RESERVOIR-INDUCED EARTHQUAKES

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ABSTRACT – *The best known site of reservoir-induced earthquakes in the world is located at Koyna, India where the largest known reservoir-induced earthquake of M 6.3 occurred on December 10, 1967 and activity still continues. There are a dozen other sites of possibly induced earthquakes in India. Indian scientists have contributed significantly in this field. Delineation of common characteristics of reservoir-induced earthquakes which in turn help to discriminate reservoir-induced earthquakes from normal earthquakes is one major contribution. Recent work has shown that possibly, reservoir-induced earthquakes of magnitude ≥ 5 are preceded by a couple of magnitude ≥ 4 earthquakes during the fortnight preceding the earthquake. At Koyna, and other reservoir sites of the world, rate of loading, highest levels reached and duration of retaining high levels are important factors in triggering reservoir-induced earthquakes.*

INTRODUCTION

Carder[1] for the first time pointed out the association of the Lake Mead reservoir, Colorado, USA with earthquakes in late 1930s and early 1940s. Over the years the number of cases of reservoir-induced earthquakes has increased considerably and according to the latest review[2] there are over 70 such examples. Figure 1 and table 1 give this information. A considerable amount of work has been done by Indian scientists. The scope of this review article does not permit us to deal with these papers individually. Hence, we shall briefly discuss the Koyna reservoir seismicity, discriminatory characteristics of reservoir-induced seismicity (RIS), other possible sites of RIS and a bibliography where an effort is made to include all important papers by Indian scientists in this field.

KOYNA EARTHQUAKES

Among the earthquakes associated with the impounding of artificial water reservoirs, the Koyna earthquake of December 10, 1967 with a magnitude of 6.3 is the most significant. This earthquake claimed over 200 human lives, injured over 1500 and rendered thousands homeless. The Koyna Nagar township was worst affected wherein more than 80% houses were totally damaged or were uninhabitable. Earthquakes at Koyna region have been dealt in detail by Gupta and Rastogi[3] and Gupta[2]. Some outstanding features of Koyna seismicity are presented here.

Epicentres

Before impoundment of the Shivaji Sagar lake in 1962, no seismic stations were operating in the vicinity, and hence there is no instrumental record available for possible weak tremors. After filling started in 1962, mild tremors accompanied by sounds similar to blasting, began to be prevalent. The frequency and intensity of these tremors increased considerably from the middle of 1963. Figure 2, taken from Guha *et al.*[4] shows the seven seismic stations which were operational in the region by the end of 1969 as well as the epicentres located by Guha *et al.*[4] for the period 1967 through December 1971. The relocated epicentres by Rastogi and Talwani[5] for 39 events of M $\geq$ 4.0 and about 300 smaller events are included in figure 3. A majority of events, including the epicentre of the December 10, 1967 earthquake, are found to be located on a NNE trend (figure 3). There is another NNE trend having a small group of events located some 20 km west of the reservoir. The second major trend is in NW direction cutting across the NNE trend. The focal depth of the events is less than 12 km. In another interesting study[6], focal parameters of twelve

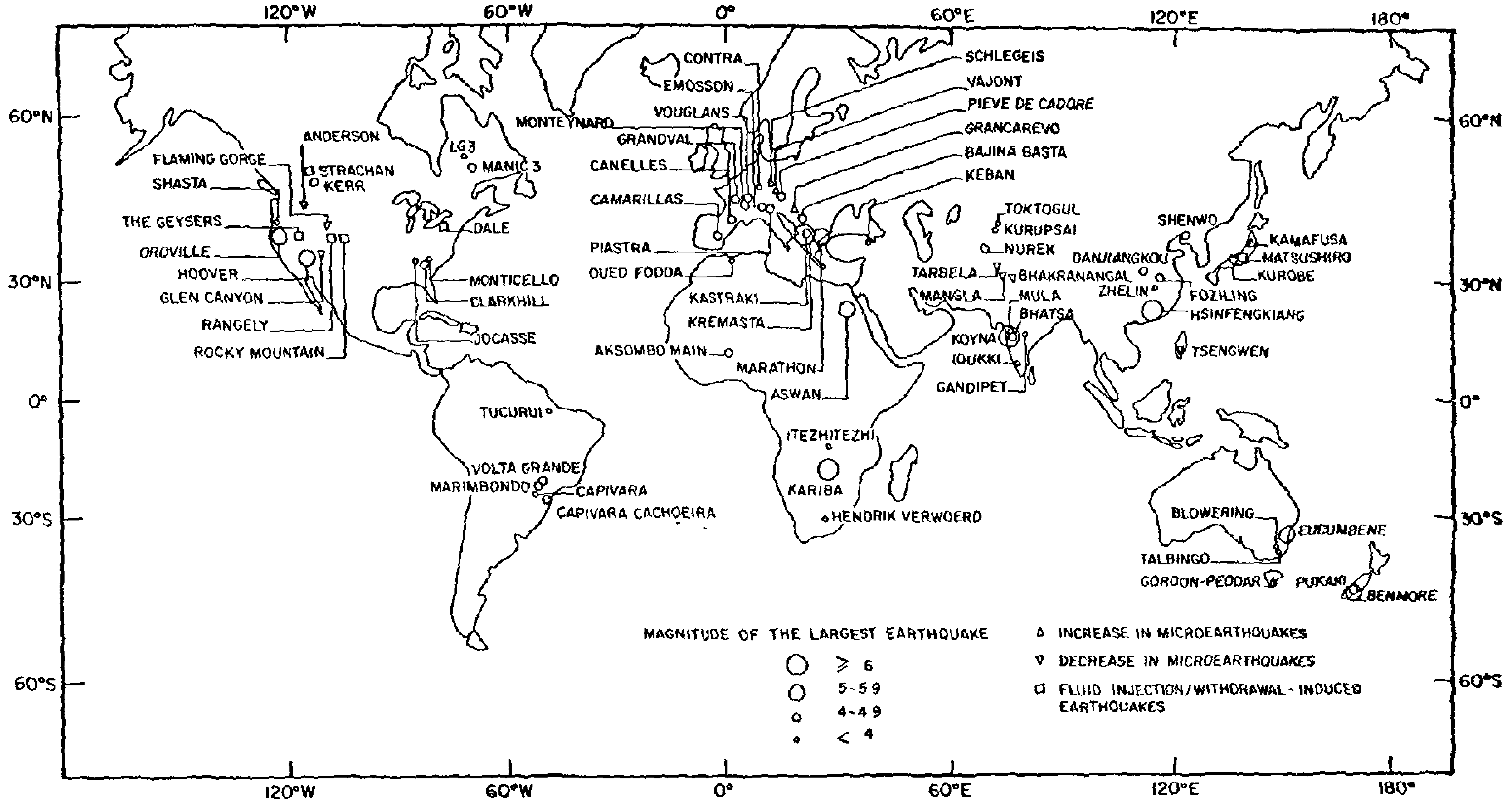


FIGURE 1 Worldwide distribution of the reservoir-induced changes in seismicity. The figure is updated from Gupta[2] to include all cases of magnitude ≥ 4.0. Sites where RIS events of magnitude < 4.0 occurred are too numerous and not updated.

TABLE 1 Reported cases of reservoir-induced changes in seismicity (updated from Gupta[2]).

Name of the dam/reservoir	Country	Height of dam (m)	Reservoir volume (10^6 m^3)	Year of impounding	Year of largest earthquake	Magnitude/intensity
Earthquakes having magnitude ≥ 6.0						
Hsinfengkiang	China (PRC)	105	13,896	1959	1962	6.1
Kariba	Zambia/ Zimbabwe	128	175,000	1958	1963	6.2
Koyna	India	103	2,780	1962	1967	6.3
Kremasta	Greece	160	4,750	965	1966	6.2
Earthquakes having magnitude between 5.0 and 5.9						
Aswan	Egypt	111	164,000	1964	1981	5.6
Benmore	New Zealand	110	2,040	1964	1966	5.0
Eucumbene	Australia	116	4,761	1957	1959	5.0
Hoover	U.S.A.	221	36,703	1935	1939	5.0
Marathon	Greece	67	41	1929	1938	5.7
Oroville	U.S.A.	236	4,400	1967	1975	5.7
Earthquakes having magnitude between 4.0 and 4.9						
Aksombo Main	Ghana	134	148,000	1964	1964	V
Bajina Basta	Yugoslavia	90	340	1966	1967	4.5–5.0
Bhatsa	India	88	947	1981	1983	4.9
Camarillas	Spain	49	37	1960	1964	4.1
Canelles	Spain	150	678	1960	1962	4.7
Capivari-Cachoeira	Brazil	58	180	1970	1971	VI
Clark Hill	U.S.A.	60	3,517	1952	1974	4.3
Danjiangkou	China (PRC)	97	16,000	1967	1973	4.7
Foziling	China (PRC)	74	470	1954	1973	4.5
Grandval	France	88	292	1959	1963	V
Kastraki	Greece	96	1,000	1968	1969	4.6
Kerr	U.S.A.	60	1,505	1958	1971	4.9
Kurobe	Japan	186	149	1960	1961	4.9
Lake Pukaki	New Zealand	106	9,000	1976	1978	4.6
Manicouagan	Canada	108	10,423	1975	1975	4.1
Marimbondo	Brazil	94	6,150	1975	1975	IV
Monteynard	France	155	275	1962	1963	4.9
Nurek	U.S.S.R.	317	1,000	1972	1972	4.6
P. Colombia/ V.Grande	Brazil	40/56	1,500/2,300	1973/1974	1974	4.2

