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Non-linear dynamics of the lithosphere and intermediate-term earthquake prediction

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Abstract

The lithosphere of the Earth is structured as a hierarchical system of volumes of different sizes, from about 10 tectonic plates to about 10^{25} grains of rock. Their relative movement against the forces of friction and cohesion is realized to a large extent through earthquakes. The movement is controlled by a wide variety of independent processes, concentrated in the thin boundary zones between the volumes. The boundary zone has a similar hierarchical structure, consisting of volumes, separated by boundary zones, etc. Altogether, this hierarchy of volumes and multitude of processes compose the lithosphere into a large non-linear complex system. Upon coarse graining the integral mesoscale empirical regularities emerge, indicating a wide range of similarity, collective behavior, and the possibility of earthquake prediction. This approach led to new paradigms in the dynamics of the lithosphere and, on the practical side, created a capacity to predict from 70 to 90% of large earthquakes, with alarms occupying 10–20% of the time–space considered. Such predictions may be used to undertake earthquake preparedness measures, which would prevent a considerable part of the damage (although far from the total damage). The methodology linking prediction with preparedness was developed; it may help a disaster management authority to choose the preparedness measures, allowing for the currently realistic accuracy of predictions. A large-scale experiment in advance prediction of large earthquakes worldwide has been launched to test the prediction algorithms. The test is unprecedented in rigor and coverage. The forecasts are communicated, with due discretion, to several dozen leading scientists and administrators in many countries. Among already predicted earthquakes are all the last eight great ones with magnitude 8 and more. The major drawback is the rate of false alarms. The possibility is outlined to develop a new generation of prediction methods, with fivefold increase in accuracy and the transition to short-term prediction. The links with prediction of geotechnical and engineering disasters are established: scenarios of transitions to a large earthquake happen to share some features with a broader class of catastrophes. This experience now opens as yet untapped possibilities for reduction of technological disasters.

Keywords: seismicity; prediction algorithms; models of lithosphere dynamics; natural disaster reduction

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1. Introduction

Earthquakes are generated in the outer shell of the solid Earth called lithosphere. The lithosphere presents a hierarchy of blocks where the largest blocks are the major tectonic plates. They are divided into smaller blocks, like shields or mountain chains. After 15–20 divisions, about 10^{25} grains of rock of millimeter scale are obtained. The blocks are separated by less rigid boundary zones, 10–100 times thinner than the corresponding blocks. Each boundary zone presents a similar hierarchical structure: it consists of blocks divided by zones of smaller ranks. The boundary zones bear different names: fault zones (10^5–10^7 m), faults (10^1–10^4 m), cracks (10^{-2}–10^0 m), microcracks (10^{-4}–10^{-3} m), interfaces (less than 10^{-5} m). The blocks, from plates to grains, interact along and across the hierarchy and move relative to each other under control of exceedingly diverse and unstable mechanisms. In large part, these movements are realized through formation and subsequent healing of failures on surfaces where displacements are discontinuous as defects, slips, fractures, or earthquakes (Keilis-Borok, 1997).

About a million earthquakes with magnitude greater than 2 are registered each year; about a thousand of them are large enough to be felt; about a hundred earthquakes cause considerable damage, and once in a decade or two a catastrophic event occurs. The occurrence of a particular earthquake cannot be entirely isolated from the dynamics of the lithosphere. That is why the problem of earthquake prediction consists of consecutive step-by-step narrowing of the time–space domain where large earthquakes are expected. This process is in accordance with the hierarchical nature of the lithosphere.

The research on non-linear dynamics of the lithosphere and intermediate-term earthquake prediction was set up in order to develop a methodology for a scientific earthquake prediction and for its application to earthquake preparedness. This methodology enhances our capability to reduce the damage from large earthquakes. These applied problems are entwined with studies of the dynamics of the earthquake-generating lithosphere of the Earth, both by theoretical modeling and by analysis of relevant observations. The scope of the research determined the following specific objectives: (1) to find *the symptoms and scenarios of critical transitions* in the lithosphere of the Earth; (2) to develop *methods for intermediate-term earthquake prediction* with a characteristic duration of alarm of about a few years; (3) to test these methods by *systematic advance prediction of large earthquakes* in several regions worldwide; (4) to provide the disaster management authorities with a *methodology to reduce damage* from earthquakes using predictions with their currently realistic accuracy; such a methodology ensures the necessary interaction between scientific community responsible for prediction and disaster management authorities responsible for *earthquake preparedness*; (5) to explore *symptoms and scenarios of critical transitions* to be used in prediction of geotechnical and engineering disasters.

Initially, the research was almost entirely focused on the dynamics of seismicity, since earthquake catalogs present the most complete data set, covering the longest time interval. Eventually, the framework was developed for analysis of other prediction-relevant fields such as source mechanism, slow deformations, stress and strain fields, and fluid regime.

Theoretical and numerical models of phenomena premonitory to large earthquakes were studied. Lattice models, as developed in mathematics and statistical physics, describe 'universal' symptoms and scenarios of critical transitions common to many chaotic systems, not necessarily related to the Earth. 'Earth-specific' models of dynamics of the blocks-and-faults systems show main features of dynamics of the seismically active lithosphere. These models reproduce the geometry of the blocks and faults and allow for the impact of mantle currents.

The development and test of prediction algorithms, based on modeling and phenomenology, consisted in advance prediction of large earthquakes in seismic regions worldwide. The interface between prediction and preparedness is provided by a methodology that optimizes safety measures taken in response to a forecast. Optimization is based on the theory of optimal control. Accuracy of a prediction method and probabilities of false alarms are accounted for.

