IJES *Iranian Journal of Earth Sciences*
Vol. 12, No. 4, 2020, 225-239.

Seismic study and spatial observations of a & b – values for the different earthquake hazard zones of India

Narayanakumar Somasundaram*[1], Surendra Nadh Somala[1], Svetlana Rodina[2], Evgenii Rogozhin[2]

1. Department of Civil Engineering, Indian Institute of Technology, Hyderabad, India
2. Schmidt Institute of Physics of the Earth, Russian Academy of Science, Moscow, Russia

Received 21 October 2019; accepted 3 June 2020

Abstract

This paper study the recent seismicity in Earthquake hazard zones in India. A large historical earthquake event catalog to cover the period of 1900-2018, the parameters date, time, latitude, longitude, depth and magnitude has been used to calculating frequency-magnitude distribution (b-value) of seismic hazard zones in India. To convert different magnitude scales into a single moment magnitude scale, the general orthogonal regression relation is used. Gamma distribution used for variable corrections also de-clustering method has used for removal of any non-Poisson distribution. The Indian seismic hazard zones are divided into five major seismic sources zones. The seismicity is characterized by Gutenberg-Richter relation. The parameter 'b' of FMD and relationship have been determined for these five seismic zones having different vulnerability environment. The 'b' values ranges between 0.43 to 1.16. The difference between the b parameters and seismic hazard level from seismic zones II to V considered for the study of high seismo-tectonic complexity and crustal heterogeneity, the parameter 'a' value changes accordingly the seismicity of the regions. The lowest b-values found in seismic zone II. The highest FMD b-value has been found in the seismic zone IV. Such high seismicity b-values may be associated with high heterogeneity. In this high b-value predict the low strength in the crust as well as seismic instabilities of that zone. These observations recommend not suggesting the location of important projects like atomic power stations, hydroelectric power stations, neutrino observatory projects, satellite town projects.

Keywords: *Seism-genic zones, b-value, Frequency-magnitude distribution, Seismicity*

1. Introduction

Natural disasters are inevitable, researchers attempt numerous times to understand and try to predict this natural phenomenon, but it has yielded partial successes. The primary goal of this study, mainly focusing the relation and ratio of the parameters *a* and *b* from the Gutenberg-Richter relation from the different seismic zone of India, also comparing the relation between the tectonic structures and value differences. Several researchers calculated different parameters of seismicity from various seismic active zones of India. Gutenberg-Richter (G-R) relates the empirical relationship between frequency and magnitude of earthquake occurrences. Also, Gutenberg-Richter (1944) estimated the parameters *a* and *b*, frequently these parameters are used to statistical calculation of seismicity. From region to region and seismicity rate, the parameter *a* varies greatly (Olsson 1999). Tectonic characteristics of a region and focal material are deciding the parameter *b* (Wang 1988). Large magnitude earthquakes because of the regions with low apparent stresses resulting in low *b-value*. For different regions, high module values are presented, also cross variations of the parameters (a & b) values (Yusuf et al. 2002). Parameter *b* is related to properties of focal materials (Schorlemmer et al. 2003). High *b*-values characterized populations of body-wave magnitudes (Emile AO et al. 1994). Changes in *b* values show temporal variation in a broad range also drops in *b* at the of two large events 2002 & 2004 in Andaman, this *b* value deflection observation helps in medium-term (months, years) earthquake forecasting (Paiboon et al. 2005). Different regions with various time intervals some empirical scaling functions-based *a* and *b* values proposed (Yilmazturk et al. 1999). High and low seismic zones of Turkey's detailed images provided by a/b value distributions (Yilmazturk et al. 1999; Bayrak et al. 2000). Before high intensity earthquakes spatial and temporal *b* value variations has been observed (Wyss et al. 1988). Furthermore, *b*-value slowly decreasing with increases in depth (Mori et al. 1997). In volcano and magma findings, anomaly high *b*-value indicate the location of the magma sources, also *b*-value mapping helps to proposing the locations of magma chambers (Wiemer et al. 1996). Recently, (Zhou et al., 2018) discussed about crustal structure's weak layers using *b*-value. At low magnitude range, the *b*-value reduced two-third, increasing the *b* value about *b = 2* before the onset of fault width saturation. In this paper, we have discussed *b*-value changes of various regions of India. Particularly we have chosen four seismic hazard zones in India (Fig 1) and three historical major seismic zones and analysis the significances of results. Some of the researchers found '*b'* parameter changes as shown in Table.1.

----

*Corresponding author.
E-mail address (es): narayanakumar@iith.ac.in

Table 1. b-values parameter ranges

Authors	b- parameter changes for different tectonic areas
Gutenberg and Richter (1954)	0.45 to 1.5
Miyamura (1962)	0.4 to 1.8
Tsapanos (1990)	0.75 to 0.85 (for 11 different seismic region)

2. Indian Seismic hazard zones

India has been classified into different seismic hazard zones. These zones are classified according to the intensity of the damages and frequency observed due to earthquake magnitude occurrences. These seismic hazard zonation map, (Fig 1) developed on subjective observations of earthquake magnitude from recent earthquake catalog information, geo-physical, geology and tectonic structures of India. In view of earthquake catalog, magnitude intensity, frequently number of times occurred in such a way that, Seismologist has classified four major seismic zones of India, totally 59% of land area in India as different earthquake prone zones –Zone V has 11% in very high risk zone, Zone IV has 18% in high risk zone and Zone III has 30% moderate risk zone, rest parts are low risk zone II. The major and capital cities of Guwahati, Srinagar, whole northeast states, some part of Gujarat are located in seismic zone V, while national capital Delhi is in zone IV and mega cities of Mumbai, Kolkata and Chennai in zone III, 38 cities with population half million and above each and a combined population of million are located in these three regions. During the last century, few earthquakes measuring Magnitude 8 or more had struck different Indian regions; 1819 Gujarat (8.2M_W), 1833 Bihar-Kathmandu (8.0M_S), 1897Shillong (8.0M_W), 1905Kangra earthquake (7.8M_S), 1934 Bihar-Nepal earthquake (8.4M_S), 1941 Andaman Island earthquake (8.1M_W), 1950 Assam earthquake (8.6M_W) had caused enormous damage to infrastructure and public and private property. In the recent years, earthquake damages had been experienced in different regions of India. Such as1988 Assam (7.2M_W), 1988 Bihar-Nepal (6.5M_W), 1991 Uttarkashi (6.6M_W), 1993 Latur (6.4Mw), 1997 Jabalpur (6.0M_W), 1999 Chamoli (6.8M_W) and 2001 Bhuj (6.9M_W), 2004 Indian ocean earthquake (9.1-9.3 M_W), 2005 Kashmir (7.6M_W) and 2015 Gorkha-Nepal (7.8M_W).

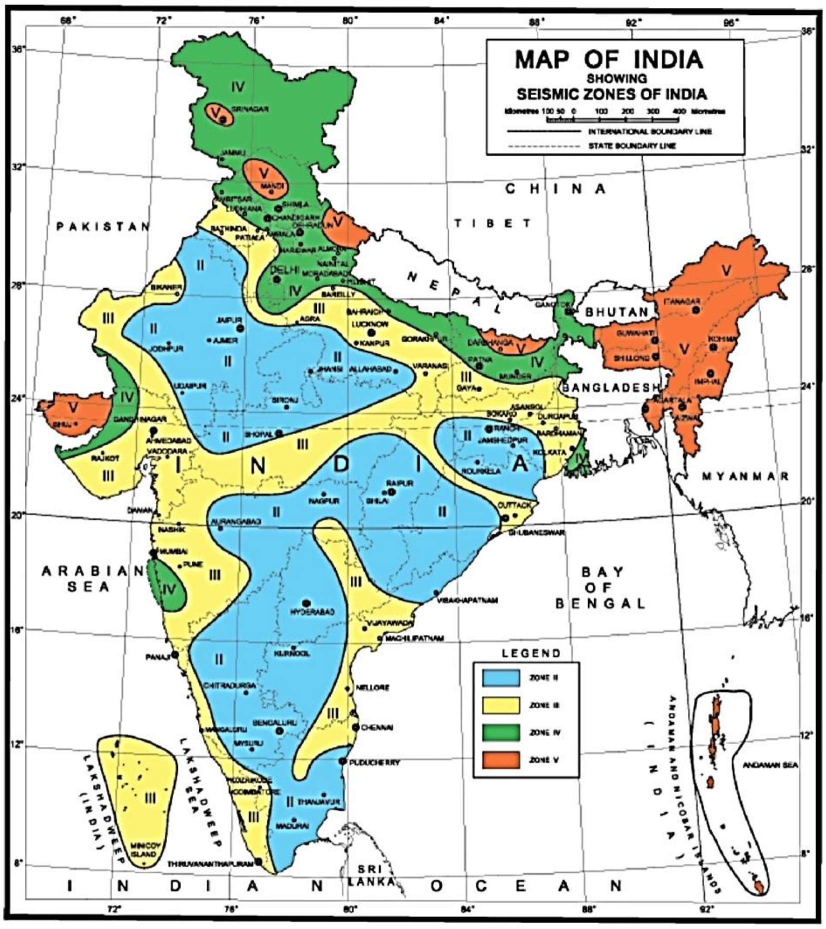


Fig 1. Seismic Zones of India, IS 1893 (Part 1): 2016.

