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Real Time Test of the Long-range Aftershock Algorithm as a Tool for Mid-term Earthquake Prediction in Southern California

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Abstract—Result of the algorithm of earthquake prediction, published in 1982, is examined in this paper. The algorithm is based on the hypothesis of long-range interaction between strong and moderate earthquakes in a region. It has been applied to the prediction of earthquakes with $M \geq 6.4$ in Southern California for the time interval 1932–1979. The retrospective results were as follows: 9 out of 10 strong earthquakes were predicted with average spatial accuracy of 58 km and average delay time (the time interval between a strong earthquake and its best precursor) 9.4 years varying from 0.8 to 27.9 years. During the time interval following the period studied in that publication, namely in 1980–1988, four earthquakes occurred in the region which had a magnitude of $M \geq 6.4$ at least in one of the catalogs: Caltech or NOAA. Three earthquakes—Coalinga of May, 1983, Chalfant Valley of July, 1985 and Superstition Hills of November, 1987—were successfully predicted by the published algorithm.

The missed event is a couple of two Mammoth Lake earthquakes of May, 1980 which we consider as one event due to their time-space closeness. This event occurred near the northern boundary of the region, and it also would have been predicted if we had moved the northern boundary from 38°N to the 39°N; the precision of the prediction in this case would be 30 km.

The average area declared by the algorithm as the area of increased probability of strong earthquake, e.g., the area within 111-km distance of all long-range aftershocks currently present on the map of the region during 1980–1988 is equal to 47% of the total area of the region if the latter is measured in accordance with the density distribution of earthquakes in California, approximated by the catalog of earthquakes with $M \geq 5$. In geometrical terms it is approximately equal to 17% of the total area.

Thus the result of the real time test shows a 1.6 times increase of the occurrence of C-events in the alarmed area relative to the normal rate of seismicity. Due to the small size of the sample, it is of course, beyond the statistically significant value. We adjust the parameters of the algorithm in accordance with the new material and publish them here for further real-time testing.

Key words: Earthquake prediction, long-range interaction of earthquakes, real time test.

Introduction

The hypothesis of long-range aftershocks was originally formulated for the regional catalog of Pamir and Tien-Shan (PROZOROV and RANTSMAN, 1972). According to the hypothesis strong earthquakes generate not only ordinary after-

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shocks in their time-space vicinity, but also trigger seismic activation throughout the region. This activation is especially significant in places where the strength/stress ratio has already reached a critical level. Evidently, those places are the most probable candidates for future strong earthquakes.

We denote initial strong seismic events as type *A*, the remote seismic events which make the activation detectable as type *B* or long-range aftershocks, and the expected future strong earthquakes as type *C*. The latter are expected near *B* events. All shallow earthquakes of magnitude $M \geq 5.5$ in the region and deep focus earthquakes of $M \geq 6$ in the Pamir-Hindu-Kush zone were considered as type *A* events. Shallow earthquakes of $M \geq 5.5$ were considered as type *C* events. We tested for anomalous seismic activation within a 1° radius around *C*-events which occurred after all *A*-events during $T_{AC} = 1$ year before the *C*-events. An earthquake of magnitude $M = 3 - 5$ within 1° radius of a *C*-event was called a long-range aftershock, or a *B*-event, if the interval of time T_{AB} between the *B*-event and preceding *A*-event had a low probability, assuming the hypothesis of a Poissonian model of the occurrence of seismic events with a time invariant probability density function. Seismicity rates for five different magnitude ranges were estimated within a 1° radius of a *C*-event. The seismicity rate was taken to be the average number of events during the entire period of observation for each of the five different magnitude ranges. Three out of ten *C*-events have statistically significant *B*-forerunners which gave an overall statistical significance on the order of 0.99. The most significant interconnections of *A*-*B*-*C*-type were observed in cases of deep focus *A*-events.

Later, this hypothesis was tested on the global NOAA catalog of earthquakes (PROZOROV, 1975), and the most significant *A*-*B*-*C*-connections were situated along the circum-Pacific and Alpide seismic belts. A similar algorithm was independently developed by GUSEV (1976). Recently, positive results were obtained in tests of this long-range aftershocks hypothesis in China (DIAO *et al.*, 1988), they called them "induced foreshocks."

Small earthquakes ($M = 3$ in Central Asia and $M = 4$ in the global NOAA catalog) considered as B-events lead to unavoidable limitation of the algorithm to very short times of response T_{AB}. Long-term earthquake prediction studies empirically established the fact that the strong earthquakes are preceded by anomalies of seismicity in the middle range of magnitudes rather than in the lower one (KEILIS-BOROK *et al.*, 1980). Therefore, to predict earthquakes of magnitude M_C we have to search for an anomaly among *B*-events in the magnitude range $(M_C - \Delta M, M_C)$ rather than $M \geq M_0$, where M_0 is the lower magnitude threshold of the catalog.

The algorithm of earthquake prediction based on the hypothesis of long-range aftershocks within such magnitude range $(M_C - \Delta M, M_C)$, where $M_C = 6.4$, $\Delta M = 1.4$, was applied to the catalog of earthquakes of the Southern California region for the period 1932–1979 (PROZOROV, 1982; subsequently it will be referenced as P–82). In this paper we shall briefly review the results of that work and verify the application of the algorithm to the following period 1980–1988.

Definition of the P–82 Algorithm and Retrospective Results in 1932–79

The algorithm of earthquake prediction via long-range aftershocks consists of the following steps:

i) detection of the ordinary aftershocks in the catalog and their exclusion from further consideration; groups of strong earthquakes which occurred closely in space and time are substituted by one equivalent event with the same coordinates as the epicenter of the strongest earthquake in the group and with the magnitude calculated from the summarized energy of all events of the group by the GUTENBERG-RICHTER (1956) formula: $\lg E = 11.8 + 1.5\,M$;

ii) compilation of the list of triggers or A-events, which consists of all earthquakes in the region with the magnitude $M \geq M_{\mathrm{A}}$;

iii) detection of all B-events after every A-event. The earthquake in the region with parameters $(t, \mathbf{x}, M)$ is considered as a B-event of the A-event $(t_A, \mathbf{x}_A, M_A)$ if the following conditions are satisfied: $t \geq t_A$; $\tau_{AB} = t - t_A \leq T_{AB}$; $|\mathbf{x}_A - \mathbf{x}| \leq d_{AB}$; where $|\mathbf{x} - \mathbf{y}|$ is the distance between the epicenters of A- and B-events.

iv) compilation of the current map of areas of increased probability of future strong earthquakes as the map of B-events surrounded by circles of the radius d_{BC}. A B-event appears on the current map at the time of its occurrence t_B and remains on the map until time $(t_B + T_{BC})$ if it is not cancelled earlier by any C-event;

v) a C-event is considered as predicted if at least one B-event is present on the map at the time of the C-event in its d_{BC}-vicinity;

vi) after every C-event (an earthquake in the region with $M \geq M_C$) all the B-events in its d^1_{BC}-vicinity ($d^1_{BC} \geq d_{BC}$) are cancelled from the current map as retrospectively associated with this C-event.

