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WORKSHOP ON PATTERN RECOGNITION AND ANALYSIS OF SEISMICITY

(5 - 16 December 1983)

BURSTS OF AFTERSHOCKS, LONG-TERM PRECURSORS OF STRONG EARTHQUAKES

V.I. KEILIS-BOROK
L. KNOPOFF
I.M. ROTWAIN

Reprinted from Nature, Vol. 283, No. 5744, pp. 259-263, January 17 1980

Bursts of aftershocks, long-term precursors of strong earthquakes

V. I. Keilis-Borok*, L. Knopoff† & I. M. Rotvain*

* Institute of the Physics of the Earth, Academy of Sciences, Moscow, USSR
† Institute of Geophysics and Planetary Physics, University of California, Los Angeles, California 90024

Earthquakes that are followed within a short time by abnormally large numbers of aftershocks are hypothesised to be long-term precursors of stronger earthquakes. In a test of the hypothesis, 18 out of 23 strong earthquakes, in five regions worldwide, were predicted retrospectively. In comparison with a random model the precursory pattern occurs at a satisfactorily high confidence level.

The hope that patterns of seismicity exist that are premonitory to strong earthquakes relies on the fact that the occurrence of earthquakes is controlled by the distribution of stresses and strengths within the Earth and that each earthquake in turn changes these fields. At present we cannot anticipate what such patterns should be, because the theoretical basis is inadequate. One reason for this is the absence of firmly established empirical regularities in seismicity which would provide a factual basis for theoretical studies of earthquake occurrence.

Searches for premonitory patterns of seismicity have attracted much attention, as these may possibly be established by the analysis of earthquake catalogues which are the longest record of the relevant observations. With regard to precursors of large earthquakes, there have been many purported descriptions of premonitory patterns of seismicity. These patterns are of three main types—quiescence, activation and migration of epicentres. Although the results from some of these studies support the hope that premonitory patterns of seismicity exist, nevertheless, with a few exceptions, their definition is not specific enough to measure the reliability of the pattern. To obtain such estimates one should be able to detect the pattern by a formal algorithm and to count how often it is successful as a precursor. Without such estimates of reliability, any premonitory pattern would be uncertain.

We present here an attempt to derive a formal definition of some premonitory seismicity patterns from the analysis of an earthquake catalogue, which yields a reasonable success-to-failure ratio in retrospective long-term earthquake prediction. The definition also provides constraints on the theory of earthquake occurrence.

One reason why the search for premonitory patterns of seismicity has not been successful is that aftershocks are usually disregarded as being highly predictable phenomena. The results we describe below show that, while aftershocks are indeed highly predictable, some specific traits of aftershock sequences are highly informative. These traits may represent important, descriptive aspects of the distribution and redistribution of stresses and strengths within the Earth.

Definitions

Let t be the origin time of an earthquake, λ, ϕ the longitude and latitude of its epicentre (west and south are negative), h its focal depth, and M its magnitude. The subscript j will indicate the sequence number of an earthquake in the catalogue, $t_i < t_{i+1}$.

We seek precursors of earthquakes with magnitudes $M \geq M_0$. These are called strong earthquakes. Our patterns will be constructed from earthquakes in the magnitude range $M_2 \equiv M_0 - \mu_2 \leq M \leq M_0 - \mu_1 \equiv M_1$ and in a time interval of duration s; the values of μ_1, μ_2 and s may be different for each of the three patterns that we will discuss.

