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IMPROVEMENT AND UPDATES OF THE NATIONAL DATABASES FOR SEISMOGENIC SOURCE MODELING IN THE CONTEXT OF REVISING THE NATIONAL HAZARD MODEL FOR NORTH MACEDONIA

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Abstract

The official adoption of Eurocode standards in North Macedonia, compared to developed EU countries, was only in recent years, leaving a significant gap that needs to be tackled. The new generation of Eurocode standards is posing demands to seismic hazard assessment's outputs to use the most updated seismic hazard models, which will be crucial for the development of national annexes. To improve and refine the national seismic hazard model, it is essential to update and curate the existing datasets (i.e., earthquake catalogues, tectonics information and active faults), particularly in a country that has shown significant tectonic activity in the past decades with the occurrence of moderate to strong earthquakes. In just the last century, 12 earthquakes with magnitudes greater than 6.0 have occurred within the territory of North Macedonia and the surrounding areas, confirming the constant threat of earthquake to society.

The main task in developing a refined national seismogenic source model is to improve and update the national database by increasing the quality and thoroughness of all available national and regional seismotectonic databases. This activity involves compilation and statistical analyses of the updated national earthquake catalogue that chronologically ranges from 1000 to 2020. In its compiling, priority was given to the national catalogue from the National Seismological Observatory at the Faculty of Natural Sciences and Mathematics (SORM), which was then supplemented by events from the International Seismological Centre (ISC). Additionally, an overview of the latest defined active faults in North Macedonia will be presented, serving as an input for the new national seismic hazard model.

With recently collected and compiled data, along with updated information on seismically active faults in the region, we are now capable of elevating and upgrading the probabilistic seismic hazard assessment of the country, which previously was built primarily upon seismological data, i.e., data from past earthquakes.

Keywords: Seismogenic model, Earthquake catalogue, Active faults, Seismic Hazard, North Macedonia

1. Introduction

The Republic of North Macedonia is located in the Balkan Peninsula, an active seismic region with a complex tectonic structure that causes frequent earthquakes, especially moderate ones. The moderate to high seismicity points out the necessity for comprehensive seismic hazard assessment of the country. This study provides an effort in the enhancement and update of the national databases, more specifically the earthquake catalogue and the fault database, which constitute the backbone of the updated national seismogenic source model. The update of the seismogenic source model as an initial part of the new seismic hazard assessment of the country plays a key role in the development of the national annexes for the new generation of Eurocodes.

The compilation and the main features of the updated earthquake catalogue are presented, both for the instrumental period, 1900-2020, and the historical period, pre-1900. The catalogue contains 4993 events, integrating data from the updated national earthquake catalogue of the Seismological Observatory as its core, the International Seismological Centre ISC [1], and other regional sources. For the first time faults are intended to be introduced as a branch tree in the seismogenic model, thus, improvements in the identification and parametrization of active faults have been done. The methodologies and results of such updates are discussed hereinafter, highlighting their importance to improve the probabilistic seismic hazard assessment (PSHA) of the country.

2. Earthquake catalogue

2.1. Catalogue compilation and main characteristics

Understanding the seismicity of a region relies on records of past earthquakes, which are obtained from instrumental data, direct analysis of earthquake-induced damage in recent times, or chronicles from both the recent and distant past [2]. This information is typically compiled into documents known as earthquake catalogues. Earthquake catalogues are the most important seismological product in regions, since earthquake hazard assessments heavily rely on the analysis of historical and instrumental earthquake data [3] [4].

The area of interest is defined by the coordinates 39.8˚N≤φ≤43.3˚N, 19.3˚E≤λ≤24.2˚E which includes the territory of N. Macedonia and the surrounding regions. Thus, assessing the seismic hazard in North Macedonia requires considering contributions from neighbouring regions. In the compilation of the updated and the improved earthquake catalogue that will be used in the refined national seismogenic source model, priority was given to the national earthquake catalogue from the Seismological Observatory at the Faculty of the Natural Sciences and Mathematics (SORM). The latest edition of the national earthquake catalogue [5], still in publishing and updated this year, includes data for earthquakes whose epicentres are located within the territory of the Republic of North Macedonia and its neighbouring regions, extending up to a 100 km buffer from the national borders. This update covers only the instrumental period (1900-2020) while retaining the data for pre-instrumental events from the previous version of the catalogue.

Table 1. Relations between moment magnitude M_w and other earthquake size measures

Eq.	Mag	Catalogue	Relation	Reference
1	**M_{ms}**	national	$M_L = 0.96 * M_{ms} + 0.19$	[6] as referred in [7], eq. 3
2	**M_L**	national	$M_W = 0.9203 * M_L + 0.3989$	[8], as referred in [7], eq. 1
3	**MD**	ISC bulletin	$M_W = 1.472 * M_D - 1.49$	[9], eq. 13
4	**M_S**	ISC bulletin	$M_W = \exp(-0.044 + 0.227 * M_S) + 2.26$	[10], eq. 5
5	**mb**	ISC bulletin	$M_W = \exp(-1.401 + 0.227 * mb) + 2.28$	[10], eq. 6
6	**M_L**	EQs in Albania	$M_W = 1.22 + 0.813 * M_L$	[10], eq. 7
7	**M_L**	EQs in Serbia	$M_W = 0.7 + 0.858 * M_L$	[10], eq. 10
8	**M_L**	EQs in Kosovo	$M_W = 0.56 + 0.913 * M_L$	[10], eq. 11
9	**M_L**	EQs in Montenegro	$M_W = -0.01 + 1.028 * M_L$	[10], eq. 8

