Bulgarian Chemical Communications, Volume 47, Special Issue B (pp. 380–389) 2015

Temporal variations of the fractal properties of seismicity

E. Marekova*

Faculty of Physics, Paisii Hilendarski University of Plovdiv, 24 Tsar Asen Str., BG-4000 Plovdiv, Bulgaria

For many natural phenomena and objects a state of chaos and independence from the scale at which they are studied is typical. Examples of such phenomena are earthquakes, the study of which shows that many of their properties are independent from their scale. In the study of earthquakes the property of scale independence has first been established for their distribution in magnitude (*Gutenberg-Richter* law), as well as for the decline in the aftershocks intensity in time (*Omori* equation). Newer studies show that other properties of the earthquakes are also characterized by independence from the scale of realization. Both the aftershock occurrence and the regional seismic process, for example, exhibit fractal properties. This paper evaluates the temporal variation of the fractal coefficients of the earthquake distribution by area for a number of seismic regions. In the analysis of the spatial structure the so-called two-point correlation integral has been used. Analogical estimations of the **b**-value of the *Gutenberg-Richter* law of repeatability have been made. A negative correlation between the fractal coefficients of the earthquake series and their corresponding **b**-values has been found. The temporal variation of the fractal coefficients of the earthquake distribution by area has been similarly analyzed for several aftershock series. A positive correlation between the fractal coefficients of the aftershock series and their corresponding **b**-values has been established.

Key words: seismicity, fractal dimension, b-value, temporal variations

INTRODUCTION

Fractal structures are observed for a wide range of fractures – from microfractures (10^{-6} m) to megafaults (10^{5} m) [1–4]. In such systems the numbers of fractures that are larger than a specified size are related by power law to the size. The physical laws governing the fractal structures are scale-invariant in nature.

The fractal structures may be either homogeneous or multiscaling characteristics. It is considered nowadays that many physical quantities disobey the conventional scaling laws.

Seismic activity in a given region has a fractal structure in relation to time, space and in magnitude [5]. The occurrence of earthquakes is causally linked to destructions, having a fractal structure. Fractal dimensions give a quantitative measure of the spatial clustering of epicenters/hypocenters, as well as of seismicity of the region. Therefore this approach can also be used for evaluation of the probabilistic seismic hazard [6].

Some authors have used this method in different seismically active regions in order to study the fractal nature of the earthquake occurrence, the fault structures, and the resultant seismic hazard, e.g., Kanto Japan [7], Mexican subduction zone [8], North Anatolian block [9], Himalayan region [10], Koyana-Warna region [11], Hokkaido, Japan [12], East Java-Indonesia [13], Northwest Himalayan region [14].

Aki [15] shows theoretically that the fractal dimension (**D**) holds a simple relation with the **b**-value of the Gutenberg-Richter law (i.e. **D**=2**b**). The **b**-value characterizes the fractal dimension in the domain of energy of the earthquakes [15, 16], whereas **D** provides a measure of the fractal dimension of the earthquake distribution in space. One could therefore expect a correlation between **D** and b values, but the character of the correlation can change [5, 17–19].

For an aftershock sequence, Ponomarev et al. [20] have shown that the **b**-values tend to increase with time, while the fractal dimension values tend to decrease. They have proposed that the temporal change in **D**- and **b**-values characterizes the specific evolution of the aftershock sequences. For the 2001 Bhuj earthquake sequence, the **b**-values and the spatial correlation dimensions suggest a negative correlation for the first 2 months, while they show a positive correlation for the remaining months of 2001 [21].

In this work, the correlation integral method [22, 23] is used to determine the correlation dimension and its variations with time. The temporal variation studies are carried out to see its variation by considering consecutive windows with overlapping. Similar kinds of studies have been realized by other workers and similar results have been reported [24].

* To whom all correspondence should be sent:
eligeo@uni-plovdiv.bg

RESEARCH METHODOLOGY

The application of the methods of the fractal sets [25] has become widespread in geophysics. This reflects the fact that fractal analysis is one of the methods developed for studying self-similar phenomena and processes, and self-similarity plays an important role in geophysics [26, 27].

One example of a self-similar structure is the seismic regime, i.e., the set of earthquakes considered as points in space and time and associated with an additional parameter of energy. A classical example, confirming the self-similarity of the seismic regime is the Gutenberg-Richter law of repeatability, having fundamental significance in seismology. For the average number of earthquakes on a given area N (M) with magnitudes bigger than M, attributed to a single time interval, it is given by the expression:

$$\lg N(M) = a - bM, \qquad (1)$$

where a and b are parameters of the law of recurrence.

Estimation of the value of the parameter b is made by the method of maximum likelihood [28]:

$$b = \frac{\lg e}{\overline{M} - M_C} \qquad (2)$$

Where $\overline{M}$ is the average value of the magnitudes and M_C is the minimum value of completeness of the earthquake catalog.

