Proc. Indian Acad. Sci. (Earth Planet. Sci.), Vol. 98, No. 4, December 1989, pp. 309–318.

On self-similarity of premonitory patterns in the regions of natural and induced seismicity

V G KOSSOBOKOV*, B K RASTOGI† and V K GAUR**
National Geophysical Research Institute Hyderabad 500007 India
* Institute of Physics of the Earth, Bulshaya, Gruzinskaya Street No. 1, Moscow. D 242, USSR
** Present address: Department of Ocean Development, 12, Lodi Road, New Delhi 110003, India

MS received 20 March 1989; revised 21 September 1989

Abstract. Anticipating the scale invariance of rock fracturing processes, we applied Keilis-Borok's algorithm *M*8, originally designed for identifying times of increased probability (TIPS) of occurrence of strong earthquakes ($M > 8{\cdot}0$), retrospectively to Koyna earthquakes which occurred in the region after the impoundment of the Shivaji Sagar reservoir in 1962. The algorithm which enables diagnosis of TIPS from the 7th year onwards after the commencement of the earliest available data set showed that the 5·3 magnitude earthquake of 20 September 1980 indeed occurred within a time of increased probability. This result, apart from its potential application to recognizing future TIPS in the region, points to self-similarity between the premonitory patterns of natural and induced earthquakes and to scale-invariant nature of their processes. Further, a typical precursory rise in seismicity followed by a relative quiescence was also found to precede all the three larger earthquakes of the sequence.

Keywords. Earthquake prediction; pattern recognition; reservoir-induced seismicity

1. Introduction

Koyna lies about 230 km south-southeast of Bombay, behind the western ghats which form the land edge of the passive continental margin that shaped the western coast of India. The region, lying in the peninsular shield, had been historically regarded as being largely aseismic until mild earthquakes began to be felt shortly after the impoundment in 1962 of the Koyna reservoir, by a dam near the town that bears its name. This newly developed seismicity grew rather rapidly, reaching a climax in the damaging earthquake of magnitude 6·0 that occurred south of the dam on 10 December 1967. This earthquake was followed within 2 years by an unusually prolific sequence of aftershocks including two of magnitude 5, several hundreds of magnitude $\geqslant 3$ and several thousands smaller ones (figure 1). Since then, the region has exhibited continued seismicity, frequently rocked by earthquakes of magnitude 4 and atleast twice by magnitude 5, in 1973 and 1980. Catalogues of these earthquakes have been published by Guha *et al* (1974) for events until 1974, by Padale *et al* (1983) for those up to 1981, and in the reports of the Maharashtra Engineering Research

---

† to whom correspondence should be addressed.

