1. Woodward, R B and Hoffmann, R, *The Conservation of Orbital Symmetry*, Verlag Chemie, Weinheim/Academic Press, New York, 1970
2. Paquette, L. A, *Angew Chem. Int. Ed. Engl*, 1990, **29**, 609–626
3. Berson, J A, Jones, M and Jones, M Jr., *J. Am. Chem Soc*, 1964, **86**, 5017–5020.
4. Evans, D A. and Golob, A. M., *J. Am. Chem Soc.*, 1975, **97**, 4765–4766.
5. Dewar, M J. S and Xie, C., *J. Am Chem Soc.*, 1987, **109**, 5893–5900.
6. Mehta, G, Azario, P., Barone, R. and Chanon, M., *Tetrahedron*, 1989, **45**, 1985–1994
7. Paquette, L. A, He, W and Rogers, R. D., *J. Org Chem.*, 1989, **54**, 2291–2300
8. Paquette, L A., DeRussy, D. T. and Gallucci, J. C., *J. Org Chem*, 1989, **54**, 2278–2291.
9. Paquette, L. A, DeRussy, D. T. and Cottrell, C. E., *J. Am. Chem Soc*, 1988, **110**, 890–896
10. Cieplak, A. S, *J. Am Chem. Soc.*, 1981, **103**, 4540–4552
11. Marvell, E. N and Whalley, W., *Tetrahedron Lett.*, 1970, **11**, 509–512.
12. Macdonald, T. L., Natalie, K. J., Jr., Prasad, G. and Sawyer, J. S, *J Org Chem*, 1986, **51**, 1124–1126.
13. Schreiber, S. L. and Santini, C., *Tetrahedron Lett*, 1981, **22**, 4651–4654
14. Still, W C., *J. Am Chem Soc.*, 1977, **99**, 4186–4187.
15. Kuwahara, S. and Morie, K., *Heterocycles*, 1989, **28**, 167–170.
16. Ganesh Raj, S. P., Janardhanan, S. and Rajagopalan, K., *Synth Commun.*, 1989, **19**, 1341–1346.
17. Swaminathan, S., Srinivasan, K. G. and Venkataramani, P. S, *Tetrahedron*, 1970, **26**, 1453–1461.
18. Uma, R, Rajagopalan, K. and Swaminathan, S., *Tetrahedron*, 1986, **42**, 2757–2769.
19. Gadwood, R. C. and Lett, R. M, *J Org. Chem.*, 1982, **47**, 2268–2275.
20. Gadwood, R. C., Lett, R M. and Wissinger, J. E., *J. Am Chem Soc.*, 1986, **108**, 6343–6350
21. Koto, T., Kondo, H., Nishino, M, Tanaka, M, Hata, G. and Miyake, A., *Bull. Chem. Soc. Jpn.*, 1980, **53**, 2958–2961.
22. Rhoads, S. J. and Raulins, N. R., *Org React. (NY)*, 1975, **22**, 63.
23. Geetha, P., Hug, C. A. M. A, Rajagopalan, K. and Swaminathan, S., *Tetrahedron Lett.*, 1982, **23**, 569–570.

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RESEARCH ARTICLE

A study of seismicity of Northeast India and adjoining areas based on statistical analyses

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Seismicity data from 1912 to 1977 of northeast India (18°N to 32°N and 84°E to 100°E) for large earthquakes with magnitude $M \geq 6.0$ have been used to discuss seismicity variation by stationary model of seismicity rates and seismic energy released during three-year intervals. Seismicity rates vary from 0.73 to 2.15 events/year. Seismicity data of 66 years show that earthquake occurrence follows Poisson distribution. The time series of considered events for different range of magnitude consists of random ($6.0 \leq M \leq 7.8$) and non-random ($7.9 \leq M \leq 8.7$) shocks.

SEISMICITY data have been statistically analysed by several earlier researchers to study seismic quiescence, seismicity rates and seismicity fluctuations before the occurrences of medium to large earthquakes[1-6]. Based on statistical calculation of seismicity data, the Mexico earthquake of Central America was predicted[7,8]. These studies had used the seismicity data of small regions to study the seismic behaviours. If long duration of seismicity data for large areas is considered, it may reveal the temporal behaviour of seismic activity of the region. Seismicity data of strong earthquakes in large areas have revealed the possibility of seismic cycles for the regions[9-11].

The north-east region of India is seismically active as two large earthquakes of magnitude $M \geq 8.4$ occurred in this zone since 1912. Besides, the area shows widespread distribution of seismic activity where a large number of earthquakes of $M \geq 6.0$ occurred during the past hundred years. Seismicity data has also been analysed to draw conclusions[12]. Deviation of seismicity rates from the normal before and after large earthquakes has been reported by Khattri and Wyss[13] who also stated that all earthquakes of $M \geq 6.6$ were preceded by seismic quiescence. Khazanchi and Dutta[14] however pointed out a return period of 25 years for earthquake of $M \geq 8.0$. The present study attempts an analysis of the temporal variation of seismic activity in northeast India and concludes that seismic energy release has a periodicity of 20 years.

Temporal variation in seismic activity

The periodic nature of seismic activity over a vast area has been proposed earlier[9–11]. Such studies reflect the periodic nature of accumulation-relaxation of tectonic stresses in a region and may be used to indicate future seismic activity in a region. The temporal variation of seismic activity of a region requires consideration of large earthquakes generated by plate movements. A stationary model of seismicity rates and energy released in a specific time interval has been proposed for such studies. The latter is based on the number of seismic events in the region. This model has a disadvantage in that it gives the same weight to all size of earthquakes despite the vast energy variation between them. The energy release model uses energy in each time interval and is dominated mainly by shocks of largest magnitude. Thus the analyses of data in both models should complement each other.

