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Multifractal analysis of 2001 Mw7.7 Bhuj earthquake sequence in Gujarat, Western India

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HIGHLIGHTS

- 2001 Mw7.7 Bhuj earthquake sequence.
- Multifractal behavior.
- Self-organized criticality.

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ABSTRACT

The 2001 Mw7.7 Bhuj mainshock seismic sequence in the Kachchh area, occurring during 2001 to 2012, has been analyzed using mono-fractal and multi-fractal dimension spectrum analysis technique. This region was characterized by frequent moderate shocks of Mw $\geq$ 5.0 for more than a decade since the occurrence of 2001 Bhuj earthquake. The present study is therefore important for precursory analysis using this sequence. The selected long-sequence has been investigated first time for completeness magnitude Mc 3.0 using the maximum curvature method. Multi-fractal Dq spectrum ($Dq \sim q$) analysis was carried out using effective window-length of 200 earthquakes with a moving window of 20 events overlapped by 180 events. The robustness of the analysis has been tested by considering the magnitude completeness correction term of 0.2 to Mc 3.0 as Mc 3.2 and we have tested the error in the calculus of *Dq* for each magnitude threshold. On the other hand, the stability of the analysis has been investigated down to the minimum magnitude of Mw $\geq$ 2.6 in the sequence. The analysis shows the multi-fractal dimension spectrum *Dq* decreases with increasing of clustering of events with time before a moderate magnitude earthquake in the sequence, which alternatively accounts for non-randomness in the spatial distribution of epicenters and its self-organized criticality. Similar behavior is ubiquitous elsewhere around the globe, and warns for proximity of a damaging seismic event in an area. OS: Please confirm math roman or *italics* in abs.

1. Introduction

Model developed by Mandelbrot [1] based on Fractal Multi-fractal theory is usually exploited as a tool to demonstrate complex natural objects and phenomena having scale invariant property. This behavior exists in many natural systems like

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clouds, mountains, coastlines, trees, faults, rock faults, neurons, solar wind, etc. [1–5]. Turcotte [6] illustrated that many geological phenomena are scale invariant, which include frequency size distribution of rock fragments, faults, earthquakes, volcanic eruptions, mineral deposits, and oil fields. The spatial distribution of earthquake and its magnitude distribution, which shows the complex behavior of seismicity, have now been accepted as scale invariant properties by the analysis of various seismic catalogs around the world [7–13]. In a fractal distribution, the number of objects larger than the specified size has a power law dependency. In particular, seismicity distribution presents a fractal behavior and has an interesting multi-fractal dynamics [14,15]. The fractal dimension (Dq) is a reliable parameter to characterize the spatial distribution of earthquake epicenters, especially the degree of clustering. The fractal dimension is a useful tool to characterize the dynamic evolution of a system, and evolving method applied in seismicity analysis, considering a series of complex phenomena, like the interaction between stress and strain, local fluid pressure, etc. [16–22]. The generalization from fractal sets to multi-fractal measure involves the passage from objects that are characterized primarily by one number, namely, a fractal dimension to objects that characterized by a function [23]. Several studies [14,15], and shows that the spatial distribution of earthquakes follow multi-fractal law.

Earlier study on multi-fractal detrended fluctuation analysis (MFDFA) by Aggarwal et al. [24] for the earthquake sequence of Kachchh region using catalog for duration between 2003 and 2012 shows multi-fractal characteristics and indicating a stronger dependence of the multi-fractality on the large magnitude fluctuations. The Kachchh area is seismically active and experienced two great historical earthquakes and several moderate to large shocks over a span of 182 years [25]. The 26 January 2001 Mw 7.7 Bhuj earthquake and its subsequent shocks allowed us to study the Fractal and Multi-fractal behavior for the Kachchh rift. A time sequence of earthquake dataset from 2001 to 2012 has been compiled for the present analysis. The present study was carried out considering a specific window of 200 earthquake events over the entire seismic sequence using the multi-fractal dimension spectrum ($Dq \sim q$) analysis to find the behavior of Dq against q preceding the occurrence of a large earthquake and its subsequent moderate shocks [26]. There generally exist a scale-invariant structure at spatial distribution of earthquake and a co-existence and superposition of other small fractals. This existence can be useful to predict an earthquake of moderate mainshock. The study can be useful for precursor study for an impending future earthquake in the region.

2. Seismotectonics of the area

The Kachchh region (Fig. 1) in Gujarat State of Western India is one of the most seismically active intra-continental region of the world [25,27] and suffered from a flurry of moderate to large magnitude earthquakes since historical times. The largest historical earthquake occurred in the region on June 16, 1819, and created a ∼E–W striking 100 km long highland known as Allah Bund [28,29]. Another damaging earthquake of Mw 6.0 with maximum intensity of IX on MM Scale occurred near Anjar, Gujarat in 1956. The recent one is the 26 January 2001 Mw 7.7 Bhuj earthquake jolted the entire Gujarat state. This earthquake was the strongest ever happened in this part of India over last more than 175 years. The moderate shocks are still continuing within this seismic zone. Although the region lies ∼400 km away from the boundary between the Indian and Eurasian Plates [30] and their ongoing convergence is presumably bearing the current tectonics of this region [31]. The major geological and tectonic proceedings of this region is: (i) break-up of Africa from the Indian block holding Madagascar and Seychelles; (ii) subsequent break-up of Madagascar from India due to Marion hotpot activity and (iii) break-up of the Seychelles plateau from India followed by eruption of Deccan volcanism related to interaction of Reunion hotspot activity occurred during the Mesozoic and Cenozoic periods [32–35]. Thus, the passive continental margin of western India has imprints of two hotspots Marion and Reunion, evolved through several stages of rifting, crustal thinning, magmatic under plating and transient thermal effects [36–38]. The Kachchh rift was initially subjected to extension, later transformed into zone of N–S compression giving rise to strike-slip and thrust tectonics under compressional regime. The continued seismicity in Kachchh region is apparently caused by active operative tectonic environment and the present precursory study will definitely be helpful for understanding the tectonic behavior of the region.