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10	**M_L**	EQs in Bulgaria	$M_W = M_L + 0.43$	[11] as referred in [12], Table 2a, Table 2c
11	**M_L**	EQs in Greece	$M_W = M_L + 0.19$, (1969-2007)	[13]
12			$M_W = 0.964 * M_L + 0.147$, (2008-2016)	[14], Figure 7., Area 1

The national earthquake catalogue was then supplemented by events from the European Preinstrumental Earthquake Catalogue – EPICA [15] in the historical period (1000 to 1899) and by events from the reviewed ISC - International Seismological Centre bulletin event catalogue [1] and ISC GEM catalogue in the instrumental period (post 1900) [16] [17] [18] [19]. The renewal was mainly for the surrounding regions, specifically targeting areas of interest not included in SORM's national earthquake catalogue. The earthquake catalogue chronologically ranges from the year 1000 to 2020. The magnitude type for all events in the catalogue is the moment magnitude M_W, as it is the standard magnitude used in PSHA applications. Thus, for the events that were reported not in M_W, but in magnitudes of various types, different published relations were used for conversion to M_W (Table 1).

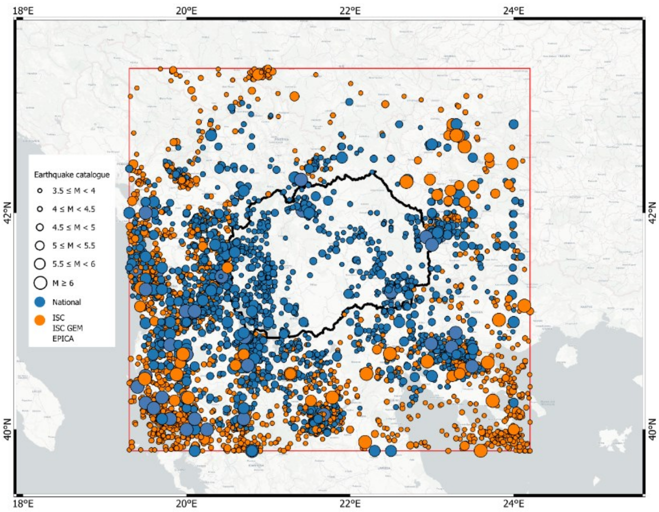

Figure 1. Distribution of historical and instrumental earthquakes observed in North Macedonia and the surrounding regions

The minimum threshold magnitude of the earthquake catalogue was set to 3.5 as a value typically detectable that provides useful data for seismic hazard analysis. While these events aren't usually destructive, they offer important insights into the local seismic activity, helping to improve the accuracy of hazard assessments. Including these smaller but frequent events also contributes to a more comprehensive understanding of long-term seismic risk in the region. The total number of events in the final version of the earthquake catalogue is 4993 (Fig 1).

Most recorded events are small to moderate earthquakes, with magnitudes around 4 being the most frequent (Fig. 2).

The dataset also includes some significant high-magnitude events, which although rare, are crucial and critical for seismic hazard analysis since they often release the most seismic energy and have the greatest potential for damage. The smooth distribution of magnitudes indicates a reliable dataset free from major gaps.

The depth distribution (Fig. 3) shows that most earthquakes occur at shallow depths, with 75% of events occurring at depths of 16 km or less. The average depth of 12.5 km is consistent with typical crustal seismic activity, while the maximum depth of 82.5 km indicates the presence of deeper tectonic activity, potentially fault systems reaching the lower crust. However, the number of events exceeding depths of 40-45 km remains relatively small. The overall shallow-depth concentration of the earthquakes reflects tectonic settings where crustal earthquakes dominate.

The dataset spans from the year 1000 to 2020 (Fig. 4, Fig. 5), with the earliest reported event dating back to 1153. Covering a period of 867 years, it provides a comprehensive historical record of seismic activity, including both instrumentally recorded and historically documented events. In the earlier years, particularly before the 20th century, the records mainly document significant, high-magnitude earthquakes due to the limited capabilities of observation and documentation at the time. During the

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20th century, with advancements in seismic monitoring and record-keeping, the dataset expanded to include smaller and more frequent seismic events.