The present study uses the fractal correlation dimension $\mathbf{D_2}$ of the earthquake epicentral distribution. The so-called *correlation integral* $C(\Delta)$ is used as statistical estimation of the fractal dimension in the realization of the N vector $\{x_1, \ldots, x_N\}$:

$$C(\Delta) = \frac{2}{N(N-1)} \sum_{i,j} H(\Delta - |\mathbf{x}_i - \mathbf{x}_j|) \qquad (3)$$

where $H(z)$ is the Heaviside step function, equal to 1 at $z \geq 0$ and equal to 0 at $z < 0$, and the summation is carried out in all different pairs (x_i, x_j) [22, 23]. If the set of points is scale-invariant, then $C(\Delta)$ is represented by a power law: $C(\Delta) \propto \Delta^{\mathbf{D_2}}$, where $\mathbf{D_2}$ is defined as *correlation fractal dimension*.

$$\mathbf{D_2} = \lim_{r \to 0} \frac{\lg C(r)}{\lg r} \qquad (4)$$

where N is the total number of points (earthquakes), $r = |\mathbf{x}_i - \mathbf{x}_j|$ is the distance between the vectors $\mathbf{x}_i$ and $\mathbf{x}_j$, which define the location of the points. The distance between two events in km is calculated by the formula:

$$r = 111 \arccos \Big[\cos\theta_1 \cos\theta_2 + \sin\theta_1 \sin\theta_2 \cos(\phi_1 - \phi_2) \Big] \qquad (5)$$

where (θ_1, ϕ_1) and (θ_2, ϕ_2) are the latitude and longitude of each two earthquakes from the series.

Defined this way, the parameter gives a measure of the level of fractal clusterization of the points. The lower values define tighter clusters [3]. If the points are randomly distributed in a two-dimensional space, then $\mathbf{D_2}$ is 2. Reduction of its value to less than 2 means that the distribution of points tends to clustering to a greater extent than if it is completely random.

These two parameters - **b** and $\mathbf{D_2}$ - are independent measures of the scale-invariant properties of the earthquake distribution in magnitude, and, respectively, of the earthquake spatial clustering.

DATA AND OBTAINED RESULTS

Seismic Regions

For studying the temporal properties of seismicity the following data have been used: from the regions Riverside and Parkfield in California; from California North Coast; and from Central Asia. Each catalogue contains several thousands of earthquakes for the period 1900-2006.

The catalogues have first been filtered in order to remove the aftershock (secondary) events. This has been carried out by means of the program Zmap [29], in which the *Reasenberg* [30] method of declusterization has been embedded. In order to provide homogeneity of the declusterized catalogue, a check for data completeness has also been performed to define the minimum magnitude $\mathbf{M_C}$ of the catalogue data, over which all events in the considered spatial and temporal range, covered by the catalogue, have been registered.

This study defines the **b**-value from the *Gutenberg-Richter* law (1) and the fractal correlation dimension $\mathbf{D_2}$ – (3) and (4) – of the earthquake epicentral distribution. The graph of the cumulative number of distances between the pairs of epicenters in a double-logarithmic scale is used. The fractal coefficient is obtained from the slope of the straight-line portion of the dependency, built by the method of least squares.

Only the coordinates of the earthquake epicenters have been considered in the present study, although the analysis of the hypocenters in the real three-dimensional space would be more natural from a physical point of view. This is justified by the fact that in the existing catalogues the depth of the earthquakes is defined with lowest precision.

A major task is to trace the variation of the parameters **b** and $\mathbf{D_2}$ over time. In order to calculate the values of these parameters, a program in FORTRAN has been developed. A "sliding window" with a fixed number of events, for which **b** and $\mathbf{D_2}$ are obtained, has been used. The parameters are related to the period of time, covered by the corresponding window. Then this "window" is shifted at a certain pace, overlapping part of the data from the previous calculation, and the procedure is repeated again. The choice of windows with a certain number of events is a better option than fixing the duration of a time interval for making the same calculations.

After that diagrams are drawn to trace the development of both parameters over time and the availability of a correlation between them.

Table 1 presents the number of earthquakes for each studied region, remaining after the removal of the aftershock events, as well as the magnitude of completeness $\mathbf{M_C}$. The parameters of the "sliding windows", as well as the number of the overlapping earthquakes are also given in the table. The last column shows the obtained correlation between the parameters **b** and $\mathbf{D_2}$.

Parkfield region, California, is situated in a relatively straight-line section of the fault San Andreas in Central California. In this region the movement on the fault occurs as a right-lateral slip during earthquakes and also as an aseismic slip ("creep"). The catalogue contains 607 earthquakes with magnitude between 3.0 and 5.8 for the period (1932-2006). The catalogue data about the considered region are within the geographic window: $(35.5 \div 36.5°N)$ and $(119.8 \div 121°W)$. The depth interval of the hypocenters deployment is up to 30 km [31].

The results from the calculations related to this region are shown in Fig. 1. As it can be seen, both studied parameters develop in time, and the biggest dynamics is observed for the period (1983-1987), which is associated with the occurrence of two strong earthquakes in the region.