TABLE 1 (continued) (Page 2)
Reported cases of reservoir-induced changes in seismicity

Name of the dam/reservoir	Country	Height of dam (m)	Reservoir volume (10^6 m^3)	Year of impounding	Year of largest Earthquake	Magnitude/intensity
Piastra	Italy	93	13	1965	1966	4.4
Pieve de Cadore	Italy	116	69	1949	1950	V
Shenwo	China (PRC)	50	540	1972	1974	4.8
Vouglans	France	130	605	1968	1971	4.4
Earthquake having magnitude < 4.0						
Blowering	Australia	112	1,628	1968	1973	3.5
Capivara	Brazil	59	10,500	1976	1976	3.7
Carmo do Cajuru	Brazil	22	192	1954	1972	3.7
Contra	Switzerland	220	86	1963	1965	3.0
Emborçacgo	Brazil	158	17,600	1981	1984	~2.0
Emmosson	Switzerland	180	225	1973	1973	3.0
Huangshi	China (PRC)	40	610	1970	1974	2.3
Gandipet	India	36	117	1920	1982	3.5
Grancarevo	Yugoslavia	123	1,280	1967	1967	3.0
Hendrik Verwoerd	S. Africa	66	5,000	1970	1971	2.0
Idukki	India	169	1,996	1975	1977	3.5
Itezhitezhi	Zambia	65	5,000	1976	1978	3.8
Jocasse	U.S.A.	107	1,431	1971	1975	3.2
Kamafusa	Japan	47	45	1970	1970	3.0
Keban	Turkey	212	31,000	1973	1973	3.5
Kurupsa	U.S.S.R.	100	500	1981	1983	Micro-earthquakes
Lake Gordon-Lake Peddar	Australia	140	13,500	1974	1978	Micro-earthquakes
LG 3	Canada	80	-	1981	1983	3.7
Makio	Japan	105	75	1961	1978	earthquakeswarm
Monticello	U.S.A.	129	500	1977	1979	2.8
Mula	India	56	1,017	1972	1972	1.0
Nagawado	Japan	155	123	1969	1969	earthquakeswarm
Nanchong	China (PRC)	45	15	1969	1974	2.8
Oued Fodda	Algeria	101	225	1932	1933	3
Paraibuna-Paraitinga	Brazil	94/105	4,700	1975/1976	1977	3.0

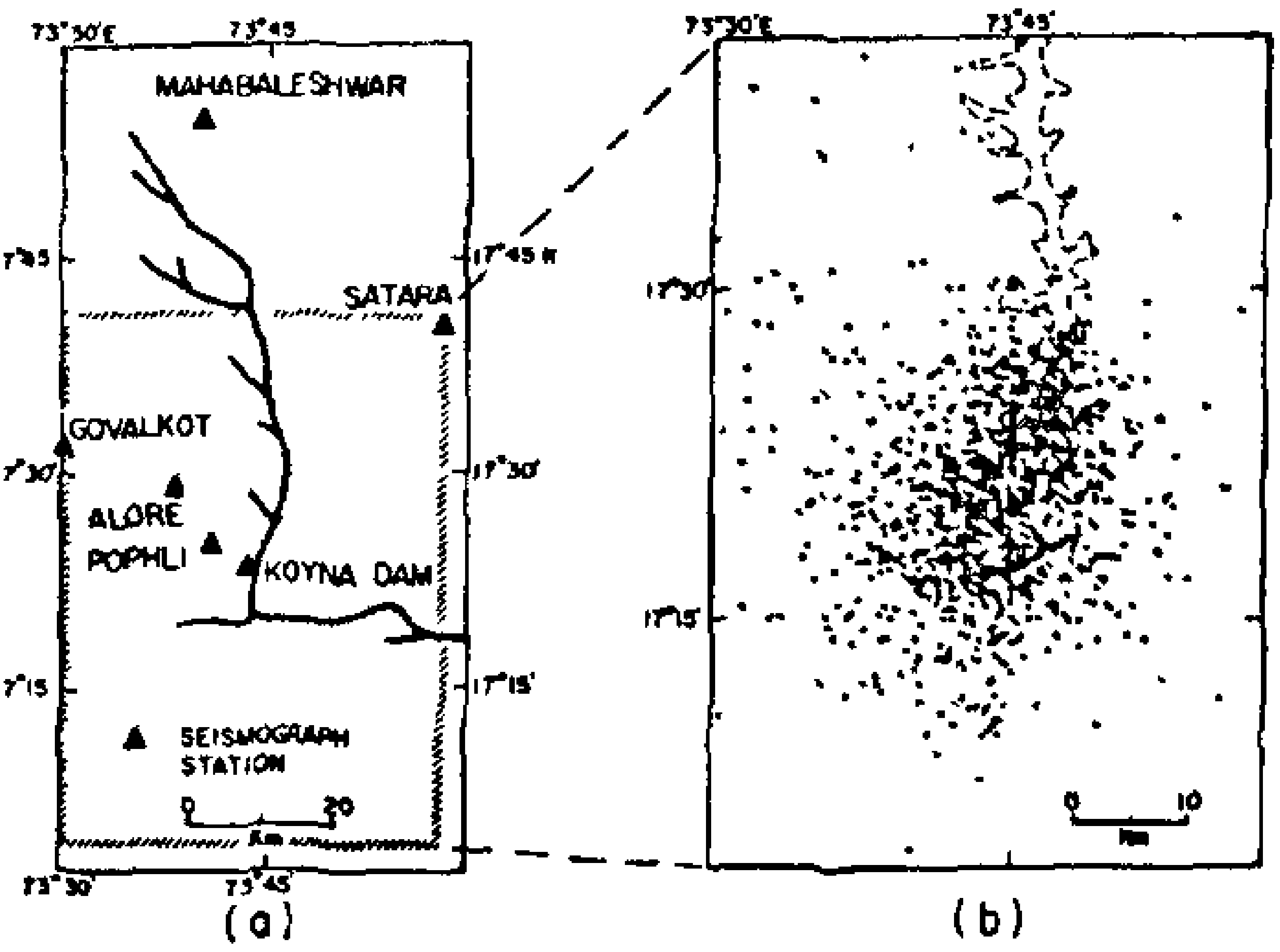
TABLE 1 *(continued)* *(Page 3)*
Reported cases of reservoir-induced changes in seismicity

Name of the dam/ reservoir	Country	Height of dam (m)	Reservoir volume $(10^6\ m^3)$	Year of impounding	Year of largest Earthquake	Magnitude/ intensity
Qianjin	China (PRC)	50	20	1970	1971	3.0
Schlegeis	Austria	117	128	1970	1971	2.0
Shasta	U.S.A.	183	5,615	1944	1944	3.0
Sobradinho	Brazil	43	34,100	1977	1979	~2.0
Sriramsagar	India	43	32,000	1983	1984	3.2
Talbingo	Australia	162	935	1971	1973	3.5
Toktogul	U.S.S.R.	215	19,500	1977		
Tucurui'	Brazil	100	45,800	1984	1985	3.4
Vajont	Italy	262	150	1960	1960	
Zhelin	China (PRC)	62	7,170	1972	1972	3.2
Decrease in microearthquake activity						
Anderson	U.S.A.	72	110	1950		
Bhakranangal	India	226	9,868	1958		
Flaming Gorge	U.S.A.	153	4,674	1962		
Glen Canyon	U.S.A.	216	33,305	1963		
Ikawa	Japan	104	151	1957		
Mangla	Pakistan	116	7,250	1967		
Tarbela	Pakistan	143	13,960	1974		
Tsengwen	Taiwan	128	708	1973		
Other possible cases						
Cabin Creek	U.S.A.	49				
Clark Canyon	U.S.A.	40				
Coyote Valley	U.S.A.	50				
Disposal Wellsh Northeastern Ohio	U.S.A.			1986		5.0
El Grado	Spain	130				
Ghirni	India	16				
Kinnersani	India	61				
Palisades	U.S.A.	82				
Parambikkulam	India	73				
Rockey Reach	U.S.A.					
San Luis	U.S.A.	116				
Sefid Rud	Iran	106				

TABLE 1 (continued) (Page 4)

Reported cases of *reservoir-induced changes* in seismicity

Name of the dam/reservoir	Country	Height of dam (m)	Reservoir volume ($10^6 m^3$)	Year of impounding	Year of largest Earthquake	Magnitude/ Intensity
Sleepy Hollow Oil Field	Canada					
Ukai	India	69				
Warragamba	Australia	137				
Fluid injection/withdrawal induced earthquakes (not a complete list)						
Buena Vista Hills Oil Field	U.S.A.					
Dale	U.S.A.					
Fashing Gas Field	U.S.A.					
Gobles Oil Field	U.S.A.					
Goose Creek *Oil Field*	U.S.A.					
Imogene Oil Field	U.S.A.					
Matsushiro	Japan					
Pau Basin	France					
Rangely	U.S.A.					
Rockey Mountain	U.S.A.					
Strachan Field	Canada					
The Geysers	U.S.A.					
Wilmington Oil Field	U.S.A.					



