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SEISMOGEOLOGICAL EFFECTS OF STRONG EARTHQUAKES ($M_L \geq 6.0$) AT THE TERRITORY OF THE REPUBLIC OF NORTH MACEDONIA

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A b s t r a c t: Earthquakes are natural processes that, depending on their magnitude, can generate significant seismogeological effects on the Earth's surface as well as within the shallow subsurface environment. This paper focuses on the identification and analysis of seismogeological effects caused by strong earthquakes with magnitudes $M_L \geq 6.0$, whose epicenters are located within the territory of the Republic of North Macedonia. The study considers the consequences of earthquake activity, including the activation of faults, landslides, soil liquefaction, ground cracks, and changes in hydrogeological conditions. Particular emphasis is placed on the relationship between the geological structure, lithological characteristics, and local site conditions, and their influence on earthquake intensity and the spatial distribution of the observed effects. Based on seismological data and geological indicators, this research highlights the importance of seismogeological investigations for seismic risk assessment and geohazard evaluation. The obtained results are of considerable importance for spatial planning and for reducing the potential impacts of future earthquakes.

Key words: earthquake; intensity; seismogeological effects

1. INTRODUCTION

Earthquakes are among the most significant natural disasters and cannot be predicted with sufficient accuracy in terms of their location, time, or magnitude. They represent major geodynamic processes through which the Earth's tectonic activity is expressed. Their occurrence is directly related to the accumulation of energy within the Earth's interior and the activation of fault dislocations, which leads to the generation of seismic waves that propagate through the Earth and cause various changes in the natural environment (Arsovski, 1996).

In addition to their direct impact on infrastructure and population, earthquakes also produce numerous seismogeological effects on the surface and within the shallow subsurface environment. Seismogeological effects represent physical and morphological changes in the geological environment that occur as a consequence of strong seismic motion. These effects may manifest as ground fissures, landslides, liquefaction, as well as changes in hydrogeological conditions, including variations in groundwater levels or the appearance of new sources. The intensity and spatial distribution of these phenomena depend on the magnitude and depth of the earthquake, the distance from the epicenter, as well as on the local geological and geomorphological conditions.

The territory of the Republic of North Macedonia is located in the central part of the Balkan Peninsula and has a complex geological and structural framework. Structurally, the territory is modeled into two uplifted blocks – Western Macedonia and Eastern Macedonia – and one subduction block known as the Vardar zone (Arsovski and Hadžievski, 1970). This morphostructural division is the result of long-term tectonic processes, including compression, extension and fault tectonics (Drogreshka et al., 2024). The diversity in the geological division reflects the complex tectonic history of the region and provides a basis for the analysis of the geodynamic processes and seismological characteristics of the territory (Dumurdžanov et al., 2005). The seismotectonic framework of the region is further constrained the receiver function method, which reveals significant lateral variations in crustal thickness and internal structure, especially across the Vardar Zone and adjacent tectonic units (Najdovska, 2018, Najdovska and Drogreška, 2025). These variations are closely related to the distribution of seismic zones and play an important role in controlling the localization and propagation of seismic energy, while simultaneously influencing the propagation of seismic waves and contributing to differences in the intensity and spatial distribution of seismogeological effects.

The territory of the Republic of North Macedonia is also characterized by relatively high seismic activity, as evidenced by several strong earthquakes that have produced significant seismogeological effects.

SEISMICITY OF THE TERRITORY OF NORTH MACEDONIA

The territory of the Republic of North Macedonia and neighboring countries are within a prominent active seismic area of the Balkan Peninsula, exposed to earthquakes from seismically active areas.

The spatial distribution of earthquakes for the analyzed period (1901–2023) is presented on the epicentral map. In addition to earthquakes with epicenters located within the territory of the Republic of North Macedonia, the analysis also includes earthquakes from neighboring border regions. Although these events are located outside the national territory they belong to the same or related seismotectonic zones and have a direct influence on local seismicity and seismic hazard.

The total number of recorded and located earthquakes amounts to 33 853 events (Figure 1).

