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Determination of the maximal expected magnitude of the main neotectonic zones in North Macedonia

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Determination of the maximal expected magnitude (M_{max}) of future earthquakes is one of the most important parts of seismic hazard and risk assessment. In this research, an attempt for determining the M_{max} of the three neotectonic zones in North Macedonia was made, based on available seismological data for the last 42 years. Two approaches were used: first one determining *Mmax* using the magnitude-frequency relationship (Gutenberg-Richter law) and the second one using the sum of energy released by earthquakes (Benioff diagram).

Key words: maximal magnitude, Gutenberg-Richter law, energy diagram

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1. Zonation of the territory of the Republic of North Macedonia

The Balkan Peninsula is one of the most active regions in Europe by geodynamical aspect. The present-day geodynamics of the Balkan region is controlled by the active tectonic processes in the Eastern Mediterranean: the subduction of the Adriatic (Apulian) microplate beneath the Dinarides; the subduction of oceanic Ionian and Levantine lithosphere under the Hellenic arc-and-trench system and the collision between Eurasia and Arabia with a related westward movement of Anatolia block along the North Anatolian dextral strike-slip fault [1]. The present seismic activity in the territory of the Republic of North Macedonia, according to the data sources available to the Seismological Observatory [2], is due to the permanent different intensities of movements of the higher order tectonic units within the three main seismic zones: West-Macedonian, Vardar and East-Macedonian seismic zone (Figure 1).

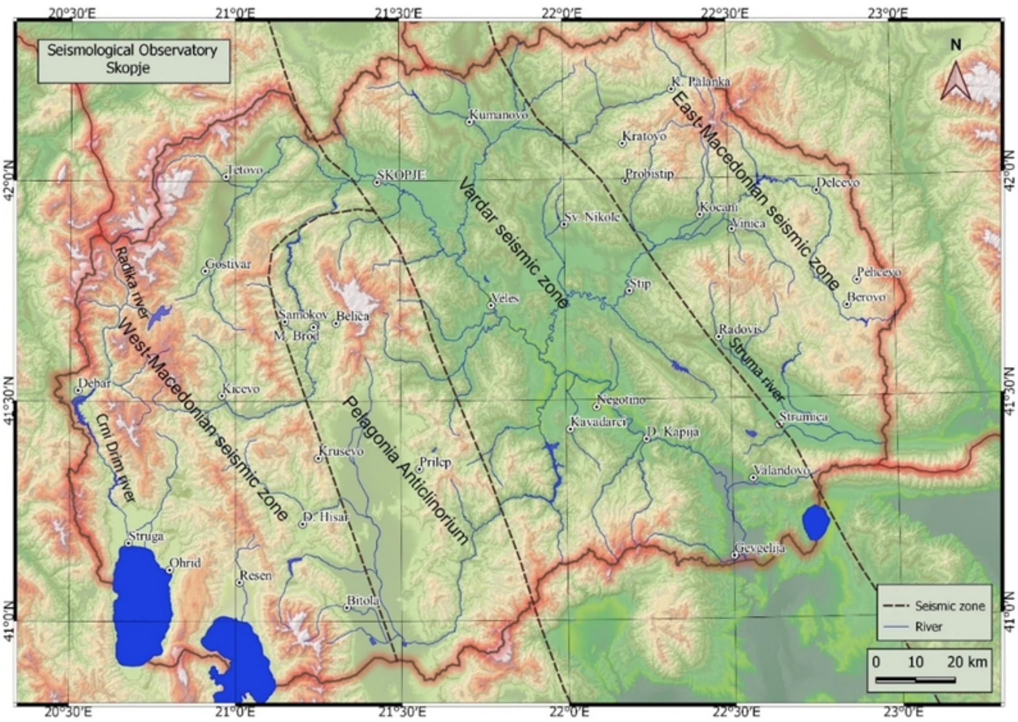

Figure 1 Zonation of the Republic of North Macedonia

Each of these zones is characterized by a specific time and space distribution of earthquake locations, with frequent seismic microactivity and a considerable number of minor ($2.0 \leq M_L \leq 3.0$) to light ($3.0 \leq M_L \leq 4.0$) earthquakes (Table 1). The three main seismic zones contain nearly all of the seismic sources in our territory even some parts of the zones express a distinct tendency of forming secondary perpendicular seismic zones - the area along the Radika River-Debar-Tetovo, Ohrid-Kicevo area, Stip-Kocani-Radovis area, etc.

