Active fault beneath the Tehri dam, Garhwal Himalaya – seismological evidence

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We present here seismological evidence for an active fault beneath the Tehri dam based on mapping of the earthquake distribution in the Kumaon–Garhwal Himalaya using 40 broadband digital seismographs operated over a period of 39 months during 2005–2008. The earthquake distribution shows two well-defined bands: (i) following the surface trace of the Munsiari Thrust and (ii) a significant EW trend in the Lower Himalaya following the Tons Thrust Fault in the west and the Ramgarh Thrust in the east. The Tehri dam is in close proximity of the south-dipping Tons Thrust Fault. We also recorded over 20 earthquakes (*M* 1.6–2.8) in 20 km radius of the dam site. Most of these earthquakes have a thrust mechanism. The tectonic loading on this active Tons Fault due to local seismicity coupled with the reservoir loading and unloading may generate earthquake(s) and cause additional seismic risk in this critically stressed region.

Keywords: Active fault, earthquake, seismological evidence, Tehri dam, thrust mechanism.

THE Himalaya occupies a unique place among the world's mountain belts and has resulted from a long evolution, beginning about 50 Ma with the closure of the Tethys Ocean and collision of the Asian and the Indian land masses[1,2]. The geodynamic complexities of the Himalaya are manifested in several surface features such as the Southern Tibetan Detachment (STD), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT). The region to the north of STD is widely referred to as the Tethys Himalaya, between MCT and STD as the Higher Himalaya, between MBT and MCT as the Lower Himalaya and between MBT and MFT as the Sub Himalaya (Figure 1). The three southernmost fault systems (MFT, MBT, MCT) are believed to emanate from the Main Himalayan Thrust (MHT); the MFT being the youngest among these (Figure 1, inset A). The MCT in the Kumaon–Garhwal region is a ~50 km wide zone bounded in the south by the Munsiari Thrust (MT) and in the north by the Vaikrita Thrust (VT). The rocks in the Lower Himalaya are largely composed of unmetamorphosed to low-grade metasediments predominantly of Proterozoic age and deformed by upper-crustal, brittle thrusts[3]. In stratigraphic framework, the Lower Himalaya sequence can be further divided into the inner (older) and the outer (younger) Lower Himalayan sequence units[4], demarcated by the Tons Thrust (TT), roughly halfway between MBT and MT. Other major faults within the Lower Himalaya include the Berinag Thrust (BT) and Ramgarh Thrust (RT) (Figure 1). TT, locally known as the Srinagar Thrust, has a strike continuation of over 100 km and is a south-dipping overturned thrust[3,5,6].

The Tehri dam (Figure 1), located near Tehri town in Uttarakhand in the Kumaon–Garhwal Himalaya, has height of 260.5 m and maximum power generation capacity of 2400 MW (6532 MU of annual energy), of which 1000 MW (3532 MU of annual energy) has been functional. It has been built downstream from the Bhagirathi and Bhilangana river confluence, and in a narrow gorge with steep-side slope within the Lower Himalaya. It is situated about 5–7 km south of the surface trace of the TT. The region falls in zone-IV of the zoning map of India[7] and forms the western part of the proposed ~700 km long seismic gap of the Himalaya[8]. The Uttarakhand region has been the site of several recent, moderate-sized earthquakes, the most prominent being the 1991 *M* 6.6 Uttarkashi and the 1999 *M* 6.3 Chamoli earthquakes. The recurrence interval for great earthquakes in the Dehradun region (nearly 27 km from Tehri) has been estimated[9] as 290–980 years. No great earthquake (magnitude 8 or greater) has, however, occurred in the last 200 years in this seismic gap of the Himalaya (Figure 1,

