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Seismites in the Kathmandu basin and seismic hazard in central Himalaya

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ABSTRACT

Soft-sediment deformation structures have been analyzed at six sites of the Kathmandu valley. Micrigranulometric study reveals that silty levels (60 to 80% silt) favor the development of soft-sediment deformation structures, while sandy levels (60 to 80% sand) are passively deformed. Nonetheless well sorted sand levels (more than 80% sand) generate over-fluid pressure during compaction if located beneath a silty cap, leading to fluidization and dike development. 3-D geometry of seismites indicates a very strong horizontal shearing during their development. Using a physical approach based on soil liquefaction during horizontal acceleration, we show that the fluidization zone progressively grows down-section during the shaking, but does not exactly begin at the surface. The comparison of bed-thickness and strength/depth evolution indicates three cases: i) no soft-sediment deformation occurs for thin (few centimeters) silty beds; ii) the thickness of soft-sediment deformation above sandy beds is controlled by the lithological contrast; iii) the thickness of soft-sediment deformation depends on the shaking intensity for very thick silty beds. These 3 cases are evidenced in the Kathmandu basin. We use the 30 cm-thick soft-sediment deformation level formed during the 1833 earthquake as a reference: the 1833 earthquake rupture zone extended very close to Kathmandu, inducing there MMI IX–X damages. A 90 cm-thick sediment deformation has therefore to be induced by an event greater than MMI X. From a compilation of paleo and historic seismology studies, it is found that the great (M ~ 8.1) historical earthquakes are not characteristic of the greatest earthquakes of Himalaya; hence earthquakes greater than M ~ 8.6 occurred. Kathmandu is located above one of the asperities that laterally limits the extent of mega-earthquake ruptures and two successive catastrophic events already affected Kathmandu, in 1255 located to the west of this asperity and in ~1100 to the east.

1. Introduction

The present-day tectonics of the Himalaya is characterized by under-thrusting of the Indian lithosphere along the Main Himalayan Thrust (MHT from Zhao et al., 1993; Fig. 1). Although some earthquake ruptures occur out-of sequence (Kaneda et al., 2008; Mugnier et al., 2005), most of them occur along the MHT (Avouac, 2003). Historical archives indicate that large earthquakes with >8 moment magnitude (M) have episodically ruptured several hundred kilometers long segments of the southern part of the MHT (Chandra, 1992). Several observations suggest the occurrence of mega earthquakes along the MHT (greater than the ~8.1 M historic earthquakes): a) a summation of the seismic moment for the Himalayan arc reveals that the frequency of great earthquakes during the past three centuries is insufficient to explain the transfer of the South Tibet/India convergence toward the frontal thrust belt (Bilham et al., 2001); b) trenching at the front of the belt indicates events with more than 10 m displacement (Kumar et al., 2006; Lavé et al., 2005); c) historical seismicity underlines seismic gaps (e.g. Seeber and Armbruster, 1981), the major one being located in western Nepal between the 1803 Kumaon and the 1934 Bihar–Nepal earthquakes; these gaps are potential places for very great earthquakes. The seismic hazard in Himalaya is therefore obvious, but an uncertainty remains concerning the level of destruction that could affect the Kathmandu area.

To improve the seismic hazard estimation, we have performed an extensive survey of the soft-sediment deformation and dikes preserved in the Plio–Pleistocene fluvio-lacustrine sediments of the Kathmandu Valley. The aim of this paper is to: a) perform a geometric and granulometric analysis of the soft-sediment deformation; b) propose a simplified physical approach in order to confirm that soft-sediment deformations are related to earthquake events i.e. are “seismites”; c) compare the pre-historic seismites with seismites related to well known historic events; d) propose a catalog of the great earthquakes that occurred in the Kathmandu area by taking into account our paleo-seisms study, trenching at the front of Himalaya (Kumar et al., 2006, 2010; Lavé et al., 2005) and historical earthquakes (Ambraseys and Douglas, 2004; Bilham, 1995; Chitrakar and Pandey, 1986). Finally our results are discussed using recent concepts about seismic (Avouac, 2003; Feldl and Bilham, 2006) and inter-seism behaviors (Berger et al., 2004) of the central Himalaya.

