Nepal earthquake 25 April 2015: source parameters, precursory pattern and hazard assessment

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1. Introduction

Nepal earthquake of great intensity (Mw: 7.8) occurred on 25 April 2015 in Pokhara district of central Nepal and took a toll of more than 8500 human lives in Nepal, besides injuries to about 20,000 persons (NSET Nepal 2015). Loss of lives also occurred in India and Tibet and damage extended to Bhutan and Bangladesh. Maximum deaths were reported from Kathmandu valley, which suffered extensive damage from many earthquakes in the past as well. Heritage sights in the Kathmandu valley like Kathmandu Durbar Square and the Bhaktapur Durbar Square were flattened during the recent earthquake (ICIMOD 2015; Martin et al. 2015). Out of two large aftershocks, one (M: 6.6) occurred within a few minutes while the second large aftershock (M: 6.9) occurred after about 24 hours next day causing more damage to houses and panic. The earthquake triggered avalanche on Mount Everest killing at least 19 persons and yet another avalanche in Langtang valley where about 250 people were reported missing.

The largest aftershock (Mw: 7.3) occurred in eastern Nepal (Namche Bazar) after 16 days on 12 May 2015 (figure 1; table 1). Its secondary aftershock sequence gave another large aftershock of magnitude 6.2 about 32 minutes later. These shocks caused further loss of life and injuries in Nepal and India.

Four large/great earthquakes, namely Shillong 1897 (Mw: 8.1); Kangra 1905 (Mw: 7.8–8); Bihar Nepal 1934 (Mw: 8.1) and Assam Tibet 1950 (Mw: 8.4–8.6), since the instrumental era caused thousands of deaths and huge damage to houses and other infrastructural facilities in the Himalayan region (Tandon & Srivastava 1974). These large/great shocks are also called the plate boundary...
earthquakes because the Indian plate slipped about 5 to 10 metres in each of these shocks (Chen & Molnar 1977) notwithstanding some difference of opinion about Shillong earthquake, 1897 (Mw: 8.1) (Rajendran & Rahjendran 2011). Srivastava, Verma et al. (2013) also included 1505, 1555, 1803 and 1947 earthquakes in redefining seismic gaps in Himalaya with their discriminatory characteristics based on return period and largest magnitude. While seismologists were awaiting the recurrence of a great earthquake in Himalaya due to the accumulation of stresses caused by the movement of Indian plate after 1950 earthquake, an intraplate earthquake recurred in Kutch (Bhuj) region only after about 182 years since the last destructive earthquake in 1819 in the same region (Tandon & Srivastava 1974). During recent past, several contradicting inferences have also been drawn for various regions of Himalayas about the place and largest magnitude for the expected earthquakes on the Indian plate boundary. Some researchers infer that the magnitude of the largest earthquake may

![Figure 1. Epicentral location of main shock (25 April 2015; M: 7.8) and its largest aftershock (12 May 2015, M: 7.3) of Nepal earthquake, seismotectonic and aftershock distribution (25 April 2015 to 11 July 2015; fault plane from Harvard CMT catalogue). MFT, MBT and MCT represent the Main Frontal Thrust, Main Boundary Thrust and Main Central Thrust, respectively.](image-url)

| Date       | Origin time (UTC) | Latitude (° N) | Longitude (° E) | Depth (km) | Magnitude | Agency         |
|------------|-------------------|----------------|-----------------|------------|------------|----------------|
| 25 April 2015 | 06:11:25          | 28.1           | 84.6            | 10         | 7.9        | IMD            |
| 25 April 2015 | 06:11:25          | 28.23          | 84.731          | 8.2        | 7.8        | USGS           |
| 12 May 2015  | 07:05:19          | 27.7           | 86.0            | 10         | 7.3        | IMD            |
| 12 May 2015  | 07:05:19          | 27.809         | 86.066          | 15         | 7.3        | USGS           |

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be 8.5 to 9.0 (Jouanne et al. 2004; Bilham & Wallace 2005; Kumar et al. 2010; Ader et al. 2012; Bollinger et al. 2014). However, Srivastava, Bansal et al. (2013) and Gupta and Gahalaut (2015) after detailed re-examination of all geophysical aspects found that the largest earthquake in Himalaya cannot be as large as in subduction zones. The recent Nepal earthquake of 2015 occurred in the central Nepal Bihar seismic gap wherein the magnitude of the largest earthquake was assessed as 8 (Srivastava, Verma et al. 2013).

