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Premonitory Transformation of Hierarchical Fracturing

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Premonitory transformation of steel fracturing and seismicity

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Abstract

Transformation of microfracturing preceding the break up of steel and rock samples is similar to transformation of earthquakes flow prior to strong earthquakes in Southern California. The break up in a sample is preceded by transition from formation of new microcracks to coalescence or expansion of existing cracks. This is reflected in the relation between the length and the number of the cracks. Similar transformation of seismicity precedes Southern California earthquakes with magnitude $M \geq 6.6$, 1935–1994. Specifically, magnitude–frequency relation bends downward for magnitudes from 3 to 4.5 and upward for magnitudes from about 4.5 to 6; in the usual notations the 'b-value' becomes larger in the first interval and smaller in the second one. This transformation is accompanied by the increased share of aftershocks in the earthquakes flow. In such a way the approach of a strong earthquake is reflected in both major traits of seismicity: magnitude–frequency relation and earthquake clustering. Imprecision of the earthquake catalog and reasonable variations in its analysis do not change our conclusions. This phenomenon explains, so far—qualitatively, a wide set of premonitory seismicity patterns. We give it a formal definition, allowing to test whether it takes place in other seismic regions.© 1997 Elsevier Science B.V.

1. Introduction

We continue in this paper the study of transformation of earthquakes flow in the medium magnitude range prior to a strong earthquake. We look for such transformation in the scale, corresponding to intermediate-term earthquake prediction (years $\times 10^2$ km). According to the previous studies reviewed in (Keilis-Borok, 1996), premonitory changes of earthquake flow can be qualitatively summarized as follows: it becomes more intense and irregular; earthquakes become more clustered in space and time; the range of their correlation in space probably increases. These changes are reflected in premonitory seismicity patterns, defined in detail by Keilis-Borok et al. (1980); Caputo et al., 1983; Keilis-Borok, 1990; Vorobieva and Levshina (1992).

Owing to the lack of an adequate theory most of such patterns were found first in the observed seismicity and then in mathematical models; only few of them were found in reverse order, that is first in mathematical models or in a laboratory, and then in observations (e.g. Zhurkov et al., 1978; Narkunskaya and Shnirman, 1994; Kossobokov and Carlson, 1995).

According to current understanding, premonitory phenomena, seismicity patterns included, are to large extent of a universal nature: they reflect the symptoms of growing instability which are common for many non-linear systems of interacting elements.

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This follows from the fact, that these phenomena, in robust definitions, are reproduced in the models of a simple design—e.g. in lattices of point elements interacting in a non-linear fashion—which contain no mechanisms intrinsic to the Earth only (Allegre and Le Mouel, 1982, Allegre et al., 1995; Knopoff et al., 1982; Smalley et al., 1985; Newman and Gabrielov, 1991; Shaw et al., 1992; Newman et al., 1995).

Apart from that, premonitory phenomena may also depend on geometry of the fault system (Sherman et al., 1983; Gabrielov et al., 1996). And finally, some of them may be owing to Earth-specific processes or properties of the rocks (e.g. Barenblatt et al., 1983; Knopoff and Newman, 1983; Pertsov and Traskin, 1992).

Here, we continue the study of 'universal' premonitory phenomena: the laboratory experiments on multiple fracturing are used to formulate a hypothetical premonitory seismicity pattern, which is then tested on the observed seismicity.

Our point of departure is the hierarchical, step by step, increase of prevailing size of fractures in a sample of solid material eventually leading to its break up. This phenomenon is described by Syh et al. (1985) as follows. A sample of steel is subjected to cyclic loading. At the first stage microcracks of a certain dominant size appear and their number gradually grows while the size remains about the same. When the density of microcracks reaches a certain threshold the next stage starts: most of the new cracks are formed now by extension or coalescence (fusion) of pre-existing ones. Accordingly the number of cracks of the original size drops and the cracks of a larger size dominate. Such fusions occur consecutively resulting in hierarchical fracturing, until the sample breaks up. This phenomenon is not specific to any particular steel; it was observed in experiments with rocks (Brace and Bombolakis, 1963; Shamina et al., 1980; Scholz, 1990), clay (Sherman et al., 1983) and other solid materials (Zhurkov et al., 1978; Hirata et al., 1987). Theoretical analysis of this phenomenon is given by Barenblatt (1982, 1993), Knopoff and Newman (1983), Barenblatt and Prostokishin (1993), Barenblatt and Botvina (1983, 1993), Botvina et al. (1995a).

An easiest-to-observe consequence of this phenomenon is that the distribution of the size of the fractures l is changing in a certain way, described below, with the approach of a break up. We will show that at least in Southern California the distribution of the magnitude of the earthquakes M is changing in a similar way with the approach of a strong earthquake. In the first approximation these distribution are usually represented as $\mathrm{d}N \sim 10^{-bS}dS$, where S is a measure of the event (lgl or M), $\mathrm{d}N$ is the average number of events in the interval (S, $S+\mathrm{d}S$). Each of the measure is defined both for fracturing and for seismicity: M as a logarithmic measure of elastic energy release, and l as a characteristic linear dimension of either faultbreak in an earthquake source or a fracture. However, M is usually determined for earthquakes and l for fractures; nevertheless their distributions are comparable, since lgl is roughly proportional to M. A comprehensive discussion of both distributions can be found in Molchan and Podgaetskaya, 1973, Molchan et al., submitted); Barenblatt (1993); Turcotte (1992). The distribution of M is called in seismology the magnitude–frequency relation (Gutenberg and Richter, 1954), since N, normalized by time, is the frequency of earthquakes occurrence.

Relevant to our study is the similarity of these distributions in a remarkable variety of conditions. The evidences of this are the following.

(i) These distributions are reproduced by a diversity of models, stochastic and deterministic ones, not specific to a solid body only (e.g. Gabrielov et al., 1990; Yamashita and Knopoff, 1992; Newman et al., 1994; Blanter et al., 1996; Langer et al., 1996).