(a) (b)

FIGURE 2 (a) Seismic stations in the Koyna region. (b) Epicentres located in the Koyna region for the period December 1967 through December 1971 by Guha *et al*[4].

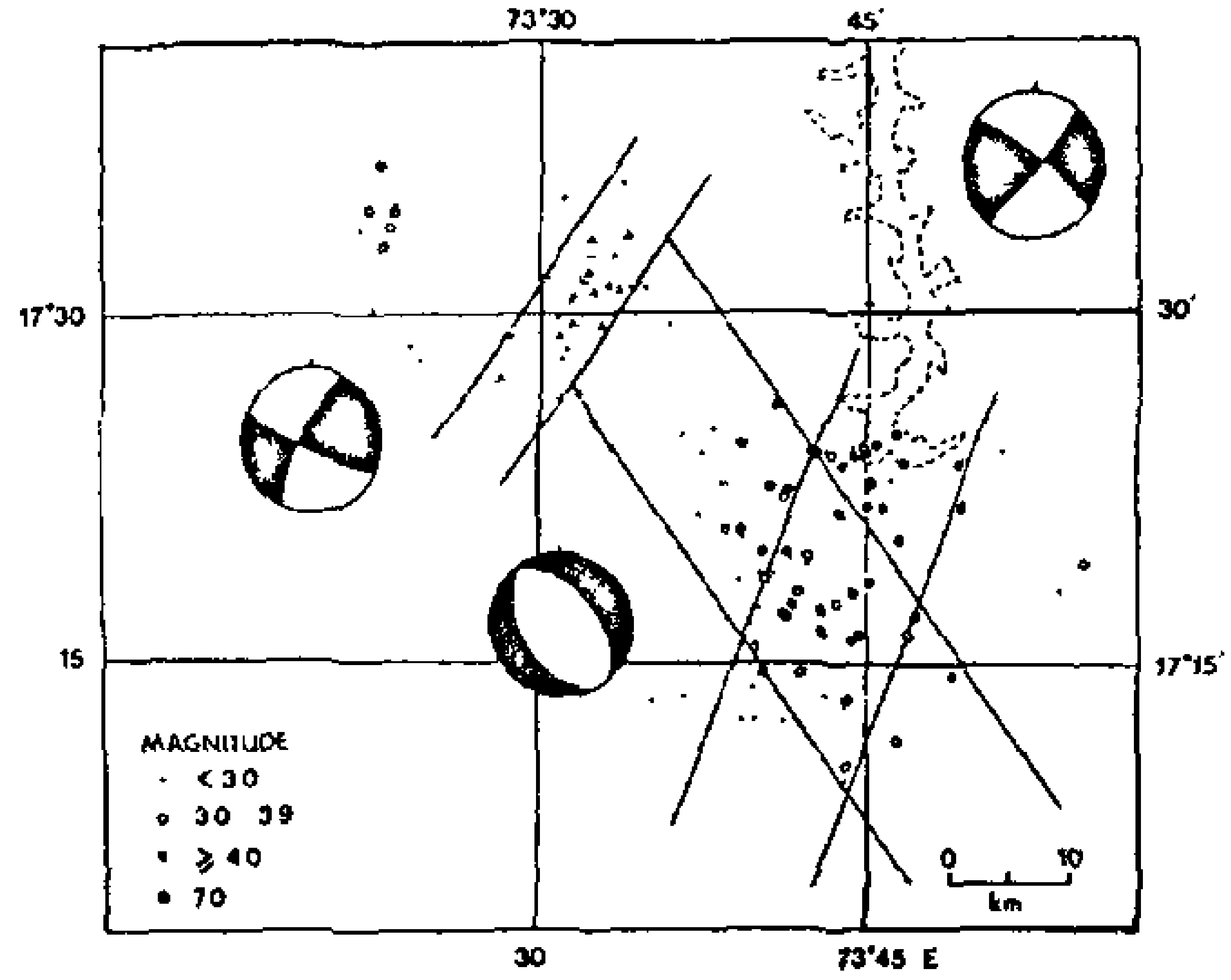


FIGURE 3 Relocated epicenters and composite focal mechanism solutions by Rastogi and Talwani[5]. Magnitudes are from Guha *et al*[4]. For details see text.

earthquakes of Ms ≥ 4.0 in the Koyna region that occurred during the period October 1973 through December 1976, their foreshocks and aftershocks were estimated. The seismic activity is found to be much less diffused and a N-S trending fault at 73° 45′ E longitude could easily be identified (figure 4). A number of epicentres, including that of the mainshock of December 10, 1967 lie on this longitude. The three groups identified by Rastogi and Talwani[5] are also depicted in figure 4.

The seismic activity continues in the Koyna region. Table 2 adopted from Gupta[2] shows details of earthquakes of magnitude ≥ 4.0 that have occurred in the Koyna region till the end of 1989.

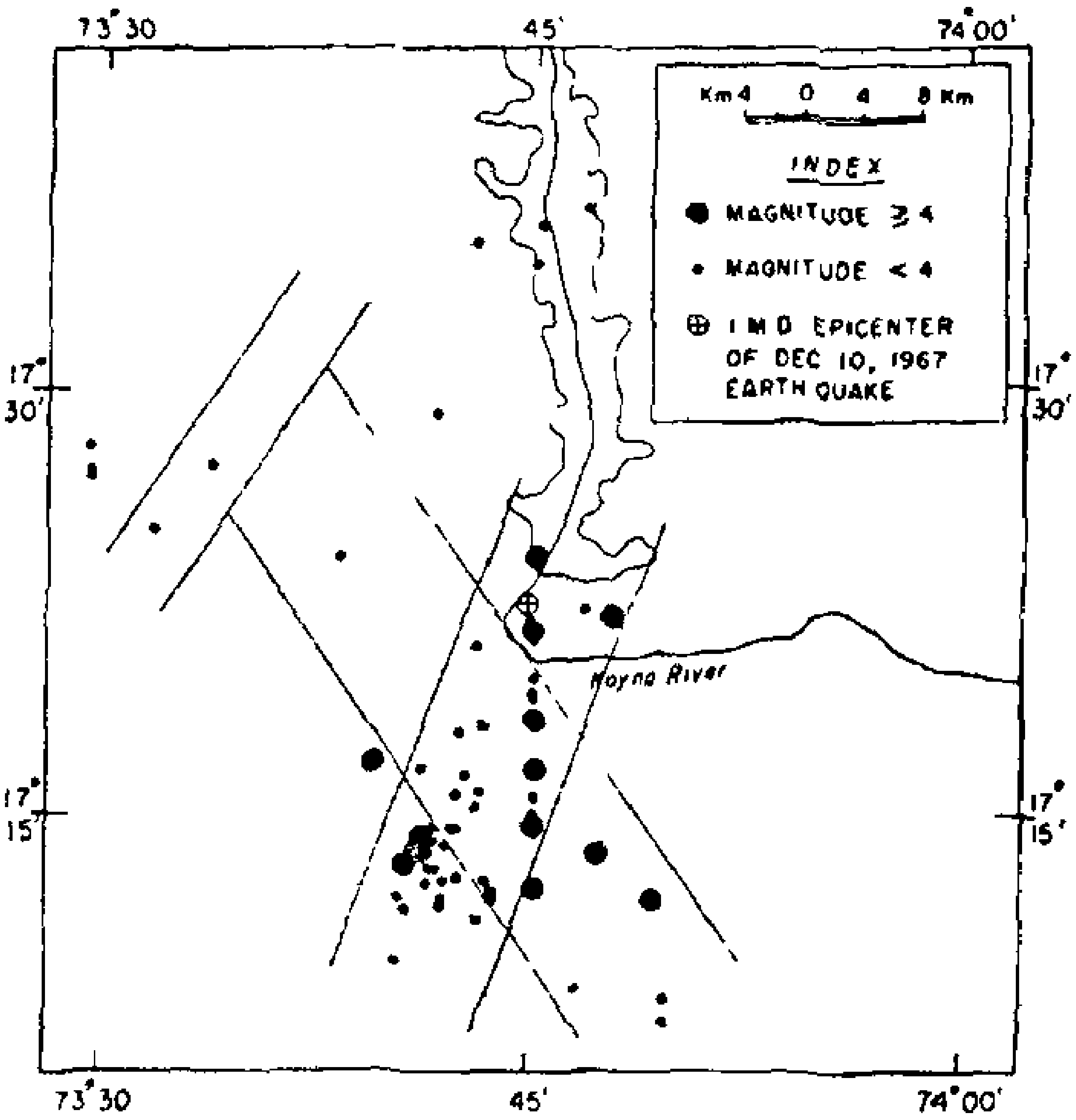


FIGURE 4 Epicenters for the period 1973 through 1976 for M ≥ 4 earthquakes, their foreshocks and aftershocks located by Gupta *et al*[6]. The three trends, from Rastogi and Talwani[5] are shown by parallel lines.

