DSS profile earlier by Reddy *et al.*[14], the corresponding pseudo-depth density graph was derived. In keeping with the expected geology of the region, similar patterns of variation between members of the constituent blocks of the Dharwar craton, both at the surface (along the Jadcharla–Panaji subtransect) as well as with depth (along the Kavali–Udipi profile) were observed.

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How long will triggered earthquakes at Koyna, India continue?

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Continued occurrence of triggered earthquakes in the vicinity of the artificial water reservoir at Koyna, India over the past 39 years is comprehended in terms of Kaiser effect (water level exceeding the previous maxima), rate of loading and duration of retention of high water levels. It is inferred that the increase in heterogeneity of the media due to mechanical changes caused by the impoundment of the reservoirs may not permit occurrence of another M 6.3 earthquake. However, smaller ($M \sim 5$) earthquakes will continue for another 3 to 4 decades.

KOYNA, located near the west coast of India is known to be the most significant site of artificial water reservoir-triggered seismicity[1–5], which started soon after the initiation of filling of the lake in 1961 (ref. 6). Over the past 39 years, the site has experienced globally the largest reservoir-triggered earthquake of M 6.3 on 10 December 1967 (ref. 7), seventeen earthquakes of $M \geq 5$, over 150 earthquakes of $M \geq 4$ and several thousand smaller events. Impoundment of another reservoir, Warna, some 30 km south of Koyna, started in 1985 and it was filled to a depth of 60 m in 1993. Earthquakes exceeding M 5 occurred during 1967–68, 1973, 1980, 1993–94 and 2000. Gupta *et al.*[8,9] showed the correspondence between the earthquake occurrence and factors like rate of increase in water level in the reservoir, maximum level reached and the duration for which higher levels are retained. It has also been pointed out that a rate of loading of 12 m/week is a necessary, but not a sufficient condition for $M \geq 5$ events to occur in the Koyna region[10]. It is hypothesized that the region between Koyna and Warna and capable of generating an earthquake of M 6.8, was stressed close to critical when Koyna Dam was impounded. As demonstrated amply by study of b values in earthquake magnitude–frequency relation, foreshock–aftershock patterns and ratio of the largest aftershock to the mainshock magnitude in earthquake sequences observed at Koyna, the heterogeneity of the media has increased. With the occurrence of one earthquake of M 6.3, 17 earthquakes of $M \geq 5$ and other smaller earthquakes, about one-half of the stored energy for an M 6.8 earthquake has been released. The remaining stored strain energy is likely to be released through smaller earthquakes during the next 3 to 4 decades. Occurrence of $M \sim 5$ earthquakes will be governed by Kai-

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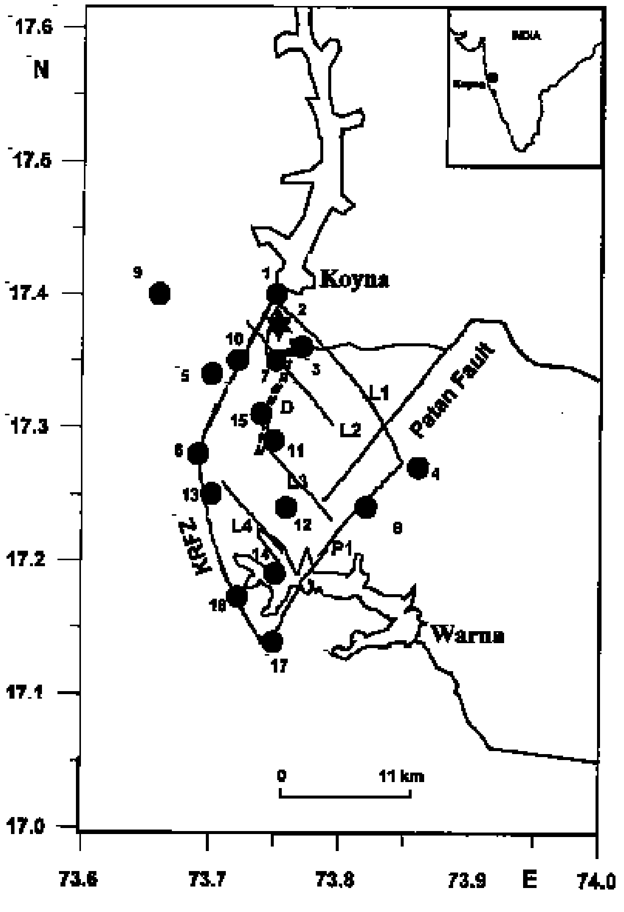
ser effect, rate of loading of the reservoirs and duration of retention of high water levels.

Kaiser[11], for the first time, reported that acoustic emission, under monotonically increasing stress, shows an appreciable increase after the applied stress exceeds the previously applied maximum stress. Yoshikawa and Mogi[12] used this approach successfully, for estimation of crustal stresses from cored rock samples. The relation between high reservoir water level exceeding or near to the previous maximum and the occurrence of reservoir-triggered/induced events was reported for the seismicity associated with Nurek Dam, USSR[13]. It has been noted that earthquakes of $M \geq 5$ in the Koyna area in 1973 and 1980 occurred within one month of the water level in Koyna exceeding previous maximum[14,15]. Filling of the Warna reservoir, located some 30 km south of Koyna, started in 1985, and it was filled to a depth of 60 m, reaching a level of 618 m above mean sea level. This triggered the $M \geq 5$ earthquake sequences in December 1993 and February 1994, and Kaiser effect is observable in the Koyna–Warna region[15,16].



