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Abstract. The Earth is a hierarchy of volumes of different size. Driven by planetary convection these volumes are involved into joint and relative movement. The movement is controlled by a wide variety of processes on and around the fractal mesh of boundary zones, and does produce earthquakes. This hierarchy of movable volumes composes a large non-linear dynamical system. Prediction of such a system in a sense of extrapolation of trajectory into the future is futile. However, upon coarse-graining the integral empirical regularities emerge opening possibilities of prediction in a sense of the commonly accepted consensus definition worked out in 1976 by the US National Research Council. Implications of the understanding hierarchical nature of lithosphere and its dynamics based on systematic monitoring and evidence of its unified space-energy similarity at different scales help avoiding basic errors in earthquake prediction claims. They suggest rules and recipes of adequate earthquake prediction classification, comparison and optimization. The approach has already led to the design of reproducible intermediate-term middle-range earthquake prediction technique. Its real-time testing aimed at prediction of the largest earthquakes worldwide has proved beyond any reasonable doubt the effectiveness of practical earthquake forecasting. In the first approximation, the accuracy is about 1-5 years and 5-10 times the anticipated source dimension. Further analysis allows reducing spatial uncertainty down to 1-3 source dimensions, although at a 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 December 26, 2004 Indian Ocean Disaster seems to be the first indication that the methodology, 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) and for mega-earthquakes of M9.0+. The monitoring 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. It makes feasible reestablishment of seismic monitoring aimed at prediction of large magnitude earthquakes in Caucasus and Central Asia, which to our regret, has been discontinued in 1991. The first results of the monitoring (1986-1990) were encouraging, at least for M6.5+.

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INTRODUCTION

The extreme catastrophic nature of earthquakes is known for millennia due to resulted devastation in many of them. Although the origins of observational seismology could be dated back to the East Han Dynasty in China, when Zhang Heng (78-139 AD; 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 earthquake detection instrument, it would be misleading to pretend that state-of-the-art physics of earthquakes is a well-developed branch of science. To the contrary most of seismologists clearly understand the pioneering and, therefore, juvenile nature of the present day physical problems related to earthquakes [1] when addressing the challenging questions of Quantitative Seismology, which still remain pressing: What happens during an earthquake? How to size earthquakes? Why, Where and When do earthquakes occur? The fundamental difficulty in answering these questions comes from the fact that no earthquake has been ever observed directly and just a few of them were subject to an in situ verification of their physical parameters. The recent seismic events, in particular, the "anticipated" (at the end of 1980ies) September 28, 2004 Parkfield, California earthquake, the December 26, 2004 Sumatra-Andaman, Indian ocean mega-earthquake, which consequences shock the whole civilized world, and the October 8, 2005 Muzafarrabad, Pakistan earthquake have demonstrated the shortcomings and limitations of the commonly accepted routine seismological methods for assessing location and size of an earthquake as well as groundlessness of many theories that claim to explain earthquake preparation process. The human tragedies caused by the Sumatra-Andaman earthquake (moment magnitude 9.3) and Muzafarrabad, Pakistan earthquake are difficult to comprehend. The first one is the largest earthquake in 40 years. This mega-thrust has left seismologists searching for explanations to describe its complexity and the numerous geological processes involved.

The mature wisdom of any science is determined by its ability to predict phenomena under study, i.e., earthquakes in Seismology. The abruptness along with apparent irregularity and infrequency of occurrences facilitate formation of a common perception that earthquakes are random unpredictable phenomena. The controversy of earthquake prediction got fertilized from numerous discussions and debates (e.g. [2-4]), supported, on one side, by a surprisingly small number of basic systematic studies and, on the other side, by a multitude of inadequate numerological exercises. As a result, although hundreds, if not thousands of observed phenomena have been claimed to precede large earthquakes, there are almost no reproducible quantitative definitions of "precursors". The IASPEI Call for precursor nominees came out with 31 candidates [5], none of which was found to fully satisfy its Guidelines, mainly due to the eventual inability of authors to provide a precise definition of the observed phenomenon. The situation practically did not change in the second round of the initiative [6]: only five out of the forty candidates submitted, seemed to deserve further study as possibly related to earthquake prediction. None of them could be considered yet as a validated precursor. There is a hope that "A seismic shift in thinking" [7] from condemning "the p-word" towards basic Science will result a renaissance of strict definitions and systematic experiments in the field of earthquake prediction, some of which were developed and used persistently over decades by academician Vladimir Keilis-Borok and his group [8] since pioneering “Seismology and logics” [9] and “One regularity in the occurrence of strong earthquakes” [10].

