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Anomalous b-value in seismogenic layer of Bhuj Region

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ABSTRACT

The earthquake size distributions follow, in most instances, a power law and slope of this power law, defines the 'b-value'. The parameter b is believed to depend on the stress regime and tectonic character of the region. High and low b-value probably means low and high stressed zone, respectively. Fault/faults has tendency to accumulate the stress. Depth wise, unalike segments of fault act in their own way for stress accumulation, depending on geology and rheology. For study, Bhuj aftershock zone is considered, which chiefly underlies two faults i.e. North-Wagad (NWF) and Bachau fault (BcF). The b-value study of this zone, distinctly demarcates faulted line and its different segment linked b-value are found in correlation with the stress-accumulation. It gives a very clear picture that b-value is not only helpful in demarcation of faulted depth line but also in prediction of segments of stress accumulation. This may help in study of earthquake prediction.

The studies reveal that the b-value more often decreases with depth. This worldwide behavior is found to be valid for about 32% of the entire seismically active crust, at the 99% confidence level. About 2% of the crust only displays the opposite b-gradient. Kachchh is among the rare seismically active crust, which shows negative b-gradient. One plausible explanation for reverse characteristic of b-value could be the styles of faulting.

INTRODUCTION

The classical frequency-magnitude distribution, FMD (Gutenberg & Richter 1944) is commonly used, especially in association with earthquake precursors. The FMD describe earthquakes occurring in a given region as a function of their magnitude M as:

$$\log N = a - b M \quad \text{.................... (1)}$$

where, N is the cumulative number of earthquakes with magnitude equal to or larger than M, and 'a' and 'b' are real constants that may vary in space and time. Often instead of magnitude M, the log of seismic moment or log of seismic event energy is used. The parameter 'a' characterizes the general level of seismicity in a given area during the study period i.e. higher the 'a' value, the higher the seismicity. The parameter b is believed to depend on the stress regime and tectonic character of the region (Allen et al., 1965; Mogi 1967; Scholz 1968; Tsapanos 1990). General "global" average value of the b parameter, obtained by mixing different crustal rock volumes and different tectonic regimes, is close to unity. Regionally, changes in b-value are believed to be inversely related to changes in the stress level (Bufe 1970; Gibowicz 1973). An increase of applied shear stress or effective stress results in decrease of b-value (Urbancic et al., 1992). A smaller b-value probably means that the stress is high in the examined region. Decreasing b-value within the seismogenic volume under consideration has been found to correlate with increasing effective stress levels prior to major shocks (Kanamori 1981). Recent studies reveal that the b-value is also related to the depth (Weimer & Benoit 1996; Mori & Abercrombie, 1997; Wyss, Shimazaki & Weimer 1997; Wyss et al., 2001).

The b-value in eq. (1) can be estimated either by linear least squares regression or by maximum-likelihood using the equation (Aki 1965; Ustu 1965; Bender 1983)

$$b = \log e / [M_{mean} - M_{min}] \quad \text{...(2)}$$

where, M_{mean} denotes the mean magnitude and M_{min} the minimum magnitude of the given sample. The determination of M_{min} relies on the magnitude distribution (eq.1). In most cases, the minimum magnitude of the data set is determined by plotting the cumulative number of events as a function of magnitude. These plots are then fitted with a straight line and M_{min} is the level at which the data fall below the line. The magnitude of completeness, Mc, has to be corrected by ΔM/2 to compensate for the bias of rounding magnitude to the nearest ?M bin. Therefore a correction of

$$M_{min} = Mc - \Delta M/2 \ldots\ldots\ldots\ldots.(3)$$

must be applied. More details are described by Wossener & Wiemer (2005).

The Spatial variations of b-value have been studied in a number of seismically active areas by other researchers. Statistically significant changes of b-value have been observed in various stress regimes such as a subducting slab (Wyss et al., 2001), along fault zones (Wiemer & Wyss 1997) and in aftershock zones (Wiemer & Katsumata 1999). Gerstenberger, Wiemer & Giardini (2001) used the depth distribution of b-value to study structural anomalies and stress level in the crust and in the upper mantle. Schorlemmer, Weinner & Wyss (2004) demonstrated that b-value systematically varies for different styles of faulting. Normal faulting is associated with the high b-value; strike-slip and thrust events correspondingly show intermediate and low values.

