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ACKNOWLEDGEMENTS. We thank Dr R. R. Navalgund, Director, Space Applications Centre (SAC), for encouragement; Dr J. S. Parihar, DD-EPSA/SAC, Ahmedabad for guidance, and Greg Michael, Freie Universiat, Berlin, for help and suggestions while implementing CSFD. We also thank Dr B. S. Shylaja, Jawaharlal Nehru Planetarium, Bangalore and Thomas Kniessl, Freie Universitat, Berlin, for help.

Received 21 December 2011; accepted 30 January 2012

Tectonic implications of the September 2011 Sikkim earthquake and its aftershocks

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This study presents results of the spatial patterns of 292 aftershocks of the *Mw* 6.9 Sikkim earthquake of September 2011, accurately located through analysis of three component waveforms registered by a five station broadband network operated immediately after its occurrence. Refined hypocentral parameters achieved through application of the hypoDD relocation scheme reveal tight clustering of events along a NW–SE trend with focal depths reaching ~60 km. These trends viewed in conjunction with the strike–slip mechanisms of past earthquakes in Sikkim, including the main shock, affirm the predominance of transverse tectonics in this segment of the Himalaya where the Indian plate convergence seems to be accommodated by dextral motion along steeply dipping fault systems.

Keywords: Aftershocks, earthquakes, hypocentral parameters, spatial patterns, transverse tectonics.

THE devastating *Mw* 6.9 earthquake that occurred to the northwest of Sikkim on 18 September 2011, presents a fresh opportunity to reassess the seismotectonics of this intriguing segment of the Himalaya, which otherwise presents a classic example of continental collision. The epicentre of this earthquake, which claimed at least 100 lives, is located near the border between India and Nepal, at 27.72°N and 88.14°E, with a focal depth[1] of about 50 km. A preliminary account of this earthquake, including description of the damage to the landscape and engineering structures, the seismotectonic scenario, and discrepancies in the hypocentral locations reported by various agencies, is succinctly summarized in a recent paper[2]. The strike–slip nature of the 2011 Sikkim earthquake (Figure 1) reiterates the dominance of transverse tectonics in the regions of Sikkim and Bhutan[3,4], in contrast to a thrust environment in other segments of the Himalaya (Figure 2) manifested as shallow underthrusting of the Indian tectonic plate beneath Eurasia along the plane of detachment coinciding with the Main Himalayan Thrust. Whether the strike–slip motion is associated with the Indian plate or the overriding Himalayan wedge remains contentious in view of the uncertainty in the hypocentral parameters of this earthquake, although knowledge of the accurate geometry, fine structure and thickness of the crust in the Sikkim and adjacent Nepal Himalaya exists from receiver function studies[5,6]. Also, given the earthquake focal mechanism, even to a high degree of accuracy, the implicit ambiguity in choosing the true fault plane imposes constraints on identifying the causative tectonic features apparent on the surface or concealed within the subsurface. For instance, considering the NE–SW plane as the true fault plane of the 2011 Sikkim earthquake and the *M* 6.6 Udaipur earthquake of 20 August 1988, which had a similar focal mechanisms, it was suggested that these earthquakes occurred in response to the subducting Munger–Sahasra ridge under the Himalayan arc[7]. On the contrary, if the NW–SE plane is the true plane, dextral motion along steeply dipping lineaments like Gantok and Tista would be accommodating the Indian plate convergence, assuming that these lineaments extend to lower crustal/upper mantle depths[3,4]. Study of the spatial distribution of aftershocks is, therefore, the ideal way to resolve the fault plane ambiguity and identify the causative faults, since these shocks would occur on the fault plane in response to slip due to the main shock.

Akin to the rest of the Himalaya, the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT) are geologically well expressed in Sikkim, albeit a peculiar overturn of the latter. In addition to these, the prominent tectonic features in this province are the two near-parallel, NNW–SSE trending Tista and Gangtok lineaments, the WNW–ESE trending Goalpara lineament and the SW–NE trending Kanchanjangha fault (Figure 3). Previous seismicity studies in the region using data from local networks, reveal that the epicentres are mainly confined between MBT and MCT[4,8]. However, the recent earthquake appears to have occurred further north of these thrust zones, with two of its largest aftershocks (*M* 4.8 and 4.7 on the same day), located SE of the epicentre of the main shock, close to MCT (Figure 3).