Focal Mechanism

A number of authors[7–15] have investigated the focal mechanism of the main Koyna earthquake of December 10, 1967. Singh *et al.*[13] compared the computed radiation pattern of fundamental mode Rayleigh waves for a suite of probable fault parameters with long period vertical component seismograms of 30 WWSSN stations. The favoured solution is strike of the fault N 10° E, dip 78° W, slip 175°, and a focal depth of 10 km. The seismic moment is estimated to be 8.2×10^{25} dyne-cm. The values of average dislocation, apparent stress, apparent strain and seismic energy are found to be 108 cm, 15.4 bars, 5.3×10^{-5} and 2.25×10^{21} ergs respectively. This solution is shown in figure 5. Composite focal mechanisms solutions obtained by Rastogi and Talwani[5], and Gupta *et al.*[6] are also included in figure 5. It may be noted in this figure that earthquakes south of 17 15′ N latitude indicate normal faulting, while solutions north of this latitude basically are strike-slip fault movement on a NNE trending plane. The normal fault solutions probably correspond to NNW zone of Rastogi and Talwani[5]. It is noteworthy that south of 17°15′ N latitude, the epicentre trend changes and the sense of faulting changes from strike-slip to normal faulting. As may be seen in figures 4 and 5, the Koyna river flows in a N-S direction to 17 20′ N latitude and then takes a sharp turn to the east. These

TABLE 2 Earthquakes of Ms ≥ 4.0 in Koyna region.

Date	Magnitude	Date	Magnitude
January 21, 1969	4.1	February 6, 1980	4.6
February 13, 1969	4.2	August 19, 1980	4.3
March 7, 1969	4.4	September 2, 1980	5.3
June 3, 1969	4.2	September 2, 1980	4.5
June 27, 1969	4.5	September 20, 1980	5.5
July 22, 1969	4.0	September 20, 1980	5.9
November 3, 1969	4.1	September 20, 1980	4.5
November 4, 1969	4.2	September 20, 1980	4.0
April 16, 1970	4.0	September 20, 1980	4.2
May 27, 1970	4.8	September 21, 1980	4.0
June 8, 1970	4.1	September 21, 1980	4.0
June 17, 1970	4.1	September 21, 1980	4.0
September 21, 1970	4.0	September 21, 1980	4.2
September 25, 1970	4.6	September 22, 1980	4.3
September 26, 1970	4.6	September 25, 1980	4.3
January 23, 1971	4.2	September 27, 1980	4.5
February 14, 1971	4.0	September 30, 1980	4.2
August 10, 1971	4.0	October 3, 1980	4.6
August 10, 1971	4.3	October 4, 1991	5.1
May 1, 1972	4.2	October 4, 1980	4.3
May 11, 1972	4.5	October 5, 1980	4.0
November 11, 1972	4.1	October 16, 1980	4.1
April 19, 1973	4.1	October 21, 1980	4.2
October 17, 1973	4.0	October 26, 1980	4.5
October 17, 1973	4.1	October 26, 1980	4.4
October 17, 1973	5.1	January 25, 1981	4.0
October 24, 1973	4.6	April 25, 1982	4.4
November 11, 1973	4.6	May 5, 1982	4.2
February 17, 1974	4.5	September 10, 1982	4.4
April 28, 1974	4.0	February 5, 1983	4.3
May 29, 1974	4.2	March 21, 1983	4.1
July 29, 1974	4.8	May 8, 1983	4.1
August 7, 1974	4.1	May 28, 1983	4.2
August 28, 1974	4.5	September 25, 1983	4.8
November 11, 1974	4.3	October 1, 1983	4.5
December 20, 1974	4.2	September 25, 1984	4.6
February 10, 1975	4.1	November 14, 1984	4.7
September 2, 1975	4.2	December 21, 1984	4.1
December 2, 1975	4.2	May 27, 1985	4.1
December 24, 1975	4.8	October 29, 1985	4.2
April 22, 1976	4.3	October 29, 1985	4.2
		November 15, 1985	4.3
June 2, 1976	4.5	November 21, 1985	4.0
September 16, 1976	4.2	November 21, 1985	4.1
September 26, 1976	4.3	November 21, 1985	3.9
December 12, 1976	4.2	December 15, 1985	4.3
September 19, 1977	4.7	December 28, 1985	4.0
November 4, 1977	4.0	July 24, 1988	4.8
November 4, 1977	4.2	August 15, 1988	4.0
November 4, 1977	4.4	August 15, 1988	4.1
December 12, 1978	4.7	September 11, 1988	4.4
January 26, 1979	4.0	October 29, 1989	4.2
September 26, 1979	4.0		

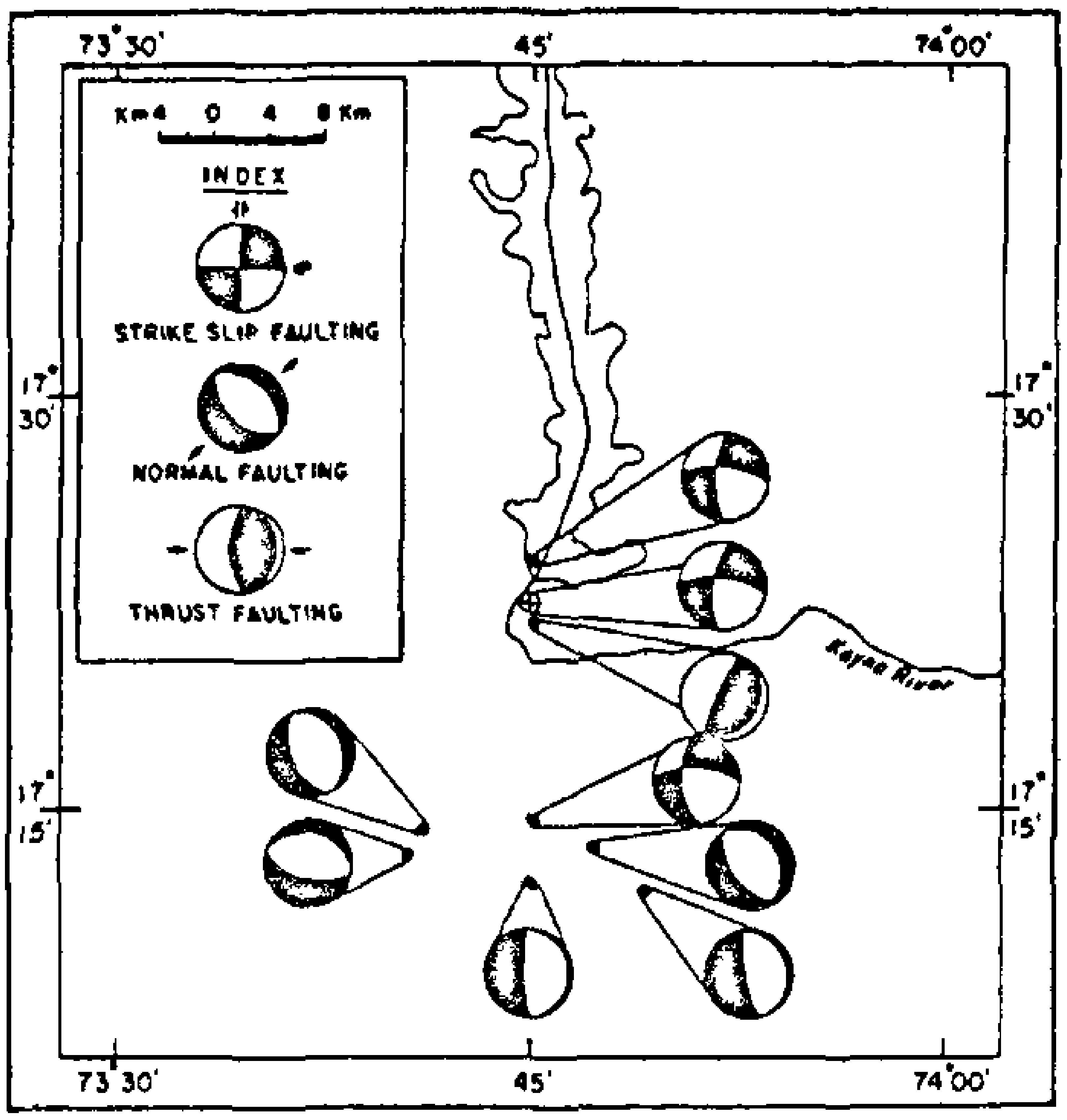


FIGURE 5 Composite focal mechanism solutions for nine $M \geqslant 4$ Koyna earthquake (adopted from Gupta *et al*[6]. Focal mechanism for December 10, 1967 earthquake is from Singh *et al*[13], shown by a circle with an × sign. Earthquakes south of 17° 15' latitude have normal fault mechanism.

observations are consistent with a set of conjugate faults, with strike-slip and normal faulting sense of motion basically associated with the epicentres in the vicinity of the Koyna dam.