The parameters of the algorithm in a major variant of P–82 have been chosen as follows:

—boundaries of the region	114° – 124°W; 31° – 38°N
—period of time	1932–1979
—magnitude thresholds	$M_A = 6.0$; $M_B = 5.0$; $M_C = 6.4$
—distance thresholds	$d_{AB} = 300$ km; $d_{BC} = d^1_{BC} = 111$ km (1°)
—time thresholds	$T_{AB} = 1$ year, T_{BC} is unlimited

Ordinary aftershocks were eliminated in circles of a radius of 0.5° for one year after the earthquakes with a magnitude $M \geqslant M_A$ (KEILIS-BOROK *et al.*, 1980). The aftershock area of the 1952 Kern County earthquake (the largest event in the catalog, $M = 7.7$) was contoured more accurately using ellipses that contain major aftershocks with $M \geq 5.5$ and the duration of the period of aftershocks was 1.5 years in this case.

At the beginning of the catalog, the C-event, which consists of two interrelated earthquakes of December 30 and 31, 1934 separated by the distance of 76 km, were not predicted in P–82, possibly due to the lack of B-events generated before 1932. All C-events since 1935 were successfully indicated by B-events with an average value of precision of $d_{BC} = 58$ km, and in no case was the closest B-event farther than 70 km from the corresponding C-event. Most (21 of 23) B-events were finalized by corresponding C-events, and consequently erased the map; average delay time between B- and C-events was $T_{BC} = 9.4$ years.

Real Time Test

We continued here the P–82 algorithm for the time period 1980–1988, with no changes of its parameters, by using the latest available version of the earthquake catalog of the region. The list of all A-, B- and C-events and time-space parameters of their hypothetical interaction is given in Table 1. The maps of B-events immediately preceding in time the C-events occurrences in the region are given in Figure 1a–e for all C-events since the time of the Imperial Valley earthquake of October, 1979. The first event (1979 Imperial Valley) is included in Figure 1 because the parameters of the P–82 algorithm had been settled in the spring of 1979 using the set of the first eight C-events since 1935. The Imperial Valley earthquake, which occurred 6 months after presentation of the algorithm at Keilis-Borok's seminar, is 67 km from an indicating B-event (Figure 1a). This was the first real-time confirmation of the algorithm and it encouraged the author to further thorough statistical testing of the algorithm and its publication.

The indicating B-event (Figure 1a) has been generated by the San Fernando earthquake of February, 1971. The NW direction of vectors **AB** and **BC** perfectly coincides with the orientation of major faults in this area. The values of the distance of **AB** interaction $d_{AB} = 283$ km and the delay between the B-forerunner and the C-event $T_{BC} = 8$ years are typical for the algorithm. At the time of the C-event (October, 1979), there were also two other B-events on the map generated by the

Table 1

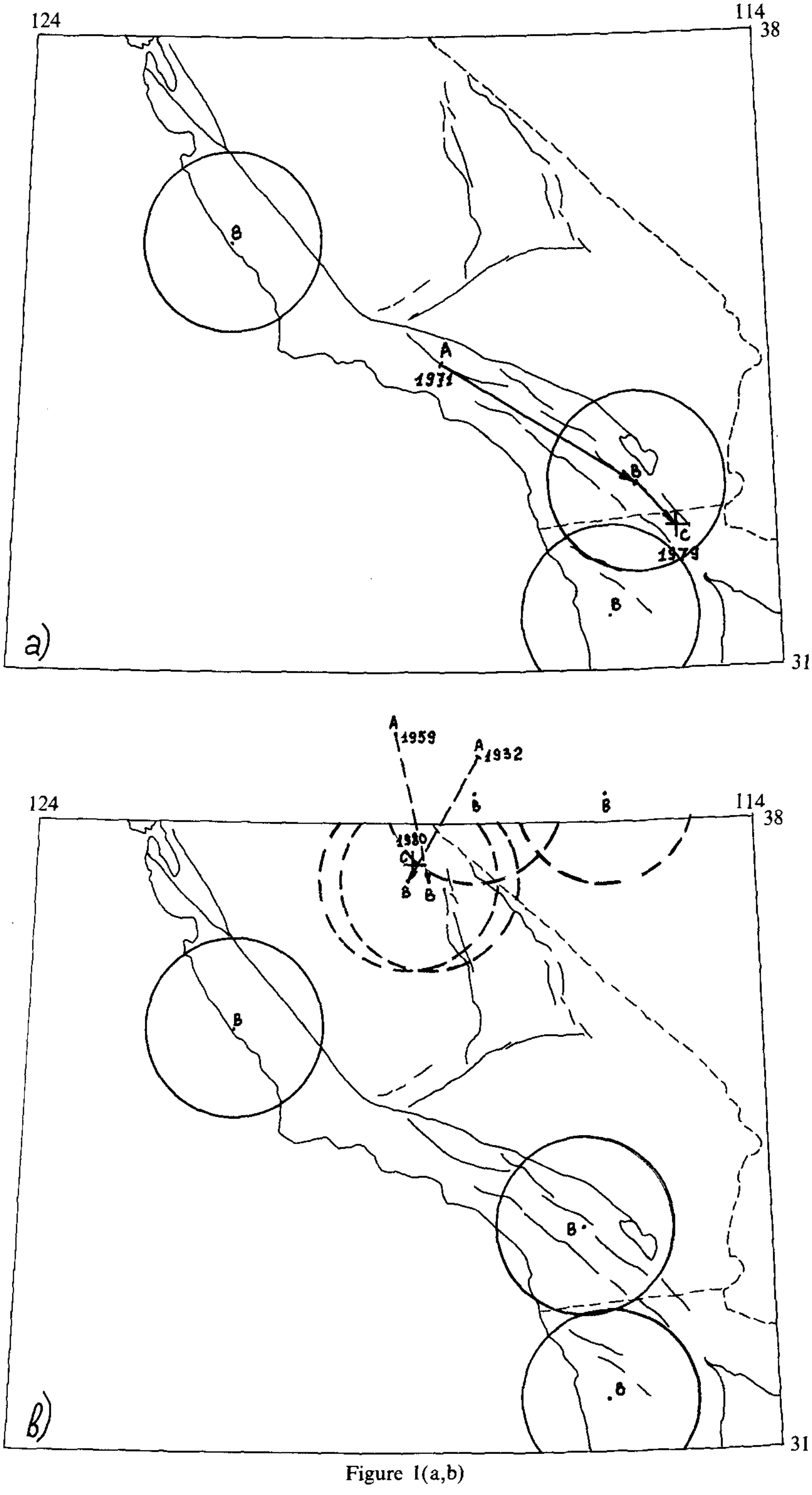
List of A-B-C-events and parameters of their interaction in the P–82 definition of the algorithm