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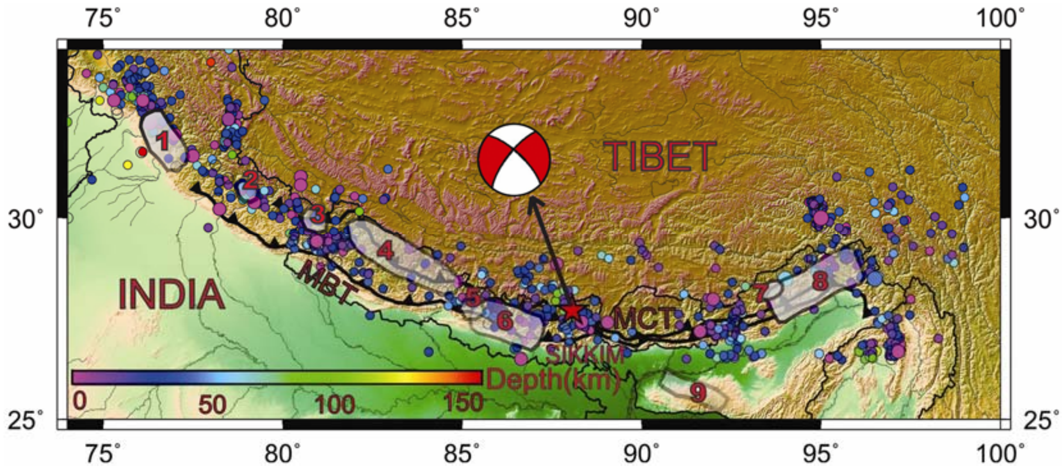

Figure 1. Map of the Himalaya–Tibet region with the major tectonic features and earthquakes of *M* > 4.5 (source: Nath *et al.*[14]). Circles indicating the epicentral locations are colour-coded according to depth. Shaded regions (grey colour) indicate rupture areas of major earthquakes in the Himalaya. (1) 1905 (*M* 7.8), (2) 1803 (*M* 7.3), (3) 1916 (*M* 7.5), (4) 1505 (*M* 8.1), (5) 1833 (*M* 7.3), (6) 1934 (*M* 8.3), (7) 1947 (*M* 7.8), (8) 1950 (*M*8.4) and (9) 1897 (*M* 8.1), MBT, Main Boundary Thrust; MCT, Main Central Thrust. The epicentre of the 2011 *Mw* 6.9 Sikkim earthquake (red star) and its focal mechanism (beach ball) are also shown.

