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Aftershock characteristics in Himalayan mountain belt and neighbourhood

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ABSTRACT. The aftershock activity associated with five earthquakes in the Nepal-India border, Kashmir, Kashmir,-Tibet border (Ladakh) and West Pakistan was studied in relation to the magnitude, strain release, time and spatial distribution.

The study showed that the rate of decay of aftershock activity may be related to the differences in the mechanical structures of the crust. The value of constant *b* in Gutenberg and Richter's magnitude-frequency relationship may not reflect the seismotectonics of different regions.

1. Introduction

Recent studies (Mogi 1967, 1968) have brought out that the aftershock activity is remarkably different from one region to the other. This has been attributed to the differences in the mechanical conditions of the earth's crust. The rate of decay of aftershock activity is also different in various tectonic regions.

Geotectonically, the Himalayan mountain belt and neighbourhood are comparatively weak and flexible portion of the earth's circumference that has undergone a great deal of deformation. Rock folds, faults, thrust planes and other evidences of movements within the earth are observed in this region on a very wide scale.

The object of the present paper is to study the variations of the aftershock parameters based on five earthquakes in Kashmir, India-Nepal border and West Pakistan region during 1966 to 1968.

2. Data

For the present study, the records from a close network of mobile and permanent seismological observatories equipped with highly sensitive Hagiwara Electromageetic Seismographs ($T=1$ sec, $Tg=1$ sec, $V_{max} =50000$ to 100000), Wood Anderson and IMD electromagnetic seismographs were used. The locations of the observatories with reference to the epicentres of the five main shocks are shown in Fig. 1.

Some details of the earthquakes whose aftershocks have been studied in this paper are briefly given below.

(*i*) *Nepal-India border earthquake of 27 June 1966* — It was reported that 80 persons were killed and many injured due to this earthquake. Within 20 min. of its occurrence, another shock (which could be considered as an aftershock) of almost equal magnitude occurred in the same region. This earthquake was followed by a large number of aftershocks of magnitudes ranging from 3·5 to 5·4.

The specific destruction defined as the number of deaths per unit seismic energy is given by,

$$f=\log \{C(N_k H)/E\} \qquad (1)$$

(where N_k=number of people killed, $E=$ Seismic wave energy and $C=$a constant). f was found to be 5·9 corresponding to the USCGS magnitude of 6·1.

(*ii*) *Kashmir earthquake of 20 Feb 1967* — This was widely felt in Kashmir with its epicentre near Anantnag. A foreshock of magnitude 4·9 (CGS) occurred about 10 days before the occurrence of this earthquake. The aftershocks were recorded till April 1967.

(*iii*) *Kashmir shock of 2 August* — This was preceded by a large number of foreshocks and followed by aftershocks of magnitude ranging from 3·0 to 5·5.

(*iv*) *The West Pakistan shock of 7 February 1966* — Felt at Bhawalpur, Multan, Lahore and some other places.

Since no deaths were reported, the specific destruction could not be worked out for the above three earthquakes.

(*v*) *The second West Pakistan earthquake of 1 August 1966* — It was reported that 2 persons were killed, 15 injured and 45 villages were destroyed
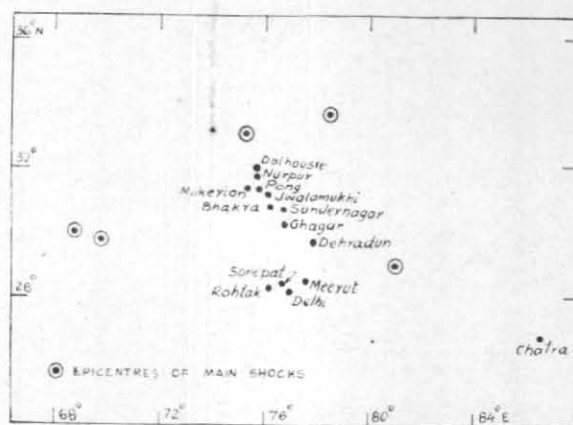
Fig. 1. Location of seismological observatories

due to this shock. It was felt at Quetta and many other places in West Pakistan. The specific destruction was found to be 4·37 which is in agreement with the average value for India. This earthquake which occurred about 100 km west of first shock of 7 February may be considered as secondary aftershock (Drakopoulos and Srivastava 1970).