(ii) In the samples of metals and rocks the b-value happens to be very close for different microstructures; for plastic and superplastic flows, creep and brittle fracturing; for fractures and other defects, such as pores; and for compression and tension. Comprehensive summary of the evidences of such similarity is given by Botvina and Barenblatt (1985).

Also, that statistics of rock's fragmentation is self-similar, with a uniform self-similarity index, independent of microstructure (Turcotte, 1992).

(iii) The changes of such distributions in favor of the larger events were observed in models, samples and seismicity. This change is expressed in the decrease of the average b-value, or in the upward bend of the large-size end of a distribution (see references to (i)).

These evidence support, though do not prove, the hypothesis, that the phenomenon, considered here, takes place in seismicity.

2. Transformation of magnitude–frequency relation

2.1. Hypothesis

Size distribution for different stages of fracturing of steel is shown in Fig. 1 (after Botvina et al., 1995b). Different curves correspond to different time remained until the break up; this time is measured by the ratio $\omega = 1 - n/n_f$ where n is the number of cycles, and n_f is the value of n at the break up point.

Each curve on Fig. 1 may be roughly divided into three straight segments. The left one is horizontal; the b values for other two are shown in Table 1. We see that far from the break up point ($\omega = 0.83$ and $\omega = 0.57$) $b_1 \lesssim b_2$. However, with the approach of the break up point ($\omega = 0.15$ and $\omega = 0.03$) the following transformation occurs: b_2 decreases and b_1 becomes larger than b_2. This transformation is schematically illustrated in Fig. 2. Our hypothesis is that a similar premonitory transformation takes place in magnitude–frequency relation for the earthquakes.

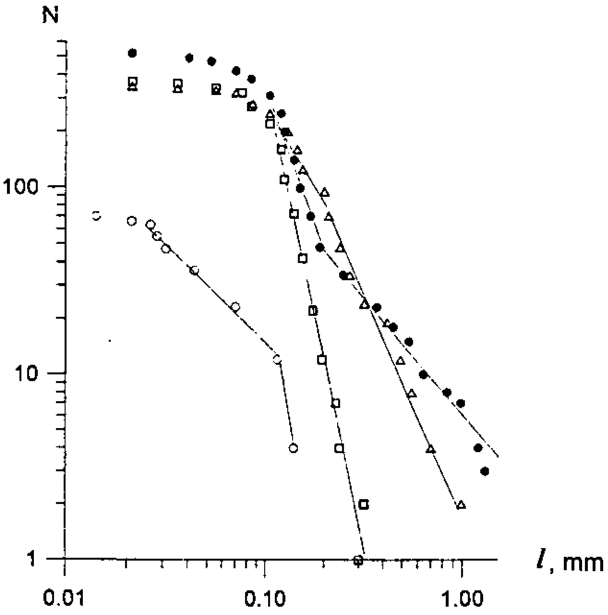

Fig. 1. Magnitude–frequency relation for the fractures in steel samples (after Botvina et al., 1995b). Time, remained until the break up, is characterised by parameter ω defined in the text. Value of ω: 0.83 (circles), 0.57 (squares), 0.15 (triangles), 0.03 (dots).

Table 1
Values of b in magnitude–frequency relation for different stages of steel fracturing

ω	b_1	b_2
0.83	1.03	5.5
0.57	4.5	5.0
0.15	2.8	2.2
0.03	1.57	1.4

2.2. The problem

As in the search of premonitory seismicity patterns (e.g. Keilis-Borok and Rotwain, 1990) we distinguish time intervals of three types: **D**, q years before a strong earthquake, **X**, q years after it, and **N**, all remaining intervals. Our problem is to find the difference of magnitude frequency relation in intervals **D** and **N**. We will explore representation of the magnitude–frequency relation as a continuous broken line

$$lgN(M) = a_i - b_i M, \underline{M}_i \le M \le \underline{M}_{i+1}, i = 1,2,\ldots$$

Here N is the average annual number of earthquakes with magnitudes $M \pm c$; a_i, b_i and c are

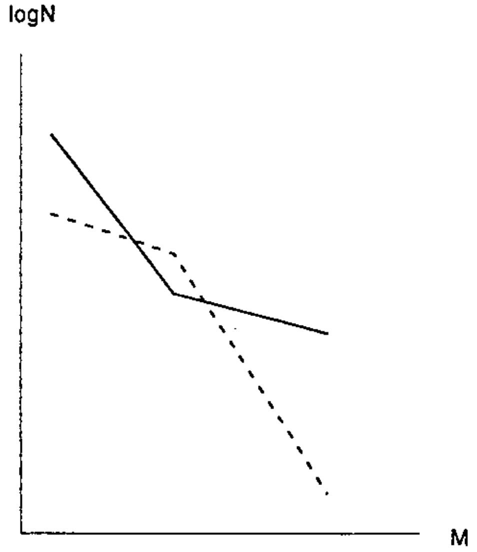

Fig. 2. Scheme of premonitory transformation of magnitude–frequency relation: solid line corresponds to approach of the break up.

numerical parameters, and M_i are the thresholds which divide the curve $lgN(M)$ into approximately straight segments.

2.3. Observations

We consider the earthquakes in Southern California (Fig. 3) for the period 1935 to February 1994. This territory is chosen because the quality of the earthquake catalog is exceptionally high there since the times of B. Gutenberg. We used the Catalog of Earthquakes of Southern California, 1994. The distribution of earthquakes of different magnitudes (Table 2) shows that it is reasonably complete at least for $M \geq 3$. The values of magnitudes in this catalog are rounded up to 0.5 before 1944, to 0.25 for 1944–1966 and to 0.1 henceforth; we assume the lowest resolution, 0.5, for the whole period.

