Earth Planets Space, **56**, 715–724, 2004

Advance short-term prediction of the large Tokachi-oki earthquake, September 25, 2003, M = 8.1 A case history

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(Received November 27, 2003; Revised May 10, 2004; Accepted May 26, 2004)

Tokachi-oki earthquake in northern Japan, September 25, 2003, magnitude 8.1, was predicted six months in advance by a short-term earthquake precursor "*chain*" that reflects an increase of the correlation range among small earthquakes. This prediction is part of the ongoing test of a new short-term prediction method; the test covers territories of Japan, California, and Eastern Mediterranean. Qualitatively, precursory chain is a dense sequence of small earthquakes that had quickly extended over a long distance. A strong earthquake is expected within nine months after such chain is formed, in its formally defined vicinity. Chains are analyzed in conjunction with intermediate-term precursors, emerging with characteristic lead time of years. Methodology of prediction is named "Reverse Tracing of Precursors" (*RTP*), since precursors are considered in the reverse order of their appearance. That allows detecting short-term precursors not detectable with direct order of analysis. *RTP* was tested retrospectively for California, Japan, and Eastern Mediterranean, where 22 more strong earthquakes occurred during the time considered. The concept underlying *RTP* is interaction of lithosphere dynamics on different temporal scales. The described results enhance our fundamental understanding of lithosphere dynamics and, on the practical side, our capability for earthquakes preparedness.

Key words: Advance short-term earthquake prediction, earthquake correlation, Tokachi-oki.

1. Case History

A prediction method remains hypothetical until validated by advance predictions. Here we describe the first results of ongoing experiment in advance short term prediction of strong earthquakes by the "Reverse Tracing of Precursors" (*RTP*) method (Keilis-Borok *et al*., 2004). This method considers precursors in reverse order of their appearance. First we detect the candidates for short-term precursors emerging months before the earthquake targeted by prediction; in our case the candidates are the chains of small earthquakes capturing the rise of earthquake correlation range. Then we check, for each chain, whether it was preceded within few years by intermediate-term precursors in its close vicinity (Section 2.3). If yes, we regard this chain as a precursory one; in prediction it would start a short-term alarm. If *not*—the chain is disregarded and alarm is not started. Thus we consider the short-term patterns (chains) first, although they emerge later. This makes possible to detect the precursors undetectable by direct analysis.

Following is a case history of prediction of Tokachi-oki earthquake.

March 27, 2003: Precursory chain emerged.

July 2, 2003: Precursory chain is put on record, as shown in Fig. 1 and Table 1; they are copied from the poster presented on July 2, 2003 at the Hagiwara Symposium on earthquake prediction during the XXIII Assembly of IUGG.[1]

Sept. 25, 2003: Tokachi-oki earthquake (near Hokkaido island, Japan, magnitude 8.1) occurred as predicted, that is in the vicinity of the chain (Fig. 1), almost six months after the chain emerged (Table 1); this is within the duration of alarm, 9 months, set up by retrospective analysis.

This completes the case history per se. In Section 2 we briefly describe prediction methodology, in Section 3—its applications.

2. Methodology[2]

The problem of earthquake prediction consists of narrowing down the time interval, area, and magnitude interval, where a strong earthquake should be expected. Five major stages of earthquake prediction are usually distinguished. *The background* stage is estimation of seismic hazard. Other

[1]Comparing with the figures in the poster we added for convenience the epicenter of the subsequent Tokachi-oki earthquake.

[2]*RTP* methodology takes advantage of the concept and ample know-how developed during previous research in non-linear dynamics and intermediate-term earthquake prediction. To make the present paper self-contained one may add to it the overview of previous findings (Keilis-Borok, 2002) available at http://arjournals.annualreviews.org/doi/full/10.1146/annurev.earth.30.100301.083856. More detailed description of these findings is given in (Keilis-Borok and Soloviev (eds.), 2003) and references therein.

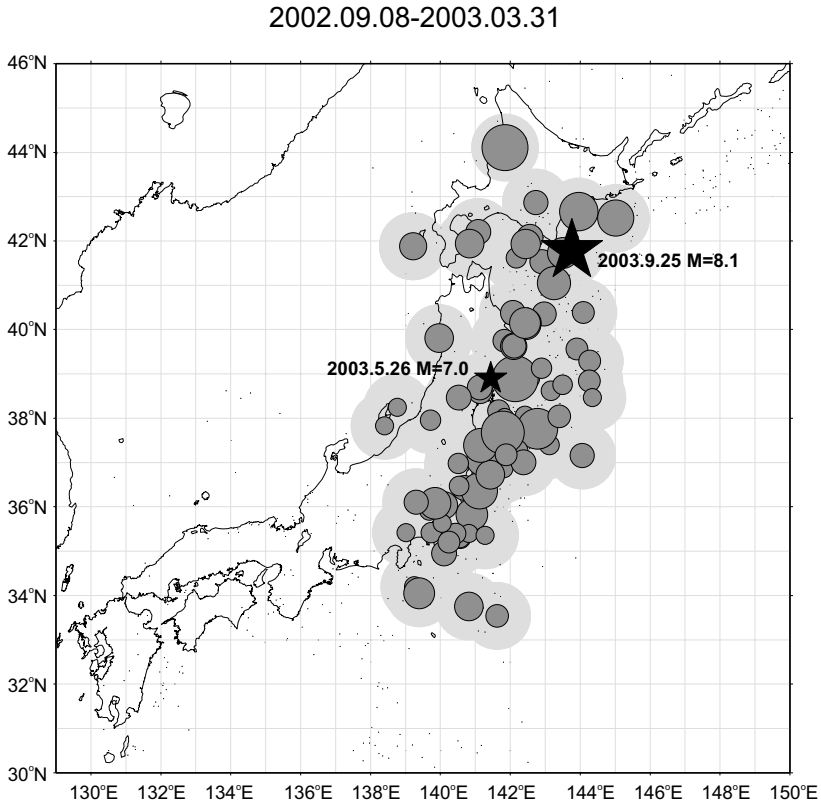

Fig. 1. Japan: precursory chain reported in Shebalin *et al.* (2003). Circles show epicenters forming the chain; their size is proportional to magnitude. The shadowed area shows R-vicinity of the chain. Large star shows the epicenter of Tokachi-oki earthquake, M = 8.1, predicted by the chain 6 months in advance.

