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Reverse tracing of short-term earthquake precursors

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Abstract

We introduce a new approach to short-term earthquake prediction named "*Reverse Tracing of Precursors*" (RTP), since it considers precursors in reverse order of their appearance. First, we detect the "candidates" for the short-term precursors; in our case, these are newly introduced chains of earthquakes reflecting the rise of an earthquake correlation range. Then we consider each chain, one by one, checking whether it was preceded by an intermediate-term precursor in its vicinity. If *yes*, we regard this chain as a precursor; in prediction it would start a short-term alarm. The chain indicates the narrow area of possibly complex shape, where an intermediate-term precursor should be looked for. This makes possible to detect precursors undetectable by the direct analysis.

RTP can best be described on an example of its application; we describe retrospective prediction of two prominent Californian earthquakes—Landers (1992), $M = 7.6$, and Hector Mine (1999), $M = 7.3$, and suggest a hypothetical prediction algorithm. Its validation is considered in subsequent studies, starting from [Shebalin et al., Phys. Earth Planet. Int., in press]. The goal of this paper is to describe RTP methodology, since it has potentially important applications to many other data and to prediction of other critical phenomena besides earthquakes. In particular, it might vindicate some short-term precursors, previously rejected as giving many false alarms.

Validation of the algorithm per se requires its application in different regions with a substantial number of strong earthquakes. First (and positive) results are obtained for 21 more strong earthquakes in California ($M \geq 6.4$), Japan ($M \geq 7.0$) and the Eastern Mediterranean ($M \geq 6.5$); these results are described elsewhere. The final validation requires, as always, prediction in advance for which this study sets up a base. We have the first case of a precursory chain reported in advance of a subsequent strong earthquake (Tokachi-oki, near Hokkaido island, Japan), 25 September 2003, $M = 8.1$.

Possible mechanisms underlying RTP are outlined.

Keywords: Short-term earthquake prediction; Long-range correlation; Earthquake chains; Precursors; Instability

1. Introduction

1.1. Generation of strong earthquakes—a non-localized process

Seismicity is commonly recognized as a part of the geodynamics (Aki, 2003; Bird, 1998; Keilis-Borok,

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1990; King et al., 2002; Press, 1965; Rundquist and Soloviev, 1999; Scholz, 1990); in seismically active areas the earthquakes accommodate a considerable fraction of tectonic development of the lithosphere. That development goes on in multiple time-, space-, and energy-scales and preparation of strong earthquakes is not an exception. Accordingly, while the target of earthquake prediction—a strong earthquake—is a localized event, the process of its generation is not localized. Strictly speaking, its time scales range from geological to seconds in time, and spatial scales—from global to microscopic (Turcotte, 1997; Keilis-Borok, 1990); however, in prediction research a truncated scaling is usually considered: from tens of years to days, and from hundreds of kilometers to kilometer.

This multiplicity of scales is reflected in the general concept of the seismically active lithosphere as a hierarchical dissipative non-linear system, persistently self-organizing from time to time into the critical phenomena—the strong earthquakes (Blanter and Shnirman, 1997; Bowman et al., 1998;Gabrielov et al., 1994, 2000; Jaume and Sykes, 1999; Keilis-Borok, 1990; Rundle et al., 2000; Sornette, 2000; Turcotte, 1997; Zaliapin et al., 2002a). Among manifestations of that selforganization are premonitory seismicity patterns—the spatio-temporal patterns of seismicity emerging as a strong earthquake approaches (Aki, 2003; Buffe and Varnes, 1993; Caputo et al., 1983; Gabrielov and Newman, 1994; Jin et al., 2003;Keilis-Borok, 1990, 1996, 2000; Keilis-Borok et al., 1990a,b, 1964, 1999, 2002; Knopoff et al., 1996; Kossobokov et al., 1995, 2003; Ma et al., 1990; Mogi, 1985; Newman et al., 1995; Novikova et al., 2002; Press, 1965; Press and Allen, 1995; Romanowicz, 1993; Rotwain and Novikova, 1999; Shebalin et al., 2000; Turcotte, 1997; Zaliapin et al., 2002a,b, 2003; Zöller et al., 2001). A multitude of such patterns have been reported in rather different scales. Systematically tested are the intermediate-term patterns (with characteristic lead time of years). Here, we suggest a method to detect the short-term patterns, which have the lead time of months.

1.2. Reverse Tracing of Precursors (RTP)

We consider the short-term patterns in conjunction with intermediate-term ones. This is done by RTP analysis, in which these patterns are detected in the reverse order of their appearance: short-term patterns are analyzed first, although they emerge later. Our findings can best be described on a specific example of data analysis.

1.3. Region and data

We describe detection of short-term patterns before two prominent Californian earthquakes—Landers (1992), $M = 7.6$, and Hector Mine (1999), $M = 7.3$. These are the largest Californian earthquakes since 1965—the period, when the earthquake catalog is sufficiently complete for our analysis. Territory considered is shown in Fig. 1. The earthquake catalog is taken from (ANSS/CNSS and NEIC).

2. Chains

Our point of departure is provided by the short-term patterns *Roc* and *Accord* capturing a premonitory increase in earthquake correlation range. They were found first in models (Gabrielov et al., 2000) and then in observations (Keilis-Borok et al., 2002; Shebalin et al., 2000; Novikova et al., 2002). Other patterns capturing that phenomenon are suggested in Zöller et al. (2001) and Zaliapin et al. (2002b). Here, we introduce the pattern *chain* which is a generalization of *Roc* and *Accord*. Qualitatively, a chain is a rapidly extended sequence of small earthquakes that follow each other closely in time and space.

