Patterns preceding major earthquakes in north-east India

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Major earthquakes in north-east India are generally preceded by precursory earthquake swarms and quiescences. Developing regression equations relating the main-shock magnitude (M_m), the average magnitude of the largest two events in the swarm (M_p) and the time interval (T_p) between the onset of the swarm and the occurrence of the mainshock, Gupta and Singh in 1986 made a medium-term forecast of a $M \sim 8$ magnitude earthquake in the vicinity of the India–Burma border[1]. This forecast has come true. However, the mainshock was not preceded by any short-term seismicity pattern precursor.

Introduction

SEISMICALLY, north-eastern India is one of the most active intra-continental regions of the world. Since 1897, the region has been the site of ten earthquakes of $M \geq 7\frac{1}{2}$ including the two great earthquakes of 1897 and 1950, both of M 8.7 (Figure 1). The last earthquake $M \geq 7\frac{1}{2}$ occurred on 17 August 1952. North-east India is geologically and tectonically very complex[2–4]. Earthquake focal mechanisms, stress pattern, and the regional gravity and travel time studies have been reported in a number of recent papers[5–8]. In the past three decades, there has been a worldwide effort to recognize patterns of spatial and temporal variation of seismicity that precede major earthquakes[9–20].

The temporal and spatial variation of seismicity preceding moderate to great earthquakes in the north-east India region has been investigated in detail by Gupta and Singh[1,21]. They found that moderate to great earthquakes there are found to be generally preceded by well-defined epochs of earthquake swarm and quiescence. Recognizing earthquake swarms and quiescence they forecast a medium-term earthquake $M \sim 8$ magnitude in the vicinity of the India–Burma border. This forecast has come true. However, the main-shock was not found to be preceded by any 'short-term' seismicity pattern. These results are presented in this note.

The precursory earthquake swarms

Evison[22] noted that in California and New Zealand a single main shock event is preceded by a single swarm, and the time interval between the onset of the swarm and the occurrence of the main-shock is dependent on the magnitude of the mainshock.

The December 30, 1984 earthquake

Gupta and Singh[1] investigated the seismicity pattern of the Cachar earthquake ($m_b = 5.6$) of 30 December, 1984 which claimed more than 30 human lives. Due to poor location capabilities, only earthquakes of $m_b > 4.5$ were located without failure in the 1980s. To investigate the possible precursory sesimicity pattern, an area bounded by 23° N and 28° N latitudes, and 89° E and 94° E longitude was chosen and shallow earthquakes ($h < 70$ km) of $m_b > 4.5$ were considered. During 1980 and 1981 only three events occurred (Figure 2*a*, A). This was followed by occurrence of 14 events during the period 1 January, 1982 through 3 February, 1983 constituting a well-defined earthquake swarm (Figure 2*a*, B). Subsequently, the seismic activity decreased considerably as only 5 events occurred during

