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Paleoseismic evidence from trench investigation along Hajipur fault, Himalayan Frontal Thrust, NW Himalaya: Implications of the faulting pattern on landscape evolution and seismic hazard

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ABSTRACT

The study area falls within the mesoseismal zone of 1905 Kangra earthquake (Mw 7.8). Two parallel NNW–SSE striking active fault scarps named as *Hajipur Faults* (HF1 and HF2) along the northwestern end of the Janauri anticline in the foothill zone, have displaced floodplain sediments of the Beas River. The HF1 and HF2 represent the imbricate faults of the Himalayan Frontal Thrust (HFT), and are the result of lateral propagation of deformation from two fold segments i.e., JF1 and JF2 respectively in northwest direction along the strike. Ground Penetrating Radar (GPR) profiles and trenching across the HF2 reveal two low-angle thrust fault strands (F1 and F2). Displacements of ~7.5 m on F2 and ~1.5 m on the associated branching faults (f_a, f_b and f_c) were observed. Total four stratigraphic units: unit A (gravel) – with a lens of medium sand (unit A′) is the oldest; overlain by units B – medium to coarse sand; unit C – with fine to medium sand; and unit D – fine to medium sand with scattered gravel were observed in trench. Radiocarbon ages of the charcoal samples from unit B and unit D, optical ages of sediments from units A′, B and C, GPR data and trench log, suggest two major events along F1 and F2 strands. Event I along F1 occurred during 2600–800 yr BP and Event II along F2 around 400 yr BP and before 300 yr BP. Given the uncertainty in dates it is suggested that the latest event occurred during 1500–1600 AD. Considering the oldest unit (unit A) exposed in trench with vertical displacement of 7.5–8 m, age of 2600 ± 500 yr BP and net displacement of ~9 m during single event along low-angle fault ($\theta = 25°$), implies slip rate $= 7.6 \pm 1.7$ mm/yr, uplift rate $= 3.2 \pm 0.6$ mm/yr, shortening rate $= 6.9 \pm 1.4$ mm/yr and recurrence interval $= 1160 \pm 250$ yr for large-magnitude event with Mw >7.0. With the recurrence of 1100 yr, the penultimate event probably occurred at around 1400–1500 yr BP. Given the recent GPS based slip rate of 14 ± 1 mm/yr in Kangra reentrant (Baneerjee and Burgman, 2002), the present study suggests that about half of this slip is consumed along the HFT and that this fault is more active compared to those in the hinterland.

1. Introduction

The continued convergence between Indian and Eurasian plates has made the Himalayan arc a seismically active region that experienced moderate to large earthquakes. In last 100 years the Himalaya has experienced three major large-magnitude events during 1905 Kangra (Mw 7.8), 1934 Bihar (Mw 8.1) and 1950 Upper Assam (Mw 8.4) earthquakes (Seeber and Armbruster, 1981; Yeats et al., 1997; Ambraseys and Bilham, 2000; Ambraseys and Douglas, 2004) (Fig. 1a). The recent October 8, 2005 Muzaffarabad earthquake (Mw 7.6) occurred along an earlier identified active fault named *Balakot–Bagh fault* causing extensive damage in Pakistan as well as in Indian side (Nakata, et al., 1991; Kaneda et al., 2008). Seismic hazard evaluation in Himalaya is one of the most crucial problems. Historic records and instrumental data available so far is not so comprehensive and also little or no written records are available from much of the Himalayan belt, hence actual appraisal of hazard from this dataset is difficult (Iyengar and Sharma, 1999; Bilham et al., 2001). For proper seismic hazard estimation,

