EARTHQUAKE PREDICTION RELATED STUDIES IN INDIA

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ABSTRACT – *An earthquake is one of the worst of natural calamities. Internationally, serious and scientifically acceptable earthquake prediction studies started only about three decades ago. 'Short Term' prediction of the Heicheng earthquake of February 4, 1975 in China is a land mark. No acceptable short term predictions have yet been made in India. A medium term prediction made for a major earthquake in the vicinity of Indo-Burma border region in 1986 has come true. A number of studies, relevant to earthquake precursors have been reported by Indian scientists which are reviewed in this paper. Prediction of possible earthquake hazards and suggesting ways and means to mitigate the same, particularly in the Indian part of the Alpide seismic belt, is an important area which deserves special attention.*

INTRODUCTION

Among the natural calamities earthquake is one of the worst. having claimed an estimated 50 million human lives and inflicted damage worth hundreds of billions of dollars in recorded history. The July 27, 1976 Tangshan earthquake in China claimed 5,00,000 lives[1]. The October 18, 1989 Loma Prieta earthquake of magnitude 7.3 in California is estimated to be the most expensive natural disaster[2], costing some 6 billion dollars.

The first scientifically well-documented earthquake prediction was made on the bases of temporal and spatial variation of ts/tp relation in the Blue Mountain Lake, New York area by Aggarwal *et al.*[3]. Sino-seismologists successfully predicted the Heicheng earthquake of February 4, 1975 of magnitude 7.3 and saved an estimated 1,00,000 human lives, as documented by Cha Chi-Yuan[4], and raised the hopes that through a multi-disciplinary approach it should be possible to make reliable earthquake forecasts. The Sino-seismologists had narrowed down from a 'long term' prediction lasting several years to 'medium term' and then to the 'short term' prediction (immediately prior to the earthquake).

It is not uncommon for individuals to issue [illegible]ted earthquake forecasts, without giving the scientific basis of prediction and the necessary parameters of the event forecasted. Following is the definition given by U.S. National Academy of Sciences:[5] "An earthquake prediction must specify the expected magnitude range, the geographical area within which it will occur, and the time interval within which it will happen, with sufficient accuracy so that the ultimate success or failure of the prediction can be easily judged. Only by careful recording of failures as well as successes can the eventual success of total efforts be evaluated and total efforts charted. Moreover, scientists should also assign a confidence level to each prediction .... even low confidence predictions should be considered and evaluated".

Although earthquake prediction has been taken up seriously only some three decades ago, a suite of excellent books and review articles have appeared dealing with the techniques of earthquake prediction.[6–12] The scope of the present article does not permit to comment on these works. In [illegible], not much earthquake prediction related work [illegible] carried out. No scientifically acceptable [illegible], which are necessary to understand the earthquake processes and possible precursors have been reported. A 'medi[illegible] term' forecast for the north-east India region[13] of a 8 ± [illegible] magnitude earthquake reported internationally in [illegible] materialized in 1988. These efforts are briefly reviewed in this paper.

UNIQUENESS OF INDIAN SEISMICITY

There are at least two features which are unique to India, as far as earthquakes are concerned. Firstly, the Himalayan frontal arc, flanked by the Arakan Yoma fold belt in the east and the Chaman fault in the west constitutes seismically one of the most active intra-continental regions in the world. Four earthquakes exceeding magnitude 8 occurred in a short span of 53 years. These are the Assam earthquakes of 1897 and 1950, the Kangra earthquake of 1905 and the Bihar–Nepal earthquake of 1935. Figure 1, updated from Chandra[16], shows earthquakes of $M \geq 7$ and the ones that claimed human lives along the Himalayan frontal arc. Secondly, the site of reservoir induced earthquakes in the vicinity of the Koyna Dam in Maharashtra had the largest reservoir induced earthquake of magnitude 6.3 on December 10, 1967. The reservoir induced earthquakes have continued to occur in the vicinity of the Koyna Dam since 1962. We shall deal with earthquake prediction related studies for these two areas separately.

EARTHQUAKE PREDICTION STUDIES

One of the earliest earthquake prediction related studies is by Khazanchi and Dutta[17] where they statistically estimated the return periods of large magnitude earthquakes in the north-east India region. A symposium organized by the India Meteorological Department[18] in 1978 reviewed the earthquake prediction related work. Another symposium held a few years back reviewed the more recent work as compiled by Guha and Patwardhan[19]. The work carried out so far could broadly be classified under the technique of spatio-temporal variation by seismicity[20–26]; microearthquakes[27–33]; earthquake frequency-magnitude relation[34–36]; statistical methods using earthquake catalogues[37,38]; teleseismic P-wave travel time delays[39,40]; geodetic and levelling measurements[41]; radon emission anomalies[42–45]; variations in the geomagnetic and geoelectric fields[46,47]; resistivity[30]; and animal behaviour[48].

