Active tectonics of Himalayan Frontal Thrust and Seismic Hazard to Ganga Plain

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We review the existing work on one of the principle thrusts, namely, that of Himalayan Frontal Thrust (HFT), caused by the collision between Indian and Asian plates. HFT is the only structure that has observed most of the N–S shortening across the Himalaya. We have carried out an excavation of a 55 m long trench across a scarp (Black Mango Fault) that has displaced the HFT at Kala Amb, Himachal Pradesh. The exposed trench-wall has revealed four low angle thrusts. Analysis of the trench-wall stratigraphy, structure and ^{14}C dating has revealed evidence of two large surface-rupture earthquakes. We have also carried out field study of piedmont zone between Fatehpur and Roorkee. The active deformation observed along the HFT zone suggests increased seismic hazard to the adjoining the Ganga–Yamuna plain. The seismic zonation of India (2001) needs revision in view of geological conditions and past historical seismicity; specifically, we believe that the region between HFT and MBT should be included under zone V category. Multidisciplinary and integrated studies have to be initiated, on a priority basis, covering the central seismic gap region, Uttaranchal.

THE Himalaya originated as a result of continent–continent collision between India and Asia. The northward convergence of India resulted in crustal shortening of the northern margin of the Indian continent, accommodated by south-verging thrusts. The principal thrusts, namely the Main Central Thrust (MCT), the Main Boundary Thrust (MBT) and the Himalayan Frontal Thrust (HFT) show younging age and shallowing depth, suggesting southward migration of the main deformation front. Neotectonic activity and active faulting related to the thrusts are observed on the surface in some restricted segments. The MCT remains largely inactive, except some reactivated segments showing lateral strike-slip movement as in Central Nepal[1]. The MBT in certain localized areas exhibits neotectonic activity[2]. The Himalayan Frontal Fault (HFF), also referred to as the HFT, shows active faulting and associated uplift (Figures 1 and 2). The HFT represents a zone of active deformation between the Sub-Himalaya and the Indian plain. It demarcates the principal present day tectonic displacement zone between the stable Indian continent and the Himalaya with a convergence rate of 10–15 mm/yr[3]. There is an uplifted piedmont zone south of the HFT, extending from Yamuna to Ganga and suggesting active deformation related to the HFT[3].

There is multiplicity in nomenclature of the HFF, e.g. HFF[4,5], HFT[6] and MFT[7]. Here it will be referred to as the HFT that marks a sharp physiographic and tectonic boundary between the Himalayan foothills and the recent alluvial plain (Figure 1).

A NW–SE trending and a few metre high scarp of discontinuous nature is observed in front of the HFT at several localities between Pinjor Dun and Dehra Dun. Several trenches have been excavated by different workers across the scarp for palaeoseismological study. Evidence of large historical earthquakes has been found in the HFT zone[8,9]. An attempt is made here to review the existing work on the HFT zone and make seismic hazard assessment.

Nakata[1,5] was the first to map the active faults in the Himalayan foothills of Darjeeling in eastern Himalaya and Pinjor Dun and Dehra Dun in western Himalaya. In the HFF zone of Darjeeling foothills, east of Tista, four sets of active faults trending east-west and characterized by escarpments, have faulted the extensive alluvial fans[1]. In eastern Pinjor Dun, Nakata[1,5] recognized Kalka and Pinjor geomorphic surfaces which are dislocated by active faults expressed in modified scarp topography.

In Dehra Dun, the Krol group of the rocks of Lesser Himalaya override the post-Siwalik Dun gravels, indicating neotectonic activity dating post-upper Siwalik (0.5 Ma). Across a contact between the Siwaliks and the alluvial plain, in an excavated trench, the middle Siwalik sandstone overlies the Holocene alluvial sediments along the HFT dipping NE30° (Figure 3). Dehra Dun and its adjoining area to the northwest show post-Siwalik folding and thrust-faulting. The Mohand anticline in the frontal Siwalik range and Dun synclinal valley were developed in a fault-bend fold thrust system with simultaneous displacement on the HFT (Figure 2). The initiation age of the HFT is constrained between an interval of 500 and 100 Ka in post-Siwalik time. Several strath terraces are located 20 to 30 m above the modern stream level in Khajanawara, Shahjahanpur and other raos (streams) along the Siwalik range front, south of Dun Valley in Garhwal Himalaya. These terraces are interpreted to have been uplifted by displacement on the underlying HFT[6]. A slip rate of $\geq 13.8 \pm 3.6$ mm/yr on the HFT has been estimated on the basis of a radiocarbon date, $\leq 3666 \pm 215$ yr BP, of the terrace and assuming the observed NE 15–30° dip of the HFT[6].

