The 18 September 2011, North Sikkim earthquake

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The 18 September 2011, magnitude *Mw* 6.9 earthquake close to the Nepal–Sikkim border caused significant damage due to ground shaking and caused several landslides. Observations from the post-earthquake surveys in the affected areas within Sikkim suggest that the poorly engineered, multistoried structures were relatively more impacted. Those located on alluvial terraces were also affected. The morphology of the region is prone to landslides and the possibility for their increased intensity during the forthcoming monsoon need to be considered seriously. From the seismotectonic perspective, the mid-crustal focal depth of the North Sikkim earthquake reflects the ongoing deformation of the subducting Indian plate.

Keywords: Epicentre, focal depth, post-earthquake survey, seismotectonic setting.

A MODERATE earthquake of magnitude *Mw* 6.9, which we hereafter refer to as the 'North Sikkim earthquake' occurred in the evening (18 h 11 min, IST) of 18 September 2011, close to the Sikkim–Nepal border. Bordered by Nepal, Bhutan and Tibet, the Sikkim region comprises a segment of relatively lower-level seismicity in the 2500 km-stretch of the active Himalayan belt (Figure 1 *a*). The largest historically known great earthquake in its vicinity is the 1934 Bihar–Nepal border earthquake of *M* 8.3, located to the southwest of Sikkim, an event that caused intensity VIII damage in the Sikkim Himalaya (Figure 1 *a*)[1]. The north Sikkim earthquake was felt in most parts of Sikkim and eastern Nepal; it killed more than 100 people and caused damage to buildings, roads and communication infrastructure, mostly due to the failure of the mobile telephone network towers. Several landslides and rock falls followed the earthquake, which increased the death toll and impaired rescue operations.

The India Meteorological Department (IMD) reported the epicentre as 27.7°N and 88.2°E, located close to the northwestern terminus of a previously reported structure, the Tista lineament[2,3]. The main event was followed by a few aftershocks, and three of these were of magnitude ≥ 4.2 (Table 1). Preliminary report of the IMD (http://www.imd.gov.in) provided a centroid moment tensor (CMT) solution, which indicates reverse faulting at a centroid moment depth of 10 km. An alternate solution by IMD suggests strike–slip faulting at a moment tensor depth of 59 km. The IMD also reports that the 18 September event had a complex source and its focal mechanism needs further revisions.

The National Earthquake Information Centre (NEIC)/US Geological Survey (USGS) located the epicentre of the main event to the immediate west of the IMD location. There is some uncertainty regarding the depth as well as the location provided by these agencies and the Global CMT solutions. For example, the initial estimate of depth provided by USGS was 20 km, which has been revised as 50 km (preliminary determination of epicentres). However, the CMT solution by NEIC suggests a focal depth of 35 km, which is also the estimated hypocentral depth of the two larger aftershocks. The Global CMT solution suggests a depth of 47.4 km and an epicentre located to the southeast of the IMD and NEIC locations (Figure 1 *b*). Thus, the event seems to be a complex one as noted both by IMD and USGS, based on their initial models and the focal parameters would require further revisions.

The National Geophysical Research Institute (NGRI) and the Indian Institute of Technology Kharagpur (IITKgh) have been monitoring the seismicity of Sikkim in the past using local seismic networks, which have now been resumed. Other national organizations (IMD, Geological Survey of India and the Wadia Institute of Himalayan Geology among them) are also involved in the post-earthquake studies. These studies will provide a clearer picture of the aftershock activity and the source processes. This communication presents observations during our post-earthquake surveys conducted during 29 September–5 October 2011, in regions within Sikkim affected by the earthquake. Further, based on the data available for this region, we try to understand the seismotectonic setting and effects of this earthquake.