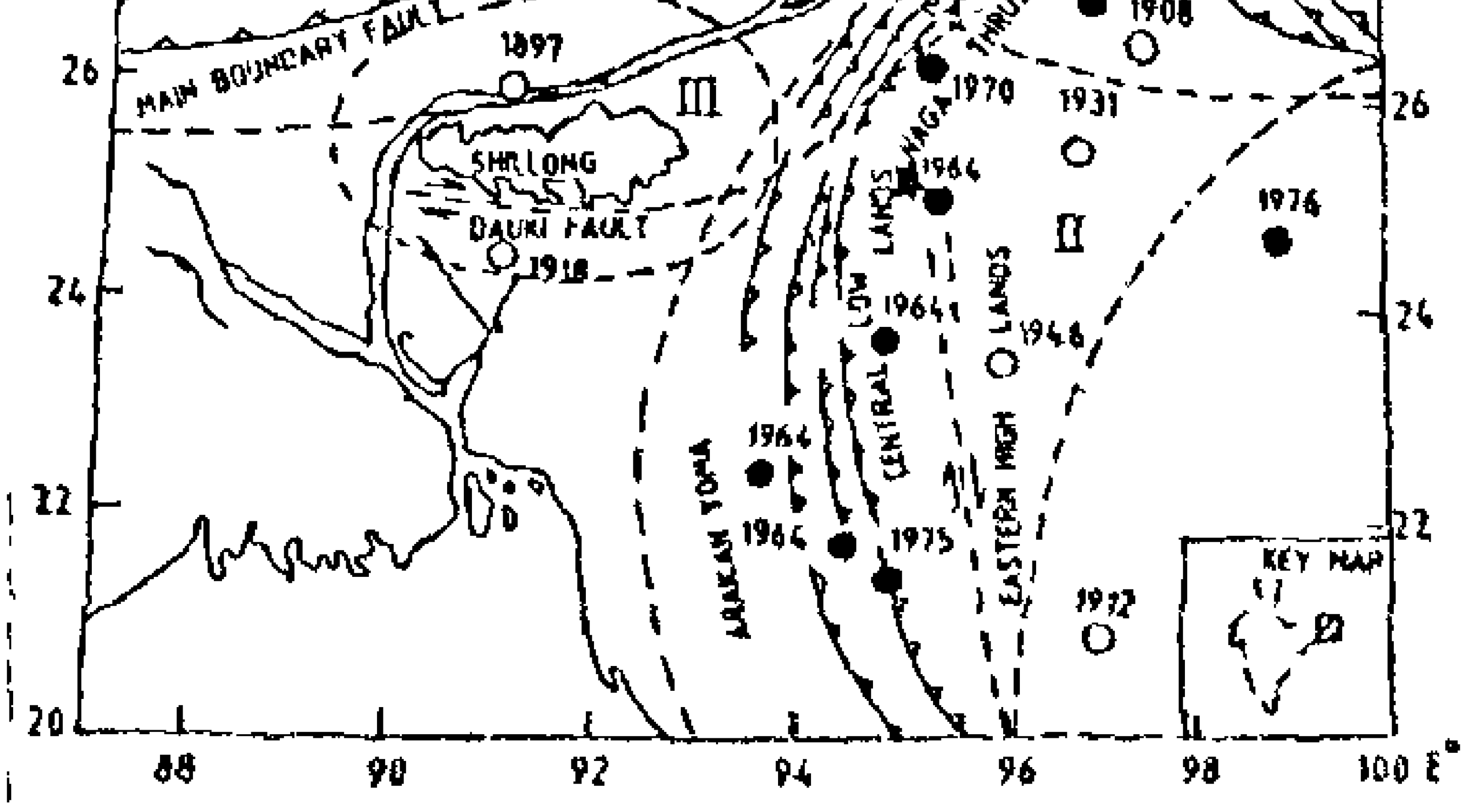

Figure 1. Epicentres of earthquakes of $M \geq 7\frac{1}{2}$ for the period 1897–1962 (open circles), $m_b \geq 6.1$ for the period 1963–1985 (solid circles) in north-east India (Gupta and Singh[1]). Star: epicentre of the M 7.3 6 August, 1988 earthquake.