3. Data and its windowing

We carried out the statistical analysis over the sequence of 2001 Bhuj Mw 7.7 earthquake occurring between 2001 and 2012 (Fig. 1). The seismicity was distributed between Latitude 22.5 to 25°N and Longitude 68.0 to 71.5°E. The earthquakes are located in crustal parts and has maximum hypocenter depth up to 40 km. The compiled Kachchh sequence has total of 13 521 shocks recorded instrumentally. We perform the analysis of sequence for completeness magnitude (Mc), which is foremost requirement of any fractal and multi-fractal study. The Mc has been investigated using the maximum curvature method [39] considering the whole sequence. Fig. 2 illustrates the variation of Mc with time and indicates the minimum completeness magnitude 3.0 for the entire sequence. The time variations in frequency of occurrence and magnitude of earthquake are exclusively being controlled by operative stresses or quiescence or clustering phenomena adequately prevails in certain tectonic environment. Workers like Dimri et al. [12], Rastogi et al. [27] and Aggarwal et al. [24] reported the existence of both the quiescence and clustering of events in the Kachchh area. So, we should try here to understand this peculiar phenomenon through windowing of the data.

The point process of an earthquake series can be analyzed in two ways: (1) using the inter-event interval series, and (2) forming its relative counting process. In the first method, the time series is formed by the rule $T_i = (t_i + 1) - t_i$, where

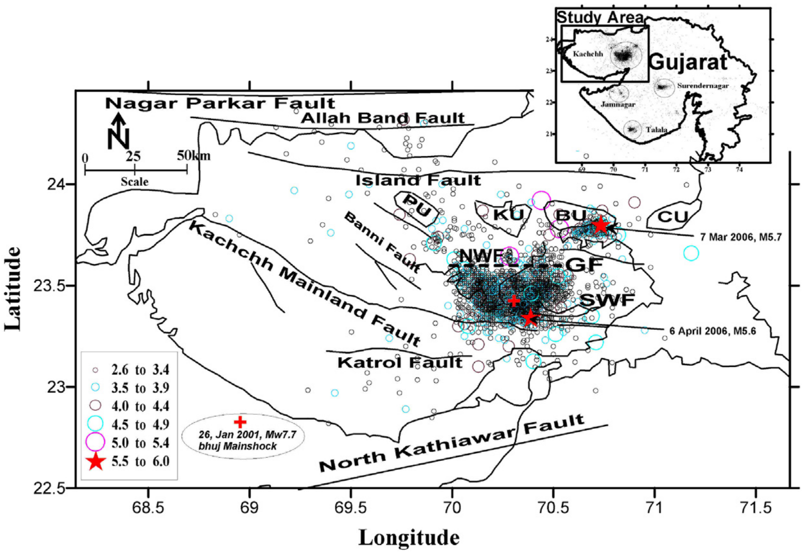

Fig. 1. Map shows the sequence of earthquakes occurring between 2001 and 2012 in Kachchh region, Gujarat, Western India. Solid black lines represent faults and curved line shows the boundary of Kachchh. The inset map at the top right corner show the location of the study area.

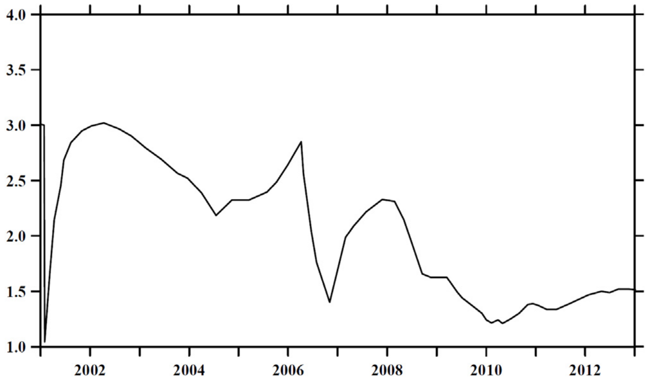

Fig. 2. Time variation of the completeness magnitude Mc computed by maximum curvature method [39].

t_i indicates the occurrence time of the ith event. While in the second method, the time axis is divided into equally spaced contiguous counting windows in a sequence of counts N_i, where N_i represents the number of events falling in the ith window. The latter approach considers the earthquakes as the events of interest and assumes that there is an objective clock for the timing of the events. The former approach emphasizes the inter-event intervals and uses the event number as an index of the time. Both representations allow us to apply several statistical techniques to an earthquake sequence. In this study, generalized dimension Dq or Dq spectra technique is applied using the second approach. Legrand et al. [26] identified the most interesting behavior of decrease of fractal dimension Dq before the occurrence of large earthquake. Legrand et al. [26] and Pasten and Comte [15] using the same methodology derived the equations as expressed in Eqs. (1)–(5). These equations explains the basic methodology to use the moving window over the seismic sequence. For this analysis we have considered only the epicenter distribution of earthquakes, because the depth introduces great errors [40].