Water Level in Shivaji Lake and Earthquake Frequency

In a detailed study[16], close relations among reservoir level, rate of loading and earthquake frequency have been established for the Koyna region. Daily reservoir levels are averaged (arithmetic mean) weekly, plotted and corrected. It may be noted from figures 6, 7 and 8 that the highest reservoir levels reached every year have been upto 2160 ft. or more. During the period 1975 through 1980, the rate of loading has been less than 40 ft./week with the exception of the year 1980 (figure 6). Three earthquakes exceeding magnitude 5 occurred in September 1980 (one on September 2, and two on September 20). In the earlier years, earthquakes of $M \geq 5$ occurred in 1967 and 1973. In these years also, the rate of loading exceeded 40 ft./week (figure 7). Similar information for the years 1968 through 1972 and 1974 is given in figure 8 Data are not included for 1968 as there were several aftershocks of $M \geq 5$ following the December 10, 1967 event. It may be noted from figure 8 that although the loading rate of the reservoir exceeded 40 ft./week in 1969 and 1971, still no earthquake of $M \geq 5$ occurred. It therefore, appears that a necessary, but not sufficient condition for earthquakes of $M \geq 5$ to occur in the Koyna region is that the rate of loading should exceed 40 ft./week.

It appears that through proper manipulation of reservoir levels in the Shivaji Sagar lake, earthquakes of $M \geq 5$, which are locally damaging, can be avoided. Similar results are reported by Simpson and Nagmatullaev[17] for the Nurek Dam in USSR. Smooth filling and emptying appears to be the key to reduce the hazard of reservoir-induced earthquakes.

BHATSA DAM

Bhatsa Dam is located some 200 km north of Koyna. When full pond levels are reached, the reservoir will have a capacity of 947 million m^3 and the height of the water column will be 88.5 m. The reservoir will irrigate 23,000 hectares of land and meet one half requirement of the drinking water of Bombay city. The impoundment started in 1977 with 17 m of initial impoundment. Later, the water column height rose to 51 m in 1982 and 58 m in 1983. Earthquakes started becoming evident in mid May 1983 and significant earthquakes of magnitude 4.4. and 4.9 occurred on August 17 and September 15, 1983. Being set up in a geological environment similar to Koyna, there was a great concern whether RIS of the magnitude of Koyna will be witnessed at Bhatsa. However, in the subsequent years, no significant earthquakes have occurred.

Rastogi *et al.*[18] have located more than 400 tremors from among several thousands recorded, depicted in figure 9. The estimated location errors are less than 1 km for the epicentre and less than 3 km for focal depths. The epicentres are mostly confined to small areas of 5 km × 7 km. Rastogi *et al.*[18] summarized that intense seismic activity between August and September 1983 occurred soon after rapid loading of the reservoir in July 1983, when the water level rose by 18 m. The enhanced seismic activity in August 1984, could be correlated with the increase in water level from July to August 1984. The enhanced activity during 1983 and 1984 occurred with a delay of about a month's time after peak levels.

In recent years, the instrumentation at Bhatsa reservoir has been further strengthened by the installation of a telemetering seismic array by the Bhabha Atomic Research Centre, Bombay (S. K. Arora, Personal communication, 1989). However the seismic activity is at a much lower level compared to 1983.

RIS AT OTHER RESERVOIR SITES IN SHIELD AREA

In additon to Koyna and Bhatsa, several other reservoir sites in the Peninsular shield of India are

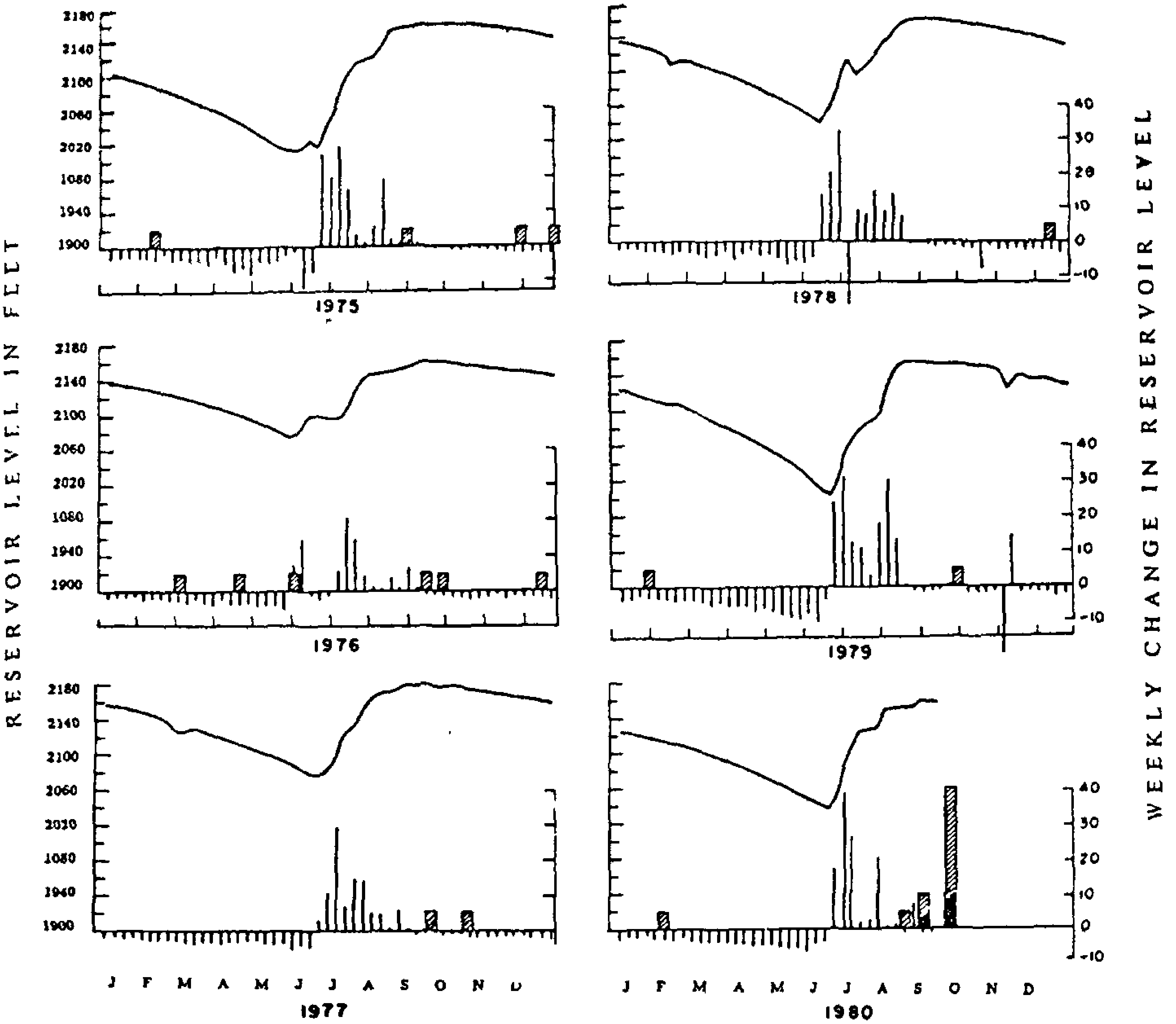


FIGURE 6 Water levels at the Shivajisagar Lake (curve, scale on the left), weekly change in water levels (vertical bars, scale on the right), earthquakes of magnitude $\geqslant 4$ (hatched column) and magnitude $\geqslant 5$ (filled column). The height of the column is proportional to the number of earthquakes (e.g., one earthquake of magnitude $\geqslant 4$ occurred on September 20, 1980). Figure adopted from Gupta[16].

known to have induced earthquakes. Guha *et al.*[4] considered the seismic status of seventeen reservoirs and noted that eight of them have evidenced some seismic activity. Reservoirs like Kinnersani, Parambikulam, Sharavathi, Bhandra and Ukai dams had definite seismic activity following the impoundment (figure 10) while isolated shocks occurred at Ghirni, Mangalam, Sholayar etc. Numerous microearthquakes are reported to have occurred at Mula.

Other important sites of induced seismicity are Idukki[19,20], Osman Sagar[21] and Sriramsagar[22].