The above list is not exhaustive and some papers may not have been included. It would not be possible

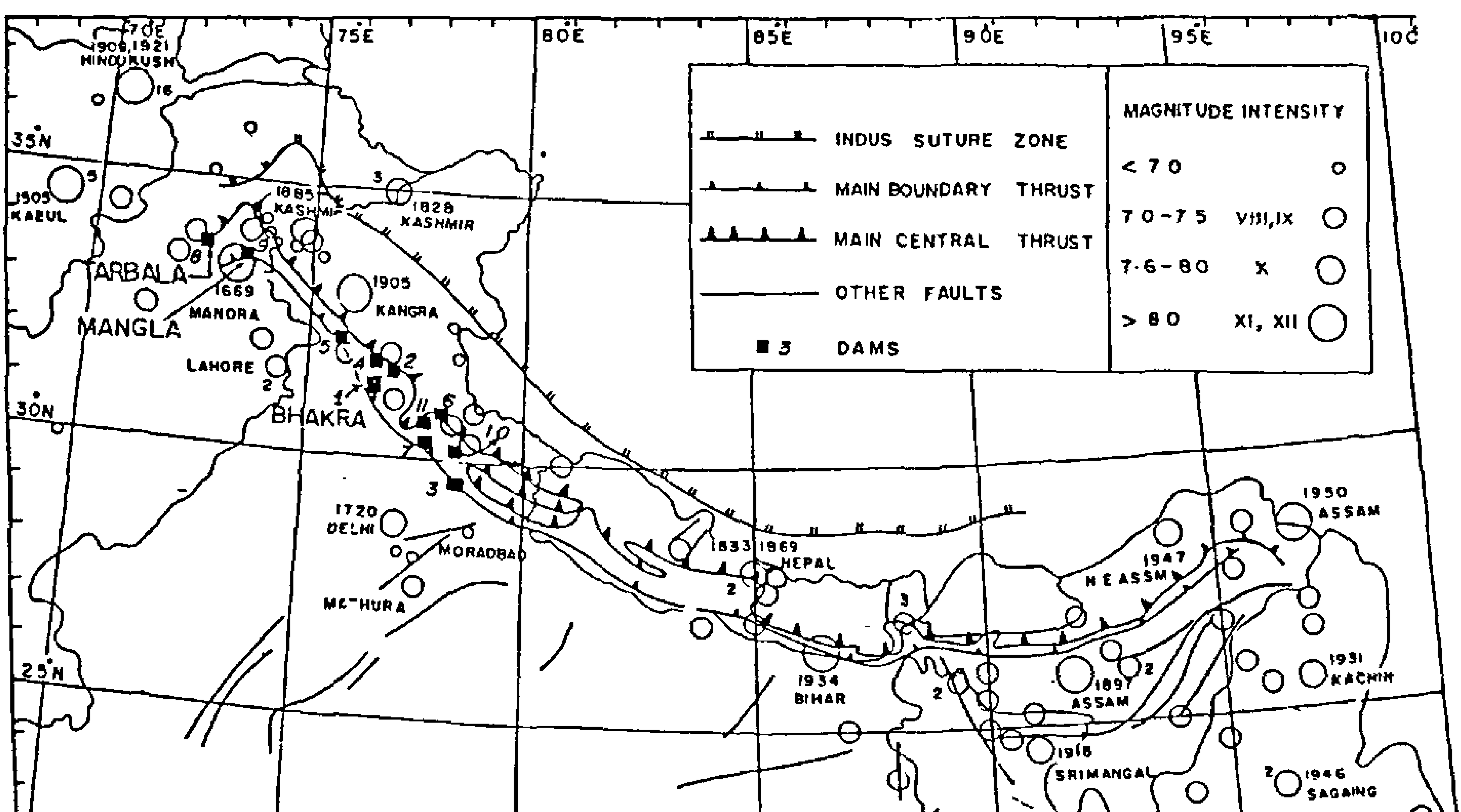

FIGURE 1 An epicentral map of the Himalayan part of the Alpide seismic belt and the vicinity showing earthquakes of $M \geq 7.0$ and the ones that claimed human lives (updated from Chandra[16]).

to discuss the merits and limitations of these investigations in this paper. However, the above list does demonstrate that some initial work related to possible precursors has been initiated.

THE HIMALAYAN FRONTAL ARC

For long term prediction of great earthquakes and identification of possible gap areas, it is useful to develop a suitable model for the region. From among the models available, we prefer the one developed by Seeber and Ambruster[49] for the Himalayan frontal arc. Structurally the continental subduction along the Himalayan frontal arc is similar to the oceanic lithospheric subduction along the areas. Therefore, Seeber and Ambruster[49] argue that the concept of earthquake gaps should hold good for this region. In both cases the detachment is ruptured by great earthquakes. It is estimated that out of a total length of about 1700 km of the Himalayan frontal arc, some 1400 km has been broken during the last four great earthquakes of 1897, 1905, 1934 and 1950. Now a portion of about 300 km length is left to be broken in a future earthquake (figure 2). During the period before the 1897 earthquake in the nineteenth century, there were probably three great earthquakes, i.e. the 1803 earthquake in Uttar Pradesh, the 1833 earthquake in western Bihar and the 1885 earthquake in Kashmir. From the available information, it is difficult to estimate the length of tne portions of the Himalayan frontal arc broken by these earthquakes. However, looking at the distribution of the past 7 great earthquakes, one could infer that the unruptured gaps exist between the 1803 and the, 1833 earthquakes in Uttar Pradesh and between 1885 and 1905 ruptures in Kashmir. Seeber and Ambruster[49] also infer that the entire Himalayan frontal arc detachment will rupture in 180 to 240 years and the repeat time of a typical 300 km rupture for a magnitude 8 earthquake would be by 200–270 years. It should however be pointed out that different estimates exist. For example, the 300 km long rupture inferred by Seeber and Ambruster for the 1934 Bihar–Nepal earthquake is much longer than the estimated 130 km long rupture by Singh and Gupta[50] obtained from the spectral ratio of the surface waves travelling in opposite direction from the rupture. Nonetheless, Seeber and Ambruster[49] provide a good working model for future work.