The West-Macedonian zone has a predominantly meridional extensional direction and most of the epicenters of the earthquakes are related to the dislocation zone of the Crni Drim River. The seismicity of the zone is characterized by the frequent appearance of strong earthquakes, $M_L \geq 6.0$, most of them followed by a great number of aftershocks. Nowadays, the zone is characterized by relatively weaker earthquake [3].

The activity of the Vardar zone is a consequence of the existence of contemporary depressions, mostly with longitudinal character. The seismic sources appear at the crossings of the dislocations with both longitudinal and perpendicular directions. Tectonically, the zone is compiled by a mosaic structure, as a result of the crossing of dislocations with different directions. The activity of the zone is demonstrated by the not-rare appearance of strong earthquakes, $M_L \geq 6.0$ [3].

The East-Macedonian zone is predominantly associated with the development of longitudinal depressions along the Struma River. The depressions are separated from the surrounding mountain massif by neotectonic and contemporary active faults, contrasty pronounced to the relief, conditioning the seismicity [3].

2.Data

The archive of earthquake data accessible to the Seismological Observatory in Skopje contains three types of evidence: written documents for the historical events, macroseismic data for the earthquakes felt by the population that occurred during the first half of the 20th century and instrumental data for the contemporary events starting from 1957, the year when the first mechanical seismograph at the Observatory started to work. Until now, the instrumental seismological data were always obtained with instrumentation that followed world trends. Assembling all of the types of available data, a comprehensive earthquake catalog of earthquakes registered on the territory of the Republic and neighboring regions was formed, containing more than 30 000 events. Usually, for recent calculations and analyzes, a catalog of data for the period from 1901 to 2021 is used, which means that the historical events before the 20th century are not included. During the instrumental era, the Observatory has changed three generations of instruments, each with a different method of operation and different accuracy of the results. Furthermore, keeping in mind that a precise location of the earthquake epicenters is needed for the calculations explained in the next part, the interval of interest is shortened for the period 1979-2021 and the buffer zone is taken to be less than 10 km from the country border because of the existence of cross-border faults and the macroseismic effects on the territory of our country. Providing a homogeneous earthquake catalog is very important for detailed seismic hazard assessment, so a correct value of magnitude of completeness (M_C) of the catalog needs to be implemented. Using various of statistical methods for determining the M_C, a value of 2.5 was amount. The final catalog of data [2] used for further calculations contains 1582 earthquakes with Richter magnitude $2.5 \leq M_L \leq 5.2$. Fig. 2 presents the epicentral map of the separated earthquakes in the territory of the Republic of North Macedonia and neighboring regions for the period 1979–2021, together with the neotectonic faults, and the stations of the present seismological telemetric network.