3. Earthquake parameters

Determination of Epicentres—To determine the epicentres of the aftershocks, the two layered model was used to calculate the velocities in the region. The following velocities of different phases were thus obtained.

$P_n=8·15$ km/sec, $P^*=6·6$, $P_g=5·7$, $S_n=6·4.$, $S^*=3·8$ and $S_g=3·35$ km/sec.

Based on the above data, the transit times of various phases for different epicentral distances were computed, taking into account the depth of focus. With these travel time curves, the epicentral distances were computed for each observatory. These were plotted on a map of scale 1 mm=1 km, whose intersection gave the epicentre. If the intersection was not proper, the origin time was slightly shifted till the (obs.—cal.) time was reduced to minimum. The depth of focus was also varied until the epicentral coordinates were well determined.

Determination of the magnitudes—A large number of aftershocks of small magnitudes were determined by reading the maximum amplitudes on east-west and north-south components correct to 0·1 mm with the help of a microfilm reader. The period of the wave corresponding to the maximum amplitude was read correct to 0·01 sec and from the magnification curve for each component, the maximum amplitude was reduced to that of the ground amplitude. Knowing the

epicentral distance, the magnitude of each shock was calculated from the Wood-Anderson nomogram by converting the ground amplitude to the trace amplitude in a standard Wood Anderson seismograph. In order to assess the magnitudes determined by this method, the magnitude of several earthquakes which were recorded on both the instruments were compared with W.A. magnitude and the mean correction was found to be +0·2. This method was employed to determine the magnitudes of aftershocks in Kashmir and West Pakistan regions, utilizing the records of Jawalamukhi Observatory. The magnitudes of the aftershocks in the Nepal India border were, however, determined directly by Wood Anderson seismograph at Delhi.

The magnitudes of the aftershocks were determined for those events which have been clearly identified on the basis of epicentral coordinates. For those aftershocks which were recorded at only two observatories, the magnitudes were determined on the basis of S-P interval and the direction of epicentre.

Magnitude difference between the main shock M and its largest aftershock M_1— Table 1 may be used to study the difference between the main shock and its largest aftershock. It may be seen that this difference varies from 0·4 to 1·2 and thus Bath's law has been found to hold good only in the case of the West Pakistan earthquake on 1 August 1966. Recently Vere-Jones (1970) has advocated that Bath's law is a reflection of a purely statistical feature since the difference between the largest and the next largest number of a sample randomly chosen from such a distribution is independent of the sample size. It is, in fact, exponentially distributed with the same parameters as the distribution of the individual sample members.

TABLE 1

Region	Date	Epicentre of focal depth (USCGS)		Origin time (USCGS)			Focal depth in km (USCGS)	Magnitude	
		Lat. (°N)	Long. (°E)	h	m	s		US CGS	ML
(a) *Parameters of the main shocks in the Himalayan Region*									
Nepal-India border	27 Jun 1966	29·7	80·9	10	41	8·6	37	6·1	5·8
Kashmir	20 Feb 1967	33·7	75·3	15	18	38·8	24	5·7	5·6
Kashmir-Tibet	11 Feb 1968	34·2	78·6	20	38	29·4	44	5·1	5·2
West Pakistan I	7 Feb 1966	29·8	69·7	04	26	13·9	33	6½	6·8
West Pakistan II	1 Aug 1966	30·0	68·7	21	02	59·6	33	6·2	7·2
(b) *Parameters of the largest aftershocks of the sequence*									
Nepal-India border	27 Jun 1966	29·7	81·0	10	59	8·1	40	6·0	5·6
		29·7	80·8	11	21	43·0	33	5·4	
Kashmir	21 Feb 1967	33·7	75·4	12	37	46·1	31	5·1	5·3
Kashmir-Tibet border	11 Feb 1968	34·3	78·2	23	18	16·0	33	4·5	4·3
West Pakistan I	7 Feb 1966	30·2	69·8	23	06	34·5	10	5·8	—
West Pakistan II	1 Aug 1966	30·0	68·9	22	06	54·8	33	5·2	—

