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THE CAUSES AND MECHANISM OF EARTHQUAKES IN CROATIA IN THE MODERN PERIOD – AN EDUCATIONAL PERSPECTIVE

Abstract: *Earthquakes are among the most devastating and worst natural disasters on Earth. Due to their extremely negative effects, they are the topic of extensive scientific research on a global scale. There is a special branch of geophysics that studies earthquakes called seismology. Due to the overall scientific progress made in the past two centuries, geoscientists have developed revolutionary knowledge about the structure, composition, and dynamics of our planet and the associated earthquake causes and mechanisms of their origin. These findings are of utmost importance in terms of protecting buildings and people from natural disasters. Currently, the origin of earthquakes is explained at a satisfactory level within neomobilism based on the theoretical concept of plate tectonics. A great contribution to the study of earthquakes was also made by Croatian science through the work of Andrija Mohorovičić, a world-renowned geophysicist. His work and the efforts of other Croatian seismologists stem from the fact that significant parts of the Croatian territory are located in seismically active areas. As a result, there have been several devastating earthquakes in the territory in the past, and there is a high probability that they will occur in the future. They are a consequence of the movement of the African tectonic plate (and the Adriatic microplate, located in its periphery) toward the Eurasian tectonic plate. It is precisely because of the collision of these tectonic plates that a large amount of energy is released in the lithosphere to manifest itself in the form of earthquakes. Although modern science has managed to understand the mechanism that generates earthquakes, the geographical distribution of earthquake zones in the world, and the seismicity of certain parts of the world, it is still not possible to predict the moment when earthquakes will occur. Therefore, research, aided by today's fascinating scientific development and technical and technological progress, continues with undiminished intensity. This paper presents essential findings about the most devastating earthquakes in Croatia in the modern period as well as about the mechanism that generates earthquakes in the Croatian territory. Different insights about the main earthquake zones in Croatia were also analyzed along with the representation of earthquake-related teaching material for primary school students with an emphasis on earthquakes in the territory of Croatia.*

Keywords: *seismism, tectonics, Earth*

INTRODUCTION

Earthquakes are natural phenomena with an exclusively negative impact on human society. They present an occasional phenomenon whose devastating consequences still have not been successfully resolved by modern humans, despite thorough scientific research. Humans have been confronted with earthquakes since the very beginnings of evolution, and thus, with the dawn of the first civilizations, the first interpretations of the mechanisms of earthquake origin occurred. The ancient Greeks believed that earthquakes were related to the wrath of the god of the sea Poseidon, who would cause earthquakes by striking the ground with a trident. Hindu mythology attributed the occurrence of earthquakes to the elephant and turtle carrying the world on their backs, while the great monotheistic religions attributed earthquakes (especially those of catastrophic proportions) to the wrath of God caused by human religious and ethical deviations.

Since the 19th century and the emergence of modern science, interpretations of the mechanism of earthquake origin have passed into the domain of human rationality. Although many elements of earthquake occurrence are known today, along with partially effective ways of reducing their negative effect (primarily through choosing the appropriate method of construction), science still cannot predict the moment of earthquake occurrence. However, despite the accumulated knowledge and insights about the mechanism of earthquake origin and the causes of earthquakes, traditional interpretations that look for the causes of earthquakes in other natural phenomena, such as droughts, floods, or global climate change, still exist. There are various unscientific and pseudoscientific “theories” supported by wide circles of the average and below-average educated population and rapidly spreading thanks to modern digital technology (various websites, online platforms, and social media).

This paper presents modern scientific knowledge about the mechanism of earthquake origin and the causes of earthquakes from a global and national perspective. This is an essential topic for Croatia, a country that recently suffered several extremely strong earthquakes with devastating consequences. In some parts of the world, earthquakes occur less frequently, and in other parts of the world, they occur continuously. Why is that so? What is the main reason for earthquake occurrence, and how does the mechanism of earthquake origin work? What causes earthquakes in Croatia, and what are the main earthquake zones in the Croatian territory?

The answers to these questions and the analysis of modern knowledge about the causes of earthquakes were also provided from the point of view of the curriculum for natural science subjects in Croatian primary schools. One of the goals of this paper is to present content that can serve to deepen general knowledge about earthquakes. A special focus was placed on the analysis of the causes and mechanisms of earthquakes in Croatia, the analysis of the largest historical earthquakes in the area of today’s Croatia, and the identification of modern earthquake zones in the Croatian territory.