2.1. Definitions

2.1.1. Earthquake catalog

As in most premonitory patterns of that family (Keilis-Borok, 1996; Kossobokov and Shebalin, 2003) aftershocks are eliminated from the catalog; however, an integral measure of aftershocks sequence b is retained for each remaining earthquake (main shocks and foreshocks). We use a common representation of the earthquake catalog $\{t_j, \varphi_j, \lambda_j, h_j, m_j, b_j\}$, $j = 1, 2, \ldots$. Here, t_j is the time of an earthquake, $t_j \geq t_{j-1}$; φ_j and λ_j, latitude and longitude of its epicenter; h_j, focal depth; and m_j, magnitude. We consider the earthquakes with magnitude $m = m_{\min}$. Focal depth is not used in this study.

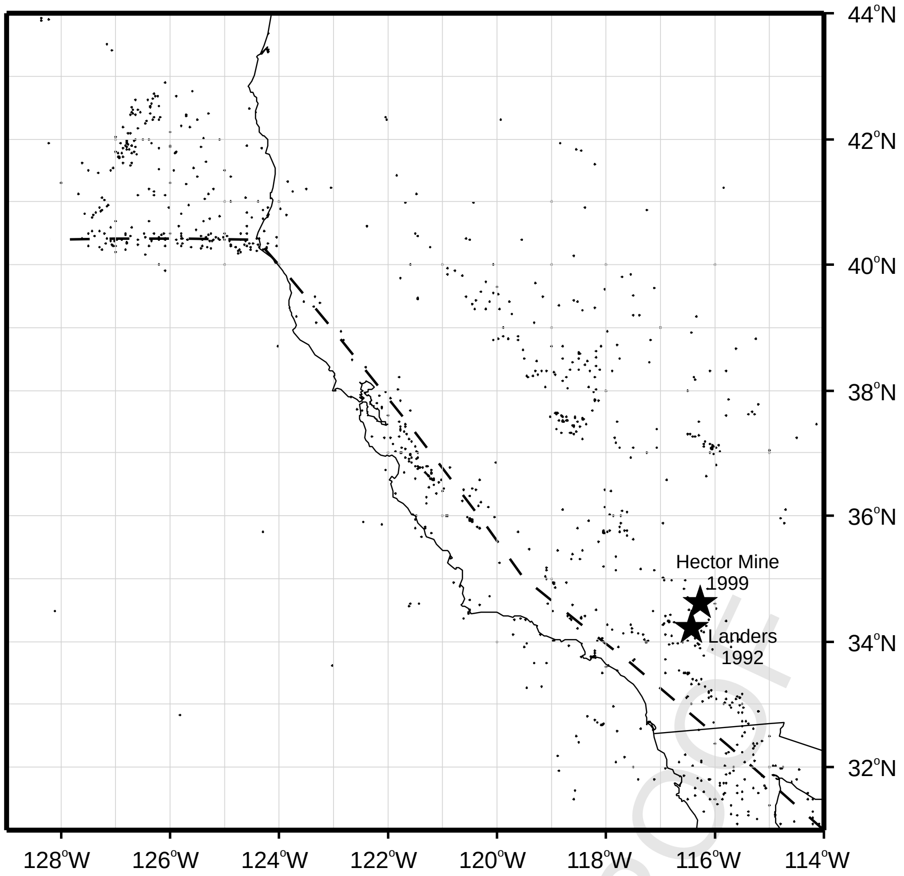

Fig. 1. Territory considered. Stars mark large earthquakes, targeted for prediction. Dots show background seismicity for the time considered (1965–2003): epicenters of earthquakes with magnitude $m \geq 3$ with aftershocks eliminated. Dashed line is used for time–distance projection of epicenters (Fig. 3 below).

2.1.2. Chain

Let us call two earthquakes "*neighbors*" if: (i) their epicenters lie within a distance 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 does not have neighbors outside the sequence*. The threshold r is normalized by the average distance between the earthquakes with lowest magnitude m in a pair considered. We use a coarse normalization $r = r_0 10^{cm}$, c being a numerical parameter.

Let k be the number of earthquakes thus connected and l—the maximal distance between their epicenters. We look for precursors only among the chains with $k \geq k_0$ and $l \geq l_0$. These thresholds ensure that our chains are exceptional phenomena.

2.1.3. Chain's vicinity

To compare location of a chain with locations of strong earthquakes we consider its R-vicinity formally defined as the union of circles of the radius R centered at the epicenters of the chains forming the chain. To smooth the borders of that area we add the dense sequence of circles along the lines connecting each epicenter in the chain with the two closest ones. The envelope of all the circles is the border of R-vicinity of the chain; it is similar to the "Wiener sausage", introduced by N. Wiener in the theory of probability.

Table 1
Parameters for detecting the chains

$m_{\min}$	r_0 (km)	c	τ_0 (days)	k_0	l_0 (km)	R (km)
3.3	50	0.35	20	8	350	75

Notations are given in the text, Section 2.1.

2.2. Data analysis

We detected the chains defined above using numerical parameters listed in Table 1. Aftershocks have been identified by a coarse windowing, as described in (Keilis-Borok et al., 2002). The remaining catalog contains 3940 earthquakes. We have found among them nine chains, altogether containing 116 earthquakes: this shows that our chains are indeed exceptional phenomena. Maps of the chains are shown in Fig. 2; shaded areas are their vicinities, defined above. Vital characteristics of each chain are given in Table 2. Fig. 3 juxtaposes the chains and strong earthquakes on the time–distance plane; distance is counted along the dashed line shown in Figs. 1 and 2.

As we see in Fig. 2 (two panels in the bottom row) and Fig. 3, only the two last chains (#8 and #9) might be regarded as the local short-time precursors to the Landers and Hector Mine earthquakes: short-term—because they emerge with the short-term lead times (respectively, 1.7 and 4.6 months); and local—because the target earthquakes occur in their vicinities. However, the other seven chains, if used as precursors, would give false alarms. To reduce their number we introduce the RTP analysis.

