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550.341.5 (235.243)

# Temporal and spatial variation in seismicity connected with few earthquakes in Himalayas as precursor to earthquakes

R. K. DUBE and S. N. CHATTERJEE

*India Meteorological Department, New Delhi*

ABSTRACT. Experiments made on rock samples in laboratory and rock bursts in mines (Brady 1975, 1976) have shown that four phases, *viz*., dilatant, inclusion, crack closure and finally failure, precede fault growth. These behavioural phases have been found to be scale invariant and thus find application to earthquake processes. Spatial and temporal variations of seismicity in the aftershock area of seven earthquakes, within magnitude ($M_b$) range of 5 to 6.2, which took place in Himalayas, have been observed and the above concept has been used for earthquake prediction. Empirical relations have been obtained to predict the magnitude and time of occurrence of an impending earthquake.

## 1. Introduction

Ever since the advancements made in seismic instrumentation, it has been reported that more than a million earthquakes occur annually on the earth. While most of them are of very small magnitudes, nearly an average of about twenty happen to be of moderate/strong intensity and cause damage to life and property near their source. Due to this effect, which has tremendous bearing on human life and activities, the study of earthquakes in general and prediction of earthquakes in particular has special practical significance.

Seismologists and other earth scientists have been trying since long to find out ways for reliable prediction of earthquakes. Highly sophisticated instruments are being used in many countries to measure changes in various physical parameters connected with the occurrence of an earthquake. While no fool proof result has so far emerged out of such studies, quite good progress has been made towards the goal.

More recently, studies on temporal and spatial variation in seismicity in many small regions have revealed encouraging results about the prediction of earthquakes (Rikitake 1976, Brady 1976, Ohtake 1976). In this paper spatial and temporal changes in seismicity, connected with few earthquakes of magnitude ($M_b$) five and avove, which occurred in Himalayas, have been studied with a view to evolve an emipirical relationship for prediction of earthquakes in Indian subcontinent.

## 2. Theoretical consideration

It has been experimentally demonstrated that four distinct phases precede fault growth in rock on a small scale (Brady 1975, 1976). The phases are : dilatent phase, inclusion phase, closure phase and phase of failure. These behavioural phases have been shown to be scale invariant over a wide range of sample sizes and, therefore, can be applied to earthquake process.

During dilatent phase cracks form within the rock mass in response to the applied far field stresses. This phase culminates in the formation of crack clusters (deformation band) within the anomalous volume when the rock mass is within a few per cent of its ultimate strength. In inclusion phase, additional cracks develop in response to local stress conditions existing within the deformation band as the applied far field stresses continue to increase. Thus an inclusion zone termed as "primary inclusion zone" develops within the deformation band. This zone represents a region of highly concentrated dilatancy that forms at a time before failure. This time of formation is dependent only on the magnitude of failure to follow and time rate of change of the far field applied stresses (Brady 1975, 1976). The primary inclusion zone is characterised by deviations in seismicity rate from their normal pre-earthquake value. Crack closure occurs in the focal region in response to the decrease in magnitude of the local shear stress and the corresponding increase of the least principal stress. During this phase strain energy density increases throughout the focal region and approaches its maximum possible value when all cracks that formed during the dilatant phase are closed. Also, when the focal region of the impending failure is dry the seismic wave velocities for $P$ and $S$ will increase during the closure phase for rays passing through the focal region. However,

