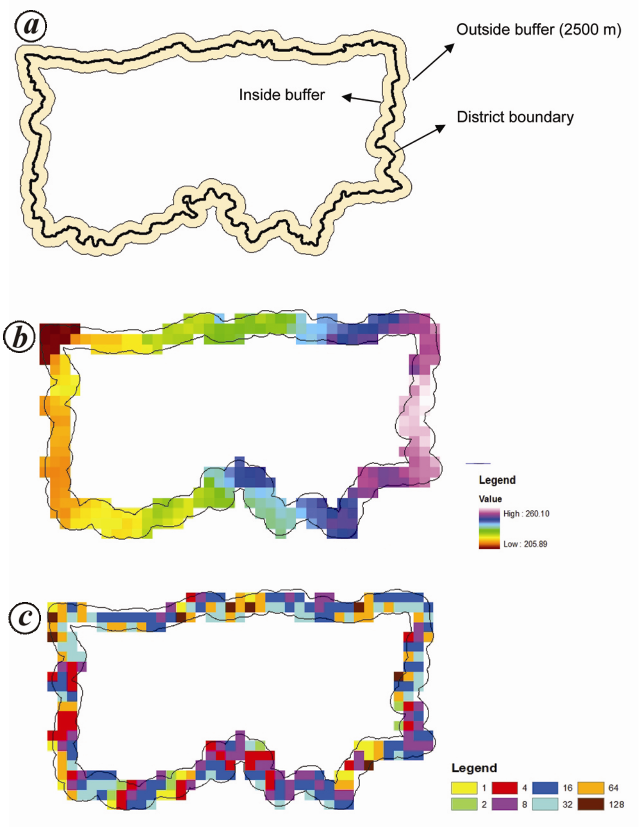

Figure 5. ***a***, Boundary shape file; ***b***, extracted hydraulic head; ***c***, flow direction raster (2001).

Table 1. Groundwater fluxes and change in groundwater levels in Ludhiana district, Punjab

Year	Influx ($m^3 yr^{-1}$)	Outflux ($m^3 yr^{-1}$)	Net flux ($m^3 yr^{-1}$)	Change in groundwater level ($m yr^{-1}$)
2001	24.1	18.2	5.9	0.002
2002	19.3	17.8	1.4	0.000
2003	22.1	17.4	4.7	0.001
2004	24.3	21.2	3.1	0.001
2005	23.6	20.9	2.7	0.001
2006	24.3	21.3	3.0	0.001
2007	25.4	21.5	3.9	0.001
2008	22.5	17.6	4.9	0.001
2009	21.7	19.8	1.8	0.000
Average	23.0	19.5	3.5	0.001

The presented methodology, based on utilizing a sequence of GIS-based tools to calculate gradient across the boundary and then fluxes across such boundaries using Darcy's law from readily available data of water level and transmissivity, helps identify specific cells contributing to fluxes in the boundary region, which can be incorporated in MODFLOW by recharge/well package in these cells. However, estimates could be made more reliable if the water-level data are available at a shorter interval and the aquifer hydraulic parameters are obtained from pumping test data.

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Seismogenic active fault zone between 2005 Kashmir and 1905 Kangra earthquake meizoseismal regions and earthquake hazard in eastern Kashmir seismic gap

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The 2005 Kashmir earthquake of magnitude *Mw* 7.6 produced 75 km surface rupture showing 3–7 m vertical offset. The surface rupture nearly coinciding with the bedrock geology-defined Balakot-Bagh Fault (BBF) indicates reactivation of the fault. The BBF extends SE with right-step to the Reasi Thrust in Jammu

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region. Further SE extension of the Reasi Thrust has been mapped with different nomenclature to the 1905 Kangra earthquake meizoseismal region, suggesting linkage between the earthquake and the active fault. There is no historical record of a large magnitude *Mw* > 7 event for the last ~1000 years in the eastern segment of the Kashmir seismic gap, may imply ~12 m slip deficit in the region.

Keywords: Active fault, earthquake hazard, seismic gap, slip deficit.