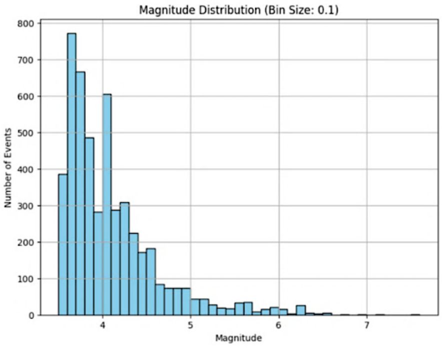

Figure 2. Magnitude distribution of the catalogue

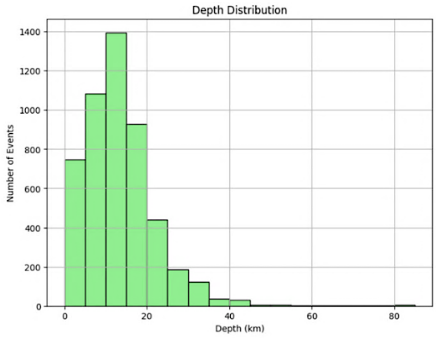

Figure 3. Depth distribution of the catalogue

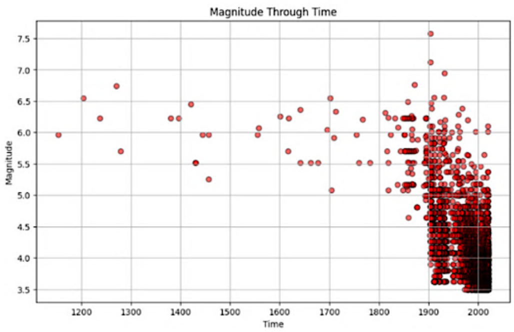

Figure 4. Magnitude-time plot

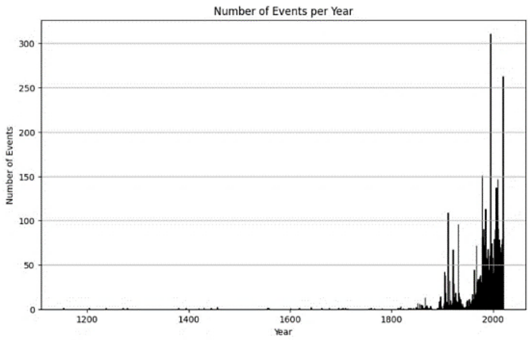

Figure 5. Number of events per year

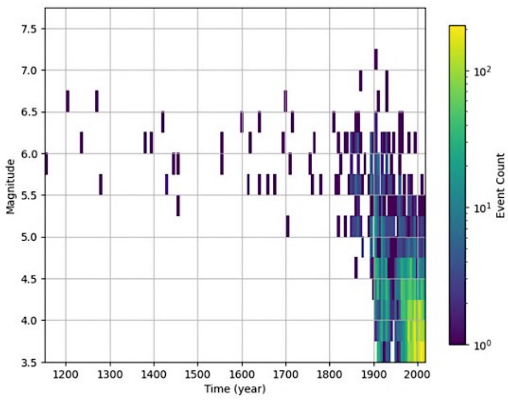

Figure 6. Magnitude - time density plot

This earthquake catalogue offers a comprehensive view of seismic activity over several centuries. The predominance of shallow depths and moderate magnitudes suggests that the data primarily represents crustal earthquakes. Clusters of events over specific time periods point to episodes of increased activity, that could provide insights into tectonic processes. This analysis underscores the importance of maintaining comprehensive and accurate earthquake catalogues for assessing seismic hazard and risk.

2.2. Catalogue completeness

For a catalogue to be considered complete, nearly all events above a certain magnitude threshold must be recorded [20]. One of the most fundamental issues faced in statistical analyses of any catalogue is estimating the intervals of catalogue completeness. It is evident that completeness levels vary over time. For the pre-instrumental era, catalogues only contain data on significant events of higher magnitudes. The shift of completeness levels toward lower magnitudes is driven by the development of

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seismographs, their increased sensitivity, and the substantial and continuous increase in station network density throughout the 20th century [10].

The completeness of catalogues is determined to evaluate their spatial and temporal homogeneity. To obtain more reliable forecast parameters, complete catalogues are an essential requirement.

Identifying completeness thresholds and their temporal and spatial variations is a challenging and often controversial task, with no universal solution. In assessing completeness, the simplified approach proposed by [21] can be used, involving a visual inspection of the cumulative plot of the number of events as a function of time. This method appears to be highly efficient and accurate, even when applied to small datasets. If the most recent change in slope occurs when the data becomes complete for magnitudes above the reference magnitude [22], completeness intervals for different magnitude ranges are shown in Table 3.

The Stepp method [23] is also widely used approach for assessing the completeness of earthquake catalogues. This method is currently implemented in the current version of the Modeller's Toolkit in OpenQuake engine [24].

The Stepp method works by examining the average recurrence rate of earthquakes within predefined magnitude and time intervals. By analysing the standard deviation of the mean rate and its changes over time, the method can determine when the catalogue achieves completeness for specific magnitudes [24].

While the Stepp method is simple and robust, its effectiveness depends on careful selection of magnitude and time intervals, as well as thoughtful interpretation of results [24].

Catalogue completeness analysis was done by using the Stepp method but also the classical visual inspection of the cumulative plot of the number of events as a function of time. In Fig. 7 the completeness of the catalogue is shown in the magnitude-time density plot by the Stepp method.

Cumulative rates of magnitudes are evaluated within each of the magnitude intervals to determine completeness years.

Based on the analysis of the results obtained through both approaches, with priority given to visual inspection, the final decision defines the catalogue's completeness across seven intervals, i.e., the catalogue can be considered complete from the year 1978 for $M_W \geq 3.5$, from the year 1963 for $M_W \geq 4.0$, from the year 1952 for $M_W \geq 4.5$, from the year 1891 for $M_W \geq 5.0$, from the year 1846 for $M_W \geq 5.5$, from the year 1560 for $M_W \geq 6.0$, and from the year 1270 for $M_W \geq 6.5$. The cumulative number of events versus year is shown in Fig. 8, while completeness years are given in Table 2. The completed earthquake catalogue contains 4180 events.

