Fractal structure of the positive free-air gravity anomalies within the Balkan Peninsula

Tzanko Tzankov[1], Rosen Iliev[2], Boyko Ranguelov[3]

[1,2]Department of Geography, Ecology and Environment Protection, South-West University "Neofit Rilski", Blagoevgrad, Bulgaria

[3]Department of Applied Geophysics, University of Mining and Geology "St. Ivan Rilski", Sofia, Bulgaria

tzankov1936@abv.bg[1], rosen_faust@abv.bg[2], branguelov@gmail.com[3]

Abstract

The investigations of the fractal structure and properties of the different geophysical elements is new and fast developing area of research among the geophysical society. The fractal properties of the earthquake clusters, faults and folds at different scale, even the plutonic bodies and other elements of the positive landforms are the most exploited areas of research. In our caste the special attention is paid to the gravity field (free-air anomalies) as the most expressive element of the surface elevated structures and their influence to the relief. The Balkan Peninsula is well known as the one of the most variable Earth's surface elevation area in the world. The fractal properties of gravity field in such area could be useful to try to establish formal relationships to the surface elevation, as well as to prove the possibility to get some information about the self-organization and the origin of the mountain landforms in the same area.

Keywords: free-air gravity field, fractal properties, landforms, Balkan Peninsula

Introduction

The research and exploration of the theory of fractals and the fragmentation of different elements of the earth's surface and interior is larger developed during the last years. The results obtained are frequently used for explanation of the self-similarity and the self-organization of the different elements related to the Earth science. The recent paradigm of the geodynamics accepted the nonlinear behavior in time and space. For example a lot of publications are related to the fractal properties of the Plate tectonics [1], seismotectonic models of the Balkan Peninsula [2], local morphostructural analysis ([3]; [4]; [5]), the seismicity development of the time series ([6]; [7]; [8]; [9]; [10]; [11]; [12]; [13]; [14], etc. The present study aims to analyze and interpret the probability of fractal structure of positive free-air gravity anomalies within the Balkans. For this purpose is used data from Global Gravity Model- WGM2012 [15]. The possibility of a positive correlation between the positive gravity field and the distribution of the mountain morphounits within the studied area has also been investigated. This would put a new light on the nature of the tectonic processes in the region and the principles of mountain building in particular.The subject of this study is the mainland of the Balkan Peninsula (43° 00′ 00″ N; 23° 00′ 00″ E) (Fig.1). The adjacent islands and water areas are not included in the study. The Balkan Peninsula is bordered by the Adriatic Sea on the northwest, to the southwest by the Ionian Sea, by the Aegean Sea and Marmara Sea to the south and southeast, and by the Black Sea to the east and northeast. The northern border of the peninsula starts from the Trieste bay of the Adriatic Sea, tracks the river valleys of the Socha, Idriya and Sava rivers, and reaches the Black Sea along the Danube River. The peninsula from the west to the east has a length of about 1250 km and a width from north to south 930 km. The total area of the Balkan Peninsula amounts to 505,000 km^2. The topography of the peninsula has a fragmentary character, equally representing the positive and negative landforms. The highest point of the Balkan Peninsula is Musala peak (2,925 m), located within the Rila Mountains (Bulgaria).

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Fig.1: Survey map of the Balkan Peninsula

Materials and Methods

Fractals – an expression of the fragmentation of the Earth’s elements

The classical example of a fractal object is defined by Mandelbrot [16]. If the length of an object P is related to the measuring unit length l by the formula:

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

then P is a fractal and D is a parameter defined as the fractal dimension. This definition was given by B. Mandelbrot in the early 60-s of the 20-th century. His ideas support the view that many objects in nature cannot be described by simple geometric forms, and linear dimensions, but they have different levels of geometric fragmentation. It is expressed into the irregularities of the different scales (sizes) – from very small to quite big ones. This makes the measuring unit extremely important parameter, because measuring of the length, the surface or the volume of irregular geometric bodies could be obtained so that the measured size could 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 is accepted that definition of the different “fractals” as real physical objects is most often connected to fragmentation [17]. This reveals that each measurable object has a length, surface or volume, which depends on the measuring unit and the object’s form (shape) irregularity. The smaller the measuring unit is, the bigger is the total value for the linear (surface, volume) dimension of the object and vice versa. The same is valid for 2D and 3D objects.