THE Himalaya has been affected by three very large earthquakes of magnitude $Mw > 7.8 > 8$ during the span of the last 115 years – the 1905 Kangra, 1934 Bihar–Nepal, and 1950 Assam (Arunachal) earthquakes[1]. These earthquakes were earlier considered to have been generated along the blind reverse faults, as no surface ruptures were reported. This notion has now changed with the surface rupture reported in the 2005 Kashmir earthquake[2,3] and the surface ruptures of the 1934 Bihar–Nepal and AD 1255 Nepal events identified on the Sub-Himalayan front[4]. The role of active faults in the occurrence of several destructive earthquakes has been reported, e.g. 1994 Northridge[5], 1999 *Mw* 7.6 Chi-Chi[6] and 2005 *Mw* 7.6 Kashmir[7]. The observed events have focused attention to recognize the hazards posed by such structures to the community, highlighting the need to understand the relationship between seismicity and active faults. The Himalayan rivers have a great potential for renewable and clean hydroelectric power, and efforts are on by the South Asian countries to tap this source of energy. The earthquake hazards posed by the seismogenic active faults is real and hence their identification and understanding the association between seismicity and active faults is important to build safer better engineered structures.

Tectonic framework in Kangra and Kashmir, west of River Beas, is different with regard to two aspects from that of east of Satluj to central Himalaya in Nepal (Figure 1). (i) In Garhwal–Kumaun–Nepal, the Higher Himalaya slab with Tethys Himalaya sequence over its back is thrust upon the wide zone of Lesser Himalaya along the Main Central Thrust (MCT) shear zone. This structural framework of the MCT is not the same west of Beas in Kangra and Kashmir, wherein the Lesser Himalaya sequence occurs in a narrow, few kilometres wide, imbricate belt between the MCT and the Main Boundary Thrust (MBT) in front of the Dhauladhar and Pir Panjal ranges. Also the Lesser Himalaya sequence duplex is exposed in the Larji–Rampur and Kishtwar windows[8,9]. (ii) The main Higher Himalayan Crystalline (HHC) zone, extending northwest from River Satluj to Lahoul and Zanskar, is flanked to the north by the Zanskar Tethys sequence and to the south by the Kashmir Tethys sequence. The Chamba sequence is the southeast extension of the Kashmir Tethys separated by deeply eroded Chenab valley exposing the HHC and the underlying Lesser Himalaya formations in the window zone.

A well-defined instrumental seismicity belt with moderate earthquakes, about 50 km wide, located along the topographic front between the Higher and Lesser Himalaya[10], extends from Nepal[11] through Kumaun–Garhwal[12] to Kangra–Chamba in Himachal Pradesh[13,14] and Kashmir[15]. The Indus Kohistan Seismic Zone (IKSZ)[16], is a major broad microearthquakes belt concentrated over the Hazara syntaxis[17], represents the northwestern extension of the main instrumental seismicity belt. In western Himachal Pradesh between the Ravi and Beas rivers, geodetic measurements (GPS) indicate 14 ± 1 slip on the southern edge of the Higher Himalaya where the Indian plate descends aseismically (creep) to a greater depth[18] demarcating the locking line. The area, including Chamba nappe and Kangra re-entrant, between the locking line and the Sub-Himalayan front, is locked showing very little deformation during the interseismic period. The locking segment width is 100 km and the locking line lies at the northern extent of the microseismicity belt. In Kashmir Himalaya, 11 ± 1 mm/yr convergence and 5 ± 1 mm/yr dextral shear are estimated in Zanskar north of the Kashmir valley. A 130 km wide segment between the locking line and the Sub-Himalayan front is locked and decoupled creep occurs at a depth of 25 ± 4 km (ref. 19). The epicentres of the 2005 and 1905 earthquakes are located within the locked segment.

The 2005 Kashmir earthquake which occurred on 8 October in POK, magnitude $Mw = 7.6$ with 26 km focal depth, was the most devastating of the Himalayan earthquakes in terms of loss of about 80,000 lives. Its epicentre lies at 34.493°N, 73.629°E in POK, at a distance of 19 km NE of Muzaffarabad in Pakistan and 125 km WNW of Srinagar in India (Figure 2)[20,21]. The Harvard CMT solution indicates a northeast dipping fault plane striking N 133°E with a 40° dip[7]. The Kashmir earthquake occurred in the IKSZ[16], and aftershocks are clustered farther northwest of the epicentre[17]. A northwest trending surface rupture produced by the 2005 earthquake was reported for the first time in a Himalayan earthquake[3,20]. Sub-pixel correlation of ASTER images shows average 4 m fault offset and seismic waveform analysis indicates ~4.2 m average slip on rupture surface[7]. The mean slip triggered slip of ~1.8 m on a blind wedge thrust to northwest of the main rupture with the clustering of aftershocks[22]. The surface rupture extending for ~75 km from the north of Balakot to northwest of Bagh was mapped showing vertical separations varying 3–7 m (refs 2, 3). The surface rupture lies along the Tanda Fault and Muzaffarabad Fault mapped earlier as active faults[23]. The Tanda Fault and its northwest continuation into the Muzaffarabad Fault were earlier mapped based on bedrock geology by the Pakistan Geological Survey and the faults were collectively called the Balakot-Bagh Fault (BBF)[20]. Mapping of surface rupture[2,3], remote sensing