This paper aims to provide an overview of the causes and mechanisms of earthquakes in Croatia using relevant scientific literature. The compilation method was primarily used but was also combined with other scientific methods: analysis and synthesis, induction and deduction, abstraction and concretization, and genetic methods.

ANALYSIS OF THE CURRICULUM OF NATURE AND SOCIAL SCIENCES AND THE CURRICULUM OF GEOGRAPHY WITH A FOCUS ON EARTHQUAKES

Primary school students are offered basic scientific knowledge about earthquakes in the school subjects of *Nature and Social Sciences* (in lower grades) and *Geography* (in higher grades).

Although earthquakes are rarely mentioned in lower grades of primary school, they are an essential topic for Croatian society because every lower-grade student should be familiar with them in an age-appropriate way. In some teaching units of *Nature and Social Sciences*, students are introduced to responsible behavior in critical situations, telephone numbers that need to be used in case of danger, and signs for leaving the school and other facilities in case of danger. Unfortunately, there is no teaching unit that introduces students to the concept of earthquakes, safe procedures during earthquakes, or evacuation plans, which would be very useful. Learning through play is very entertaining, and this is the way students can be instructed on how to safely leave the room, house, building, or other facility in which they may find themselves during an earthquake through an organized evacuation exercise at school. Of course, students should be informed that safe evacuation is not always feasible and that in these situations, where every moment is important, they should find an adequate place in the room where they would be safe. They should also be informed in more detail about such places. There are various myths and misconceptions about earthquakes that would further spark student interest in the topic of earthquakes, which could be discussed in the homeroom class or in the *Nature and Social Sciences* classes.

During primary education, earthquakes are mostly mentioned within the subject *Geography*, where in Grade 5, students become acquainted with the occurrence of earthquakes, procedures and behavior in case of an earthquake, and the relief changes under the influence of internal (endogenous) and external (exogenous) processes of shaping the Earth relief. On the other hand, the same students, within the classes of *Nature*, learn about natural phenomena with high energy, such as strong winds, lightning, earthquakes, volcanic eruptions, and fires.

In Grade 8 in the subject *Geography*, students become acquainted with the type of boundaries of lithospheric plates and areas prone to frequent earthquakes and large eruptions on Earth.

Although this is very useful and interesting information, it would be of great importance if attention would be focused on the Republic of Croatia, where students would be acquainted in more detail with the largest earthquakes in the Croatian territory in the past, the causes and mechanism of earthquakes in Croatia, and the most active seismic areas in the country. The evacuation plan should be organized and implemented every teaching year, as should the information on how to behave, what to do, where to hide to be safe, and which phone number to call in case of emergency.

Therefore, the authors of this paper sought to provide an overview of modern knowledge on general issues of earthquake origin, with a special focus on earthquakes in Croatia. Since understanding the mechanism of earthquake origin requires understanding the basic concepts regarding the structure and composition of the Earth and tectonics (with an emphasis on the tectonics of lithospheric plates), modern insights from these areas are also included in the paper.

THE EARTH STRUCTURE AND COMPOSITION

Research shows that earthquakes often occur as a result of the internal dynamics of our planet, as confirmed by illustrative data from the 2020 seismicity catalog: approximately 350 000 earthquakes were recorded worldwide that year (of which more than 200 000 earthquakes had a magnitude less than 2.0) (Tkalčić, 2022).

Most earthquakes last less than a minute. An earthquake is one of the worst natural disasters that cannot be predicted. Currently, there is growing interest in earthquake research, and a large number of scientists around the world are engaged in it. To understand the mechanism of earthquake origin, one must understand the structure of the Earth.

Our planet formed from a scorching mass approximately 4.5 billion years ago. Gradual cooling of the surface formed parts of the crust that merged and increased over time, thus shaping the continents and oceans (Oluić, 2015).

Scientists have determined that the Earth has a layered (zonal) structure and consists of three parts: the core, the mantle, and the crust.

The deepest layer, with a temperature of up to approximately 5000 °C, is the core, which is divided into internal and external parts and is composed mainly of iron and nickel (Herak, 1990). It is assumed that due to the high temperature but also due to the increase in pressure with depth, the outer core is liquid, and the inner core is solid (Oluić, 2015).