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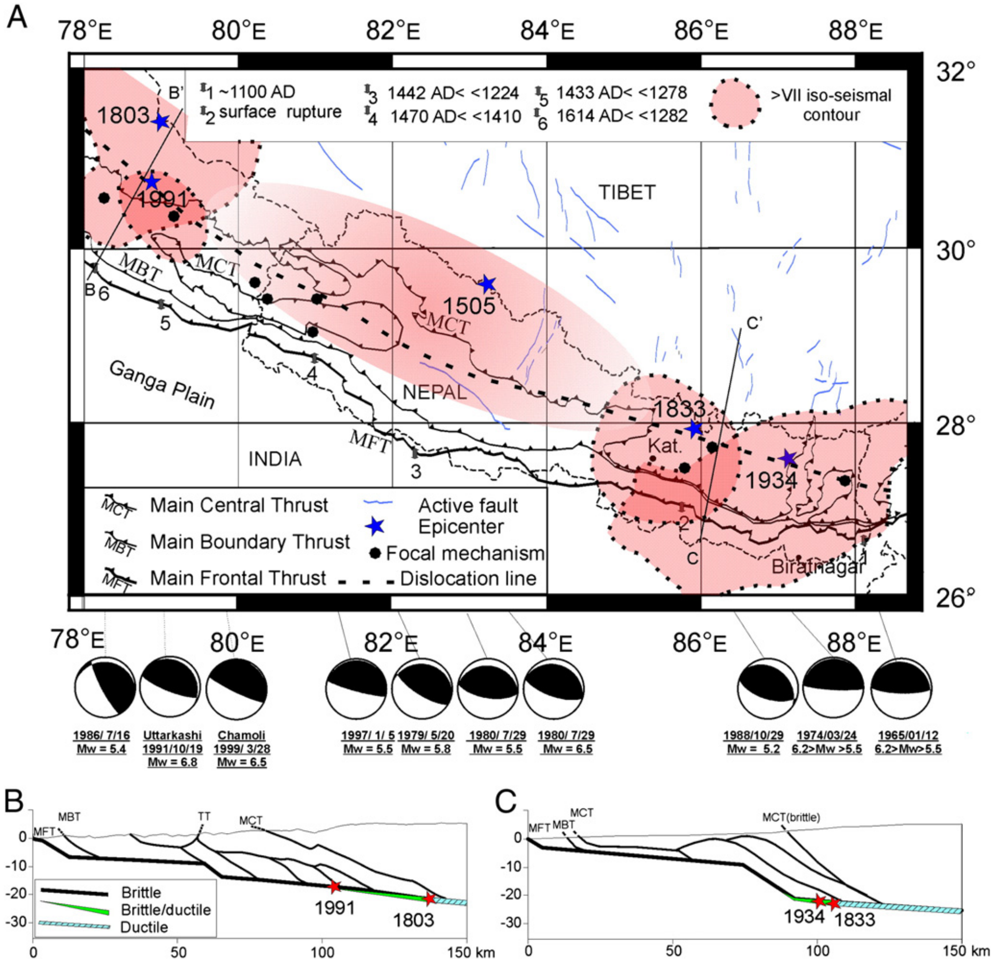