Seismicity data

In the present study, seismicity data pertaining to smaller earthquakes have been discarded on the assumption that they might have been generated due to local geological environments. Verma and Mukhopadhyay[15] reported elevation and seismicity relationship and suggested gravity force to be the cause of smaller magnitude earthquakes. Secondly, a small amount of energy is released in smaller earthquakes as compared to large ones.

The earthquake catalogues prepared by the National Geophysical Data Centre (NGDC)[16] have been used. The present study uses the seismicity data since 1912 to 1977 for events with $M \geq 6.0$. Although it might appear that 66 years is a small period for such studies in a region, it should suffice for the northeast India region due to its high seismic activity. The data have been examined carefully and foreshocks and aftershocks have not been considered. A total of 63 earthquakes with $M \geq 6.0$ occurred in the region during the 66 years, of which 16 ($M \geq 6.0$) have been identified as foreshocks and aftershocks.

Spatial distribution

Epicentral distribution of large earthquakes with focal depth up to 100 km is shown in Figure 1. During the period 13 earthquakes with $h > 100$ km have been excluded from the study. Maximum activity is observed around 24°N which decreases towards north and south confining the concentration of intermediate focal depth earthquakes between 21° and 27°N of the 15 intermediate earthquakes, 11 are confined to the arcuate-shaped zone (Figure 1). The seismicity of the region does not show any demarcation among Tibetan plateau, Indian and Burma plates. Clustering of events is observed at some places revealing some of the zones to be very active. A and b values for large earthquakes of

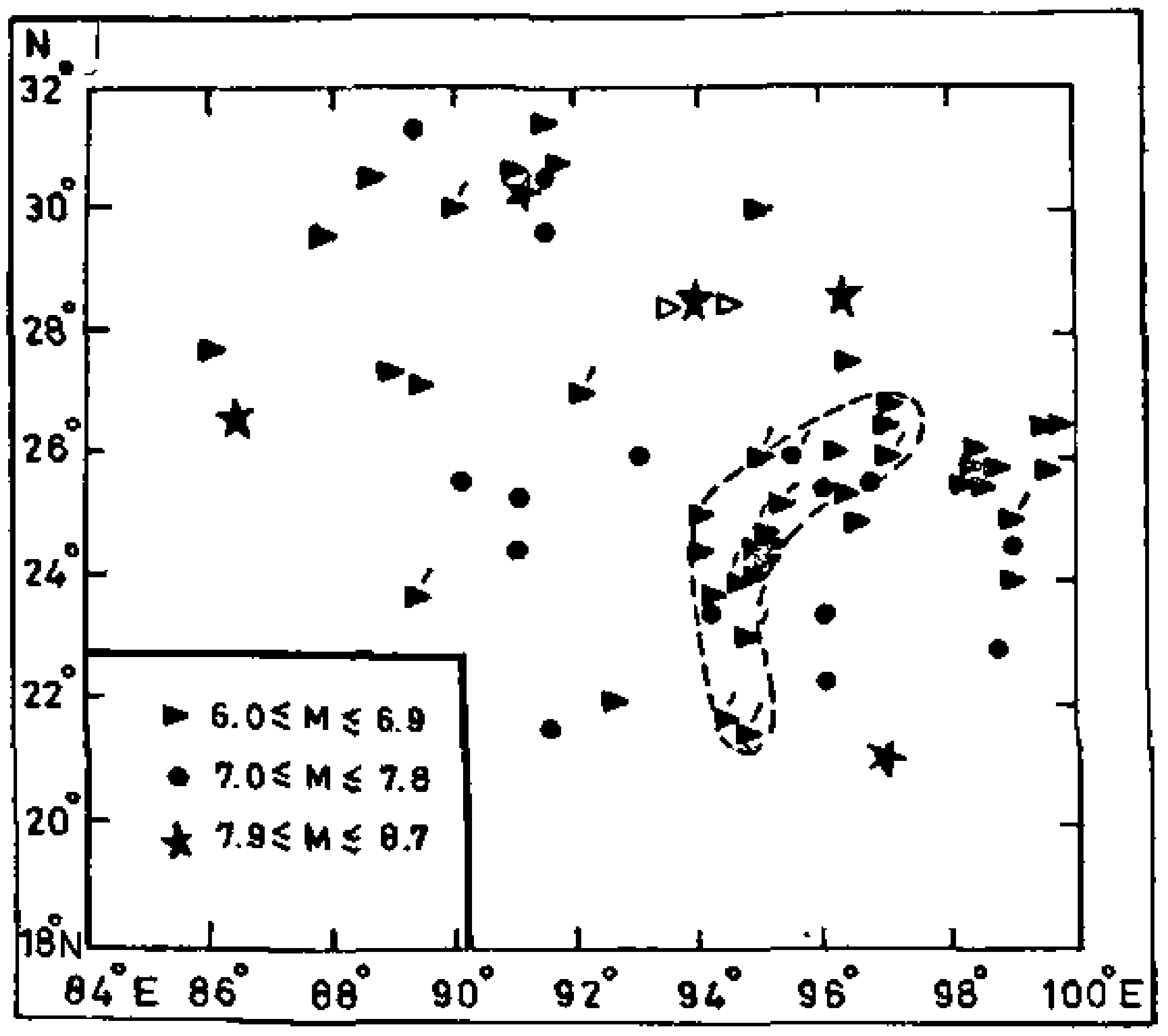

Figure 1. Spatial distribution of large earthquakes $M \geq 6.0$ ►, ● and ✱ respectively denote earthquakes with magnitude 6 to 6.9, 7 to 7.8 and 7.9 to 8.7. Dash shows the earthquakes with focal depth ≥ 70 km. Note that intermediate earthquakes are observed around 24°N which reduces in space and time on either sides along the arc

