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Validity of time-predictable seismicity model for Nepal and its adjoining regions

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ABSTRACT

Earthquake generation model for the Nepal Himalaya and its adjoining regions was studied using seismicity data from 1963 to 2004 reported in the catalogues of National Geophysical Data Centre, Colorado and U. S. Geological Survey. The earthquakes having a surface wave magnitude $M_s \geq 5.1$ were considered to establish the statistical relation. Four seismogenic sources based on clusters of earthquakes have been identified in the region. It is observed that the time interval between two consecutive main shocks depends on the preceding main shock magnitude (M_p) and not on the forthcoming main shock magnitude (M_f). The result supports the applicability of time-predictable model for Nepal and its adjoining regions. A linear relation is established connecting the logarithm of the inter-event times between two successive main shocks (T) and magnitude of preceding main shock in the form $\log T = cM_p + a$ where parameter a is a function of the minimum magnitude of the earthquake considered and the tectonic loading, and c is a positive constant. The physical meaning of the model is that larger the magnitude of the preceding main shock the longer will be the time interval for the forthcoming earthquake. The values of constants c and a for Nepal Himalaya and its adjoining regions are computed to be 0.25 and -0.65 respectively. This result can be utilised to compute the time of occurrence of the impending strong earthquake within the delineated seismogenic sources and may be used for assessing the long-term seismic hazard in the region.

Keywords: Time-predictable sesismicity model, seismogenic sources, seismic hazard, Nepal, Central Himalaya

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INTRODUCTION

The important aspect connecting elastic rebound and earthquake periodicity is the steady application of loading motions and accumulation of strain due to plate motion. Strain accumulates along a fault because of relative motions on either side of fault (Reid 1910). Once the strain reaches a critical value, the fault overcomes the frictional resistance resulting in relaxation of strain and earthquake occurs. A new cycle of strain accumulation begins after the earthquake. Failure of faults with certain periodical nature is very important for earthquake prediction and related hazard mitigation. If so, earthquake should occur along a fault at a regular interval.

Over last five decades or more, numerous probabilistic and deterministic models have been developed to display several aspects of seismic events. Most of these earthquake generation models for seismic hazard evaluation assume a Poisson distribution or other memoryless distributions (Cornell 1968). Most of the studies related to seismicity and the seismic hazard estimation assume that the seismicity does not change with time but only with space (Papazachos et al. 1994). Such time-independent models are commonly based on the Gutenberg-Richter formula (Gutenberg and Richter 1944) for the distribution of magnitudes, and the Poisson distribution for the time. However, during the last three decades, several efforts have been made to examine the validity of time-dependent seismicity model and it is established that the repeat times for earthquakes occurring in a single fault or simple plate boundaries favour the time-predictable model. This model suggests that the time of occurrence of a future earthquake in a fault is related to the size and time of occurrence of the last earthquake in the fault. In addition to repeat times, the time variation of the foreshocks and aftershocks strongly supports this model (Mogi 1985). Repeat times of strong earthquakes in the Aegean area were used to show that the time-predictable model holds for seismogenic sources also, which include major faults as well as other faults in a region (Papazachos 1989, 1992). This research led to the development of a regional time- and magnitude-predictable model.