Present work deals the study of the b-value depth variation for Bhuj aftershock zone which lies in Kachchh rift, Gujarat, India.

SEISMICITY HISTORY OF KACHCHH REGION

The Kachchh region is one of the seismically most active intraplate in the world. The most disastrous event for this region in this century was that of January 26, 2001, that occurred at latitude 23.4420 °N and longitude 70.3100 °E (ISC).The earthquake triggered number of aftershocks, which are still enduring.

The past seismicity of Kachchh region includes; seismic event of May, 1668 which jolted the western part of the Kachchh, epicenter was found in Samaji town (presently in Pakistan). Another earthquake on 16 June 1819, of M_w 7.8 occurred in the Great Rann of Kachchh. This earthquake formed a 90-km long scarp, gave maximum vertical displacement of 6 m (and 3 m subsidence), and was named "Allah Bund" (The Wall of God). On 19 April 1845, earthquake hit Lakhpat (of M 6.0) with 60 strong aftershocks followed by earthquake of M 6.3 on June 19, 1845. Then, Anjar earthquake of 21 July 1956 occurred and recently Bhuj earthquake on 26 Jan 2001 of Mw 7.7 shook whole of the Indian continent.

The Kachchh region is a rift basin and is distinguished by E-W oriented highlands and low laying basins or 'Ranns'. A number of faults control the structural trend of Kachchh rift. The strike of faults is approximately E-W. But NPK, ABF (North of Kachchh) swings to NE-SW trend and merges with the Delhi-Aravalli strike trend while KMF follows NW-SE trend. The Kachchh basin is filled with sediments ranging from middle Jurassic to Tertiary age. The Deccan traps lavas, late cretaceous to early Paleocene, divide the Mesozoic and tertiary stratigraphy of Kachchh basin. After the initial period of extension (rifting) (Talwani & Gangopadhyay 2001) the Kachchh rift basin (KRB) has been subjected to compression by resultant back push of Himalaya at least since 20 ma (Likhar, Kulkarni & Kayal 2006).

THE DATA

For the present following studies:-
1. Locked and unlocked segment of faulted block,
2. Depth variation of aftershocks and b-value,
3. Ratio of shallow to deep b-values (r_b),

we made use of a highly reliable data set with 2498 events reported by Hirosaki University, Japan (Bhuj2) to ISC, covering a time period (28 Feb to 6 March' 2001) of seven days, following the 2001 Bhuj earthquake. From 2498 events we have selected 745 events of magnitude greater than 1.2 i.e. M_{min}=1.2. Here, in all studies we have utilized 745 data only because of its good depth resolution and accuracy.

Hypothetical Model: The locked and unlocked segments of a faulted block

The faulted block encloses two kind of segment, locked and unlocked segments. The locked segments oppose the faulting while unlocked segment go through creep, and continuously releases the stress. Large stress builds up in the locked segment of the fault which leads to main shock, though the creeping segments contribute in a main rupture by smaller amounts of co-seismic slip. A fault may involve one or several locked zone, depending on which it generate large to great earthquakes. Varying pore pressure is another parameter that is capable of causing the observed differences in locked and unlocked segments (Byerlee & Savage 1992; Miller 1996). Given the fault model described above, one should expect variations in b values in different fault segments because fault properties and stresses vary. The reason for the low b-value is likely the state of stress near the locked segment. Creeping segments of faults on the other hand display high b values. To map the faults with the above idea, the depth cross section of b-value of Bhuj aftershock is studied.

