Fluctuation of seismic activity associated with 1999 Chamoli earthquake

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Abstract

The Chamoli earthquake of March 28, 1999 (M_b 6.6, Origin time: 19:05:12, epicenter at 30.5°N 79.4°E and Focal depth 23 km) occurred in the Himalayan front arc which caused severe damage in the region. Anomalous seismic activity associated with this recent devastating earthquake in the Central Himalaya region in an area bounded by 30.0°-31.0° N and 79.0°-80.0° E have been studied using seismicity data from 1980-2000. The preparatory zone is delineated using the temporal and the spatial distribution of earthquakes, considering the events with cutoff magnitude $m_b \geq 4.3$. Daily number of events as well as cumulative number of earthquake with time within the preparatory zone has been considered as basis for identification of anomalous seismicity. Accordingly four anomalous episodes: Normal/ background (N); Anomalous/ swarm (A); Precursory gap (G) and Mainshock sequence (M) are identified. It is observed that the event was preceded by well defined patterns of anomalous seismicity/ precursory swarm which was lasted for about seven month and had started about three years and four months prior to mainshock.

Key words: *Anomalous seismicity, Central Himalaya, Precursory swarm, Earthquake forecast.*

Introduction

The seismic activity in the Himalaya region is directly related to the collision between Indian and Tibetan plate. Four great earthquakes and a large number of major earthquakes have occurred in the region since 1897. Main Central Thrust, Main Boundary Thrust and Main Frontal Thrust control the fundamental tectonic framework of the Himalayan region. These northward dipping thrusts are the continuous structure throughout the Himalayan range having offset at many places by nearly N-S transverse fault. The trend of most of the tectonic stress is north south where thrust faulting is dominant. All seismic activity within the region is due to release of stress along the major faults and lineaments.

Various precursors are known to precede medium to large earthquakes (Rikitake, 1976, 1982). Anomalous seismicity is the first to take place as compared to other precursory phenomena due to formation of various ruptures where considerable strain energy is accumulated (Sekiya, 1977). Hence it may be an important parameter for the prediction of long-range earthquake related hazards in a region. Noticeable fluctuations in seismicity, mostly prior to significant earthquakes, have been observed in various regions of the world. In the pending focal region of a large earthquake, numerous ruptures or heterogeneities probably exist on the main fault that can produce earthquakes in response to the loading process. The phenomenon of seismic quiescence, in which the background seismic activity drops to almost zero, has often been observed prior to the mainshock. The quiescence is often broken by stress buildup resulting in an increase in the number of earthquakes, known as pre-shocks. Such seismic quiescence often ends with foreshock activity that takes place just before the mainshock. The seismicity level drops to a low background level after the completion of a mainshock sequence.

Precursory seismic quiescence, defined by a decreased seismicity rate, and has been used authentically for earthquake predictions (Habermann and Wyss, 1987; Habermann, 1988). Mogi (1969, 1985) was the first to suggest that seismic quiescence may precede large mainshocks, based on his observation of a doughnut pattern associated with earthquakes having M>6, in which the seismicity rate was reduced in and near the epicentral area. A swarm is a succession of earthquakes clustered in space and time without having any principal mainshock. A precursory earthquake swarm occurs in and around the focal region of a major earthquake several years before its occurrence (Evison, 1977 a,b). Evison (1982) proposed a generalized precursory swarm hypothesis for the occurrence of multiple earthquake swarms, precursory gap and multiple mainshock events. The hypothesis was tested in Japan and New Zealand (Evison and Rhoades, 1993, 1997, 1999) and updated accordingly. Following a similar methodology, several cases of the earthquake swarm pattern were reported in different parts of Himalaya and its adjoining region, such as: Singh et al. (1982) for Burma Szechwan region; Singh and Singh (1984, 1985, 1986) for Pamir and its adjoining region; Gupta and Singh (1986, 1989) and Singh et al. (2005) for north-east India; Shanker et al. (1995) for Himachal Pradesh, India. Singh and Singh (1986) proposed a hypothesis for occurrence of an earthquake swarm sequence and related mainshock sequence based on identification of such a pattern in the Himalayan region. Such anomalous phenomena also observed prior to 1980 Bajhang earthquake of Ms 6.5 (Paudyal, 2008) and 1988 Udayapur Earthquake of Ms 6.6 (Paudyal, 2011) in the Nepal Himalaya.