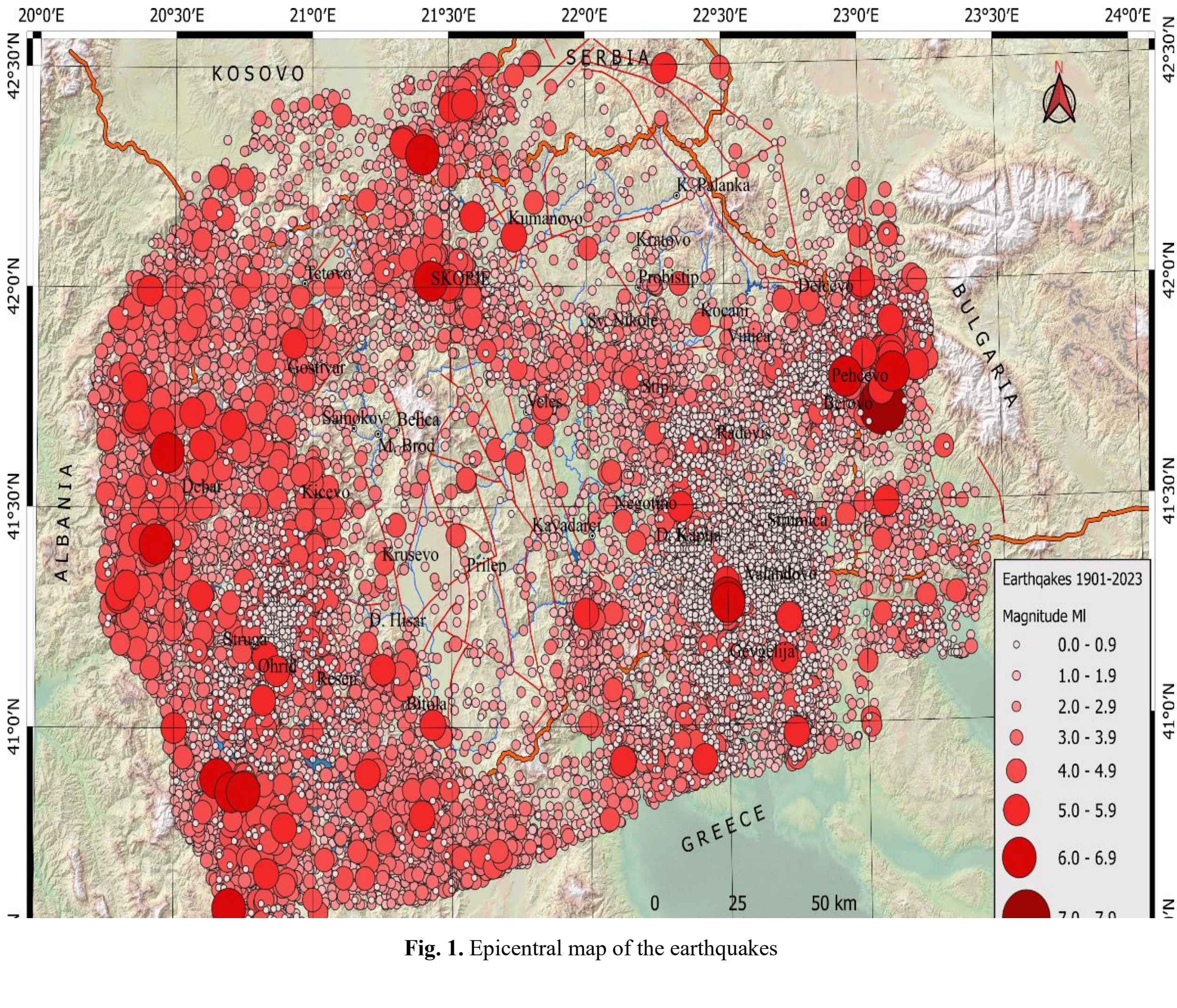

Fig. 1. Epicentral map of the earthquakes

The present seismic activity in the territory of the Republic of North Macedonia, according to the data sources available to the Seismological Observatory at the Faculty of Natural Sciences and Mathematics, Ss. Cyril and Methodius University, Skopje, is due to the permanent different intensities of movements of the higher order tectonic units within the three seismic zones: West-Macedonian, Vardar and East-Macedonian seismic zone (Figure 2). These seismic zones in the North Macedonia are only the segments of the much larger seismic lineaments, which stretch through the Balkan region. The most active part in these three zones with respect to the number and released earthquake energies are the suture junction zones of the faults with different length and orientations.

