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Seismic a-value and the Spatial Stress-Level Variation in Northeast India

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ABSTRACT

The present study aims at understanding the variation of stress level vis-à-vis crustal heterogeneity based on seismicity distribution and a-values in the northeast part of India. The study area lies between latitude 24.5° and 27.2°N and longitude 89° and 96°E, and bounded by major thrust sheets of the Himalaya and Indo-Burman Ranges towards north and east. A crustal scale transcurrent Dauki fault demarcates its southern boundary, while the Yamuna lineament and the tail end of the Brahmaputra and Ganga rivers encompass all along the eastern boundary. Regarding seismicity, the area recorded several moderate to large earthquakes during the historical past, and the most damaging well-known 1897 Shillong earthquake was famous for its own kind. In the present study, we have analysed a-values using a comprehensive database recorded by the network jointly run by RRL, Jorhat and NGRI, Hyderabad. A total of 3655 events were used under the present study.

Seismicity distribution shows three major clusters of higher concentration over the study area. Contours based on estimated a-values over 240 square grids of dimension 0.6°×0.6° show wide variation. However, the near uniform a-values over specific five zones allowed us for depth probing of a-values. The higher a-values in different layers towards the eastern part are correlated with the reactivation of fractures at lower stress level, whereas the minimum a-values with higher gradient towards the southwestern part of the study area can be associated with higher stress level and linked to the thinner crustal root, and uplifted Moho. The area between the Main Boundary Himalayan Thrust and the Shillong Plateau account higher a-values, and might be indicating brittle failure of the weaker crust at lower stress level around the Tura region. Finally, it may be inferred that the seismicity of the northeast India is due to tectonic adjustment of different geomorphologic features presumably caused by the orogenic processes in the Himalaya and Indo-Burman Ranges.

INTRODUCTION

The complicated tectonics resulted from the collision and continued north-south and east-west convergence of the Indian plate towards the Himalaya (Dewey & Bird 1970; Molnar, Fitch & Wu 1973; Seeber, Armbruster & Quittmeyer 1981) and Burmese arc apparently accounts for higher level and diffused seismicity in the northeast India (Kayal 1996; Mukhopadhyay & Dasgupta 1998; Khan & Chakraborty, 2007). During the last 100 years, 18 large earthquakes ($8.0>M\geq7.0$) including two great earthquakes ($M\geq8.0$) occurred in these areas. Along with the major earthquakes, several smaller to moderate size earthquakes ($M<7.0$) have also been quite phenomenon (Verma, Mukhopadhyay & Ahuluwalia.1976; Mukhopadhyay 1984; Kayal 1987), and drawn attention of several geoscientists over decades to its high vulnerability of earthquake hazards. Discrete studies pertaining to seismicity, including of the great 1897 Shillong earthquake (near the central part of the Shillong Plateau; Bilham & England 2001) and other moderate magnitude shocks (Verma, Mukhopadhyay & Ahluwalia 1976; Mukhopadhyay 1984; Kayal 1987; Kayal & Zhao 1998) are available for these areas. Tools like Gravity anomaly (Verma & Mukhopadhyay 1977), seismic b-values (Kayal 1987; Bhattacharya, Majumder & Kyal 2002, Bhattacharya & Kayal 2003), seismic tomography (Kayal & Zhao 1998), receiver function (Mitra et al., 2005) were used for identifying both the role of major lineaments (e.g., Brahmaputra, Kopili, Dauki, etc.) (Evans 1964; Mukhopadhyay 1984; Kayal 1987) as well as heterogeneities in the crust and upper mantle. In our recent studies (Khan 2005a; Khan & Chakraborty 2007), stress-level in the crust and its variation towards deeper part has been assessed, and finally a causal relationship between Bouguer gravity anomaly gradient and seismic b-value has been established for the Shillong Plateau area. This study clearly exhibits wide variation of stress level over the region with a relatively higher value towards its southern boundary.

It is well appreciated in the literature (Gansser 1964; Ben Menahem, Aboodi & Schild 1974; Le Fort 1975) that the southward movements in response to the last phase of the Himalayan orogeny triggered the 1897 Shillong earthquake and the oblique convergence of the Indian plate against the Burmese micro-plate resulted northwestward rupture propagation during the 1950 Sadiya earthquake. These observations including the eastward motion of the Shillong Plateau along the transcurrent Dauki fault exhibit varying tectonic of the northeastern part of India. Further, relatively higher Bouguer and isostatic gravity anomalies (Verma & Mukhopadhyay 1977) those advocated the uncompensation of the elevated Shillong Plateau apparently consistent with the underlying strong Indian lithosphere supporting the Shillong area (Chen & Molnar 1990), and hence the concept of thickened crust below the plateau is readily ruled out. All these features envisage complex tectonics and variable stress at different depth level below the Shillong Plateau area (Khan 2005a, Khan & Chakraborty 2007), and thus clearly endorse an in-depth research for the whole northeast area. The present work therefore aims at understanding the spatial variation of seismic a-values for the northeast part of India and addresses all the above discussed issues. An attempt has also been made to appreciate the regional tectonics as well as the sub-crustal configuration based on depth probing of a-values, and hence the identification of source zone for future earthquakes has been central to the present study.

GEOLOGY AND TECTONIC SET UP

The study area lies between latitude 24.5° and 27.2°N and longitude 89° and 96°E, and is evidenced as a strong seismic domain and highly vulnerable to earthquake hazards. The entire northeast area was tectonically active since the Mesozoic, and along with the mountain building processes in the Burma and Himalaya towards east and north, there has been large scale vertical movements that have resulted in the upliftment of the Shan plateau in Burma and the Shillong Plateau in the northeast India during the Tertiary. The major features in the northeast India are the Shillong Plateau, Mikir Hills, and Upper and Lower Assam Valley, and mainly consist of crystalline rocks that are partly covered by gently dipping younger

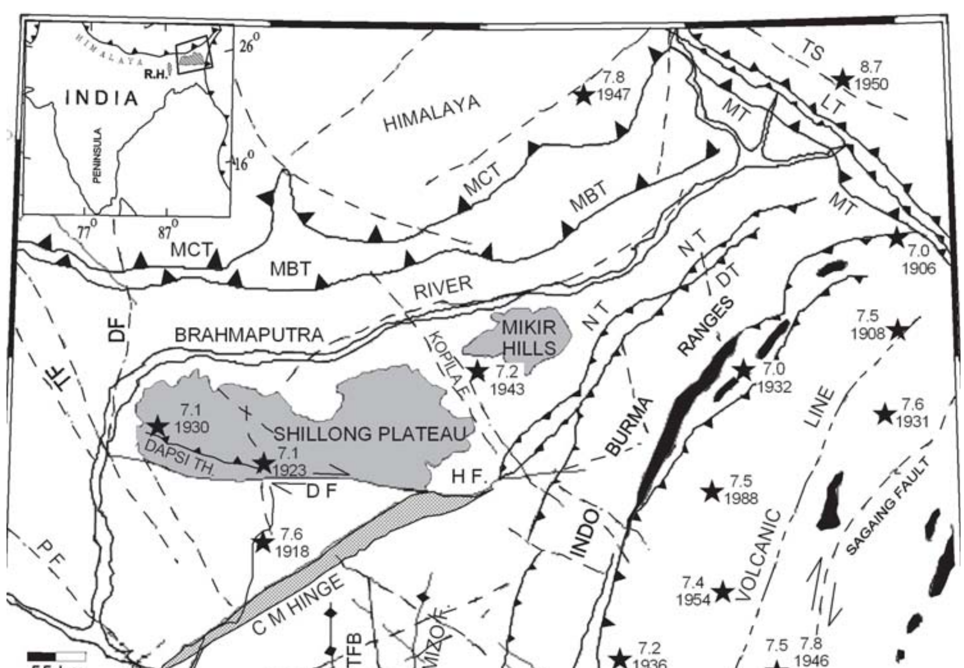


Figure 1. Map showing the tectonic setting of Northeast India (After Krishnan, 1960; Evans, 1964). Inset map represents the location of the study area. D.T.: Disang thrust; M.B.T: Main Boundary Thrust; M.C.T: Main Central Thrust; N.T: Naga Thrust; D.F.: Dauki Fault; P.F: Padma Fault; T.F.: Tista fault; H.F.: Halflong fault; L.T.: Lohit thrust; M.T.: Mishmi Thrust.