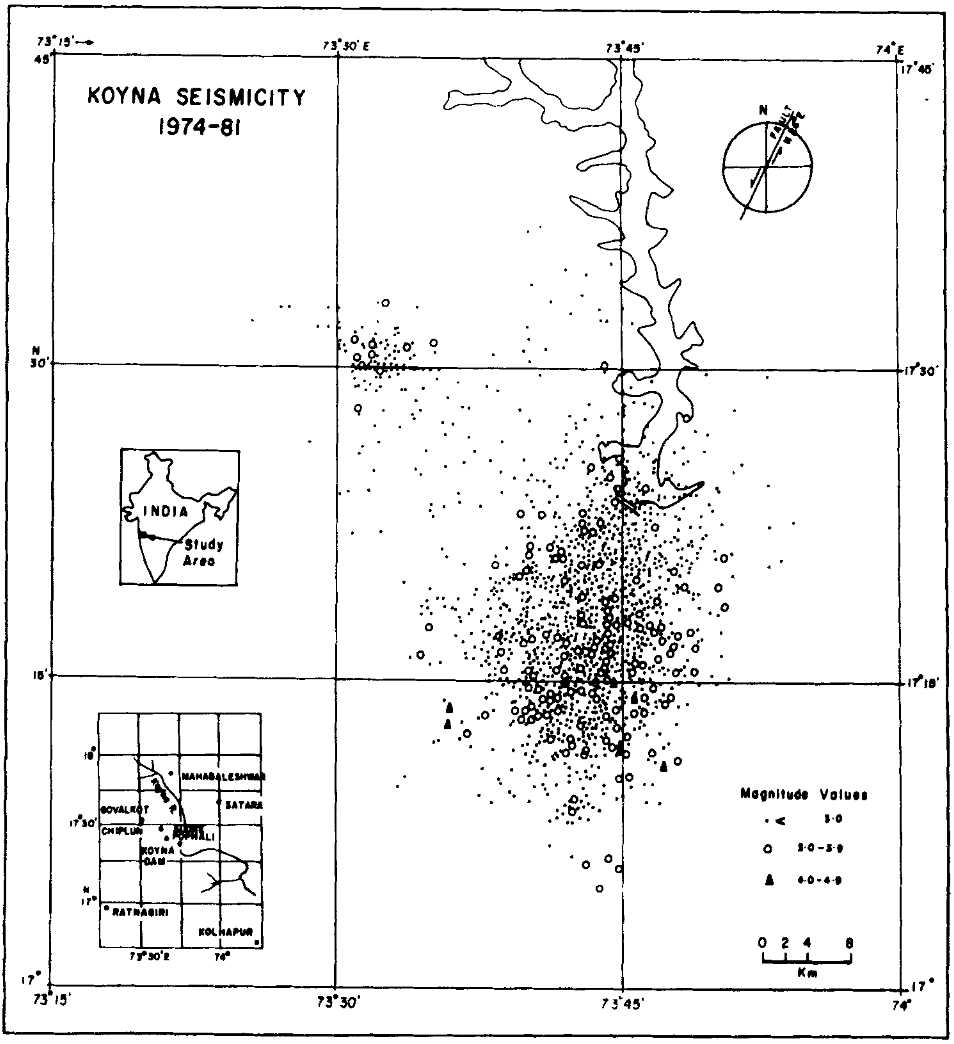

Figure 1. Epicentres near Koyna reservoir during 1974 to 1981. Fault-plane solution for the main earthquake on 10 December 1967 is also shown. The locations of seismic stations are shown in the inset. The figure is modified after Padale *et al* (1983).

Institute, Nasik for the subsequent ones up to 1987. In order to discern diagnostic patterns, if any, in the available records of Koyna events, which could be reliably applied to predict future earthquakes, we analysed these, using the pattern recognition algorithm $M8$ for earthquake prediction designed by Keilis-Borok and Kossobokov (1984). We applied this algorithm without changing any parameters. For different regions what is usually changed is magnitude level to be predicted and the dimensions of the blocks in which parameters are calculated.

The $M8$ algorithm had been originally designed for major earthquakes ($M > 8$) and successfully tested by Keilis-Borok and Kossobokov (1984) and Dmitrieva *et al* (1987) for different regions of the world. It has also been satisfactorily tested for earthquakes in a lower magnitude range of 6–8 (Gabrielov *et al* 1986; Keilis-Borok *et al* 1988; Gieseke *et al* 1989; Brown *et al* 1989; Bhatia *et al* 1989).

As this test of algorithm $M8$ on worldwide data is retrospective, it cannot be considered conclusive. But it does support the concept of global self-similarity of earthquake flow and warrants similar tests to be performed for other regions.

In the present study, it was tested whether the algorithm $M8$ was applicable or not for prediction of still lower level of magnitude ($M = 5$). For the first time in this study this algorithm was applied to a reservoir-induced earthquake sequence. If the algorithm originally designed for natural earthquakes is also found applicable to reservoir-induced sequence, it will indicate self-similarity of the earthquake process of reservoir-induced sequence and the natural earthquake sequence as far as the diagnostic traits (and hence the fracturing processes) are concerned.