The earthquake catalogue related to the northern part of the coastal region of California contains 2057 events with magnitude of $M \geq 3.0$ for the period (1971-2001). The earthquakes are located in the geographic window $(36.5 \div 39.0°N)$, $(120.5 \div 123.0°W)$. [32]. The results from the analysis are shown in Fig. 1. Both studied parameters show development over time and the most variation is observed for the period (1984-1990), during which a number of strong earthquakes happened and in 1989 an earthquake with magnitude $M = 7.9$ occurred in this region.

The region of Central Asia is characterized by a high level of intercontinental seismicity, justified by intensive geodynamic interaction between a number of big lithospheric plates - the European, Asian, Indian, and Chinese. The catalogue contains 5218 earthquakes with magnitude between 3.3 and 7.7 for the period (1962-1993) [33]. The events are located in the following geographical window: $(35.0 \div 45°N)$, $(65 \div 82°E)$. A depth interval of up to 100 km has been chosen in order to analyze only the crustal seismicity. For this region the biggest variations are characteristic for the period (1971-1975).

South California is one of the most seismic regions in the world. Riverside region's geology is complex, mainly as a result of the interaction between the fault tectonics of San Andreas fault and the compression movements of the Peninsular Ranges chain. The full catalogue of the Riverside region contains 9263 earthquakes with magnitudes from 3.0 to 7.7 and depth up to 60 km, for the period (1932-2006) [34]. The data are placed in the geographical

Table 1. Data about the researched regions

Seismic zone/region	**Number of earthquakes**	**Magnitude of completeness $\mathbf{M_C}$**	**Number of events in "sliding window"**	**Number of overlapping events**	**Correlation equation**
Parkfield, California	527	3.3	100	90	$\mathbf{b} = 1.72 - 0.68\mathbf{D_2}, R = -0.79$
North Bay, California	2057	3.0	200	180	$\mathbf{b} = 1.72 - 0.68\mathbf{D_2}, R = -0.68$
Central Asia	3170	3.3	300	200	$\mathbf{b} = 1.23 - 0.32\mathbf{D_2}, R = -0.54$
Riverside, California	5131	3.0	200	180	$\mathbf{b} = 1.16 - 0.09\mathbf{D_2}, R = -0.14$