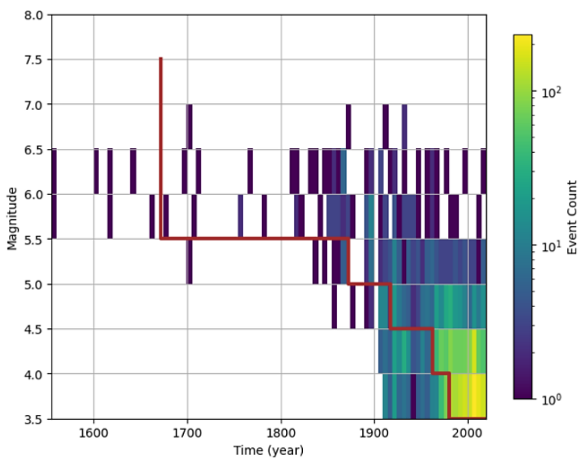

Figure 7. Completeness by Stepp method

Table 2. Completeness years for corresponding magnitude ranges

Magnitude range	Completeness year
$3.5 \leq M_W < 4$	1978
$4 \leq M_W < 4.5$	1963
$4.5 \leq M_W < 5$	1952
$5 \leq M_W < 5.5$	1891
$5.5 \leq M_W < 6$	1846
$5.5 \leq M_W < 6$	1560
$M_W \geq 6.5$	1270

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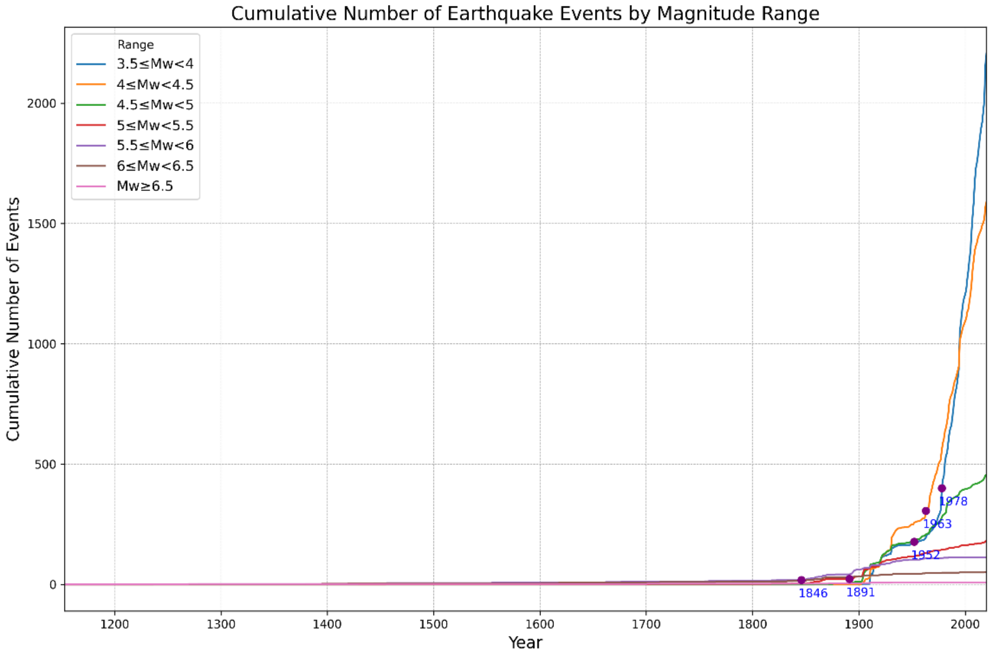

Figure 8. Cumulative number of events for different magnitude ranges – completeness analysis

2.3.Catalogue declustering

The analysis of seismic hazards often treats seismicity as a Poisson process where events are regarded as random, independent, and constant in rate over time [20]. Earthquake sequences, on the other hand, are not independent and typically include dependent events such as aftershocks and foreshocks, which are necessarily associated with a mainshock.

Declustering is the process of removing these dependent events (foreshocks and aftershocks) from seismic catalogues to estimate the long-term average rate of independent seismic events under the assumption of a homogeneous Poisson process [20].

There are numerous algorithms used as declustering techniques, based on different assumptions. One of the most used algorithms are the windowing techniques with space-time windows. These windowing methods function under the premise that all earthquakes in the catalogue from which they were established become aftershocks when certain timing and distance criteria are met in relation to any event [25]. Likewise, foreshocks are identified in this way, except when the largest earthquake happens after the sequence; in such cases, the foreshock is redefined as an aftershock. Hence, the time and space windows are modified according to the size of the maximum earthquake in the sequence [25].

Different adjustments to the time and distance windows have been proposed, as outlined by [26]. The original windows are formulated by Garner and Knopoff [27]. An alternative formulation is proposed by Grünthal (as reported in [26]) and by Uhrammer [28] (as reported in [26]). A sensitivity analysis is done using the three methods regarding the number of events for different magnitude ranges. The frequency-magnitude distribution plot of the main non declustered complete catalogue is shown in Fig.9.

The parameters such as total number of events and number of events for different magnitude ranges are summarized in Table 3. In summary, Uhrhammer's method is the most inclusive, Grünthal's approach is the most selective, and Gardner-Knopoff sits in between.

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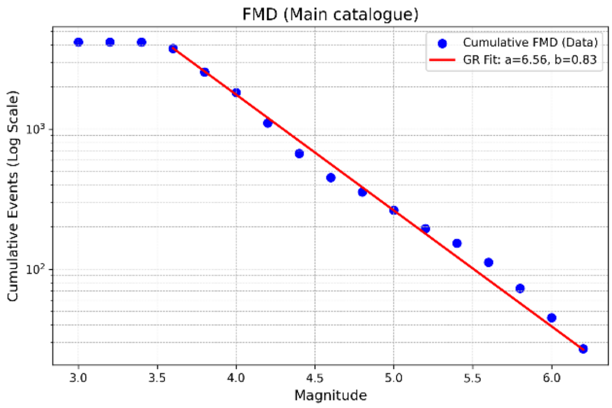

Figure 9. FMD of the non declustered complete catalogue

The Gardner-Knopoff [27] windowing method was chosen for declustering our earthquake catalogue.