Table 1. Precursory chain of earthquakes before Tokachi-oki earthquake, M = 8.1, September 25, 2003.

#	Date	m	24	2002.10.25	4.5	48	2002.12.20	3.7	72	2003.02.13	3.9
1	2002.09.08	3.8	25	2002.10.26	4.8	49	2002.12.28	3.8	73	2003.02.14	3.8
2	2002.09.09	4.1	26	2002.10.31	4.1	50	2003.01.06	3.6	74	2003.02.16	5.0
3	2002.09.17	3.8	27	2002.11.02	4.0	51	2003.01.14	3.7	76	2003.02.20	3.8
4	2002.09.25	4.0	29	2002.11.04	3.7	52	2003.01.15	4.2	77	2003.02.21	3.6
5	2002.09.25	3.7	28	2002.11.03	6.1	53	2003.01.15	3.9	75	2003.02.19	6.1
6	2002.09.28	4.4	30	2002.11.14	4.0	54	2003.01.24	3.8	78	2003.02.23	4.2
7	2002.09.30	4.2	31	2002.11.14	4.1	55	2003.01.25	4.0	79	2003.02.24	4.6
8	2002.09.30	3.6	32	2002.11.16	4.2	56	2003.01.27	4.2	80	2003.02.26	3.6
9	2002.10.01	3.6	33	2002.11.20	4.2	57	2003.01.27	3.9	81	2003.02.27	3.7
10	2002.10.02	3.6	34	2002.11.22	3.6	58	2003.01.27	3.7	82	2003.02.28	4.1
11	2002.10.03	3.7	35	2002.11.22	3.9	59	2003.01.28	3.7	83	2003.03.02	4.0
12	2002.10.03	3.9	36	2002.11.22	4.0	61	2003.01.28	3.6	84	2003.03.02	3.8
13	2002.10.05	3.8	37	2002.11.24	4.3	60	2003.01.28	4.9	86	2003.03.04	4.4
14	2002.10.07	3.9	38	2002.11.26	3.7	62	2003.01.30	3.7	87	2003.03.09	3.6
16	2002.10.11	3.9	39	2002.11.30	5.2	63	2003.01.31	3.8	85	2003.03.03	5.8
15	2002.10.11	5.2	40	2002.12.01	5.4	64	2003.01.31	4.4	88	2003.03.09	4.5
17	2002.10.11	3.7	42	2002.12.04	3.6	65	2003.02.03	4.3	89	2003.03.09	3.9
19	2002.10.13	4.2	41	2002.12.04	4.7	66	2003.02.04	3.9	90	2003.03.13	4.8
18	2002.10.12	5.6	43	2002.12.08	4.1	67	2003.02.08	3.9	91	2003.03.17	4.1
21	2002.10.17	3.6	44	2002.12.09	4.6	68	2003.02.11	4.5	92	2003.03.18	3.6
20	2002.10.16	4.8	45	2002.12.11	4.5	69	2003.02.12	3.6	93	2003.03.26	4.1
22	2002.10.20	4.1	46	2002.12.18	4.6	70	2003.02.12	4.5	94	2003.03.27	4.7
23	2002.10.21	5.2	47	2002.12.20	4.1	71	2003.02.12	4.7			

stages, fuzzily divided, differ in characteristic duration (lead time) of alarms: *long-term* (tens of years); *intermediate-term* (years); *short-term* (months), and *immediate* (days and less). To the best knowledge of the authors most if not all prediction methods, validated one way or another, concern the first three stages; the very possibility of short-term and immediate predictions is often doubted (Geller, 1997), while their paramount importance is well recognized. Here, we describe underlying concept of *RTP* (2.1) and its major elements (2.2–2.5).

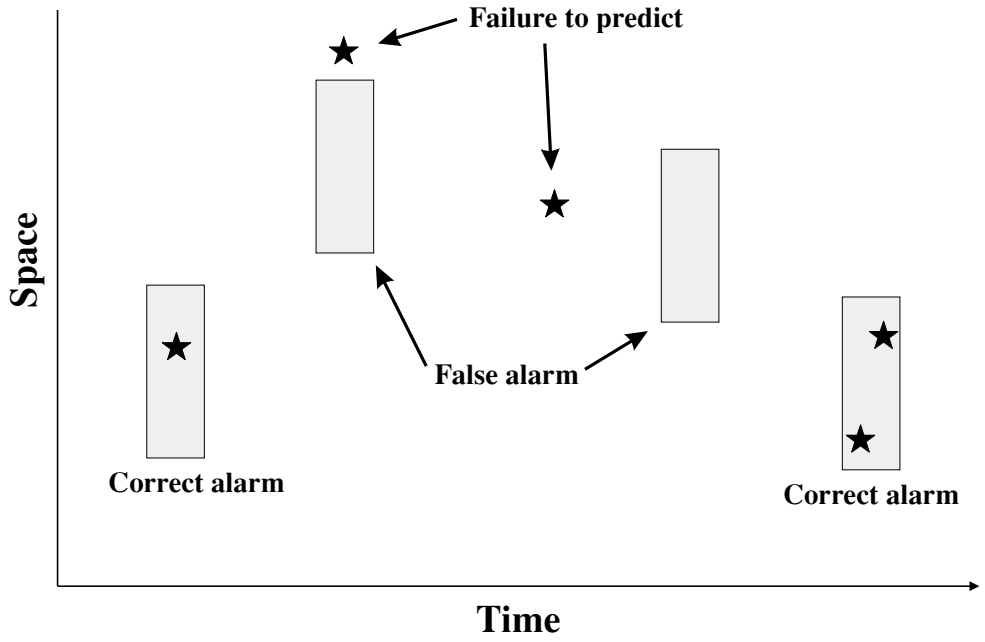

Fig. 2. Possible outcomes of prediction (Keilis-Borok *et al.*, 2004). Stars mark strong earthquakes, targeted by prediction. A box represents the time-space covered by an alarm. A prediction is correct if a strong earthquake occurs within an alarm. Otherwise, this is a false alarm. Failure to predict is the case when a strong earthquake occurs outside of an alarm. Probabilistic component of prediction is represented by the score of errors (Molchan, 2003).