Earthquakes with $M \geq M_0$ are regarded as strong; the value of M_0 is chosen as in previous studies on earthquake prediction (e.g. Keilis-Borok and Rotwain, 1990)—by condition that their average recur-

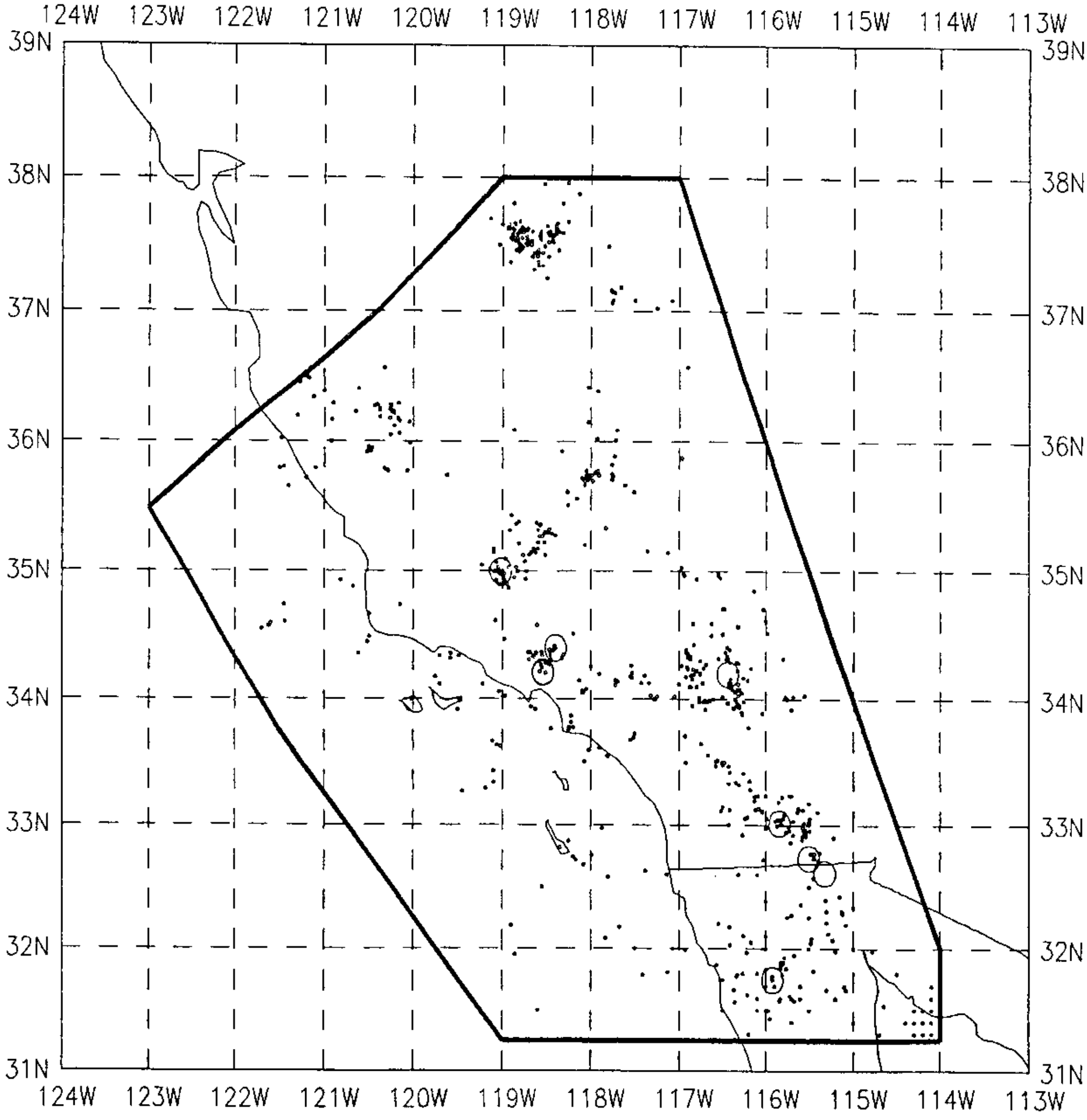

Fig. 3. Earthquakes in S. California, 1935–1994. Epicentres: dots, $M \geq 4.5$; circles, $M \geq 6.6$. Solid line is the boundary of the territory considered.

Table 2
Cumulative number of earthquakes in 2 years time-window, after CIT catalog 1994. The first column shows the beginning of the window

$M \leq$ years	3.0	3.5	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5
1935	548	247	110	31	7	1	1			
1937	381	190	83	24	5	2	1			
1939	500	298	146	57	14	6	2	1		
1941	463	261	138	48	16	7	2	1		
1943	351	173	68	20	4					
1945	423	222	81	26	15	4	1			
1947	520	205	82	33	9	2	2	1		
1949	539	233	73	29	7	4				
1951	567	361	229	88	25	14	5	1	1	1
1953	752	294	131	49	19	8	3			
1955	499	279	199	134	32	9	4	1		
1957	326	157	65	25	6	2				
1959	326	152	72	16	2					
1961	360	133	57	19	7					
1963	364	179	77	23	5	2				
1965	297	130	51	17	4	2	1			
1967	495	176	62	12	4	1	1	1		
1969	502	189	82	50	27	5				
1971	705	285	80	21	6	3	1	1		
1973	386	101	28	8	2					
1975	568	170	57	18	5					
1977	415	123	36	8	4	1				
1979	1734	566	182	60	19	10	5	2		
1981	653	205	59	16	5	4				
1983	1057	373	106	36	13	6	2			
1985	1024	287	92	34	12	5				
1987	650	190	64	29	10	4	2	1		
1989	358	76	26	9	2					
1991	1953	646	209	59	21	7	3	1		
1993	769	256	80	32	11	5	3	2		

rence time is about 7 years. With the catalog used here this condition gives $M_0 = 6.6$ (Table 3); for the previous version of the catalog $M_0 = 6.4$.

Aftershocks are analyzed separately. They were identified by time and space windows $R(M_m)$, $T(M_m)$, M_m being the magnitude of a main shock. We used the same robust estimations, as in the previous studies of this region: $R = 50$ km and T increasing from 23 days for $M_m = 3$ to 730 days for $M_m \geq 6.4$. The fixed distance $R = 50$ km is too large for the smallest and possibly too low for the strongest main shocks considered. The results of our analysis remain about the same with the alternative windows given by Gardner and Knopoff (1974).