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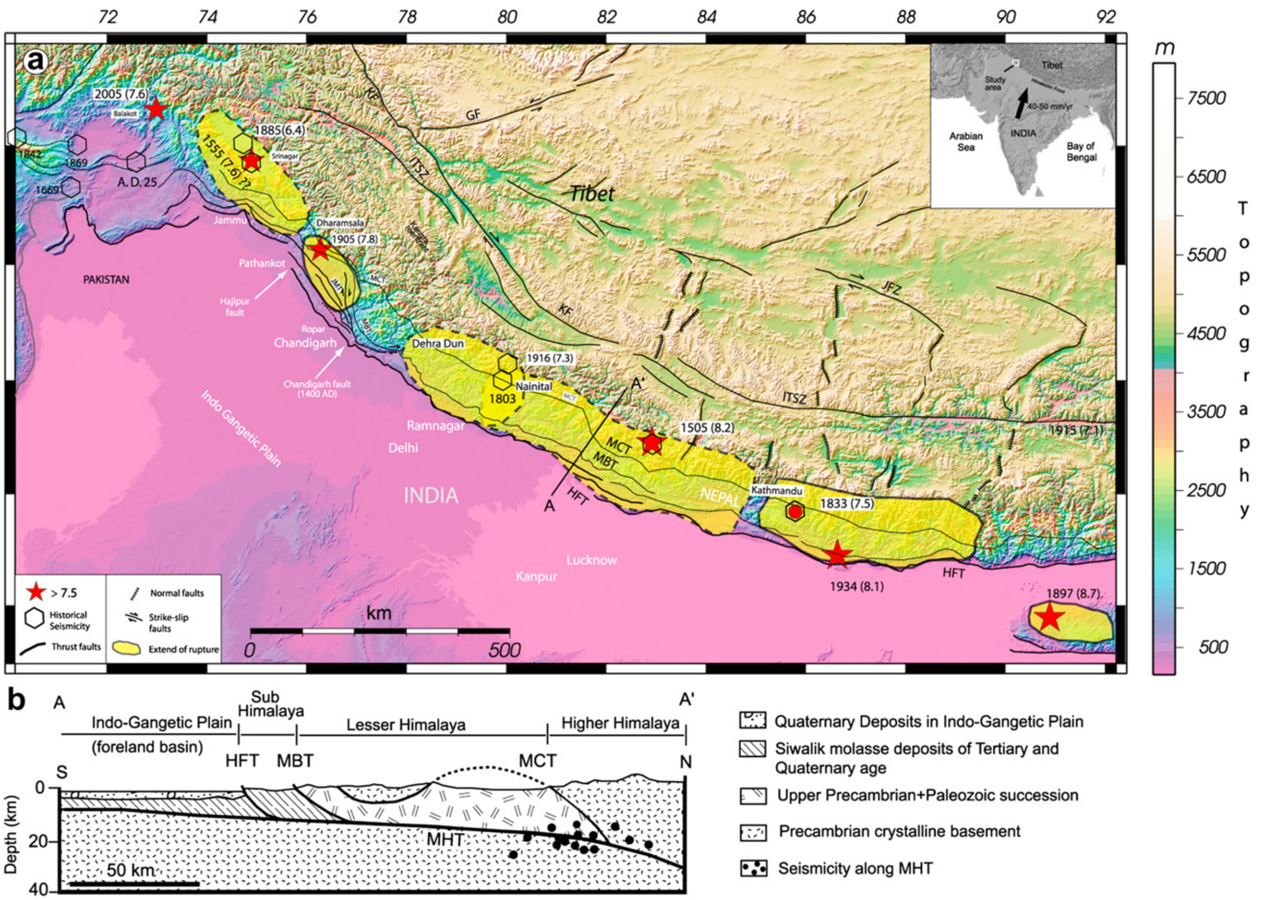