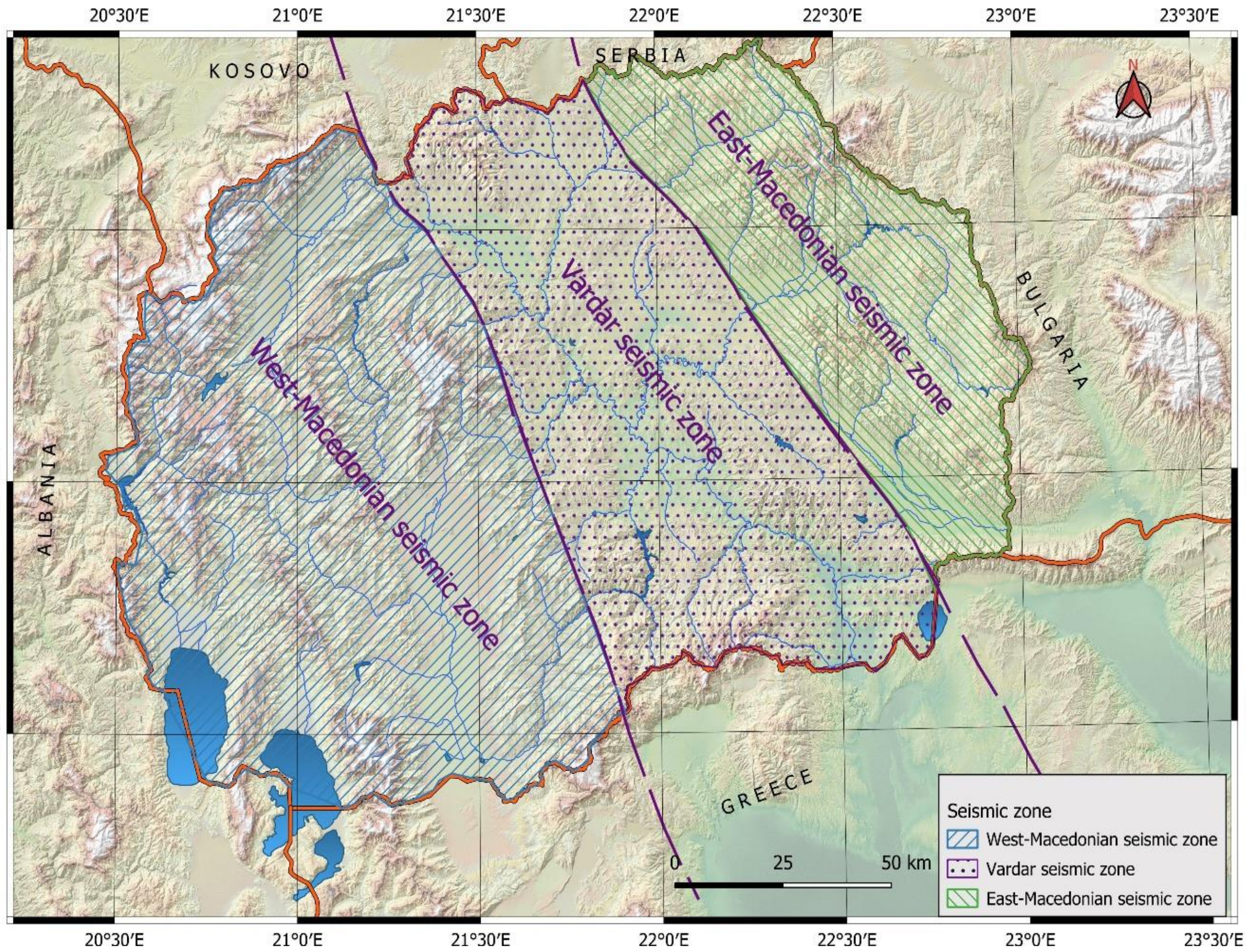

Fig. 2. Seismic zones of the Republic of North Macedonia

Each of these zones is characterized by a specific temporal and spatial distribution of earthquake locations, with frequent seismic microactivity and a significant number of smaller ($2.0 \leq M_L \leq 3.0$) to weak ($3.0 \leq M_L \leq 4.0$) earthquakes, but also the occurrence of moderate to strong earthquakes ($5.0 \leq M_L \leq 7.8$) (Drogreshka et al., 2026).