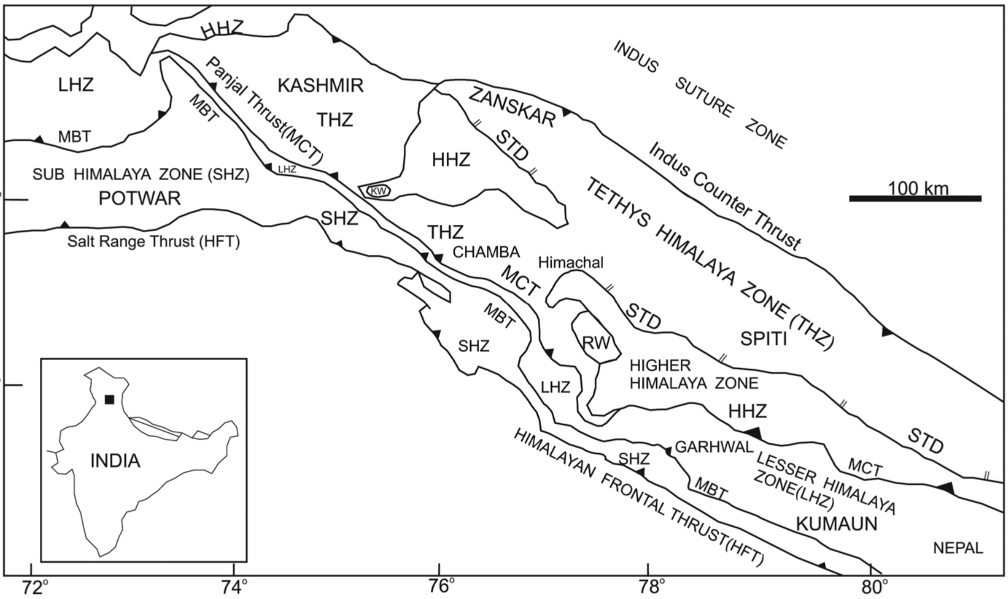

Figure 1. Tectonic framework map of the Western Himalaya showing principal thrusts, tectonic zones and important regions. RW, Rampur window; KW, Kishatwar window.