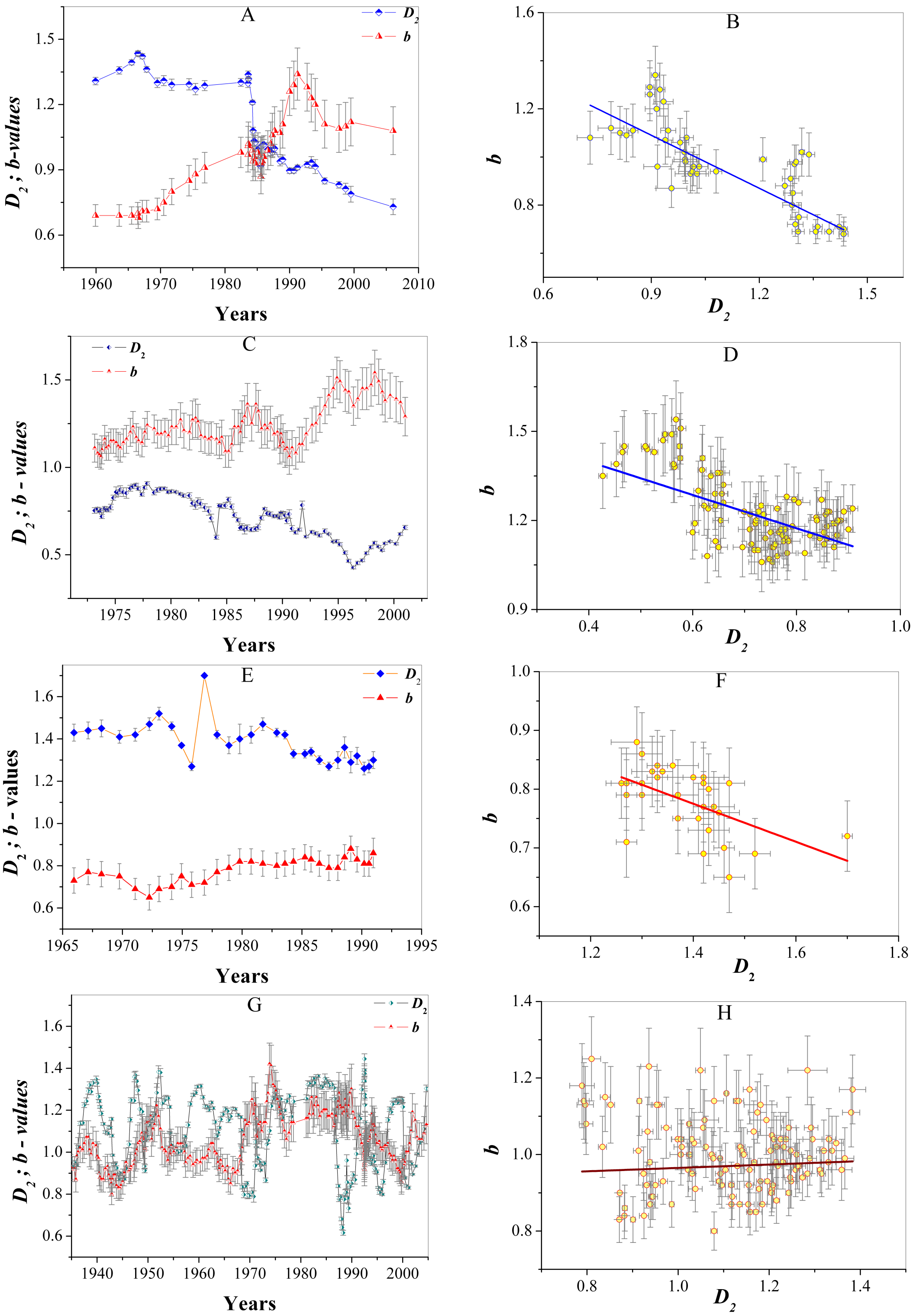

Fig. 1. Temporal variations of the parameter **b** and the fractal coefficient $\mathbf{D_2}$ for the studied seismic regions: A – Parkfield; C – North Bay, California; E – Central Asia; G – Riverside (The temporal coordinate corresponds to the date of the last earthquake, falling into the corresponding window of calculations.). Correlation between the parameter **b** and the fractal coefficient $\mathbf{D_2}$: B – Parkfield; D – North Bay, California; F – Central Asia; H – Riverside. For each value of the shown parameters the standard deviations are also depicted.

window $(32.5 \div 35.5°N)$, $(114 \div 119°W)$. As it can be seen from Fig. 1, the variations in both studied parameters - **b** and $\mathbf{D_2}$ - are very dynamic. For the period (1932-2006) thirteen (13) earthquakes occurred there with magnitude $M \geq 6.0$ and 50 - with magnitude $5.0 \leq M < 6.0$, not taking into account the aftershocks, observed after some of the strongest quakes. Strong activation was observed for the periods (1945-1952), (1968-1971), (1986-1992).

All studied seismic regions are characterized by a negative correlation between **b** and $\mathbf{D_2}$, whose parameters are given in Table 1.

Aftershock series

As a second stage of this research, the following aftershock series were considered: Sumatra 2004 and Sumatra 2007, Indian ocean; Kashmir 2005, Asia; Parkfield 2004, California; Kobe 1995, Japan; Loma Prieta 1989, California.

On 26.12.2004 a destructive earthquake with magnitude $M_W9.0$ occurred on the island of Sumatra in the Indian Ocean. The catalogue of the aftershock series contains 6386 events with magnitude $M \geq 3.2$ for the period (2004-2008). For the second aftershock series of the earthquake with magnitude $M_W8.5$ on the island of Sumatra on 12.09.2007, data about 607 events with $M \geq 3.2$ have been obtained for the period (2007-2008) [35].

The initial catalogue of earthquakes in the region of Kashmir, Northeren Pakistan, contains 710 quakes with magnitude $M \geq 2.9$ for the period (2005-2008). The main quake from 08.10.2005 was with $M_W7.6$ [35].

Another studied aftershock series is related to an earthquake near Parkfield, California, which occurred on 28.09.2004. The series contains 10299 events with magnitude $M \geq 0.0$ for the period (2004-2008) [32].

On 17.01.1995 a destructive earthquake occurred in Kobe, Japan, with magnitude $M7.2$. The Earthquake Information Center (EIC), Earthquake Research Institute, University of Tokyo is compiling observed data [36]. The catalogue contains 3464 events with magnitude $M \geq 2.0$ for the period (January-December 1995). After a preliminary analysis only the quakes at depth of up to 20km were included into the series.

For the earthquake sequence near Loma Prieta, California, which happened on 18.10.1989, 11132 events with magnitude $M \geq 0.1$ were registered in the period (1989-1991). The magnitude of the main shock was defined as $M_W6.9$ [37].

All aftershock series have been analyzed for completeness. The numbers of earthquakes for each studied series, as well as the magnitude of completeness M_C, are given in Table 2. This table also shows the parameters of the "sliding windows" and the overlapping. The obtained correlation between **b** and $\mathbf{D_2}$ appears in the last column.

It is typical of this research that the correlation between the parameters **b** and $\mathbf{D_2}$ is positive; the only exception is the series of Sumatra 2004, for which the correlation is negative – Fig. 2. The correlation equations are shown in Table 2 together with the corresponding coefficient of correlation.

DISCUSSION AND CONCLUSIONS

The correlation fractal dimension $\mathbf{D_2}$, defined by the formulae (3) and (4), finds wide application in seismology, especially in description of the earthquakes spatial distribution. The fractal dimension is a measure of the spatial clustering of the set of seismic events, considered as points in a two- or three-dimensional space, i.e., it can be applied both for the epicentral distribution and for the distribution of the hypocenters of the earthquakes.