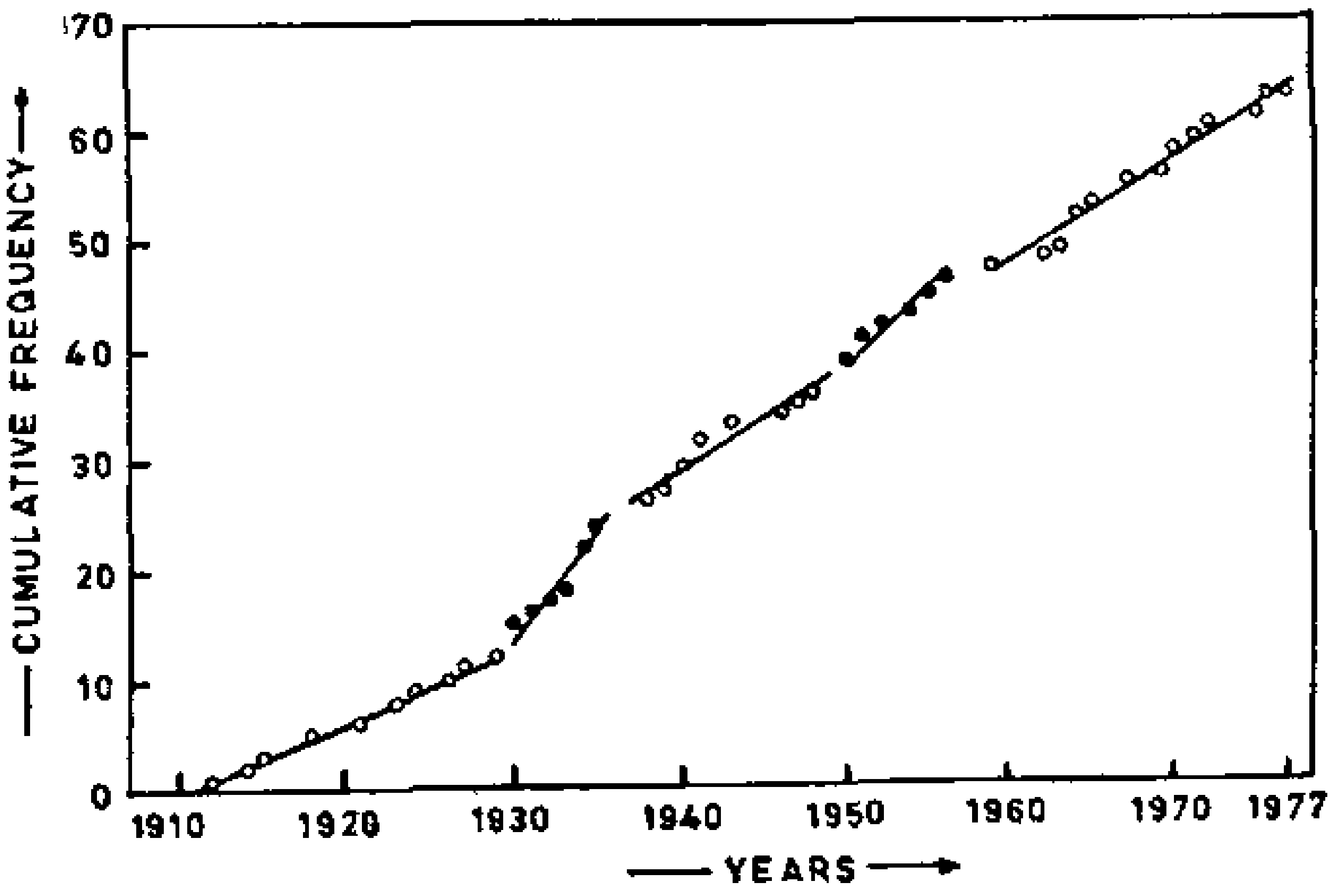

Figure 2. Cumulative frequency versus time for the earthquakes of the considered region. Open and closed circles represent earthquakes for low and high periods respectively

the region are estimated to be 6.11 and 0.69 respectively.

Seismicity rates

The cumulative number of earthquakes as a function of time (Figure 2) clearly reflects the long-term seismicity rate changes. Least square lines have been drawn for various segments to study seismicity rates. The stationary model requires all earthquakes to have an independent origin, and hence requires omission of foreshocks and aftershocks. If two consecutive earthquakes occurred within 6 months separated by a distance of 50 km, the lower magnitude earthquake has been identified as foreshocks or aftershock depending on the time of occurrence with respect to the main events. The seismicity rates for various seismicity phases are given in Table 1. The mean rate for the entire period is 0.96 event per year. The region shows low rates for the periods 1912–1928, 1936–1949 and 1957–1977 and high rates for 1929–1935 and 1950–1956. The extent of time for low and high rates is 15.24 to 20.15 years and ~6 years respectively. The low and high seismicity rates range from 0.73 to 0.84, and 1.68 to 2.15 respectively. To study the significance of these rates and the differences of low and high seismicity rates with the preceding and succeeding seismicity phases, *t*-test was performed which suggests that the rates are statistically significant. The confidence level for the differences in rates (Table 1) is greater than 90% in all cases.