WHAT DO WE KNOW ABOUT EARTHQUAKES?

Fracturing of the Earth’s crust produces earthquakes that radiate seismic waves and cause ground shaking. 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.

Since the last decades of the 19th century Seismology accumulates the instrumental data on earthquakes recorded by seismographs of different kinds, which provide the opportunity for an objective assessment of the origin time, the location, and the size of an earthquake. Seismological laws start to emerge since about that time (e.g., [11]). However, it was only in the 1930ies when the concept of earthquake magnitude was introduced by Charles F. Richter. His original definition held only for California earthquakes occurring within 600 km of a particular type of seismograph. In the following years the Richter's original magnitude scale (M_L) was extended to observations of earthquakes of any distance and of focal depths ranging between 0 and 700 km ([12]). There are many magnitude scales, which are an obvious source of controversies 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 m_b and M_S. 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

$$M_0 = \mu S \langle d \rangle ,$$

where μ is the shear modulus, 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.

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 well-known 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.

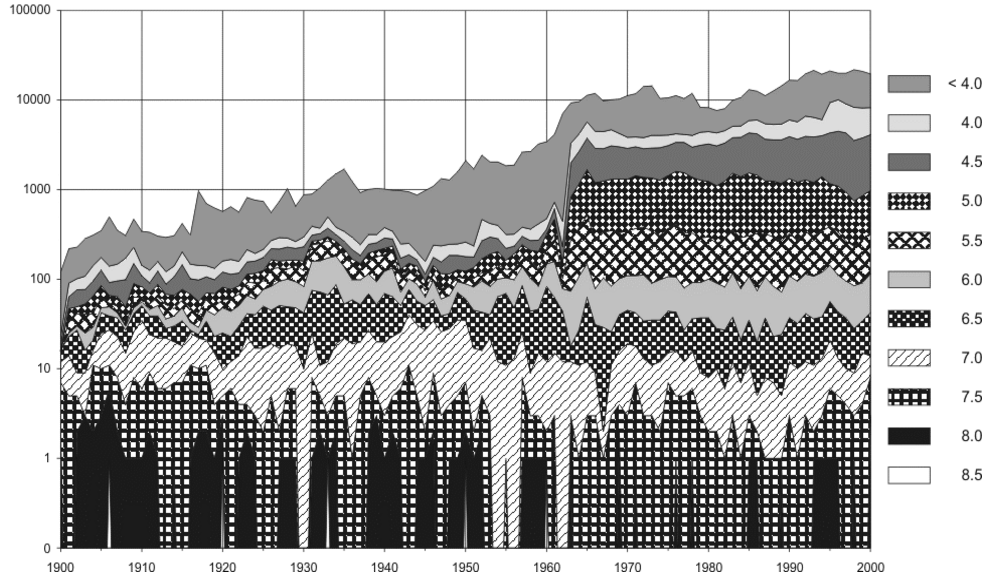

FIGURE 1. Annual number of earthquakes recorded in the 20th century (according to the NEIC/US GS Global Hypocenter Data Base).

While Fig. 1 predicts the annual number of magnitude 6 or larger earthquakes in the range from 90 to 200, the 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 seismic region occur and interact on a wide range of scales, from thousands of kilometers to millimeters or less. The whole lithosphere of the Earth is structured into a hierarchy of volumes of different size, from about ten major tectonic plates to about 10^{25} grains of rock [13]. 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 these 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's model predictable” by Evans et al. [14] 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 [15].

Despite high degree of complexity and 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 [16]: Averaged over a large space-time volume the number of earthquakes equal or above certain magnitude, $N(M)$ scales as

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

where, for M being MS scale magnitude, constant b is generally in the range $0.8 < b < 1.2$ [17] 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 [18-20] and, perhaps, to extreme energies of “starquakes” [21]. 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 generalizations [22-25], e.g.,

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

where N is the expected annual number of earthquakes with magnitude M in a seismic 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^2.