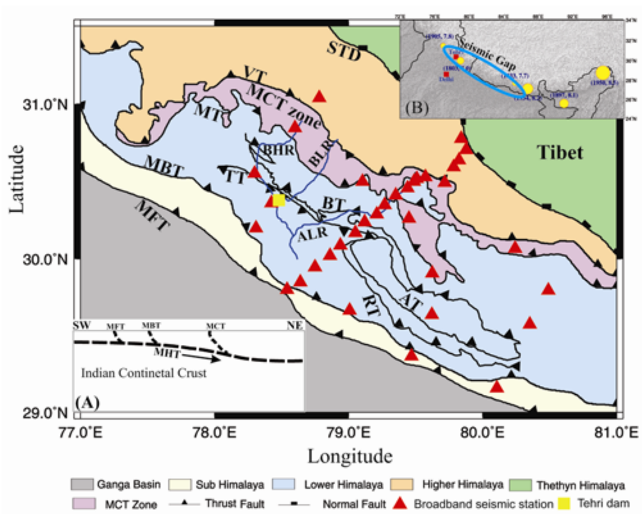

Figure 1. Tectonic map of Kumaon–Garhwal Himalaya showing the location of the Tehri dam (square), seismograph (filled triangles) and major tectonic boundaries (lines). MFT, Main Frontal Thrust; MBT, Main Boundary Thrust; MT, Munsiary Thrust; VT, Vaiktrita Thrust; MCT, Main Central Thrust; STD, Southern Tibetan Detachment; TT, Tons Thrust; RT, Ramgarh Thrust; BT, Berinag Thrust and AT, Almora Thrust (modified after Valdiya[3]). (Inset A) Generalized tectonic model of the Himalayas. (Inset B) Topography map showing Himalaya region with great earthquakes (circles), seismic gap[8] and the location of the Tehri Dam (small rectangular box).

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inset B). Bilham *et al.*[10], based on seismological records and recent space geodetic measurements, suggest significant seismic potential for the region.

The Tehri dam was initially designed for peak ground acceleration (PGA) of 0.5 *g* (ref. 11), effective peak ground acceleration (EPGA) of 0.25 *g* considering the maximum credible earthquake of magnitude 7.2, and accordingly was made as an earth and rock-filled dam, which can withstand the maximum credible earthquake, and has very little risk of failing due to earthquake activity. The rationality of selecting these numbers has been questioned by many due to the choice of the 50th percentile risk instead of the 84th percentile risk, minimum acceptable value for the design of critical structures of the ground motion. It has been argued that the acceleration in the Tehri can reach over 1 *g* if an earthquake of magnitude 8 or more, like the 1905 Kangra earthquake, occurs in the proposed seismic gap region[11–13].

Location of earthquake source region is pivotal to assess the seismic hazard potential to any man-made structure. In this region many portable seismic networks have been operated[14–18] intermittently since 1979. Seismicity data from these networks do not show any definite pattern in the neighbourhood of the Tehri dam. Further, we did not find any seismic cluster or pattern near the dam site in the regional distribution of earthquakes based on data from the International Seismological Centre[19] (Figure 2).

We present here the seismicity pattern in the Kumaon–Garhwal Himalaya region in general and around the Tehri dam in particular, using observations from a temporary seismological network operated by us in the region.

We operated 40 broadband seismological stations during April 2005–June 2008 (Figure 1) recording seismic waveforms continuously at 50 samples/sec. All the stations were equipped with Guralp CMG-3T/3ESP broadband sensors and 24-bit REFTEK (RT 130-01) data recorders with 4 GB swappable hard disk and GPS[20,21].