Active faulting is observed along the MBT and HFT in the Himalayan front of southeast Nepal[1]. The river terraces along the MBT show both vertical and horizontal displacements. The terrace surfaces along Timai Khola in southeast Nepal are uplifted and back-tilted along the active trace of HFF. Active folding of fluvial terraces and active fault-bend folding of the HFT have been described from Bagmati and Bakeya river sections in the Sub-Himalaya Central Nepal[7] (see inset, Figure 1). According to these

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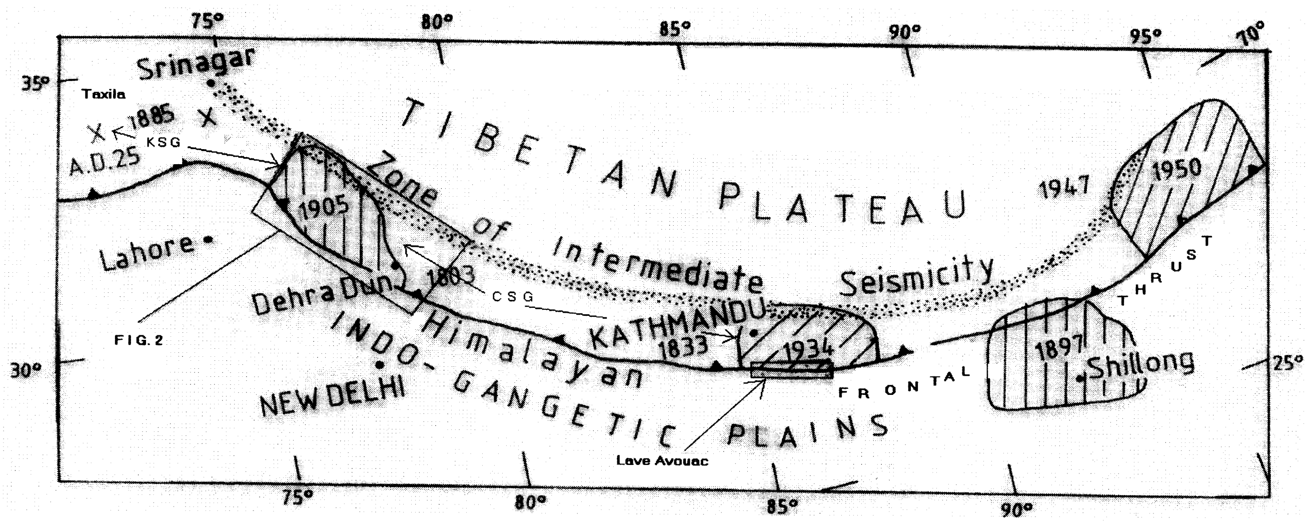

Figure 1. Sketch map of Himalaya showing Himalayan Frontal Thrust Zone, isoseismal zones of four great earthquakes and a belt of high instrumental seismicity and intermediate earthquakes, and location of other large earthquakes. KSG, Kashmir Seismic Gap; CSG, Central Seismic Gap. The region between Kangra and Dehra Dun of Figure 2 is shown in square inset[29].