The b value depth cross-section (Fig 1) is

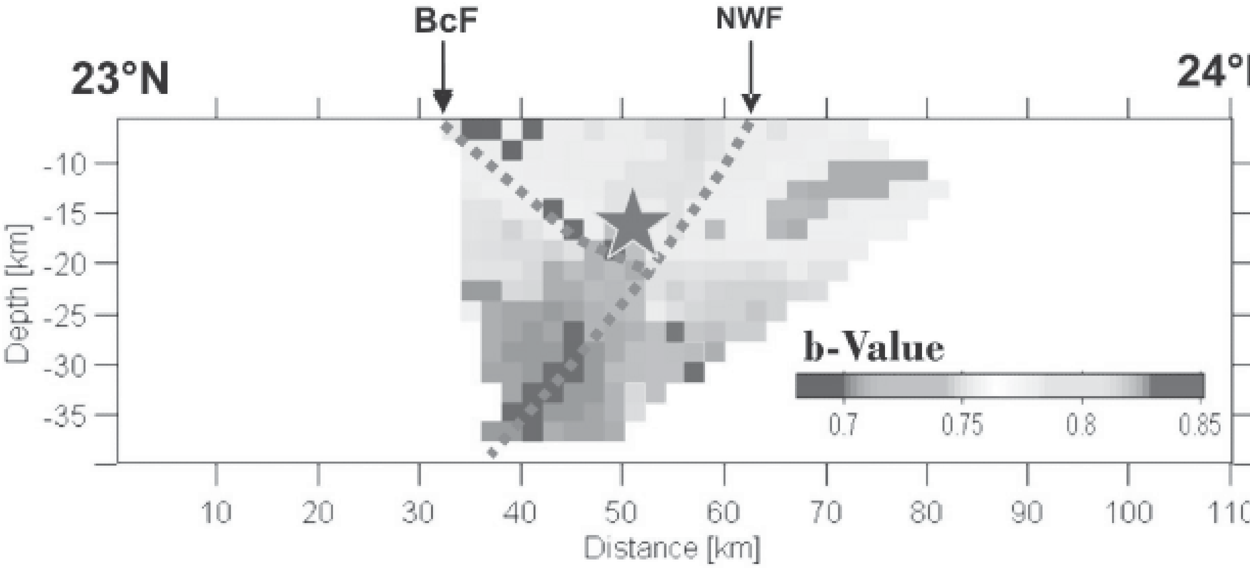


Figure 1. The depth cross-section of b-value between latitude 23 N to 24 N, along a 50 km wide profile (to cover the most of the aftershock event) at 70.31 E. The location of faults is marked by broken lines. The star is representing the location of main shock. The low *b*-value zones are indicative the potential locking zones of the fault.

