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Fractal Nature of Earthquake Occurrence in Northwest Himalayan Region

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ABSTRACT
The Himalaya has seen many earthquakes in past ranging from low to very high magnitude causing massive losses. Earthquakes in Himalaya are mainly caused due to release of elastic strain energy created and replenished by persistent collision of the Indian plate with the Eurasian plate. In this paper the fractal analysis were done for earthquakes (mb≥3) occurred during 1973 - 2008, which led to the detection of a clustering events in three consecutive fifty events window having low Dc value ranging from 0.932 to 0.533 during the period between 12.9.2004 to 28.2.2005.Spatio-temporal clustering of events apparently indicates a highly stressed region, leading to increase of shear strain causing weak zone from where the rupture propagation may eventually nucleate causing large earthquake. This kind of clustering pattern study using well-constrained catalogue data for the Himalayan fault systems of seismically active region can eventually help in the preparedness and mitigation of earthquake hazard.

INTRODUCTION

Himalayan large earthquakes of magnitude > 7 has affected the MHT (Main Himalayan Thrust) among them the recent October 8, 2005 the Muzaffarabad earthquake of Mw=7.7 left the Northwest Himalayan region in catastrophe.

The concern is now about the extent of the Central gap lying between the rupture zones of the 1905 and 1934 earthquakes is very long and has the potential for sustaining two future great earthquakes. In Bilham, Bodin & Jackson (1995) hypothesis, assumption of constant convergence rate of 20 mm yr^{-1} were taken, the maximum slip deficit in the seismic gap may be estimated to be 15m, which may cause one or several magnitude > 8 earthquake.

The need for meticulous scientific efforts for the mitigation of earthquake hazard in earthquake prone areas is very much in need. Recent advances in the understanding of physical processes leading up to the catastrophic occurrences of earthquake permits the assessment of seismic hazard in seismically prone areas to a useful level of accuracy. The spatial correlation dimension (Dc) provides a quantitative measure of the spatial clustering and hence the crustal deformation in space and time nucleation events indicating seismicity of a region (Aki, 1981, 1984; King 1983; Ito & Matsuzaki 1990; Main 1996; Legrand, Cisternas & Dorbath et al. 1996; Oncel & Wilson 2002; Nakaya & Hashimoto 2002; Oncel & Wilson 2004; Ram & Roy 2005; Oncel & Wilson 2006; Roy & Ram 2006; Roy & Padhi 2007; Roy & Nath 2007). The physical laws governing the fractal structures are scale-invariant in nature. The fractal dimension(s) provide a quantitative measure of the spatial clustering of epicenters and also the seismicity of a region. Generally speaking, a fractal distribution means that there is invariance of scale. The generating process has a high level of recursion and the phenomenon is able to cover the embedding space determined by fractal dimension.

In the present study correlation integral method (Grassberger & Procaccia 1983) is exercised on a catalogue of earthquakes to determine correlation-dimension and generalized fractal dimension. Analysis of temporal variations of Dc, are done by considering fifty events consecutive windows for the Northwest Himalayan region including Western Nepal area extending of Latitude 28°N-33°N and Longitude 76°E-82°E is taken separately to study the fractal spatial distribution of events to detect the possible highly stressed region prior to the impending large earthquake.

METHODS

In the present study correlation integral method (Grassberger & Procaccia 1983) is exercised on a catalogue of earthquakes in order to determine the correlation-dimension. The methodology to obtain Dc is given in details as follows:

The fractal correlation dimension is derived from the correlation integral (Grassberger & Procaccia 1983; Hilarov 1998; Ram & Roy 2005; Roy & Padhi 2007;Roy & Nath 2007), which is a cumulative correlation function that measures the fraction of points in the 2-dimensional space and 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 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, *rij* the distances between the points of a set, which is obtained through spherical triangle method explained above, *H* is the Heaviside step function. Therefore, *C(r)* is proportional to the number of pairs of points of the fractal set separated by a distance less than *r*. If the system of points examined belongs to a fractal set, the graph of *C(r)* versus r in logarithmic coordinates must be a linear function with slope D_C equaling to the fractal dimension of the system. The graph of *C(r)* at different stages of the fracture process is shown in Fig.1. 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.