In the histogram presentations (Figures 3, 4, 5) the distribution of earthquakes for each seismic zone are shown for the period 1901–2023, according to magnitude intervals of one degree on the Richter scale.

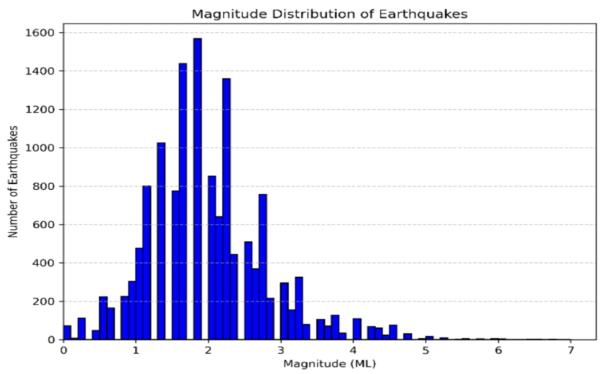

Fig. 3. Magnitude distribution of earthquakes for West-Macedonian seismic zone

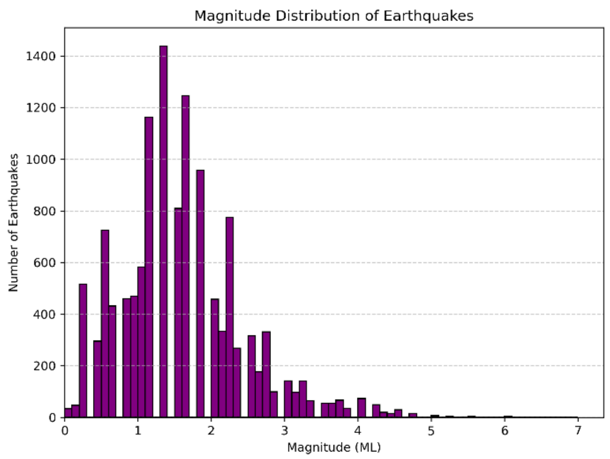

Fig. 4. Magnitude distribution of earthquakes for the Vardar seismic zone

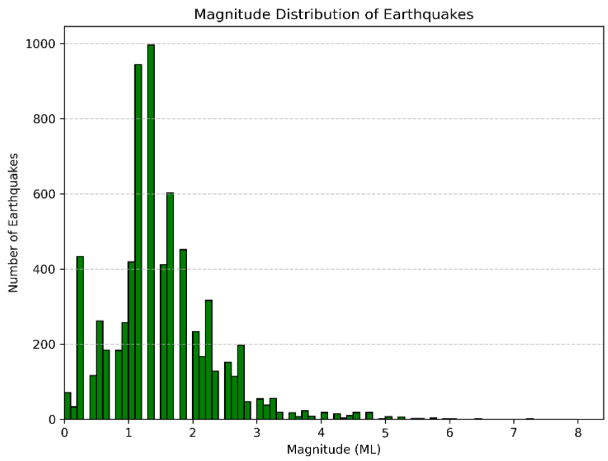

Fig. 5. Magnitude distribution of earthquakes for the East-Macedonian seismic zone

In each of the seismic zones, a certain regularity can be observed in the release and attenuation of seismic energy, as well as a specific distribution of earthquake hypocenters (Figure 6). In all seismic zones, a shallow distribution of earthquake hypocenters predominates, generally ranging from 5 km to 40 km, and most commonly between 10 km and 25 km. This indicates that the seismicity of the territory of North Macedonia is related to deformations in the upper parts of the lithosphere, more specifically to the fracturing and deformation of the Earth's crust caused by tectonic movements (Dumurdžanov et al., 2004; Burchfiel et al., 2006). The maximum seismic intensity on the territory of Macedonia is *X* degrees according to EMS-1998 (European Macroseismic Scale), determined for several strong earthquakes.