Major earthquakes in the north-east India region are found to be preceeded by quiescence. Khattri and Wyss[20] have identified a seismic gap between the meizoseismal areas of the great earthquakes of 1897 and 1950, which could be the site of a major earthquake (figure 3). However Seeber and Ambruster[49] are of the opinion that the 100 km long gap between the ruptures of the 1897 and 1950 earthquakes may have been filled by the 1943 and 1947 earthquakes of M = 7 1/4 and 7 3/4 respectively.

A seismicity gap has been identified in the Himachal

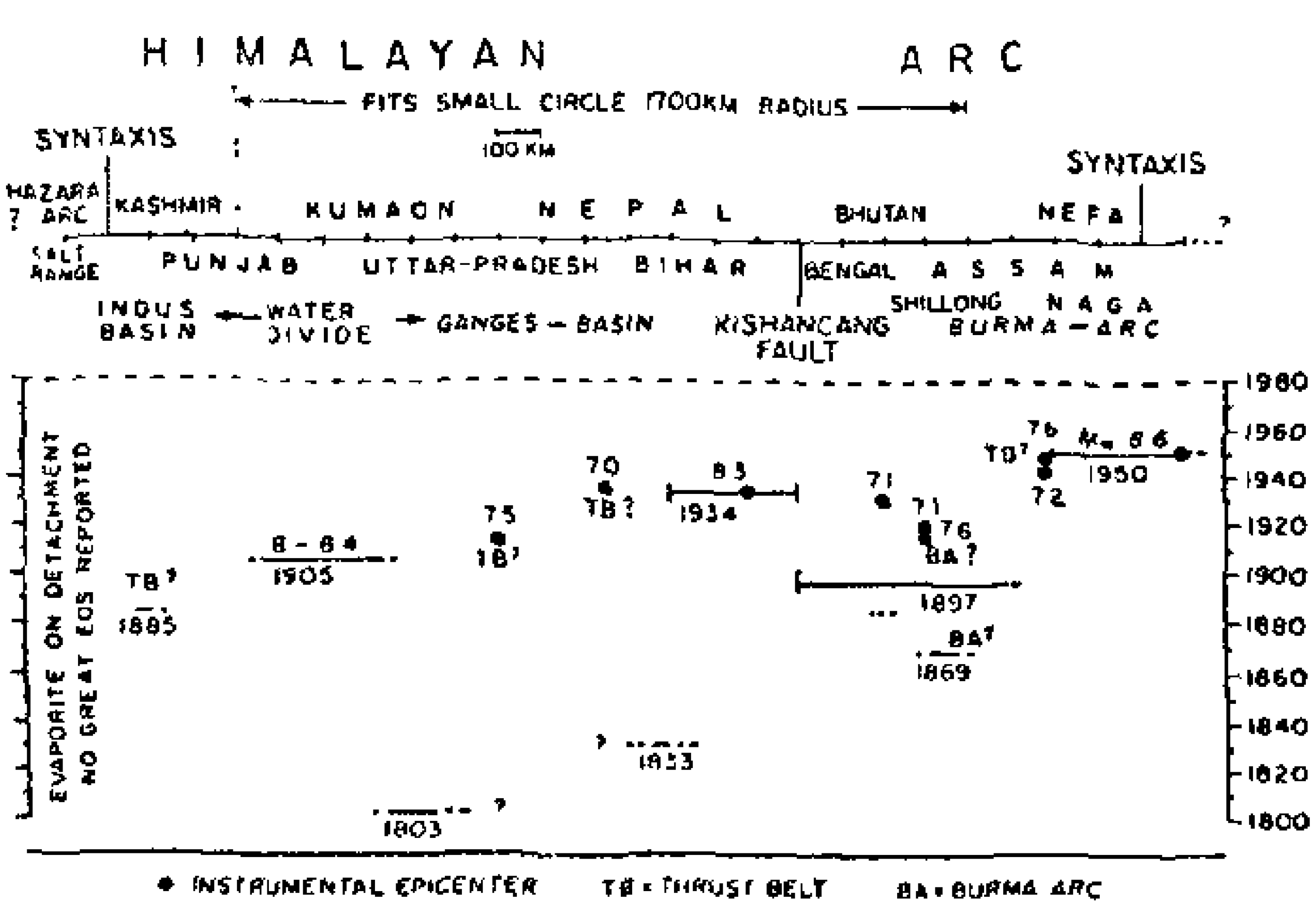

FIGURE 2 Space-time diagram of detachment ruptures in the Himalayan arc since 1800 (after Seeber and Ambruster[49]). The data before 1897 may be imcomplete. The most likely gaps unruptured since 1800 are in Kashmir and in Uttar Pradesh, between the 1833 and 1803 ruptures. The gap between the 1897 and 1950 ruptures was probably filled by the 1943 and 1947 earthquakes. If the 1833 and 1803 ruptures abut, the entire Himalayan detachment, excluding Hazara and Kashmir where aseismic slip may play an important role, has probably ruptured since 1800.