Table 3
Strong earthquakes, $M \geq 6.6$, 1935–1994, after CIT catalog, 1994

No.	Date	Time	φ (°,N)	λ (°,W)	H (km)	M
1	5.19.1940	4:36	32.73	115.50	0	6.9
2	7.21.1952	11:52	35.00	119.02	0	7.7
3	2.9.1956	14:32	31.75	115.92	0	6.8
4	2.9.1971	14:0	34.41	118.40	8	6.6
5	10.15.1979	23:16	32.61	115.32	12	6.6
6	11.24.1987	13:15	33.01	115.84	2	6.6
7	6.28.1992	11:57	34.20	116.44	1	6.7
8	1.17.1994	12:30	34.21	118.54	18	6.6
9	1.17.1994	12:30	34.22	118.54	17	6.6

Last earthquake (No. 9) is disregards, as a close second to preceding one.

2.4. Magnitude–frequency relation for D and N intervals

Choosing $q = 3$ years, we have the intervals **D**, **N**, and **X** as listed in Table 4; in case of overlaps priority is given to intervals **X**. Let us first lump together all the intervals of the same kind. Total duration of intervals **D** and **N** is 17.58 years and

Table 4
D, **N** and **X** intervals

Time interval	Type of the interval	Duration, years	Number of mainshocks, $M \geq 3$
1935.1.1–1937.12.31	**X**	3	244
1937.12.31–1940.5.19	**D**	2.42	174
1940.5.19–1943.5.19	**X**	3	191
1943.5.19–1946.5.19	**N**	3	187
1946.5.19–1949.5.19	**N**	3.17	229
1949.5.19–1952.7.21	**D**	3	231
1952.7.21–1955.7.21	**X**	3	226
1955.7.21–1956.2.9	**D**	0.58	36
1956.2.9–1959.2.9	**X**	3	210
1959.2.9–1962.2.9	**N**	3	234
1962.2.9–1965.2.9	**N**	3	222
1965.2.9–1968.2.9	**N**	3	206
1968.2.9–1971.2.9	**D**	3	299
1971.2.9–1974.2.9	**X**	3	297
1974.2.9–1976.10.15	**N**	2.7	224
1976.10.15–1979.10.15	**D**	3	266
1979.10.15–1982.10.15	**X**	3	231
1982.10.15–1984.11.24	**N**	2.1	203
1984.11.24–1987.11.24	**D**	3	265
1987.11.24–1990.11.24	**X**	3	257
1990.11.24–1992.6.28	**D**	2.58	153
1992.6.28–1994.2.9	**X**	1.7	179

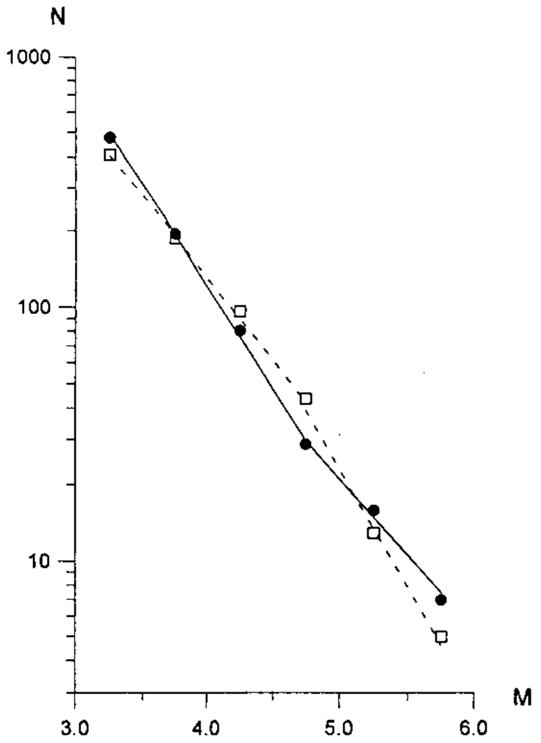

Fig. 4. Magnitude–frequency relation for the intervals **D** (dots and solid lines) and **N** (squares and dashed line). Aftershocks are not counted in. $N(M)$ is the average number of earthquakes per 10 years in the magnitude range ($M \pm 0.25$).

19.97 years respectively, average annual number of main shocks with $M \geq 3$ is 81 and 75. The corresponding magnitude–frequency relations are compared in Fig. 4. Comparison of b-values is given in Table 5; b_1 corresponds to $3 \leq M < 5$, and b_2 to $4.5 \leq M < 6$. The earthquakes with $6.0 \leq M \leq 6.5$ are not included, since their number is too small. We see, that at least qualitatively transformation of magnitude–frequency relation is the same as described above for fracturing (Fig. 2).

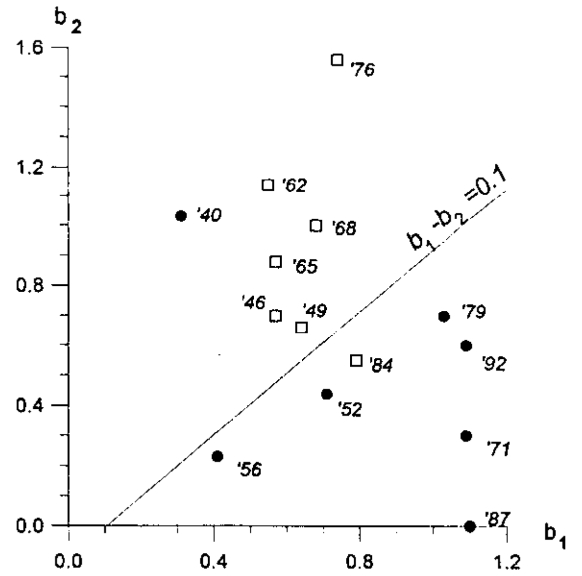

Fig. 5. Values of b_1 and b_2 for individual intervals **D** (dots) and **N** (squares). Year refers to the end of an interval. Aftershocks are not counted in.

