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Seismotectonics and crustal stress field in the Kumaon–Garhwal Himalaya

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ABSTRACT

We present fault plane solutions of 94 well located small-to-moderate sized ($1.5 \leq ML \leq 5.4$) earthquakes, which occurred in the Kumaon–Garhwal Himalaya during 2005–2008, using P-wave polarity and body wave amplitudes. These earthquakes show a mixture of thrust, normal and strike-slip type mechanism, with a majority of thrust type. Most of the thrust earthquakes occur at a depth of 8–22 km in the Main Central Thrust (MCT) zone and the Lower Himalaya. The spatial distribution of these earthquakes suggest that the strain resulting from the ongoing collision of the Indian plate with the Eurasian plate is being consumed by thrust fault movement mainly on the north dipping Munsiari Thrust and south dipping Tons Thrust. The strike-slip earthquakes are mainly observed in the Lower Himalaya as well as around the Munsiari region in the MCT zone. The normal earthquakes are also observed in different parts of the Kumaon–Garhwal Himalaya and the Gangetic plain. Their occurrence is attributed to the local structure(s) as well as the flexure of the Indian plate. Stress tensor inversion of the calculated fault plane solutions indicates that the maximum compressive stress in the Gangetic plain is N–S directed and near vertical; whereas in the Kumaon–Garhwal Himalaya, it is near horizontal and NNE–SSW directed, and correlating with the prevailing stress condition due to northward movement of Indian plate.

1. Introduction

The Himalayan arc is formed by the northward movement of the Indian plate that continues to push the Eurasian plate since ~50 Ma (Basse et al., 1984; Patriat and Achache, 1984). In the process, it has created several fault systems south of the Indus-Tsangpo Suture Zone (ITSZ), marked by distinct litho-tectonic boundaries. These are, from north to south, the Southern Tibetan Detachment System (STDS), Main Central Thrust (MCT), Main Boundary Thrust (MBT) and Main Frontal Thrust (MFT) (Fig. 1) (Patel et al., 2011a; Thakur, 1993; Valdiya, 1980; Yin, 2006). These thrusts in the Himalayan arc are characterized by topographic breaks, which divide the entire Himalaya into four physiographic subdivisions viz., from north to south, Tethyan Himalaya, Higher (or Great) Himalaya, Lower (or Lesser) Himalaya and Sub (or Outer) Himalaya extending southwards to the Himalayan foredeep, also called the Gangetic plains/Ganga basin (Fig. 1). In depth, the last three faults (MFT, MBT, MCT) are believed to emanate from the top of the underthrusted Indian plate beneath the Himalaya, popularly known as plane of detachment or the Main Himalayan Thrust (MHT, Fig. 1, inset A) (Nelson, 1996; Schulte-Pelkum et al., 2005; Zhao et al., 1993). A mid-crustal ramp has been suggested on the MHT (e.g., Berger et al., 2004; DeCelles et al., 2001; Lavé and Avouac, 2001; Lemonnier et al., 1999; Pandey et al., 1995) and its presence has been reported through various structural cross-sections along the Himalayan arc (e.g., Mugnier et al., 2003; Srivastava and Mitra, 1994). Although varying along the Himalayan arc, in its location and dip, the mid-crustal ramp is located approximately beneath the physiographic boundary between the Lower and Higher Himalaya (Wobus et al., 2006). Detailed geology and tectonics of the Himalaya arc have been reviewed by several researchers (e.g., Avouac, 2003; Molnar, 1990; Yin, 2006).