The selection of sample volume (N) for windowing the data sequence from an earthquake time series is an important aspect for computation of Dq. A longer window (time span) is essential condition for reliable estimation of Dq. However, a shorter window (time span) is sometime required for detection of sudden temporal change of generalized dimension in a given space. Hence an optimum window is needed. After different trials with different number of data-sample, these conflicting requirements are optimized empirically. We then found the N to be 200 for the best estimation of Dq for the study region Kachchh. It does not mean the absolute value is precise, but it is believed that it will provide relative changes accurately. A moving window of 20 events were chosen for detecting the temporal variation of Dq. We made the test with different number of data for visualizing the decreasing of the Dq value with q, and optimized to be 200 data samples. We have calculated Dq for each window of 200 events with overlap of 180 events for a total of 204 windows.

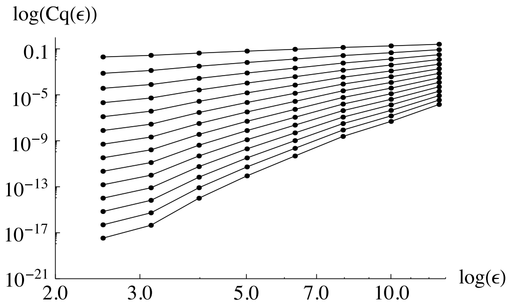

Fig. 3. Linear range for the Kachchh seismic sequence with Mc 3.0 for $\varepsilon = 10^{0.4}$ to $\varepsilon = 10^{1.2}$. The color line is the linear adjustment for each $C_q(\varepsilon)$.

4. Multifractal analysis

The spectrum of fractal dimensions was computed using the method of correlation-integral partitioning for complete fractal analysis [40,41]. This includes the multi-fractal analysis where the number of data points is calculated inside a sphere of radius ε, centered in each event x_i excluding the point itself, N_i [15]. The shifting window (space) is divided in overlapping spheres of radius ε. Now, N_i is given by

$$N_i\left(\epsilon\right) = \sum_{|j-1|\geq 1} \Theta\left(\varepsilon - \left\|x_j - x_i\right\|\right) \tag{1}$$

Using this value, we calculate the generalized Rényi entropy, H_q as follows

$$H_q(\varepsilon) = \frac{1}{1-q}\log_{10}\left(\frac{1}{N}\sum_{i=1}^{N} p_i^{-(q-1)}\left(\varepsilon\right)\right) \tag{2}$$

where

$$p_i\left(\varepsilon\right) = \frac{N_i\left(\varepsilon\right)}{N-1}. \tag{3}$$

A generalized correlation function is defined following the method of Grassberger [42], which is given by,

$$C_q\left(\varepsilon\right) = \left\{\frac{1}{N}\sum_{j-1}^{N}\left[\frac{1}{N-1}\sum_{i=1,i\neq j}^{N}\Theta\left(\varepsilon\left\|x_i - x_j\right\|\right)\right]^{q-1}\right\}^{\frac{1}{q-1}}. \tag{4}$$

Now, the multi-fractal spectrum dimension is given by

$$\frac{\log_{10}\left(c_q\left(\epsilon\right)\right)}{\log_{10}\left(\varepsilon\right)}. \tag{5}$$

For sequence of completeness magnitude Mc 3.0 the above relationship is valid over the linear range of $\log_{10}(C_q(\varepsilon))$ against $\log_{10}(\varepsilon)$ (Fig. 3). In order to find the best linear range we have used $r_{\min} = \max\{2R(N/(d+1)^{1/d}), \eta\}$, to $r_{\max} = R/(d+1)$, following Ref. [40].

The slop of $\log_{10}(C_q(\varepsilon))$ against $\log_{10}(\varepsilon)$ corresponds to Dq for a given value of q. Finally, the plot of different values of Dq against the respective values of q, ranging between 2 and 20 provides the fractal dimension spectrum for the entire dataset under the present study (Fig. 4). The linear range was used as $(\varepsilon) = 10^{0.4}$ to $10^{1.2}$ (Fig. 3). This range is valid for the multi-fractal and moving window spectrum dimensions, Figs. 4 and 5.

The $Dq \sim q$ analysis accounts for space-time clustering in earthquake sequence and has to be windowed because the change in spatial pattern will not account for only single individual earthquake event. A change in spatial pattern of earthquakes is reflected in generalized dimension Dq or Dq spectra when seismicity is considered in windows. Teotia et al. [43] has studied the generalized dimension Dq or Dq spectra of the spatial distribution of earthquake epicenters in the Himalayan region for the time series windowing of events during the period 1964 to 1993. Therefore, the temporal variation in Dq is relatively understood by change in seismicity structure by windowing before and after the occurrence of large earthquake. Multi-fractal spectral analysis is performed using a moving window of sequence occurring in the region (Fig. 5). The number of data points in window have also been varied for comparing the fractal behavior of the region with other regions around the world (cf. Figs. 5–9 of Pasten and Comte [15]), and found the data window of 200 data points and an overlapping window of 180 data points are reliable for the analysis.