No.	Type ABC	Year	Month	Day	Mg	x	y	d_{AB} km	T_{AB} months	d_{BC} km	T_{BC} years	$N_{A/B}$
3	A	1933	3	10	6.3	−117.9	33.6					
7	A	1934	6	7	6.0	−120.3	35.8					
9	A	1934	12	29	6.5	−115.5	32.2					
10	A	1934	12	30	7.1	−114.7	32.0					
11	T	1935	9	7	5.0	−115.2	32.9	76	.68			9
12	T	1935	10	23	5.1	−116.8	34.1	238	.81			9
17	A	1937	3	24	6.0	−116.2	33.4					

Table 1 (*Contd*)

No.	Type *ABC*	Year	Month	Day	Mg	x	y	d_{AB} km	T_{AB} months	d_{BC} km	T_{BC} years	$N_{A/B}$
32	*A C*	1940	5	18	6.7	−115.5	32.7			32	4.6	11
33	*T*	1940	6	3	5.1	−116.4	33.0	91	.04			32
34	*T*	1940	7	6	5.0	−115.0	31.6	124	.13			32
35	*AT*	1940	12	6	6.0	−115.0	31.6	124	.55			32
36	*AT*	1941	4	8	6.0	−114.0	31.0	238	.88			32
39	*A*	1941	9	13	6.0	−118.7	37.5					
40	*T*	1941	9	20	5.2	−118.9	34.8	300	.01			39
45	*A C*	1942	10	20	6.5	−116.0	32.9			40	2.3	33
48	*T*	1943	8	28	5.5	−116.9	34.2	169	.85			45
57	*A*	1946	3	14	6.3	−118.0	35.7					
59	*T*	1946	7	17	5.6	−115.9	34.5	229	.34			57
60	*T*	1946	9	27	5.0	−116.8	33.9	224	.53			57
61	*A*	1947	4	9	6.2	−116.5	34.9					
62	*T*	1947	7	23	5.5	−116.5	34.0	106	.28			61
65	*A C*	1948	12	3	6.5	−116.3	33.9			14	1.3	62
68	*T*	1949	4	31	5.9	−115.6	34.0	65	.40			65
70	*T*	1949	11	3	5.7	−116.5	32.2	192	.91			65
78	*A C*	1952	7	20	7.7	−119.0	35.0			16	10.8	40
79	*T*	1952	8	22	5.0	−118.1	34.5	93	.09			78
80	*AT*	1952	11	21	6.0	−121.2	35.7	213	.33			78
87	*A*	1954	3	18	6.2	−116.1	33.2					
89	*T*	1954	5	30	5.2	−115.2	31.6	207	.19			87
90	*T*	1954	10	16	5.7	−116.5	31.5	199	.58			87
91	*AT*	1954	10	23	6.0	−116.0	31.5	198	.59			87
92	*AT*	1954	11	11	6.3	−116.0	31.5	198	.65			87
93	*T*	1955	4	24	5.2	−115.0	32.3	131	.50			91
98	*A C*	1956	2	8	6.8	−115.9	31.7			28	1.2	91
100	*AT*	1956	12	12	6.0	−115.0	31.0	120	.84			98
101	*T*	1957	4	24	5.2	−115.8	33.2	255	.36			100
123	*A*	1966	8	6	6.3	−114.5	31.8					
127	*A C*	1968	4	8	6.4	−116.1	33.1			29	10.9	101
129	*A C*	1969	3	20	6.8	−114.2	31.2			29	27.8	36
131	*B*	1969	6	9	5.0	−116.2	31.6	195	.22			129
137	*A C*	1971	2	8	6.4	−118.4	34.4			24	18.4	79
138	*T*	1971	9	29	5.1	−115.8	33.0	282	.63			137
150	*A C*	1979	10	14	6.6	−115.3	32.6			66	8.0	138
151	*T*	1980	2	24	5.5	−116.5	33.5	148	.36			150
152	*A*	1980	5	24	6.5	−118.7	37.5					
154	*T*	1980	9	6	5.7	−118.4	37.9	58	.28			152
161	*A C*	1983	4	31	6.7	−120.2	36.2			101	30.3	80
162	*A*	1984	11	22	6.2	−118.5	37.4					
165	*B*	1985	8	3	5.8	−120.0	36.1	195	.69			162
168	*A C*	1986	7	19	6.5	−118.4	37.5			45	5.8	154
171	*A C*	1987	11	23	6.7	−115.8	33.0			83	7.7	151
172	*B*	1988	1	24	5.6	−115.7	31.7	144	.16			171

B-events are denoted by letters *T* (true), if they are finalized by *C*-events.


124
114
38
B
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a)
31
A
1959
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1980
C
B
B
B
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b)
31

Figure 1(a,b)

