasts for NW and SW Pacific (http://scec.ess.ucla.edu/~ykagan/predictions_index.html; *Kagan, Jackson, 2000*) cannot be a non-trivial prediction unless one specifies the probability threshold outlining the geographical areas of prediction. Moreover, an independent evaluation of the predictions arising from setting a threshold probability or a threshold probability ratio on top the daily forecasts has shown that in either case the effectiveness of prediction is hardly better than random guessing, even when predicted aftershock is regarded as success (*Kossobokov, 2003*).

Rethinking Earthquake Prediction, Lynn Sykes et al. (1999) write:

> "The public perception in many countries and, in fact, that of many earth scientists is that earthquake prediction means short-term prediction, a warning of hours to days. They typically equate a successful prediction with one that is 100% reliable. This is in the classical tradition of the oracle. Expectations and preparations to make a short-term prediction of a great earthquake in the Tokai region of Japan have this flavor. We ask instead are there any time, spatial and physical characteristics inherent in the earthquake process that might lead to other modes of prediction and what steps might be taken in response to such predictions to reduce losses?"

Following common perception many investigators usually overlook as well spatial modes of predictions and concentrate their efforts on predicting the "exact" fault segment to rupture (e.g., the Parkfield earthquake prediction experiment), which is by far a more difficult and might be an unsolvable problem. Being related to the rupture size $L = L(M)$ of the incipient earthquake of magnitude M, such modes could be summarized in a classification of location of a source zone from a wider prediction ranges (Table 1).

From a viewpoint of such a classification, the earthquake prediction problem is naturally approached by a hierarchical, step-by-step prediction technique, which accounts for multi-scale escalation of seismic activity to the main rupture (*Keilis-Borok, 1990*). Table 1 disregards termless predictions although identification of earthquake-prone areas, e.g., by pattern recognition methods (*Gorshkov, Kossobokov, Soloviev, 2003*), deliver a zero-approximation for a target earthquake location. Moreover, the Gutenberg-Richter law suggests limiting magnitude range of prediction to about one unit. Otherwise, the real-data statistics would be related to dominating smallest earthquakes and, therefore, attributing it to larger events may become misleading.

Table 1. Classification of earthquake predictions

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

Citing Christopher Scholz (*1997*):

> "Predicting earthquakes is as easy as one-two-three. Step 1: Deploy your precursor detection instruments at the site of the coming earthquake. Step 2: Detect and recognize the precursors. Step 3: Get all your colleagues to agree and then publicly predict the earthquake through approved channels."

No need to explain that some "precursor detection instruments" are already deployed worldwide, e.g., routine seismological observations are compiled into data bases such as the US GS/NEIC Global Hypocenter Data Base, and their record available for general use. Some "precursors" are already detected, e.g. reproducible intermediate-term algorithms such as the M8 and MSc algorithms (*Keilis-Borok, Kossobokov, 1990*; *Kossobokov, Keilis-Borok, Smith, 1990*). And, finally, some earthquakes were already "publicly predicted" (*Keilis-Borok et al., 1990; Harris, 1998*).

The on-going real-time monitoring of the global seismic activity aimed at intermediate-term middle-range prediction of the largest earthquakes has a long history now (*Healy, Kossobokov, Dewey, 1992; Kossobokov et al., 1999*). Several largest earthquakes were predicted and some were missed. Table 2 gives the up-to-date summary of the prediction outcomes for magnitude 8.0 or more earthquakes.

Table 2. Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 8.0 or more.

Test period	Large earthquakes			Percentage of alarms		Confidence level, %	
	Predicted by		Total				
	M8	M8-MSc		M8	M8-MSc	M8	M8-MSc
1985-2003	9	7	11	34.9	18.0	99.80	99.90
1992-2003	7	5	9	30.2	15.3	99.55	99.39

It is notable that to drive the achieved confidence level below 95%, the real-time monitoring should encounter four failures-to-predict in a row, which seems unlikely. The results require special comments since the estimates presented in Table 2 use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters (measure μ described below).