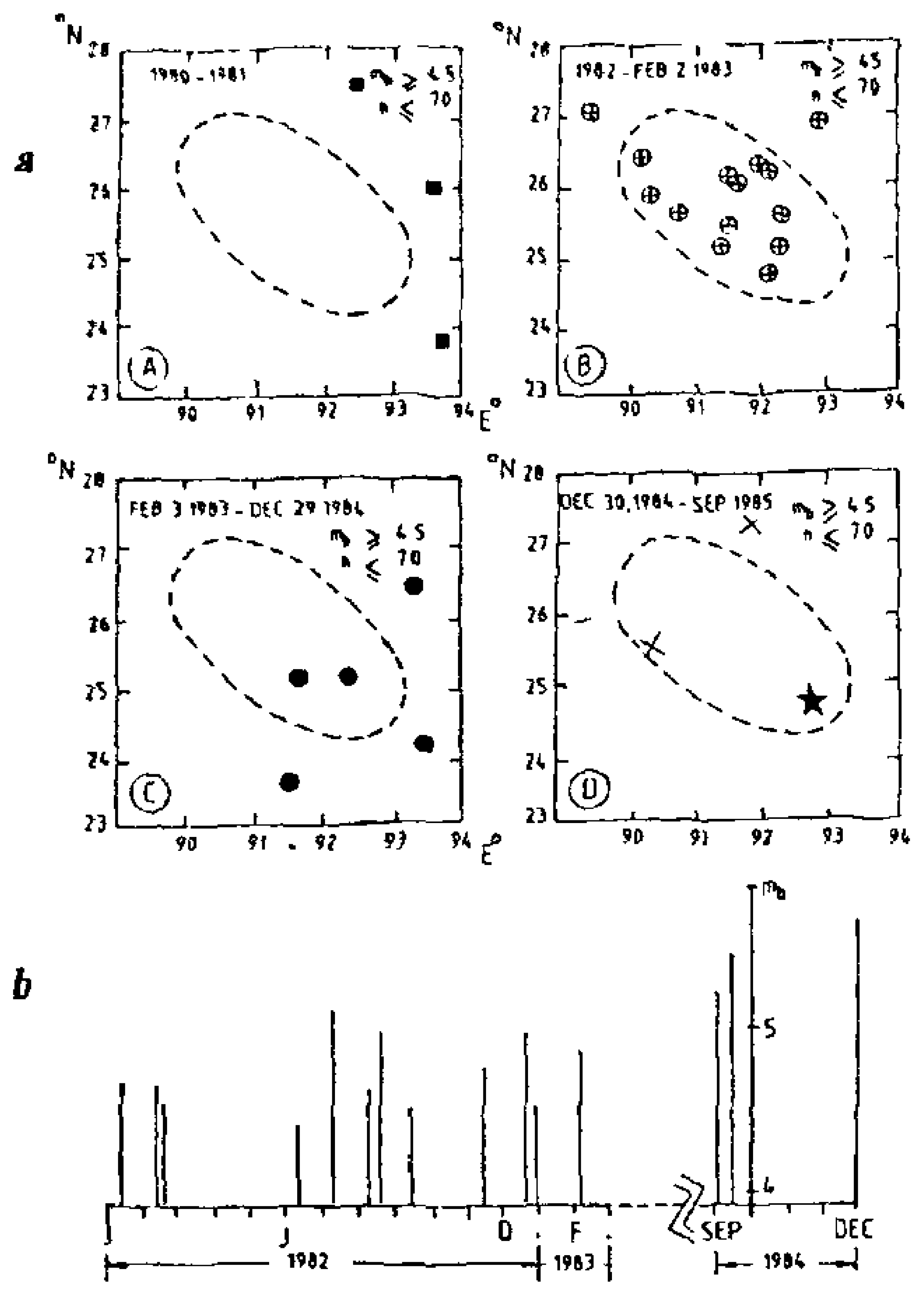

Figure 2. Earthquake of 30 December, 1984 and the associated precursory seismicity patterns. (a) Spatial distribution of epicentres of $m_b \geq 4.5$ and $h < 70$ km. (b) Magnitude correspondence among the precursory swarms events and the mainshock in the elliptical zone. A-Background normal seismicity, B-swarm, C-quiescence, D-main shock (star) and aftershocks (crosses).

the period 3 February, 1983 through 29 December, 1984 (Figure 2 *a*, C). The 30 December, 1984 mainshock was followed by two aftershocks (Figure 2 *a*, D). The mainshock occurred in the well-defined preparation zone demarcated by the earthquake swarm (Figure 2 *a*, B). Figure 2 *b* depicts the temporal distribution and the magnitude of the events occurring within the elliptical zone. It is clearly demonstrated that the Cachar earthquake of 30 December, 1984 was preceded by well-defined epochs of background/normal seismicity, an earthquake swarm and a seismic quiescence.

Earthquakes of $M \geq 7\frac{1}{2}$

Encouraged with the recognition of precursory swarm and quiescence before the 30 December, 1984 Cachar earthquake, Gupta and Singh[1] systematically investigated earthquakes of $M \geq 7\frac{1}{2}$ for possible precursory seismicity patterns. It was felt necessary to critically examine the available data base and prepare an acceptable catalogue free from the problems identified by Gupta *et al.*[23].

