5.3.1. GEODYNAMICS OF THE SOUTH BALKANS – SEISMOTECTONIC MODEL, FRACTALITY AND NONLINEAR PROPERTIES

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5.3.1.1. Introduction

This study presents some of the investigations of the authors published during the last decade and summarizing the knowledge and some selected views about the geodynamics of the South Balkans and the Aegean region. It is not pretended of the full reflection of the previous research and results made on these areas. This is not the aim of this study. The area is extensively investigated by many authors and different views and interpretations are expressed (McKenzie, 1972, Papazachos, 1966, Ranguelov, 1987, etc.). Our aim is just to focus on some summary results about the seismotectonics and the fractal properties and nonlinearities observed there.

5.3.1.2. Neotectonic background

The neotectonic movements of the Balkan Peninsula occurred after the last intense thrusting (Early Miocene), and after the Early – Middle Miocene planation. (Zagorchev, 1992). They were controlled by extensional collapse of the Late Alpine orogen, and by extension behind the Aegean arc, and were influenced by the complicated vertical and horizontal movements in the Pannonian region. The Balkan mountain and the Dinarian Hellenic linear neotectonic morphostructures inherited the Alpine orogenic zones and bounded the Central-Balkan neotectonic region. The linear morphostructures were tilted towards the Pannonian and Euxinian basins and the North-Aegean though.

The Central-Balkan neotectonic region has a complicated block structure (horst and graben pattern) dominated by the NNW-SSE Struma and Vardar lineaments and the Middle-Mesta and North Anatolian fault zones. The Struma lineaments consist mainly of normal fault and right-lateral strike-slip faults. Vertical neotectonic amplitudes along some of the faults reached up to 3-3.5 km, and the thickness of Neogene deposits in the Struma graben complex, up to 1.6 km and 3 km. a general tilting of the grabens to the east is recorded corresponding to their position in the eastern flank of the Serbo-Macedonian swell. The Vardar lineament is located in the western flank of the swell, and accordingly, the orthoplain and the Neogene sediments are dipping west. The thickness of the Neogene sediments in some of the depressions is up to 2-3 km, and the vertical neotectonic amplitudes may be as high as 5 km. the Vardar and Struma lineaments and Serbo - Macedonian swell form a complicated continental rift structure with maximum subsidence along the lineaments (graben complexes).

The Middle-Mesta fault zone (lineaments) is traced at a distance of about 300 km in west-east direction. It is marked by differentiated neotectonic block movements most contrasting at the northern and southern slopes of the Belasica horst at the intersection of the serbo-Macedonian swell. The vertical amplitudes reach up to 2-2.5 km. the

Middle-Mesta lineament represented the northern boundary of Neogene marine ingressions from the North-Aegean trough. A right-lateral displacement along some of the faults is inferred from the remote sensing imaginary.

Transversal fault zones striking SW-NE are most important for the development of the Vardar and Struma lineaments and the whole Central-Balkan neotectonic region. They have been traced at distances of about 100 km. Their intersections with major faults of the Struma and Vardar lineaments are characterized by most contrasting (3 – 4 km) vertical neotectonic movements, and represent seismotectonic knots of very intense seismicity.

The Earth's crust on the Balkan Peninsula is highly heterogeneous due to former plate motions and continental collisions. Subduction of the African under the Eurasian plate is now located in the Hellenic subduction zone, and neotectonic movements are dominated extension (Arsovski, 1997).

The crust of the Serbo-Macedonian swell and Struma and Vardar lineaments is of intermediate thickness: between 30 and 40 km. Subsided into an imperfect rift structure, this area is situated between areas of thickened crust corresponding to the Pelagonian and Rila-Rhodope swells.

The most thickened crustal lens of the Rila – Rhodope massif (40 -50 km) coincides with a pronounced isostatic anomaly and the most intense (up to 5 mm/a) recent vertical uplift

5.3.1.3. Seismicity and the GPS measurements supporting the study of the recent stress field

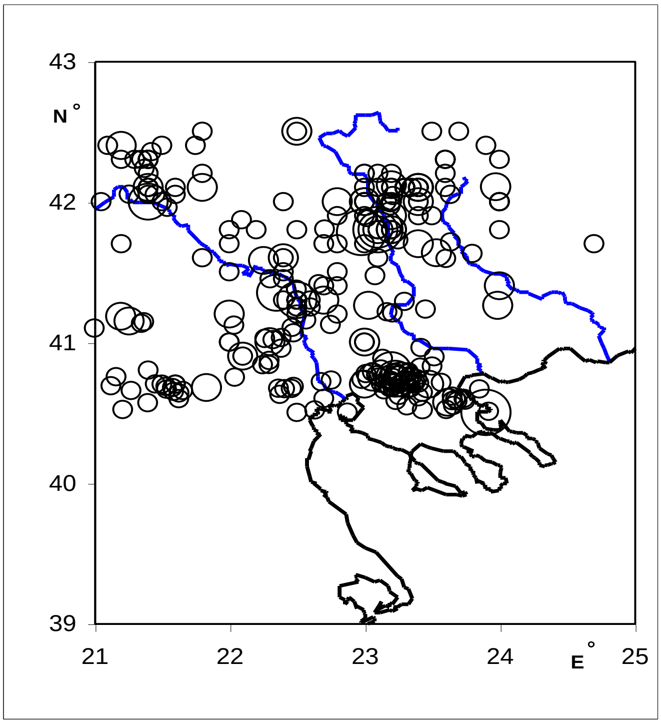


Fig. 5.3.1.1. Epicentral map of the earthquakes with M>4 for the time period 1900-2000

The recent observed seismicity shows specific spatial distributions. Our interpretation is that the stress field is located almost perpendicularly to the main displacement directions (Dimitrova, Ranguelov, 2002)