7. HOW TO MEASURE SPACE OCCUPIED BY SEISMIC ACTIVITY?

Are the results of the prediction experiment "good" or not? A statistical conclusion about that could be attributed in the following general way:

Let **T** and **S** be the total time and territory considered; A_t is the territory covered by the alarms at time t; $\tau\times\mu$ is a measure on $\mathbf{T}\times\mathbf{S}$ (we consider here a direct product measure $\tau\times\mu$ reserving a general case of a time-space dependent measure ν for future more sophisticated null-hypotheses); **N** counts the total number of large earthquakes with $M \geq M_0$ within $\mathbf{T}\times\mathbf{S}$ 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

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

By common definition the *statistical significance level* of the prediction results equals

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

where B is the cumulative binomial distribution function. The smaller is the significance level α, the larger is the *confidence level* $1-\alpha$ and the higher is the significance of the predictions under testing.

When testing temporal predictability of earthquakes it is natural to make the following choice of the product measure $\tau\times\mu$: Take the uniform measure τ, which corresponds to the Poisson, random recurrence of earthquakes and the measure μ proportional to spatial density of epicenters. Specifically, determine the measure μ of an area proportional to the number of epicenters of earthquakes from a sample catalog, for example, earthquakes above certain magnitude cutoff M_c. This empirical spatial measure of seismic distribution is by far more adequate than the literal measure of territory in km^2 for estimating statistical significance of the prediction results (the last one equalizes the areas of high and low seismic activity, at the extreme, the areas where earthquake happen and do not happen).

8. SEISMIC ROULETTE

The actual, empirical distribution of earthquake locations is the best present day knowledge estimate of where earthquakes may occur. The recipe of using μ-measure and counting $\boldsymbol{p}$ is the following: Choose a sample catalog. Count how many events from the catalog are inside the territory considered; this will be your denominator. At a given time, count how many events from the catalog are inside the area of alarm; this will be your numerator. Integrate the ratio over the time of prediction experiment. This is the exact way of computing Percentage of alarms and Confidence level in Table 2. (The sample catalog includes all earthquakes of magnitude 4 or larger from the NEIC *Global Hypocenter's Data Base* in 1963-1984.)

This simple recipe has a nice analogy that justifies using statistical tools available since Blaise Pascal (1623-1662). 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 you can win and lose systematically. In this case, if you are smart enough so that your predictions are effective, the first will outscore the second! The results of the global test of the prediction algorithms M8 and MSc did confirm such an "imperfection" of Nature (*Kossobokov et al., 1999;* Table 2) in recurrence of great earthquakes.

9. WHAT STANDS BEHIND M8 AND MSC?

Both are reproducible earthquake prediction methods that satisfy the consensus definition (*Allen et al., 1976*) and make use of seismic activity reported in routine seismic catalogs. The M8 is applied first. It scans the territory in question for the areas in alarm (Figure 2), so-called Time of Increased Probability (TIP). The MSc is applied to reduce the area of alarm by analyzing dynamics at lower magnitude levels of seismic hierarchy. Sometimes, the data is enough to get a near-perfect outline of the incipient large earthquake. More often the catalog of earthquakes is exhausted already at the M8 analysis and the prediction remains in the medium range.