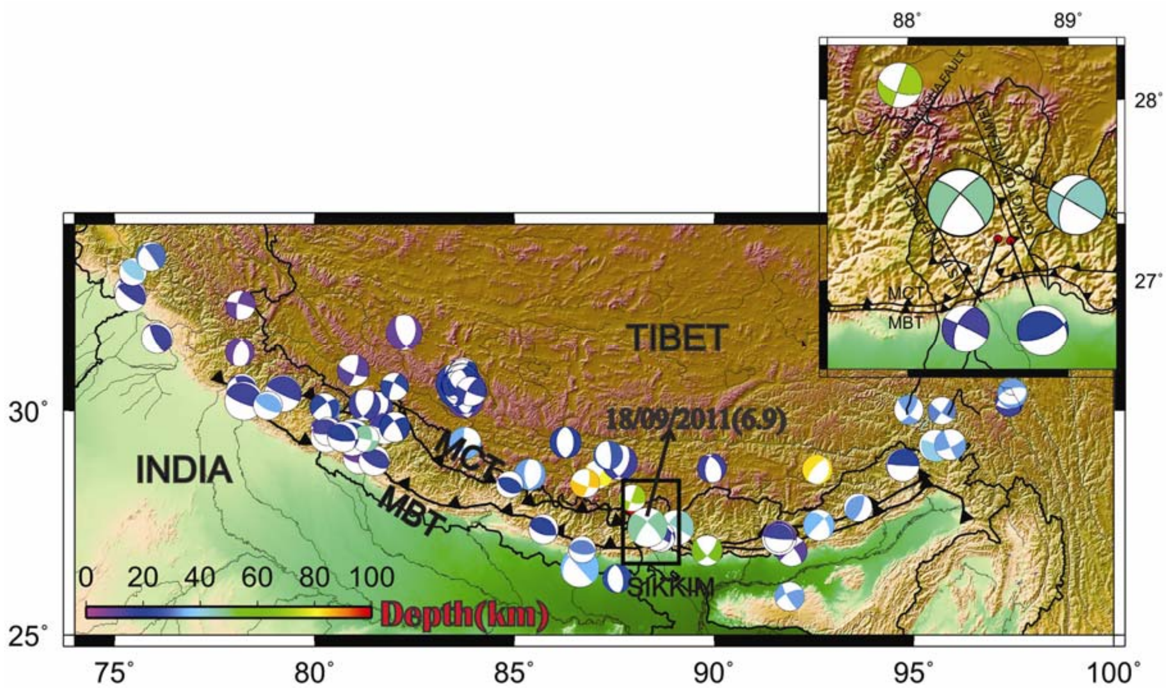

Figure 2. Global CMT solutions[15] since 1976, indicating the distribution of earthquake mechanisms in the Himalaya. The size of the beach ball is proportional to magnitude, while the colour indicates hypocentral depth. (Inset) Earthquake mechanisms in Sikkim Himalaya (black rectangle).

Soon after the 2011 Sikkim earthquake, the National Geophysical Research Institute (NGRI) established a network of five broadband seismic stations to monitor the aftershock activity (Figure 3). These units deployed at Peshok (PSK), Singtham (SIN), Legshp (LEG), Phodong (PHG) and Mangan (MGN) comprise REFTEK 151–120 sensors and REFTEK 130 data loggers time-tagged with GPS receivers set to record data continuously at 100 samples/s. Due to several landslides, approach to areas north of Mangan was cut-off, making it extremely difficult to install stations close to the epicentre of the main shock. However, the distribution of the stations was adequate to obtain constraints on a majority of the aftershocks, by analysing their waveforms using the SEISAN software[9]. A histogram of the local magnitude (Ml) determined for all the 292 aftershocks registered by the stations during the period 22 September 2011 to 23 November 2011, reveals a peak in the magnitude range 2.5–3 (Figure 4) and six aftershocks having a magnitude > 4. Based on our previous experience of locating earthquakes in the Sikkim region, the three-layer velocity model[10] (used in earthquake location for the HIMNT data) was chosen, which yields the lowest root mean square (rms) location errors. Out of all the recorded shocks, a total of 189 aftershocks could be well constrained using data from three or more stations. The rms errors of these selected events are less than 0.1 s. A map view of these single event locations although scattered, indicates a NW–SE trend, with many of the aftershocks situated to the north of MCT, in the proximity of the main shock (Figure 3), lending credence to its epicentral location. In order to further refine the hypocentral parameters of the aftershocks, we relocated them using the well-established hypoDD program, which uses a double-difference technique for earthquake locations[11]. The advantage of this method is that it minimizes the relative location errors without relying on accurate velocity models and station corrections. The differential travel times of P and S arrivals and the single event locations obtained earlier, serve as primary inputs for hypoDD. Utilizing 660 P and 600 S arrivals of events recorded at three or more stations, a total of 128 aftershocks were relocated using the conjugate gradient method. The criterion adopted for parameterization described elsewhere[4].

