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Fractal Approach: Quantification of Seismicity in South Central Tibet

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Abstract

The South Central Tibet (SCT) region is inferred to be an extensional regime since it is predominantly associated with normal faulting with E-W oriented horizontal tension axis representing extension in east-west direction. In this paper the fractal analysis is carried out using the seismicity data ($m_b \geq 3.5$) for last 47 years (1963-2009) in SCT to the north of Central Himalaya. The entire study area is bounded by 29^o-31^o N and 85^o-90^o E. The study escorted to the recognition of a clustering events in two consecutive fifty events window having low spatial fractal correlation dimension (Dc) value ranging from 0.3638 to 0.5451 during the period between 07.26.1998 to 03.23.2002. Relatively two lower Dc obtained prior to strong event. Spatial-temporal clustering of events during low Dc period actually specifies a highly stressed region, leading to increase of shear strain causing weak zone from where the rupture propagation may ultimately nucleate causing large earthquake. This type of clustering pattern study using the well-constrained catalogue data for the SCT region, which has a record of high seismic activity for the entire last two decades, can assist to enhance the understanding and mitigation of earthquake hazard.

Keywords: Fractal spatial; correlation dimension (Dc); clustering; seismicity

1. Introduction

Fractal distributions are the units that are scale invariant and self similar. These behaviors are reflected in several empirical power laws of different branches in geology and geophysics [1]. Seismic activity in a region has fractal structure with respect to time, space and magnitude [2] hence a fractal approach can be used to make probabilistic seismic hazard assessment [3]. Several authors used this method in various seismically active region to study fractal nature of earthquake occurrence, fault systems and which imposed hazard for example Kanto Japan [4], Mexican subduction zone [5], North Anatolian block [6], Himalayan region [7], Koyana- Warna region [8], Hokkaido, Japan [9], East Java-Indonesia [10], Northwest Himalayan region [11].

The spatial fractal correlation-dimensions (Dc) provide a quantitative measure of clustering of seismic events in space indicating the seismicity of a region. Such parameter measures quantitative seismicity spatio-temporally from sliding windows with time containing certain number of events. In the present paper, we use the fractal approach to study the seismic hazard of SCT region bounded by 29^o-31^{o}N, 85^o-90^{o}E to the north of Central Himalaya. The region is considered for consecutive period with a single entity of 50 events sliding window for which fractal analysis is carried out.

2. Seismotectonics characters of the SCT region

The earthquake activity of SCT region lying to the north of Central Himalaya is influenced by several factors such as highly deformed structures and large crustal thickness, intense geothermal activity as well as high vertical temperature gradient etc. [12]. The region is dominated by normal faulting in which most of the tectonic stresses have orientation along north-south striking normal faults. The Indus Tsangpo Suture (ITS) separates the Himalayas from the Gangdise block which lies just north of it. The Indus suture reflects the relative motion of Indian plate and complex micro-plates towards the north. The Tibetan plateau, to the north of the ITS, has an average elevation of 3 km and some of the hills rise up to 4.5 km. The origin and the evolution of this plateau are directly related to the process of continental collision of Indian lithospheric plate with Asia along the Himalayan arc [13]. This wide tectonic zone consists of Tethyan sediments with marine deposits that range in age from the Late Precambrian to the Eocene [14, 15, 16]. The region has a multilayered composition where earthquake activities occur adjacent to the ITS and north of it. The plateau was uplifted to its present position 10 Ma ago [15, 16] with a crustal thickness of about 70 km in the central part of the plateau. By determining the velocities and propagation characteristics of P_n and S_n waves beneath the Tibetan plateau, Barazangi and Ni [17] reported that the shield like material exists in the uppermost mantle beneath Tibet. The Tibetan plateau is characterized by predominantly normal faulting with extension in the east-west direction [18]. Many transverse lineaments are present between the Gangetic fore–deep and the ITS across the Himalaya. Strikes of these transverse lineaments, in general, vary from northwest to northeast, and are parallel to the outline of the sub-surface ridges underlying the fore-deep [19]. Some of them are reported to be seismically active.

