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SPATIAL AND TEMPORAL VARIATION OF SEISMIC *b*-VALUE BENEATH DANUBIAN AND HATEG-STREI SEISMOGENIC AREAS

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Abstract. In this paper, we have studied the seismic activity in relation with geology, and tectonics in order to highlight seismogenic processes recorded in Danubian area and Hateg-Strei Basin. The Danubian seismogene area presents a complex geological structure, being characterized by the following tectonic units: Median Dacides (Getic and Supra-Getic nappes), Marginal Dacides (Danubian Unit) and External Dacides (Severin nappe). The recent seismic activity in this area, starting from 1990 until present, is described by the seismic sequence from 2002, in the Moldova Noua area, in connection to Oravita-Moldova Noua fault and by the seismic sequence from 1991, in the Baile Herculane area, belonging to the Cerna-Jiu fault system. Also, the Teregova area is present with the seismic sequence from 2014 and another two smaller sequences. From a statistical point of view, the seismicity is mainly described by the *b*-value coefficients from the empirical relation between the frequencies and magnitudes. Determination of spatial and temporal variations of the *b*-value is thought to reflect the stress conditions in the crust.

Key words: aftershocks, seismicity, *b*-value.

1. INTRODUCTION

The South-Western part of Romania can be divided into two distinct areas, the Banat seismogenic zone, located to the East and North-West, and the Danubian seismogenic area located to the East and South-East.

The Danubian area represents the western extremity of the orogenic unit of the Southern Carpathians and it presents two groups of seismicity: Moldova Noua–Oraviţa–Resita, in the Western part of the area and Baile Herculane–Mehadia–Oroşova, in the eastern part of the area. These groups are linked to two important crustal faults: the Oraviţa (West) fault and the Cerna–Jiu (East) fault system.

Responsible for these earthquakes are the fault systems, Oravita–Moldova Noua, Cerna–Jiu and Sichevita–Retezat, as well as the major thrust faults, which dominate the entire area. The orientation of these faults is NNE–SSV and dipping towards the West.

In the present study we analyzed the spatio temporal of *b*-value in relation with geology, and tectonics in order to highlight the seismogenic processes recorded in Danubian area and Hateg–Strei Basin.

General average value of the *b* parameter obtained by mixing different crustal rock volumes and different tectonic regime, is close to unit.

Regionally, changes in *b*-value are related to changes in the stress level. The *b*-value is calculated using maximum likelihood method.

Authors like [1] estimate M_c using the stability of the *b*-value as a function of cutoff magnitude M_{co}. This model is based on the assumption that *b*-values ascend for M_{co}.

In the '80–'90 period, the data recorded in the area are not so relevant (background seismicity), the catalog extracted data are non-conclusive in order to realize the right representation of the temporal variation of swarm activity in Moldova Noua and Mehadia areas.

For Teregova and Hateg-Strei areas was generated a representation of the temporal variation of seismic activity.

2. GEOLOGICAL AND SEISMOTECTONIC AREA

The South Carpathians tectonics is a result of a main, clockwise rotation (North-East oriented) and a secondary, right-lateral movement of the tectonic units of the Median, Marginal Dacides, and Danubian Nappe around of the Moesian Platform.

Strike-slip deformations played a significant role in the tectonic development of the area. As a result of this tectonic regime, in the South Carpathian Mountains several pull-apart intramountain basins such as: Hateg Basin, Caransebes-Mehadia Basin, Petrosani Basin, Bozovici Basin and Orsova Basin formed [2].

A complex combination of nappes, closed rifts, magmatic bodies and suture zones form the Pre-Neogene basement. Different changes of stress regimes during the Alpine period reactivated fault systems that border the tectonic units of the study area [3]. The Supragetic, Getic (Median Dacides), Severin (External Dacides) and Danubian (Marginal Dacides) nappes are thrusted and stacked over the Moesian Platform [4].

Three of the nappes are of continental origin: the Getic, Supragetic and Danubian. The Severin nappe is of oceanic origin [5, 6].