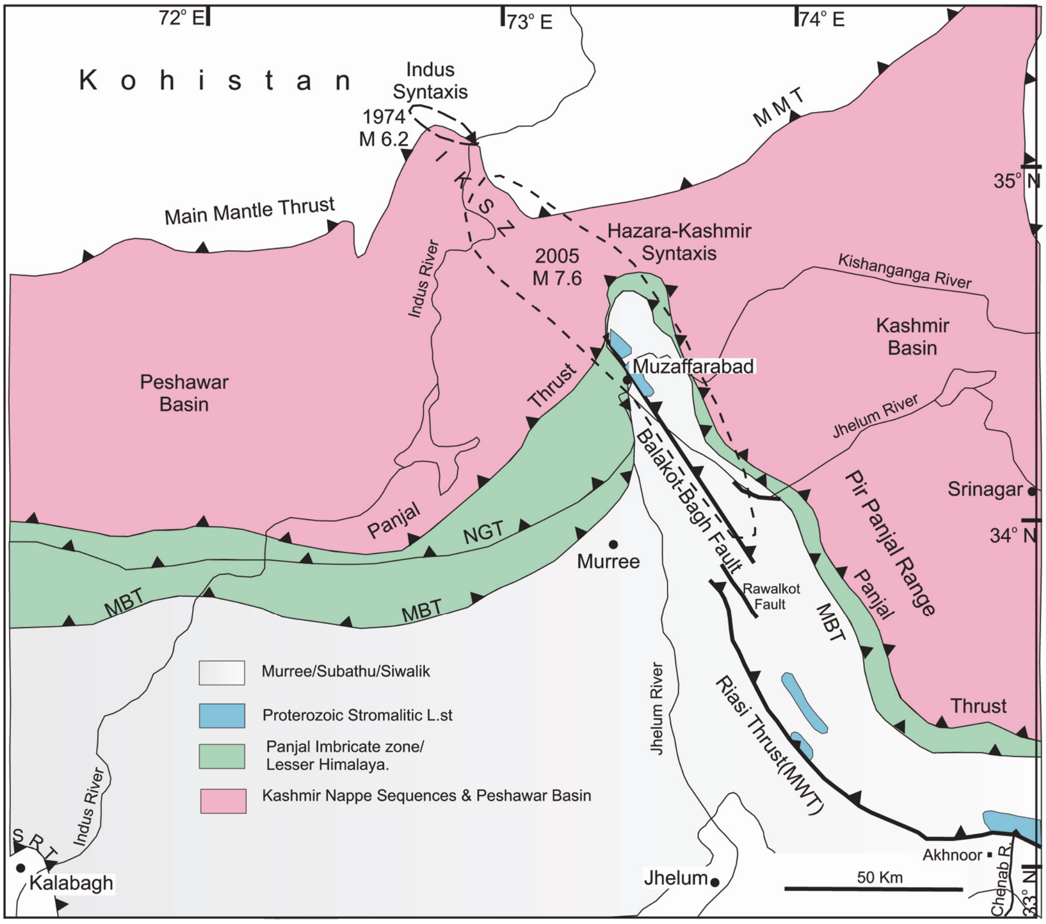

Figure 2. Outline tectonic map of the Western and part Northwest Himalaya showing isoseismals of the 2005 Kashmir and 1974 Patan earthquakes, and Balakot-Bagh Fault (BBF) and Riasi Thrust having similar tectonostratigraphic setting. Rawalkot Fault (RW) is right-step to Reasi Thrust and BBF is right-step to RW. IKSZ, Indus Kohistan Seismic Zone; HLSZ, Hazara Lower Seismic Zone; NGT, Nathia Gali Thrust; ACR, Attock Cherat Range; MBT, Main Boundary Thrust (after Hussain *et al.*[20]).