2. New scientific findings and ensuing possibilities

The 'holistic' approach used in earthquake prediction is summed up in Table 1. It was developed by phenomenological and theoretical studies in the dynamics of seismicity. This approach is part of a much broader range of studies in non-linear dynamics of the lithosphere, earthquake prediction included (Newman et al., 1994; Sornette and Sammis, 1995; Keilis-Borok, 1996a,b; Turcotte, 1996, 1999).

2.1. Test of prediction algorithms

Advance prediction is the only definitive test of any prediction method. A large-scale experiment in advance prediction of large earthquakes in many regions worldwide has been started (Table 2). We believe this test to be unprecedented in rigor and coverage. Predictions are completely reproducible, since they are made by rules defined a priori. These include (1) an unambiguous definition of the algorithm, published and implemented in software; (2) specification of database; (3) specification of the earthquakes targeted by prediction, that is, the territory and the magnitude range. We use routine seismic catalogs compiled by the NEIC (Boulder, CO) and prediction algorithms published and distributed as computer codes at series of workshops on non-linear dynamics and earthquake prediction at the Abdus Salam International Centre for Theoretical Physics at Trieste (Kossobokov, 1997). That makes our results fully reproducible by independent investigators. Yet, this test falls short of being absolutely rigorous, since most of the forecasts have not been filed formally. A rigorous and much broader test is recently set up, with a routine for formal filing of forecasts that are communicated in advance (in web-site http://www.mitp.ru/predictions.html) to several dozen scientists and administrators.

High statistical significance at the 95–99% confidence level has been found for three intermediate-term earthquake prediction algorithms. The first two lines of Table 2 sum up the performance of the M8 and Mendocino Scenario (MSc) algorithms. Specifically, prediction was made first by the M8 algorithm (Keilis-Borok and Kossobokov, 1990).

Table 1
Two complementary approaches to earthquake prediction

'Reductionism' (from details to the whole)	'Holism' (from the whole to details)
Premonitory phenomena	
are specific to mechanisms, e.g. friction, fluid percolation, stress corrosion, buckling, etc.	are divided into: (1) 'universal' ones common to many chaotic systems[a] (2) those depending on geometry of blocks-and-faults system[b] (3) Earth-specific ones
Premonitory phenomena in different regions and energy ranges	
are different	are to a great extent similar[c]
Premonitory phenomena preceding an earthquake with linear source dimension L are formed	
on a fault segment of linear size from L to $2L$	in a system of blocks and faults of the following linear size: (1) up to $50L$ (in the time scale of tens of years[d]) (2) from $3L$ to $10L$ (in the time scale of a few years[e]) (3) from L to $2L$ (in the time scale of a few years or months[f])
Constitutive equations	
are local	are non-local
Triggering of earthquakes is controlled	
by stress vs. strength relation on a fault segment	by the geometric incompatibility, near junctions of faults, which may supersede a stress/strength criterion[g]

[a] Newman et al. (1994), Keilis-Borok (1996a) and Turcotte (1996), and references therein.
[b] Gabrielov et al. (1996) and Rotwain et al. (1997).
[c] Papers in Keilis-Borok and Shebalin (1999) and Rotwain et al. (1997).
[d] Press and Allen (1995), and references therein.
[e] Papers in Keilis-Borok and Shebalin (1999).
[f] Kossobokov et al. (1999), Molchan et al. (1999) and Shebalin and Keilis-Borok (1999), and references therein.
[g] Gabrielov et al. (1996).

Table 2
Performance of the algorithms illustrated in Figs. 1–4. (M8 analyzed seismicity within 170 overlapping circles of 1333 km diameter to predict magnitude 8.0 or above earthquakes. Other regions where M8 is being applied on a routine basis are not given in this Table. At the moment, we have relatively low estimate of statistical significance of CN. It would rise above 95% after three or four more earthquakes are predicted with about the same success-to-failure score. Methods used for estimation of statistical significance are described in Molchan et al. (1990), Kossobokov et al. (1997, 1999) and Rotwain and Novikova (1999))

Algorithm	Regions	Large earthquakes predicted/total	Time–space of alarms (%)	Confidence level (%)
M8	Circum-Pacific	7/7	39	> 99
M8 + MSc	Circum-Pacific	6/7	20	> 99
CN	20 regions worldwide	12/21	24	83
NLE	Areas associated with 18[a] large earthquakes worldwide	3/4[a]	28	96

[a] Out of 18 large earthquakes, four were followed by large events and three of them were predicted.

The alarms determined by the algorithm for several years extend over the territories about 5–10 times larger than the source of incipient large earthquakes. Among the earthquakes predicted were all the eight last great earthquakes with magnitude 8 or more. In the second approximation, the MSc algorithm (Kossobokov et al., 1990) was applied. It has reduced the area of alarm by a factor of 5–20. The second approximation requires more complete data not always available. In many cases, the reduced area of alarm comes close to the source of a predicted earthquake as exposed by the distribution of aftershocks. This may be the best accuracy possible at the intermediate-term phase. Thus, the major drawback of the first approximation (i.e. the spatial inaccuracy) is eliminated, so far at the cost of more failures-to-predict (for example, one of the seven great earthquakes was missed by the MSc algorithm). More monitoring is necessary to establish significance for the CN algorithm. Independently, the algorithm Next Large Earthquake (NLE) was applied to predict a large aftershock or a next main shock in a sequence. It gives a particularly low rate of errors. Examples of the performance of the algorithms are illustrated in Figs. 1–4.

The statistical validity of the above-mentioned predictions confirms the paradigms underlying the prediction algorithms (Keilis-Borok, 1996a). Among them: (1) the long-range correlation in the fault system and, accordingly, a large area involved in formation of premonitory phenomena; (2) the existence of premonitory phenomena that are unambiguously descriptive; (3) certain partial similarity of these phenomena in a wide diversity of tectonic environment; (4) dual nature of premonitory phenomena: same are “universal” and some Earth-specific (see Table 1).