The SCT region is characterized by the isolated clustering of seismic activity where shallow focus seismic activities occur throughout the region but more frequent in the identified active regions.

However, some intermediate seismic activities (from 70 to 110 km) also occur mainly to the north of the ITS which coincide with the clusters of shallow focus earthquake activity. Further, it has been observed that there exists a non-uniform pattern of seismic energy release with depth estimated at 10 km interval, the distribution of maximum seismic energy released (85%) with depth lies 10-20 km in SCT [12].

The seismicity in and around Tibetan plateau is largely controlled by the convergence of the Indian and Eurasian plates [13, 20]. The seismic characteristics of the region are reported by several workers mainly using spatial- temporal distribution of events [21, 22, 23]. Verma and Reddy [22] reported that the Tibetan plateau is not behaving as a single seismotectonics unit, whereas several blocks within it, having different seismic characteristics, move relative to each other. Sato et al. [23] observed that the seismicity is diffused and bears no long linear trend to the north of the ITS. The earthquakes are mainly shallow, but some intermediate depth events have also been observed in certain isolated pockets.

The tectonic environment of this region is almost uniform with extensive north-south trending normal faulting and the isolated clustering of seismic activities are found in association with these faults. Clusters of events was observed to the north of the ITS and it is evident that this might have been caused by the local normal fault, and the influence of Himalayan mega thrusts seems to be remote. The activity has been low for the period 1963-1980, moderate during 1980-1994, and followed by a drastic increase since 1995 [24]. It may be said that the general view of the seismic processes in the SCT region governed by the high heat flow associated with large internal temperature gradient and a large crustal thickness.

Probably, the seismic activities are caused by the change in the physical properties due to the high heat flow associated with plumes prevailing at depths coupled with abnormally large crustal thickness of the region [12]. The distribution of earthquakes in the study region during 1963-2009 is shown in Figure 1.

Although the earthquake frequency is more in recent time, indicating the region is moderately active since large earthquakes are infrequent compared to adjacent Himalayan compression zone. In the region to the north of the ITS concentrated shallow and intermediate events occur frequently. Recently moderate size events are also found to be preceded by anomalous seismic activity prior to mainshock [12].

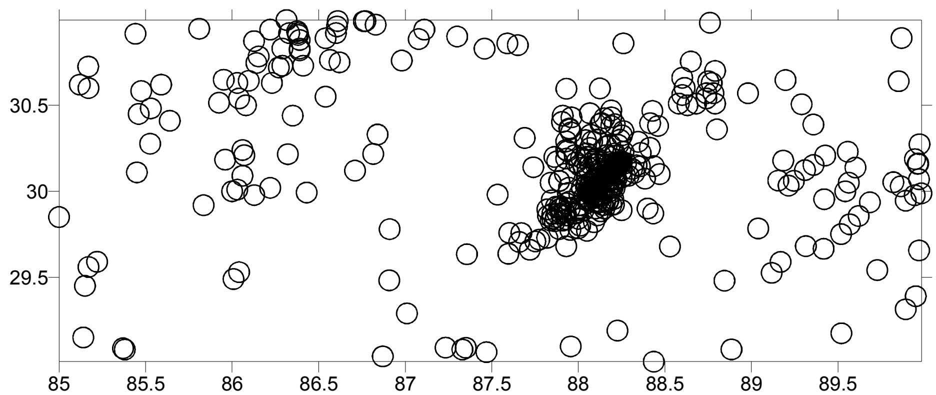

Fig. 1: *Seismicity of South Central Tibet region (1963-2009).*

3. Data and method

The earthquake data base prepared ($m_b \geq 3.5$) from all existing catalogs [12] which has been used for the period 1963-2009 for the study of SCT region. The consecutive 8 windows formed for each 50 events period totaling to 400 earthquakes in the region with latitude 29°N-31°N and longitude 85°E-90°E. Fractal analysis was carried taking 50 events window to investigate the fractal nature of earthquake in the specified region. The scaling range for the linear portion of log r vs. log *C(r)* plot is about 5km - 90km, which is well within the region of the study considered. The value of scaling region is approximately smaller than 1/3 ~ 1/4 of the side length of analysis region complying with the study [4] ruling out boundary effect on our analysis.