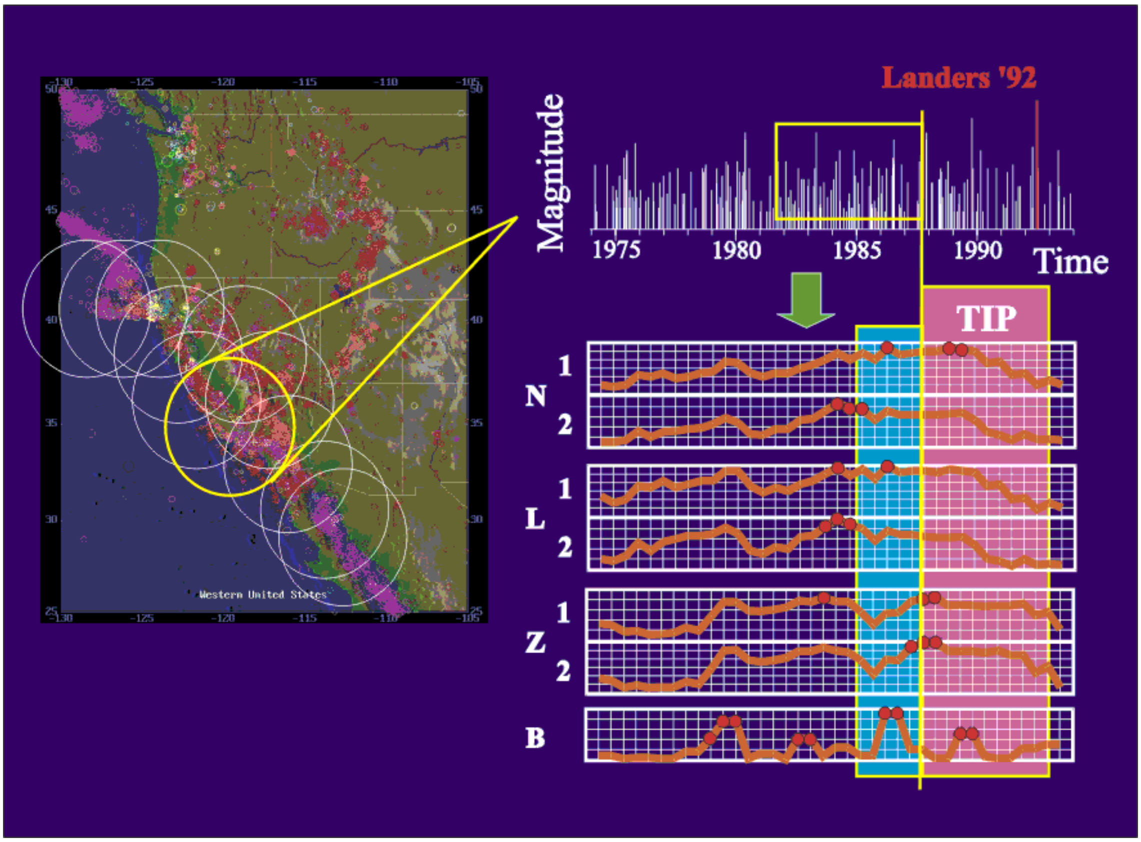

Figure 2. General scheme of applying reproducible earthquake-prediction algorithm: Areas of investigation overlay seismic region; seismic sequences in each area gives reproducible description of the present state, which is then used to diagnose an alert, so-called *time of increased probability*, *TIP*.

The M8 intermediate-term earthquake prediction algorithm 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, Kossobokov, 1984*) and the original version (*Keilis-Borok, Kossobokov, 1987*) were tested retroactively at recorded epicenters of earthquakes of magnitude 8.0 or greater from 1857-1983. The algorithm M8 uses traditional description of a dynamical system (Figure 3) adding to a common phase space of rate (i.e. number of mainshocks, *N*) and rate differential (i.e., deviation of *N* from a longer-term average, *L*) the dimensionless concentration (i.e., the average source size divided by the average distance between sources, *Z*) and a characteristic measure of clustering (i.e., maximum number of aftershocks, *B*). The Unified Scaling Law for Earthquakes implies re-normalization of the algorithm parameters for applications aimed at magnitude ranges lower than M8.0+. Furthermore, the analysis of seismic activity in one region may distinguish a number of magnitude ranges and deliver a hierarchy of predictions (*Keilis-Borok, Kossobokov, 1990a*).

The algorithm recognizes criterion (Figure 3), 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 effective provision of a catastrophic event. The exact definitions and computer code of the M8 algorithm are published (*Keilis-Borok, Kossobokov, 1990; Healy, Kossobokov, Dewey, 1992; Kossobokov, 1997*).

Retrospectively the standard version of the algorithm (*Keilis-Borok, Kossobokov, 1990*) was applied to predict earthquakes with magnitudes from above 8.0 to 4.9 in a number of regions worldwide. Its modified versions apply also in regions of seismic activity lower than required by the original version (*Bhatia et al., 1989; Kossobokov, Rastogi, Gaur, 1989; Latoussakis, Kossobokov, 1990; Gahalaut et al., 1992; Romachkova et al., 1998*).