The arrival times of *P*- and *S*-phases of the events recorded by the network were picked and assigned a time uncertainty to each phase: 0.05–0.50 sec for *P*-arrivals, and 0.1–1.5 sec for *S*-arrivals for events inside the network. A total of 1150 local earthquakes with at least 5 *P*-arrivals and 3 *S*-arrivals were located using the HYPO71 program[22]. One-dimensional velocity model (Figure 3) was calculated by inversion of phase data from the Kumaon–Garhwal Himalaya seismic network and using an average V_P/V_S ratio of 1.73, derived from the Wadati diagram. The hypocentre parameters of all the recorded 1150 earthquakes were computed using the optimum 1D velocity model of the region[21]. The errors in epicentre, focal depth and time residual were found to vary in the range 1.0–3.5 km, 1.0–5.0 km and 0.1–1.2 sec. The hypocentral locations were further constrained by relocating clustered 950 earthquakes using the HypoDD algorithm[23], which exploits similarities in the event-station paths of a closely spaced cluster of events recorded at a relatively farther distance. The differential travel times of *P*- and *S*-wave arrivals and locations determined earlier were used as inputs for HypoDD. The average rms residual decreased from the earlier estimate of 0.30 sec to 0.05 sec, and errors in relative locations, on an average, reduced from 2.5 to ~ 0.3 km horizontally and from 4.0 to 0.4 km vertically.

Figure 4 shows the epicentre distribution of the recorded earthquakes during the experiment period. The nature of the seismicity in the Kumaon–Garhwal Himalaya is provided study by Mahesh *et al.*[21]. While the earthquakes are distributed all over the region, they follow a well-defined band of the surface trace of MT. This is at variance with the distributed seismicity in the MCT zone, as reported by the global network[19] (Figure 2) and earlier local seis-mological networks as well[14,15,18]. This we attribute to our improved earthquake location capability

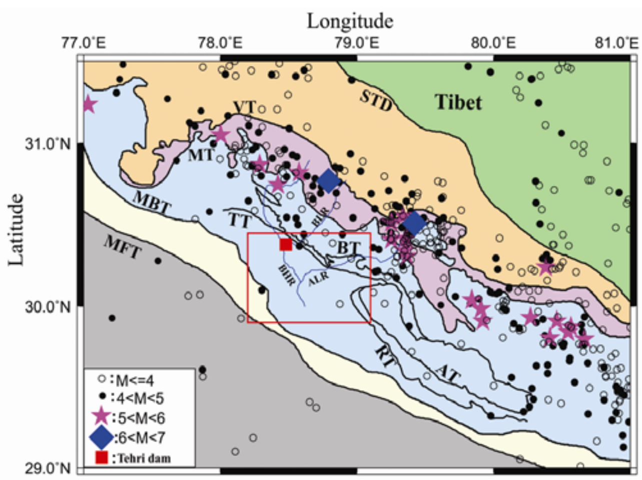

Figure 2. Distribution of earthquakes recorded on global networks[19] during 1967–2011. Red box shows the region discussed in Figures 5 and 6. Major tectonic features are the same as shown in Figure 1.

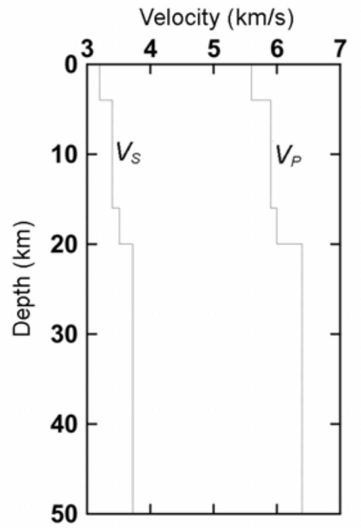

Figure 3. One-dimensional *P*- and *S*-wave velocity models calculated for the study region and used for earthquake locations in the region.

in the region. Additionally, we observe significant EW-trending seismicity in the Lower Himalaya nearly parallel and between the MBT and MCT. The pattern of seismicity follows the NW–SE trending Tons Fault and in the east it coincides with the RT (Figure 5). Depth variation of earthquakes along the latitude and longitude is also shown in Figure 5. The magnitude of these earthquakes varies between 1.6 and 2.8. With a few exceptions, focal depths are primarily confined up to 25 km.

Figure 6 shows seismicity around the Tehri region, as observed by our network and by other earlier local seismic networks[14–17]. Earthquakes within a radius of 20 km from the Tehri dam closely follow the Bhagirathi River. Such a pattern was absent in data from earlier networks. Our search of the ISC catalogue during 1967–2011 did not provide any evidence for a globally recorded earthquake originating from the Tehri region.

