INTERNATIONAL ATOMIC ENERGY AGENCY
UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION

INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
34100 TRIESTE (ITALY) - P.O.B. 586 - MIRAMARE - STRADA COSTIERA 11 - TELEPHONES: 224281/2/3/4/5/6
CABLE: CENTRATOM - TELEX 460392-1

SMR/107 - 1

WORKSHOP ON PATTERN RECOGNITION AND ANALYSIS OF SEISMICITY

(5 - 16 December 1983)

SELFSIMILAR LONG-TERM PREMONITORY SEISMICITY PATTERNS IN CALIFORNIA AND W. NEVADA

C. ALLEN
K. HUTTON
V.I. KEILIS-BOROK
I.V. KUZNETSOV
I.M. ROTWAIN

[illegible] C., [illegible] K., Keilis-Borok V.I.,
Kuznetsov I.V. and Rotwain I.M.

Selfsimilar long-term premonitory seismicity patterns in California and W.Nevada.

I. Non-localized patterns for $M \geqslant 6.4$ and $M \geqslant 7$.

Abstract

A set of seismicity patterns is described which precede the earthquakes with $M \geqslant 6.4$ in San Andreas faults system and adjacent fault zones of Sierra Nevada and Basin and Ranges. The definition of the patterns is normalized to the magnitude range, to the level of seismicity and to the gize of the area. Combination of patterns allows to diagnose the Time of Increased Probability (TIP) for the earthquakes with $M \geqslant 6.4$. The relevance of the patterns is confirmed by their transfer to the earthquakes with $M \geqslant 7$.

Introduction. Premonitory seismicity patterns, so far reported [1, 2, 4, 6–10], can be roughly divided into the following types: activization; quiescence; their combination; clustering; concentration of the sources; long-range interaction; migration. Almost all of these patterns were defined retrospectively; however, in spite of the freedom of retrospective data-fitting, any single pattern does need improvement as a base for the earthquake prediction. This paper describes the attempt to use a combination of premonitory patterns for the diagnosis of the Time of Increased Probability (TIP) of a strong earthquake. The patterns are represented by variation of several functions, defined on the sequence of the earthquakes. We are trying to find at least partially selfsimilar definition of these functions, independent on magnitude range, level of seismic activity and the size of the region. Such selfsimilarity, if estabilished, would be of significant consequence for the theory of the occurence of the earthquakes. It would allow also a compatible analysis of premonitory patterns in diverse seismological environments, in partial compensation of insufficiency of the earthquake statistics for instrumental period.

Traits of seismicity. Seismicity is described by several functions, defined on the sequence of the earthquakes in the region considered. Following the experience of the study [6], we consider the sequence of main shocks only, (t_i, M_i); t is the origin time, M – magnitude, i – the sequence number of a main shock, $t_i < t_{i+1}$. Elimination of the aftershocks prevents the undue influence of strong earthquakes on some of the functions. Let us introduce first the parameters, common in definition of several functions.

We call strong the earthquake with $M \geqslant M_0$.

Parameters $\underline{c}$ and $\bar{c}$ mean that the main shocks are counted in the magnitude range $M_0 - \underline{c} \leq M_i \leq M_0 - \bar{c}$.

Parameter s, when indicated, means, that the main shocks are counted on the sliding time - interval

$$t - s \leq t_i \leq t;$$

Parameter $\bar{n}$ means, that main shocks are counted in the magnitude range $M_i \geqslant M(\bar{n})$; the threshold $M(\bar{n})$ is defined by condition, that average annual number of such main shocks is equal to $\bar{n}$. We introduce this parameter, following [6], in order to make compatible the regions with different levels of seismicity.

$n_Q(\rho)$ and $n_A(\rho)$ are the lower and upper ρ% quantiles of the function $n(t)$ (during % of the time $n < n_Q$ and during other ρ% of the time $n > n_A$).

We shall define now several functions, wich describe integral traits of seismicity. *Introduction of the parameters $\underline{c}$, $\bar{c}$ and $\bar{n}$ makes the definition of these traits partially selfsimilar.*

Level of seismicity

$n(t \mid s, \bar{n})$ – the number of the main shocks.

$$\Sigma(t \mid s, \underline{c}, \bar{c}, \beta, \alpha) = \sum_i E_i^{\alpha} = \sum_i 10^{\beta(M_i - \alpha)}$$

Here E_i is the energy of the i-th main shock, recalculated from M_i.