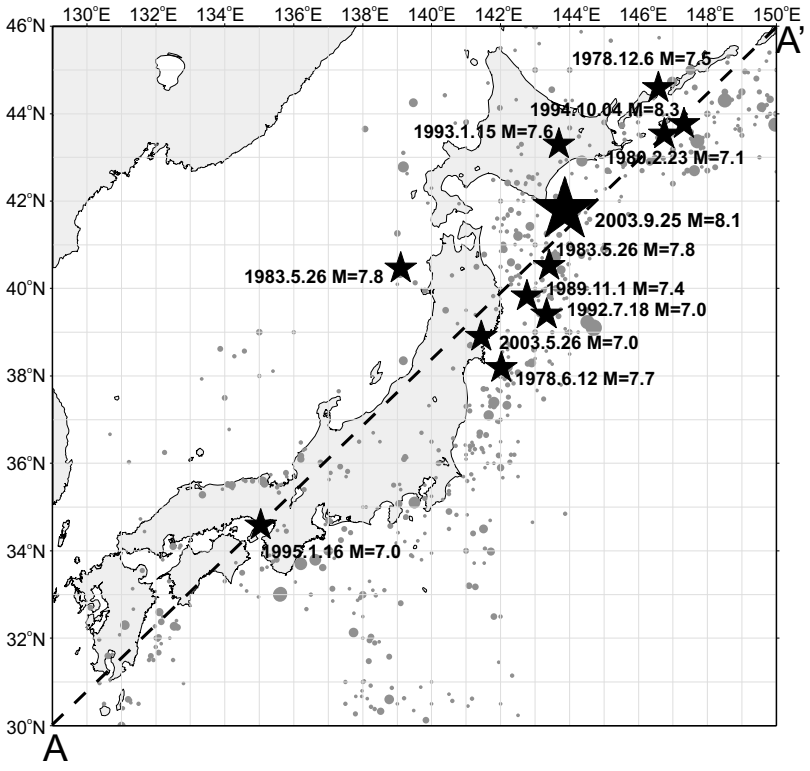

Fig. 3. Japan: territory considered. Stars mark strong earthquakes, targeted for retrospective prediction. Dots show background seismicity for the time considered: epicenters of earthquakes with magnitude $M \geq 5$ with aftershocks eliminated. Large star is the epicenter of Tokachi-oki earthquake, which was predicted by precursory chain, shown in Fig. 1. Dashed line is used in time-distance projection shown in Fig. 4 below.

2.1 Underlying concept

The process leading to strong earthquakes is not localized near incipient earthquake source but, being a component of geodynamics, extends over large time and space and evolves in multiple scales (Aki, 2003; Bird, 1998; Blanter and Schnirman, 1997; Bowman *et al.*, 1998; Gabrielov *et al.*, 2000a; Jin *et al.*, 2003; Keilis-Borok, 1996, 2002; Keilis-Borok and Soloviev, 2003; Newman *et al.*, 1994; Rundle *et*

Table 2. Functions F_P capturing different premonitory phenomena.

Functions are computed in R-vicinity of a chain within T years preceding it. They are defined in the "event window" (Prozorov and Schreider, 1990; Keilis-Borok *et al.*, 2002) that is for the sequences of N consecutive earthquakes ($j-N+1$, $j-N+2, \ldots, j$); value of a function $F_P(t)$ is attributed to the moment of the last earthquake in a sequence, $t = t_j$.	
	Rise of activity
"Activity"	$U(t_j) = \frac{1}{t_j - t_{j-N+1}}$
"Sigma"	$\Sigma(t_i) = \sum_{k=j-N+1}^{j} 10^{M_k}$
"Acceleration of magnitudes"	$Acm(t_j) = \frac{2}{N}\left\{\sum_{k=j-N/2}^{j} M_k - \sum_{k=j-N+1}^{j-N/2} M_k\right\}$
"Acceleration of number of earthquakes"	$Acn(t_j) = \frac{2}{N}\left\{\sum_{k=j-N/2}^{j} \frac{1}{t_k - t_{k-1}} - \sum_{k=j-N+1}^{j-N/2} \frac{1}{t_k - t_{k-1}}\right\}$
	Rise of clustering
"Swarm"	$W(t_j) = \frac{A_r^{\cap}}{\pi r^2}$
"b-micro"	$b_\mu = \sum_{k=j-N+1}^{j} \sum_l 10^{M_{kl}}$
	Rise of correlation range
"Accord"	$A(t_j) = \frac{A_r^{\cup}}{\pi r^2}$
	Transformation of G.-R. relation
"Gamma"	$\gamma(t_j) = \frac{2}{N} \sum_{M_j \geq M_{1/2}} M_k$
Notations:	
$M_{1/2}$—median of magnitudes.	
$A_r^{\cup}$—area of the union of the circles of radius r centered at N epicenters in the sequence; their sequence numbers are $j-N+1$, $j-N+2, \ldots, j$.	
$A_r^{\cap}$—total area of intersections of two or more circles of radius r in the same sequence.	
M_{kl}—magnitudes of the aftershocks of the k-th main shock, $l = 1, 2, \ldots$; as usually (e.g. Kossobokov and Shebalin, 2003), we consider immediate aftershocks within given time and magnitude intervals.	

Table 3. Prediction procedure.