The objective of this paper is to examine the source parameters of the Nepal earthquake of 25 April 2015 and its largest aftershock and compare them with other major/great earthquakes of Shillong (1897), Kangra (1905), Bihar Nepal (1934) and Assam Tibet (1950) in the Himalayan region. Precursory observations like spatio-temporal pattern of seismicity and decadal changes in the $b$-value in the Gutenberg–Richter magnitude frequency relation have also been studied. Broadband digital data of Indian stations has been used to obtain source parameters and stress drop for this earthquake and compare them with the results reported for other earthquakes in interplate and intraplate regions (Singh et al. 2006).

2. Geology and tectonics of Nepal region

Nepal region lies in the seismically active portion of central Himalayas where several moderate to large/great earthquakes have occurred in the past. The multiple collisions of Indian and Eurasian plates have resulted in the formation of Himalaya and several thrusts. The whole 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 (Gansser 1964). These are separated by major dislocation zones. Major portion in lesser Himalaya consist of low-grade metapelites of Daling group. The granitoid gneises is found within the Daling group of rocks. It is separated by medium-to high grade crystalline complex. The main tectonic features in the Nepal Himalaya consist of several north dipping thrust faults called Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT)(Gansser 1964). Of these, the MFT separates the Siwalik rocks in the north and the Gangetic plain towards south. The boundary between the Siwaliks and lesser Himalaya is called MBT. The boundary between lesser Himalaya and higher Himalaya is marked as MCT. These thrusts which are generally younger from north to south are inferred to branch off the major basal detachment of the Himalayan thrust belt which is called the main Himalayan thrust (MHT) (Jouanne et al. 2004). This localizes the under thrusting of Indian lithosphere beneath the Himalaya and Tibet (Zhao & Nelson 1993). The tectonic map of Nepal and the surrounding area is shown in figure 1 (modified after Gansser 1964). Molnar and Chen (1982) proposed that the medium-sized thrust events occur along the part of the detachment beneath the northern Himalaya and perhaps also along the down dip projections of MCT and nearby subsidiary faults. The shallow north dipping zone apparently defines a part of the detachment that separates the under thrusting Indian plate from the Lesser Himalayan crustal block (Baranowski et al. 1984).

It was suggested by these authors that the great Himalayan earthquakes occur along the same detachment surface as defined by the thrust-type medium-sized events. Large earthquakes of magnitude about 8 or more have ruptured segments of hundreds of kilometres of the Indian plate boundary and are generally associated with the MHT (Jouanne et al. 2004). Many segments still remain unruptured which are considered as the potential sources of great earthquakes in future. However, larger probability of recurrence of major/great earthquakes occurs in the zones effected in the past (Srivastava, Verma et al. 2013). Several transverse folds and faults are also concentrated in eastern Nepal, adjoining Sikkim and Bhutan. Arun anticline in eastern Nepal extends along the axis of the river Arun folds. Other transverse folds in the region are Kunchandzongha–Dharan bazar syncline, Sunkoshi anticline, Trisuli anticline, Tila anticline and Karnali anticline in Nepal (Nakata 1989). Further south, in the Ganga Basin, major transverse features are Monghyr Saharsa ridge and Patna fault in Bihar. Focal mechanism solutions of earthquakes in the Himalayan region generally show thrusting but some limitations in the regional plate tectonics model were observed (Ichikawa et al.
1972; Tandon & Srivastava 1975; Baranowski et al. 1984; Ni & Barazangi 1984). It is interesting to note that different geometry of MHT has been suggested in central and western Nepal (Pandey et al. 1999). The former is described as a single large ramp 100 km from the MFT, while the latter comprises a series of smaller ramps.