2. Algorithm *M8*

The algorithm $M8$ is based on a combined analysis of the following four characteristics (traits) described by appropriate numerical functions evaluated on the sequence of main shocks equal to or exceeding a predetermined magnitude, along a sliding time window: (i) the number of main shocks; (ii) its deviation from long-term trend; (iii) spatial concentration of sources, and (iv) clustering of sources, measured by the maximal number of aftershocks. Each of the first three functions is determined twice, for two different magnitude thresholds M_1 and M_2. Hence, a total number of seven functions are evaluated in four groups. The values of M_1 and M_2 are determined by the criteria that the average annual number of such main shocks is greater than or equal to the predetermined numbers $n_1 (= 10)$ and $n_2 (= 20)$ respectively.

The value of M_0, the magnitude to be predicted is chosen from the past history of strong earthquakes. For Koyna area, earthquakes of magnitude $\geqslant 5$ have been damaging and prediction of these earthquakes is of interest. Hence M_0 is taken as 5. Moreover, algorithm $M8$ can best be tested for $M_0 = 5$ for the Koyna catalogue considered in this study. It cannot be tested effectively for $M_0 < 5$ as the catalogue considered is down to magnitude 3 only. For magnitude > 5 also it cannot be tested effectively. There was only one earthquake of magnitude 6 or greater i.e., the largest shock of the sequence. Enough data prior to this earthquake were not available. Hence for larger M_0, only the false alarms could be considered and not the failure to predict.

In defining the spatial concentration, the main shock to be considered lies within the magnitude range M_1 to $(M_0 - 0{\cdot}2)$ while for clustering they lie in the range $(M_0 - 2{\cdot}0)$ to $(M_0 - 0{\cdot}1)$. The time window for which the functions are evaluated is 6 years for the first three functions and one year for clustering. This time window was arbitrarily chosen in the original work and retained as such. The sliding step for time window is 6 months.

The threshold level of functions is fixed by the analysis of data in the first 6-year period. The functions are considered anomalous if they exceed the threshold level.

Pattern $M8$ is said to have occurred if at two successive instants of time $K - 1$ and K, at least a prescribed number H of individual functions attain abnormally large values, and there are atleast a prescribed number G of groups which have atleast one member that attains an abnormally large value. A time of increased probability (TIP) is then declared at the time instant K, the threshold values of G and H were taken to be 4 and 6 respectively, the same as used in the application of $M8$ in other parts of the world. The TIPS are arbitrarily assigned a duration of 5 years.

3. Koyna earthquake record

We examined the sequence of Koyna earthquakes from 1964 to June 1987 containing over 1000 earthquakes of magnitude $\geqslant 3{\cdot}0$. A catalogue of 267 mainshocks was then abstracted from these by excluding their aftershocks recognized according to the following time and spatial thresholds after Gardner and Knopoff (1974):

M	3	3·5	4·0	4·5	5·0	5·5	6·0	6·5	7·0
$T(M)$, days	11	22	42	83	155	290	510	790	915
$R(M)$, km	22	26	30	35	40	47	54	61	70

Some general properties of the catalogue of mainshocks are presented in tables 1 to 3. These are (a) temporal variations of the number of mainshocks in different magnitude ranges and (b) spatial distributions of their number and maximal magnitude. Table 1 shows that there were relatively smaller number of earthquakes until 1967. It is possible that there were really fewer earthquakes. Alternatively the catalogue is incomplete as only 5 seismograph stations were operating until then near the Koyna reservoir (Rastogi and Talwani 1980).

Table 1. Temporal distribution of mainshocks in Koyna region.