DATA: Earthquake catalogue (Section 2.2)

↓

PREPROCESSING of catalogue: Identification of aftershocks (Section 2.2)

↓

DETECTION OF CHAINS (Section 2.3) and monitoring their extension (Section 2.5) (absorbing one by one the subsequent earthquakes)

↓

DETERMINATION OF R-VICINITY of each chain (Section 2.3), and its consecutive extensions, if any

↓

DETECTION OF INTERMEDIATE-TERM PATTERNS emerging in the R-vicinity of each chain, within T years before the chain started (Table 2, Section 2.3)

↓

PATTERN RECOGNITION OF PRECURSORY CHAINS (Section 2.4). Algorithm "Hamming distance" was used so far

↓

DECLARATION OF ALARM (Section 2.5): It predicts a target earthquake in the R-vicinity of the chain, and in the time interval $(t_e, t_e + \tau)$; here t_e is the moment of the last earthquake in the chain; τ is the initial duration of an alarm; if a chain extends, the alarm is extended too.

Table 4. Parameters of the chains.

Region	$M_{\min}$	r_0, km	c	τ_0, days	k_0	l_0, km
Central California	2.9	50	0.35	30	6	200
Southern California	2.9	50	0.35	20	6	200
Japan	3.6	50	0.35	20	10	350
Eastern Mediterranean	3.0	50	0.35	40	6	200

al., 2000; Scholz, 1990; Sornette, 2000; Turcotte, 1997; Zaliapin *et al.*, 2003).

RTP captures interaction of geodynamics on the intermediate- and short-term scales. Among earthquake precursors reflecting this process are multi-scale premonitory seismicity patterns—the spatio-temporal patterns of seismicity that emerge as a strong earthquake approaches (Caputo *et al.*, 1983; Gabrielov *et al.*, 2000b; Keilis-Borok, 1996; 2002; Knopoff *et al.*, 1996; Kossobokov and Shebalin, 2003; Ma *et al.*, 1990; Mogi, 1985; Prozorov and Schreider, 1990; Turcotte, 1997; Shaw *et al.*, 1992; Zaliapin *et al.*, 2002, 2003; Sykes and Jaume, 1990; Kanamori, 2003). Patterns used in *RTP* reflect two conditions necessary and sufficient to generate a target earthquake: accumulation of energy, to be released by that earthquake; and accumulation of instability, necessary to release this energy triggering that earthquake. Energy is carried by the stress field, instability—by {strength-stress} field.

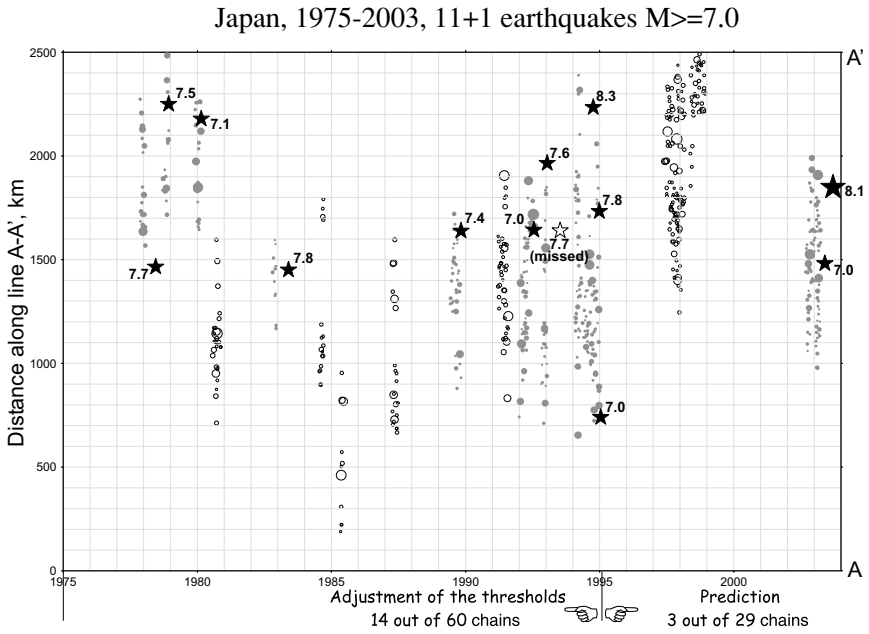

Fig. 4. Japan: chains and strong earthquakes on the time-distance plain. Distance is counted along the dashed line shown on the map in Fig. 3. Filled circles show precursory chains, open circles show the false alarms. Other notations are the same as in Fig. 1.

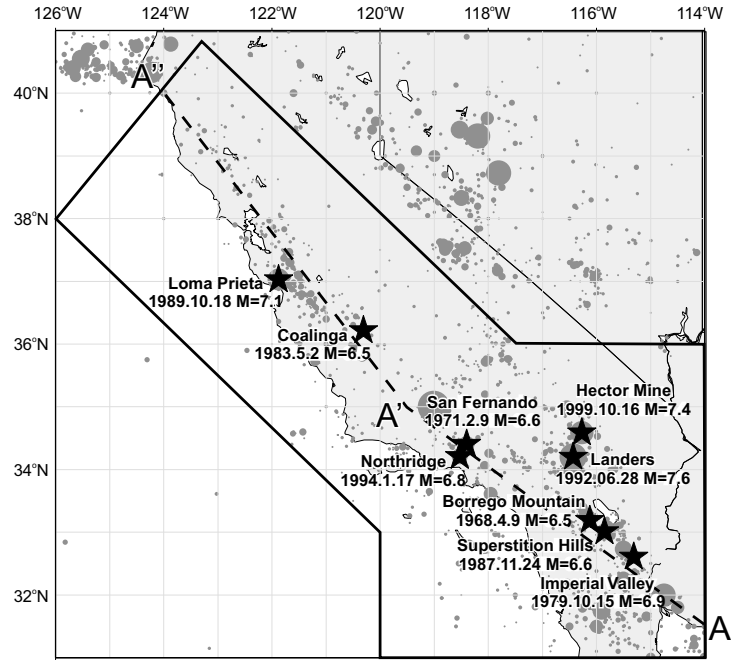

Fig. 5. Southern and Central California: territory considered. Dots show background seismicity: epicenters of earthquakes with magnitude $M \geq 3$ with aftershocks eliminated. Other notations are the same as in Fig. 3.