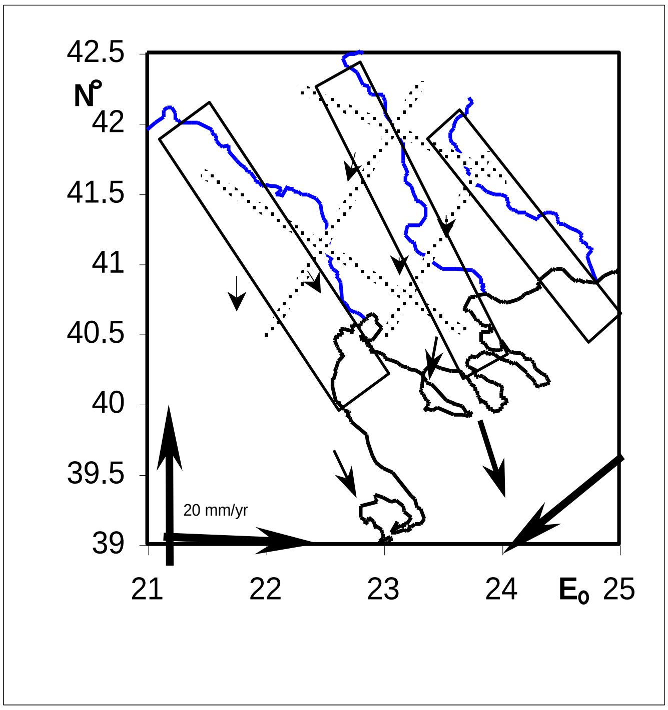


Fig. 5.3.1.2. Sketch of the general active lineaments according the grabens of Struma, Mesta and Vardar rivers. The arrows show the movements established by the GPS measurements. The dotted linear areas expressed the stresses local distribution according authors' interpretation

5.3.1.4. Recent geodynamic model

The recent geodynamic model has been compiled generally by the last publications of the authors (Ranguelov et al., 2003).

North Aegean Sea Geodynamic Model (NASDM)

The North Aegean Sea geodynamic model considers the geodynamic peculiarities to the North of the east branches of the North Anatolian Fault system. It is characterized by the dominant influence of the North Anatolian recent movements established very reliable by the GPS measurements. The direction of these movements is to the Southwest and the amplitude of about 20-25 mm/y. Due to these relatively fast movements the surface block elements of the earth crust are moving to the same direction. As a result – the openings (clearly expressed grabens fulfilled by the rivers going to the south – such as Srtuma, Mesta, Vardar and Maritza), show clear extension to the North-South direction. The grabens started their recent development during the Neogene, so their position and shape have a relatively long lasted formation during the geological times. The recent GPS measurements show relatively small amplitudes – up to 2 mm/y. The "dragging" effect of the North Anatolian Fault movements is presented by the surface relief expressions of the asymmetrical opening of the grabens. The direction is to the west. The 'three fingers" location of the smaller peninsulas of the Halkidiki peninsula is due to the same effect. All other smaller riverbeds located

between Vardar and Maritza riverbeds show similar behavior. The seismic regime (as a resent expression of the stress distribution and the redistribution) is very active there.

Several large destructive earthquakes occurred during the last century:
1902 – an earthquake NE of Thessaloniki (M~6.6)
1904 – two very strong earthquakes (M=7.2 and 7.8) near Kresna village.
1931 – Valandovo earthquake – M= 6.7
1963 – Skopje earthquake M=6.1
1978 – Thessaloniki earthquake M=6.4

Most of the strong earthquakes show normal faulting Ritsema A.,(1974) expressed as well on the surface coseismic cracking with vertical movements from tens of centimeters (Thessaloniki earthquake, 1978) up to meters (Kresna-Kroupnik earthquakes, 1904) (Ranguelov et al., 2001). The presented geodynamic regime is dominant for this area and thus is the main reason for the formation of the recent, so called Balkan-Aegean Graben System (BAGS).

South Aegean Arc Subduction Zone Model (SAASZM)

The subduction zone dominates this model, and signalizes the collision of the Northeast part of the African plate to the Southeast part of the European plate. The total length of the zone is about 1 500 km. The zone has a big sharp curve trajectory expressed most clearly near the region of Crete Island.

Many authors indicate the Benioff zone (Caputo, 1970), dipping to the north in average with 35 degrees due to the presence of the intermediate earthquakes going down to the depths of 100-160-200 km. Some previous investigations (Ranguelov, 1987) show the depth penetration of the different segments of this zone as well as the most significant areas of the bigger seismic energy emission. Using the simple geometry calculations the dip angels of the four different subducted plaques of the Earth crust are calculated and presented at the Table 5.3.1.1.

Table 5.3.1.1. Dimensions and deeping angels of the subducted plaques (according Ranguelov, 1987)

Dimensions/ No of plaques	I	II	III	IV
Length [km]	135	200	160	320
Depth [km]	160	130	100	160
Deep angle [o]	52	33	32	26

It's interesting to note that the recent volcanism are located to the north of the subducted part and outlines the area of the volcanic islands – Cyclades and Sporades (Nichols, 1971). A zone with lower seismicity exists near to the north, which often is connected by different authors with a "mantle dome" of low velocity astenosphere. The bottom relief show clear evidences typical to all world wide presented subduction zones. Using the previous knowledge (Ranguelov et al., 1982) and the recent image of the subducted zone, a model of the locations of the Earth's crust elements and the forces acting on them is constructed. Due to the stress distribution and redistribution, the whole Aegean zone is a seismically active region.

Very often the submarine earthquakes generated tsunamis (for example – the most significant recent one of 1952). The zones of extension follow the classical presence of a subduction zone with compression regime to the north. The volcanism is expressed to the frontal part of the zone, which makes this area a typical case. The location to the north of the North Anatolian transform fault makes the situation more complicated, which is indicated by some zones questionable with not clear geodynamic regime (Fig. 5.3.1.3.).

