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"SOURCE CHARACTERISTICS OF THE 18 SEPTEMBER 2011 SIKKIM EARTHQUAKE"

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ABSTRACT

Using detailed waveform analysis of Pn, sPn depth phases from the nearby seismic stations, attempts were made to resolve the focal depth of the 2011 Sikkim earthquake. Focal depth of 46.8 km thus determined was found closer to the GCMT source mechanism solution as compared to ISC solution (29.6 km). Re-examination of its source mechanism with the spatial/ depth distribution of its aftershocks suggested that both the nodal planes oriented WNW or ENE, initially ruptured but the orientation of meizoseismal area and larger concentration of its aftershocks parallel to the Tista lineament conformed WNW striking nodal plane relatively more active. The large value of the stress drop derived from S-wave spectra based on the data of Indian stations was attributed to its strike-slip mechanism and deeper focal depth. The stress drop of its foreshock was much lower than that the main shock. The b-value also showed a decrease during the last decade prior to the main earthquake.The recent Sikkim earthquake (Mw 6.9) has brought out the limitations of the microzoning of the Sikkim region attempted earlier.

1. INTRODUCTION

The earthquake of 18 September 2011 occurred in the northwestern Sikkim region of India close to the Nepal and Tibet border. It took a toll of about 100 human lives and injured many in India, Nepal and adjoining regions. Numerous landslides were triggered due to this earthquake after heavy rains during southwest monsoon when the mountain slopes were wet [Martha et al., 2014]. According to the media reports, heavy damage to modern buildings occurred at Chungthan and Sorthang. The brick and mortar churches collapsed at Mangan, giant boulders blocked roads and landslides flattened the entire localities. Some tunnels collapsed near the 1200 MW Tista Stage III Hydel Project Site. In the Gangtok capital of Sikkim state, a number of structures including monasteries in the city were badly damaged and some buildings completely collapsed over downhill rocks [Rajendran et al., 2011; Rai et al., 2012; Sharma et al., 2013]. Damage also extended to some parts of Tibet, Nepal, Bhutan, Assam, North Bengal and adjoining Bihar. The maximum intensity due to this earthquake was assessed as IX (or VIII+) MM [Mahajan et al., 2012; Singh and Shukla, 2013; Prajapati et al., 2013]. Due to ambiguity in the assessment of their values based on the media reports or limited field surveys, the isoseismal patterns differed and higher intensities appear to have been estimated by Prajapati et al. [2013]. The recent 2011 Sikkim earthquake was unique due to its deeper focal depth, epicentral location away from known faults and lack of large aftershocks. The preliminary bulletins of this earthquake by the US Geological Survey (USGS) and India Meteorological Department (IMD) gave its focal depth as 19.7 km and 10 km respectively, which was revised to 46 km to 60 km based on GCMT solutions by them and other agencies. The widely accepted earthquake catalog of the International Seismological Centre (ISC) gave its focal depth as 29.6 km, which necessitated its re-examination due to wide divergence from the earlier results (USGS, IMD, IRIS). Also, Barua et al. [2018] reported the focal depth of the main earthquake as 19.7 km based on CMT solutions of some Indian stations which also needs to be reconciled. The most reliable method to resolve the focal depth issue is based on the identification of depth phases from the regional or nearby stations [Bhattacharya et al., 1997; Devi et al., 2009; Dengwei et al., 2011]. This methodology was attempted in this paper using the broadband data recorded at the IMD stations. The difference of opinion in associating this earthquake with different lineaments namely the Tista or a fault nearly parallel to it based on one of the nodal planes [Dasgupta et al., 2012; Kumar et al., 2012; Paul et al., 2015], Kanchendzonga fault or even subducting Monghyr-Saharsa ridge under the Himalayan arc [Gahalaut, 2011] also needs to be addressed. Further, the low-stress drop of 2011 Sikkim earthquake based on the P-wave spectra [Paul et al., 2015; Baruah et al., 2018] needs to be validated from S-wave spectra keeping in view its strike-slip focal mechanism and deeper focal depth.

The objective of this paper is, therefore, to re-examine the hypo-central parameters of the 18 September 2011 Sikkim earthquake using different velocity models and determine its focal depth from the depth phases recorded at the Indian seismological stations. Its stress drop was determined from the Indian stations based on the S-wave spectra using Brune's model. Its foreshock, aftershocks and source characteristics have been studied. The precursory parameters like foreshock, stress drop and decadal change in b-value have also been examined. The recent Sikkim earthquake (Mw 6.9) provided an opportunity to examine the validity of the microzoning map attempted earlier for the Sikkim region [Nath, 2005; Nath et al., 2005]

2. GEOLOGY AND TECTONICS OF THE SIKKIM REGION

The whole of the Himalayan region has been divided into a series of longitudinal tectono–stratigraphic domains called (1) Sub-Himalaya (2) Lesser Himalaya (3) Higher Himalaya and (4) Tethys Himalaya. These are separated by major dislocation zones [Gansser, 1964]. Within Sikkim, these different lithological units lie in an accurate regional fold pattern. The major portion in the lesser Himalaya consists of low-grademetapelites, in Daling group. The granitoid genesis is found within the Daling group of rocks. It is separated by medium to high-grade crystalline complex. Alternate horst and structures in the region are attributed to a set of faults in north-south direction. The region is composed of several north dipping thrusts traversed by NW or NE oriented lineaments. The main tectonic features in the Sikkim Himalaya are Main Frontal Trust (MFT), Main Boundary Thrust (MBT), and Main Central Thrust (MCT). Of these, the MBT developed since Pliocene time and is active through middle Pleistocene while the MCT formed since tertiary time. On the other hand, the MFT lies along the late Tertiary-Quaternary formations which are fold and thrust faulting. The Indus-Tsangpo suture zone towards north Sikkim is characterized by the ophiolite suite and demarcates the northern limit of the Indian plate (Figure 1). Several transverse folds

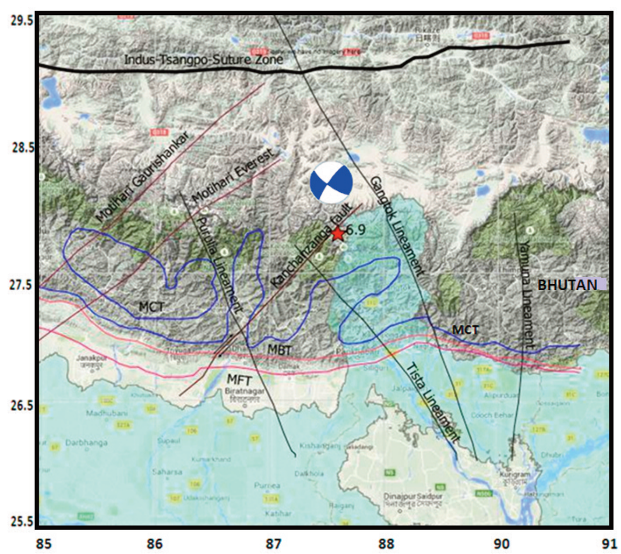

FIGURE 1. Seismotectonic map showing the 2011 Sikkim earthquake of Mw 6.9 and its CMT solution (IMD) (Overlaid on the political map, Google map and prominent fault system of the region).

and faults are concentrated in eastern Nepal, adjoining Sikkim and Bhutan. Of these, mention may be made of NE-SW oriented Kanchendzonga and NW-SE oriented Tista lineaments which were close to the 2011 Sikkim earthquake. The spatial distribution of ages across the former shows older ages (12 to 16 Ma) to the south and north and younger ages (8 Ma) in the middle portion of the transect [Larson et al., 2017]. The core of the Tista culmination is occupied by Proterozoic Lesser Himalaya low-grade metapelites of Daling group of rocks. This lineament is generally aligned along the Tista river and extends from east Nepal to Gangetic West Bengal.