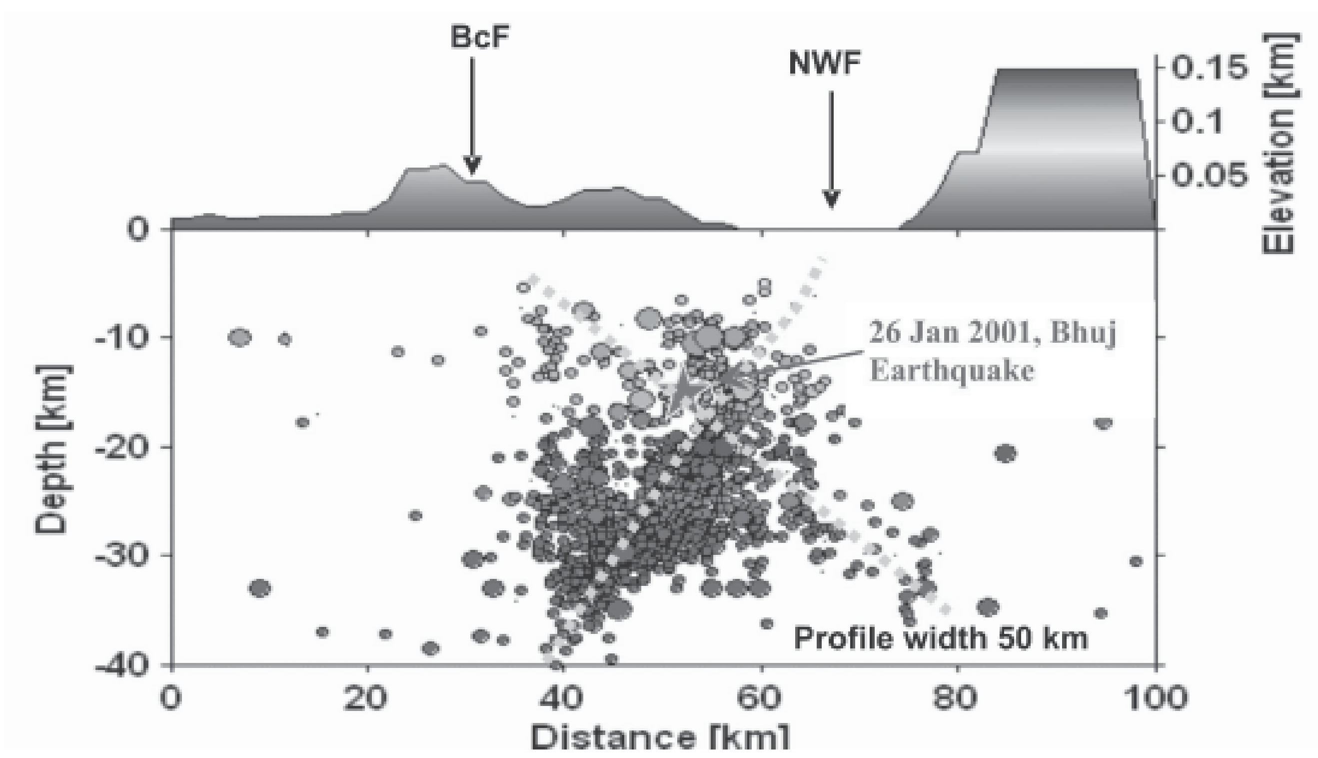


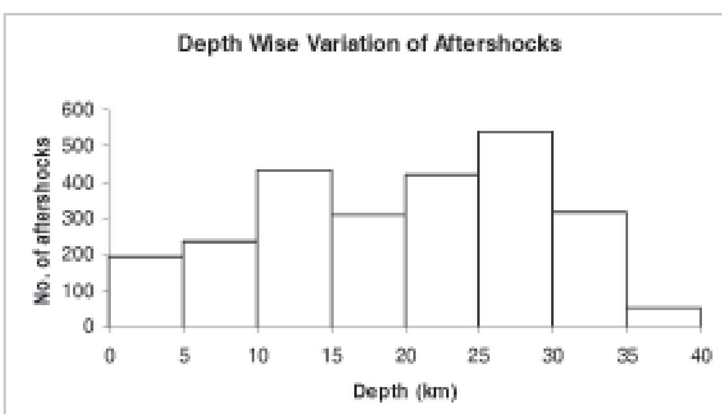
Figure 2. Profile at longitude 70.31°E, covering the hypocenters in 10 km width along the central profile line in between latitude 23°N to 23.91°N, showing the presence of conjugate fault (broken line) along with the topographical elevation. The representation of hypocenters is magnitude sensitive.

calculated, with minimum 150 events in grids of (2 x 2) km^2 along a 50 km wide profile (to cover the most of the aftershock event) at 70.31 E, between latitude 23 N to 24 N. The 10 km wide magnitude judicious depth cross-section of the Bhuj aftershocks is shown (Fig 2), to demarcate the presence of two intersecting faults i.e. south dipping (NWF) and north dipping (BcF) (Bhatt et al., 2009). Along these fault trends the low b-value patches (b < 0.8) are evident, which is distinguishing the faulted zone in depth cross section, (Fig 1) representing the effectiveness of b-value in probable demarcation of fault zone. Above the fault intersection vicinity, the zone demarcates low b value i.e. stressed zone. This is the location of Bhuj main shock (i.e. Star) Mw 7.7). The fault BcF, showing three strong patches of low b-value, at depth greater than 10 km, signifies that these segments of the fault may act locking zones and may hinder the creeping and rupture propagation. The hindered segment of fault may accumulate stress and thus become act as the potential zone for future earthquakes. It is evident (Fig 1) that the deeper portion of NWF also shows the strong low b-value. Despite that the maximum rupture of the main event has propagated along NWF fault (Mandal et al., 2004), strong patches of b-value may represent that these segments can generate strong earthquake / earthquakes. The above idea, with lucid demarcation helps in identifying the fault and different locked/unlocked segments, is found working well for the Bhuj region. The utilized data for the study is of Feb.-March of year 2001, from April 2001 to 2007, the hypocenters of numbers of earthquakes are found to happen in the zone of strong low b value patches. Itself it is sufficient to verify the affectivity and applicability of the above idea.