Shimazaki and Nakata (1980) proposed two kinds of time-dependent models based on a long earthquake history in the vicinity of Kyoto and measured coastal uplifts during the earthquakes. The first is a time-predictable model and the second is a slip-predictable model. Later on several investigators improved the time-predictable model (e.g., Sykes and Quittmeyer 1981; Anagnos and Kiremidjian 1984; Papazachos 1989, 1992) and the slip-predictable model (e.g., Kiremidjian and Anagnos 1984). Using the similar statistical methods, a magnitude-predictable model was developed. This model relates the magnitudes of preceding and following earthquakes and implies that the larger the magnitude of the preceding mainshock, the smaller the magnitude of the following mainshock (Papazachos 1992). Later on the time-predictable and magnitude-predictable models were integrated to a regional time- and magnitude-predictable seismicity model, which holds for seismogenic regions (or sources) that include main fault and other smaller faults (Papazachos and Papaioannou 1993). The time- and magnitude-predictable models are the statistical methods for long-term earthquake prediction and have been employed in different seismically active regions to estimate the magnitude and time of occurrence of a forthcoming earthquake. Some examples of such regions are: eastern Anatolia (Sayil 2005), Taiwan (Wang 2005), Hindu Kush–Pamir–Himalaya and northeast India (Shanker and Papadimitriou 2004; Shanker and Singh 1996), China (Qin et al. 2001), Circum-Pacific belt (Papadimitriou et al. 2001), Greece and Japan (Karakaisis 2000), Alpine–Himalayan belt (Papazochos et al. 1997), Italy (Mulargia and Gasperini 1995), Indonesian region (Papadimitriou and Papazachos 1994), Greece (Papazachos 1989), and Western coast of south and central America (Papadimitriou 1993).

The time-predictable model predicts earthquakes when strain accumulation on the fault attains to a critical level but the stress drop and the magnitude of the earthquakes vary among the seismic cycles (Fig. 1a). The time to the next earthquake can be estimated from the slip in the previous earthquake assuming a constant tectonic loading on the fault. Thus the recurrence interval depends on the size and time of occurrence of previous earthquakes in a fault. In the slip-predictable model, the earthquake on a fault resets the stress to some constant level irrespective of the magnitude and hence the size (magnitude, coseismic slip) of a future earthquake in a seismic source depends on the time elapsed after the last earthquake (Fig. 1b).

In principle, only the size of a future earthquake can be predicted by the slip-predictable model, and only the time of future earthquake by the time-predictable model. The models

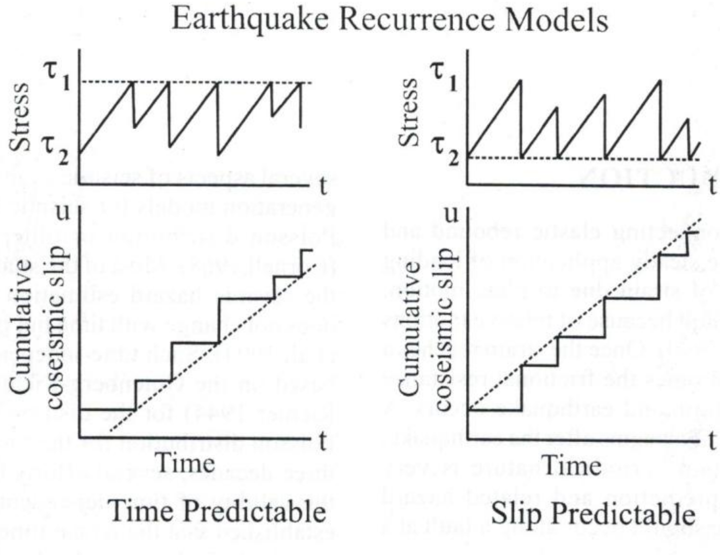

Fig. 1: Schematic earthquake recurrence models: a. time-predictable model illustrating stress buildup to a certain level (τ_1) and non-uniform stress drop; and b. slip-predictable model showing non-uniform stress buildup and stress drop to a certain level (τ_2) (after Shimazaki and Nakata 1980).

assume a constant rate of accumulation of tectonic stress in a region. In a time-predictable model, the time interval between two large earthquakes is proportional to the slip amount of the preceding earthquake, and large earthquakes occur when the stress has reached a fixed limiting value (τ_1), whereas the base stress level (τ_2) is variable. The slip-predictable model is specified with varying τ_1 and constant τ_2, thus producing a variable stress drop. In the latter model, the time interval between the large earthquakes is proportional to the slip amount of next large earthquake. Hence the slip of a future earthquake can be predicted from the date of occurrence of a previous earthquake. Several investigators (Mogi 1985; Papazachos 1989; Shanker and Singh 1996) used the time-predictable model for different regions of the world. The present work is aimed at testing the validity of the time-predictable model in the seismogenic sources of the Nepal Himalaya and its vicinity.