D: Donichiwada Fault   Pl: A NE–SW trending fault parallel to Patan Fault

Figure 1. Epicentral locations of $M \geq 5$ Koyna–Warna earthquakes along with a key map for the region. Location for event number 18 is same as that of 17. KR and WR are Koyna and Warna rivers, respectively. The epicentral location of 1967 main shock is shown by a star and the epicentres of other $M \geq 5$ events are shown by solid circles. Numbers represent $M \geq 5$ earthquakes, as mentioned in Table 1. KRFZ, D and P1 represent the Koyna River Fault Zone, Donichiwada Fault and a NE–SW trending fault parallel to the Patan Fault, respectively. L1, L2, L3 and L4 are NW–SE trending fractures representing steep boundaries of crustal blocks. Fault geometry is after Talwani[4].

Figure 1, after Talwani[4], depicts tectonic features for the Koyna–Warna region deduced from detailed field observation after the Koyna earthquake of 1967 and interpretation of detailed aeromagnetic, geophysical and geological mapping of the area. The Koyna River Fault Zone (KRFZ), which consists of a NNE trending north KRFZ and a NW trending south KRFZ binds seismicity in the west. The steeply west-dipping south KRFZ fault is a southward continuation of the N–S Koyna river, extending some 33 km in S10°W direction. Slightly east of KRFZ is the NNE–SSW trending Donichiwada Fault (D) which dips 60° WNW[17,18]. In the east, the NE–SW trending Patan Fault and another satellite parallel fault (P1) bind the seismicity. The area between KRFZ and Patan Fault is intersected by a number of NW–SE fractures extending to hypocentral depths, shown as L1, L2, L3 and L4 in Figure 1. KRFZ, Patan Fault, P1, L1, L2, L3 and L4 form steep boundaries of crustal blocks and provide access for fluids to flow to hypocentral depth[4]. During 1995–98, twenty-one bore-wells were drilled which resulted in a significant observation of some step-like changes of the order of 2.1–6.5 cm for two M 4 earthquakes recorded at 1.8–2.4 km epicentral distances[19]. This important observation suggests a hydraulic connectivity between the seismogenic zone and the

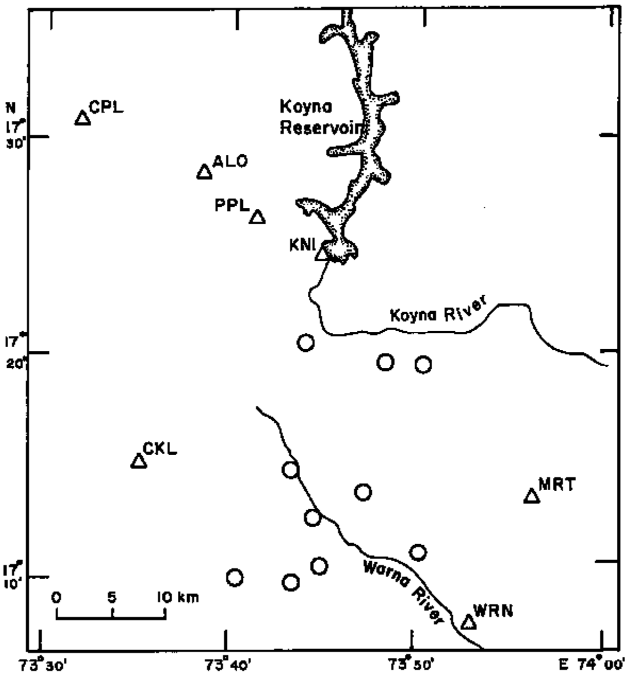


Figure 2. Relocated epicentral locations of $M \geq 4$ Koyna earthquakes between 1974 and 1982 (after Talwani *et al.*[4]).

Table 1. List of $M \geq 5.0$ Koyna–Warna earthquakes (1967–2000)

Serial no.	Month	Date	Year	Origin time		Latitude (N)	Longitude (E)	Magnitude			Focal depth (km)	Focal mechanism solution	Magnitude used
				Hours	Minutes			NGRI	MERI	USGS			
1	09	13	67	06	23	17.40	73.75		5.2			S–S	5.2 (Gu*)
2	12	10	67	22	51	17.38	73.75	6.3	7.0	6.0	10.0	S–S	6.3
3	12	10	67	23	52	17.36	73.77		5.0				5.0
4	12	11	67	20	49	17.27	73.86		3.5	5.2			5.2
5	12	12	67	06	18	17.34	73.70		3.6	5.4		Normal	5.4
6	12	12	67	15	48	17.28	73.68		3.6	5.0			5.0
7	12	12	67	18	20	17.35	73.75		4.7	5.0			5.0
8	12	24	67	23	49	17.24	73.82		5.0	5.5			5.5
9	12	25	67	17	37	17.40	73.66		4.6	5.1			5.1
10	10	29	68	10	00	17.35	73.72		5.2	5.4	5.0		5.4
11	10	17	73	15	24	17.29	73.75	5.2	5.2	5.0	5.9	S–S	5.2
12	09	02	80	16	39	17.24	73.76	5.3	4.3	4.9	8.0		5.3
13	09	20	80	10	45	17.25	73.70	5.9	4.9	5.3	12.0	Normal	5.3
14	12	08	93	01	42	17.19	73.75	5.2	5.1	5.0	8.4	Normal	5.2
15	02	01	94	09	31	17.31	73.74	5.5	5.4	5.0	10.6	S–S	5.4
16	12	03	2K	18	03	17.16	73.73	5.6	5.2	4.9	5.0	S–S + minor normal	5.2
17	06	04	2K	22	30	17.15	73.74	5.1	4.8	5.0	7.8	S–S + minor normal	5.1
18	05	09	2K	00	32	17.17	73.75	5.6	5.2	5.3	6.9	Normal	5.3

Gu*, Guha *et al.*[22].