Above the core, there is a mantle that envelops it, and it is divided into lower (reaching from the border with the outer core to a depth of 1000 km), middle (from the border with the lower mantle to a depth of approximately 400 km), and upper mantle (Herak, 1990) layers.

The surface part forms a crust, with an average thickness of 40 km in the continental area and from 10 to 12 km below the ocean. The continental crust is also called granite crust after the main rock from which it is composed, while silicon and aluminum predominate among the elements. The oceanic crust is composed predominantly of basalt, silicon, and magnesium (Herak, 1990).

The Earth's crust and the upper part of the mantle form the *lithosphere* (also called the *tectosphere*), a rocky part exposed to tectonic changes caused by the dynamics of the middle mantle. Namely, the middle mantle in the surface part is in a semimelted state (Herak, 1990), which creates convection currents and provides plastic properties to this part of the mantle, reinforced by differences in temperature between the upper and lower parts (Oluić 2015).

At different depths in the Earth's interior, discontinuities or transition zones separate the layers. They are the boundaries of extreme changes in the speed of the expansion of seismic waves in the Earth's interior. The Wiechert-Oldham-Gutenberg discontinuity is located at a depth of 2900 km and forms the boundary between the lower mantle and the outer core (Herak, 1990). At depths of 30 to 40 km, there is a Mohorovičić discontinuity (Moho discontinuity[1]), which represents the border between

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[1] Named after the Croatian geophysicist Andrija Mohorovičić, who was the first to establish the existence of a sudden transition between the crust and the mantle.

the lighter crust and the heavier and denser mantle. In this transition zone, there are sudden changes in physical quantities, some of which include the density, pressure, and speed of seismic waves (the speed of seismic waves is greater in the area below the Moho discontinuity).

TECTONICS

Today, great importance is attached to tectonics when studying the seismicity of terrain because it is known that earthquakes are primarily the result of tectonic movements inside the Earth. Tectonics is a branch of geology in which spatial shaping and relations between the structural units of the lithosphere are studied. These relationships are the result of the action of endogenous (internal) forces inside the Earth, the most important of which is thermal energy. It is released during the upward movement of lighter elements inside the Earth, slowing down of the Earth's rotation and decaying of radioactive elements (Župan et al., 2019).

The scientific theory based on the interpretation and description of the movement of large parts of the lithosphere is called plate tectonics. The model solution for the movement of tectonic plates (from which the term *mobilist theory* derives) was proposed in 1912 by the German geophysicist Alfred Wegener. He believed that the surface of the Earth consists of oceanic and continental plates that move on a plastic surface. Wegener's theory was met with numerous criticisms, so the mobilist theory was refuted in the following decades. However, it was supplemented in 1962 by the ideas of American geologist Harry Hess and his *neomobilist theory* of plate tectonics, which is universally accepted today. According to this theory, the lithosphere, or the Earth's upper layer, consists of seven larger fragments and a significant number of smaller fragments called tectonic plates. They are in constant motion due to the warmth of the Earth's interior. Thus, the Earth's crust is cracked into larger and smaller tectonic plates separated by regional dislocations. The plates move at different speeds and in different directions, approaching or moving away from each other. On average, the speed of movement of the plates is 2.5 cm per year; thus, the plates gradually connect and separate continents. When the plates collide, large mountain ranges are formed (Oluić, 2015).

There are seven large tectonic plates of different dimensions and shapes: African, Antarctic, Eurasian, Indo-Australian, South American, Pacific, and North American (*Figure 1*). The size of tectonic plates changes over time: depending on the amount of magma, they increase, and in the process of subduction, they decrease. Tectonic plates are in constant motion, forming three types of boundaries between them: divergent (when the plates move away from each other), convergent (when they come together), and transform (when they slide past each other) (*Figure 2*) (Oluić, 2015).

When the plates move away from each other, rifts or grooves are formed: in areas of tension in the Earth's mantle, the tectonic plates overcome the resistance of the rock crust, and the ocean crust cracks and stretches. In convergent boundaries, subduction (diving beneath) of one tectonic plate under another or collision may occur. Subduction occurs when the oceanic crust dives beneath another oceanic or continental crust, while collision occurs when two continental plates collide. This is how volcanic island chains (subduction) or mountain chains (collision) are formed. Translation involves the horizontal shear of two plates that usually move in parallel in opposite directions. Tectonic movements in the interior of the Earth are intense at the edges of large tectonic plates, as this is where the greatest disturbances in the Earth's crust occur. A large amount of energy is released, and earthquakes (in rare cases, volcanic eruptions) also occur as a result (Oluić, 2015).