Depth distribution of the Bhuj aftershocks and b-value

The bar diagram and depth distribution table showing the earthquakes spread with depth are shown in Fig 3. It is clearly evident, the maximum earthquakes have happened in depth range 25 to 30 km. This depth ranges contribute 22% of total seismicity. The depth range 20 to 25 km and 10 to 15 km, each contributed 17 % of total event. By increasing the bin size from 5 to 10 km, the depth range 20 to 30 km would contribute maximum seismicity and is 40% of total seismicity. This depth zone (i.e. 20-30 km) is the seismogenic zone as shows the occurrence of maximum number of aftershocks. The depth distribution of b-value estimated with minimum 50 events and maximum 100 events and fixed Mc = 1.2 (fig 4). The maximum likelihood method allocates marked increase in b-value in the seismogenic zone (22-30km) (fig 4). Gerstenberger, Wienner & Giardini (2001) presumed that differences in stress level are main factor in controlling the depth dependency of b-value. This does not seems plausible for Kachchh region as showing high b-value i.e. low stress. The increase in b-value in seismogenic zone may likely indicate reasons like i) weak stress, ii) creeping between footwall and hanging wall and accordingly low magnitude earthquakes only, or iii) faulting style.

The likelihood of weak stress in these depths done may be ruled out as this zone has contributed maximum 40 % of total seismicity. Creeping is seismogenic zone is plausible but seems not as contains many big magnitude earthquakes. Finally, the strongest reasonable source then may be the faulting styles where cumulative engage between different size



Depth	Total no. of Earthquake	Percentage %
0-5	191	8
5-10.	236	10
10-15.	431	17
15-20.	307	12
20-25	420	17
25-30.	542	22
30-35.	317	12
35-40.	52	2

Figure 3. Bar diagram along with data table showing the depth distribution aftershocks. It is evident from the figure that 40% of total events are confined in depth zone of 20 to 30 km, representing for its seismogenic in nature.