SEISMOGENIC SOURCES IN NEPAL AND ITS ADJOINING REGIONS

The Nepal Himalaya (26°–31° N, 79°–90° E) is situated near the boundary of the Indian and Eurasian plates. The pattern of earthquakes in the region manifests the collision between these two plates. The Main Central Thrust (MCT), Main Boundary Thrust (MBT), Main Frontal Thrust (MFT), and a number of transverse faults and lineaments control the seismotectonic activity of the region. A number of geoscientists have carried out geological as well as tectonic investigation in the Himalaya and its adjoining areas. Some recent reviews on the geology and structural framework are presented by Upreti (1999) for the Nepal Himalaya, Avouac (2003) for the central Himalaya, and Hodges (2000) and Yin (2006) for the entire Himalayan region.

Following Papazachos (1989), seismotectonic criteria, recent and historical seismicity levels, type of faulting, geological condition and clustering pattern of events for $Ms \geq 5.1$, four seismogenic sources: CH-1 (Central Himalaya seismogenic source zone), CH-2 (Nepal–Bihar border region), CH-3 (Eastern Nepal Himalaya and its vicinity), and CH-4 (between south-central Tibet and north of the Indus–Tsangpo Suture, ITS) were delineated in the Nepal Himalaya and its surrounding regions (Fig. 2). In addition, the following points were also considered while demarcating the sources: (a) in each source at least one main shock of magnitude $Ms \geq 5.9$ occurred during 1963–2004 and (b) each source has some distinct characteristic properties different from the surrounding region (such as faulting, seismicity level etc). Information on the earthquakes occurred during the period with $Ms \geq 5.1$ for each seismogenic source is given in Table 1. The cumulative magnitude (M) corresponds to the total moment released by the main shock sequence (main shock, large foreshocks and aftershocks) according to the relation between surface wave magnitude, seismic moment and moment magnitude as given by Purcaru and Berckhemer (1978) and Hanks and Kanamori (1979). The minimum magnitude (M_{min}) is considered in each case to define the corresponding cumulative magnitude (M_p), the magnitude of the following earthquake (M_f), and the repeat time (T). The repeat time represents the time from the beginning of one seismic sequence to the beginning of the next seismic sequence.

The source CH-1 situated in the western Nepal and vicinity is found to be the most active in the considered period as compared to other sources. This source is characterised by intense microseismic activity (Pandey et al. 1999) in which Bajhang earthquake of 1980 with *M 6.5* caused a loss of 178 lives. The MBT and some transverse faults such as the Karnali and Tanakpur are responsible for the seismicity in this zone and most of the events are located between the MCT and the MBT. The source CH-2, which covers the bordering regions of Bihar and Nepal, produced the great earthquake of *M 8.4* in 1934. After this earthquake, the region has been quite for a long period. After a quiescence period of about 55 years, another catastrophic medium-size earthquake with *Ms 6.6* has rocked the same epicentral tract in and around Udayapur in 1988 killing about 1100 lives and producing widespread destruction in southeastern Nepal and Bihar. In this region, the MCT, MBT, and MFT run close to each other. A number of transverse faults such as the Motihari– Everest, Dudh Kosi, Arun, and East Patna are also reported to be seismically active. The source CH-3 is located in far eastern Nepal and also occupies part of the southern Tibet. Here, the MCT and MBT come close to each other. In this source region, the NNW– SSE trending lineaments such as the Tista and Gangtok are also responsible for the seismic activity. The seismogenic source CH-4 situated to the north of ITS in Tibet shows a concentrated abnormal seismic activity. An active local fault produces moderate-size events in this zone. The zone CH-4 is in southern Tibet whereas the remaining three zones are associated with the MCT, MBT, and MFT.