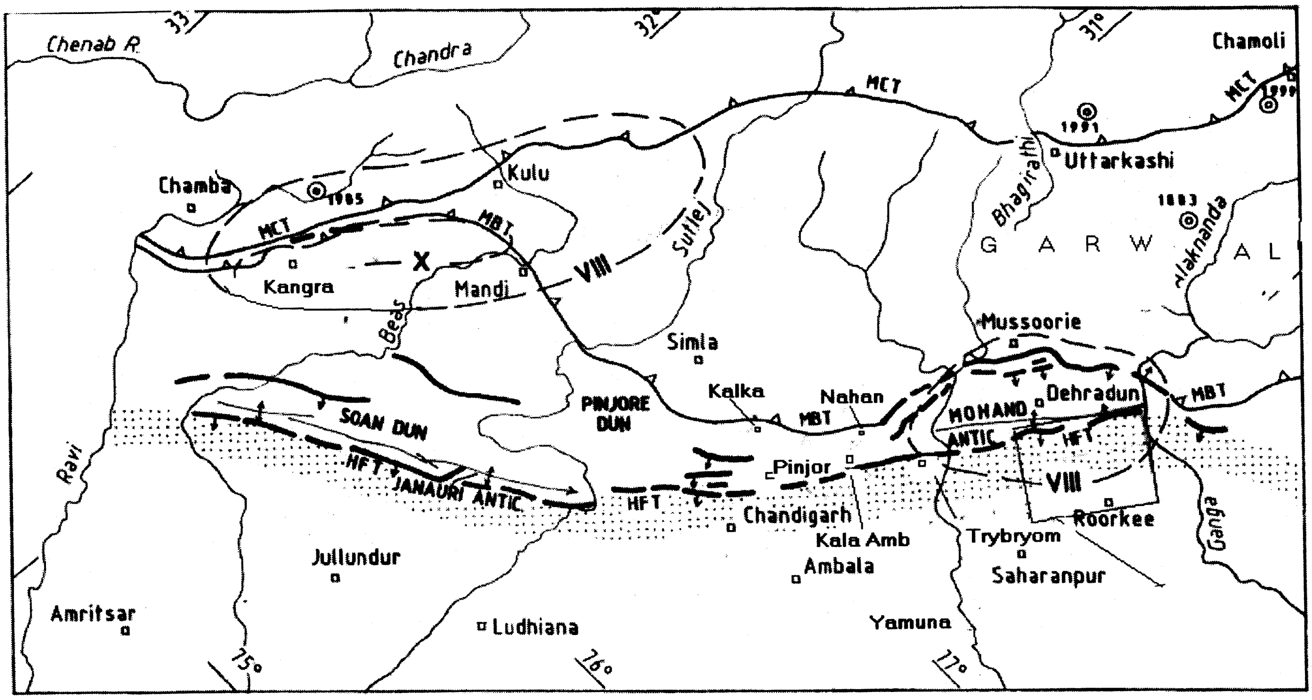

Figure 2. Outline of active tectonic map of 1905 Kangra earthquake rupture zone and adjoining areas of Garhwal and Himachal Himalaya (modified after Yeats *et al.*[4]). Thick bold lines represent traces of active faults, with arrows pointing to footwall. Intensity VIII isoseismals (Rossi–Forrel) of 1905 Kangra earthquake; and epicentres of Kangra, Uttarkashi, Chamoli and 1803 earthquakes are shown. South of HFT, the dotted region represent uplifted piedmont. Piedmont zone of Figure 5 is shown in a square inset south of Dehra Dun.

workers[7], the HFT is the only active structure in the area which has absorbed most of the N-S shortening across Himalaya at an average rate of 21 ± 1.5 mm/yr during the Holocene.

Near Kala Amb, ~10 km south of Nahan, Himachal Pradesh the HFT is displaced by the Black Mango tear fault. This fault transforms the motion between two segments of the HFT. We have excavated a 55 m long trench across a scarp of the Black Mango Fault in younger alluvium[8], and the trench log is depicted in Figure 4. Four low-angle thrusts, F_1, F_2, F_3 and F_4 were recognized on the exposed wall of the trench. Three distinct stratigraphic units are recognized on the trench-wall surface. Unit 1 is made up of the highly sheared package of

Siwalik-derived colluvium and bed rock. The fan gravel unit 2a is pebble–cobble supported, and unit 2b consists of fine and medium-grained silty sand. Unit 3 comprises fine and medium-grained silty sand and fine sand with buried soil horizons. 16 AMS ^{14}C dates were obtained from different locations in the trench-wall surface. Analysis of trench-wall stratigraphy, structure and ^{14}C dating revealed evidence of two large surface-rupture earthquakes within 600 years, post-dating AD 1294 and AD 1423, and possibly another rupture at about AD 260. The slip (displacements) for the post- AD 1294 and AD 1423 AD events was at minimum 4.6 m and 2.4–4 m respectively, and for AD 260 possibly larger than the two.

Recently, Javed[9] and coworkers have described the occurrence of two parallel-to-subparallel active faults branching out from the HFT system in a trench excavated near Chandigarh. A total displacement of 3.5 m along the thrust fault indicative of a large prehistoric earthquake is described from the trench. Similarly, we have found evidence of surface-rupture earthquakes along the HFT is several trenches excavated for palaeoseismological study in an area extending from Chandigarh to Ramnagar (Senthil Kumar, pers. commun.).