3. Precursory chains

3.1. Hypothesis

We hypothesize that *a precursory chain* (*as opposed to a chain giving a false alarm*) *is preceded by the local intermediate-term precursors formed in the chain's R-vicinity*. This vicinity is not known, until the chain is formed, and its shape might be rather complicated (see Fig. 2). To overcome that impasse we introduce the two-step RTP analysis schematically illustrated in Fig. 4.

(i) *Search for the chains and determination of their R vicinities* (Section 2). Each chain is regarded as a "candidate" for a short-term precursor.

(ii) *Search for the local intermediate-term patterns in the R-vicinities of each chain*. They are looked for within T years before the chain; T is an adjustable numerical parameter. If (and only if) such patterns are detected, we regard this chain as a short-term precursor; in prediction it would start a short-term alarm.

To complete that description we have to specify intermediate-term patterns used at the second step.

3.2. Definitions

We use the *pattern* Σ which reflects premonitory rise of seismic activity. This pattern, introduced in Keilis-Borok and Malinovskaya (1964), is successfully used in different prediction algorithms, alone or in combination with other patterns (Keilis-Borok, 1990, 1996, 2000; Keilis-Borok et al., 1999, 2002; Kossobokov et al., 1995, 2003; Rotwain and Novikova, 1999). It is defined as a premonitory increase of the total area of the earthquake sources. Emergence of this pattern is captured by the function $\Sigma(t)$ defined in a sliding time-window (Keilis-Borok and Malinovskaya, 1964):

$$\sum\left(\frac{T}{s,\,B}\right)=\sum_i 10^{Bm_i},\quad m_i\geq m_{\min};\quad t-s<t_i\leq t$$

Summation is taken over all main shocks within the time window $(t-s,\ t)$ in the R-vicinity of the chain. We take $B\sim 1$, so that the sum is coarsely proportional to the total area of the fault breaks in the earthquakes' sources (Keilis-Borok, 2002); with $B=0$ this sum is the number of earthquakes, with $B=3/2$ it is proportional to their total energy. The emergence of pattern Σ is identified by condition $\Sigma(t)\geq\Sigma_0$; this threshold depends on the magnitude of target earthquakes. In previous applications cited above pattern Σ was used as non-local one. We renormalize its numerical parameters to make it local.

3.3. Data analysis

We detected precursory chains and determined their R-vicinities (Section 2). In each vicinity we computed the function $\Sigma(t)$ within time interval $T=5$ years and summation interval $s=6$ months. We identified as precursory three chains preceded by largest peaks of