2.2. Modeling of premonitory phenomena

Modeling provides the possibilities to explore premonitory phenomena, which have to be tested subsequently by observations. Models of three types were developed: (1) dynamic systems reproducing ‘universal’ features of seismicity common to a wide class of non-linear systems; (2) models specific to the solid Earth only, reproducing the features of seismicity specific to the geometry of a fault system; (3) structure of the seismic source and the stress field in the fault zone. The results are set forth below.

2.2.1. Dynamic systems

Several possible types of critical behavior have been found in a single heterogeneous hierarchical model. These types include, besides the well-known self-organized criticality also stability, catastrophe, and unstable criticality (Fig. 5). The inhomogeneity of strength in the system determines what particular behavior is realized. Since the strength can change with time, e.g. due to fracturing or fluid migration, transitions from one type to the other are possible (Blanter and Shnirman, 1997; Shnirman and Blanter, 1999).

A new type of instability, ‘weak chaos’, has been

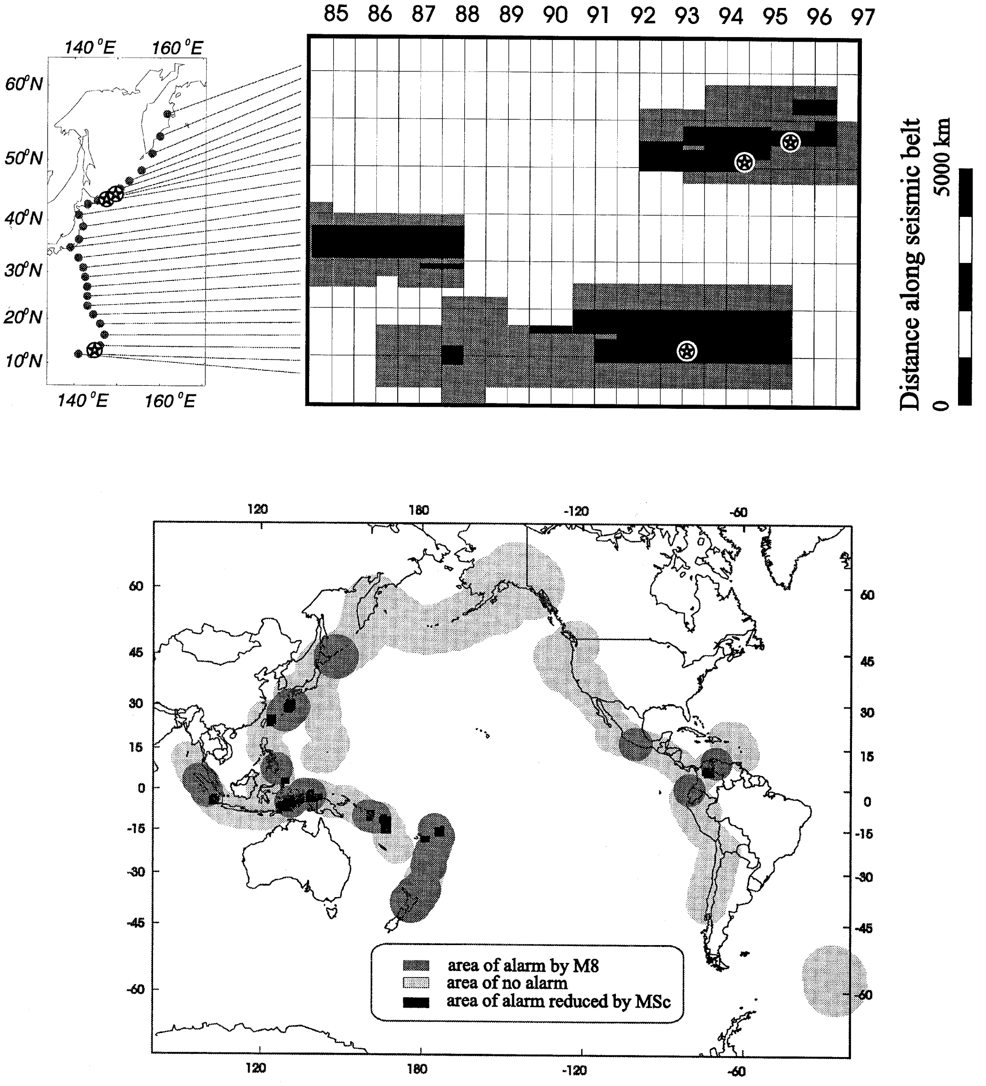
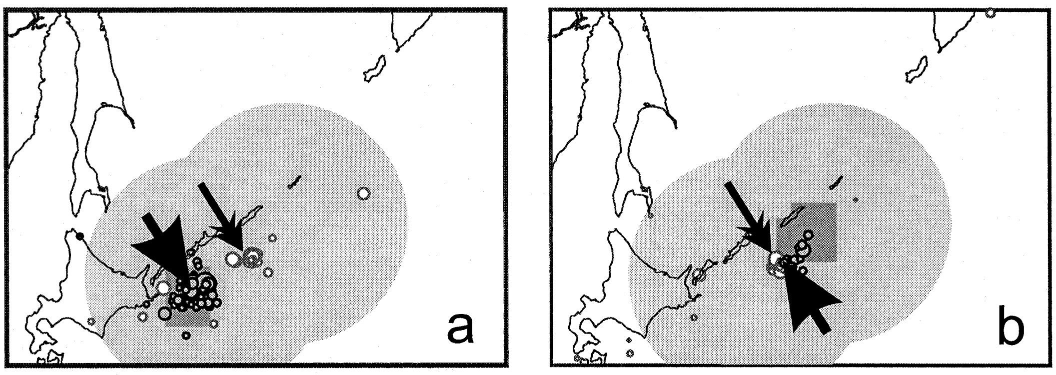


Fig. 1. Prediction of great (magnitude 8 or more) earthquakes (after Kossobokov et al., 1999). Upper panel: The spatial–temporal distribution of the M8 and MSc alarms in the northwestern part of the Circum-Pacific seismic belt, 1985–1997. The territory considered (light) along with the alarms for the second half of 1997 (dark for M8 and darker for MSc; note the absence of the MSc, i.e. second approximation, alarms in this period) is on the left. The spatial–temporal distribution of real time alarms and the great earthquakes (stars) are given on the right. Space coordinate is given as the distance along the belt. Bottom panel: an example of predictions for the whole Circum-Pacific: July 1, 1997–January 1, 1998.