It can be seen that the relocated aftershocks are predominantly clustered in the NW–SE direction (Figure 5), suggesting that the true fault plane of the main shock is likely to be oriented in this direction. Although the proximity of the main shock to the Tista lineament prompts us to identify it as the causative fault, lack of correlation of the aftershocks with this feature suggests existence of

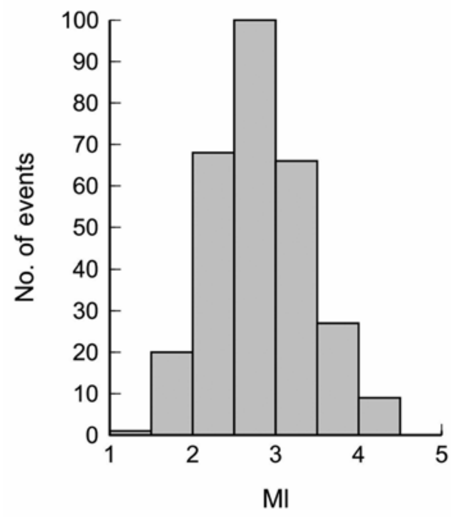

Figure 4. Histogram of the magnitudes of all the recorded aftershocks of the September 2011 Sikkim earthquake.

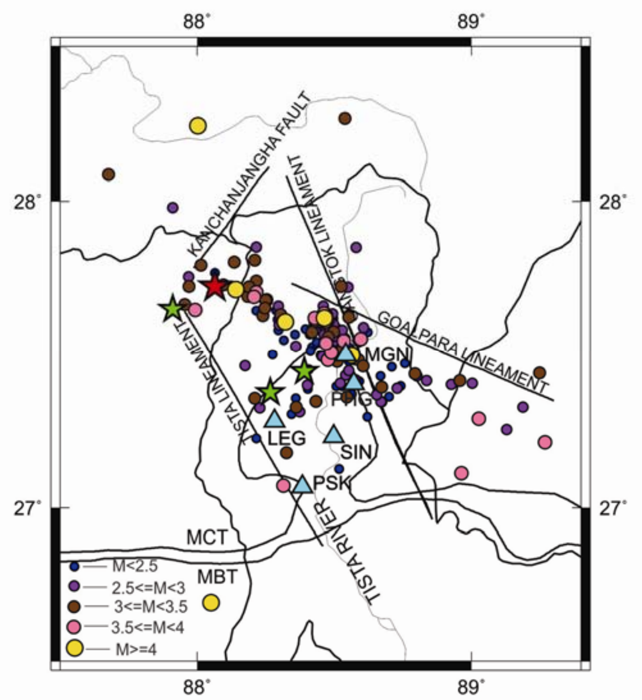

Figure 3. Locations of the seismic stations (triangles) of the NGRI seismic network and epicentres of all the aftershocks recorded by at least three stations. USGS locations of the main shock (red star) and the aftershocks that occurred on the same day (green stars) are indicated. Legend indicates the magnitude of the events.

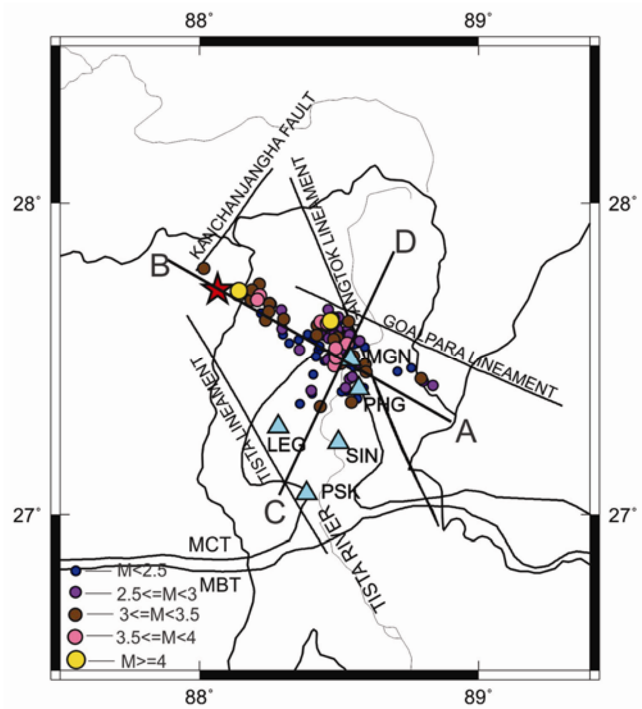

Figure 5. Epicentres of the aftershocks relocated using hypoDD. The red star is the main shock that occurred on 18 September 2011 of *Mw* 6.9. Legend indicates the magnitude of the shocks. AB and CD are the profiles along which depth sections are presented in Figure 6.