The main fault systems in the area are orogenic and basement structures, delimiting the edges of the major geotectonic units [3]. The faults are either thrusts (Sichevita–Retezat and Closani–Baia de Arama Thrusts) or vertical trans-crustal (Oravita–Moldova Noua and Cerna–Jiu) [4]. These faults are mainly NE–SW oriented, with the exception of the Bistrita Fault which is EW oriented [3, 4]. The vergence of the thrust faults separates them in two categories: the ESE verging Closani–Baia de Arama thrusts and the WNW verging Sichevita–Retezat thrusts [4].

Oravita–Moldova Noua fault is situated in the west part of our study area. This fault can be a master fault of the Oravita–Moldova Noua fault system having secondary structures that become more numerous towards the surface. This fault system is part of the Resita – Moldova Noua seismogenic zone, a complex of synclines and anticlines with their Eastern margins fractured by NE–SW orientated faults [7] as seen in Fig. 1 – Geological Map of Romania, scale 1:200.000.

This fault system is intersected by E–W oriented trans-crustal faults resulting in higher seismic activity registered in the areas where they intersect. The same type of behavior and characteristics are observed also for the Cerna–Jiu fault system with the mentions this represents an old graben system with a long seismic activity.

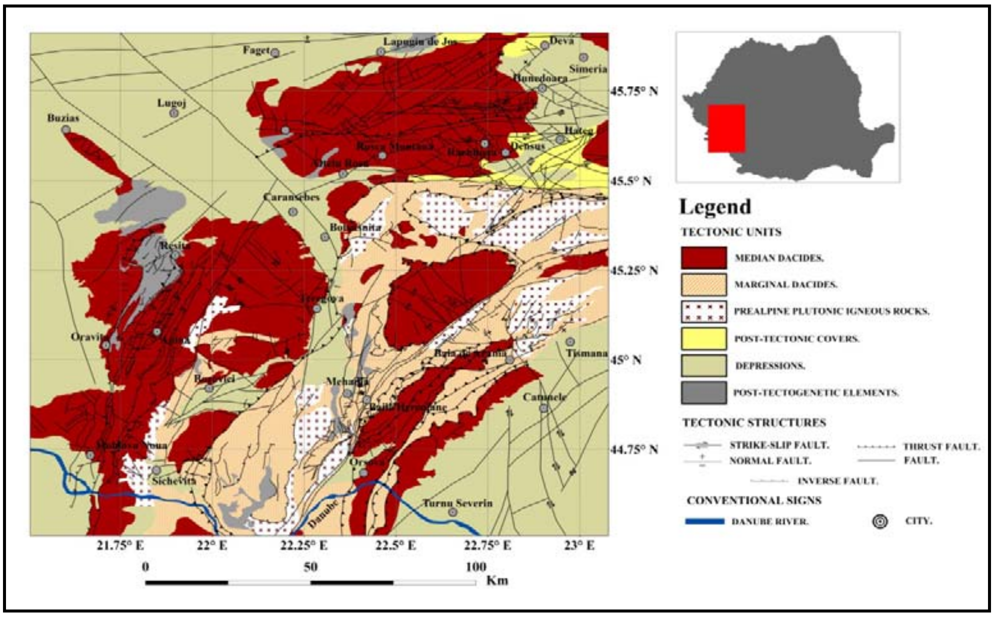

Fig. 1 – Tectonic map of the area of interest (after [4], Geological map 1:200.000).

The intramountainous basins started forming during the final stages of the Early Cretaceous. The first that began forming was the Hateg Basin which evolved from thrust sheet top (in the Early Cretaceous) to pull-apart strike-slip basin in the Paleogene-Miocene period being associated with a major fault system. The Petrosani Basin develops during late Oligocene age through right-lateral strike-slip deformations produced by the Cerna–Jiu fault [5].

The development of Orsova Basin is also associated with the activity of the Cerna–Jiu Fault [5]. The last basin to develop is Caransebes–Mehadia. The sediments of Upper Badenian age cover metamorphic rock formations and Jurassic rock formations [8]. For all the upper mentioned basin the sedimentary facies are similar with some discrepancies (coal deposits of the Petrosani basin) and can be associated with continental deposition environment.

3. SEISMICITY

The studied areal is characterized by a seismic activity with earthquakes not exceeding magnitudes greater than 5.6 (M_w) –18 July 1991.

For the seismicity study, 1648 seismic events were selected from the Romplus catalogue recorded in 1990–2018, using a compilation with revised catalogues [9–11].