However, earthquakes do not have to occur only on the edges of plates. They can also appear inside the plates by injecting magma into weakened parts of the plates, i.e., in places of large cracks called faults. In these cases, earthquakes occur along large faults or at intersections of faults of different orientations (Oluić, 2015). Along the fault, the mobility of the terrain is greater, so the effect of earthquakes is stronger in this direction. Otherwise, faults most often appear in groups called *fault systems* and are actually the result of tectonic disturbances of larger (usually regional) dimensions (Herak, 1990).

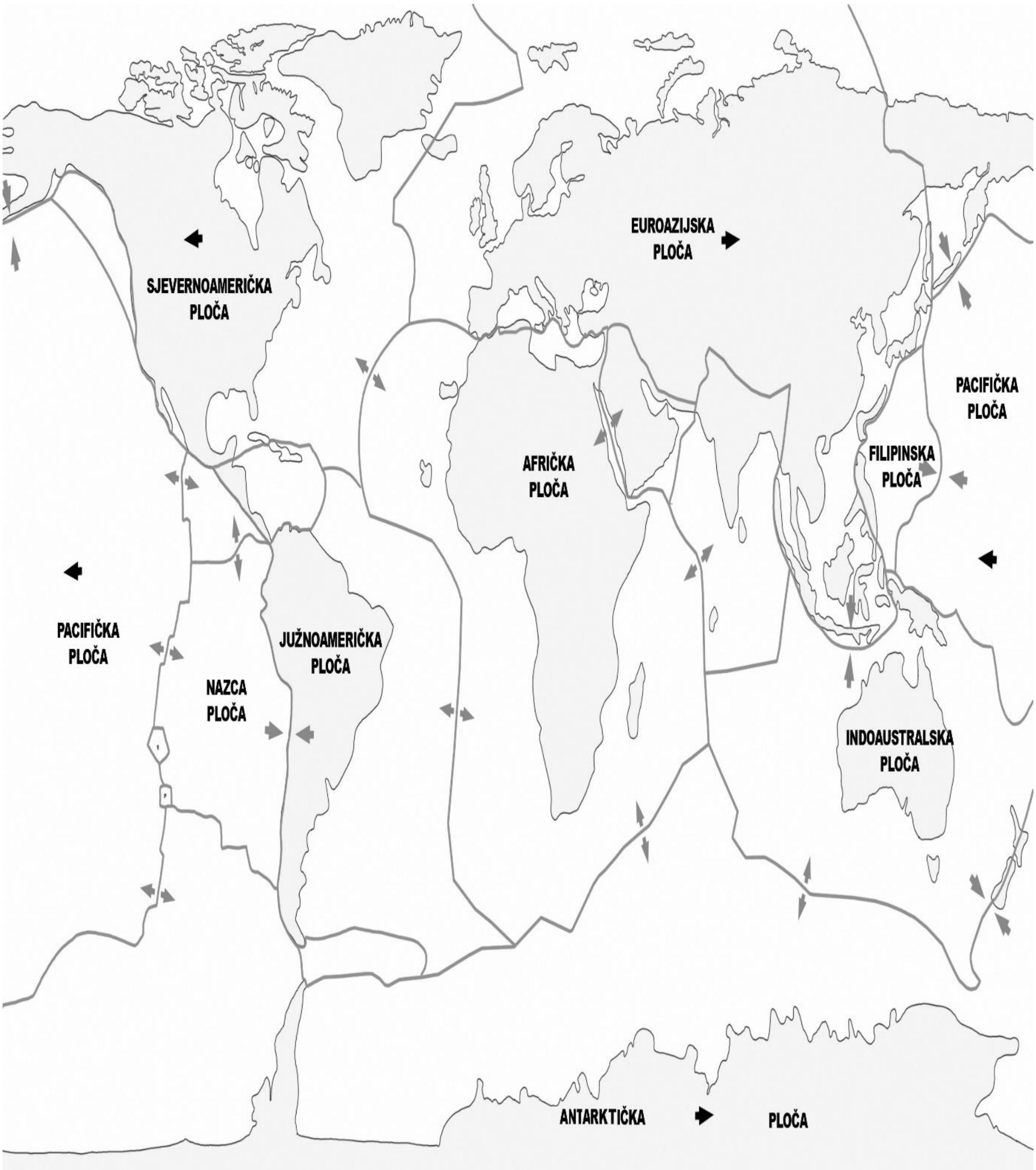

Figure 1. Geographical distribution of large tectonic plates and directions of their movement (source: Herak, 1990)