3. SEISMICITY OF THE SIKKIM REGION

The seismicity study of the Sikkim region was undertaken using the earthquake catalogs of IMD, USGS, and ISC. During the pre-instrumental era, a few large earthquakes were reported in the Nepal/Sikkim border during 1833, 1849, 1852 and 1899 [Tandon and Srivastava, 1974]. The earthquake of magnitude 6.5 in 1852 in the Kanchendzonga hills reported several thousand square meters of the south-west portion of its peak being thrown down [Tandon and Srivastava, 1974]. The largest earthquake (15 January 1934, M 8.3) in the Bihar-Nepal region caused the maximum intensity of VIII in some parts of Sikkim. A few earthquakes of moderate intensity were reported around the epicentral distance of 100-150 km during 1935 to 1963 in the eastern Nepal and Tibet besides a cluster near the Kanchendzonga fault [Tandon and Srivastava, 1974]. However, the earthquakes of 30 August 1964 (M 5.1) and 30 January 1965 (M 6.1) occurred close to the epicenter of Sikkim 2011 earthquake. The earthquake of November 1980 with its epicenter near Sikkim-West Bengal border (M 6.1) caused major damage in Gangtok where 18 people were injured. In the recent past, the earthquake of February 2006 (M 5.3) caused two deaths and damage in the north-central Sikkim [Raju et al., 2007]. The earthquake of 20 May 2007 (M 5.0) with its epicenter about 40 km south of Gangtok caused panic and minor damage in Sikkim. The micro earthquake survey in the east Nepal and Bhutan regions also recorded a cluster of earthquakes close to the Sikkim border [Monsalve et al., 2006; de la Torre et al., 2007]. The active zone of micro-seismicity extended from Kanchendzonga to the Himalayan Frontal Thrust (HFT), roughly along longitude 87°E. Several earthquakes of focal depth about 50 km were detected west of the 2011 Sikkim earthquake. Short term micro-earthquake surveys [De and Kayal, 2003; Hazarika et al., 2010] and strong motion stations [Nath et al., 2005] in Sikkim region showed only a few events close to the 2011 Sikkim earthquake. Majority of these micro-earthquakes occurred between the MCT and MBT in the Sikkim region or towards south on MBT between the Tista and Gangtok lineaments and a few events close to MBT. But these results were constrained due to the geometry of the network in the region which had a profound influence on their epicentral parameters, particularly in the focal depth. The dominant focal mechanism of the earthquakes in this region has been reported as a strike-slip type by several workers. The first study which showed strike-slip faulting in the Sikkim region was based on the focal mechanism of 12 January 1965 earthquake [Ichikawa et al., 1972]. The source mechanism of 19 November 1980 (M 6.0) earthquake in theregion suggested a predominantly strike-slip faulting [Ni and Barazangi, 1984]. The earthquake of 26 February 1970 in eastern Nepal also showed strike-slip movement but with a component of normal faulting [Tandon and Srivastava, 1975]. The east Bhutan earthquake of 21 September 2009, however, occurred on a shallow north dipping plane as inferred by the moment tensor solutions by the USGS and Harvard but Kayal et al. [2010] associated it with the Kopili lineament. Based on the seismic history including the largest earthquake, GPS data and the predominance of strike-slip faulting, Sikkim was placed in type 2 of the seismic gap where the largest earthquake of magnitude 7 to 7.5 could be expected [Srivastava et al., 2013b]. The recurrence interval for larger/great earthquakes in this gap is longer as compared to those classified as the seismic gap of type 1. The seismicity of the Sikkim region during the period 1973 to August 2011 based on the USGS data is shown in Figure 2a. Figure 2b shows the epicenter of the main shock of 2011 Sikkim earthquake and its aftershocks in the region based on the data of the IMD.

4. EPICENTRAL PARAMETERS OF THE 2011 SIKKIM EARTHQUAKE

The hypo-central parameters of the 2011 Sikkim earthquake, estimated by the different agencies are given in Table 1. In the present study, the epicentral parameters of the recent earthquake were improved using regional velocity models as given in Table 2a. Tandon et al. [1976] worked out the crustal structure of the northeast Himalaya and found two layers of granite with at hickness of 22.0 km and 12.3 km respectively. Other velocity models had a single layer of granite [Monsalve et al., 2006; Chaudhury and Srivastava, 1977]. The final epicenter estimate having lowest RMS errors was based on the velocity model of Tandon et al. [1976] as shown in Table 2b. This epicenter was close to the results given by the USGS and IMD. Although the velocity model of Monsolve et al. [2006] was based on a large number of micro-earthquakes recorded by the local network, slightly larger RMS values favored the model by Tandon et al. [1976]. Its focal depth estimate was refined by identifying depth phases Pn and sPn, using waveforms from the

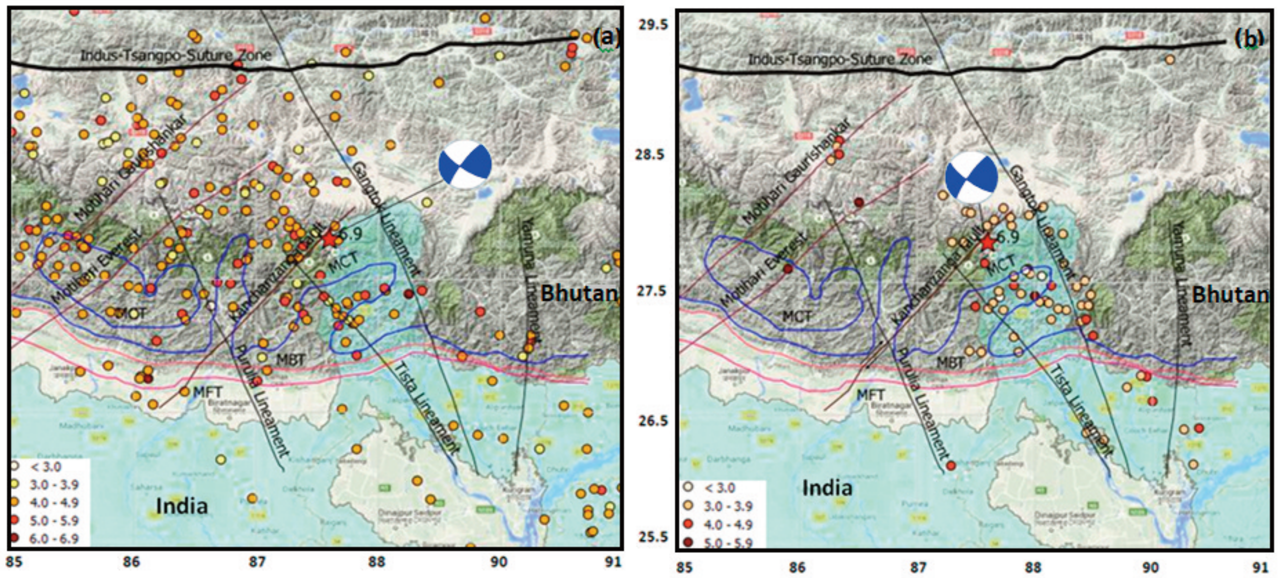

FIGURE 2. (a) Seismicity in and around Sikkim during 1973 to prior Sikkim earthquake 2011. (b) The main shock of 2011 Sikkim earthquake and its aftershocks.