The theoretical approach for the linear case and for the 2D and 3D cases was developed by [18; 19]. They focused the attention on the relations between the smallest measuring unit and object’s size in analyzing linear (1D), 2D and 3D objects (Fig.2).

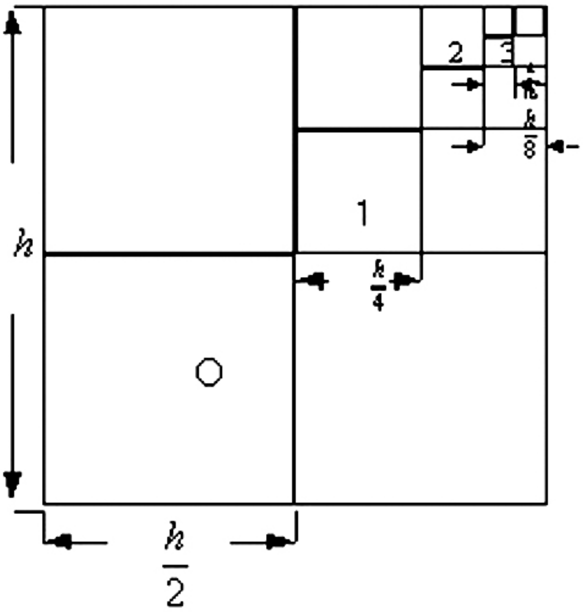

Fig.2: 2D fractal scheme – each linear element is ½ of the larger one.

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 according to Turcotte [20] is:

$$N_m = (1 - p_c)\left(1 + \frac{n}{m}p_c + \left[\frac{n}{m}p_c\right]^2 \dots \left[\frac{n}{m}p_c\right]^m\right) \qquad (2)$$

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

Using formulas (1) and (2) we obtain the following formulas:

$$\frac{N_{m+1}}{N_m} = 2^D \qquad (3)$$

for liner elements, and

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

for any area elements (surfaces).

Another definition of a fractal dimension is related to the serial number of measurement to each of the measuring units used and the object dimensions. If the number of the concrete measurement with a selected linear unit is bigger than r, then it might be presented by:

$$N \sim^{r-D} \qquad (5)$$

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, which indicates the level of fracturing of the upper earth layers [21]. Same approach was carried out for the fractal properties of the major elements of the Plate tectonics models [1].

The present study methodology based on the correlation number-area is following the algorithm presented and effectively applied in a number of publications [21], [22], [2], [1], [23]:

- Calculation of the number of positive free-air gravity anomalies (N) with corresponding area (in km^2) for the graphic.

- Presentation of the results on the graphic – on the X axis in logarithmic scale the areas of the positive free-air gravity anomalies are plotted, and on the Y axis in linear scale the corresponding number are plotted.

- The fractal dimension (D) has been calculated using the data from the graphic and results discussed.

The research of the large structures of the Earth's crust (plates, subduction zones, ridges, rift zones, etc.) shows clear expressed nonlinearity easily defined as fractals with different dimensions [1].

The analysis of the absolute positive free-air surface gravity anomalies (values above 80 mgal as mostly clear expressed peculiarity) was performed on the basis of GRID data from Global Gravity Model- WGM2012 [15]. The calculation of the areas of the free air gravitational anomalies has been explored using GIS software (GoogleEarthPro) and the corresponding area measurement function from the menu.