The hypocenters of the selected seismic events are located at depths which do not exceed 51 km. Most of the seismic activity in the area is focused in the first 20 km of the crust.

The representative magnitude interval (M_w) for the study area is between 1 and 3 (M_w). Magnitude values greater than 3 were recorded for 81 earthquakes, from which 23 have magnitude (M_w) values greater than 4 M_w. Only 3 seismic events exceed magnitude 5 (M_w).

The earthquakes with magnitude higher than 5 are: the 10.10.1879 ($M_w = 5.3$) and 11.10.1879 ($M_w = 5.3$) located near Moldova Noua, the 18.07.1991 ($M_w = 5.6$) located near Mehadia. The 18.07.1991 earthquake of magnitude 5.6 (M_w), with its hypocenter at depth of 12 km, located to the South-West of Mehadia, is the earthquake with the largest magnitude in the study area.

The distribution of smaller events $M_w < 3.5$ define small clearly clusters and alignments Moldova Noua (MN), Mehadia (ME), Teregova (TE), Hateg (HT) is shown in Fig. 2.

The recent seismic activity is characterized by four spatial clusters in the Moldova Noua (MN), Mehadia (ME), Teregova (TE) and HT (Hateg-Strei Basin).

3.1. MN – MOLDOVA NOUA CLUSTER

The first zone could be distinguished in the South-West part of the map shown in Fig. 1 and Fig. 2, along an alignment from West of Resita, East of Oravita, to South of Moldova Noua following the Moldova Noua – Oravita fault. To the South-East of Moldova Noua, between 2010 and 2018 were recorded 111 seismic events. The hypocenters of these seismic events were located above 30 km of depth. The magnitude M_w values for the 111 earthquakes, do not exceed 3. The depth distribution of the hypocenters is suggesting high seismic activity at depth not greater than 10 km (Fig. 2).

The 1879–1880 Moldova Nouă earthquake sequence, one of the most important in the region, lasted for seven months. Within this time interval, 2 strong main-shocks (M_s = 5.6) occurred in two days and more aftershocks with I_0 = VII MSK occurred until April 1880 [9, 10].

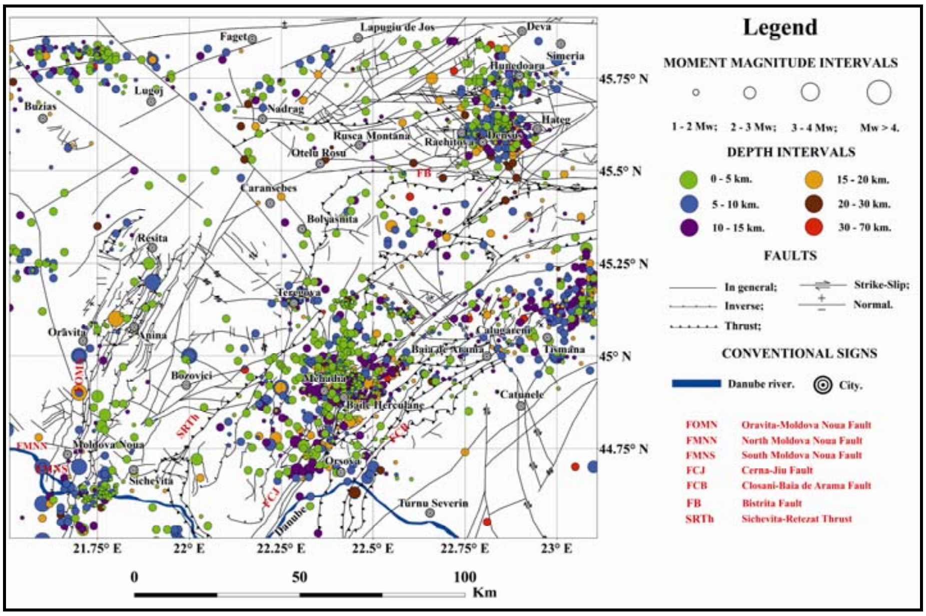

Fig. 2 – The mapping of the epicentres seismic activity in the area (1990–2018).