Instrumental data for the north-east India region earthquakes are available for the period onward from 1897 (Table 1). The 10 earthquakes of magnitude $\geq 7\frac{1}{2}$ were carefully examined for possible precursory swarms and quiescence[1]. Five among these (i.e. # 1, 5, 6, 8 and 9 in Table 1) are clearly found to be associated with precursory swarm and quiescence epochs. The 1931 earthquake of M 7.6 (Table 1, #7) belonged to the precursory swarm of the M 8.7 earthquake of 1950 (Table 1, #8), and the 1952 earthquake of M 7.5 (Table 1, #10) was an aftershock of 1951 M 8 earthquake (Table 1, #9). Events #2, 3 and 4 occurred in the early part of the century when the location capabilities were very poor. Whether these earthquakes were indeed preceded by swarms and quiescences is difficult to assess. Table 2 gives the relevant information about T_p, M_m, M_p, for $M \geq 7\frac{1}{2}$ earthquakes.

The August 6, 1988 earthquake

Gupta and Singh[1] identified an area in the vicinity of India–Burma border region where four earthquakes of $m_b > 6.1$ had occurred in quick succession in 1964. To examine this swarm, an area bound by 20° and 26° N latitudes, and 92° E and 98° E longitude was tentatively selected, and hypocentral data from 1950 through 1985 were considered. Figure 3 depicts the earthquakes of

Table 1. Earthquakes of $M > 7\frac{1}{2}$ in north-east India since 1897

No.	Date	Epicentre °N	Epicentre °E	Focal depth (km)	Magnitude (M)	Reference set No. in Table 2
1.	12 June, 1897	26	91	60	8.7	1
2.	12 December, 1908	26 6	97.5	–	$7\frac{1}{2}$	–
3.	23 May, 1912	21	97	60	8	–
4	8 July, 1918	24 5	91	–	7.8	–
5.	12 September, 1948	23.5	96	60	$7\frac{3}{4}$	2
6.	29 July, 1947	28.5	94	60	$7\frac{3}{4}$	3
7.	27 January, 1931	25 8	96 8	60	7.6	4
8.	15 August, 1950	28 5	96.5	25	8.7	4
9.	18 November, 1951	31 1	91.4	–	8	5
10.	17 August, 1952	30.5	91.5	60	7.5	5

Table 2. Earthquake sets (see Table 1) associated with $M \geq 7\frac{1}{2}$ earthquakes in north-east India

Set No.	Date of mainshock	Beginning of earthquake swarm activity	Duration for which earthquake data are examined	Study area	Area of preparation zone (approximate)	M_m	T_p	M_p
1.	12 June, 1897	2 May, 1874	1860–1906	24–28° N 89–95° E	1.18×10^5	8.7	8436	7.3
2.	12 Sep, 1946	5 Dec, 1934	1920–1947	21–26° N 92–98° E	7.88×10^4	$7\frac{3}{4}$	4296	7.0
3.	29 July, 1947	11 Feb, 1936	1920–1948	24–29.5° N 88.5–94.5° E	1.33×10^5	$7\frac{3}{4}$	4183	6.6
4.	15 Aug, 1950	30 Jan, 1924	1900–1953	22–33° N 93–100° E	3.70×10^5	8.7	9687	7.3
5.	18 Nov, 1951	14 Dec, 1934	1915–1955	28–33° N 85–93° E	1.67×10^5	8	6210	6.8

T_p = precursory time period (days) calculated from the onset of the swarm until the occurrence of the mainshock; M_m = mainshock magnitude; M_p = average magnitude of the two largest earthquakes in the precursory swarm.