Free-air gravity anomalies- reflection of the Earth's elevation model and its positive elements

Free-air gravity anomalies are considered as the best expressed relationship between the low depths gravitational bodies reflecting the gravity influence of the elevated structures (mountains, hills, horsts, etc.) (Fig.3)

By definition the free air anomaly (frequently called Faye's anomaly) at the representative point is:

$$gF = gm-[g0 - 0.3088(H+h)] = gm + 0.3088(H+h) - g0 \qquad (6)$$

Where gF is the free-air gravity anomaly, g0 is the absolute gravity value at the point where the measured value is gm. H is the height above sea level and the h – is the level difference between the spheroid and the geoid at the same point. The calculated by this way values of the free-air anomalies reflect the gravity field originated from the Earth's surface elevations above the sea level. That's why they are considered as the most reflective anomalies related to the earth's elevated structures.

Figure 3 clearly shows that the positive free-air gravity anomalies in the Balkans have a clear fragmentation of geographical distribution. In practice, this is consistent with the mosaic pattern of topography in the region. The positive gravity field (especially the highest values) marks the highest elevated parts (earth crust blocks) of the peninsula (Fig.3).

The regional analysis shows that there is an absolute correlation between the positive gravity and some smaller mountains (Rila, Pirin, Slavyanka; etc.), partial correlation with the larger mountain morphounits such as the Stara Planina Mountains, the Rhodopes, the Pind, the Dinaric Alps, etc., however, where in the local relief some negative morphostructures (kettles) are clearly expressed. In some other low to medium peripheral mountains (such as Strandzha, Maleshevo, Forebalkan, etc.) gravity has normal or slightly elevated values but not high. Surely, however, with those parts of the peninsula whose altitude exceeds 2000 m, correlation is absolute.