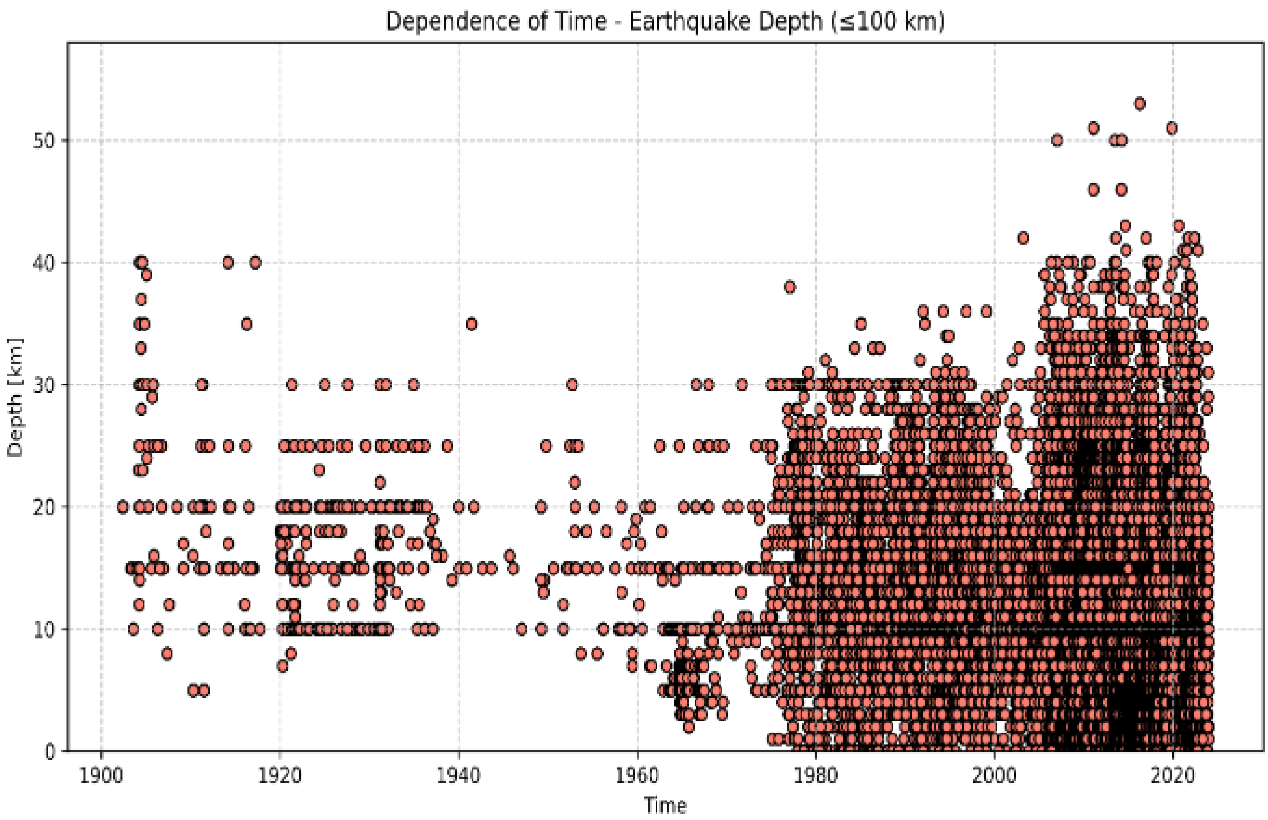

Fig. 6. Distribution of earthquakes by depth

HISTORY OF EARTHQUAKES WITH SEISMOGEOLOGICAL EFFECTS

Several strong earthquakes that caused significant seismogeological effects occurred on the territory of North Macedonia in the period 1901–2023. These are earthquakes whose epicenters belong to the Pehčevo-Kresna epicentral area (1904), the Valandovo epicentral area (1931), the Skopje epicentral area (1963), and the Debar epicentral area (1967) (Poceski, 1969; Sulstarova, 1980; Hadžievski, 1981; Jordanovski et al., 1998; Ambraseys, 2001; Milutinović et al., 2017; Drogreshka et al., 2026).