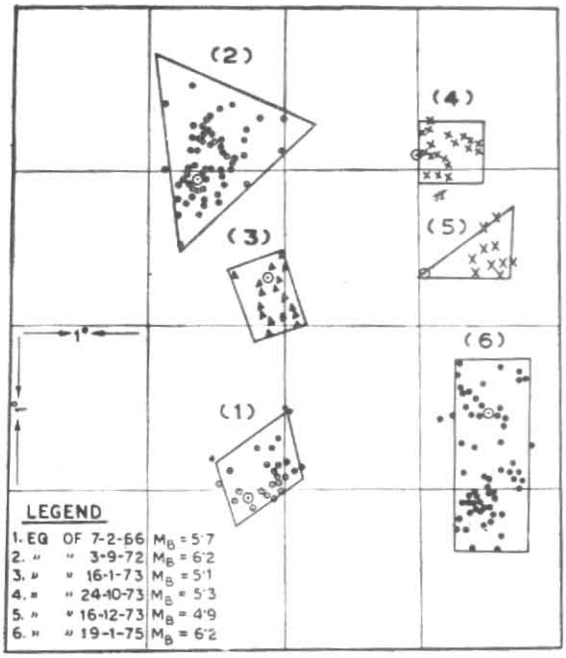

Fig. 1. Aftershock area of earthquakes

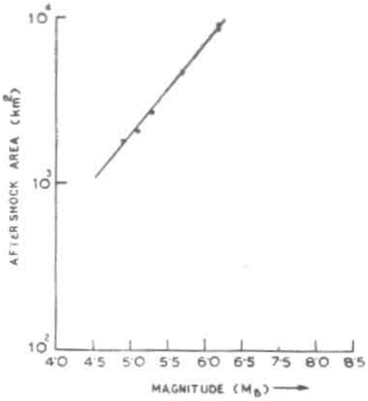

Fig. 2. Aftershock area *versus* magnitude

when the focal region is wet these velocities will decrease for the ray paths through the focal region. The velocities will recover to pre-dilatant values only when the closure front has passed.

It has been shown by Brady (1975) that when no changes take place in the far field tectonic stresses (strains) during the precursor time interval $T_0$ (time interval between the termination time of formation of inclusion zone and time of failure) the relationship between $T_0$ and the focal region area $A$ can be written as :

$$T_0 = \alpha A \tag{1}$$

Here $\alpha$ is a constant to be determined by experiments. Rockbrusts, whose precursor time is small enough, have been used by Brady (1976) to determine the value $\alpha$.

Utsu (1969), in a study of aftershocks in Japan, found a relationship between aftershock area $A$ and magnitude $M$ as

$$\log_{10} A = aM + b \tag{2}$$

Combining Eqns. (1) and (2) we find

$$\log_{10} T_0 = \log_{10} \alpha + aM + b \tag{3}$$

If $A_i$ is the area of inclusion zone and $T_{d0}$ the time of the formation of inclusion zone, it has been shown by Brady (1976) that

$$T_{d0} = \alpha A_i \tag{4}$$

and

$$\frac{A_i}{A} = u \tag{5}$$

Combining (2), (4) and (5) we have

$$\log_{10} T_{d0} = \log \alpha + \log u + aM + b \tag{6}$$

Since the values of constants in Eqn. (6) are known for a region, knowing the value of $T_{d0}$ the magnitude of the impending earthquake ($M$) and time of occurrence ($T$) can be predicted with the help of Eqns. (3) and (6).

It is, however, well known that conditions prevalent in case of laboratory experiments and rock brusts cannot easily be met within case of earthquakes. Brady, therefore, suggested a relationship between actual precursor time ($T$), and theoretical precursor time ($T_0$) applicable for earthquakes :

$$T = T_0 \left(\frac{V_0}{V}\right) = \alpha \left(\frac{V_0}{V}\right) A \tag{7}$$

where $V_0$ denotes the average velocity of crack closure front in focal region of primary inclusion zone when far field stresses remain constant during the time interval of precursor time and $V$ is the velocity with which changes in the far field stresses occur. By taking up a case study of few earthquakes the value of $V_0/V$ can be found out.