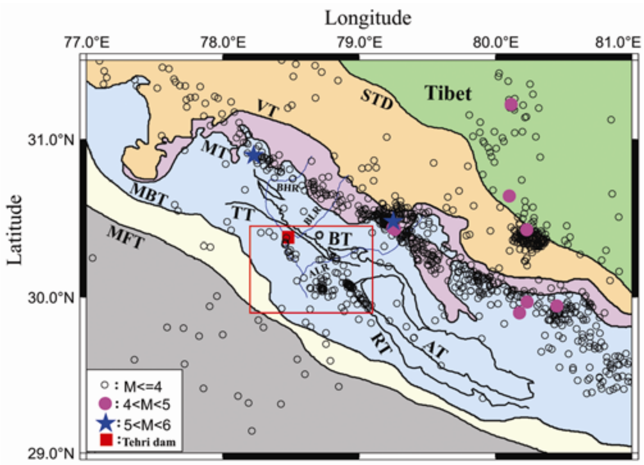

Figure 4. Distribution of earthquakes recorded by our network during 2005–2008. Other details are the same as in Figure 2.

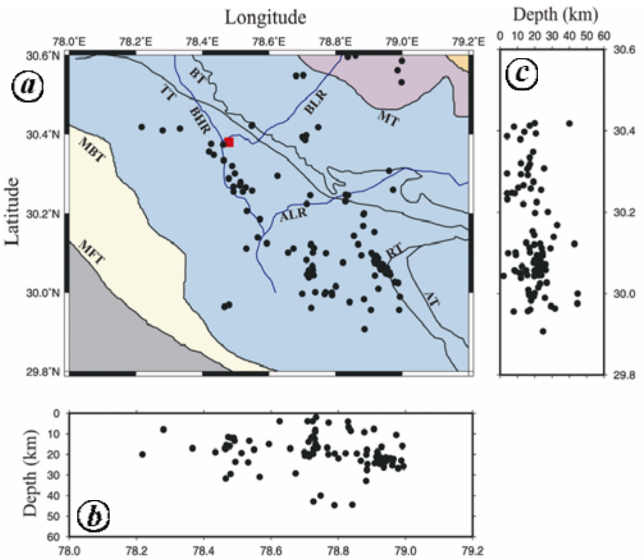

Figure 5. ***a***, Earthquake epicentre distribution in the Tehri dam region. ***b***, ***c***, Depth distribution of earthquakes along longitude (***b***) and latitude (***c***). All the earthquakes have been collapsed along the longitude and latitude directions in (***b***) and (***c***).

We also computed fault plane solutions (FPSs) for well-recorded earthquakes (average rms ~ 0.2 sec) and having clear *P*-wave first motion polarity. Figure 7 shows the depth variation of earthquakes (and FPSs), within 20 km on either side of the SW–NE cross-section (shown in Figure 6) through the Tehri dam. These earthquakes with dominantly thrust mechanism, lie either on the south-dipping TT or where it meets MHT (Figure 1, inset A).

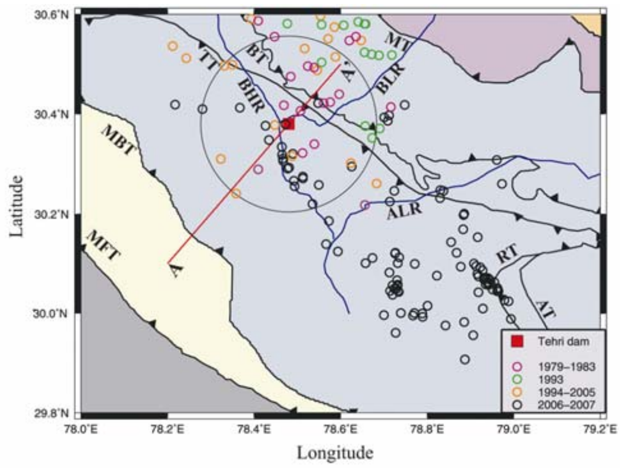

Figure 6. Distribution of earthquakes recorded by various networks. Circle shows the 20 km radius from the Tehri dam. AA′ shows the profile along which depth distribution of earthquakes is projected in Figure 7.