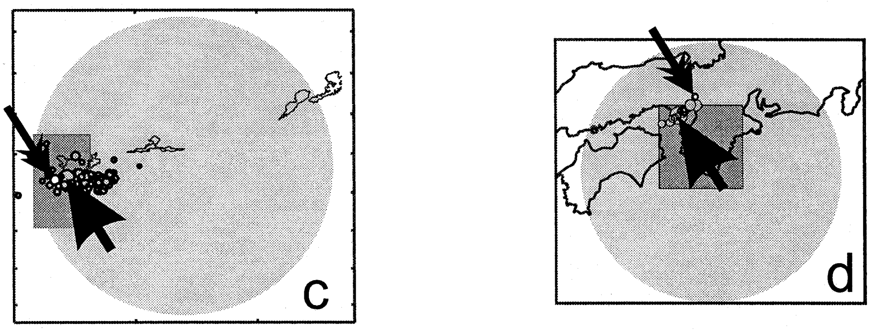
found in a toy model of seismicity. Perturbed trajectories in that model are diverging with time according to a power law instead of the classical exponential law. Predictability of such a system may be higher than expected from its chaotic behavior (Primakov and Shnirman, 1999).

Healing and redistribution of loading, caused by driving forces, was accounted for in the renormalization-type SOFT model ('Scaling organization of fracture tectonics'; Allègre et al., 1995) making it much closer to reality (Allègre et al., 1998). Direct numerical simulations by the improved model now



Shikotan Isl., 04 Oct 1994, M=8.1

Iturup Isl., 03 Dec 1995, M=8.0



Delaroff Isl, 10 Jun 1996, M=7.6

Kobe (Japan), 16 Jan 1995, M=7.2

●	area of M8 alarm	↘	points to area of anomalous seismic activation
▨	area of M8-MSc alarm	↖	points to epicenter of mainshock
○	earthquakes preceding mainshock	◍	aftershocks

Fig. 2. On transition to short-term prediction: Recent case histories often indicate an anomalous activation within M8 alarm shortly before a large earthquake: unusual swarms preceded the two great earthquakes in southern Kuril arc (a) and (b) and a disastrous earthquake in Kobe (c) while Delaroff Island earthquake had a large (magnitude 6.5) foreshock (d). Note also that the area of the M8–MSc alarm is close to the area of aftershocks, i.e. to the source of incipient large earthquake. For Shikotan earthquake these areas coincide (a). Thus, the spatial accuracy of predictions may be already close to the best possible one on intermediate-term stage.

reproduce cycles of seismic activity, foreshocks and aftershocks; temporal decay of aftershocks obeys a power law (Omori law) (Fig. 6).

Probability of large-scale events in multiplicative random cascades was found to be larger than previously believed; this vindicates the log-normal hypothesis of Kolmogoroff–Obukhov and suggests that usual determinations of the Gutenberg–Richter relation may underestimate the probability of the largest earthquakes (Molchan, 1997a).

Frequency of occurrence of great earthquakes is the key background parameter in earthquake prediction research. Probabilistic methodology is developed to overcome the major difficulty in its determination, i.e. the rarity of the largest earthquakes in each region. The methodology uses

