FRACTAL PROPERTIES OF THE SPATIAL DISTRIBUTION OF CRUSTAL AND SUBCRUSTAL VRANCEA EARTHQUAKES

I.A. MOLDOVAN[1*], E. POPESCU[1], M. RADULIAN[1,2,3], B. ENESCU[1,3, 4], A.O. PLACINTA[1], C. GHITA[1], A.P. CONSTANTIN[1]

[1] National Institute for Earth Physics, Calugareni Str. 12, 077125, Magurele, Romania

[2] Romanian Academy, Bucharest, Romania

[3] Romanian Academy of Scientists, Bucharest, Romania

[4] Department of Geophysics, Kyoto University, Kyoto, Japan

E-mail: irenutza_67@yahoo.com

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Abstract. Seismicity clustering characterizes the seismic process. We compute the fractal dimension for the Vrancea earthquakes recorded between 1995 and 2008, both in the crust and in the mantle. The fractal dimension shows a visible decreasing anomaly preceding the largest Mw=6.0 earthquake in the dataset occurred on 27th of October 2004.

Key words: seismicity, earthquakes clustering, fractal dimension, Vrancea source.

1. INTRODUCTION

Clustering of seismicity in space and time is a fundamental characteristic of the seismic process [1, 2] and that is why any program of seismic forecasting should include among its objectives the modeling of the phenomena of grouping of earthquakes, using the analysis of the fractal properties of the spatial distribution of earthquakes, as well as the temporal variation of the fractal dimensions.

The concept of fractal geometry and dimension was introduced by [3] to describe the scale invariance in natural phenomena. Fractals provide a means of testing whether clustering in time or space is a scale-invariant process. The concept of fractal structure has been applied further by many researchers to understand the complex mechanism of earthquake occurrence and to the test its potential to forecast earthquakes [4-11]

The goal of the present study is to analyze the properties of clustering in space of the earthquakes produced in the Vrancea region (located at the South-Eastern Carpathians arc bend in Romania), both in the crust and in the upper mantle, using the correlation integral defined by [12]. The same procedure was applied in previous studies [13 – 15] for a smaller data set (1995 – 2002) including solely Vrancea intermediate-depth earthquakes.

The Vrancea seismic zone represents a unique case of isolated seismicity located beneath the South-Eastern Carpathians arc bend in a narrow focal volume imbedded in the upper mantle at intermediate depths (60 – 180 km). Major shocks with magnitude above 7 are triggered frequently in this source (2 to 5 per century). The maximum event recorded in 1802 was evaluated to M_w 7.9. The associated crustal seismicity generated in the overriding crust is significantly weaker as rate of seismicity and earthquake size (magnitude below 5.7).

A series of previous papers have highlighted possible clustering features of the Vrancea earthquakes suggesting also some precursory aspects [16 – 18]. At the same time, clustering properties have been related to spatial inhomogeneities in the lithospheric slab revealed by seismicity analysis, tomography images, petrology and rheology investigations. Note in this context the pronounced seismic gap in the 40 – 60 km depth range which separates the seismicity in the crust from the one in the mantle. Also, another deficit of earthquakes, less obvious and identified in a very narrow area around 100 km depth. This can be ascribed to a transition zone from an oceanic slab to a continental one [19] or to a weakness layer that coincides with the conditions of instability of hydrated minerals (amphibole pargasite) in the lithosphere [20]. It is worth noting that this zone can be assumed to be rich in fluids apparently acting as a very efficient separation between two active segments which characterize the seismogenic zone [21].

Some precursory elements for Vrancea earthquakes came out from previous investigations, both on seismicity, but also on geophysical data [22 – 25], but the question remains open as to how safe and reliable they are. Similar investigations in other seismic areas of the globe suggested that the temporal variation of fractal dimension of seismicity can provide some hints of preparation process for the large size earthquakes. Several large earthquakes in different parts of the world have been studied statistically and have been found to be associated with some clustering of earthquakes before the main shock earthquake [26, 27].

2. THE MATHEMATICAL METHOD

The data set is represented by the time series $\{X_i,M_i\}_{I=1}^{N}$,, where X_i is the hypocenter of the event "i" of coordinates (φ_I,λ_i), M_i is the magnitude of the earthquake produced at time t_i and N represents the number of events in the earthquake catalog. In order to analyze the temporal variation of the fractal dimension of the distribution of hypocenters, the set of events is divided into subsets, shifted by a moving window of n events.