Table 2. Data about the considered aftershock series

Earthquake	**Number of earthquakes in series**	**Magnitude of completeness $\mathbf{M_C}$**	**Number of events in "sliding window"**	**Number of overlapping events**	**Correlation equation**
Sumatra 2004	3561	4.5	500	250	$\mathbf{b} = 1.69 - 0.51\mathbf{D_2}, R = -0.69$
Sumatra 2007	290	4.7	50	20	$\mathbf{b} = 0.57 + 0.13\mathbf{D_2}, R = 0.42$
Kashmir 2005	594	3.5	50	40	$\mathbf{b} = 0.41 + 0.32\mathbf{D_2}, R = 0.52$
Parkfield 2004	141	2.6	10	5	$\mathbf{b} = 0.58 + 0.67\mathbf{D_2}, R = 0.34$
Kobe 1995	3134	2.0	300	100	$\mathbf{b} = 0.70 + 0.32\mathbf{D_2}, R = 0.36$
Loma Prieta 1989	1052	2.0	100	50	$\mathbf{b} = 0.54 + 0.25\mathbf{D_2}, R = 0.42$

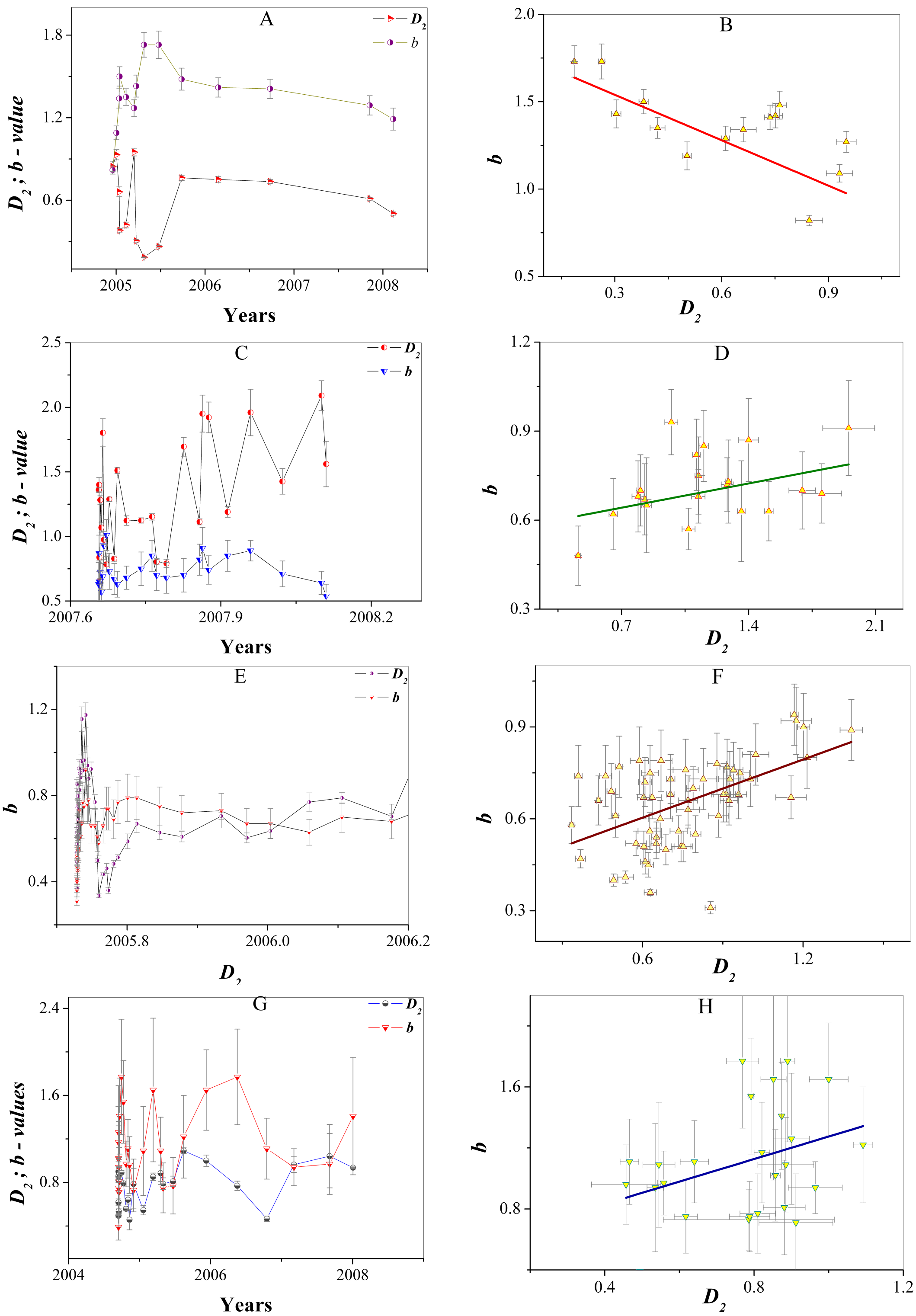

Fig. 2. Variations of the parameter **b** and the fractal coefficient $\mathbf{D_2}$, defined for the aftershock series: A – Sumatra 2004; C – Sumatra 2007; E – Kashmir 2005; G – Parkfield 2004; I – Kobe 1995; K – Loma Prieta 1989 (The temporal coordinate corresponds to the data of the last earthquake, falling into the respective window of calculations). Correlation between the parameter **b** and the fractal coefficient $\mathbf{D_2}$: B – Sumatra 2004; D – Sumatra 2007; F – Kashmir 2005; H – Parkfield 2004; J – Kobe 1995; L – Loma Prieta 1989. For each value of the shown parameters the standard deviations are also depicted.