METHODOLOGY AND CALCULATION

The relation between inter-event time (T) between two successive main shocks in a region and the magnitude of the preceding main shock, M_p, may be represented in the form of

$$\log T = \boldsymbol{c}\, M_p + \boldsymbol{a} \qquad (1)$$

where $\boldsymbol{c}$ is a gradient of least square line and is a positive constant, and $\boldsymbol{a}$ is a constant function of the magnitude. Since the magnitude M_p is linearly related to the logarithm of the coseismic slip, Equation (1) indicates that the time between two successive main shocks in a seismogenic source is linearly related to the coseismic slip of the previous main shock. This supports the time-predictable model, which predicts that the repeat time is proportional to the coseismic slip of the last main shock (Shimazaki and Nakata 1980). The

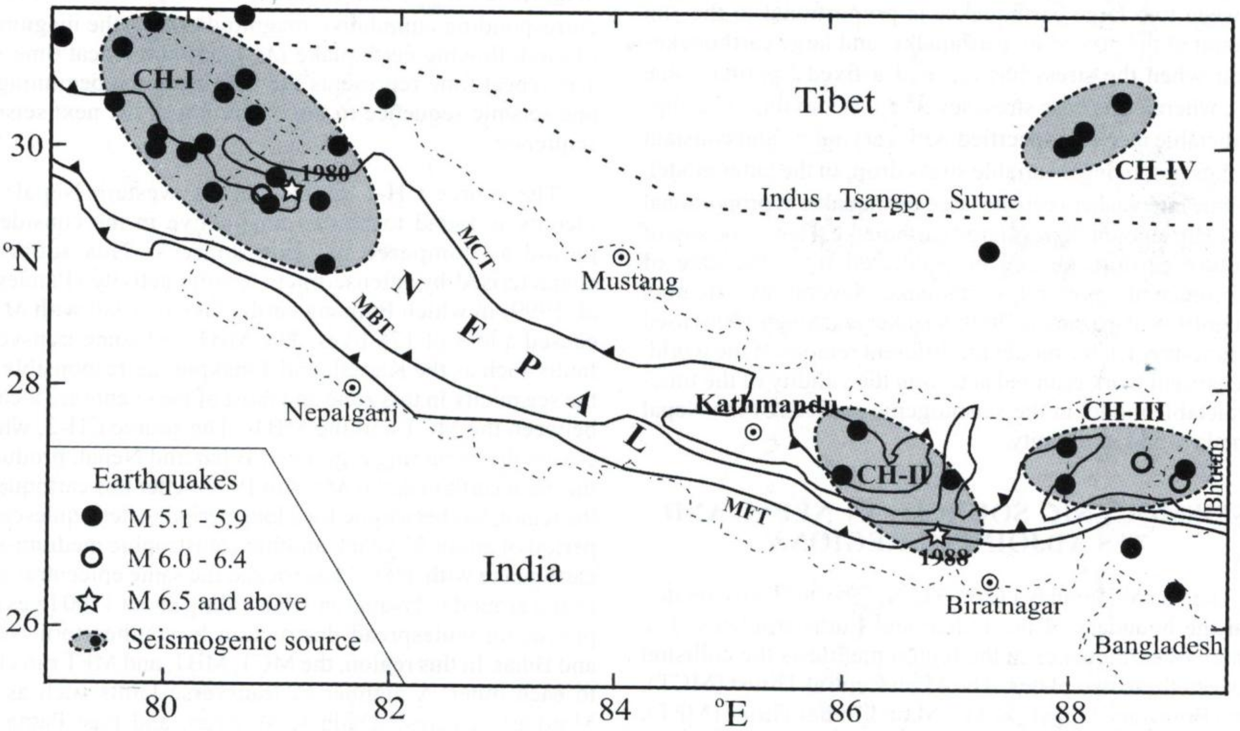

Fig. 2: Distribution of earthquakes with *Ms ≥5.1* for the period 1963–2004 in Nepal and its vicinity in four seismogenic sources (CH-1, CH-2, CH-3, and CH-4) are shown over major tectonic features of the region. These seismogenic sources are demarcated by dotted elliptical boundaries based on spatial distribution of these earthquakes (CH = Central Himalaya).

time-predictable model established for a region can only be valid if the value of ***c*** (i.e., the coefficient of M_p) are always positive (Qin et al. 1999). The global value of this coefficient is 0.33 (Papazachos and Papadimitriou 1997). The regional value of ***c*** for Greece, northeast India, Aegean area, and for western coast of south and central America is estimated at 0.32, 0.36, 0.35, and 0.21 respectively.