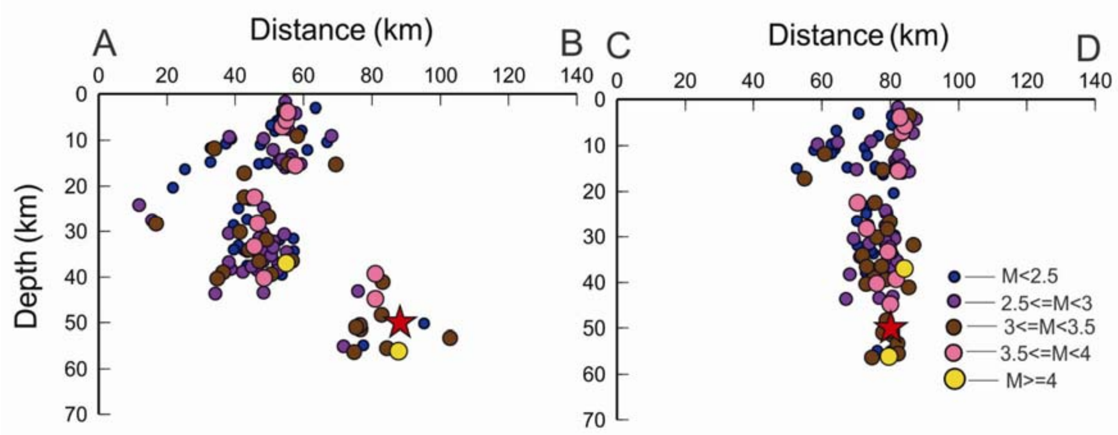

Figure 6. Depth sections of the relocated events along profiles AB and CD in Figure 5. Red star denotes the main shock of September 2011 (*Mw* 6.9).

a system of faults (including the Gangtok and Golpara lineaments) that are experiencing transcurrent deformation generating strike–slip earthquakes. Although a NW trend of the causative fault is highly probable, associating the earthquakes with the known lineaments/faults seems far-fetched, in view of the uncertainties in the location of the main shock and more importantly, lack of precise knowledge of the geometry of these features. Figure 6 shows depth sections of the relocated hypocentres along two profiles AB and CD (marked in Figure 5). A vertical distribution of a narrow cluster of aftershocks down to 60 km in the section CD confirms the idea of strike–slip faulting on a near-vertical fault that extends to deeper levels. Interestingly, the depth section AB reveals that the aftershocks towards NW, in the proximity of the main shock also occur deeper, between 40 and 60 km, while those in SW towards MBT have shallower, upper crustal depths (Figures 5 and 6). Given the discrepancies in the depth of the main shock reported by various agencies, the deeper nature of the aftershocks validates the focal depth of about 50 km reported by USGS, confirming the occurrence of the earthquake in the crust of the Indian plate rather than the overlying Himalayan crystallines near MCT. In fact, the aftershock distribution as seen in the depth section AB indicates a dipping trend of the underthrusting Indian plate beneath the Himalaya. Moreover, direct estimates of the geometry of the Indian plate obtained through modelling of receiver functions in the Sikkim and Nepal Himalaya constrain the crustal thickness to be ~60 km in the proximity of the epicentre of the 2011 Sikkim earthquake[5], implying that this earthquake is associated with the Indian lower crust. Occurrence of strike–slip earthquakes at depths of 70–100 km and thrust earthquakes at shallower depths has also been reported from eastern Nepal and southern Tibet regions[12], suggesting accommodation of the Indian plate convergence through shear along vertical fault planes that extend to Moho depths. However, the reasons for a strong lower crust in Sikkim and the adjacent Himalaya, which otherwise is ductile and incapable of brittle failure, remain to be explored. Eclogitization of the Indian lower crust in Sikkim[5] and southern Tibet[6] is a strong possibility. The two well-known models to define the strength of continental lithosphere are dubbed jelly sandwich, where strength resides in crust and upper mantle while another one is dubbed crème brûlée, where mantle is weak and the strength is limited only in the crust[13]. A strong lower crust and uppermost mantle endorse the jelly-sandwich model to explain seismogenesis in this tectonic setting as opposed to the crème-brûlée model applicable elsewhere.