It represents a credible windowing technique and the most widely applied windowing method. It classifies aftershocks using predefined time and distance thresholds that scale with the mainshock's magnitude. After applying the Gardner-Knopoff method, 1766 events remained out of 4180

Table 3. Parameters of the main non-declustered catalogue and the declustered catalogue

Parameter	Complete catalogue	Gardner-Knopoff	Grünthal	Uhrhammer
Total number of events	4180	1766	1224	2585
Events with M < 4	2279	839	513	1348
Events with 4 ≤ M < 5	1594	752	556	1040
Events with 5 ≤ M < 6	250	131	113	151
Events with M ≥ 6	57	44	42	46

3. Compilation of the fault database

3.1. Local tectonic setting in North Macedonia

As a result of the complex geotectonic evolution, several tectonic regimes have been altered [29] on the Balkan Peninsula, including the territory of the Republic of North Macedonia. The known cycles of differently oriented geodynamic movements of the South Balkan Extensional System [30], [31], [32], [33] have formed and modified the relief, mostly during the Neogene–Quaternary period.

The present relief on the territory of interest, the Republic of North Macedonia and the neighbouring regions up to 100 km from the state border, is defined as a complex mosaic of uplifting and sinking blocks, divided by edge, boundary faults [34]. Because of the different amplitude of the recent tectonic movement of the blocks, most of the neotectonic and many of the pre-neotectonic faults are active, stipulating less or more intense seismic activity.

Many faults have regional and deep character, longitudinal orientation and spread over the whole terrain, resulting in composite occurrence of earthquakes on both sides of the state border.

Merging all the mentioned, a new neotectonic map of neotectonic and reactivated pre-neotectonic faults located in North Macedonia and neighbouring areas was assembled [35], presenting a complex network of differently oriented and sized rupture structures (Fig. 10), considering the area of frequent and strong seismicity.

The updated neotectonic map consists of 152 faults – 116 on the territory of North Macedonia and 36 from the neighbouring regions added for of the effects of their activity in North Macedonia. Using this map, the tectonic causes of earthquakes can be fully explained.

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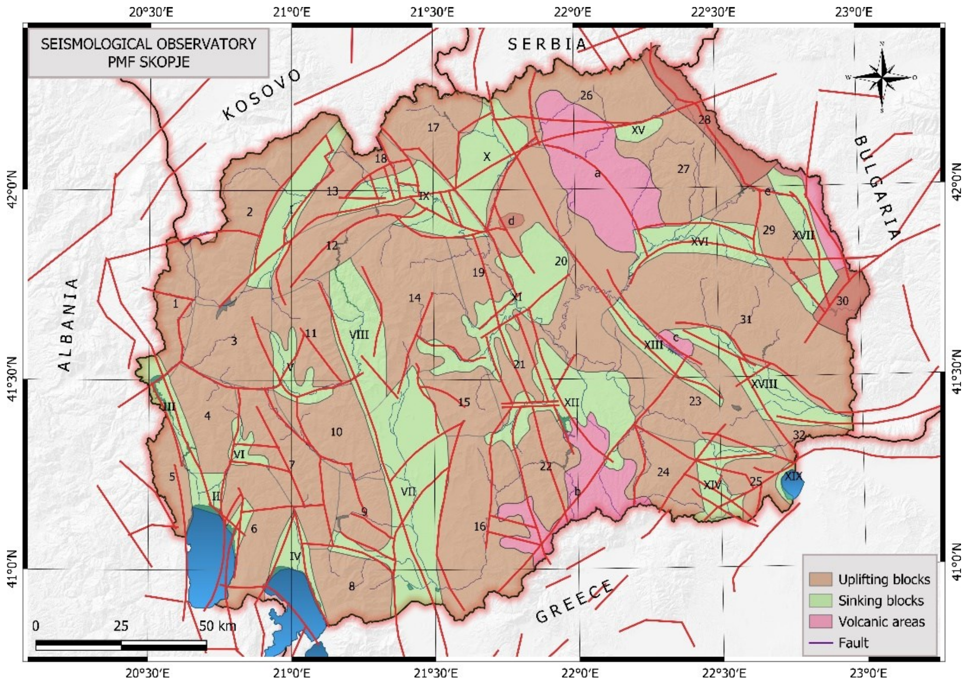

Figure 10. Neotectonic map of North Macedonia and neighbouring regions – block mosaic of the relief and orientation of the faults

3.2. Active faults in North Macedonia

The results of the tectonic characteristics of the territory of North Macedonia, presented in [36], of all defined faults in the tectonic map, distinguish 11 of them as barriers of seismicity in distinct parts of the country, called representative faults.

The representative faults are defined as faults along which the largest number of epicentres of earthquakes are distributed, for which the parameters of the accessible solutions of source mechanisms, determined by the method of the first longitudinal (P) displacements, correspond to spatial and geological characteristics of a given fault [36].

Thus, for the territory of North Macedonia, for the period 1960-2010, as representative faults were defined: Sharplanina, Elbasan-Debar, Galichki, Belchishki, Prespa, Pelister, Skopje-Kustendil, Lakavichki, Valandovo, Kozhuf and Dojransko-Gevgeliski fault, shown in Fig. 11.