The correlation integral defined for the spatial distribution of the hypocenters of a subset $\{X_i\}_{i=1}^N$ (with N=100) is of the following form:

$$C(r) = \frac{2}{N(N-1)} K(R < r) \tag{1}$$

where K (R<r) is the number of epicenter pairs (X_i, Y_i) with the R distance between them lower than r [12].

If the distribution of hypocenters has a fractal structure, we obtain the following relationship:

$$C(r) \propto r^{D_2} \tag{2}$$

where D_2 is the correlation dimension. The logarithm of C(r) is

$$\log C(r) = D_2 \log r + a \tag{3}$$

with slope equal to the fractal dimension D_2 of the distribution of earthquake hypocenters.

3. ANALYSIS OF THE GROUPING PROPERTIES OF THE VRANCEA SUBCRUSTAL EARTHQUAKES

3.1. ANALYSIS OF SEISMIC ACTIVITY

We analyzed the seismic activity characteristics of the Vrancea intermediate-depth zone using a catalog of 2251 Vrancea subcrustal earthquakes occurred between January 1, 1995- December 31, 2008, completely relocated (determination of all hypocentral parameters) in a homogeneous and unitary way, using the same velocity model and magnitude calculation formula. Work is currently underway to relocate the entire catalog of earthquakes. The largest intermediate-depth earthquake occurred during this period is the Mw=6.0 earthquake of 27th of October 2004 [28, 29]. The epicenters of the earthquakes are shown in the map in Figure 1.

As suggested by previous studies [30], the earthquakes in the Vrancea seismogenic slab appears to be generated in two distinct segments, between ~60 and 110 km (upper segment, denominated A segment) and between 110 and 180 km (lower segment, denominated B segment). The seismicity regimes in the two segments seems to be decoupled one from the other. The narrow zone located around 110 km depth is probably acting as a transition zone as a result of weakening processes taking place here (fluid release, melting). This zone is not able to trigger events larger than 5.5 magnitude, while the two segments located above and below produce major earthquakes with magnitudes greater than 6.5 (e.g., March 4, 1977 and May 30, 31, 1990 in A and November 10, 1940 and August 30, 1986 in B).

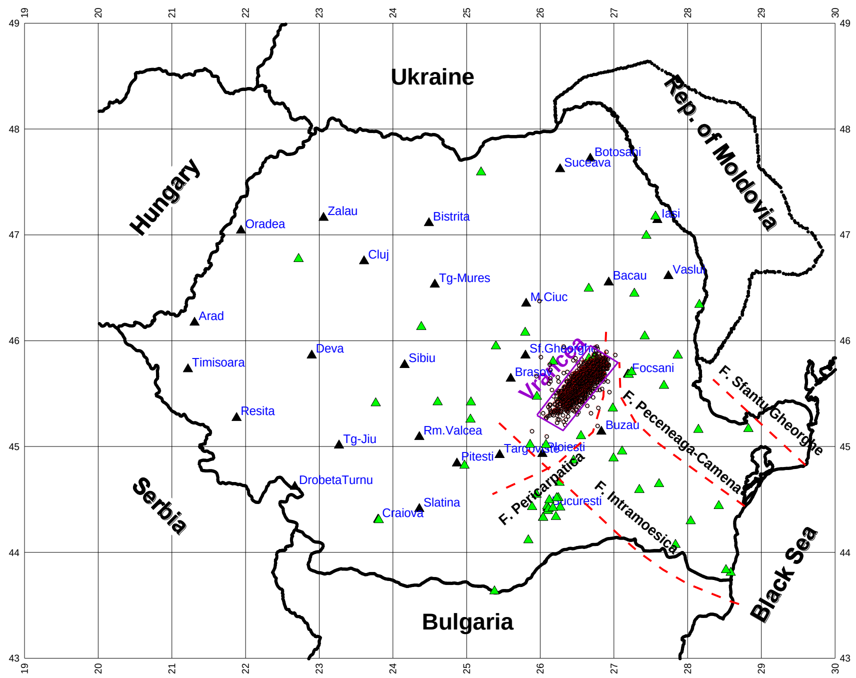

Fig. 1 - Vrancea subcrustal earthquakes with $M_L \geq 2.8$ localized in the1995-2008 period

The time variation of seismic activity presented in Figure 2 for the two active segments and for the entire seismogenic volume shows a higher rate of earthquake generation in the lower segment compared with the upper segment [31, 32].

