Seismic dynamics prior to and after the great earthquakes worldwide, 1985-2001

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Regions of Increased Probability of Magnitude 8.0+ Earthquakes as on July 1, 2001 (subject to update on January 1, 2002)
A novel understanding of seismic process, as an essential part of dynamics of a hierarchical system of blocks-and-faults, has already led to reproducible intermediate-term earthquake prediction technique that passed successfully the testing in forward application, 1985-2001. The algorithms suggested in 1986 (Sadovsky, Ed., 1986) for intermediate-term prediction of large earthquakes were derived in applications of pattern recognition methods to a set of observable integral variables measured in a seismic area.
Earthquakes, at least the largest of them, occur after a comparatively large area of lithosphere experiences rise of seismic activity and after smaller earthquakes probe parts of its source.

The first happens at intermediate-term scale of years and can be efficiently detected. The second arises in a scale of weeks and shorter. It is hard, if possible, to distinguish this stage of precursory seismic rise without an intermediate-term analysis.
Inverse and direct cascading of earthquakes

- Evident direct cascade of aftershocks
- Debatable, although proved statistically (Kossobokov, Romashkova, Keilis-Borok, and Healy, 1999), inverse cascade of seismic activity
- Scaling and stages of cascading activity
Scaling and stages of cascading activity

- Detectable inverse cascading = earthquake prediction methods based on seismic activity rise, *e.g.*, Keilis-Borok and Malinovskaya, 1964; Varnes, 1989; Bufe and Varnes, 1998

- **What is 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.”

- **Stages of earthquake prediction**
Stages of earthquake prediction

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

<table>
<thead>
<tr>
<th>Temporal, in years</th>
<th>Spatial, in source zone size L</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long-term</td>
<td>10</td>
</tr>
<tr>
<td>Intermediate-term</td>
<td>1</td>
</tr>
<tr>
<td>Short-term</td>
<td>0.01-0.1</td>
</tr>
<tr>
<td>Immediate</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>Long-range up to 100</td>
</tr>
<tr>
<td></td>
<td>Middle-range 5-10</td>
</tr>
<tr>
<td></td>
<td>Narrow 2-3</td>
</tr>
<tr>
<td></td>
<td>Exact 1</td>
</tr>
</tbody>
</table>
Zero approximation:
The epicenter is located at 37.5 km distance from one of 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.
First approximation:
The M8 algorithm aimed at M6.5+ events in circles of investigation centered at the 73 D-intersections and run on July 1, 1999 determines alarms in two of them. In both circles the alarms in progress started in July 1998.

Second approximation:
The MSc algorithm narrows down the prediction to a location between 34.68N-33.82N and 117.23W-116.17W, where the epicenter of the Hector Mine earthquake and most of its aftershocks occurred on October 16.
Reproducible earthquake prediction methods:

Reproducible earthquake prediction methods: 

The M8 algorithm is based on a simple physical scheme of prediction, which can be briefly described as follows:

Prediction is aimed at earthquakes of magnitude $M_0$ and above. If the data permits, we consider different values of $M_0$ with a step 0.5.

Overlapping circles with the diameter $D(M_0)$ scan the territory seismic region under study. Within each circle the sequence of earthquakes is considered with aftershocks removed $\{t_i, m_i, h_i, b_i(e)\}$, $i = 1, 2 \ldots$. Here $t_i$ is the origin time, $t_i \leq t_{i+1}$; $m_i$ is the magnitude, $h_i$ is focal depth, and $b_i(e)$ is the number of aftershocks with magnitude $M_{aft}$ or more during the first $e$ days. The sequence is normalized by the lower magnitude cutoff $M = M_{min}(\bar{N})$, $N$ being the standard value of the average annual number of earthquakes in the sequence.

