FRACTAL PROPERTIES OF THE ELEMENTS OF PLATE TECTONICS

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ABSTRACT. The new idea about possible fractal properties of the elements of plate tectonic is explored. The elements are divided according to their geodynamic properties - subduction, orogenesis, rifting, transform faulting, collision, etc. Area, linear and spot elements are considered as fractal objects and their fractal dimensions are established. If the hypothesis of the fractal characteristics of most elements of plate tectonics is correct, this could be a new direction of investigations related to the creation, development and the geological history of the main global tectonic units. The obtained results could be useful to the new approaches related to the search, exploration, and exploitation of ores, gas and oil, coal and all other aspects of geodynamics, the mining industry, and geology.

Keywords: fractal, tectonics, plates, subduction, rift, collision, transform fault, orogeny

ФРАКТАЛНИ СВОЙСТВА НА ЕЛЕМЕНТИТЕ ОТ ТЕКТОНИКАТА НА ПЛОЧИТЕ

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РЕЗЮМЕ. Изследвана е нова идея за възможните фрактални свойства на различните елементи от тектоника на плочите. Елементите са разделени според техните геодинамични свойства - субдукция, орогенеза, рифтинг, трансформни разломи, колизия и др. Площните, линейните и точковите елементи са приети за фрактални субекти и са определени техните фрактални размерности. Ако хипотезата за фракталните характеристики е правилна, това би могло да даде нова насока на изследванията, свързани с образуването, развитието и геоложката история на тектонските плочи. Получените резултати са полезни за използването на нови подходи, свързани с търсенето, проучването и експлоатацията на рудни полезни изкопаеми, нефт и газ, въглища, както и във всички други аспекти на геодинамиката, минната индустрия и геологията.

Ключови думи: фрактал, тектоника, плочи, субдукция, рифт, колизия, трансформен разлом, ороген

Introduction

The present study is focused on the assessment of the fractal properties and the coefficients of the nonlinearity (fractal dimensions) of the spatial distribution of the major elements of Plate Tectonics.

The idea to investigate these properties was born from another research of the fractal properties of the used European-Mediterranean Seismotectonic Model (EMSM) generated by Jimenez et al. (2001). Some other publications by B. Ranguelov and joined teams (Ranguelov and Dimitrova, 2002, Ranguelov et al. 2003, 2004) suggested that such fractal properties are rather common in Geosciences. (Turcotte, 1986; Hirata, 1989).

The Plate Tectonics theory was built on the idea that major continental plates are moving over a substrate and have fragmentation as an explicit internal property. Later on, the theory of ocean spreading confirmed the effectiveness of this idea, including oceanic plates and all other elements – rifts, transform faults, subduction zones, etc.

The development of these theories led to their integration in a simple and highly effective model of the "Living Earth". The simple and elegant explanation of almost all geodynamic processes observed on the Earth, and fruitful practical applications of the Plate Tectonics, make it one of the most popular paradigms of recent Geosciences that is practically accepted by the science community. For first time Sorette and associates (Sorette and Pisarenko, 2003) suggested the idea of Fractal Plate Tectonics. They calculated the power low for 42 plates, known at that time. Much later Mallard (Mallard et al, 2016) explored the idea that subduction is the main driving mechanism and is responsible for the plate's fragmentation. So far, no one has investigated the fractal properties of all other components of plate tectonics.

Methodology and theoretical assumption

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

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

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 an extremely important parameter because by 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.

Geology and geophysics accept that the definition of 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 (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.

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:

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

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 (Ranguelov, Dimitrova, 2002).

The theoretical approach for the linear case and for the 2D and 3D cases was developed by Turcotte (1986a) and Hirata, (1989). They focused the attention on the relations between the smallest measuring unit and the object's size in analyzing linear (1D), 2D and 3D objects (Fig. 1).

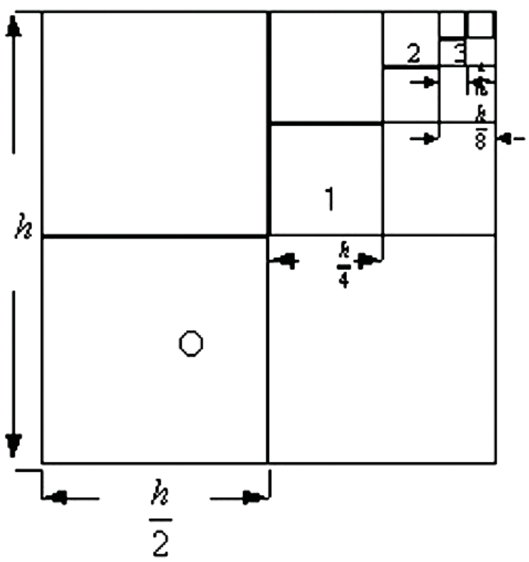

Fig. 1. 2D fractal scheme – each linear element is ½ of the larger one.