In the present paper spatial fractal correlation-dimensions (Dc) and their variation with time is determined using correlation integral method [25] on the catalogue of earthquakes of Central Himalaya. The methodology to compute Dc is as follows:

The fractal correlation dimension is derived from the correlation integral [25-29] which is a cumulative correlation function that measures the fraction of points in the 2-dimensional space. It is defined as,

$$C(r) = \frac{2}{N(N-1)} \sum_{j=1}^{N} \sum_{i=j+1}^{N} H(r - r_{ij}) \quad (1)$$

Where N (for 100 events window, N will be $^{100}C_2$ i.e 2500 and for 50 events window, N will be $^{50}C_2$ i.e 1225) is the total number of pairs of vectors with respect to one another in the fractal set to determine D_C, *r* is the length scale, r_{ij} the distances between the points of a set, *H* is the Heaviside step function. The value of r_{ij} is computed through spherical triangle method [7, 30]. Consequently, *C(r)* is proportional to the number of pairs of points of the fractal set separated by a distance less than r. The fractal correlation dimension is given as

$$Dc = \lim_{r \to 0} \frac{\log_{10} C(r)}{\log_{10}(r)} \quad (2)$$

If the system of points examined fits into a fractal set, the graph between *C(r)* and r in logarithmic coordinates must be a linear function with slope D_C equivalent to the fractal dimension of the system. The graph of C*(r)* versus *r* at different stages of the fracture process, with 50 event windows, is shown in Fig.2. The curves show a clear self-similar behaviour in a wide range of about two orders of magnitude on the space scale. Deviations from linear dependence in the range of large scales are connected with the finite size of samples, while the other deviation in the range of small scales reflects the boundary effect of data for the region of investigation.

4. Results

The spatial distribution of earthquake depicts that epicenters are clustered in different pockets (Fig. 1). Hence to quantify such distribution, the present study is carried out using fifty events window. The study of correlation fractal dimension (Dc) of all events with $m_b \geq 3.5$ occurring in the SCT region during 1963 to 2009 shows that its value fluctuating with time considerably (Fig. 2). The values of variation of spatial correlation dimension with time are given in Table 1 for all considered eight windows. The correlation integral method as described above is used to compute the correlation fractal dimension. It provides information how the past events are having correlation with each other. In heterogeneous region like SCT, the correlation integral approach helps to recognize the cause of strong events.

In the considered SCT region, clustering were observed for events with low Dc values estimated as 0.3638 (for the window 26/07/1998 -08/09/1998) and 0.5414 (for the window 10/09/1998 -23/03/2002) indicating highly stressed period. The variation in correlation dimension from region to region represents seismic clustering within the study region (Fig. 2). The second window having the Dc value 0.9401 for the period 06/05/1990 -10/05/1996 led to a moderate event of m_b 5.9 in 17 March 1996. The fourth window with the Dc value 0.9913 for the period 25/08/1996 -23/07/1998 led to another moderate event of m_b 5.8 in 20 July 1998. However, we can see in Fig. 2 that prior to fifth window low value of Dc indicates shear stress increase. Basically after fifth window we have two consecutive low Dc in windows six and seven; they may be attributed to large number of aftershocks.