Several running averages are computed for this sequence in the trailing time window \( (t - s, t) \) and magnitude range \( M_0 > M_i \geq M \). The averages include:

\[
N(t) = N(t \mid M, s), \text{ the number of main shocks of magnitude } M \text{ or larger in } (t - s, t);
\]

\[
L(t) = L(t \mid M, s, t_0), \text{ the deviation of } N(t) \text{ from longer-term trend, } L(t) = N(t) - N_{cum}(t - s) \cdot (t - t_0)/(t - s - t_0), \text{ where } N_{cum}(t) = N(t \mid M, t - t_0) \text{ being the cumulative number of main shocks with } M \geq M \text{ from the beginning of the sequence } t_0 \text{ to } t;
\]

\[
Z(t) = Z(t \mid M, M^*, s, \alpha, \beta), \text{ linear concentration of the main shocks } \{i\} \text{ from the magnitude range } M \leq M_i < M^* \text{ and interval } t - s \leq t_i < t \text{ estimated as the ratio of the average diameter of the source, } I, \text{ to the average distance, } r, \text{ between them; and}
\]

\[
B(t) = B(t \mid M, M^*, s', M_{aft}, e) = \max\{b_i\}, \text{ the maximal number of aftershocks (i.e. a measure of earthquake clustering)}.
\]

The sequence \( \{i\} \) is considered in the trailing time window \( (t - s', t) \) and in the magnitude range \( (M, M^*) = (M_0 - p, M_0 - q) \).
Reproducible earthquake prediction methods: Algorithm M8


Each of the functions N, L, Z is calculated twice for $M = M_{\text{min}}(\bar{N})$, $\bar{N} = 20$ and $\bar{N} = 10$. As a result, the earthquake sequence is given a robust averaged description by seven functions: N, L, Z (twice each), and B.

"Very large" values are identified for each function using the condition that they exceed Q percentiles (i.e., they are higher than Q percent of the encountered values).

An alarm or a TIP, "time of increased probability", is declared for five years, when at least six out of seven functions, including B, become "very large" within a narrow time window ($t - u$, t). To stabilize prediction, this criterion is required for two consecutive moments, t and t+0.5 years. In course of a forward application, the alarm may extend beyond or be terminated before five years in case the updating causes changes in determination of the magnitude cutoffs and/or the percentiles.
Reproducible earthquake prediction methods: 

The following standard values of parameters indicated above are prefixed in the algorithm M8: \( D(M_0) = \{ \exp(M_0 - 5.6) + 1 \}^0 \) in degrees of meridian (this is 384 km, 560 km, 854 km and 1333 km for \( M_0 = 6.5, 7.0, 7.5 \) and 8 respectively), \( s = 6 \) years, \( s' = 1 \) year, \( g = 0.5, p = 2, q = 0.2, u = 3 \) years, and \( Q = 75\% \) for B and 90\% for the other six functions.

The running averages are defined in a robust way, so that a reasonable variation of parameters does not affect the predictions. At the same time, discrete character of seismic data and strict usage of the prefixed thresholds result in a certain discreteness of the alarms.

Reproducible earthquake prediction methods: 

It is worth mentioning, that qualitatively, algorithm M8 uses rather traditional description of a dynamical system adding to a common phase space of rate (N) and rate differential (L) dimensionless concentration (Z) and a characteristic measure of clustering (B).

The algorithm recognizes *criterion*, defined by extreme values of the phase space coordinates, as a vicinity of the system singularity. When a trajectory enters the criterion, probability of extreme event increases to the level sufficient for its efficient prediction. The choice of the M8 criterion determines a specific intermediate-term rise, *inverse cascade*, of seismic activity at the middle-range distance.
Reproducible earthquake prediction methods: Algorithm MSc (Mendocino Scenario) (Kossobokov, Keilis-Borok and Smith, 1990)

Given a TIP diagnosed for a certain territory $U$ at the moment $T$, the algorithm is designed to find within $U$ a smaller area $V$ where the predicted earthquake can be expected. An application of the algorithm requires a reasonably complete catalog of earthquakes with magnitudes $M \geq (M_0 - 4)$, which is lower than the minimal threshold usually used by M8. In case this condition is not fulfilled we rely that dynamics of earthquakes available in the database inherit the behavior from the lower levels of seismic hierarchy. The detection of the MSc criteria in such a case is more difficult and might result additional failures-to-predict.
Reproducible earthquake prediction methods:  
**Algorithm MSc** *(Mendocino Scenario)*  
(Kossobokov, Keilis-Borok and Smith, 1990)

The essence of MSc can be summarized as follows. Territory $\mathbf{U}$ is coarse-grained into small squares of $s \times s$ size. Let $(i,j)$ be the coordinates of the centers of the squares. Within each square $(i,j)$ the number of earthquakes $n_{ij}(k)$, aftershocks included, is calculated for consecutive, short time windows, $u$ months long, starting from the time $t_0 = (T-6$ years) onward, to allow for the earthquakes which contributed to the TIP's diagnosis; $k$ is the sequence number of a time window. In this way the time-space considered is divided into small boxes $(i,j,k)$ of the size $(s \times s \times u)$. "Quiet" boxes are singled out for each small square $(i,j)$; they are defined by the condition that $n_{ij}(k)$ is below the $Q$ percentile of $n_{ij}$. The clusters of $q$ or more quiet boxes connected in space or in time are identified. Area $\mathbf{V}$ is the territorial projection of these clusters.