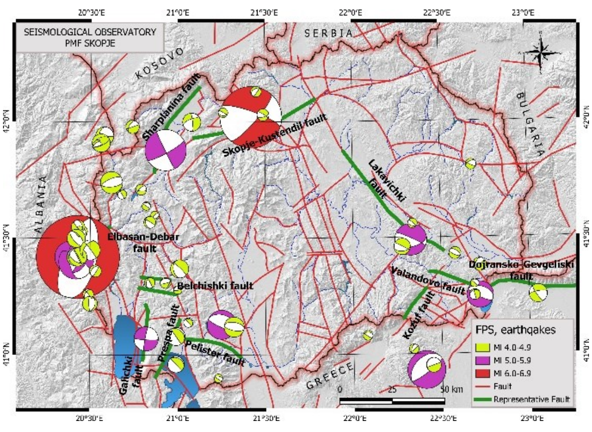

Figure 11. Tectonic map of the representative faults in North Macedonia and the available data for focal mechanisms for the period 1960-2010

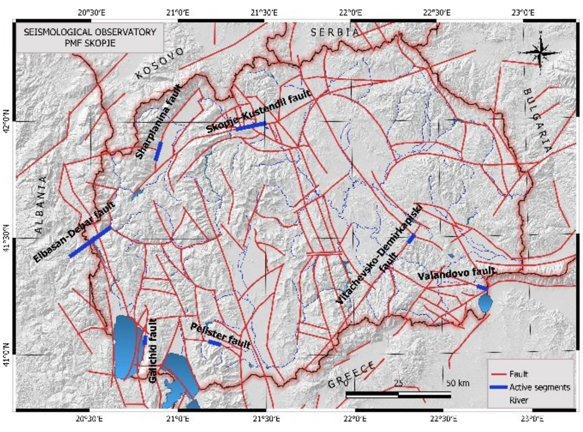

Figure 12. Map of the named active faults and their most active segments (blue lines) in North Macedonia for the period 1960-2010

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For the necessities of seismic hazard assessment and further detailed seismological research, an additional database of active faults is compiled. An active fault is generally defined as a fault that is expected to cause destructive earthquakes ($Mw \geq 5.0$). A fault commonly is considered as active if there has been movement observed in the considered period.

Applying these criteria, 6 out of the 11 representative faults can be classified as active. Namely, Sharplanina, Elbasan-Debar, Galichki, Pelister, Skopje-Kustendil and Dojransko-Gevgeliski fault meet the criteria. Additionally, the seismological data that meet the defined criteria permit the Vitachevsko-Demirkapiski fault to be added as an active fault.

Applying the parameters of the focal plane solutions (Fig. 11) and relations for the geometry of the source given in [36], parametrization of the active segments of the faults was obtained.

3.3. Parametrization of the active faults

Combining all the available neotectonic, geodynamic and seismological data, for the first time in the seismological research in North Macedonia, robust parametrization of the defined active faults was made. It is called robust because of the lack of available seismological data for the considered period (1960-2010). However, to determine geometric parameters (strike, dip, slip, length, area, observed M_{max}) of the fault, firstly, the focal mechanism of earthquakes with $M_W \geq 5.0$ were analysed to determine if the source belongs to the same fault. A lower limit of $M_W \geq 5.5$ as worldwide accepted value for active fault definition was defined because of the significance of the soil classification with a high sensitivity at the most vicinities of the active faults. The main criterion of correctness was the acceptable mathematical difference in the values of the segment plane parameters. Confirmation of the results was made with the spatial distribution of the epicentres of the weaker earthquakes. The rest of the parameters of the corresponding segment were determined using the previously defined formulas and relations [36].

Table 4 shows the parameters for the two active faults out of seven, with specific examples The map in Fig. 12 illustrates the spatial distribution of the most active fault segments within the faults.

Table 4. Fault parametrization example (Vitachevo - Demirkapiski fault, Valandovo fault)

Fault Name	**Vitachevo - Demirkapiski**	**Valandovo**
Fault type	Sinistral normal strike-slip	Sinistral normal strike-slip
Max depth	22 km	17 km
Strike [min/max]	24/39	116/133
Dip [min/max]	33/38	69/89
Rake [min/max]	-165/-175	-79/-81
Total fault length [along trace] (km)	77	23.6
Fault width [km]	7.41	11.61
Area (km^2)	68.71	230.14
Slip rate [mm/y]	<1	<1
M_{WMAX}	5.74[37]	6.38[37]
Activity	Active	Active

4. Conclusions

The present study underlines the developments and the updates of the national earthquake and fault databases which are essential in improving and enhancing the seismic hazard model of North Macedonia.

The updated earthquake catalogue includes data from the national Seismological Observatory, the International Seismological Centre (ISC) and regional catalogues. It reports a total number of 4993 events in the time span from 1000-2000 by including historical and instrumental seismicity. Since for use in PSHA applications, all earthquakes are described by moment magnitude M_W, unification of

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moment magnitude was established by different magnitude conversions. Most of the events are small to moderate and occurring at shallow depths.

The completeness analysis demonstrated that the catalogue is reliable with completeness years differing for different magnitude intervals. The complete earthquake catalogue has 4180 events. By doing the completeness we evaluate the spatial and temporal homogeneity of the seismic activity.