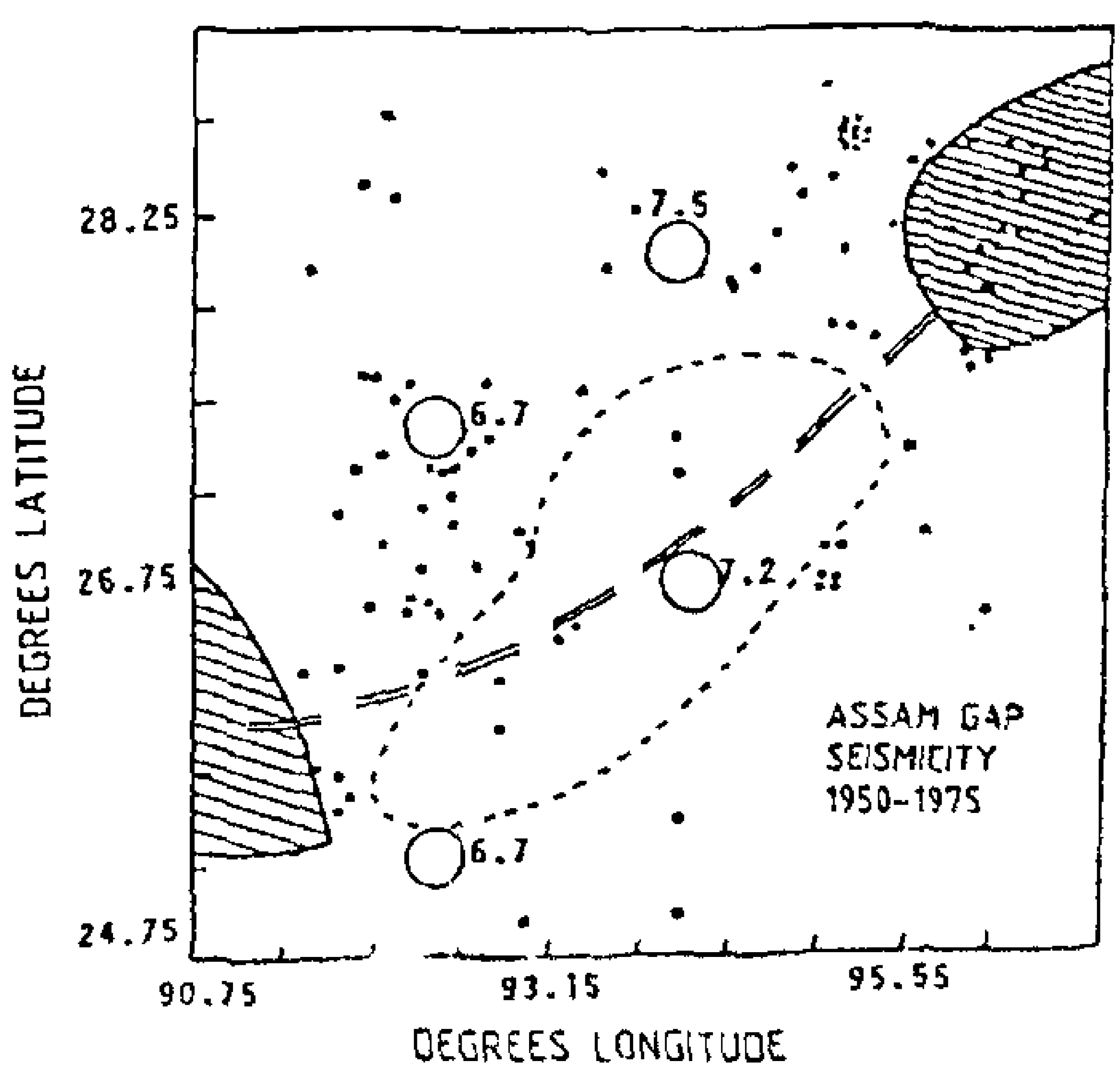

FIGURE 3 Bounded by the meizoseismal areas of 1897 and 1950 great earthquakes of northeast India, both of M 8.7, the Assam Gap is the area within dotted lines identified by Khattri and Wyss[20].

Himalaya by Srivastava and Chaudhury[21]. This gap also shows up in a well-constrained microseismicity survey for the period 1981–1984 (figure 4). However, *Srivastava*[24] *is of the opinion that in view of the lack of* historical data and other pertinent geophysical information the parameters of the impending earthquake cannot be forecasted.