Aftershocks are defined as follows. Consider two earthquakes with sequence numbers i and j, $j > i$. The second earthquake is

Table 1 Score of patterns B

Regions	1 Southern California	2 N. California–Nevada (excluding Mendocino area)	3 Southern Japan	4 Northern Japan	5 New Zealand	Totals
Catalogue ref.	4, 11, 12	9	10, 14	10, 14	13	
Span of catalogue (yr)	1932–78	1945–76.5	1926–76.5	1940–76.5	1945–77	201.5
M_0	6.5	6.2	8	7.6	6.6	
C	11–13	6–12	4–10	4–6	9–14	
Strong earthquakes						
total	6	4	2	4	7	23
'predicted'	5	3	2	4	4	18
Relative time of alarms	0.46	0.27	0.18	0.36	0.27	0.31
N_m	36	39	9	45	65	194
N_A/N_B	9/14	3/6	2/4	7/13	7/8	28/45
T_τ/T	0.37	0.28	0.10	0.27	0.53	0.30
P	96%	79%	95%	96%	95%	

N_m, total number of main shocks; N_B, number of main shocks which generate pattern B $b_i \geq C$, for upper value of C; N_A, number of occurrences of pattern B which are followed by strong earthquakes within τ yr; T_τ, sum of times τ before each strong earthquake, counting overlapping parts only once; T, span of the catalogue (yr); C, threshold for identification of pattern B. A variation of C within the limits indicated in the table will introduce either zero or one additional error; P, confidence level for upper value of C.

aftershock of the first if the following conditions are satisfied: the distance between their epicentres is less than $R(M_i)$; $t_j - t_i \leq T(M_i)$; $h_j - h_i \leq H(M_i)$; $M_j \leq M_i$. Here $T(M)$, $R(M)$ and $H(M)$ are empirical functions. If we apply this definition to an earthquake catalogue, starting with the first earthquake, we can separate the catalogue into main shocks and their aftershocks. The first earthquake of the catalogue is identified as a main shock. Each succeeding main shock can be identified after the deletion of aftershocks of the preceding main shocks. Formulas of this type have been developed[1-3] for both the worldwide and southern California[4] catalogues for use in other aspects of the study of aftershocks and sequences or chains of interdependent earthquakes.

Pattern B (burst of aftershocks). Let $b_i(e)$ be the number of aftershocks following the ith main shock within time interval e. We consider only those main shocks with magnitudes between M_2 and M_1 and only aftershocks with magnitudes at or above some threshold $m \equiv M_0 - \mu_3$. We invoke the thresholds M_2 and m for practical reasons as all catalogues are incomplete and inhomogeneous for small magnitudes. However, these thresholds may be of some value in explaining physical relationships, as the details of premonitory patterns may be different in different magnitude ranges.

Pattern B consists of a main shock and its aftershocks for which $b_i \geq C$. A more flexible definition of a threshold for b_i can be given[5], but it is not required for the present purposes.

An alarm is declared for a period of τ years after pattern B is diagnosed. A strong earthquake is expected during this period, having been predicted by pattern B. The alarm is terminated either at the time a strong earthquake takes place or at the end of this period, whichever comes first.

Pattern S ('swarms') was introduced elsewhere and its parameters were adjusted to the Italian earthquake catalogue[6]. We count the number of earthquakes in a time-window from $(t - s)$ to t, in the same magnitude range as above and in a restricted depth range. Let $N(t)$ be the total number of such earthquakes in the region. A reduced number of earthquakes $n(t)$ is obtained from $N(t)$ by the elimination of aftershocks of strong earthquakes. We then consider the map of the epicentres that are counted to determine $n(t)$. From this map we determine a third function $r(t)$ which is the maximum number of epicentres that can be surrounded by a small rectangular cell of dimensions $\Delta\phi$ in latitude and $\Delta\lambda$ in longitude.