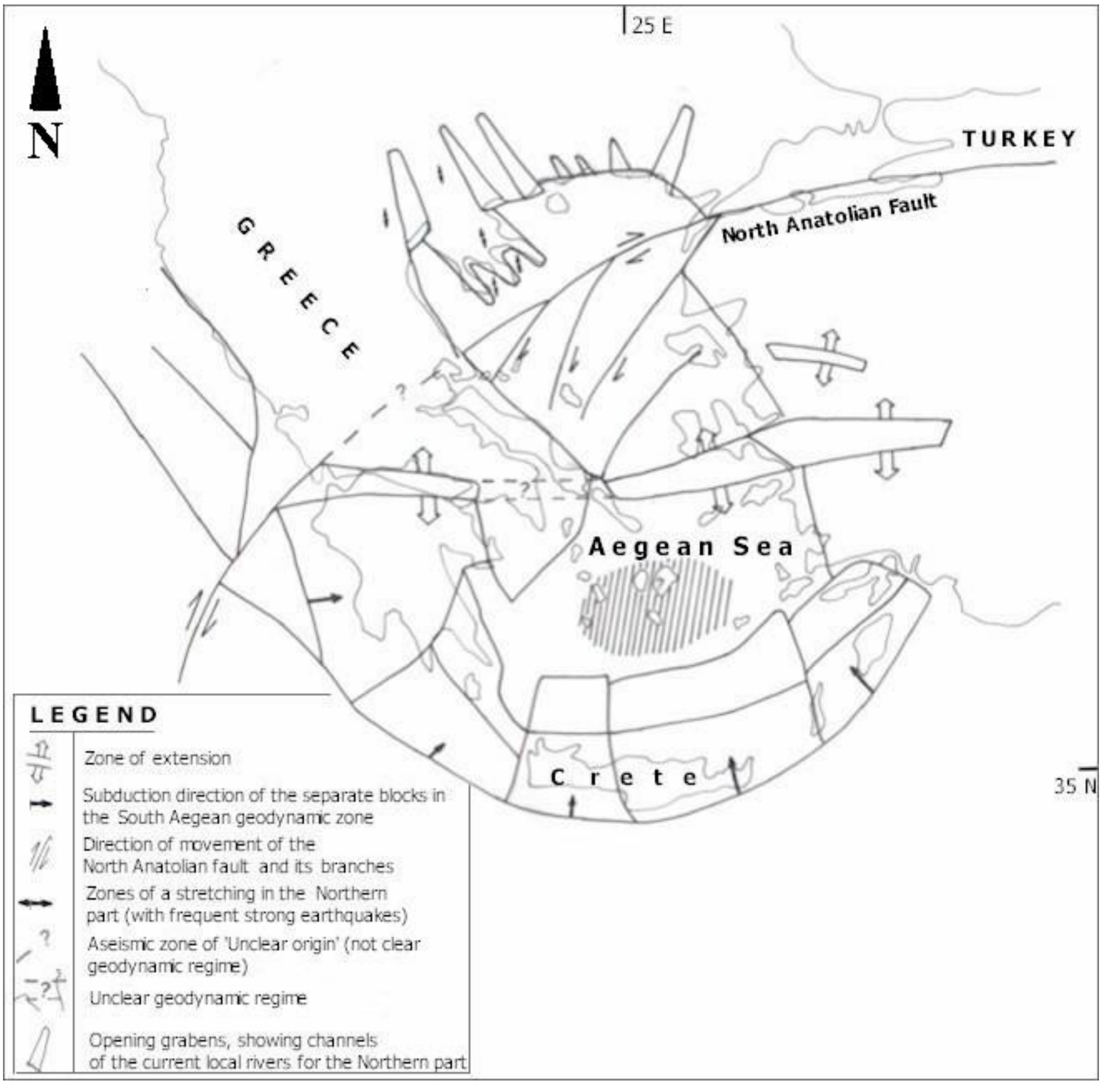


Fig. 5.3.1.3. General Integrated Scheme

Combining the North Aegean Sea model (NASDM) and South Aegean arc model (SAASZM), an integrated geodynamic scheme is constructed - Fig. 5.3.1.3. It explains the existence of the complicated extensional-compression zones located on mosaic and irregular way. The main "actors" of this geodynamic drama are The North Anatolian Transform fault and the Aegean Subduction zone. The simultaneous action of both big tectonic units leads to the complicated and irregular picture of the region. Areas of extension follow areas of clear compression. Transform (strake-slip), normal and complicated faulting are often observed. The main expression of the recent activity of these structural units are: many strong and smaller earthquakes, sometimes generating

tsunamis, submarine and surface landslides and rockfalls, recent volcanism and the fast relief changes due to the inner Earth forces.

The specific behavior of the Aegean arc subduction zone is investigated as well. The specificity is dominated by several factors:
- the sharp curve outline the subduction zone;
- a practically aseismic zone exist to the inner (northern) part of the subduction zone;
- not very active volcanic activity on one side and very high seismic activity on the other, reaching depths to 200 km.;
- existence of zones of extensional and compressive geodynamic regime;
- existence of the clearly expressed transform fault (North Anatolian);
- high horizontal displacement velocities measured by GPS;
- clear normal faults generated by the earthquakes in the extensional regions and clear strike-slip faults connected with the North-Anatolian fault earthquakes, etc.

All these peculiarities focused our attention and investigating the observed phenomena we suggested a common model trying to explain all observed facts on this very interesting geodynamic zone of the Aegean Sea.

Strong, destructive earthquakes located in the area covered by the Struma, Mesta and Vardar riverbeds are frequent and high intensive. Most of them occurred during the XX-th century. They generated facilities destruction and people victims. The recent geodynamic movements can be observed by the riverbeds tectonic development (as an active geomorpholocical expressions, high seismic activity (as more recent fast geodynamic expressions) and earth crust displacements registered by the recent GPS techniques (as measurable movements during the last decades). The new constructed geodynamic model explains the observed evidences. The expectations of the future strong earthquakes at the same area are high and the measures against their influence must be considered.

The suggested geodynamic model reflects almost all observed phenomena in the Aegean region. The complicated structure of the inner parts of the Aegean subduction zone is reflected by different zones with different orientation and different (extensional, compression and transform) geodynamic regime even with some rotational movements.

The location of the fault structures, observed seismicity (with its spatial and temporal specific behavior) and the surface and deep earth crust movements (some of them detected by the GPS measurements) gives an image about the complicated geodynamics of this very specific boundary zone between European and African plates. The volcanism is also an expression of the recent geodynamic activity.

5.3.1.5. Seismotectonic model and its fractal properties

The present study is focused as well as on the estimation of the fractal properties and coefficients of the seismogenic zones in the Mediterranean region. The area is divided into several seismotectonic provinces in accordance with the corresponding fragmentation and the specific seismogenic properties of the earth crust for the separate zones. The Mediterranean seismotectonic model (MSM) is presented by (Jimenez et al,. 2001). The separate zones could be characterized by their specific seismogenic properties which could lead to different seismic impact on buildings and constructions. In that way this analysis gives the possibility for zone identification and comparison between different provinces each of them being most probably characterized by specific seismic hazard.

To study the fractal properties (distributions and dimensions) we used the methodology described by (Ranguelov et al., 2003).