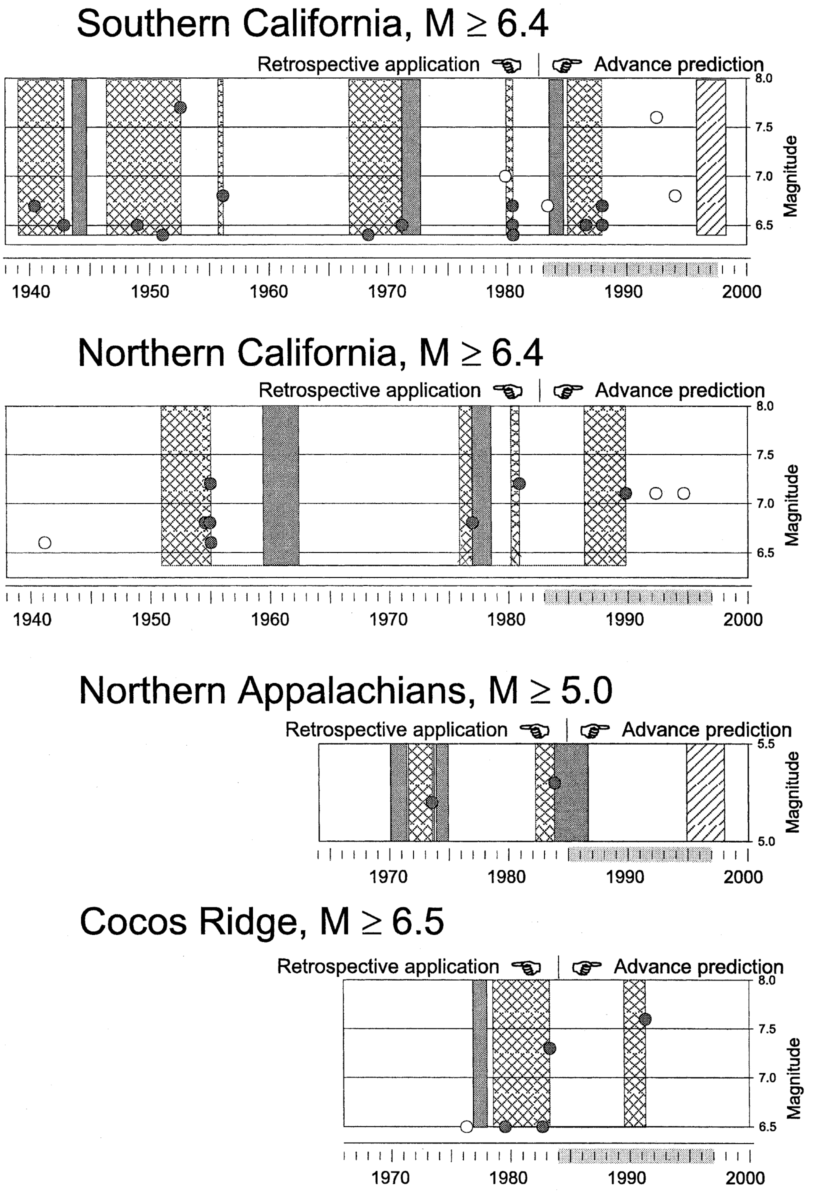


Fig. 3. Earthquake prediction by algorithm CN (after Rotwain and Novikova, 1999). Time of increased probability of large earthquakes for southern and northern California, northern Appalachian, and the Cocos Ridge.

multiscale approach in which the frequency of earthquakes is determined at several spatial scales that depend on magnitude range. A test of the methodology for Italy and the Caucasus gave promising results (Molchan et al., 1997).

A new premonitory seismicity pattern has been found — transformation of the size distribution, i.e. Gutenberg–Richter relation, in favor of relatively larger earthquakes (Narkunskaya and Shnirman, 1994; Rotwain et al., 1997).

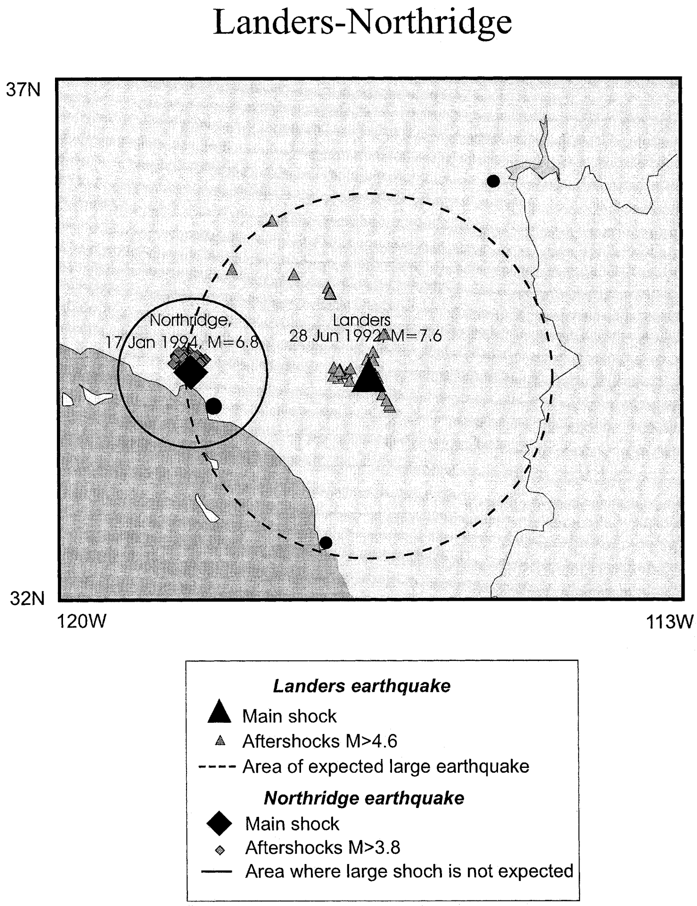


Fig. 4. Prediction of the next large earthquake by the NLE algorithm: the Landers and Northridge earthquakes and their aftershocks (after Vorobieva, 1999). Note that the Northridge $M = 6.8$ earthquake happened in 19 days after termination of the alarm, and therefore, was counted in Table 2 as the only failure-to-predict.

2.2.2. Blocks-and-faults models

Major processes determining occurrences of earthquakes are integrated by the models of blocks-and-faults systems. These models link together (i) the hierarchical structure of the lithosphere, (ii) the driving forces (interaction with mantle included), (iii) the movements in a broad velocity range (from seismicity to creep), and (iv) GPS, neotectonics, and stress and strain fields. The models consist of rigid blocks separated by thin deformable fault zones with a given rheology.

The modeling has already given new insights into the dynamics of observable fields in terms of internal (directly unobservable) processes in the lithosphere. Major features of dynamics of seismicity underlying the premonitory seismicity patterns, such as the Gutenberg–Richter law, clustering, long-range correlation, spatial fractality, and migration of seismicity (Keilis-Borok et al., 1997) are investigated and compared to the observed ones. Blocks-and-faults models applied to the Vrancea region and island arc subduction zone are described below in more detail.