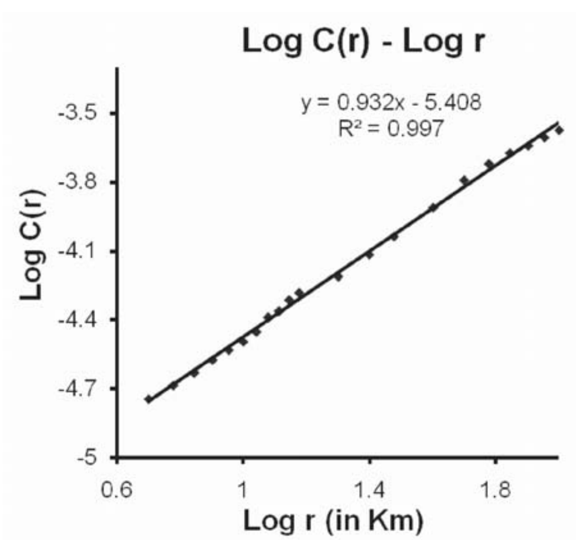

Figure 1. Log C(r) versus Log r is shown for ninth time window for the Northwest Himalayan region with latitude (*28°N–33°N*) and longitude (*76°E–82°E*), the slope gives D_C. Arrows demarcate the scaling region obeying power law i.e. scale invariance. R^2 represents correlation coefficients of the regression line.

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 catalogue.

DATA

The USGS PDE data (mb≥3.5) has been used for the period 1973-2008 for the study of Northwest Himalayan region. The consecutive 16 windows formed for each 50 events period totaling to 834 earthquakes in the region with latitude (*28°N–33°N*) and longitude (*76°E–82°E*) is shown in Table 1. Analysis was done for an active tectonic setting area extending of Latitude 28°N-33°N and Longitude 76°E-82°E to find the Himalayan earthquake fractal nature. The Wadia Institute of Himalayan Geology local network data for the period of 2004 to 2006 were also included for the analysis. 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 (Hirata & Imoto 1991) ruling out boundary effect on our analysis.

Table 1: Correlation Dimension Dc variation with time for the events lying in the region of latitude (*28°N–33°N*) and longitude (*76°E–82°E*) as depicted in Figure 2A

S.No.	Mean Time(t) of each fifty event widow (in months/Remarks)	D_C
1	14.58	1.464
2	72.74	1.437
3	148.44	1.692
4	214.58	1.413
5	264.77	1.699
6	308.21 (6.6Ms,28.03.99)	0.968
7	342.25	1.163
8	371.68	1.323
9	387.66 (Precursor, 17.11.04)	0.932
10	390.51 (Precursor, 08.02.05)	0.618
11	391.727 (Precursor 14.03.05)	0.533
12	393.11	1.308
13	395.31	1.178
14	398.06	1.482
15	402.79	1.687
16	407.12	1.573

RESULTS

The initial study of correlation fractal dimension of all events with mb≥3.5 occurring in the Northwest Himalayan region during 1973 to 2008 shows that its value fluctuating with time (Fig.2A). Dc values have been plotted against mean time of each fifty event window for consecutive periods to study the variation of spatial correlation dimension with time. The correlation integral method is used to obtain the correlation fractal dimension.

Himalayan region of Latitude 28°N-33°N and Longitude 76°E-82°E :

Clustering were observed for events lying within a region of latitude (*28ºN–33ºN*) and longitude (*76ºE–82ºE*) with low Dc values estimated as 0.968 (for the window with mean time on 28.03.1999), 0.932, (for the window with mean time on 17.11.2004), 0.618(for the window with mean time 08.02.2005) and 0.533(for the window with mean time14.03.2005) as indicated in Fig.2A.

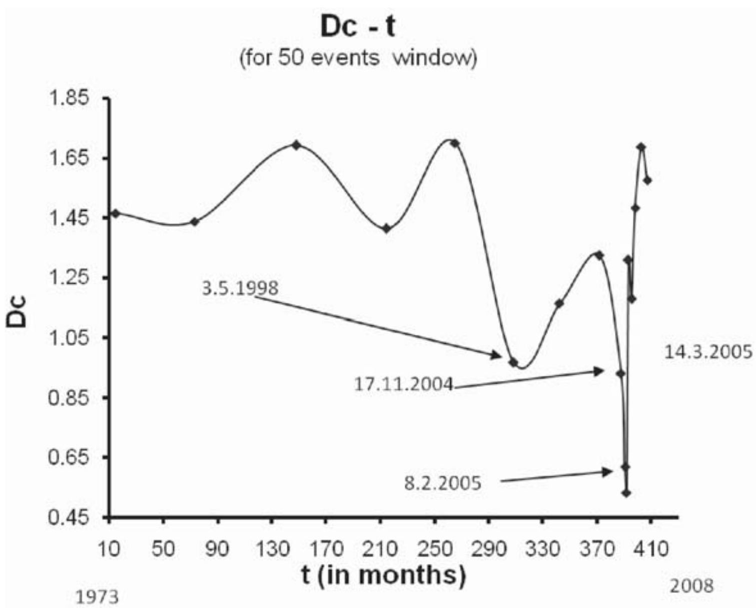

Figure 2A. The temporal variation of Dc for fifty events window is shown, where point given by boxes (28.03.1999), 17.11.2004, 08.02.2005 and (14.03.2005) represents significant clustering of events with low Dc value 0.968, 0.932, 0.618 and 0.533 respectively for the latitude (*28ºN–33ºN*) and longitude (*76ºE–82ºE*).