The classical example of a fractal object is defined by (Mandelbrot, 1982). If the length of an object P is related to the measuring unit length by the formula

(1) $$P \sim l^{1-D}$$

then P is a fractal and D is defined as the fractal dimension. This definition was given by Beno Mandelbrot in the early 60-s of the 20-th century. His ideas support the view that many objects in nature can not be described by simple geometric forms but they have different levels of geometric fragmentation. It is expressed in irregularities of different scale – from very small to quite big ones. This makes the measuring unit extremely important because measuring of the length, the surface or the volume of irregular geometric bodies is strongly dependent on the smallest measuring unit in a way that the parameter value changes vary hundred to thousand orders. This fact was first determined when measuring the coastal line length of West England and this gave Mandelbrot the idea to define the concept of a fractal.

In geology and geophysics it is accepted that defining the different 'fractals' as real physical objects is most often connected to fragmentation (Korvin, 1992). This reveals that each measurable object has a length, surface or volume, which depends on the measuring unit and the object's form irregularity. The smaller the measuring unit is, the bigger the common sum for the linear dimension of the object is and vice versa. The same is valid for 2D and 3D objects.

Another definition of a fractal can be made by the relation between the serial number of measuring to each of the measuring units and the object dimensions. If the number of the concrete measuring with a chosen linear unit is bigger than r, then it may be presented by:

(2) $$N \sim r^{-D}$$

and the fractal is completely determined by D as its characteristic fractal dimension. Applying this definition for the elements of faulting and faults fragmentation, some authors use this idea to depict formal models of the earth crust fragmentation (citing foreign authors), which indicate the level of fracturing of the upper earth layers.

The theoretical approach for the linear case and for the 2D and 3D cases was developed by (Turcotte, 1986, Hirata, 1989). They focused attention on the relations between the smallest measuring unit and object's size in analyzing linear, 2D and 3D objects (Fig. 5.3.1.4).

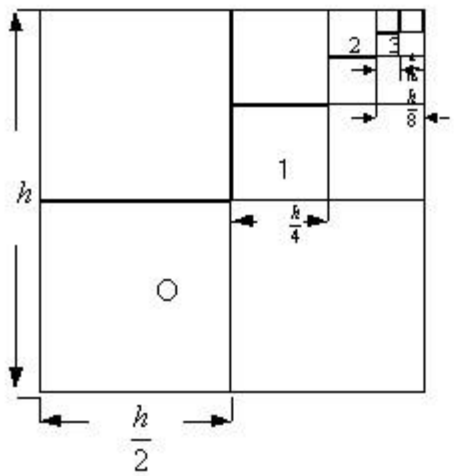


Fig. 5.3.1.4. 2D fractal scheme

If l is the measuring unit and with m we denote the obtained value for N at each measuring cycle, then the common sum of the lengths N at level m is according to Turcotte (1986)

(3) $$N_m = (1 - p_c)(1 + \frac{n}{m} p_c + [\frac{n}{m} p_c]^2 \ldots [\frac{n}{m} p_c]^m)$$

where Pc denotes the probability for measuring of each length for the corresponding cycle of measuring.

Using formulae (1) and (2) by Turcotte we obtain the formula

(4) $$\frac{N_{m+1}}{N_m} = 2^D$$

(5) $$\frac{N_{m+1}}{N_m} = \left(2^2\right)^D$$

Using this approach we studied and analyze the elements of the Mediterranean seismotectonic model and compare them with the Balkans seismotectonic model. The existence of different geometrical objects of similar type like the different seismic hazard zones in various Mediterranean areas makes it suitable to use such an approach when determining the fractal features of the considered seismotectonic models.

To study the fractal features of the Mediterranean seismotectonic model offered by M.Jimenez et al. (2001), we have used data from the map (Seismicity Source Regions for the Mediterranean Region). The map scale is 1:28 000 000 – Fig. 5.3.1.5.

We have determined the number and the size of all lines delineating each of the surface elements of the model. The error in determining the size is less than 5%. The authors of the map have divided the region into several seismotectonic provinces (we follow their denoting):

- **The Adriatic (AD)**
- **Central and West Europe (CWE)**

- The Pyrenees and West Africa (PWA)
- Greece (GR)
- Bulgaria and the Northern Balkans (BG NB)

Each province was considered separately at first. Finally some general studies have been made for the whole Mediterranean region.