Let us consider now individual **D** and **N** intervals, listed in Table 4. Estimations of b_1 and b_2 for the end of each interval are given in Fig. 5; we can see that intervals **D** and **N** of two types (with only two exceptions) are well separated by the line $b_1 - b_2 = 0.1$. Fig. 6 shows the change of $\Delta b(t) = b_1(t) - b_2(t)$ with time. The values of $\Delta b(t)$ are computed in the sliding time-window ($t - 3$, t) years, with a step of 2 months. We see that each strong earthquake, except the first one, is preceded by a rise of Δb above the level 0.45, with the lead time from 0 to the half of year; and 4 times such rise followed a strong earthquake within 3 years. Maximal of $\Delta b(t)$ may be reached not immediately before a strong earthquake;

Table 5
Values of b in magnitude–frequency relation for **D** and **N** intervals

	D intervals		N intervals	
Aftershocks	b_1	b_2	b_1	b_2
included	0.81	0.58	0.64	0.94
eliminated	0.89	0.87	0.85	1.09

b_1 correspond to magnitude interval $3 \leq M < 5$.
b_2 correspond to magnitude interval $4.5 \leq M < 6$.

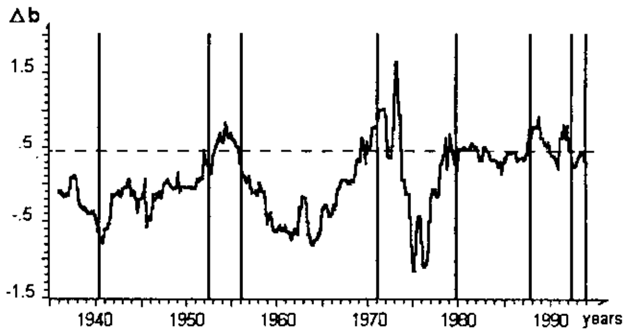

Fig. 6. Function $\Delta b(t) = b_1(t) - b_2(t)$ in a sliding time window of ($t - 3$ years, t) With a step of 2 months. Vertical lines show the moments of strong earthquakes; dashed horizontal line is retrospective threshold for prediction.

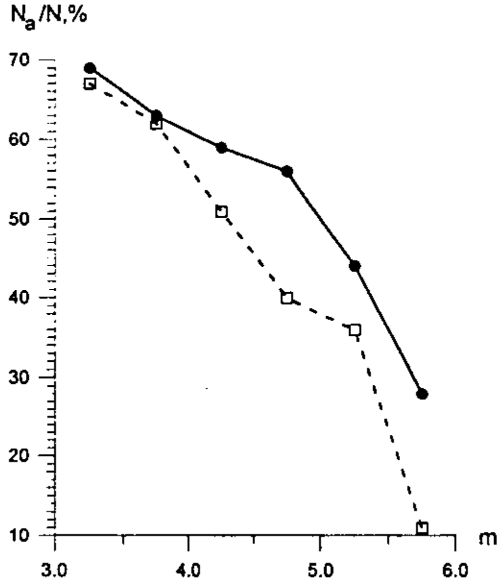

Fig. 7. Values of Na/N for the intervals **D** (dots and solid line) and **N** (squares and dashed line).

hence the difference between the thresholds 0.1 in Fig. 5 and 0.45 in Fig. 6.

2.5. *Transformation of clustering*

Here we demonstrate that the transformation of magnitude frequency relation described above is connected with the changes in the earthquakes clustering. This is indicated by the fact, that transformation of the whole seismicity is much less pronounced (Table 5, last line).

Exploring further evidence, we consider the relative number of aftershocks, $N_a(m)/N(m)$, where N is the total number of earthquakes, N_a is the number of aftershocks among them; both are counted in the magnitude range $M \geq m$. (Note, that we consider the aftershocks, generated by the main shocks with medium magnitude $3 \leq M < 6$, and not by strong earthquakes; practically all the aftershocks of strong earthquakes are anyhow eliminated, since they belong to the 3 years long intervals **X**, following each strong earthquake.) The values of this function in the intervals **D** and **N** are compared in Fig. 7; we see that distinctly more aftershocks are generated during the intervals **D**. However, this particular measure of clustering does not allow to discriminate the individual intervals **D** and **N**.

3. On earthquake prediction

Here we show that the transformation of magnitude–frequency relation (Sections 1 and 2) and of earthquake clustering (Section 3) may explain—so far, qualitatively—many other premonitory phenomena. We formulate then a hypothetical prediction algorithm, to be tested in other regions and in the models.

3.1. *Premonitory phenomena*

(i) Several algorithms for intermediate-term earthquake prediction are based on the following characteristics of earthquake flow, which tend to increase before a strong earthquake:

- The number of aftershocks (abnormally large clusters of aftershocks appear).
- The average area of rupture in a source.
- Spatial concentration of sources: the ratio of their average radius to average distance between them.
- The ratio $n(M+d)/n(M)$, where $n(M)$ is the number of main shocks with magnitude above M, d is a numerical parameter.

Different combinations of these characteristics are used in different algorithms; exact definitions are given by Keilis-Borok (1990).

Premonitory raise of the first characteristics can be explained by the increase of the rate of aftershocks, and by the decrease of Δb for the other three. The above mentioned algorithms consider also premonitory variations of the number of main shocks; this is not necessarily connected with parameters b_1, b_2 and may reflect the changes of the level of seismicity a_1, a_2.

(ii) Premonitory 'upward bend' of the large size end of the magnitude frequency relation was found in a mathematical model of seismicity called 'Shnirman tree' (Narkunskaya and Shnirman, 1990). In the subsequent test on observations such bend precedes about 75% of strong earthquakes in several regions of the world (Narkunskaya and Shnirman, 1994). This is accordance with premonitory decrease of Δb.

In cases (i) and (ii) the averaging of earthquake flow was about the same as in the present study. In the following cases the intervals of averaging were more narrow.