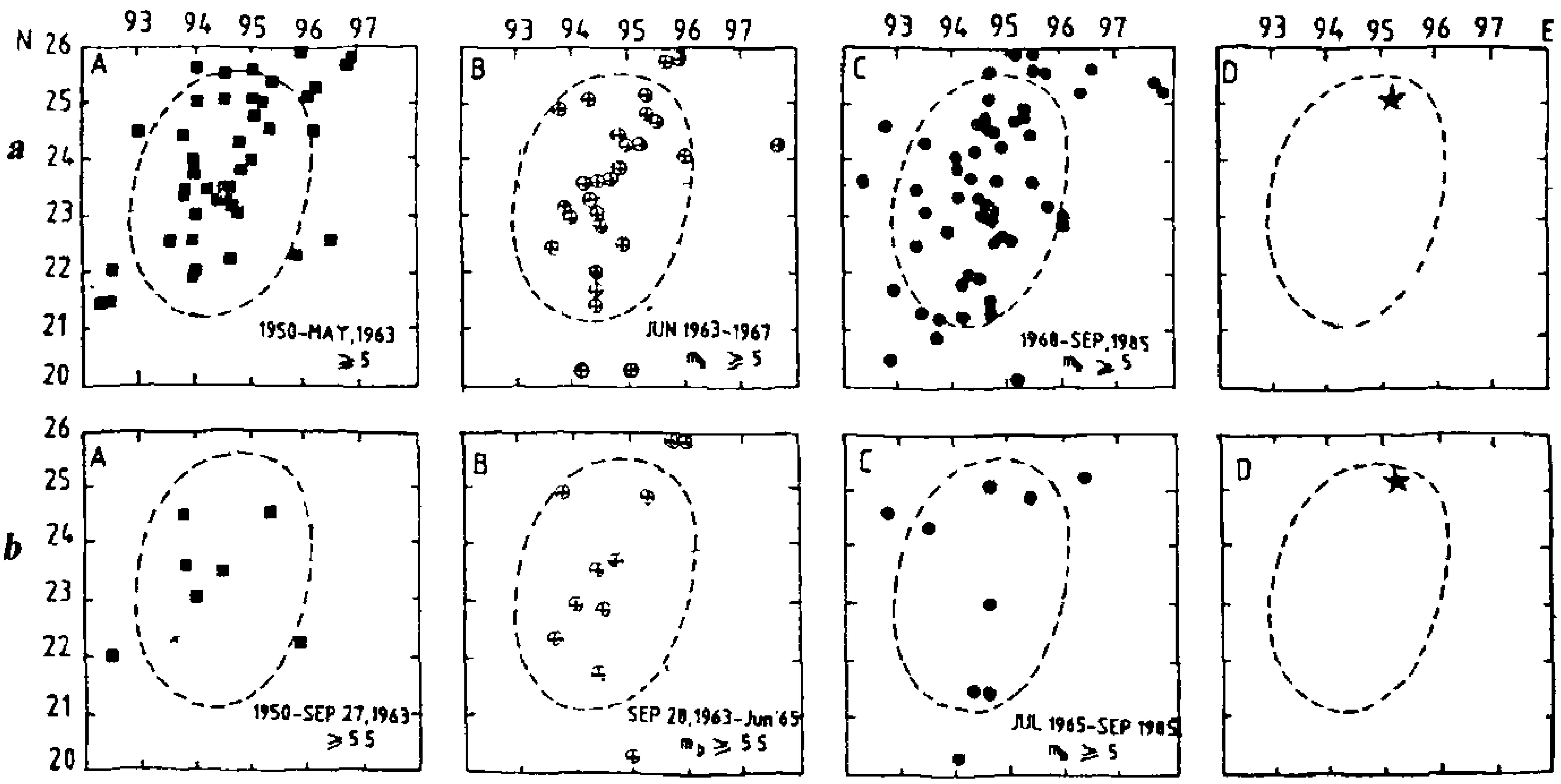

Figure 3. Earthquakes in the vicinity of the India–Burma border for the period 1950 through September, 1985. (**a**) Earthquakes of $m_b \geq 5$. (**b**) Earthquakes of $m_b \geq 5.5$. Epochs of background/normal seismicity (A, solid squares), swarms (B, circle with cross), and quiescence (C, solid circles) are well defined. Earthquake (star) of 6 August, 1988 occurred in the elliptical zone, identified on the basis of precursory swarms (Gupta and Singh[1]).