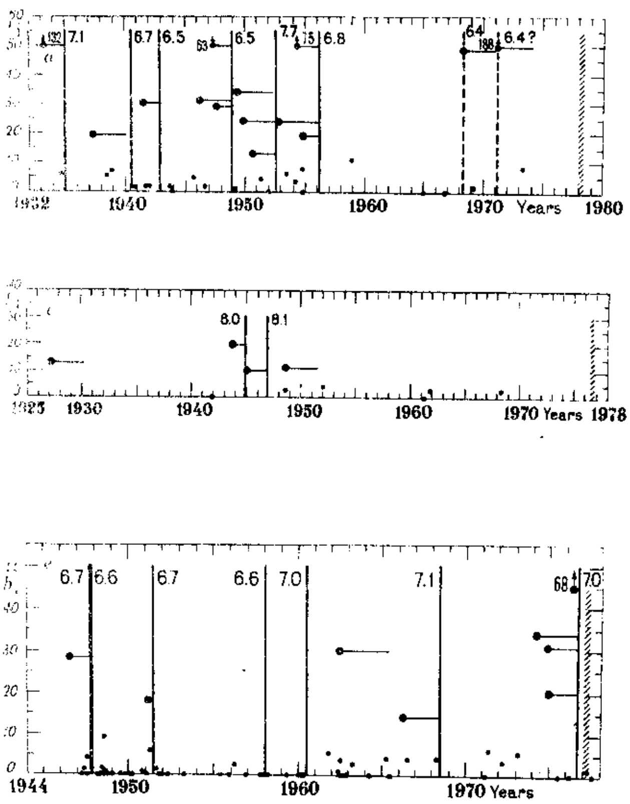
Pattern S consists of a group of earthquakes such that $n(t) > \max\{C_1, C_2\bar{N}(t)\}$ and $r(t) > C_3 n(t)$. $\bar{N}(t)$ is the average of $N(t)$ over the interval t_0 to t or from $(t - ks)$ to t. The threshold M_1 plays no part in the identification of this pattern.

Pattern Σ has been introduced elsewhere[7] and its parameters were adjusted to some of the strongest earthquakes of the world. It is represented by a peak of the function $\Sigma(t) = \sum_i G(M_i)$ where the summation takes place over the same band of time and magnitude intervals as above. Aftershocks of strong earthquakes are eliminated from the summation. $G(M)$ is specified[7] to be $G(M) = 10^{d(M-f)}$ where d and f are numerical parameters. Pattern Σ consists of earthquakes satisfying the condition $\Sigma(t) \geq \bar{\Sigma}$. The values $\bar{\Sigma} = cG(M_0)$, $c = 0.5$, $d = 0.91$ have been assumed elsewhere[7].

Alarms after patterns S and Σ are declared in the same manner as indicated after pattern B.

Data processing

We have tested pattern B in a retrospective 'prediction' of strong earthquakes in the five regions indicated in Table 1. Arbitrary decisions have had to be made regarding the definition of the geographical boundaries of these regions as well as the values of all parameters. No *a priori* theoretical limits can be imposed on these decisions and we have to obtain them by data fitting. This creates a danger of self-deception as the number of these decisions is rather large. To decrease this danger we have tried to make these decisions simple, uniform and, if possible, *a priori*. Also we have accepted, when possible, the arbitrary choices of parameters or thresholds made in previous studies, and we have



