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Spatial and Temporal Distribution of Seismicity Parameters in Northeast India Constrained to Indo-Myanmar Region

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Abstract

In this study, a homogenous and complete earthquake catalogue is compiled from the data recorded by field stations of National Seismological Network (NSN) of India Meteorological Department (IMD) / National Center for Seismology (NCS) for the period 2011 to 2016. This homogenized catalogue (with local magnitude, M_L) is employed to estimate the spatial distributions of seismicity parameters such as *b-value* and D_C by using overlapping windows of 1^0x1^0 along the Indo-Myanmar arc. Then, correlation of spatial mappings and their values are presented along with the seismotectonic set-up to assess the seismic hazard scenario in every grid of the study region. From the frequency-magnitude distribution plot, the study region exhibits magnitude of completeness, m_c, *a*, and *b* values of 3.1, 4.6, and 0.65(±0.03), respectively, indicating continuous stress accumulations underneath the fractured rock masses. Though m_c varies from 2.0 to 3.5 across the study region, low values (i.e., 2.0-2.7) that are found to be scattered in the Naga and Disang Thrusts and Sagaing fault of the northern part of the study region suggest the spreading out of seismic network along with low recurrence intervals of earthquakes. The study region is also preoccupied by high (2.7-3.5) *a*-value in between the Main Central Thrust and Naga Thrust, Mizo folds and Indo-Myanmar ranges in the western part of the study region probably due to high seismic activity rates in these particular regions. On the contrary, the spatial distribution of low *b*-values (i.e.,0.52–0.95) obtained from the stress accumulation in the asperity zones during ongoing subduction of Indian plate beneath Burmese plate is seen in the northern and southern parts of Sagaing fault. Moreover, the region comprising the Main Central Thrust and Main Boundary Thrust in the north-western part, Mizo Folds and Chin Hills in the south-western part and Indo-Myanmar Ranges and Volcanic Line in the central part of the study region exhibit small D_C values due to concentration of hypocenters into a point or distributed all along the fault lines in these areas. We also observed almost negative correlation between *b*-value and D_C with high b-value and low D_C in the adjoining areas of Main Central Thrust and Main Boundary Thrust in north-western part, Mizo Folds and Chin Hills in south-western part and Naga Thrust and Disang Thrust in north-eastern part of study region, suggesting frequent occurrences of low magnitude earthquakes from the fault zones which might be due to creeping. From this present analysis, the seismic zones can thus be identified from these spatial mappings for assessment of seismic hazard along this Indo-Myanmar arc.

Key Words: Seismicity, North-east region, Indo-Myanmar region

1. Introduction

From seismicity point of view, the northeast India and the northern Burma are one of the most active regions of Asia. The area has experienced two devastating earthquakes in Indian history, the Shillong earthquake of 1897, (magnitude 8.7) and the Assam earthquake of 1950 (magnitude 8.5). In addition, historical earthquakes exceeding intensity IX (RF scale) have taken place at Dhubri (1930), near Darjeeling (1899), Chittagong (1869) and Srimangal (1918). The Arakan-Yoma Folded Belt of northern Burma has experienced earthquakes of intensity IX to X at Amarapoora (1839), Kachin (1931) and Sagaing (1946). On account of considerable importance of the region from seismicity point of view, several organizations including NGRI Hyderabad, RRL (now NEIST) Jorhat and India Meteorological Department have established seismological observatories in the region. In addition, University of Roorkee and GSI have also established MEQ stations to monitor the seismicity for short periods of time. A brief analysis of seismicity of the region is presented here.

The geology and tectonics of the region have been discussed by Brunschweiler (1966) and Evans (1964). The area comprises the following major tectonic units (Fig. 1):

(i) Eastern Himalaya
(ii) Mishmi Block, including Mishmi and Lohit Thrusts
(iii) Assam Valley
(iv) Shillong Plateau and Mikir Hills
(v) Arakan-Yoma Folded Belt
(vi) Bengal Basin

The geology and tectonics of different regions is briefly discussed below. A tectonic map of the region after Evans (1964) is shown in Fig. 1. The eastern Himalayas lie between Latitudes 27° - 29° N and Longitudes 88° - 96° E and are composed of Paleozoic, Mesozoic and Tertiary formations. The tectonics of the region is dominated by extensive thrust sheet including the Main Boundary Fault (MBF) and the Crystalline Thrust (CRT), both dipping towards north. The Himalaya folded belt, which has a NESW trend takes a sharp turn near 95° E and assumes a strike of NW - SE, in the region known as “Assam Syntaxis”. Two prominent thrusts in this region are the Mishmi Thrust and the Lohit Thrust.