The cumulative magnitude *M* corresponding to the moment released by the main shocks, foreshocks, and aftershocks of each earthquake sequence has been calculated using relations

$\log M_o = 1.5M_s + 16.5$ (Purcaru and Berckhemer 1978)

and moment magnitude

$M_w = 2/3 \log M_o - 10.7$ (Hanks and Kanamori 1979)

where M_0 is the moment released. M_{min} is considered in each source to define the corresponding preceding magnitude and repeat time in years. The calculated values of *M*, M_{min} and repeat times are given in Table 1. To explain the procedure for estimating these parameters, we consider the seismogenic source CH-1. The sixth column in Table 1 denotes the cumulative magnitude *M 6.4* (1966), *6.6* (1980), and *5.8* (2002) for three cases. On considering $M_{min} = 5.8$, there are three earthquakes with two repeat times corresponding to each M_p and M_f which precedes and follows each period as for M_p *6.4* (*T 14.09* years) and for M_p *6.6* (*T 21.85* years). The value of M_f for the first (between events *6.4* and *6.6*) and the second (between events *6.6* and *5.8*) return periods are 6.6 and 5.8 respectively. In this case, the further, for $M_{min} = 6.4$ (here the calculation is done after excluding the shock with $M = 5.8$), then only two earthquakes remains which are *M 6.4* (1966) and *M 6.6* (1980), and provide only one repeat time of *T 14.09* years corresponding to M_p *6.4*. Following similar procedure, all the related calculations were done in each seismogenic source and the final results are reported in Table 1.

Using the data furnished in Table 1 for M_p and *log T*, the following linear relation was developed:

$$\log T = 0.2478\, M_p - 0.343 \qquad (2)$$

Table 1: Earthquake Data for Ms ≥5.1 used to test the validity of the time- and magnitude-predictable model; a and f **represent aftershocks and foreshocks, respectively. M is cumulative magnitude.**

Seismogenic sources	Date (dd/mm/y)	Location		M_s	M	M_{min}	M_p	M_f	T (years)
		Lat °N	Long °E						
CH-I	26.09.1964	29.96	80.64	5.9	f	5.8	6.4	6.6	14.09
	27.06.1966	29.62	80.83	6.1	6.4		6.6	5.8	21.85
	16.12.1966	29.6	81	5.9	a	6.4	6.4	6.6	14.09
	31.05.1968	29.9	80	5.7	a				
	05.03.1969	29.2	81	5.2	a				
	12.02.1970	29.4	81.6	5.4	a				
	20.05.1979	29.93	80.27	5.9	f				
	29.07.1980	29.63	81.09	6.5	6.6				
	27.11.2001	29.61	81.86	5.5	f				
	04.06.2002	30.59	81.44	5.6	5.8				
CH-II	22.02.1963	27.2	87.1	5.3	5.3	5.2	5.3		6.99
	26.02.1970	27.2	85.6	5.2	5.2		5.2		4.85
	24.03.1974	27.7	86.1	5.7	5.7		5.7		14.40
	20.08.1988	26.77	86.81	6.6	6.6	5.3	5.3	5.7	11.84
							5.7	6.6	14.4
						5.7	5.7	6.6	14.4
CH-III	27.03.1964	27.2	89.3	6.3	6.4	5.1	6.4		8.39
	12.01.1965	27.6	88	6.1	a		5.1		8.24
	21.08.1972	27.2	88	5.1	5.1		6.1		22.65
	19.11.1980	27.4	88.75	6.1	6.1	5.5	6.4	6.1	16.64
	25.03.2003	27.26	89.33	5.5	5.5		6.1	5.5	22.65
						6.1	6.4	6.1	16.64
CH-IV	22.02.1980	30.51	88.58	5.9	5.9	5.9	5.9	6.0	18.51
	31.07.1996	30.17	88.18	5.5	f				
	20.07.1998	30.13	88.17	5.2	f				
	25.08.1998	30.08	88.11	5.9	6.0				