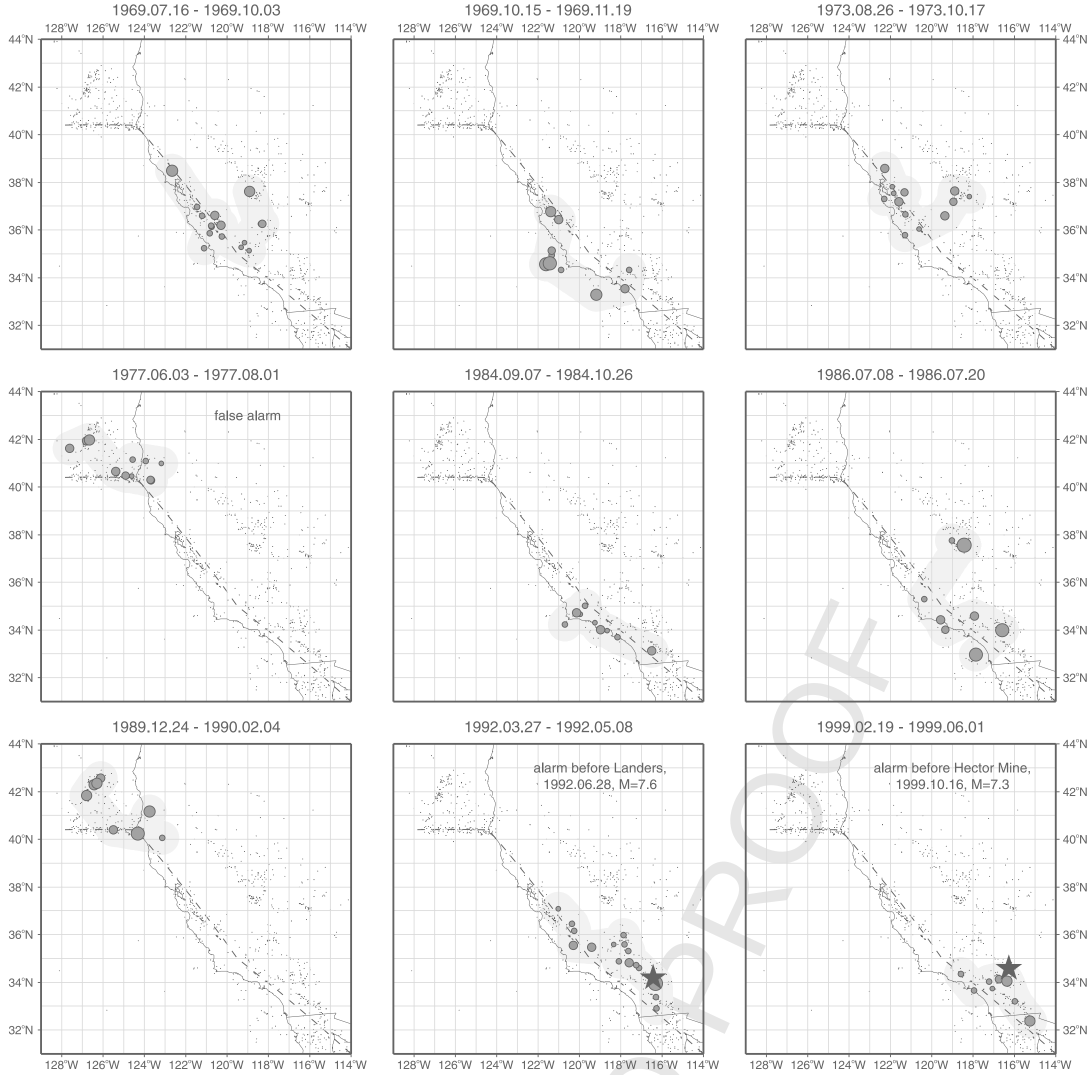

Fig. 2. Maps of the chains. Detected chains are shown in separate boxes. Circles show epicenters of earthquakes in a chain; their size is proportional to magnitude. The shadowed areas show *R*-vicinities of the chains. Dates of the beginning and the end of a chain are given at the top of each box. Three chains (1977, 1992, and 1999) shown in bold are identified as precursory ones. The first chain gives a false alarm; two other chains are followed within few months by target earthquakes, Landers and Hector Mine. Other notations are the same as in Fig. 1.

$\Sigma(t)$; they can be recognized with the threshold $\Sigma_0 = 10^{6.7}$. Table 2 shows these chains in bold. As we see, identification of the first chain, in 1977, is wrong; in prediction it would give a false alarm. Identification of two other chains, in 1992 and 1999, is correct; each is followed by a target earthquake within few months. The same chains would the selected with the tenfold smaller time interval, $T = 6$ months. The corresponding threshold is $\Sigma_0 = 10^{5.4}$; it is smaller since smaller number of earthquakes is included in summation.

3.4. Hypothetical prediction algorithm

It remains to define alarms triggered by that precursor. This is a final step in transition from a precursor to algorithmic prediction. We adapt the standard

Table 2
Characteristics of the chains

#	Start	End	Duration (days)	Lead time (months)	Distance from a strong earthquake (km)	Number of earthquakes, k	Maximal distance, l (km)	Largest magnitude	Area of the R-vicinity, $\times 10^3$ (km^2)
28.06.1992: Landers earthquake, $M = 7.6$									
1	16.07.1969	03.10.1969	80			17	499	5.3	150
2	15.10.1969	19.11.1969	35			12	485	5.6	113
3	26.08.1973	17.10.1973	53			13	381	4.5	150
4	**03.06.1977**	**01.08.1977**	**60**			11	377	**4.7**	**104**
5	07.09.1984	26.10.1984	49			9	408	4.6	90
6	08.07.1986	20.07.1986	12			10	543	5.9	122
7	24.12.1989	04.02.1990	41			8	373	5.7	101
8	**27.03.1992**	**08.05.1992**	**42**	**1.7**	**29**	17	635	**6.1**	**161**
16.10.1999: Hector Mine earthquake, $M = 7.4$									
9	**19.02.1999**	**01.06.1999**	**102**	**4.6**	**60**	11	380	**4.9**	**98**

Chains recognized as "precursory" by RTP analysis (Section 3) are shown in bold. Chain #4 would trigger in prediction a false alarm, Chains #8 and #9 would trigger correct alarms.

general scheme of prediction algorithms, widely used in intermediate-term earthquakes prediction and many other problems (Keilis-Borok, 2002; Kossobokov and Carlson, 1995, and references therein).

(i) Prediction is targeted at the main shocks with magnitude M or more; usually the magnitude intervals $(M, M + 1)$ are considered separately.

(ii) When a precursory chain is detected, a short-term alarm is triggered. It predicts a target earthquake in R-vicinity of the chain, within time interval $(t_e, t_e + \tau)$; here t_e is the moment when chain emerged, τ a numerical parameter (duration of alarm). Results of the data analysis suggest to take $\tau = 6$ months.

Possible outcomes of such prediction are illustrated in Fig. 5. Probabilistic component of prediction is represented by the total time–space covered by alarms and probabilities of false alarms and failures to predict (Molchan, 2003).

4. Discussion

4.1. Summary

This paper introduces RTP analysis in the study of selforganization of seismicity, culminated by a strong earthquake. Precursors with different lead times are considered in reverse order of their appearance. First, we detect the candidates for short-term precursors; in our case, those are the chains of small earthquakes capturing the rise of earthquake correlation range. A chain determines its narrow vicinity where we look for the local intermediate-term precursor(s), pattern Σ in our case. Its presence in turn indicates the precursory chains. We describe RTP on an example: detecting precursory chains months before two prominent California earthquakes, Landers (1992) and Hector Mine (1999), well isolated in time and space from other comparable earthquakes in that region.

4.2. Methodological advantage of RTP

The opposite (direct) analysis would start with tracing of the intermediate-term patterns hidden in the background seismicity. Almost all of them, known so far, are not local, pattern Σ included. They emerge in the areas whose linear size is up to 10 times larger than the source of the incipient target earthquake (Bowman et al., 1998; Keilis-Borok and Soloviev, 2003); some patterns—even up to 100 times larger (Press and Allen, 1995; Romanowicz, 1993). We have found pattern Σ that became local after renormalization: it emerges in the same narrow area (R-vicinity of the chain), where epicenter of a target earthquake lies. As we see in Fig. 2, the shape of that area might be rather complex, and its size—diverse. To find this area by trying different shapes, sizes, and locations is not realistic.