Two relative increases in the seismic activity can be identified near the dates of the occurrence of two Mw>5.0 earthquakes recorded in the study interval: October 27, 2004 (M_w 6.0) in zone A and April 28, 1999 (M_w5.3) in zone B. The existence of the two distinct zones, A ($60 \leq h \leq 110$ km) and B ($110 < h < 220$ km), is also confirmed by the distribution of the number of earthquakes with depth, but also by the spatial distribution of hypocenters (Figure 3).

In order to apply the statistical tests on the seismic catalog, we first determined the completeness magnitude for the earthquakes belonging to the analyzed lithosphere segments, using the cumulative and non-cumulative frequency-magnitude distribution [33] for segments A, B and A+B. The values are: for (A) Mc=2.5, (B) Mc=2.8 and for (A+B) Mc=2.8.

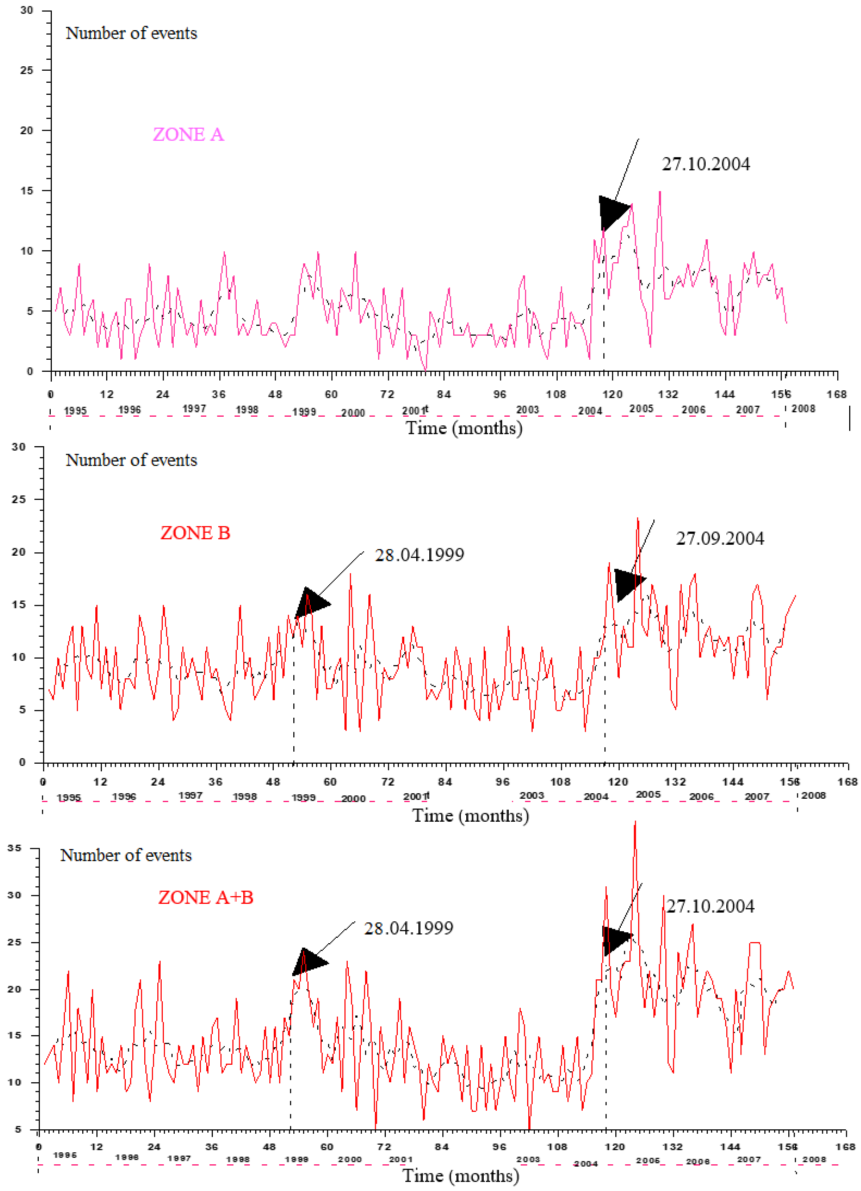

Fig. 2 - The monthly seismic activity for the seismic catalog containing the newly localized earthquakes generated in the period 1995-2008: continuous purple line for zone A; and continuous red lines for zones B and A+B; the dashed gray lines for all zones are the moving averages of the seismic activity

