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Seismotectonics of Bhutan: Evidence for segmentation of the Eastern Himalayas and link to foreland deformation

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ABSTRACT

The instrumental record of Bhutan is characterized by a lower seismicity compared to other parts of the Himalayan arc. To understand this low activity and its impact on the seismic hazard, a seismic network was installed in Bhutan for 22 months between 2013 and 2014. Recorded seismicity, earthquake moment tensors and local earthquake tomography reveal along-strike variations in structure and crustal deformation regime. A thickened crust imaged in western Bhutan suggests lateral differences in stresses on the Main Himalayan Thrust (MHT), potentially affecting the interseismic coupling and deformation regime. Sikkim, western Bhutan and its foreland are characterized by strike-slip faulting in the Indian basement. Strain is particularly localized along a NW–SE striking mid-crustal fault zone reaching from Chungthang in northeast Sikkim to Dhubri at the northwestern edge of the Shillong Plateau in the foreland. The dextral Dhubri–Chungthang fault zone (DCF) causes segmentation of the Indian basement and the MHT between eastern Nepal and western Bhutan and connects the deformation front of the Himalaya with the Shillong Plateau by forming the western boundary of the Shillong block. The Kopili fault, the proposed eastern boundary of this block, appears to be a diffuse zone of mid-crustal seismicity in the foreland. In eastern Bhutan we image a seismogenic, flat portion of the MHT, which might be either related to a partially creeping segment or to increased background seismicity originating from the 2009 M_W6.1 earthquake. In western-central Bhutan clusters of micro-earthquakes at the front of the High-Himalayas indicate the presence of a mid-crustal ramp and stress buildup on a fully coupled MHT. The area bounded by the DCF in the west and the seismogenic MHT in the east has the potential for M7–8 earthquakes in Bhutan. Similarly, the DCF has the potential to host M7 earthquakes as documented by the 2011 Sikkim and the 1930 Dhubri earthquakes, which were potentially associated with this structure.

1. Introduction

The ongoing convergence between India and Asia has produced several megathrust earthquakes ($M \geq 7.5$) in the Himalayas and at the Shillong Plateau in the eastern foreland (Fig. 1A). The analysis of historical megathrust earthquakes and geodetic rates along the Himalayan arc suggest that similarly devastating earthquakes are overdue in several parts of the Himalaya (Bilham and England, 2001; Avouac et al., 2015; Stevens and Avouac, 2016). The Bhutan Himalaya has been previously identified as an apparent gap in recent instrumental seismicity (Gahalaut et al., 2011). The relatively low activity in instrumentally recorded seismicity in Bhutan is apparent in global earthquake bulletins such as the USGS/NEIC catalog shown in Fig. 1. Bilham and England (2001) suggested that this seismic gap could be the result of strain partitioning, in which up to one third of the total shortening of 18 mm/yr in the Eastern Himalayas can be accommodated by the basement-cored uplift of the Shillong Plateau in the foreland (Fig. 1B). The proposed reduction in shortening rate across the Bhutan Himalayas, however, is inconsistent with recent geodetic studies (e.g., Banerjee et al., 2008). The contraction rate of 14–17 mm/yr across Bhutan seems only slightly smaller than in Nepal (Vernant et al., 2014; Marechal et al., 2016) and the net convergence between India and Tibet (including shortening accommodated by the Shillong Plateau) is therefore