A gradual increase in seismic activity in a region has been explained by a slow increase of tectonic stress through the dilatancy hypothesis; whereas a decrease in seismic activity was observed in the dilatancy hardening stage (Scholz et al., 1973). A burst of seismic activity reflects the onset of the precursory sequence that follows a period of abnormal quiescence which continues till the occurrence of the major event (Evison, 1977a). The entire preparatory period may be classified into four episodes as: Normal (or background) seismicity sequence (measured till the onset of swarm activity); anomalous seismicity (or precursory swarm) sequence (period from the onset to end of swarm activity); precursory gap (or seismic quiescence) sequence (from the date of termination of swarm activity to the onset of the mainshock sequence); and the mainshock sequence (duration of mainshock and its associated aftershocks) (Evison, 1977a; Singh and Singh, 1984). Within the preparatory area, the episodes of normal (N), anomalous (A), gap (G) and mainshock (M) sequences represent anomalously low, high, low and high seismic activities, respectively.

A reliable seismicity database spread over a wide range of magnitudes in a region is essential for the understanding of earthquake processes and precursory phenomena (Rikitake, 1982). The importance of seismicity data for earthquake prediction has been demonstrated in a number of studies (Habermann and Wyss, 1987). Further, Habermann and Wyss (1984) have stressed the importance of evaluating the background seismicity level and its changes for estimating abnormal fluctuation in the seismicity pattern prior to large earthquakes. In the present study, the existence of anomalous seismicity patterns in the region prior to the occurrence of large earthquakes is examined. The earthquake database compiled for the period 1963-2006 for Central Himalaya region by Paudyal (2008) using existing catalogues of NEIC, National Seismological Center (NSC) and International Seismological Center (ISC) has been used for the identification of seismicity patterns.

Chamoli earthquake of 28 March 1999 (m_b 6.6)

In the Central Himalaya regions, the cutoff magnitude for the period 1963-2006 is estimated to be $m_b \geq 4.3$ using b-value method (Paudyal, 2008). Hence only earthquakes with $m_b \geq 4.3$ have been considered for identifying seismic anomalies. The mainshock occurred in Chamoli region of India in close association with a surface trace of the MCT, and is the largest among the recent earthquakes in the Central Himalaya region. The distribution of the events in this region (79–80^o E) prior to the Chamoli earthquake (1963-1990) followed clearly the surface trend of the MCT. The area considered is bounded by 29.9^o-31.0^o N and 79^o-80.2^o E (Fig. 1a). The earthquakes from 1981 to 1999 were considered to investigate the precursory seismic activity. The space, time and depth distribution of events during this period is used to identify four anomalous episodes preceding the mainshock. The delineated preparatory area is oriented in the northwest-southeast direction (Fig. 1a). Four identified episodes are given in Table 1.

Table 1: Seismic characteristics in the identified seismic episodes in the preparatory area of Chamoli mainshock

Seismic episodes	Duration	Days	Total events	Level of activity
Normal/ background (N)	19 Jun. 1981–26 Nov. 1995	5574	7	Extremely low
Anomalous/ swarm (A)	27 Nov. 1995 –18 Jun. 1996	205	4	Extremely high
Precursory gap (G)	19 Jun. 1996 –27 Mar. 1999	1012	1	Extremely low
Mainshock sequence (M)	28 Mar. 1999 –02 Jun. 1999	-	-	Extremely high

In the normal episode, a total of 15 earthquakes occurred in two clusters, extending from the epicenter of Chamoli earthquake to the west-southwest (within ~10-30 km); and towards the southeast (within ~50-80 km). Seven of these events were within the delineated preparatory area (Fig. 1a) having focal depths in the range 20-70 km (Fig. 1c). These represent very low seismic activity, with a frequency of one event every two years. After the termination of normal seismicity, a burst of seismic activity occurred in a short period of about 205 days (Table 1) with the occurrence of four events in sequence in the magnitude range of 4.3-5.3. This gives a very high annual frequency of ~8 events that represents a sixteen fold increase in the seismicity rate. These four events are distributed almost in a line about 30 km long trending in a NW-SE direction out from the epicenter of the mainshock. The events in the anomalous sequence are confined to a narrow depth segment of 15 km (27-42 km focal depth) and hence constitute a very well defined pattern of anomalous seismic activity (Fig. 1a, c). The anomalous seismicity episode was followed by a long quiescence of about thirty-three months until the occurrence of the mainshock (Table 1; Fig. 1b). During this period, two events occurred, of which only one event of 28 February 1999 is located within the delineated preparatory area, providing an extremely low seismic activity as compared to that of the anomalous episode.