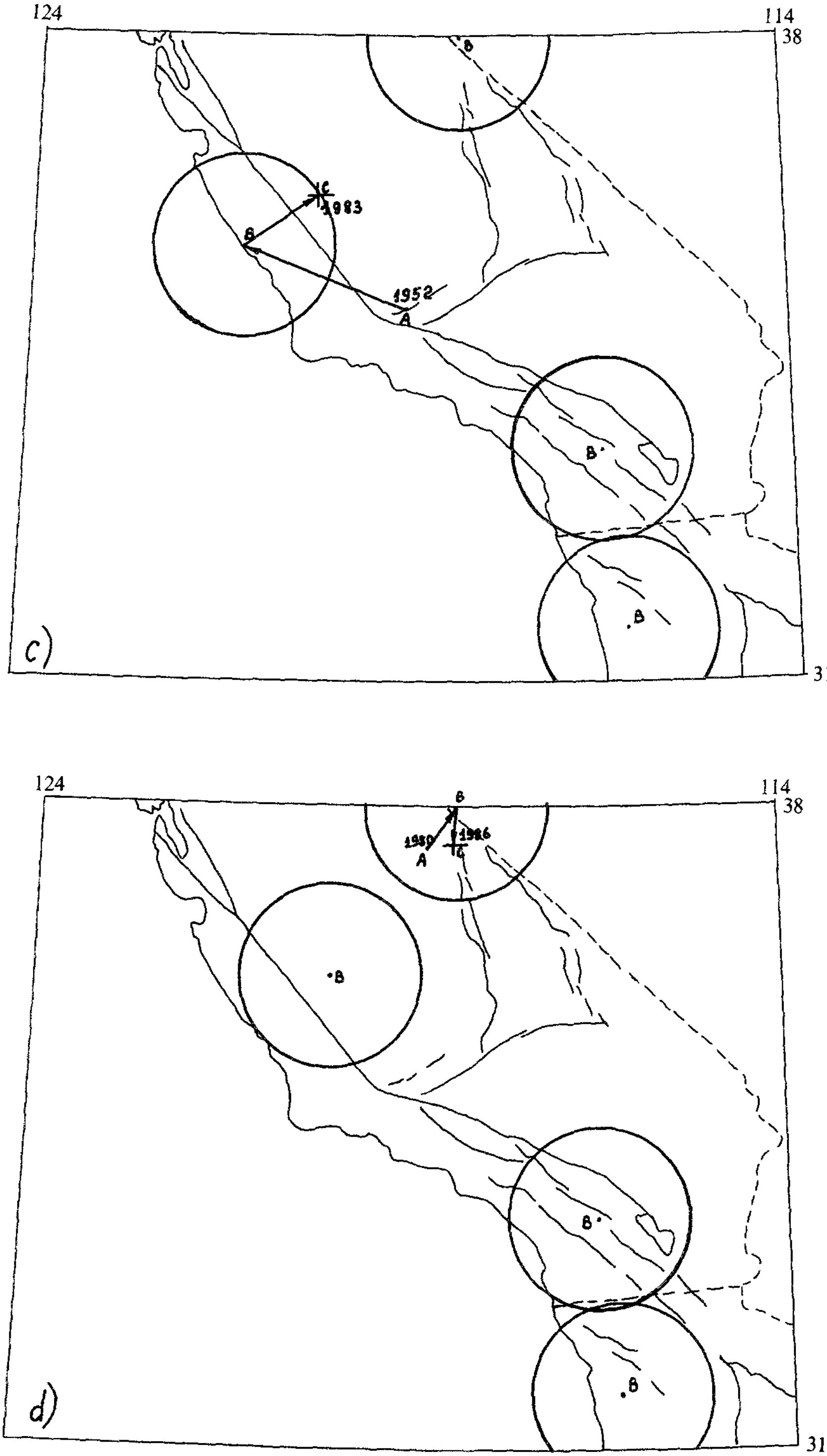

Figure 1(c,d)

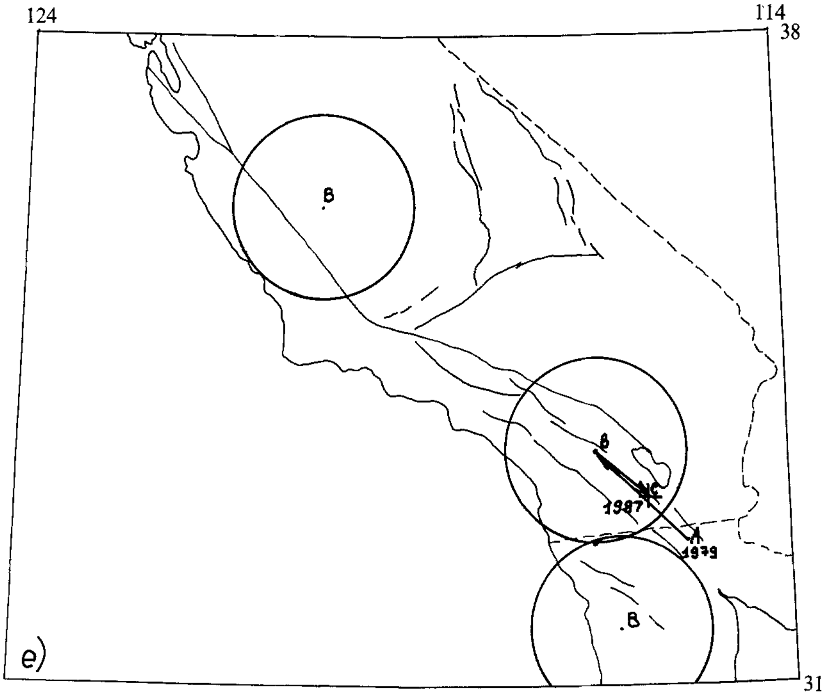

Figure 1(e)

Figure 1

Maps of areas of increased probability of future earthquakes with $M \geq 6.4$ (C-events) according to the algorithm of long-range aftershocks published in 1982 just before every C-event since October 1979 to the end of 1988. The areas are those inside circles around long-range aftershocks or B-events. Arrows indicate the A-B-C long-range interaction scheme for the given C-event on each map. Parameters of all A-, B- and C-events are given in Table 1. Major tectonic faults are after HILEMAN *et al.* (1973).

Kern County earthquake of 1952 and by the large swarm of 1969. The 1°-circles around the B-events cover approximately 15% of the (31°N–38°N, 114°W–124°W) rectangle and about 40% of the seismically active area within this rectangle.

During the following nine years (1980–1988) four seismic events can be classified as C-events. A couple of Mammoth Lake earthquakes of May, 1980 with magnitudes 6.4 and 6.5, respectively were considered as one event because the distance between them is less than 10 km and the time interval is about 3 hours. The Coalinga earthquake of May, 1983, with a magnitude 6.3 by the Caltech catalog, strictly speaking is below the 6.4 threshold established by the algorithm for C-events, but the maximum estimate of the magnitude for this earthquake given in the NOAA catalog is equal to 6.7 and we shall consider it as a C-event. The third event is the swarm in Chalfant Valley of July, 1986. The three strongest earthquakes of this swarm have the following magnitudes in a preliminary version of the Caltech catalog: 6.2 (July 20), 6.6 (July 21) and 5.9 (July 31). The latest version of the Caltech catalog assigns all three events equal magnitudes of 5.9 (magnitude calculated via equivalent energy of the three events would be 6.2) and the maximum estimates of magnitudes in the NOAA catalog are 5.9, 6.5 and 5.7. The fourth C-event is the pair of Superstition Hills earthquakes of November, 1987. The preliminary Caltech catalog assigns to them magnitudes 5.8 and 6.0, but the maximum estimates in the NOAA catalog are 6.5 and 6.7.

The first C-event in the 1980–1988 period of time (the 1980 Mammoth earthquake, Figure 1b) was not predicted by the P–82 algorithm. It occurred near the northern boundary of the region and lost its B-forerunners due to the evident drawback of the algorithm which does not provide area for A- and B-events wider than for C-events. If we move the northern boundary of the region from 38°N to 39°N the 1980 Mammoth Lake C-event would have been predicted as it is shown by the broken lines in Figure 1b. Two A-events of 1932 and 1959 which occurred outside the 38°N boundary generated long-range aftershocks at distances of 25 km and 33 km from the Mammoth Lake C-event. The direction of the 1959 **AB** vector coincides with the orientation of the major geological structures at this area.