2.1. Seismicity of Nepal region

Nepal has suffered a lot since the historical times due to earthquakes. The earliest record of a major earthquake in central Nepal based on paleoseismic data was inferred to occur in 1100 AD (Lave et al. 2005) which is referred to in the authentic historical catalogue of Nepal earthquake as severe earthquake in 1255 (M: 7.7) causing total destruction of several towns and huge loss of life (National Society of Earthquake Technology, Nepal 2011). Other large earthquakes in Nepal occurred in 1260, 1344, 1408, 1681, 1810, 1823, 1833, 1834, 1866 and 1869 (National Society of Earthquake Technology, Nepal 2011). After 1900, earthquakes of magnitude 5 to 6 occurred in 1902, 1906, 1909, 1918, 1926 and 1927 (Tandon & Srivastava 1974). During this period, large earthquake (M: 7.5) occurred on 27 August 1916 when all the houses collapsed in Dharachula. The largest earthquake occurred in the Bihar—Nepal region (Mw: 8.1) on 15 January 1934 which caused huge loss of life (~10,000 lives) and destruction of property. Large-scale liquefaction occurred in the plains of Bihar near the river Ganga due to this earthquake (Dunn et al. 1939). Earthquakes of magnitude 5 to 6 continued to occur in different parts of Nepal during the years 1935 to 1957 which included a few aftershocks of 1934 earthquake. On 28 December 1958, an earthquake of magnitude 6.5 occurred in Kapkote, about 110 km from Almora which caused ground ruptures and opening cracks with landslides and damage to buildings (Tandon & Srivastava 1974). This earthquake was associated with a thrust fault striking WNW dipping ENE at an angle of 36° (Tandon 1975). In the adjoining Uttarakhand region in India, two damaging earthquakes occurred during 1991 (Uttarkashi) and 1999 (Chamoli), respectively. The Uttarkashi earthquake of 20 October 1991 (M: 6.6) close to western Nepal took a toll of 768 human lives, injured 5066 persons and caused partial to severe damage to about 0.1 million houses. Its focal mechanism solutions by US Geological Survey (USGS) and Harvard show thrust faulting with NW—SE nodal plane as the fault plane. Later, the Chamoli earthquake (M: 6.9) of 29 April 1999 also caused extensive damage to property and loss of 103 lives in Uttarakhand. The centroid moment tensor solution by USGS suggested a thrust faulting trending WNW—ESE direction with a dip of 9°. Of several earthquakes (M: 5—6) in Nepal during 1960 to 1990, the 1966 and 1980 earthquakes of magnitude 6 caused significant damage in Dharachula and neighbouring regions (Srivastava & Gautam 1987). The focal mechanism of these earthquakes showed thrust faulting in conformity to the local tectonics (Srivastava & Gautam 1987). Loss of life and property was also reported during other earthquakes in 1993, 1994, 1995, 1997, 2001, 2002 and 2003 in the western and/or central Nepal (National Society of Earthquake Technology, Nepal 2011 and USGS). The earthquake of 21 August 1988 (M: 6.8) which had a large focal depth of 57 km caused the death of 721 persons in Nepal and 282 persons in Bihar besides about 10,000 injured and damage to hundreds of houses. The