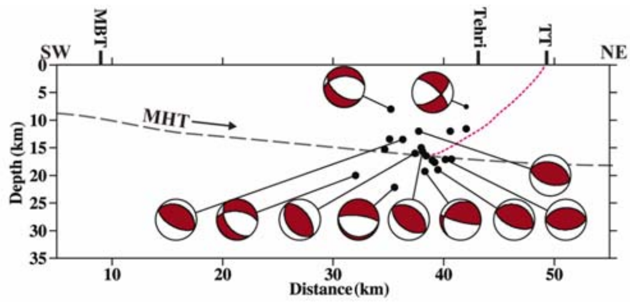

Figure 7. Depth distribution of the earthquakes occurring within 20 km along the SW–NE section AA′ as shown in Figure 6, and through the Tehri dam. Fault plane solutions of earthquakes are also projected.

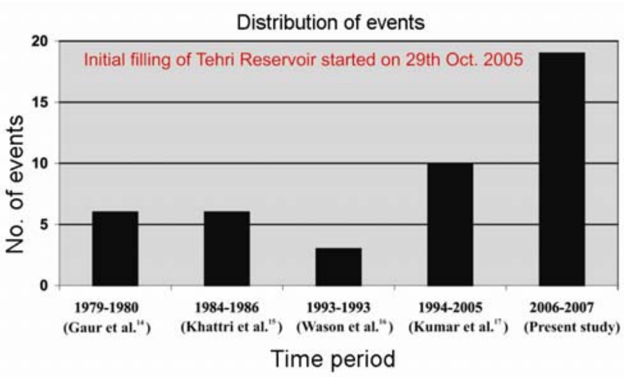

Figure 8. Histogram showing the earthquakes within 20 km radius of the Tehri dam region, recorded by various temporary seismological networks[14–17] from 1979 to 2007.

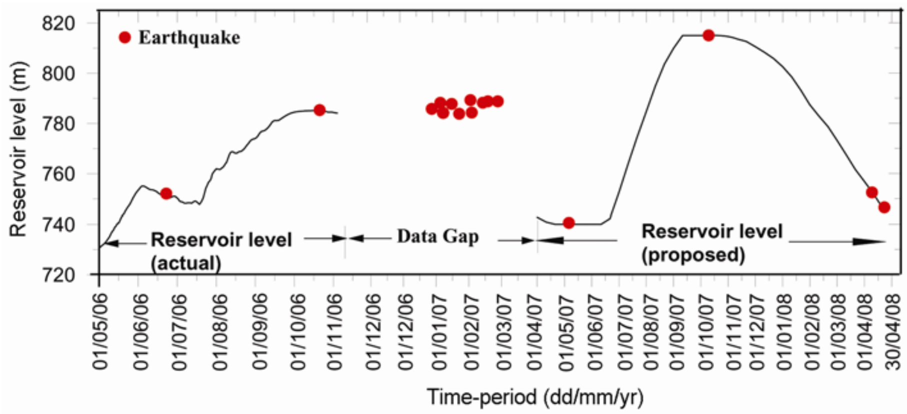

Figure 9. Tehri reservoir (actual and projected) filling level with time[34]. The recorded earthquakes (our network) of magnitude range 1.6–2.8 and within 20 km radius of the Tehri dam are also projected.

The active nature of TT has also been observed by a number of spectacular geomorphological features, viz. many pulses of movement, including uplift of the mountain in the geological recent past (~ 11,000 years ago), and huge fans of debris avalanches[5].