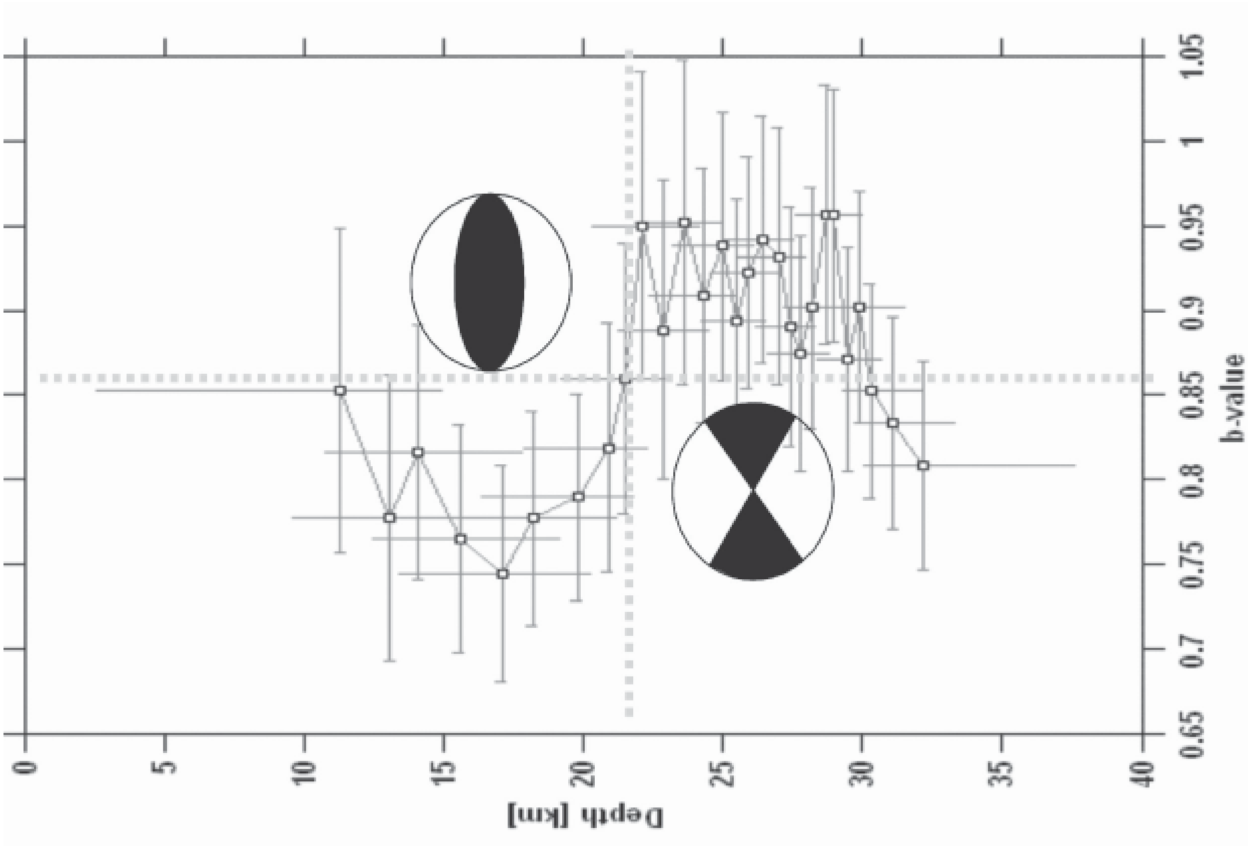


Figure 4. Graph showing the b-value variation with depth. Between depth zone 12 to 22 km and 22 to 32 km b-values are respectively lower and higher than 0.85. The lower and higher b-value may represent thrust and strike slip faulting respectively.

earthquake and their number plays significant role in b-value change. We will back on this issue in the discussion section.

Ratio of shallow to deep b-values (r_b)

In order to spatially map the r_b, the study area were gridded at 5 km node spacing. The grid is interactively created and seismically inactive areas are excluded. The earthquakes are selected by sampling the closest 100 earthquake to each node, based on horizontal distance. This resulted in cylindrical sample volumes. Only cylinders with radii of 10 km or less were used. This radius was chosen to limit the amount of smoothing between grid nodes and also to maintain the uniformity in cylinder size. Smaller and larger radius cut offs are tested and displayed no difference other than the area covered. Each of these cylinders are then separated in to two depth zones, a top zone from 10 km to 22 km , and a bottom zone from 23 km to 35 km. The gap between the zones is present to maximize the difference in characteristic of two zones and to insure that, when taking in to account errors in depth location, minimal overlap would occur between the top and bottom zones. When mapping b-values, the estimation of magnitude of completeness (Mc) is critical (Wiemer and Wyss, 2000). For each node Mc value is calculated for each depth zone, using forward modeling technique, as described in Wiemer and Wyss, (2000).Once the Mc value computed the b- value could be calculated for both depth zones at every grid node. A minimum of 50 event of magnitude greater than Mc is required for each depth zone otherwise b-value is not calculated at that grid. The calculation of b-value is done by using maximum likelihood method (Aki, 1965). Further, the b-value depth ratio rb is calculated by simply dividing the top zone b-value btop by bottom zone b-value bbottom. The depth ratio rb map, top b-value map and bottom b- value map are shown in Fig 5 a), b), and c) respectively. The depth ratio rb map revels that in the vicinity of 26 Jan 2001 main shock, depth ratio is less. This verifies that for Bhuj aftershock region b-value increases with depth.

RESULTS AND CONCLUSIONS

The low b-value represents the zone of strong events (i.e stressed zone). The strong low b-value patches of fig 1 are found in the vicinity of fault zones, representing the characteristics of the different segment of the fault. The segment which will not participate in the creeping, due to geological and rheological properties, will accumulate high stress. This locked stress with time facilitate earthquake. The locking/creeping model is plausible for the Bhuj aftershock region, as many event's hypocenter has been found falling in low b-value patches. Events falling in low b-value patches are found to have the characteristic magnitude of greater than 3.0.

Supplementary to the locked/unlocked segment isolation, the model is found also helpful in identifying the faulted zone of a fault (fig 1 & 2). Overall, model with lucid demarcation helps in identifying the fault and their locking/creeping sections, differing in geological and rheological properties, is found working well for the Bhuj region.

The depth distribution of aftershock characterizes for events concentration in the zone of 10 to 35 km, contributing 80% of total events. Between depth range 10 to 20 km and 20 to 35 comprises total of respectively 41% and 37%. Kayal et al., (2002) studied the different depth events and concluded the results that shallow and deep events show the strike slip faulting while the intermediate event (15 $<d(km)<$ 25) shows the dominant reverse faulting with little strike slip component. Correlating the Kayal et al., (2002) fault plane solution results with Schorlemmer, Weinner & Wyss (2004) result that b-value systematically varies for different styles of faulting. It is evident that the depth variation of b-value systematically varies for the different styles of faulting (fig 4). The Ratio of shallow to deep b-values (rb) supports the above observation of increase in b-Value with depth.