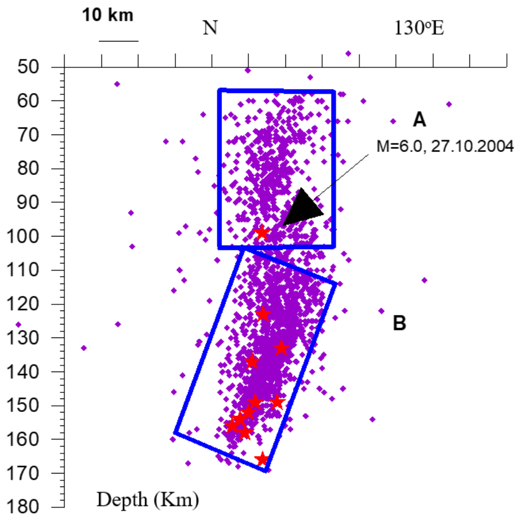

Fig. 3 - Distribution of hypocenters of subcrustal events in Vrancea occurred between January 1, 1995 and January 31, 2008: vertical projection N130°E; The red stars are the hypocenters of the Vrancea earthquakes with M≥5.5 produced between 1995 and 2008

3.2. THE FRACTAL DIMENSION OF THE DISTRIBUTION OF HYPOCENTERS OF INTERMEDIATE DEPTH EARTHQUAKES IN VRANCEA

We studied the fractal nature of the spatial distribution of hypocenters on the following depth domains:

a) A: $60 \le h \le 110$ km;
b) B: $110 < h < 220$ km;
c) A+B: $60 \le h < 220$ km.

To determine the fractal dimension of the spatial distribution of hypocenters, D_2 and its variation over time, the method proposed by [12] was used on the selected catalog (2251 earthquakes - Figure 1).

In order to analyze the temporal variation of the fractal dimension of the distribution of hypocenters, the set of events was divided into subsets of N=100 earthquakes shifted by a moving window of n=10 events.

Fractal dimension is estimated from Eq (3) for the three areas A, B and A+B and are presented in Figure 4. For the inter-event distance, we considered $5 \le r \le 15$ km with a step of 2 km. From the graphic representation of equation (3), we determine the fractal dimension from the linear dependence range for which the spatial distribution of the hypocenters is fractal; this domain of linearity of the distribution is, for all cases, $\log r \in [0.7, 1.1]$, respectively $r \in [5, 13$ km].

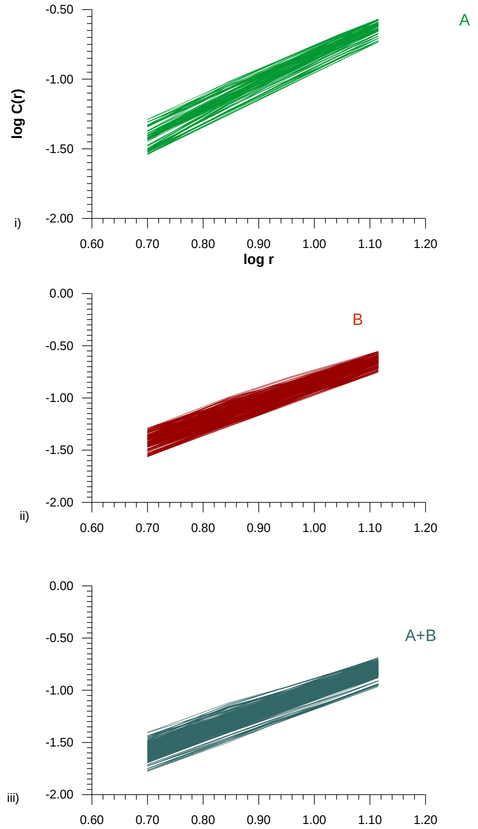

Fig. 4 - Examples of log C(r)~log(r) relationships for areas A - (i) and B - (ii) and for the entire seismogenic area A+B - (iii), for the case of subsets of *N*=100 events with a moving window of n=10 events.