This equation has a correlation coefficient of 0.64. This equation facilitates to establish the relation between four seismogenic sources. The value of ***c*** is affected by both ***a*** and M_{min} considered in each case. To reduce the value of *logT* in the same level, the value of parameter ***a*** was determined for all available values of *T* and corresponding M_p using $c = 0.2478$. This gives the average value. Similarly, the values of a_{mn} for each case were calculated for the corresponding set of M_{min} and *T* which give the average value as $\bar{a}_{mn} = -0.041$. The differences $\bar{a}_m - \bar{a}_{mn}$ were added to the corresponding *logT* and obtained the value of *logT** as

$$logT^* = logT + \bar{a}_m - \bar{a}_{mn}$$

where *T** is the average repeat time of the event for all the seismogenic sources.

The plot of *logT** and M_p were fitted in the least square relation (Fig. 3a) as

$$logT^* = 0.25\,M_p - 0.65 \qquad (3)$$

This equation has a correlation coefficient of 0.69. It demonstrates that the average repeat time increases with increasing M_p. The positive value of the coefficient of M_p (Equation 3) implies that longer quiescence periods precede the large-magnitude earthquakes, which agree with the concept of the time-predictable model. It means that the time-predictable model can help to understand the generation of earthquakes in the Nepal Himalaya and its adjoining regions.

The relation between *T** and the following main shock magnitude M_f is computed using the same procedure and the same data set (Fig. 3b):

$$log\,T^* = -\,0.09\,M_f + 2.46 \qquad (4)$$

The value of M_f is very small for M_{min} *5.1* and *5.2*, hence the corresponding values of M_f has been excluded to compute above equation (Table 1). This equation has a small