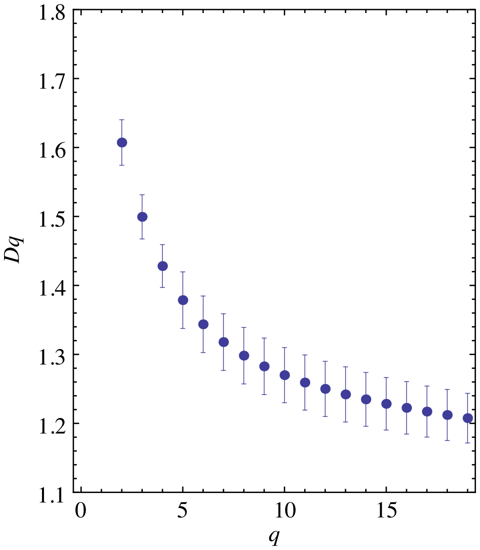

Fig. 4. Plot illustrates the fractal spectrum dimension for epicenters of earthquake sequence Mc 3.0 of 2001 Kachchh seismic sequence for $q = 2$ to $q = 20$.

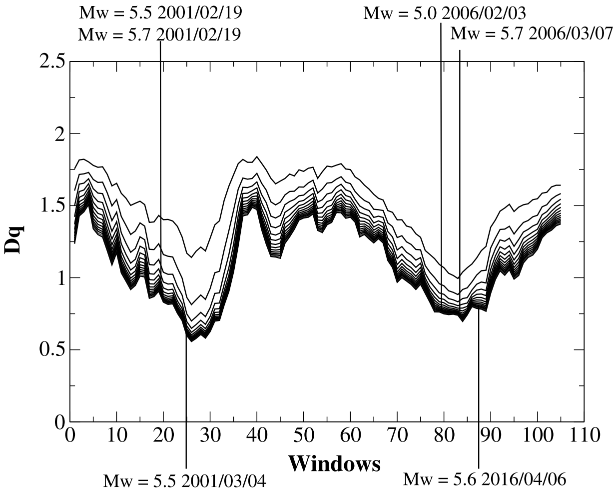

Fig. 5. Plot shows the fractal spectrum dimension computed using the moving window at Mc 3.0. Note the decrease in fractal dimension preceding the occurrences of moderate magnitude shocks.

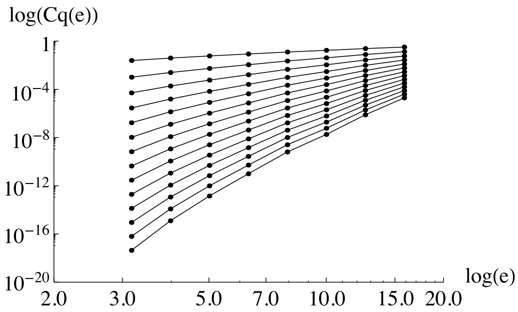

Fig. 6. Linear range for the Kachchh seismic sequence with Mw $\geq$ 3.2 for $\varepsilon = 10^{0.5}$ to $\varepsilon = 10^{1.3}$. The color line is the linear adjustment for each $C_q(\varepsilon)$.

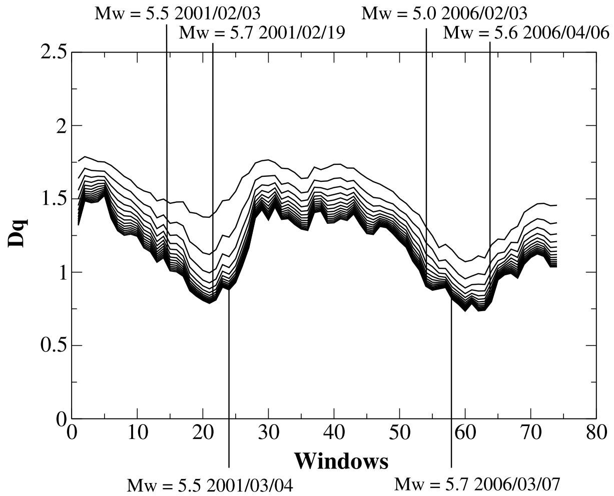

Fig. 7. Plot shows the fractal spectrum dimension computed using the moving window for Kachchh seismic sequence with Mw $\geq$ 3.2. Note the decrease in fractal dimension preceding the occurrences of moderate magnitude shocks.

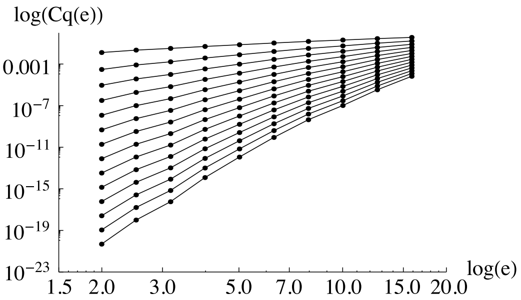

Fig. 8. Plot illustrates the linear range for the Kachchh seismic sequence with Mw $\geq$ 2.6 for $\varepsilon = 10^{0.5}$ to $\varepsilon = 10^{1.5}$. The color line is the linear adjustment for each $C_q(\varepsilon)$.