			Magnitude																
Y	M	D	3·0		3·5		4·0		4·5		5·0		5·5		6·0		6·5	Total	Total
																		3 months	6 months
64	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
			·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
64	7	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
			·	1	1	·	·	·	·	·	·	·	·	·	·	·	·	2	2
65	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	2
			·	1	·	·	·	·	·	·	·	·	·	·	·	·	·	1	1
65	7	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	1	2
			·	·	·	1	·	·	·	·	·	·	·	·	·	·	·	1	2
66	1	1	1	·	1	·	·	·	·	·	·	·	·	·	·	·	·	2	3
			·	·	·	1	·	·	·	·	·	·	·	·	·	·	·	1	3
66	7	1	3	1	·	·	·	·	·	·	·	·	·	·	·	·	·	4	5
			1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	1	5
67	1	1	3	·	·	·	·	·	·	·	·	·	·	·	·	·	·	3	4
			1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	2	5
67	7	1	2	·	·	·	·	·	·	·	·	·	1	·	·	·	·	3	5
			·	·	·	·	·	·	·	·	·	·	·	·	1	·	·	1	4
68	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	1
			·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
68	7	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
			·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0

(*Continued*)

Table 1. (*Continued*)

			Magnitude																
Y	M	D	3·0		3·5		4·0		4·5		5·0		5·5		6·0		6·5	Total	Total
																		3 months	6 months
69	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
			·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
69	7	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
			·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
70	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	0
			1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	2	2
70	7	1	·	1	1	·	1	1	·	·	·	·	·	·	·	·	·	4	6
			2	·	·	·	·	·	·	·	·	·	·	·	·	·	·	2	6
71	1	1	1	·	2	·	1	·	·	·	·	·	·	·	·	·	·	4	6
			2	1	·	1	1	·	·	·	·	·	·	·	·	·	·	5	9
71	7	1	1	1	1	·	1	·	·	·	·	·	·	·	·	·	·	4	9
			1	1	·	·	1	·	·	·	·	·	·	·	·	·	·	3	7
72	1	1	3	2	·	·	·	·	·	·	·	·	·	·	·	·	·	5	8
			3	·	3	1	·	·	·	·	·	·	·	·	·	·	·	7	12
72	7	1	·	5	1	·	·	·	·	·	·	·	·	·	·	·	·	6	13
			3	1	·	·	·	·	·	·	·	·	·	·	·	·	·	4	10
73	1	1	1	1	1	·	·	·	·	·	·	·	·	·	·	·	·	3	7
			1	1	1	1	·	·	·	·	·	·	·	·	·	·	·	4	7
73	7	1	2	2	2	·	·	·	·	·	·	·	·	·	·	·	·	6	10
			1	·	·	1	·	·	·	·	1	·	·	·	·	·	·	3	9
74	1	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	1	4
			·	1	3	1	·	·	·	·	·	·	·	·	·	·	·	5	6
74	7	1	2	·	2	·	·	1	·	·	·	·	·	·	·	·	·	5	10
			2	2	·	2	·	·	·	·	·	·	·	·	·	·	·	6	11
75	1	1	2	·	2	·	·	·	·	·	·	·	·	·	·	·	·	4	10
			3	1	1	1	·	·	·	·	·	·	·	·	·	·	·	6	10
75	7	1	1	·	·	·	1	·	·	·	·	·	·	·	·	·	·	2	8
			1	·	2	2	·	·	·	·	·	·	·	·	·	·	·	5	7
76	1	1	1	·	·	1	·	·	·	·	·	·	·	·	·	·	·	2	7
			1	1	2	·	·	·	·	·	·	·	·	·	·	·	·	4	6
76	7	1	1	2	2	·	·	·	·	·	·	·	·	·	·	·	·	5	9
			1	1	1	1	·	·	·	·	·	·	·	·	·	·	·	4	9
77	1	1	·	1	·	·	·	·	·	·	·	·	·	·	·	·	·	1	5
			·	1	·	·	·	·	·	·	·	·	·	·	·	·	·	1	2
77	7	1	3	1	·	·	1	·	·	·	·	·	·	·	·	·	·	5	6
			1	·	3	·	·	·	·	·	·	·	·	·	·	·	·	4	9
78	1	1	2	2	·	·	·	·	·	·	·	·	·	·	·	·	·	4	8
			1	2	1	·	·	·	·	·	·	·	·	·	·	·	·	4	8
78	7	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	1	5
			3	·	2	·	1	·	·	·	·	·	·	·	·	·	·	6	7
79	1	1	3	3	·	1	·	·	·	·	·	·	·	·	·	·	·	7	13
			1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	1	8