(iii) Premonitory increase in the number of aftershocks was noticed in the rocks fracturing (Hirata, 1987). It was expressed in the lowering of the parameter p in the Omori law, $n(t) = K/(1+t)^p$. Here, n is the number of the aftershocks; time t is discretized by days. This is in accordance with premonitory increase of clustering, described above.

(iv) Premonitory decrease of the average b-value was found also within few months before a strong earthquake, in the vicinity of its source (Knopoff et al., 1982). Particularly prominent decrease, by factor 2, is established for the foreshocks which were identified by statistical analysis of seismicity (Molchan and Dmitrieva, 1990). This is in accordance with premonitory drop of b_2, described above.

4. A possible premonitory pattern (a conjecture)

The increase of the function $\Delta b(t)$ before a strong earthquake (Fig. 6) suggests the following hypothetical prediction algorithm: an alarm is declared, while $\Delta b \geq \delta$ for τ days more. We add also a condition, that within θ days after each strong earthquake the alarms are not declared. Here δ, τ, θ are adjustable numerical parameters.

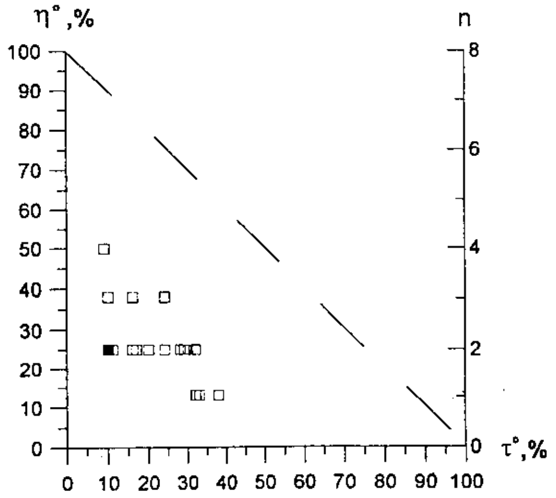

Fig. 8. The error diagram. Vertical axis shows the rate of failures to predict $\eta^\circ = n/N$; N is the total number of strong earthquakes, n shows how many of them are not predicted by the algorithm. Horizontal axis shows the relative duration of alarms $\tau^\circ = \tau_\Sigma/T$; here τ_Σ is the total duration of alarms and T is the time period considered. Different squares correspond to combinations of adjustable parameters listed in Table 6. Solid square correspond to minimal value of $\eta^\circ + \tau^\circ$).

Table 6
Parameters of the prediction algorithm and η°, τ° values

δ	τ, days	θ, days	η° (%)	τ° (%)
0.45	365	0	25	32
0.45	270	0	25	30
0.45	210	0	25	29
0.45	180	0	25	28
0.45	210	365	25	24
0.45	210	730	25	17
0.45 *	210	1095	25	10
0.45	365	1095	25	11
0.4	365	1095	25	16
0.35	365	1095	25	17
0.3	365	1095	25	20
0.35	365	365	13	33
0.4	365	365	13	32
0.4	365	0	13	38
0.48	365	1095	38	10
0.5	365	1095	50	9
0.48	365	730	38	16
0.48	365	365	38	24

* Corresponds to a minimal value of $\eta^\circ + \tau^\circ = 35\%$.

Fig. 8 shows for this algorithm an error diagram such as introduced in seismology by Molchan (1994). It indicates the rates of errors of two kinds: the relative number of failure to predict, η° and the part of time, occupied by all alarms, τ°. Different points on the diagram correspond to different combinations of adjustable parameters listed in Table 6. The choice of combination to be used for prediction depends of the relative price of alarms and failures to predict. If his ratio is not specified, the quality of prediction may be characterized by the sum $\eta^\circ + \tau^\circ$. Points, corresponding to a random (binomial) prediction, lie on the diagonal $\eta^\circ + \tau^\circ = 1$, shown by the dotted line. The points below it correspond to predictions, which are better than random; this alone does not guarantee their high statistical significance, not mentioning that the whole analysis here is a retrospective one. Minimal rate of errors of both kind (35%) corresponds to parameters marked by star in Table 6. With these parameters, the above algorithm gives the alarms shown in Fig. 9. We see that they occupy 10% of total time and: precede 6 out of 8 strong earthquakes with one false alarm in 1982–1984 and two failures-to-predict. Obviously, this algorithm remains a hypothetical, one until it is tested by ad-

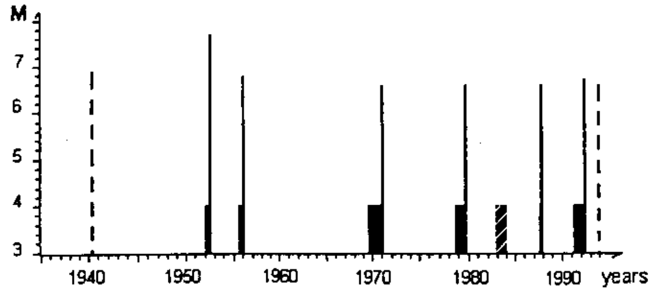

Fig. 9. 'Alarms' and strong earthquakes. Bars show the alarms; striped bar is the false alarm. Solid and dashed vertical lines indicate strong earthquakes, respectively preceded and missed by the alarms.

vance predictions in different regions and explored on the models.

5. Discussion

5.1. Alternatives in the data analysis: Could they change our conclusions?

5.1.1. Uneven distribution of strong earthquakes

The time span 1979–1984 contains three intervals D and only one interval N (Table 4); moreover, the latter was not discriminated by the values of Δb (Fig. 6). The question may arise—what is really the reason for the transformation of earthquake flow, described above: is it the approach of a strong earthquake or the general change of seismicity since 1979? The first answer is supported by the fact that after and before 1979 the high values of Δb are equally confined to a time preceding a strong earthquake.