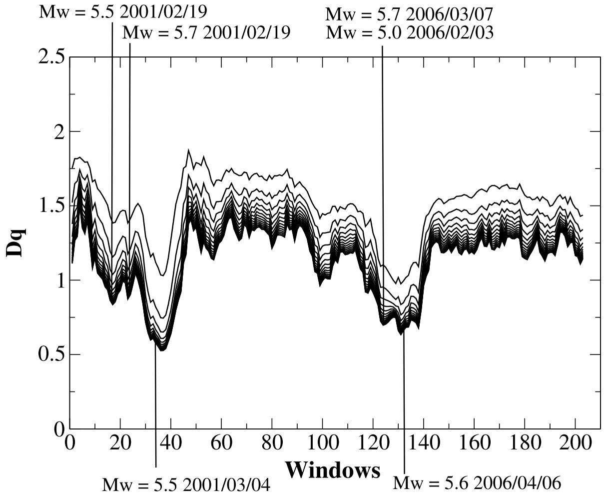

Fig. 9. Fractal spectrum dimension computed using the moving window of 180 data points at Mw $\geq$ 2.6. Note the decrease in fractal dimension preceding the occurrences of moderate magnitude shocks.

The robustness of the analysis has been investigated by considering the completeness correction term 0.2 to Mc 3.0 as Mc 3.2 [44] and stability of the analysis was tested using the minimum magnitude of Mw $\geq$ 2.6 for fractal and multi-fractal studies. The testing of linearity through plotting of $\log_{10}(C_q(\varepsilon))$ against $\log_{10}(\varepsilon)$ and analysis of window fractal spectrum

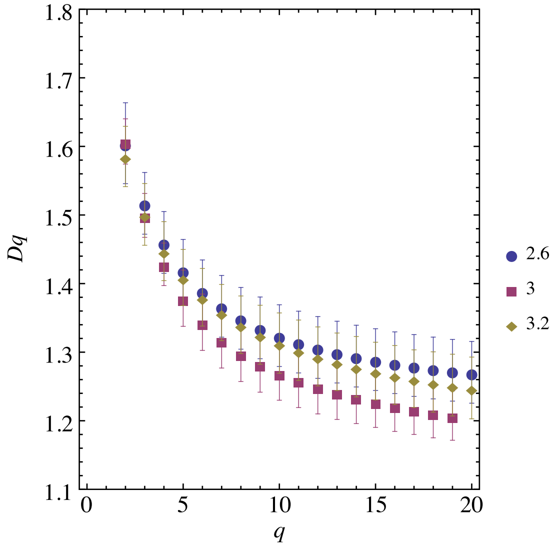

Fig. 10. Fractal spectrum dimension computed for the epicenters of Kachchh seismic sequence Mw $\geq$ 2.6, Mw $\geq$ 3.0 and Mw $\geq$ 3.2 for $q = 2$ to $q = 20$.

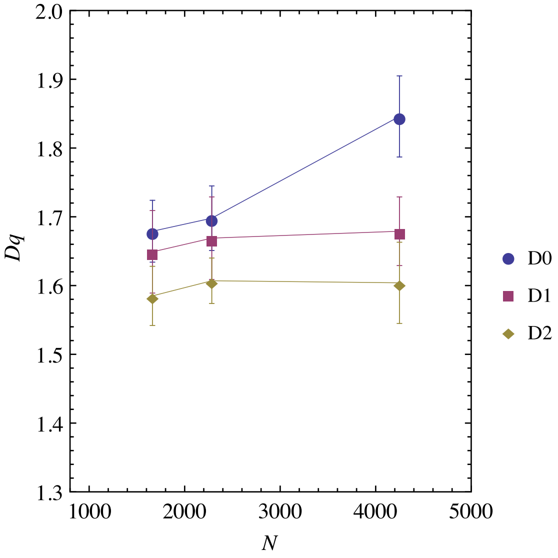

Fig. 11. Values of D_0, D_1 and D_2, versus the number of data of each magnitude threshold studied. For Mw $\geq$ 2.6, we have used 4249 seismic events, for Mw $\geq$ 3.0 were 2284 and for Mw $\geq$ 3.2 we have used 1663 seismic data points.

dimension have been carried out for the sequence with magnitude Mw $\geq$ 3.2 and Mw $\geq$ 2.6, respectively (Figs. 6–9). The robustness and stability test results for fractal multi-fractal analysis are consistent with results of minimum Mc. On the other hand, the fractal spectrum dimension for the epicenter distributions in Kachchh region, for the three magnitude thresholds used, has also been determined (Fig. 10) and compared between them and to compare our results with other earlier studies. Fig. 11 shows a comparison between the values of D_0, D_1 and D_2, for the three magnitude thresholds used in this analysis and the different number of data that each threshold has, for $M_C > 2.6$ we have used 4249 seismic events, for $M_C > 3.0$ we have considered 2284 seismic events and for $M_C > 3.2$ we have used 1663 seismic data points. The overall comparison is discussed in detail in the following section.

5. Discussion

The fractal dimension for epicenter distributions is normally ranges from 0 to 2 [10], when all events clustered into one point the $D_c = 0$, and when homogeneously distributed over a 2D embedding space the $D_c = 2$ [45]. Generally, the fractal dimension possess in the range 0.5–1.8 for seismically active fault systems [8,9,11]. The fractal dimension for the Kachchh

Table 1
Windows in which the decrease of fractal dimensions D_q occurs before the occurrence of moderate earthquake in the Kachchh seismic sequence.