(*Continued*)

Table 1. (*Continued*)

			Magnitude																
Y	M	D	3·0		3·5		4·0		4·5		5·0		5·5		6·0		6·5	Total	Total
																		3 months	6 months
79	7	1	2	·	1	·	·	·	·	·	·	·	·	·	·	·	·	3	4
			3	·	·	·	·	·	·	·	·	·	·	·	·	·	·	3	6
80	1	1	3	·	·	·	·	1	·	·	·	·	·	·	·	·	·	4	7
			2	2	·	·	·	·	·	·	·	·	·	·	·	·	·	4	8
80	7	1	4	·	1	·	·	1	1	·	·	1	·	·	·	·	·	8	12
			1	·	1	·	·	·	·	·	·	·	·	·	·	·	·	2	10
81	1	1	3	1	1	·	·	·	·	·	·	·	·	·	·	·	·	5	7
			3	·	1	·	·	·	·	·	·	·	·	·	·	·	·	4	9
81	7	1	2	1	·	·	·	·	·	·	·	·	·	·	·	·	·	3	7
			6	2	·	·	·	·	·	·	·	·	·	·	·	·	·	8	11
82	1	1	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	2	10
			·	·	·	·	·	1	·	·	·	·	·	·	·	·	·	1	3
82	7	1	·	·	1	1	·	·	·	·	·	·	·	·	·	·	·	2	3
			1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	2	4
83	1	1	1	·	1	1	·	1	·	·	·	·	·	·	·	·	·	4	6
			3	1	1	1	·	·	·	·	·	·	·	·	·	·	·	6	10
83	7	1	1	1	·	·	·	·	1	·	·	·	·	·	·	·	·	3	9
			·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	0	3
84	1	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	1	1
			·	·	1	·	·	·	·	·	·	·	·	·	·	·	·	1	2
84	7	1	·	·	·	1	·	·	·	·	·	·	·	·	·	·	·	1	2
			·	·	·	·	·	1	·	·	·	·	·	·	·	·	·	1	2
85	1	1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	·	1	2
			3	1	1	·	·	·	·	·	·	·	·	·	·	·	·	5	6
85	7	1	2	·	1	·	·	·	·	·	·	·	·	·	·	·	·	3	8
			2	·	2	1	1	·	·	·	·	·	·	·	·	·	·	6	9
86	1	1	3	·	·	·	·	·	·	·	·	·	·	·	·	·	·	3	9
			·	2	·	·	·	·	·	·	·	·	·	·	·	·	·	2	5
86	7	1	2	·	·	·	·	·	·	·	·	·	·	·	·	·	·	2	4
			4	·	·	·	·	·	·	·	·	·	·	·	·	·	·	4	6
87	1	1	3	·	·	·	·	·	·	·	·	·	·	·	·	·	·	3	7
			2	·	1	·	·	·	·	·	·	·	·	·	·	·	·	3	6
87	7	1	·	2	·	·	·	·	·	·	·	·	·	·	·	·	·	2	5
			1	1	·	·	·	·	·	·	·	·	·	·	·	·	·	2	4

4. Test of algorithm *M8*

For the purpose of this study, the mainshocks having a magnitude $\geqslant 5$ were considered as strong earthquakes. These are: $m_b = 6{\cdot}0$ (10 December 1967), $m_b = 5{\cdot}0$ (17 October 1973), and $m_b = 5{\cdot}3$ (20 September 1980). For these strong earthquakes, the magnitude values are those of body-wave magnitudes given by the US Gological

Table 2. Spatial distribution of the number of mainshocks.