Probabilistic approach

It was reported that the seismicity of a large area over a long time can be assumed to be a stationary Poisson process[9, 11, 17] and hence the probability of occurrence of x earthquakes, i.e. $P(x)$ in a time interval t can be expressed by the Poisson distribution.

$$P(x)=\frac{\exp(-rt)\,(rt)^{x}}{\lfloor\underline{x}} \qquad (1)$$

where r is the mean seismicity rate and x the number of earthquakes in time interval t. The average frequency of earthquake per three years is estimated to be 2.88. The

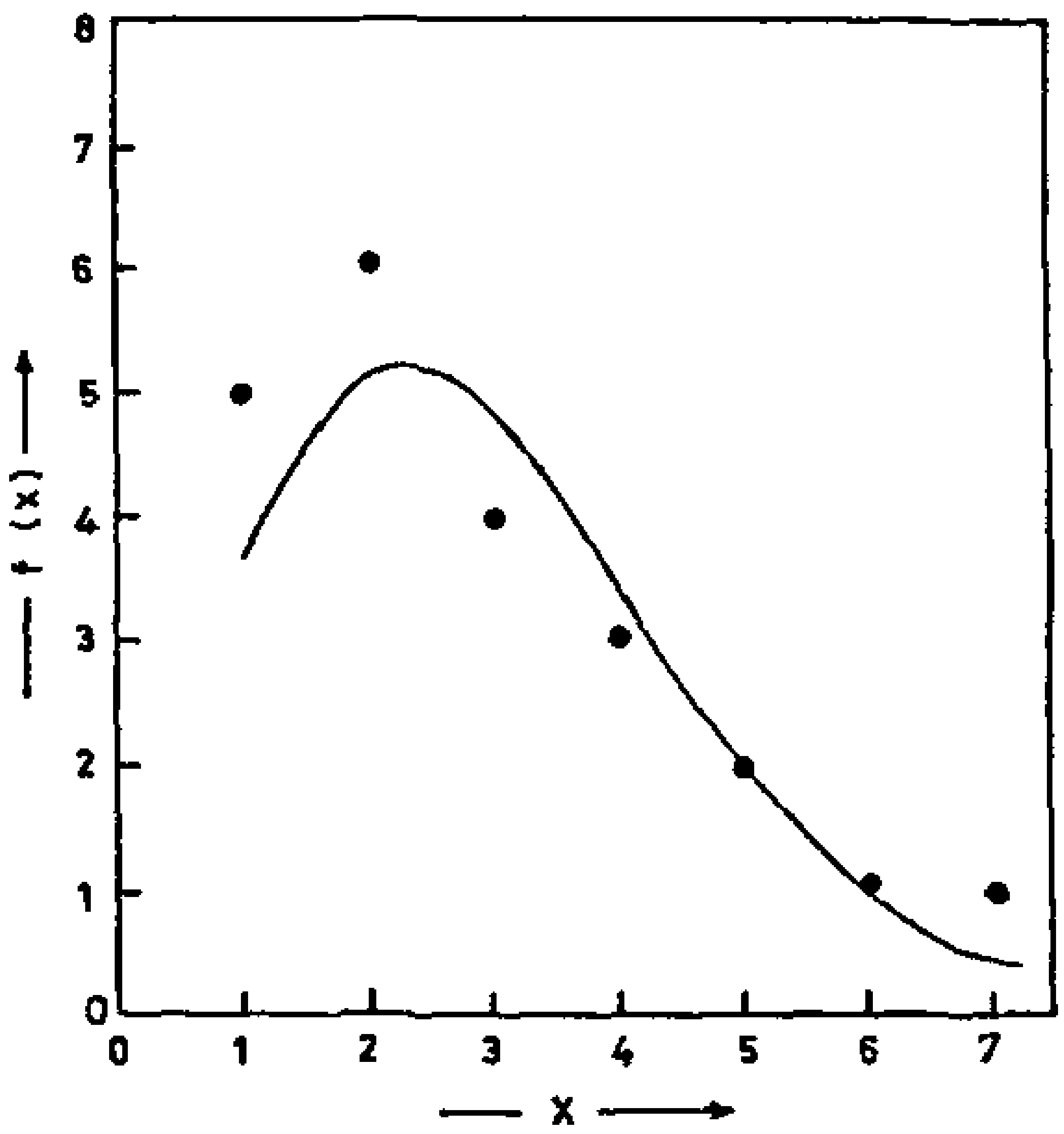

Figure 3. Frequency distribution of the number x of earthquakes of the region for 3-year time interval.