The main-shocks caused substantial damage in Moldova Nouă area (*e.g.* 93% of the houses of Moldova Nouă were severely affected). Surface faulting about 1.2 m width and 1,200 m length was also reported in the epicenter area. The two strongest earthquakes were felt at long distance, into an area of 76,000 km^2 [12]. Seventy earthquakes (1.8 ≤ M_D ≤ 4.8) were recorded between 1 April 2002 and 31 August 2002 [9, 10]

3.2. ME – MEHADIA HERCULANE CLUSTER

The second seismic zone can be observed between Mehadia and Baile Herculane. This seismic zone follows the Cerna–Jiu fault system and an alignment North to South (center of the map in Fig. 1 and Fig. 2). 454 earthquakes were located, from 2006 till 2018, in this zone. The magnitude values of the 454 earthquakes, ranges from 1.3 to 3.5 (M_w). The hypocenters are located at depth which do not exceed 42.4 km. Area with increased seismic activity are spotted to the North and North-East of Mehadia, to the West of Baile Herculane. On 18th of July 1991 a strong earthquake (I_0 = VII EMS/ M_w = 5.7) occurred at Mehadia (ME). More recently, a sequence of seventy earthquakes (2.0 ≤ M_w ≤ 3.6) occurred in the Moldova Noua region (according to Romplus catalogue) between 1 April and 31 August 2002 [5].

3.3. TE – TEREGOVA CLUSTER

The Teregova area is where the seismic sequence from October–November 2014 was generated. The main shock of the seismic sequence 4.1 (M_w) was followed by a total of 51 aftershocks with an East-West elongation of the epicentral distribution. The maximum magnitude observed was 4.1 (M_w) for the earthquake produced on October 31, 2014.

In contrast with the sequences from the Hațeg Depression, the earthquake sequence from in the Teregova (TE) area started clearly with a main event of 4.1 (M_w), while all the aftershocks were of small size.

East of Teregova two seismic swarms were identified. The first swarm consists of 20 earthquakes and occurred between 06.01.2015 and 15.01.2015. The magnitude M_w values interval for the 20 earthquakes is between 1.4 and 2 (M_w) and the hypocenters were located at depth which do not exceed 12 km. The second swarm consists of 35 earthquakes and occurred between 28.07.2016 – 01.08.2016. The magnitude (M_w) values for the earthquakes of this second swarm are between 1.2 and 2.5. The hypocenters of the 35 earthquakes were located at depth which do not exceed 15.5 km.

3.4. HT – HATEG-STREI BASIN CLUSTER

The fourth zone is situated in the Hateg (HT) area part of Hateg-Strei basin. Here were recorded two seismic sequences, one in March 2011 followed by 19 aftershocks [5] and the other in September 2013 followed by 31 aftershocks [5]. The depths of the hypocenters not exceed 39 km. The intervals of magnitude (M_w) for the seismic events in this area is between (1.2–3.5). The epicenters of the two sequences occurred in 2011 and 2013 in HT are represented in Fig. 1 and Fig. 2.

4. MAGNITUDE OF COMPLETENESS AND SPATIAL AND TEMPORAL *b* VARIATION

The empirical relation between the frequency and magnitudes of earthquakes where a and b are constants is given in equation 1:

$$\log N(M) = a - bM, \tag{1}$$

where M is the magnitude, and $N(M)$ is the number of events with magnitude larger or equal to M. Based on the selected data, the probability density function of the magnitude events $\geq M$ of the studied area is calculated according to the Gutenberg-Richter law:

$$f(m) = \beta \cdot e^{-\beta \cdot (m - M_c)}, \quad m \geq M_c. \tag{2}$$

$$\beta = b \cdot \ln 10. \qquad (3)$$

Parameter *b*-value represents the best statistical estimator or MLE (maximum likelihood estimator). Spatial variation *b*-value (Fig. 3) with (M_w), broad range between $0.5 \leq b \leq 1.5$. Significantly *b* approximately 1.1 value indicates three regions of the stress concentration Teregova, Hateg Strei and Mehadia areas.