The temporal variation of the fractal dimension of the distribution of hypocenters D_2 is presented in Figures 5 for the three subareas delimited by depth.

Note that the fractal dimension D_2 of the spatial distribution of the hypocenters of the Vrancea subcrustal events has a slight decreasing tendency (from 2.00 to 1.67) for zone A (48 subsets) and a stationary behavior both for area B (112 subsets) and for the entire area A+B (144 subsets), over the analyzed time interval, January 1, 1995-January 31, 2008.

The value of the fractal dimension, D_2, is somewhat smaller in the lower segment compared to the upper one, indicating a greater tendency of grouping in space in the lower area of the subducted volume. The observed fluctuations are between 1.72 and 2.00 in the case of zone B, and between 1.63 and 2.00 in the case of zone A+B.

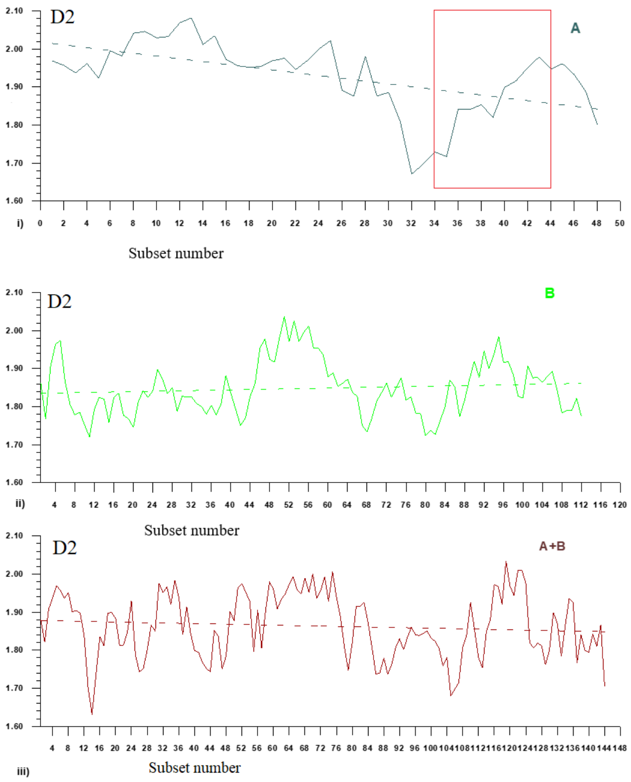

Fig. 5 - Temporal variation of the fractal dimension of the spatial distribution of hypocenters and of the fractal dimension of the distribution of hypocenters for the 3 areas: i) area A; ii) area B; iii) zone A+B, for subsets of *N*=100 earthquakes with a moving window of *n*=10 events. The earthquake from 27.10.2004 occurred inside the red rectangle.

4. ANALYSIS OF THE GROUPING PROPERTIES OF THE VRANCEN CRUSTAL EARTHQUAKES

4.1. ANALYSIS OF SEISMIC ACTIVITY

In the second section of our work, we analyzed the characteristics of the seismic activity of the Vrancea crustal zone using a catalog of seismic events with magnitude $1.7 \leq M_D \leq 4.4$ and depth $1 \leq h \leq 53$ km, completely relocated extending over the time interval January 1, 2006 – December 31, 2008 (Figure 6). The epicentral area of the selected data is shown in the same figure. It overlaps the epicentral area for Vrancea intermediate-depth earthquakes and extends a bit to the east.

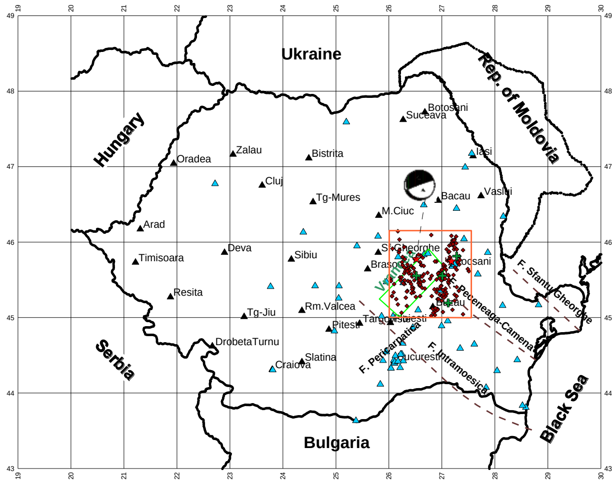

Fig. 6 - The distribution of the epicenters of the earthquakes in the crustal area of Vrancea (orange square). - the diamonds represent the epicenters of the 199 identified earthquakes; -green crosses are the epicenters of earthquakes with magnitudes $3.5 \leq M_D \leq 3.9$ (4 events); the red stars represent the epicenters of earthquakes with magnitudes in the range $4.2 \leq MD \leq 4.4$ (2 events); the blue triangles represent the location of the seismic stations that recorded the events.