The standard values of parameters adjusted for the case of the 1980 Eureka earthquake are as follows: $u = 2$ months, $Q = 10\%$, $q = 4$, and $s = 3D/16$, $D$ being the diameter of the circle used in algorithm M8.
Reproducible earthquake prediction methods:  
Algorithm MSc  (Mendocino Scenario)  
(Kossobokov, Keilis-Borok and Smith, 1990)

Qualitatively, algorithm MSc outlines such an area of the territory of alarm where the activity, from the beginning of seismic inverse cascade recognized by algorithm M8, is **continuously high and 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 premonitory rise of seismic activity near the incipient source of main shock. The anomalous quiescence used in the definition to distinguish the precursory intermittent pattern in dynamics of seismic region should not be mixed with a prolonged state of “seismic quiescence” advocated by Wyss (Wyss and Habermann, 1988).
Global testing of algorithms M8 and MSc

- Database and rules of its updating (Global Hypocenters Data Base CD-ROM, version III, 1994. NEIC/USGS, Denver, CO. and its PDE and QED updates)
- Fixed codes, rules and profiles
- Real-time monitoring
- Null-hypothesis

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Real-time monitoring (http://www.mitp.ru or http://www.phys.ualberta.ca/mirrors/mitp)
Space-time diagram of M8-MSc alarms
04 October 1994, M8.3
Shikotan earthquake and its aftershocks
07 April 1995, M8.1 Samoa earthquake and its aftershocks
03 December 1995, M8.0
Iturup earthquake and its aftershocks

IMA Workshop "Spatio-temporal Patterns in the Geosciences"
10/1/01 IMA Workshop "Spatio-temporal Patterns in the Geosciences"

04 June 2000, M8.0
Sumatera earthquake and its aftershocks

South Sumatera, 2000/06/04, M=8.0

Time
09 June 1994, M8.2 Bolivia Deep earthquake and its aftershocks
Modified version of M8 adapted for application in seismic regions of low activity
Seismic Roulette

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IMA Workshop "Spatio-temporal Patterns in the Geosciences"
Worldwide performance of earthquake prediction algorithms M8 and M8-MSc: Magnitude 8.0 or more.

<table>
<thead>
<tr>
<th>Test period</th>
<th>Large earthquakes</th>
<th>Percentage of alarms</th>
<th>Significance level, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>M8</td>
<td>M8-MSc</td>
</tr>
<tr>
<td>1985-2001</td>
<td>9</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td>1992-2001</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
</tbody>
</table>

The significance level estimates use the most conservative measure of the alarm volume accounting for empirical distribution of epicenters.
The collection of cascades is more diverse and complicated than a power-law family. It reflects certain properties of behavior associated with the second-order phase transitions prior to and following a catastrophe in complex non-linear systems. The lithosphere of the Earth appears to be such a system. 

(Romashkova and Kossobokov, 2001)
The Benniof strain prior to the largest earthquakes is hardly following a power-law rise, although certain activation of seismicity can be recognized on a time-scale of years.
The Omori power-law decay of the rate of aftershocks following the largest earthquakes is by no means a characteristic behavior.
Real Life is more complicated than a model

- Heterogeneity of the lithosphere
- Hierarchy of blocks and faults
- Geometrical on-path irregularities, *incompatibilities* (*Gabrielov, Keilis-Borok and Jackson, 1996*)
- etc…
Conclusions

- Our analysis confirms a positive statement on predictability of the largest earthquakes.
- It suggests the existence of premonitory rise of seismic activity evolving through long, intermediate, short term, and, perhaps, immediate stages, *inverse cascade*.
Next Steps

- Although of limited accuracy, the predictions by M8 and MSc algorithms can be used for prevention of damage and losses.
- The accuracy could be improved by a systematic monitoring of the alarm areas and by designing a new generation of earthquake prediction methods.
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