COMMON CHARACTERISTICS OF RIS

In a couple of pioneering studies[23,24] the common features of reservoir-induced seismicity (RIS) were identified. These features are also helpful in discriminating RIS from normal earthquakes (those not induced), also occurring in the vicinity of a reservoir. Tremors were initiated and/or their frequency increased considerably following the lake filling. The earthquakes occur in the vicinity of the reservoir. A majority of the epicentres are located within 25 km from the deepest

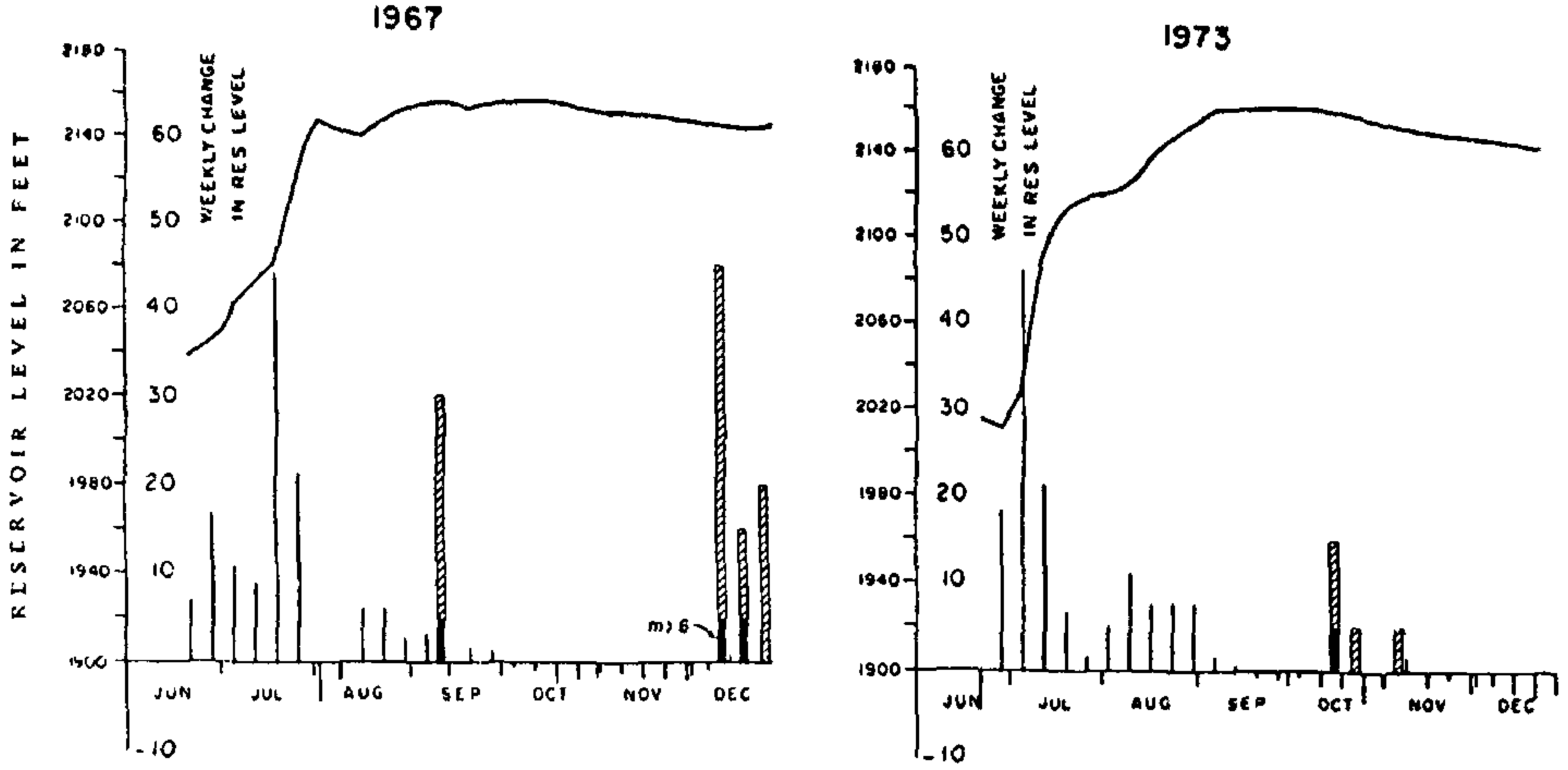


FIGURE 7 The scheme of the figure is the same as for figure 6. The December 10, 1967 earthquake had a magnitude 6·3. Figure adopted from Gupta[16].

portions of the reservoir. The factors influencing earthquake frequency and magnitude include the rate of increase of water level, duration of loading, maximum water level reached and the duration for which the high level is retained. For RIS sequences, the 'b' values are high in the earthquake frequency-magnitude relations, and the ratio of the magnitude of the largest aftershock to the main shock is also high (~ 9). This is different for the normal earthquake sequences of the concerned regions as these are normally characterised with low 'b' values and low ratios of the largest aftershock to the main shock magnitude. It is further observed that the foreshock–aftershock pattern of the RIS sequences corresponds with type II of Mogi's models, whereas the normal earthquake sequences of the corresponding regions belong to type I of Mogi's models. The after shock activity of RIS events attenuates very slowly compared to normal earthquake sequences. It is noticed that for large RIS events in normal fault environment, the dip-slip component of the fault motion is such that the lakes are situated on the down thrown blocks. RIS sites are normally found to be located in regions characterised by a volcanic past and the presence of easily corrodable rocks. One of the most important factors in inducing earthquakes is the height of the water column in the reservoir. Most RIS events of magnitude ≥ 5 have occurred in the vicinity of the reservoirs where the water column height exceeded 100 m. In a recent work[2], the above mentioned characteristics are discussed in detail and several examples are cited.

RIS AND HIMALAYAN RESERVOIRS

The Himalayan part of the Alpide Belt is seismically one of the most active intra-continental regions in the world. Figure 11 updated from Chandra[25] depicts epicentres of all earthquakes of magnitude ≥ 7 and earthquakes that claimed human lives (for some of them instrumental magnitudes are not available). Figure 11 also depicts large reservoirs which have been completed or are under construction in the Himalayan foothills. A large reservoir, in the parlance of the world community of the engineers, has a storage volume exceeding 1 km^3 and/or a water column in the reservoir exceeding 100 m. Gupta and Rajendran[26] have pointed out that there are 11 large reservoirs in the foothills of Himalaya, 9 of which have been already impounded. However, there is no evidence of RIS from any of these 9 impounded reservoirs. Jacob *et al.*[27], on the contrary, have reported a minor decrease in seismicity within a distance of upto 100 km from the dam site after the initial filling of the Tarbela Reservoir. It should, however, be kept in mind that these reservoirs have been impounded recently and the delayed effect of pore pressure diffusion may become significant with the passage of time.