sediments (Fig.1). Shillong plateau and Mikir Hills after detaching from the Peninsular India shifted over 200 km through the gap between Rajmahal and Garo Hills, and several criss-cross patterns of faults in the ancient basement rocks characterizes the topography of Shillong plateau and Mikir Hills areas (Evans 1964). The belt of Schuppen, elongated over 330 km with a lateral extension of ~20 km fringes the alluvial valley of Brahmaputra in the Upper Assam area.

The combined gravity, aeromagnetic and seismic data indicate that the basement below the alluvial cover of Upper Assam was extended as a buried ridge towards northeast. To the northern part of the Shillong Plateau, the basement of the Lower Assam Valley is exposed to low-lying ridges on either side of the Brahmaputra River. Satellite imagery (Nandy & Dasgupta 1986) shows a number of buried lineaments (e.g., Brahmaputra fault, Kopili lineament, etc.) beneath the alluvium in the Lower Assam Valley. The Shillong plateau is separated from the western part of the Surma valley by a narrow strip of southerly dipping beds associated with an important EW fault, the Dauki fault. Disang thrust, southwestwards from the Naga Hills, passes near Haflong to part of a narrow but complex fracture belt known as the Haflong fault, and this fracture belt traced westwards, passes into Dauki fault. Near Haflong the fracture changes direction from NE-SW to run nearly due west. The eastern Himalaya thrusts south and southeast over the spur and the Naga Hills region was thrust Northwest. In the Naga Hills the thrusting continued along the fractures.

DATA AND SEISMICITY

The seismological observatory network in northeast India was constructed jointly by the National Geophysical Research Institute (NGRI), Hyderabad and the Regional Research Laboratory (RRL), Jorhat in the early eighties (Bhattacharya, Majumder & Kayal 2002; Bhattacharya and Kayal, 2003), and has been recording local seismicity for over two decades. The earthquake data used for the present study were collected from the catalogues published by RRL, Jorhat. A total of 3655 events occurring in the areas between latitude 24.2 and 27.5°N and longitude 89.3 and 96.2°E (Fig.2) during the period between 1986 and 1999 were considered for the present analysis. The extended area surrounding the study region is occupied for high-resolution investigation along the peripheral zone. The magnitude (M_L) of the earthquakes events are predominantly lies between 2.0 and 4.6, and maximum concentration is noted around 3.2 (Fig.3a).

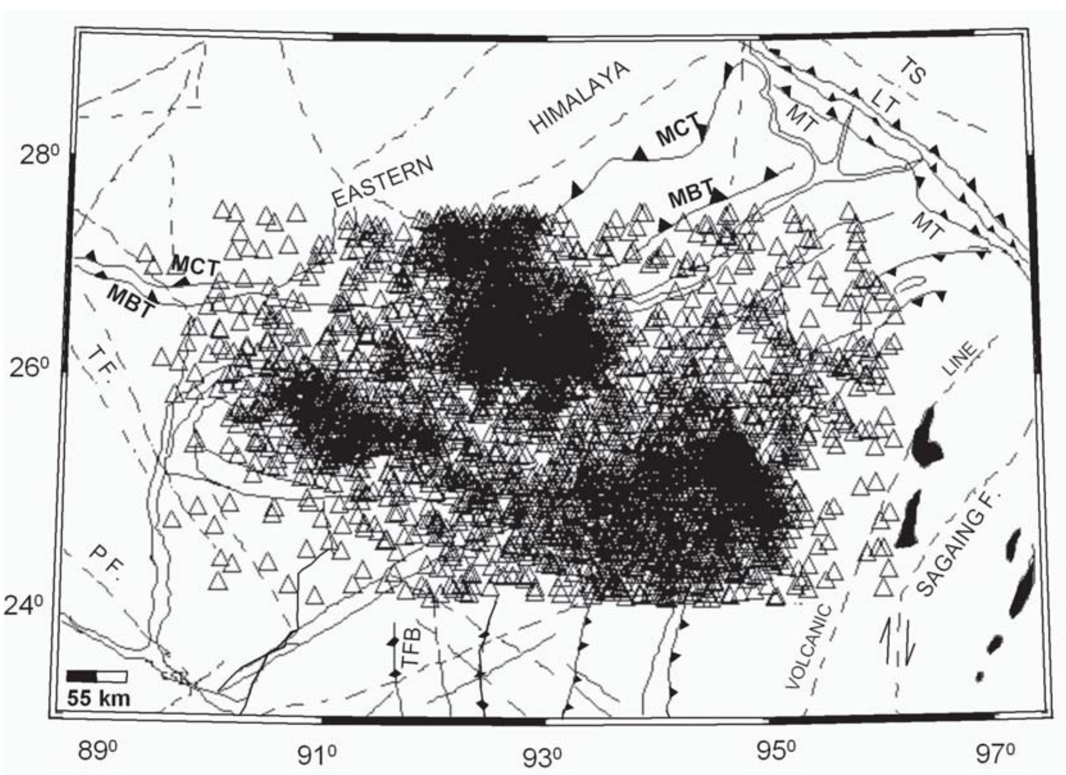


Figure 2. Map showing the distribution of seismicity in Northeast India. Earthquake data for the period between 1986 and 1999 were taken from the Catalogue of Regional Research Laboratory, Jorhat.