2.1. The study of the four major seismic hazard zones of India.

2.1.1. Seismic zone – V: Most seismic active regions and very Huge damage risk zone, such as Rann & kutch in Gujarat, portion of Jammu & Kashmir, Himachal Pradesh, Uttaranchal, entire Andaman & Nichobar islands and Northeast states of India, some part of Bihar. In 1905 the largest Kangra earthquake magnitude 8.6 epicenter located in this zone V. around 20,000 people were killed.

2.1.2. Seismic zone – IV: Lesser risk by earthquakes as compared to zone V and high-risk zone. It is including major positions of Jammu &Kashmir, Himachal Pradesh, National Capital Territory (NCT) of Delhi, Sikkim, North part of Uttar Pradesh, Bihar and remaining portions of West Bengal, Gujarat, Maharashtra near the west coast and Rajasthan.

2.1.3. Seismic zone – III: Lesser risk by earthquakes, moderate damage risk zone. Comprises Tamilnadu, Kerala, Karnataka, Andhra Pradesh, Odisha, Goa, Madhya Pradesh, Jharkhand, Lakshadweep islands and Positions of Rajasthan, Bihar, Punjab.

2.1.4. Seismic zone – II: Covers maximum remaining positions of India, these positions are least risks and low damages from earthquakes.

3. Seismic data source & surveillance

For this present frequency-magnitude analysis, the seismic data has been cumulated from various observatory sources. These observatory earthquakes compiled for the period from 1900 to 2018, data has been collected from United States Geological Survey (USGS), Indian Meteorological Department (IMD), International Seismological Center (ISC) U.K., The main reason for chosen these catalogs it is more reliability of the location and quality of seismic data and all the earthquake magnitudes are converted into same scale and specific time periods. For this construction of uniform catalogue, around the world seismic observation centers are not using uniform magnitude scales they are following different observation scales, like M_b(body wave magnitude), M_S (Surface wave magnitude), M_L(local magnitude), M_D(Duration magnitude), M_W(Moment magnitude), M_N (Nuttli magnitude), M_{UK}(Unknown type of magnitude and intensity). For finding the *b*-values all the non-uniform magnitude scales are converted and constructed into a uniform moment magnitude, only MMI measurement for pre-instrumental period of the catalogue also preparation of datasets. These different types of magnitude scaling have been converted to moment magnitude numbers using empirical relation Mw = (2/3 MMI+1), in USGS catalogues magnitude below 4 it is only available in body wave magnitude (M_b). The conversion of M_b to M_w the following conversion formula derived by Scordilis (2006).

$$M_w = 0.85m_b + 1.03, \text{ for } (3.5 \leq m_b \leq 6.2) \quad (1)$$

The sources data has been compared with each parameter and remaining two observation center's datasets. The record of every zone's the dataset collected from these three-observation center's maximum number of earthquakes. By comparing the location and event time the duplicate events were carefully removed. This comparison done for each zone till the database is completed. Final catalog consists of total 2773 number of earthquake events consider for these four seismic zones. Seismic hazard zone wise number of earthquakes has been considering for this analysis as shown in below Table 2.

Table 2. Different Seismic zones in India with recorded earthquakes since 1900-2018

Seismic Zones	Regions	Number of earthquakes. 1900-2018
V	Kutch region Srinagar region Himachal Uttarakhand Some part of Bihar Northeast India Andaman & Nicobar Islands	1923(Magnitude > 2)
IV	Some part of Maharashtra Some part of Gujarat Himalayan region Some part of West Bengal	474 (Magnitude >2)
III	Yellow position in the seismic map (Fig 1)	352 (Magnitude > 2.2)
II	Blue position in the seismic map (Fig 1)	24 (Magnitude > 2.2)

4. Methodology

Generally available earthquake catalog contains the following parameters like Data, Time, Latitude, Longitude, Standard Deviation, Earthquake magnitude and Region. For the preparation of this catalog, researchers have been using two types of methods. First method consists of macroseismic observations of major seismic events that occurred over a period of a few hundred years, second method consists of complete instrumental method seismic observations using seismometer recorded seismic data for relatively short period of time. These methods are generally used to estimate the seismic activity parameters (b-value in G-R equation). All investigations were performed using ZMAP, this software allows to user to examine earthquake catalog from various different angle such as, earth cross-section, time sequence parameters, analyze historical earthquake catalog data, traditional map, epicenter depth, data exploration, finding information about volcano and magma, frequency-magnitude relations, tectonic studies, catalog quality assessment and stress-tensor inversion on a grid to measure the heterogeneity of a stress field, estimating *a* and *b* values, mapping the magnitude of complete reporting, etc. (Wimer 2001), also facilitate spatial mapping in various seismotectonic regions. Seismic zone wise latitude, longitude and magnitude separation was done by using

QGIS mapping open source software. This software support user to analysis the geospatial data, data virtualization, edit spatial information, composing and exporting graphical maps. Collected data have been plotted latitude, longitude and magnitude, also we have clustered above mentioned seismic zones using selection method. We have eliminated the poor-quality data when we plotted the cumulative cure with time and number of events.

5. Seismic zone wise b-value estimation

We will describe and create a model for populations and intensities of earthquakes in various seismic zones using Gutenberg and Richter's (1954) relationship. Also, relation defines seismic wave distribution with respect to magnitude.

The validity of the empirical recurrence relation for earthquakes.

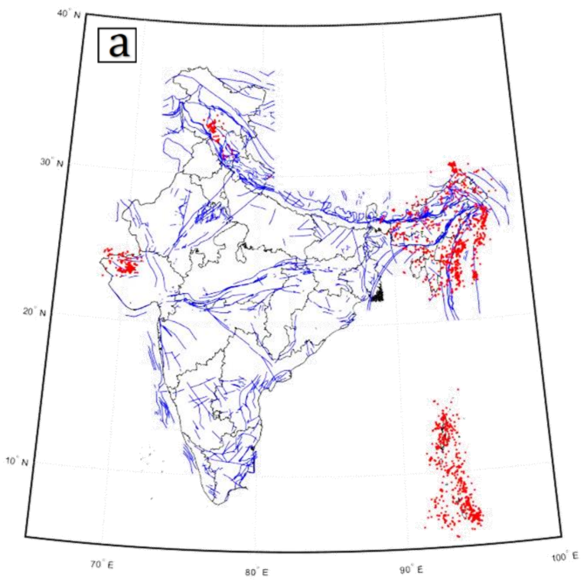
$$\text{Log}_{10}\, N = a + bM \qquad (2)$$

Where N is the number of events (earthquakes) in the catalog whose magnitude greater than M, M denote magnitude. 'a' denote a constant whose value may vary from region to region. 'b' will indicate the size of the events, it will be constant established from an observed data sample, it has been confirmed in many seismicity studies also the slop of the Gutenberg-Richter relationship between frequency-magnitude distribution. Most possibly a and b are constants linked to the activity and earthquake size distribution (Gutenberg and Richter, 1944). M_c magnitude has been estimated from Frequency-Magnitude Distributions after completeness of the seismic dataset (earthquake catalog). For completeness M_c, entire magnitude range (EMR) method detecting self-duplicate datasets of the frequency-magnitude distribution (FMD) for providing comprehensive, complete, error free seismicity datasets. Maximum-likelihood method used for finding the b-value.

$$b = \frac{log_{10}\,(e)}{\left[\langle M\rangle - \left(M_c - {}^{\Delta M_{bin}}/_{2}\right)\right]} \qquad (3)$$

Where, Average magnitude of the events ⟨M⟩, bucketing width of the earthquake catalogue ΔM_{bin} (Jochen 2005; Wiemer 2005). The maximum fault area (crustal segments) is the main reason for larger size of earthquakes. From the historical catalog, Gutenberg-Richter's frequency-magnitude analysis produce $N(M_{max})=1$. The frequency-magnitude distribution (*b*-value) and the seismicity rate (*a*-value) both are constant with respect to time. In whole source volume solution, the parameters a and b are constant. (Wiemer and Wyss, 1997). All investigations of these four seismic zones were performed using ZMAP. Also, we performed additional three regions such as west, north, and east part of India as shown in figures 2 to 10.