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 (Turcotte, 1986b) is:

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

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

Using formulas 1 and 2, we obtain the following formulae:

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

for linear elements, and

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

for any area elements (surfaces).

Using this approach, we studied the elements of the Global Plate Tectonics model derived by Bird (2003). Following the outlined tectonic plates, orogens, rift zones, transform faults, subduction zones, and all other elements of the internationally recognized model, we investigated the possible fractal properties of all elements separately and calculated the fractal dimensions for each component.

Typology of the Components of Plate Tectonics and Graphical Fractal Analysis

The graphical fractal analysis has been performed after the separation of the major elements of the Plate tectonics theory - tectonic plates, orogens, rift zones, transform faults, subduction zones, etc. using the internationally recognized model by P. Bird. (2003). The methodology follows the algorithm presented in other publications (Ranguelov, 2010, Ranguelov et al. 2003, 2004):

- Presentation of the data for each selected element (total number, investigated parameter, dimensions – (only linear (1D) and surface sizes (2D) are considered)
- Calculation of the number for the graphics (selection of the calculation step for X and Y axes, scale on X and Y axes, values for each selected parameter).
- Presentation of the results on the graphics – on the X axis the semi-logarithmic scale is most convenient, on the Y axis z denotes in linear scale the numbers calculated for each element.
- In the next chapter the fractal dimensions will be calculated and results discussed.

The elements of the plate tectonics according to this theory have their common meaning and present some of the most important components under investigation – tectonic plates, rift zones, orogenies, subduction zones, collision zones, and transform faults. The typology and data, as well as the graphics are displayed below:

Tectonic Plates - total number - 52, investigated parameter - area size - Table 1.

Table 1.
Tectonic Plates and surface sizes

TYPE	N	TECTONIC PLATE	AREA [SQ. KM]
MAJOR (> 20M SQ. KM)	1	Pacific	104 600 300
	2	African	58 504 000
	3	Antarctic	58 202 000
	4	North American	55 501 000
	5	Eurasian	48 600 700
	6	Australian	46 000 600
	7	South American	41 800 900
MINOR [1M, 20M] SQ. KM	8	Somali	19 150 200
	9	Nazca	16 100 100
	10	Indian	12 450 000
	11	Sunda	8 900 200
	12	Philippine Sea	5 450 000
	13	Amurian	5 300 200
	14	Arabian	4 900 100
	15	Caribbean	3 000 800
	16	Okhotsk	3 000 200
	17	Cocos	2 950 090
	18	Yangtze	2 200 300
	19	Scotia	1 700 100
	20	Caroline	1 550 200
MICRO (< 1M SQ. KM)	21	North Andes	970 100
	22	Altiplano	830 070
	23	Banda Sea	700 200
	24	New Hebrides	650 400
	25	Anatolian	580 300
	26	Bird's Head	530 000
	27	Burma	520 100
	28	Kermadec	500 020
	29	Woodlark	450 200
	30	Woodlark	450 050
	31	Mariana	420 200
	32	Molucca Sea	420 070
	33	North Bismarck	390 000
	34	Timor	350 100
	35	Okinawa	330 080
	36	Aegean Sea	320 100
	37	South Bismarck	310 200
	38	Panama	270 070
	39	Juan de Fuca	260 100
	40	Tonga	250 050
	41	Balmoral Reef	200 080
	42	South Sandwich	180 400
	43	Easter	170 500

Table 1 - continued

TYPE	N	TECTONIC PLATE	AREA [SQ. KM]
	44	Conway Reef	140 000
	45	Solomon Sea	130 070
	46	Niuafo'ou	120 400
	47	Maoke	120 200
	48	Rivera	100 120
	49	Juan Fernandez	100 090
	50	Shetland	70 010
	51	Galapagos	15 400
	52	Manus	8 060

The calculated number (z) is presented on Figure 2 in semi-logarithm scale.