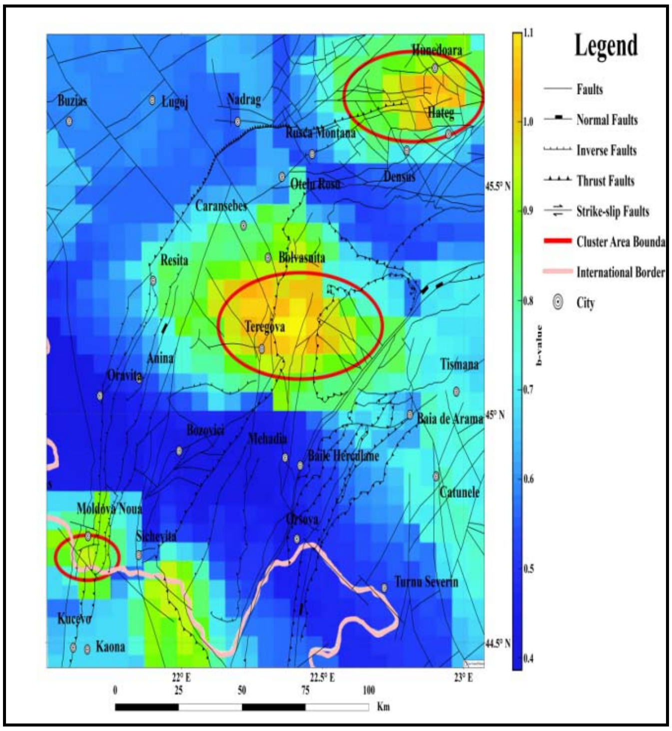

Fig. 3 – Spatial variation of *b*-value for the Danubian area.

The M_c (magnitude of completeness) map parameter (Fig. 4) is essential in seismology studies and represents the minimum magnitude value for which all events in a particular region are correctly detected.

M_c, the completeness magnitude, is the magnitude value for which the deviation Δb is inferior to the uncertainty $\delta\beta$ for determining the *b*-value:

$$\delta b = 2.3 b^2 \sqrt{\frac{\sum_{i=1}^{N} (M_i - \overline{M})}{N(N-1)}} . \qquad (4)$$

Equation 4 provides a realible estimation also in the presence of posibile variations in time or in space of the *b*-value.

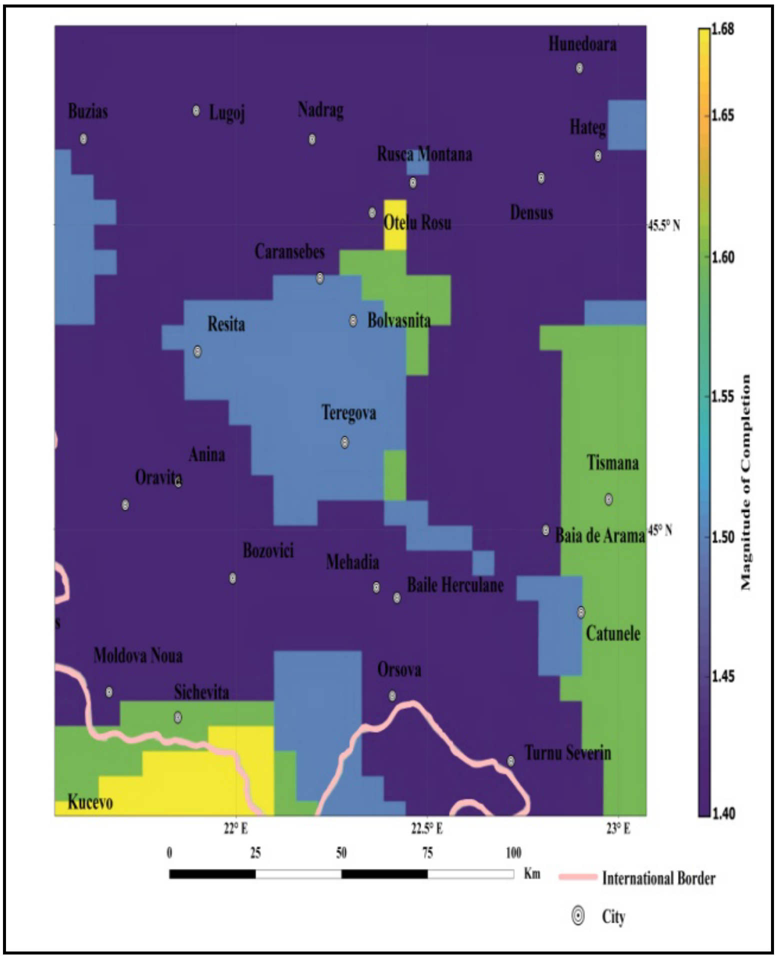

Fig. 4 – Magnitude of completeness region 1990–2018.