5.1. Zone V



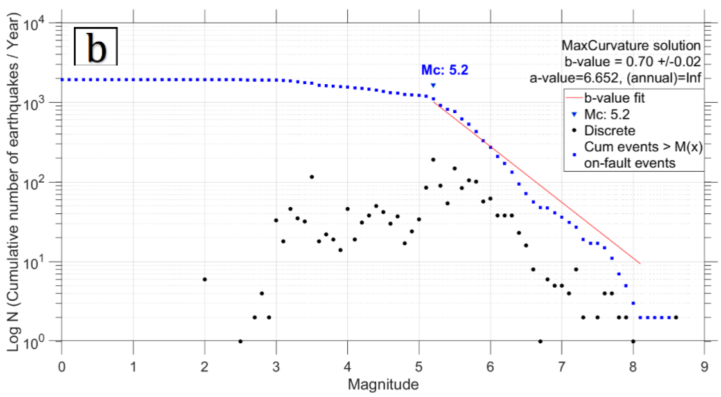


Fig 2. Seismic zone V with 1900-2018 recorded earthquakes. (A) Seismicity map of zone V of Indian region with recorded earthquakes. (B) Frequency-magnitude distribution for seismic zone V, total number of events containing 1923: here *a* = 6.652, *b*= 0.70, lower magnitude cut-off, M_c = 5.2, above samples is considered for calculation.

5.2. Zone IV

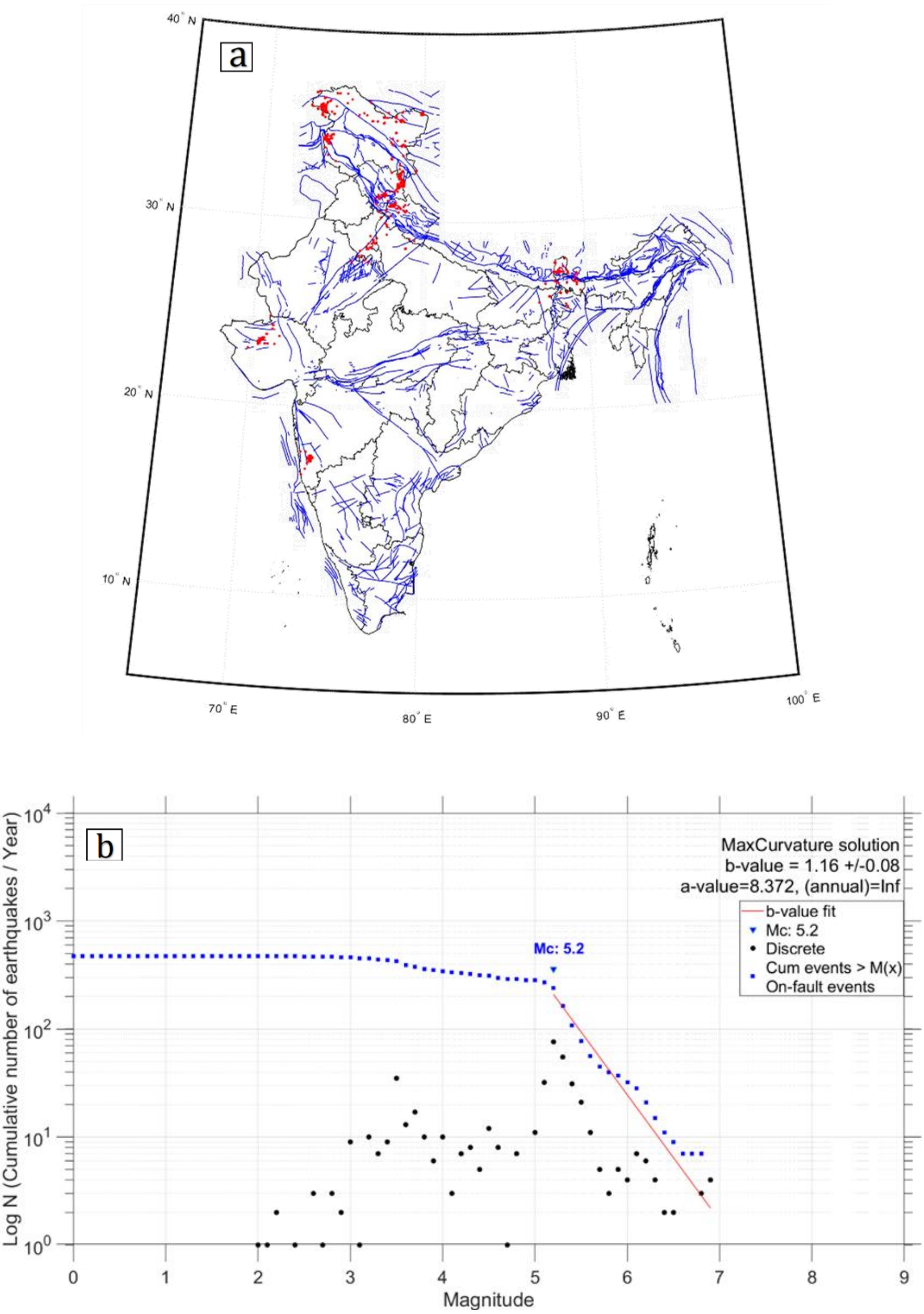


Fig 3. Seismic zone V with 1900-2018 recorded earthquakes. (A) Seismicity map of zone IV of Indian region with recorded earthquakes. (B) Frequency-magnitude distribution for seismic zone IV, total number of events containing 475: here *a* = 8.372, *b*=1.16, lower magnitude cut-off, M_c = 5.2, above samples is considered for calculation.