	Longitude																
Latitude	73·2		73·3		73·4		73·5		73·6		73·7		73·8		73·9		74·0
18·00	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
17·90	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
17·80	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
17·70	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	1	·	·	·	·
17·60	·	1	·	·	·	·	·	1	·	·	·	1	1	·	·	·	·
	·	·	·	·	·	·	2	1	·	·	1	1	·	·	·	·	·
17·50	·	·	·	·	·	·	3	1	·	1	1	1	2	·	·	·	·
	·	·	·	·	·	·	·	1	·	·	3	7	5	·	·	·	·
17·40	·	·	·	·	·	·	·	·	·	3	15	23	3	·	·	·	·
	·	·	·	·	·	·	·	1	1	6	20	16	4	1	·	·	·
17·30	·	·	·	·	·	·	·	1	3	12	30	21	1	1	·	·	·
	·	·	·	·	·	·	·	·	1	13	23	8	·	·	·	·	·
17·20	·	·	·	·	·	·	·	·	·	2	7	5	1	·	·	1	·
	·	·	·	·	·	·	·	1	1	1	3	3	·	·	·	·	·
17·10	·	·	·	·	·	·	·	·	·	2	2	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
17·00	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·

Survey. For smaller shocks, the magnitude values were accepted as given in the Koyna earthquakes catalogue.

The algorithm $M8$ as described in the previous section was applied to the Koyna catalogue. For $M_0 = 5$, the side length (L) of the square for the analysis is considered to be 86 km according to the formula $L\ (M_0) = \exp(M_0 - 5{\cdot}6) + 1$ which gives the length in degrees. As the Koyna epicentral area is about 60 km × 40 km area, it is encompassed in just one block. The algorithm allows one to diagnose TIPS from the 7th year after the commencement of the catalogue, which in this case would be 1974 onwards. Although earthquake monitoring in the region began in 1964, records are incomplete until 1967. However, the functions are evaluated from 1970 onwards as all earthquakes during 1968 and 1969 are treated as aftershocks in terms of the considerations of table 1. The results obtained are presented in figure 2. The first identifiable TIP was terminated by the earthquake of 20 September 1980. Previous earthquakes of 1967 and 1973 occurred too early for this algorithm to be applicable. The TIPS occupy 16% of the total space-time volume and precede the only strong earthquake for which they could be expected. There were no false alarms. Though this success is not statistically significant, the following may however be surmised:

(a) that more robust test of algorithm $M8$ on reservoir-induced seismicity is warranted, and

Table 3. Spatial distribution of maximal magnitude.

	Longitude																
Latitude	73·2		73·3		73·4		73·5		73·6		73·7		73·8		73·9		74·0
18·00	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
17·90	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
17·80	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
17·70	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	3·5	·	·	·	·
17·60	·	3·2	·	·	·	·	·	3·2	·	·	·	3·0	·	·	·	·	·
	·	·	·	·	·	·	3·1	3·5	·	·	6·0	3·2	·	·	·	·	·
17·50	·	·	·	·	·	·	3·9	3·3	·	3·1	3·1	3·5	3·7	·	·	·	·
	·	·	·	·	·	·	·	3·1	·	·	3·8	3·7	3·6	·	·	·	·
17·40	·	·	·	·	·	·	·	·	·	4·4	5·5	4·2	4·2	·	·	·	·
	·	·	·	·	·	·	·	3·6	3·8	3·7	4·1	4·3	3·5	3·7	·	·	·
17·30	·	·	·	·	·	·	·	3·1	3·8	3·9	4·2	4·4	3·0	3·0	·	·	·
	·	·	·	·	·	·	·	·	3·1	3·8	5·3	4·7	·	·	·	·	·
17·20	·	·	·	·	·	·	·	·	·	3·2	3·8	4·4	3·2	·	·	3·3	·
	·	·	·	·	·	·	·	3·2	3·2	3·2	3·6	3·4	·	·	·	·	·
17·10	·	·	·	·	·	·	·	·	·	3·2	3·6	·	·	·	·	·	·
	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·
17·00	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·	·

(b) self-similarity between natural and induced earthquakes and the scale-invariant nature of their process seems to be valid.