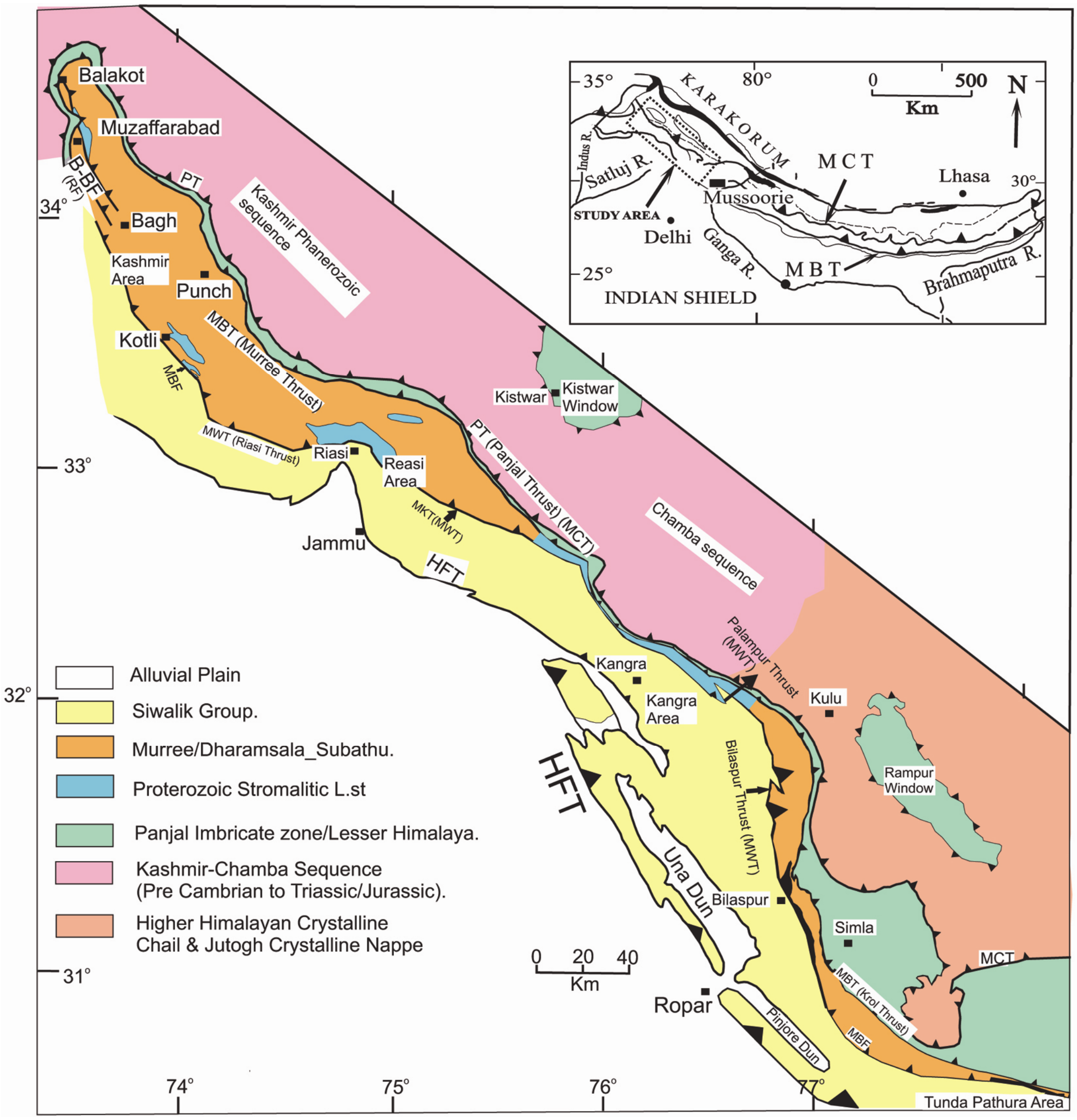

Figure 3. Outline tectonic map of northwest Sub-Himalaya and adjoining tectonic zones. In the Sub-Himalaya the lower Tertiaries comprising Subathus and Dharamsala/Murrees with stromatolite-bearing Proterozoic limestone belt is thrust over the Siwaliks along the BBF, Main Boundary Fault (MBF), Reasi Thrust, Palampur Thrust and Bilaspur Thrust, collectively designated as the Medlicot–Wadia Thrust (MWT) (after Thakur *et al.*[30]).

analysis[7], and InSAAR study[24] show reactivation of the BBF by 2005 Kashmir earthquake.

Between Balakot and Bagh, the BBF brings into juxtaposition the Proterozoic Muzaffrabad Formation, comprising predominantly stromatilite-bearing limestone with shale and Murrees against the non-marine Kamlial (Siwalik) Formation[20]. Further southeast of Bagh in Kotli area, now in POK, Wadia[25] in his map demarcated the Main Boundary Fault (MBF) separating the hanging wall units of limestone, nummulitics and Murrees from the footwall Siwaliks. This tectonostratigraphic setting continues to the Reasi area, where ONGC workers gave local area name to the MBF as the Riasi Thrust (RT)[26]. Hussain *et al.*[20] described an intervening Rawalkot Fault between RT and BBF. In their mapping, the Rawalkot Fault is stepped right from RT and the BBF is further stepped right from the Rawalkot Fault (Figure 2).

In Reasi–Katra area of Jammu region, the stromatolite-bearing Proterozoic Reasi/Sirban Limestone overlain by Subathu and Murree formations, constituting the hanging-wall, is faulted against the Upper Siwalik group along the RT. However, as the limestone body pinches out in its NW and SE extension along the regional strike, the Murree Formation rides directly over the Siwaliks along the RT (Figure 3). The Reasi Limestone (also called the Great Limestone) is interpreted as upthrust wedge of Proterozoic basement in a piggy-back sequence[27]. At many places in the area, the limestone directly overlies the late Quaternary Vaishno Devi gravel, indicating active nature of the fault. Reactivation of the RT as late as the Pleistocene