The most significant earthquakes known to have occurred in the vicinity of the recent event are the *M* 7.7, 1833 and the *M* 6.6, 1988 events (Figure 1 *a*). A more recent one in this area is the *M* 5.3, 14 February 2006 earthquake, located southeast of the 2011 event, at a location where the Main Central Thrust (MCT) takes a peculiar overturned configuration (Figure 1 *b*). At the time of the 2006 earthquake, NGRI was operating a network of seven stations in Sikkim, and thus the source parameters of the main shock and aftershocks are quite well-constrained[3,4]. Based on the CMT solution that suggested a thrust faulting mechanism sourced at 20 km depth on a near E–W-oriented fault, with a dip of 27°, Hazarika *et al.*[4] interpreted the mechanism of this earthquake as typical of the Main Himalayan Thrust (MHT) system. Further, they related the distribution of well-constrained aftershocks with the E–W-oriented fault. Such earthquakes originate on the thrust faults associated with MHT, which accommodates the geological shortening,

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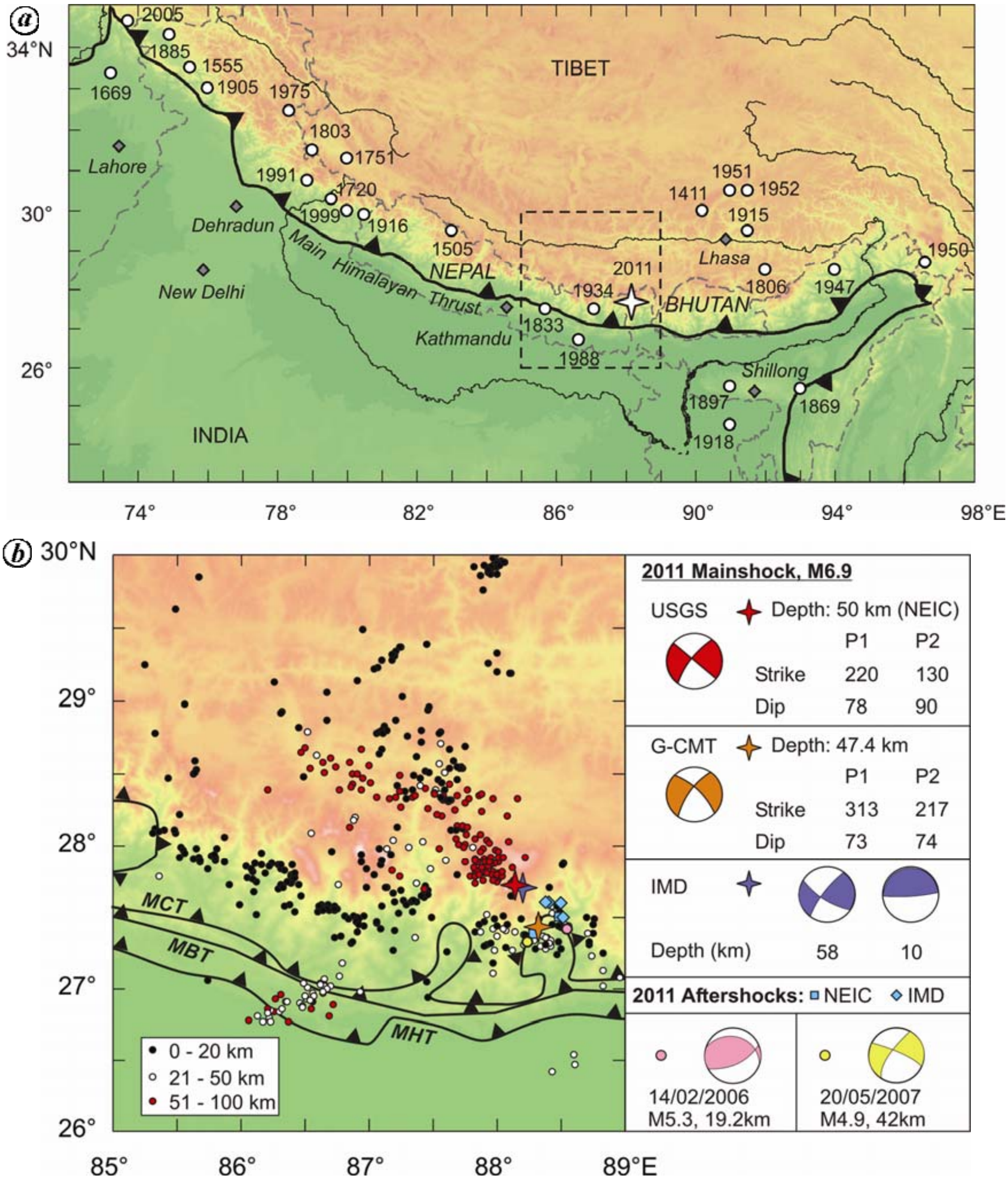