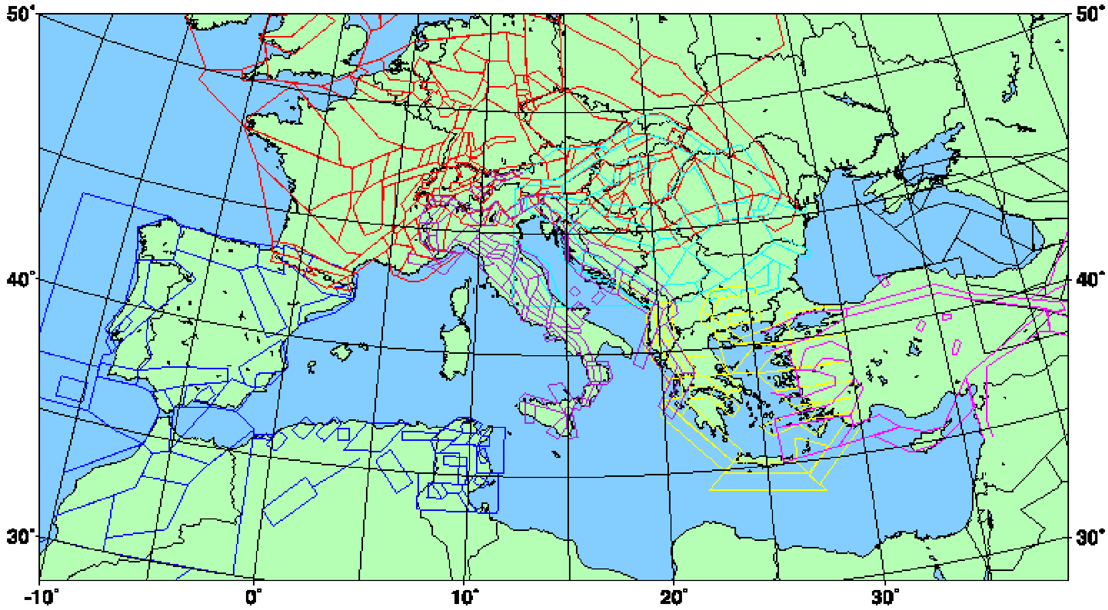
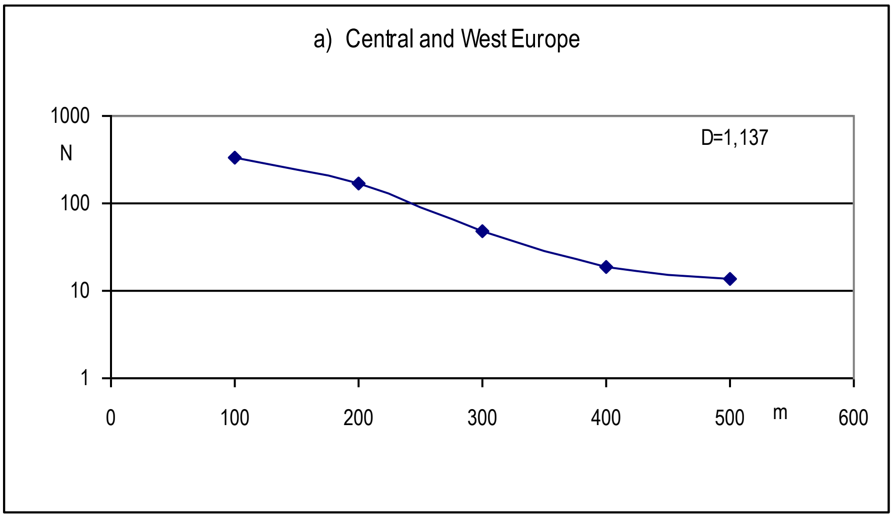
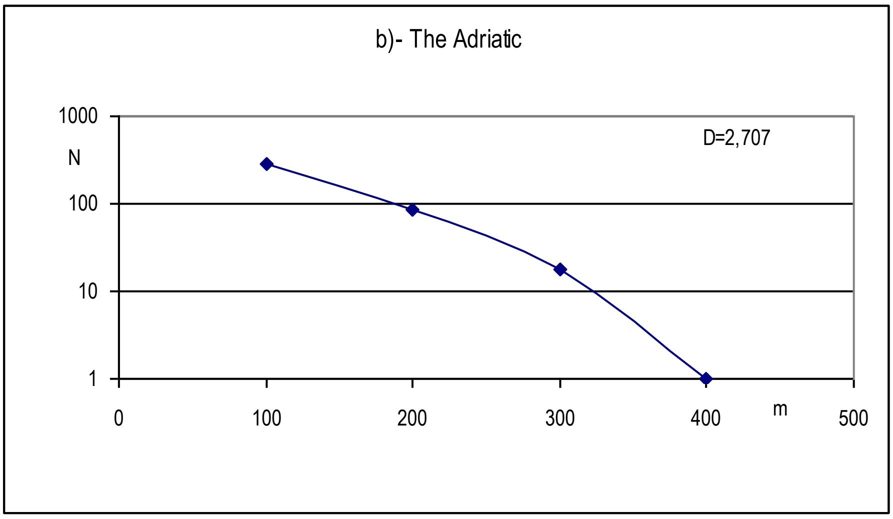
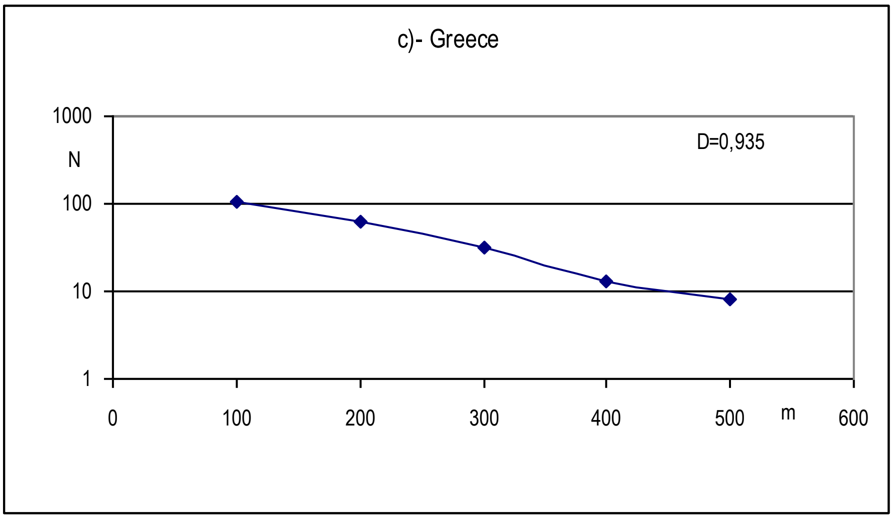


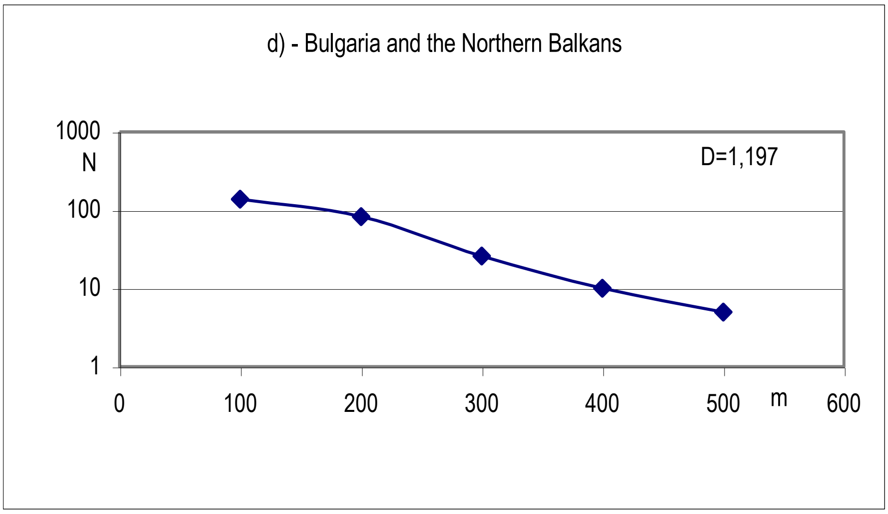
Fig. 5.3.1.5. The Euro Mediterranean seismotectonic model

