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Earthquake recurrence in NW and central Himalaya

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ABSTRACT

In this study we compare Himalayan seismic moment release estimates derived from strain rate observations with those derived from large historical earthquakes, and to this end we use a reassessed catalogue of historical earthquakes from western and central Himalaya since the beginning of the 16th century. We have computed seismic moment rates within six contiguous segments along the Himalayan arc and compared these, using Kostrov's formula, with moment rates computed from recent global strain rate estimates and regional studies. While the ratios between strain-based moment-rate estimates and those inferred from observed seismicity vary significantly between the segments, we find on the average consistently larger strain-based values by about a factor of two, based on seismicity from the last 515 years. The moment-rate ratio is, however, significantly reduced when shorter catalogues are used, to 1.28 for the last 215 years and to 1.05 for the last 115 years, which is an almost perfect match. The possible inclusion of afterslip in the model would further improve the 515-year match. This is indicating that a significant part of the difference, possibly most of it, is likely to be caused by incompleteness of the longer earthquake catalogue, possibly combined with underestimated magnitudes. The difference between geodetic and seismic estimates for the more complete part of the catalogue is smaller than previously reported along the western Himalayan frontal thrust. In fact, the only region where a significant moment-rate difference is found in our study is in SE Himachal Pradesh. In terms of seismic hazard it is found that the moment rate reduction of about a factor of two, when going from 115 to 515 years, leads to a reduction in the 475-year PGA of about 26%. It is also found that using 50 years of USGS seismicity data between 1963 and 2012 leads to a 40% lower hazard as compared to using moment release for the last 115 years.

1. Introduction

With a total length of about 2400 km, the highest mountains, the deepest lithospheric roots and the highest uplift rates within a continent, the Himalayan mountain chain is an undisputed end member on the scale of seismotectonic significance. Given the large-scale motions it may appear surprising that several earlier studies have predicted an earthquake deficit in this region, with a GPS-based moment release rate exceeding the observed rate. Such studies, albeit based on quite different methods and approaches and also with quite different deficit estimates, include Bilham and Ambraseys (2005), Meade (2010), Ader et al. (2012), Schiffman et al. (2013) and Stevens and Avouac (2015, 2016). Ader et al. (2012) find, using a subduction zone inversion technique, that the Main Himalayan Thrust (MHT; Fig. 1) appears to be fully locked from its foothill surface expression to beneath the front about 100 km to the north, and that the moment deficit accumulates at a rate of 6.6×10^{19} Nm/yr, which corresponds to a seismic moment deficit of about a factor of five. Stevens and Avouac (2015) also find that the fault is fully locked along its complete length and over about 100 km width (see also Li et al., 2016 and Jouanne et al., 2017), and that the moment deficit builds up at a rate of $15.1 \pm 1 \times 10^{19}$ Nm/yr for the entire length, which is more than twice the rate of Ader et al. (2012). Based on a different approach and one not much different from what is used here, Bilham and Ambraseys (2005) report a deficit of about a factor of 3 to 4. All of these studies are predating the 25 April 2015 M_W 7.8 Gorkha earthquake and the connected 12 May 2015 M_W 7.3 earthquake, which ruptured locked portions of the MHT (e.g., Avouac et al., 2015).

Here we start with a re-evaluation of the largest historical earthquakes along the western and central Himalayan arc, and propose a segmentation based on combined tectonic and seismological criteria (Fig. 2). The observed seismic moment rates are first compared with estimates directly from the GPS velocity vectors,

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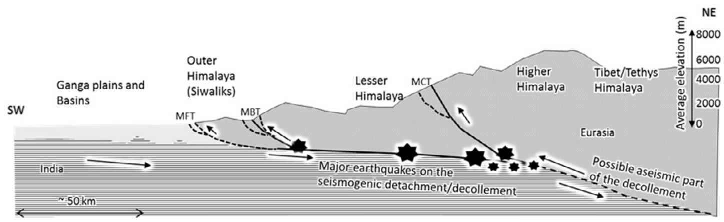

Fig. 1. A general SW-NE vertical cross section across the Himalayan arc showing the seismically active and aseismically slipping detachment. The detachment zone is often denoted as the Main Himalayan Thrust (MHT). MFT = Main Frontal Thrust, MBT = Main Boundary Thrust, MCT = Main Central Thrust.