TABLE 2
Foreshock activity

Date	Region	Largest fore-shock epicentre		Magni-tude	H (km)	Time of origin		
		Lat. (°N)	Long. (°E)			h	m	s
	Nepal-Indian border	—	—	—	—	—	—	—
10 Feb 1967	Kashmir	33·0	75·5	4·9	27	05	46	27·9
10 Feb 1968	Kashmir-Tibet border	34·1	78·5	5·2	37	17	03	3·8
24 Jan 1966	West Pakistan I	29·9	69·8	5·3	4	15	32	48·1
1 Aug 1966	West Pakistan II	29·9	68·8	5·7	33	20	30	57·0

From the study of a large number of aftershocks in Greece, Drakopoulos (1968) found the following relation between M and M_1 for $M > 5·3$.

$$M_1 = (1·28 \pm 0·42) + (0·65 \pm 0·06) \ M \qquad (2)$$

The high values of the standard deviations in this relationship again justifies the arguments against the general validity of Bath's law.

Regional variation of aftershock activity — Utsu (1961) suggested the use of the difference in magnitude between the main shock and the largest aftershock $(M-M_1)$ as a measure of the aftershock activity. Mogi (1968) found that in Japan, the aftershock activity shows systematic regional variation which is most remarkable in the entire seismic zone in Japan, particularly east of northern Japan. Along the main boundary fault in the Himalayan region $M-M_1$ (USCGS magnitude given in Table 1) is of the order of 0·6 to 0·7 for all the earthquakes except for West Pakistan shock of 7 February 1966. In the case of Nepal-India border earthquake, $M-M_1$ was found to be 0·1 only if the largest aftershock which occurred within a few minutes of the occurrence of the mainshock is taken into consideration. Similarly $M-M_1$ varied markedly from one aftershock sequence to the other, in the West Pakistan region, also thus making it difficult to conclude about the utility of this parameter as a measure for study of regional aftershock activity.

4. Foreshocks

All the five earthquakes were preceded by foreshocks. The parameters of the largest fore-shock given in Table 2 show that with the exception
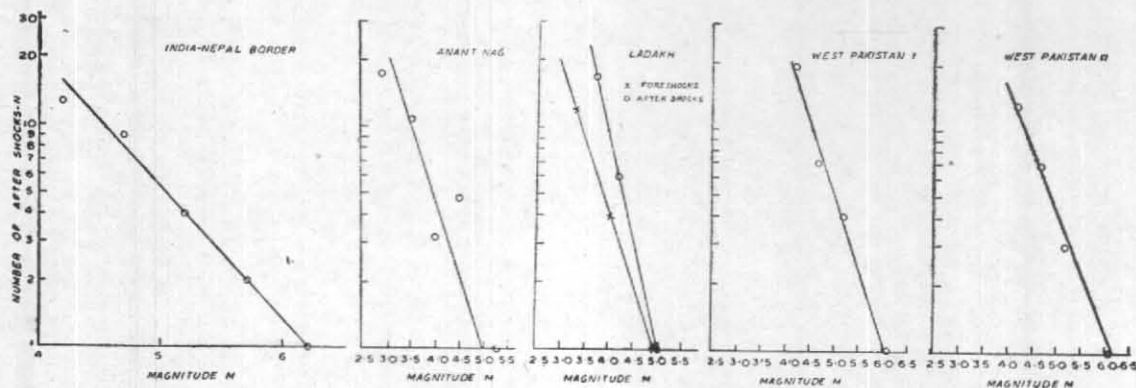
Fig. 2. Magnitude frequency distribution for earthquakes

TABLE 2

b, h and energy released in the mainshock ·

Region	b	h	Energy released in main-shock (%)
Nepal-India border	0·51±0·16	1·28	94
Kashmir	0·58±0·12	1·49	70
Kashmir-Tibet border	0·80±0·22	1·31	84
West Pakistan (7 Feb 1966)	0·69±0·16	1·27	91
West Pakistan (1 Aug 1966)	0·92±0·30	1·32	96
Koyna	—	1·10	—

of Kashmir shock of 20 Feb 1967, the magnitude was generally comparable to that of the largest aftershock (Table 1b.). The number of foreshocks was quite small for these sequences except in the case of Kashmir earthquake of 11 February 1968 when 20 foreshocks were recorded at Jawalamukhi. The magnitude distribution was studied by fitting the data in Gutenberg-Richter's relationship given by—

$$\text{Log} \quad N = a - bM \tag{3}$$

where, N is the frequency of earthquakes of magnitude $M+dM$ and $M-dM$, and a and b are constants. The value of b was found to be 0·65 ±0·30 from the plot of N versus M (Fig. 2). Recent study by Lahr and Pomeroy (1970) has shown

that if we were to use b values in earthquake prediction from a relatively small number of events in a foreshock sequence random fluctuations in the estimation of b of the order of ± 0·2 may be expected. Mogi (1968) has explained the mechanism of foreshock occurrence and concluded that the regions where earthquakes are frequently preceded by foreshocks are moderately fractured regions. Thus it is reasonable to infer that the Himalayan mountain belt and neighbourhood area falls under Mogi's Type II classification.