focal mechanism of this earthquake showed strike slip faulting with some thrust component (Srivastava & Rao 1991). The Geological Survey of India associated it with Monghyr—Saharsa ridge (GSI 1993). Sikkim earthquake of 18 September 2011 (Mw: 6.9) which had focal depth of 52 km, also caused major damage in east Nepal extending upto Kathmandu. The worst-affected districts in Nepal were Panchthar, Taplejung and Terathun, where a number of public and private buildings either sustained heavy damage or were completely destroyed. This earthquake also showed strike slip motion along nodal planes parallel to Kunchandzonga and Tista lineaments (Harvard). It is interesting to note that Kathmandu valley has recorded localized high intensities during many significant earthquakes in Nepal and its neighbourhood which is attributed to amplification of seismic waves due to lake deposits in the valley. However, the earthquake of 2015 generated moderate peak ground acceleration of 0.2 g in Kathmandu valley (Grandin et al. 2015) despite of seismic intensity of IX MM around the region (Nepal Society of Earthquake Technology 2015 and
Prabhas Pande, personal discussion after his field visit). Galetzka et al. (2015) inferred that whole basin resonance at 4–5 second period caused collapse of tall structures including cultural artefacts. The Himalayan—Nepal—Tibet seismic experiment yielded excellent data on microseismicity and the focal mechanisms of earthquakes by moment tensor inversion (Torre et al. 2007). Three distinct group of seismicity were found, namely (1) along the Himalayan front with less than 20 km focal depth, (2) in southern Nepal extending upto MFT at 20–60 km depth (Bollinger et al. 2014) and (3) beneath the Himalayan and Tibetan plateau at depths more than 60 km. Micro earthquake survey in east Nepal showed concentration of earthquakes along the front of the Himalaya arc with a seismic gap between longitudes 87.3°N and 87.7°E and a cluster of earthquakes close to the Sikkim border (Monsalve et al. 2006). Seismic activity in the sub Himalaya and Terai plains was well marked near the 1988 earthquake in east Nepal Bihar border and could have resulted from the aftershocks of the earthquake (Pandey et al. 1999). The active zone of micro-seismicity extending from Kun-chandzonga to MFT shows strike slip, normal and thrust faulting in the upper and lower crust but mostly strike slip faulting near or below Moho. The strike slip earthquakes near the Moho in Himalaya at depths greater than 60 km absorb the continental collision (Torre et al. 2007). It was suggested that body forces may play larger role at shallower depths than at deeper depths where plate boundary forces may predominate. Closer examination of the earthquakes around the recent earthquake of 2015 in central Nepal shows its occurrence in a region with scattered low seismicity all round the main earthquake. Two earthquakes of magnitude 5 and 4.4 occurred in Nepal on 21 and 22 April 2015 about 230 km away from the main earthquake of 25 April 2015 but no foreshocks in the immediate vicinity of the deadly earthquake were recorded.