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 [26, 27]. 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.

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 [28]. 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 [29].

ARE EARTHQUAKES PREDICTABLE?

The temporal predictability of large earthquake occurrences requires a special comment on the recently revived discussions [2-4, 7]. 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 [15, 30] the high statistical significance of the two methods, algorithms M8 [31] and MSc [32], which short descriptions are given below, did confirm a positive statement on predictability of earthquakes. Furthermore, it appears that in some cases the inverse cascading of seismic activity to a catastrophe evolves through long-, intermediate-, short-term and even nucleation [33] phases.

Let us first 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 ([34], 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 [5, 6]. For example, according to this definition one the most developed and daily updated Short-term forecasts for NW and SW Pacific ([35]; http://scec.ess.ucla.edu/~ykagan/predictions_index.html) 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 a success [36].

Rethinking Earthquake Prediction, Sykes et al. [37] 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 [13]. Table 1 disregards term-less predictions although identification of earthquake-prone areas, e.g., by pattern recognition methods [38], delivers some kind of 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.

Citing Christopher Scholz [39]:

> "*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.*"

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

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 [32, 40]. And, finally, some earthquakes were already “publicly predicted” [15, 41, 42].

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 [15, 43]. 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
1985-2005	9	7	11	33.24	17.14	99.87	99.92
1992-2005	7	5	9	28.42	14.37	99.69	99.54

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 in the following sessions. Since the estimates presented in Table 2 use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters, called measure μ below, we describe it first, and then explain what stand behind M8 and MSc and their global and regional testing.

HOW TO MEASURE SPACE OCCUPIED BY SEISMIC ACTIVITY?

Are the results of the prediction experiment in question better than the random guessing or they are 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 **T**×**S** (we consider here a direct product measure $\tau\times\mu$ reserving a general case of a time-space dependent measure ν for future more sophisticated null-hypotheses); **N** counts the total number of large earthquakes with $M \geq M_0$ within **T**×**S** and **n** counts how many of them are predicted. The time-space occupied by alarms, $A = \bigcup_{\mathbf{T}} A_t$, in percentage to the total space-time considered equals

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

By common definition the two dual *levels of statistical significance and confidence* of the prediction results equal to

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

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 $\tau \times \mu$: 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 hypo- or 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 measures of volume in km^3 or territory in km^2 for estimating statistical significance of the prediction results. Evidently, the literal measures of volume or territory equalize the areas of high and low seismic activity, at the extreme, the areas where earthquake happen and do not happen.

The actual, empirical distribution of earthquake locations is the best present day knowledge estimate of where earthquakes may occur. The recipe of using the μ-measure and counting $\boldsymbol{p}$ is the following: Choose a sample catalog. Count how many events from the catalog are inside the volume or 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 (where the catalog sampled 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, called *Seismic Roulette*, 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 you play seismic roulette systematically, then you win and lose systematically. If the roulette is not perfect and you are smart enough to choose an effective strategy, then your wins will outscore loses! The results of the global test of the prediction algorithms M8 and MSc did confirm such an "imperfection" of Nature in recurrence of the great earthquakes and suggests using it for the benefit of the population exposed to seismic hazard.

This simple comparison with random guessing could be applied easily to any prediction method, including the well-known Fedotov-Sykes-Nishenko gap theory, the Habermann-Wyss quiescence hypothesis, the VAN method, the Jackson-Kagan forecast probability maps, etc. Surprisingly, most of the authors seem avoiding the evaluation and verification of the real-time forecast/prediction results achieved by their methods.

THE M8 AND MSC ALGORITHMS

Both algorithms are reproducible earthquake prediction methods that satisfy the consensus definition [34] 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 (Fig. 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. 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 [44] and the original version [45] 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 (Fig. 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 [40].

The algorithm recognizes criterion (Fig. 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 [31, 40, 43, 46].

Retrospectively the standard version of the algorithm [31, 40] was applied to predict earthquakes with magnitudes above 8.0 in a number of regions worldwide. Its modified versions apply also in regions of seismic activity lower than required by the original version [47-51].