With the underthrusting of the Indian plate beneath the Eurasian plate at a rapid rate of ~20 mm per year (Jade et al., 2014), the collision force builds up pressure continually to generate earthquakes, some times as large as magnitude (M) 8 or more (Fig. 1 inset B). The historical seismicity of the region prior to year 1800 is not well documented. Subsequent instrumental seismic records and maximum intensity data provide evidence for the occurrence of several significant earthquakes (Fig. 1 inset B), namely the 1803 (Kumaon, M ~7.7), the 1833 (Kathmandu, M ~7.7), the 1897 (Shillong, Mw ~8.1), the 1905 (Kangra, Mw ~7.8), the 1934 (Bihar/Nepal, M ~8.3) and the 1950 (Assam, M ~8.7) earthquakes (Ambraseys and Jackson, 2003; Gahalaut, 2008; Rajendran and Rajendran, 2005). These large magnitude earthquakes in the Himalayan arc seem to rupture the seismogenic part of the MHT beneath the Sub and Lower Himalaya and accumulate strain during the

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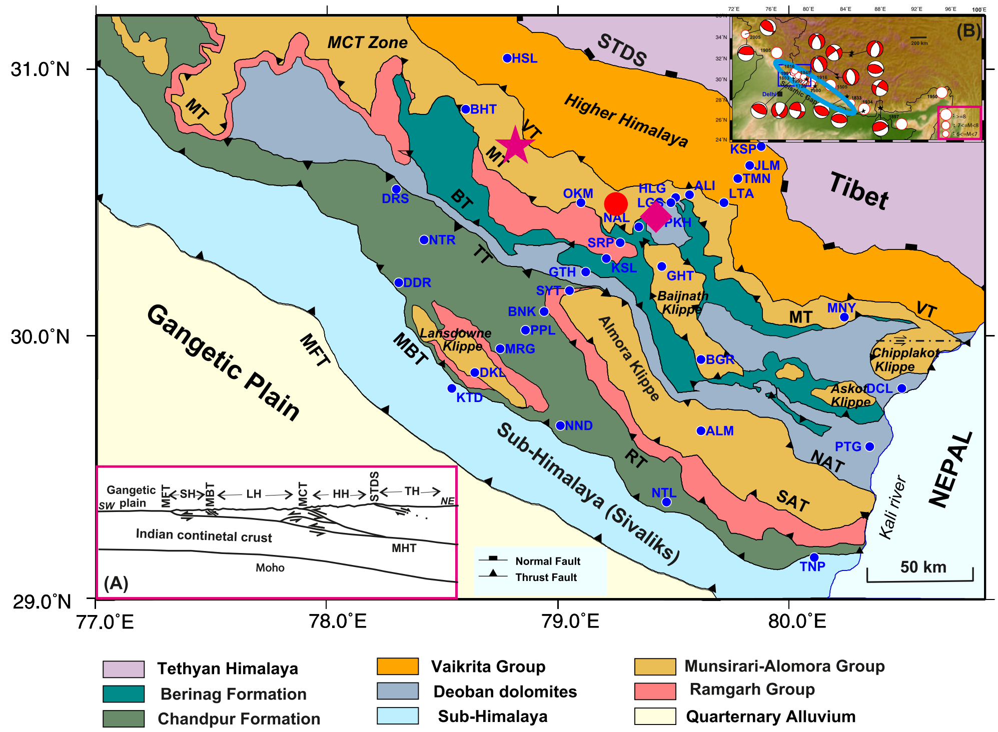

Fig. 1. Geology and tectonic map of study area showing subdivisions of Kumaon–Garhwal Himalaya by major thrusts (continuous lines) viz., MFT: Main Frontal Thrust, MBT: Main Boundary Thrust, MCT: Main Central Thrust, MT: Munsiari Thrust, VT: Vaikrita Thrust, STDS: Southern Tibetan Detachment System, TT: Tons Thrust, RT: Ramgarh Thrust, BT: Berinag Thrust, NAT: North Almora Thrust, SAT: South Almora Thrust. The seismic stations used in the study are shown as filled blue circles. Moderate size earthquakes in the region are shown with different symbols (Star: 1991 Uttarkashi, M 6.6; Diamond: 1999 Chamoli, M 6.3; Circle: 2005 Chamoli, M 5.3). Insert A: A schematic cross section across the Himalaya (modified from Avouac, 2007). SH: Sub Himalaya, LH: Lower Himalaya, HH: Higher Himalaya, TH: Tethyan Himalaya. Insert B: The topography map of Himalaya showing historical earthquakes (circles along with the year of occurrence), central seismic gap (blue ellipse; Seeber and Armbruster, 1981), focal mechanisms of the earthquakes (Harvard CMT Data Base), which occurred during our experiment period (2005–2008); and the present study region (small rectangle).