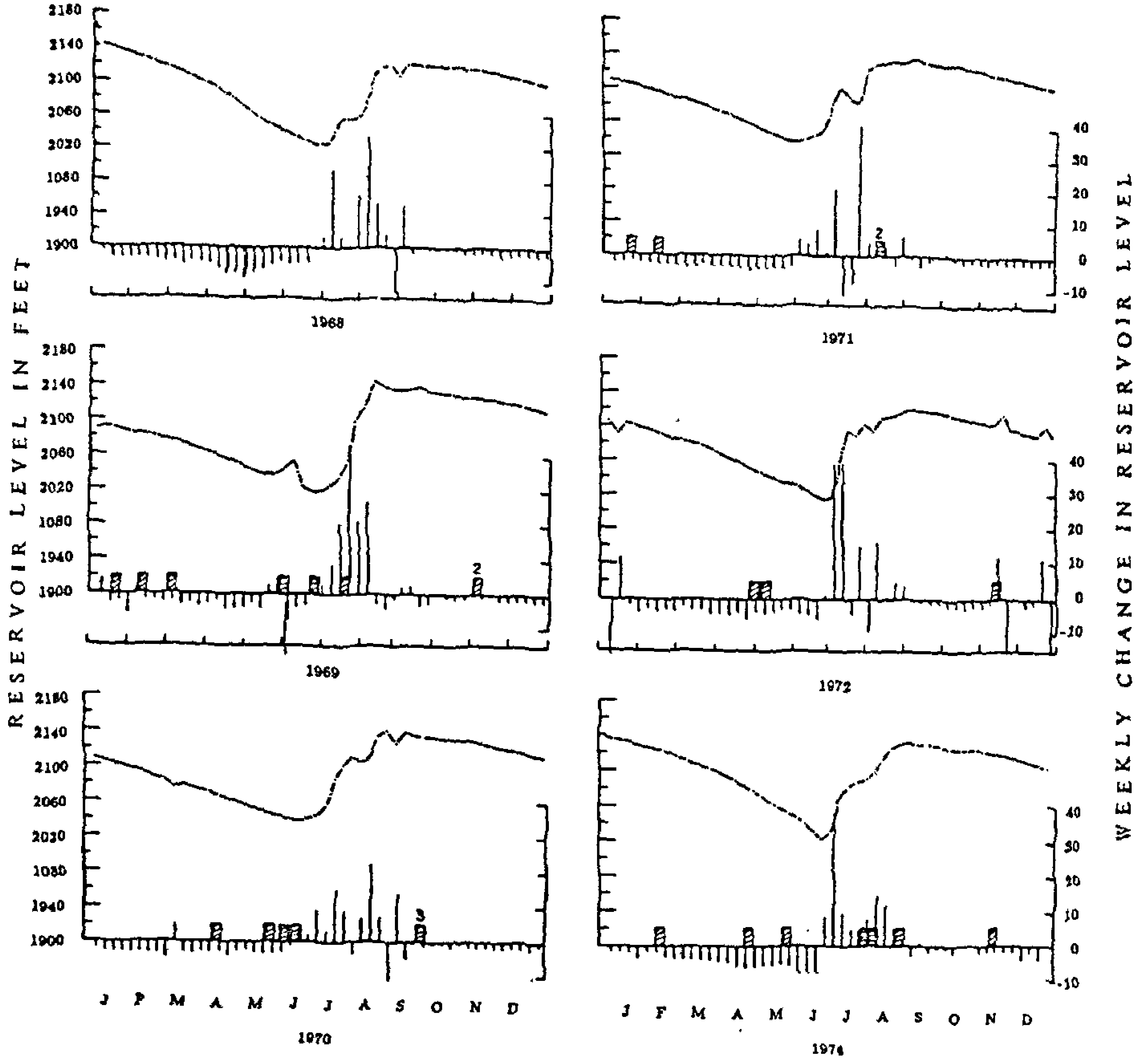


FIGURE 8 Same as for figure 6 for the years 1968 through 1972 and 1974. Occurrence of more than one earthquake of *magnitude ≥ 4·0 is indicated by a number (e.g., 3 earthquakes of magnitude ≥ 4·0 in 1 week of September 1970).* Earthquake data are not shown for 1968 since there were numerous aftershocks of magnitude ≥ 4·0 of the December 10, 1967 earthquake (after Gupta[16]).

Non-occurrence of RIS in the vicinity of the Himalayan reservoirs is comprehended primarily due to thrust fault environment mostly prevailing in the Himalayan foot hills which is non-conducive for RIS. Additionally, a pre-requisite for RIS is availability of critically stressed rock strata within shallow (N 10 km) depths, so that the effect of reservoir leading on the stress regime could trigger earthquakes. This condition is not met within the foothills of Himalaya where a thick strata of relatively mechanically incompetent sedimentary formations exist. For the Himalayan reservoirs, the threat of natural seismicity (where earthquakes of magnitude exceeding 8 have occurred) is much more severe than that posed by RIS.

ARE RIS EVENTS OF M ≥ 5 PRECEDED BY A COUPLE OF FORESHOCKS OF M ≥ 4?

Gupta and Iyer[28] had pointed out that there is a 50% probability of occurrence of a magnitude ≥ 5 in Koyna

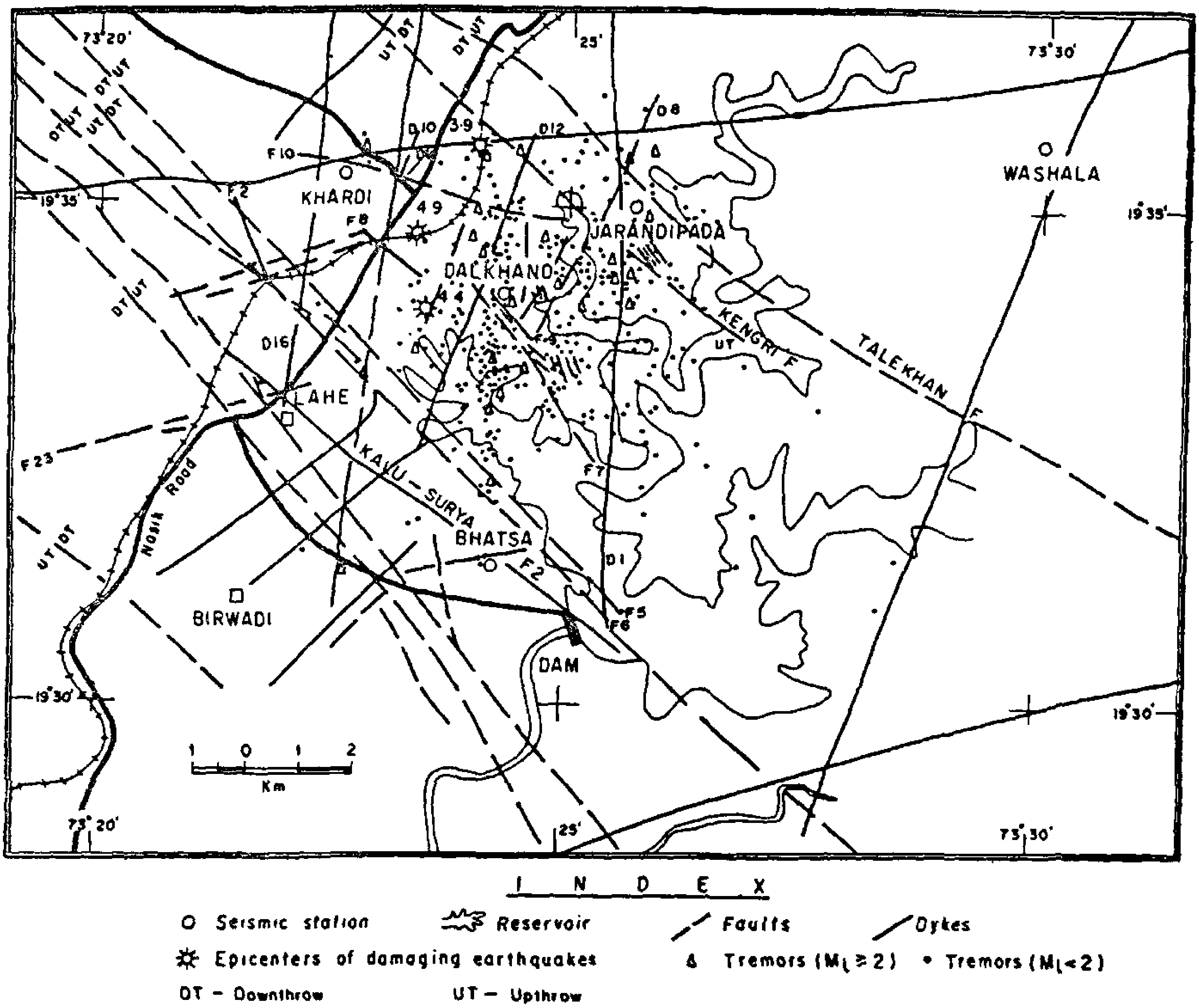


FIGURE 9 Earthquakes in the vicinity of Bhatsa for the period October 1983 through April 1985. The density of epicentre is high on the north and northwestern periphery of the reservoir. Epicenters are located by the 8 station seismic array. (adopted from Rastogi *et al*[18]).

region if two earthquakes of magnitude ≥ 4 are closely spaced in time (within 15 days). In a recent study this work has been extended to all reservoir sites (Gupta[29]). *It has been found that induced earthquakes exceeding* magnitude 5 that occurred at Kariba, Kremasta, Koyna, Oroville and Aswan were preceded by a couple of foreshocks of M ≥ 4 during the two weeks preceding the main shock. However, unlike these sites, there is definite information that induced earthquakes exceeding magnitude 5 at Xinfengjiang, China and Lake Mead, USA were not preceded by a couple of magnitude ≥ 4 earthquakes.

Globally, there are ten reservoir sites where induced earthquakes exceeding magnitude 5 have occurred. Among these, at five sites earthquakes were preceded by a couple of M ≥ 4 foreshocks, and at two sites such foreshocks did not occur. Definite information is not available to carry out a similar analysis at the remaining three sites.

Recognition of foreshocks, as foreshocks, soon after their occurrence is one of the most important problems in earthquake prediction studies. Gupta[29] has pointed out that the above finding is purely empirical and required physical explanation. However, earthquakes of M ≥ 5 are locally damaging and there is a great concern when a M ≥ 4 earthquake occurs in the vicinity of a reservoir, whether it will be followed by a stronger earthquake or not. The above study indicates an enhanced probability of occurrence of an $M \geq 5$ earthquake when two foreshocks of $M \geq 4$ occur in a close space of time.