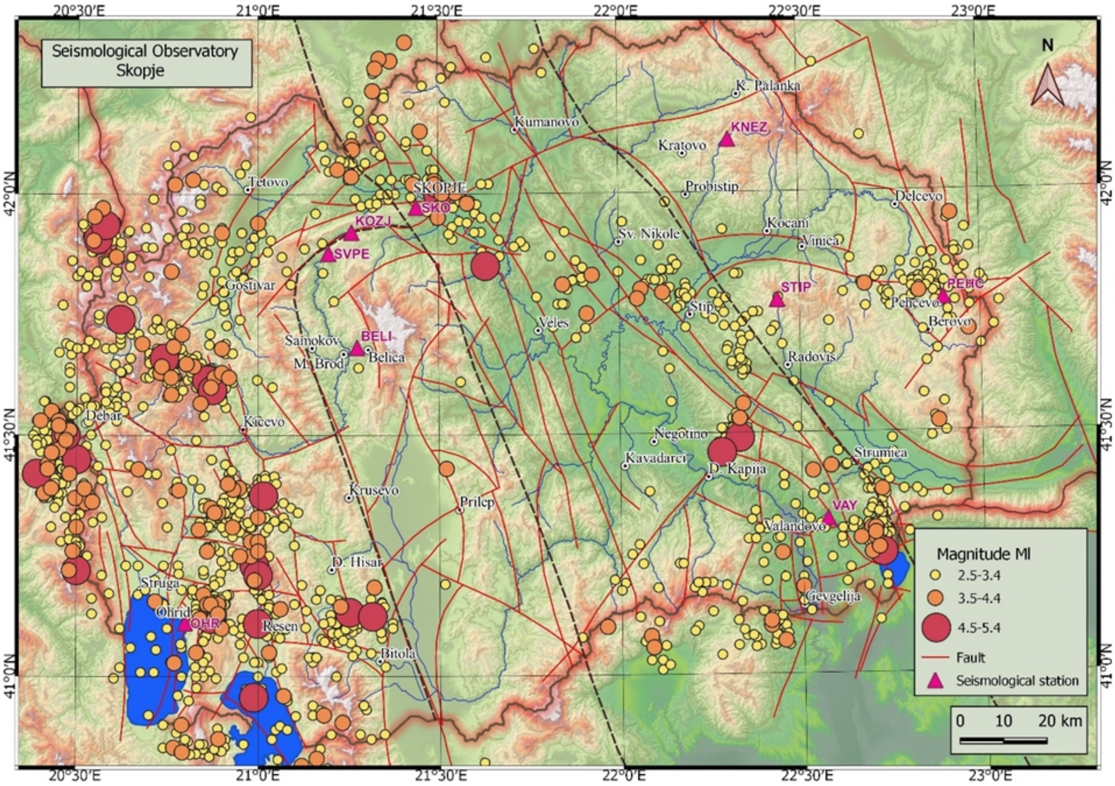

Figure 2 Epicentral map of the earthquakes for the period 1979–2021

As it can be seen from Fig. 2, nearly all the parts of the territory were seismically active even though the activity rate is different comparing the zones as the numbers presented in Table 1 show.

Magnitude M_L / Seismic zone	$2.5 \leq M_L \leq 3.4$	$3.5 \leq M_L \leq 4.4$	$4.5 \leq M_L \leq 5.4$	Total
East-Macedonian	130	8	/	138
Vardar	367	58	5	430
West-Macedonian	851	145	18	1014

Table 1 Distribution of earthquakes from the main seismic zones for the period 1979-2021 by magnitude

Seismicity of the East-Macedonian seismic zone in the period 1979–2021 was characterized by 138 earthquakes with local magnitudes M_L in the wide range from nearly 2.5 to 5.4, for Vardar seismic zone the number of located earthquakes is 430 and for the West-Macedonian seismic zone, this number amounts to 1014.

3.Methodology

Reliable estimations of seismic risk and seismic hazard are common problems in seismology that need to be answered. One of the most important parameters to determine is the maximum expected magnitude (M_{max}) of the upcoming earthquakes. For this purpose, two different methods were applied: firstly, the most common Gutenberg-Richter law representing the frequency–magnitude dependence and secondly, graphical method of estimation, plotting the cumulative energy released as a function of time for a certain region. In order to determine the maximum expected magnitude using the Gutenberg-Richter law, a graph of the previously prepared catalog of earthquake data was created using the special software ZMap7 [3] even though the plotting can be done manually using the relation (1)

$$LogN(M)=a-bM \quad (1)$$

Where $N(M)$ is the number of earthquakes with magnitude M and a and b are parameters dependent by the seismicity (a) and tectonic (b) conditions of the exact region. The fit line needs to be linear. The procedure for determining the M_{max} using this method is pretty simple: it is needed to determine the interception of the fit line with the magnitude axis (x-axis). This value depends on the b value that characterizes the level of spatial dissipation of stress and strain. The stationary and the accuracy of M_{max} is related to the stationarity of the parameters a and b [4] which means a richer catalog of events leads to more reliable values of the parameters mentioned and the M_{max}.