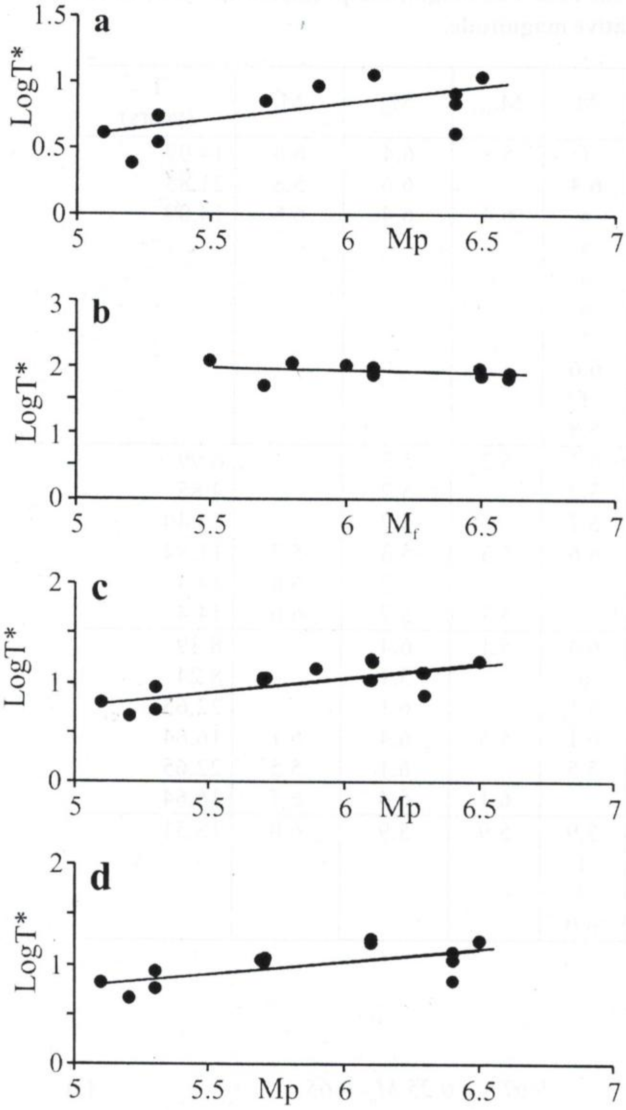

Fig. 3: Plot of repeat time T^* against M_p (the preceding main shock magnitude) and M_f (the following mainshock magnitude). a) and b) considering all the earthquakes; c) when aftershock and foreshocks were excluded; and d) excluding the seismogenic source CH-4.

correlation coefficient of 0.33. The negative slope of the curve advocates that lesser time is needed for a larger forthcoming earthquake, which is impossible. Therefore the result does not support the slip predictable model for the region.

A similar examination for the same data set, excluding foreshocks and aftershocks (Fig. 3c) yields

$$log\ T^* = 0.30M_p - 0.747$$

with a regression coefficient of 0.69.

The source CH-4 is situated in south central Tibet and is associated with a different tectonic setup as compared to the other three sources in the Himalayan compression zone. Hence, by excluding the source CH-4 in the statistical analysis, the relation between the recurrence time and the magnitude of the preceding earthquake becomes (Fig. 3d):

$$log\ T^* = 0.25M_p - 0.462$$

with a regression coefficient of 0.64.

DISCUSSIONS AND CONCLUSIONS

It has been reported by several workers that the time-predictable model holds for earthquakes generated in a single fault or in simple plate boundaries. However, Papazachos (1989) showed based on his study in Greece that the time-predictable model can also be applied in several seismotectonic environments with multiple fault systems. On the other hand, the model does not hold well in various regions having a complex tectonic setting such as Parkfield, California (Murray and Segall 2002). It is significant to estimate recurrences of strong earthquakes rupturing an active fault to study long-term seismicity pattern and associated hazards. Since earthquakes do not occur periodically on a certain fault, an average recurrence period of earthquakes is usually computed either for a certain area or for a particular fault (Wang 2005). It is easier to estimate the recurrence period for certain areas having a complex tectonic setting than that for a single fault. However, an average recurrence period for different earthquakes occurring on different faults in certain area cannot provide an accurate value of recurrence period for a particular fault. It is also reported that the average recurrence period of large earthquakes associated with a particular fault could be enormously large (several hundreds to even a few thousand years, Wang 2005). The information derived through palaeoseismicity and historical documents can help estimate the recurrence period for a particular fault. The time- and magnitude-predictable model may be useful for reducing the uncertainties involved in the estimation of seismic hazards derived through a time-independent model (Sayil 2005).

The identified seismogenic sources in the Nepal Himalaya and its surrounding areas show diverse tectonic environments. A number of fault-plane solutions in the seismic sources CH-1, CH-2, and CH-3 show mostly thrust faulting and thrusting with strike-slip components, whereas only normal faulting is observed in the seismic source CH-4 situated to the north of the ITS in the Tibetan region (Molnar and Tapponnier 1978; Ni and Barazangi 1984; Verma and Krishna Kumar 1987; Molnar and Lyon-Cae, 1989; Singh 2000).

A strong positive correlation between $logT$ and M_p derived in the present study indicates the applicability of a time-predictable model, and it can be used to estimate the recurrence period of earthquakes in seismogenic sources in the Nepal Himalaya and its adjoining regions. Hence the results can be useful in long-term earthquake prediction and time-dependent seismic hazard evaluation in the region.

As cumulative magnitude is an accurate representation of the size of the earthquake, the relation between the recurrence period and the magnitude of the preceding mainshock can be used to estimate the time of occurrence of the forthcoming earthquake in each seismic source.

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