2. Seismicity in the Indo-Myanmar Region

The strike of Tertiary Folded Belt changes abruptly near 27° N, 96.5° E, where it continues in the form of Naga Hills, which consists of Tertiary succession ranging in age from Eocene to Paleocene. The Assam– Brahmaputra Valley lies between the eastern Himalaya and the Naga Hills. The Valley has been formed by sediments, which have been brought by the river Brahmaputra and its tributaries. The Shillong Plateau and Mikir Hills consist of Archaean gneisses complex with Proterozoic intracratonic Shillong series. The Mikir Hills lie to the NE of Shillong Plateau and are separated from it by Kopili Fault/Lineament. At the southern edge of Shillong Plateau lies the Dauki Fault, which separates it from the Bengal Basin. To the east of the Bengal Basin lies the Arakan-Yoma Folded Belt of Burma, between 22° - 27° N, 92° - 94° E. The Folded Belt consists of a series of thrusts and thrust sheets. A Flysch trough (Paleogene) lies over the western side, while the Central Burma Molasse Basin lies to the east of the folded belt, approximately between 94° - 96° E. The Arakan-Yoma Folded Belt extends up to the Naga Hills in the north. The northeast India region produced two great earthquakes (~ M 8.7), one in 1897 in the Shillong Plateau and the other in 1950 in the Assam-Tibet border at the Assam syntaxis zone (Fig. 1).

About 19 large earthquakes 7.0 ≥ M_L <8.0 occurred in the region during the last 100+ years since the 1897 Great Shillong Earthquake. In the Shillong Plateau area the earthquakes are mostly confined within a depth of 35 km (Kayal & De, 1991). To the east of the Shillong Plateau lies the Mikir massif, which is separated from the Shillong massif by the long northwest-southeast Kopili fault (Fig. 1). Intense seismic activity is recorded along this fault down to 45 km depth in Indo-Burma (Kayal et. al., 2006).