Earthquake Pehčevo – Kresna 1904, $M_L = 7.8$, I_{max} = X EMS-1998

It is the strongest modern earthquake on the mainland of the Balkan Peninsula with an epicenter between the cities of Pehčevo and Kresna (Bulgaria). Several settlements on the territory of North Macedonia suffered great destruction: Pehčevo, Kočani, Berovo, the villages of Sušica, Gabrovo, Ratevo, Razlovci, Trabotivište, Stamer, Zvegor, Blatec, Laki, etc.

Seismic deformations on the Earth's surface are several large cracks in the mountains around Pehčevo; at the foot of Pirin Mountain, the appearance of a wide and long crack; the appearance of cracks in alluvial and other soils, but also in rocks; in the wider area of the epicentral zone, in the vicinity of Kočani, the appearance of hot and cold water springs, which disappeared after a short time; in Kočansko Pole, the appearance of many cracks, the flow of water from the surrounding hills that flooded parts of the villages in the field, and then receded; in the vicinity of Štip, the earthquake caused trees to fall, large cracks appeared in the soil, from which water gushed high up (according to some reports, up to 100 m). Near the village of Dren, a hill fell during the earthquake, which has since been called the Torn Hill. In many settlements, the appearance of liquefaction has been determined. Liquefaction effects were observed along the courses of the Bregalnica, Struma, Rilska rivers, some parts of the Vardar river, the Morava river, but also some other smaller rivers in the region. There is data that 12 km from Kočani, near the villages of Jakimovo and Oblešsevo, geysers appeared that ejected groundwater 2 – 3 m in height, but also data that southeast of Blagoevgrad (Bulgaria), hot water springs appeared that caused the melting of large areas under snow in the higher surrounding regions. Liquefaction effects were also observed in some larger settlements such as Kočani, Delčevo, Demir Kapija, Negotino, etc.

Earthquake Valandovo 1931, $M_L = 6.7$, I_{max} = X EMS-1998

The strong earthquake of March 8, 1931, with its epicenter in the Valandovo area, represents one of the most destructive seismic events in our territory. Its consequences were reflected in significant human losses and extensive material damage. High-intensity destruction was also recorded in the wider surroundings, including the Gevgelija and Strumica regions, as well as parts of the Kavadarci and Štip areas, where numerous residential and public buildings, along with infrastructure (bridges, railway lines, and other public facilities), were damaged. In addition to material damage, the earthquake caused pronounced seismogeological effects, indicating a severe disturbance of the natural balance of the terrain. The most characteristic were ground fissures that appeared in multiple locations (Pirava, Valandovo, Josifovo, the Strumica field, and along the Gevgelija–Bogdanci and Strumica–Radoviš routes), some of which reached considerable dimensions and were accompanied by the eruption of water, sand, and mud. Liquefaction phenomena were observed in the village of Pirava and along the stretch between Bogdanci and Gevgelija, while ground subsidence was recorded in Pirava and Valandovo. Landslides and rockfalls were registered, particularly in hilly and mountainous areas (Pirava, Gradec, Klisura, Sermenin), in some cases leading to blocked roads and damage to railway infrastructure.

Significant changes were also observed in hydrogeological conditions. These included the drying up of wells and springs, the emergence of new springs (especially mineral and thermal ones), water turbidity, and variations in the temperature of thermal waters. In Negorci Spa, an increase in both water temperature and discharge was recorded, while in other areas there was a temporary disappearance of water resources.

Earthquake Skopje 1963, $M_L = 6.1$, I_{max} = IX EMS-1998

The strong earthquake, with a maximum intensity of *IX* on the EMS-1998 scale in three main areas (central Skopje, the municipality of Petrovec, and the northern surroundings of the city), represents one of the most significant seismic events in the region. Besides the catastrophic damage to buildings and the numerous human losses, it also caused pronounced seismogeological changes in the epicentral area and its wider surroundings.

In the Skopje valley, ground fissures appeared in alluvial soils, ranging from 1 to 10 cm in width and up to several tens of meters in length, most commonly along the course of the Vardar river and at various locations, including Kale, Mojanci, Dolno Nerezi, Šuto Orizari, Gluvo, Čučer, Kučevište, Mirkovci, Creševo, Trubarevo, Jurumleri, Dolno Lisiče, Dračevo, Studeničani, Belimbegovo, Marino, Kadino, Idrizovo, Čojlija, Petrovec, Ržaničino, Bunardžik, Ajvatovci, Taor, Gradmanci, Divlje, Brazda, Katlanovo, and Zlokućani. No fissures were observed in solid rock masses. Landslides and rockfalls were also recorded, particularly in hilly and mountainous areas, locally causing terrain instability and blocking certain routes, with the most pronounced occurrences identified on the slopes of Kale and in the Mojanci area.