5.3. Zone III

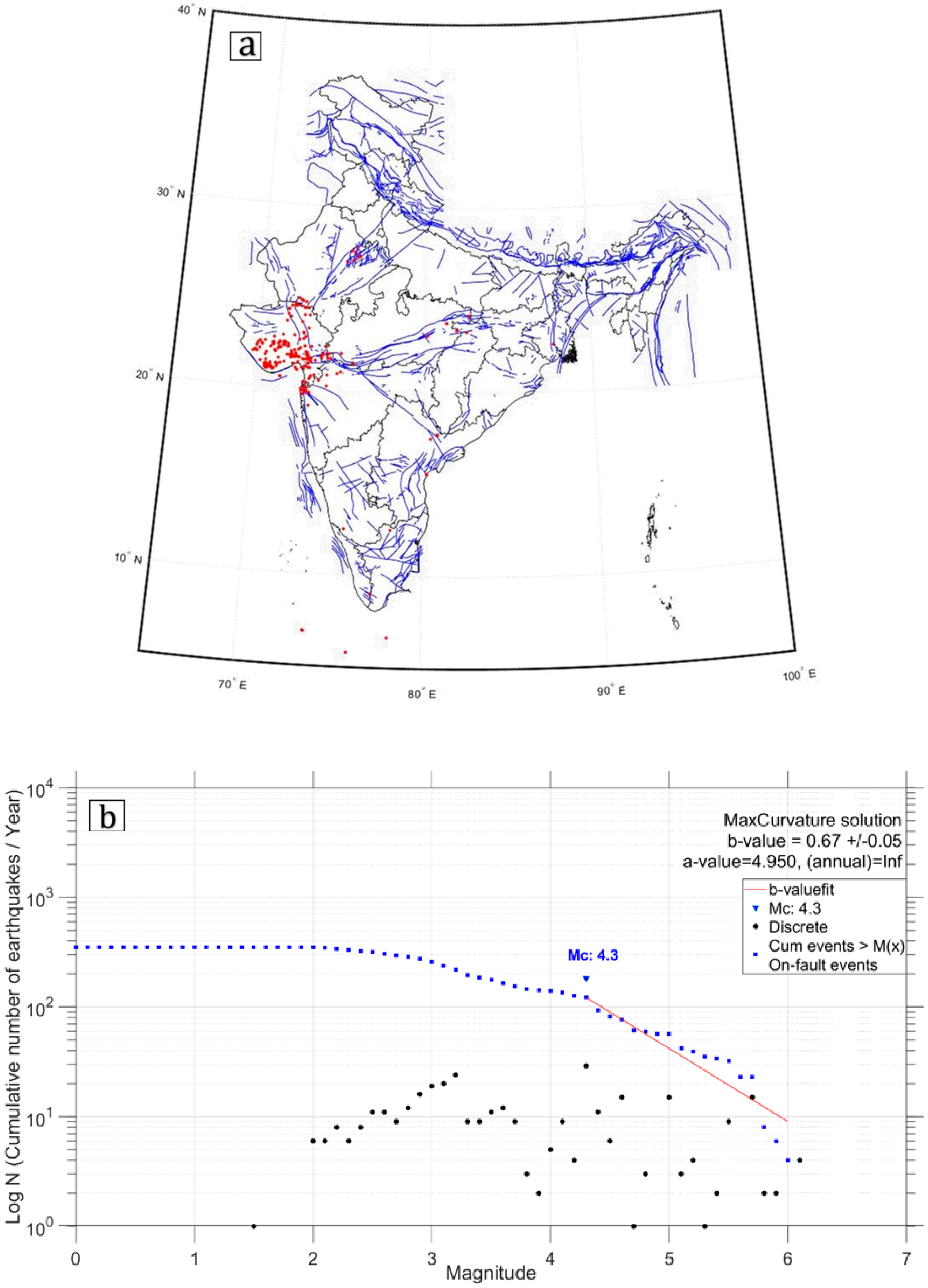


Fig 4. Seismic zone III with 1900-2018 recorded earthquakes. (A) Seismicity map of zone III of Indian region with recorded earthquakes. (B) Frequency-magnitude distribution for seismic zone III, total number of events containing 352: here a = 4.950, b= 0.67, lower magnitude cut-off, M_c = 4.3, above samples is considered for calculation.

5.4. Zone II

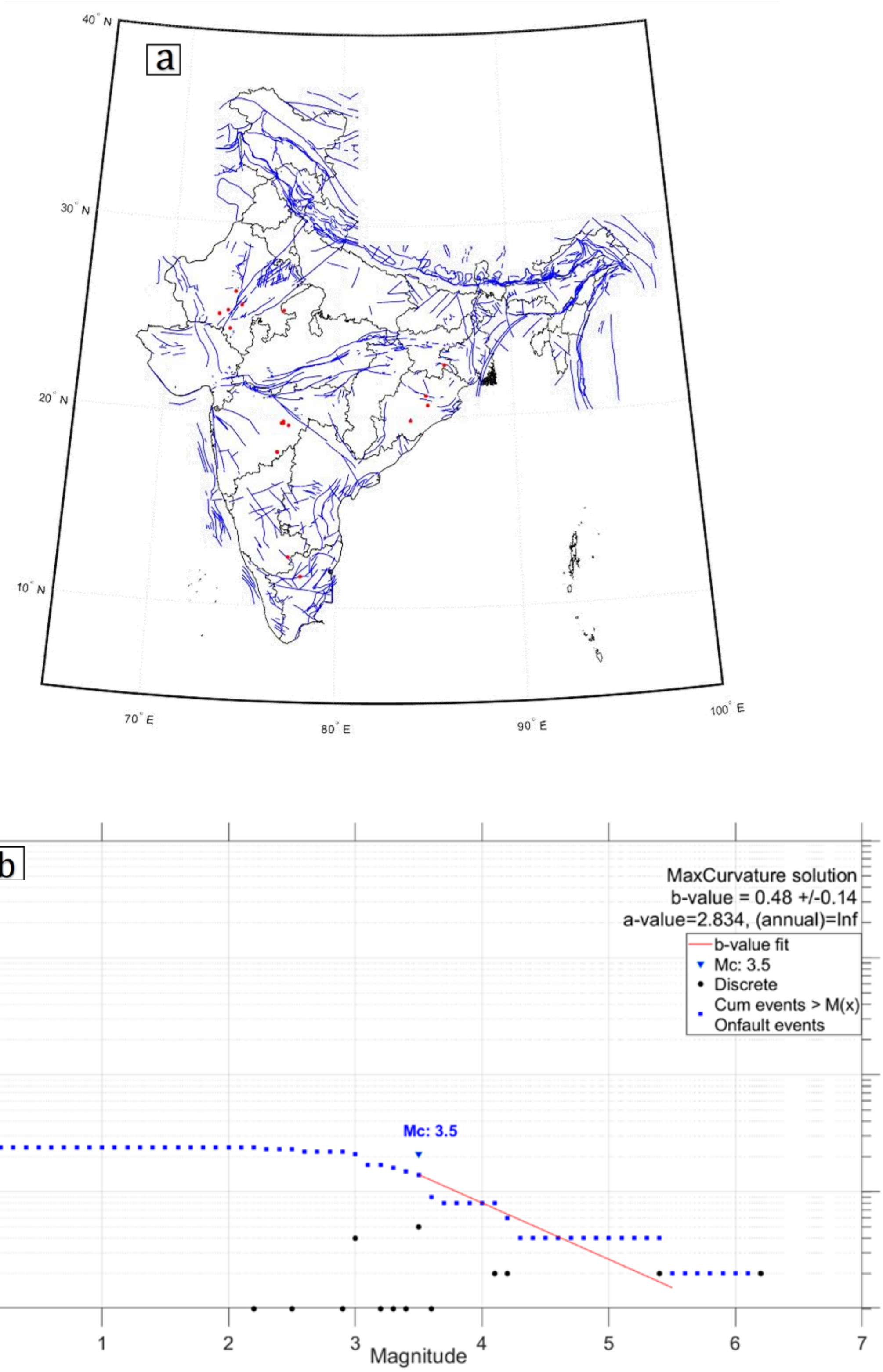
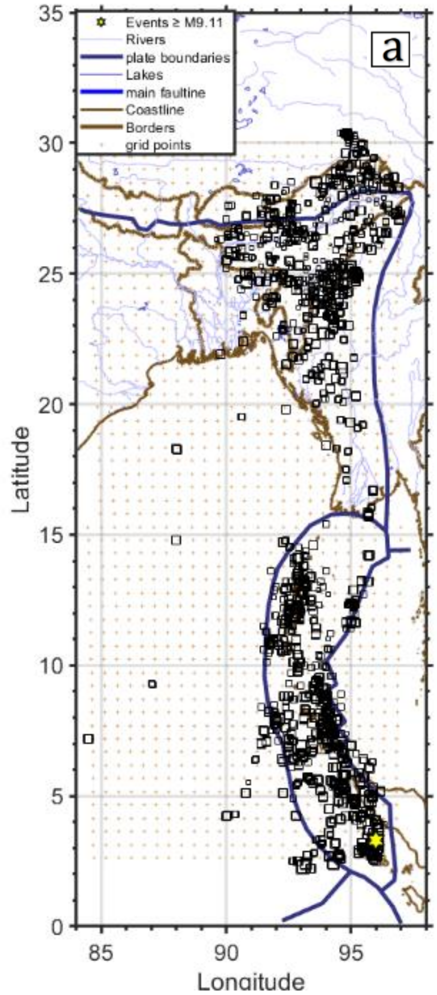


Fig 5. Seismic zone II with 1900-2018 recorded earthquakes. (A) Seismicity map of zone II of Indian region with recorded earthquakes. (B) Frequency-magnitude distribution for seismic zone II, total number of events containing 24: here a = 2.834, b= 0.48, lower magnitude cut-off, M_c = 3.5, above samples is considered for calculation.

5.5. East part of India



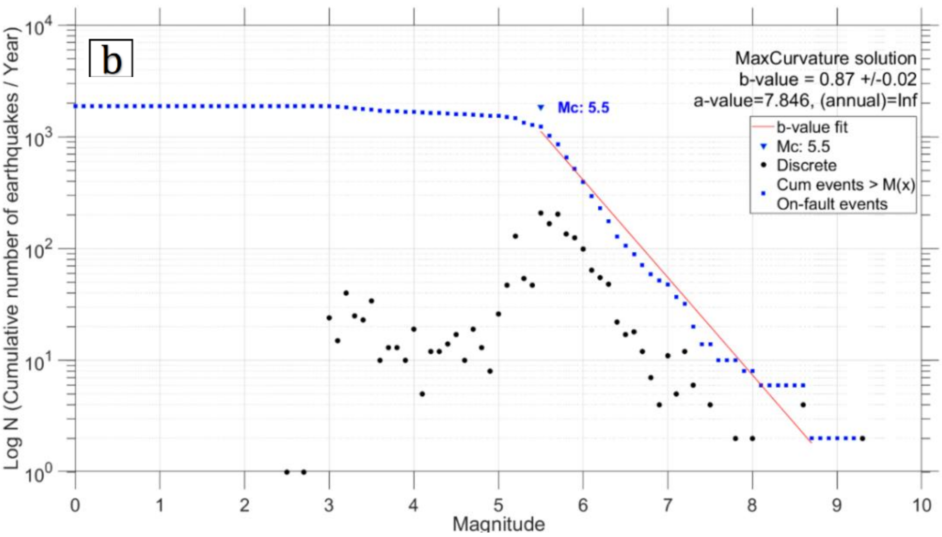


Fig 6. Seismic zones of entire east part of India with 1900-2018 recorded earthquakes. (A) Seismicity map of east Indian region with recorded earthquakes. (B) Frequency-magnitude distribution, total number of events containing 1873: here a = 7.846, b= 0.87, lower magnitude cut-off, M_c = 5.5, above samples is considered for calculation.