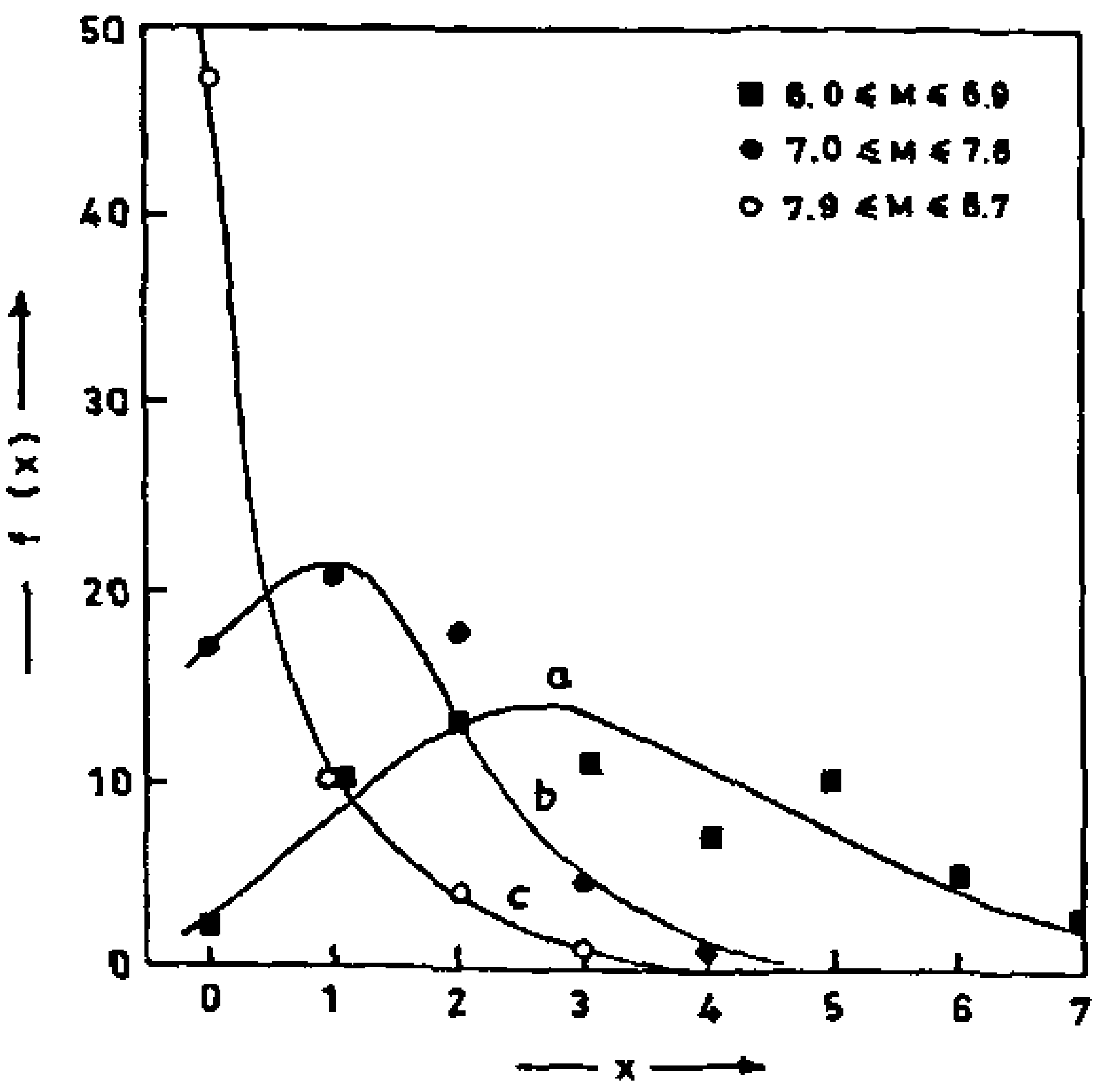

Figure 4. Frequency distribution of the number x of earthquakes of magnitude 6 to 6 9, 7 to 7.8 and 7.9 to 8.7 is shown in a, b and c curves respectively. For the data set, 5-year time interval overlapping by 4 years has been considered. The curves a and b indicate Poisson distribution whereas c is of exponential form.

Table 1. Elements for time variation of seismicity in northeast India

Duration	Rate (events per year)	Time (yrs)	No. of events in time T	$P(x)$	Rate differences $(r_i - r_{i+1})$	Confidence level by t-test (%)
23 5 12 to 16 10.29	0.73	16.41	12	0.06749	− 1.42	95
17.10 29 to 21.5 35	2.15	5.58	12	0 00588	1 37	95
22 5 35 to 7.50	0 78	15.24	12	0 0864	− 0.9	90
15 8 50 to 16 7.56	1 68	5 92	10	0 03445	0.84	90
17.7 56 to 12.77	0 84	21.40	17	0 09627		

frequency distribution of events in three years time interval for the period 1912–1977 is shown in Figure 3. The value of $P(x)$ calculated using equation (1) (Table 1) shows low probabilities for all these rates suggesting that seismicity rates are not accidental. The frequency distribution curve shows that the events are randomly distributed. As the region is seismically active and has experienced some of the large events, it is essential to study the nature of frequency distribution of larger magnitude events. For this purpose earthquakes have been classified into three groups of magnitude 6.0–6.9, 7.0–7.8; and 7.9–8.7. The nature of frequency distribution is shown in Figure 4. Here, the 5-year time intervals overlapping by 4 years have been considered. The frequency distribution for $7.9 \leq M \leq 8.7$ is an exponential curve of the form

$$f(x) = A/(K)^x, \qquad (2)$$

where A and K are constants and $f(x)$ the frequency distribution of x. The equation for curve (c) is derived as

$$f(x) = 42.73/(3.48)^x. \qquad (3)$$

The distribution of earthquakes with magnitudes in the range $6.0 \leq M \leq 6.9$ and $7.0 \leq M \leq 7.8$ approximates the Poisson distribution of the form

$$P(x) = \frac{\exp(-\lambda)(\lambda)^x}{\lfloor x}, \qquad (4)$$

where λ is the average frequency of earthquake in 5 years and x the number of earthquakes in the same period.

The nature of frequency distribution for two magnitude ranges is estimated to be:

$$f(x) = \frac{\exp(-3.27)(3.27)^x}{\lfloor x}; \text{ (for } 6.0 \leq M \leq 6.9), \qquad (5)$$

$$f(x) = \frac{\exp(-1.23)(1.23)^x}{\lfloor x}; \text{ (for } 7.0 \leq M \leq 7.8). \qquad (6)$$

The frequency distribution curve (Figure 4 c) suggests that large earthquakes in the magnitude range $7.9 \leq M \leq 8.7$ are nonrandom events and this can be justified by the occurrence of major events and clustering of lower magnitude events during the high seismicity phases as shown in Figure 5.

Seismic energy release

The time variation of $\log E_q$ (where E_q is the total amount of energy released in ergs in 3-year time interval) is shown in Figure 6. The time variation of energy released may be represented by a harmonic curve of the form