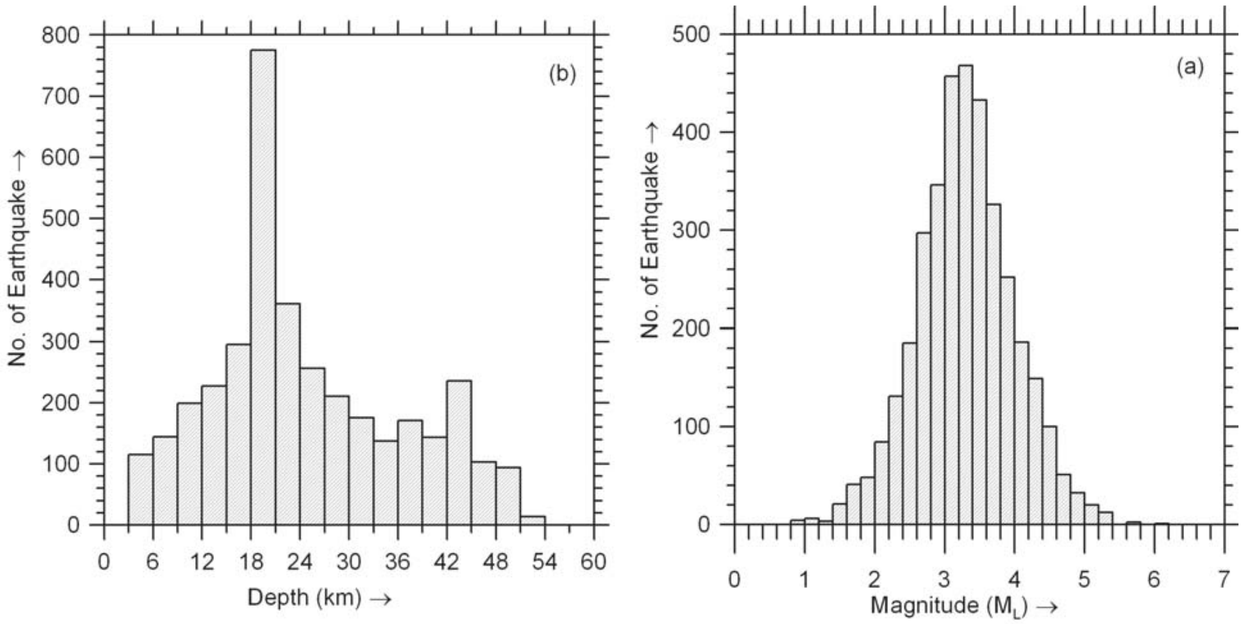


Figure 3. Histograms illustrating concentration of seismicity with respect to magnitude (a) and depth (b) for northeast part of India.

Figure 2 represents the distribution of seismicity over the northeast part of India. It reveals moderate to high seismic activity over most of the part of the area, and maximum concentration is observed in form of three prominent clusters in north, west and southeast part. In other parts, particularly towards southwest, the seismicity decreases phenomenally. The distribution of seismicity towards north and east, surrounding the major thrust sheets of the Himalaya and Indo-Burman Ranges, is fairly uneven. Depth-wise distribution of seismicity beneath the northeast region is also significantly uneven. At the shallowest level below 3 km, seismicity is entirely absent, and it again drops to a minimum in the deepest part exceeding 51 km depth (Fig.3b). Beyond 3 km, seismicity increases almost linearly, and continued to a depth of 18 km. The maximum concentration is noted between 18 and 21 km depth, and thereafter, the distribution is again decreases linearly, and becomes nearly uniform beyond 36 km depth.

SIGNIFICANCE AND ESTIMATION OF A-VALUE

Gutenberg & Richter (1954) proposed an important empirical relationship between occurrence-frequency and magnitude of earthquakes in a finite duration for a given region. Like many others self-organised, self-similar non-equilibrium systems, earthquake magnitude-frequency relation for a region follows an exponential relation, and can be represented empirically by the given equation as

$$\text{Log } N(M) = a - bM \qquad \text{Eq.1}$$

Where N(M) is the number of earthquakes having magnitude ≥ M, and occurred over a finite duration. Other parameters i.e., 'a' is a measure of seismic activity that depends on size of the area, observation period length, largest seismic magnitude, and moreover, the stress level of the area (Allen 1986). The b value is the slope on the log N ~ M regression line and is a constant parameter that determines the rate of fall in the frequency of events with increasing magnitude. High b values indicate a large number of small earthquakes, which is to be expected in regions of low strength and large heterogeneity, whereas low values indicate high resistance and homogeneity (Tsapanos 1990; Wason et al., 2002; Khan 2003). In natural situation 'a' and 'b' values are found to lie in the range between 2 and 8, and 0.5 and 1.8, respectively. The parameter 'b' is generally used for quantifying seismicity (Allen et al., 1965) or for dealing problems of earthquake prediction (Suyehiro, 1966; Papazachos, 1975). Attempts were made in the laboratory by Mogi (1963, 1967) and Scholz (1968) to study the behaviour of the b values during fracturing of the rocks. While the study of Mogi (1967) was mainly concerned with the mechanical behaviour of the rocks, Scholz (1968) inferred that the state of stress, rather than the heterogeneity of the material constituting the rocks, plays the most important role in determining the b value. Their observations were supported by numerous studies such as those in

Taiwan (Wang 1988) and along the Circum-Pacific subduction zones (Carter & Berg 1981). Characterising the temporal variation in b value over a seismic zone, Scholz (1968) and Wyss (1973) observed that low b values correspond to periods of increasing shear stress or effective stress, and higher seismic moment release. The b value may also decrease with increasing depth (Mori & Abercrombie, 1997; Wiemer & Wyss 1997), possibly due to increasing applied stress at deeper levels (Bhattacharya & Kayal 2003). Increased rock mass heterogeneity or crack density results in high b values (Mogi 1967) and resistant blocks (asperities) embedded in rocks decrease the b value. The b values can also be related to plate subduction rate, for ex. in the subduction zones of NE Japan Island Arc the b value is found decreasing with increasing subduction rate (Cao & Gao 2002). Similar interpretation can also be extended for a-value variation because a positive relationship between a and b values exists (Kaila & Narain 1971; Kaila, Madhava Rao & Narain 1974).

The study area (Fig.1) was divided into 240 square grids for high-resolution investigation. Each grid has a dimension of 0.6°×0.6° (geographical window). A moving window (overlapping area) of 0.3°×0.3° size was considered over the entire area for a comprehensive analysis of a-values, and moreover, the continuity of the data points from grid to grid is inherently maintained. The dimension of the geographic window under the present study is selected in such manner to have sufficient number of events representing the a and b-values for each grid. Few grids, those have insufficient events, were excluded from the analysis.