3. Data analysis

Seismicity data used in this paper is based on the catalogues by Tandon and Srivastava (1974), India Meteorological Department (IMD), National Society of Earthquake Technology, Nepal 2011, USGS and International Seismological Centre.

The spatial distribution of aftershocks of Nepal earthquake 2015, based on data from IMD is shown in figure 1. It may be noticed that most of the aftershocks were spread over an area of about 135 km × 40 km with a higher concentration towards east. The well-marked concentration of these aftershocks could be noticed near MHT and activating the faults called Thaple, Gauri Shanker and Mt. Everest as shown in figure 1. Spatio-temporal variations of seismicity were studied using data from USGS catalogue available, namely 1971—April 2015. Similarly long-term averaged value of b' in Gutenberg Richter relationship was also worked out for the same period. The decadal periods to compute b-values were taken as 1975—1984, 1985—1994, 1995—2004, 2005—April 2015. The last decade was extended by about 4 months to understand whether any anomaly if observed is continued till the occurrence of the earthquake. In these computations, care was taken to remove the aftershocks of 1980, 1988, 2004 and 2008 earthquakes which had magnitude of 6 or slightly larger.

The source parameters of this earthquake were worked out from the broadband digital data of Indian seismological stations using Brune's model of circular fault and the seismic moment (M0), stress drop (Δσ) and source radius (r) were computed from S-wave amplitude spectra (Brune 1970). The computation was done using SEISAN: Earthquake Analysis Software (spectral analysis program tool) using first 10 seconds spectra of S-wave from the selected S-wave window length (Ottemoller et al. 2012). The radiation pattern of S-wave and shear wave velocity were taken as 0.85 (Fletcher 1980) and 3.35 km/s, respectively. It may be mentioned that a few stations had shown clipping of S phase and a few others had noisy background noise. Only eight stations, namely Bhopal (23.24°N, 77.42°E), New Delhi (28.68°N,77.21°E), Bhuj (23.25°N, 69.65°E), Tezpur (26.61°N, 92.80°E), Campbell Bay (07.00°N, 93.91°E), Goa (15.49°N, 73.82°E), Hyderabad (17.41°N, 78.55°E) and Diglipur (13.24°N, 92.97°E), and data having good ground motion records and clear S-wave phases were used in this study. These stations cover azimuthal range of about 120° in the near field from the main Nepal earthquake, 2015.
The average values of seismic moment, stress drop and source radius were estimated as $5.5 \times 10^{20}$ Nm, 3.4 MPa and 41 km, respectively. The moment magnitude Mw was estimated as 7.75 (~7.8). The seismic moment and Mw estimated using S-wave spectra matches with the USGS seismic moment tensor solution (Mo: $5.5 \times 10^{20}$ Nm; Mw: 7.76). The seismic moment for the largest aftershock was $9 \times 10^{19}$ Nm.

The representative S-wave spectra from two Indian stations, Bhopal and Campbell Bay, are shown in figure 2(a) and (b) and figure 3(a) and (b), respectively.

**Figure 2.** (A) Spectral analysis of S-wave (radial) recorded at Bhopal field station. (B) Spectral analysis of S-wave (transverse) recorded at Bhopal field station.
The source mechanism and epicentral parameter of the main earthquake, 2015 and its largest aftershock of 12 May 2015 based on USGS and Harvard CMT solutions are given in Table 2.

The spatial distribution of aftershocks extended eastwards from the main shock (Figure 1), suggesting the strike direction of the fault parallel to MHT in conformity with the focal mechanism solutions (Table 2). The respective dipping of the nodal plane of 7° and 11° of the main shock and its largest aftershock of 12 May 2015 based on Harvard solution suggested very shallow dipping of the fault plane towards NE.

Figure 3. (A) Spectral analysis of S-wave (radial) recorded at Campbell Bay field station. (B) Spectral analysis of S-wave (transverse) recorded at Campbell Bay field station.
3.1. Precursory observations

3.1.1. Precursory seismicity pattern

Seismicity patterns preceding earthquakes help in understanding the earthquake preparatory process. Srivastava et al. (1996) have shown that self-similar dynamics operates within 150 to 300 km around Shillong. This suggests that adequate justification exists to include earthquakes within 3 degrees radius from the main earthquake to study precursory seismicity patterns. Figure 4 shows spatio-temporal changes in seismicity preceding the earthquake based on USGS catalogue as mentioned earlier. The seismic quiescence marked ‘A’ in figure 4, prior to the Nepal earthquake, 2015 could be noted from 2007 to 2013 which is similar to that of other Himalayan earthquakes in Bihar—Nepal border, 1988 (Srivastava and Rao 1991), Uttarkashi, 1991 and Chamoli, 1999 (Prakash et al. 2004) and Muzaffarabad, 2005 (Singh et al. 2008). It may, however, be noted that the seismicity pattern preceding earthquakes in the Himalayan collision zone is somewhat diffused than those described by five phases of seismic activity (Kanamori 1981).

3.1.2. b values

The $b$-value computed from the Gutenberg–Richter relationship for the period 1971 to April 2015 and its decadal variation for the periods 1974—1984, 1985—1994, 1995—2004 and 2005—22 April 2015 are shown in figures 5, 6(a)–(d). The estimated $b$-value for the whole period from 1974 to 22 April 2015 was $0.94 \pm 0.11$. The decadal variation in the $b$-value estimated was $1.18 \pm 0.64$ (period 1974—1984), $1.35 \pm 0.33$ (period 1985—1994), $1.16 \pm 0.15$ (period 1995—2004) and $0.74 \pm 0.1$

Figure 4. Spatio-temporal variation of seismic activity from epicentre of Nepal earthquake 25 April 2015.
The low value of $b$ during the last decade suggests the possibility of a large earthquake within 300 km radius. Similar decrease in the $b$-value has been found prior to several shallow earthquakes in the Himalayan region (Srivastava 2004; Prakash et al. 2004; Singh et al. 2008).