Figure 4 shows, as an example of the M8 prediction in the real time, the case history of the 04 June 2000, M_S8.0 Sumatra earthquake. The Andaman-Sumatra-Java segment of the global prediction map issued in January 2000 along with epicenters of the great main shock and its first aftershocks are given on the left.

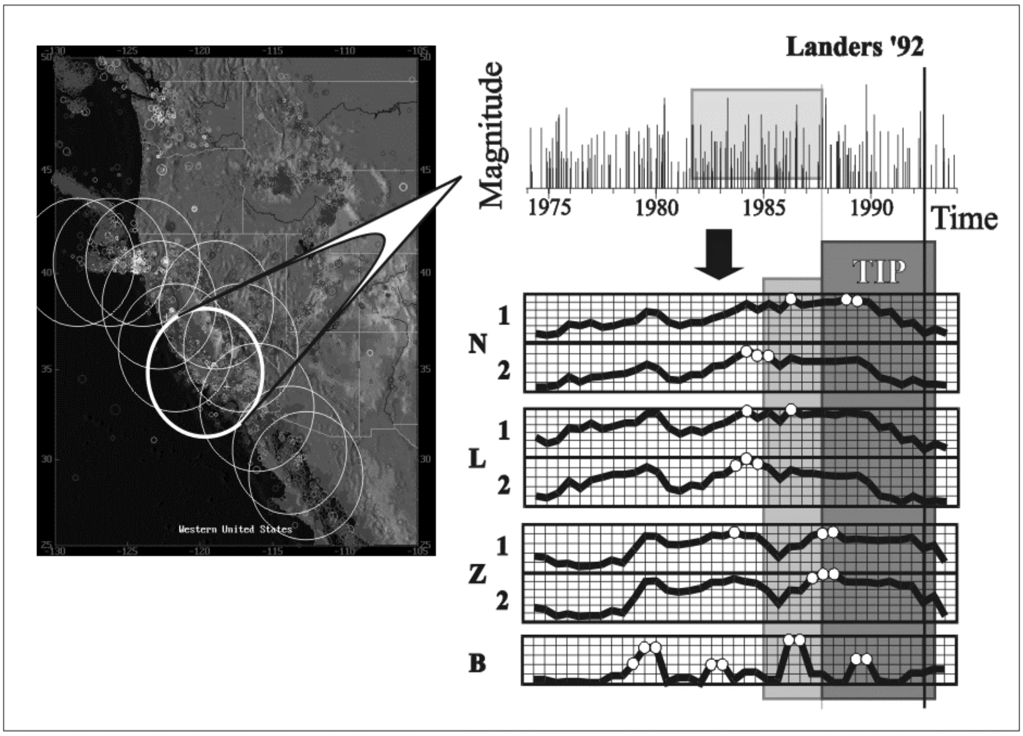

FIGURE 2. General scheme of applying reproducible earthquake-prediction algorithm: Areas of investigation overlay seismic region; seismic sequences in each area gives reproducible description of the present state, which is then used to diagnose an alert, so-called *time of increased probability*, TIP.

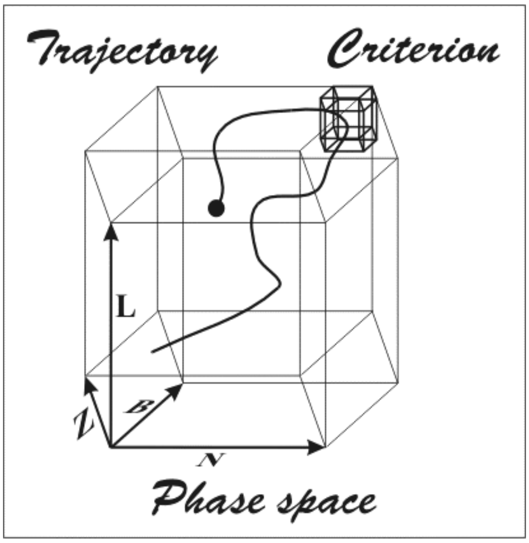

FIGURE 3. The trajectory describing an area of investigation in the phase space (4D-cube). A criterion is a part of the phase space so that an entry of the trajectory into it indicates abnormal behavior of the system. The M8 algorithm determines a TIP after the parameters of description – *N, L, Z, B*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