Since earthquakes in the Vrancea region are rather deep, about 100–150 km, they are destructive in a particularly large area, reaching about 20 vulnerable nuclear power plants, Bucharest and even such distant cities as Kiev, Kishinev, and Moscow. Spatial distribution of epicenters, level of seismic activity,

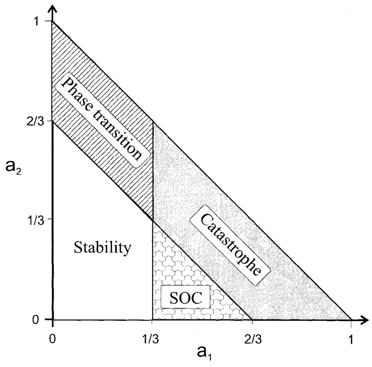


Fig. 5. Different parametric areas for a system with two types of defects. The triangle is divided by two straight lines: $a_1 = 1/3$ and $a_1 + a_2 = 2/3$, where a_i $(i = 1, 2)$ is a fraction of elements with defects of type *i* (after Shnirman and Blanter, 1999).

and relative activity on different faults in the Vrancea region were studied (see Fig. 7) as functions of driving forces (Panza et al., 1997; Soloviev et al., 1999a,b). A mantle flow was incorporated into the model to reproduce large intermediate-depth earthquakes (Ismail-Zadeh et al., 1999, 2000). Realistic synthetic earthquake catalogs were produced by the model, enhancing the reliability of the premonitory phenomena which were explored in it. Numerical experiments for various model parameters showed that the spatial distribution of synthetic events was significantly sensitive to directions of block movements. Changes in a synthetic seismicity due to small variations in slab rotation are in overall agreement with the hypothesis of Press and Allen (1995) that small changes in the direction of plate motion control the pattern of seismic release.

Soloviev et al. (1999a,b) applied the model of blocks-and-faults to analyze the dynamics of island

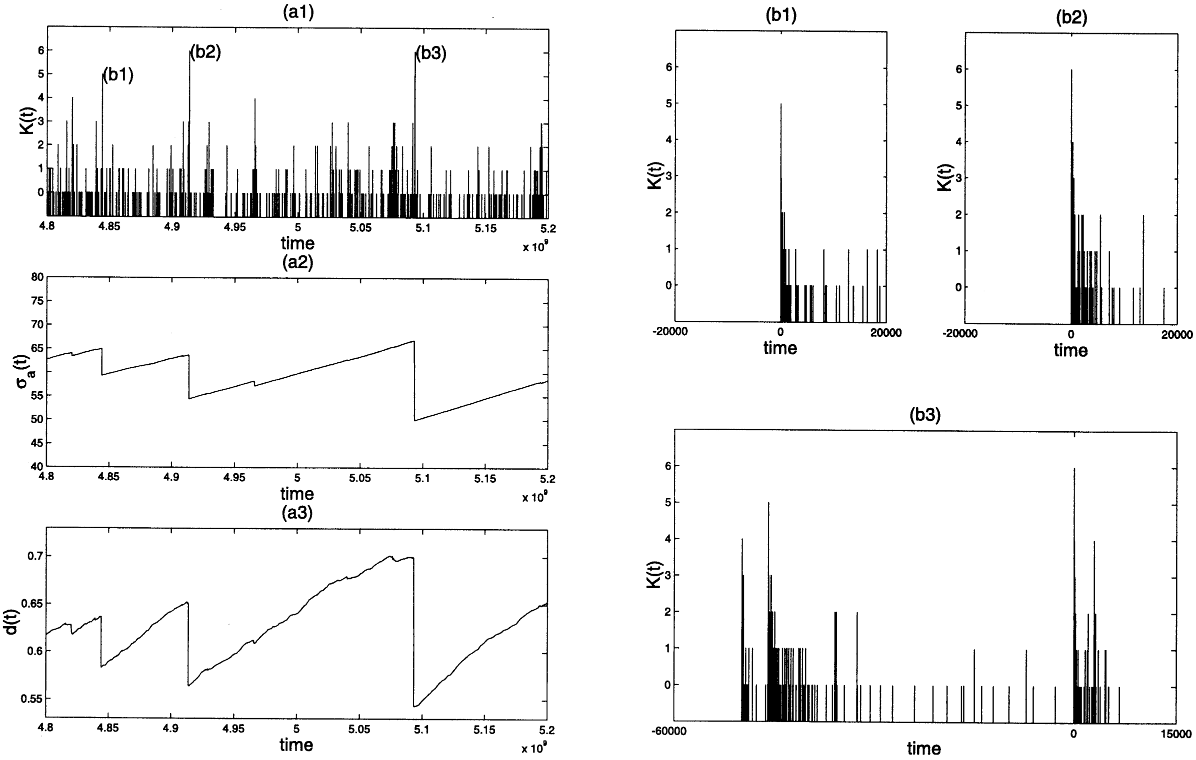
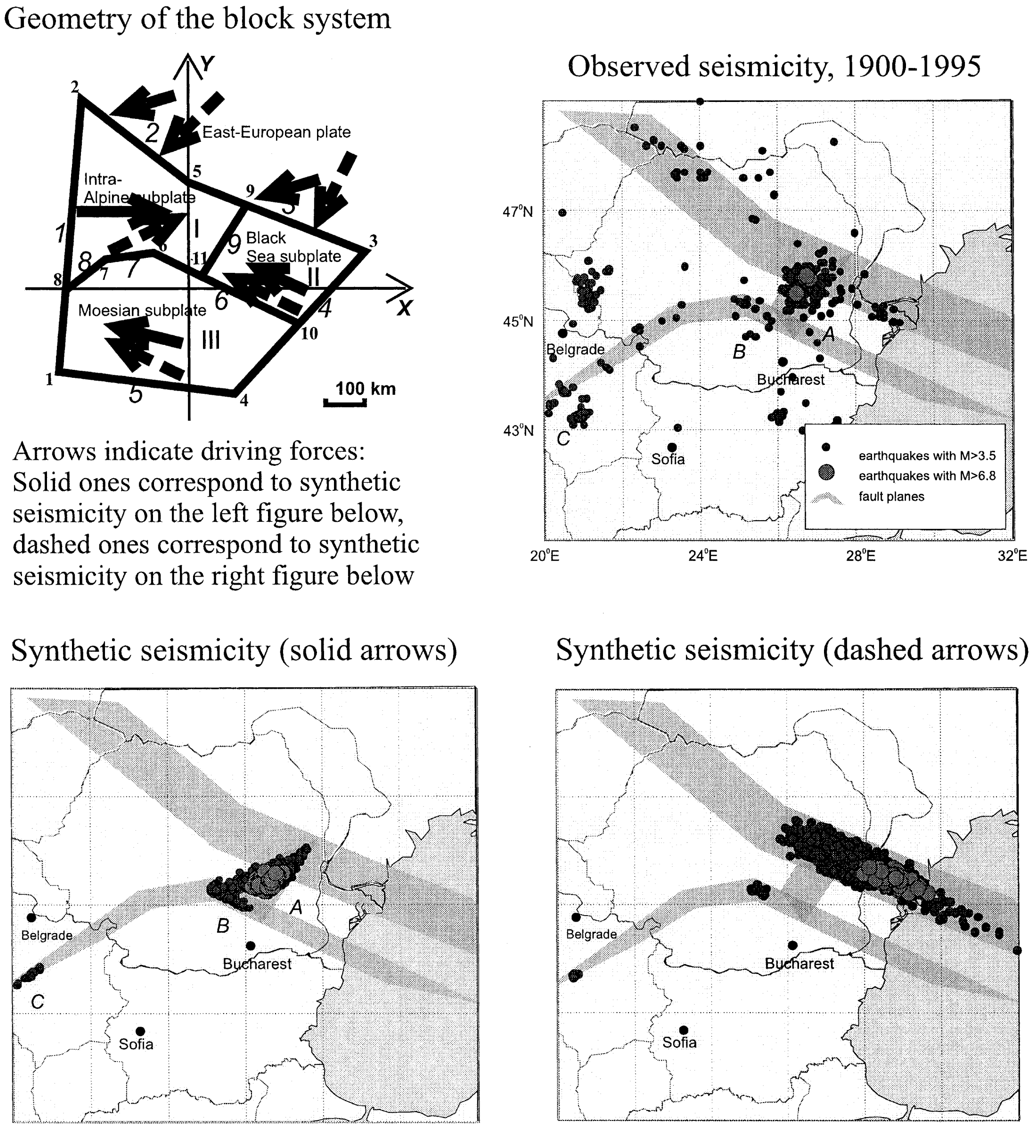