4. Discussion

Rupture length of the great earthquakes in Kangra, 1905; Bihar—Nepal, 1934 and Assam Tibet, 1950 has been estimated as 100–280 km, 100–300 km and 250 km, respectively (Molnar & Pandey 1989). However, Srivastava et al. (2010) showed that the second meizoseismal area near Dehradun and Mussourie during 1905 Kangra earthquake had arisen due to site response and hence the associated rupture length could be about 150 km and not as large as 250 km. Similarly, three meizoseismal areas were reported during 1934 earthquake (Dunn et al. 1939). Tandon and Srivastava (1974) showed uncertainty about the rupture zone associated with the earthquake. If the primary zone of the largest intensity IX on the MMI scale in east Nepal—Bihar border is considered, the rupture length would be approximately about 150 km (Pandey & Molnar 1988). The rupture length of 1505 earthquake in western Nepal shown by Cannon and Murphy (2014) extends for about 400 km which is inconsistent with its magnitude which was constrained to 8–8.2 (Ambraseys & Douglas 2004; Srivastava, Verma et al. 2013). Accordingly, the rupture length associated with this earthquake would be about 200 km. The rupture length associated with the Nepal earthquake, 2015 was estimated 135 km from aftershock data. The corresponding displacement was computed as 3.5 metres for the main shock and about a metre for the largest aftershock of 12 May 2005, assuming the rigidity of the granitic rocks as $3 \times 10^{10}$ N/m². The rupture progressed southeastwards towards 1833 earthquake (Bilham 1995) where the largest aftershock (Mw: 7.3) occurred after 16 days.

Surface ruptures in Himalayan earthquakes have been found for Pakistan (Muzaffarabad, 2005) (Kaneda et al. 2008), central Nepal (1255) and Bihar—Nepal (1934) earthquakes (Sapkota et al. 2013). Although the epicentre of 1934 earthquake is questionable, no surface rupture was reported during the recent Nepal earthquake 2015, except some dislocation in the roads in Kathmandu.
caused by site response. The maximum seismic intensity near the epicentre was assessed as IX on MMI scale and was in agreement with the other large/great earthquakes in Himalaya (Tandon et al. 2001). The radius of perceptibility of this earthquake was more than 1500 km and in agreement to 1897, 1905 and 1934 earthquakes (Tandon et al. 2001). The aftershocks of Nepal, 2015 earthquake, migrated eastwards indicating the direction of rupture propagation. This also triggered the largest aftershock of 12 May 2015 near the 1833 earthquake. Comparison of aftershocks of the great/large earthquakes suggests that the maximum number of earthquakes of magnitude 6 to 7 occurred after the great Assam—Tibet earthquake of 1950, which had the largest magnitude in Himalaya (Tandon & Srivastava 1974). By comparing the number of large aftershocks of Muzaffarabad (2005) and Bhuj (2001) earthquakes, which had the same magnitude (Mw: 7.6) in different plate tectonic

Figure 6. (A, B) Decadal b-value estimate; (A) 1974—1984, (B) 1985—1994. (C, D) Decadal b-value estimate; (C) 1995—2004, (D) 2005—2015.
environment, it was noted that their number was larger (41) in the Himalayan region as compared to the intra plate region (9) if we take all the aftershocks of magnitude 5 and above during a 2-year period after each main shock (Srivastava, Singh et al. 2013). Tahir and Grasso (2014) also corroborated this inference but suggested the number of large aftershocks of Muzaffarabad earthquake (2005) as anomalous. The recent Nepal earthquake (2015) produced four aftershocks of magnitude more than 6 with the largest magnitude of 7.3 occurring after 16 days during the decaying phase of the aftershocks. During this period (25 April to 11 May 2015), the decay constant $p$ in Omori’s law and the $b$-value in Gutenberg–Richter frequency magnitude relations were found to be 0.93 (figure 7) and 0.6 (figure 8) based on the aftershock data recorded by IMD. The rapid decay of aftershocks and low $b$-value after the main earthquake (figure 8) were suggestive of seismic quiescence and higher in situ stresses resulting in the largest aftershock (Mw: 7.3) of Nepal earthquake on 12 May 2015. Similar quiescence was reported prior to the largest aftershock of Bhatasa earthquake of September 1983 (M: 4.9) in peninsular India (Srivastava et al. 1991). Occurrence of the largest aftershock of Nepal, 2015 earthquake being only 0.5 less than the main shock suggests that large asperities exist in the region.