$g(t \mid s, \bar{n}, a) = n(t\ s, a\bar{n}) : n(t \mid s, \bar{n})$, $a < 1$ – the ratio of the number of the main shocks in magnitude ranges $M_i \geqslant M(a\bar{n})$ and $M_i \geqslant M(\bar{n})$.

$$Q(t\ s, \bar{n}, p) = \int_{t-s}^{t} \left[n_Q(p) - n(t\ s, \bar{n}) \right]^{+} dt$$

Here $^{+}$ means the integration over intervals, where $n_Q \geqslant n$.

Temporal changes of seismicity.

$$D(t \mid s, \bar{n}) = n(t \mid t - t_0, \bar{n}) - n(t - s \mid t - t_0, \bar{n}) \; \frac{t - t_0}{t - t_0 - s}$$

– the deviation from the long-term trend.

$K(t \mid s, \bar{n}) = n(t\ s, \bar{n}) - n(t - s \mid s, \bar{n})$

$V(t \mid s, \bar{n})$ – variation of $n(t \mid s, \bar{n})$ on the time interval from the last maxima of n to t.

The contrast of seismicity of adjacent regions.

We consider the region to be in a state of quiescence (Q) or activation (A) when $n(t \mid s, \bar{n}) < n_Q(p)$ or $n(t \mid s, \bar{n}) > n_A(p)$ respectively. The contrast of seismicity is characterized by the function $T_{AQ}(t \mid s, \bar{n}, p)$ it shows, how long ago this and adjacent regions were in opposite states (A and Q) for a year or more.

Clustering.

$$B(t \mid s, e, \underline{c}, \bar{c}) = \max_i b_i(e).$$

Here b_i is the number of aftershocks of the i-th main shock; the aftershocks are counted in the time interval $(t_i, t_i + e)$ and in magnitude range (M_a, M_i)[3]. *Main shocks are counted according to the values of $\underline{c}$, $\bar{c}$ and s.*

Average concentration of the sources.

$$S_l(t \mid s, \underline{c}, \bar{c}, \beta, \alpha) = \max_i \; n^{-1} \Sigma(t \mid s, \underline{c}, \bar{c}, \beta, \alpha) \quad , l = 1, 2$$

$$S_3(t \mid s, \underline{c}, \bar{c}, \beta, \alpha) = \max_i \; n^{-2/3} \Sigma(t \mid s, \underline{c}, \bar{c}, \beta, \alpha)$$

Here n is the number of the main shocks, counted in Σ; maximum is taken over three consequtive years, from (t – 3 years) to t. S_1, with $d \sim 2/3$, roughly corresponds to the average area of the sources, assuming the same stress – drop for all of them. S_2 is empirical modification of S_1. S_3, with $d \sim 1/3$, roughly corresponds to the ratio of average radius of the sources to average distance between them, according to concentration criteria by Zhurkov–Sobolev [9].

Long – range interaction.

$M_{LA}(t \mid s, Y, \underline{c})$ – maximal magnitude of "long-range aftershock" [7], i.e a main shock, which occured within Y years after a preceding sufficiently strong main shock anywhere in the region *of higher rank.*

$N(t\ s, \underline{c})$ – the number of main shocks within a region of higher rank, which includes the region under consideration.

We considered the abovementioned functions with free parameters indicated in Table 1.

Reduction to pattern recognition. Consider several regions, forming a wider region of higher rank. Seismicity of each region can be described by a vector

$$P_m(t) = \{p_{km}(t)\}, \quad k = 1, 2, \ldots, \bar{k}.$$

Here m is the index of a region, p_{km} is one of the functions, defined above. Different k may refer to different functions, or to the same function with different free parameters.

Our problem is - knowing vector $P_m(t)$, to find, whether the period $(t, t + \tau)$ is or is not the Time of Increased Probability for an earthquake with $M \geq M_o$.

The reduction to the pattern recognition is now natural. Object is a combination of a region and time, (t, m). Description of an object is the vector $P_m(t)$. A priori division of the objects is the following:

Class D - regions during τ years before each strong main shock: combinations of (t, m) for $0 < T_{m,j} - t < \tau$; here $T_{m,j}$ is the moment of the j-th strong main shock in m-th region, j = 1,2, ...

Class N - regions outside these years and not in the aftermath of a strong main shock (T_{mj}, T_{mj} + 3 years). The last condition eliminates the periods of general activization, possible after a strong earthquake.

Class X - all other (t, m).

Our problem is - how to recognize (t, m) of the class D, knowing $P_m(t)$.