Epicentral locations have been taken from Gupta *et al.*[23], Rastogi and Talwani[24], Talwani *et al.*[15] and Maharashtra Engineering Research Institute (MERI), Nasik. There is some discrepancy in the magnitudes reported by MERI, National Geophysical Research Institute (NGRI) and USGS. The last column gives the re-estimated magnitudes.

wells. Further, it would be important to note that $M \geq 4$ events during 1994–2000 have occurred in the month of February–April, suggesting a delayed pore-fluid-controlled reservoir-triggered seismicity for the region[2,3,15]. Thus, it seems that large pore-fluid pressure at the hypocentral depths might be the key factor in triggering earthquakes in this area. We reproduce in Figure 2, the relocated earthquakes of $M \geq 4$ for the period 1974 through 1982 from Talwani[4]. It may be noted that earthquakes occurred in the vicinity of Warna river in addition to the south of Koyna river. This is to demonstrate that the region up to Warna river, some 30 km south of the Koyna dam, had been activated much before the impoundment of the Warna reservoir, which began in 1985.

In Table 1, we provide the focal parameters of $M \geq 5$ earthquakes in the Koyna–Warna region. All of these eighteen events are plotted in Figure 1. The first $M \geq 5$ earthquake of 13 September 1967 was associated with the KRFZ. The 10 December 1967 M 6.3 earthquake had several $M \geq 5$ aftershocks, five of them (nos 3–7) occurred within two days. The main shock and two of its aftershocks (nos 3 and 7) were associated with KRFZ and Donichiwada fault. Another $M \geq 5$ aftershock (no. 4) occurred at the junction of L1 and P1, while two other aftershocks (nos 5 and 6) were associated with north KRFZ. Another $M \geq 5$ aftershock (no. 8), which occurred after 14 days, is associated with P1. Aftershock no. 9 is an outlier, which is away from the seismically-active crustal volume between Koyna and Warna reservoirs, probably associated with NW extension of L3. Event no. 10 is again associated with north KRFZ. After an interval of 5 years, the next $M \geq 5$ earthquake occurred on 17 October 1973 (no. 11) and is associated with L3 and Donichiwada fault. Next $M \geq 5$ events occurred after a lapse of 7 years in 1980 (nos 12 and 13) between L3 and L4 and south KRFZ. The $M \geq 5$ events of 1993–94 (nos 14 and 15) occurred after a lapse of 13 years, and were associated with L4 and Donichiwada Fault, respectively. The events of 2000 (nos 16 and 17) have occurred along the south KRFZ and close to the junction of KRFZ and Patan Fault, respectively. Reliable focal mechanism solutions are available for 10 of these eighteen $M \geq 5$ earthquakes. The sense of motion is basically left-lateral strike-slip on a steeply dipping N10°E to N10°W trending north as well as south KRFZ and Donichiwada faults (nos 1, 2, 11, 15, 16 and 17) and normal along NW trending fractures (nos 13 and 14). Event no. 13, which occurred on the junction of L4 and south KRFZ, has a normal solution. Event no. 14 associated with L4 also has a normal solution. Recent events are again basically strike-slip with minor normal components and are associated with KRFZ and the Patan Fault. Figure 3 further supports this fact, where we have shown events of $M \geq 3.0$ associated with the March–April 2000 earthquakes (nos 16 and 17) and also their focal mechanisms. The epicentres follow south KRFZ, terminate at the junction of KRFZ and P1 and show a strike-slip sense of motion with a minor normal component. It will be important to note that the latest M 5.3 event of 5 September 2000 (no. 18) occurred in the vicinity of the Warna reservoir between L4 and south KRFZ. The focal mechanism of this earthquake suggests a normal faulting. It will be worth to mention here that the focal depths for M 5 events during 1993–2000, as listed in Table 1, are quite well constrained by good azimuthal coverage, more number of stations (analogue + digital) and GPS timing system. It must be noted that with the passage of time, accuracy of epicentral location has improved considerably compared to the sixties and seventies, where errors of a few km could not be ruled out.

Details of water levels and derived statistics are given for Koyna (1961 through 1999) and Warna (1985 through 1999) reservoirs in Tables 2 and 3. An attempt is made to show the influence of Kaiser effect and importance of rate of loading and duration for which high water levels are retained, on triggering $M \geq 5$ events (Figures 4*a* and *b*). Following the monsoon, water level normally peaks during the months of July/August. However, in a few years this has been delayed till the month of October, due to changes in the catchment area and delay in the onset of monsoons. However, the lowest water levels are invariably reached during June and therefore it is appropriate to consider an annual filling–emptying cycle of reservoirs between the months of July in a year and June in the next year.