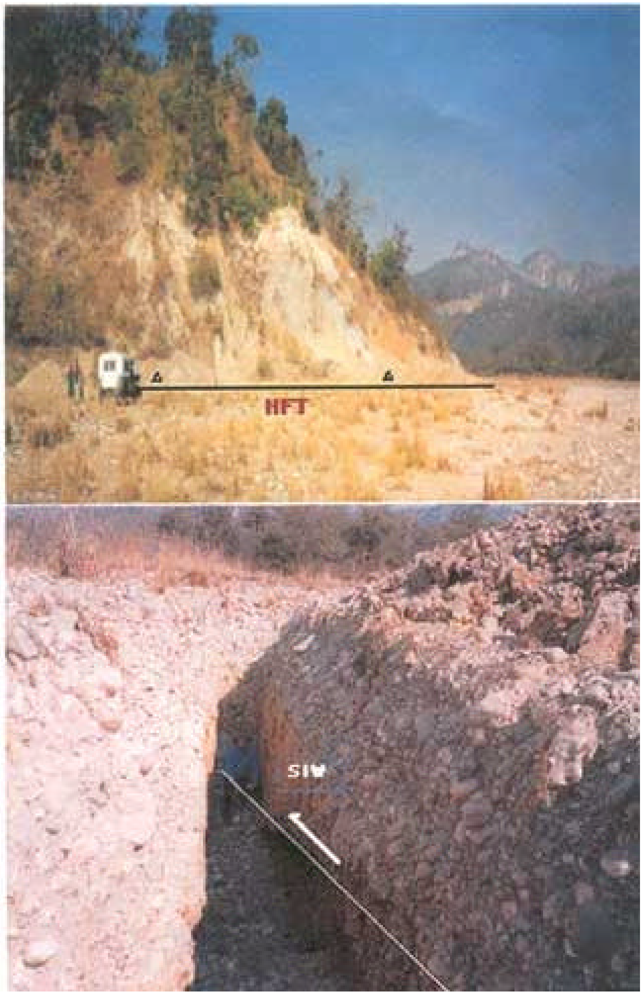

Figure 3. (Top) Himalayan Frontal Thrust (HFT) defined by topographic break between frontal Siwalik hill and alluvial plain sediments, exposed at Khajanawar rao, near Mohand. (Bottom) Trench excavated on the stream bed, alluvial plain shows middle Siwalik sandstone (brown) bed overlying the older alluvium along the HFT, and in turn overlain by younger alluvium. SW, Siwalik sandstone.

South of HFT, in an area extending in front of the foothills, an uplifted piedmont zone is recognized between rivers Beas and Ganga (Figure 2). Prakash[10] and coworkers observed 10–25 km wide piedmont zone between Yamuna and Ramganga on the basis of satellite images and soil formation, which, in my interpretation, appears to be tectonically uplifted with respect to the alluvial flood plain.

We have carried out detailed field study on the piedmont zone between Fatehpur and Roorkee[4] (Figure 5). The piedmont zone is made of coalescing fans with proximal facies of gravels and coarse sands and distal facies of sand and silt, poorly consolidated and weakly stratified at places. The Biharigarh ridge, trending NE is a remnant of the uplifted piedmont zone. The frontal face of this ridge, exposed at Biharigarh, is 15 m high and composed of sand and silt. Its lateral view is best exposed at Lalokhala stream section, where 18 m thick strata in a section dip NE5–8°. West of Biharigarh, there are two levels of raised ground, 3 and 5 m high terraces, observed while going from the main Delhi highway towards village Sherpur. East of Biharigarh, a scarp 15 m high is observed along the left bank of Mohanrao stream, ~ 1 km north of Biharigarh road-crossing. North of Bhagwanpur, Imlikhera and Ibrahimpur villages and the road section between Patti Danda and Kheri, the piedmont zone is exposed at higher elevation (15–20 m), above the flood plain. These locations represent the remnants of uplifted piedmont zone, located at higher elevation than the recent flood plain. In areal photographs and satellite imagery, a NW-trending fault is identified as a lineament that marks the southern face of the scarp. The orientation and location of this fault corresponds to sharp knee-bend turn taken by streams flowing from northeast to southeast. The uplifted upwrap of the piedmont zone may have resulted due to deformation related to southward propagation of the HFT. An imbricate branching-out of the HFT, developing on its footwall as a low-dipping thrust fault, may have caused the uplift of the piedmont zone. The fault may remain blind during the initial stage or may rupture on the surface as active fault, referred to as Solani Piedmont Fault.