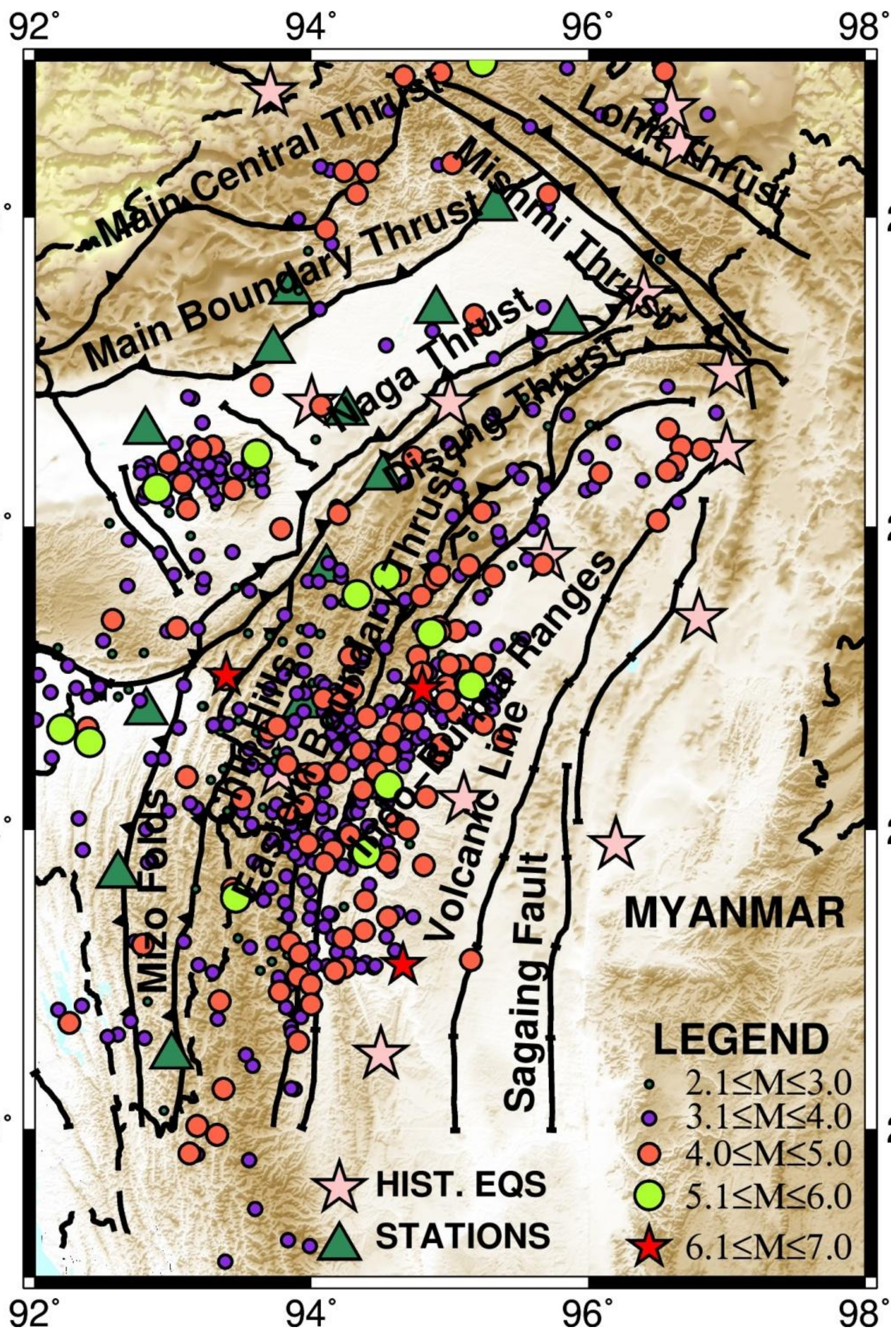

Figure1: Seismotectonic setting & plot of Indo-Myanmar arc during the period 2011-2016. Major faults are indicated by black lines. Different symbols and colours are used to represent the ranges of magnitudes of

earthquakes. Green triangle and light pink star indicates seismic stations and occurred historical earthquakes greater than $M_L \geq 7$, respectively, in the study region.

In this study, we have analyzed about 901 de-clustered earthquakes $M_L \geq 2.1$, recorded during 2011-2016 in the northeast India region. These earthquakes are recorded locally by field stations of National Seismological Network maintained by India Meteorological Department / National Center for Seismology, New Delhi during routine monitoring and reporting the seismic activities in and around the Indian sub-continent. Here, Coordinated Universal Time (UTC) is maintained for all these digital seismic stations along with GPS configurations. These digital waveform data are finally transmitted from field stations to IMD, New Delhi through semi-automatic transmission facility. Higher precisions of P- and S-waves arrival times of upto order ±0.01 s and ±0.05 s respectively are considered in these stations for preliminary estimating hypocentral parameters using IASP91 velocity model. As such, the average and maximum root-means-square (RMS) error of the 901 events are found to be below 0.50 s and 1.0 s, respectively. All these processing and preparation of catalogue have been accomplished using SEISNET and SEISAN analysis software (Havskov and Ottemoller, 2000), at IMD HQ, New Delhi. The earthquake catalogue for the particular study region can be easily downloaded from the seismological bulletins (www.imd.gov.in/pages/earthquake-prelim.php) published by the National Center for Seismology, New Delhi for the Indian sub-continent. The catalogue is, then, cleaned by using spatial and temporal windowing method of Knopoff (2000) to remove the foreshocks and aftershocks of the main events. The spatial distribution of b-value and D_C are investigated along with the seismotectonic setting of the study region to investigate the differential stress accumulations within the fractured rock mass and the clustering pattern of earthquakes respectively. The spatial correlation between b-value and D_C can provide more insight into the characteristics of earthquake occurrences and thus can primarily act as an indicator for possible prediction of major earthquakes in the study region.

3. Methodology: Seismicity Quantification:

Distribution of earthquakes with respect to magnitudes exhibits scale invariability and appears to be self-similar thereby obeying a power law or fractal scaling. This implies the absence of a characteristic event size (theoretical limits on the maximum earthquake size). An empirical formula, i.e.,

$$\log N(M) = a - bM \qquad (1)$$

defines the distribution of earthquakes with respect to the magnitude. The time interval equation (1), provides the number of earthquakes as “N” with magnitude “M” where “a” and “b” are positive real constants and “a” describes the seismic activity (log no. of events with M=0). It depends on several factors such as size of the area, observational period length, largest seismic magnitude and the stress level of the area (Allen, 1986). It is determined by the event rate for certain region depends upon the volume and time window considered. The b-value is estimated normally as 1.0 to 1.5 depending on the tectonic settings of the seismically active region. Relation (1) is usually referred as the Gutenberg-Richter (G-R) magnitude frequency relationship (MFR). Many recent studies have also shown that the b-value is scale invariant that is related to the spacing or clustering properties of epicenters or distribution of fault segments. Oncel et al., (1996) reported a lower b-value associated with a higher fractal dimension and hence a greater degree of clustering of epicenters is observed. A lower b-value infers that the region is