Filling of the Koyna reservoir started in 1961 and a level of 624.7 m (above mean sea level) was reached in the same year. In the next year, the level reached 636.7 m and during 1963, a near-full pond level of 654.1 m was achieved. Small events began to occur in 1962 and were mostly located north of the Koyna dam. The lake was filled to only 652.7 m during 1966. Next year, the lake was filled to 656.9 m, exceeding the previous maxima by 1.7 m (column no. 11, Table 2). The maximum rate of loading was 12.6 m/week and the high water level (one way is to calculate the number of days taken for water level to reduce to peak level – 5 m; there could be several other approaches) was retained for the longest time so far (126 days, column no. 9, Table 2). An intense seismic activity followed this filling with ten $M \geq 5$ events, including the 10 December 1967 earthquake of M 6.3.

The next $M \geq 5$ event occurred on 17 October 1973 after a lapse of 5 years. However, this was the first time since 1967, when the previous water level maxima was exceeded. The maximum rate of loading was 22.6 m/week and the high water level was retained for 137 days. There was no $M \geq 5$ earthquake for the next 7 years. During 1980, the previous water level maxima were once again exceeded and there were two $M \geq 5$ earthquakes. The maximum rate of loading was 13.9 m/week and high water level was retained for 98 days. We must also note that during 1975–1978, the peak water levels had equalled the previous maxima. So there could be a combined effect of both: the water level and the rate of loading. Next earthquakes of $M \geq 5$ occurred after a lapse of 13 years during 1993–1994.

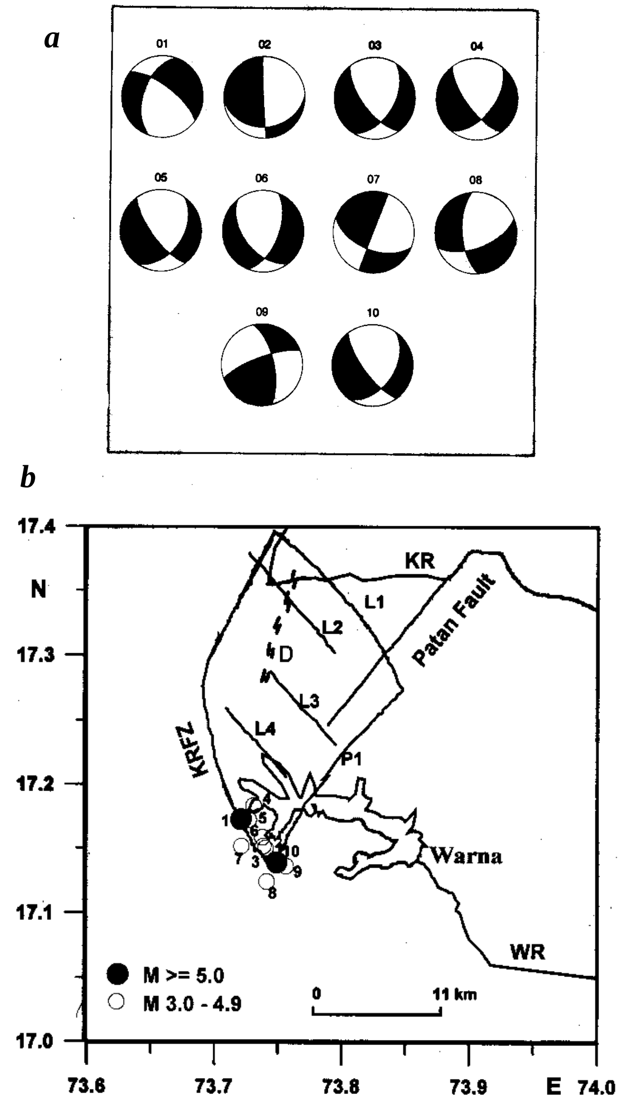


Figure 3. *a*, Local earthquake moment tensor (LMT) solutions and *b*, epicentral locations of significant aftershocks ($M \geq 3$) for the latest March–April 2000 Koyna–Warna earthquake sequence associated with event of 12 March (label 1 or #16) and 6 April (label 10 or #17). The labels in the local earthquake moment tensor solutions indicate epicentre number, as used in the lower part of (***b***) date (YMD), and origin time within brackets which represent the following Koyna–Warna events: 1, 12 March 2000 (18 : 03), 2, 12 March 2000 (18 : 09), 3, 12 March 2000 (18 : 17), 4, 12 March 2000 (18 : 22), 5, 12 March 2000 (20 : 03), 6, 12 March 2000 (21 : 33), 7, 13 March 2000 (10 : 25), 8, 13 March 2000 (13 : 24), 9, 13 March 2000 (17 : 33) and 10, 6 April 2000 (20 : 30). LMT solutions suggest that the region is mainly characterized by left-lateral strike-slip faulting with a minor normal component.