Table 2 also gives the time of occurrence when the first foreshock was observed for all the five sequences. The data is useful for the prediction
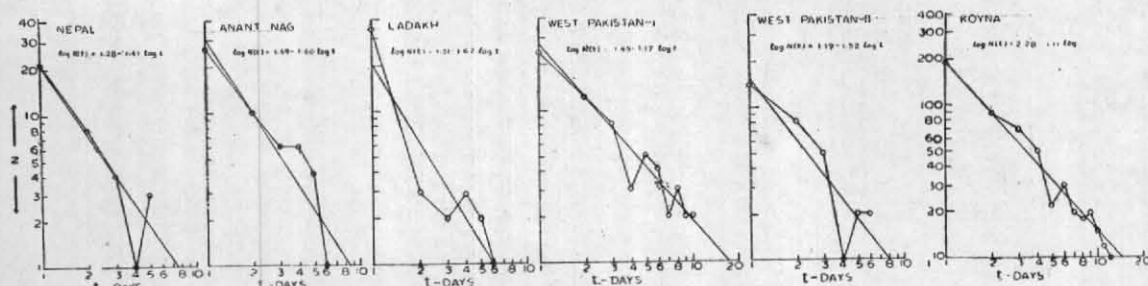
Fig. 3. Decay of aftershock activity

of earthquakes by estimating the probability for an occurrence time to fall in different time ranges on account of foreshocks (Rikitake 1969). The limitation is due to the fact that there is possibility of recording events of smaller magnitudes earlier than that given in Table 3 if the sensitive instruments were located close to the epicentral region.

5. Results and discussion

Magnitude distribution — It is well known that the statistical formula given in equation (3) holds good for foreshocks, aftershocks and general seismicity. The value of the constant b may also be estimated for a group of earthquakes from,

$$b = \frac{0 \cdot 4343}{M - M_{\min}} \qquad (4)$$

where, M is the average magnitude of the sample and $M_{\min}$ is the lowest magnitude used. This equation gives the maximum likelihood estimate of b for a sample of n earthquakes (Aki 1965) and holds good if the range of magnitudes in the sample is greater than two magnitude units (Page 1968). The aftershock data used in the present paper satisfies this condition. The approximate 95 per cent confidence limits for the estimate of b are $\pm 1 \cdot 96 \; b / \sqrt{n}$

The plot of N *versus* M for the different aftershock sequences are shown in Fig. 2. The value of b determined with the help of equation (4) are given in Table 3.

Comparison of b from aftershocks and seismicity— The average value of b in Himalayan region was about $0 \cdot 60$ from the aftershock sequences which is lower than that derived from the seismicity studies (Tandon and Chatterjee 1968, Chaudhuri *et al.* 1970). This is in contrast with the results of Suzuki (1959) who did not find any significant difference in the values of b determined from aftershocks and seismicity data in the same region. The low values of b in Nepal-India and Anantnag-Kashmir regions compare favourably with

that determined independently by Tandon (1971) who determined the parameters of Anantnag sequence for a large number of aftershocks. In fact, low values of b have been reported by several workers from accurate and reliable aftershock data (Udias 1965, Drakopoulos 1968) and also for micro-earthquakes (Greensfelder 1968).

It is interesting to note that relatively low value of b occurred in Kashmir (Anantnag) when the data was large and high value of b occurred in West Pakistan with a smaller population. If low value of b for aftershock sequence is attributed to insufficient data as concluded by Suzuki (1959), the result would have been opposite.