## 3. Data

In order to apply what has been described in the previous section, it becomes pertinent to know whether Utsu's relationship between aftershock area and earthquake magnitude holds good for Indian sub-continent. Therefore, aftershock area of seven earthquakes between magnitude ($M_b$) range of 5 to 6.2, whose parameters are given in Table 1, were calculated on the basis of observed aftershock data. A plot of the aftershocks of each earthquake can be seen in Fig. 1. Aftershock area

**TABLE 1**

| Date | 0 time (GMT) | | | Location of epicentre | | Depth of focus (km) | Magnitude ($M_b$) | After-shock area (km²) |
|---|---|---|---|---|---|---|---|---|
| | *h* | *m* | *s* | Lat. (°N) | Long. (°E) | | | |
| 7 Feb 66 | 04 | 26 | 11·5 | 29·92 | 69·68 | 10 | 5·7 | 2880 |
| 3 Sep 72 | 16 | 48 | 29·5 | 35·94 | 73·33 | 45 | 6·2 | 7100 |
| 16 Jan 73 | 21 | 31 | 21·0 | 33·29 | 75·83 | 39 | 5·1 | 1600 |
| 24 Oct 73 | 05 | 23 | 50·9 | 33·10 | 75·92 | 37 | 5·3 | 1800 |
| 14 Jul 73 | 04 | 51 | 20·0 | 35·10 | 86·40 | 22 | 5·9 | — |
| 16 Dec 73 | 09 | 16 | 14·1 | 32·30 | 76·00 | 33 | 4·9 | 1440 |
| 19 Jan 75 | 08 | 02 | 02·5 | 32·50 | 78·40 | 33 | 6·2 | 7200 |

(km²) of each earthquake has been plotted against the magnitude of the shock in Fig. 2. A close look at the figure indicates that a linear relationship between logarithmic value of *A* and $M_b$ holds good for the region as expected. The relationship obtained is as given below :

$$\log_{10}A(\text{cm}^2) = (0.54 \pm 0.07)M_b + 10.48 \pm 0.36 \quad (8)$$

It may thus be seen that the values of constants *a* and *b* in the equation are significantly different from those of Utsu (1969). In a similar study Tandon and Srivastava (1974) also obtained a different relationship between *A* and *M* for Indian region.

In order to study the spatial and temporal variation in the seismicity confined to the aftershock region of each earthquake (Table 1), details of earthquakes originating from aftershock zone only were collected from the bulletins of International Seismological Centers, India Meteorological Department and unpublished data from Beas Project network stations. Monthly frequency of earthquakes within a period of 8 to 12 years, depending upon the magnitude of the earthquake, have been plotted against each month (Fig. 3). This plot facilitates in calculation of the value of *T* and $T_{d0}$ in each earthquake. The observed values of *T* has been given in Table 2.

The $\alpha$ value in Eqn. (3) has been computed by making use of Eqn. (8) and data from rock bursts taken after Brady (1976). Here *T*, in case of a rock burst of magnitude (*M*) 2.3, is 21.6 hours. The value of $\alpha$ thus obtained is $\alpha = 0.14757 \times 10^{-6}$ sec/cm². Based on this value of $\alpha$, values of $T_0$ for earthquakes, between magnitudes ($M_b$) 4 and 7 were computed and shown in Table 2.

**TABLE 2**

| Magnitude ($M_b$) | $T_0 \times 10^{-1}$ (month) | $T$ (month) |
|---|---|---|
| 4·0 | 2·5 | — |
| 5·0 | 8·6 | — |
| 5·1 | 9·8 | 34 |
| 5·3 | 12·5 | 37 |
| 5·9 | 26·4 | 70 |
| 6·0 | 29·9 | — |
| 6·2 | 38·3 | 91/96 |
| 7·0 | 103·5 | — |