CONCLUDING REMARKS

Indian scientists have contributed significantly in the field of reservoir-induced seismicity. The above review has not covered all the work. In the References, 31 of

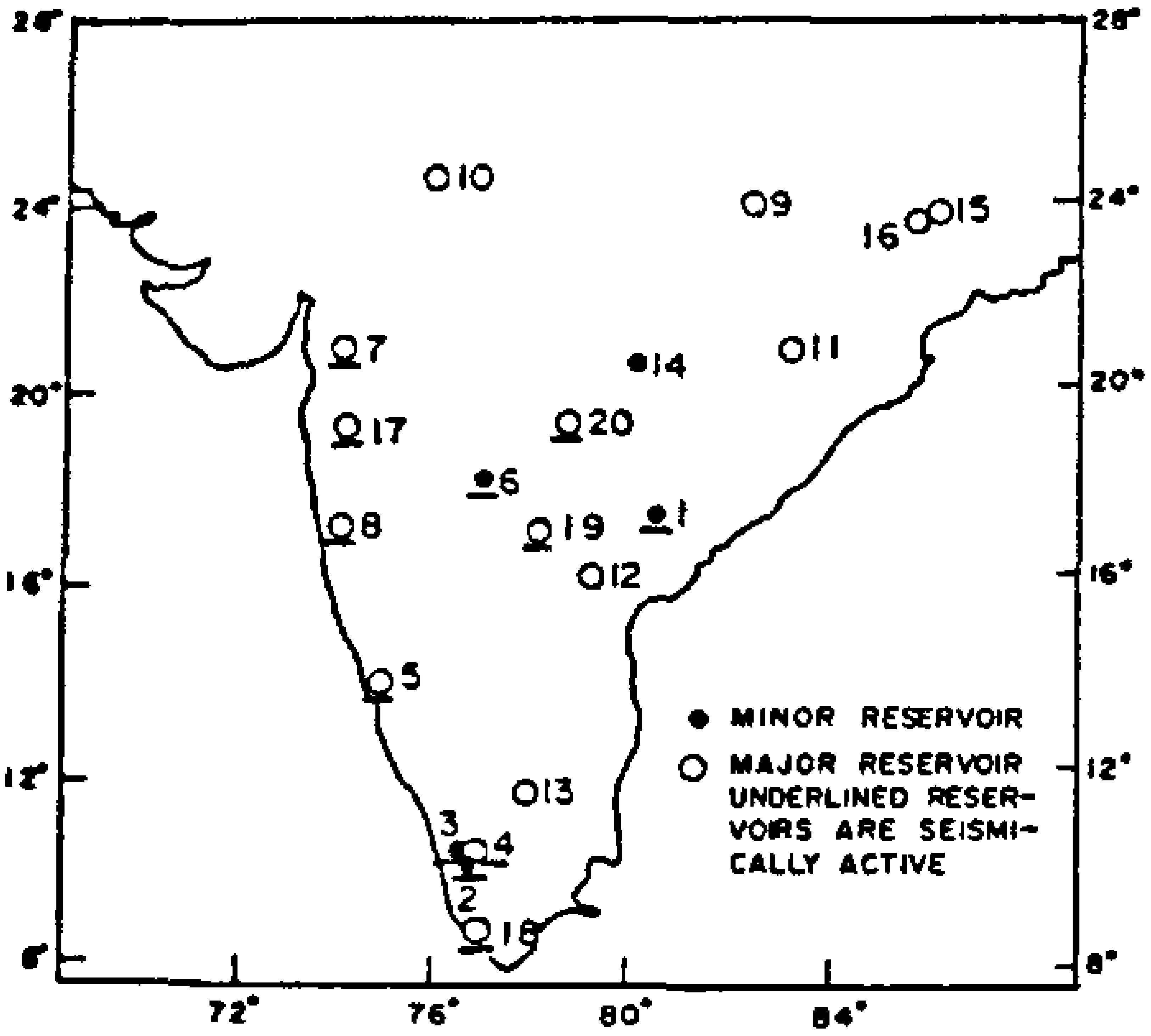


FIGURE 10 Water reservoirs in Peninsular India. The underlined reservoirs are seismically active. 1 = Kinnersani, 2 = Sholayar, 3 = Mangalam, 4 = Parambikulam, 5 = Sharavathi, 6 = Ghirni, 7 = Ukai, 8 = Koyna, 9 = Rihand, 10 = Rana Pratap Sagar, 11 = Hirakud, 12 = Nagarjuna Sagar, 13 = Mettur, 14 = Itiadom, 15 = Maithon, 16 = Panchet, 17 = Bhatsa, 18 = Idduki, 19 = Osman Sagar, = 20 Sriramsagar. Figure modified from Guha *et al*[4].

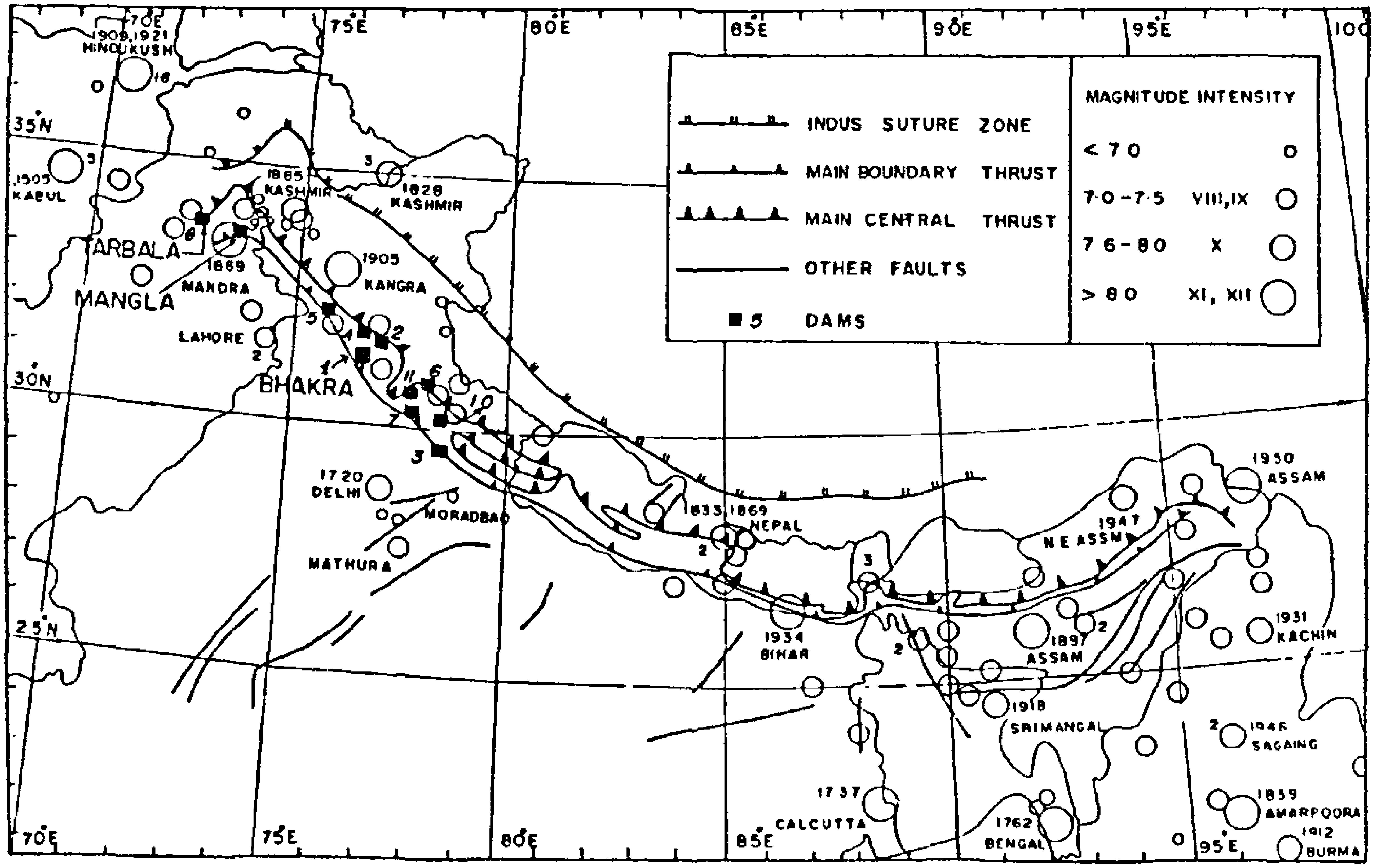


FIGURE 11 Earthquakes of $M \geq 7{\cdot}0$ and recent earthquakes that claimed human lives in the Himalaya and nearby areas (modified from Chandra[25]. Dams taller than 100 m are shown by filled squares).

the papers (30 to 60) not specifically covered in the text, have been added as bibliography.

In conclusion, I would like to point out that the reservoir-induced seismic activity in the Koyna region is unique. It has continued for the past 28 years and medium size (magnitude ≥ 4) earthquakes occur frequently. The fact that these earthquakes occur in a fairly small volume, that the epicentral region is easily accessible from all sides and that there is no other seismically active region in the vicinity, all these make the Koyna region most suitable for detailed earthquake physics and precursor related studies.

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