2.2 Chain—a candidate for a short-term precursor (Keilis-Borok *et al.*, 2004)

Definition. A chain is defined as a generalization of patterns *Roc* and *Accord* capturing premonitory increase of earthquakes correlation range; these patterns have been found in the modeled seismicity (Gabrielov *et al*., 2000a, b) and then in observations (Shebalin *et al*., 2000; Keilis-Borok *et al*., 2002). Let us call two earthquakes "*neighbors*" if: (i) the distance between their epicenters does not exceed a threshold r; and (ii) the time interval between them does not exceed a threshold τ_0. A chain is the sequence of earthquakes connected by the following rule: each earthquake has at least one neighbor in that sequence and no neighbors outside the sequence.

To connect in a chain only the unusually close earthquakes we normalize the threshold r as follows: $r = r_0 10^{c(\underline{m}-2.5)}$, where $\underline{m}$ is the magnitude of the smaller earthquake in a pair considered.

Let k be the number of earthquakes in a chain, and l—the maximal distance between their epicenters. To ensure that our chains reflect a considerable rise of the earthquake correlation range, we consider only the chains with k and l

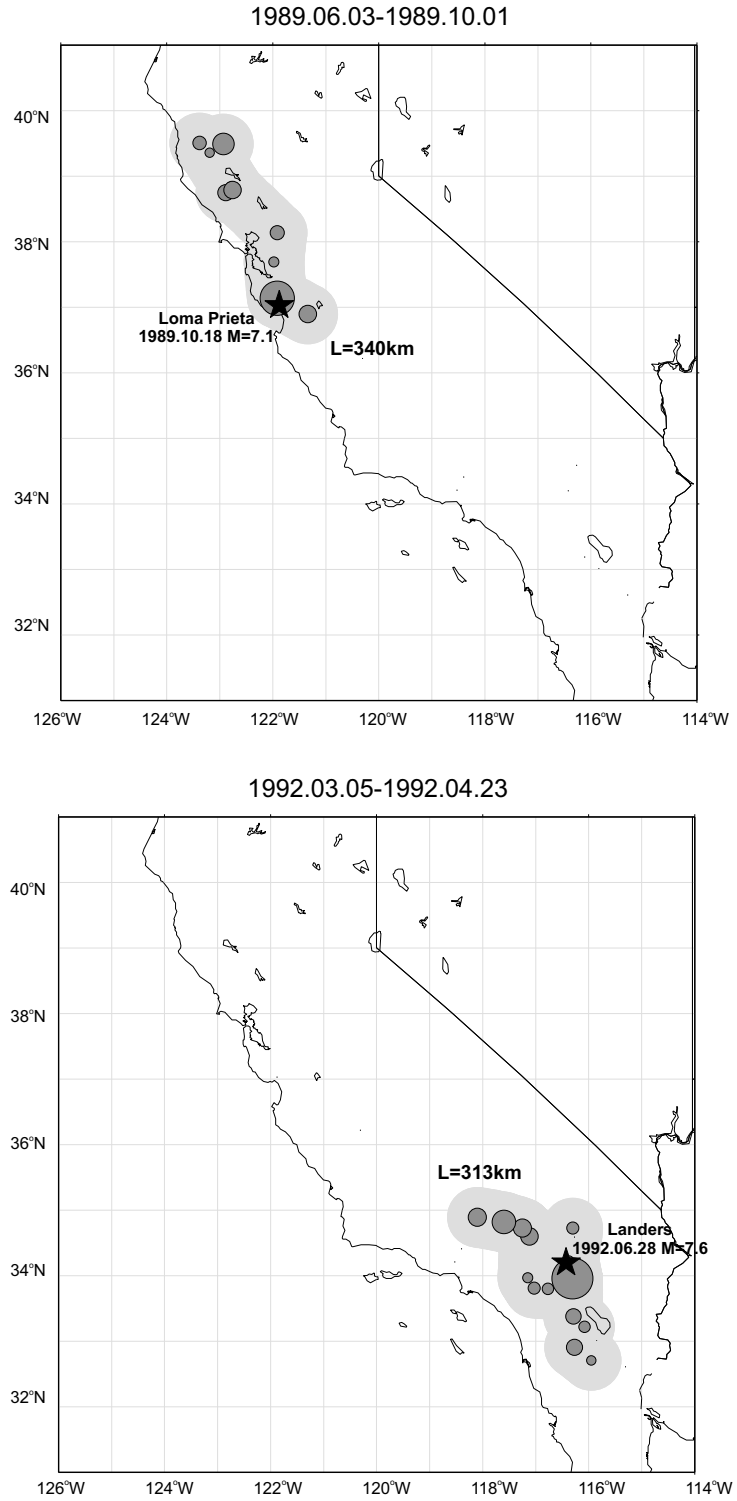

Fig. 6. Southern and Central California: examples of precursory chains. Notations are the same as in Fig. 1.

sufficiently large, $k \geq k_0$ and $l \geq l_0$.

The need for RTP. Data analysis demonstrates that the chains thus defined do precede most of the target earthquakes with a lead time of months; however up to 80%–90% of the chains would give false alarms if used as short-term precursors. With *RTP* approach we drastically reduce this rate by considering the chains in conjunction with intermediate-term precursors.