The second approximation prediction method MSc (*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. Qualitatively, the MSc algorithm outlines such an area of the territory of the first approximation alarm where seismic activity is continuously high from the beginning of precursory inverse cascade and is infrequently interrupted for a short time. Such an interruption 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. MSc outperforms at least by a factor of 2 a few simple alternatives in reduction of territorial uncertainty of the M8 predictions, i.e. earthquake-prone cells and the most active of them that contain certain part of the recent seismic activity (*Kossobokov, Keilis-Borok, Smith, 1990*)

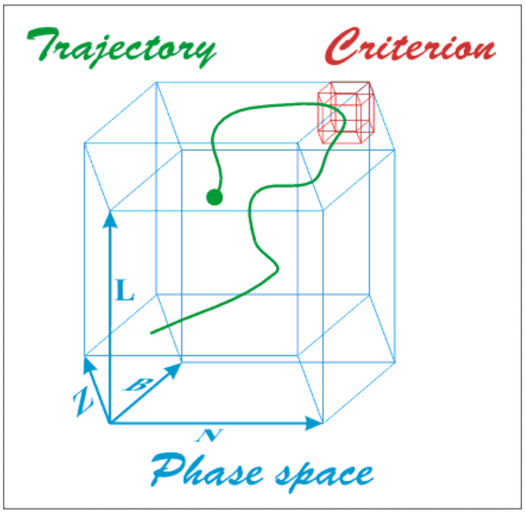

Figure 3. The trajectory describing an area of investigation in the phase space (4D-cube). A criterion is a part of the phase space so that an entry of the trajectory into it indicates abnormal behavior of the system. The M8 algorithm determines a TIP after the parameters of description – N, L, Z, B – show up extremely large values, i.e., after the trajectory enters the M8 algorithm criterion, smaller 4D-cube of the top values of parameters.

10. GLOBAL TESTING OF THE ALGORITHMS M8 AND MSC

After successful prediction of the Loma Prieta 1989 earthquake J. H. Healy, V. G. Kossobokov, and J. W. Dewey designed a rigid test to evaluate the M8 algorithm (*Healy, Kossobokov, Dewey, 1992*). Since 1991 each half-year the algorithm has been applied in a real time prediction mode to monitor seismic dynamics of the entire Circum Pacific (that is the reason for distinguishing the two periods of testing in Table 2: since the design of the algorithm in 1985, and since the formal publication of the settings for global monitoring in 1992). More extended testing, for all seismically active territories on Earth where seismic data is enough to run the standard version of algorithm M8 was carried on in parallel (*Kossobokov et al., 1992, 1999; Kossobokov, Khokhlov, 1993*). Unfortunately, testing in seismic regions of the FSU aimed mostly at M6.5+ earthquakes were discontinued due to the collapse of the state and its seismological structures.

Aimed at M8.0+ earthquakes the algorithms M8 and MSc were applied in 262 overlapping circles of investigation, of which 170 scan near-uniformly Circum-Pacific and its surroundings, 92 circles taken from Alpine-Himalayan Belt and Burma (25 in Mediterranean, 25 in Asia Minor and Iran, 28 in Pamirs-Hindukush, and 14 in Burma). These cover about 80-90% of the major seismic belts of the Earth. The complete set of predictions in 1985-2003 could be viewed at http://mitp.ru/predictions.html, although the access to those in progress is restricted. In general, the alarms last for about five years, but could expire before or extend beyond this limit under unusual local changes of seismic regime. The probability gain in confirmed predictions depends on locality and varies from 2-3 in regions of extremely high activity, like Tonga-Kermadek, to 20-100 in regions where recurrence of great earthquakes is much lower than average, like Southern Sumatra or Tibet.

Aimed at M7.5+ earthquakes the algorithms were applied in 180 circles, which in total cover about 75% of the major seismic belts. 147 of them represent seismic regions of Circum Pacific, while the remaining 33 ones compose of 15 from Mediterranean, 4 from Iran, 11 from Pamirs-Hindukush, and 3 from Burma. For where prediction is made, On average the M8 alarms cover 40% of the whole territory considered (in accordance with measure μ), while MSc reduces this area to 12%. Out of 43 earthquakes of magnitude 7.5 or higher in 1985-2003, the M8 algorithm predicted 27, and MSc provided a correct second approximation for 16 of them. That signifies confidence level above 99% for either of the algorithms. However, certain decay in performance is observed in the recent years: Since 1992 out of the total 31 earthquakes, 16 are predicted by M8 and 9 of them by MSc, which results only 87.2% and 98.8% confidence. (There are indications (*Kossobokov et al., 1999*) that most of the failures-to-predict occurred during the unusual rise of seismic energy release, have magnitude below 7¾ and are thrust or normal faulting. Moreover, starting form 1993 the NEIC changed the procedures of the global database compilation, substituting MS from Pasadena and Berkley with values of MW from Harvard and USGS. It is of common knowledge that, in general, Mw is larger than MS.)