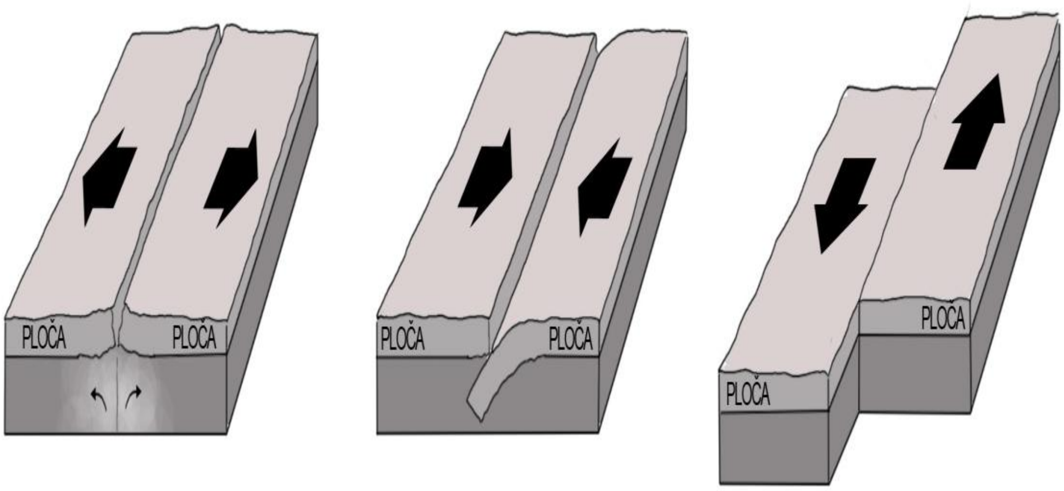

Figure 2. Three modes of tectonic plate movements: divergence, convergence, and translation (source: Herak, 1990)

EARTHQUAKES – THE MECHANISM OF THEIR ORIGIN

The study of earthquakes is called seismology, a branch of geophysics that defines an earthquake as short-term shaking of the ground caused by disturbances and movements in the Earth's crust and lithosphere. These movements are due to the sudden and unexpected release of energy in the lithosphere that creates seismic waves (Humski et al., 2021). Earthquakes can range from weaker ones that cannot even be felt to those whose strength causes great destruction. They cannot be predicted or stopped, and the level of damage caused by an earthquake depends on the depth at which it occurs. On the surface of the Earth, earthquakes are manifested by ground collapse, movement, or shaking; they last for a short time and have a sudden and violent beginning.

A device that automatically detects and records the magnitude, direction, and duration of an earthquake is called a seismograph, and the record that a seismograph produces is called a seismogram.

Earthquakes occur in the Earth's interior at a point called the *hypocenter* (focus). On the other hand, the *epicenter* is the point on the surface of the Earth where the earthquake is most strongly felt. The hypocenters are located at depths greater than 700 km. In shallow earthquakes, the hypocenter is between Mohorovičić's discontinuity and the Earth's surface; otherwise, it is deeply focal (Obradović and Šarko, 2021).

From the hypocenter, the seismic waves spread to all sides. There are two groups of seismic waves, depending on the velocity and mode of propagation. These are *body* waves, which are created in the hypocenter and move toward all sides within the body of the Earth, and *surface* waves (which travel at the Earth's surface and are created by the interaction of body waves).

Body waves are further divided into longitudinal and transverse waves. Longitudinal or primary waves (P-waves) propagate the fastest and most rapidly in the direction of their propagation. They cause the clamping and stretching of substances through which they pass and can spread through solid, liquid, and gaseous substances. Transverse or secondary waves (S-waves) propagate only through the solid, and their flicker is perpendicular to the direction of energy expansion (Herak, 1990). We distinguished two types of transverse waves: SH-waves (polarized in the horizontal plane) and SV-waves (polarized in the vertical plane) (*Figure 3*).