'b' versus seismotectonics — Mogi (1968) showed experimentally that the value of b increases as the degree of heterogeneity increases and as the degree of symmetry of the applied stress decreases. It may be seen from Table 3 that if the experimental results are extended to include b values from aftershock sequences, some discrepancies regarding b *versus* seismotectonics may be brought to light. The earthquakes in Nepal-India and Kashmir (Anantnag) regions located close to the main boundary fault shows a lower value of b as compared to that in Kashmir-Ladakh and West Pakistan region. It may be pointed out that the Nepal-India border region near 30°N , 80°E has high seismicity as compared to the adjacent regions and thus the value of b being indicative of the heterogeneous and fractured nature of the crust in the region, was expected to be higher. Similarly for the micro earthquake swarms which occur in a markedly heterogeneous medium, the value of b in Matsushiro region was found to vary from $0 \cdot 8$ to $1 \cdot 2$ (Drakopoulos *et al.* 1970).

It may, therefore, be inferred that the value of b from aftershock studies may not reflect the seismotectonics of the region. It is, however, difficult to judge whether this result arises from some local peculiarity in the rocks in contact with
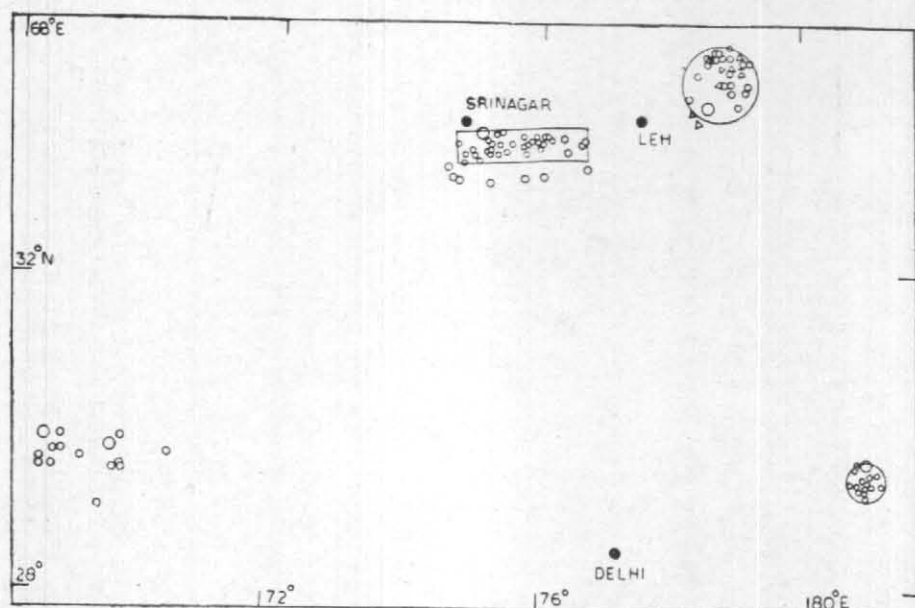
Fig. 4. Spatial distribution of the aftershocks

the slip surface or from the depth controlled variation in the behaviour of rocks in the earth's crust.

Comparison of b for foreshocks and aftershocks— The value of b for foreshocks of Kashmir earthquake on 11 February 1968 was found to be slightly less than that from the aftershocks. This is in agreement with the results of earlier workers (Suyehiro *et al.* 1964, Suyehiro 1966). However, Lahr and Pomeroy (1970) did not find any significant difference in b for foreshocks and aftershocks.

Time distribution of the aftershocks — The relationship between the number of shocks n per day, and the time after the mainshock, t, is given by,

$$n = A t^{-h} \qquad (5)$$

Fig. 3 shows the number of shocks per day after the occurrence of the main shock *versus* time at Jawalamukhi. The constants A and h determined by the least square method are given in Table 3.

It may be seen that the value of h lies between 1·1 and 1.5. On the basis of 41 Japanese aftershock sequences, Utsu (1968) found that h generally varies between 1·0 and 1·3. Mogi (1968) has reported the differences in h ranging from 0·9 to 1·8.

The value of h from the aftershock data of Koyna earthquake of 10 December 1967 in tectonically homogenous Peninsula was found to be 1·10 which is significantly lower than that in the

Himalayan mountain belt. This represents a lower rate of decrease of aftershock activity in Koyna region as evinced from our observations. The higher value of h in the Kashmir region may be characteristic of the difference in the tectonic structure. Mogi (1968) also found that the aftershock frequency decreases in time more rapidly in the Japan sea side as compared to that in the Pacific Ocean side. Thus it is possible that the rate of decay of aftershock activity may be related to the tectonic features of that region.