Fig. 1. A) Map of the historical great earthquakes of the central Himalaya. Kat, Jum and Nep respectively for Kathmandu, Jumla and Nepalgunj. 1934 epicenter from Chen and Molnar (1977), 1505 and 1803 epicenters from Ambraseys and Douglas (2004), 1991 epicenter from Rastogi and Shadha (1995) and IMD, 1833 event from Thapa (1997). MKS isoseismal contours for Intensity = VII from Ambraseys and Douglas (2004) for the 1934, 1803 and 1833 events and inferred from Ambraseys and Jackson (2003) for 1505 event. MMI intensity from Rastogi and Chadha (1995) for 1991 event. Location of the trenches associated to the following events: (1) ~1300 ≪ 1050 AD (Nakata, 1998), (2) ~1100 AD (Lavé et al., 2005), (3) 1442 ≪ 1224 AD (Mugnier et al., 2005 and this paper), (4) 1470 ≪ 1410 AD (Kumar et al., 2010), (5) 1433 ≪ 1278 AD (Kumar et al., 2006); (6) 1614 ≪ 1282 (Kumar et al., 2006). The focal mechanisms are from Larson (1999, CMT Harvard catalog) and from Molnar (1990) for those between 1965 and 1976. Dislocation line (~brittle–ductile transition along the MHT) adapted from Banerjee and Burgmann (2002), Berger et al. (2004) and Bettinelli et al. (2006). B) Structural cross-section of Kumaon (location on Fig. 1) adapted from Srivastava and Mitra (1994). TT: Tons Thrust. C) Structural cross-section in eastern Nepal (location on Fig. 1) adapted from Berger et al. (2004) and Schelling and Arita (1991).

2. Geological setting of the seismites of the Kathmandu basin

2.1. Structural control of great Himalayan earthquakes

The Himalaya formed by a pile of thrust sheets (Le Fort, 1975). The major thrusts (MCT for Main central thrust and MBT for Main Boundary Thrust) are presently passively displaced above the Main Himalayan Thrust (MHT). This major fault absorbs about 20 mm/yr convergence (Bilham et al., 1997). Geometry of the MHT is characterized by (e.g. Schelling and Arita, 1991) a southern frontal ramp (MFT for Main Frontal Thrust), a shallow décollement at the boundary between the Indian craton and the syn-orogenic sediments (Mugnier et al., 1999), a detachment beneath the Lesser Himalaya, a crustal ramp cutting through the crust of the Indian craton and a lower flat that extends far to the north beneath the Tibetan plateau (Fig. 1).

The crustal ramp along the MHT has been deduced from balanced cross-sections (De Celles et al., 1998; Srivastava and Mitra, 1994) and some geophysical data (e.g. Avouac, 2003; Schulte-Pelkum et al., 2005; Zhao et al., 1993) that indicate a clear difference in depth of shallow detachment beneath the external part of Himalaya and deeper detachment beneath the Higher Himalaya. This ramp is also inferred from modeling (Berger et al., 2004; Lavé and Avouac, 2001; Pandey et al., 1995; Robert et al., 2011) and it is found that the location and size of the crustal ramp vary along strike (Fig. 1B). The ramp is located to the north of the MCT surface trace in the central Nepal, whereas it is rather small and located to the south of the MCT in the western Nepal (Berger et al., 2004; Pandey et al., 1999; Robert et al., 2011).

Most of the great earthquakes occur along the MHT (Seeber and Armbruster, 1981; focal mechanisms on Fig. 1 from Larson, 1999). Some of them reach the surface along the MFT (see trench location on Fig. 1) and some along out-of sequence thrusts (Mugnier et al., 2004; Mugnier et al., 2005), like the 2005 Kashmir earthquake (Kaneda et al., 2008). However, all earthquakes do not reach the surface, like the 1991 (M~7) Uttarkashi event (Cotton et al., 1996; Rastogi and Chadha, 1995).

The ruptures of the great Himalayan earthquakes nucleate close to the brittle–ductile transition (location on Fig. 1 from Banerjee and Burgmann, 2002; Bettinelli et al., 2006) and propagate towards the Indian plain along the MHT. Lateral extent of the great earthquake ruptures is probably controlled by structural complexities that trend obliquely to the Himalayan chain. Molnar (1987) showed that lateral ramps caused the segmentation of the 1905 earthquake in several