Surface or long waves (L-waves) are the slowest, with circular expansion, and consist of two components: one that vibrates circularly (Rayleigh waves) and the other that vibrates horizontally (Love waves) (Ros Kozarić, 2020). Rayleigh waves (named after the British mathematician and physicist Lord Rayleigh, who first studied and described them) have horizontal and vertical dimensions, and when moving, they create an ellipse. Love waves (discovered by the British mathematician Augustus Edward Hough Love) are faster and have only a horizontal component (*Figure 4*).

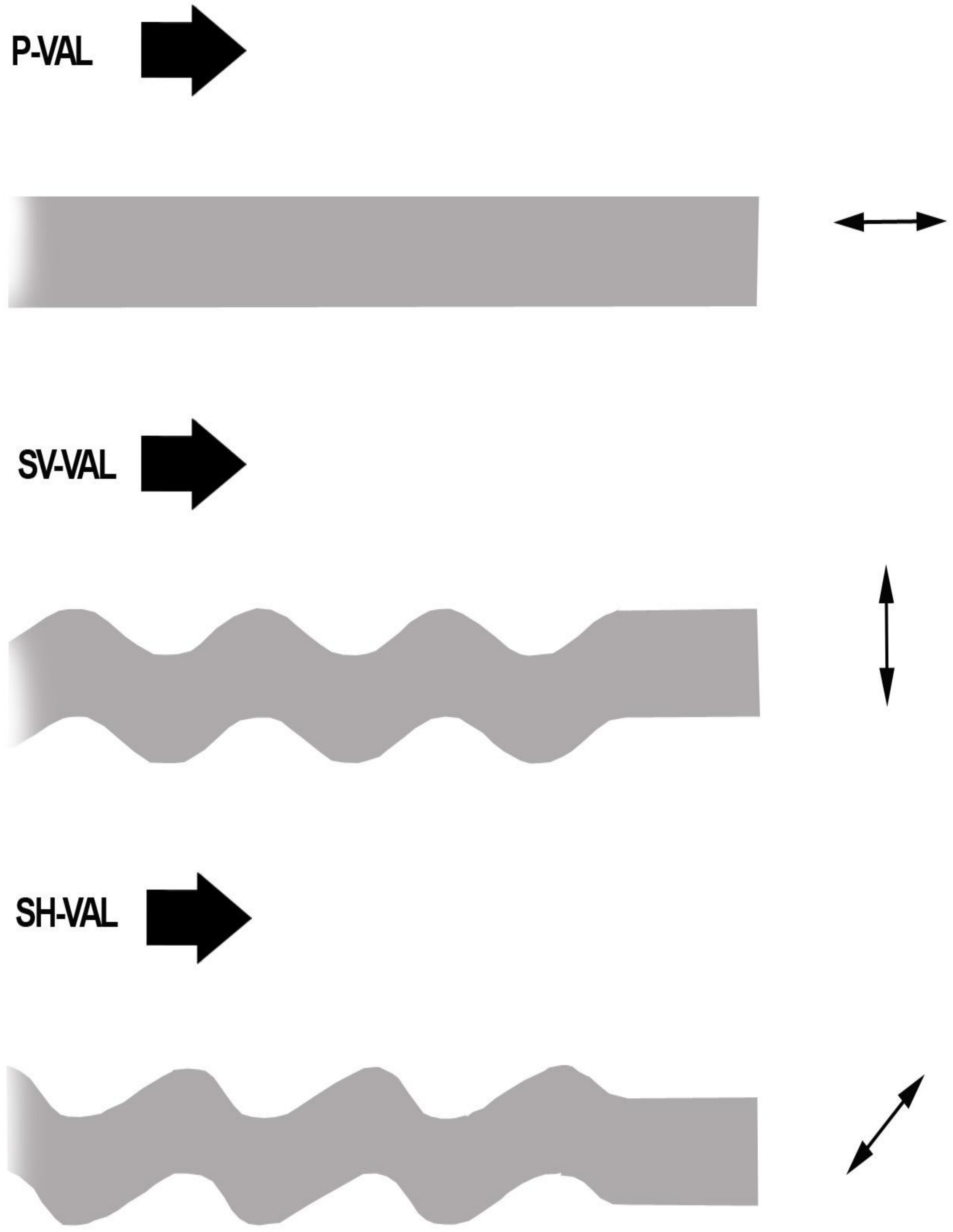

Figure 3. Scheme of longitudinal (primary) and transverse (secondary) waves (source: Seismological Glossary – Department of Geophysics, unizg.hr)