The lengths of the delineating elements for each seismotectonic zone vary between 100-500 km (they are very rarely bigger, but the number of such cases is small enough). Cumulative plots have been developed in order to calculate the fractal dimension of each zone. The results are presented on Fig. 5.3.1.6 (a-f).




b)- The Adriatic
1000
N
100
10
1
0
100
200
300
400
m
500
D=2,707


c)- Greece
1000
N
100
10
1
0
100
200
300
400
500
m
600
D=0,935


d) - Bulgaria and the Northern Balkans
1000
N
100
10
1
0
100
200
300
400
500
m
600
D=1,197

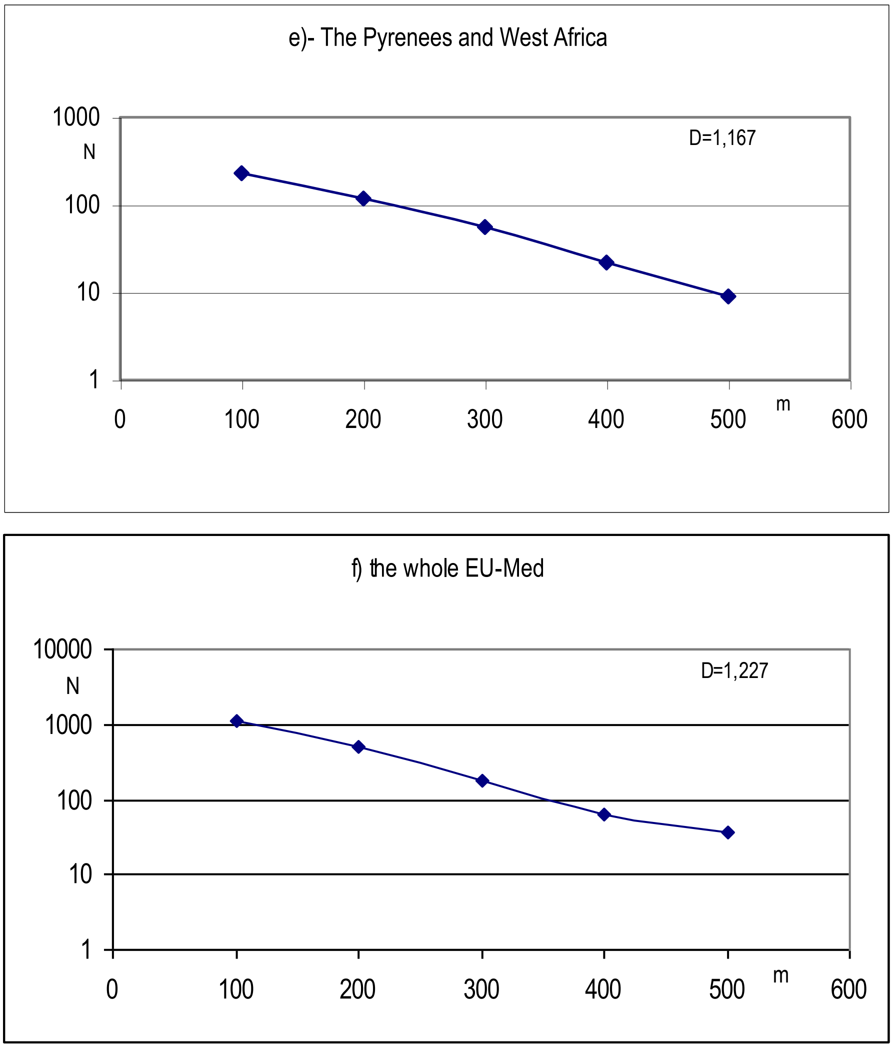


Fig. 5.3.1.6. (a-f) Fractal distributions for the studied seismotectonic model – linear elements

We have also determined the surface fractal dimensions of the separate seismotectonic elements for the same region. All surface areas have been determined and we have plotted the relations - number – area surface for each zone. For this purpose we have used the map M. Jimenez et al., (2001), which is in a scale 1:30 000 000 and the separated zones. The measured surface areas vary from 500 to 2500 km^2.

The obtained results for the different provinces reveal on Table 5.3.1.2:

Table 5.3.1.2. Fractal dimensions about the linear (D_L) and surface (D_S) elements

Zone	$D_{(L)}$	$D_{(S)}$
AD	2,71	1.67
CWE	1,12	0.41
PWA	1,18	0.24
GR	0.94	0.40
BG NB	1.20	0.25
All zones	1.23	0.38

The dimension values for the 'Adriatic' zone - AD differ substantially from the other zones values. This concerns both the linear elements and the 2D elements, and it is reflected in both studied parameters the level of non-linearity (the D-value respectively) being the biggest.

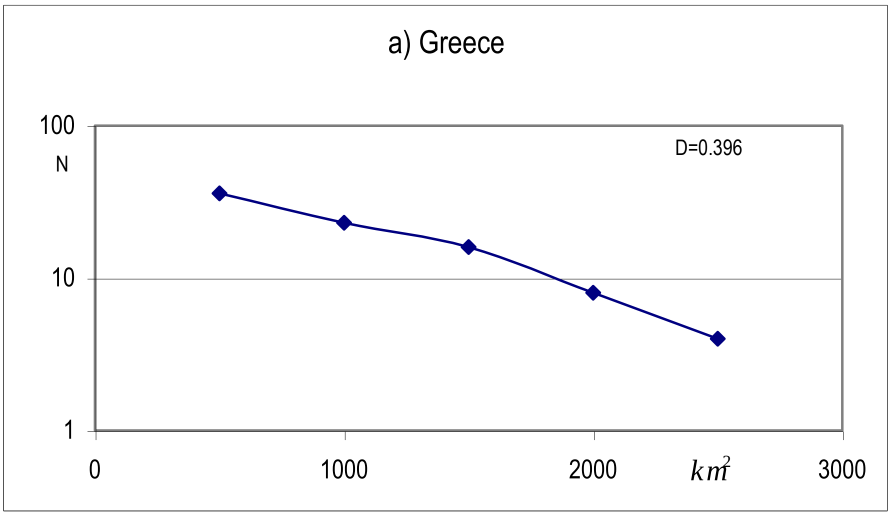
All remaining zones are similar according to their non-linear behavior (considering their linear boundaries). The dimension values vary from 1.1 to 1.25 with Greece making an exception with a dimension under 1.0 (0.94).