We considered crustal earthquakes in an area delimited by the following geographic coordinates: 45.00-46.20 North latitude, 26.00-27.50 East longitude (orange square). Figure 6 shows the distribution of the epicenters of 199 crustal earthquakes in the Vrancea crustal area. The largest crustal earthquake in the analyzed period (M_D=4.4 and h= 13 km) was recorded on September 9, 2008, at 19:48. The largest earthquake known in the area is the one with Mw = 5.9 occurred on March 1, 1894, with magnitude estimated from historical information (possibly overestimated) [34- 36].

In order to apply statistical tests to the selected earthquake catalog, we determined the completeness magnitude for the earthquakes belonging to the analyzed lithosphere segments, using the non-cumulative and cumulative frequency-magnitude distribution of [33] and obtained the completeness magnitude for the studied period as Mc=1.7.

4.2. THE FRACTAL DIMENSION OF THE DISTRIBUTION OF HYPOCENTERS OF CRUSTAL EARTHQUAKES IN THE VRANCEA AREA

To determine the fractal dimension of the spatial distribution of D_2 hypocenters and its variation over time, 199 crustal earthquakes generated in the area of interest were selected ($1.7 \leq MD \leq 4.4$, $1 \leq h \leq 53$ km). In order to analyze the temporal variation of the fractal dimension of the distribution of hypocenters, the set of events was divided into subsets of N=100, 50 and 30 earthquakes shifted with a moving window of n=10 events. To check for the credibility of the results, we also used subsets of different sizes.

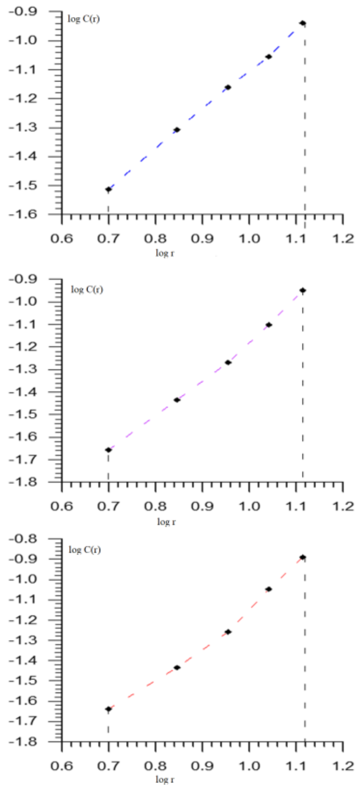

Fig. 7 - Examples of log C(r)~log (r) relations for the three cases in the case of the distribution of hypocenters of crustal earthquakes: blue (upper graph) - subsets of N=100 events with a moving window of n=10 events; purple (middle graph) - subsets of N=50 events each with a moving window of n=10 events; red (bottom graph) - subsets of N=30 events each with a moving window of n=10 events.

Relations (1) estimated for the subsets of the three previously mentioned cases are presented in Figure 7 for subsets of N=100, 50 and 30 events respectively with the moving window of n=10 events. To determine the fractal dimension from relation (1), distances $5 \leq r \leq 15$ km with a step of 2 km were considered. From the graphic representation of equation (1), the range on which it is linear was determined and therefore the spatial distribution of the hypocenters is fractal; this domain of linearity of the distribution is, for all cases, log r $\in$ [0.7, 1.1], respectively r $\in$ [5, 13 km] (Figure 7).

To determine the temporal variation of the fractal dimension of the spatial distribution of D_2 hypocenters, the reliable database of events produced between

January 1, 2006 and September 2008 (199 crustal earthquakes) was used. Figure 8 shows the time variation of the fractal dimension D_2 for the cases mentioned above.