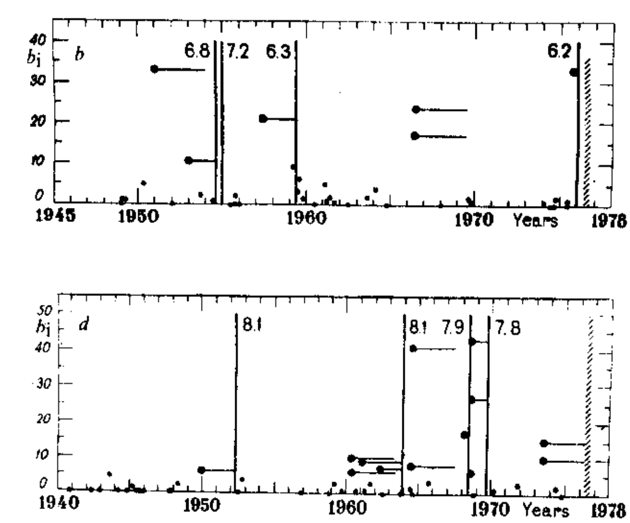


Fig. 1 Pattern B and strong earthquakes for *a*, southern California, $M_0 = 6.5$; *b*, northern California-Nevada, $M_0 = 6.2$; *c*, southern Japan, $M_0 = 8.0$; *d*, northern Japan, $M_0 = 7.6$; *e*, New Zealand, $M_0 = 6.6$. Hatching indicates the end of the catalogue. Vertical lines denote the times of strong earthquakes. Large dots are the values of *b* for main shocks which excited pattern B($b_i \geq C$); the subsequent alarms are shown by the horizontal lines. Small dots are the values of *b* for main shocks which did not excite pattern B($b_i < C$). The two dashed lines denote the times of the Borrego Mountain (1968) and San Fernando (1971) earthquakes; the two false alarms associated with these events disappear if the magnitude of the San Fernando earthquake is at least 0.1 greater than catalogued. The magnitudes of all events are body wave magnitudes m_b with the exception of the Kern Country earthquake of July, 1952 which has $M_s = 7.7$ indicated. This latter earthquake has had a body wave magnitude assigned[15] (of $m_b = 7.2$).

Table 2 Pattern B and strong earthquakes

Month-day-year	epicentre ϕ	λ	M	b_i $R=50(100)$ km $e=2$ d	$e=7$ d	δT (yr)	n_m
Southern Japan							
Polygon: (30; 130), (33; 139), (39; 136), (33; 127.5)							
3- 7-27	35.6	135.1	7.5	13	18	7.8	
9-10-43	35.5	134.2	7.4	20	25	1.24	
12- 7-44	33.7	136.2	8.0	3	3		[illegible]
1-13-45	34.7	137.0	7.1	10	17	1.94	
12-21-46	33.0	135.6	8.1	2	3		[illegible]
6-28-48	36.1	136.2	7.3	11	11	≥30	
Northern Japan							
Polygon: (33; 139), (37; 145), (40; 146), (45; 154), (49; 150), (45; 140), (39; 136)							
12-26-49	36.7	139.7	6.7	6	7	2.19	
3- 4-52	42.2	143.9	8.1	6(21)	9(28)		[illegible]
3-21-60	39.8	143.5	7.5	10(13)	19(30)	3.56	
3-23-60	39.3	143.8	6.7	6	6	3.56	[illegible]
1-16-61	36.0	142.3	6.8	9(13)	9(13)	2.74	
4-12-62	38.0	142.8	6.8	7(8)	10(12)	1.50	
10-13-63	43.8	150.0	8.1	4(8)	9(16)		[illegible]
5- 7-64	40.3	139.0	6.9	8	10	4.03	
6-16-64	38.4	139.2	7.5	41(42)	48(52)	3.92	
1-29-68	43.2	147.0	6.9	17(21)	23(33)	0.30	
5-16-68	40.7	143.6	7.9	12(45)	17(65)		[illegible]
5-16-68	41.4	142.8	7.5	27	50	1.24	[illegible]
5-17-68	39.8	143.5	6.7	6	7	1.24	
6-12-68	39.4	143.1	7.2	43(45)	51(55)	1.17	
8-12-69	42.7	147.6	7.8	7(37)	18(66)		[illegible]
6-17-73	43.0	146.0	7.4	15(30)	18(45)	>4	
6-24-73	43.0	146.8	7.1	10(30)	16(45)	>4	[illegible]

Values of b_i for $R=100$ km are indicated only if they are not the same as for $R=50$ km; δT, time from the given pattern B until the next strong earthquake; n_m, the number of all main shocks between the given and preceding strong earthquakes, or since the beginning of the catalogue in the case of the first strong earthquake; * denotes a main shock, that would have been identified as an aftershock with $R=100$ km.

tested the stability of our results with regard to variations in each of these choices. We have considered only those earthquakes with $h \leq 100$ km.