inter-seismic period, when it is locked. Whereas, small and moderate earthquakes occur on the downdip part of the seismogenic MHT or on the mid-crustal ramp, which connects the gentle dipping seismic and aseismic (lying under the Higher and Tethys Himalaya) parts of the MHT (e.g., Avouac, 2003; Gahalaut, 2008; Molnar, 1990; Seeber and Armbruster, 1981). Recently, lateral variation in the mid-crustal ramp on the MHT in the NW-Himalaya (Patel and Carter, 2009; Singh et al., 2012) and Nepal Himalaya (Robert et al., 2011) have also been reported.

Along the Himalayan arc, there is spatial variation in the seismicity and rupture extents of the large magnitude earthquakes. The locations of rupture areas of the large magnitude earthquakes show seismic gaps along the Himalayan arc. One such seismic gap has been identified between the rupture zones of the 1905 Kangra and the 1934 Bihar great earthquakes (Fig. 1 inset B) and referred as Central Seismic Gap (Bilham et al., 2001; Seeber and Armbruster, 1981). The Kumaon–Garhwal Himalaya (77°–81°E, west of Nepal Himalaya), the focus of present investigation, falls in this ~700 km long seismic gap. This region had experienced significant seismicity (discussed in Section 2.2), and is a part of high earthquake risk zone in the Himalayan arc. The modeling results and geological data suggest that the entire accumulated deformation over interseismic time has not been released (Berger et al., 2004). Geodetic and microseismicity observations indicate the building up of stress and strain in this part of Himalaya capable of generating great earthquake(s) along the MHT (Banerjee and Burgmann, 2002; Bilham et al., 2001; Jade et al., 2014).

To study the seismotectonics and the regional stress pattern in the Kumaon–Garhwal Himalaya, we compute focal mechanism solutions of the well located 94 earthquakes from an earlier study by Mahesh et al. (2013) and use them to understand the regional stress pattern in the region.

2. Overview of Kumaon–Garhwal Himalaya

2.1. Tectonic setting

Following the tectonic framework of the Himalayan arc, the MCT zone in Kumaon–Himalaya is bounded by the Munsiari Thrust (MT) in the south and by the Vaikrita Thrust (VT) in the north (Valdiya, 1980) (Fig. 1). Other major fault systems include the Tons Thrust (TT), Berinag Thrust (BT), Ramgarh Thrust (RT), North Almora Thrust (NAT), and South Almora Thrust (SAT) (Fig. 1). Among these the TT and NAT are the south dipping thrusts, whereas the other thrusts are the north dipping thrusts. Thermochronological studies in the Kumaon–Garhwal Himalaya show spatial and temporal variations in tectonic and exhumation (Patel et al., 2011b; Singh et al., 2012). Recently, the MHT as having flat-ramp-flat geometry is mapped in Kumaon–Garhwal Himalaya using receiver function analysis (Caldwell et al., 2013). This mid-crustal ramp is mapped beneath the MT and dips at an angle of ~16°. Detailed geology and tectonics of the region have been reviewed by several authors (e.g., Célérier et al., 2009; Singh et al., 2012; Srivastava and Mitra, 1994; Valdiya, 1980; Yin, 2006).

2.2. Seismicity and fault plane solutions

The Kumaon–Garhwal Himalaya region, in the Central Himalaya seismic gap, is a part of high earthquake risk zone, where no great earthquake has occurred in the last two centuries. The latest great earthquake possibly occurred in 1803 in Kumaon region and the other possibly in the year 1255 (Bilham et al., 1995). Paleo-seismological studies and historical seismic records indicate possibility of other big earthquake(s) in the past in this region (Ambraseys and Jackson, 2003; Kumar et al.,