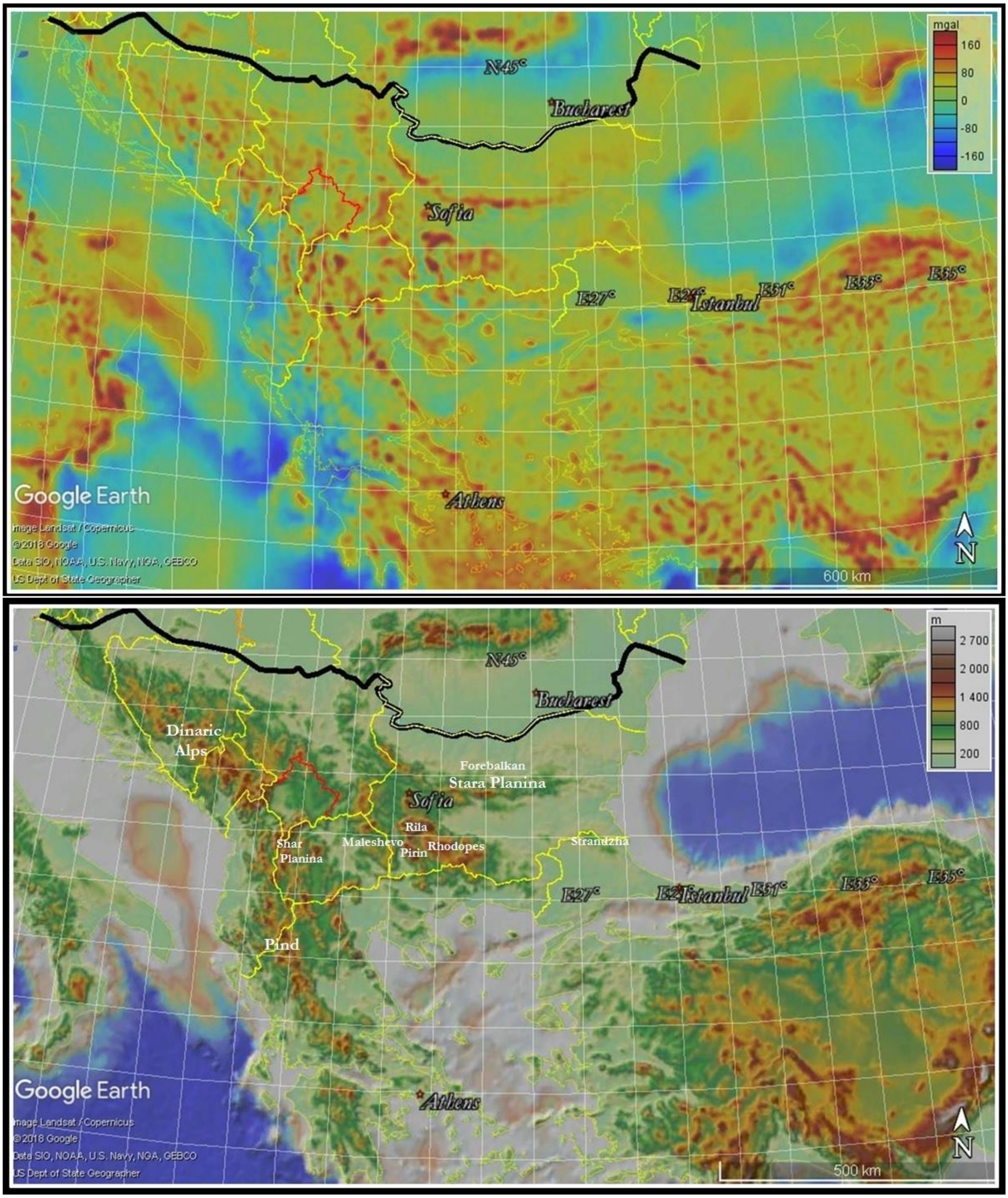

Fig.3: Correlation between positive Free-Air gravity anomalies (above) and DEM (below) within the Balkan Peninsula

This distribution is determined primarily by the plate tectonic processes creating and shaping the relief within the Balkan Peninsula. The subduction processes (south of the island of Crete and the western edges of the peninsula in the Adriatic Sea), as well as the collision processes at the regional level (intercontinental collision between Gondwana (African plate) and Neo Europe (southern edge of Eurasian plate) [24] and at the local level (for example, the collision between the Bulgarian and Moesian continental microplates [24;25] in the Stara Planina Mountains region).