The standard deviation of *b*-value map is presented in Fig. 5 to show the significance level of anomalies. As it can be seen, the reported standard deviation of anomalous areas is all less than 0.07, in Teregova cluster [13] and this means that the observed differences in *b*-values can be established with significance.

The spatial variations map of Danubian area is presented in Fig. 5, this map are constructed using a compilation at revised catalogues [9] that was completed with data from the Romplus catalogue implemented in Matlab.

Spatial variation on *b*-value for the Danubian area shown on Fig. 5, were realized using a number of 1648 seismic events recorded between 2009 and 2018. For processing the data, we used the ZMap software package [15], where $N_{min} = 50$ events, with cells of subdivided $0.5^0 \times 0.5^0$, *b*-value are calculated for circular epicentral areas centred at grid nod.

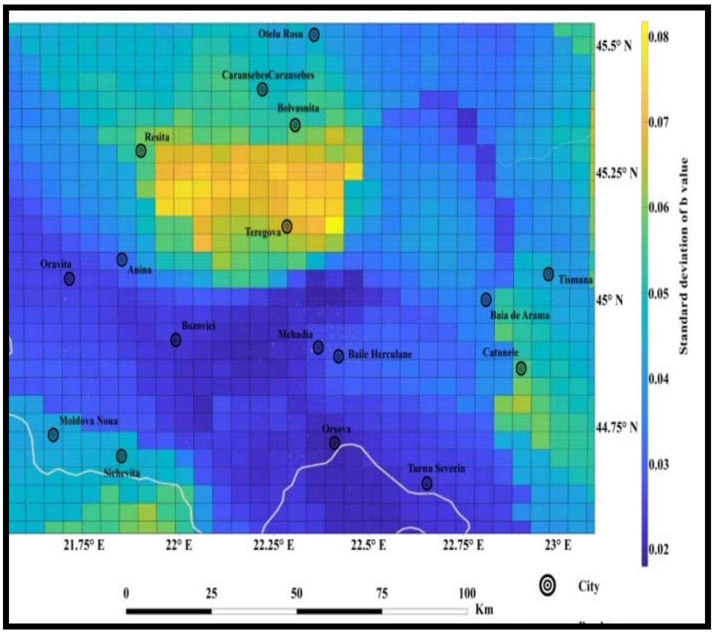

Fig. 5 – Standard deviation of *b*-value.

The map with the temporal variation of *b*-value for the Mehadia and Moldova Noua area and could not be realized because for the ninteen years we did not have recorded seismicity (background seismicity) in the area due to the reduced number of seismic stations in the seismic area.

An increase (or decrease) in effective stress as seen in Fig. 6 acting on a fault system is resulting in a corresponding decrease (or increase) in the *b*-value. Examples of studies that document this behavior are included in: [15–17]. Other studies, however, report *b*-value increases before a major earthquake [18, 19]. Variations in *b*-value as seen in Fig. 6 have long been known to precede and follow the occurrence of large earthquakes, but the variations appear to be expressed in different ways.

Reported variations include an increase in *b*-value for a number of years before an earthquake, followed by a decrease after its occurrence; or, an increase long before the earthquake, followed by a drop before the earthquake and a major decrease after its occurrence.

Analyses of the Teregova (TE) and Hateg Strei (HT) sequences highlight variations in *b*-value (Fig. 7 and Fig. 8) and reveal precursory potential wich could be used in a medium-term (months, years) earthquake forecast.

The occurrence of foreshocks may result in a slight *b*-decrease (Fig. 7) a few days, or more before the major earthquake [18]. Aftershock activity results in further variations in *b*-value.