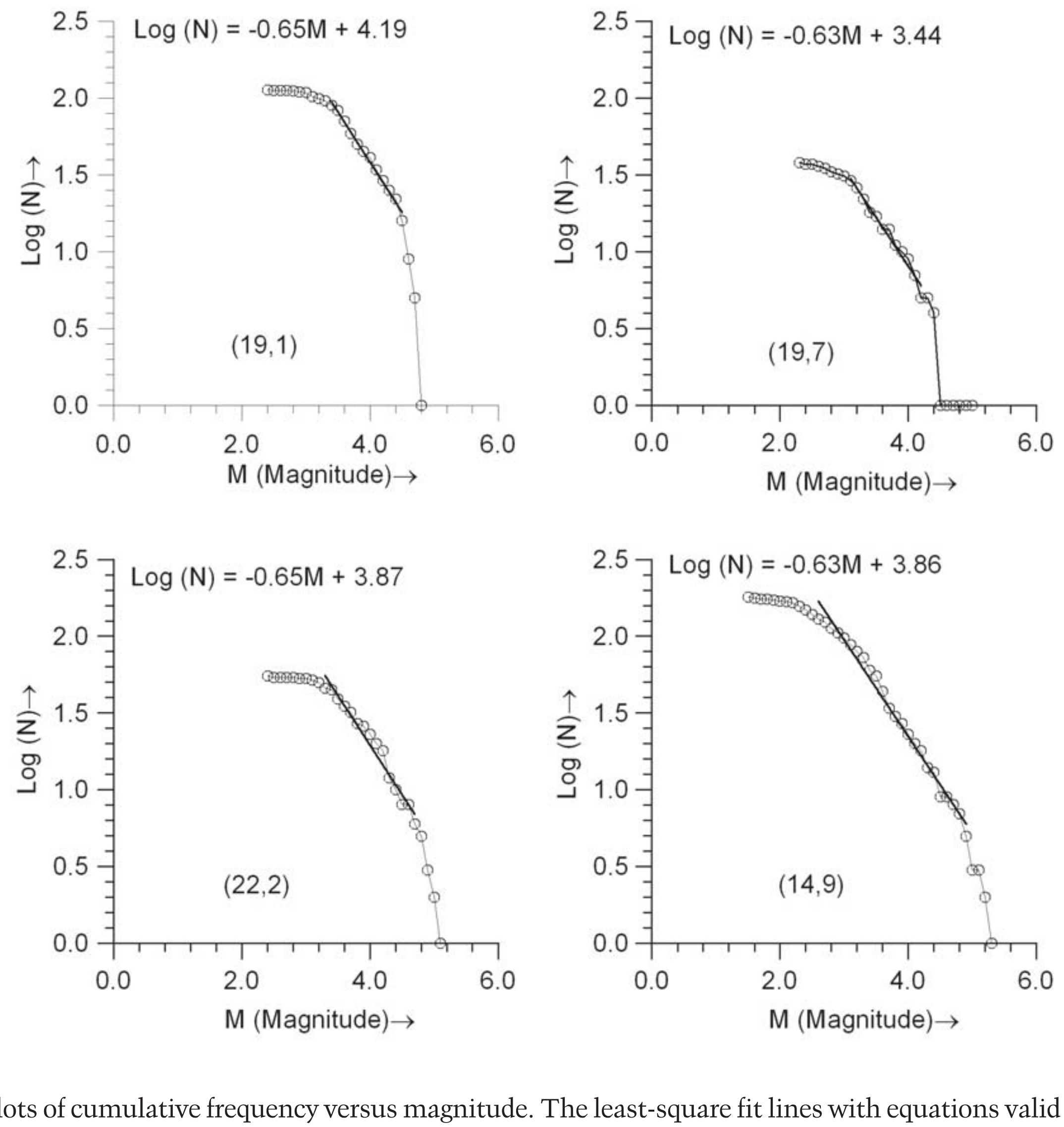


Figure 4. Plots of cumulative frequency versus magnitude. The least-square fit lines with equations valid for different seismic blocks (19, 1), (19, 7), (22, 2) and (14, 9), respectively.

Table 1a. a-value for seismic zone I.

Sl. No.	Depth ('h' in km)	Projection point (depth in km)	N	N_o	MRAE	MRBE	% of events used $[(\frac{N_0}{N})\times 100]$	a value
1	0.0≤h<12.0	6.0	14	11	2.0-5.1	2.5-4.7	78.87	2.03
2	6.0≤h<18.0	12.0	25	19	2.2-5.1	2.8-4.8	76.0	3.02
3	12.0≤h<24.0	18.0	41	33	2.1-5.4	2.7-4.3	80.49	3.45
4	18.0≤h<30.0	24.0	38	30	2.1-5.4	2.6-4.6	78.95	3.16
5	24.0≤h<36.0	30.0	20	15	2.7-4.9	3.1-4.6	75.0	2.70
6	30.0≤h<42.0	36.0	16	12	3.1-4.7	3.3-4.4	75.0	2.59
7	36.0≤h<48.0	42.0	14	11	2.6-4.4	2.9-3.7	78.57	2.69
8	42.0≤h<54.0	48.0	91	89	1.8-5.4	2.4-4.9	97.80	2.95

N, total number of events; N_o, total number of events used to estimate the a-value; MRAE, magnitude range for all events; MRBE, magnitude range for events used to estimate a-value.

Table 1b. a-value for seismic zone II.

Sl. No.	Depth ('h' in km)	Projection point (depth in km)	N	N_o	MRAE	MRBE	% of events used $[(\frac{N_0}{N})\times 100]$	a value
1	0.0≤h<12.0	6.0	96	89	1.0-4.5	2.4-4.4	92.71	3.83
2	6.0≤h<18.0	12.0	187	130	1.0-4.8	2.6-4.3	69.52	4.41
3	12.0≤h<24.0	18.0	319	309	1.1-5.4	2.0-5.0	96.38	4.18
4	18.0≤h<30.0	24.0	276	266	1.1-5.4	1.8-5.0	96.38	3.76
5	24.0≤h<36.0	30.0	90	85	1.1-5.0	1.9-4.7	94.44	3.15
6	30.0≤h<42.0	36.0	58	50	1.5-5.4	3.3-4.9	86.21	4.95
7	36.0≤h<48.0	42.0	53	39	2.1-5.4	3.0-4.2	73.58	3.87
8	42.0≤h<54.0	48.0	25	20	2.1-4.3	2.9-4.0	80.00	3.10

Table 1c. a-value for seismic zone III.

Sl. No.	Depth ('h' in km)	Projection point (depth in km)	N	N_o	MRAE	MRBE	% of events used $[(\frac{N_0}{N})\times 100]$	a value
1	0.0≤h<12.0	6.0	94	89	1.1-5.1	1.8-4.8	94.68	3.21
2	6.0≤h<18.0	12.0	155	90	1.1-5.1	2.3-4.6	58.06	3.89
3	12.0≤h<24.0	18.0	316	290	1.0-4.9	1.8-4.3	91.77	3.67
4	18.0≤h<30.0	24.0	326	280	1.0-5.0	2.3-4.5	85.89	4.09
5	24.0≤h<36.0	30.0	173	119	1.5-5.3	2.7-4.9	68.79	3.87
6	30.0≤h<42.0	36.0	143	118	1.6-5.3	2.5-4.8	82.52	3.72
7	36.0≤h<48.0	42.0	146	102	1.8-5.2	2.7-4.9	69.86	4.30
8	42.0≤h<54.0	48.0	97	95	1.8-5.2	1.9-5.0	97.94	3.30

Table 1d. a-value for seismic zone IV.

Sl. No.	Depth ('h' in km)	Projection point (depth in km)	N	N_o	MRAE	MRBE	% of events used $[(\frac{N_0}{N})\times 100]$	a value
1	0.0≤h<12.0	6.0	111	91	1.7-4.8	2.8-4.6	81.98	4.72
2	6.0≤h<18.0	12.0	240	211	1.7-5.2	3.0-4.8	87.92	5.67
3	12.0≤h<24.0	18.0	563	376	1.4-5.2	3.0-5.0	66.79	6.22
4	18.0≤h<30.0	24.0	593	410	1.4-5.7	3.0-5.1	69.14	5.77
5	24.0≤h<36.0	30.0	288	280	1.2-5.7	2.1-5.0	97.22	4.07
6	30.0≤h<42.0	36.0	242	160	1.8-5.3	3.2-4.9	66.12	6.06
7	36.0≤h<48.0	42.0	251	244	1.6-6.2	2.0-5.0	97.12	4.32
8	42.0≤h<54.0	48.0	153	112	1.6-6.2	3.2-5.1	73.20	4.75

Table 1e. a-value for seismic zone V.