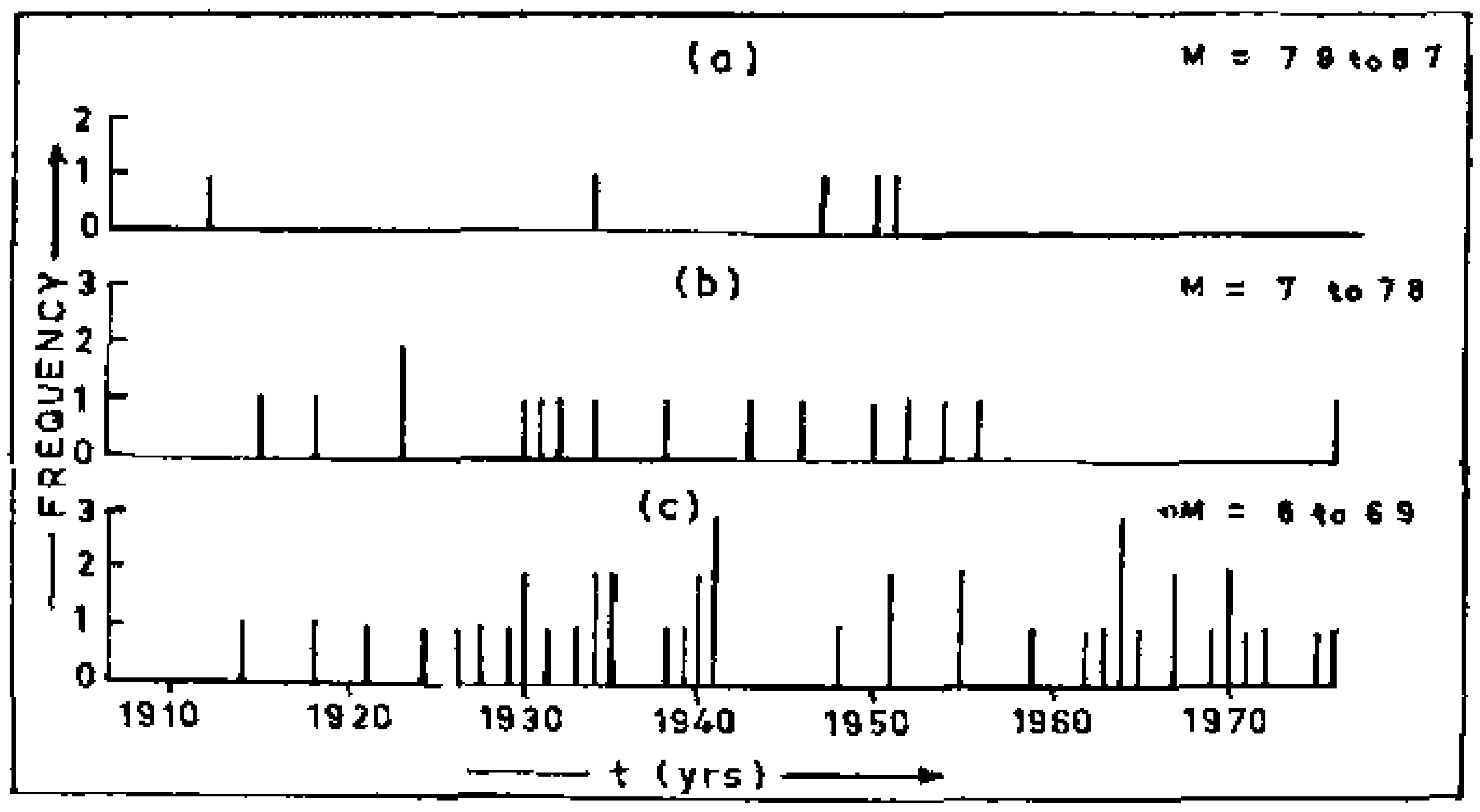

Figure 5. Earthquake frequency with time from 1910 to 1977 It shows clustering of strong earthquakes of magnitude 7 to 7 8 and 7 9 to 8 7 in high active periods