Agency	Origin Time (UTC)	Epicenter		Focal Depth (km)	Magnitude
		Lat (°N)	Long (°E)		
IMD	12:40: 46	27.73	88.13	45.9*	Mw 6.9; Mb 6.8; Ms 6.6
USGS	12:40: 46	27.723	88.064	50.0*	Mw 6.9
ISC	12:40:49.58	27.8039	88.1536	29.6	Mw 6.9; Mb 6.5; Ms 6.7

TABLE 1. Hypocentral parameters of the 18 September 2011 Sikkim earthquake. *(revised).

SN	Source	Depth (km)	Vp (km/sec)	Vs (km/sec)
1	A. N. Tandon et al., 1976	0.0	5.65	3.42
		22.0	6.03	3.60
		34.3	6.49	3.90
		50.4	7.97	4.53
2	Monsalve et al., 2006	0.0	5.6	3.2
		23.0	6.5	3.7
		55.0	8.1	4.6
3	Chaudhury and Srivastava,1977	0.0	5.60	3.30
		33.0	6.67	3.65
		49.0	8.20	4.40

TABLE 2a. Velocity models used for the Sikkim region.

IMD stations (Figure 3a) after applying low pass filter cut off at 2Hz (Figure 3b). This method has the advantage that the time difference between sPn and Pn remains constant for a wide range of source station distances and consequently identificationof sPn phase is easy. The approach is also less sensitive to location errors which give major advantage when sparse data is available [Bhattacharya et al., 1997; Devi et al., 2009; Dengwei et al., 2011]. The onset time of Pn and sPn phases which were clearly discernible at some Indian stations are given in Table 3.

It may however, be noted that the difference between the stations in northeast India with almost similar crustal structure gave almost same difference between the two phases but increased to 19.96 sec at New Delhi and decreased to 13.3 at Shimla (Table 3), possibly due to the differences in the crustal structure of the regions. By taking an average value of sPn-Pn time (15.47 sec) from the stations in the northeast India where the crustal structure was less uniform, the focal depth for the 2011 Sikkim earthquake was computed as 46.8 km. This was close to that based on the

Model	Origin time (UTC) (HH:MM:SS.S)	Epicenter		RMS error
		Latitude (° N)	Longitude (°E)	
1 of Table 2 (a)	12:40:46.9	27.705	88.010	1.2
2 of Table 2 (a)	12:40:48.0	27.702	88.060	1.3
3 of Table 2 (a)	12:40:47.9	27.704	88.057	1.3

TABLE 2b. Epicentral parameters of the Sikkim earthquake estimated using different velocity models (Table 2a).

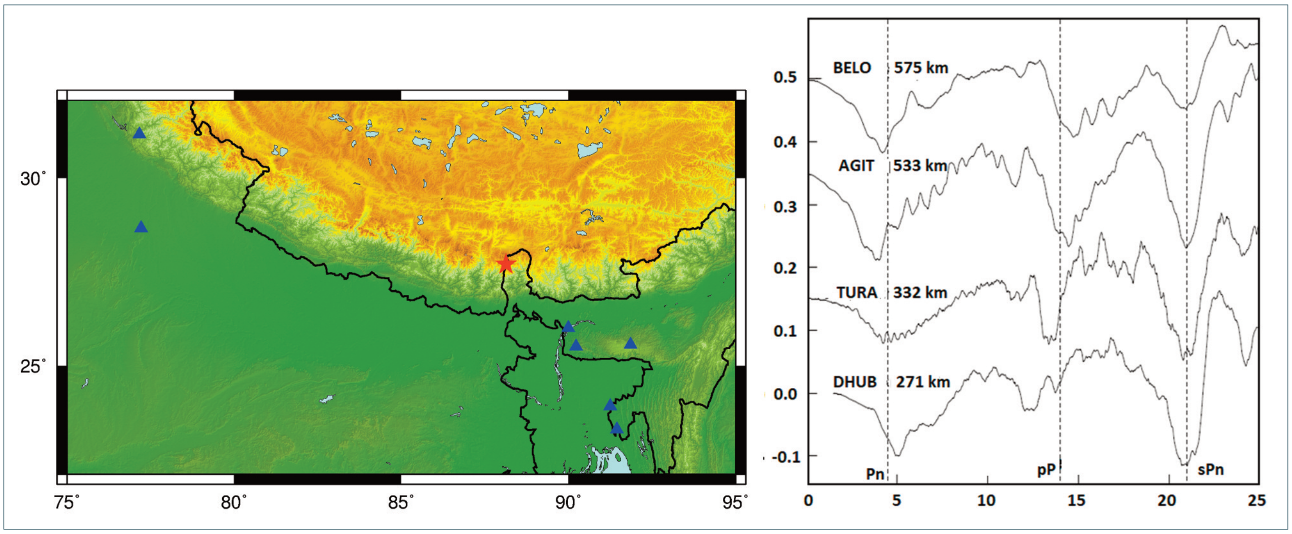

FIGURE 3. (a) Map showing stations used in depth phase estimation. (b) Pn and sPn phases shown for different stations after low pass filter (2 Hz). The vertical displacement seismograms have been visually aligned with the Pn arrival (left vertical dashed line). The time on the x-axis is arbitrary. The phases arriving at the middle and the right vertical dashed lines are interpreted as the depth phases pP, and sPn respectively.

S. No	Stations	Pn phase (hh:mm:ss.s)	sPn phase (hh:mm:ss.s)
1	Belonia	12: 42: 09.02	12: 42: 25.10
2	Tura	12: 41: 35.41	12: 41: 50.62
3	Agartala	12:42: 01.0	12: 42: 16.97
4	New Delhi	12: 43: 05.14	12: 43: 25.10
5	Shimla	12: 43: 12.07	12: 43: 25.40
6	Dhubari	12: 41: 28.48	12: 41: 44.00
7	Shillong	12: 41: 50.4	12: 41:64.98

TABLE 3. Travel time (UTC) of the Pn and sPn depth phases at Indian stations.

Agency	Nodal Plane I			Nodal Plane II			Depth (km)
	Strike (°)	Dip(°)	Rake (°)	Strike (°)	Dip (°)	Rake (°)	
IMD	216.7	79.9	15.3	124.0	75.0	169.5	58
USGS (CMT)	220	78	0	130	90	168	52
USGS (W phase)	217	75	-4	308	86	-164	60
Harvard	216	72	-12	310	79	-162	46

TABLE 4. CMT solutions from different agencies for 18 September 2011 Sikkim earthquake.

CMT solution given by the Harvard (Table 4). It may thus be surmised that the focal depth based on the worldwide data given by the ISC as 29.6 km needs to be revised. Keeping in view the crustal structure of the region [Tandon et al., 1976; Monsalve et al., 2006], it may be inferred that the recent Sikkim earthquake occurred close to Moho.

5. SOURCE PARAMETER ANALYSIS

The strength of an earthquake source is represented by its seismic moment (Mo). The seismic moment, source radius and stress drop were obtained by the amplitude spectra of S-waves based on the Brune's model [1970] on a circular fault. The seismic moment is given by

$$M_0 = (4\pi\rho \ \beta^3 \ R \ A_0) / R_{\theta\varphi} \quad (1)$$

Where A_o is the low-frequency spectral amplitude of S-waves, R is the hypocentral distance, $R_{\theta\varphi}$ is the radiation pattern of S-wave, β is the S-wave velocity at the source and ρ is the density at the source. The radiation factor for S-waves takes care of free surface amplification and other effects. Corner frequency fc is the frequency at which the low frequency and high-frequency asymptotes of amplitude spectra intersect. This frequency is used to calculate the radius of circular fault, r by

$$r = (2.34\beta) / (2\pi \ fc) \quad (2)$$

The rupture area is given by πr^2.