The values of the functions determined for the period 1981–1987 were found to be generally very low. Except the last function i.e. aftershocks, all others were 10 to 75% lower than the threshold levels. The values of G and H were only 1 which is considerably lower than the threshold values of 4 and 6, respectively. This analysis was done in the beginning of 1988 and it indicated a little possibility of any earthquake of magnitude 5 or greater during 1988 and it has been found to be true. This prediction is valid until the next one year from any instant of observations as the evaluated functions should be anomalous for two consecutive time windows of 6 months each in order to declare a TIP.

Though the functions have not been evaluated after 1987, it is known to us that the level of seismicity during 1988 and until middle of 1989 is of the same order as that during 1981–87. Hence, a magnitude 5 earthquake is not expected until the middle of 1990.

5. Precursory rise of activity

In addition to the above analysis, we also examined the quiescence of seismicity prior to strong shocks. Duration of quiescence is expected to be about a year or less. Hence, a time window of 3 months was considered. Analysis was done in the following way:

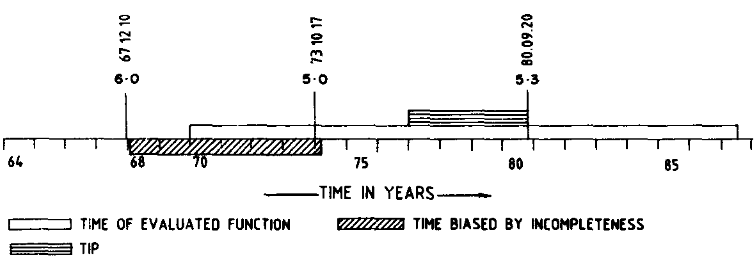

Figure 2. Figure showing times of evaluated functions and TIPS identified with the application of $M8$ algorithm. Times of stronger earthquakes of magnitude 5 or greater are also indicated.

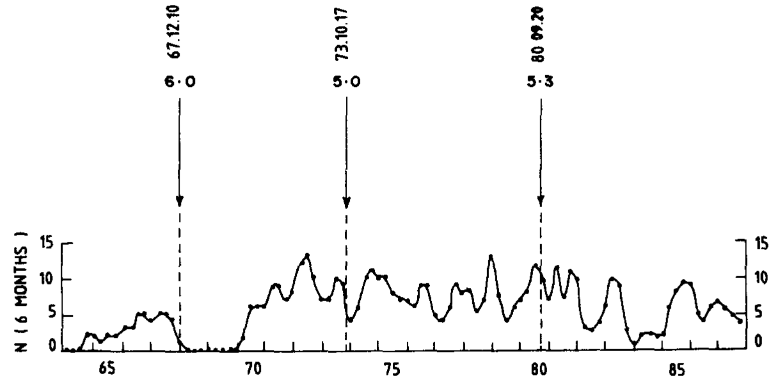

Figure 3. Temporal variation of seismicity shown as a moving sum for every 6-month period calculated from the quarterly catalogue of mainshocks. Times of stronger earthquakes of magnitude 5 or greater are also indicated.

From the quarterly catalogue of mainshocks (N(3 months) last-but one column of table 1), a moving sum (N(6 months) for every 6-month period was obtained (last column of table 1)), and plotted in figure 3. The last column is obtained by adding the rows 1 and 2, 2 and 3, 3 and 4 etc of the last-but one column.

Table 1 shows that a maximum in the number of mainshocks N(6 months), preceded both earthquakes of 1973 and 1980. The graph (figure 3) of N(6 months) shows the precursory pattern rising to a maximal activity rate of 13 mainshocks per half-year, then dropping in less than $1\frac{1}{2}$ years before rising again to meet the next earthquake of magnitude $M > 5$. The same pattern can be seen to occur before the strongest Koyna earthquake of 10 December 1967, though on a smaller scale owing perhaps to incompleteness of the catalogue.