About ~ 12 km west of Yamuna at village Trybryon, a scarp running parallel to the range front is exposed south of the HFT[6]. The scarp cuts through the alluvial gravel and is 9 m in height. Similar uplifted and modified topography of the fault scarp and uplifted piedmont zone is exposed in a discontinuous manner south of the HFT at several localities between Satluj and Ganga (Figure 2).

In Garhwal and Kumaun Himalaya, a belt of microseismicity and frequently occurring moderate earthquakes, magnitude between 5 and 7 is distributed close to the MCT zone and northern part of the Lesser Himalaya[11]. A

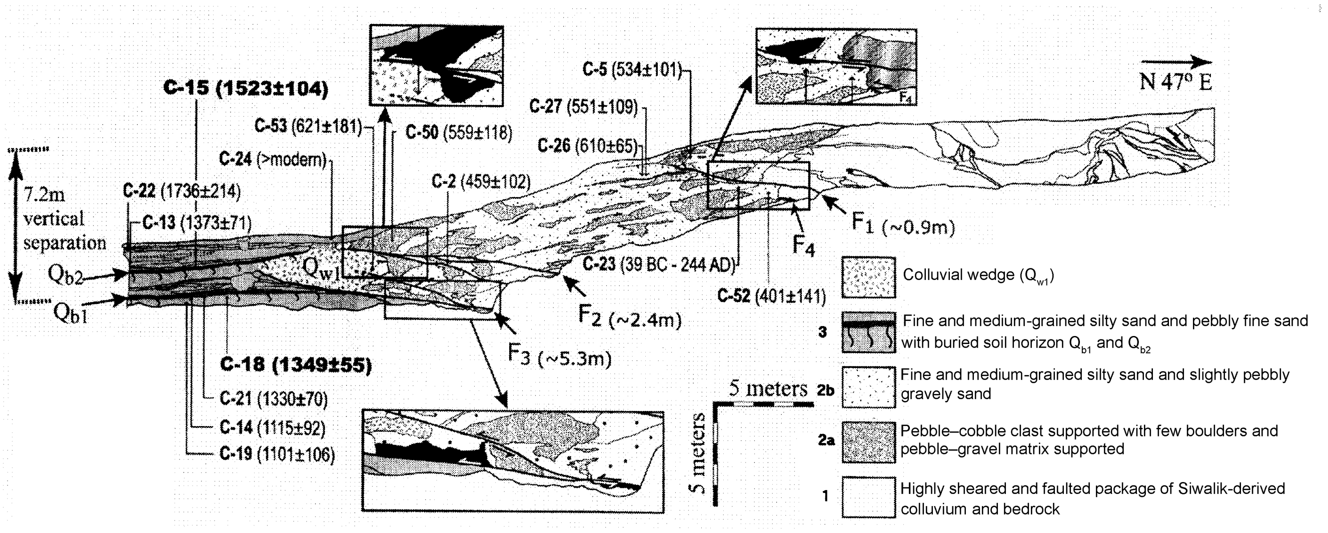

Figure 4. Map of trench-wall showing fault traces with amount of offsets and radiocarbon dates with sample locations. Enlarged offsets of Faults, F_1, F_2 and F_3 shown in insets (After Kumar *et al.*, 2001)[8].

cluster of nine earthquakes, including 1991 Uttarkashi and 1999 Chamoli, with magnitude 5.6–6.5 and focal depth varying from 10 to 18 km, were caused by low-dipping thrust faults[12]. The fault plane solutions and aftershocks data of Uttarkashi and Chamoli earthquakes analysed by the GSI team[13,14] also indicate shallow dip, 15–20°, of the thrust faults. These workers[13,14] have proposed that the Uttarkashi and Chamoli earthquakes were generated at the 'faults ends' of the Uttarkashi fault and the Alaknanda fault respectively, on the plane of detachment. However, both these faults do not show any surface geomorphological and structural features indicative of active faulting, and no surface-ruptures showing displacement along the faults were observed in Uttarkashi and Chamoli earthquakes. In case a pre-existing fault is reactivated by an earthquake, the new rupture may not initiate along the old sealed plane of the fault. Instead an imbricate may branch out from the old fault.