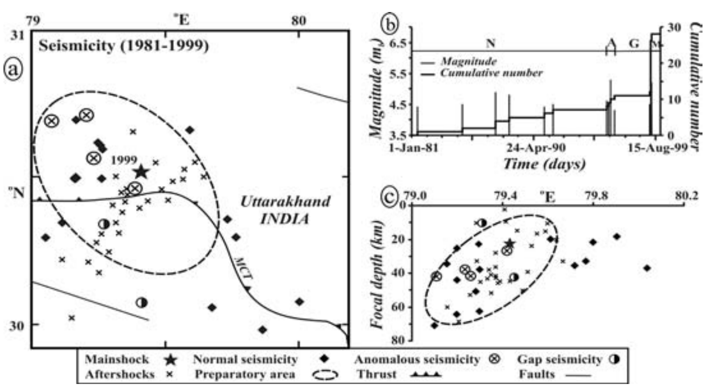

Fig.1: (a) Spatial, (b) temporal and (c) focal depth distribution of events ($m_b \geq 4.3$) associated with Chamoli earthquake. The dotted NW-SE trending elliptical area is the preparatory zone for the main shock which has been delineated based on spatial and temporal clustering of events in four seismic phases. The relation between the cumulative/ daily number of events and magnitude with time that occurred during 1981-1999 are shown in (b). Four anomalous seismic phases identified are: Normal seismicity (N); Precursory swarm (A); Precursory gap (G); and Mainshock and its associated aftershocks (M). The Fig. c represents the foci distribution of these events with longitudes.

The quiescence period was terminated by the occurrence of the Chamoli mainshock on 28 March 1999 (focal depth 23 km) to the north of the MCT, close to the second swarm event (Fig. 1). The mainshock was followed by a series of aftershocks which continued until 2 June 1999, with seven aftershocks in the magnitude range of 5.0-5.5. The mainshock and almost all the aftershocks are located in a narrow zone either side of the MCT (Fig. 1a). The delineated preparatory area for this earthquake is oriented almost perpendicular to the major trend of aftershocks activity. The time and magnitude distribution of events in the preparatory area is depicted in Fig. 1b. The majority of events in all four identified episodes are confined to a small area in the depth range 10-50 km and the longitude range 79.1°-79.6° E (Fig. 1c). The overall focal depth distribution shows that events became progressively deeper from east to west. It is clear that, the Chamoli earthquake was preceded by a well defined swarm of earthquakes which lasted for 205 days from November 1995. The mainshock was preceded by a precursory time period of 1217 days. It is noted that the region was quiet for two years following the termination of the aftershock sequence on 03 June 1999, with the occurrence of only two small events since then. After the Chamoli earthquake, the analysis of seismicity data from 1999 to 2006 indicated eastward migration of seismicity ~150 km away and clustered between MCT and MBT.

Conclusion

The spatial and temporal changes in seismic activity may be causally related to the time of occurrence and the magnitude of the mainshocks. In view of this, an attempt has been made here to search for the pattern of the seismicity changes in space and time domains prior to Chamoli earthquake. The earthquake was found to be associated with a well defined anomalous seismic activity both in space and time during 27.11.1995 to 18.06.1996 some three years and four months prior to the mainshock. The seismicity fluctuated in the order of low-high-low-high in the characteristics four phases from 1981 to 1999. The anomalous seismic phase within the preparatory zone was characterized by considerably high seismicity (~14 folds) as compared to its preceding background seismicity phase and the following precursory gap phase. Clustering of these events and associated aftershocks in all the phases was also observed with depth.

Anomalous seismicity pattern has some kind of casual relationship with the time of occurrence and magnitude of the mainshock. Such patterns follow episodes of relatively very low seismic activity, which is an important finding to visualize that an area might be preparing for the forthcoming mainshock. It may be inferred here that the patterns of anomalous seismicity/ earthquake swarms can be considered as an important parameter for the forecasting of long-range earthquake hazards in the region. If any region is observed in which anomalously low precursory quiescence period is continuing, efforts have been made to search for other short term premonitory phenomena.

Acknowledgements

The author is grateful to Prof. VP Singh and Associate Prof. Dr. HN Singh, Department of Geophysics, Banaras Hindu University India for critically examining the manuscript and offering useful comments and suggestions. UGC Nepal is thankful for fellowship and Dean Office of Institute of Science and Technology, Tribhuvan University for providing sabbatical leave.

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