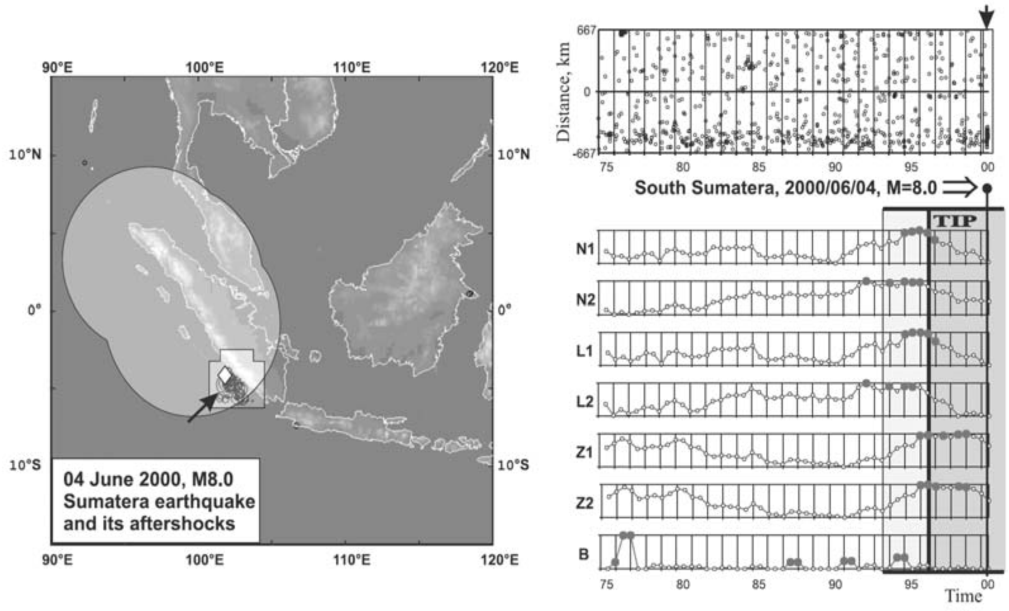

FIGURE 4. Global testing of algorithms M8 and MSc, M_0 = 8.0 [30]: The 4 June 2000 Sumatra earthquake. Observe the highlighted circular areas of alarm in the first approximation determined by algorithm M8 and the highlighted rectangular areas of alarm in the second approximation determined by algorithm MSc. A foreshock of magnitude 4.7 (diamond) occurred within a day in advance of the great shock.

On the right panel of Fig. 4, the figure depicts the space–time diagram of seismic activity in the circle of investigation (Test Number #34) with radius 667 km where the alarm was in progress when the great earthquake happened and below it presents the functions of algorithm M8 with their abnormal values marked by heavy dots. The arrows indicate the great shock, and small circles stand for smaller magnitude earthquakes used by the algorithm for determining the alarm. The distance along the seismic belt measured in kilometers from the center of the circle is plotted on the vertical axis. Time is plotted along the horizontal axis.

The second approximation prediction method MSc [32] 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, *Mendocino Scenario*, and an abbreviation. Figure 5 shows how effective the MSc reduction of the alarm area could be when applied on top of the M8 algorithm prediction. 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 the main shock. In reduction of territorial uncertainty of the M8 predictions, the MSc algorithm outperforms by at least a factor of

2 a few simple alternatives like the earthquake-prone cells in the area of alarm or the most active cells that contain certain part of the recent seismic activity [32].