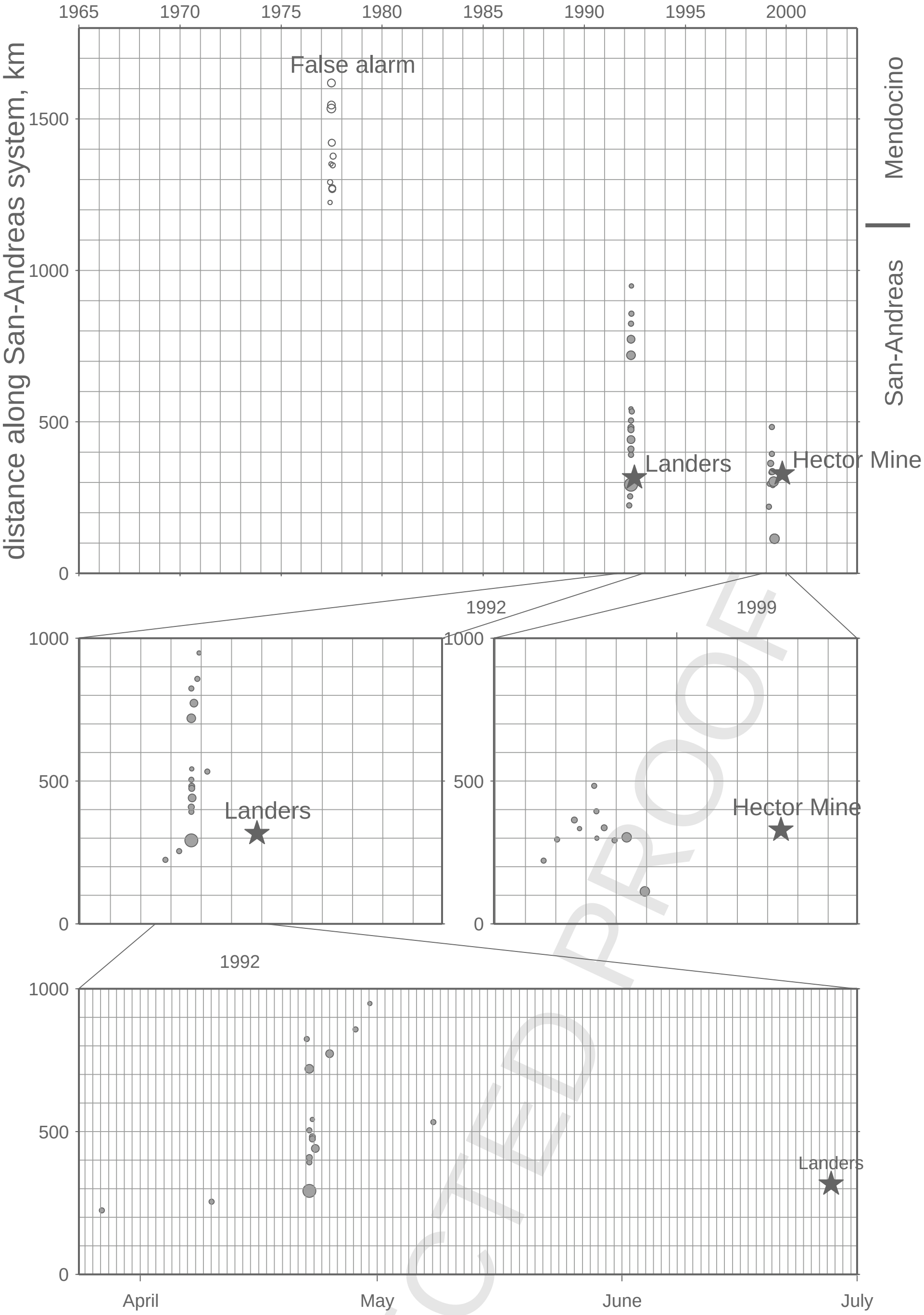

Fig. 3. Chains and strong earthquakes on the time–distance plain. Distance is counted along the dashed line shown in Fig. 1. Filled and open circles show the chains identified, respectively, as precursory and non-precursory. Other notations are the same as in Fig. 1.

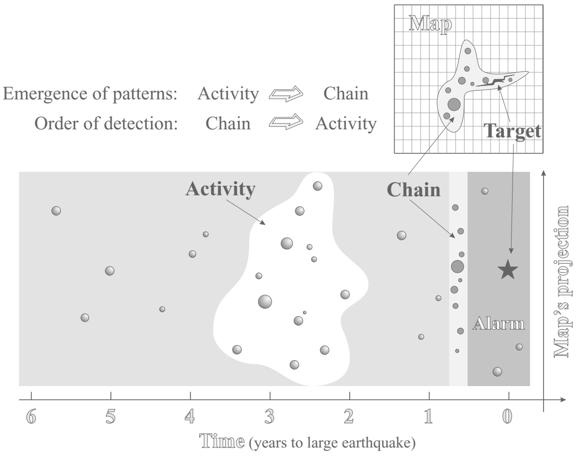

Fig. 4. Schematic illustration of the *Reverse Tracing of Precursors* (RTP). (Top) Map showing precursory chain and the source of the target earthquake (black). (Bottom) Scheme of analysis in time–space projection. Circles show epicenters forming the chain (dark gray) and preceding it (light gray). The "*R*-vicinity" of the chain is shown in light gray. Star is projection of the epicenter of the target earthquake. The gray rectangle before the chain shows the time–space where rise of activity (pattern Σ) is looked for. White area shows the time–space where this pattern was found; its presence indicates a precursory chain. The chain is detected first, although it emerges after the pattern Σ. Note how a narrow chain determines a much larger time interval where a pattern Σ is looked for. Dark gray area shows the time–space covered by an alarm: within ô months after precursory chain a target earthquake is expected in its *R*-vicinity.