Unlike the association of seismicity with reservoirs like the Aswan[24], Koyna[25] and South Carolina[26] due to perturbation in the stress and pore pressure regimes in the rocks around the reservoir[27], no reservoir-induced seismicity has been reported from the nine impounded reservoirs in the Sub Himalaya. This is argued due to non-conducive thrust fault environment mostly prevailing in the Himalayan foothills[28,29] considering only elastic deformation of the system[24]. However, theoretical analyses indicate that if suitably located in relation to the reservoir, even a thrust fault may be destabilized by impoundment and thus the possibility of reservoir-induced seismicity as a whole cannot be ruled out in the Himalaya[30,31]. More detailed recent simulations for elastic stress due to the proposed Tehri reservoir load suggest that the reservoir load could change slightly, but not prevent the occurrence of natural earthquakes[32,33].

In this context, we present initial results showing temporal variation in the seismic trend near Tehri dam as the reservoir was being impounded. The initial filling of the Tehri reservoir was started on 29 October 2005 (ref. 34). No moderate earthquake occurred in the region except on 1 February 2006 (magnitude 4.8; 30.15°N, 80.00°E), nearly 160 km NE of the Tehri dam. Figure 8 shows the histogram of seismicity, within 20 km of the Tehri dam, from 1979 to 2007. Most of the seismicity prior to 2005 occurred to the north of the Tehri dam and very few were close to it (Figure 6). It may be noted that most of the earlier seismic networks had station(s) near the Tehri dam, and earthquakes from this area should have been recorded with reasonable accuracy in their epicentre, though the focal depth may have error. Seismicity associated with the first filling of the reservoir has been hypothesized due to change in the strength of the crust, that perturbs the stress and pore pressure regimes in the rocks around the reservoir[27]. We observed increase in seismicity near the Tehri dam from December 2005 onwards, after its first filling. The reservoir is proposed to be charged in the monsoon, during 21 June to 31 October every year and brought back to minimum draw down level (MDDL) in the non-monsoon season by releasing water[34]. There is noticeable relationship between earthquake occurrence near the Tehri dam with the change of reservoir level (Figure 9). Earthquakes are observed to occur with the maximum (i.e. 785.25 m on 16 October 2006 and 815 m on 7 October 2007) and minimum (i.e. 751.1 m on 19 June 2006 and 740 m on 7 May 2007) reservoir levels. We, thus, speculate that seismicity in the vicinity of the Tehri dam may have linkage with instability created by loading and unloading of the reservoir. This, however, could only be over-riding the stress field generated primarily due to reactivation of TT because of tectonic loading.

The Tehri dam site in the Lower Himalaya was chosen in 1961, at the time when the plate tectonics theory was taking birth and researchers were not well-educated with the fundamental mechanism responsible for earthquakes in the Himalaya[11]. Since then, much has changed in the context of our theoretical understanding and observations related to the evolution of the Himalaya and the associated earthquake hazards. The Tehri dam falls in a region of possible future great earthquakes[10]. The last major earthquake of M_w 7.7 occurred 209 years ago, in 1803, close to Srinagar-Garhwal[35] and many intermittent earthquakes including the 20 October 1991 Uttarkashi earthquake (M_w 6.8) have rocked the region and released parts of energy stored elastically due to the movement of the Indian plate. Still a large amount of residual stress has to be released by an earthquake of magnitude, possibly not less than 8 (ref. 11). Geodetic levelling observations in the region also suggest possibility of great earthquakes to release the recoverable elastic strain stored in the upper crust of the outer Himalaya in this part of Himalaya[36,37].

Here we present evidence for the presence of an active fault beneath the Tehri dam through the analysis of highresolution digital seismological observations generated in this region. Also, we present initial results suggestive of linkage between the seismicity near the Tehri dam, and loading and unloading of the reservoir. In view of the close proximity of the seismically active fault to the dam and its serious implications to the earthquake hazard scenario, there is greater need for re-assessment, analysis and further examination of our results using dedicated ground and space-based seismic and geodetic networks.

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