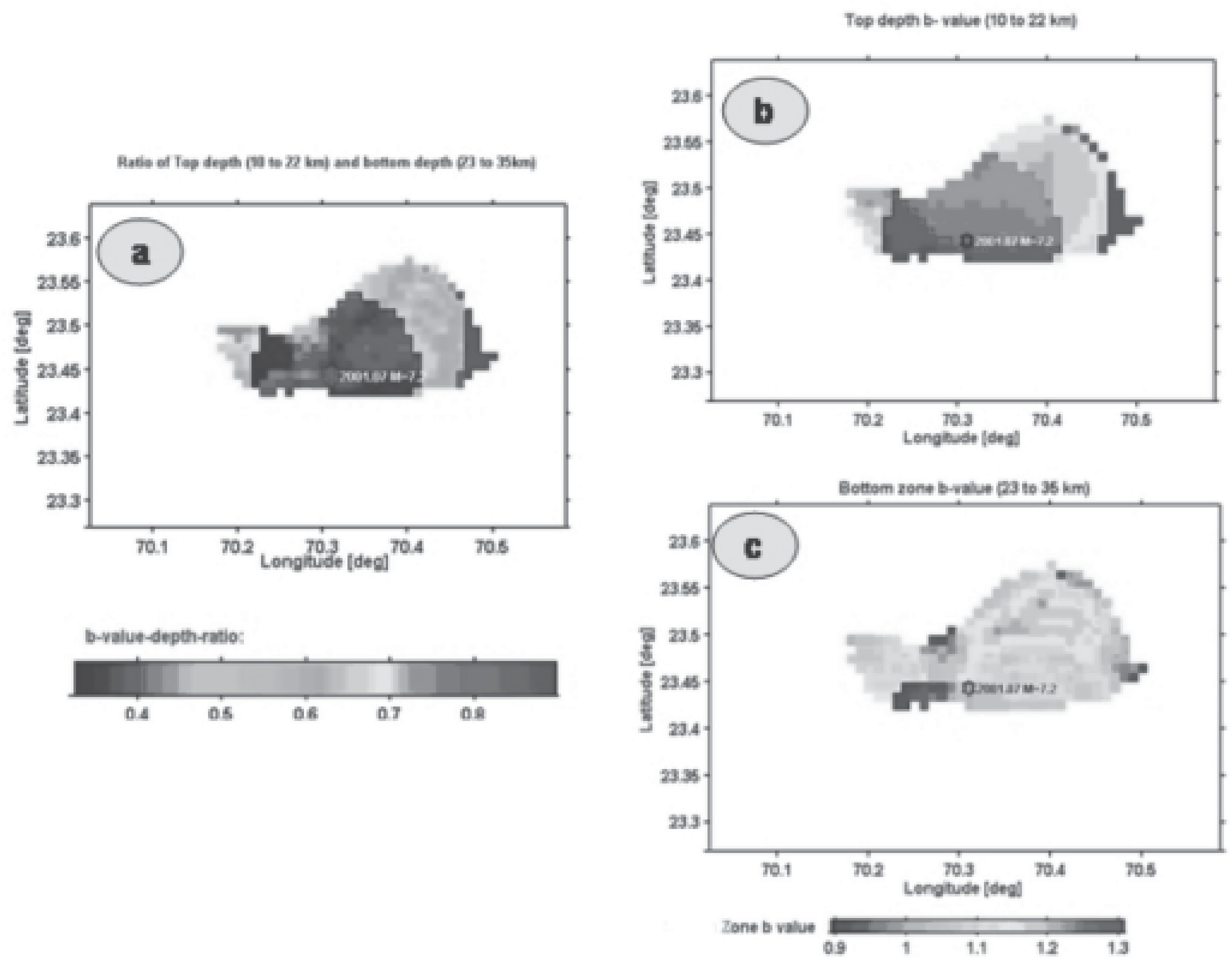


Figure 5. a) Representing the depth ratio r_b map obtained by dividing the top zone (10-22 km) and bottom zone (23 to 35 km) b-value. b) Map representing the b-value variation of depth zone 10 to 22 km. c) Map showing the same as type b) but representing the variation for depth zone 23 to 35 km.

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