For declustering our earthquake catalogue, we selected the Gardner and Knopoff [27] windowing method. This approach is widely recognized and commonly used, as it assumes that any event occurring within a defined time and spatial window of a stronger event is likely dependent on it. The size of these windows is adjusted based on the magnitude of the largest earthquake in the sequence. The method strikes a balance between conservative and non-conservative approaches, making it suitable for standard aftershock removal using well-calibrated time-distance windows. After applying this method, the catalogue was reduced from 4180 events to 1766.

The study also included the update of the fault database with focus on the active faults in North Macedonia and the surrounding regions. A total of 152 faults were mapped. 116 of them on the territory of North Macedonia. Out of 11 representative faults, 6 of them were identified as active based on the focal mechanism analysis and the seismic active criteria. The seismological data satisfying the established criteria allowed also for the inclusion of the Vitachevsko-Demirkapiski fault as an active fault. For the first time, robust parametrization of fault geometries, such as strike, dip, slip rate, and maximum depth, was achieved. Even though as a result of this research parametrization of the active faults for the period 1960-2010 was made, further research is needed. Namely, the detailed seismological observations and analyses brought us valuable information that most faults have block structures and do not have unified fault planes and orientations even if the strike of the fault line has the same orientation. Knowing this, additional research is needed to define the different block parameters of the same faults. However, at this stage, the presented robust results for defining and parameterizing the active faults in North Macedonia provide a good foundation for the seismic hazard assessment.

The work in this study, allow us to refine the seismogenic source model which directly affects the accuracy and the reliability of the national seismic hazard assessment, thereby contributing to the development of national annexes.

References

[1] International Seismological Centre (20XX), On-line Bulletin, https://doi.org/10.31905/D808B830

[2] Michele Caputo, Comparison of five independent catalogues of earthquakes of a seismic region, Geophysical Journal International, Volume 143, Issue 2, November 2000, Pages 417–426, https://doi.org/10.1046/j.1365-246X.2000.01235.x

[3] Lenhardt, W., Svancara, J., Melichar, P., Pazdirkova, J., Havir, J. and Sykorova, Y. (2007). "Seismic activity of the Alpine-Carpathian-Bohemian massif region with regard to geological and potential field data". Geologica Carpathica, 58, 397-412

[4] Grünthal, G. and GSHAP Region 3 Working Group (1999). "Seismic hazard assessment for central, north and northwest Europe: GSHAP Region 3". Annali di Geofisicia 42, 999-1011

[5] Catalogue of earthquakes, Seismological Observatory, Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University, Skopje, 2024 (in publishing)

[6] Jordanovski, Lj., Pekevski, L., Chejkovska, V., Chernih, D., Hristovski, B., and N. Vasilevski, 1998, Fundamental Characteristics of the Seismicity of the Territory of the Republic of Macedonia, Skopje, "Ss. Cyril and Methodius" University, Faculty of Natural Sciences and Mathematics, Seismological Observatory. (292 pages with maps and tables; ISBN 9989-631-01-8.) (in Macedonian)

[7] Čejkovska, V., et al. (2016) Report under the project of the Institute for Standardization of the Republic of Macedonia titled 'National Annexes for the Eurocodes'. Skopje: Institute for Standardization of the Republic of Macedonia (in Macedonian)

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.136

[8] Čejkovska, V., 2006-2007: Empirical relations of seismic moment and earthquake moment magnitude to earthquake local magnitude for the Vardar and West Macedonia seismic zones, Contributions, Sec. Math. Tech. Sci., MANU, XXVII-XXVIII, 1-2, pp.93-115 (in Macedonian)

[9] Grünthal, G. and Wahlström, R. (2012) 'The European-Mediterranean Earthquake Catalogue (EMEC) for the last millennium', Journal of Seismology, 16(4), pp. 535–570. doi: 10.1007/s10950-012-9302-y

[10] Markušić, S., Gülerce, Z., Kuka, N., Duni, L., Ivančić, I., Radovanović, S., Glavatović, B., Milutinović, Z., Akkar, S., Kovačević, S., Mihaljević, J., and Šalić, R. (2016) 'An updated and unified earthquake catalogue for the Western Balkan Region', Bulletin of Earthquake Engineering, 14(1), pp. 321–343. doi: 10.1007/s10518-015-9833-z

[11] Baba, A. B., Papadimitiou, E., Papazachos, B. C., Papaioannou, C. A., and Karakostas, B. G.: Unified local magnitude scale for earthquakes of south Balkan area, Pure Appl. Geophys., 157, 765–783, 2000

[12] Bayliss, T. J. and Burton, P. W. (2007) 'A new earthquake catalogue for Bulgaria and the conterminous Balkan high hazard region', Natural Hazards and Earth System Sciences, 7(3), pp. 345–359. doi: 10.5194/nhess-7-345-2007

[13] Roumelioti, Z., Kiratzi, A., and Benetatos, C. (2009) 'The instability of the Mw and ML comparison for earthquakes in Greece for the period 1969 to 2007', Journal of Seismology, 14(2), pp. 309–337. doi: 10.1007/s10950-009-9167-x

[14] Konstantinou, K. I. and Melis, N. S. (2017) 'The relationship between local and moment magnitude in Greece during the period 2008–2016', Pure and Applied Geophysics, 175(4), pp. 851–871. doi: 10.1007/s00024-017-1750-4