The low magnitude of dips of the causative faults corresponds to the dip of decollement at mid-crustal ramp beneath the Higher Himalaya, implying the faults initiated from the detachment. With no evidence of surface faulting observed associated with these earthquakes and the low angle of fault planes suggest the blind nature of the faults in generating the earthquakes. The overburden cover overlying the top of the Indian plate, Plate Boundary Fault, increases in thickness from ~ 3–5 km over the HFT zone to ~ 15–18 km over the MCT zone. The lesser thickness of the cover in the HFT zone may be the factor for the fault to emerge on the surface, whereas the moderate-to-large earthquakes in the Lesser Himalaya and MCT zones remain buried as blind faults due to large thickness of overburden and comparatively lower magnitude.

In its westward extension, the seismicity belt of Garhwal–Kumaun joins the seismicity observed in Kangra–Chamba region[15], which recorded the most devastating 1905 Kangra earthquake[16]. In eastward extension of Kumaun, a narrow belt of seismicity follows approximately the topographic front of the Higher Himalaya in Nepal[17]. The hypocentres of the earthquakes in central and western Nepal tend to cluster at mid-crustal level at a depth between 10 and 20 km[17]. The 1934 Bihar–Nepal earthquake, with magnitude 8, had its epicentre located east of Kathmandu in the Lesser Himalaya[18]. The rupture zone of this earthquake extended 200–300 km east-west and spread ~ 150 km north-south[19]. The earthquake produced a zone of high intensity extending from Kathmandu Valley to the Gangetic plain, including the slump belt in northern Bihar[20] with near-total destruction.

The detachment, representing a plane of decollement, is proposed between the top of northward-converging Indian plate and southward propagating wedges of Himalayan rocks[21] (Figure 6). The detachment is imaged in a seismic profile underneath the Dun Valley, Sub-Himalaya of Garhwal at 3–8 km depth from the HFT towards the MBT[22]. Based on microseismicity data, the detachment is interpreted at a depth of 15–18 km underneath the Lesser Himalaya of Garhwal[11] and at 18 km depth in Chamba region[23]. Further north of the Higher Himalaya, the decollement is imaged in seismic reflection profiles of INDEPTH beneath the Tethys Himalaya and southern Tibet at 25–35 km depth, where it is referred to as the Main Himalayan Thrust (MHT)[24]. Study of convergence rate across the rupture zone of the 1905 Kangra earthquake from GPS measurements indicates that the HFT is locked across a width of ~ 100 km in Garhwal Himalaya[25]. That means slip-deficit is accommodated north of the locked portion in the Higher Himalaya and farther north. A mid-crustal ramp geometry of the decollement underneath the Higher Himalaya is interpreted on the basis of structural geological evidence[26], stepping of Moho inferred from gravity anomalies[27] and concentration of microseismicity in the ramp region[17]. As the Indian plate underthrusts (subducts) under the Higher Himalaya, the Higher Himalaya moves up south over the ramp producing high relief and intense microseismicity. The locked portion of the Indian plate in Sub and Lesser Himalaya may behave like seismogenic coupling zone, as proposed in Central Chilean margin of oceanic–continental convergent margin[28].

The detachment (MHT) is also referred to as the Plate Boundary Fault, and at least three (1905, 1934 and 1950) of the great earthquakes were produced as a result of rupture on this fault[29]. The elastic strain accumulating interseismically underneath the Higher Himalaya is relieved through the rupture of the locked Plate Boundary Fault[30] (Figure 6). The large-to-great earthquakes originated in the locked portion, ~ 100 km from the HFT to Lesser Himalaya, and the rupture zone propagated south to the range front. The epicentre of the 1905 Kangra earthquake was located north of the MBT, in the Lesser Himalaya zone of Chamba region, and the isoseismal VIII (Rossi–Forrel) extended from Kangra southeastward to the HFT zone in Dehra Dun (Figure 2). Similarly, the estimated rupture zone of the 1934 Bihar–Nepal earthquake extended south from ~ 150 km east of Kathmandu in Lesser Himalaya to Bihar alluvial plain[18,20].