Stress drop of all the four great/major earthquakes (1897, 1905, 1934 and 1950) in the Himalayan region could not be precisely quantified due to non-availability of digital seismographs. The stress drop for the Nepal earthquake of 2015 was found as 3.4 MPa based on digital broadband data of Indian stations which is in agreement with the results reported by Mitra et al. (2015) but much less than that reported by Denolle et al. (2015) from teleseismic data. It is well known that the stress drop may change with the crustal structure, nature of faulting and coefficient of friction. It also depends upon the Q-value. Singh et al. (2006) suggested an average value of Q as 500 and $f$ as 0.62 for the computation of source parameters of Muzaffarabad earthquake (2005) from Indian stations. These values have been adopted in this paper since the path of all the observatories in India covers similar tectonic regimes.

The stress drop of Nepal, 2015 earthquake is much less than that of Muzaffarabad earthquake, 2005 (Mw 7.6) which was reported as 11.5 MPa (Singh et al. 2006). This leads us to infer that the asperity in Nepal region is less heterogeneous than Muzaffarabad region due to difference in tectonics near MHT and syntaxial bend in the northwest Himalaya (Srivastava, Bansal et al. 2013). However, if we compare stress drop values in Himalaya with stable continental region of peninsular India, it is noticed that Himalayan regions shows much less stress drop (Singh et al. 2006) for similar
magnitude intraplate Bhuj earthquake (2001). Scholz et al. (1986) found that large intra plate earthquakes obey a scaling law similar to large inter plate earthquakes, implying that intra plate faults have a higher frictional strength than do plate boundaries. The higher stress drop of intra plate earthquakes is supported by a simple spring slider dashpot model (Iio et al. 2004). However, Allmann and Shearer (2009) suggested four times stress drop for strike slip earthquakes in the India Asia collision belt. The stress drop (11.5 MPa) of Sikkim earthquake of September 2011 (Mw: 6.9) with strike slip type faulting was comparable to that of Muzaffarabad earthquake 2005 (Mw: 7.6) which had thrust faulting (R.K. Singh, personal communication). It may, therefore, be inferred that the criteria of stress drops to distinguish plate boundaries in inter plate and intra plate regions in the Indian region may be restrained for thrust faults only. However, larger data are needed to refine this criteria for different focal mechanism of major/great earthquakes.

It may be interesting to examine different inferences drawn by various authors about the largest magnitude and return period of earthquakes in Nepal. Rajendran and Rajendran (2011) considered the whole region extending about 800 to 900 km between 1905 and 1934 earthquakes and cautioned about the threat of a great earthquake (M: 8.5) by giving weightage to an earthquake during 1100–1290. This study ignored 1505 (M: 8.1) and 1803 (M: 7.8) earthquakes which may have released stresses corresponding to a total seismic slip of about 10 to 12 metres if we compare with the slips of 4 to 7 metres during Muzaffarabad (2005) and about 4 metres during Nepal (2015) earthquake. On the other hand, Bilham and Wallace (2005) inferred that due to overlapping seismic zones of 1833 and 1934 earthquakes, stresses have been released implying that there is no immediate threat from any great earthquakes in the Nepal—Bihar region. Bilham and Szeliga (2008) also classified the earthquakes of 1125, 1400 and 1505 as mega earthquakes by overestimation of their magnitudes from reports of damage, ignoring the site response from scanty and populated pockets. They also suggested that seismic quiescence during 1500 to 2000 has ended and another era of mega earthquake has commenced. The respective magnitudes of 7.6 and 7.8 reported for Muzaffarabad

Figure 8. $b$-value during the period 25 April 2015 to 11 May 2015 (aftershocks prior to M: 7.3 earthquake of 12 May 2015).
(2005) and Nepal (2015) earthquakes do not support the commencement of the phase of mega earthquakes in Himalaya.