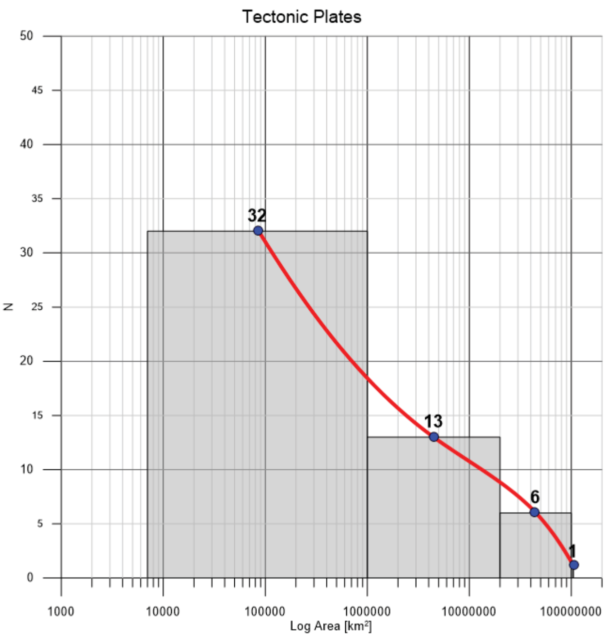

Fig. 2. Fractal distributions of the investigated tectonic plates.

Rift Zones - total number - 14; investigated parameter - lengths - Table 2

Table 2.
Rift Zones and lengths

N	RIFT	LENGTH [KM]
1	East African	5 350
2	Red Sea	2 400
3	West Antarctic	2 200
4	Keweenawan	2 000
5	Northern Cordilleran Volcanic Province	1 250
6	Gulf of California	1 130
7	Baikal	720
8	Rio Grande	660
9	Ottawa-Bonnechere Graben	520
10	Gulf of Suez	325

Table 2 - continued

N	RIFT	LENGTH [KM]
11	Upper Rhine	310
12	Reelfoot	240
13	Oslo	175
14	Gulf of Corinth	130

The calculated number (z) is presented on Figure 3 in semi-logarithm scale.

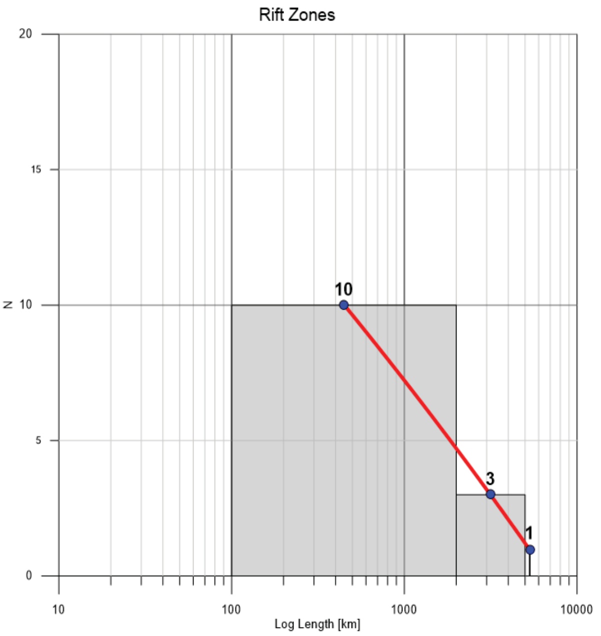

Fig. 3. Fractal distributions of the investigated rift zones.

Orogenies - total number - 13; investigated parameter - area size - Table 3

Table 3.
Orogens and surface sizes

N	OROGENS	AREA SIZE [SQ. KM]
1	Persia - Tibet - Burma	16 600 000
2	Ninety East - Sumatra	8 080 000
3	Alps	2 801 000
4	Alaska - Yukon	2 300 700
5	New Hebrides - Fiji	1 507 000
6	West Central Atlantic	1 501 100
7	Gorda - California - Nevada	1 350 100
8	Puna - Sierras Pampeanas	1 350 070
9	Peru	1 150 100
10	Philippines	1 000 070
11	Laptev Sea	420 000
12	Western Aleutians	190 000
13	Rivera - Cocos	24 000

The calculated number (z) is presented on Figure 4 in semi-logarithm scale.