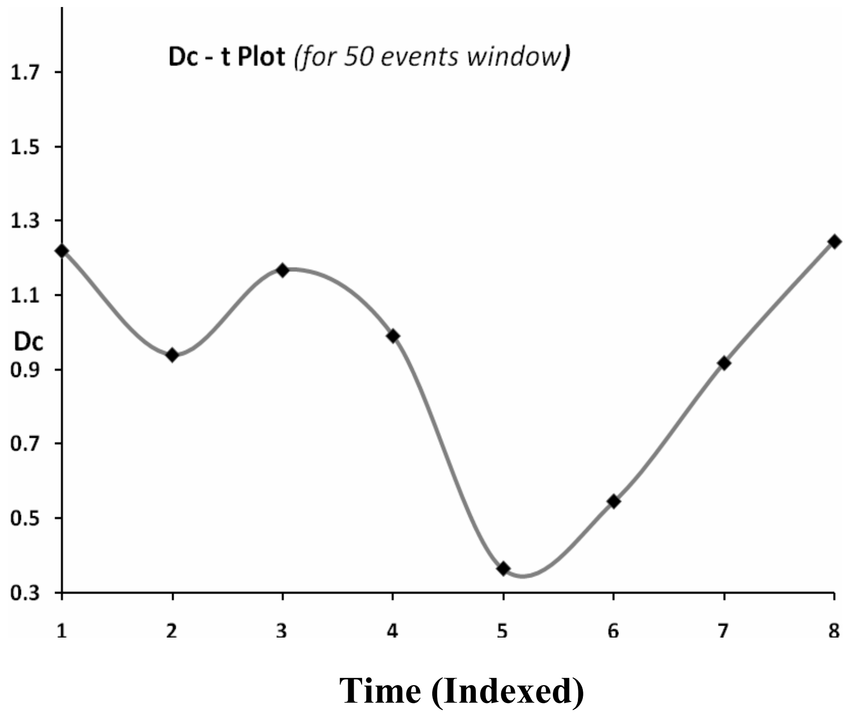

Fig. 2: The temporal variation of Dc for fifty events window is shown, where point given by A and B represent clustering of events with Dc value 0.9401 and 0.9913 for second and fourth windows respectively.

Table 1: Correlation dimension Dc variation with time for the events occurred in the region as shown in Figure 2. Low Dc values correspond to fifth and sixth window.

SN	Time for 50 events	Dc	SN	Time for 50 events	Dc
1	11/06/1963 -18/02/1990	1.221	5	26/07/1998 -08/09/1998	0.3638
2	06/05/1990 -10/05/1996	0.9401	6	10/09/1998 -23/03/2002	0.5451
3	10/05/1996 -23/08/1996	1.1684	7	23/03/2002 -30/09/2003	0.9181
4	25/08/1996 -23/07/1998	0.9913	8	11/11/2003 -07/11/2009	1.2459

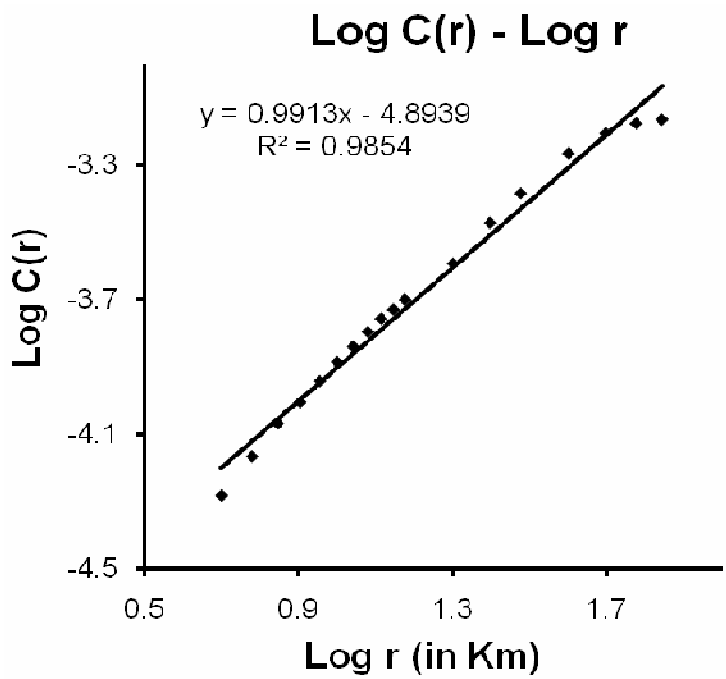

Fig. 3: Log C(r) versus Log r is shown for fourth time window for the SCT region, the slope gives Dc 0.9913. The fitting of trend line demarcates the scaling region obeying power law i.e. scale invariance. R^2 represents correlation coefficients of the regression line.