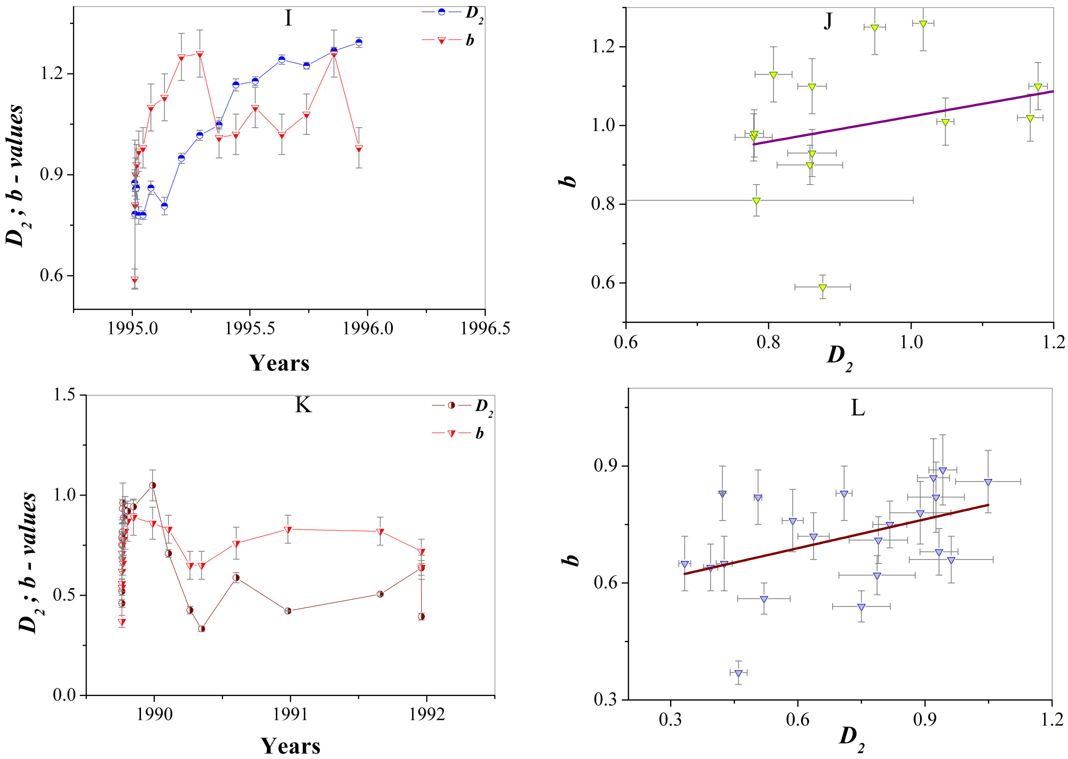

Fig. 2. (continued)

Many authors carry out research of the temporal evolution of seismicity, characterized by the two parameters: the **b**- value from the law of repeatability and the corresponding correlation fractal dimension $\mathbf{D_2}$ of their epicentral distribution. Such results are obtained for the region of Tohoku, Japan [5, 38]; for parts of California [39, 40]; for North-East Brazil [39]; Italy [41]; the region of the North Anatlolian fault in Turkey [9]; for region Koyna Dam, India [42], Central Alborz, Iran [43]. For all these cases a negative correlation between the two studied parameters has been obtained.

The results presented here correspond to the published results. It means that the described type of correlation between the **b**-value and the fractal coefficient $\mathbf{D_2}$ is also valid for the seismic regions studied in this paper. It is noteworthy that the correlation equation between **b** and $\mathbf{D_2}$ for the two studied regions - Parkfield and the Northern coast of California - is the same.

The study of the temporal variations of the **b**-value and the fractal dimension $\mathbf{D_2}$ is carried out mainly with the aim of looking for prognostic phenomena before strong earthquakes. Although the seismologists are far from finding a stable prognostic picture, considerable reduction of the **b**-value and increase in the value of the fractal dimension $\mathbf{D_2}$ before a strong earthquake have been described in many publications. It means reduction of the dominance of the weak earthquakes and at the same time a tendency for formation of tight clusters of earthquakes in the fault region.

When studying aftershock series another type of equation is obtained for the correlation between the parameters **b** and $\mathbf{D_2}$ - a positive one. The only exception is the series of earthquakes on the island of Sumatra from 2004. There are various hypotheses, explaining this positive correlation. Such a behavior could be due to the change in the properties of the rocks, caused by the main quake of the series. Fluids migrate into the destroyed region after that, and this leads to increase of the stress in the pores of the rock massifs. As a result groups of weaker earthquakes, clustered in space, appear. Observations of rock samples in laboratory experiments show that the variations in the **b**-value can be related to the stress in the environment. When the stress goes up, the **b**-value decreases.