5.6. North part of India

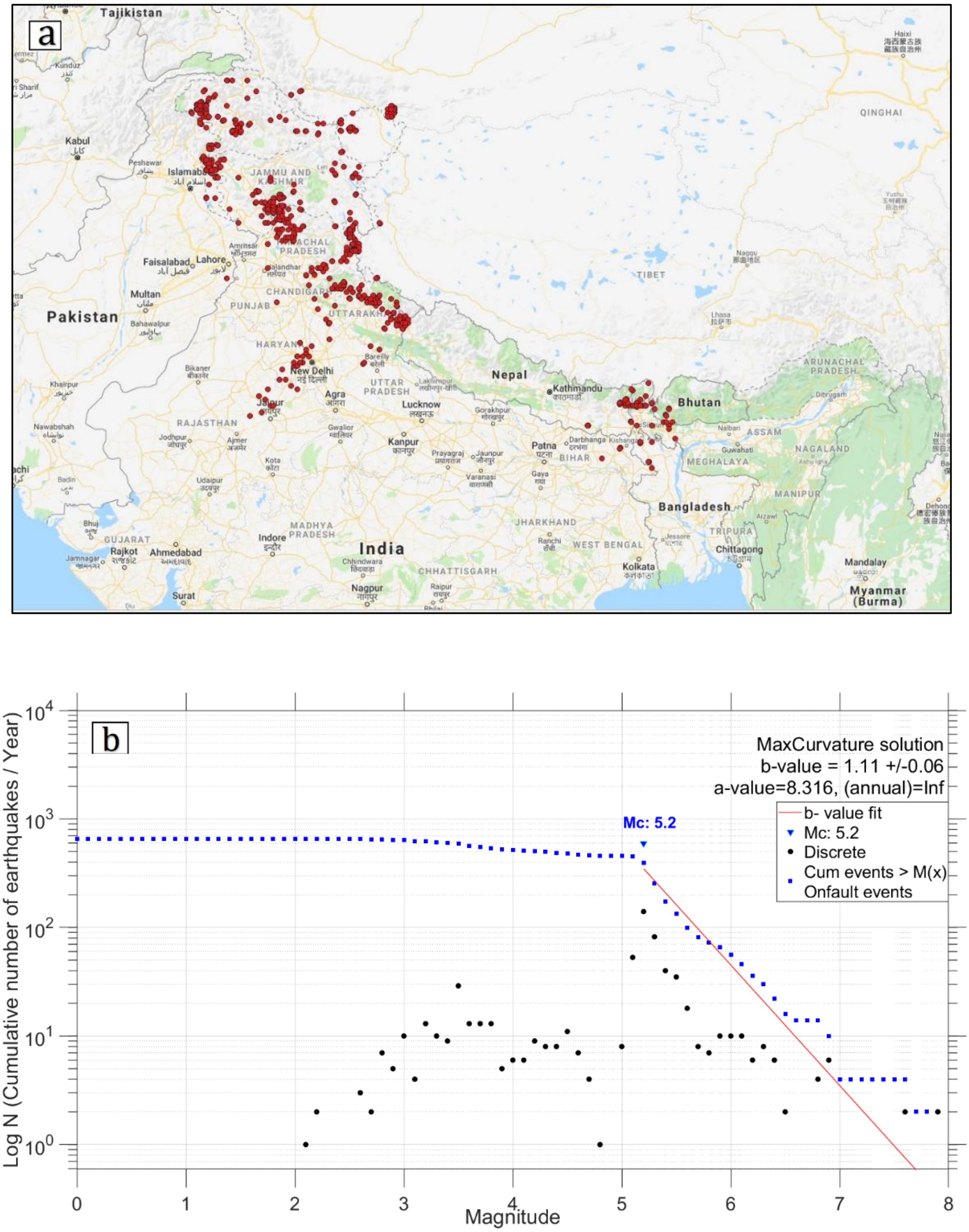


Fig 7. Seismic zones of entire North regions of India with 1900-2018 recorded earthquakes. (A) Seismicity map of north regions with recorded earthquakes. (B) Frequency-magnitude distribution, total number of events containing 656: here *a* = 8.316, *b*=1.11, lower magnitude cut-off, M_c = 5.2, above samples is considered for calculation.

5.7. West part of India

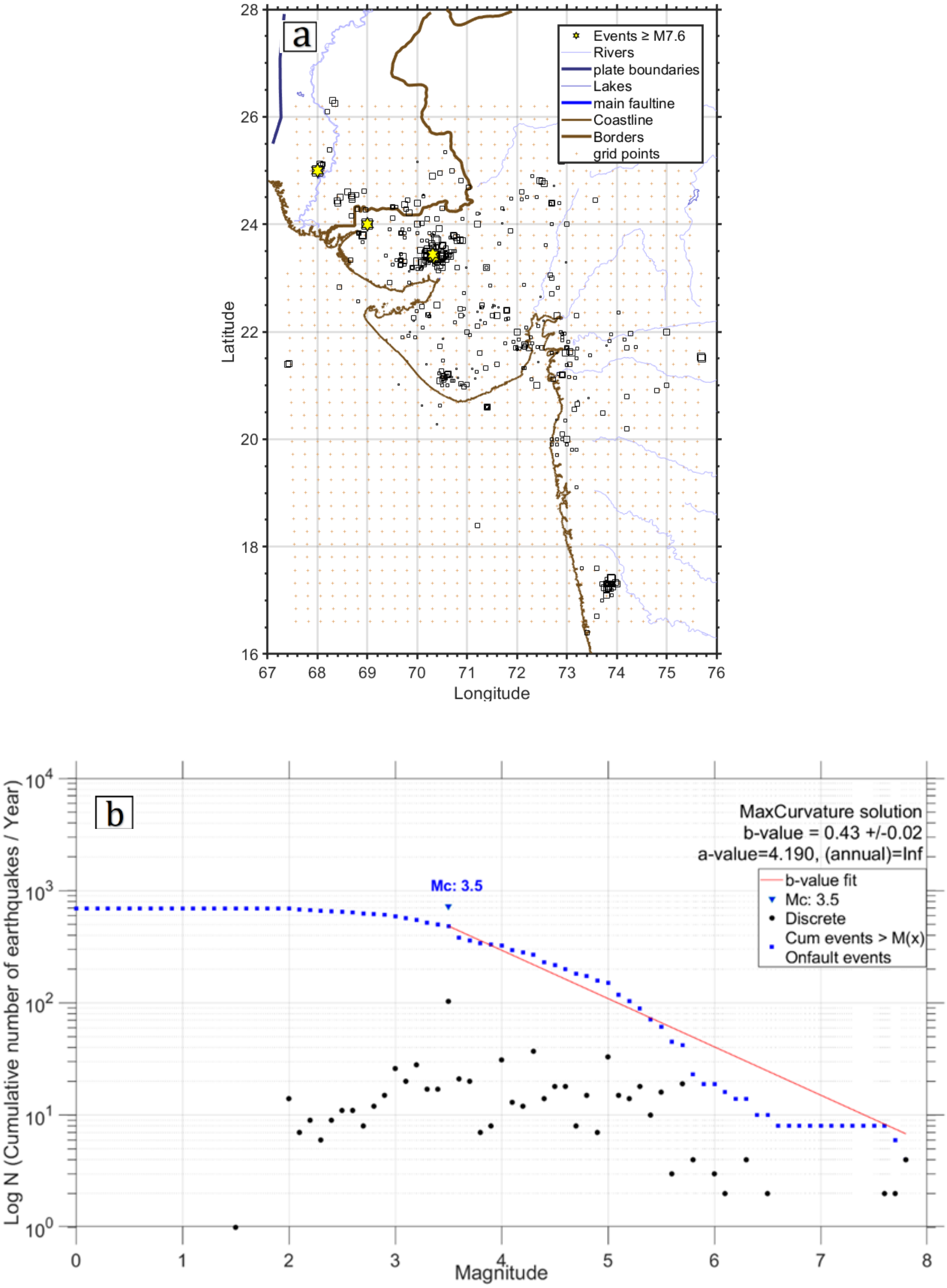


Fig 8. Seismic zones of entire west regions of India with 1900-2018 recorded earthquakes. (A) Seismicity map of west regions with recorded earthquakes. (B) Frequency-magnitude distribution, total number of events containing 695: here a = 4.190, b= 0.43, lower magnitude cut-off, M_c = 3.5, above samples is considered for calculation.