5.1.2. Potential artifacts caused by compilation of the catalog

The average annual number of earthquakes with magnitudes from 3 to 3.5 jumped from 130 between 1935–1978 to 373 since 1979 (Table 2). One cannot exclude a possibility, that actual numbers were about the same, but after 1978 the catalog became more complete for lower magnitudes, causing an apparent increase of b_1. The evidence that follows shows that this is not the case. We shifted the lower magnitude cutoff M, from 3.0 to 3.1, starting from 1967 (when the decimals became indicated for magnitudes). The number of earthquakes became about the same for the whole time considered; however the results of retrospective prediction did not change much: $\eta^\circ + \tau^\circ$ is decreased from 35% to 39%. Furthermore, one may always suspect, that an observed phenomenon is caused by unannounced change of the magnitude scale. It is hardly possible however, that such changes preceded strong earthquakes as it is shown in Fig. 9. Foreshocks were counted together with the main shocks. To check, that premonitory increase of b_2, described above, is not owing to the foreshocks, we eliminated them from the catalog; this did not change our results.

5.2. What did we learn about premonitory seismicity patterns?

(i) Introduction of a premonitory phenomena is inevitably followed by the question—what specific mechanism is it owing to? Here, we learned that coalescence and expansion of the cracks is a mechanism, which may explain a wide set of premonitory seismicity patterns. This mechanism is specific not to the Earth only, but also to fracturing in solids under wide variety of conditions. One should note, however, that this mechanism probably reflects even more general features of hierarchical non-linear systems, since it is reproduced on the models, not specific to fracturing only (Allegre and Le Mouel, 1994; Narkunskaya and Shnirman, 1990; Turcotte, 1992; Newman et al., 1994, 1995).

(ii) Premonitory patterns, mentioned above, reflect the change in the two major features of the earthquakes flow: magnitude–frequency relation and earthquake clustering. Accordingly, these patterns may be possibly expressed through a limited number of parameters, e.g. Δb, N_a/N and a_1 or a_2. This offers the hope in a long-standing problem: how to reduce the number of adjustable parameters in a definition of a set of premonitory patterns. In practice, however, it may remain necessary to use a sufficient diversity of such patterns, even if they are interdependent: in this way it is easier to cope with random fluctuations of earthquake flow.

(iii) Premonitory change of the magnitude–frequency relation in favor of strong events was reported in numerous studies of fracturing and of seismicity. Our results suggest more comprehensive transformation of magnitude–frequency relation, schematically shown in Fig. 2; at least in seismicity, this transformation is accompanied with an increase of clustering.

(iv) The next problem is to outline the conditions, under which the phenomenon, described here, takes place; first of all it has to be tested on observations in other regions. The studies, discussed above, demonstrate, that many premonitory phenomena are similar in a wide variety of conditions; this may be a natural consequence of the partly universal nature of these phenomena. However this similarity is still limited. In particular, under certain conditions strong events may occur on the low background, without significant activity in the medium magnitude range. Model of such kind is described by Knopoff and Newman (1983), among possible natural examples are American Midwest and Mid Atlantic rift.

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References

Allegre, C.J., Le Mouel, J.L. and Provost A., 1982. Scaling rules in rock fracture and possible implications for earthquake prediction. Nature, 297: 47–49.

Allegre, C.J. and Le Mouel, J.L., 1994. Introduction of scaling technique in brittle fracture of rocks. Phys. Earth Planet. Inter., 87: 85–93.

Allegre, C.J., Le Mouel, J.L., Chau, H.D. and Narteau, C. 1995. Scaling organisation of fracture tectonics (SOFT) and earthquake mechanism. Phys. Earth Planet. Inter., 92: 215–233.

Barenblatt, G.I., 1982. Similarity, Self-similarity and Intermediate Asymptotics, Consultants Bureau, New York.

Barenblatt, G.I., 1993. Micromechanics of Fracture, Elsevier, TUTAM, pp. 25–51.

Barenblatt, G.I. and Botvina, L.R., 1983. Self-similarity of fatigue fracture. Damage accumulation. Bull. Acad. Sci. U.S.S.R. Mechanics of Solids, 4: 161–165 (in Russian).

Barenblatt, G.L. and Botvina, L.R., 1993. Self-oscillatory modes of fatigue fracture and the formation of self-similar structures at the fracture surface. Proc. R. Soc. London A, 442: 489–494.

Barenblatt, G.I., Keilis-Borok, V.I. and Monin, A.S., 1983. Filtration model of earthquake sequence. Dokl. Akad. Nauk SSSR, 169: 831–834.

Barenblatt, G.I. and Prostokishin, V.M., 1993. A mathematical model of damage accumulation taking into account microstructural effects. Eur. J. Appl. Mathematics, 4: 225–240.

Blanter, E.M., Shnirman, M.G., Le Mouel, J.-L. and Allegre, C.J., 1996. Scaling laws in block dynamics and dynamic self-organized criticality. Phys. Earth Planet. Inter., in press.

Botvina, L.R. and Barenblatt, G.I., 1985. Self-similarity of damage accumulation. Problems of Strength, 12: 17–24 (in Russian).

Botvina, L.R., Fradkin, Ju L. and Bridge, B., 1995a. Power laws and generalised dimensional analysis in ultrasonic NDE. J. Non Destructive Testing and Evaluation, 12: 103–118.

Botvina, L.R., Rotwain, I.M., Keilis-Borok, V.I. and Oparina, J.B., 1995b. On the character of the Gutenberg–Richter relation on different stages of damage accumulation and earthquake generation. Dokl. RAN, 345(6): 809–812.

Brace, W.F. and Bombolakis, A.G., 1963. A note on brittle crack growth in compression. J. Geophys. Res., 68: 3709–3713.

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

Catalog of Earthquakes of Southern California, 1994, Californian Institute of Technology, electronic FTP file.

Gabrielov, A.M., Keilis-Borok, V.I. and Jackson, D., 1996. Geometric incompatibility in a fault system. Proc. Natl. Acad. Sci. USA, 93: 3838–3842.