Sl. No.	Event	Magnitude	Window
1	11 Feb 2001	5.2	18–20
2	15 Feb 2001	5.2	18–20
3	17 Feb 2001	5.2	18–20
4	19 Feb 2001	5.5	18–20
5	19 Feb 2001	5.7	18–20
6	22 Feb 2001	5.1	18–20
7	04 Mar 2001	5.5	32–38
8	16 April 2001	5.1	32–38
9	27 April 2001	5.1	32–38
10	03 Feb 2006	5.0	122–140
11	07 Mar 2006	5.7	122–140
12	06 April 2006	5.6	122–140

region was estimated first time by Dimri et al. [12] to be $D = 2.06$. They estimated it at the central source zone of 2001 Bhuj mainshock using small dataset of only 532 earthquakes with Mw $\geq$ 3.0 during January–March, 2001. They analyzed the sequence using wavelet variance method, which identify the region having 2D plane and being filled up with various small source fractures. Their results indicate that only aftershock sequence is having multi-scale nature of seismicity which sustain up to certain scales. They expressed the major slip occurred on secondary faults as compared to primary fault, which indicate multi-fractal nature of fault system. Subsequently, Mandal and Rastogi [13] studied the same region with extended dataset of 997 earthquakes with magnitude 3.0 and above occurred during 2001–2003. They identified the seismicity is extended towards northeastern direction of source zone and the fractal dimension was estimated to be 1.71, which indicates seismicity approaches to two dimensional plane. They also suggested the temporal correlation dimension is 0.78, which confirming the structure of mono-fractal in time domain, means seismicity was clustered before the occurrence of mainshock. Recently, Kayal et al. [46] studied the fractal correlation dimension (D_c) for the same small dataset of 795 shocks with Mc 3.0. The shocks were estimated precisely. They identified the seismic cluster characteristics observed in two seismogenic trends, one along western zone and another along eastern zone of mainshock. The computed D_c was 1.2–1.35 in the western zone and 0.8–1.15 in the eastern zone.

The fractal dimension using epicenters from earlier studies indicate seismic cluster characteristics in Kachchh region. Our calculated D_0 for epicenters as $D_0 = 1.69 \pm 0.05$ (Fig. 11), using a large dataset of 12 years period is relatively less to $D_0 = 1.71 \pm 0.02$ as estimated by Mandal and Rastogi [13] using 997 earthquakes with $M \geq 3.0$ during 2001 to 2003. However, $D_0 = 1.2$–1.35 was estimated by Kayal et al. [46] for only three-months aftershocks of 2001 Bhuj earthquake occurring in the western side of main shocks region and little less as $D_0 = 0.8$–1.15 in the eastern side. This shows the spatial correlation varies in certain space, and our present estimates are reliable for total Kachchh region based on the large duration dataset. The earlier study involving multi-fractal detrended fluctuation analysis (MFDFA) [24] for the earthquake magnitude sequence of Kachchh region catalog for 2003–2012 also shows multifractal characteristics and indicating a stronger dependence of the multifractality on the large magnitude fluctuations.

We find a consistent behavior in the decreasing of the fractal dimension for all values of *Dq* before the occurrence of an important seismic event [15,45]. The clustering of seismic events before an event with a magnitude greater than 5.0 seems to be a robust fact in different regions around the globe. Robustness of the result is checked with different threshold magnitudes for Mw $\geq$ 3.2 and down to Mw $\geq$ 2.6 in the sequence. The consistency in the stability of our estimates is explained in Figs. 7 and 9. On the other hand, Figs. 10 and 11 show a very stable values of the $Dq > 1$, in the linear range used. The error bars in Figs. 10 and 11 show a low variation in the value of *Dq* between the three magnitude thresholds, suggesting that the linear range used gives the best fitting. Figs. 3, 6 and 8 show the linear adjustment for the three magnitude threshold. Other precursor parameter studies involving *k–M slope* (the slope of the line fitting the relationship between the magnitude of the events and their connectivity degrees) for Kachchh earthquake sequence [47] also seems to sharply increase significantly before the occurrence of the largest shocks (Mw $\geq$ 4.5) of the sequence. Telesca et al. [48] also estimated the decrease of earthquake time connectivity $\langle Tc \rangle$ for Kachchh seismic sequence, which is compatible with the recent observation that the fluctuations of the seismicity in natural time exhibits remarkable minima before the strongest earthquakes [49–51]. That results show new evidence of the existence of a transition caused by a large earthquake [52]. This kind of results have been obtained in different zones of the Earth, showing a universal behavior on the seismicity [15,52].

6. Concluding remarks

This study has established the scale for *Dq* in forecasting of moderate size 12 earthquake events of Mw $\geq$ 5 (Table 1) occurring in Kachchh seismic sequence during 2001 to 2012. The six event with Mw 5.5 on 19 Feb., 2001, Mw 5.7 on 19 Feb., 2001, Mw 5.5 on 04 March, 2001, Mw 5.0 on 03 Feb., 2006, Mw 5.7 on 07 March, 2006, Mw 5.6 on 06 April, 2006 for which *Dq* decrease substantially and proceed with them in same corresponding windows for other six events. The value of *Dq* for epicenters is changing between $D_0 = 1.69 \pm 0.05$ to $D_{20} = 1.27 \pm 0.05$ for the 2001 Bhuj seismic sequence over the period from 2001 to 2012. Our analysis for fractal dimension D_0 and multi-fractal spectrum dimension suggest that the spatial distribution of epicenters in this region is not random, and shows a self-organized critical behavior. Similar ubiquitous behavior in other regions around the globe obviously warns for the proximity of a seismic event that could produce damage.