$m_b \geq 5.0$ and 5.5, where epochs of background, swarm and quiescence seismic activity are well defined. For example, the annual frequency of $m_b \geq 5.5$ events within the elliptical zone is found to be 0.4, 4.4 and 0.3 during the epochs of normal/background, swarm and quiescence seismic activity respectively (Table 3). An elliptical area of about 130,000 km^2 was tentatively delimited as the preparation zone for the future earthquake on the basis of the spatial distribution of swarm events. It was noted that since the occurrence of

Table 3. Seismic activity in the elliptical preparation zone (Figure 3) for a possible future earthquake for events of $M \geq 5.5$ (Gupta and Singh[21])

Particulars	Background	Swarm	Quiescence
Duration	1950 Sept, 1963	Oct 1963 June 1965	July 1965 Sept 1985
No. of events	5	8	6
Annual frequency	0.4	4.4	0.3

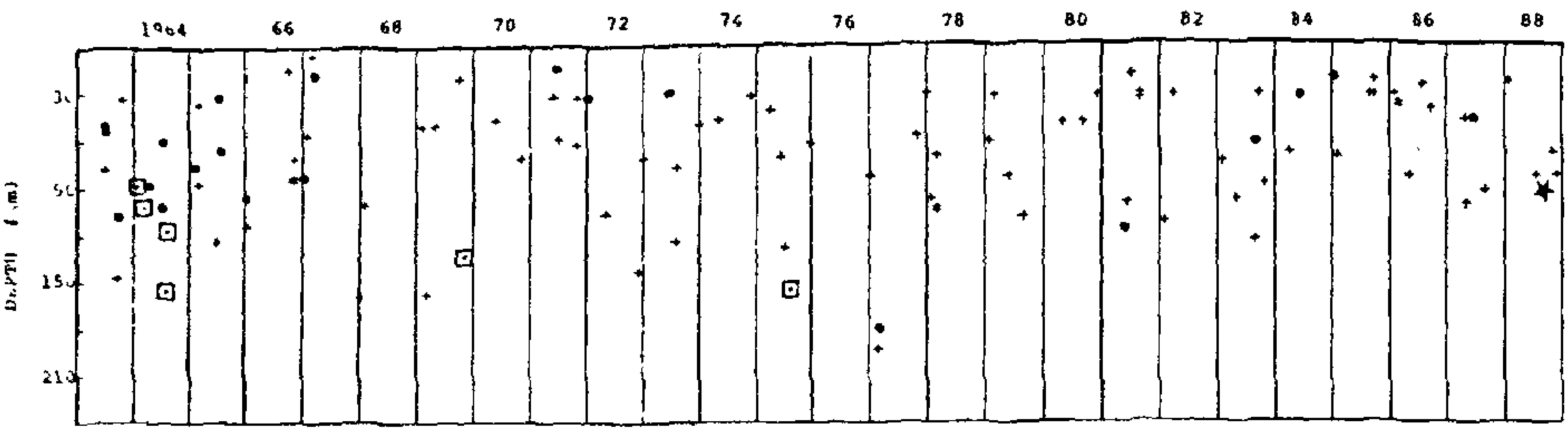

Figure 4. Temporal and depth distribution of earthquakes within the elliptical preparation zone of 1988 earthquake, $m_b = 5.0$–5.4 (+ sign), $m_b = 5.5$–5.9 (filled circle), $m_b \geq 6$ (square with a dot) and 6 August, 1988 earthquake (star).

the swarm some 23 years had passed. The M_p value for swarm was 6.6. Using these parameters, a forecast for a major event, as per the parameters of Table 4 was made. A focal depth of 100 $\pm$40 km was estimated on the basis of focal depth of the swarm events. The T_p for $M \geq 7\frac{1}{2}$ events varied from 11 to 27 years. The two great earthquakes had T_p of 23 and 27 years. It was, therefore, estimated that the forecast will be valid till the end of 1990 (27 years after the initiation of the swarm). Occurrence of the 6 August, 1988 earthquake has made this medium term forecast true (Table 4).

Short-term seismicity patterns

After the occurrence of the 6 August, 1988 earthquake, a search was made for the possible short-term seismicity pattern precursors. However, none was found, either in terms of increase of seismic activity, or clustering in the preparation zone. Figure 4 depicts the temporal and depth distribution of the seismic activity within the elliptical preparation zone (Figure 3) of the 1988 earthquake. While the precursory swarm (1963 through 1965) can easily be detected, there is no specific change in the seismicity characteristics before the 1988 earthquake. The annual frequency of earthquakes also did not change from the quiescence period, which remained 0.3 for earthquakes of $m_b \geq 5.5$ during quiescence (Table 3). For three years from September 1985 till 6 August, 1988, only one earthquake of $m_b > 5.5$ occurred in the preparation zone, giving an annual frequency similar to the quiescence period.