### 4. Discussion of results

Perusal of Table 2 indicates an appreciable difference between the computed value of precursor time $T_0$ and the observed time *T* in case of all the earthquakes studied in the present investigation. As pointed out in section 2 changes in far field stress conditions applicable in case of rock samples subjected to these stress (strains) in laboratory or rock bursts in mines, may not be similar to those in case of earthquakes; and therefore, difference between the values of $T_0$ and *T* is inevitable. Such differences have been reported by Brady (1976) for a few earthquakes and, therefore, suggested use of Eqn. (7) to compute the $\alpha$ value for a particular region which facilitates prediction of future earthquakes. The values of the ratio $T/T_0$, for each earthquake, were thus computed and given in Table 3. Based on these values of $T/T_0$ the values of $\alpha$ in case of each earthquake were calculated on the basis of Eqn. (7) and are also given in Table 3. Values of $\alpha$ were also computed for each earthquake using Eqns. (3) and (8) and shown in Table 3 for comparison. The two sets of values have been designated as $\alpha_1$ and $\alpha_2$ respectively. It is seen that a very good,

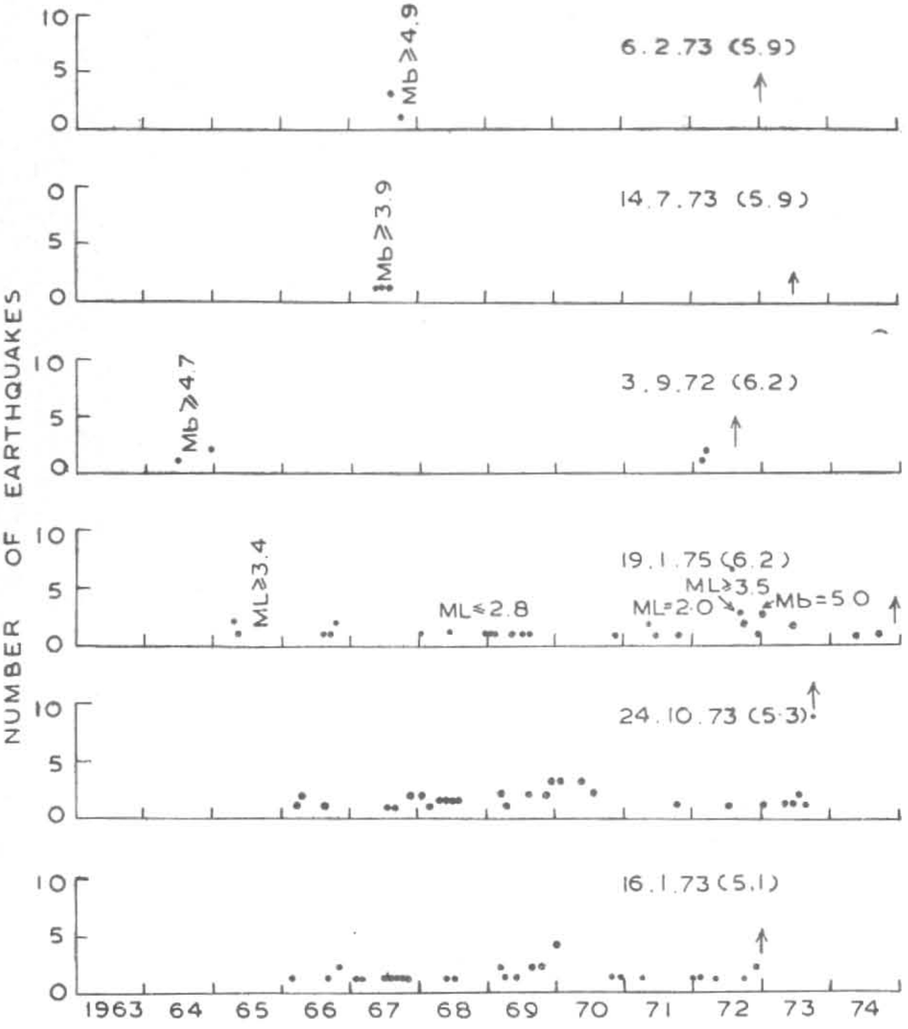

Fig. 3. Temporal variation of seismicity in the aftershock area of earthquake

TABLE 3

| Date of earthquake | Magnitude $M_b$ | $(T/T_0)\times 10^{-1}$ | $a_1$ (sec/cm$^2$) | $a_2$ (sec/cm$^2$) | Value of $T_d$(month) | |
|---|---|---|---|---|---|---|
| | | | | | Obs. | Comp. |
| 3 Sep 72 | 6·2 | 2·377 | $0\cdot34676\times10^{-5}$ | $0\cdot35075\times10^{-5}$ | 7 | 10·2 |
| 16 Jan 73 | 5·1 | 2·754 | $0\cdot40551\times10^{-5}$ | $0\cdot51286\times10^{-5}$ | 4 | 2·6 |
| 14 Jul 73 | 5·9 | 2·649 | $0\cdot39084\times10^{-5}$ | $0\cdot38905\times10^{-5}$ | 3 | 7·0 |
| 24 Oct 73 | 5·3 | 2·951 | $0\cdot43652\times10^{-5}$ | $0\cdot43652\times10^{-5}$ | 5 | 3·3 |
| 19 Jan 75 | 6·2 | 2·512 | $0\cdot36983\times10^{-5}$ | $0\cdot3327\times10^{-5}$ | 19 | 10·2 |