The earthquake also triggered significant hydrogeological changes, manifested through the emergence of water (in the village of Zlokućani), turbidity in wells (in Brazda), splashing in reservoirs, and changes in the discharge and temperature of thermal and mineral springs. In Katlanovo, an increase in the discharge of four springs was recorded, along with a rise in water temperature of about 3°C. Liquefaction was observed in the northeastern parts of the city, particularly in the village of Trubarevo.

IDENTIFICATION OF AREAS SUSCEPTIBLE TO SEISMOGEOLOGICAL EFFECTS

The intensity of an earthquake and the spatial distribution of seismogeological effects are strongly controlled by geological structure, lithological composition, and local site conditions. Each environment responds differently to seismic activity and may amplify seismogeological effects compared to the baseline geological setting (i.e., hard or consolidated rock masses).

In unconsolidated sediments, particularly alluvial deposits, the amplification of seismic effects relative to the underlying geological medium can reach several degrees according to EMS-1998, indicating greater susceptibility to ground deformation processes such as landslides, rockfalls, ground cracking, and liquefaction. In contrast, consolidated rocks generally exhibit lower susceptibility to ground deformation processes (Mitrov, 1976).

The earthquakes considered in this study, together with their associated seismogeological effects, have intensities of *IX* and *X* according to EMS-1998. Their epicenters are located in seismically sensitive environments prone to ground deformation processes. The high intensity levels and the spatial distribution of epicenters within such environments are associated with a wide range of effects, including hydrological changes, landslides and rockfalls, ground ruptures, and liquefaction phenomena.

At such levels of seismic intensity, the occurrence of pronounced deformations and disturbances in the natural environment represents a typical and expected response, strongly controlled by the local geological and geotechnical conditions (Čejkovska, 2011).

The faults responsible for these earthquakes belong to the group of active faults characterized by frequent occurrence of weak to moderately strong earthquakes ($2.0 \leq M_L \leq 6.0$), and occasional occurrence of very strong earthquakes ($M_L \geq 6.1$). These include the Elbasan–Debar, Skopje–Kyustendil, Valandovo, and Berovo–Krupnik fault systems, all of which have the capacity to accumulate energy for strong seismic events (Shyqyri, 2021; Čejkovska, 1995; Drogreška and Jovanov, 2026).

The integration of seismological data with geological and lithological characteristics provides a solid basis for identifying areas with increased exposure to seismogeological effects, contributing to a more accurate assessment of seismic risk and the development of appropriate mitigation measures and spatial planning strategies.

The identification of areas exposed to seismogeological effects was carried out exclusively on the basis of the recorded seismogeological phenomena caused by the considered earthquakes. The analysis is based on the spatial distribution of the observed effects such as landslides, liquefaction, surface cracks and other deformations of the terrain. These areas are characterized by an increased probability of the occurrence and recurrence of seismogeological effects during future seismic events (Figure 7).