The possible reasons for the negative correlation were discussed by Henderson [17], who compared the observations of a local seismic sequence with an acoustic emission during a rock sample destruction. He found similarity in the distribution of the events magnitudes. This leads to considering a model of seismicity, characterized by a law of increase of the fractures, derived from Fracture Mechanics, which includes possibilities for both types of correlation - positive and negative. The model describes a process as a transition from a period of earlier scattered seismic events with small magnitude to a period of greater magnitudes (lower value of **b**) and greater clustering after that (accompanied by a higher value of the fractal coefficient $\mathbf{D_2}$).

The correlation between the **b**-value from the Gutenberg-Richter law and the fractal dimension $\mathbf{D_2}$ has been widely discussed over the past years. After Aki [15] proposed a simple relationship between the two parameters of the type $\mathbf{D_2} = 2\mathbf{b}$, both positive and negative correlations were described in different publications about the variations between these two scale coefficients. In some cases they can even change from one type into the other.

The variations in the **b**-value depend mainly on the degree of stress or the level of heterogeneity of the fault environment, while the variations of the fractal dimension depend mostly on complexity or the level of heterogeneity of the fault systems. Change in the **b**-value from $\mathbf{b} < 1$ to $\mathbf{b} > 1$ is observed immediately before and after a strong earthquake.

The negative correlation means that there is considerable occurrence probability for an earthquake with a greater magnitude, indicating release of stress over faults with greater fault planes.

A positive correlation means that the probability for a strong earthquake reduces in response to the increasing fragmentation of the fault region. This indicates further that the release of stress occurs on faults with narrower surface stretch.

Such variations in the correlations between **b** and $\mathbf{D_2}$ can be explained in terms of increasing stress on the main branch of the self-similar fault system before rupture and subsequent release of stress on and around the main fault and on secondary branches of the fracture system after the main quake.

Fractal properties of seismicity can be measured by fractal dimensions that are introduced as a statistical tool to quantify the dimensional distribution of seismicity, its randomness or clustering.

The fractal dimension may be used as a quantitative measure of the degree of heterogeneity of seismic activity in fault systems of a region, and it is controlled by the heterogeneity of the stress field and the existing and preexisting geological, mechanical, or structural heterogeneity. A change in the fractal dimension corresponds to the dynamic development of the states of the system.

One of the most important seismological parameters used to describe an set of earthquakes is the **b**-value in the Gutenberg-Richter frequency-magnitude equation. It characterizes the distribution of earthquakes over the observed range of magnitudes. It is a basic parameter in seismology for its association with geotectonic features of an seismic area. The b-value is influenced by the degree of heterogeneity and fracture density in the area. The **b**-value is influenced by the degree of heterogeneity and fracture density in the area. The state of stress, rather than the heterogeneity of the material constituting the rocks, plays the most important role in the **b**-value variation.

Therefore it is important to understand the frequency-magnitude relation and fractal dimension of seismicity in assessing the earthquake hazard of a tectonically active region.

Acknowledgments*. I would like to thank my colleague Associate Professor Alexander Marinov for development of programs, needed for the present research.*

REFERENCES

[1] C. A. Aviles, C. H. Scholz, and J. Boatwright, *J. Geophys. Res.* **92**, 331–344 (1987).

[2] S.R. Brown, and C.H. Scholz, *J. Geophys. Res.* **90**, 12575–12582 (1985).

[3] T. Hirata, T. Satoh, and K. Ito, *Geophys. J. R. Astron. Soc.* **90**, 360–374 (1987).

[4] P.G. Okubo, and K. Aki, *J. Geophys. Res.* **92**, 345–355 (1987).

[5] T. Hirata, *J. Geophys. Res.* **94**, 7507–7514 (1989a).

[6] D.L. Turcotte, *Tectonophysics* **167**, 171–177 (1989).

[7] T. Hirata, and M. Imoto, *Geophys. J. Int.* **107**, 155–170 (1991).

[8] F. Brown-Angulo, A. H. Ramirez-Guzman, E. Yepezl, A. Rudolg-Navarrol, and C. G. Pavial-Miller, *Geofisica International* **37**, 29–33 (1998).

[9] A.O. Öncel, O. Alptekin, and I. Main, *Nonlin. Process. Geophys.* **2**, 3/4, 147–157 (1995).

[10] S.S. Teotia, K.N. Khattri, and P.K. Roy, *Current Science* **73**(4), 359–365 (1997).