Fig. 1. (a) Map showing area of the Himalaya and its neighborhood with major fault systems, historic and recent large-magnitude earthquakes (after Nakata et al., 1990; Yeats et al., 1992; Powers et al., 1998; Wesnousky et al., 1999; Lavé and Avouac, 2000; Tapponnier et al., 2001; Kumar et al., 2001; Malik and Nakata, 2003). Extent of inferred rupture areas during 1505 (Mw 8.2), 1555 (Mw 7.6), 1905 (Mw 7.8), 1934 (Mw 8.4) are shown by shaded portion with dashed line (after Yeats et al., 1992; Ambraseys and Bilham, 2000; Ambraseys and Douglas, 2004; Bilham and Ambraseys, 2005). HFT – Himalayan Frontal Thrust, MBT – Main Boundary Thrust, MCT – Main Central Thrust, ITSZ – Indus-Tsangpo Suture Zone, JFZ – Jiali fault zone, KF – Karakoram fault, (b) North–South generalized geologic section across the Central Himalaya, seismicity along the Main Himalayan Thrust is marked by black dots (Ni and Barazangi, 1984). Location of the section is marked by A–A′ line in Fig. 1a (after Seeber and Armbruster, 1981).

identification of active faults bears significant importance, it is also necessary to know the accurate locations and geometry of active faults (Gross et al., 2002). Paleoseismic investigation is one of the most commonly adopted techniques towards identification/cataloguing the historic and pre-historic earthquakes in tectonically active regions of the world (McCalpin, 1996).

The studies carried out during several decades have provided important data on the ongoing crustal deformation in the Himalaya. However, not much effort is directed to site-specific studies (Nakata, 1989; Valdiya, 1992; Yeats et al., 1992; Wesnousky et al., 1999; Malik et al., 2003; Malik and Nakata, 2003). Recent paleoseismic investigations from India, Pakistan and Nepal along the Himalaya arc have added valuable information towards the occurrence of large-magnitude earthquake during recent historic past. Investigations along Sirmuri Tal fault in Dehra Dun valley along Main Boundary Thrust (MBT) suggests two major earthquakes have struck Dehra Dun region in the last 1000 years (Oatney et al., 2001). Paleoseismic investigations along Black Mango (Kala Amb) tear fault along the Himalayan Frontal Thrust (HFT) in the NW Himalaya have revealed evidence of two large earthquakes with surface ruptures during the past 650 years; subsequent to 1294 AD and 1423 AD and yet another at about 260 AD (Kumar et al., 2001). Also studies from NW Himalaya have indicated major event at around ~1400–1500 AD along HFT (Kumar et al., 2006; Malik et al., 2008). Paleoseismic evidence from east central Nepal reveals a single earthquake rupture along the Frontal Thrust during ~1100 AD (Lavé et al., 2005). Trench investigation performed along Balakot–Bagh fault after the 2005 Muzaffarabad earthquake suggests recurrence interval of 1000–3300 yr and shortening rate of 1.4–4.1 mm/yr (Kaneda et al., 2008).

Earthquakes along active faults are periodic (Yeats et al., 1997; McCalpin, 1996) and a proper seismic hazard assessment needs an active fault map with paleoseismic history. The Muzaffarabad 2005 event has raised more concerns towards the seismic hazard assessment in areas along Himalayan foothills, where practically no historic or no active fault-paleoseismic data is available. In this paper we document the geomorphic manifestation of newly identified active faults, named as *Hajipur faults* in the mesoseismal zone of 1905 Kangra earthquake (Mw 7.8) along the northwestern end of the Janauri anticline (Fig. 1a). These faults along the Himalayan front were identified using CORONA satellite (stereo pair) photos, Digital Elevation Model (DEM) generated from SRTM data followed by detail field investigations (Figs. 2–4). GPR (Ground Penetrating Radar) profiling was conducted to understand the geometry of the faulting and to locate the appropriate site for further paleoseismic investigation. Paleoseismic investigation revealed occurrence of two major events during 2600–800 yr. BP and another at around 400 yr BP. The 1905 Kangra and 2005 Muzaffarabad events are the only well documented events from NW Himalaya (Iyengar and Sharma, 1999; Ambraseys and Jackson,