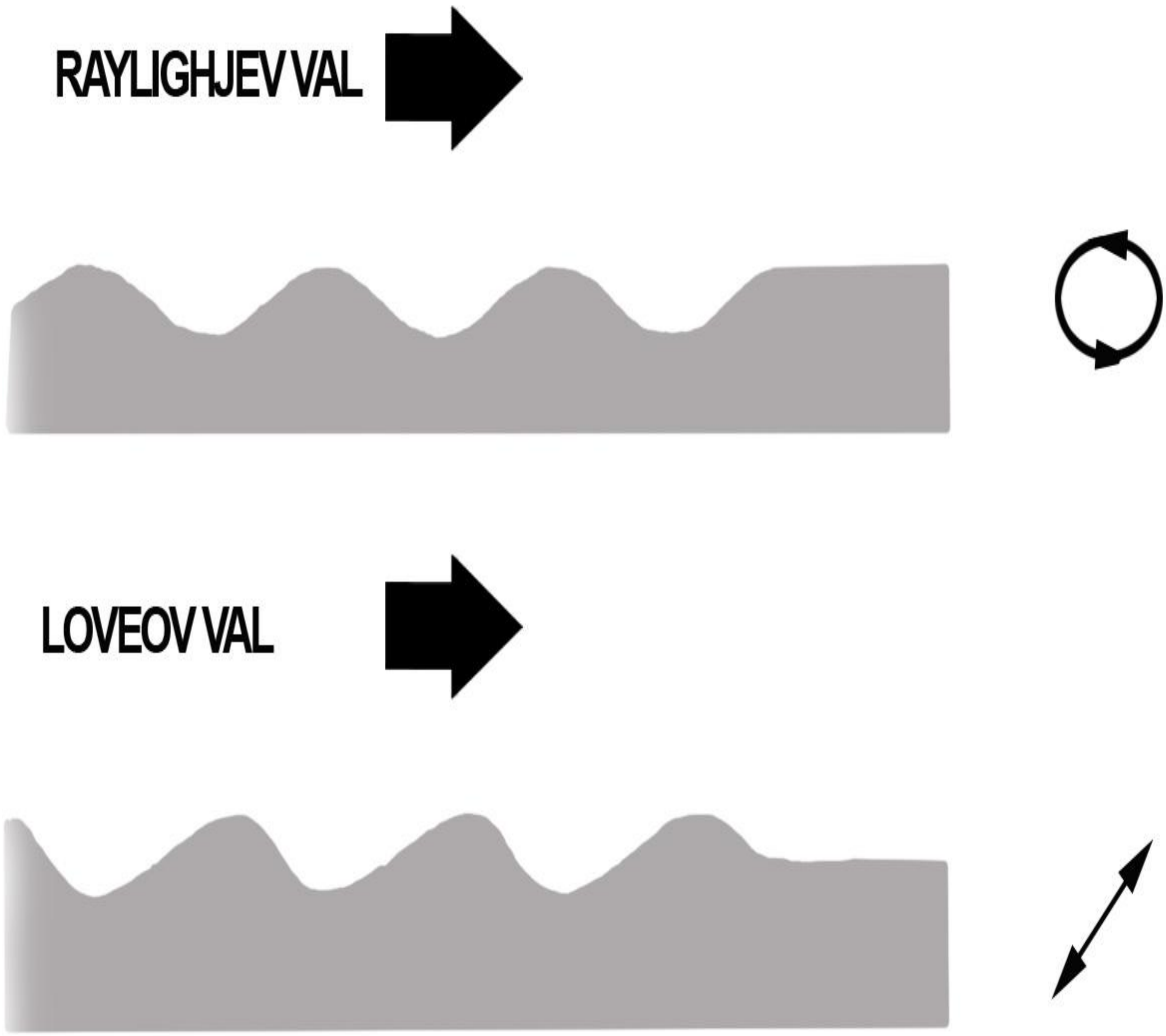

Figure 4. Scheme of surface (long) waves (source: Seismological Glossary – Department of Geophysics, unizg.hr)

Seismic waves propagate at different speeds through rocks, depending on their hardness: the harder the rock is, the faster the seismic waves propagate. The measure of earthquake energy, released in the form of elastic waves and determined by seismograms, is called magnitude (Obradović and Šarko, 2021). The magnitude is measured using the Richter scale[2], while the intensity is expressed using the Mercalli-Cancani-Sieberg scale[3] (MCS). Thus, the magnitude according to Richter shows the amplitude, i.e., the amount of energy released in the hypocenter (*Table 1*), while the MCS scale is descriptive and shows the effect of earthquakes on the Earth's surface (*Table 2*)[4] (Ros Kozarić, 2020).