Medium term forecast in the India–Burma Border region

North-east India is seismically a very active region where ten earthquakes of $M \geq 7\ 1/2$ have occurred since 1897. Gupta and Singh[13,14] systematically examined these ten earthquakes (figure 5) for possible precursory swarm and quiescences following Evison's[51,52] method. The earthquake data sets had been critically examined for completeness[53]. They found that the mainshock magnitude (M_m) has a correspondence with the largest events (M_p) in the swarm and the time interval (T_p) between the onset of the swarm and occurrence of the mainshock in days. The following regression equations were found:

$$M_m = 1.37\ M_p - 1.41 \text{ and}$$
$$M_m = 3\ \text{long}_{10}\ T_p - 3.27$$

Gupta and Singh[13] pointed out that it is important to recognize the swarm and quiescences before the occurrence of the main shock and reported that they have recognized one such region in the vicinity of the India–Burma border region. Their conclusions were;

- Moderate magnitude to great earthquakes in the north-east India are found to be preceded, by well-defined earthquake swarms and quiescence periods.
- On the basis of an earthquake swarm and quiescence period, an area bound by 21°N and 25 1/2°N latitude and 93°E longitude is identified to be the site of a possible future earthquake of $M\ 8 \pm 1/2$ with a focal depth of 100 ± 40 km. This earthquake should occur any time from now onwards. Should it not occur

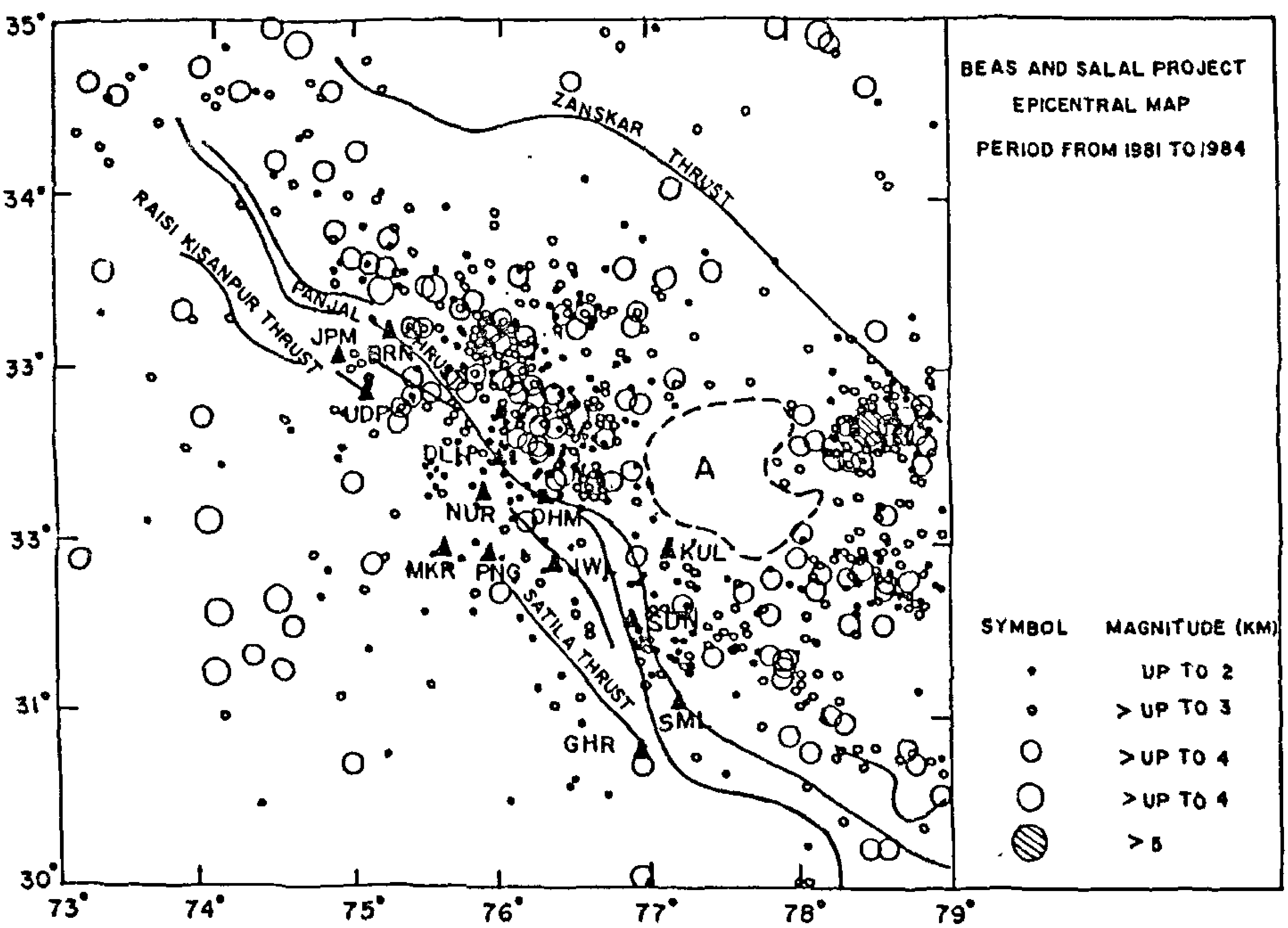

FIGURE 4 Seismic gap in Himachal Himalaya on the basis of meizoseismicity survey for the period 1981–84 after Srivastava *et al.*[34].