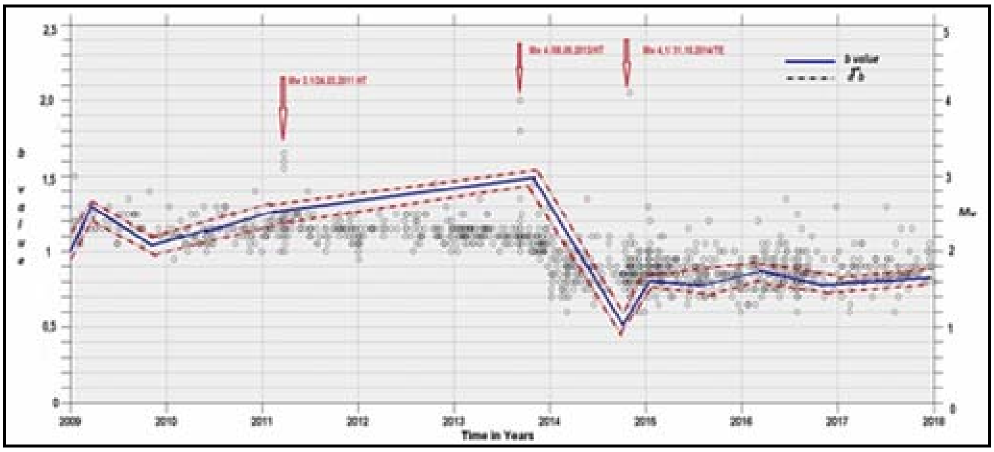

Fig. 6 – Temporal variation for a Danubian region, based on Romplus data from 2009–2018 modified from [14], occurrence time for mainshock sequences are with red.

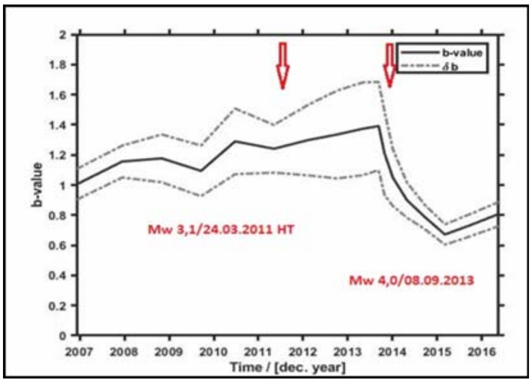

Fig. 7 – Temporal variation *b*-value sequences Teregova.

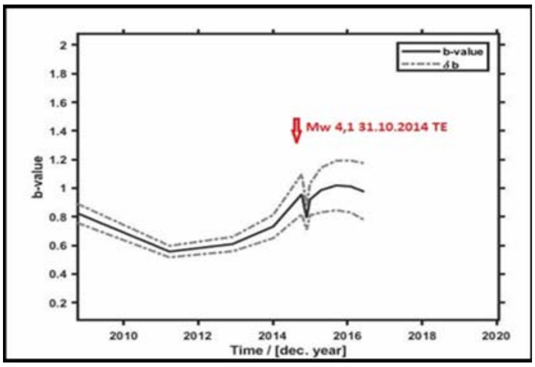

Fig. 8 – Temporal variation *b*-value sequences Hateg Strei.

Variation in *b*-value from one area to the other along a major fault (Fig. 5), are in particular, creeping sections along faults with high *b*-values, whereas asperities exhibit low *b*-values [20, 21, 22].

4. RESULT AND DISCUSSION

The variety of *b*-value observations cannot be interpreted unambiguously, given that the *b*-value most likely depends on a combination of fault-zone characteristics like local stress conditions, heterogeneity of the crust and damage distribution.

Low *b*-values have been correlated with areas of asperity, locked part of a fault where the nucleation of earthquakes is likely to happen [20]. Large heterogeneities correspond to higher *b*-values.

Analyses of the Teregova (TE) and Hateg Strei (HT) sequences observed variations in *b*-value presented in Fig. 7 and Fig. 8, reveal precursory potential wich could be used in medium-term (months, years) earthquake forecast [23].

An increase (or decrease) in effective stress in (Fig. 3) acting on a fault system resulting in a corresponding decrease (or increase) in the *b*-value.

The values of *b* that fall within the range ($0.5 \leq b \leq 1.5$), are generally correlated with geotectonic structures in the studied region.

The distribution of *b* reveals a high concentration of stress in the *b*-area > 0.8 (Teregova, Mehadia and Hateg–Strei) where three clustering zones are distinguished – shown in Fig. 3.

Their distribution suggests a high heterogeneous state of stress highlighted through an alternation between: 0.7 and 1.2 *b*-values, what does it means that high stress concentration associated with strain accumulation exists in the region.

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