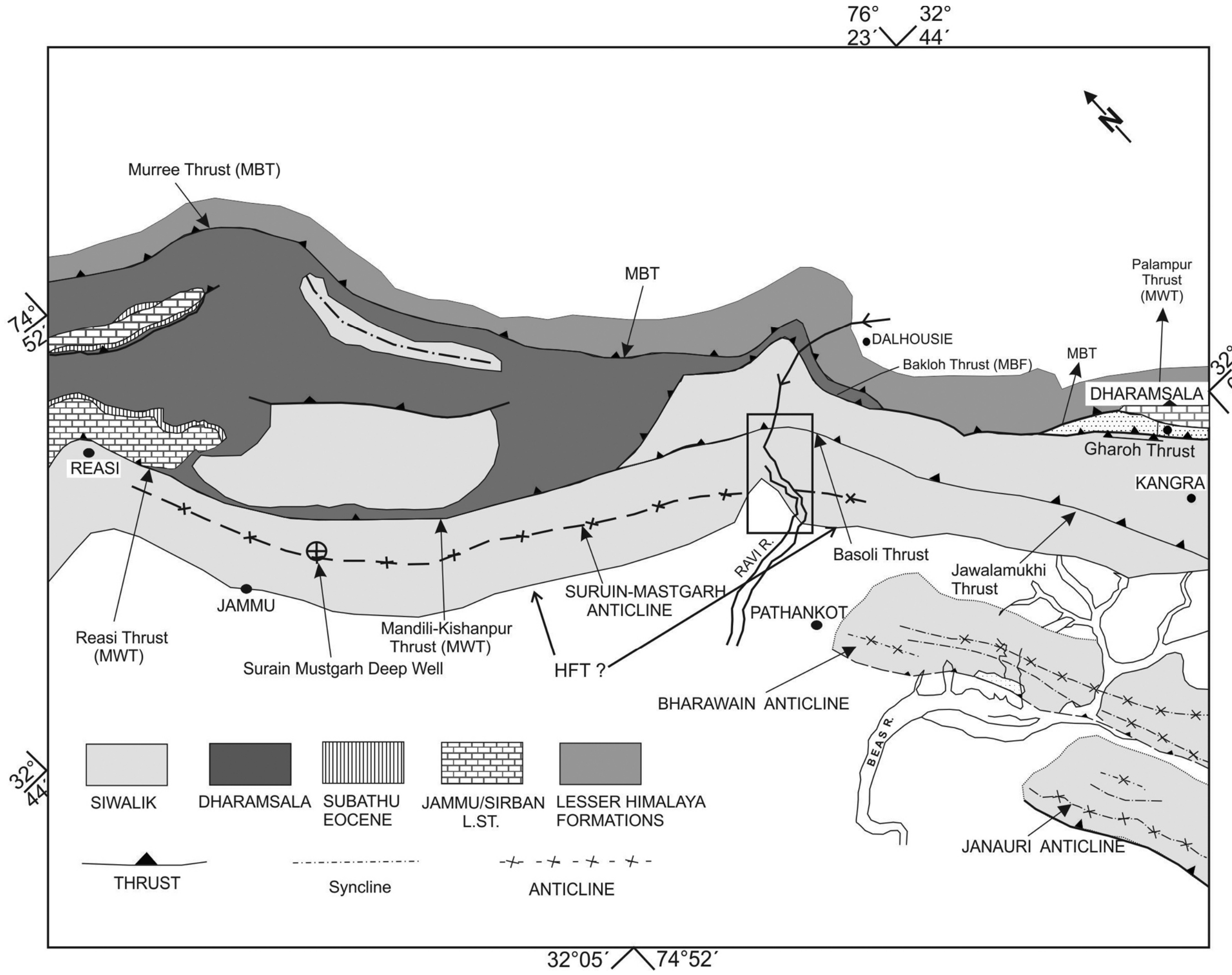

Figure 4. Outline geological map of the Sub-Himalaya zone between Reasi and Kangra showing major structures and local area names to the MWT (after Karunakaran and Rao[26]).

and Holocene was reported earlier by the GSI workers[28,29]. We have studied the active tectonics of RT in Reasi and the adjoining Katra area to understand the extension of the BBF[30]. The tectonostratigraphic framework at Muzaffarabad, Kotli and Reasi–Katra is the same, indicating that the BBF and MBF defined by Wadia belong to the same active fault system designated as RT in Jammu region. We have further extended RT eastward up to Yamuna on a regional scale and redefined the old MBF defined by Wadia in Jammu and by Medlicot in Simla hills as the Medlicot–Wadia Thrust (MWT) on a regional scale[30] (Figure 3). The MWT demarcates the contact between the Proterozoic limestone, Subathus and Dharamsala/Murrees on the hanging wall and the Siwaliks on the foot wall. The Reasi Thrust (MWT) has been described as an out-of-sequence thrust by a French team working[31] in the area. Based on their mapping and dating of terraces in the Reasi area, reactivation of the RT through foot-wall imbrications occurred over the period 36–14 ka, and 13 ± 1 mm/yr slip over the MWT has been estimated[31].

East of Jammu based on our field traverses in the Sub-Himalaya belt between Chenab and Satluj rivers, we validate and follow the ONGC mapping to extend the RT (Figure 4). Wherein SE extension of RT is designated as the Mandili Kishanpur Thrust which in turn continues eastward into two splays as Jawalamukhi Thrust and Medlicot Wadia Thrust[30], with local names Basoli Thrust, Bakloh Thrust, Palampur Thrust and Bilaspur Thrust for the same in different locations[26].