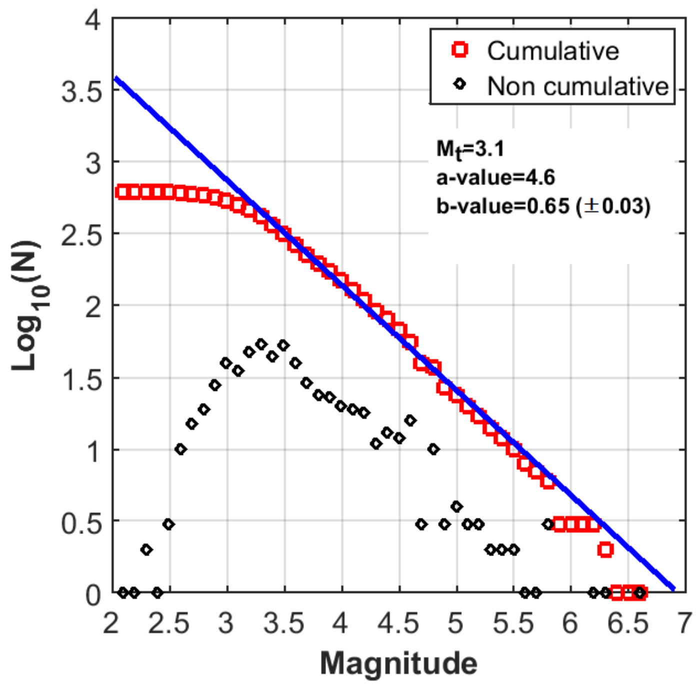

Figure 2: Frequency–magnitude distribution plot shows departure from the linearity on the lower magnitude

under higher applied shear stress and a higher b-value indicates that the area has already gone through the tectonic events.

The b-values are estimated using two methods: (1) Least-square fit method and (2) Maximum likelihood method. In the least square fit method, the log values of the cumulative number of earthquakes (N) are plotted with magnitude sequence. The b-value is estimated from the slope of the least square fit line, the log-linear relation between N and M.

In the maximum likelihood method, Aki (1965), based on theoretical considerations, gave an estimate of b-value as:

$$\mathbf{b = \log_{10}(e) / (M - M_0)} \quad \textbf{(2)}$$

where M is the average magnitude of events exceeding the threshold magnitude M_0 and $\log_{10}e=0.4343$. An estimate of error, standard deviation δb of the b-value was given by Aki (1965), then modified formulation was given by Shi and Bolt (1982) as follows:

$$\delta b = 2.3b^2 \sqrt{\frac{\sum (M_i - \{M\})^2}{n(n-1)}} \quad \textbf{(3)}$$

where M_i is the magnitude of the i^{th} event, M is the average magnitude for a set of earthquakes and n is the number of earthquakes in the set.

In this study we have estimated b-value by the maximum likelihood method because it is reported to be more appropriate way to compute a better estimation of b-value since it is inversely proportional to the mean magnitude. Frequency-magnitude relation should be examined carefully as the self similarity may break with the following three stages: smaller events (M_L<3.0), medium events ($3.0 \leq M_L \leq M_{L,saturate}$) and larger events ($M_L \geq M_{L,saturate}$). The smaller events may give lower b-value because of shortage of smaller events recorded in the catalogues, while bigger events may give higher b-value because of the saturation of the magnitude (Scholz, 1990), We have however estimated b-values for the medium events 3.0≤ M ≤6.4 and we believe that self similarity is maintained in this magnitude range (Fig. 2).

Though major surface traces of the faults are generally well mapped, significant fractions of regional seismicity occur on secondary and sometimes on the hidden structures (Jones et al., 1990). Fractal dimension provides a measure of the degree of fractal clustering of points in the space. Tosi (1998) illustrated that possible values of fractal dimension (D) are bound to range between 0 and 2.0 which is dependent on the dimension of the embedding space. Interpretation of such limit values is that a set with D ~ 0 has all events clustered into one point. On the other end of the scale, D ~ 2 indicates that the events are randomly or homogenously distributed over a two-dimensional embedding space. Idziak and Teper (1996) suggested that the D ~ 2 is an evidence of multiple external forces which acts on the rock mass. Multiple tectonic stresses, from the Himalayan arc and the Burmese arc in this region are reported by several authors (e.g. Chen and Molnar, 1990; Kayal, 1996 and Kumar and Rao, 1995). Hence the evaluation of fractal dimension is significant in case of the studied area.

Most commonly used methods for calculation of fractal dimension are (1) Box counting method which measures the capacity dimension D_0 and (2) Correlation dimension D_2 (Grassberger and Procaccia, 1983). In Box counting method an active fault system of a given region is overlaid with a grid of square boxes. Grids of different size boxes are used. This method does not consider the number of seismic events. It takes into account only the fact that the boxes are occupied or not. The method is not reliable especially when the number of data points is limited (Hirata, 1989). In case of seismology the correlation dimension is widely applied, especially to the spatial distribution of earthquakes. The correlation integral technique is preferred to the box-counting method that gives a fractal correlation dimension (D_2) because of its greater reliability and sensitivity to small changes in clustering properties (Kagan and Knopoff, 1980; Hirata, 1989).