[15] Rovida A., Antonucci A., Locati M. (2022). The European Preinstrumental Earthquake Catalogue EPICA, the 1000–1899 catalogue for the European Seismic Hazard Model 2020. Earth System Science Data. https://doi.org/10.5194/essd-14-5213-2022

[16] International Seismological Centre (20XX), ISC-GEM Earthquake Catalogue, https://doi.org/10.31905/d808b825

[17] Storchak, D.A., D. Di Giacomo, I. Bondár, E.R. Engdahl, J. Harris, W.H.K. Lee, A. Villaseñor and P. Bormann (2013). Public Release of the ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009). Seism. Res. Lett., 84, 5, 810-815, doi: 10.1785/0220130034

[18] Storchak, D.A., D. Di Giacomo, E.R. Engdahl, J. Harris, I. Bondár, W.H.K. Lee, P. Bormann and A. Villaseñor (2015). The ISC-GEM Global Instrumental Earthquake Catalogue (1900-2009): Introduction, Phys. Earth Planet. Int., 239, 48-63, doi: 10.1016/j.pepi.2014.06.009

[19] Di Giacomo, D., E.R. Engdahl and D.A. Storchak (2018). The ISC-GEM Earthquake Catalogue (1904–2014): status after the Extension Project, Earth Syst. Sci. Data, 10, 1877-1899, doi: 10.5194/essd-10-1877-2018

[20] Baker, J.W., Bradley, B.A. and Stafford, P.J., 2021. Seismic Hazard and Risk Analysis. Cambridge: Cambridge University Press. DOI: 10.1017/9781108425056

[21] Mulargia F, Gasperini P, Tinti S (1987) Contour mapping of Italian seismicity. Tectonophysics 142:203–216

[22] Gasperini, P. and Ferrari, G. (2000). "Deriving numerical estimates from descriptive information: the computation of earthquake parameters". In Catalogue of Strong Italian Earthquakes from 461 B.C. to 1997, Annali di Geofisica, Vol. 43, N.4, 729-746

[23] Stepp, J. C. (1971). "An investigation of earthquake risk in the Puget Sound area by the use of the type I distribution of largest extreme". PhD thesis. Pennsylvania State University (cited on pages 9, 25–27)

[24] Weatherill, G. A. (2014) OpenQuake Hazard Modeller's Toolkit- User Guide. Global Earthquake Model (GEM). Technical Report

[25] Danciu L., Nandan S., Reyes C., Basili R., Weatherill G., Beauval C., Rovida A., Vilanova S., Sesetyan K., Bard P-Y., Cotton F., Wiemer S., Giardini D. (2021) - The 2020 update of the European Seismic Hazard Model: Model Overview. EFEHR Technical Report 001, v1.0.0, https://doi.org/10.12686/a15

[26] Stiphout, T. van, J. Zhuang, and D. Marsan (2012). Theme V-Models and Techniques for Analysing Seismicity. Technical report. Community Online Resource for Statistical Seismicity Analysis. URL: http://www.corssa.org (cited on page 22)

DOI: https://doi.org/10.5592/CO/3CroCEE.2025.136

[27] Gardner, J. K. and L. Knopoff (1974). "Is the sequence of earthquakes in Southern California, with aftershocks removed, Poissonian?" In: Bulletin of the Seismological Society of America 64.5, pages 1363–1367 (cited on pages 9, 22–24)

[28] Uhrhammer, R. (1986). "Characteristics of Northern and Central California Seismicity". In: Earthquake Notes 57.1, page 21 (cited on pages 22, 23)

[29] Dumurdzanov N., Serafimovski T., Burchfiel B. C., Evolution of the Neogene–Pleistocene Basins of Macedonia, Geological Society of America Digital Map and Chart Series 1 (accompanying notes), 2004

[30] Dumurdzanov N., Serafimovski T., Burchfiel B. C., Cenozoic tectonics of Macedonia and its relation to the South Balkan extensional regime, Geosphere, v.1 n.1, 2005

[31] Matev K., GPS constrains on current tectonics of southwest Bulgaria, northern Greece, and Albania, PhD thesis, Universite de Grenoble, 2006

[32] Burchfiel B. C., Nakov R., Dumurdzanov N., Papanikolaou D., Tzankov T., Serafimovski T., King R. W., Kotzev V., Todosov A., Nurce B., Evolution and dynamics of the Cenozoic tectonics of the Southern Balkan extensional system, Geosphere, v. 4 n. 6, pp. 919–938, 2008

[33] N D'Agostino, A Copley, J Jackson, R Koçi, A Hajrullai, L Duni, N Kuka, Active tectonics and fault evolution in the Western Balkans, *Geophysical Journal International*, Volume 231, Issue 3, December 2022, Pages 2102–2126, https://doi.org/10.1093/gji/ggac316

[34] Arsovski M., Hadzievski D., Correlation between neotectonics and the seismicity of Macedonia, Tectonophysics, vol. 9, pp. 129-142, 1970

[35] Jovanov Lj., Contemporary tectonic and seismic characteristics of the territory of the republic of North Macedonia and neighboring regions, MSc. Thesis, Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University, Skopje, 2024 (in Macedonian)

[36] Drogreshka K., Use of the dislocation theory in defining the epicentral areas and tectonic conditions in the territory of the Republic of Macedonia, Skopje, 2018 (in Macedonian)

[37] Petkovski R., Seismotectonic characteristics of Macedonia, Phd. Thesis, Faculty of Mining and Geology, University of Belgrade, Belgrade, 1992 (in Serbo-Macedonian)