| 22 Mar 69 | 5·1 | 2·138 | $0\cdot31352\times10^{-5}$ | $0\cdot31003\times10^{-5}$ | 5 | 2·6 |
| 6 Feb 73 | 5·9 | 2·388 | $0\cdot35196\times10^{-5}$ | $0\cdot35237\times10^{-5}$ | 3 | 7·0 |

agreement between the two results has been obtained. It is significant to note that a very good agreement between the values of $\alpha$ exists for each earthquake. An average value of $\alpha = 0.3921 \times 10^{-5}$ sec/cm$^2$ has, thus, been accepted for prediction of earthquakes in this part of Himalayas. The following equation has been deduced to calculate the value of $T$ in case of future earthquake. :

$$\log_{10} T \text{ (sec)} = 0.54 \; M_b + 5.07329 \qquad (9)$$

To make use of Eqn. (9) we must first know the value of $M$ in Eqn. (6). Due to limitations in the detection capabilities of the Indian network of seismographic stations, it was not always possible to get the precise value of $A_i$ in case of shocks given in Table 3. It has therefore not been attempted to get the value of $u$ from the available data of these earthquakes. Brady (1976), however, reported the value of $A = 400$ km$^2$ and of $A_i = 40$ km$^2$ in case of California earthquake of 9 February 1971. This leads to the value of $u = 0.10$ which has been accepted to be used for Indian region also. Substituting the value of $u$ and that of $\alpha$ and making use of Eqns. (6) and (8) we establish the following relationship :

$$\log_{10} T_d = 0.54 M_b + 4.07329 \qquad (10)$$

Making use of Eqn. (10). values of $T_d$ in case of each earthquake of Table 1 have been computed (Table 3). Observed values of $T_d$ are also given in the same table for comparison. There appears to be a fair agreement between the computed and observed values of $T_d$ for all earthquakes except two which took place in Kinnaur region on 19 January 1975 and the other in Tibet on 14 July 1972. While detection level in case of Kinnaur earthquake region is very good due to Beas Project network the same is not true for Tibet region. Low value of $T_d$ obtained in case of Tibet earthquake may thus be due to lower detection level (shocks of $M_b > 4$ only have been detected).