The fractal dimension of the spatial distribution of seismicity is calculated from the correlation integral given by Grassberger and Procaccia (1983) as

$$D_{wr} = \lim_{r \to 0} \frac{\log(C_r)}{\log(r)} \tag{4}$$

where Cr is the correlation function that measures the spacing or clustering of a set of points and is given as

$$C(r) = \frac{1}{N(N-1)} N_{(R<r)} \tag{5}$$

where $N_{(R<r)}$ is the number of pairs (X_i ; X_j) with a smaller separation "r". Kagan and Knopoff, 1980 indicate that the correlation integral is related to the standard correlation function as given by:

$$C(r) \sim r^{D2} \tag{6}$$

where D_2 is the fractal dimension or correlation dimension (Grassberger and Procaccia, 1983); now onwards, we call it D_C. The distance "r" between two events ($\theta_1 : \phi_1$) and ($\theta_2 ; \phi_2$) is calculated by using a spherical triangle as given by Hirata (1989):

$$r = \cos^{-1}(\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2)) \tag{7}$$

where θ_1 and θ_2 are the latitudes and ϕ_1 and ϕ_2 are the longitudes of event 1 and event 2, respectively.

Kagan (2007) reviewed various methods for determining fractal dimension of earthquake epicenters and hypocenters, paying special attention to the problem of error, biases and systematic effects. They have shown that any value of correlation dimension can be obtained if the errors and inhomogeneities in observational data as well as deficiencies in data processing are not properly considered. In the practical calculations, the fractal dimension analysis based on a power law and is turned into linear law after logarithmic transformation. Therefore, sufficient data points are the key for a reliable estimate of fractal dimension based on ensuing linear regression (Xu and Burton, 1999). Smith (1988) suggested the minimum number of points or events required for a reliable calculation of a correlation dimension as:

$$N_{\min} = \cos^{-1}(\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2))$$

According to Smith (1988) the minimum number of points required for a reliable calculation of correlation dimension in two-dimensional case (in the present study epicenters of earthquakes) is 42 and the grid having the events less than 42 is not considered in this study. The grid having events greater than or equal to 42 are used as a single data set for analysis. Considering the center of the grid as the reference point shifting of window are made.

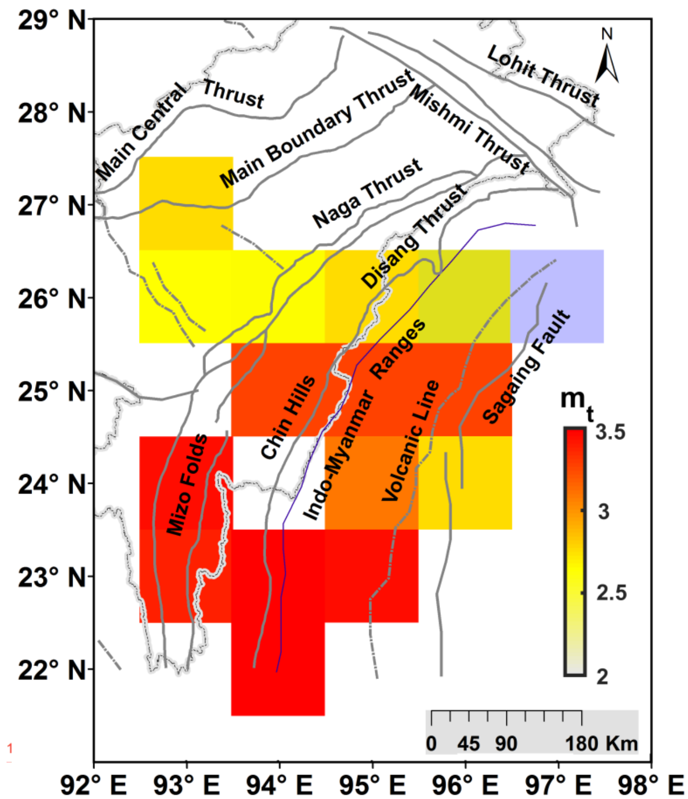

Figure 3: The spatial distribution of magnitude of completeness, m_c, prepared with the earthquakes from the data catalogue covering a recording period from 2011 to 2016.

In order to map the spatial variations of seismicity parameters (eg, m_c, a, b-values and D_C) a moving square window of 1^0x1^0 with a slide of 0.5^0 every time is employed to cover the entire study region. The calculated value is assigned to the center of the window for comprehensive picture of the spatial maps of seismicity parameters (Fig. 3, 4, 5 & 6). Only those windows having at least 50 events have been regarded as criteria for meaningful statistical analysis within the m_c can be employed to estimate a-value, b-value and D_C (Utsu 1965; Thingbaijam et al. 2008; 2009; Chingtham et al, 2014; 2015). Due to this constrained on the number of events, the spatial window technique introduce spatial gaps in the estimation process. Positive and negative correlation between b-value and D_C can provide more information on the seismotectonic process of the region. Both the correlations are reported on this highly active fault network (Thingbaijam et al. 2008).