Data. Two regions, shown on fig.1, were considered. Their boundary is drawn not unambigously, especially its Eastern part, where we had to draw [illegible] rather [illegible] strip [illegible]

centers on the longitude of Owens valley. We used the catalog [11] for Southern and [12]- for Northern region. Since the catalog [11] starts at 1932, we could compute vector $P_m(t)$ only from 1938 outward. Main shocks were separated from the aftershocks by the algorithm, described in [4]. The list of the main shocks with $M \geq 6.4$ is given in Table 2.

Algorithm. We used algorithm of pattern recognition, named SUBCASSES [3]. Class D was formed by the combinations (T_{mj} - 1 hour, m), (T_{mj} - 1 year , m), (T_{mj} - 2 years, m). Three such combinations for the same main shock formed a subclass. We used for learning the subclasses, which correspond to 15 out of 16 strong earthquakes (Table 2); two years preceding the last earthquake, ~~6.2.83~~ were not used for learning, due to incerntainty in its magnitude.

In the class N 24 out of 36 objects were used for learning.

All objects considered are shown in Table 3. Its first colums shows the moments t, for which the vector $P_m(t)$ was computed. It has to be discretized and represented by binary code, before algorithm SUBCLASSES can be applied. To reduce a posteriori data fitting, we discretized the components $p_{k,m}(t)$ independently on their distribution between classes D and N, in such a way, that each interval of discretization has equal number of the objects of both classes together - one half or one third. The thresholds of discretization, thus obtained, are shown in Table 1.

Results. Characteristic traits of classes D and N are shown in Table 4. They give a satisfactory separation of objects D and N. This can be seen from the Table 3, where the number of traits of D and N (r_D and r_N respectively) is shown for

Table 3 suggests the following a posteriori criterion for the diagnosis of a TIP:

TIP starts, when $n_D - n_N \geqslant 5$ and lasts 18 months.

The stability of the diagnosis of the TIPs can be illustrated by the following tests.

Elimination of functions $p_{km}(t)$, one at a time; a significant change - the increase of the number of false alarms - is caused only by the elimination of $K(t)$ or $V(t)$.

Elimination of the objects from the learning, also one at a time. Only three additional errors, all in Northern region, were generated: failure to diagnose the TIP before the strong earthquake of 2.26.76 (voting gave $n_D - n_N = 3$ for corresponding years); false alarms in 1960 and 1961, with $n_D - n_N = 5$.

In total, the stability of the results seems acceptable. Crucial will be the tests of the reliability of the a posteriori criteria, by which the TIPs were identified. Here we shall describe one test.

Transfer of the criteria to $M \geqslant 7$ in the joint region. The change of M_o from 6.4 to 7 leads to unambigous changes in the functions $p_{k,m}(t)$ and in their discretization. Ambigous is only the expansion of the region. We considered the traditional region

formed by the merger of Northern and Southern regions on the Fig.1. The count of $n_D - n_N$ (voting) was made with the same characteristic traits as for $M_o = 6.4$. The results, shown in the last column of Table 3, seem satisfactory: all 3 main shocks with $M \geqslant 7$ are preceded by the TIPs; the total duration of TIPs is 30%.

Conclusion.

The traits of seismicity, considered here, seem relevant to the preparation of strong earthquakes. The relevancy is confirmed by the successfull transfer of criteria from $M_o = 6.4$ to $M_o = 7$. Further confirmation - by the application of these traits to $M_o = 8$ worldwide - is described in [5].

The score of predictions by the TIPs, considered here, still needs improvement. It is about the same, as for the bursts of aftershocks [4], though much better, than for random alarms. However, for practical purposes the uncertainty in time - space remains too large: TIPs occupy up to a half of the time.

Hopefully, the traits, defined here, due to their partial selfsimilarity, may constitute a common base for the further study of premonitory patterns in a wider variety of regions and magnitude ranges, and for the attempts to narrow further the time-space domain, where a strong earthquake has to be expected.

Acknowledgement. This is a product of Project III of Soviet--American cooperation in earthquake prediction.