5. Discussion and conclusion

The advances in statistical analysis of seismological data were discussed by several research papers [31-34]. Such studies provides a new understanding of the scaling parameters of seismicity, which gives an opportunity to evaluate seismic hazard and to estimate short to long term rate of future seismic activity in a given region. The correlation fractal dimension (Dc) provides a quantitative measure of the spatial clustering of epicenters and also of the seismicity of the region. The D_c value is inversely related to the degree of clustering and it requires higher degree of accuracy in both space and time of occurrence of events, as the present analysis depends on the spatio-temporal distribution of earthquake sequences. Thus, it is utmost important to use well constrained complete and homogeneous catalogue.

The SCT zone has complex geodynamic process due to combination of several factors such as northward movement of Indian plate, resistance provided by the thick Tibetan plate and high heat flow [35]. Fractal analysis of seismicity for such a region is useful to correlate the seismogenesis and hence indicator for possible cause of large events. Clustering of events in a short period is an apparent feature of shallow seismic activity whereas long period clustering must be studied in the presence of a much stronger signal. Such clustering for a short period is essential for obtaining the efficient and fruitful model. Therefore a model is necessary to explain such clustering pattern, time- space –focal mechanism regularities of events sequences [36].

The time period of increased moment release in moderate size event has correlations with the regional stress field [37]. Moreover, the critical point model for regional seismicity hypothesized that during low Dc periods the region is in or near to self organized critical (SOC) state in which small events fall into larger events. This may be featured to self similarity of earthquakes of different sizes that may allow fractures to self-organize order to gain criticality as computed by the clustering of events in the region of stress accumulation ultimately causing the main shock (Figs. 4, 5A, 5B, 6A and 6B). It is clear that for the first five time window the clustering is mainly in the central part (Figs. 5A and 5B) where seismic activity is very high with two moderate size events having m_b 5.9 (03/17/1996) and 5.8 (20/07/1998). Both of these events are followed by large number of aftershocks.

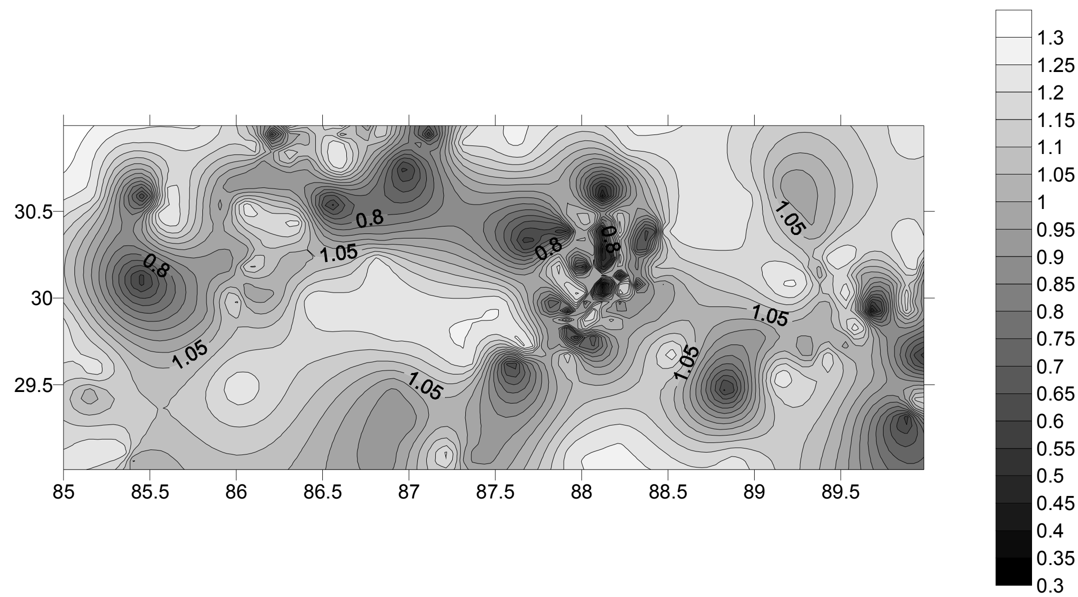

Fig. 4: Dc value contour for the SCT of all eight windows of consecutive fifty events. The lowest D values patch represents possible highly stressed region and clustering of events.