Reverse analysis resolves this impasse, indicating a limited number of chains to consider.

4.3. Physical interpretation

RTP seems to be a promising general approach to prediction of critical transitions in non-linear systems: it identifies a rare small-scale phenomenon that carries a memory of the larger scale history of the system. At the same time, this approach has a natural earth-specific explanation: it follows from the concept that strong earthquake is a result of a lasting large-scale process whose different stages involve different parts of the fault network. Earthquakes in the chain mark the part of the fault network that has started to move in unison months before a target earthquake. Pattern Σ indicates that this synchronization started much earlier, albeit expressed in a more subtle form. A similar step-by-step escalation of instability was observed in direct analysis: by algorithms M8&MSc (Kossobokov and Shebalin, 2003), and by some other algorithms (Aki, 2003; Shebalin et al., 2000; Keilis-Borok and Soloviev, 2003).

Both the chains and the peaks of Σ are sporadic short-lived phenomena not necessarily reflecting the steady trends of seismicity. This is typical for all premonitory patterns of that family (Keilis-Borok, 2002; Kossobokov and Shebalin, 2003). Probably, both patterns are the symptoms but not causes of a strong earthquake: they signal its approach but do not trigger it. Similarly sporadic are many observed precursors to other critical phenomena, e.g. economic recessions (Keilis-Borok et al., 2000).

4.4. Implications for earthquake prediction

- We have applied RTP analysis to target earthquakes of more diverse magnitudes in California and two other regions, Japan and E. Mediterranean, normalizing the parameters of the algorithm and considering all known (eight) major types of intermediate-term patterns (Keilis-Borok and Soloviev, 2003). We have first two earthquakes predicted in advance: Tokachi-oki earthquake in Northern Japan (M8.1, 25 September 2003) and San Simeon in Central California, M6.5, 22 December 2003). The results, highly encouraging, are described in Shebalin et al., in press.
- It seems natural to apply the RTP analysis to earthquake precursors, expressed in other fields. First positive results are obtained with precursors gauging interaction between the ductile and brittle layers of the crust (Aki, 2003; Jin et al., 2003; Shebalin et al., in press). Other promising applications include electromagnetic fields (Uyeda and Park, 2002), fluid regime (Keilis-Borok, 1990; Ma et al., 1990), GPS, InSAR, etc.
- We detect intermediate-term patterns only after a chain has emerged so that its vicinity can be determined; this is too late to declare an intermediate-term alarm. Accordingly, our results concern only short-term prediction.
- "Pre-chain" precursors might emerge with a short lead time too.
- There are no reasons not to explore RTP analysis for prediction of different critical phenomena in hierarchical non-linear systems: other geological dis-

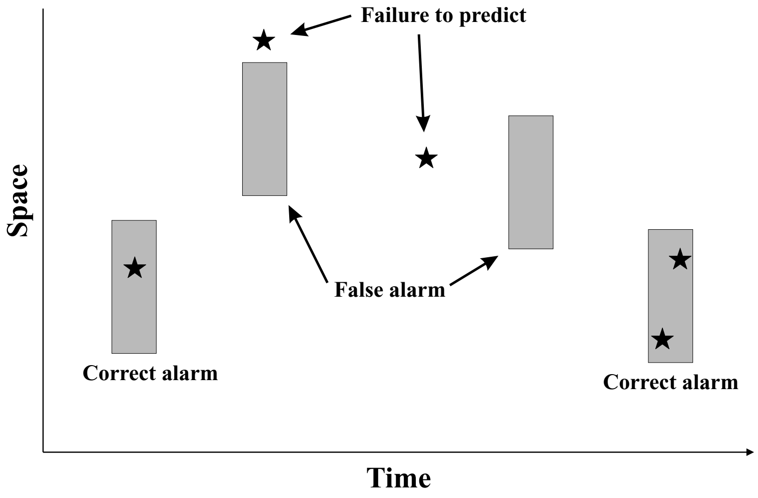

Fig. 5. Possible outcomes of prediction. Stars mark epicenters of strong earthquakes, targeted by prediction. A box to the right of the chain (dark gray) is the time–space covered by an alarm. A prediction is correct if a strong earthquake occurs within an alarm. Otherwise, this is a false alarm. Failure to predict is the case when a strong earthquake occurs outside of an alarm. Probabilistic component of prediction is represented by the rates of false alarms and failures to predict and the time–space covered by alarms (in % to total time–space considered).

asters; geotechnical, and even socio-economic disasters. Qualitatively similar approach is routinely used in medicine, criminology, etc.

- However, accurate the short-term prediction would be it will not render unnecessary the predictions with a longer lead time. One can find in seismological literature a reappearing mistake: that only precise short-term (or even immediate) prediction is practically useful. Actually, protection from earthquakes requires a hierarchy of preparedness measures, from building codes, insurance, and issuing bonds, to reinforcement of high risk objects, to red alert. It takes different time, from decades, to years, to seconds to undertake different measures. Accordingly, earthquake preparedness requires all stages of prediction (Keilis-Borok, 2002; Molchan, 2003; Kantorovich and Keilis-Borok, 1991). Such is the case in preparedness to all disasters, war included.

4.5. Questions arising

- We considered only one short-term precursor—a chain of earthquakes—and one intermediate-term one—the pattern Σ. In subsequent applications (Shebalin et al., in press), all major types of intermediate-term seismicity patterns have been used with similar renormalization. The question arises which set of precursors provides the optimal prediction strategy, as defined for example in (Molchan, 2003; Zaliapin et al., 2003).
- It is not yet clear how to make the scaling of RTP analysis self-adapting to the regional seismic regime, e. g. to parameters of the Gutenberg–Richter relation.
- Earthquake precursors emerge with the broader range of the lead times than considered here. They are divided, albeit fuzzily, into *long-term* (*tens of years*) ⇒ *intermediate-term* (*years*) ⇒ *short-term* (*months*) *and* ⇒ *immediate* (*days or less*). The question arises how to apply RTP analysis to the whole sequence or to its different parts.