Spatial distribution of the aftershocks — Fig. 4 shows the spatial distribution of the aftershocks for the five earthquakes sequences. Due to the large epicentral distance of the West Pakistan earthquakes from the Indian observatories and the sparsity of observations for most of the aftershocks, the epicentral parameters could not be determined. For these two sequences, therefore, the epicentres as determined by USCGS were plotted.

It may be seen that the epicentre of the main shock is generally located near one edge of the aftershock zone.

Energy release — The energy of each earthquake was calculated from the equation,

$$\text{Log } E = 2 \cdot 88 + 1 \cdot 92 \, ML - 1 \cdot 02 \, M_1{}^2 \qquad (6)$$

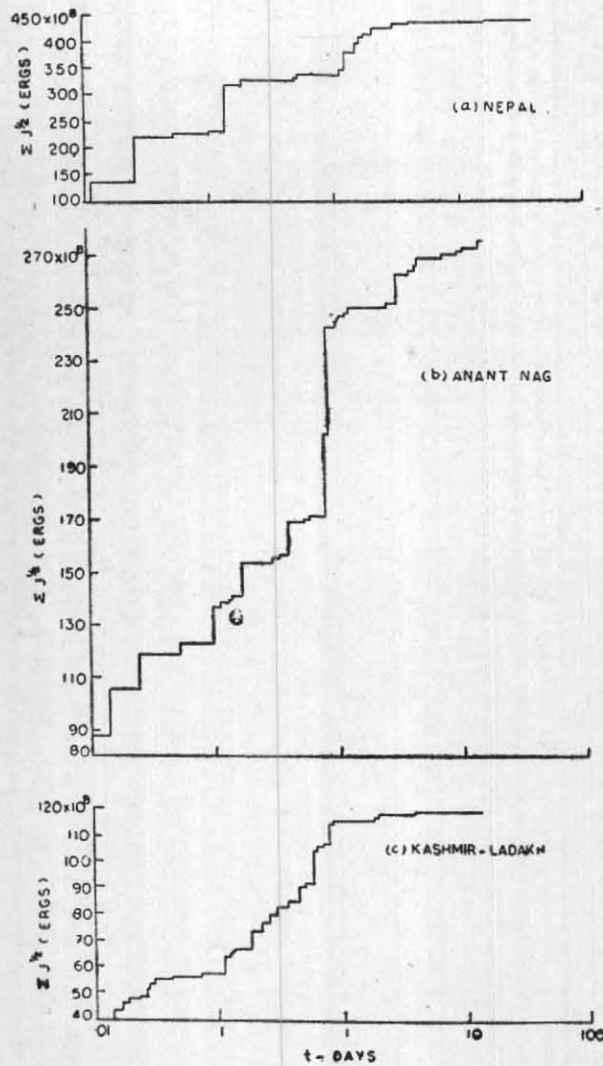where, ML is the magnitude of the earthquake. The amount of engergy released in the main shock

Fig. 5

Strain energy release *versus* time

the main shock itself. In the case of Nepal-India border earthquake, however, the energy released in the main shock comes as 49 per cent., if we consider the largest aftershock of magnitude 6·0 (almost equal to that of the main shock). This instance highlights the difficulty of classifying an earthquake as an aftershock or as a double event.

Strain energy release—Fig. 5 shows the cumulative strain energy release, S *versus* time. The cumulative strain energy is related to the energy released by,

$$S = \Sigma E^{1/2} \qquad (7)$$

It may be seen that except for the earthquake of 20 February 1967 in Kashmir which more or or less depicts the usual elastic strain released increments in shear and compressional phases, the results are less conspicuous in India-Nepal and Kashmir-Tibet border regions. Study of more aftershocks in Himalayan region may perhaps resolve this problem.

6. Conclusions

The above study has shown that the rate of decay of aftershock activity may be related to the differences in the mechanical structure of the crust. The constant b in Gutenberg-Richter frequency magnitude relationship does not reflect the seismotectonics of different regions. More studies of the aftershock sequences should be undertaken to study the strain energy release pattern and the spatial distribution of the aftershocks *versus* the geotectonics in the Himalayan region.

as compared to that from all the aftershocks is given in Table 3. It may be seen that on an average 70 to 90 per cent of the total energy is released in

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