Figure 1. ***a***, Map showing the Main Himalayan Thrust (MHT) and the significant earthquakes (modified from Rajendran and Rajendran[9]). The star shows the location of the 2011 North Sikkim earthquake. Square in dashed line is the area shown in (***b***). ***b***, Area identified in (***a***) showing the major thrust faults (MHT, MBT and MCT) and the selected subset of micro earthquakes (M_L 2.0–5.0) located by HIMNT[8]. Right panel shows focal mechanism solutions for selected earthquakes. Location of the 2011 earthquake is shown by stars; IMD (purple) NEIC (red) and Global CMT (orange). Note the NW–SE oriented cluster of deep crustal (> 50 km) earthquakes marked by the red dots.

estimated as 21 ± 1.5 mm yr^{-1} on an average, over the Holocene[5].

Later analysis of the data collected by the local network operated by NGRI suggested transverse tectonics rather than underthrusting in this region[4]. Other studies based on relocation and re-evaluation of focal mechanism solutions[6], as well as analysis based on the Himalayan Nepal Tibet Seismic experiment (HIMNT)[7,8] have also suggested mid-to-deep crustal strike–slip faulting as the dominant style of deformation in this region. The well-constrained microearthquake data recorded by the close network of 29 seismic stations of HIMNT, located between 80–92°E and 26–30°N, have identified a cluster of earthquakes ($M_L \leq 4.0$) at sub-Moho depths (> 60 km), trending in the WNW to ESE direction beneath the High Himalaya and Southern Tibetan Plateau (Figure 1 *b*). The

Table 1. Epicentral parameters of the main shock and significant aftershocks

Date	Origin time	Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude	Source of data
18/09/2011	12 : 40 : 51.78	27.72	88.14	50	6.9	NEIC
18/09/2011	18 : 11 (IST)	27.70	88.20	10	6.8	IMD
18/09/2011	13 : 11 : 59.58*	27.48	88.50	35	4.8	NEIC
18/09/2011	13 : 11 : 59.00	27.60	88.50	–	5.0	IMD
18/09/2011	13 : 54 : 20.01*	27.28	88.30	35	4.7	NEIC
18/09/2011	13 : 54 : 17.00	27.50	88.40	–	4.5	IMD
18/09/2011	21 : 51 : 52.00	27.60	88.40	–	4.2	IMD
22/09/2011	16 : 44 : 43.00	27.60	88.40	–	3.9	IMD

*Same event reported by different agencies.

Figure 2. Map of Sikkim showing the approximate location of the epicentre and areas most affected by the earthquake and the subsequent landslides (dashed area). Sites discussed in the text are shown.

focal depth estimates of the earthquakes located by HIMNT are based on a close network of stations and better velocity model derived from the experiment. We believe that the depth estimate of 47.4 km provided by the Global CMT for the 18 September earthquake may be more representative of the seismogenic source in this region. Thus, the North Sikkim earthquake, located at the southeastern edge of the NW–SE-oriented cluster of earthquakes reported based on the data from the HIMNT network[7,8], may be considered as the largest event in this group of mid-to-deep crustal earthquakes.

The focal mechanism solution for the main shock suggests dextral strike–slip faulting, possibly along a NW–SE oriented fault. This trend is consistent with the structural trend defined by the well-located microearthquakes as well as the fault plane inferred from well-constrained focal mechanisms[7,8]. Another recent earthquake of magnitude 4.9 located to the southeast of the 2011 epicentre, also belongs to the category of mid-to-deep crustal, dextral strike–slip faulting events originating on the NW–SE-oriented fault plane (Figure 1 *b*, bottom right panel). There is disparity in depth estimates between NEIC and Global CMT for this event too, as the former places it at 15 km and the latter at 42 km. Thus, there seems to be some discrepancy in the depth estimates for earthquakes in this region, probably due to the differences in the velocity models used. However, considering the consistency with the range of depth based on the HIMNT data, we consider that the 18 September earthquake occurred by right lateral strike–slip faulting on a NW–SE-oriented fault. The role of the morphologically conspicuous Tista lineament in generating these strike–slip faulting earthquakes in this region as previously suggested[2], needs to be explored.