We have assigned the following values: $\tau=3$ yr; $e=2$ days; $\mu_1=0.1$; $\mu_2=1$; $\mu_3=3.5$. These values were obtained by data fitting for southern California[5]. To define aftershocks we took $R=50$ km; $T(M)=0.5$ years for $5.0 \leq M \leq 5.4$, $T(M)=1$ yr for $5.5 \leq M \leq 6.4$ and $T(M)=2$ yr for $M \geq 6.5$. The values of $R(M)$, $T(M)$ given elsewhere[3] for the southern California catalogue give better results, but these fine gradations are hardly warranted in view of the accuracy of some of the other catalogues used in this study. The values of $R(M)$ and $T(M)$ assumed here have the advantage that they can be used for a fast diagnosis of pattern B even before the epicentres of aftershocks are determined precisely.

The values of M_0 and C listed in Table 1, have been chosen separately for each region due to lack of experience and a satisfactory theory. The fact that these two parameters have been chosen *a posteriori* contributes the single largest difficulty in the evaluation of the significance of our results.

We have chosen the other parameters to be the same for all regions, even if they are unreasonably simple. This suffices for our present purpose which is to test the existence and stability of pattern B. For actual predictions, the parameters could probably be better adjusted to match the specific geophysical characteristics of the region as well as its own earthquake catalogue. More detailed studies of pattern B in some specific regions will be published elsewhere[8].

The boundaries of the southern California as well as the northern California–Nevada regions are defined elsewhere[illegible]. We straightened these boundaries slightly from the original definitions, and have deleted the area around Cape Mendocino from the northern California study as it has a distinctly isolated cluster of epicentres. The boundaries of the other regions are based on large-scale neotectonics and on the densities of epicentres.

Results

The results are summarised in Table 1. Examples of the details are documented in Table 2 and displayed in Fig. 1. The total span of all five catalogues is 202 yr. Twenty-three strong earthquakes occurred in the five regions during these time intervals. Eighteen of these earthquakes were retrospectively predicted, that is, they took place during the intervals of alarms sounded after each instance of pattern B. The total duration of these alarms is 60 yr or 30% of the total span of the catalogues. If we exclude the results for southern California, which were highly involved in the data fitting, that is, in the adjustment of parameters, we have 13 out of 17 strong earthquakes predicted for the remaining four regions; the total duration of alarms is [illegible] out of 155 yr or 25% of the total time.

Although these numerical values illustrate the practical efficiency of pattern B as a tool in prediction, they cannot be used in statistical tests of the existence of pattern B as, by the definition above, an alarm is terminated by the occurrence of a strong earthquake. To perform this statistical test (of the existence of pattern B), the values of the three parameters, N_A, N_B, and T_r/T were tabulated and listed in Table 1.

The probability that a random binomial process could do as well or better than pattern B in anticipating strong earthquakes is given by the quantity $(1-P)$. This is the probability that N_A events or more will occur out of N_B tries in the fraction T_r/T of the total catalogue time T according to a random binomial process. The values of P strongly support the hypothesis that B is a premonitory pattern, although these values of probability should only be used in a qualitative sense rather than literally. The fact that some thresholds were chosen *a posteriori* leads to an overestimation of P. On the other hand, the fact that some thresholds are chosen to be the same for all regions, leads to an underestimation of P. For example, the earthquake in southern Japan of 28 June 1948 could be deleted as a cause of a false alarm (Table 2) either by (1) changing e from 2 to 7 days, and/or (2) changing m to 5.0 from 4.5. Both of these changes are not unreasonable: in the first instance because $M_0 = 8$ is especially large and in the second because the catalogue[10] is more reliable for magnitudes greater than 5 than it is for magnitudes between 4.5 and 5. The last two false alarms for the southern California catalogue (Fig. 1) disappear if we assume that the magnitude of the San Fernando earthquake of 9 February 1971 is 6.5 instead of 6.4; this question is discussed elsewhere[5]. Similarly, the values of P could be increased by adjusting some of the parameters to take into account specific traits of the observed seismicity for each region separately. However, these adjustments would be non-unique; for the purpose of testing the existence of pattern B as a precursor, it is better to keep the criteria for all regions as uniform as possible, and that we make them, insofar as possible, *a priori*, and hence avoid tampering with the results by intuitive 'improvements' after inspection of the tabulations.