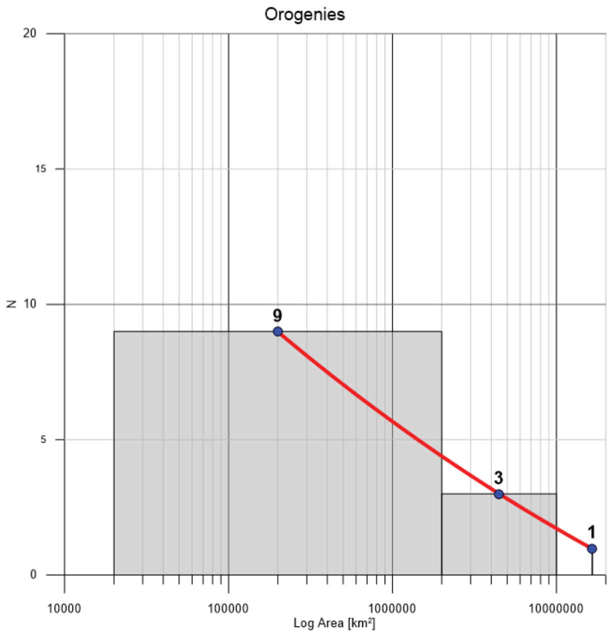

Fig. 4. Fractal distributions of the investigated orogens.

Subduction Zones - total number - 18; investigated parameter-area size - Table 4.

Table 4.
Subduction Zones and area sizes

N	SUBDUCTION ZONES	AREA SIZE [SQ. KM]
1	Nazca / South American	4 002 000
2	Pacific / Okhotsk	2 001 000
3	Indian, Australian / Sunda, Burma	1 600 300
4	Pacific / Australian	1 250 070
5	Pacific / Philippine Sea	1 100 100
6	Pacific / North American	900 100
7	Philippine Sea / Eurasian	780 090
8	Australia / New Hebrides	460 100
9	North America / Juan De Fuca	410 080
10	Solomon Sea / South Bismarck, Pacific	300 070
11	Aegean sea / Africa	250 900
12	Caroline / Bird's Head	250 010
13	Sunda Plate / Philippine Sea	200 100
14	South American / South Sandwich	140 000
15	Eurasian / Philippine Sea	60 100
16	Australian / Pacific	60 010
17	Antarctica / Scotia	35 100
18	Cocos / Caribbean	25 020

The calculated number (z) is presented on Figure 5 in semi logarithm scale.

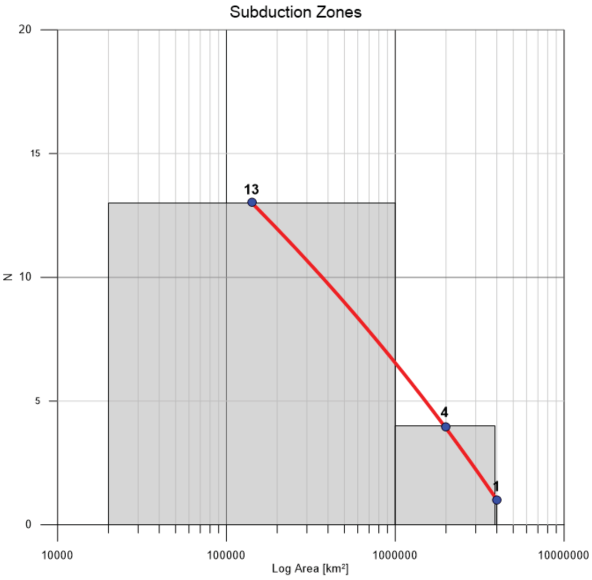

Fig. 5. Fractal distributions of the investigated subduction zones.

Major Collision Zones - number - 18, investigated parameter-area size - Table 5.

Table 5.
Major Collision Zones and area sizes

N	MAJOR COLLISION ZONES	AREA SIZE [SQ. KM]
1	Indo-Asian	2 502 000
2	Arabian-Eurasian	2 030 000
3	Izmir-Ankara-Erzincan	470 100
4	Maghrebides-Tell	460 200
5	Dinarides-Albanides-Hellemides	370 300
6	Apennines	200 400
7	Pyrenees	180 600
8	Carpathians	180 100
9	Beltics-rif	170 070
10	Molucca Sea	142 080
11	Western Alps	110 600
12	Eastern Alps	100 100
13	Inner Tauride Suture	75 000
14	Intra-Pontide Suture	50 300
15	Izu-Honshu	50 100
16	Taiwan	50 050
17	Balkanides	30 100
18	Hidaka	20 020

The calculated number (z) is presented on Figure 6 in semi logarithm scale.