Data source—the earthquake catalogs. Precursors considered are premonitory seismicity patterns determined by analysis of an earthquake catalog with aftershocks eliminated; however the number of immediate aftershocks is retained for each main shock (Keilis-Borok, 2002) Accordingly, earthquake catalog is represented as $\{t_j; \varphi_j, \lambda_j, h_j; m_j; b_j\}$, $j = 1, 2, \ldots$. Here t_j is the time of an earthquake, $t_j >= t_{j-1}$; φ_j and λ_j—latitude and longitude of its epicenter; h_j—focal depth; and m_j—its magnitude. We consider the earthquakes with magnitude $M \geq M_{\min}$. Focal depth is not used in this

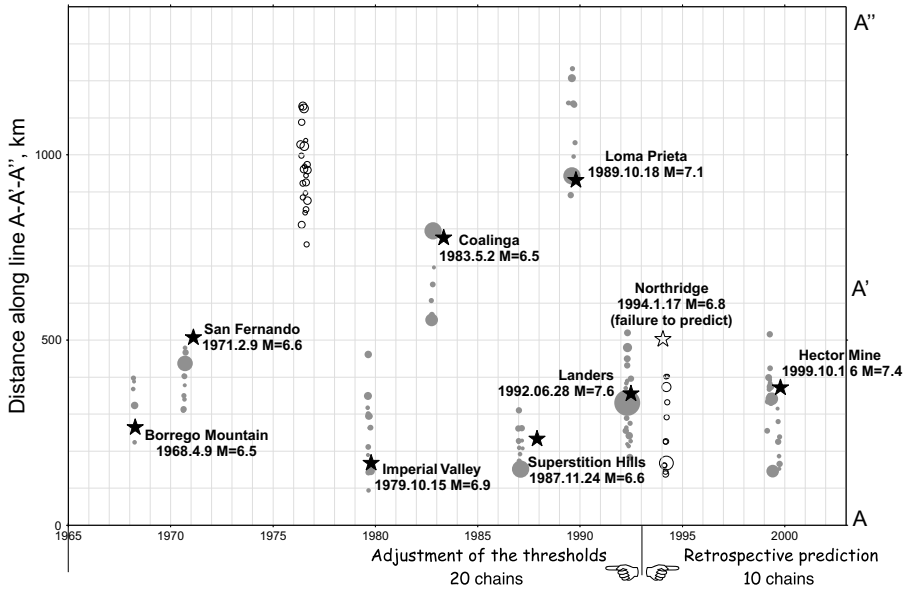

Fig. 7. Southern and Central California: chains and strong earthquakes on the time-distance plain. Notations are the same as in Fig. 4.

study, except that we consider the earthquakes with $h_j \leq 100$ km. Aftershocks have been identified by the windowing described in Keilis-Borok *et al.* (2002) and Knopoff *et al.* (1996).

2.3 Intermediate-term patterns discriminating precursory and non-precursory chains

The problem. We hypothesize that a precursory chain (as opposed to a false alarm) is preceded by intermediate-term precursors formed in its vicinity. If that hypothesis is correct, reverse order of analysis has an important advantage: it indicates the areas and time intervals where one should look for the intermediate-term precursors. To test that hypothesis we have to define formally these precursors and the vicinity of the chain.

R-vicinity of a chain. It is defined as the union of circles of radius R centered at the epicenters of the chain; its border is a smoothed envelope of these circles (Keilis-Borok *et al.*, 2004). In the R-vicinity of each chain we will look for intermediate-term patterns within T years preceding the chain, that is in the time-interval $(t_0 - T, t_0)$; here t_0 is the time of the first earthquake in the chain.

Intermediate-term patterns (Keilis-Borok, 1990; Keilis-Borok and Shebalin, 1999; Kossobokov and Shebalin, 2003; Keilis-Borok *et al.*, 2004). We consider here eight patterns; four of them capture premonitory rise of seismic activity, two-rise of clustering, one-rise of correlation range (more specifically—spreading of seismicity over the fault network) and one—transformation of magnitude—frequency (Gutenberg-Richter's) relation. Let us briefly remind their formal definition (Keilis-Borok, 1990, 1996, 2002; Keilis-Borok and Shebalin, 1999; Gabrielov *et al.*, 2000b; Kossobokov and Shebalin, 2003; Zaliapin *et al.*, 2002, 2003). To detect a pattern P we compute a function $F_P(t)$ defined on the earthquake sequence. Emergence of a pattern at the moment t is captured by condition $F_P(t) \geq C_P$, where C_P is an adjustable threshold. Functions considered here are given in Table 2.

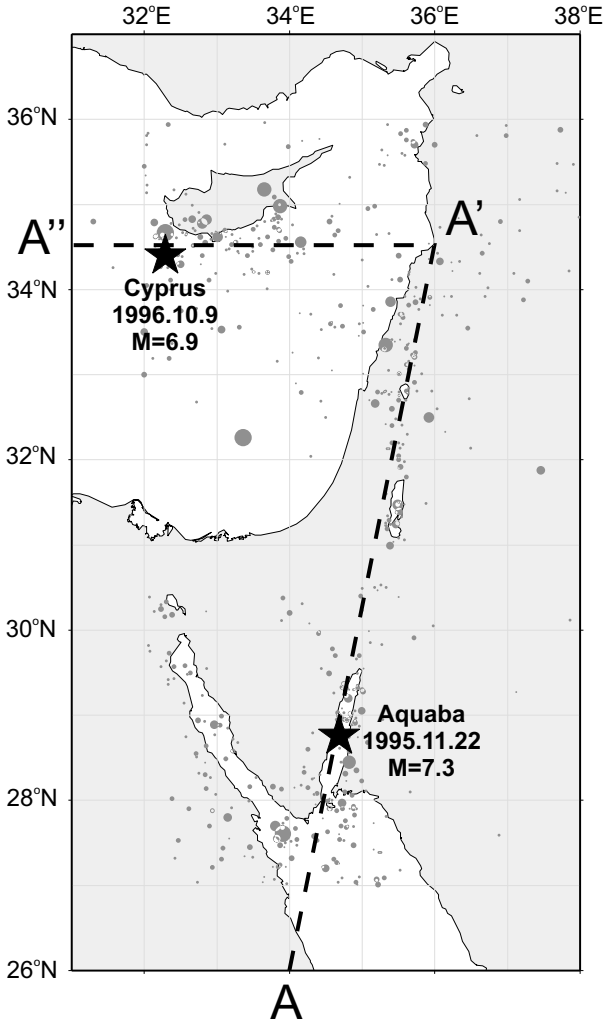

Fig. 8. Eastern Mediterranean: territory considered. Dots show background seismicity: epicenters of earthquakes with magnitude $M \geq 3$ with aftershocks eliminated. Other notations are the same as in Fig. 3.