In the case of the northern California–Nevada catalogue we took $m = 3$, instead of $m = 2.7$ which would have been obtained from a literal application of our uniform definition $\mu_3 = 3.5$; this catalogue is especially inhomogeneous for $m < 3$. The errors in prediction with $m = 2.7$ and $m = 3$ are the same.

Table 2 lists the strong shocks as well as the main shocks that trigger pattern B; the strong shocks are underlined. Thus it is possible to see whether or not a strong shock was preceded by pattern B within 3 yr. Table 2 shows that our results remain essentially unaltered when the value of R is changed to 100 km and/or e to 7 d. Similar results have been obtained for the other catalogues.

We have indicated in Table 2 those events that would have been identified as aftershocks of the event immediately preceding had we used $R = 100$ km; deletion of these events from our listing would have improved our success rate as these invariably result in a reduction in N_B without a corresponding decrease in N_A. There are two examples of entries of this type in the southern California catalogue and none in the northern California and New Zealand catalogues.

A more detailed analysis of the stability of pattern B as well as the choice of the optimum parameters for the diagnosis of pattern B requires a separate study for each region. We have tried here to emphasise that pattern B can score quite satisfactory success-to-failure ratios, even with parameters that are uniform for all regions, despite the fact that each region has widely different tectonics, seismicity and quality of earthquake catalogue from the others.

A speculation on generalisation

The same catalogues were processed to detect the presence of patterns S and Σ (Fig. 2). The value of M_0 is assumed to be the same as for pattern B. As in the papers where these patterns were introduced[6,7], the parameters were taken to be as follows: $C_1 = 0$, $C_2 = 1$, $C_3 = 0.5$, $\mu_2 = 2$, $\mu_1 = 0.5$ for Σ (absent for S), $d = 0.91$, $f = 4.5$, $s = 1$ yr for S. For Σ we varied $\bar{\Sigma}$ and s for each of the regions (Fig. 2). The absence of a pattern signifies that it

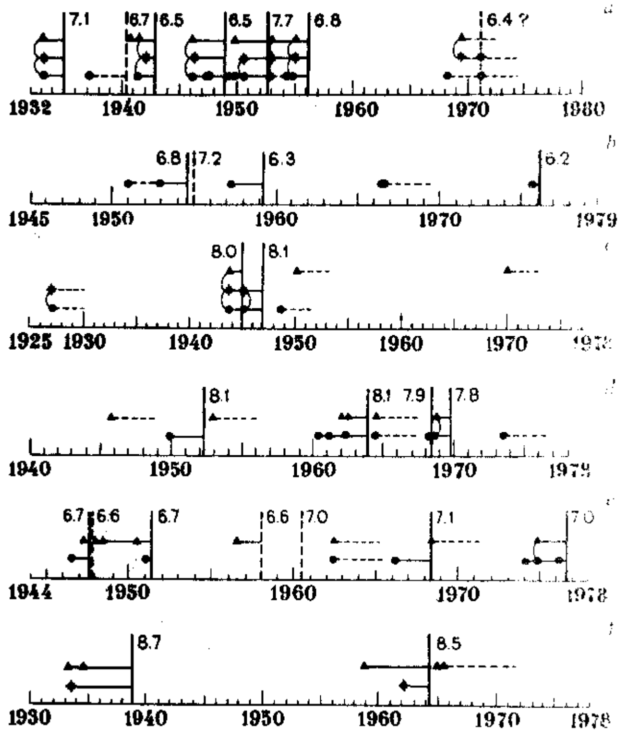


Fig. 2 Occurrence of patterns B (●), S (◆) and Σ (▲).