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References

[1] B.B. Mandelbrot, The Fractal Geometry of Nature, W. H. Freeman and Company, San Francisco, 1982.
[2] H.E. Stanley, P. Meakin, Multi-fractal phenomena in physics and chemistry, Nature 335 (1988) 405–409.
[3] A.B. Chhabra, Ch. Meneveau, R.V. Jensen, K.R. Sreenivasan, Direct Determination of the $f(\alpha)$ singularity spectrum and its Application to fully Developed Turbulence, Phys. Rev. A 40 (1989) 5284–5294.
[4] D.S. Lee, K.T. Goh, B. Kahng, D. Kim, Sand-pile avalanche dynamics on scale-free networks, Physica A. 338 (2004) 84–91.
[5] A. Szczepaniak, W.M. Mace, Asymmetric multifractal model for solar wind intermittent turbulence, Nonlinear Proc. Geophys. 15 (2008) 615–620.
[6] D.L. Turcotte, Fractals and Chaos in Geology and Geophysics, Cambridge University. Press, Cambridge, 1992.
[7] P.G. Okubo, K. Aki, Fractal Geometry in the San Andreas Fault System, J. Geophys. Res. 92 (1987) 345–355.
[8] T. Hirata, Fractal dimension of fault system in Japan: Fracture structure in rock fracture geometry at various scales, Pure Appl. Geophys. 11 (1989) 157–170.
[9] A. Idziak, L. Teper, Fractal dimension of fault network in the upper silesian coal basin (poland): Preliminary studies, Pure Appl. Geophys. 147 (1996) 239–247.
[10] P. Tosi, Seismogenic structure behavior revealed by spatial clustering of seismicity in the Umbria-Marche Region (central Italy), Ann. Geophys. 41 (1998) 215–224.
[11] L.A. Sunmonu, V.P. Dimri, Fractal analysis and seismicity of Bengal basin and Tripura fold belt, Northeast India, J. Geol. Soc. India 53 (1999) 587–592.
[12] V.P. Dimri, N. Vedanti, S. Chattopadhyay, Fractal analysis of aftershock sequence of the Bhuj earthquake: A wavelet based approach, Current Sci. 88 (2005) 1617–1620.
[13] P. Mandal, B.K. Rastogi, Self-organized fractal seismicity and b value of aftershocks of the 2001 Bhuj earthquake in Kutch (India), Pure Appl. Geophys. 162 (2005) 53–72.
[14] D. Pasten, V. Muñoz, A. Cisternas, J. Rogan, J.A. Valdivia, Mono-fractal and multi-fractal analysis of the spatial distribution of earthquakes in the central zone of Chile, Phys. Rev. Lett. 84 (2011) 066123.
[15] D. Pasten, D. Comte, Multi-fractal analysis of three large earthquakes in Chile: Antofagasta 1995, Valparaiso1985, and Maule 2010, J. Seismol. 18 (2014) 707–713.
[16] K. Gotoh, M. Hayakawa, N. Smirnova, K. Hattori, Fractal analysis of seismogenic ULF emissions, Phys. Chem. Earth 29 (2004) 419–424.
[17] T. Hasumi, M. Kamogawa, Y. Yamazaki, Model of earthquakes exhibiting self-organized criticality with roughness of sel-afine fault surfaces: statistical properties of constant stress drop and b-value of 1, Geophys. Res. Lett. 7 (2004) 09265.
[18] G. Currenti, C. Del-Negro, V. Lapenna, V. Telesca, Multifractality in local geomagnetic field at etna volcano, sicily (southern Italy), Na. Hazards Earth Syst. Sci. 5 (2005) 555–559.
[19] Y. Ida, M. Hayakawa, A. Adalev, K. Gotoh, Multifractal analysis for the ULF geomagnetic data during the 1993 guam earthquake, Nonlinear Proc. Geophys. 12 (2005) 157–162.
[20] S. Abe, N. Suzuki, Complex-network description of seismicity, Nonlinear Processes Geophys. 13 (2006) 145–150.
[21] C. Papadimitriou, M. Kalimeri, K. Eftaxias, Nonextensivity and universality in the earthquake preparation process, Phys. Rev. Lett. 35 (2008) L14102.
[22] I. Zaliapin, A. Gabrielov, V. Keilis-Borok, H. Wong, Clustering analysis of seismicity and aftershock identication, Phys. Rev. Lett. 101 (2008) 018501–1–4.
[23] B.B. Mandelbrot, Multifractal measures, especially for the geophysicist, Pure Appl. Geophys. 131 (1989) 5–42.
[24] S.K. Aggarwal, M. Lovallo, P.K. Khan, B.K. Rastogi, L. Telesca, Multi-fractal detrended fluctuation analysis of magnitude series of seismicity of Kachchh region, Western India, Physica A 426 (2015) 56–62.
[25] P.K. Khan, S.P. Mohanty, S. Sinha, D. Singh, Occurrences of large-magnitude earthquakes in the Kachchh region, Gujarat, western India: Tectonic implications, Tectonophysics 679 (2016) 102–116.
[26] D. Legrand, A. Cisternas, L. Dorbath, Multifractal analysis of the 1992 Erzincan aftershock sequence, Geophys. Res. Lett. 23 (1996) 933–936.
[27] B.K. Rastogi, S. Kumar, S.K. Aggarwal, Seismicity of Gujarat, Nat. Hazards 65 (2013) 1027–1044.
[28] A.C. Johnston, Seismic moment assessment of earthquakes in stable continental region. Historical Seismicity, Geophys. J. Int. 125 (1996) 639–678.
[29] R. Bilham, Slip parameter for Rann of Kachchh, India, 16 June 1819 earthquake quantified from contemporary accounts, in: I.S. Stewart, C. Vita-Finzi (Eds.), Coastal Tectonics, Vol. 146, Geol. Soc. London Spec. Publ., 1999, pp. 295–319.
[30] S. Stein, G.F. Sella, E.A. Okal, The January 26, 2001 Bhuj earthquake and the diffuse western boundary of the Indian plate, in: In Plate Boundary Zones, in: Geodynamics series, vol. 30, American Geophysical Union, Washington, DC, 2002, pp. 243–254.
[31] S.K. Aggarwal, P.K. Khan, S.P. Mohanty, Z. Roumelioti, Moment tensors, state of stress and their relation to faulting processes in Gujarat, western India, J. Phys. Chem. Earth 95 (2016) 19–35.
[32] B.R. Naini, M. Talwani, Structural framework and the evolutionary history of the continental margin of western India, Mem. 34 (1983) 167–191.
[33] J. Besse, V. Courtillot, Paleographic maps of the continents bordering the Indian Ocean since the early Jurassic, J. Geophys. Res. 93 (1988) 11791–11808.
[34] R.S. White, D.P. Mckenzie, Magmatism at rift zones: the generation of volcanic continental margins and flood basalts, J. Geophys. Res. 94 (1989) 7685–7729.
[35] M. Storey, J.J. Mahoney, A.D. Saunders, R.A. Duncan, S.P. Kelley, M.F. Coffin, Timing of hot spot related volcanism and the breakup of Madagascar from India, Science 267 (1995) 852–855.
[36] D.P. McKenzie, Some remarks on the development of sedimentary basins, Earth Planet. Sci. Lett. 40 (1978) 25–32.
[37] K.G. Cox, A model for flood basalt volcanism, J. Petrol. 21 (1980) 629–650.