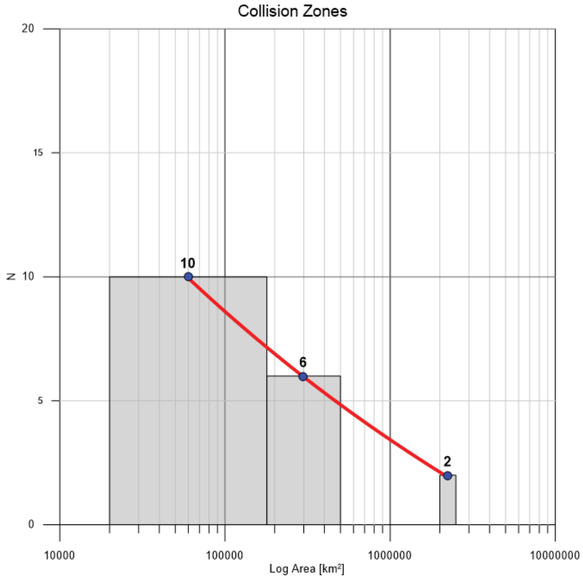

Fig. 6. Fractal distributions of the investigated collision zones.

Major Transform Faults - number - 18; investigated parameter-lengths - Table 6.

Table 6.
Major Transform Faults and lengths

N	MAJOR TRANSFORM FAULTS	LENGTH [KM]
1	Owen	1 840
2	Ulakhan	1 750
3	North Anatolian	1 160
4	San Andreas	1 100
5	Romanche	915
6	Queen Charlotte	830
7	Enriquillo-Plantain Garden	680
8	Puerto Rico	640
9	Walton	580
10	Dead Sea	555
11	Apline	550
12	Chaman	480
13	Rivera	400
14	St. Paul	385
15	Blanco	355
16	Ascension	275
17	Chain	255
18	Mendocino	240

The calculated number (z) is presented on Figure 7 in semi logarithm scale.

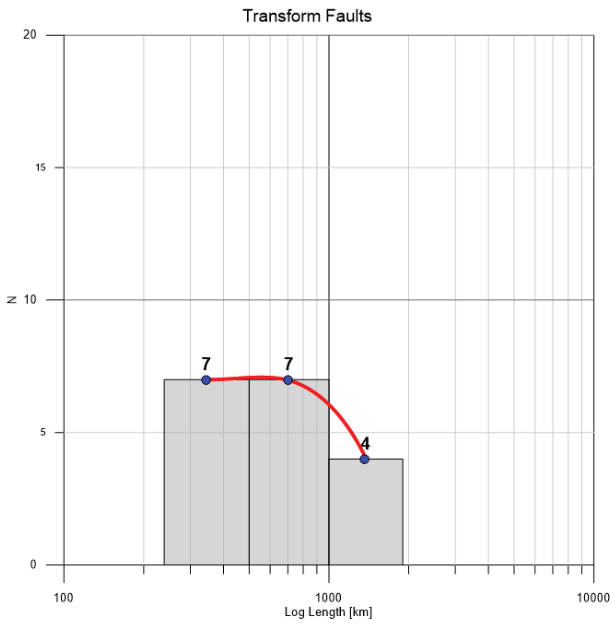

Fig. 7. “Fractal” distributions of the investigated transform faults.

Fractal Properties of Plate Tectonics

The fractal dimensions (D) have been calculated using the data from the graphics and tables. It is important to mention that all dimensions have negative numbers, but for easier perception are presented as positive values in the following table (Table 7).

Table 7.
Fractal Dimensions (linear and surfaces)

Plate Tectonics' Component	Linear	Surface	Notes
Tectonic Plates		3.01	High fragmentation
Rift Zones	1.81		Lowest fragmentation
Orogens		5.32	Highest fragmentation
Subduction Zones		3.07	High fragmentation
Major Collision Zones		3.28	High fragmentation
Major Transform Faults	N/A		Seems not to be a fractal

The analysis of the fractal dimension of all elements shows some specifics and trends and needs more details to be explained:

- All elements show relatively high fragmentation and strong non-linear trends.