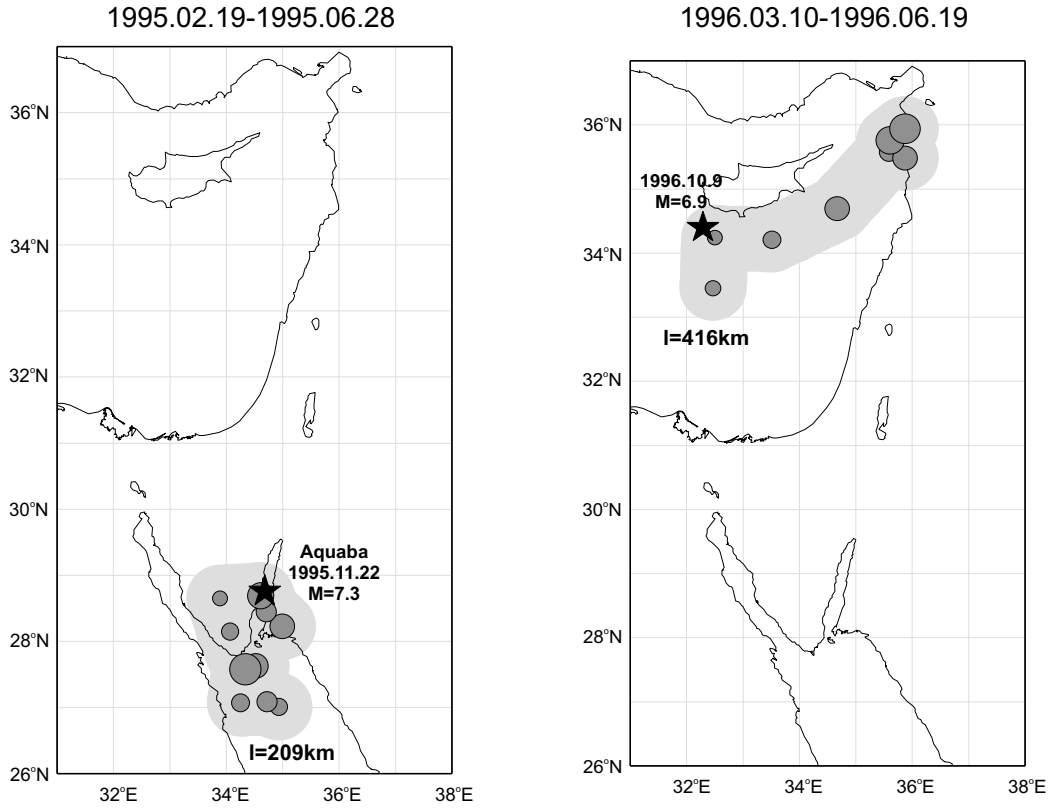

Fig. 9. Eastern Mediterranean: examples of precursory chains. Notations are the same as in Fig. 1.

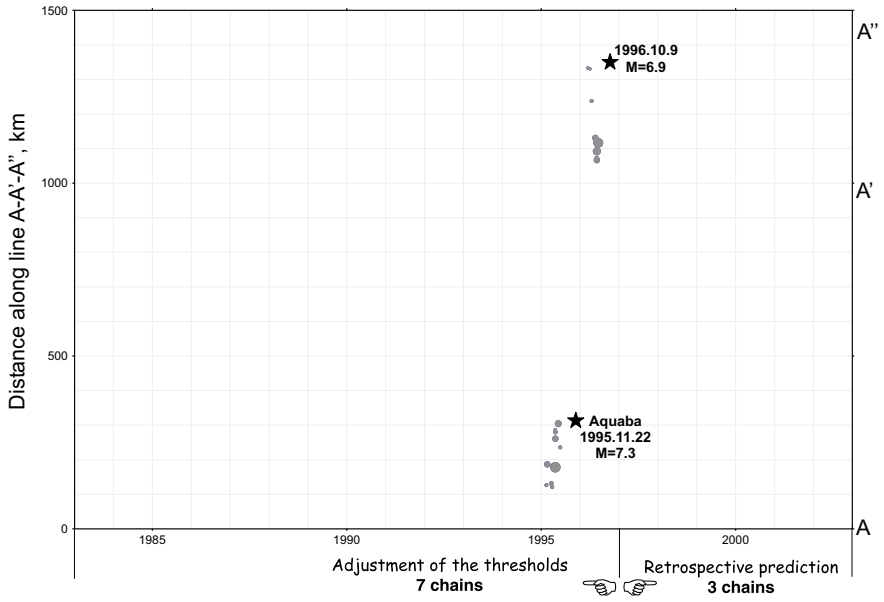

Fig. 10. Eastern Mediterranean: chains and strong earthquakes on the time-distance plain. Notations are the same as in Fig. 4.

Adjustment of parameters. We had to adjust for each region the values of numerical parameters in definition of the chains and intermediate-term patterns, and the values of thresholds C_P. Each threshold C_P is determined automatically; it minimises the total rate of the errors of each kind—failures to predict and false alarms—in prediction with a single pattern P. As always, the retrospective results should be tested on independent data, not used in obtaining these results (Gelfand *et al.*, 1976; Keilis-Borok and Soloviev, 2003). To save the data for such tests, we used for adjustment only the first two thirds of the chains in each region. The remaining chains have been used to estimate the rate of the errors.

2.4 Recognition of precursory chains

We have now a classical pattern recognition problem: to find a combination of patterns that discriminate precursory and non-precursory chains. We used the relatively simple pattern recognition algorithm "Hamming distance" that has

a good track record in geophysics (e.g. Vorobieva, 1999). Its application gives the following recognition rule. Each of the eight patterns listed in Section 2.3 was computed with eight sets of numerical parameters, so that altogether 64 patterns are considered. A chain is recognized as precursory if it is preceded by C or more different patterns out of 64 considered. Threshold C controls the tradeoff between the rates of false alarms and failures to predict (Molchan, 2003).