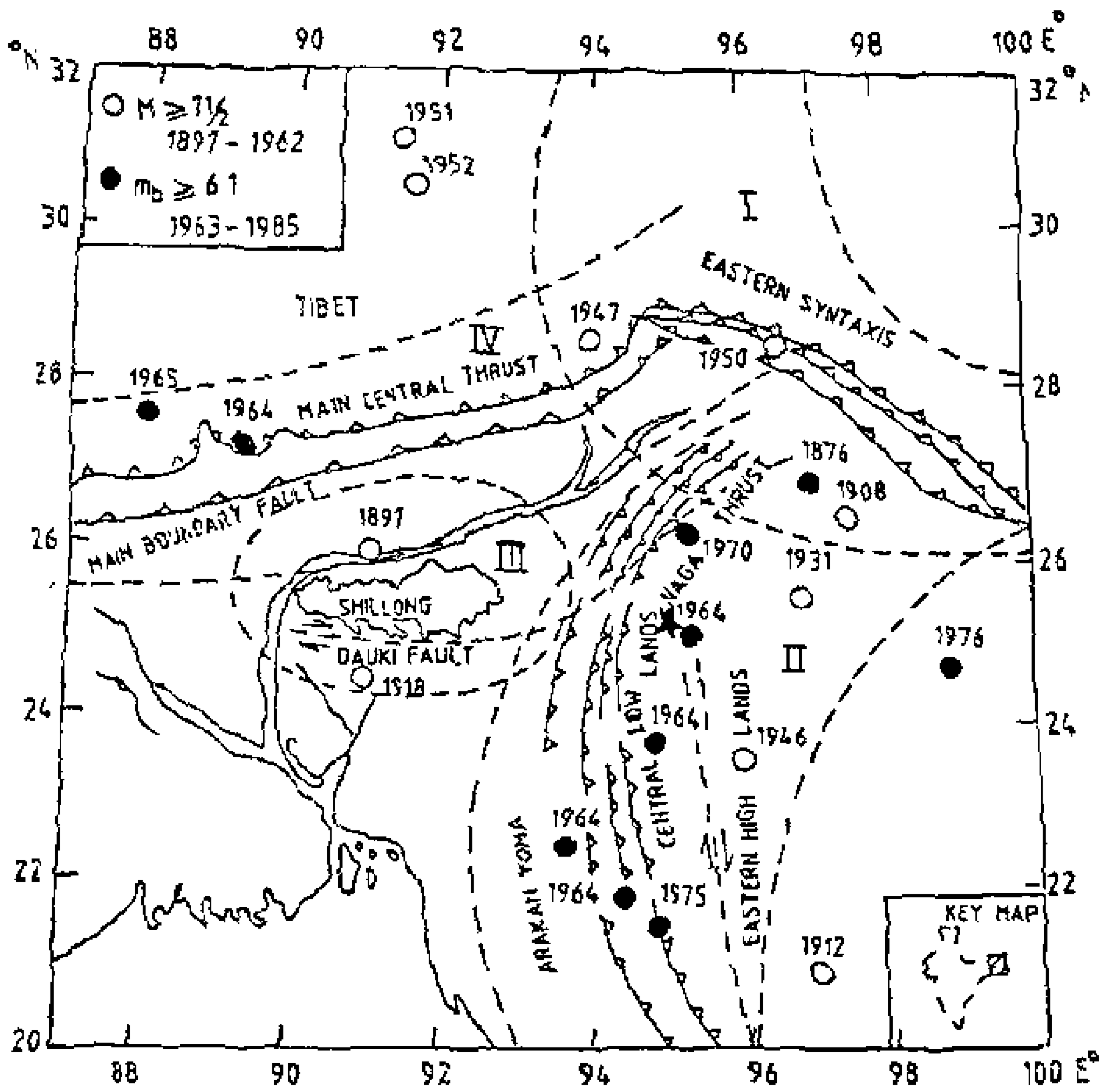

FIGURE 5 Epicentres of earthquakes of $M \geq 7\frac{1}{2}$ for the period 1897–1962 (open circles) and $m_b \geq 6.1$ for the period 1963–1985 (solid circles) in the northeast India region (Adapted from Gupta and Singh[13]). Star: epicentre of M 7.3, August 6, 1988, earthquake.

till the end of 1990, this forecast could be considered as a false alarm.

Gupta and Singh[13,14] have pointed out several shortcomings in their analysis. For example, they have not formulated rigorous criteria for identification of background seismicity, swarm and quiescence. Another problem is the forecast being singular. Ideally, several such locations should be globally identified. Occurrence of the 7.3 magnitude earthquake on August 6, 1988 (figure 6, table 1) has fulfilled this forecast. It should be noted that the August 6, 1988 event ocurred some 31 years after the last comparable event in the entire region bound by 20°N and 32°N latitudes, and 87°E and 100°E longitudes (figure 5). The past comparable event occurred on July 1, 1957 with a magnitude of 7 1/4. We also believe that this is the first medium term forecast for an intermediate focus earthquake which has come true.