Sl. No.	Depth ('h' in km)	Projection point (depth in km)	N	N_o	MRAE	MRBE	% of events used $[(\frac{N_0}{N})\times 100]$	a value
1	0.0≤h<12.0	6.0	58	42	2.6-4.7	3.0-4.7	72.41	3.51
2	6.0≤h<18.0	12.0	107	80	2.5-5.2	3.1-4.6	74.77	3.87
3	12.0≤h<24.0	18.0	214	135	1.7-5.2	3.1-5.1	63.08	5.54
4	18.0≤h<30.0	24.0	234	231	1.7-5.2	2.1-5.0	98.72	4.02
5	24.0≤h<36.0	30.0	125	101	2.2-5.3	3.2-5.0	80.80	4.57
6	30.0≤h<42.0	36.0	100	97	2.3-5.3	2.5-5.0	97.00	3.49
7	36.0≤h<48.0	42.0	130	70	2.7-5.2	3.4-4.6	53.85	5.31
8	42.0≤h<54.0	48.0	131	107	2.2-5.1	3.3-5.0	81.68	4.81

For a defined magnitude range, a and b-values for each block were computed using Eq. 1. Fig. 4 illustrates the estimations of a and b-values from cumulated frequency-magnitude relationship for four grid squares. The plots definitely reveal systematic deviations from linearity at both higher and lower end of the data values, which was accounted in terms of statistical fluctuations because of the scarcity of large magnitude (M) events and from incompleteness because of a detection threshold at small M (Fig.3a). The bending of the best fit lines in the ranges of small and large magnitudes earthquakes restricted the estimation of a and b values over the dataset fall on the linear parts of the curves. On the map the estimated a-values for each square grid was spatially assigned at a point that define the intersection of two diagonals of the square block and the projected values were thereafter used for a-values mapping over the entire study area (Fig. 5). Based on a comparative analysis of contour values, five broad zones of nearly uniform a-values were identified, and depth-probing of a-values was done through computation of a and b-values specific to each individual zone at every 12 km depth interval, starting from surface down to 54 km depth (Tables 1a-e) for understanding the intra- and inter-zone variations in a-values with respect to depth. An overlapping depth of 6 km (moving window) was considered for maintaining inherent continuity of the data points and high-resolution study. The five zones were further divided into different sub-blocks (Fig. 6) for changing the rectangular area into near squared-geometry and maintaining the inherent uniformity of a-values. The a-value specific to these sub-blocks were plotted at the intersection of two diagonals of each block in different layers, and hence contouring maps (Figs. 7a-h) were reconstructed.

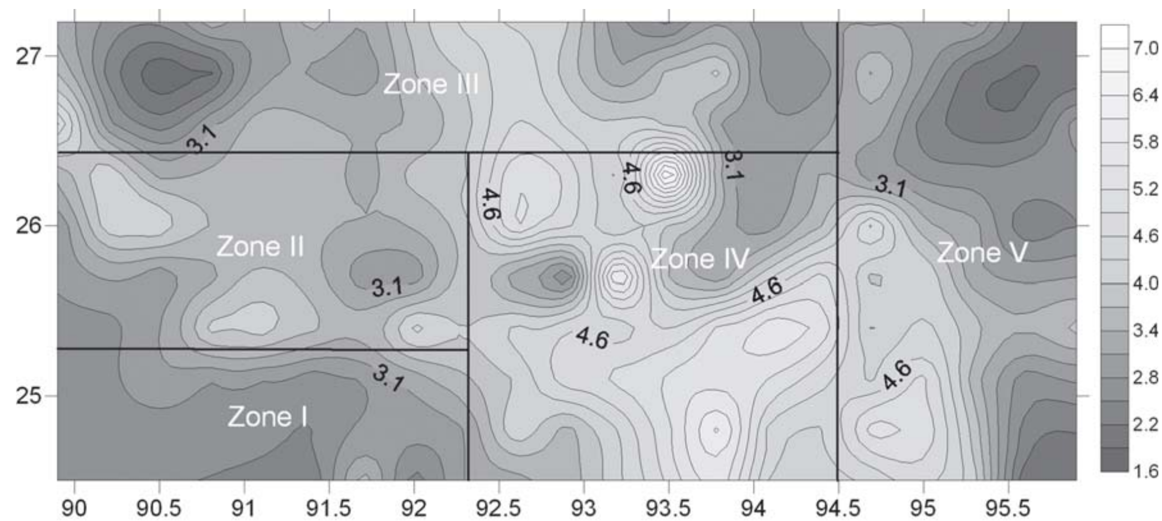


Figure 5. Contour map for a-value over the study area. Heavy lines demarcate the different seismic zones delineated under the study using variation in a value.

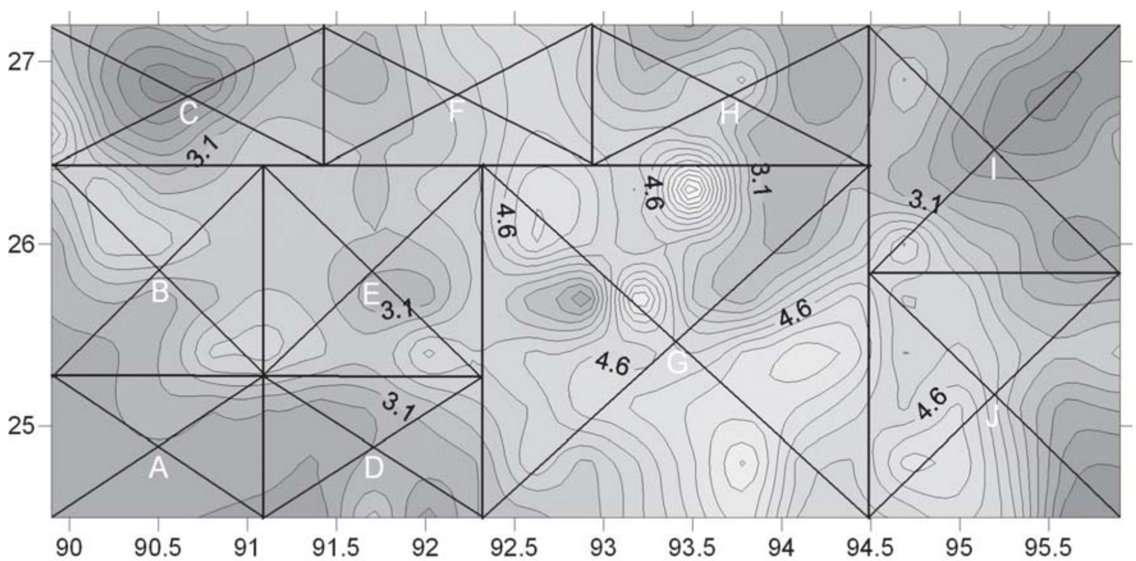
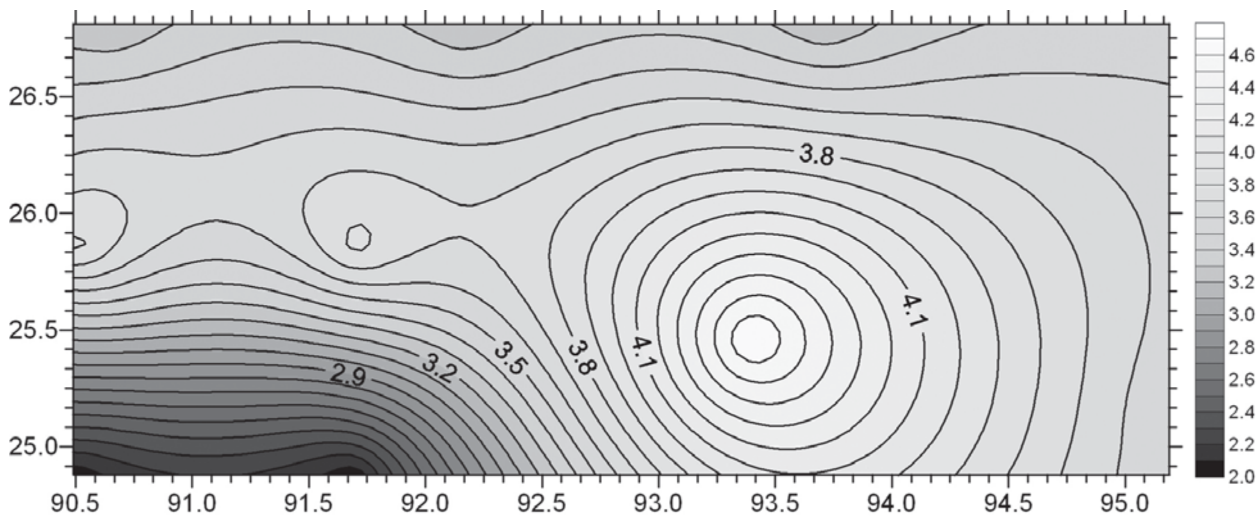