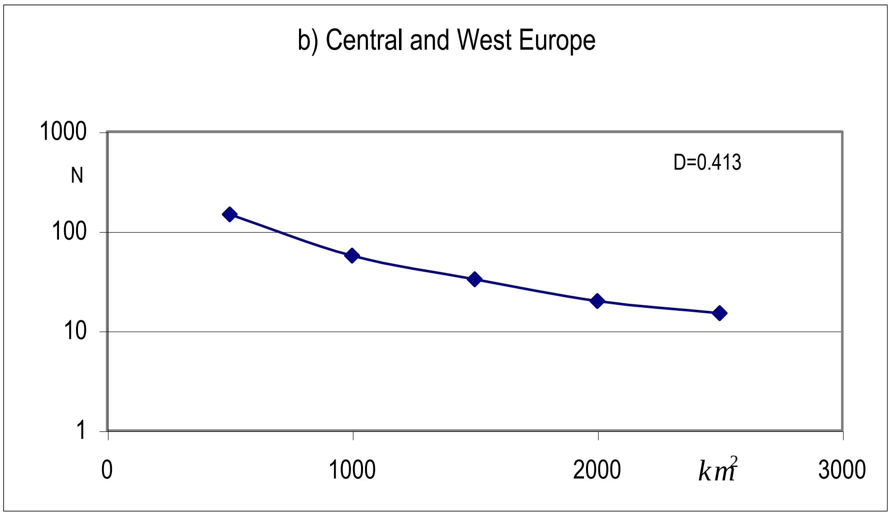
Regarding the 2D fractal features, the differences are smaller with the exception of the Adriatic zone again. Some grouping can be identified of different zones according to their fractal dimension values – 'Greece' and 'Central and West Europe' (0.41-0.40). These zones are quite different by their seismic activity but they are similar concerning their seismically hazardous areas.

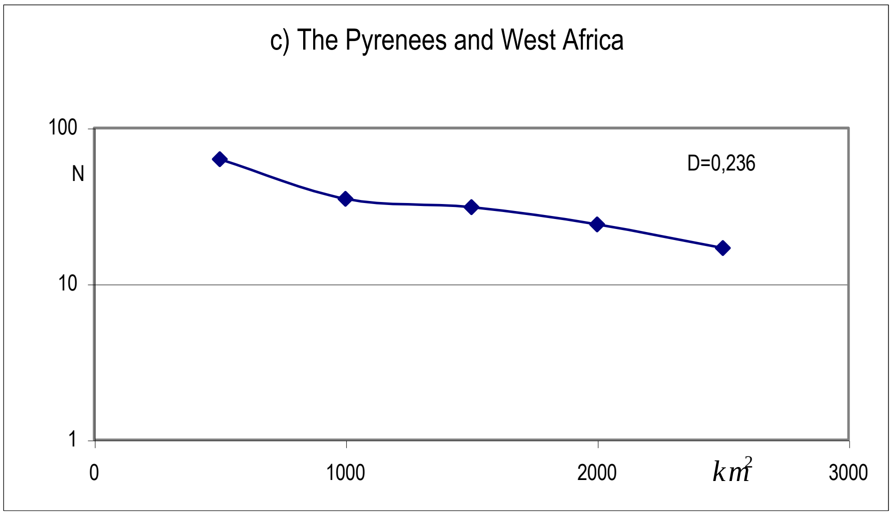
Other similar zones (by their linear dimensions) are 'The Pyrenees and West Africa' and 'Bulgaria and the Northern Balkans' (025-0.24). These provinces hardly have similar geodynamic features but they are formally similar for sure according to the distribution of their seismically dangerous areas. In one way or another, the hazardous areas have similar sizes. The results are presented on Fig. 5.3.1.7.

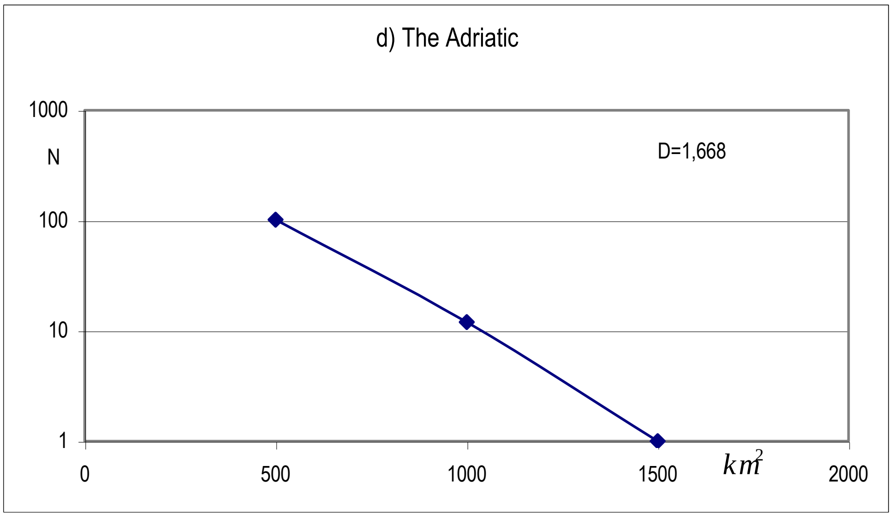
The same methodology has been applied especially about the Balkan seismotectonic model (Fig. 5.3.1.8.) extracted by the same source (Jimenec et al., 2001). The comparison of the results obtained shows that the Balkan model has bigger fractal dimension about the surface elements – D=0.88 (0.38 for the whole Mediterranean) and smaller for the linear elements D= 1.13 (1.23 for the whole Mediterranean area)