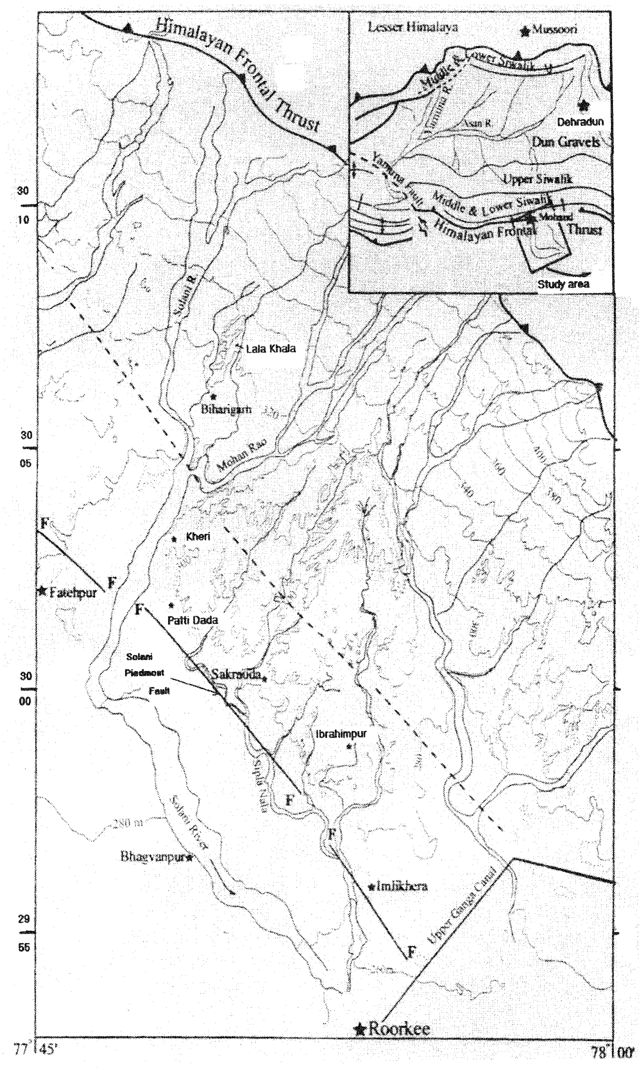

Figure 5. Tectonic–geomorphologic map of piedmont zone south of HFT between Fatehpur (near Chhutmalpur) and Roorkee showing uplifted and dissected topography of piedmont zone. SW-flowing streams take knee-bend turn to SE. Solani Piedmont Fault marked on the basis of areal photographs and satellite imagery.

A record of two large surface-rupture earthquakes along the HFT during the last 600 years[8] has been described earlier. Further evidence of fault scarps and surface-ruptures as a result of seismic events has been observed from other localities along the HFT zone[9]. The uplift of piedmont zone is interpreted to be related to southward propagation of an imbricate fault branching out of the HFT as a result of seismic events. These observations lend support to the model that large-to-great earthquakes originated in the locked part of the detachment and propagated southward to the range front, producing surface-ruptures, fault scarps and uplifts.

A recently published map of the seismic zones of India, under Government of India copyright 2001, shows three areas under Zone V in northwest Himalaya, covering Kashmir Valley, Kangra–Mandi area of 1905 earthquake and Higher-Tethys Himalaya of Garhwal–Kumaun with moderate earthquakes. This map also depicts the entire northeastern India and slump belt area[18,20], including Darbhanga in Bihar Gangetic plain under Zone V.

An active deformation showing surface-rupture earthquakes, uplift of stream terraces, active folding and uplift of piedmont zone indicates that the HFT is seismotectonically the most active zone across the whole of the Himalaya. The locking of ~ 100 km wide segment, the HFT to topographic front of the Higher Himalaya (MCT), from where the great-to-large earthquakes will originate with rupture zone propagating south to the range front. The active deformation observed along the HFT zone suggests increased seismic hazard to the adjoining Ganga–Yamuna plain. This region is much more densely populated than the Himalaya. The plain is underlain by thick (~ 1–3 km) cover of alluvial sediments with likely liquefaction effects and enhanced earthquake hazard.

In view of these observations and other factors like geological condition and past historical seismicity, the seismic zonation map of India needs revision. It appears the Zone V shown in the map may extend south to the HFT zone and the adjoining, 30–50 km wide, Gangetic plain.

The regions lying between the rupture zones of 1905 Kangra and 1934 Bihar–Nepal earthquakes and between the 1905 Kangra and AD 25 Taxila earthquakes are recognized as seismic gaps in western Himalaya and Nepal[29]