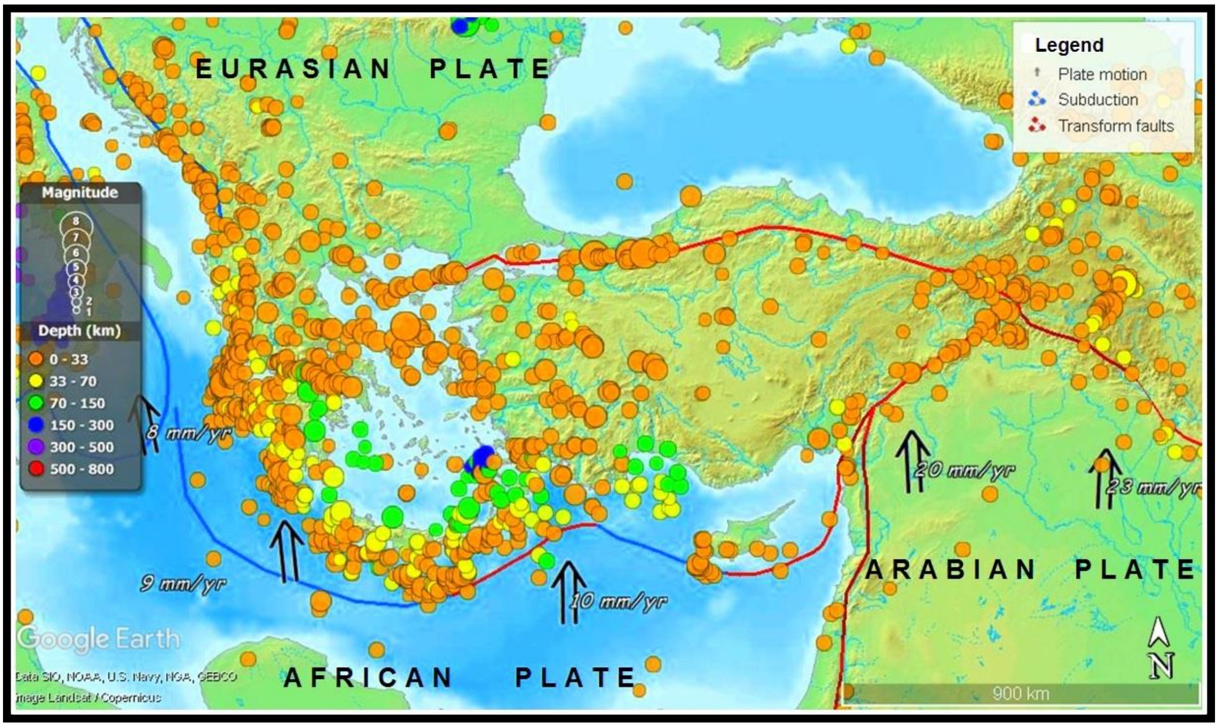

Fig.4: Main tectonic processes (subduction, faulting, earthquakes – circles on the figure) in the Eastern Mediterranean region (GIS data: [26])

Results and Discussion

The results from the analysis of the fractal geometry of the positive free-air gravity anomalies within the Balkan Peninsula are presented in graphical form in Figure 5.