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ACKNOWLEDGEMENTS. We thank Dr Y. J. Bhaskar Rao, Director, NGRI, Hyderabad for support and releasing funds necessary for the installation and operation of seismic stations. Part of the work has been performed under the project supported by the Ministry of Earth Sciences, Government of India. We thank Dr H. V. Satyanarayana for sparing a broadband sensor and logger, and N. Purnachandra Rao for discussions.

Received 22 December 2011; accepted 27 January 2012

Triggering of aftershocks of the Japan 2011 earthquake by Earth tides

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The aftershock sequence of the devastating Japan earthquake of March 2011 is analysed for the presence of periodicities at the Earth tide periods. We use spectral analysis as well as a time-domain method, KORRECT, developed earlier to detect the presence of diurnal and semi-diurnal periodicities in the sequence of aftershocks ($M \geq 4$). This suggests that large aftershocks in the fault zone of the Japan 2011 earthquake were strongly influenced by Earth tides.

Keywords: Aftershock triggering, Earth tides, Japan 2011 earthquake, spectral analysis.

THE elastic rebound theory is now well accepted as the reason for the occurrence of earthquakes. When fault stresses rise above a critical threshold for rupture[1], the Earth slips along the fault and an earthquake results. It is then only intuitive that any additional stress acting on a fault system that approaches failure could trigger the rupture process that produces the earthquake. The stresses responsible for the occurrence of an earthquake are tectonic in origin, but the final onset of rupture can be affected by other kinds of stresses superimposed on tectonic stresses during the build-up to failure. We use the term 'affected' here because the additional stress may advance or retard the onset of rupture, depending on the sense in which it acts.

Perhaps the strongest candidate for earthquake triggering is the Earth tide. Gravitational attractions, primarily of the sun and moon, cause periodic elastic deformation of the solid Earth, thus exerting additional stresses. These tidal stresses are oscillatory in nature and their magnitude is of the order of 10^3 Pa. This is much less than average stress drops in earthquakes[2] (10^5–10^7 Pa), but the rate of tidal stress change is much higher than the build-up rate of tectonic stress[3] rate, and this makes tidal triggering of earthquakes possible.

The question of whether earthquakes are triggered by Earth tides was raised over a century ago[4,5] and since then, numerous efforts have been directed towards answering it. These studies investigated different kinds of datasets and employed a variety of methods[6], but owing to mixed results[2,7–10], no conclusive evidence had emerged until recently for earthquake triggering by the Earth tides. In the last decade, tests on tidal triggering have produced more homogeneous and positive results. A breakthrough was achieved recently[11] when the triggering effect of the earth tide was demonstrated in earthquakes of all magnitudes (> 2.5) and all types of focal mechanisms, using the largest global earthquake catalogue (NEIC world seismic catalogue) available. In 2004, a study of seismicity in Japan[12] found that regions which experienced a large earthquake showed the best earthquake–tide correlations. These two findings were the motivation for our search for tidal triggering of aftershocks of the recent earthquake in Japan. Additionally, an aftershock sequence is a type of dataset that is amenable to the simple methods of analysis employed in this study[13].

The Tohoku-Oki earthquake (magnitude $Mw = 9$) off the east coast of Honshu, Japan, occurred at 05:46:24.56 UT on 11 March 2011. The epicentre location was 38.299°N, 142.373°E and focal depth was 32 km. At the time of this study, an almost complete record of aftershocks of magnitude $Mw \geq 4$ occurring in the first 30 days following the main shock was available from the NEIC PDE catalogue of the US Geological Survey. Aftershock data obtained consisted of origin time, magnitude, epicentre location and focal depth. Since we are interested only in the events which occurred in the fault zone of the main shock, we have restricted this study to those events which occurred in the rectangular area between latitudes 34–41°N and longitudes 139.5–145.5°E. In this region, 1370 aftershocks (of $M \geq 4$) have been recorded by USGS in the one month following the main shock. These numbers make our dataset much larger than those used in previous studies of triggering of aftershocks[14–16]. We tested the completeness of the catalogue by linear least-squares fitting of the Guttenberg–

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