Table 2. Koyna water level and derived statistics (1961–2000)

1	2	3	4	5	6	7	8	9	10	11
Serial no. of $M \ge 5$ earthquakes	Date of occurrence of $M \ge 5$ earthquakes	Date when water level reached minimum	Minimum water level (m) (LWL)	Date when water level reached maximum	Peak water level (m) (P1)	Filling days	Level rise (m)	Duration required for water level to P1–5 m	Maximum filling rate (m/week)	Difference between P1 and previous maximum
		07.05.61	586.7	11.07.61	624.7	56	39.0	76	14.1	
		04.07.62	615.5	15.08.62	636.7	43	21.2	102	17.3	12.0
		28.06.63	617.5	14.08.63	654.1	45	36.6	88	13.8	17.4
		26.06.64	635.2	13.08.64	654.9	49	19.7	74	8.0	0.8
		18.06.65	635.3	22.07.65	655.2	35	19.9	60	10.0	0.3
		20.06.66	630.5	03.08.66	652.7	45	22.3	101	9.8	–2.5
1	13.09.67 (M 5.2)	29.06.67	620.7	04.10.67	656.9	98	36.3	126	12.6	1.7
2	10.12.67 (M 6.3)									
3	10.12.67 (M 5.0)									
4	11.12.67 (M 5.2)									
5	12.12.67 (M 5.4)									
6	12.12.67 (M 5.0)									
7	12.12.67 (M 5.0)									
8	24.12.67 (M 5.5)									
9	25.12.67 (M 5.1)									
10	25.10.68 (M 5.4)	04.07.68	616.8	29.08.68	646.7	57	30.6	93	9.3	–10.2
		19.06.69	614.7	08.08.69	653.7	51	39.0	80	13.2	–3.2
		14.06.70	620.8	21.08.70	653.6	69	32.8	77	8.1	–3.3
		04.06.71	620.3	01.09.71	653.3	88	33.1	68	10.5	–3.6
		26.06.72	612.7	28.08.72	645.8	64	32.8	66	14.4	–11.1
11	17.10.73 (M 5.2)	10.06.73	610.6	27.09.73	657.9	79	47.3	137	22.6	+1.0
		03.07.74	614.8	02.09.74	649.6	62	34.8	98	12.0	–8.3
		20.06.75	611.6	07.09.75	657.9	80	46.3	106	9.6	0.0
		03.06.76	631.8	05.09.76	657.9	95	26.1	94	7.0	0.0
		24.06.77	626.4	31.08.77	657.9	69	31.5	97	9.6	0.0
		16.06.78	621.2	25.08.78	657.9	71	36.7	87	9.6	0.0
		25.06.79	610.9	19.08.79	656.5	56	45.6	97	14.4	–1.4
12	02.09.80 (M 5.3)	22.06.80	621.2	03.09.80	658.1	74	36.9	98	13.9	+0.2
13	20.09.80 (M 5.3)									
		26.06.81	620.7	01.10.81	657.8	98	37.0	72	12.0	–0.3
		19.06.82	625.5	01.09.82	657.5	75	32.0	90	8.0	–0.6
		20.06.83	625.0	27.09.83	657.9	100	32.9	86	7.5	–0.2
		13.06.84	628.0	03.09.84	657.5	83	29.5	95	6.2	–0.6
		16.06.85	628.7	07.09.85	656.4	84	27.8	100	8.0	–1.7
		18.06.86	631.0	26.08.86	656.8	70	25.8	103	6.0	–1.3
		30.06.87	618.5	23.10.87	650.7	116	32.2	94	11.9	–7.4
		04.07.88	623.6	26.09.88	658.0	85	34.4	85	14.4	–0.1
		15.06.89	629.2	04.10.89	654.2	112	25.0	71	10.0	–3.9
		17.06.90	623.9	30.08.90	658.1	75	34.2	126	8.0	0.0
		06.06.91	630.4	29.08.91	657.9	85	27.5	75	7.2	–0.2
		09.07.92	614.1	07.09.92	658.0	61	43.9	77	13.2	–0.1
14	08.12.93 (M 5.2)	15.06.93	621.9	06.09.93	658.0	85	36.2	140	9.4	–0.1
15	01.2.94 (M 5.4)	13.06.94	623.6	02.09.94	658.2	82	34.6	70	8.0	+0.1
		22.06.95	615.2	15.09.95	652.0	85	36.9	97	13.8	–6.2
		16.06.96	618.4	07.10.96	655.3	111	37.0	91	12.8	–2.9
		16.06.97	634.4	23.08.97	658.1	68	23.7	123	7.3	–0.1
		26.06.98	627.0	03.10.98	657.9	99	31.0	95	9.2	–0.3
		16.06.99	635.3	05.10.99	657.9	111	22.7	95	7.3	–0.3
16	12.03.2K (M 5.2)									
17	06.04.2K (M 5.1)									
18	05.09.2K (M 5.3)	04.05.2K	633.35	09.09.2K	655.9	128	22.3	***	10.5	–2.05

During 1993, the previous maximum of water level at Koyna was not exceeded and it was lower than the previous maximum by 0.1 m. However, the high water level was retained for 140 days. This is the longest du-

Table 3. Warna water level and derived statistics (1985–2000)