Summing up, the RTP approach seems to open new possibilities in the quest for the short-term prediction. We hope that this study sets up a base for further development of this approach in the intertwined problems of earthquake prediction, fundamental understanding of dynamics of the lithosphere, and non-linear dynamics.

Uncited references

Gabrielov et al., 1999, Jordan, 2003, Zaliapin et al., in press.

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References

Aki, K., 2003. Introduction to seismology for earthquake prediction. In: Proceeding of the Seventh Workshop on Non-Linear Dynamics and Earthquake Prediction, International Center for Theoretical Physics, Trieste (Preprint).

ANSS/CNSS Worldwide Earthquake Catalog. Produced by Advanced National Seismic System (ANSS) and hosted by the Northern California Data Center (NCEDC), 1965–2003, http://quake.geo.berkeley.edu/anss.

Bird, P., 1998. Testing hypotheses on plate-driving mechanisms with global lithosphere models including topography, thermal structure, and faults. J. Geophys. Res. 103 (B5), 10115–10129.

Blanter, E.M., Shnirman, M.G., 1997. Simple hierarchical systems: stability, self-organized criticality and catastrophic behavior. Phys. Rev. E 55 (6), 6397–6403.

Bowman, D.D., Ouillon, G., Sammis, C.G., Sornette, A., Sornette, D., 1998. An observational test of the critical earthquake concept. J. Geophys. Res. 103, 24359–24372.

Buffe, C.G., Varnes, D.J., 1993. Predictive modeling of the seismic cycle of the Great San Francisco Bay region. J. Geophys. Res. 98, 9871–9883.

Caputo, M., Console, R., Gabrielov, A.M., Keilis-Borok, V.I., Sidorenko, T.V., 1983. Long-term premonitory seismicity patterns in Italy. Geophys. J. R. Astron. Soc. 75, 71–75.

Gabrielov, A., Newman, W.I., 1994. Seismicity modeling and earthquake prediction: a review. In: Newman, W.I., Gabrielov, A., Turcotte, D.L. (Eds.), Non-linear Dynamics and Predictability of Geophysical Phenomena, vol. 18. American Geophysics University, International University of Geodesy and Geophysics, Geophysical Monograph 83, IUGG, pp. 7–13.

Gabrielov, A., Newman, W.I., Turcotte, D.L., 1999. An exactly soluble hierarchical clustering model: inverse cascades, self-similarity and scaling. Phys. Rev. E 60, 5293–5300.

Gabrielov, A.M., Zaliapin, I.V., Newman, W.I., Keilis-Borok, V.I., 2000. Colliding cascades model for earthquake prediction. Geophys. J. Int. 143, 427–437.

Jaume, S.C., Sykes, L.R., 1999. Evolving towards a critical point: A review of accelerating seismic moment/energy release prior to large and great earthquakes. Pure Appl. Geophys. 155, 279–306.

Jin, A., Aki, K., Liu, Z., Keilis-Borok, V.I., 2003. Brittle–ductile interaction hypothesis for earthquake loading. Abstract, Hagiwara Symposium, XXIII General Assembly of IUGG, 2003, Sapporo, Japan.

Jordan, T.H. (Ed.), 2003. Living on an Active Earth. The National Academy Press, Washington, DC, 432 pp.

Kantorovich, L.V., Keilis-Borok, V.I., 1991. Earthquake prediction and decision making: social, economic, legislative and civil defense domains. In: Proceedings of International Conference on Earthquake Prediction: State-of-the-Art, 15–18 October, Strasbourg, France, pp. 586–593.

Keilis-Borok, V.I., 1990. The lithosphere of the Earth as a non-linear system with implications for earthquake prediction. Rev. Geophys. 28 (1), 19–34.

Keilis-Borok, V.I., 1996. Intermediate-term earthquake prediction. Proc. Nat. Acad. Sci. U.S.A. 93, 3748–3755.

Keilis-Borok, V.I., 2002. Earthquake prediction: state-of-the-art and emerging possibilities. Annu. Rev. Earth Planet. Sci. 30, 1–33.

Keilis-Borok, V.I., Kossobokov, V.G., 1990a. Premonitory activation of earthquake flow: algorithm M8. Phys. Earth Planet. Inter. 61 (1-2), 73–83.

Keilis-Borok, V.I., Malinovskaya, L.N., 1964. One regularity in the occurrence of strong earthquakes. J. Geophys. Res. 69 (14), 3019–3024.

Keilis-Borok, V.I., Rotwain, I.M., 1990b. Diagnosis of time of increased probability of strong earthquakes in different regions of the world: algorithm CN. Phys. Earth Planet. Inter. 61 (1-2), 57–72.

Keilis-Borok, V.I., Shebalin, P.N. (Eds.), 1999. Dynamics of Lithosphere and Earthquake Prediction. Phys. Earth Planet. Inter. (Special Issue), 111, 179–330.

Keilis-Borok, V.I., Shebalin, P.N., Zaliapin, I.V., 2002. Premonitory patterns of seismicity months before a large earthquake: five case histories in Southern California. Proc. Natl. Acad. Sci. U.S.A. 99 (26), 16562–16567.

Keilis-Borok, V.I., Soloviev, A.A. (Eds.), 2003. Nonlinear Dynamics of the Lithosphere and Earthquake Prediction. Springer–Verlag, Heidelberg, 335 pp.