Figure 6. Plots of different blocks (A-J) used for mapping a-value in different layers (I-VIII). The a-value was projected at the intersection point of diagonals for each block.

RESULTS

Maximum and minimum a-values over the northeast part of India are estimated as 7.97 and 1.64. Based on the range, a-values were classified into three categories; viz. low ($a \leq 3.0$), moderate ($3.0 < a \leq 4.6$) and high ($a > 4.6$). It was observed that the southwestern part, eastern part (i.e., exceeding ~95.2° longitude), and northwest corner of the region document low a-values. Relatively high a-value is noted in the central part between latitude 24.5 and 26.5°N and longitude 92.3 and 94.5°E. The remaining part of the region records predominantly moderate a-values. This analysis based on a-values estimated over a single-layer of thickness 54 km is however critical (as the strength of the lithosphere is non-uniform over the entire depth range for continental region, Molnar 1988), and therefore, the analysis ought to be extended over a more thinner layer through depth-probing of a-values. This high-resolution study noticeably indicates wide variation of a-values between different layers (Figs. 7a-h).

Nearly in all layers the southwestern part of the area documents lower a-values, and changes sharply towards its boundary. In the shallower part of northern and eastern boundaries, a-value contours follow the trend of major regional structures (Figs.7a-c), whereas towards deeper part at more than 18 km depths, contours do not show any such pattern except in layer 6 (Fig.7f). It is thus worth mentioning that the change in a-value patterns around 18 and 36 km depths can apparently be correlated with sharp changes in rheology of the lithosphere (Mitra et al., 2005; Khan & Chakraborty 2007). Increasing a-values from shallower to deeper part might be indicating more fracturing in the lithosphere caused by eastward subduction of the Indian plate beneath the Burma plate. Higher a-values are also prominent around latitude 25.5 and longitude 93.5°, and possibly related with the mutual tectonic adjustment between Shillong Plateau, Mikir Hills, Naga Hills and Indo-Burman Ranges. Towards western part, East-West trend of comparatively lower a-values in different layers between Shillong Plateau and MBT might be related with heterogeneities/fracturing of the lithosphere caused by the orogenic processes of the Himalaya against the Shillong Plateau. Therefore, it may be interpreted that the tectonic processes of the northeast part of India is apparently controlled by the tectonic movement of the various Hills/Plateau induced either by the orogenic movements of the Eastern Himalaya or the Indo-Burman Ranges.



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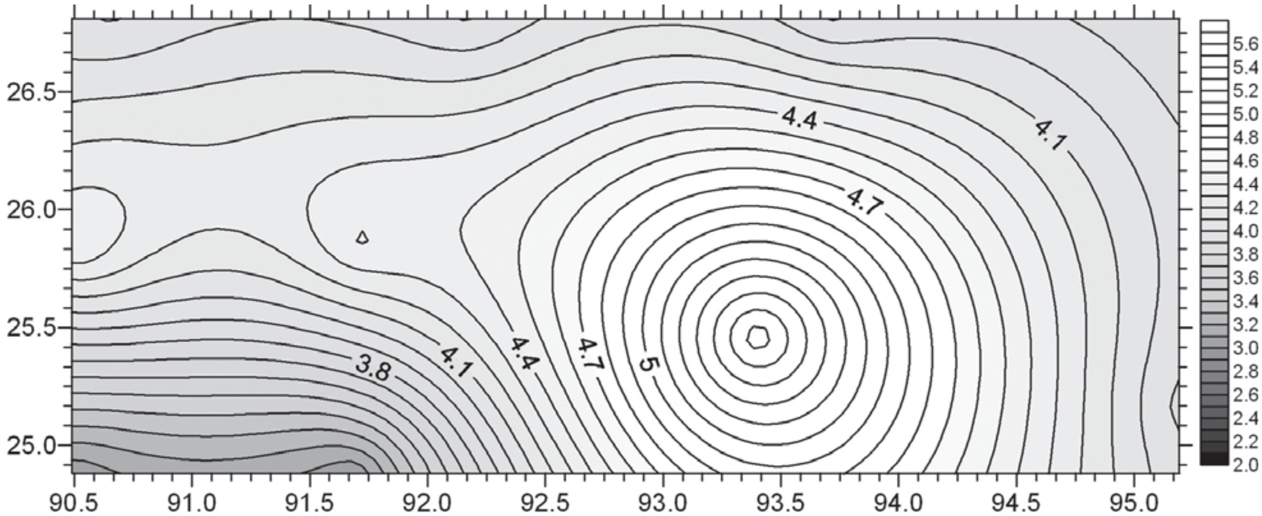