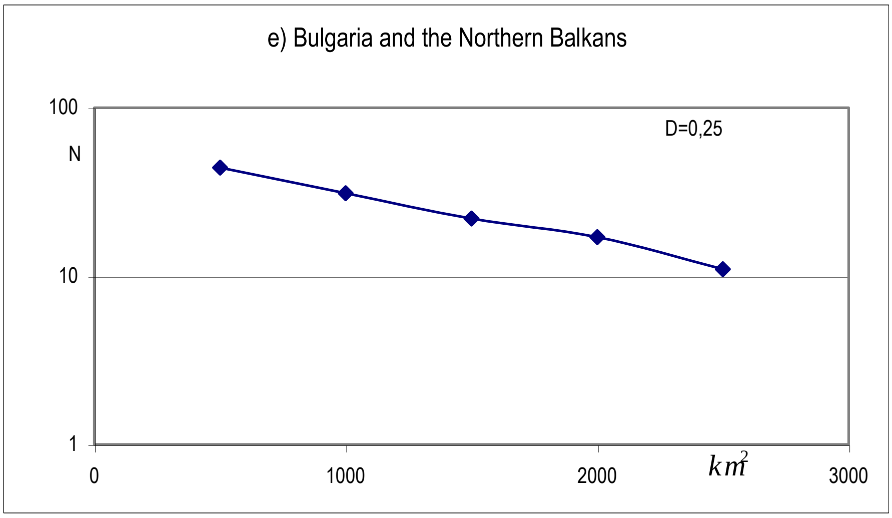
The obtained results of this "fractal approach" reveal that the applied method can be useful in comparing the behavior of the seismogenic elements of the different seismotectonic provinces. The existence of clearly defined non-linear features of the seismic hazard distribution reveals again, that this sensitive part of human knowledge about the practical assessment of seismic hazard can not be described by simple elementary relations. It becomes evident that more punctual and refined methods of the mathematical analysis are obligatory in order to avoid generalizations made only on analogs, which was done in many case up to now.




b) Central and West Europe
1000
N
100
10
1
D=0.413
0
1000
2000
km²
3000


c) The Pyrenees and West Africa
100
N
10
1
D=0,236
0
1000
2000
km²
3000


d) The Adriatic
1000
N
100
10
1
D=1,668
0
500
1000
1500
km²
2000



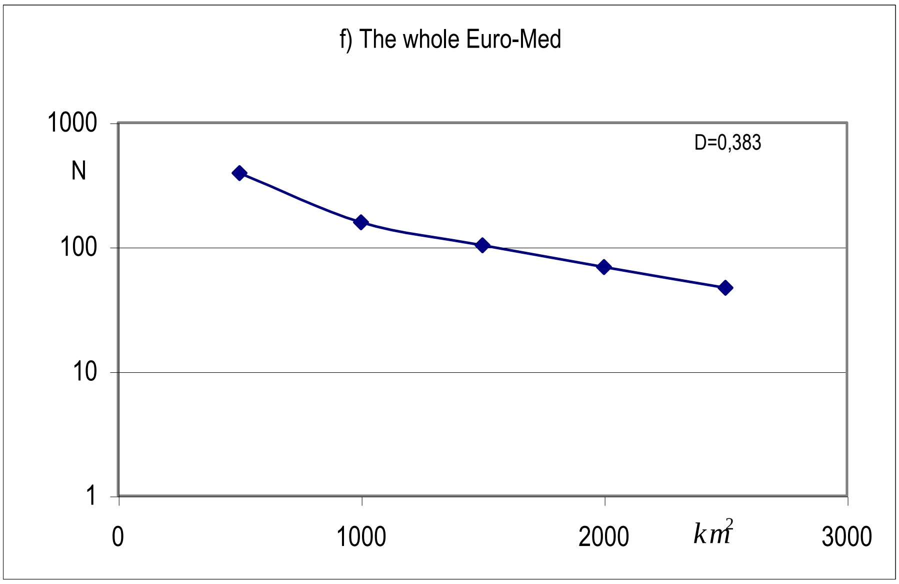


Fig. 5.3.1.7. (a-f). Fractal distributions for the studied seismotectonic model – surface elements

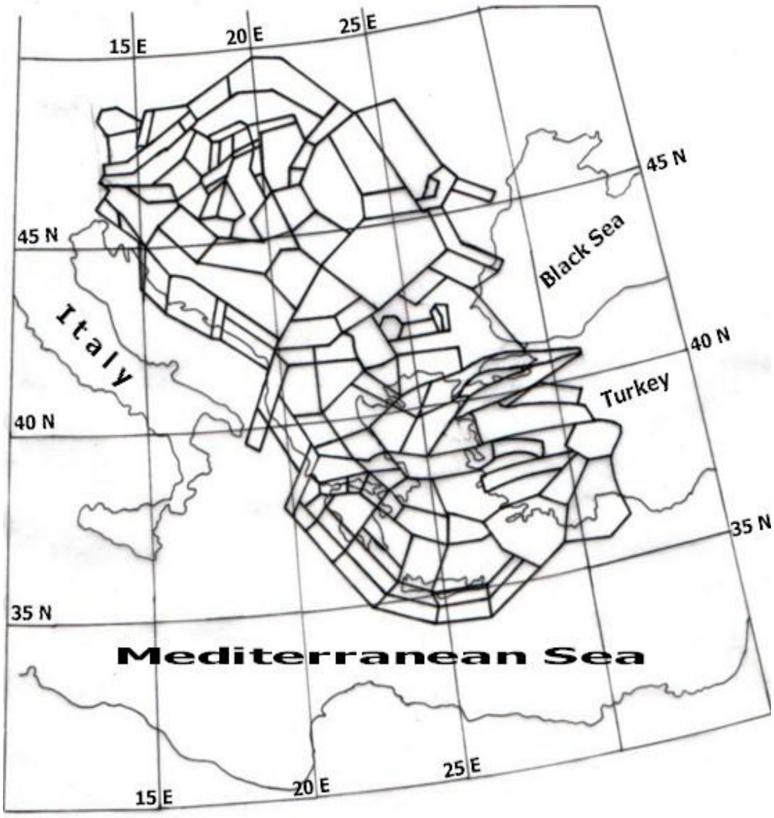


Fig. 5.3.1.8. The seismotectonic model of the Balkan area (after Jimenez et al., 2001) under fractal analysis (Ranguelov et al., 2004)

5.3.1.6. Conclusions

The presented analysis shows the results of the research of the investigated area. Recent seismicity, geomorphology and the GPS measurements appear as strong tools to obtain new knowledge about the South Balkans and surroundings from the geodynamic point of view. The fractal analysis is a useful approach to prove the strong nonlinearity concerning the geometry distributions of the seismic active zones. Both approaches are summarizing the knowledge about the really complicated geodynamics of this very interesting and important region.

5.3.1.7. Acknowledgements

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5.3.1.8. References

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