1 Serial no. of $M \geq 5$ events	2 Date of occurrence of $M \geq 5$ earthquakes	3 Date when water level reached minimum	4 Minimum water level (m) (LWL)	5 Date when water level reached maximum	6 Peak water level (m) (P1)	7 Filling days	8 Level rise (m)	9 Duration required for water level to reduce to P1–5 m	10 Maximum filling rate (m/week)	11 Difference between P1 and previous maximum
		08.06.85	560.7	01.08.85	581.3	56	20.6	26	9.8	
		30.05.86	574.6	30.06.86	586.2	32	11.5	187	7.9	4.9
		27.05.87	578.0	09.07.87	588.5	44	10.5	85	7.5	2.3
		31.05.88	577.7	19.07.88	592.7	50	15.0	99	5.0	4.2
		08.06.89	577.1	24.07.89	601.5	47	24.5	62	12.9	8.8
		03.06.90	578.3	16.07.90	604.1	44	25.5	100	9.0	2.6
		05.06.91	583.9	28.07.91	609.1	54	25.2	94	7.7	5.0
		16.06.92	585.0	19.08.92	617.9	65	32.9	72	12.9	8.8
14	08.12.93 (M 5.2)	12.06.93	577.6	04.08.93	621.8	54	44.2	124	13.7	3.9
15	01.02.94 (M 5.4)	01.06.94	579.9	02.09.94	622.1	99	42.1	116	13.2	0.3
		16.06.95	580.5	03.09.95	621.3	79	40.8	89	13.8	– 0.8
		17.06.96	594.9	04.08.96	620.7	48	25.8	144	12.1	– 1.4
		18.06.97	581.8	24.08.97	622.0	67	40.2	87	11.0	– 0.1
		28.06.98	580.2	28.09.98	625.8	92	45.6	94	18.7	3.7
		18.06.99	591.7	15.10.99	625.5	119	33.8	71	10.6	– 0.3
16	12.03.2K (M 5.2)									
17	06.04.2K (M 5.1)									
18	05.09.2K (M 5.3)	02.07.2k	587.86	16.10.2K	626.30	106	38.44	***	16.02	0.5

***, Water level has not reached the (P1–5 m) level till 7 December 2000.

ration for retention of high water level so far for the Koyna reservoir. It is also to be noted that filling of the Warna reservoir was initiated in 1985 and a near-full pond level of 621.8 m was reached in 1993, exceeding the previous maxima by 3.9 m (Table 3). The maximum rate of loading at Warna had been 13.7 m/week and the high level of water retained for a long time of 124 days. This must be an additional contributing factor to the Koyna–Warna seismicity with two earthquakes of $M \geq 5$ occurring on 8 December 1993 and 1 February 1994, respectively. Although the previous maximum level was exceeded by 0.1 m at Koyna reservoir, no $M \geq 5$ earthquake occurred after the annual filling during 1994. The water level maximum at Warna was also exceeded by 0.3 m during 1994. The absence of $M \geq 5$ earthquakes could be due to a very low rate of loading at Koyna (maximum being 8 m/week) and a short duration of retention of high water level (70 days).

No $M \geq 5$ earthquake occurred in the Koyna–Warna region after the 1 February 1994 event till the 12 March 2000 event. At Koyna, the previous water level maxima have not exceeded since 1994. At Warna, the previous water level maxima exceeded in 1998. However, no $M \geq 5$ event occurred. It is also noted that 12 March 2000 and 6 April 2000 events of $M \geq 5$ are the first ones to occur in the month of March/April in Koyna–Warna region (Table 1), and these could have been triggered by the instability caused due to unloading of the Koyna–Warna reservoirs (as suggested by Rajendran and Harish[20]). It is also worth noting that these two earthquakes (nos 16 and 17 in Table 1) had a minor normal fault component. The other $M \geq 5$ events having normal faulting were associated with L4 (events nos 13 and 14, Figure 1). The latest sequence of $M \geq 5$ earthquake occurred on 5 September 2000. It is important to note that the highest reservoir level reached 655.9 m on 9 September 2000 at Koyna and 626.30 m on 16 October 2000 at Warna, respectively. At Koyna, the previous water level maximum was not exceeded and filling rate (10.5 m/week) was less than 12 m/week (Table 2). Nevertheless, at Warna the previous water level maximum was exceeded by 0.5 m and filling rate (16.05 m/week) exceeded the critical rate (12 m/week) for a $M \sim 5$ event to occur in the region (Table 3).

As found by Gupta *et al.*[8], global nature of artificial water reservoir-triggered earthquake sequences share the following characteristics. One, the foreshock *b*-value is higher than the aftershock *b*-value, both being, in general, higher than the *b*-values for natural earthquake sequences in the regions concerned and the regional *b*-values. Two, in addition to a high *b*-value, the magnitude ratio of the largest aftershock to the main shock is also high. Three, aftershocks have a comparatively slow rate of decay, and four, the foreshock–aftershock patterns are identical and correspond to Type-II of Mogi's model, whereas the natural earth-