5.8. Himalayan region

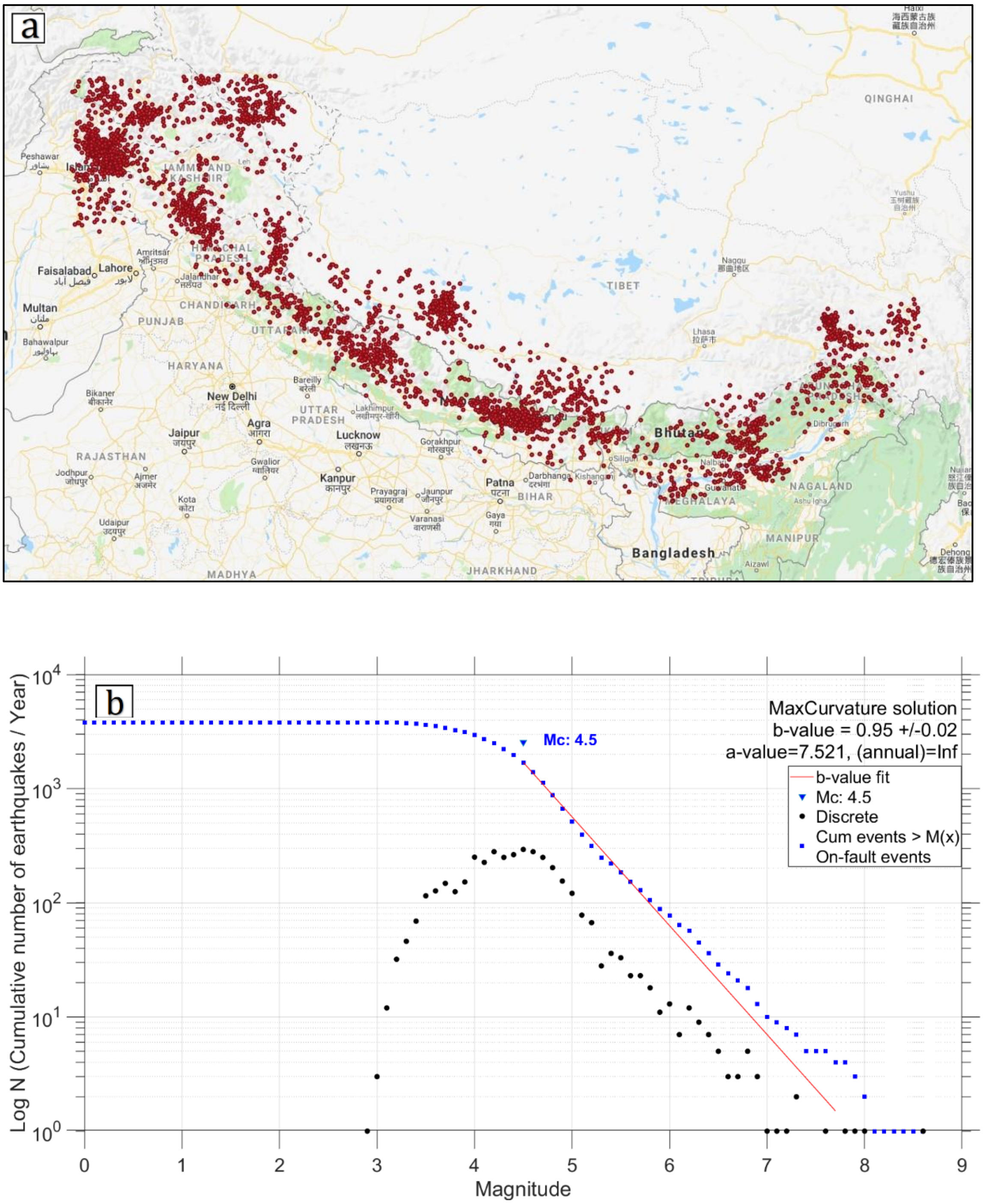
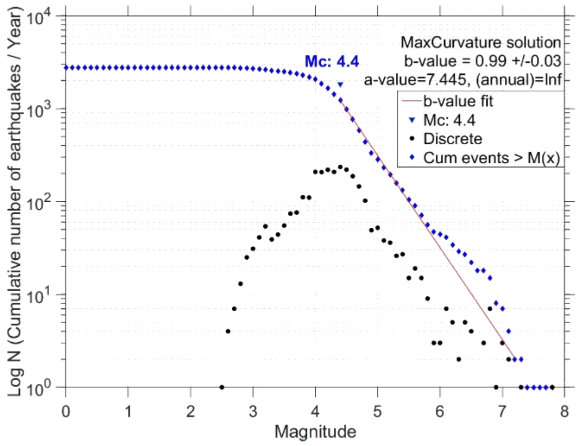
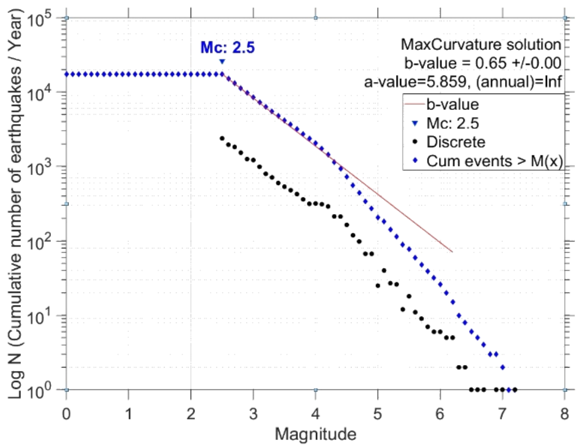


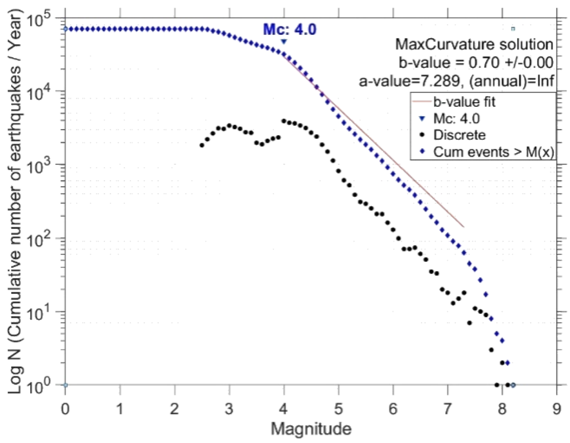
Fig 9. Seismic zones of entire Himalayan region, with 1900-2018 recorded earthquakes. (A) Seismicity map of Himalayan region with recorded earthquakes. (B) Frequency-magnitude distribution, total number of events containing 3797: here a = 7.521, b=0.95, lower magnitude cut-off, M_c = 4.5, above samples is considered for calculation.