2.5 Alarms

Emergence of precursory chain triggers an alarm in its R-vicinity for the τ months; statistics of past alarms, mainly retrospective so far, suggests τ = nine months. An alarm is not called off after a target earthquake occurred, since a second target earthquake might occur in the same time-area. After a chain reached the thresholds $k \geq k_0$, $l \geq l_0$ it may keep growing. Then *RTP* analysis is repeated when chain accumulates each new earthquake. After each such extension the identification of chain may remain the same or reverse. New alarms will be announced accordingly, while the previous alarms are not called off.

Possible outcomes of such predictions are illustrated in Fig. 2. Probabilistic component of predictions is expressed in the probabilities of errors (Molchan, 2003). Similar formulation is used in many intermediate-term prediction algorithms (Kossobokov and Shebalin, 2003; Keilis-Borok (ed.), 1990; Keilis-Borok and Shebalin (eds.), 1999). Performance of prediction algorithm is characterized by the rate of false alarms f, rate of failures to predict n, and time-area τ occupied by all alarms in % to the total time-area considered (Molchan, 2003). We measured the areas by the number of main shocks with $M \geq 4.0$ (Kossobokov and Shebalin, 2003). Sequence of operations realising *RTP* data analysis is summed up in Table 3.

3. Data Analysis

We applied RTP approach to Japan (1975–2003), southern and central California (1965–2003), and Eastern Mediterranean (1980–2003). In total 23 target earthquakes were considered. Values of numerical parameters are given in Tables 4, 5.

3.1 Japan, January 1975–March 2003

Territory considered is shown in Fig. 3, along with epicenters of 12 target earthquakes, $M \geq 7$. We analyzed the catalog of Japanese Meteorological Agency (JMA). Numerical parameters have been adjusted on the data for 1975–1994, and used in the test for 1995–2003. Two of the target earthquakes occurred within the test period: May 26, 2003, M = 7, and Sept. 25, 2003, M = 8.1; the last one is Tokachi-oki earthquake (Section 1).

We have found 60 chains in the period of adjustment and 29 chains in the test period. Respectively 14 and 3 chains have been selected as precursory; they are juxtaposed with target earthquakes in Fig. 4. Within test period two precursory chains gave false alarms. Alarms occupy 7.4% of the total time-area considered.

The last chain, ended on March 27, 2003 (see the last date in Table 1) gave a correct alarm; it preceded two target earthquakes by two and six months respectively.

Table 5. Parameters of intermediate-term patterns.

Variant	R, km	n^*	N	r, km	T, years
1	100	20	50	50	2
2	50	10	50	50	2
3	100	20	20	50	2
4	50	10	20	50	2
5	100	20	50	50	0.5
6	50	10	50	50	0.5
7	100	20	20	50	0.5
8	50	10	20	50	0.5

3.2 Southern and Central California, January 1965–June 2003

Territory considered is shown in Fig. 5, along with epicenters of 9 target earthquakes, $M \geq 6.4$. We analyzed the catalogs of Advanced National Seismic System (ANSS). Numerical parameters have been adjusted on the data for 1965–1998, and used in the test for 1999–2003. Two of the target earthquakes occurred within the test period:

We have found 20 chains in the period of adjustment and 10 chains in the test period. Examples of the chains are given in Fig. 6. Respectively 8 and 2 chains have been selected as precursory; Figure 7 juxtaposes them with target earthquakes. Within the test period one precursory chain gave a false alarm, one gave correct prediction, and one target earthquake (Northridge, 1994) was missed by prediction. Alarms occupy 7.4% of the time-area considered.

3.3 Eastern Mediterranean, January 1980–June 2003

Territory considered is shown in Fig. 8, along with epicenters of 2 target earthquakes, $M > 6.5$. We analyzed the catalog of Geophysical Institute of Israel (GII). Numerical parameters have been adjusted on the data for 1980–1997, and used in the test for 1998–2003. Both target earthquakes occurred in the adjustment period.

We have found 7 chains in the adjustment period and 3 chains in the test period. Examples of the chains are given in Fig. 9. Retrospectively only 2 chains have been selected as precursory (Fig. 9), both in adjustment period; Figure 10 juxtaposes them with target earthquakes on time-distance plain. Comparing to other regions we see less target earthquakes, less chains, and (possibly due to that)—no errors. In the test period no target earthquakes occurred and no chains have been detected. Alarms occupy 2.9% of the time-space considered.

We hope that this overview of *RTP* method gives an idea how the precursor to Tokachi-oki earthquake has been detected. Detailed description of that method is far beyond the scope of this paper and will be published elsewhere.

Altogether the described results well justify continuation of experiments in advance prediction. In further development of *RTP* analysis two problems seem to deserve particular attention: using other relevant fields (Press, 1965; Uyeda and Park, 2002); and development of prediction algorithm with complete self-adaptation to a region considered.

Acknowledgments. This study was made possible by the 21st Century Collaborative Activity Award for Studying Complex Sys-

tems, granted by the James S. McDonnell Foundation (project "Understanding and Prediction of Critical Transitions in Complex Systems") and by ISTC project 1538. The staple of our work are the earthquake catalogs, laboriously, timely and competently compiled by Japanese Meteorological Agency (JMA), Advanced National Seismic System (ANSS), Southern California Earthquake Data Center (SCEDC), Geophysical Institute of Israel (GII). JMA catalog was received through the Japan Meteorological Business Support Center. We are grateful for tough constructive criticism to K. Aki, M. Ghil, A. Jin, A. Soloviev, D. Turcotte and to D. Shatto for patient help in preparation of the manuscript. Extremely useful were discussions at Hagiwara Symposium and at the Seventh Workshop on Non-Linear Dynamics and Earthquake Prediction in the Abdus Salam International Centre for Theoretical Physics, Trieste.

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