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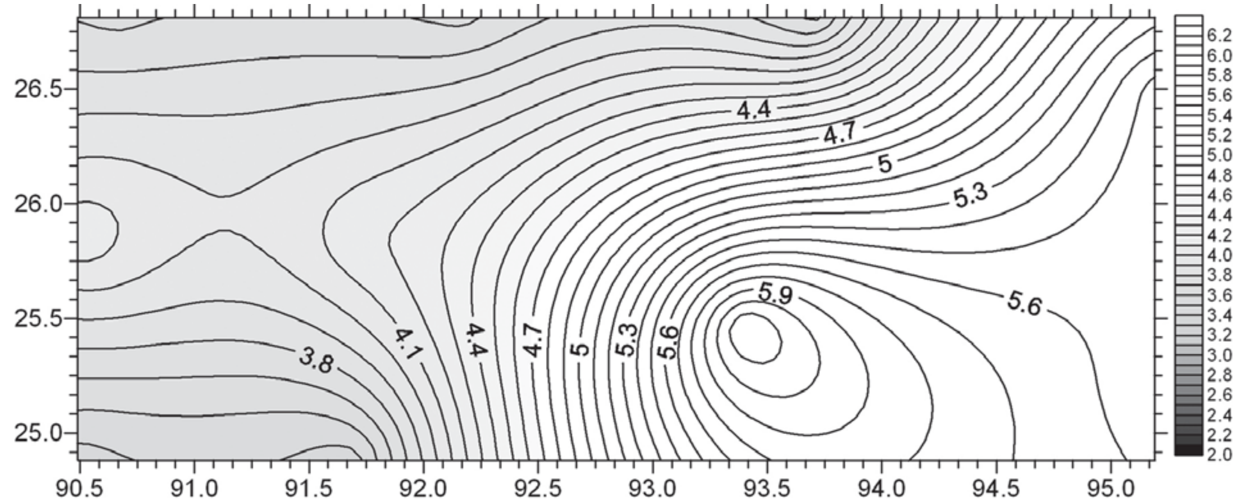
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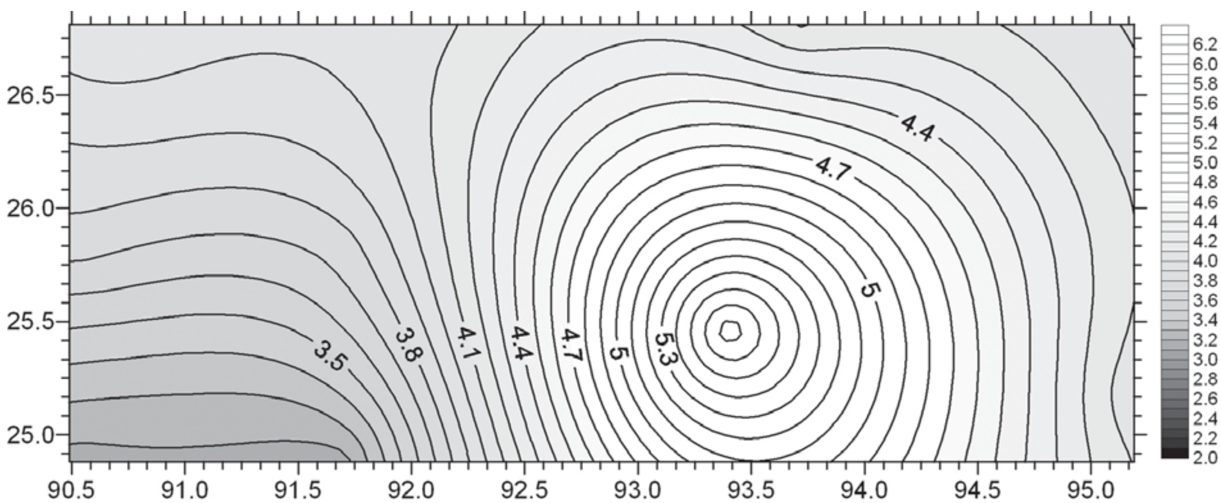
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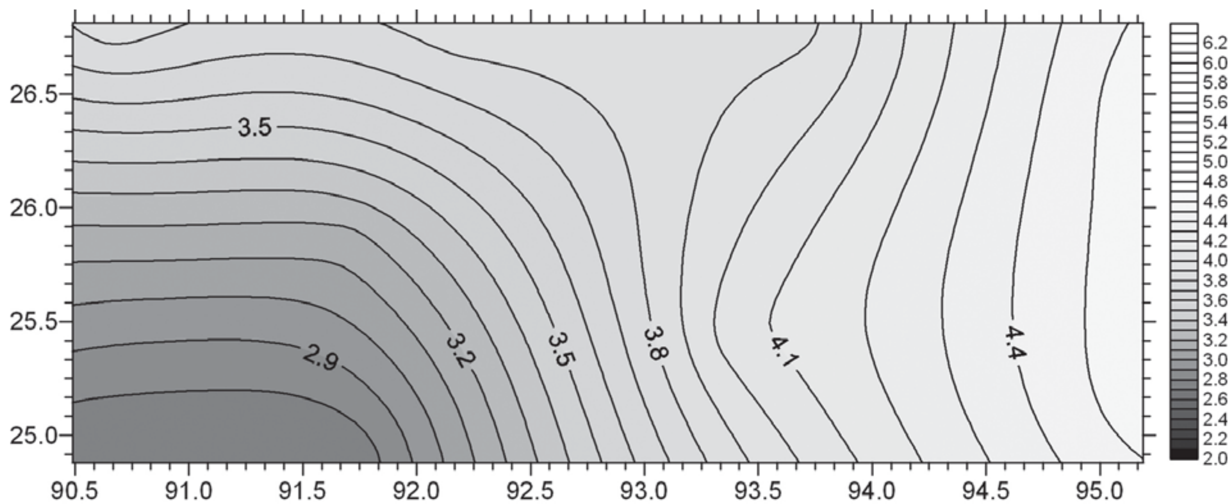
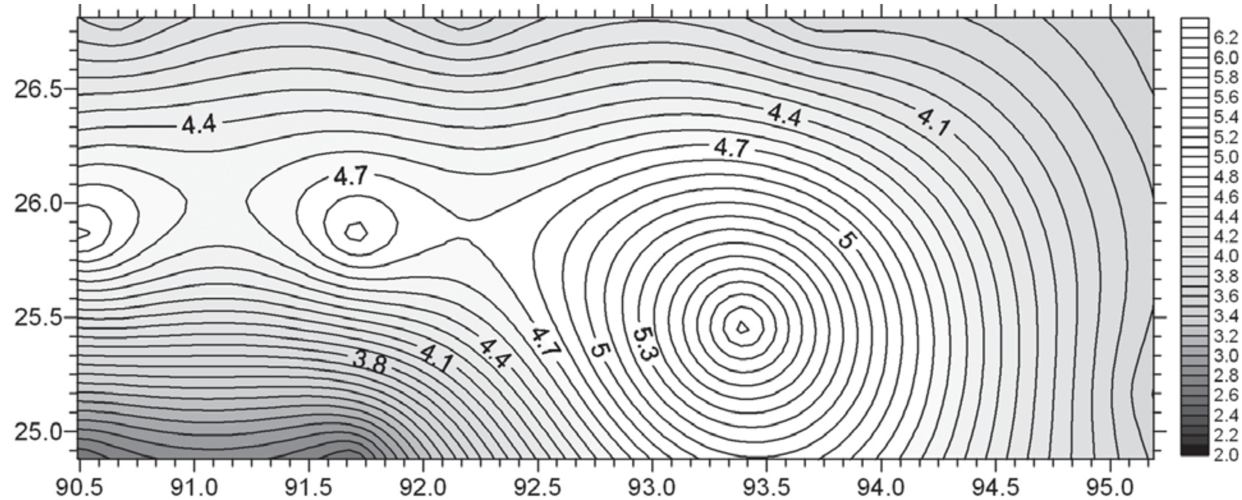
5.3