The Coalinga C-event (Figure 1c) is predicted by the P–82 algorithm. However, the distance $d_{BC} = 101$ km is rather large and the vector **BC** is oriented across the geological structures.

The **AB** and **BC** interactions predicting the Chalfant Valley C-event (Figure 1d) are most probably the consequences of the sporadic seismic activities in the vicinity of the 1980 Mammoth Lake swarm. They satisfy the conditions of the P–82 algorithm, but, strictly speaking, it is more a local than a long-range interaction.

The Superstition Hills C-event (Figure 1e) is also predicted by the algorithm. The **AB** and **BC** vectors of interaction are the NW direction which is typical for major geological structures here. The map with the B-event near Palm Spring (Figure 1e) was presented on the Spring AGU-meeting in Baltimore (PROZOROV and SCHREIDER, 1987).

Thus, the last three C-events of four during the period 1980–1988 are predicted by the P–82 algorithm with no change of their parameters. The average area occupied by the 1° radius circles around the B-events currently present on maps of the region, is equal to about 17 percent of the total size of the (31°N–38°N, 114°W–124°W)-rectangle. Evidently, the rectangular area is not uniformly seismically active and this value as the percentage of the alarmed area is underestimated. To obtain a nonbiased estimate of this value, let us approximate the rate of C-events by the more numerous earthquakes with magnitudes $m \geq 5$ (aftershocks excluded) with their times made uniformly distributed in the 1980–1988 time period. The percentage of the alarmed area measured by this method is equal to 47. Thus, three of four events hit 47% of the area already selected by the moderate earthquakes distribution as potentially dangerous. This means a 1.6 times increase in the rate of C-events in the alarmed area relative to the normal seismicity rate as it was measured by GUSEV (1976). The result is better than random coincidence, but, of course, due to the small size of the sample, it is not statistically significant.

Statistical Tests

For an algorithm with such a large number of parameters it is very important to test the statistical significance of its results. For example, with a slight shift of the boundary of the region, the C-event of 1980 changed its status from missed event to successfully predicted one.

The first method of statistical testing is the transformation of the discrete distribution of B-events into a continuous danger function $A(\mathbf{x}, t)$

$$A(\mathbf{x}, t) = \begin{cases} \sum_{i=1}^{N} \frac{1}{2\pi\sigma^2} \frac{\theta_i(t)}{n(t)} \exp\left\{-\frac{|\mathbf{x}-\mathbf{x}_i|^2}{2\sigma^2} - \frac{t-t_i}{T}\right\}, & n(t) \neq 0 \\ f(\mathbf{x}) & , \quad n(t) = 0 \end{cases}$$

where $(\mathbf{x}_i, t_i)$ are coordinates of epicenter and time of i-th B-event, σ and T are parameters of the algorithm responsible for the accuracy of prediction in space and time, $f(\mathbf{x})$ is the density distribution of seismic activity,

$$\int_G f(\mathbf{x})\, d\mathbf{x} = 1,$$

G is the seismic region, $n(t)$ is the number of B-events which are currently present on the map of the region at time t,

$$\theta_i(t) = \begin{cases} i, & \text{if } B_i \text{ is present on the map,} \\ 0, & \text{otherwise.} \end{cases}$$

An event B_i is present on the map of the region either during the time interval (t_i, t_i^C), where t_i^C is the time of the first C-event which occurred in d_{BC}-vicinity of the B_i-event after its occurrence or during time interval $(t_i, t_i + T_{BC})$, if the B_i-event is a false alarm, e.g., it is not finalized by an C-event during the time interval T_{BC} after its occurrence.

Let us freeze the actual sequence of B-events with the durations of their presence on the map of the region and assume as 0-hypothesis that C-events are distributed in time uniformly, in space with the density distribution function $f(\mathbf{x})$ and their occurrence does not depend on previous seismicity and consequently has no relation to the B-events. The number of C-events is too small to approximate the density function $f(\mathbf{x})$, where x is the two-dimensional vector. Consequently we make another assumption that their distribution is the same as the distribution of moderate earthquakes with $M \geq 5.0$.

Algorithm of earthquake prediction with function $A(\mathbf{x}, t)$ can now be formulated as follows: at any given time t we declare an area $G_a(t)$ as the area of increased probability of C-events where $G_a(t)$ is defined by the following condition

$$A(\mathbf{x}, t) \geq a, \quad \text{if } \mathbf{x} \in G_a(t).$$

Table 2

Confidence levels of retrospective prediction of C-events by the algorithm based on the danger function $A(x, t)$ with different parameters of smoothing in time T (in years) and in space σ (in km)

C-event number	Number in Table 1	$T = 100$ $\sigma = 40$	$T = 40$ $\sigma = 40$	$T = 20$ $\sigma = 20$	$T = 5$ $\sigma = 20$	$T = 5$ $\sigma = 10$
1	32	.99	.99	.97	.98	.89
2	45	.91	.95	.87	.93	.85
3	65	.98	.99	.98	.98	.98
4	78	.88	.88	.95	.94	.95
5	98	.92	.95	.90	.98	.89
6	127	.83	.85	.87	.87	.87
7	129	.69	.66	.81	.74	.84
8	137	.75	.72	.87	.81	.87
9	150	.75	.67	.74	.66	.73
10	152	.12	.12	.00	.00	.00
11	161	.41	.39	.41	.40	.00
12	168	.62	.65	.70	.78	.71
13	171	.88	.87	.93	.88	.96

We may estimate the probability distribution of statistic A in the assumption of the 0-hypothesis as the empirical distribution of A_k for a large number of points $(\mathbf{x}_k, t_k)$, $k = 1, \ldots, K$, where $\mathbf{x}_k$ are coordinates of moderate earthquakes in the catalog, K is the total number of earthquakes in the catalog with $M \geq 5$ and t_k are random numbers uniformly distributed in time interval (T_1, T_2).

Using this distribution we can estimate the statistical significance of the values $A(\mathbf{x}, t)$ for actual C-events. Results for different values of the parameters T and σ and all other parameters as in the P–82 algorithm are shown in Table 2; they are rather stable to the variation of parameters T and σ. They exist over 95 percent in 2–4 cases, over 90 percent in 3–5 cases and over 80 percent in 7–9 cases. If we use the Erlang statistic $E = \Sigma_{j=1}^{J}(-\ln P_j)$ with the distribution $P(E) = 1 - e^{-E}\,\Sigma_{j=1}^{J}\,E^{k-j}/(k-j)!$ (PROZOROV, 1975), where P_j are the probabilities of the individual cases from Table 2, the estimate of the overall significance for the total sample of C-events will be over 99 percent for all combinations of parameters T and σ given in Table 2. However, the results for the sample of the last 4–5 earthquakes do not qualify for the statistical significance by the Erlang statistic.