The 1905 Kangra earthquake was also a devastating event that killed 20,000 people. Its earlier estimated magnitude *ML* was ≥ 8 with isoseismal VIII contour extending arc parallel for ~300 km between Kangra and Dehradun[16,32]. In revised interpretation, the magnitude $Mw = 7.8$ Kangra earthquake[33] triggered the Dehradun event with deep (~40 km) focus[34]. The rupture parameters of the earthquake estimated through re-measurements of historic triangulation points in the epicentral area indicate a 100 × 55 km rupture, NE dipping with ~4 m slip. The southern extent of this rupture is interpreted as to

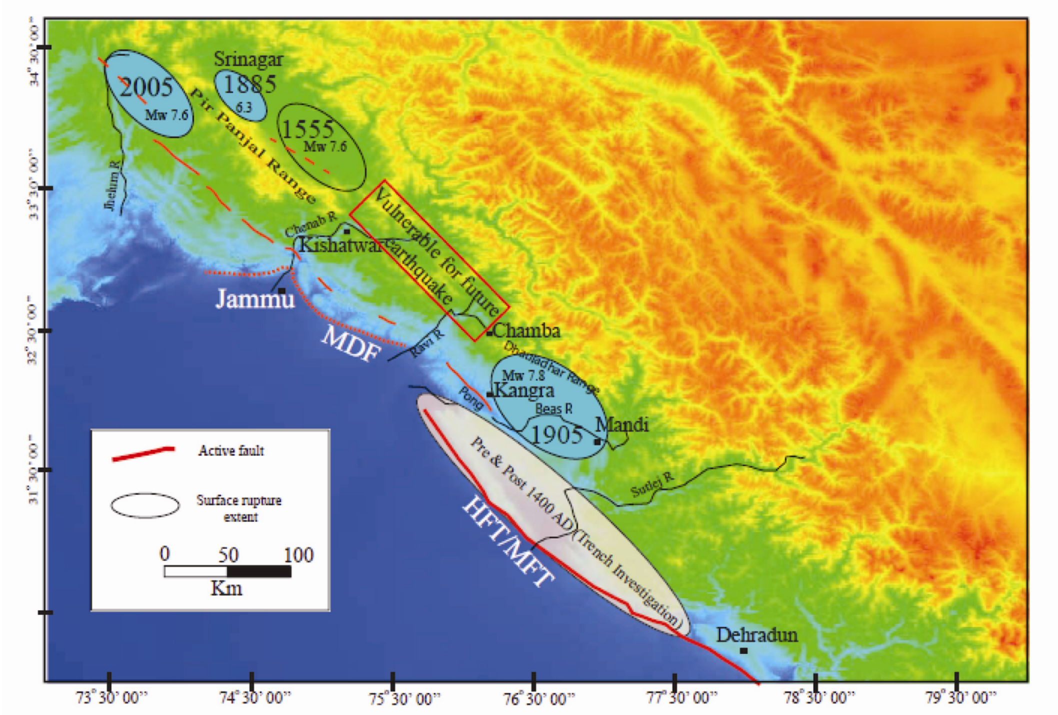

Figure 5. SRTM (shuttle radar topography mission) image of Western and part Northwest Himalaya showing inferred rupture areas of 1555, 1885, 1905 and 2005 earthquakes. Unruptured segment lies between 1905 and 1555 earthquakes. Trench investigation data adapted from Jayangondaperumal *et al.*[41].