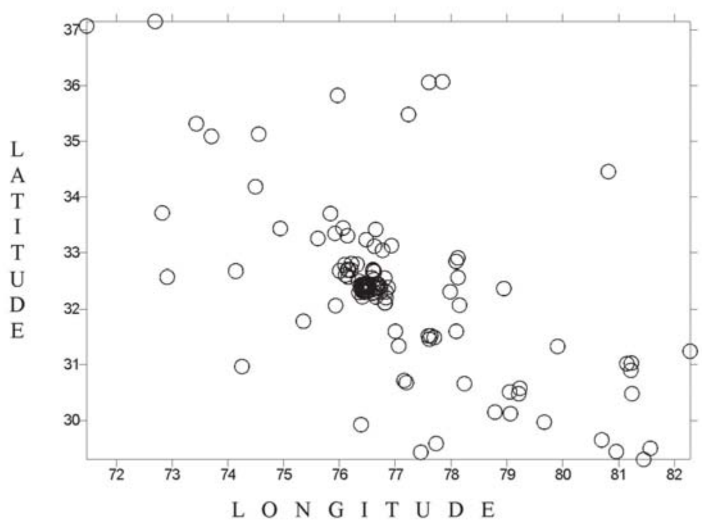

Figure 2B. Spatial distribution for the latitude (*28ºN–33ºN*) and longitude (*76ºE–82ºE*) of three time windows of consecutive 50 events each with three low Dc values estimated during the period 17.11.04 – 14.03.05.

DISCUSSION & CONCLUSIONS

Initially, the correlation- dimension was calculated with the correlation integral and it gave a point of view as to how the past events are having correlation with each other. In other words it can be said that correlation integral approach is a tool, which help to understand the cause of major events in heterogeneous crust. The correlation dimension derived from the above approach reveals that seismic clustering within the subdivisions of the study; the spatial fractal dimension Dc varies from region to region. Short-term clustering is an obvious feature of shallow seismicity, whereas long-term clustering must be studied in the presence of a much stronger signal. The short-term clustering is necessary for obtaining the efficient and faithful model where no practical results can be obtained from long-term effects. Hence a model is needed to explain the short-term, time-space-focal mechanism regularities of earthquake sequences (Kagan 1999).

The combined observational and simulation evidence suggest that the period of increased moment release in moderate earthquakes signal to the establishment of long wavelength correlations in the regional stress field (Jaume & Sykes 1999). The central hypothesis in the critical point model for regional seismicity is that it is only during these time periods that a region of the earth's crust is truly in or near a "self-organized critical" (SOC) state, such that small earthquakes cascade into much larger events. This may be attributed to self-similarity of earthquakes of different scales, which may allow fractures to self-organize in order to attain criticality as detected by the clustering of events at or in the immediate vicinity of the zone of stress accumulation ultimately causing the main shock (figs 2B, 3A & 3B) . These clustering can be monitored by the correlation integral technique for the major earthquakes by considering well-constrained earthquake catalogue of seismically active region of the world. Sornette & Sammis (1995), Sammis, Sornette & Saleur(1996), Saleur, Sammis & Sornette (1996 a, b), and Sammis & Smith (1999) also argue that the observed power-law buildings of intermediate events before a great earthquake represent the approach of the appropriate region toward a state of SOC.

Thus, in order to study the presence of high seismic regime, the favourable condition for the release of accumulated strain; accelerating seismic activity of moderate-sized earthquakes can, therefore, be assessed through the precursory spatio-temporal Dc variation study. Even Kagan (1994,1997) and Main (1995,1996) discuss the advances in statistical analysis of seismological data, and new understanding of the scaling properties of seismicity, including possible universality of major properties of earthquake occurrence provide a unique opportunity to evaluate seismic hazard and to estimate the short-term and long-term rate of future earthquake occurrence i.e., to predict earthquake statistically.