6. Conclusion

The successful diagnosis of a TIP from algorithm $M8$ for the only strong earthquake in Koyna after 1975 without any false alarm or failure to predict, supports the hypothesis of self-similarity between the premonitory patterns of natural and induced seismicity though in a very optimistic way. Of course, the statistical significance of the results has yet to be established in the light of future pattern of earthquake occurrences, before it can be routinely applied to earthquake prediction in the region.

Ten to 75% lower values of the functions of algorithm $M8$ during 1981–87 indicated little possibility of a magnitude $\geqslant 5$ earthquake for the year 1988 which was later found to be true. Though the analysis has not been done for the data after 1987, it is known that the level of seismicity is low until the middle of 1989 indicating little possibility of magnitude $\geqslant 5$ earthquake until the middle of 1990.

A typical pattern of precursory increase in seismicity followed by a relative quiescence and again an increase is observed preceding all three earthquakes of $M \geqslant 5$ when we considered the catalogue of mainshocks only. Hence the phenomenon of seismic quiescence appears to be applicable in the area for prediction.

Acknowledgements

This work was carried out within the framework of a joint co-operative project on earthquake prediction established by the agreement between the USSR Academy of Sciences and the Department of Science and Technology, Government of India. M/s S C Bhatia and S V Chalam provided invaluable help in installing the software at the NGRI and providing useful suggestions. The authors are especially indebted to Academician V I Keilis-Borok for many thought-provoking discussions.

References

Bhatia S C, Chalam S V, Gaur V K, Keilis-Borok V I and Kossobokov V G 1989 On intermediate-term prediction of strong earthquakes in the Himalayan arc region using pattern recognition algorithm $M8$; *Proc. Indian Acad. Sci. (Earth Planet. Sci.)* **98** 111–123

Brown D, Li Q, Nyland E and Weichert D H 1989 Premonitory seismicity patterns near Vancouver Island, Canada, Preprint

Dmitrieva O E *et al* 1987 Diagnosis of periods of increased probability of strong earthquakes in seismically active regions of USSR and a number of other countries; *Comput. Seismol.* **20** 97–107

Gabrielov A M *et al* 1986 Algorithms of long-term earthquake prediction; *Rev. Geofis.* (in press) Historia (Commision de Geofisica), Lima (Peru)

Gardner J K and Knopoff L 1974 Is the sequence of earthquake in Southern California with aftershocks removed Poissonian; *Bull. Seismol. Soc. Am.* **64** 1363–1367

Gizike A *et al* 1989 Diagnosis of periods of high probability of the strongest earthquakes of South America based on a set of seismological parameters; *Comput. Seismol.* **21** 21–26

Guha S K, Gosavi P D, Nand K, Padale J G and Marwadi S C 1974 Koyna Earthquakes (October 1963 to December 1973); Central Water and Power Research Station, Khadakwasla, Poona 344 pp

Gupta H K and Rastogi B K 1976 *Dams and earthquakes* (Amsterdam: Elsevier) 229 pp

Keilis-Borok V I and Kossobokov V G 1984 A set of premonitory seismicity patterns before strongest earthquakes of the world. In; *Earthquakes and mitigation of natural hazards* XXVII Congr. Geol. Int. Colloq. 06, **61** 56–66 (Moscow: Nauka)

Keilis-Borok V I, Knopoff L, Rotwain I M and Allen C R 1988 Intermediate-term prediction of occurrence times of strong earthquakes; *Nature (London)* **335** 690–694

Padale J G, Kulkarni U A, Kulkarni R C and Patil S S 1983 Koyna earthquakes Vol II (1974 to 1981); Central Water and Power Res. St., Khadakwasla, Poona 409 pp

Rastogi B K and Talwani P 1980 Relocation of Koyna earthquakes; *Bull. Seismol. Soc. Am.* **70** 1849–1868