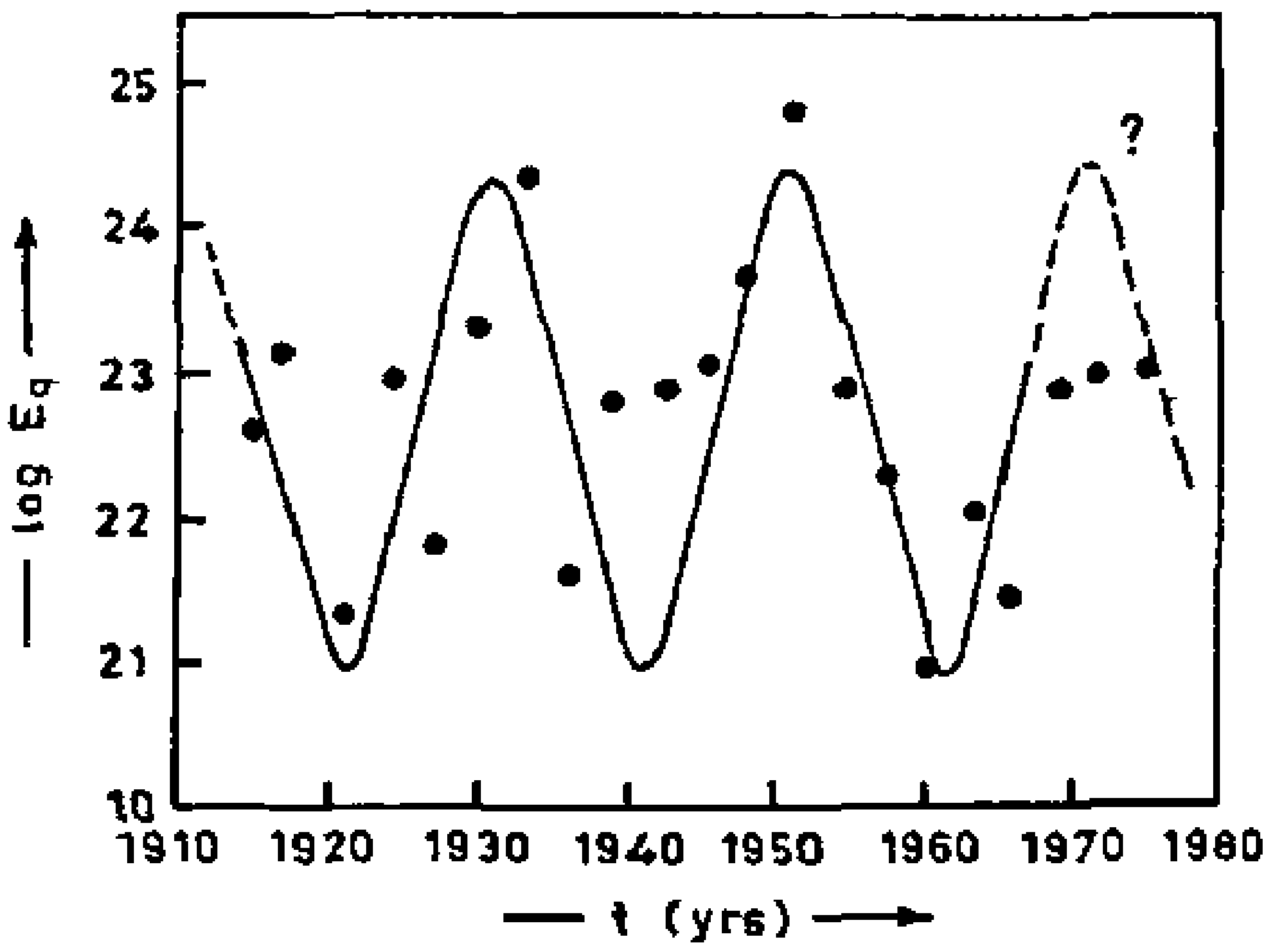

Figure 6. Variation of log E_q with time shows high energy peaks in 1930s and 1950 The present analysis does not show high activity in 1970s

$$\log E_q = \overline{\log E_q} + (\log E_{q_0}) \sin\left(\frac{360t}{T} + \varnothing\right), \qquad (7)$$

where $\overline{\log E_q}$ is the average of the $\log E_q$ values and $\log E_{q_0}$ represents the mean of the five largest

$$\left|\overline{\log E_q} - \log E_q\right| \text{ values.}$$

T denotes the period and $\varnothing$ the phase. For the best harmonic fit, the equation may be written as

$$\log E_q = 22.61 + 1.66 \sin(360t/20 - 108°). \qquad (8)$$

The time t in equation (8) is measured from the year 1911. The fitting of the curve may be considered to be satisfactory. Fedotov[9], Papadopoulos and Voidomatis[11] reported sinusoidal pattern of energy release for different seismically active zones.

Discussion

The area considered includes portions of northeastern region of Indian plate, western Burma plate and southern Tibetan plateau. The considered zone of Indian plate shows thrust faultings, Tibetan plateau demonstrates mostly normal faultings and the Burma region is a complicated zone of strike-slip and thrust faultings. The nature of faultings is different in different plates; however, the overall seismic activity of the region may be assumed to be dependent on stress generated and resistance offered by drifting of plates towards each other. Hence, the overall response of the occurrence of earthquakes and the energy released in different tectonic regimes for a large region may be studied statistically. The nature of seismic activity for large areas has been studied by others[9-11]. The zone presently considered is seismically active and has experienced many major earthquakes.

The frequency distribution (Figures 3 and 4) reflect that the events of magnitude 6.0 to 7.8 follows Poisson distribution, and hence such earthquakes cannot be predicted. However, earthquakes with $M \geq 7.9$ demonstrate nonrandom distribution. The non-randomness nature of frequency distribution of events would form the basis for prediction of magnitude and the time of occurrence of forthcoming large earthquakes.

The behaviour of seismic activity for the region has been studied by the stationary model of seismic rate and energy released in three years time window. The analyses show low and high seismic phases. Figure 2 demonstrates three lows and two highs of seismic phases. High seismicities are associated with 1934 and 1950 earthquakes. Figure 5 reflects the concentration of earthquakes in the magnitude ranges 6 to 6.9 and 7 to 7.8. This indicates that large earthquakes are preceded by high seismic activity in lower magnitude ranges. The prominent low energy released during 1920s, 1940s and 1960s is due to lower magnitude earthquakes. The stationary model also indicates similar phenomena with alternate low and high seismic activity. Hence, a 20-year probable periodicity of high seismic phases of almost cyclic nature is inferred from the energy released model for the northeast India region. Our results agree with those of Zhao *et al.*[18] who also reported a 20-year cyclic periodicity of high seismicity phases for East Asia during 1910, 1930, 1950 and 1970. If this 20-year periodicity is valid for the northeast India region, the next high seismic phase should have been initiated during 1970. Non-occurrence of such a phase even after 40 years is questionable. However, the region may probably be developing a situation for a great earthquake of $M \sim 8.7$ in the upper limit of the magnitude range ($M = 7.9$ to 8.7) for which the preparation period may be longer requiring storage of enormous strain energy.

The seismicity of the study area for the active period of 1929–1935 and 1950–1956 is shown in Figure 7. Keilis-Borok and Malinovaskaya[19] reported the involvement of large area ranging from 1.3 to 3×10^5 km^2 for earthquakes of $Ms = 6.5$. Plafker[20] reported the horizontal distortion and faulting over greater than 2.8×10^5 km^2 for the great Alaska earthquake ($M = 8.3$) of 1964. Thus earthquakes that occurred at a short distance at the active period may be considered to be linked together.