	$\bar{\Sigma}$	s (yr)	$\Delta\phi$	$\Delta\lambda$
a, Southern California	60	1	0.4°	0.6°
b, Northern California–Nevada				
c, Southern Japan	900	3	0.4	0.6
d, Northern Japan	700	1	1.0	1.4
e, New Zealand	95	0.5	0.4	0.6
f, Alaska	770	2	0.5	1.0

Solid horizontal line is period of alarm; dashed is false alarm. Solid vertical line is time of strong earthquake; dashed is strong earthquake not predicted by pattern B. Brackets denote different patterns generated by the same main shock and the appropriate parts of its aftershock series.

could not be detected for the given region. We added data for Alaska in view of the striking success of pattern Σ.

In several cases the same main shock and its aftershocks will give rise to several different patterns from among Σ, S, B. This result is not unreasonable as by definition, a main shock and its aftershocks will generate:

(1) pattern B if the number of aftershocks during the first e days is large enough;

(2) pattern S if the number of aftershocks during the time interval s, or during any part of it, is large enough; we usually take $s = 1$ yr;

(3) pattern Σ if a sufficiently large number of events have magnitudes close to the upper limit M_1.

In most cases in southern California the same main event plus its aftershocks generate two or even all three patterns. Moreover, the coincidence of a combination of two or three of the patterns eliminates false alarms without adding any failures-to-predict[5].

Patterns Σ and S also appear in conjunction before extremely strong earthquakes in the Tibet–Himalaya region[8]; in this region pattern B cannot be diagnosed, as the catalogues that are available do not include aftershocks.

We find that prediction by pattern B is successful when two conditions are satisfied: not only is a large number of aftershocks b_i required but also the main shock producing it must have a large enough magnitude; if the magnitude of a main shock is too low, but is still followed by an exceedingly large b_i, a false alarm will be generated. We have therefore introduced the threshold M_2. On the other hand we find both the numbers of false alarms and failures-to-predict increase significantly if we ignore the number of aftershocks produced by a main shock and merely consider the occurrence of a main shock itself as a possible precursor: for example, these numbers increased when we considered as a premonitor any earthquake with magnitude up to M_0, that is, by removing the gap between M_2 and M_0, by increasing M_1 and ignoring the threshold C.

We can imagine that a hypothetical generalised premonitory pattern exists which is an abnormal clustering of earthquakes in a space–time–energy domain. We call this hypothetical pattern a 'burst of seismicity'. Our three particular patterns may represent different projections of this generalised pattern. The definitions of the three are neither unique nor optimised; the use of discrete magnitude thresholds, especially in regard to large uncertainties in magnitudes of earthquakes in the catalogues, is an inadequate and troublesome aspect of the work so far. Our results indicate, however, that these patterns exist and deserve attention.

We have refrained from providing additional refinements, such as geological regionalisations or to assign probabilities to the forecasts as functions of time to the forthcoming event and its magnitude. The results of the present exploration indicate that such refinements are necessary and we hope that they would improve our success ratios, which are surprisingly high despite the simplicity of the criteria we have used.

This research was performed as part of Project III of the US–USSR cooperative programme in earthquake prediction. V.I. K.-B. was a Fairchild Scholar at the Seismological Laboratory, California Institute of Technology, and visiting professor at the Institute of Geophysics and Planetary Physics, University of California, Los Angeles. The following members of the Seismological Laboratory supported this research: C. Allen, D. Anderson, D. Harkrider, H. Kanamori, K. McNally, B. Minster. We also thank D. Eckelmann, T. Hearn, C. Johnson, J. [illegible], Y. Kagan, B. Bolt, J. Evernden, W. Lee, and R. Lamoreaux for comments and assistance. Financial support of the Office of Earthquake Studies, US Geological Survey is also acknowledged. This is publication no. 1882 of the Institute of Geophysics and Planetary Physics, University of California, Los Angeles and contribution no. 3261 of the Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena.

Received 15 December 1978; accepted 8 November 1979

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