4. Results and Discussion

In this study region, the seismicity of the region is primarily associated with the release of accumulated strains developed during the continuous collision between the Indian and Eurasian plates. As such the area of highest seismicity is concentrated in and around the Arakan-Yoma ranges and Molasse Basin of Burma, where active plate subduction processes are taking place (Fig 1). From the case study of strain energy release in north-east India, Gautam (2007) placed this area in the zone of maximum energy release. Their results (Tandon, 1954, Chaudhary and Srivastava 1976, Geller and Kanamori 1977, Goswami and Sarmah 1982, Verma and Kumar 1987) are in accordance with the epicentral plot prepared from the catalogue covering a recording period from 2011 to 2016.

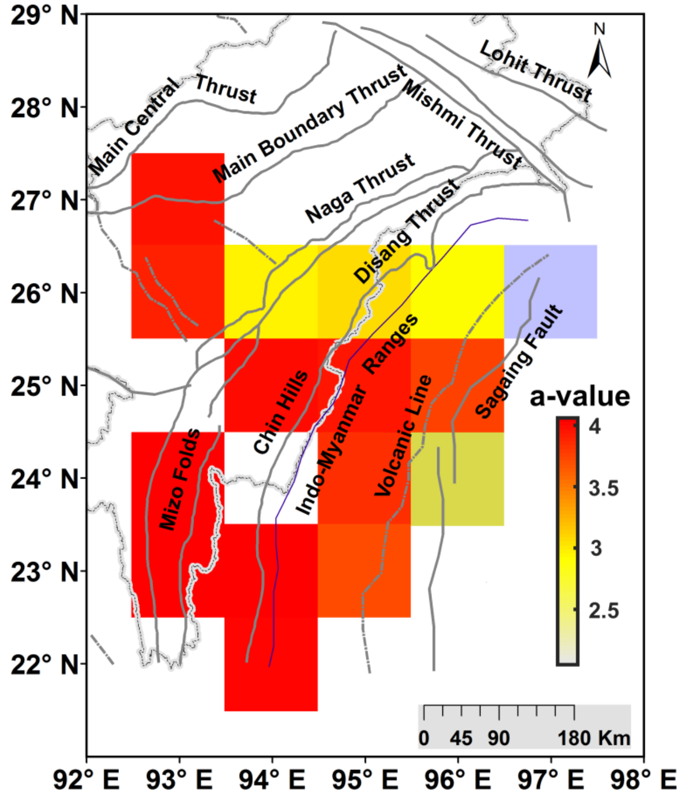

Figure 4: The spatial distribution of a-value prepared with the earthquakes from the catalogue covering a recording period from 2011 to 2016.

The frequency magnitude distribution (FMD) is generally found to deviate from linearity of the G-R relation (Eq. 1) due to geographical conditions, instrumental insensitivity, and insufficient/irregular coverage of events in time, space, and magnitude. It is observed that the magnitude of completeness, m_c, is found to improve with time depending on enhanced technology, wider seismograph coverage, and advanced methodology. In short, the lower minimum threshold can be easily correlated with the progressive expansion of seismic network in the study region. For such kind of spatial mapping of seismicity parameters, the starting time of good quality records is essential for quality data. From the frequency distribution plot depicted in Fig. 2, the study region exhibits m_c, a, and b values of 3.1, 4.6, and 0.65(±0.03), respectively, exhibiting high stress accumulations along the fractured faults.

The magnitude of completeness, m_c, varies from 2.0 to 3.5 across the study region as shown in Fig. 3. Low m_c values of the range 2.0–2.7 are found to be scattered around the Naga and Disang Thrusts and Sagaing fault of the northern part of the study region. Whereas the surrounding areas of Mizo folds, Chin Hills and Indo-Myanmar Ranges lying in the southern part of the study region exhibit high m_c values within the range 2.7-3.5. Moreover, moderate values can be associated with the central part of the study region exposed mainly in between Indo-Myanmar Ranges and Volcanic line. Advancement of seismic network along with low recurrence intervals of earthquakes are the major factors responsible for lower m_c values in the study region.