Adjustment of Algorithm Parameters for the Additional Data

Retrospective analyses of the distribution of the parameters of the algorithm in Table 1 allows for correction of some of them in the definition of the algorithm to obtain better results in terms of the accuracy of prediction, time-space volume of the area of the increased probability and percentage of missed C-events. The best results are obtained with the following set of parameters:

—boundaries of the region	114°–124°W; 31°–39°N
—period of time	1932–1988
—magnitude thresholds	$M_A = 5.8$; $M_B = 5.0$; $M_C = 6.4$
—distance thresholds	$d_{Ab} = 300$ km; $d_{BC} = 85$ km; $d^1_{BC} = 111$ km (1°)
—time thresholds	$T_{AB} = 0.7$ years, T_{BC} is unlimited.

Table 3, similar to Table 1, lists A-, B- and C-events in the final definition of the long-range aftershocks.

All C-events since 1935 are successfully indicated by B-events with an average value of precision of the indication $\overline{d_{BC}} = 39$ km. The maximum distance from the indicating B-event to the C-event was 83.4 km. Average delay time between B- and

Table 3

List of A-B-C-events and parameters of their interaction in the final definition of the algorithm

No.	Type ABC	Year	Month	Day	Mg	x	y	d_{AB} km	T_{AB} months	d_{BC} km	T_{BC} years	$N_{A/B}$
1	A	1932	12	20	7.2	−117.8	38.7					
2	T	1933	2	2	5.0	−118.8	37.3	177	.12			1
3	A	1933	3	10	6.3	−117.9	33.6					
4	A	1934	1	29	6.6	−118.5	38.3					
7	A	1934	6	7	6.0	−120.3	35.8					
9	A	1934	12	29	6.5	−115.5	32.2					
10	A	1934	12	30	7.1	−114.7	32.0					
11	T	1935	9	7	5.0	−115.2	32.9	75	.68			9
17	A	1937	3	24	6.0	−116.2	33.4					
32	$A\,C$	1940	5	18	6.7	−115.5	32.7			30	4.6	11
33	T	1940	6	3	5.1	−116.4	33.0	84	.04			32
34	T	1940	7	6	5.0	−115.0	31.6	122	.13			32
35	AT	1940	12	6	6.0	−115.0	31.6	122	.55			32
36	AT	1941	4	8	6.0	−114.0	31.0	118	.33			35
37	A	1941	6	30	5.9	−119.5	34.3					
38	A	1941	9	13	5.8	−119.7	37.5					
39	A	1941	9	13	6.0	−118.7	37.5					
40	T	1941	9	20	5.2	−118.9	34.8	78	.22			37
41	T	1941	11	13	5.4	−118.2	33.7	130	.37			37
45	$A\,C$	1942	10	20	6.5	−116.0	32.9			36	2.3	33
57	A	1946	3	14	6.3	−118.0	35.7					
58	T	1946	3	16	5.0	−117.9	38.3	286			57	
59	T	1946	7	17	5.6	−115.9	34.5	220	.34			57
60	T	1946	9	27	5.0	−116.8	33.9	221	.53			57
61	A	1947	4	9	6.2	−116.5	34.9					
62	T	1947	7	23	5.5	−116.5	34.0	106	.27			61
65	$A\,C$	1948	12	3	6.5	−116.3	33.9			14	1.3	62
68	AT	1949	4	31	5.9	−115.6	34.0	60	.40			65

Table 3 (*Contd*)

No.	Type *ABC*	Year	Month	Day	Mg	x	y	d_{AB} km	T_{AB} months	d_{BC} km	T_{BC} years	$N_{A/B}$
70	*T*	1949	11	3	5.7	−116.5	32.2	215	.50			68
76	*A*	1951	12	25	5.9	−118.3	32.8					
78	*A C*	1952	7	20	7.7	−119.0	35.0			16	10.8	40
79	*T*	1952	8	22	5.0	−118.1	34.5	189	.66			76
80	*AT*	1952	11	21	6.0	−121.2	3.57	202	.33			78
84	*A*	1954	1	11	5.9	−119.0	35.0					
87	*A*	1954	3	18	6.2	−116.1	33.2					
89	*T*	1954	5	30	5.2	−115.2	31.6	204	.19			87
90	*T*	1954	10	16	5.7	−116.5	31.5	199	.58			87
91	*AT*	1954	10	23	6.0	−116.0	31.5	198	.59			87
92	*AT*	1954	11	11	6.3	−116.0	31.5	198	.65			87
93	*T*	1955	4	24	5.2	−115.0	32.3	125	.50			91
94	*A*	1955	9	4	5.8	−121.7	37.3					
95	*T*	1955	10	32	5.2	−120.9	36.0	167	.16			94
98	*A C*	1956	2	8	6.8	−115.9	31.7			28	1.2	91
100	*A*	1956	12	12	6.0	−115.0	31.0					
101	*T*	1957	4	24	5.2	−115.8	33.2	253	.36			100
102	*A*	1958	11	30	5.8	−115.7	32.2					
104	*A*	1959	6	22	6.2	−119.0	39.0					
105	*T*	1959	8	3	5.2	−118.5	37.3	187	.11			104
113	*A*	1963	6	10	5.8	−116.2	31.7					
115	*T*	1963	9	22	5.0	−116.9	33.7	220	.28			113
116	*B*	1963	10	19	5.0	−115.6	31.1	94	.35			113
117	*T*	1964	2	2	5.0	−114.2	31.5	178	.64			113
123	*A*	1966	8	6	6.3	−114.5	31.8					
127	*A C*	1968	4	8	6.4	−116.1	33.1			27	10.9	101
129	*A C*	1969	3	20	6.8	−114.2	31.2			28	27.8	36
130	*AT*	1969	4	27	5.8	−116.3	33.3	297	.10			129
131	*B*	1969	6	9	5.0	−116.2	31.6	190	.11			130
133	*B*	1969	10	23	5.1	−119.1	33.2	242	.48			130
137	*A C*	1971	2	8	6.4	−118.4	34.4			23	18.4	79
138	*T*	1971	9	29	5.1	−115.8	33.0	266	.63			137
140	*A*	1973	2	20	5.9	−119.0	34.0					
147	*A*	1978	10	3	5.8	−118.6	37.5					
150	*A C*	1979	10	14	6.6	−115.3	32.6			63	8.0	138
151	*T*	1980	2	24	5.5	−116.5	33.5	141	.36			150
152	*A C*	1980	5	24	6.5	−118.7	37.5			24	47.2	2
153	*T*	1980	9	6	5.0	−118.2	38.0	68	.28			152
154	*T*	1980	9	6	5.7	−118.4	37.9	57	.28			152
157	*A*	1981	9	29	5.8	−118.8	37.6					
161	*A C*	1983	4	31	6.7	−120.2	36.2			62	27.4	95
162	*A*	1984	11	22	6.2	−118.5	37.4					
165	*AB*	1985	8	3	5.8	−120.0	36.1	191	.69			162
168	*A C*	1986	7	19	6.5	−118.4	37.5			45	5.8	154
170	*A*	1987	9	30	5.9	−118.0	34.0					
171	*A C*	1987	11	23	6.7	−115.8	33.0			56	18.5	130
172	*B*	1988	1	24	5.6	−115.7	31.7	144	.16			171

B-events are denoted by letters *T* (true), if they are finalized by *C*-events.