The moment magnitude of the Sikkim earthquake was computed using Hanks and Kanamori [1979] formula:

$$Mw = 2/3 * \log_{10} Mo - 10.73 \quad (3)$$

The stress drop Δσ is given by

$$\Delta\sigma = \frac{7}{16}\left(\frac{Mo}{r^3}\right) \quad (4)$$

The focal mechanism solutions of the 2011 Sikkim earthquake determined by the IMD, USGS and Harvard are shown in Table 4. The source parameters were computed in this study (Table 5a, 5b) from the displacement amplitude spectra of S-waves recorded at the IMD stations by the above model. The radiation pattern of S-wave was taken as 0.85 [Fletcher, 1980]. The S-wave spectra of a few IMD stations used in this study are shown in Figure 4. The average seismic moment was estimated as 4.91×10^{19} Nm (Table 5a). The seismic moment magnitude for the main shock was found as 6.8 and 6.9 from the S-wave spectra corresponding to the depth of focus in granite and basaltic layers with respective S-wave velocities of 3.6 km/sec and 4.53 km/sec (Table 5a, 5b) assuming the model by Tandon et al. [1976]. It may, therefore, be inferred that since larger moment magnitude was reported by worldwide data, the velocity of S-waves near Moho (4.53 km/s) close to the focus of the 2011 Sikkim earthquake was more representative for the computation of the source parameters. The epicentral parameters and the source characteristics of the foreshock and aftershock of the same magnitude (M 4.9) are given in Table 6 (for Vs 3.6 km/sec). The main shock source characteristics for Vs 4.53 km/sec are also shown in the Table 6.

6. PRECURSORY OBSERVATIONS

6.1 FORESHOCKS

The 2011 Sikkim earthquake was preceded by a foreshock on 3 June 2011 with the focal depth of 26 km. According to the fault break down model of Ohnaka [1992], the fracture initiated at a shallow depth by the occurrence of foreshock before the main earthquake. This would require the fracture to proceed much deeper up to Moho or upper mantle where the main earthquake (2011) occurred. The difference in the magnitude of the foreshock and the main shock for the 2011 Sikkim earthquake was large (~1.9) as compared to the other shallow focus earthquakes in the Himalayan region like; India-Nepal border 1966 (1.2), Kashmir 1967 (0.6), West Pakistan border, 1966 (0.7) [Srivastava and Kamble, 1972]. The stress drop of the foreshock of the Sikkim earthquake was 44 bars (Table 6) which was much less as compared to 115 bars of the main earthquake (Table 5a). However, it was comparable to that of the aftershock of March 2012 which had the same magnitude.

6.2 DECADAL VARIATION IN b-VALUE

The decadal changes in b-value were computed within the radius of 3° from the epicenter of the 2011 Sikkim earthquake using USGS earthquake catalog from 1973 to 2011 after removing the aftershocks of the August 1988 earthquake. The results for the period September 1973 - August 1981 (8 years), September 1981-August 1991, September 1991-August 2001 and September 2001 to August 2011 are shown in Figure 5. The estimated b-values during these periods were 1.05±0.2, 1.25±0.2, 0.98±0.09 and 0.85±0.08 respectively. Larger b-value during the second decade is at-

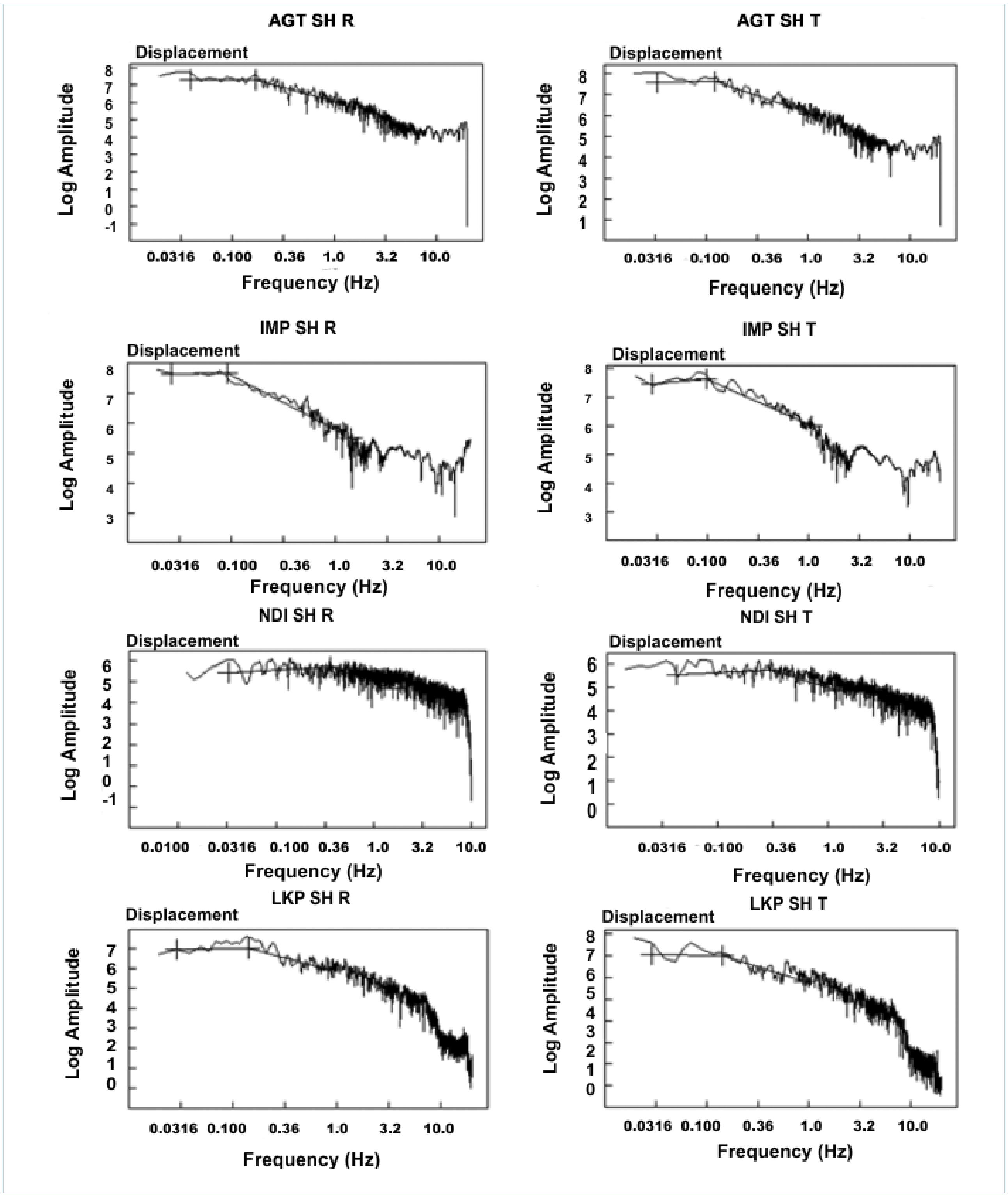

FIGURE 4. S-wave spectra of four representative stations of IMD (AGT: Agartala, IMP: Imphal, NDI: New Delhi, LKP: Lekhapani).

tributed to the occurrence of larger number of smaller magnitude earthquakes as compared to larger events. The significant decrease in b-value in the last decade suggested the possibility of the occurrence of a large earthquake. This result is similar to that for Nepal earthquake, 2015 [Prakash et al., 2016] where b-value decreased in the last decade prior to the main earthquake. The b-value in the last decade in the Sikkim region was also lower as compared to the b-value (1.19±0.1) for the whole period of 1973-2011 (Figure 6) and was in agreement with that obtained from microearthquake survey during 2006 to 2007 [Hazarika et al., 2010]. Lower b-value has also been reported prior to several shallow focus earthquakes in the Himalayan region [Srivastava, 2004].