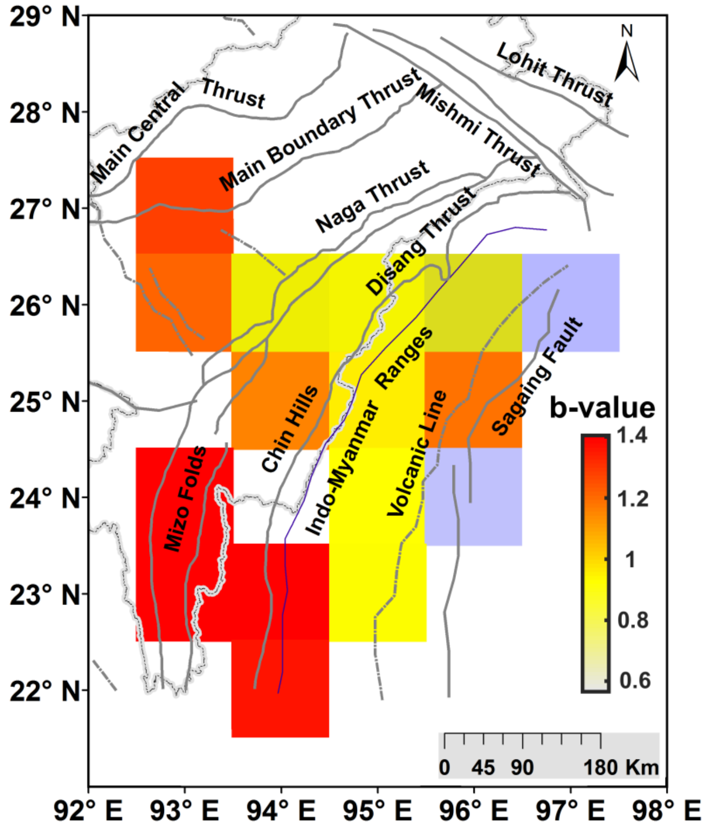

Figure 5: The spatial distribution of b-value prepared with the earthquakes from the catalogue covering a recording period from 2011 to 2016.

Spatial distribution of a-value as depicted in Fig. 4 ranges from 2.05 to 4.06. Notwithstanding, the region falling between Main Central Thrust and Naga Thrust, Mizo folds and Indo-Myanmar ranges in the western part of the study region have high a-value in the range 3.50–4.01. While, low to moderate a-value are found to be scattered in the eastern flank of Sagaing fault and the northern part of the study region. By and large, the study region exhibit positive correlation between the spatial distributions of m_t and a-value (Fig. 3 & 4).

Fig. 5 depicts that the spatial distribution of b-value varies from 0.52 to 1.56 in the studied region. Low b-value of the range 0.52–0.95 is seen in the northern and southern part of Sagaing fault. Similar low b value is also observed in between Naga and Disang thrusts and along the Indo-Myanmar ranges of eastern boundary thrust. Low b-values in these surrounding areas can be easily correlated with the fractured faults/rock mass due to ongoing subduction of Indian plate beneath Burmese plate. However, the south western part near the adjacent zones of Mizo Folds and Chin Hills are preoccupied by high b-value of 1.35–1.56. This high b-value is mainly due to existing low magnitude earthquake along the faults thereby causing high heterogeneity in the study region. Besides this, moderate b-value is found to be scattered in the remaining parts of the study region (Fig. 5). The spatial distribution of b-value obtained by Thingbaijam et al. (2008) is found to be consistent with our findings.