The graphical method is more complex than the Gutenberg-Richter method. Firstly, a calculation of the released energy of the earthquakes needs to be done to be able to graph the cumulative value as a function of time. Therefore, from the plotted graph many parameters can be derived:

1. If a linear fit line is applied, the slope of the line represents the rate of energy released by a time unit [4].
2. Since the rate of released or accumulated energy in a certain region remains nearly constant over time, even the annual rate fluctuates of the mean value (fit line), two envelope lines through the maximum and minimum energy released of an active period of the region (the minimum point represents the beginning and the maximum point represents endpoint) can be drawn (Fig 3-5). These lines should run parallel to the fit line, which means that all of them need to have the same slope value. The vertical distance $\overline{E_1 E_2}$ between these enveloping lines indicates the total amount of energy that may be released in the region [5,6]
3. The corresponding magnitude for a certain value of $\overline{E_1 E_2}$ can be obtained using the widely known relation for determining the energy class of an earthquake (2)

$$LogE=4.4+1.5M \quad (2)$$

The M in (2) represents the requested value of M_{max} [7].

4.Results and Discussion

Figures 1-6 represent the results of the research. The best way to interpret the results is to compare them. From the graphical method, several conclusions can be done. The main calculations for the Vardar zone give a value for M_{max} of 5.7 which is in good agreement with the result obtained with the Gutenberg-Richter law giving a value of 5.4 for M_{max}. The variation of the result is mostly due to the deviation of the value of parameter b (± 0.04) and the impurities of the data catalog. However, a difference of 0.3 magnitude units is within the interval of confidence lower than 10% (in this case 5% difference). Similarly, the results for the East-Macedonian zone determined by the methods mentioned above, are in very good agreement - 4.4 graphical and 4.3 analytical (with 3% difference). It is not a case with the results for the West-Macedonian zone - 5.0 graphical and 6.2 analytical. The result difference can be easily explained if it's kept in mind that the database contains earthquakes which epicenters are outside the border of the country in the buffer zone. This means that because of the activity of the continuation of the faults outside the border, the released energy remains fairly constant, resulting with a closer upper envelope to the main fit of the curve and smaller vertical distance $\overline{E_1 E_2}$. The statement is proven with the lowest value of parameter b and high annual value of the parameter a, with physical meaning that the seismic activity of the region is high (numbers in Table 1 prove that) while the accumulated stress and strain are decreasing. As the energy released graph contains two enveloping lines bounding all of the points, one of them representing the level of released energy (upper one) and the other one the level of accumulated energy (lower one), it can be easily defined if the seismic risk at a certain region is high enough or not. Hence if the energy release decreases and gets closer to the lower bound, it means that the possibility of a large earthquake appearance is much expected and vice versa. According to figures 1-3, the Vardar and West-Macedonian zone's lines of released energy are close to the upper bound (Table 2) which means the seismic risk in these regions is smaller than the risk at East-Macedonian zone. These statements are verified by the values of parameter b in the frequency-magnitude law. Keeping in mind that normally the value of b should be below 1.0, the East-Macedonian zone can be characterized as zone with the highest level of accumulated stress, main prerequisite for occurrence of strong earthquakes.