REFERENCES

1. Allen C.R. Geological criteria for evaluating seismicity. Bull. Geol., Soc., Am., 86 1975, pp. 1041-1057.
2. Evison F.F. Fluctuation of seismicity before major earthquakes. Nature (London), v. 266: 710-712, 1977.
3. Gelfand, I.M., Sh.A.Guberman, V.I.Keilis-Borok, L.Knopoff, E.Ya.Ranzman. I.M.Rotwain and A.M.Sadovsky. Pattern Recognition applied to earthquake epicenters in California, Physics of the Earth and Planetary Interior, 11: 227-283, 1976.
4. Keilis-Borok V.I., L.Knopoff and I.M.Rotwain. Bursts of aftershocks, long-term precursors of strong earthquakes. Nature, vol. 283, No 5744, 259-263, January 17 1980.
5. Keilis-Borok V.I. and Kosobokov V.G. Diagnosis of the periods of increased probability for the strongest (M 8) earthquakes of the world. In print.
6. Lamoreaux R., Keilis-Borok V.I., Johnson C. and Minster B. Swarms of main shocks in Southern California. Journal of Earthquake Prediction, No 1, 1983.
7. Prozorov A.G. Long-range aftershocks, precursors of the earthquakes in Southern California. In: Computational Seismology (Vichislitelnaya Seismologiya) v.14: 20-26, Moskwa, Nauka, 1982 (in Russian).
8. Rikitaki T. Earthquake Prediction Elsevier Amsterdam, 1976.
9. Sobolev G.A. and Zavialov A.D. A concentration criterion for seismically active fault. In: Earthquake Prediction, Ed. D.Simpson and P.Richards, AGU, Washington D.C., 337-380, 1981.
10. Wyss M. and Habermann R.E. Seismic Quiescence precursory to a past and a future Kurill Island Earthquake. Pageoph. Vol.117 Birkhauser Verlag, Basel, 1979.

Earthquake catalogs

11. Southern California hypocenters data file, 1932-1982, CIT - USGS, 1983.
12. Worlds hypocenters data file, up to 1982, USGS - NEIS, 1983.

Table 1. Functions $p_k(t)$ and the thresholds for discretization

function	free parameters: s, years	n	$\underline{c}$	$\bar{c}$	other	thresholds
n(t)	6	1.4	–	–	–	5; 8
n(t)	3	.36	–	–	–	0
n(t–6)	3	1.4	–	–	–	2
g(t)	1	3	–	–	a=.47	.33; .52
Q(t–3)	6	1.4	–	–	p=33	3; 5
D(t)	6	1.4	–	–	–	–5; 0
K(t)	2	1.4	–	–	–	–1; .5
V(t)	1	3	–	–	–	2; 4
T_{AQ}	3	3	–	–	p=33	5; 13(years)
B(t)	3	–	1.5	.1	$M_a = 2.8$ e=2days	11; 30
Σ in $S_1(t)$	1	–	1.5	.1	β=.91 α=4.5	4.8 ; 7.5
Σ in $S_2(t)$	"	–	"	"	"	2.4; 4.1
in $S_3(t)$	"	–	"	"	β=.77 α=4.5	5.3 ; 6.5
$M_{LA}(t)$	3	–	0	–	=1year	4 .6
N(t)	3	–	1	–	–	4; 8
N(t)	6	–	0	–	–	1

Table 2. Main shocks, M ≥ 6.4, 1938 – 6. 1983

	Data	epicenter φ, °N	λ°, W	M
	Northern region			
1	9 02 1941	40.05	125.25	6.6
2	6 07 1954	39.42	118.53	6.8
3	16 12 1954	39.32	118.2	7.2
4	21 12 1954	40.78	123.87	6.6
5	26 11 1976	41.29	125.71	6.8
6	8 11 1980	41.11	124.25	7.2
	Southern region			
1	19 05 1940	32.73	115.5	6.7
2	21 10 1942	32.97	116.0	6.5
3	4 12 1948	33.93	116.38	6.5
4	21 07 1952	35.0	119.02	7.7
5	9 02 1956	31.75	115.92	6.8
6	9 04 1968	33.18	116.12	6.4
7	9 02 1971	34.4	118.4	6.4
8	15 10 1979	32.6	115.32	6.6
9	25 05 1980	37.6	118.82	6.4
10	25 05 1980	37.55	118.78	6.5
11	2 05 1983	36.14	120.5	6.5?