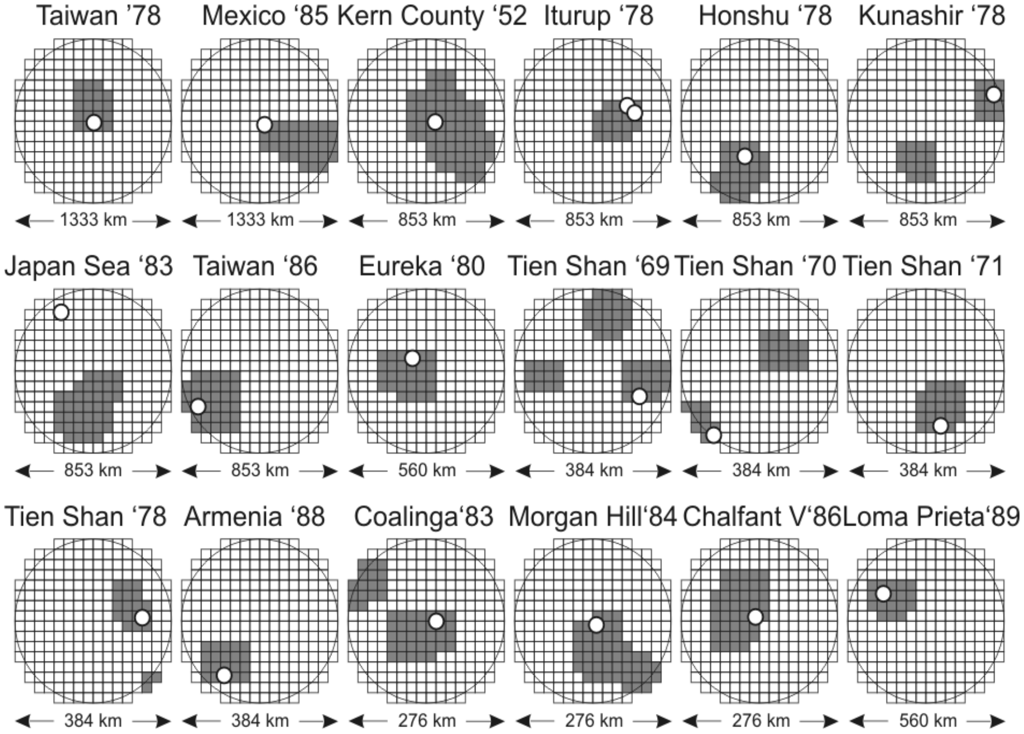

FIGURE 5. The results of retrospective reduction of spatial uncertainty of the M8 algorithm predictions aimed at the target earthquakes of magnitude from above 8.0 (1978 Taiwan and 1985 Mexico earthquakes) down to magnitude 6.0 (1983 Coalinga, 1984 Morgan Hill, and 1986 Chalfant Valley earthquakes in California) by the MSc algorithm [32]. The M8-MSc prediction of the 1989 Loma Prieta earthquake is prospective, being a subject of discussion at the U.S. National Earthquake Prediction Evaluation Council in advance of the anticipated large earthquake in California [42, 52].

TESTING EARTHQUAKE PREDICTIONS

After a 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 [43]. 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 [15, 53, 53]. Unfortunately, testing in seismic regions of the Former Soviet Union where the rescaling of the original M8 algorithm was tested first in 1986 on the "Earthquakes in the USSR" catalog aimed mostly at M6.5+ earthquakes were discontinued due to the collapse of the state and its seismological structures. The testing included Vrancea, Caucasus, Turkmen territories, Pamirs and Tien Shan. The reestablishment of seismic monitoring aimed at prediction of large magnitude earthquakes in Vrancea, Caucasus and Central Asia looks feasible nowadays, specifically after the development of a recently proposed scheme for the spatial stabilization of the intermediate-term middle-range predictions [55]. The scheme, named M8S, makes use of the multiple application of the M8 algorithm in a large number of objectively distributed circles of investigation and aims at elimination of spatially sporadic alarms. In fact, it appears to guarantee a more objective and reliable diagnosis of times of increased probability and, at the same time, is less restrictive to input seismic data [56]. At the moment it is used for the real-time monitoring of the Italian territory being aimed at M6.5+, M6.0+, and M5.5+ earthquakes [57].

In the Global Test aimed at M8.0+ earthquakes the algorithms M8 and MSc are 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 Myanmar (25 in Mediterranean, 25 in Asia Minor and Iran, 28 in Pamirs-Hindukush, and 14 in Myanmar). These cover about 80-90% of the major seismic belts of the Earth. The complete set of predictions in 1985-2005 could be viewed at http://www.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 the great earthquakes is much lower than average, like southern Sumatra or Tibet.