The Dc value varies from region to region however the lowest values are near the center of the region for all the time windows (Figs 4, 5B and 6B). A normal fault trending NE-SW located in the region [18, 19]. The activity in near to this fault is swarm like during 1996 to 1998 [12]. These clustering can be monitored by the correlation integral technique for the major events. The presence of high stress regime for the release of accumulated strain accelerates the seismic activity of moderate sized earthquakes which can be accessed by the precursory spatio– temporal Dc variation study.

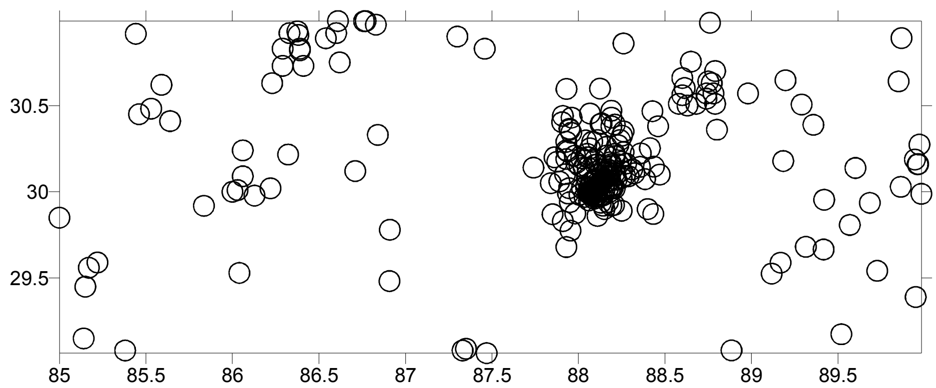

Fig. 5A: Spatial distribution of first five time windows of fifty events.

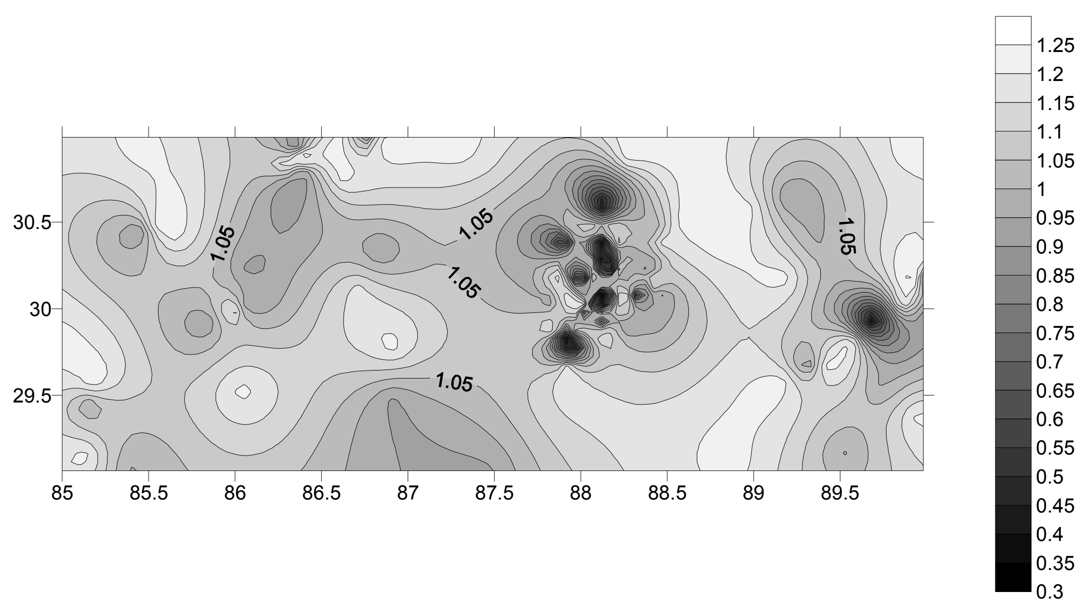

Fig. 5B: Dc value contour for the SCT of first five windows of consecutive fifty events. The lowest D values patch represents possible highly stressed region and clustering of events.