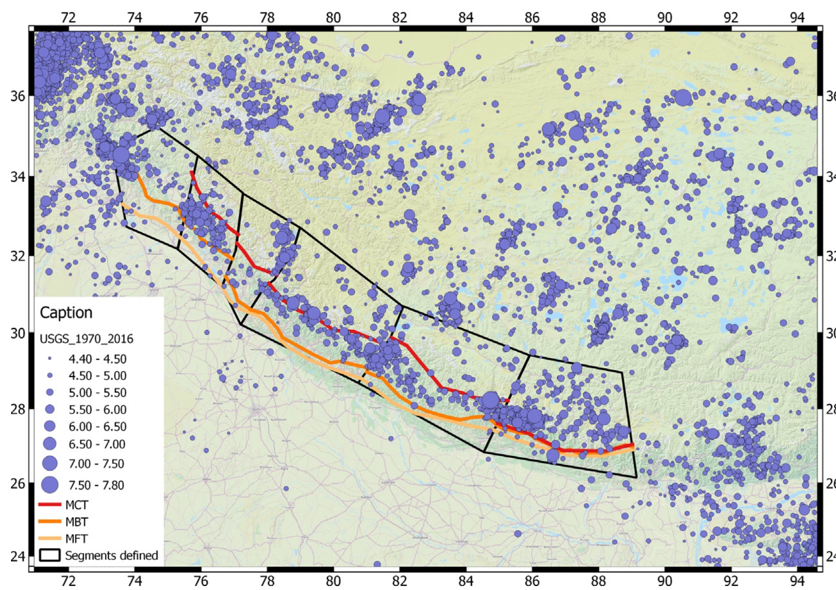

Fig. 2. Overview of the study region based on earthquake locations from U.S. Geological Service (USGS) for the time period 1970–2015, providing a reasonably homogenious picture of the regional seismicity in Himalaya. The six polygons, representing the study region, will be justified and discussed later in this paper. Shown are also the surface manifestations of the main thrusts MCT, MBT and MFT.

and subsequently by a more elaborate approach based on strain rates (Kreemer et al., 2014), using the Kostrov (1974) formula. In the first case we compare computed and observed slip rates and in the second computed and observed seismic moment rates for each of the arc segments, and for the entire arc. Finally, we discuss some seismic hazard implications.

2. Himalayan tectonics

India is colliding with the Eurasian plate (Besse et al., 1998; Dewey et al., 1989; Kreemer et al., 2014) and rotating slowly anticlockwise (Sella et al., 2002). The rate of Himalayan convergence varies from 11 to 22 mm/yr from northwest to northeast within the Himalayan region (Wang et al., 2001; Banerjee and Bürgmann, 2002; Bettinelli et al., 2006; Schiffman et al., 2013; Stevens and Avouac, 2015, 2016). The latest comprehensive assembly of geodetic information on a global scale has been conducted by Kreemer et al. (2014), also comprising a large number of GPS measurements from India (accessible under http://gsrm2.unavco.org/ and shown in Fig. 3). Along the western Himalaya arc the measured velocities of the Indian continent relative to the Indian plate are reasonably consistent in direction (NNW), and with most of the velocity vectors ranging between 12 and 16 mm/yr. Arc-normal convergence across the Himalayas results in the development of coseismic slip from large thrust earthquakes at the detachment zone, as exemplified by the 2015 Nepal earthquakes. The underplating of the Indian subcontinent beneath the Eurasian Plate gives rise to a high seismic activity in the region (Verma et al., 1976; Molnar and Tapponier, 1977; Khattri and Tyagi, 1983), resulting in high seismic hazards.

We will in this study investigate to which extent the historical seismicity reflects what could be expected from the measured convergence. The Himalayan arc is about 2400 km long and extends from the Kashmir region in the west, eastward through Nepal and Bhutan and into Arunachal Pradesh to the eastern subduction zone in northern Myanmar. The arc has been ruptured by great earthquakes over the last century, such as the 1905 Kangra (Ms 7.8), the 1934 Bihar-Nepal (Ms 8.1), and the 2015 Nepal (Mw 7.8 and 7.3) earthquakes, and the rupture lengths of these earthquakes are often confined by steeply dipping transverse features (Srivastava et al., 1987; Kumar and Mahajan, 2001). The northwest Himalayan region suffered major earthquakes also before 1905, as reported among others by Iyengar et al. (1999), Seeber and Armbruster (1981), Khattri (1999) and Bilham and Gaur (2000).

The deformation model generally accepted (Fig. 1) is the one where the Indian Plate is underplating the Eurasian continent along a low-angle décollement zone as suggested by Pandey et al. (1995); see also Lavé and Avouac (2000), Ader et al. (2012), Gahalaut and Arora (2012) and Mugnier et al. (2013).

The commonly used term for the décollement is the Main Himalayan Thrust, which is a dynamic concept related to the detachment zone in Fig. 1, being the main fault under which northern India underthrusts the Himalayas, eventually rooting into a