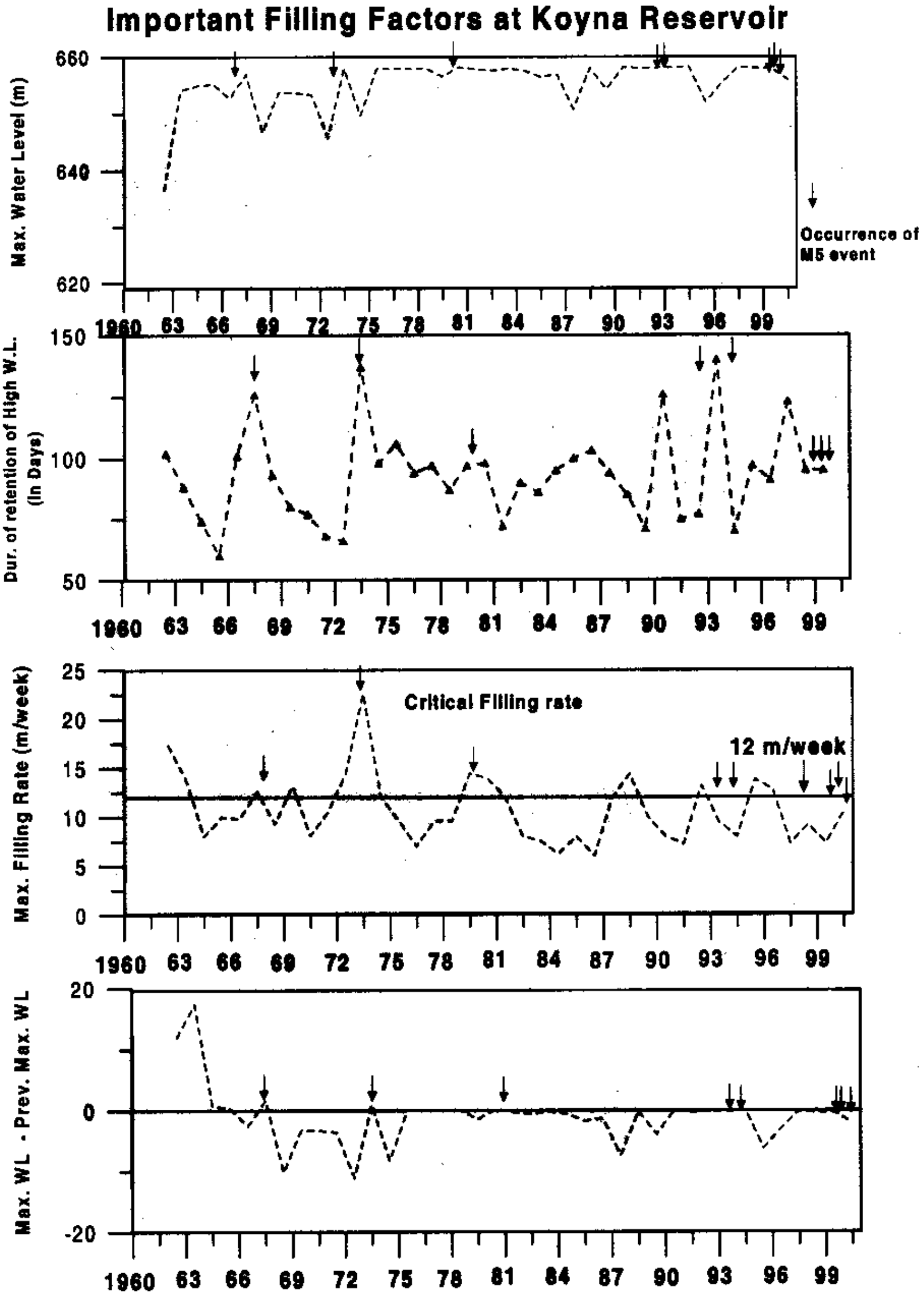


Figure 4 *a*. Maximum water level reached per year, retention period of high water level and maximum filling rate per week, Koyna reservoir (1962–2000).

quake sequences in the regions in question belong to Type I of Mogi's model.

The above-mentioned characteristics of triggered sequences are governed by the mechanical properties of the media and their deviation from normal sequences indicates a change in the mechanical properties. Johnston *et al.*[21] had debated the estimate of the largest earthquake in the Indian shield region, and on the basis of the Stable Continental Region (SCR) earthquake occurrences elsewhere, had concluded that it could be of magnitude 6.8. If we consider the extent of seismic activity in the Koyna region on the basis of $M \geq 5$ earthquakes, it is an area of about 30 km by 20 km. The KRFZ, as delineated in Figure 1 is some 33 km in length and could have generated an earthquake of $M \sim 6.8$. However, the heterogeneity introduced by fluids in the hypocentral zone changed the mechanical characteristics, and earthquake sequences belonging to