Table 2 Equations of the upper bound envelope line

Zone	Equation of upper bound line
East-Macedonian zone	$y=(0.048x-94.141)*10^{11} J$
Vardar zone	$y=(0.128x-251.205)*10^{12} J$
West-Macedonian zone	$y=(0.316x-626.517)*10^{12} J$

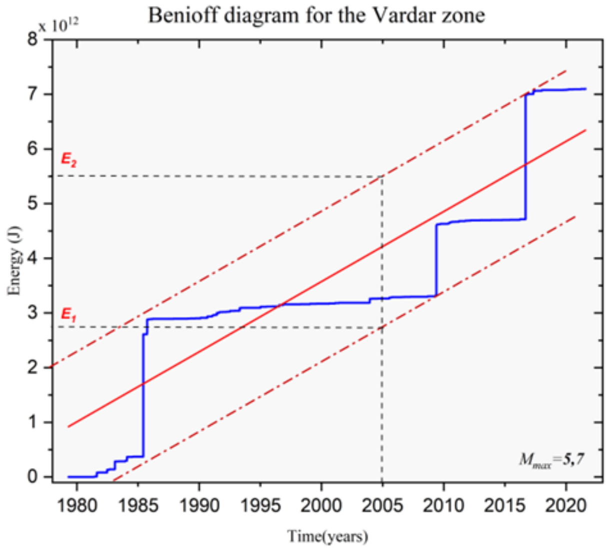

Figure 3 Benioff diagram for the Vardar zone

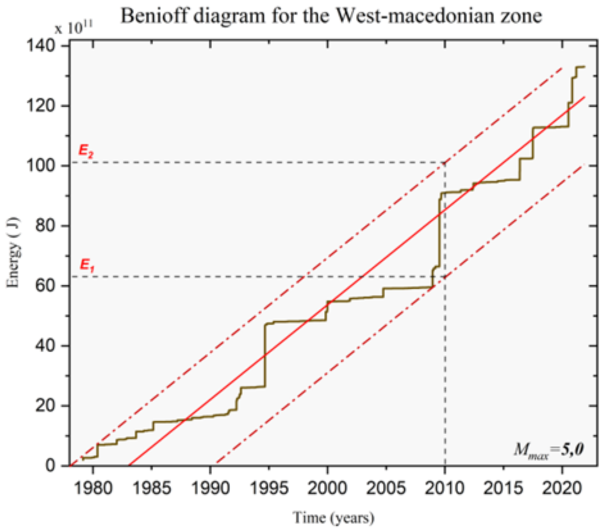

Figure 4 Benioff diagram for the West-Macedonian zone

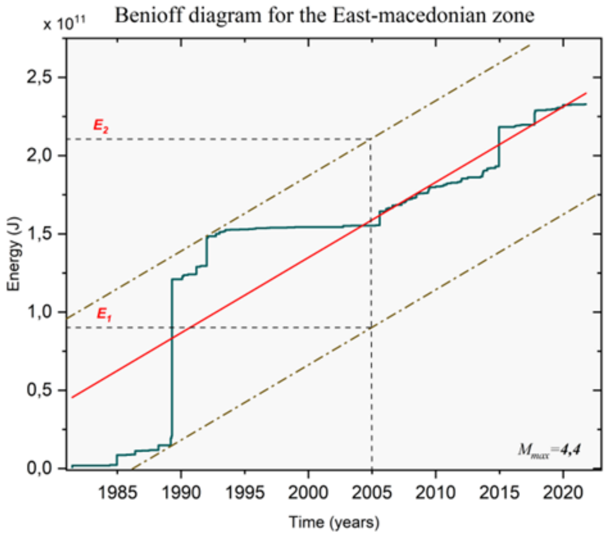

Figure 5 Benioff diagram for the East-Macedonian zone

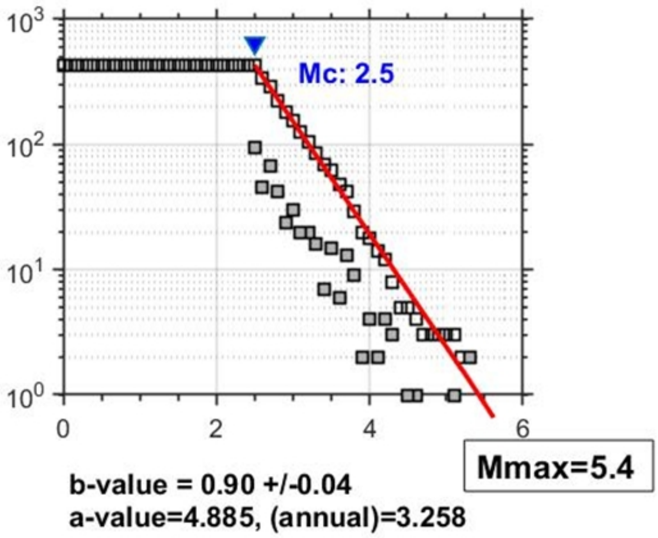

Figure 6 Frequency-magnitude law for Vardar zone

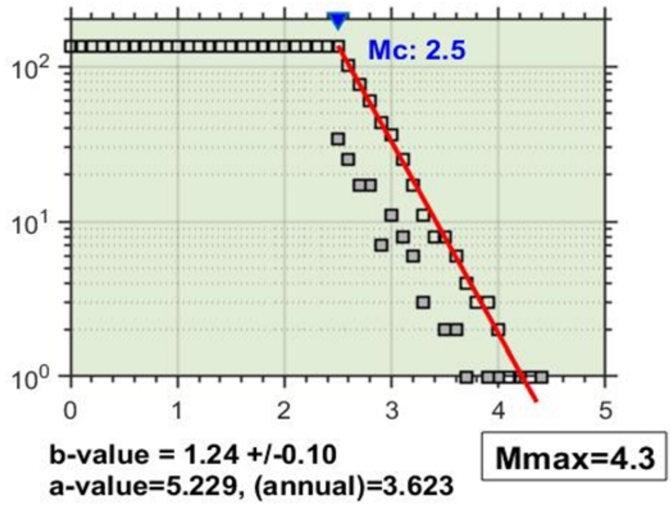

Figure 7 Frequency-magnitude law for East-Macedonian zone

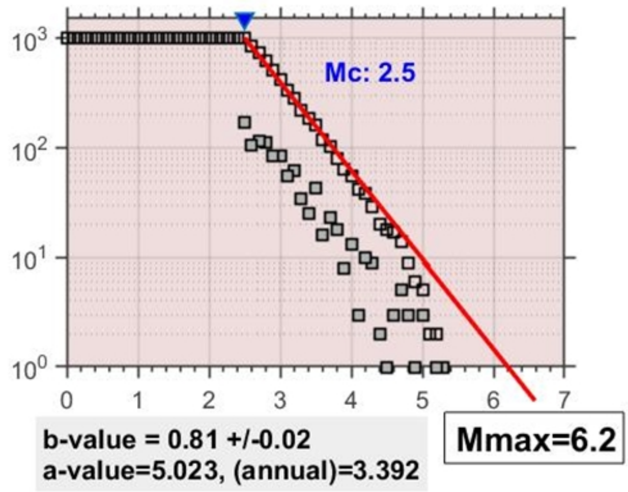

Figure 8 Frequency-magnitude law for West-Macedonian zone

5.Conclusion

As the previous section shows, the results for maximum exceeded magnitude obtained by the two statistical methods are in good agreement, but still the usage of them should be cautious, because the available data contains earthquakes with more significant magnitudes than the value of the predicted one - $M_L 7.8$ for the East-Macedonia, $M_L 6.7$ for the Vardar and $M_L 6.5$ for the West-Macedonian zone. The smaller value of $M_{max}$is as a result of a few factors that it is depend from: the length of the considered period (in this case 42 years) – a longer period, better results; correct value of M_c – pretty difficult assignment if the database has an enormous number of earthquakes and the number of operating stations is changeable with time; the graphical method's results are more accurate if the earthquakes with smaller energies/magnitudes are not used for the calculations. Finally, the results may be affected by different regional conditions on which the continuities of the faults are exposed at the neighboring countries. However, this kind of calculations, because of the statistical character have smaller confidence interval than the deterministic one, but are still good method to obtain some preliminary results, to spot the deficiencies of a given catalog and to confirm the dependance of local seismicity to the regional tectonic conditions.

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