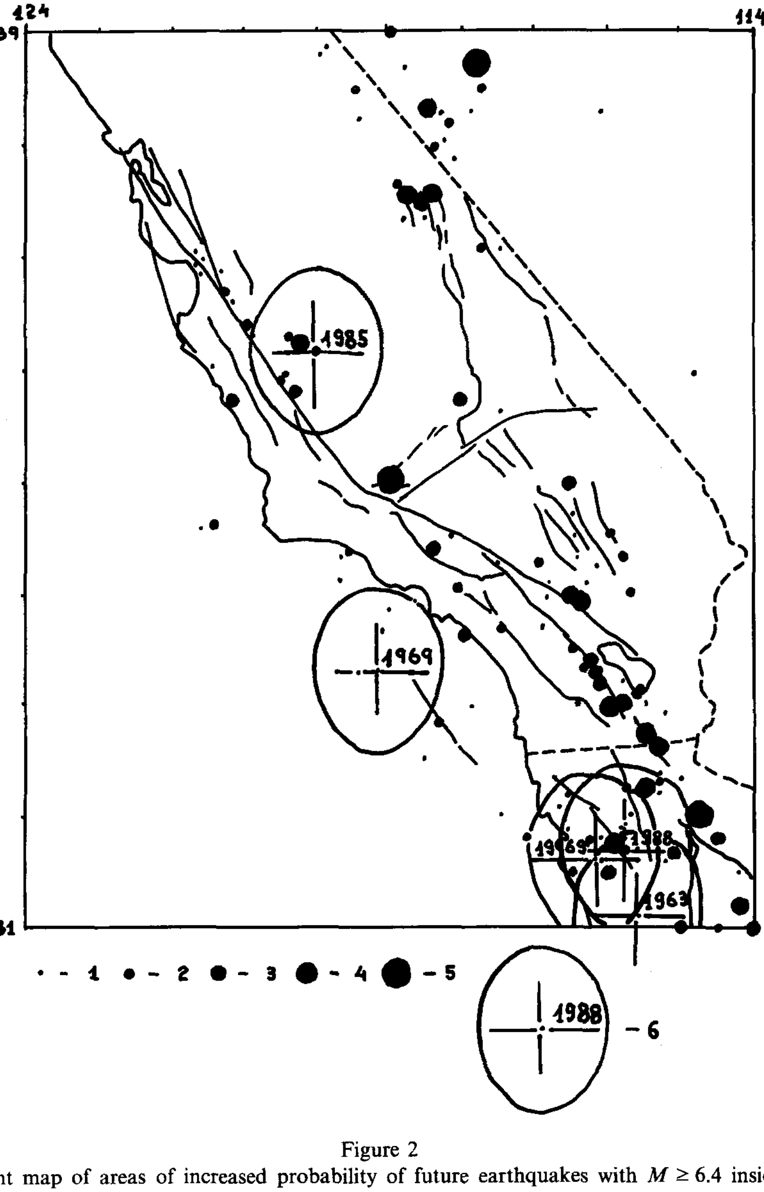

Figure 2
The current map of areas of increased probability of future earthquakes with $M \geq 6.4$ inside of d_{BC} circles around the long-range aftershocks in the final variant of the algorithm, determined via retrospective analyses of data since 1932 until the first half of 1988. The epicenters of all earthquakes with $M \geq 5$ in 1932–1988 used in the estimation of $f(x)$ and percentage of alarmed area are also shown on the map. Notation: 1—epicenters of earthquakes with $M \geq 5$; 2—with $M \geq 5.5$; 3—with $M \geq 6$; 4—with $M \geq 6.5$; 5—with $M \geq 7$. 6—d_{BC}-circles with radius 85 km around the long-range aftershocks currently present on the map (at the beginning of 1989); they are deformed because of the specific map projection used in the software for plotting the epicenters. The year of the long-range aftershock occurrence is shown within the circle.

C-events is $\overline{T_{BC}} = 13.4$ years. 30 of the total numbers of 35 B-events are finalized by corresponding C-events. The remaining five are to be considered as indications of increased probability of future C-events. They are shown on Figure 2 by circles of radius $d_{BC} = 85$ km; the epicenters of all earthquakes with $M \geq 5$ which have been used for $f(x)$ estimation are also shown in Figure 2.

Discussion

The idea of long-range aftershocks came from understanding that tectonic movement has intermittent character not only in geological time scales of millions and thousands of years but it can have sudden changes of velocity in such time intervals as dozens of years, months and days. Nonlocal variation of the seismicity rate are less evident. Seismic processes have a stochastic character complicated by grouped events, swarms and aftershocks which have local physical origins. It complicates the problem of discrimination between random fluctuations of the number of events and actually physically motivated nonlocal changes of the flow rate of seismic events.

GUTENBERG (1956) pointed out that the annual energy release by strong earthquakes was at its peak value at the turn of the century. Variations of global seismicity and its possible physical explanations were discussed more recently by PRESS and BRIGGS (1975), O'CONNELL and DZIEWONSKI (1976), KANAMORI (1977), and MOGI (1979), etc.

A recent episode of regional variation of seismicity rate can be found in California in July, 1986; the Oceanside, North Palm Springs, and Chalfant Valley earthquakes occurred within a two-weeks time interval (WESSON and NICHOLSON, 1987). The regional catalog of earthquakes with seismic moments $M_0 \geq 6.5 \times 10^{24}$ dyne-cm contains $N = 12$ events for the period $T = 10$ years (DZIEWONSKI *et al.*, 1987). Three events within a time interval of two weeks or less have the probability of nonrandom coincidence $p = .99$ by the Poissonian criterion.

The tectonic nature of a long-range interaction of these triplets of earthquakes may be confirmed by the response to each of the seismic events by the corresponding anomalous creep events at Mecca Beach about 86 km from the North Palm Spring earthquake to the SW along the San Andreas fault (WILLIAMS *et al.*, 1988).