S. No.	Station	Epicentral distance (km)	Component	Mo (dyne cm)	Mw	Stress drop (bar)
1	Dhubri (DHUB)	283.88	Radial	1.24897E+26	6.7	47.5476
			Transverse	1.57236E+26	6.8	87.9032
2	Tura (TUR)	344.20	Radial	7.58956E+25	6.6	49.0027
			Transverse	1.51432E+26	6.8	64.3378
3	Guwahati (GHT)	407.70	Radial	1.79368E+26	6.8	110.4666
			Transverse	8.98971E+25	6.6	157.8519
4	Shillong (SHL)	457.40	Radial	2.53342E+26	6.9	84.4051
			Transverse	1.26972E+27	7.4	73.6719
5	Tezpur (TZP)	492.23	Radial	4.32094E+26	7.1	94.8402
			Transverse	5.43974E+26	7.1	124.8230
6	Bokaro (BOK)	500.19	Radial	1.38851E+26	6.7	99.8178
			Transverse	2.20064E+26	6.9	100.3777
7	Agartala	545.01	Radial	4.78429E+26	7.1	210.6576
			Transverse	9.54591E+26	7.3	154.2670
8	Itanagar (ITN)	567.93	Radial	4.98547E+26	7.1	182.8089
			Transverse	6.27634E+26	7.2	189.3934
9	Ziro (ZIR)	574.91	Radial	1.59591E+26	6.8	99.8549
			Transverse	2.52935E+26	6.9	130.1273
10	Belonia (BELO)	614.78	Radial	5.39676E+26	7.1	98.4791
			Transverse	5.39676E+26	7.1	150.0848
11	Jorhat (JOR)	627.75	Radial	1.0995E+27	7.3	205.4499
			Transverse	1.0995E+27	7.3	210.3413
12	Mokokchung (MOK)	664.65	Radial	1.46556E+26	6.7	152.2827
			Transverse	5.83449E+26	7.1	146.0451
13	Imphal (IMP)	674.63	Radial	1.48755E+27	7.4	102.2579
			Transverse	9.38583E+26	7.3	78.1426
14	Dibrugarh (DIBR)	679.61	Radial	1.19034E+27	7.4	182.9839
			Transverse	9.45523E+26	7.3	185.1574
15	Lekhapani (LKP)	773.42	Radial	3.4027E+26	7.0	88.8769
			Transverse	3.4027E+26	7.0	92.6854
16	Dehradun (DDI)	1012.08	Radial	2.80948E+26	6.9	56.3062
			Transverse	4.45273E+26	7.1	89.2393
17	Bhopal (BHP)	1182.89	Radial	5.20437E+26	7.1	82.0373
			Transverse	5.20437E+26	7.1	63.1896
18	New Delhi (NDI)	1083.01	Radial	1.8969E+25	6.2	74.1903
			Transverse	1.8969E+25	6.2	46.7204
			Mean	4.91E+26	6.9	115.73

TABLE 5a. Source parameter estimation using S-wave spectra for S-wave velocity 4.53 Km/sec.

7. AFTERSHOCK CHARACTERISTICS

7.1 LARGEST AFTERSHOCK MAGNITUDE

This earthquake generated only a few aftershocks larger than magnitude 4.0 with the largest aftershock of magnitude 4.9. The magnitude difference between the main shock and the largest aftershock for the 2011 Sikkim earthquake was much larger as compared to the shallow focus Muzaffarabad [2005], Uttarkashi [1991] and Chamoli [1999] earthquakes. The relatively lesser number and lower magnitude aftershocks are attributed to the deeper focal depth of the main shock near the Moho or the upper mantle. The aftershock productivity for strike-slip earthquakes is also on average four times smaller than the productivity of aftershocks in a thrust type earthquakes in the India-Asia collision belt [Tahir and Grasso, 2014]. Since the aftershocks are caused by the subsequent slip on the asperities of a fault which remain unbroken during the main shock, the absence of large aftershocks after the 2011 Sikkim earthquake implies the presence of smaller asperities in the region.

S. No.	Station	Epicentral distance (km)	Component	Mo (dyne cm)	Mw	Stress drop (bar)
1	Dhubri (DHUB)	283.74	Radial	6.27E+25	6.5	47.5230
			Transverse	7.89E+25	6.6	87.8577
2	Tura (TUR)	344.08	Radial	3.81E+25	6.4	48.9855
			Transverse	7.6E+25	6.6	64.3151
3	Guwahati (GHT)	407.59	Radial	9E+25	6.6	110.4389
			Transverse	4.51E+25	6.4	157.8123
4	Shillong (SHL)	457.31	Radial	1.27E+26	6.7	84.3883
			Transverse	6.37E+26	7.2	73.6572
5	Tezpur (TZP)	492.15	Radial	2.17E+26	6.9	94.8239
			Transverse	2.73E+26	6.9	124.8016
6	Bokaro (BOK)	500.11	Radial	6.97E+25	6.5	99.8011
			Transverse	1.1E+26	6.7	100.3609
7	Agartala	544.94	Radial	2.4E+26	6.9	210.6280
			Transverse	4.79E+26	7.1	154.2454
8	Itanagar (ITN)	567.86	Radial	2.5E+26	6.9	182.7853
			Transverse	3.15E+26	7.0	189.3689
9	Ziro (ZIR)	574.84	Radial	8.01E+25	6.6	99.8423
			Transverse	1.27E+26	6.7	130.1109
10	Belonia (BELO)	614.72	Radial	2.71E+26	6.9	98.4683
			Transverse	2.71E+26	6.9	150.0682
11	Jorhat (JOR)	627.68	Radial	5.52E+26	7.1	205.4281
			Transverse	5.52E+26	7.1	210.3191
12	Mokokchung (MOK)	664.59	Radial	7.35E+25	6.5	152.2683
			Transverse	2.93E+26	6.9	146.0313
13	Imphal (IMP)	674.56	Radial	7.47E+26	7.2	102.2485
			Transverse	4.71E+26	7.1	78.1354
14	Dibrugarh (DIBR)	679.55	Radial	5.97E+26	7.2	182.9674
			Transverse	4.75E+26	7.1	185.1407
15	Lekhapani (LKP)	773.36	Radial	1.71E+26	6.8	88.8707
			Transverse	1.71E+26	6.8	92.6790
16	Dehradun (DDI)	1012.04	Radial	1.41E+26	6.7	56.3039
			Transverse	2.23E+26	6.9	89.2357
17	Bhopal (BHP)	1182.89	Radial	2.61E+26	6.9	82.0349
			Transverse	2.61E+26	6.9	63.1877
18	New Delhi (NDI)	1082.97	Radial	1.99E+25	6.2	74.1877
			Transverse	1.899E+25	6.2	46.7188
			Mean	2.47E+26	6.8	115.72

TABLE 5b. Source parameter estimation using S-wave spectra for S-wave velocity 3.6 Km/sec.