11. ON TRANSITION TO SHORT-TERM PREDICTION

The recent case histories often indicate an anomalous activation within the middle-range alarm shortly before target earthquake. For example, remarkable seismic swarms preceded the 1986 Kermadek, 1994 Shikotan, 1995 Samoa, 1995 Iturup great earthquakes; notable large magnitude quakes happen in advance 1989 Macquarie, 1993 Guam, 1994 Bolivia, 2000 Sumatra great earthquakes. These phenomena were separated from the main event by periods ranging from days to 4 months (*Romashkova, Kossobokov, 2001*). Thus, the rise of seismic activity prior to the recent great earthquakes (of magnitude 8 or more) first observed in intermediate-term at large distances of M8 approximation, then in the most cases it concentrates in a smaller territory, down to the size of the source, then on the background of such intermediate-term rise, episodes of activity, like swarms or sequences of foreshocks could be identified as short-term forerunners of the Big Ones. We may hypothesize that premonitory rise of seismic activity evolves through long, intermediate, short, and immediate, or even nucleation phases. This is demonstrated for the long and intermediate phases and requires more data for being established at shorter ones.

The algorithms presented here make use of seismic activation and the growing correlation of earthquakes at the approach of the Big One. The predictions could be done on the basis of earthquake catalogs routinely available in the majority of seismic regions. With more complete catalogs, the areas of alarm may be substantially reduced in the second and, perhaps, further approximations at the cost of additional failures-to-predict. There are limitations in this performance. The areas covered by reliable alarms are large (especially in the first approximation), and many of them will inevitably expire without a strong earthquake. Nevertheless, considerable damage may be prevented by knowledgeable use of such predictions when their formulation is timely and specific.

The algorithms presented here are neither optimal nor unique. Together with other methods (*Keilis-Borok et al., 1988, Keilis-Borok, Rotwain, 1990; Vorobieva, 1999; Harte et al., 2003*, etc.) they hallmark a break-through in earthquake prediction from term-less assessment of seismic hazard to reliable intermediate-term alert of increased probability. The accuracy could be improved by a systematic monitoring of the alarm areas and by designing a new generation of earthquake prediction technique. The reproducible algorithms like “Seismic Reversal”, ROC, “Accord”, and “Chains” (*Shebalin, Keilis-Borok, 1999; Shebalin, Zaliapin, Keilis-Borok, 2000; Zaliapin, Keilis-Borok, Axen, 2002; Shebalin et al., 2003*) challenge this problem.

12. CONCLUSIONS

The achievements of pattern recognition in the design of reproducible algorithms predicting the large earthquakes and the verified statistical validity of predictions over the last decade, in particular, confirm 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
- The phenomena are universal being observed in other complex non-linear systems.

Seismic Roulette is not perfect. Therefore, the existing predictions could be used in a knowledgeable way to the benefit of population living in seismic regions. The methodology linking them to optimal strategies for disaster management exists and is rather developed (*Molchan, 1997, 2003*). The intermediate-term middle-range accuracy is quite enough for undertaking earthquake preparedness measures, which would prevent a considerable part of damage and human loss, although far from the total.

There is growing understanding expressed by Kofi Annan in the 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."

The predictions provide reliable empirical constrains for modeling earthquakes and earthquake sequences. The prediction results evidence that distributed seismic activity is a problem in statistical physics. They 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*).

Finally, the achieved experience in the straight forward practical approach to earthquake prediction problem provided a unique collection of successes and failures that permit their systematic analysis and further development of the methodology. Obviously, the progress in earthquake prediction research will require more data and, other than seismic, in particular, novel pioneering studies, and verification of arising hypotheses on correlations between the occurrence of extreme events and observable phenomena.

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