The North Sikkim earthquake caused damage in a large area close to its epicentre as well as in Gangtok, the state's capital and several areas in south Sikkim. Regions in the immediate vicinity of the epicentre, located close to the Sikkim–Nepal border are occupied by high mountains bordering southern Tibet and they are sparsely populated. Accessibility to these regions was further restricted due to the landslides and rock falls that blocked the roads and mountain passes. Locations where significant damages were observed are shown in Figure 2. Sites closest to the epicentre that we could access by road are located in the village of Chungthang, about 50 km southeast of the epicentre. Several buildings, mostly multi-storied, were damaged here, and the Moonlight School, a five-storied building in Chungthang town is prominent among them. While several new buildings here developed only minor cracks, it was mostly the older buildings that suffered maximum damage, and invariably the damage could be related either to poor construction and/or the location of the building on colluvial terraces.

Lachung, located about 60 km east of the epicentre also suffered severe damage, mostly from landslides and rock falls, and the village was not accessible by road during the time of our survey. The area of maximum damage, which covers this village, as shown in Figure 2, is based on inputs from aerial surveys conducted by the Land Revenue and Disaster Management Department, Government of Sikkim, which is also involved in rescue and relief operations.

The construction activities related to the Tista River Hydel Power Project are in their final stages and the 14 km-long diversion tunnel has been completed. The interior of the tunnel, about 1.2 km below the surface at some locations, showed no evidence of shaking by way of any displacement or freshly developed cracks. The nearby colony of the hydel power project workers, popularly known as the Urja Colony, was severely affected. Many of the rubble masonry houses here, most of them about 50 years old, collapsed, typically by failure of the wall. More recent constructions, mostly single and three-storied, RCC structures in the area suffered only minor damages.

The nearest town, Mangan, was not seriously affected by this earthquake (see Figure 2 for location). Here the buildings did not suffer any notable damage, except for a few poorly engineered structures. The only notable damage was at the Rumgom Gumpa (the monastery at Rumgom), established in 1852; the rubble-wood structure collapsed at its roof level (Figure 3). A wall poster at the monastery documents that it was damaged twice in the past, once in 1913 (reason not known) and later in 1983, due to a flood. It is not clear how this monastery located at a higher elevation could have been affected by a flood. From the severity of damage to this two-storied structure, we infer that it may not have experienced similar shaking since its existence for more than 150 years.

As for the structural damage, a notable aspect is the severity of damage to buildings located on the river terraces, where the basement is mostly composed of colluvium. A typical case is the minor damage to the well-engineered RCC buildings in the campus of the Sikkim Manipal Institute of Technology at Rangpo, located ~ 70 km south of the earthquake source (see Figure 2 for location). Some of the buildings in this large complex are located on the colluvial deposits of the river terrace, which might have amplified the shaking intensity. While most of the damage to structures was in the form of minor cracks or peeling of wall plaster, there was some minor structural damage to the pagoda, an ornamental structure that adorns the roof of the college building. We also noted that almost every multi-storied building that was damaged, particularly in the capital city of Gangtok, had more than three storeys. Another critical aspect is the quality of construction. We noted instances wherein two five-storied buildings under construction in the outskirts of Gangtok collapsed completely, whereas the adjoining building remained unscathed. A few new buildings at the hilltop monastery at Rumtek, south of Gangtok, were also affected, with some significant structural damage (see Figure 2 for location).

The morphology of Sikkim is prone to landslides and the earthquake was followed by numerous landslides and rock falls in the epicentral area (Figure 4). The severe rains that occurred in the days following the earthquake also contributed to the density and severity of landslides. No evidence of surface faulting was noted; a few instances of fissures and pavement failures were reported. We noted similar failures on the road leading to the Rumtek monastery and also at one location in the Urja Colony.