Aimed at M7.5+ earthquakes the algorithms are 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 Myanmar. For where prediction is made, on average the M8 alarms cover about one third (28.77% since 1992) of the whole territory considered (in accordance with measure μ), while MSc reduces this area to about 10%. Out of 52 earthquakes of magnitude 7.5 or higher in 1985-2005, the M8 algorithm predicted 30, and MSc provided a correct second approximation for 16 of them. That signifies confidence level above 99.9% for either of the algorithms. However, certain decay in performance is observed in the recent years: Since 1992 out of the total 39 earthquakes, 19 are predicted by M8 and 10 of them by MSc, which results the confidence level just above 99%. There are indications [15] that this could be inflicted by the changes either in the global seismic regime or in reporting the magnitudes or both: (i) 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; (ii) starting form 1993 the NEIC changed the procedures of the global database compilation, substituting M_S from Pasadena and Berkley with values of M_W from Harvard and USGS (it is of common knowledge that, in general, M_W is larger than M_S).

CAN MEGA EARTHQUAKES BE PREDICTED?

The statistics given in Table 2 do not include the recent mega-earthquakes in Indonesia that are much stronger than M8.0+ events. Specifically, the size of the 26

December 2004, M_W 9.3 (M_S 8.8) off the west coast of Northern Sumatra Great Asian, Sumatra-Andaman mega-thrust and its follower the 28 March 2005, M_W 8.7 (M_S 8.4) Nias earthquake, brings them out of the list of target earthquakes of the Global Test.

First of all, the linear dimension of the source of the first one is about 1000-1300 km, i.e., about the diameter of circles of investigation used in the Global Test of M8 to predict M8.0+ earthquakes. The linear dimension of the second one is above 450 km. The source length of the M8.0+ events in 1985-2003, usually accounts to about 150-300 km. Therefore, since the logic of the methodology suggests the proportions of investigation about 5-10 times larger than the target earthquake size, it would be naive and ambiguous to expect a success of the monitoring aimed either at M8.0+ or M7.5+ earthquakes in predicting the 26 December 2004 and 28 March 2005 events. According to the M8 algorithm predictions we were not expecting any M8.0+ or M7.5+ events in the Indian Ocean neither during the second half of 2004 nor in the first half of 2005 and, in fact, these did not happen.

On the other hand, if on July 1, 2004 someone, enough ambiguous to extend application of the M8 algorithm into unexampled magnitude range aiming at M9.0+ earthquakes, then he or she would have diagnosed Time of Increased Probability in advance of the 2004 Sumatra-Andaman mega-trust event. The genuine M8 computer code run with the target earthquake magnitude threshold equal to 9.0 and the radius of CI's increased to 3000 km determines the current alarm. Figure 6 shows on the left the circle of investigation (Test Number #34), its zoom to 3000-km radius, along with the epicenter and first aftershocks of the 26 December 2004 event, while on the right – the location of smaller magnitude earthquakes and the values of the M8 functions versus time. As can be seen from the figure the current TIP expires by December 2006.