[38] C.W. Devey, P.C. Lightfoot, Volcanology and tectonic control of stratigraphy and structure in the western Deccan Traps, Bull. Volcanol. 48 (1986) 195–207.

[39] S. Wiemer, M. Wyss, Minimum magnitude of completeness in earthquake catalogs: Examples from Alaska, the Western United States, and Japan, Bull. Seismol. Soc. Amer. 90 (2000) 859–869.

[40] V.H. Marquez-Ramirez, F. Alejandro Nava Pichardo, Gabriel Reyes-Davila, Multifractality in seismicity spatial distributions: significance and posible precursory applications as found for two cases in different tecnonic environments, Pure Appl. Geophys. 169 (2012) 2091–2105.

[41] M. Potter, W. Kinsner, Direct calculation of the $f(\alpha)$ fractal dimension spectrum from high-dimensional correlation-integral partitions, in: ICASSP IEEE International Conference on Acoustics, Speech and Signal Processing, 2007, Honolulu, USA, 2007, Vol. 3, pp. 989–992.

[42] P. Grassberger, Generalized Dimensions of Strange Atractors, Phys. Lett. 97 (1983) 227–230.

[43] S.S. Teotia, K.N. Khattri, P.K. Roy, Multifractal analysis of seismicity of the Himalayan region, Current Sci. 73 (1997) 359–366.

[44] J. Woessner, S. Wiemer, Assessing the quality of earthquake catalogues: Estimating the magnitude of completeness and its uncertainty, Bull. Seismol. Soc. Amer. 95 (2005) 684–698.

[45] A. Ram, P.N.S. Roy, Fractal Dimensions of blocks using a box-counting technique for the 2001 Bhuj earthquake, Gujarat, India, Pure Appl. Geophys. 162 (2005) 531–548.

[46] J.R. Kayal, V. Das, U. Ghosh, An appraisal of the 2001 Bhuj earthquake (Mw 7.7, India) source zone: Fractal dimension and b value mapping of the aftershock sequence, Pure Appl. Geophys. 169 (2012) 2127–2138.

[47] L. Telesca, M. Lovallo, S.K. Aggarwal, P.K. Khan, Precursory signatures in the visibility graph analysis of the 2003–2012 Kachchh (Western India) seismicity, J. Phys. Chem. Earth 85–86 (2015) 195–200.

[48] L. Telesca, M. Lovallo, S.K. Aggarwal, P.K. Khan, B.K. Rastogi, Visibility graph Analysis of the 2003–2012 Kachchh, Gujarat western India, Pure Appl. Geophys. 173 (2016) 125–132.

[49] P.A. Varotsos, N.V. Sarlis, E.S. Skordas, Scale-specific order parameter fluctuations of seismicity in natural time before mainshocks, Europhys. Lett. 96 (2011) 59002.

[50] P.A. Varotsos, N.V. Sarlis, E.S. Skordas, M.S. Lazaridou, Seismic Electric Signals: An additional fact showing their physical interconnection with seismicity, Tectonophysics 589 (2013) 116–125.

[51] N.V. Sarlis, E.S. Skordas, P.A. Varotsos, T. Nagao, M. Kamogawa, H. Tanaka, S. Uyeda, Minimum of the order parameter fluctuations of seismicity before major earthquakes in Japan, Proc. Natl. Acad. Sci. USA 110 (2013) 13734–13738.

[52] D. Pasten, F. Torres, B. Toledo, V. Munoz, J. Rogan, J.A. Valdivia, Time-based network analysis before and after the Mw 8.3 Illapel earthquake 2015 Chile, Pure Appl. Geophys. 173 (2016) 2267–2275.