The present study based on fractal pattern of seimsicity showed that Dc value drops significantly in two consecutive windows from July 1998 to March 2002. Such drops represents higly accumulated stress and can be considered as a numerical warning of strong earthqukaes. Strong events following such a period reduces a sufficieent portion of the accumulated regional strain which makes the region out of a SOC state. The considered SCT region presently have high Dc values representing stress accumulation process is quite slow.

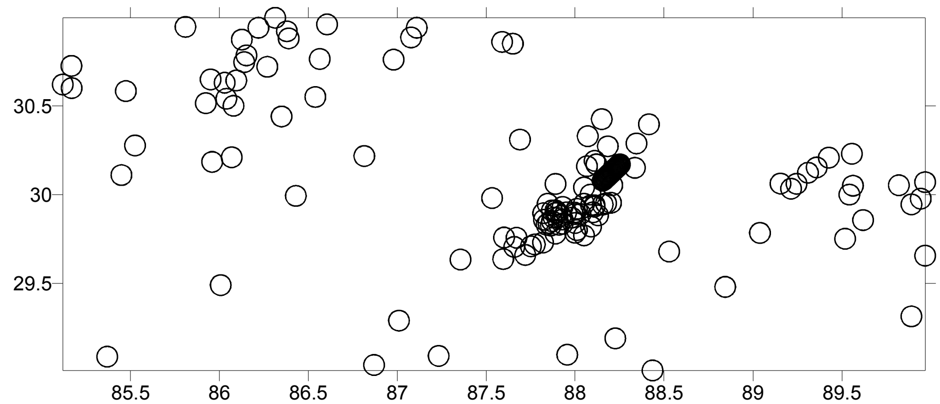

Fig. 6A: Spatial distribution of last three time windows of fifty events

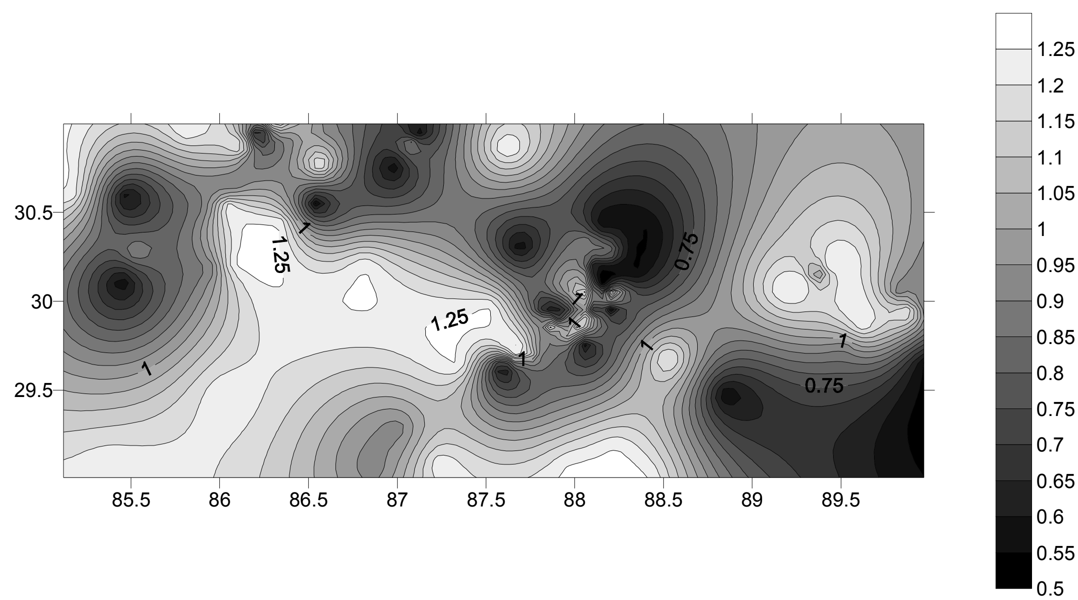

Fig. 6B: Dc value contour for the SCT of last three windows of consecutive fifty events. The lowest D values patch represents possible highly stressed region and clustering of events.

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