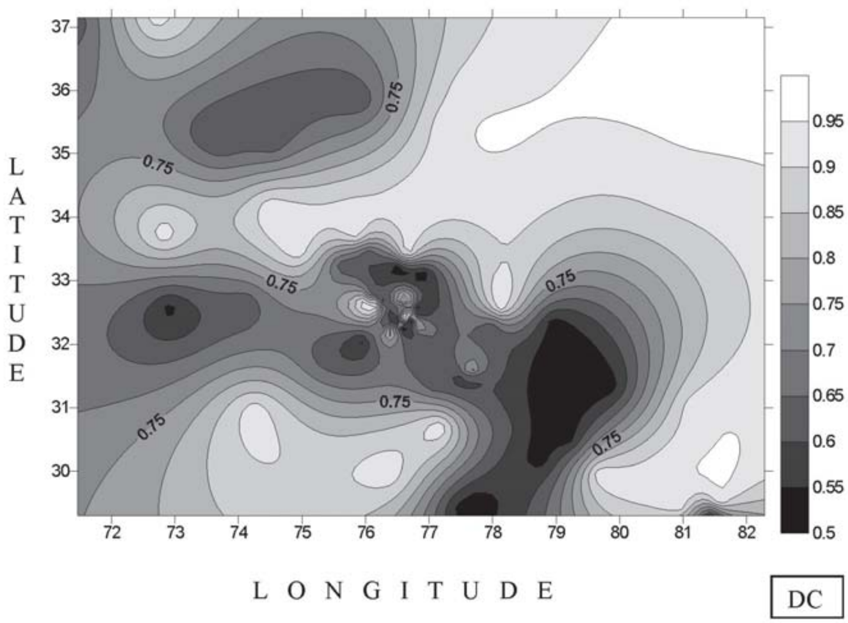

Figure 3A. Dc value contour for the latitude (*28°N–33°N*) and longitude (*76°E–82°E*) of three time windows of consecutive 50 events each with three low D_C values estimated during the period 17.11.04 – 14.03.05. The lowest D_C value patch represents the possible highly stressed region and significant clustering of events.

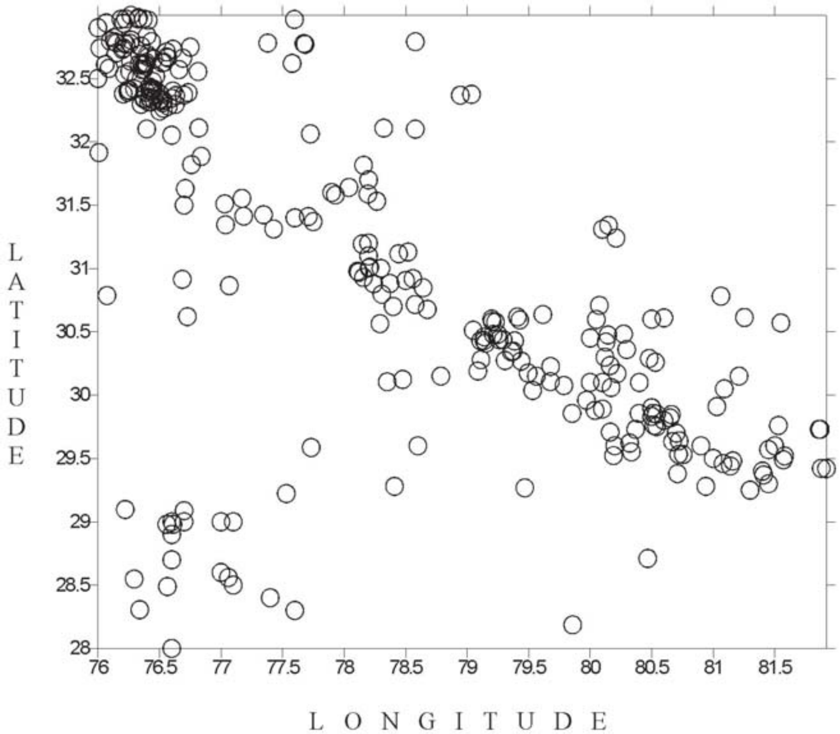

Figure 3B. Spatial distribution for the latitude (*28°N–33°N*) and longitude (*76°E–82°E*) of recent five time windows of 50 events and also the last sixth window of 33 events included, for the period 09.03.05 – 04.09.08.

What is significant in our findings is that DC drops to significantly low values at three time windows with specific mean times when an analysis is performed on an earthquake catalogue of events for the period 1973-2008 to understand the fractal pattern of seismicity. To be very specific about this analysis and its importance can be judged as numerical warning rather than earthquake prediction. The occurrence of large or great earthquake appears to dissipate a sufficient proportion of the accumulated regional strain to destroy these long wavelength stress correlations and bring the region out of a SOC state. Thus, the indicator of SOC state might help in better hazard mitigation and, therefore, disaster management for the western Nepal, seismically active Himalayan region.

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