[11] L.A. Sunmonu, and V.P. Dimri, *Pure and Applied Geophysics* **157**, 1393–1405 (2000).
[12] K. Murase, *Earth Planets Space* **56**, 3, 401–405 (2004).
[13] S. Maryanto, and I. Mulyana, *Intl J. of Mathematical, Physical and Engineering Sciences* **3**(2), 113–117 (2009).
[14] P.N.S. Roy, and S.K. Mondal, *J. Indian Geophysical Union* **13**(2), 63–68 (2009).
[15] K. Aki, A probabilistic synthesis of precursory phenomena, in *Earthquake Prediction: An International Review*, edited by Simpson, D.W. & Richards. G., AGU, Washington, DC, 1981, pp. 566–574.
[16] D.L.Turcotte, *Fractals and Chaos in Geology and Geophysics*, Cambridge Univ. Press, 1992, p. 221.
[17] J. Henderson, I.G. Main, R.G. Pearce, and M. Takeya, *Geophys. J. Int.* **116**, 217–226 (1992).
[18] I.G. Main, *Geophys. J. Int.* **111**, 531–541 (1992).
[19] I.G. Main, *Reviews of Geophysics* **34**, 433–462 (1996).
[20] A.V. Ponomarev, A.D. Zavyalov, V.B. Smirnov, and A. Lockner, *Tectonophysics* **277**, 5, 7–81 (1997).
[21] P. Mandal, and B.K. Rastogi, *Pure and Applied Geophysics* **162**, 53–72 (2005).
[22] P. Grassberger, and I. Procaccia, *Phys. Res. Lett.* **50**, 346–350 (1983a).
[23] P. Grassberger, and I. Procaccia, *Physica D* **9**, 189 (1983b).
[24] L. Telesca, V. Cuomo, V. Lapenna, and M. Macchiato, *Tectonophysics* **330**, 93–102 (2001).
[25] B. Mandelbrot, *The fractal geometry of nature*, Freeman and Co., San Francisco, 1982, p. 460.
[26] M. B. Geilikman, T. V. Golubeva, and V. F. Pisarenko, *Earth Planet. Sci. Lett.* **99**, 127–132 (1990).
[27] D. Gospodinov, A. Marinov, and E. Marekova, *Acta Geophys.* **60**, 794–808 (2012).
[28] K. Aki, *Earthquake Res. Inst., Tokyo Univ.* **43**, 237–239 (1965).
[29] S. Wiemer, *Seism. Res. Let.* **72**(2), 373–382 (2001); http://seismo.ethz.ch/staff/stefan/IntrotoZMAP6_online.htm
[30] P. Reasenberg, *J. Geophys. Res.* **90**, 5479–5495 (1985).
[31] http://earthquake.usgs.gov/research/parkfield/livedata.php - USGS
[32] S. Wiemer - CD with software package Zmap (private communication).
[33] http://seismos-u.ifz.ru/centrasia.htm ; http://earthquake.usgs.gov/data/russia_seismicity/
[34] http://www.data.scec.org/eq-catalogs/date_mag_loc.php
[35] http://www.ncedc.org/anss/catalog_search.html
[36] ftp://ftp.eri.u-tokyo.ac.jp/pub/data/junec/hypo
[37] http://www.ncedc.org/ncedc/catalog-search.html
[38] T. Hirata, *Pure Appl. Geophys.* **131**, 157–170 (1989b).
[39] J. Henderson, "Fracture-Mechanics and the Evolution of Seismicity in an Intra-Plate Setting", PhD Thesis, 1992, University of Edinburgh.
[40] D. J. Barton et al., *Geophys. J. Int.* **138**, 563–570 (1999).
[41] V. De Rubeis et al., *Geophys. Res. Lett.* **20**(18), 1911–1914 (1993).
[42] A. Kumar et al., *Earthq. Sci.* **26**(2), 99–105 (2013).
[43] M. Agh-Atabai, and M. S. Mirabedini, *Acta Geophysica* **62**(3), 486–504 (2014).

ВРЕМЕВИ ВАРИАЦИИ НА ФРАКТАЛНИТЕ СВОЙСТВА НА СЕИЗМИЧНОСТТА

Е. Марекова

Физически факултет, Пловдивски университет "Паисий Хилендарски", ул. "Цар Асен" №24, 4000 Пловдив, България

(Резюме)

За много природни явления и обекти е характерна хаотичност и независимост от мащаба, в който те се изучават. Пример за подобни явления са земетресенията, изучаването на които показва, че много техни свойства не зависят от мащаба им. При изучаването на земетресенията свойството на мащабна независимост най-напред е било установено за разпределението им по сила (закон за повторяемост на *Gutenberg-Richter*) и за спада на интензивността на афтершоците във времето. По-нови изследвания показват, че и други свойства на земетресенията се характеризират с независимост от мащаба на реализация. Така например фрактални свойства проявяват както афтершоковата реализация, така и регионалният сеизмичен процес.

В настоящата работа се прави оценка на изменението във времето на фракталните коефициенти на площното разпределение на земетресения от няколко сеизмични региона. При анализа на пространствената структура, се използва така наречения двуточков корелационен интеграл. Направени са и аналогични оценки на *b*-стойността от закона на *Gutenberg-Richter*. Между фракталните коефициенти за земетръсните серии и съответните им *b*-стойности е установена отрицателна корелационна връзка.

Аналогичен анализ е направен и на изменението във времето на фракталните коефициенти на площното разпределение на земетресения от няколко афтершокови серии. Между фракталните коефициенти за афтершоковите серии и съответните им *b*-стойности е установена положителна корелационна връзка.