7.2 DECAY OF THE AFTERSHOCK ACTIVITY

In the present study, the temporal behavior of the aftershock sequence of 2011 Sikkim earthquake was studied using the modified Omori law. The Omori law parameters *p*, *c*, and k were determined using the maximum likelihood method (Figure 7). The decay of p-value was found to be slower for the 2011 Sikkim earthquake as compared to the other shallower Himalayan earthquakes [Srivastava and Kamble, 1972; Singh et al., 2008].

7.3 AFTERSHOCK AREA

The area of the aftershocks (A) increases with the magnitude of the main earthquake. Using the aftershock data of past earthquakes in the Indian region, Srivastava et al. [2013a] found the relationship between the moment magnitude (Mw) and the aftershock area, A (km^2) as

$$\mathbf{\mathit{Log\ A} = 0.615\ \mathit{Mw} - 1.06} \qquad (5)$$

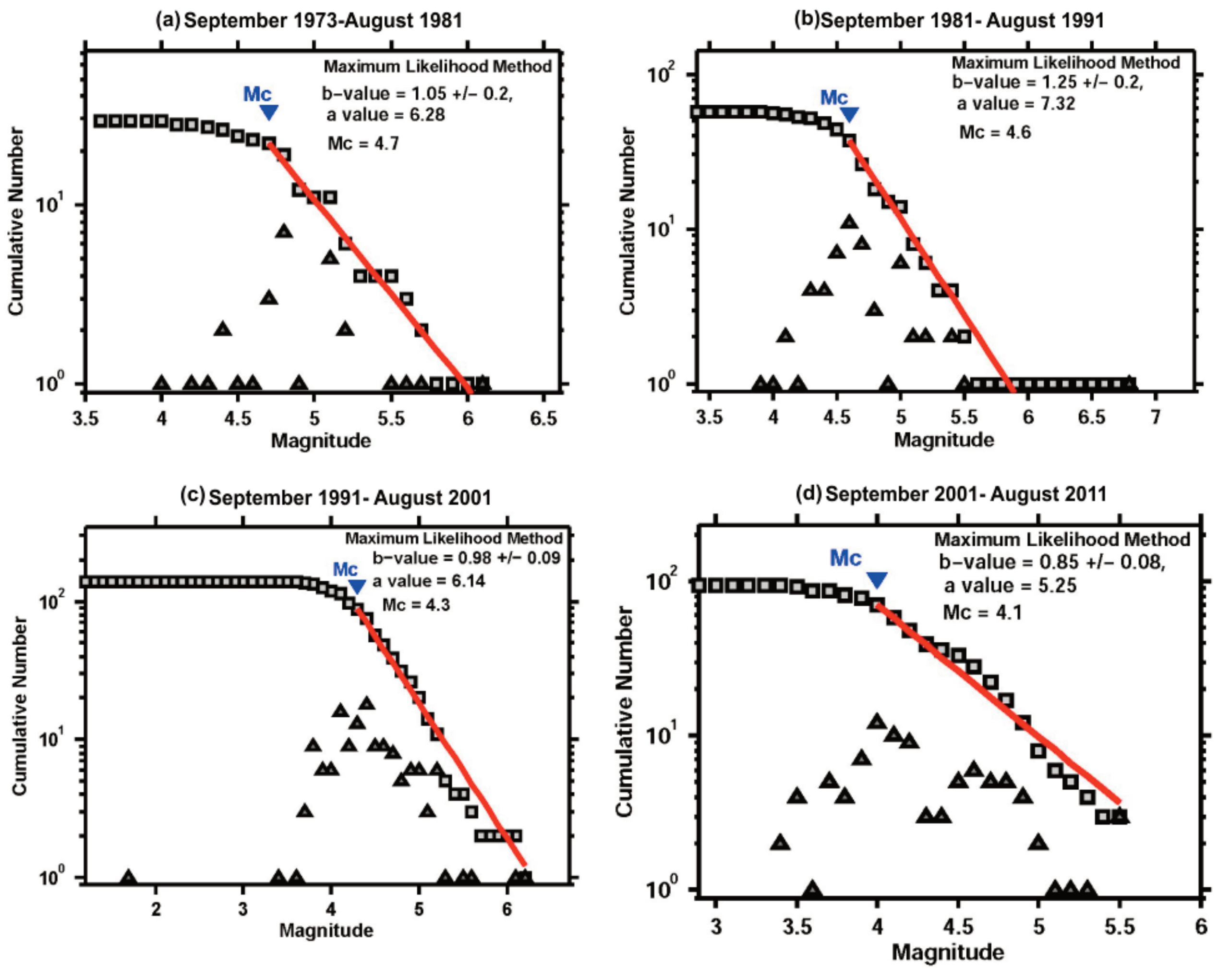

FIGURE 5. Decadal variation of b-value prior to the 2011 Sikkim earthquake (a) September 1973 - August 1981, (b) September 1981 - August 1991, (c) September 1991 - August 2001 and (d) September 2001 - August 2011). Small triangles are the derivative of the frequency magnitude relation, to compute the magnitude of completeness (M_C).

This relation gives the aftershock area as 1530 km^2 corresponding to the magnitude, 6.9 of the 2011 Sikkim earthquake. This is broadly in agreement with that obtained from the aftershock data recorded by IMD (Figure 2b) ignoring their occurrence on subsidiary faults which were triggered after some days.

8. DISCUSSION

Synthesis of the epicentral distribution of the earthquakes in the Sikkim region shows a clustering of earthquakes in an area bounded by MBT, MCT, Tista and Gangtok lineaments (Figure 2a). While the majority ofthe earthquakes are shallow-focussed (< 25 km), a few earthquakes have deeper focal depths extending up to upper mantle. However, the majority of epicen-

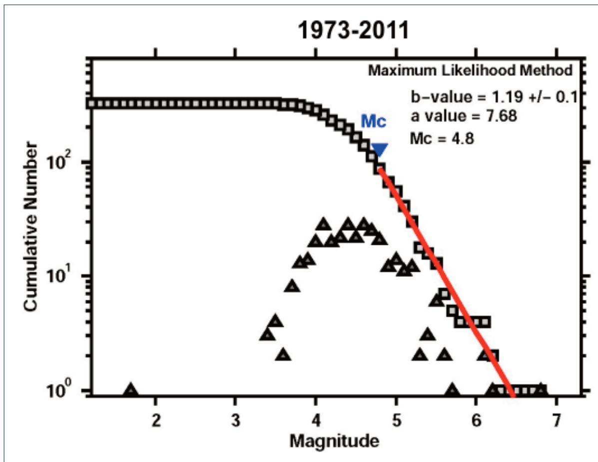

FIGURE 6. b-value prior to Sikkim earthquake 2011 (USGS data from 1973 to before the occurrence of this earthquake). Small triangles are the derivative of the frequency magnitude relation, to compute the magnitude of completeness (M_C).