Based on GPS and paleoseismic data, a few other workers infer the possibility of 8.5 to 9 magnitude earthquakes in Himalaya (Jouanne et al. 2004; Kumar et al. 2006, Kumar et al. 2010; Ader et al. 2012; Bollinger et al. 2014). However, differences in continental collisions-type plate boundary (fractured lithosphere, smaller fault length coupled with 100 km locked zone) vis-a-vis subduction zones (larger fault lengths and 200 km locked zone as given by USGS, Luttrell et al. 2011; IRIS) do not favour mega earthquakes (Srivastava, Bansal et al. 2013; Gupta & Gahalaut 2015) in Himalaya.

It is interesting to note that Jouanne et al (2004) based on GPS data surmised that the width of the locked zone between the frontal thrust and the creeping zone is of the same order but rather greater in western Nepal than in central Nepal. It was also reported that the convergence between India and south Tibet proceeds at a rate of 17.8 ± 0.5 mm/yr in central and eastern Nepal and 20.5 ± 1 mm/yr in western Nepal (Ader et al. 2012). Cannon and Murphy (2014) also bring out difference between central and western Nepal on the basis of geology, microseismicity and pattern of rock uplift providing evidence of duplexing beneath both the Lesser and High Himalayas in western Nepal. All these results bring out that the magnitude and the recurrence of earthquakes would be different in east and west Nepal justifying them to be placed in seismic gaps of type 1 and type 2 (Srivastava, Verma et al. 2013). The magnitude and place of occurrence of 2015 Nepal earthquake (Mw: 7.8) in the central Nepal—Bihar seismic gap of type 1 characterized by shorter recurrence interval supports this inference.

A question arises that how much of the unruptured portion of the Indian plate boundary remains in Nepal keeping in view 1505 and 2015 earthquakes. The fracture length of about 400 km shown by Cannon and Murphy (2014) is not commensurate with the magnitude of 1505 earthquake as discussed earlier. If the fracture length of 1505 earthquake is taken as 200 km corresponding to its magnitude of 8—8.2, the rupture zone could be extending from Long 80.5° to 82.5°E. Thus, only about 200 km in the western Nepal region remains unruptured (Long 82.5° to 84.5°E), where history of large/great earthquake is not available. By considering GPS results of 100 km locked zone in western Nepal (Ader et al. 2012), the maximum magnitude of an impending earthquake may be about 8 in this region. However, about 600 years have elapsed since 1505 earthquake in Dharachulla region. Keeping in view the recurrence interval of 500 to 600 years in Himalayas (Molnar & Pandey 1989, Bollinger et al. 2014), this region is also susceptible for a major earthquake.

However, the present data set do not provide any clue whether another major earthquake may occur earlier in the unfractured region in Nepal (Long. 82.5°E to 84.5°E) as compared to the Dharachulla region which is seismically more active.

5. Conclusions

The above study brings out the following conclusions.

(1) Seismic quiescence was observed prior to the main earthquake of April 2015 since 2007. Decadal variation in the $b$-value showed a decrease during the period 2005 to April 2015, prior to main shock which was also lower as compared to $b'$ value during the period of 1971 to April 2015.

(2) The stress drop of this earthquake from S-wave spectra from near field Indian stations is comparable to that obtained from P-waves and teleseismic stations reported earlier (Mitra et al. 2015) and much less as compared to the intra plate region.

(3) This study suggests that the unbroken plate boundary extending from 82.5°E and 84.5°E between 1505 and 2015 earthquakes in Nepal may generate an earthquake of magnitude about 8 based on unfractured zone of about 200 km and locked zone of about 100 km as inferred earlier from GPS data. However, the present data-sets do not provide any clue whether such earthquake may occur earlier than the adjacent Dharachulla region which is seismically more active.
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Disclosure statement

No potential conflict of interest was reported by the authors.

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