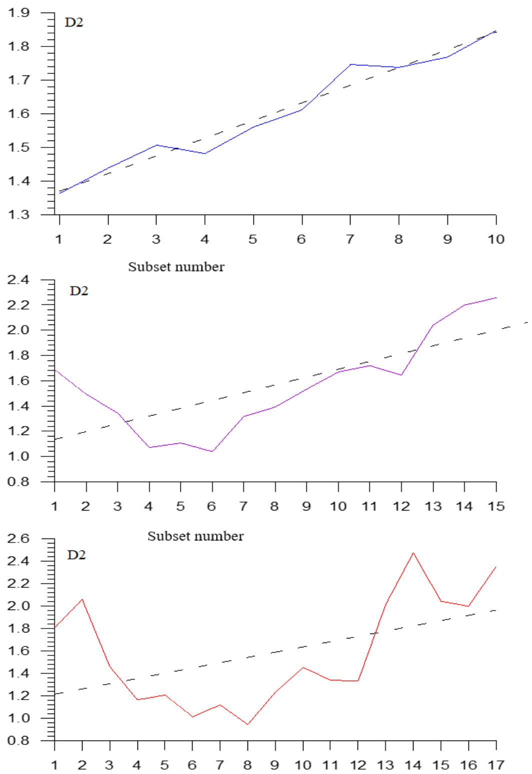

Fig. 8 - The variation of the fractal dimension of the spatial distribution of D2 hypocenters for the types of subsets defined above.

The results show that the fractal dimension D_2 of the spatial distribution of the hypocenters of the Vrancea crustal events has increasing linear trend in all three cases (from 1.36 to 1.84 for 10 subsets of 100 earthquakes, from 1.03 to 2.25 for 15 subsets of 50 events and from 0.94 to 2.47 for 17 subsets of 30 events) for the entire time interval. Clearly, the lowest statistical fluctuations are obtained for the case of 100 events with a moving window of 10 earthquakes which best satisfy the statistical requirements.

5. CONCLUSIONS

In this article, the investigation of the fractal properties of the spatial distribution of crustal and subcrustal earthquakes was carried out in the context of the depth segmentation of the subducted lithosphere and the finding of possible precursor elements of the large Vrancea earthquakes.

For the 2251 events produced in Vrancea at intermediate depth during the period January 1, 1995-December 31, 2008, complete re-localizations were made (time of origin, depth and epicentral coordinates).

In the case of the Vrancea subcrustal earthquakes, it is observed that on all three segments of the subducted lithosphere, A, B and A+B, the larger earthquakes occurred on an upward slope of the seismic activity and that the seismic activity shows two maxima near the occurrence of the largest earthquakes of our selected data: October 27, 2004 (M_w 6.0) in area A and April 28, 1999 (M_w 5.3) in area B.

The fractal dimension D_2 of the spatial distribution of the hypocenters of the Vrancea subcrustal events selected in our analysis has values in the range $1.63 \leq D2 \leq 2.08$ suggesting a tendency of clustering in space (a homogeneous non-clustered distribution would have a fractal dimension of 3 for the hypocentral distribution). The value of the fractal dimension, D_2, is somewhat lower in the lower segment (B) compared to the upper one (A), indicating a greater tendency of grouping in space in the lower area of the subducted volume.

Analyzing the data on subsets of 100 earthquakes with a moving window of 10 earthquakes, it is observed that the fractal dimension D2 of the spatial distribution of the hypocenters of the Vrancea subcrustal events has a slight decreasing tendency (from 2.08 to 1.67) for zone A (48 subsets) and a stationary behavior both for area B (112 subsets) and for the entire area A+B (144 subsets), over the analyzed time interval, January 1, 1995-January 31, 2008.The observed fluctuations (between 1.72 and 2.04 in the case of zone B, and between 1.63 and 2.01 in the case of zone A+B) fall within the expected statistical fluctuations. The fractal dimension shows a visible decreasing anomaly preceding the largest Mw=6.0 earthquake in the dataset occurred on 27th of October 2004.

The similar analysis carried out for the crustal Vrancea earthquakes shows fractal dimension D_2 values extended over the entire interval from 1 to 2, but in this case the statistics is obviously weaker. Also, the time interval for the analysis (2006 – 2008) is probably too short to be representative. In this particular case, the clustering in space seems to diminish in time in agreement with the increasing trend of D_2 values, from about 1.4 at the beginning and close to 2 at the end.

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