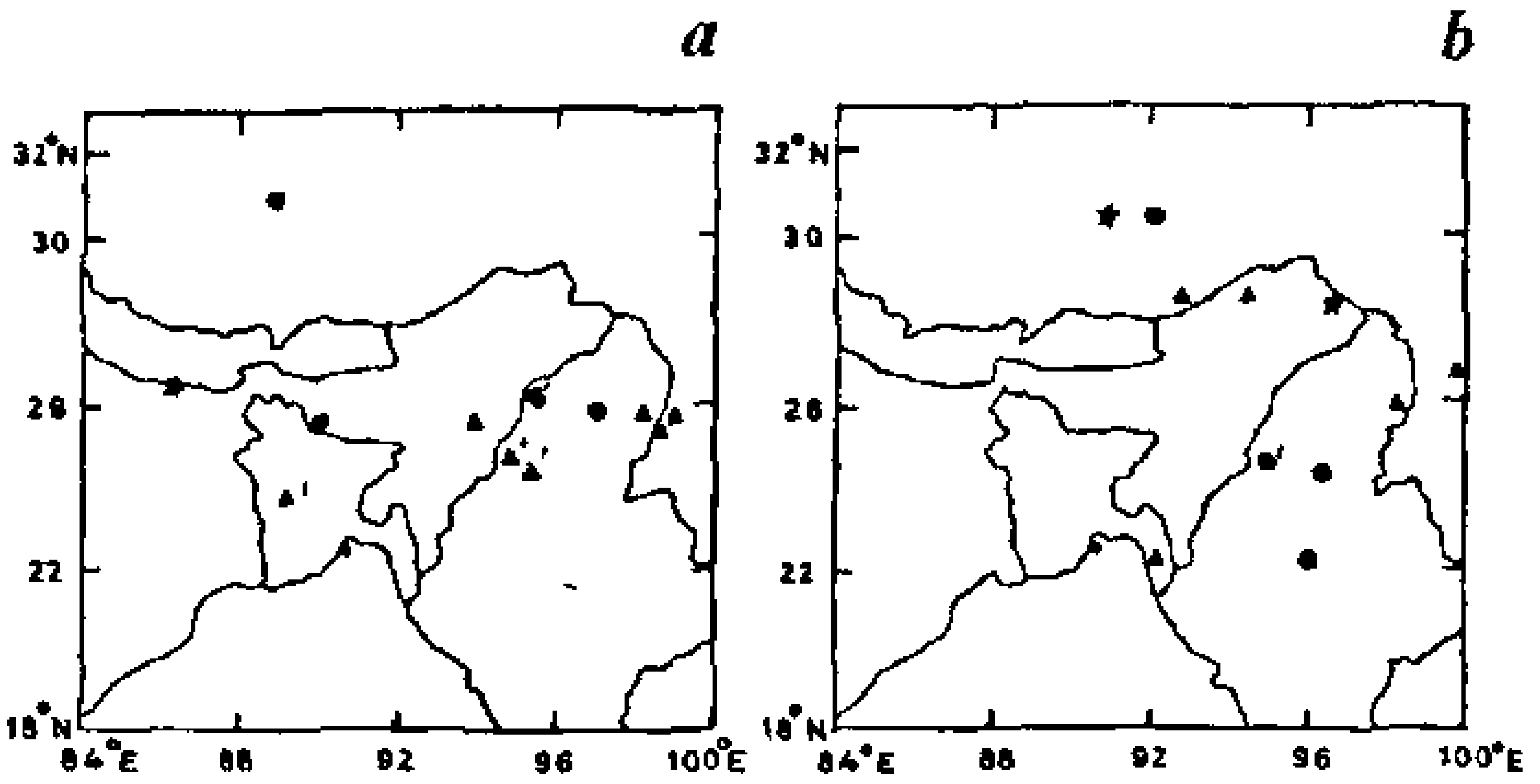

Figure 7. Spatial distribution of earthquakes of active periods during (*a*) 1929–1935, and (*b*) 1950–1956 For explanation of symbols, see Figure 1

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1 Habermann, R. E , *Earthq Predict Res* , 1982, **1**, 73–94
2. Habermann, R E. and Wyss, M , *Bull Seismol Soc Am* , 1984, **74**, 1743–1755
3. Wyss, M , Habermann, R. E. and Griesser, J C., *J Geophys Res* , 1984, **89**, 9293–9304.
4 Singh, V. P. and Singh, H. N , *Earthq Predict Res* , 1984, **2**, 245–258
5 Wyss, M , *Bull, Seismol Soc. Am* , 1986, **76**, 785–800
6. Singh, V. P and Singh, J , *Proc Indian Acad Sci (Earth Planet Sci*), 1987, **96**, 15–23
7. Ohtake, M , Matumoto, T and Latham, G V , *Pageoph*, 1977, **115**, 375–385
8 Ohtake, M., Matumoto, T. and Latham, G V., *Bull Int Inst Seismol. Earthq Engg.*, 1977, **15**, 105–123.
9 Fedotov, S. A , *Nauka*, 1968, 121–150 (in Russian)
10. Ben-Menahem, A , *Bull. Geof Teor Appl* , 1981, **23**, 349–353
11 Papadopoulos, G A and Voidomatis, P , *Pageoph*, 1987, **125**, 613–628
12. Kaila, K L and Narain, H , *Bull Seismol Soc Am* , 1971, **61**, 1275–1291
13 Khattri, K. and Wyss, M., *Geology*, 1978, **6**, 685–688
14 Khazanchi, A C. and Dutta, T. K , Third Symposium on Earthquake Engineering, Univ of Roorkee, 1978, vol 1, pp 523–528.
15. Verma, R K. and Mukhopadhyay, M , *Tectonophysics*, 1976, **34**, 117–133
16. National Geophysical Data Centre, Boulder Colorado, USA-Catalogue of Earthquakes for Northeast India Region, 1912–1977
17 Gardner, J. K and Knopoff, L., *Bull. Seismol Soc Am* , 1974, **64**, 1363–1368
18 Zhao, Z., Matsumura, K , Oike, K and Ishikawa, Y , *Zisin*, 1988, **41**, 389–400
19. Keilis-Borok, V. I. and Malinovskaya, L. M , *J Geophys Res* , 1964, **69**, 3019–3024.
20 Plafker, G., *Seismology and Geodesy*, National Academy of Sciences, Washington, 1972, pp 113–188

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