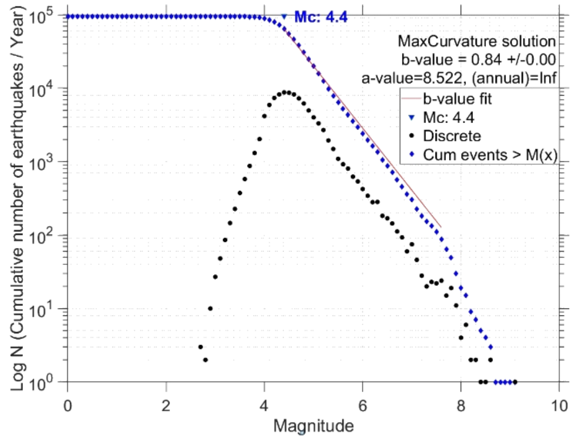
(a) Caucasus Region



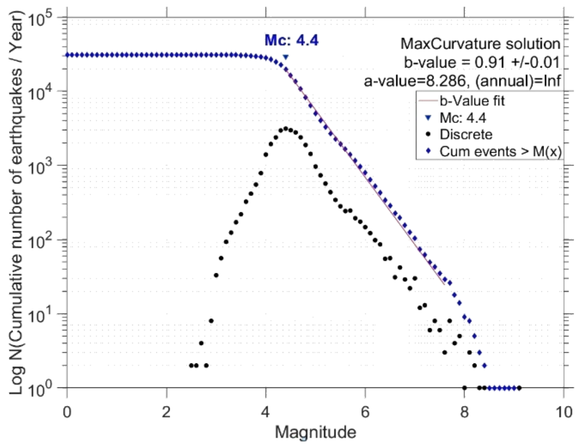
(b) Italy Region



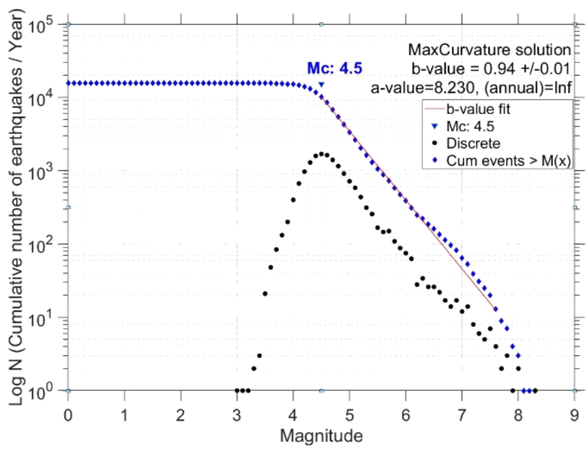
(c) Mexico Region



(d) Indonesia Region



(e) Japan Region



(f) Philippines Region

Fig 10. Earthquake frequency-magnitude distribution curves during the period 1900-2018 for the six different regions with variations of cutoff Mc values, a and b-values

Table 3. Information about data processing and zone wise *a* & *b*–value observed (1900-2018) also for comparison with some highest earthquakes zones in world

Area	Magnitude range	Original catalog	Mc	*a*-value	*b*-value
Zone V	2.0 – 8.6	1923	5.2	6.652	0.70 +/-0.02
Zone IV	2.0 – 6.9	475	5.2	8.372	1.16 +/-0.08
Zone III	2.0 – 6.1	352	4.3	4.950	0.67 +/-0.05
Zone II	2.2 – 6.2	24	3.5	2.834	0.48 +/-0.14
West part of India	2.0 – 7.8	695	3.5	4.190	0.43 +/-0.02
North part of India	2.0 – 7.9	656	5.2	8.316	1.11 +/-0.06
East part of India	2.5 – 9.3	1873	5.5	7.846	0.87 +/-0.02
Himalayan region	2.9 – 8.6	3797	4.5	7.521	0.95 +/-0.02
Caucasus region	2.5 – 7.8	2750	4.4	7.445	0.99 +/-0.03
Italy region	2.5 – 7.2	17456	2.5	5.859	0.65 +/-0.00
Mexico region	2.5 – 8.2	70769	4.0	7.289	0.70 +/-0.00
Indonesia region	2.7 – 9.1	95382	4.4	8.522	0.84 +/-0.00
Japan region	2.5 – 9.1	31020	4.4	8.286	0.91 +/-0.01
Philippines region	3.0 – 8.3	15561	4.5	8.230	0.94 +/-0.01

6. Conclusion

The frequency-magnitude (b-value) spatial distributions reflect tectonic instabilities, also with this b-value instability we can study about seismogenic structure of the region. By studying the *b*-values of four major seismic hazard zones along with three major regions in India, we obtained the following conclusions. Gutenberg-Richter relation about frequency – magnitude distributions (*b* – value), usually measuring low and high indications, the low *b* – value indicate apparent stress of the seismogenic region also subject to experience with warning of large magnitude earthquakes, Seismic zone V is the large earthquake zone. From 1900 to 2018 total 1923 earthquake records has been consider for this b-value calculation. Maximum recorded magnitude 8.6, the cutoff regions Mc = 5.2. *b*-value from this above observation b = 0.70, this may consider as highly wobbly region as shown in (Fig 2). Seismic zone IV is somewhat lesser earthquake zone, compare with zone V.

Total 475 earthquake records since 1900 to 2018 consider for this b-value finding. Maximum recorded magnitude 6.9, the cutoff regions Mc = 5.2. The highest *b*-value b = 1.16 observed in this region, stability is high compare with zone V as shown in (Fig 3). Seismic zone III is the lesser seismic zone. Total 352 earthquake records since 1900 to 2018 consider for this b-value finding. Maximum recorded magnitude 6.1, the cutoff regions Mc = 4.3. The *b*-value b = 0.67 observed in this region, compare with zone V this value less it is noted to consider this is instability as shown in (Fig 4). Seismic zone II is the least risk zone. Total 24 earthquake records since 1900 to 2018 consider for this b-value finding. Maximum recorded magnitude 6.2, the cutoff regions is very low Mc = 3.5. The low *b*-value b = 0.48 observed in this region because it may be lack of datasets as shown in (Fig 5). Among the all Indian seismic zones the low calculated *b*-value is 0.43, large earthquakes could be prone to occur at the highest depth in west part of India (Kutch regions) and the lower depth of the seismic activity area in the Himalayan region. Apart from these four seismic zones. We also consider three major Indian seismic regions such as, West part of India (Gujarat region), East part of India (Northeast India) and North part of India (Himalayan region). In Gujarat region as shown in below (Fig 8), total 695 earthquake records since 1900 to 2018 consider for this b-value finding. Maximum recorded magnitude 7.8, the cutoff region is very low Mc = 3.5. The low *b*-value b = 0.43 observed in this region. It is project that more instability region compares with other regions also extremely stress region in India. North position of India as shown in below (Fig 7), total 656 earthquake records since 1900 to 2018 consider for this b-value finding. Maximum recorded magnitude 7.9, the cutoff region Mc = 5.2. The high *b*-value b = 1.11 observed in this region, it may be somewhat stability region compare with remaining two (west & East) regions. Northeast region as shown in below (Fig 6), total 1873 earthquake records since 1900 to 2018 consider for this b-value finding. Maximum recorded magnitude 9.3, the highest cutoff region Mc = 5.5 because of it may be high magnitude earthquakes recorded found in this region.

The high *b*-value b = 0.87 observed in this region. Finally, the whole north position of India (entire Himalayan region) considering as shown in (Fig 9). for calculating the b-value, in this region total 3797earthquake records since 1900 to 2018 consider and maximum recorded magnitude 9.3, the observed b-value is 0.95 with the cutoff region Mc= 4.5. Since cut-off magnitude is low in zone II and west part of India (Gujarat region). The highest cut-off magnitude was found in the Northeast part of India. Compare with other positions of India high magnitude earthquakes were in Northeast part of India also maximum depth earthquakes were found in Gujarat region. In this comparison study, model values for various highly seismic regions has considered, the frequency-magnitude distribution of the a & b values, for the period 1900-2018 earthquake recorded in and around Caucasian (Georgia), Italy, Mexico, Indonesia, Japan and Philippines regions. A similar data observation and calculation method has been used for these seismic regions. The calculated values for each region as show in Table. 3. From these (*b*-value) observations, it is found that the *b*-values are nearly equal in Himalayan and Caucasus regions, the a& b-value observed for Himalaya: a=7.521 / b=0.95, Caucasus: a=7.445 / b=0.99 and Philippines: a=8.230 / b=0.94, it is not much variations compared with other regions. Oceanic subduction zones are the highest earthquake occurrences in the world. Major earthquakes are placed in these zones, Such as M_W = 9.5 Chile 1960, M_W = 9.2 Alaska 1964, M_W = 8.7 Rat Islands 1965, M_W = 8.5 Kurile Islands,1963. Since the size of the major earthquakes defines the slope of the cumulative regression curve, the highest frequency-magnitude distributed values are observed these regions. The highest *b*-value observed from Himalayan region compared with other regions. Compare with land region highest b-values are found only in oceanic regions.

Data and Resources

All earthquake data used in this study are taken from IMD, USGS and ISC. For seismic hazard zone separation, figures 2(a), 3(a),4(a),5(a),7(a) and 9(a) were made using the QGIS version 3.8 Mapping software, also used ZMAP tool in MATLAB R2018b. Figures 2(a),3(a),4(a),5(a),7(a) and 9(a) map source from https://github.com/vsilwal/AFDI/blob/master/India_Dasgupta2000/ xfaults.json.