Later, in February, 1987 two earthquakes with $M \geq 5$ occurred within a time interval of 7 days in the Imperial Valley and Coalinga. The second event is a standard B-event (response to the Chalfant Valley earthquake as A-event). The first event in the Imperial Valley is not a B-event because its distance from the Chalfant Valley earthquake is too large ($d_{AB} \geq 300$ km), nevertheless it does indicate the future C-event of November, 1987 quite well.

The end of 1987 gives the third example of the long-range interaction between large earthquakes: the Wittier Narrows earthquake of October 1, 1987, $M = 6.0$ in the Los Angeles area and the Superstition Hills pair of earthquakes with $M = 6.5$ and 6.7 of November 24, 1987 to the south of Salton Sea. The probability of the nonrandom character of the two-month interval between the two seismic events in Wittier Narrows and Superstition Hills with $M \geq 6$ comparative to the Poissonian model with an average rate of 1/3 of an event per year and in the last 20 years is about .95. An anomalous aseismic slip with the amplitude larger than in the previously mentioned case occurred again at Mecca Beach on November 1, 1987, e.g., within the time interval between these earthquakes (WILLIAMS *et al.*, 1988).

On June 10 and 13, 1988 two earthquakes with local magnitudes 5.4 occurred 340 km and 730 km, respectively from the Superstition Hills earthquake epicenter in the vicinity of the San Andreas fault. Both earthquakes are not qualified for long-range aftershocks ($d_{AB} > 300$ km) and consequently they are not shown in Figure 2. However, such a short time interval between them indicates the possibility of a long-range interaction through the activation of the tectonic movement along the San Andreas fault.

The anomalous coincidences in time among distant earthquakes with $M \geq 5$ in Southern California are rare events. Let us assume as a threshold value the time interval of less than 7 days between successive earthquakes (non-aftershocks) in the catalog with $M \geq 5$, then the total number of triplets will be 3 (in 1939, 1969 and 1986, respectively). The number of couples of earthquakes with time intervals less than 7 days will be 8. The 1939 triplet was followed by four couples in 1940, 1941, 1946 and 1951. This anomalously high number of interactions between M 5 earthquakes in the region can be associated with the activation of tectonic movement before the 1952 Kern County earthquake of M 7.7. The period of interactions 1939–1951, may be considered as the rough estimate of the duration of anomaly before this earthquake.

The 1969 triplet was not followed by any couples. *The 1986 triplet which was followed by couples in* 1987 *and* 1988 *may be considered as an indication of another activation period on the San Andreas fault and increased probability of a major earthquake in the region in recent years.*

Nonrandom coincidences of strong earthquakes and the existence of the long-range aftershocks can be explained by the effect of the additional tectonic or nontectonic stress applied to the area which is already under critical stress/strength conditions. The existence of such critical areas as, for example in DMOWSKA and LI's (1982) model, the areas of clustering of ordinary foreshock activity at the end of the asperity zone, has little doubts.

The existence of additional stress can be attributed to different factors. Of course, there could be astronomical factors if they have adequate amplitude to make a real contribution in the process of earthquake preparation at its final stage. It is well-known that on the moon, for example, tidal forces correlate with seismic events but only with very small ones.

Another factor is the vibrations during the remote strong earthquake which could possibly lower the strength of the rock under critical stress/strength conditions. Experimental evidence of the influence of the strong remote earthquake on the level of background noise has been reported by CHAVROSHKIN *et al.* (1987). This factor could be responsible for the short time interactions (hours or days).

Slow stress propagation after a strong earthquake through the underlying asthenosphere can have a five times larger amplitude than direct propagation of it through the lithosphere at a given distance (RICE and GU, 1983). This factor can be attributed to interactions with time intervals of a few months or years.

The last feature which can explain the nonrandom coincidences is the irregular block structure of lithosphere and as a result the intermittent character of tectonic movement with long periods when the movement is blocked and sudden activation simultaneously at remote places after a big slip at some place and redistribution of the stresses through the structure. A hierarchic fractal approach to the study of the seismic process was developed recently by SADOVSKI *et al.* (1987). A strong earthquake is considered in this approach as a failure in stability of the temporal congregation of blocks of lithosphere of a definite size. Another explanation of the possibility of an unstable situation can be found in a comparison of two concepts: of concentrated forces applied to asperity and forces distributed over a large area (GRIGORYAN, 1985, 1988). The latter situation has an unstable behavior of cracks existing in material and in our case would mean the possibility of a simultaneous occurrence of events of type A and B.

Conclusion

Without changes of parameters the algorithm of long-range aftershocks published in 1982 predicted three strong earthquakes in the region and missed one, the so-called probability gain in the nine years real time test is equal to 1.6.

In the variant with retrospectively adjusted parameters the algorithm predicts all 13 earthquakes with $M \geq 6.4$ since 1935 until 1988 in Southern California. The directions of the hypothetical long-range interactions between earthquakes are, in most cases, in agreement with the orientation of major geological structures. The average accuracy of prediction is about 40 km, the average delay time between a forerunner and its realization is about 13 years and the average area permanently affected by forerunners is about 36.4 percent in terms of the amount of background seismicity within the area covered by forerunners. The probability gain in the best retrospective variant is approximately equal to 3.

The algorithm has evident drawbacks in its present form. There are too many parameters and all of them are of a discrete nature. Some of the problems can be avoided by application of the danger function $A(x, t)$ but it deteriorates the results of the algorithm and does not solve the problem of dequantization of parameters completely. Further real time testing of the algorithm is still necessary to achieve the statistically significant results.

The long-range aftershocks feature is only one manifestation of the tectonic movement of regional scale. Other features are coincidences in time of the middle range seismic or creep events. Detailed study of these features may help to reconstruct the picture of tectonic movement and improve our ability of earthquake prediction.

Note Added in Proof

The Loma Prieta, California, earthquake of October 17, 1989 of M 6.9 with coordinates 37 1 N, 121 54 W from preliminary data from USGS have occurred in 200 km distance from the nearest B-event on our map (Fig. 2), and according to the formal algorithm should be considered as unpredicted. However, some activation of the long-range interaction of moderate earthquakes has been observed before this earthquake (see page 344, italics at proof). One of the interacting events, namely June 13, 1988 Central California earthquake with $M\,1 = 5.4$ (BRK) by the PDE data have epicenter at about 42 km distance from the Loma Prieta earthquake. According to the algorithm, all B-events shown on Fig. 2 still remain on the current map of increased probability of future earthquakes with $M \geq 6.4$. New B-events (earthquakes with $M \geq 5$, non-aftershocks) if they would occur during 0.7 years after the time of the Loma Prieta earthquake in its 300 km vicinity should be added to the map of Fig. 2.

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