Gabrielov, A.M., Levshina, T.A. and Rotwain, I.M., 1990. Block model of earthquake sequence. Phys. Earth Planet. Inter., 61: 18–29.

Gardner, J.K. and Knopoff, L., 1974. In the sequence of earthquake in Southern California, with aftershocks removed, Poissonian? Bull. Seismol. Soc. Am., 64: 1363–1367.

Gutenberg, B. and Richter, C.F., 1954. Seismicity of the Earth and Associated Phenomenon, 2nd edn., Princeton University.

Hirata, T., 1987. Omori's power law aftershock sequences of microfracturing in rock fracture experiment. J. Geophys. Res., 92: 6215–6221.

Hirata, T., Satoh, T. and Ito, K., 1987. Fractal structure of spatial distribution of microfracturing in rock. Geophys. J. R. Astr. Soc., 90: 369–374.

Keilis-Borok, V.I. (Editor) 1990. Intermediate-term earthquake prediction: Models, algorithms, worldwide tests. Phys. Earth Planet. Inter., 61.

Keilis-Borok, V.I., 1996. Intermediate-term earthquake prediction. Proc. Natl. Acad. Sci. USA, 93: 3748–3755.

Keilis-Borok, V.I., Knopoff, L., Rotwain, I.M. and Sidorenko, T.M., 1980. Burst of Seismicity as Long-Term Precursors of Strong Earthquakes. J. Geophys. Res., 85: 803–811.

Keilis-Borok, V.I. and Rotwain, I.M., 1990. Diagnosis of time of increased probability of strong earthquake in different regions of the world: Algorithm CN. Phys. Earth Planet. Inter., 61: 55–72.

Knopoff, L., Kagan, Y. and Knopoff, R., 1982. b-value for foreshocks and aftershocks in real and simulated earthquake sequence. Bull. Seismol. Soc. Am., 72 (5): 1663–1676.

Knopoff, L. and Newman W.I., 1983. Crack fusion as a model for repetitive seismicity. PAGEOPH, 121 (3): 495–510.

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

Langer, J.S., Carlson, J.M., Moyers, Ch.R. and Shaw, B.E., 1996. Slip complexity in dynamic models of earthquake faults. Proc. Natl. Acad. Sci. USA, 93: 3825–3829.

Molchan, G.M., 1994. Models for optimisation of earthquake prediction, Computational Seismology and Geodynamics, Vol. 2, AGU, Washington, D.C., pp. 1–11.

Molchan, G.M. and Dmitrieva, O.E., 1990. Dynamics of the magnitude frequency relation for foreshocks. Phys. Earth Planet. Inter., 61: 99–113.

Molchan, G.M., Kronrod, T.L. and Panza, G.F., 1997. Hazard oriented multiscale seismicity model: Italy. BSSA, submitted.

Molchan, G.M. and Podgaetskaya, V.M., 1973. Parameters of global seismicity. Computational Seismology, 6: 3–37 (in Russian).

Narkunskaya, G.S. and Shnirman, M.G., 1990. Hierarchical model of defect development and seismicity. Phys. Earth Planet. Inter., 61: 29–36.

Narkunskaya, G.S. and Shnirman, M.G., 1994. An algorithm of earthquake prediction, Computational Seismology and Geodynamics, Vol. 1, AGU, Washington, D.C., pp. 20–24.

Newman, W.I. and Gabrielov, A., 1991. Failure of hierarchical distributions of fiber bundles. I. Int. J. Fracture, 50: 1–14.

Newman, W.I., Gabrielov, A. and Turcotte, D.L. (Editors) 1994. Nonlinear Dynamics and Predictability of Geophysical Phenomena. Geophys. Monograph Series, IUGG-AGU, Washington, D.C.

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

Pertsov, N.V. and Traskin, V.Yu., 1992. Rhebinder effect in nature, Progress in Colloidal Chemistry and Physico-Chemical Mechanics, Moscow, Nauka, pp. 155–165.

Shamina, O.G., Budnikov, V.A., Vinogradov, S.D. et al., 1980. Laboratory experiments on the physics of the earthquake source. Physical Processes in Earthquake Sources, pp. 56–68 (in Russian).

Scholz, C., 1990. The Mechanics of Earthquake and Faulting, Cambridge University.

Shaw, B.E., Carlson, J.M. and Langer, J.S., 1992. Patterns of seismic activity preceding large earthquakes. J. Geophys. Res., 97: 479.

Sherman S.I., Borniakov S.A. and Buddo V.Yu., 1983. Areas of Dynamic Effects of Faults, Novosibirsk, Nauka, 111 pp. (in Russian).

Smalley, R.F., Turcotte, D.L. and Solla, S., 1985. A renormalization group approach to the stick-slip behaviour of faults. J. Geophys. Res., 90: 1894–1900.

Syh, C.M., Yuuki, R. and Kitagawa H., 1985. Fatigue microcracks in a low carbon steel. Fatigue Fract. Engng. Mater. Struct., 8(1): 193–203.

Turcotte, D.L., 1992. Fractals and Chaos in Geology and Geophysics, Cambridge University Press, Cambridge, UK.

Zhurkov, S.N., Kuksenko, V.S., Petrov, V.A. et al., 1978. Concentration criterion of volume-type fracture in solids, Physical Processes in Earthquake Sources, Moscow, Nauka, pp. 101–116 (in Russian).

Vorobieva, I.A. and Levshina, T.L., 1992. Prediction of the reoccurrence strong shock using the aftershock sequence, Computational Seismology and Geodynamics, Vol. 2, AGU, Washington, D.C., pp. 27–37.

Yamashita, T. and Knopoff, L., 1992. Model for intermediate-term precursory clustering of earthquakes. J. Geophys. Res., 97: 19873–19879.

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Knopoff, L., 1972. Model for the aftershock occurrence. In: H.C. Heard, I.Y. Borg, N.L. Carter and C.B. Raleigh (Editors), Flow and Fracture of Rocks. Am. Geophys. Union, Geophys. Monogr. Ser., 16: 259–263.
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