Reservoir induced seismicity at Koyna

The Koyna Dam site in Maharashtra is world-known for reservoir-induced earthquakes. So far, the largest known reservoir-induced earthquake occurred at Koyna on December 10, 1967 (Guha *et al.*[54]). It had a

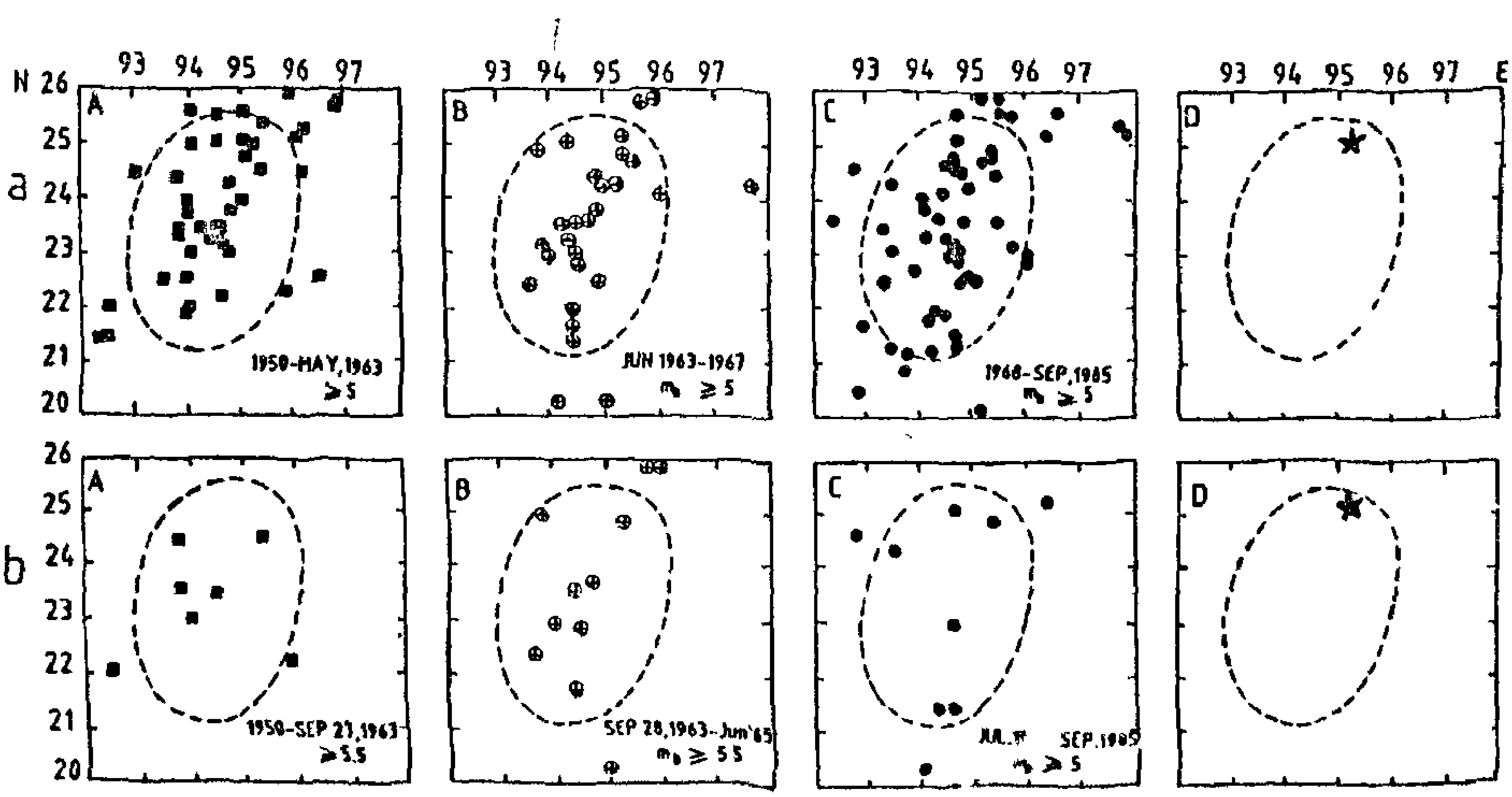

FIGURE 6 Earthquakes in the vicinity of India–Burma border region. Earthquake data from 1950 through September 1985 are presented for (a) earthquakes of $m_b \geq 5.0$ and (b) earthquakes of $m_b \geq 5.5$. The epochs of background/normal seismicity (A, solid squares); swarm (B), circle with cross), and quiescence (C, solid circle) are well identified. The August 6, 1988, earthquake (star) occurred in the elliptical zone of preparation for a future earthquake delimited by Gupta and Singh[13].

TABLE 1 Predicted and actual occurrence focal parameters of the India–Burma border region earthquake.

Earthquake parameters	Forecast (Gupta and Singh 1986)	Occurrence NEIS (preliminary determination)
Epicentre	21°N to 25 1/2°N 93°E to 96°E	25.149°N 95.127°E
Magnitude	8 ± 1/2	7.3
Depth	100 ± 40 km	90.5 km
Time	February 1986 to December 1990	August 6, 1988 (00:36:26.9 G.C.T)