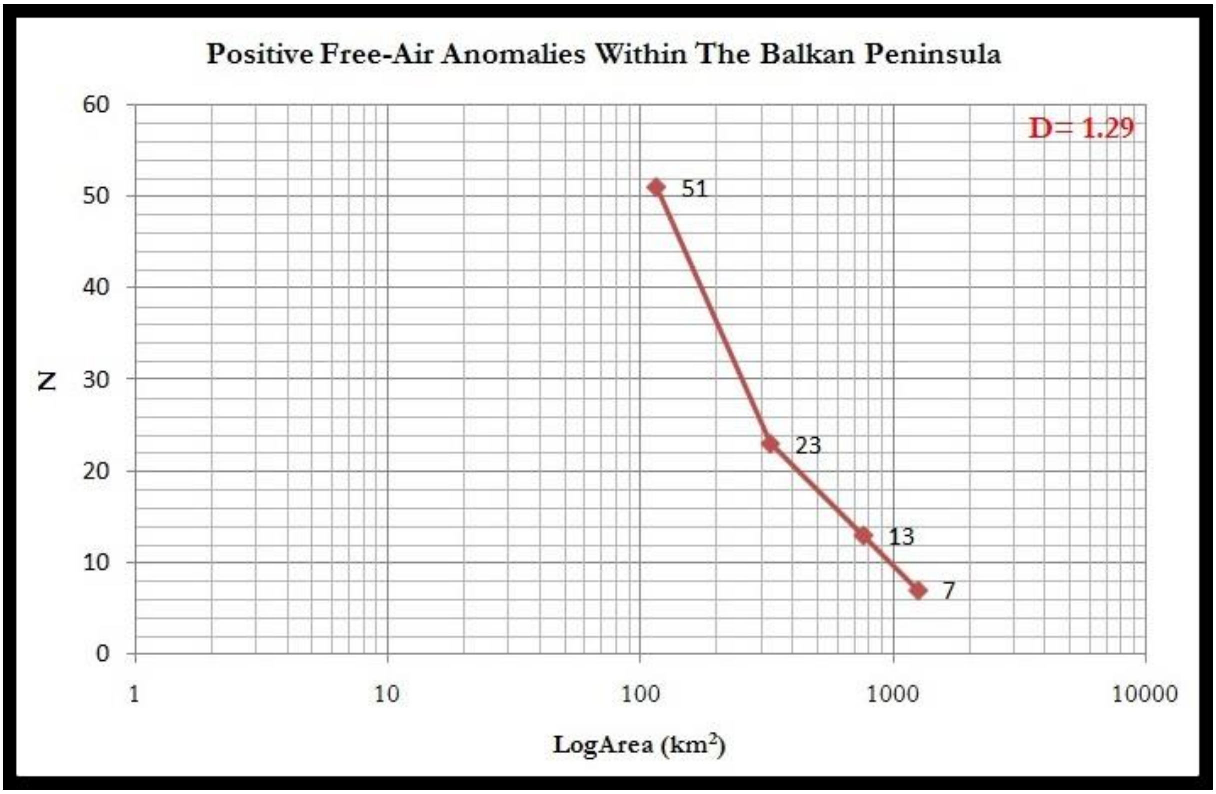

Fig.5: Fractal diagram of the positive Free-Air gravity anomalies within the Balkan Peninsula

On the basis of the results from the figures, the following main conclusions can be drawn:

1) The consecutive results in Figure 5 clearly show the fractal structure of the positive free-air gravity field within the Balkan Peninsula. The fractal dimension (D) of 1.29 points to a low degree of fragmentation, that is, the differences between the minimum and maximum values are not so large.

2) There is a spatial overlap of the positive free-air gravity anomalies with the highest elevated crustal blocks within the mountain morphostructures. This positive correlation is a clear sign of the self-organization of the morphotectonic processes operating in the region of the Balkan Peninsula.

3) The positive correlation between the gravitational field and the highest elevated blocks on the one hand and their fragmented geographic spread on the other proves the non-linear nature of the endogenous processes and phenomena acting in the bosom of the Balkans.

The fractal structure of the positive free-air gravity field throws new light on the endogenous earth processes in the Balkan Peninsula. This reflects on the mountain building processes and demonstrates the nonlinearities in these processes. Fractal geometry as a clear sign of self-organization determines the character of morphototectonics in the region. The results obtained can serve as a starting point for a number of correlation studies in the future. This would necessarily contribute to the successful collaboration between different Earth sciences and would improve our understanding of the endogenous processes in the Balkan Peninsula region.

Conclusions

The first steps to study the relationships between the free-air gravity anomalies and the high elevated lands in the Balkan Peninsula are attempted. The results obtained support the initial idea to use and correlate the fractal properties of the free-air gravity anomalies with the positive morphological elements. The calculated fractal dimension shows the nonlinear behavior of these landforms, thus supporting the self-organization and similarity in the genesis and the surface expression of the high lands located in the Balkan Peninsula. The perspective future research is under consideration to discriminate the linear and isometric high mountain landforms with the lowlands using similar methodology and revealing the origin of the investigated morphostructures.

References

1. Ranguelov, B., Ivanov, Y. (2017) Fractal properties of the elements of Plate tectonics. Journal of mining and Geological Sciences. Vol. 60, Part 1, Geology and Geophysics, 83-89.

2. Ranguelov, B., Dimitrova, S., Gospodinov, D., Spassov, E., Lamykina, G., Papadimitriou, E., Karakostas, V. (2004) Fractal properties of the South Balkans seismotectonic model for seismic hazard assessment, Proceedings 5th Intl. Symposium on East Mediterranean Geology, Thessalonica, 643-646.

3. Iliev, R. (2018) Fractality of the mountain arched morphostructures in the Rhodope Mountains. SocioBrains, 43, 366-371.

4. Iliev, R., Stankova, Sv., Tzankov, Tz. (2018) Fractal geometry of topography in the Rhodope Mountain. SocioBrains, 42, 162-167.

5. Tzankov, Tz., Iliev, R., Mitkov, I., Stankova, Sv. (2018) About Fractal Geometry of the Glacial Cirques in Rila and Pirin Mountains (Southwest Bulgaria). Universal Journal of Geoscience, 6, 73-77. Doi: 10.13189/ujg.2018.060303.

6. Bak, P., Chen, K. (1995) Fractal dynamics of earthquakes. Fractals in the Earth Sciences, Plenum Press, New York, 227-235.

7. Bhattacharya, P., Chakrabarti,B.K., Kamal, Samanta, D. (2009) Fractal models of earthquake dynamics. Reviews of Nonlinear Dynamics and Complexity, ed. by H. G. Schuster, Wiley - VCH Verlag GmbH & Co. KGaA, 107 – 158.