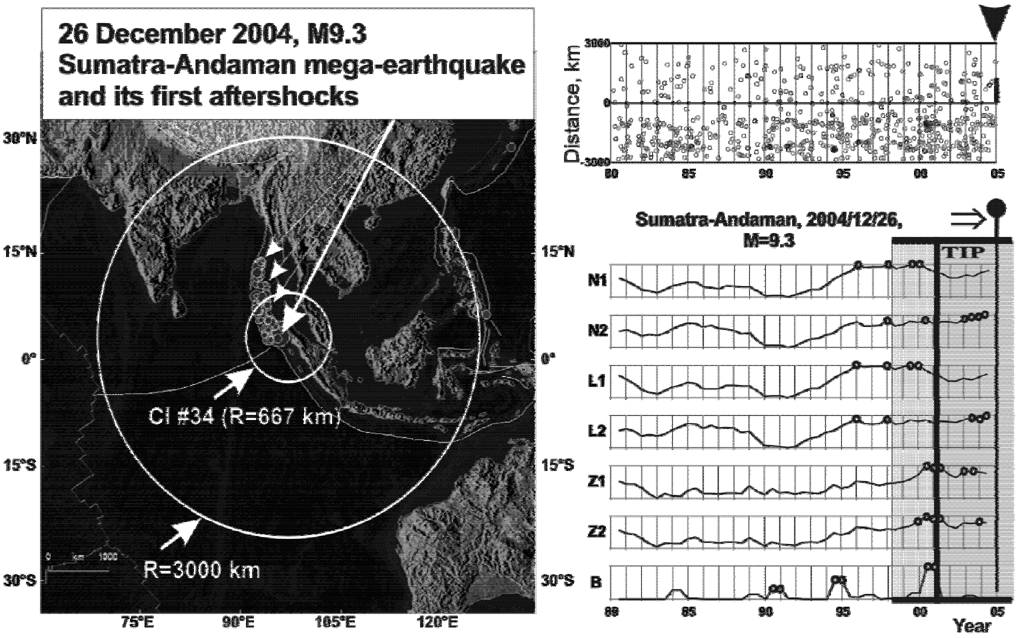

FIGURE 6. The retrospective application of the M8 algorithm aimed at M9.0+ earthquakes as on July 1, 2004.

Note that the case history of 04 June 2000, M_S 8.0 Sumatra earthquake (Fig. 4) followed by the 18 June 2000, M_S 7.8 Indian Ocean earthquake, suggests that the epicentral area of the 26 December 2004 mega-thrust was capable of producing a magnitude 8.0+ event already in 2000. Thus, one may speculate that the area bypassed this state by the end of 2001, entering the Time of Increased Probability of a much rarer M9.0+ earthquake.

In fact, we have a unique unexampled confirmation that the algorithm, designed for prediction of M8.0+ earthquakes and tested in many applications rescaled for prediction of smaller magnitude earthquakes (e.g., down to M5.5+ in Italy, http://www.mitp.ru/m8s/M8s_italy.html), is applicable for prediction of the mega-earthquakes of M9.0+. Of course, we are not that ambiguous to go from the first indication to a routine prediction, but feel the 26 December 2004 case history very important for better understanding of the methodology and the Problem of Earthquake Prediction, in general.

One may ask a question, what is the extent of the M8 algorithm M9.0+ TIPs in space and time? The answer is thought provoking: In the 25 years of retrospection here was one cluster of TIPs in 1984-1989 around western Mediterranean (a compact union of the eight out of the 262 circles of investigation) plus another one in 1994-1999 around Cascadia plate (a compact union of the five circles of investigation off coast of the western U.S.), which produce no M9.0+ event. The union of TIPs to date has global extent (124 circles of investigation in alarm) and already confirmed with the 2004 Sumatra-Andaman and 2005 Nias earthquakes. Should we expect further confirmations in the nearest future? Having in mind the evidence, which suggests clustered occurrence of seismic events including mega-earthquakes, we cannot reject such a possibility. All the four of the mega-earthquakes of the 20th century (Kamchatka, 1952/11/04, M_W 9.0; Andreanoff Islands, 1957/03/09, M_W 9.1; Chile, 1960/05/22, M_W 9.5; Alaska, 1964/03/28, M_W 9.2) happened within a narrow interval of time, which is unlikely (with a 99% confidence) for uniformly distributed independent events.

DISCUSSION AND CONCLUSIONS

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 and, hopefully, with other relevant data 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 alarms are large, especially in the first approximation, and many of them will inevitably expire without a strong earthquake.

The algorithms presented here are neither optimal nor unique. Together with other methods (e.g., [58-61]) they hallmark a break-through in earthquake prediction research that leads from term-less assessment of seismic hazard to reliable intermediate-term alert of increased probability. The accuracy could be improved in course of a systematic monitoring of the alarm areas and by designing a new generation of earthquake prediction technique of higher accuracy. The reproducible algorithms like “Seismic Reversal”, ROC, “Accord”, and “Chains” [62-65] suggested recently challenge this problem.

All together these algorithms demonstrate efficiency of the pattern recognition approach in solving the earthquake prediction problem at global and regional scales and form the basis of Quantitative Earthquake Prediction. The achievements of pattern recognition in the design of the reproducible algorithms predicting large earthquakes and the verified statistical validity of their predictions 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 reliable predictions of limited accuracy 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 [66, 67]. 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.

The predictions also 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 [29].

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 Quantitative Earthquake Prediction will require more data, novel pioneering studies, and verification of arising hypotheses on correlations between the occurrence of extreme events and observable phenomena.

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