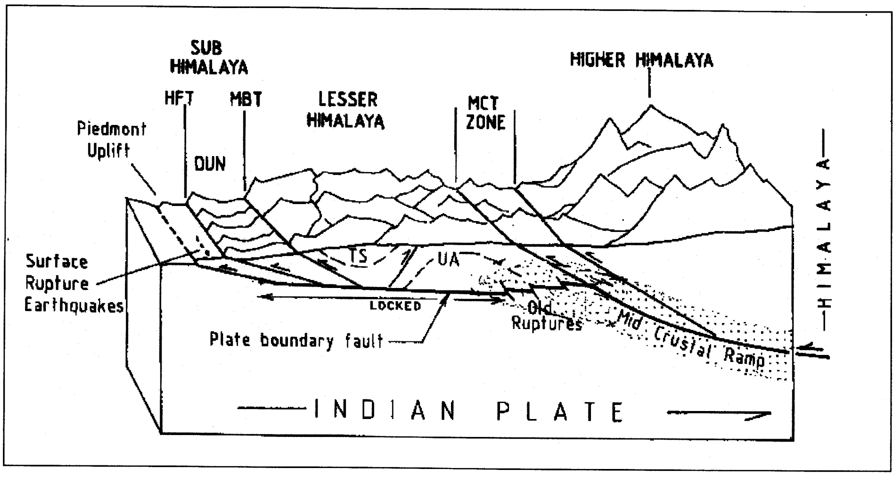

Figure 6. Schematic representation of principal seismotectonic features of Garhwal Himalaya (conceptualized after Jackson and Bilham[34]). Microseismicity and moderate earthquakes (dotted zone) are distributed along the zone at and adjoining mid-crustal ramp underneath the Higher Himalaya. Old ruptures are of past historical earthquakes. Locked portion of Plate Boundary Fault stores elastic strain energy for the rupture of the next great earthquakes. HFT, an active deformation zone, is characterized by surface-rupture earthquakes and uplift of piedmont zone. UA, Uttarkashi Antiform; TS, Tehri Synform.

(Figure 1). The former, referred to as the central seismic gap[31], located between the longitudes of Kathmandu and Delhi has not experienced a great (magnitude = ≥ 8), earthquake for the last 300 years. According to Bilham and his coworkers[30], the central seismic gap has stored potential slip of more than one great earthquake with magnitude ≥ 8. The Kashmir seismic gap, west of 1905 Kangra rupture zone, had the last great-to-large earthquake in 1555, suggesting accumulation of potential slip for a future great-to-large earthquake. The conditional probabilities of occurrence of great earthquakes with $M \geq 8$ in western Himalaya in a time window of 100 years is 27% in Kashmir gap, 6% in 1905 Kangra region, 52% in central seismic gap and 3% in 1934 Bihar–Nepal region[31]. Past historical records and palaeoseismological studies have shown that the large-to-great earthquakes occur in cycle and may have a reoccurrence interval. Lack of data in Himalaya puts a constraint in estimating more precise reoccurrence interval for a great earthquake with magnitude similar to those of the 1934 Bihar–Nepal and 1950 eastern Assam earthquakes. Estimates by various workers[32,33] for such earthquakes on the basis of slip rate and palaeoseismology suggest reoccurrence interval ranging from 180 to 500 years.

An active zone of deformation lies along the HFT as indicated by active faulting, uplift and surface-rupture earthquakes. The rupture zones of 1934 Bihar–Nepal and 1905 Kangra earthquakes extended N–S right across the HFT zone to the MBT zone. To reach the alluvial plain from the epicentre, the width of the Sub-Himalaya in Kangra region is twice (~ 30 km) that of the Bihar–Nepal region (~ 15 km). This may be the reason that the slump belt of Bihar–Nepal 1934 earthquake was not observed in the Panjab plain during the 1905 Kangra earthquake. The tectonic framework of Sub-Himalaya in the central seismic gap region is, however, similar to that of Bihar earthquake, suggesting a similarity in seismic wave propagation and peak ground acceleration. It is proposed that the seismic zonation map of India may be revised by including the region between the MBT and the HFT under Zone V.

In order to have a better understanding of seismicity and seismotectonics of Himalaya and for improved probabilistic and deterministic hazard assessment, the central seismic gap region, Uttaranchal in India, may be focused as a first priority for multidisciplinary and integrated studies in a mission-mode project for the following tasks: to run a seismological network of ~ 30 short-period stations covering the whole of Uttaranchal to elucidate lithospheric structure across N-S transects, employing wide-angle seismic reflection/refraction and near-vertical incidence reflection and receiver function analysis in broad-band seismology and finally to undertake magneto-telluric, gravity, GPS, active fault and palaeoseismological studies.

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ACKNOWLEDGEMENT. I thank CSIR for financial support through the ES scheme, and the Director, WIHG, Dehra Dun for logistic support.

Received 15 September 2003; revised accepted 10 February 2004