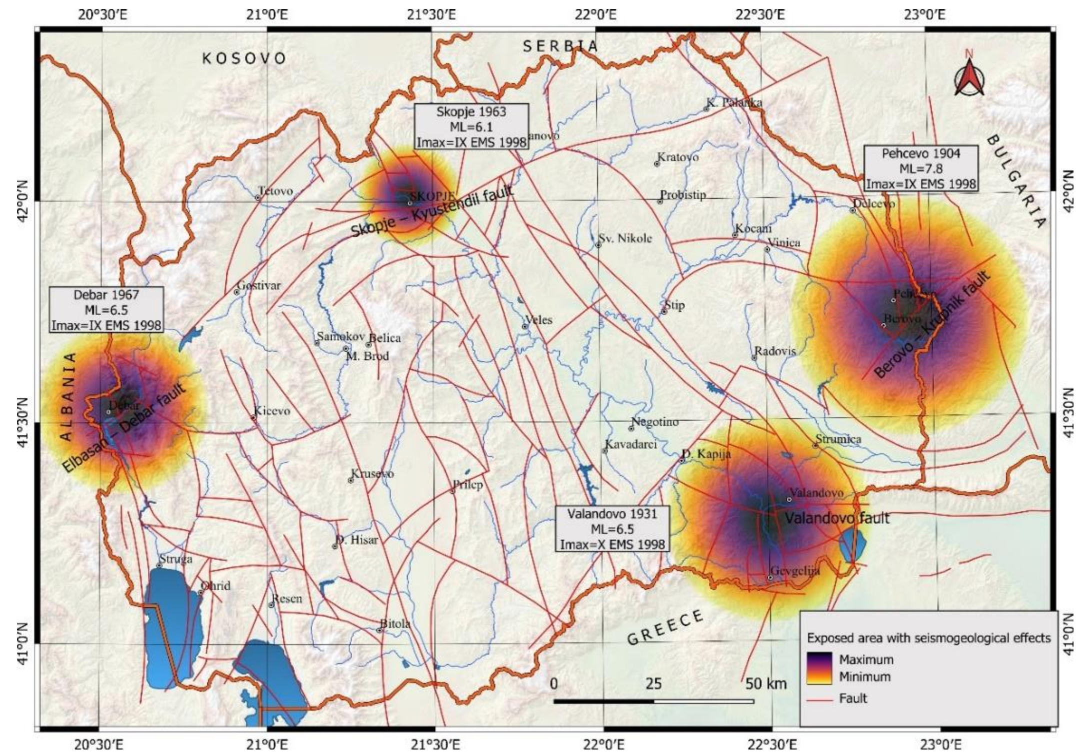

Fig. 7. Areas affected by seismogeological effects associated with earthquakes of $M_L \geq 6.0$ in the Republic of North Macedonia

CONCLUSION

The territory of the Republic of North Macedonia is characterized by complex geological and tectonic conditions, as well as relatively high seismic activity, resulting in the frequent occurrence of moderate to strong earthquakes. Earthquakes with $M_L \geq 6.0$ indicate that seismogeological effects are a common consequence of strong seismic events.

The spatial distribution of these seismogeological effects enables the identification of exposed areas, whose susceptibility depends on the geological and lithological characteristics of the terrain. Therefore, the integration of seismological data with geological and lithological information provides a reliable framework for identifying zones of increased exposure and for understanding the spatial distribution of earthquake-induced effects.

This approach improves seismic hazard assessment and supports more effective spatial planning and mitigation strategies aimed at reducing future earthquake impacts.

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Р е з и м е

СЕИЗМОГЕОЛОШКИ ЕФЕКТИ НА СИЛНИ ЗЕМЈОТРЕСИ ($M_L \geq 6.0$) НА ТЕРИТОРИЈАТА НА РЕПУБЛИКА СЕВЕРНА МАКЕДОНИЈА

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Клучни зборови: земјотрес, интензитет, сеизмогеолошки ефекти

Земјотресите претставуваат природни процеси кои во зависност од нивната јачина честопати предизвикуваат сеизмогеолошки ефекти врз површината, но и плитката подземна средина на Земјата. Овој труд е фокусиран на идентификација на сеизмогеолошките ефекти предизвикани од умерено силни до силни земјотреси со ML ≥ 6.0 чии епицентри се наоѓаат на територијата на Република Северна Македонија.

Во студијата се разгледуваат последиците од активноста на земјотресите, вклучувајќи ги активирањето на раседите, лизгањето на земјиштето, втечнувањето на почвата, пукнатините на земјиштето и промените во хидрогеолошките услови. Особен акцент е ставен на односот помеѓу геолошката структура, литолошките карактеристики и локалните услови на локацијата, како и нивното влијание врз интензитетот на земјотресот и просторната распределба на набљудуваните ефекти.

Преку сеизмолошките податоци и геолошките индикатори, трудот ја истакнува важноста на сеизмогеолошките истражувања за процена на сеизмичкиот ризик и геохазардите, а добиените резултати се од суштинско значење за просторното планирање и намалувањето на штетните последици од идни земјотреси.