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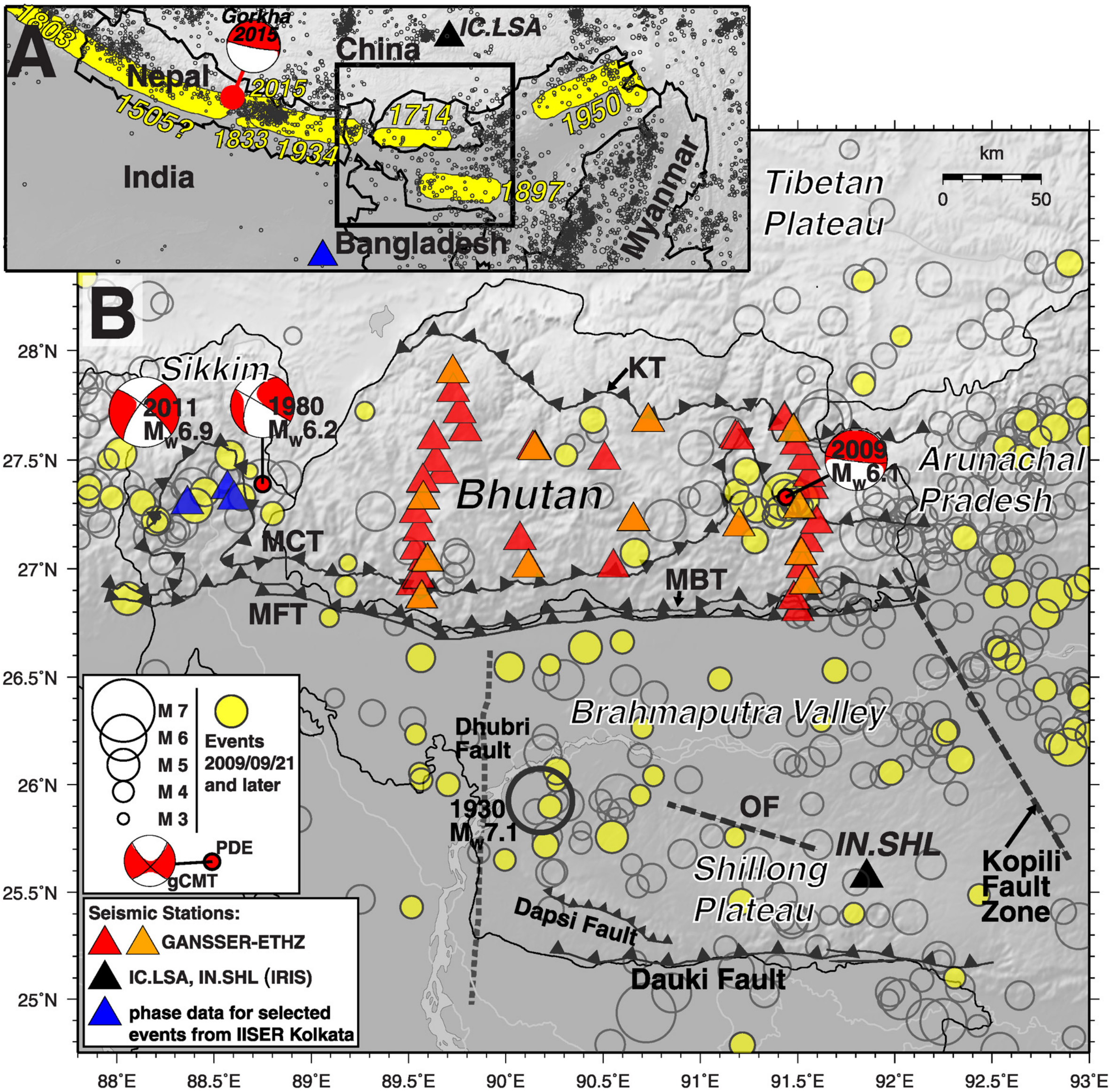

Fig. 1. A: Digital elevation model of the Eastern Himalaya and foreland with seismicity from the ISC-GEM Catalog (1900–1973) (Storchak et al., 2013) and the NEIC/USGS bulletin (1973–2015). Global Centroid Moment Tensor (gCMT) of the 2015 M_W7.8 Gorkha earthquake from http://www.globalcmt.org. Yellow areas correspond to approximate slip-patches of past large earthquakes (Hetényi et al., 2016a). Study area outlined by box. B: Study region with seismicity (as in A) and gCMT solutions with $M_W \geq 6.0$. Triangles in A and B indicate temporary GANSSER seismic network (red: operating 2013/01 to 2014/04; orange: operating 2013/01 to 2014/11) and regional stations. MFT: Main Frontal Thrust; MBT: Main Boundary Thrust; MCT: Main Central Thrust; KT: Kakhtang Thrust (Long et al., 2011); OF: proposed Oldham Fault (England and Bilham, 2015); other faults from Biswas et al. (2007), Dasgupta et al. (1987), and Kayal et al. (2012). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

larger across Bhutan than across Nepal, consistent with the general increase in convergence towards the eastern syntaxis (Burgess et al., 2012).

Recent paleoseismic studies along the Main Frontal Thrust (MFT) in Bhutan suggest the occurrence of one or more large earthquakes in the last millennium (Berthet et al., 2014; Le Roux-Mallouf et al., 2016). Re-interpretation of historical damage reports provides additional evidences for an M8 earthquake in Bhutan in 1714 AD (Fig. 1A), suggesting that there are no gaps in large earthquakes along the entire Himalayan arc (Hetényi et al., 2016a). Assuming that no great earthquake occurred since 1714, the present-day convergence rates suggest a slip potential of about 5 m in Bhutan (Vernant et al., 2014). The Main Himalayan Thrust (MHT) represents the basal décollement between the orogenic wedge and the underthrusting Indian basement and is the source of megathrust earthquakes in the Himalayas (e.g., Seeber et al., 1981). Its geometry is crucial for estimates of stress-accumulation and assessing potential rupture sizes. The MHT is not a continuous flat thrust but is characterized by a frontal ramp, the MFT, a flat segment, and a mid-crustal ramp. The former is evident from surface geology. The latter two segments have been previously imaged by the INDEPTH data (Hauck et al., 1998) and its geometry has been modeled by various datasets. Based on the joint inversion of denudation rates, GPS data, and Holocene uplift, Le Roux-Mallouf et al. (2015) find evidence for a wide MHT in western Bhutan. Their model predicts a steep mid-crustal ramp along the MHT at about 130 km north of the MFT, indicating a wider décollement compared to central Nepal and Sikkim. Models based on thermochronologic data, however, estimate a steepening of the MHT in western Bhutan further to the south, around 90 km north of the MFT (Coutand et al., 2014). This geometry is consistent with receiver function images (Singer et al., 2017a) and closer to struc-