8. Legrand, D. (2002) Fractal dimensions of small, intermediate and large earthquakes. Bulletin of the Seismological Society of America, Vol. 92, No. 8, 3318–3320.

9. Matsuzaki, M. (1994) Philosophical Transactions: Physical Sciences and Engineering. Vol. 348, No. 1688,, 449-457.

10. Mittag, R. (2003) Fractal analysis of earthquake swarms of Vogtland/NW-Bohemia intraplate seismicity. Journal of Geodynamics, 35, 1–2, 173-189. doi.org/10.1016/S0264-3707(02)00061-3

11. Öztürk, S. (2008) Statistical correlation between b-value and fractal dimension regarding Turkish epicentre distribution. Earth Sciences Research Journal, 16, 2, 103-108.

12. Pailoplee, S., Choowong, M. (2014) Earthquake frequency-magnitude distribution and fractal dimension in mainland Southeast Asia. Earth,Planets and Space, 6, 1-8. doi.org/10.1186/1880-5981-66-8

13. Srivardhan, V., Srinu, U. (2014) Potential of Fractal Analysis of Earthquakes through Wavelet Analysis and Determination of b Value as an Aftershock Precursor: A Case Study Using Earthquake Data between 2003 and 2011 in Turkey. Journal of Earthquakes, vol. 2014, 5 p. doi.org/10.1155/2014/123092.

14. Tosi, P., De Rubeis, V., Loreto,V., Pietronero, L. (2008) Space–time correlation of earthquakes. Geophysical Journal International, Vol. 173, Issue 3, 932–941; doi.org/10.1111/j.1365-246X.2008.03770.x

15. Bonvalot, S., Balmino, G., Briais, A., Kuhn, M, Peyrefitte, A., Vales, N., Biancale, R., Gabalda, G., Reinquin, F., Sarrailh, M. (2012) World Gravity Map. Commission for the Geological Map of the World. Eds. BGI-CGMW-CNES-IRD, Paris.

16. Mandelbrot B. (1982) The Fractal Geometry of Nature. San Francisco: W.H. Freeman & Co., San Francisco, 68 p.

17. Korvin, G. (1992) Fractal models in the Earth Sciences. New York: Elsevier, 236 pp.

18. Turcotte, D. (1986) Fractals and Fragmentation. 1986a. Journal of Geophysical Research. 91, B2, 1921-1926.

19. Hirata T. (1989) Fractal dimension of fault system in Japan: Fractal structure in Rock geometry at various scales. Pure and Applied Geophysics, 131, 157-173.

20. Turcotte, D. (1986) A fractal model of crustal deformation. Tectonophysics, 132, 361-369.

21. Ranguelov, B., Dimitrova, S. (2002) Fractal model of the recent surface earth crust fragmentation in Bulgaria, Comptes Rendus de l'Academy Sciences Bulgaria. 55, 3, 25-28.

22. Ranguelov, B., Dimitrova, S., Gospodinov, D. (2003) Fractal configuration of the Balkan seismotectonic model for seismic hazard assessment, Proceedings BPU-5, Vrnjacka Banja, Serbia and Montenegro, 1377-1380.

23. Ranguelov, B. (2010) Nonlinearities and fractal properties of the European-Mediteranean seismotectonic model. Geodynamics & Tectonophysics, 1, 3, 225–230.

24. Tzankov, Tz., Iliev, R. (2015) Morphostructure of the Rhodopean Mountain Massif. Publishing House "Grafika 19", Sofia, Bulgaria, 48 p.

25. Tzankov, Tz., Iliev, R., Stankova, Sv., Mitkov, I. (2018) The Bulgarian continental microplate morphotectonic position in the eastern part of Balkan Peninsula. SocioBrains, 42, 282-302.

26. USGS Seismic hazard program, Online available from https://earthquake.usgs.gov