- The linear expressed rift zones are characterized by the lowest fragmentation. It is difficult to explain why this peculiarity is demonstrated, but one probable explanation could be that this component of the plate tectonics is relatively younger than others mainly related to the oceanic crust fragmentation after the Pangea decay.
- Tectonic plates, subduction zones (mostly related to the ocean crust subducted parts of the Earth’s crust), and collision zones have very similar non-linear behavior. The fractal dimensions are between 3 and 3.3. Thus, these elements show relative synergy between them and their fractal properties like geometric surfaces. The trends are rather clear.

- The most fragmented components are the orogens. This is relatively easy to explain because these elements are strongly variable in their surface sizes. In any case, so strong a fragmentation probably needs deeper geodynamic investigations to reveal geological reasons and relationships and to try to explain why such a peculiarity exists.

- The only component that seems not to be fractal (no fractal dimension) and could be extracted from this data is the transform faults. As linear elements dominated by horizontal movements of the plate convergence, these natural items probably have different origin, not so strictly related to the geodynamic evolution. This needs deeper research and investigations to reveal the origin and evolution of these faults.

- It is important to mention that a common task to these investigations is to discover if Plate Tectonics itself has fractal properties or not. The results of these investigations show that in general the main trends established due to the researched topic show clear fractal properties of the main plate tectonics components. The only exception (the transform faults) does not have a clear origin. It could be due to the limited data used, or it could have a more complicated source. This fact definitely requires a deeper research, integration and cooperation among the Geoscience societies.

Discussion and Discussed Questions

Following the calculated fractal dimensions and presented graphics of the investigated parameters of the plate tectonics, several disputable points appear and need some additional discussion. We appreciate any questions and topics under discussion. The main are presented as Q and R format:

- Are there fractal and non-fractal elements of the plate tectonics?
R: It seems that in general the Plate tectonics elements have clearly expressed fractal properties. The only exceptions discovered so far are the transform faults.

- Are the investigated objects enough for fractal analysis?
R: Some of them seem enough (for example - tectonic plates), others have values a little over 10. We consider that these numbers are enough to outline the trends of fractality and fragmentation of the investigated objects. Nevertheless, it is not possible to find larger objects of the Plate tectonics (which mean larger values to the right part of X). As this value is dominant for the calculation of the fractal dimensions, additional numbers to the left side (smaller in size objects) cannot change drastically the calculated values of D. McKenzie (McKenzie, 1972).

- There is an exception: transform faults which do not seem to have fractal properties.
R: This means that probably the fractal and non-fractal peculiarities will need deeper investigations including some not included in this study elements (for example "hot spots").

- What about hot spots? Why they are not included in this study?
R: The hot spots are a special component of the plate tectonics which cannot be easily explained. This is one of the reasons not to include them in this study. Another one is that there are too many established hot spots (some of them with origin which is not very clear) and this might distort the calculations. The topics will be investigated in future.

- Is there any possibility to investigate 3D objects about their fractal properties?
R: There is room for deeper investigations in the 3D domain. The thickness of the tectonic plates, the penetration depths of the subductions, the blocks (including their depths) limited by the faults (Papazachos, 1966, 1973) - these are only a few directions to the possibilities to extend similar investigations, but this needs much more uniform information from Geophysics (King, 1983).

- Why are triple junctions not included in this study?
R: Triple junctions are under a special investigation by Mallard and associates (Mallard et al, 2016) in an extended paper with good interpretation and we consider that this topic is solved.

- What is the physical meaning of the presence (or absence) of fractal properties of the Plate Tectonics?
R: Looks like Mother Nature has orchestrated the Earth's "chaos" in the proper manner and shows explicitly that all components in the recent geodynamics are interrelated and it is not easy to explain all processes acting in the Earth's interior.

Conclusions

The fractal analysis is performed to prove the strong non-linearity concerning the geometry distributions of the elements of Plate Tectonics.

The non-linear behavior of the linear and surface elements of the internationally recognized Plate Tectonic Model derived by P. Bird (2003) is discovered in this study. It shows that more punctual and refined methods of the mathematical analysis are useful tools to reveal the fine structure of the geodynamic models.

The discovered fractal properties of most elements of the Plate tectonics suggested that there is synergy among them and that probably they have deeper meaning for the Erath's geodynamic machine.

The lack of fractality in such a fine system for some investigated elements (transform faults, for example) needs deeper understanding of the physical evolution of our Planet.

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