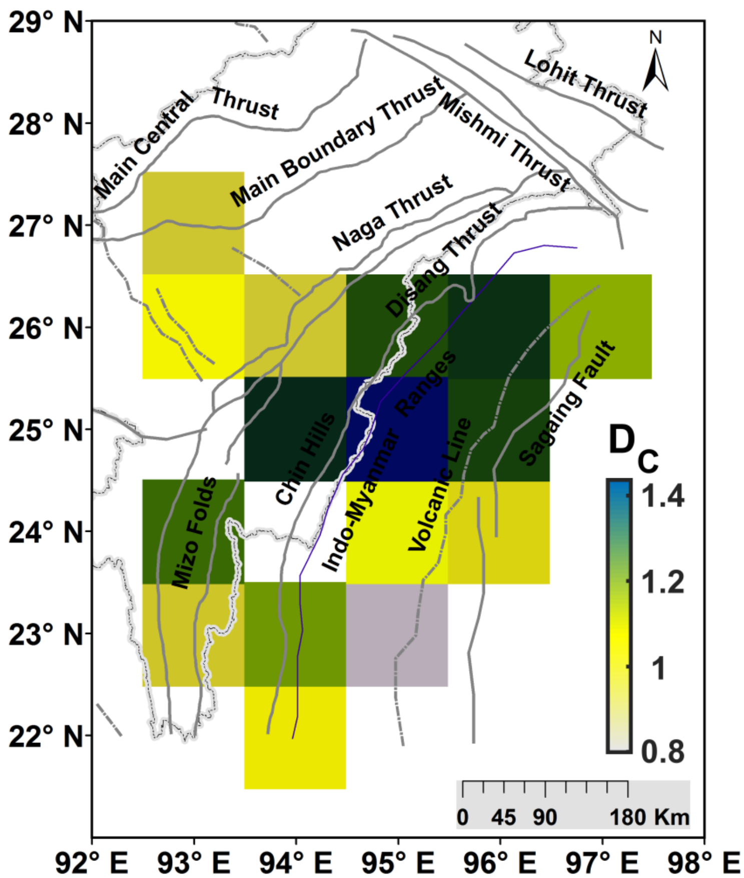

Figure 6: The spatial distribution of D_C prepared with the earthquakes from the catalogue covering a recording period from 2011 to 2016

The spatial distribution of D_C as depicted in Fig. 6 varies from 0.80 to 1.44. The region in between Main Central Thrust and Main Boundary Thrust in the north-western part, Mizo Folds and Chin Hills in the south-western part and Indo-Myanmar Ranges and Volcanic Line in the central part of the study region show small D_C values. This implies that the epicenters of earthquakes are concentrated into a point or distributed all along the fault lines in these areas (Khattri, 1995, Singh et al., 2012). Whereas, moderate to high values are predominant in the north-eastern part of the study region, adjacent to the surrounding areas of Naga and Disang Thrusts, Indo-Myanmar Ranges, Volcanic Line and Sagaing fault. This suggests that the epicenters of the earthquakes are scattered all through the fractured surface and the crustal volume (Bayrak et al. 2013, Chingtham et al. 2016).

The correlation between b-value and D_C has been examined for inferring the complex seismogenic process of the underlying dynamics of the region. It is observed from both Fig. 5 & 6 that the correlation shows almost negative in the studied region. The adjoining areas of Main Central Thrust and Main Boundary Thrust in north-western part, Mizo Folds and Chin Hills in south-western part and Naga Thrust and Disang Thrust in north-eastern part of study region exhibit negative correlation between the spatial distribution of b-value and D_C with high b-value and low D_C. These regions, therefore, indicate the presence of frequently occurences of low magnitude earthquakes from the fault zones due to creeping (Oncel and Wyss 2000). Whereas, low b-value with high D_C is observed in the central part of the study region near the surrounding areas of Chin Hills , Indo-Myanmar ranges and Disang Thrust. This low b-value with high D_C implies the formation of asperities in the underlying faults of the study region.

Moreover, the positive correlation between b-value and D_C is observed along the Sagaing fault in the central part of the study region with both low b-value and D_C.

5. Conclusion

As also discussed earlier by several researchers, this paper sheds light on the importance of systematic generation and archival of high resolution seismological data sets towards carrying out such kind of seismicity quantifications for better understanding of earthquake generation processes. The paper also highlights various methodologies for estimating the seismicity parameters and explains the existing crustal heterogeneity by correlating the estimated parameters with the seismotectonic framework of the study region. The rapid increasing of seismological instruments across the length and breadth of study region greatly lowers the minimum magnitude of detection threshold over the decades, even though the distribution is not uniform in space and time. Though the region can be divided into six tectonic blocks, most of the stress accumulation due to subducting Indian plate process is taking place in the Arakan Yoma belt and this can be evidenced from the calculated low b-value from the G-R relation. High seismic activity and its resulting heterogeneity along the fractured faults are also quite prevalent in the study region.

The spatial distribution of seismicity parameters such as m_c, a-value, b-value and fractal dimension, D_C value is investigated properly for the study region. Low values observed from the spatial distribution of m_c indicate progressive expansion of seismic network in the north-east India while highly active seismic activity with predominantly low recurrence intervals of earthquakes is observed from high values of spatial distribution of a-value. Moreover, the spatial distribution of b-value exhibits highly stress accumulation along the Indo-Myanmar ranges of eastern boundary thrust due to existing plate tectonics. Evidences of heterogeneous zones around the surrounding areas of Mizo Folds, Chin Hills and Indo-Myanmar ranges of south-western part of study region are observed from high values of spatial distribution of b-value. However, high values obtained from the spatial distribution of D_C reveal the scattering of higher magnitude earthquakes from the fractured rock mass. The formation of asperity zones beneath the tectonic faults is also noticeable from the negative correlation between b-value and D_C with low b-vale and high D_C that spread throughout the study region. No doubt, pockets of high b-value and low D_C are observed in the study area, indicating creeping process of the underlying faults. Such kind of quantifying seismicity parameters and identifying the correlations between seismicity parameters will undeniably assist in identifying highly seismic zones. This, in turn, will help in preparing probabilistic seismic hazard map for the inhabitants in and around the north-east India.

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