coincide with the Jawalamukhi Thrust (JT)[35]. Using fluvial strath terraces over the hanging wall of JT, we have estimated 2.8 mm/yr as bedrock uplift and 4.9 mm/yr as shortening rate over a period 17.4 ka, indicate that JT is an active fault[36]. We have reported the Gharoh Thrust, an imbricate of the Palampur Thrust (MWT) that displaces the late Quaternary debris flow gravels[30]. The Gharoh Thrust is an active fault (extending ~15 km) (Figure 4), indicates reactivation of the MWT post-30 ka. Microseismicity monitoring in the Kangra–Chamba region for more than a decade by the WIHG shows concentration of epicentres under the Dhauladhar range and farther north underneath the Chamba nappe at 12–15 km depth and characterized by sparse infrequent microseismicity under the Sub-Himalaya to the south[13,14]. GPS measurements in the same area indicate ~100 km wide segment between the Sub-Himalayan front, and south of the Higher Himalaya is locked showing very little deformation[18]. The abrupt topographic rise of the Dhauladhar range ranging 4000–4800 m from the > 1000 m high Siwalik ranges with the MCT and MBT lying at the topographic base of the range and the microseismicity pattern in the Kangra–Chamba region, suggest a ramp under the Dhauladhar range and upper flat under the Chamba nappe[13,14]. This seismotectonic setting suggests that the 1905 Kangra earthquake originated on the ramp and the rupture propagated south along the flat reactivating one of the foreland thrust that splayed out towards the surface from the Main Himalaya Thrust (MHT). The Pir Panjal (PP) range, south of the Kashmir valley, lies on the NW continuation of the Dhauladhar range, both having similar physiographic, structural and tectonostratigraphic setting with the narrowly spaced MCT and MBT at the base of southern topographic front. We suggest a ramp under the range. The 2005 earthquake initiated at the ramp and its rupture propagated to the south towards a shallow level of the upper flat, reactivating the BBF and emerging at the surface. The 1905 and 2005 earthquakes originated in a similar seismotectonic setting over the ramp of the MHT under Dhauladhar–Pir Panjal range, which is consistent with a model proposed for such type of Himalayan earthquakes[37].

The Kashmir seismic gap lies between the 1905 Kangra and 2005 Kashmir earthquakes (Figure 5). There are historical records of four moderate to large earthquakes in Kashmir. Of these, the 1555 and 1885 earthquakes affecting the Kashmir valley are assigned magnitudes *Mw* 7.6 and 6.2 respectively[38]. The rupture area[35] and inferred MSK intensity contour[32,38] indicate that the 1905 earthquake rupture lies east of Kangra extending 100 km to the southeast. West of Kangra, there was no damage recorded to army barracks at the Training Centre in Bakloh cantonment and 10th century temples in Chamba town. West of Chamba area including Ravi river, the 1555 event was the largest magnitude earthquake as extensive damage was reported from the Kashmir valley with aftershocks lasting for several weeks. We identify an unruptured segment between the 1905 Kangra and 1555 Kashmir

Figure 6. Chamba town located on a fluvial terrace of the Ravi river was established in AD 920. In the town, the ancient architecture of Lakshami Narayan temple (source: Wikipedia) is intact and does not show reconstruction, implying no damage by any large earthquake.

valley earthquake ruptures. This encompasses Chamba–Kishtwar region, in which there was no historical record of a large magnitude earthquake, except some moderate events, e.g. 1945 Chamba. The Chamba kingdom established in AD 920 by Sahil Varman has a continuous history till date, with the intact 10th century Lakshmi Narayan temple complex (Figure 6; Wikipedia.org/wiki/chamba_Himachal Pradesh) located on Chamba town river terrace. Considering no historical records of a devastating large earthquake for the last 1000 years and assuming GPS-estimated 11 mm/yr slip in Kashmir[19] and 14 mm/yr slip in Kangra–Chamba region[18] imply that ~12 m slip deficit exists in the Chamba–Kishtwar region. This suggests seismic hazard of a large earthquake in the eastern segment of the Kashmir seismic gap.

The epicentres of the 2005 Kashmir and 1905 Kangra earthquakes lie within the locked segment and the micro-seismicity zone where deviatoric stress accumulates during interseismic interval in preparation for the next earthquake. Both the earthquakes reactivated the out-of-sequence thrust faults, BBF in Kashmir and Jawalamukhi Thrust in Kangra. The tectonostratigraphic framework of the BBF and RT is similar, having Proterozoic limestone at the base overlain by Palaeocene–lower Eocene Subathus or equivalent succeeded by Oligocene? Murees on the hanging walls. The stromatolites-bearing Proterozoic limestone bodies represent the basement over which the lower Tertiary sequence was deposited. Exhumation of Proterozoic limestone–shale wedges is also reported along MWT in Bilaspur area. This tectonic framework involving Pre-Cambrian basement in the formation of foreland fold–thrust belt is not consistent with thin-skinned type tectonics in central Himalaya[39], and hence thick-skin tectonic may be suggested in the western part of NW Himalaya, which is similar to the recent suggestion based on fault geometry, slip distribution of the 2011 Jiashian earthquake in the Taiwan belt[31,40]. Identification and mapping of active faults and estimation of fault parameters like vertical offset, slip and recurrence interval need to be considered together with earthquake parameters for the design of safer infrastructures in hydropower projects.

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