Acknowledgements

The study was fully supported by an INT/RUS/RFBR/P-335 grant (Project No. DST/CE/F155/2018-19/G188). The authors would like to acknowledge IMD, USGS and ISC for providing details of earthquake events. The authors also sincerely thank the two anonymous reviewers for thoughtful suggestions and handling editor which have insightful feedback for greatly improved the manuscript.

References

Abu El-Nader IF, Shater A, Hussein HM (2016) Mapping b-values beneath Abu Dabbab from June to August 2004 earthquake swam, *NRIAG Journal of Astronomy and Geophysics* 5:403-412.

Andrezej K, Ansie S (2017) Estimation of the Frequency-Magnitude Gutenberg-Richter b-value without Making Assumptions on Levels of Completeness, *Seismological Research Letters* 88: 311-318.

Chandrani S, Chadha RK (2010) Variations in the frequency-magnitude distribution of earthquake with depth in the Koyna-Warna regions, India, *Elsevier Journal of Asian Earth Sciences* 39:331-334.

Chandrani S, Pankaj MB, Chadha RK (2008) Seismicity in the Koyna-Warna Reservoir Site in Western India: Fractal and b-value Mapping, *Bulletin of the Seismological Society of America* 98:476-482.

Chien-Chih C, Wei-Chien W, Yound-Fo C, Yih-Min W, Yuan-Hsi L (2006) A correlation between the *b*-value and the fractal dimension from the aftershock sequence of the 1999 Chi-Chi, Taiwan, earthquake, *Geophysical Journal International* 167:1215-1219.

El-Isa ZH, David WE (2014) Spatiotemporal variations in the b-value of earthquake magnitude-frequency distributions: Classification and causes, *Tectonophysics* 615-616.

Emad AM, Hetty AL (2011) Variation of b-value in the earthquake frequency-magnitude distribution with depth in the intraplate regions, *IJBAS-IJENS* 11:29-37.

Emile AO, Barbara AR (1994) On the variation of b-values with earthquake size, *Elsevier, Physics of the Earth and Planetary Interiors* 87:55-76.

Emmanuel JG, Douglas WB, Beth PS, Jaakko P, Bodo B (2008) Modern erosion rates in the High Himalayas of Nepal. *Elsevier, ScienceDirect, Earth and Planetary Science Letters* 267:482-494.

Godano E, Lippiello E, Arcanelis L (2014) Variability of the b value in the Gutenberg-Richter distribution, *Geophysical Journal International* 199:1765-1771.

Gutenberg B, Richter CF (1944) Frequency of earthquakes in California, *Bulletin of the Seismological Society of America* 34:185–188.

Gutenberg B, Richter CF (1954) Seismicity of the Earth and Associated Phenomena, *Bulletin of the Seismological Society of America* 40:76.

Jamie F, Stephan H, Robert BS (2009) Earthquake swarm and b-value characterization of the Yellowstone volcano-tectonic system, *Journal of Volcanology and Geothermal Research.* 188, 260-276.

Jochen W, Wiemer S (2005) Assessing the Quality of Earthquake Catalogues: Estimating the Magnitude of Completeness and Its Uncertainty, *Bulletin of the Seismological Society of America* 95:684-698

Khan PK (2005) Mapping of b-value Beneath the Shillong Plateau, *Gondwana Research* 8:271-276.

Khan PK, Parthapratim C (2007) The seismic b-value and its correlation with Bouguer gravity anomaly over the Shillong Plateau area: Tectonic implications, *Journal of Asian Earth Sciences* 29:136-147.

Legrand D, Villagomez D, Yepes H, Calahorrano A (2004) Multifractal dimension and b value analysis of the 1998-1999 Quito swarm related to Guagua Pichincha volcano activity, Ecuador, *Journal of Geophysical Research* 109:1-9.

Mallika K, Harsh G, Shashidhar D, Purnachandra RN, Amrita Y, Sunil R, Satyanarayana HVS, Srinagesh D (2013) Temporal variation of b value associated with M ~4 earthquakes in the reservoir-triggered seismic environment of the Koyna-Warna region, Western India, *Journal of Seismology* 17:189-195.

Mori J, Abercrombie R (1997) Depth dependence of earthquake frequency-magnitude distributions in California: Implications for rupture initiation, *Journal of Geophysics* 102:081-090.

Murru M, Montuori C, Wyss M, Privitera E (1999) The location of magma chambers at Mt. Etna, Italy, mapped by b-values, *Geophysics Research Letter* 26:2553-2556

Nanjo KZ, Yoshida A (2018) A *b* map implying the first eastern rupture of the Nankai Trough earthquakes, *Nature Communications* 9:1-7.

Olsson R (1999) An estimation of the maximum b-value in the Gutenberg-Richter relation, *Geodynamics* 27:547–552.

Paiboon N, Ota K, Leif P (2005) Spatial and temporal b value anomalies preceding the devastating off coast of NW Sumatra earthquake of December 26, 2004, *Geophysical Research Letters* 32:1-4.

Philippe V, Jean-Robert G, Jean-Luc C, Michel F (1992) b-value, aseismic deformation and brittle failure within an isolated geological object: evidences from a dome structure loaded by fluid extraction, *Geophysical research letter* 19:1149-1152.

Pulama T (2013) Seismic Study and Spatial Variation of b-value in Northeast India, *IOSR Journal of Applied Physics* 4:31-40.

Rachel EA (1996) The magnitude-frequency distribution of earthquakes recorded with deep seismometers at Cajon Pass, Southern California, *Tectonophysics* 261:1-7.

Rhoades DA (1996) Estimation of the Gutenberg-Richter relation allowing for individual earthquake magnitude uncertainties, *Tectonophysics* 258:71-83.

Rune O (1999) An estimation of the maximum b-value in the Gutenberg-Richter relation, *Geodynamics* 27:547-552.

Schorlemmer D, Neri G, Wemer S, Mostaccio A (2003) Stability and significance tests of b-value anomalies: Example from the Tyrrhenian Sea, *Geophysical Research Letters* 30:1-4.

Scordilis EM (2006) Empirical global relations converting M_S and m_b to moment magnitude, *Journal of Seismology* 10:225-236.

Sharma ML, Shanker D (2001) Estimation of Seismic hazard parameters in the Himalayas and its vicinity from mixed data files, *ISET Journal of Earthquake Technology* 38:93-102.

Thomas A, Jean-Philippe A, Jing LZ, Helene LC, Laurent B, John G, Jeff G, Marion T, Kristel C, Sapkota SN, Sudhir R, Prithvi S, Lin D, Mireille F (2012) Convergence rate across the Nepal Himalaya and interseismic coupling on the Main Himalayan Thrust: Implications for seismic hazard, *Journal of Geophysical Research* 117:1-16.

Tormann T, Wiemer S, Mignan A (2014) Systematic survey of high-resolution b value imaging along California faults: Inference on asperities, *Journal of Geophysical Research* 119:2029-2054.

Wang JH (1988) b values of shallow earthquakes in Taiwan, *Bulletin of the Seismological Society of America* 78: 1243–1254.

Wiemer S (2001) A software package to analyze seismicity: ZMAP, *seismological Research letter* 72:374-383.

Wiemer S, Benoit JP (1996) Mapping the b-value anomaly at 100 km depth in the Alaska and New Zealand subduction zones, *Geophysical Research Letter* 23:1557-1560.

Wiemer S, Wyss M (1997) Mapping the frequency-magnitude distribution in asperities: An improved technique to calculate recurrence time, *Journal of Geophysical Research* 102:115-128.

Woessner J, Wiemer S (2005) Assessing the quality of earthquake catalogues: estimating the magnitude of completeness and its uncertainty, *Bulletin of the Seismological Society of America* 95:684-698.

Wyss M, Habermann R (1988) Precursory seismic quiescence, *Pure Applied Geophysics* 126:319-332.

Yilmazturk A, Bayrak Y, Çakir O (1999) Crustal seismicity in and around Turkey, *Natural Hazards* 18:253–267.

Yusuf B, Serkan O (2002) Lateral variations of the modal (a/b) values for the different regions of the world, *Journal of Geodynamics* 34:653-666.

Zhou P, Xia S, Sun J, Cao J, Xu H, Zhao F, Chen C (2018) Spatial Variations of b-Values in the Coastal Area of Guangdong, *Journal of Ocean University of Chine* 17:177-185.