Keilis-Borok, V., Stock, J.H., Soloviev, A., Mikhalev, P., 2000. Pre-recession pattern of six economic indicators in the USA. J. Forecast. 19, 65–80.

King, S.D., Lowman, J.P., Gable, C.W., 2002. Episodic tectonic plate reorganizations driven by mantle convection. Earth Planet. Sci. Lett. 203, 83–91.

Knopoff, L., Levshina, T., Keilis-Borok, V.I., Mattoni, C., 1996. Increased long-range intermediate-magnitude earthquake activity prior to strong earthquakes in California. J. Geophys. Res. 101, 5779–5796.

Kossobokov, V.G., Carlson, J.M., 1995. Active zone size vs. activity: a study of different seismicity patterns in the context of the prediction algorithm M8. J. Geophys. Res. 100, 6431–6441.

Kossobokov, V., Shebalin, P., 2003. Earthquake prediction. In: Keilis-Borok, V.I., Soloviev, A.A. (Eds.), Nonlinear Dynamics of the Lithosphere and Earthquake Prediction. Springer–Verlag, Heidelberg, pp. 141–207.

Ma, Z., Fu, Z., Zhang, Y., Wang, C., Zhang, G., Liu, D., 1990. Earthquake Prediction: Nine Major Earthquakes in China. Springer, New York.

Mogi, K., 1985. Earthquake Prediction. Academic Press, Tokyo.

Molchan, G.M., 2003. Earthquake prediction strategies: a theoretical analysis. In: Keilis-Borok, V.I., Soloviev, A.A. (Eds.), Nonlinear Dynamics of the Lithosphere and Earthquake Prediction. Springer–Verlag, Heidelberg, pp. 209–237.

NEIC, 2004. NEIC Worldwide Earthquake Catalog. Produced by United States Geological Survey National Earthquake Information Center, USGS, NEIC, http://neic.usgs.gov/neis/epic/epic.html.

Newman, W.I., Turcotte, D.L., Gabrielov, A., 1995. Log-periodic behavior of a hierarchical failure model with applications to precursory seismic activation. Phys. Rev. E 52, 4827–4835.

Novikova, O., Shebalin, P., Keilis-Borok, V.I., 2002. A second approximation to intermediate-term earthquake prediction: two cases histories for southeastern Mediterranean. Problems of Theoretical Seismology and Seismicity. Comput. Seismol. 33, 186–206.

Press, F. (Eds.), 1965. Earthquake Prediction: A Proposal for a Ten Year Program of Research. Ad Hoc Panel on Earthquake Prediction, White House Office of Science and Technology, Washington, DC, 134 pp.

Press, F., Allen, C., 1995. Pattern of seismic release in the Southern California region. J. Geophys. Res. 100, 6421–6430.

Romanowicz, B., 1993. Spatiotemporal patterns in the energy-release of great earthquakes. Science 260, 1923–1926.

Rotwain, I., Novikova, O., 1999. Performance of the earthquake prediction algorithm CN in 22 regions of the world. Phys. Earth Planet. Inter. 111, 207–214.

Rundle, J., Turcotte, D., Klein, W. (Eds.), 2000. Geocomplexity and the Physics of Earthquakes. American Geophysical Union, Washington, DC, 284 pp.

Rundquist, D.V., Soloviev, A.A., 1999. Numerical modeling of block structure dynamics: an arc subduction zone. Phys. Earth Planet. Inter. 111 (3–4), 241–252.

Scholz, C.H., 1990. The Mechanics of Earthquakes and Faulting. Cambridge University Press, Cambridge.

Shebalin, P., Keilis-Borok, V., Zaliapin, I., Uyeda, S., Nagao, T., Tsybin, N., in press. Short-term advance prediction of the large Hokkaido earthquake, 25 September 2003, magnitude 8.1: a case history. Phys. Earth Planet. Int., in press.

Shebalin, P., Zaliapin, I., Keilis-Borok, V.I., 2000. Premonitory rise of the earthquakes' correlation range: lesser Antilles. Phys. Earth Planet. Int. 122 (3-4), 241–249.

Sornette D., 2000. Critical Phenomena in Natural Sciences. Chaos, Fractals, Self-organization and Disorder: Concepts & Tools. Springer Ser. Synerg., Springer–Verlag, Heidelberg, 432 pp.

Turcotte, D.L., 1997. Fractals and Chaos in Geology and Geophysics, 2nd ed. Cambridge University Press, Cambridge.

Uyeda, S., Park, S. (Eds.), 2002. In: Proceedings of the International Symposium on The Recent Aspects of Electromagnetic Variations Related with Earthquakes (Special Issue), 20 and 21 December 1999, J. Geodyn., 33, 4–5.

Zaliapin, I., Jin, A., Liu, Z., Aki, K., Keilis-Borok, V., 2003a. Temporal (un)correlations between coda Q-1 and seismicity—multiscale trend analysis. Pure. Appl. Geophys., in press.

Zaliapin, I., Keilis-Borok, V.I., Axen, G., 2002a. Premonitory spreading of seismicity over the faults' network in southern California: precursor accord. J. Geophys. Res. 107 (B10), 2221.

Zaliapin, I., Keilis-Borok, V.I., Ghil, M., 2003. A Boolean delay equation model of colliding cascades. Part II: Prediction of critical transitions. J. Stat. Phys. 111 (3–4), 839–861.

Zaliapin, I., Liu, Z., Zöller, G., Keilis-Borok, V.I., Turcotte, D., 2002b. On increase of earthquake correlation length prior to large earthquakes in California. Comput. Seismol. 33, 141–161.

Zöller, G., Hainzl, S., Kurths, J., 2001. Observation of growing correlation length as an indicator for critical point behavior prior to large earthquakes. J. Geophys. Res. 106, 2167–2176.