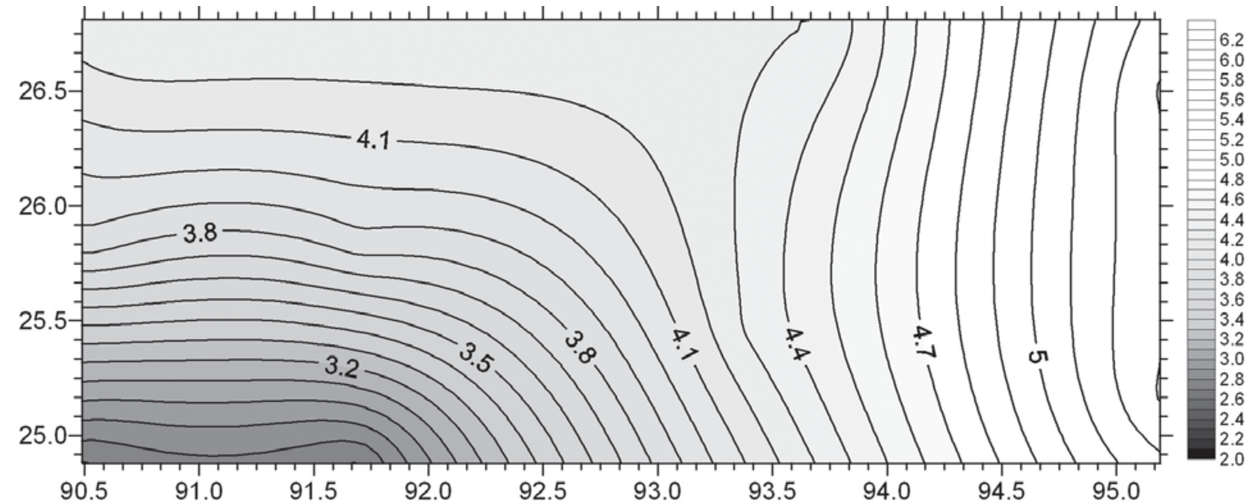
(7d)


26.5
26.0
25.5
25.0
90.5 91.0 91.5 92.0 92.5 93.0 93.5 94.0 94.5 95.0
6.2 6.0 5.8 5.6 5.4 5.2 5.0 4.8 4.6 4.4 4.2 4.0 3.8 3.6 3.4 3.2 3.0 2.8 2.6 2.4 2.2 2.0
3.5
2.9
3.2
3.5
3.8
4.1
4.4

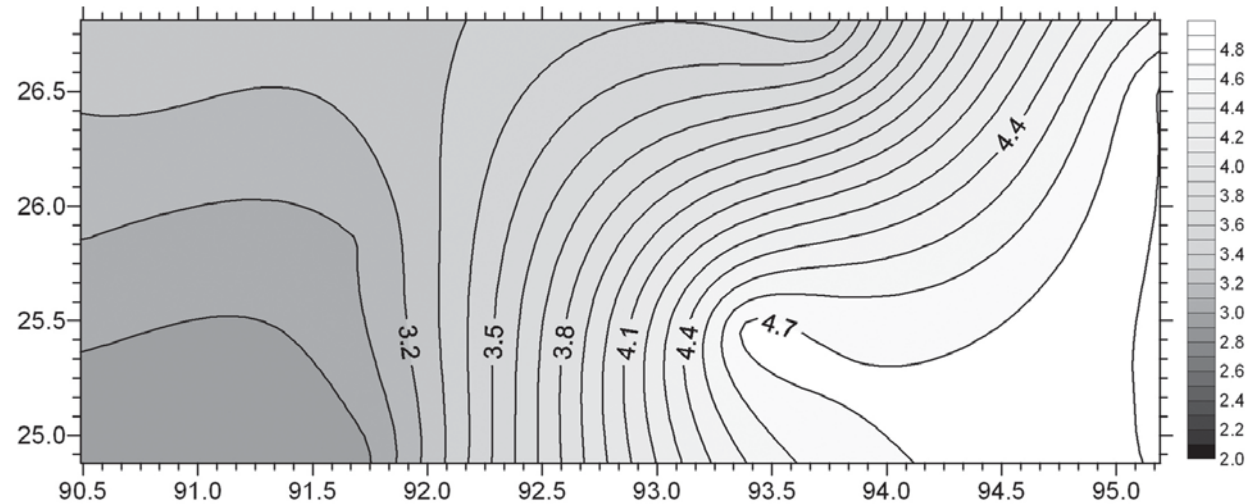
(7e)



(7f)



(7g)



(7h)

Figure 7. Mapping of a-value for different depth-levels ('h' km) beneath northeast India. a) layer I, depth: 0.0≤h<12.0; b) layer II, depth: 6.0≤h<18.0; c) layer III, depth: 12.0≤h<24.0; d) layer IV, depth: 18.0≤h<30.0; e) layer V, depth: 24.0≤h<36.0; f) layer VI, depth: 30.0≤h<42.0; g) layer VII, depth: 36.0≤h<48.0; h) layer VIII, depth: 42.0≤h<54.0.

DISCUSSION AND CONCLUSIONS

Uneven spatial distribution of seismicity and a-values (Figs. 2, 3b and 5) clearly indicates wide variation of stress level as well as heterogeneity in the lithosphere in northeast part of India. Numerous Hills, elevated lands and flat valley those evolved through vertical tectonics (Evans 1964) presumably control the seismicity of this area. Tectonic adjustment between these geomorphic features and their occasional reactivation leads more seismic activity in various parts of northeast India. Volcanism induced deep-seated fractures zones and associated vertical tectonics (Evans 1964; Verma & Mukhopadhyay 1977) is also contributing enough seismicity along the peripheral zones of the northeast India. The adequate seismicity with higher a-values in different layers along these peripheral zones can be accounted for by a high degree of heterogeneity (e.g., fractures) and low rheological strength of the crust, allowing brittle failure at lower stress levels (Lowrie 1997; Wason et al., 2002; Khan 2003). Another higher seismicity zone with higher a-values between the Himalayan thrust sheets and the Shillong Plateau possibly related with higher rock-fractures density caused by strong tectonisation of the region following several earthquakes (Khan & Chakraborty 2007).

A direct comparison of Bouguer gravity anomaly map (Fig.4 of Verma & Mukhopadhyay 1977) with the a-value maps (Fig.5) reveals very interesting results. The positive gravity anomaly, particularly with steep gradient, towards southwest of the study area is associated with low a-values at different depth level. The high a-values of the eastern parts can indirectly be linked with comparatively lower Bouguer gravity anomalies decreases to as low as -260 mgal towards further northeast in the Upper Assam area. Positive Bouguer (~+40 mgal) and Isostatic (~+100 mgal) anomalies (Figs. 4 and 13 of Verma & Mukhopadhyay 1977) rule out the compensation of the Shillong Plateau area (Chen & Molnar 1990) with the opinion that if the average elevation (~ 1km) of the Shillong Plateau was completely compensated by a thick crustal root, a negative, not positive, Bouguer anomaly would result. Similar opinion has also been advocated by Mitra et al. (2005). We thus strongly believe that the positive Bouguer anomaly values as high as +40 mgal, the steep gradient in Bouguer anomaly map, positive Isostatic anomaly of +100mgal and low a-values are all consistent with a thinner crustal root, uplifted Moho and a higher concentration of stress in the southwestern part of northeast India. However, the more refined layer in the depth range between 18 and 22 km documents highest seismicity concentration all through the northeast part of India and is suggestive of the presence of mid-crustal seismic domain. Mitra et al. (2005) from their study also postulated single seismogenic layer for the entire northeast India. This present study therefore reveals that the region beneath the northeast India accounts for various stress level, and indicates a significant variation of heterogeneity, both laterally and vertically (extends from lower crust down to upper mantle). Further, the region is under the influence of compressive stress, resulting from both the collision at the Himalaya (Tapponnier & Molnar 1976; Seeber, Armbruster & Quittmeyer 1981) and its subduction below the Indo-Burman Ranges (Fitch 1970; Verma, Mukhopadhyay and Ahluwalia 1976; Khan 2005b), and this effect is quite prominent in the deeper layer noted under the present study.

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