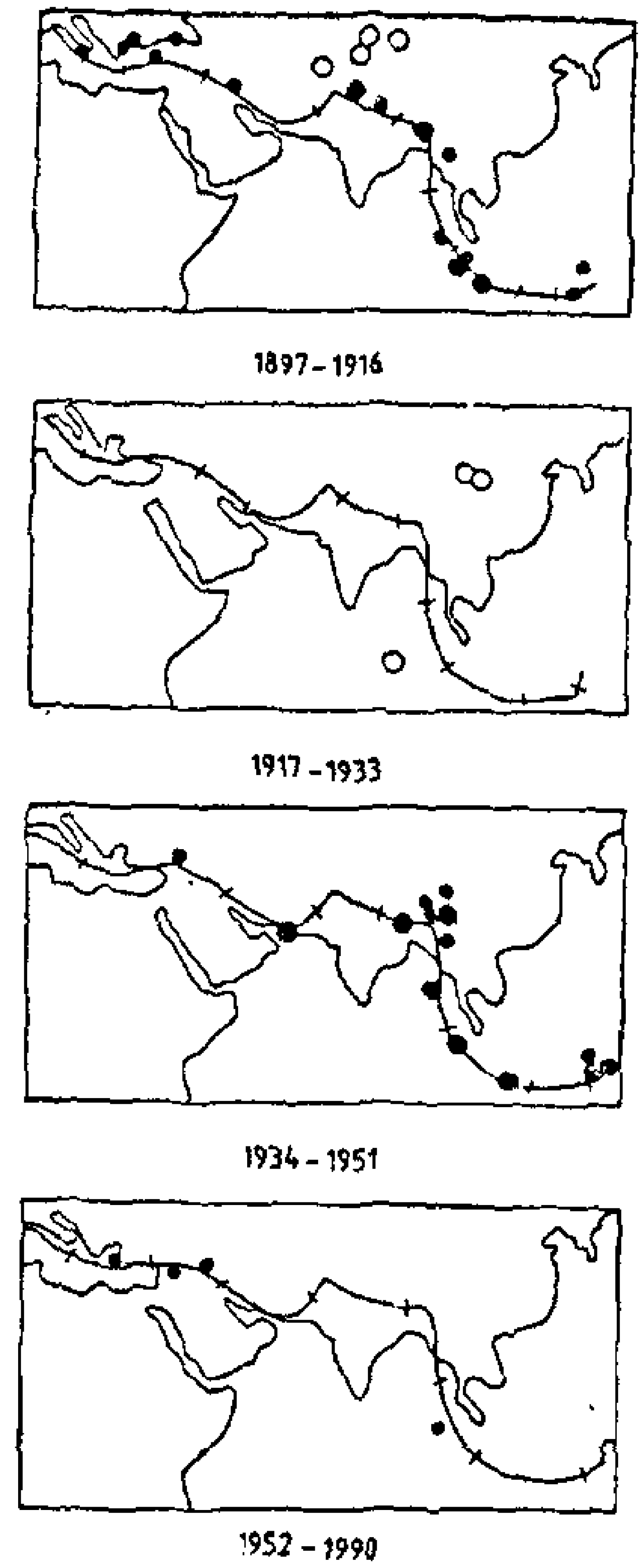

FIGURE 7 Seismicity cycles in the Alpide belt from 1897 to 1986 for shallow earthquakes of focal depth *100 km and M ≥ 7.7. Large solid* and hollow circles indicate earthquakes of M ≥ 8.0 and small hollow and solid circles are 7.7 ≤ M < 8.0. Solid circles indicate earthquakes located far away from the belt (modified from Hamada[61]), after Gupta[25].

magnitude of 6.3 and it claimed over 200 human lives. Earthquakes exceeding magnitude 5 occurred in November 1973 and September 1980. The region continues to be seismically active.

Reservoir-induced seismicity, globally, seems to be dependent on rate of loading, highest reservoir levels reached and the duration for which the high levels are retained[55–57]. As far as the Koyna region is concerned, Gupta[58] has shown that earthquakes of magnitude 5 and more occurred only when the rate of loading exceeded 40 ft/week. However, this condition is necessary but not sufficient. In another interesting study, Gupta and Iyer[59] showed that there appears to be a high probability of occurrence of a magnitude 5 earthquake when two foreshocks of magnitude ≥ 4.0 occur within a fortnight. Other precursory phenomena such as changes in 'b' values, seismic wave velocity anomaly, tilt etc. before significant earthquakes in the Koyna region has been reported by Padale *et al.*[60].

CONCLUDING REMARKS

Earthquake prediction related work has just started in India. A survey of the same has been presented in this paper. Most of the work, so far, is hind sight where a search of precursors is made after the earthquake has occurred. One medium term forecast has come true. This success should provide impetus to carry out similar work elsewhere.

Certain cycles of low and high seismicity appear to characterise the Alpide belt. For example 1897–1916 and 1934–1951 periods were of high seismicity, whereas 1917–1933 and 1952–1990 have been periods of low seismicity. In figure 7, updated from Hamada[61], earthquakes of M ≥ 7.7 in the vicinity of the Alpide belt are plotted. The low seismicity phase that started in 1952 is still continuing. Several major civil structures have been constructed after independence in the vicinity of the Alpide belt. Non-occurrence of a major earthquake over the past four decades has generated a false sense of security. The great Kangra earthquake of 1905 had claimed 20,000 human lives and had caused widespread damage. According to a damage scenario developed by Arya[62], if this earthquake were to repeat today, the range of the human lives lost will be between 88,000 and 3,44,000 depending upon the time of day and the season when it occurs. Prediction of possible earthquake hazards and suggesting ways and means to mitigate the same is an important area where much more work needs to be done.

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