Conclusion

Several shortcomings are pointed out by Gupta and Singh[1] in their analysis. No rigorous criteria have been formulated by them for identification of background

Table 4. Forecast of 6 August, 1988 earthquake

Earthquake	Forecast	Occurrence
Parameters	(Gupta and Singh[1])	NEIS (preliminary determination)
Epicentre	21° N to $23\frac{1}{2}$° N 93° E to 96° E	25.149° N 95.12° E
Magnitude (M)	$8 \pm \frac{1}{2}$	7.3
Depth	100 ± 40 km	90.5 km
Time	February 1986 to December 1990	6 August 1988 (00.36.26.9 GCT)

seismicity, swarm and quiescence. This was also a singular forecast. However, it needs to be mentioned that the 6 August, 1988 event of M 7.3 occurred some 31 years after the last comparable event of 1 July, 1957 with a magnitude $M\, 7\frac{1}{4}$ in the entire region bound by 20° N and 30° N latitudes, and 87° E and 100° E longitudes. We also note that this is the first medium term forecast for an intermediate focus earthquake that has come true.

Ideally, several geographical locations, globally, which have had intense seismic activity in the past, need to be similarly investigated for identification of seismicity patterns. In the Himalayan frontal arc, several areas have been identified (for example, Khattri[24]) with high probability of occurrence of a major earthquake. It will be useful to investigate the past major earthquakes in these areas for possible precursory seismicity patterns.

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Upper Pliocene-Quaternary vertebrate communities of the Karewas and Siwaliks

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The Karewa and Upper Siwalik fossil assemblages are of mixed types and include populations derived from different communities. The upland community is better represented in the Karewas while the aquatic community characterizes the Upper Siwalik assemblage. It is suggested that the Karewa fauna has European affinities, while the Upper Siwalik fauna has close relationship to Africa.

Introduction

THE Upper Pliocene-Pleistocene non-marine deposits occur in various tectonic settings in NW India, particularly in the submontane Siwalik and in the Himalayan intermontane basins. This paper deals with only the uppermost Pliocene and Pleistocene deposits of the intermontane Karewas of Kashmir and submontane Siwaliks, highlighting biotic similarities, affinities and differences, with a view to assessing the influence of climatic conditions in NW India.

The initiation of the Pleistocene is marked by a global event recorded by microfaunal data in deep-sea sediments and supported by palaeomagnetism, terrestrial vertebrates and evidence for climatic oscillations. Although it is difficult to evolve uniform faunal criteria for boundary demarcation applicable to both marine and continental sequences, this event is considered to have taken place at the Olduvai normal sub-chron (1.8–1.6 m.y. B.P.). This event in India is correlated with the cold (glacial) period[1] and occurrence of Holarctic arvicolid rodents[2,3] in the Karewas, and with the tectonic activity in the Main Boundary Thrust zone that was precursor to the major upliftment of the Pir Panjal Range. As a consequence of uplift there was cessation of intermontane sedimentation at about 1.7 m.y. (ref. 4) and commencement of emplacement of the Boulder Conglomerate in the Siwalik[5] around 1.7 m.y. (ref. 6). In the Siwaliks of northern Pakistan, the first occurrence of conglomerates is observed at the Olduvai sub-chron[7]. All these dates coincide well with the Plio-Pleistocene boundary at the Olduvai event[8].

The Late Cenozoic non-marine sediments of India particularly the Siwalik and the Karewas are crucial to the understanding of the ongoing sedimentation and biotic development in the Indo-Gangetic Plain. Although the Siwaliks have now been studied for more than 150 years, it is only recently that a chronological time framework has been established for the Siwalik of Pakistan, India and Nepal[7,9–14], with the advent of magnetic polarity time scale (MPTS) and micromammalian biostratigraphy. In the lacustrine basins such as the Karewas, magnetic and faunistic correlation offers high degree of precision in building up the strati-