Fig. 6. Direct numerical simulations of earthquake sequences in SOFT model. (a) Large time scale: (a1) sequences of events with hierarchy level K (analog of the magnitude); (a2) temporal change of the average stress; (a3) density of the cracks at the elementary hierarchy level. (b) Detailed time scale for the sequences (b1)–(b3) (after Narteau et al., 2000).


Geometry of the block system

Arrows indicate driving forces: Solid ones correspond to synthetic seismicity on the left figure below, dashed ones correspond to synthetic seismicity on the right figure below

Observed seismicity, 1900-1995

Synthetic seismicity (solid arrows)

Synthetic seismicity (dashed arrows)

Fig. 7. Reconstruction of driving forces from a spatial distribution of seismicity: blocks-and-faults model of seismicity in the Vrancea region (modified after Soloviev et al., 1999a).

arc subduction zones. The structure approximating Sunda Arc (Sunda Isles) was considered. Velocities were specified to define the motion of the oceanic plate and the medium underlying the continent during the simulation. It has been shown that the synthetic seismicity migrates along the arc of the subduction zone. The Gutenberg–Richter curve (frequency–magnitude relationship) of the synthetic seismicity was found to be the closest to the curve of real seismicity when the movements in the model are specified in accordance with the observed relative movement of Australia and Eurasia.

An integral measure called ‘geometric incompatibility’ has been found for instability of the blocks-and-faults system (Gabrielov et al., 1996). This measure integrates the effect of movements in different time scales, from seismicity to GPS and neotectonics. It depicts the instability caused by relative

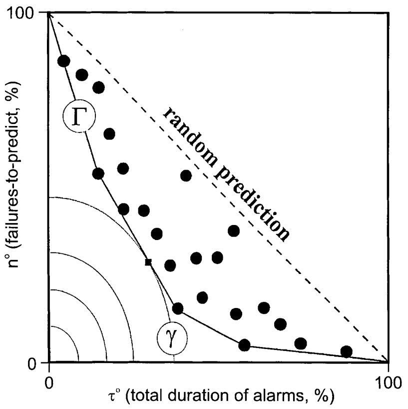


Fig. 8. Error (curve Γ) and risk (curve γ) diagrams used to optimize a prediction algorithm and the response to predictions (after Molchan, 1997b). The dots correspond to different versions of prediction algorithms. Suppose N large earthquakes occurred within a certain area during the time period T covered by prediction. The alarms cover altogether the time, t, and they have missed $n \leq N$ large earthquakes. The quality of prediction is characterized by a dimensionless parameter, $n^0 = n{:}N$, $t^0 = t{:}T$. The tradeoff between n^0 and t^0 depends on the choice of adjustable parameters. Performance of an algorithm is characterized by the error curve, Γ, which is the lower envelope of the dots on the diagram. Lines show the isolines of the loss function, γ, depicting the cost of safety measures minus the damage which they prevent. The point where γ and Γ touch each other determines both the minimal achievable loss and the optimal set of adjustable parameters in the prediction algorithm.

movements of the corners of blocks, leading to concentration of stress, strain, and fracturing around fault intersections. As a result, mosaic structures called 'nodes' are formed (e.g. Gelfand et al., 1976; Alekseevskaya et al., 1977). The nodes are well known in structural geology and geological prospecting; however, they are often overlooked in seismology despite the fact that large earthquakes nucleate there.