We used the pre- and post-earthquake landslide inventory map prepared by National Remote Sensing Centre (NRSC, http://bhuvan.nrsc.gov.in/bhuvan/PDF/sikkim_earthquake.pdf), to understand the spatial density of landslides. The available cloud-free data over Sikkim obtained on 29 and 30 September 2011 from Cartosat-1 and Cartosat-2B, covering an area of about 2000 sq. km, were used for the study. About 350 new landslides were observed in the post-earthquake satellite imageries

Figure 3. Collapsed monastery at Rumgom near Mangan.

Figure 4. An areal view of landslides along the road to Chungthang.

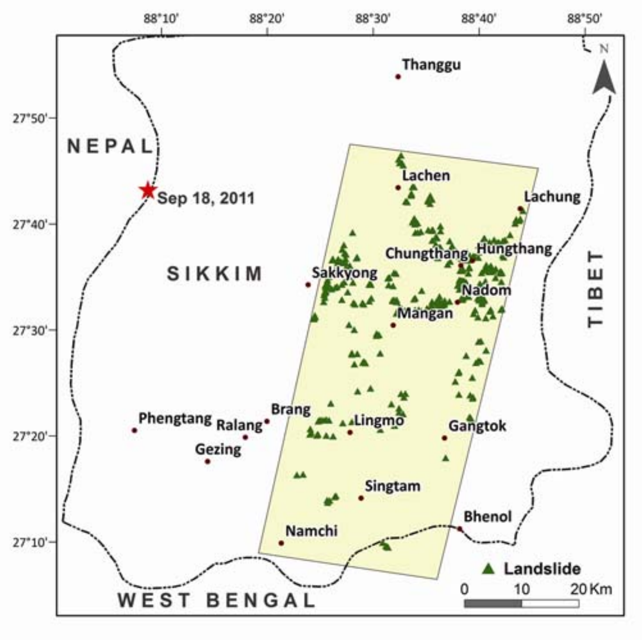

Figure 5. Distribution of co-seismically generated landslides within an area of 2000 sq. km in Sikkim from satellite data (source: NRSC, http://bhuvan.nrsc.gov.in/bhuvan/PDF/sikkim_earthquake.pdf).

(Figure 5). The spatial distribution of landslides provides useful guidelines for vulnerability assessment and planning for mitigation strategies. A more detailed analysis using imageries from adjoining areas will provide a complete inventory of landslides triggered by the earthquake. The post-earthquake scenario raises additional threats for increased landslides during the next monsoon. Disaster mitigation efforts need to be directed towards the identification of vulnerable regions, with emphasis on preventive steps as well as for planning relocation of settlements wherever necessary.

From the seismotectonic point of view, the north Sikkim earthquake is quite different from the shallow thrust earthquakes that originate on the major thrust faults, associated with MHT, or the crustal ramps and splay faults associated with these thrusts. For example, the 1991 Uttarkashi and 1999 Chamoli earthquakes are believed to have originated at the base of the crustal ramps or on the gentle slopes of the decollment[9]. Located further north of MCT, the North Sikkim earthquake is different from the typical Himalayan plate boundary earthquakes. Sourced at about 50 km depth, followed by two mid-crustal aftershocks, this earthquake may have occurred either on the overriding Eurasian plate or the subducting Indian plate, as also suggested by the preliminary report of the USGS (http://earthquake.usgs.gov/earthquakes). Where the North Sikkim earthquake originated, the Moho depth is between 50 and 60 km, and the projection of MHT[7] is at a depth of about 30 km. Data from HIMNT suggest the occurrence of earthquakes in the depth range 60–100 km in regions to the immediate northwest of the North Sikkim earthquake. Retaining a parallelism with the shallower (< 20 km) southern band of epicentres and confined to a narrow region on the southern flanks of Tibet, these earthquakes appear to originate on the leading edge of the Indian plate (Figure 1 *b*). Further analysis of the data is required to understand the source characteristics and relation to the seismogenic structures.

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