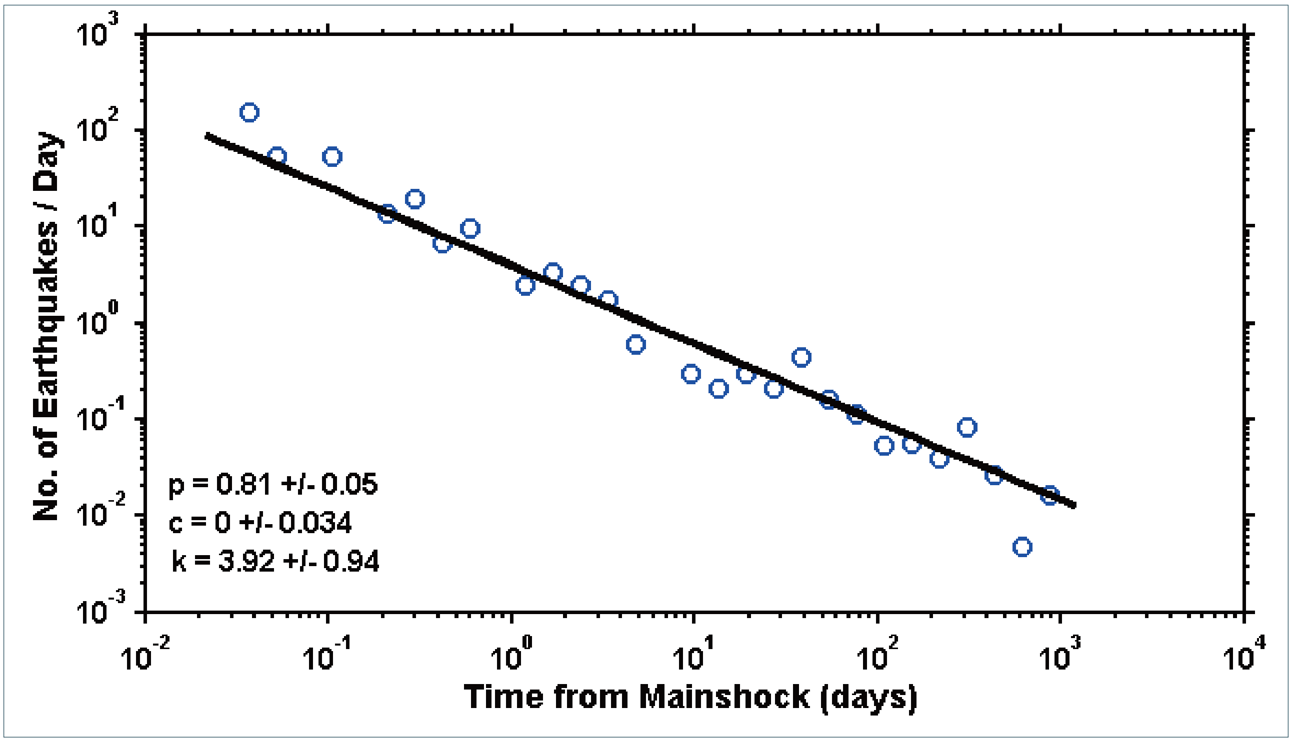

FIGURE 7. Decay of aftershocks based on the Omori's relation.

S. No.	Parameters	Foreshock	Mainshock	Aftershock
1	Date	2011-06-03	2011-09-18	2012-03-27
2	Origin Time in UTC (HH:MN:SS)	00:53:21	12:40:46	23:40:08
3	Latitude (°N)	27.5	27.705	26.1
4	Longitude (°E)	88.0	88.010	87.8
5	Depth (km)	26	46.8	12
6	Magnitude	4.9	6.9	4.9
7	Average Displacement (cm)	0.0043	1.85	0.004
8	Average Corner Frequency (Hz)	0.9	0.16	1.15
9	Average Stress Drop (bar)	44	115	55
10	Average Source radius (km)	1.78	11.52	1.26
11	Average Seismic Moment (Nm)	5.04×10^{16}	4.91×10^{19}	2.64×10^{16}
12	Mw	5.0	6.9	4.9

TABLE 6. Source parameters of the foreshock, mainshock, and aftershock of 2011 Sikkim earthquake (Vs 4.53 km/sec for main shock and 3.6 km/sec for foreshock and aftershock).

ters lying between MCT and MBT remain to be explained. A cluster of earthquakes in east Nepal could be associated with Kanchendzonga fault which suggests it to be seismically active. The 2011 Sikkim earthquake close to Nepal border occurred in an area enclosed by the Kanchendzonga fault and Tista lineament.

The epicenters of the aftershocks mostly occurred from north-west to south-east almost parallel to Tista

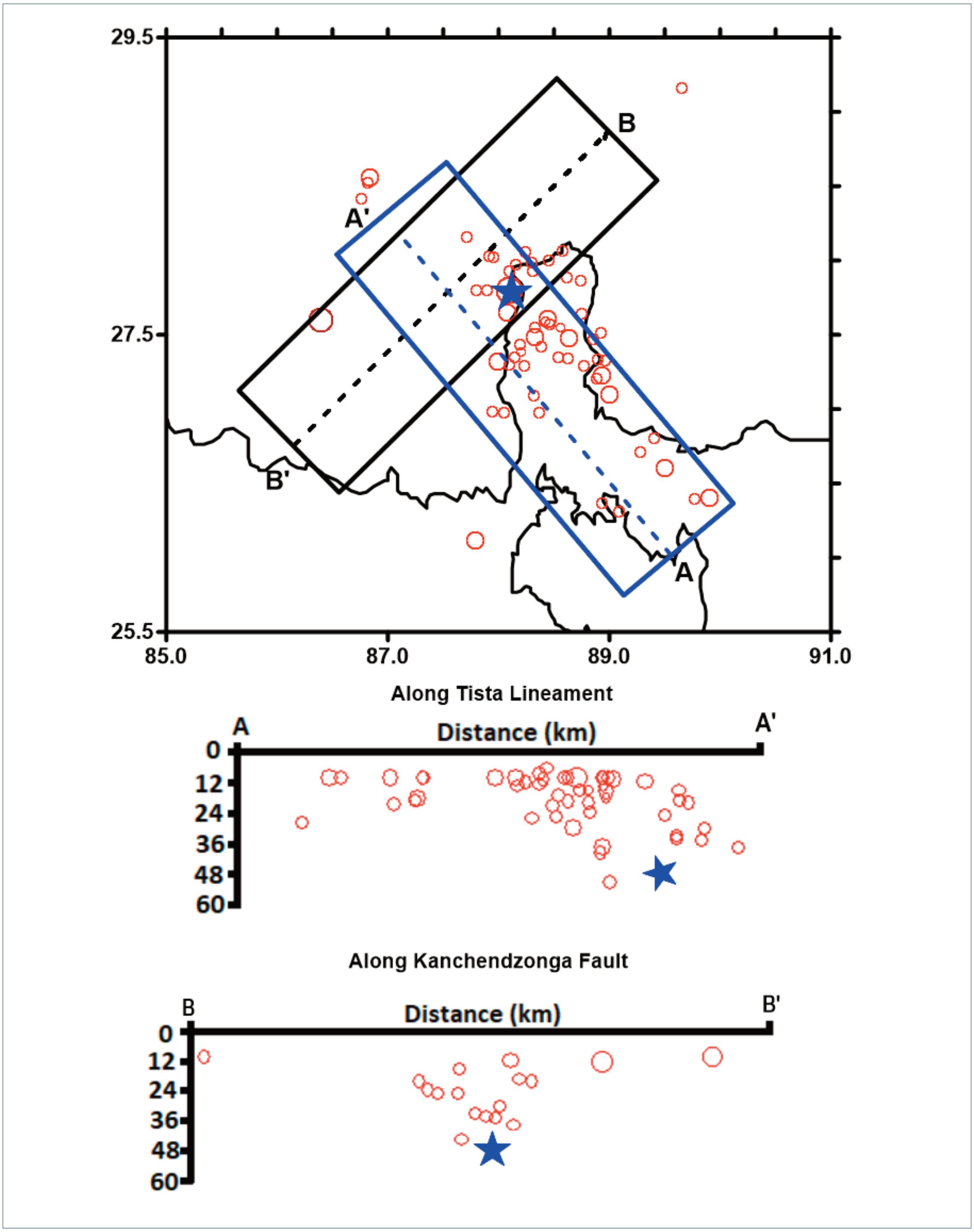

FIGURE 8. Depth cross section of aftershocks along Tista lineament (AA') and Kanchendzonga fault (BB').