2.2.3. Seismic source and stress field

Hardly any geophysical field commands such attention in earthquake prediction research as the stress field. Methods to extract new prediction-relevant information on the stress field from seismological data have been developed.

(1) Reconstruction of the stress field in seismically active faults bypassing the determination of source mechanism. This allows to use huge amounts of data (currently about 2.5 millions of arrivals) on low magnitude earthquakes for which mechanisms cannot be determined to monitor the temporal changes of the stress field (Lander et al., 1997).

(2) Methods to determine fine structure of a seismic source (matrix of the second spatial–temporal moments of slip rate density distribution) from body and surface wave spectra; this is potentially relevant to the transition to short-term prediction (Bukchin, 1995).

3. Applications to natural disaster reduction: from earthquake prediction to earthquake preparedness

Earthquake prediction developments open a possibility to reduce the casualties and economic losses inflicted by earthquakes, notwithstanding the limited accuracy of forecasts (e.g. Snieder and van Eck, 1997, and references therein). The results of the research described in the chapter provide a disaster management authority with methodology allowing the use of forecasts with their currently realistic accuracy.

The key to this is escalation or de-escalation of safety measures (scenarios of response to a forecast) depending on the content of the current prediction that includes time-interval, area, and magnitude range covered by the alarm and the rates of errors of both kinds for the prediction method.

A stock of possible safety measures is actually prepared by the authorities in many countries. The strategy of earthquake prediction developed the interface allowing to select the appropriate measures (Molchan, 1994).

This point could be illustrated by the case history of the 1994 Northridge earthquake, which caused about $30 billions of damage. Based on the NLE method, the prediction that the 1992 Landers earthquake will be followed by a magnitude 6.6 or greater one was published in advance (Vorobieva and Levshina, 1994; Vorobieva, 1999). A safety inspection in response to this prediction would be justified, if even a few percent of the damage were prevented by it.

Prediction phases. Earthquake prediction consists of a step-by-step reduction of the area and time interval where a large earthquake is to occur. Depending on the characteristic duration of alarm, five phases of prediction are usually distinguished: background as represented by maps of average recurrence time of earthquakes in different magnitude ranges; long-term (tens of years); intermediate-term (years to months); short-term (weeks to days); immediate (hours to minutes). So far, only the background phase is routinely implemented. The algorithms developed provide an opportunity of routine advance prediction on the intermediate-term scale.

Quality of a prediction is characterized by an error diagram (Fig. 8). It shows the tradeoff between errors of the two kinds — duration of alarms and rate of failures-to-predict. An important additional characteristic is the rate of false alarms.

Preparedness measures are classified in similar manner. Permanent (background) measures include land use restrictions, building codes, insurance, civil defense preparedness, and R&D. Temporary measures activated in response to prediction form an escalating sequence. It includes an enhancement of permanent measures (simulated alarms, tightening of safety control, etc.); mobilization of post-disaster services; partial suspension of high-risk industrial activities; activation of emergency legislation, all the way up to martial law; partial evacuation of population, etc. up to the red alert.

These measures are required in different forms on local, provincial, national, and international levels. Different lead times, from seconds to years, are required to activate different measures; having different costs, they can be realistically maintained for different time periods, from hours to decades; they have to be spread over different area — from selected sites to large regions. Different groups of measures cannot replace each other, for example, background measures cannot replace many temporary ones.

Cost/benefit ratio of preparedness measures is characterized by the loss curves, also shown in Fig. 8; they define the tradeoff between the costs of response to forecast and of post-disaster mitigation. The optimal set of preparedness measures is near the tangent point of the loss curve and the error curve, characterizing a given prediction method. Methods of such optimization were developed on the basis of optimal control theory (Molchan, 1994, 1997b).

4. Conclusions

About a decade ago, the powerful universal concepts of non-linear dynamics, including chaos, self-organized criticality, and scale invariance, were introduced into the dynamics of the lithosphere. Non-linear dynamics brought along a fresh flow of new ideas and methods (Keilis-Borok, 1990; Shaw et al., 1992; Turcotte et al., 1992; Newman et al., 1994; Sornette and Sammis, 1995; Turcotte, 1999). This paper sums up the research in the non-linear dynamics of the lithosphere and intermediate-term earthquake prediction for the last decade and presents a part of general quest for a unifying theory of the critical phenomena in the lithosphere.

Results of the research described here may be summed up as follows.

(1) A capacity to predict between 70 and 90% of large earthquakes, with alarms occupying 10–20% of the time–space considered, allows the prevention of much of the damage from earthquakes, though far from the whole damage.

(2) A large uniform systematic collection of confirmed predictions, false alarms, and failures-to-predict has been accumulated to date worldwide (Keilis-Borok and Kossobokov, 1990; Kossobokov et al., 1999; Rotwain and Novikova, 1999; Vorobieva, 1999). This is unique material for a new search for better prediction methods, e.g. short-term ones.

(3) Short-term seismic precursors consisting of clusters of activity are often seen within intermediate-term alarms, indicating a possibility of prediction in the third approximation.

(4) Regional differences in premonitory phenomena are beginning to emerge.

(5) Findings in modeling of premonitory phenomena open a new line — ‘prediction of predictability’ — in earthquake prediction research. Since scenarios of transition to a large earthquake may be different and may alternate, several challenging problems arise: to recognize the ongoing scenario; to predict the transfer from one scenario to another; finally, to include adaptation to such changes into the application of prediction algorithms in practice. And obviously, a new capability to explore premonitory phenomena is created.

(6) Introduction of fluid migration into fault systems allows for models of blocks-and-faults

dynamics to reproduce specific features of observed seismicity.

(7) Utilization of the geometric incompatibility for earthquake prediction.

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