Table 3. Diagnosis of TIPs

t	M_o = 6.4 Nothern region n_D:n_N	Southern region n_D:n_N	M = 7.0 Joint region n_D:n_N
1	2	3	4
19.05.1938	0:5	1:2	0:2
19.05.1939	6:2	6:0 *	0:3
19.05.1940	8:0 *	6:0 *	0:2
9.02.1941	10:0 *	12:0 *	8:2 *
21.10.1942	4:0	8:0 *	4:0
1. I.1943	4:1	7:0 *	7:0 *
1. I.1944	3:1	0:0	0:1
1. I.1945	1:6	0:4	2:3
4.12.1946	0:9	9:1 *	7:2 *
4.12.1947	0:10	9:1 *	0:6
4.12.1948	0:8	4:2	0:6
1. I.1949	12:1 *	4:2	1:4
21. 7.1950	12:2 *	14:0 *	9:3*
21. 7.1951	3:1	3:0	1:3
21. 7.1952	6:0 *	0:3	0:3
6. 7.1953	6:0 *	8:0 *	5:2
6. 7.1954	3:0	11:0 *	5:0 *
16.12.1954	8:0 *	4:0	2:0
21.12.1954	3:0	4:0	2:0
9. 2.1955	3:0	5:0 *	4:0
9. 2.1956	5:0 *	10:0 *	12:0*
1. I.1957	1:0	2:0	0:1
1. I.1958	0:5	0:4	1:1
1. I.1959	0:3	0:3	0:0

Table 3 (cont-d)

1	2	3	4
1. I.1960	3:2	0:12	2:6
1. I.1961	4:3	0:13	5:4
1. I.1962	0:12	0:15	0:7
1. I.1963	0:12	0:12	0:4
1. I.1964	0:14	0:8	0:4
1. I.1965	3:9	0:8	0:2
9. 4.1966	0:13	0:10	0:3
9. 4.1967	2:9	1:0	6:2
9. 4.1968	0:7	10:0 *	6:2
9. 2.1969	5:3	3:0	1:1
9. 2.1970	1:5	7:0 *	2:1
9. 2.1971	0:3	8:0 *	4:0
1. I.1972	0:3	1:0	2:4
1. I.1973	0:6	0:4	2:3
26.II.1974	0:7	0:4	0:3
26.II.1975	6:0 *	0:8	1:2
26.II.1976	8:0 *	0:6	5:3
15.10.1977	1:1	0:2	2:1
15.10.1978	2:3	8:0 *	4:2
15.10.1979	2:1	8:0 *	2:4
25. 5.1980	9:0 *	7:1 *	6:1 *
8.II.1980	8:I *	7:0 *	4:0
3. 5.1981	8:0 *	6:0 *	6:0 *
3. 5.1982	12:0 *	11:0 *	12:0 *
3. 5.1983	0:4	0:0	0:0

Table 3, end

Notations:

n_D, n_N – the number of characteristic traits of classes D, N respectively

* – TIPs: diagnosed when $n_D - n_N \geq 5$

solid lines – moments of main shocks with $M \geq M_0$ (not included into the diagnosis)

dashed lines – moments of main shocks with $M_0 - .3 \leq M < M_0$

Note: besides for the times indicated in the Table, n_D and n_N were determined with the 1 month interval.

Table 4. Characteristic traits of D (upper 17 lines) and N (lower 15 lines).

Each line defines a trait, as an unequality or a combination of two or three unequalities

No	n(t/6)	n(t/3)	K(t)	g(t)	S_1	S_2	S_3	D(t)	n(t-6)	$M_{LA}(t)$	B(t)	V(t)	N(t/3)	N(t/6)	$T_{AQ}(t)$
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1			> 0												≤ 5
2			>-1										> 4	> 1	
3			>-1				> 5,3					≤ 4			
4		> 0								> 4,6		≤ 4			
5			>0					>-5				≤4			
6		> 0					> 6,6					≤ 4			
7		> 0				>2,4						≤4			
8			> 0		>4,8							≤ 4			
9			> 0	≥0,33								≤ 4			
10		> 0		<0,52								≤4			
11				< 0,52			> 6,6				> 11				
12			> 0		>4,8					> 4,6					
13			> 0				> 5,3	≤0							
14			> 0			>2,4	> 5,3								
15			> 0		≤7,8		> 5,3								

Table 4 (cont-d)

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
16			> 0	≤ 0,52			>5,3								
17	≤ 8		> 0				>5,3								
1															5 ÷ 13
2											≤ 30		≤ 8		≤ 13
3		= 0									≤ 30				≤ 13
4						≤4,1				≤ 4,6					≤ 13
5							≤ 6,6							≤ 1	> 5
6			≤ 0	≤ 0,52											> 5
7		= 0	≤ 0												> 5
8							≤ 6,6						4 ÷ 8		
9							≤ 6,6			≤ 4,6			≤ 8		
10					≤4,8		≤ 6,6						≤ 8		
11			≤ -1				≤ 6,6						≤ 8		
12		= 0	≤ 0										> 4		
13									≤ 2		≤ 30				
14			≤ 0	≤ 0,52					≤ 2						
15			≤ 0			>2,4	≤ 6,6