lineament and extended upto MCT (Figure 2b). There was also a smaller cluster of earthquakes parallel to the Kanchendzonga fault. The depth distance cross-sections with respect to these two faults are shown in Figure 8. The Kanchendzonga fault is steeply inclined to vertical and a smaller portion of the fault was activated. According to Paul et al. [2015], the main shock rupture originated southeast end of the fault and propagated in the northwest direction but the aftershocks towards southeast were inferred to be connected to a fault parallel to the Tista lineament. Kumar et al. [2012] also inferred similar result but Dasgupta et al. [2012], Raghukanth et al. [2012] and Chopra et al. [2014] associated these aftershocks with the Tista lineament. The strain analysis using GPS baseline suggested that the region south-east of epicenter has undergone large deformation across the surface fault zone which was attributed to postseismic creep [Pradhan et al., 2013]. The depth cross sections of the aftershocks (Figure 8) however, suggest that both the fault planes as deduced from CMT solutions of the Sikkim earthquake ruptured but keeping in view the strike direction of the fault inferred from isoseismal maps [Mahajan et al., 2012; Singh and Shukla, 2013; Parjapati et al., 2013] and larger concentration of aftershocks, the fault parallel to Tista lineament was relatively more active.

A question arises how a fault parallel to the Tista lineament could originate in the lower crust. The dipping of Tista lineament towards northeast is ruled out from the focal mechanism of the main shock which showed the fault to be almost vertical. It is well known that multiple collisions of the Indian and Eurasian plates along the Himalayas have fragmented the crustal layers. As mentioned earlier, the model by Tandon et al. [1976] shows two granitic layers with a discontinuity near 22 km. However, magnetotelluric studies suggested a low resistivity layer between 3 to 12 km from which the presence of fluid in the Sikkim region could be inferred [Patro and Harinarayan, 2009]. It is surmised that due to the northeasterly movement of the Indian plate, differential stresses were acting at right angles to Himalaya during early quaternary which detached the lower crust from the Tista lineament due to decreased friction in the fluid layer and pushed it away towards Tibet through Indus Suture. This hypothesis could explain the occurrence of the aftershocks being located away from Tista but parallel to it at deeper focal depths. It is interesting to note that all the fault mechanism solutions of earthquakes having magnitude greater than 4.5 reported by the GCMT catalog [Kumar et al., 2012] also show a predominance of strike-slip faulting in the region supporting that the Kanchendzonga, Tista and Gangtok lineaments or faults parallel to them are more active than MCT/ MBT. Kumar et al. [2012] inferred eclogitization of the lower crust in the Sikkim and southern Tibet regions wherein jelly sandwich model could explain seismogenesis by assuming a strong lower crust and upper mantle. Rao et al. [2015] used receiver function analysis and suggested that transverse faults caused by thrust partitioning along the Himalayan arc manifest as vertical strike-slip faults cutting across the crust of the descending Indian plate down to 60 km. de la Torre et al. [2007] suggested that in the eastern Nepal and Tibet region, strike-slip earthquakes at depths of 70-100 km and thrust earthquakes at shallower depths could be attributed to Indian plate convergence accommodated through shear along vertical fault planes that extend to Moho depths. However, Paul et al. [2015] surmised that the underthrust Indian crust beneath the Sikkim Himalaya is entirely seismogenic due to the presence of dry granulite within the underthrust mid to lower crust. On the other hand, Arora et al. [2014] suggested that the competent and strong eclogitic layer in the lower crust acts as the depository of high stresses during an earthquake buildup cycle wherein the fluid pressure in the fractured rock matrix above plays a key role in the earthquake generating process. It is obvious that the presence of fluid in the crust would confine the aftershocks in two distinct layers separated by a nonseismic layer. The errors in the focal depths of the earthquakes including the aftershocks of the 2011 Sikkim earthquake do not allow us to draw a firm conclusion about the validity of the above two contrasting views. This aspect needs to be studied further by the deployment of a close network of stations covering the whole region similar to the experiment undertaken in Nepal and Bhutan [de la Torre et al., 2007].

It may be seen that the stress drop during the foreshock was 44 bars which is nearly equal to the largest aftershock of similar magnitude. As mentioned earlier, the average stress drop of the 2011 Sikkim earthquake estimated from S-wave spectra of the Indian stations was found to be 115 bars (Table 5a, 5b). This is in agreement with the results of Chopra et al. [2014] based on the strong motion data. However, Joshi et al. [2012], Paul et al. [2015] and Baruah et al. [2018] found lower stress drops of 61.5 bars, 44 bars,and 44 bars respectively from P-wave spectra, which need to be reconciled for a strike-slip earthquake. It may be mentioned that the stress drop of the main 2011 Sikkim earthquake (Mw 6.9) computed in this work is larger as compared to that of the thrust type Muzaffarabad earthquake 2005 (Mw 7.6) [Singh et al., 2006] and Nepal earthquakes 2015 [Prakash et al., 2016]. The slightly larger focal depth of the Sikkim earthquake and its strike-slip mechanism [Allmann and Shearer, 2009] could have given higher stress drop. This is further supported by large stress drop derived from the S-wave spectra for the Bay of Bengal earthquake of May 2014 which was also of the strike-slip type with deeper focal depth [Prakash et al., 2018].

Nath et al. [2005] and Nath [2005] attempted microzoning and deterministic hazard analysis for the Sikkim region and placed its northern areas (beyond Mangan) and western parts in the lowest seismic zone. But the seismic intensity due to the 2011 Sikkim earthquake was close to IX near the epicenter which decreased to VIII (MMI) near Mangam and VII to VIII (MMI) in Gangtok implying largest seismic zone in the northwest. This limitation could possibly be overcome by restricting microzonation over a small area say around Gangtok giving weight to large earthquakes in all nearby seismogenic sources instead of only one earthquake of magnitude 8.3 on MCT assumed in the earlier study. The number of stations for site response study also needs to be very large in the hilly region.

9. CONCLUSION

The above study brings out the following results:

i . The 2011 Sikkim earthquake with its focal depth constrained to 46.8 km from the depth phases using the IMD stations in northeast India showed strike-slip faulting which was in agreement with the earlier studies. It is surmised that both the nodal planes striking WNW and ENE initially ruptured but the orientation of meizoseismal area and a larger concentration of aftershocks towards the Tista lineament suggested the WNW oriented nodal plane more active. A hypothesis has been proposed to explain the detachment of the lower portion of the Tista lineament to the presence of fluids between its top and bottom layers due to the differential stresses caused by the multiple collisions of the Indian and Eurasian plates.

ii. Stress drop of the foreshock of this earthquake was much lower than that of the 2011 main shock. Changes in b-value showed a decrease during the last decade prior to the 2011 earthquake.

iii. The larger stress drop of Sikkim earthquake (2011) as compared to Nepal (2015) and Muzaffarabad (2005) earthquakes is attributed to its deeper focal depth and strike-slip focal mechanism.

iv. The Sikkim earthquake, 2011 brought out the limitations of microzoning attempted earlier for the Sikkim state and suggests such studies to be restricted to very small areas like Gangtok in a hilly region.

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