Based on observed value of $T_d$, the magnitude ($M_b$) of the impending earthquake in Kinnaur region has been computed as 6.9. The precursor time $T$ for an earthquake of this magnitude is estimated to be 20.3 years. In reality, however, an earthquake of $M_b = 6.2$ followed by an aftershock ($M_b = 6.0$) within hours, occurred about ten years earlier than estimated time; also the earthquake was followed by anomalously large number of aftershocks. Temporal variation of seismicity in the aftershock area in Fig. 3 of this earthquake reveals that besides increase in the background seismicity ($M_L \geqslant 3.5$) in the year 1965-1966, there has also been a significant increase in the months of Sep, Oct and Nov 1972 when few earthquake of $M_L \geqslant 3.5$ followed by an earthquake of $M_b = 5.0$ occurred very near the epicentre of the main shock. This distressing element perhaps triggered the occurrence of a lower magnitude event earlier. It may also be added here that detection level of Beas network increased only in 1968 and except few events of $M_L \geqslant 3$ in 1972 all were of lesser magnitude.

Brady (1976) suggested that the magnitude ($M^*$) of the earthquakes occurring in the area of inclusion zone can be given by :

$$M^* = M_n + 3.1 \qquad (11)$$

where $M_n$ can be related with the aftershock area ($A$) by the following relation :

$$\log_{10} A = 0.54 \; M_n + 3.342 \qquad (12)$$

Thus for an impending earthquake of $M_b = 6.2$, the earthquakes which form the area of inclusion zone should be of $M_b = 3.8$. Therefore, it can be suggested that the area of inclusion zone for Kinnaur earthquake formed during 1965-66 and an earthquake of higher magnitude would have occurred if distressing element as pointed out earlier was not present. Brady (1976) also observed a similar phenomenon in case of Peru earthquakes of 3 October and 9 November 1974.

Various types of precursor observations like temporal changes in seismicity, changes in $P$ and $S$ wave velocities, tilt, resistivity etc have been reported by Nersesov *et al.* (1975), Wyss (1975). In case of Garm earthquake of 22 march 1969. U.S.C. G.S. reported $M_b$ value of this shock as 5.3. This has been converted to the I.S.C. value of $M_b = 5.1$ by making use of a relation found by Chatterjee and Dube (1978). Eqns. (9) and (10) have been used to compute the values of $T$ and $T_d$ for this earthquake. While computed values of $T$ and $T_d$ are 26 and 3 months, the observed values are 20.5 and 5 months respectively. Thus a good agreement exists between the observed and calculated values of $T$ and $T_d$.

Rikitake (1976) proposed an empirical relationship between precursor time ($T$) and magnitude ($M_L$) of an impending earthquake based on comprehensive compilation of case studies of many earthquakes. According to him seismicity gap for an impending earthquake of $M_L = 6.9$, $M_b = 6.0$ should be of the order of 85 months. Ohtake (1976) also observed a seismicity gap of 90 months for an earthquake of similar magnitude. Scholz *et al.* (1973) and Whitcomb *et al.* (1973) observed a seismicity gap of 64 and 84 months respectively for a shock of $M_b = 6.0$.

## 5. Conclusions

From what has been described in the foregoing paragraphs, it can be concluded that if we successfully monitor the temporal and spatial variations in regional seismicity and are in a position to detect the formation and duration of the area of inclusion zone of an impending earthquake, the magnitude and time of occurrence of the earthquake in Himalayan region can be predicted by making use of the following empirical relations:

$$\log_{10} T_d = 0.54 \, M_b + 4.07329 \qquad (13)$$

$$\log_{10} T = 0.54 \; M_b + 5.07329 \qquad (14)$$

It may, however, be mentioned here that in case some distressing elements are present in the region, occurrence of the earthquake may be triggered and a shock of lower magnitude than that predicted may occur.

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## DISCUSSION

(Paper presented by R. K. DUBE)

G. S. MURTY (BARC) : What is the meaning of area in your computation? If all epicentres fall in a vertical plane, you get no area on the surface.

AUTHOR : Aftershock area has been calculated, after plotting the locations of epicentres of aftershocks on a map (scale 2 mm = 1 km) and delineating the area thus occupied in possible geometrical shape, using usual methods.

In case all the epicentres lie in a vertical plane, area has to be calculated by plotting hypocentral location.