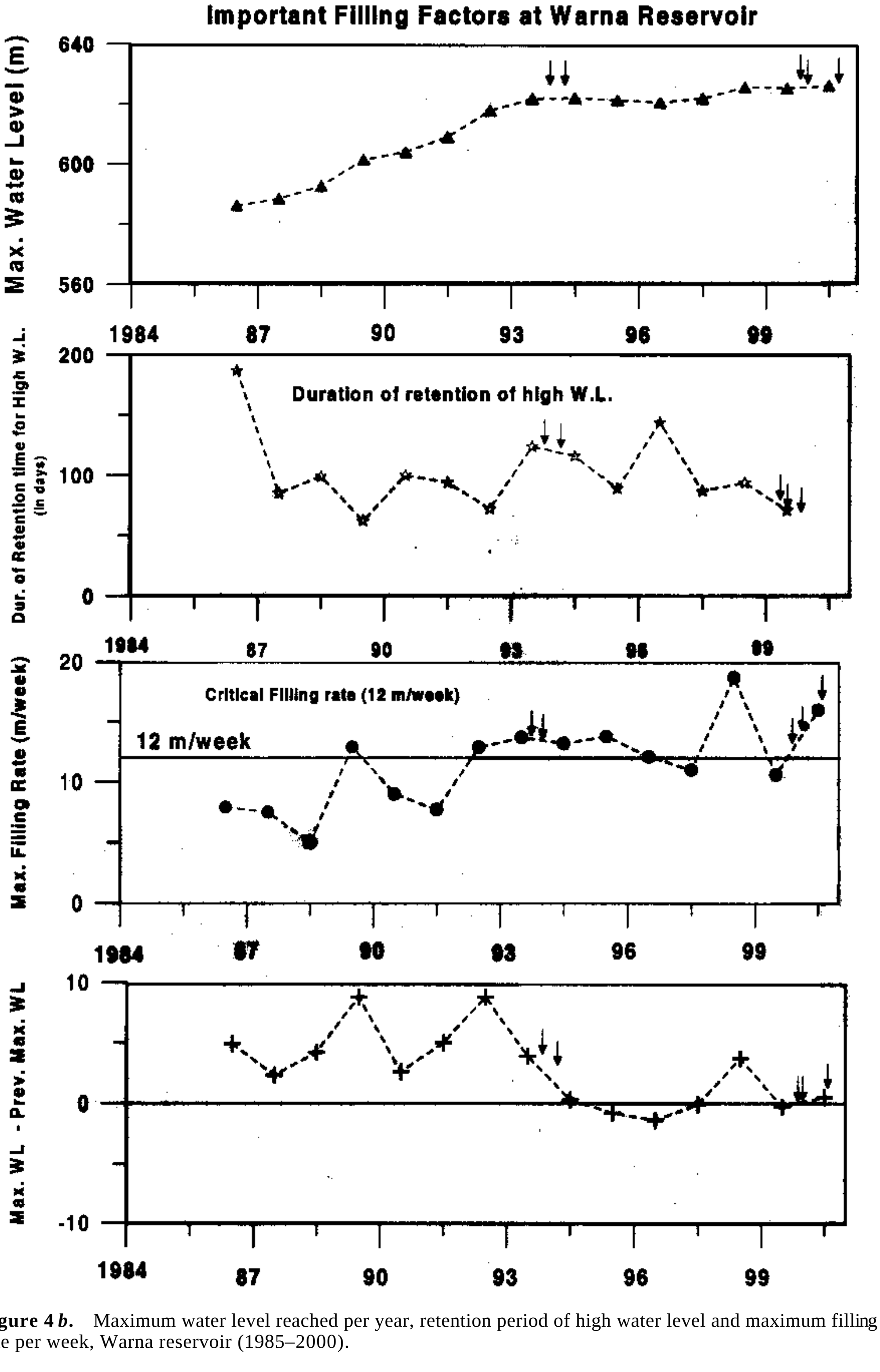


Figure 4 ***b***. Maximum water level reached per year, retention period of high water level and maximum filling rate per week, Warna reservoir (1985–2000).

Type II of Mogi's model occur. We presume that the KRFZ was stressed close to critical at the time of impoundment of Koyna dam. The heterogeneity introduced resulted in dividing the total rock volume into smaller volumes, each volume being capable of releasing its energy as and when its competence was exceeded. It is also noteworthy that no $M \geq 5$ earthquake epicentre has been repeated at any location at Koyna. If one considers that one M 6.3, seventeen $M \geq 5$ and over one-hundred and fifty $M \geq 4$ earthquakes have occurred so far in the rock volume bounded by KRFZ in the west and Patan Fault in the east, the total energy released will account for about one-half of an M 6.8 earthquake. Considering that the region got activated after beginning of the filling of the Koyna dam in 1961, the activity should continue for another period of 3–4 decades.

It may be noted that filling of the Koyna dam had activated the region in the south up to Warna river, much before the impoundment of the Warna dam (Figure 2). Impoundment of Warna dam started in 1985 and a near-full pond level was reached in 1993. Filling of the Warna dam gave an impetus to Koyna–Warna seismicity; however, there was no appreciable extension of the zone of seismic activity further south (Figure 2) and the seismicity was basically confined between Koyna and Warna reservoirs. Because of increased heterogeneity between Koyna and Warna regions, it is inferred that there is no intact fault segment long enough (~ 10 km) to generate another earthquake of $M \sim 6$ like the one on 10 December 1967. However, $M \sim 5$ events will continue and their occurrence will be governed by Kaiser effect, rate of loading of the reservoirs and duration of retention of high levels.

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Discovery of an aborted reversal (geomagnetic excursion) in the Late Pleistocene sediments of Pinjor Dun, NW Himalaya

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We report here the occurrence of an aborted reversal (geomagnetic excursion) in the Late Pleistocene sediments of Pinjor Dun near Chandigarh, NW Himalaya. The event discovered at ~ 697.5 cm level from the base of Kiratpur section corresponds to the OSL date of 40 ± 5 Ka coinciding with the Laschamp excursion[1] and palaeointensity minima[2] elsewhere. The Pinjor Dun sediments are deposited at a high rate of sedimentation that enables quite enlarged records of remanent geomagnetic field, hence suitable for further high resolution study of the excursion (under progress) to extend its utility as a stratigraphic marker in the Quaternary sediments at the foothills of the Himalaya.

GEOMAGNETIC excursions are the records of departure of the earth's magnetic field from its usual near-axial configuration for brief periods without establishing a reversal[3]. Such excursions are well established for the Brunhes Normal polarity event (< 0.78 Ma) that continues to the present geomagnetic field (see Jacobs[1] for review). Excursions have been reported in lava flows, marine sediments and lake sediments of various ages in different parts of the world[1,4]. Previously, Opdyke[5] discovered the 40 Ka Laschamp excursion in the marine cores from the Indian Ocean. Kotlia *et al.*[6] reported an

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