[2] Designed by American scientist Charles Francis Richter, and since his main collaborator was the American seismologist of German origin Beno Gutenberg, it is also called the Gutenberg-Richter scale.
[3] Developed by the Italian volcanologist Giuseppe Mercalli in 1883 as a six-degree scale that he expanded to include ten degrees in 1902. In 1904, his compatriot geophysicist Adolfo Cancani expanded the scale to include 12 degrees, present till today. It was finally supplemented in 1912 and 1923 by the German geophysicist August Heinrich Sieberg.
[4] In addition to MCS, there are other descriptive scales used in the world: CWASIS (in Taiwan), EMS-98 (in Europe), JMA Shindo (in Japan), Liedu (in China), MSK-64 (in India, Israel, Kazakhstan, and Russia) and PEIS (in the Philippines), while Hong Kong, Indonesia, and the USA use different modifications of the MCS scale.

Table 1

The Richter magnitude of an earthquake with effects (source: Kozarić, 2020, p. 9)

EARTHQUAKE MAGNITUDE	EARTHQUAKE DESCRIPTION	EFFECTS
< 2	Microquake	Not felt.
2.0 – 2.9	Minor	Not generally felt, but are recorded by seismographs.
3.0 – 3.9	Minor	Often felt, but rarely cause damage.
4.0 – 4.9	Slight	The furniture shakes, rattling noise is heard. Significant damage is rare.
5.0 – 5.9	Moderate	They cause damage to poorly constructed buildings in rural areas, possibly minor damage to modern buildings.
6.0 – 6.9	Strong	They can cause damage in populated areas up to 160 km from the epicenter.
7.0 – 7.9	Major	They cause serious damage in a large area.
8.0 – 8.9	Destructive	They can cause enormous damage up to 1000 km from the epicenter.
9.0 – 9.9	Epic	They destroy most objects within a few thousand kilometers.

Table 2

Mercalli-Cancani-Sieberg (MCS) earthquake intensity scale (source: Kozarić, 2020, p. 10)

1.	Imperceptible	Recorded only by seismographs.
2.	Very light	Sensitive people feel it on the upper floors of buildings.
3.	Light	The shaking of the ground as when a car passes by. More people feel it inside the buildings.
4.	Moderate	Felt by more people in buildings, and only by few in the open. Can wake up some sleepers. Shakes the door and the furniture. Windows, glassware, and dishes are disturbed producing a sensation of a passing truck.
5.	Moderately strong	Felt by more people in the open. Wakes up sleepers, some are fleeing houses. Objects that hang freely are swayed, pendulum clocks stop.
6.	Strong	People are fleeing buildings. Paintings fall from walls, objects fall down, dishes break, furniture moves or overturns. Smaller church bells are ringing. Some well-built houses are slightly damaged.
7.	Very strong	Tiles break and slide off the roof, chimneys collapse. Furniture in buildings is damaged. Poorly built buildings are destroyed, while the stronger ones are damaged.
8.	Destructive	Significant damage to 25% of buildings. Some houses are collapsing to the ground, and many are uninhabitable. Cracks in the soil, landslides on the slopes.
9.	Strongly destructive	Damages 50% of buildings. Many buildings are collapsing, and most are unusable. Large cracks in the soil, landslides on the slopes.
10.	Ruinous	Severe damage to 75% of buildings. A large number of well-built houses are collapsing to the ground. Bridges are collapsing, dams are cracking, railway tracks are bending, roads are being damaged. Cracks in the soil are several decimeters wide. Caves collapse, groundwater appears.
11.	Catastrophic	Almost all buildings collapse to the ground. Groundwater breaks out of the wide cracks in the soil, carrying mud and sand. The ground landslides, the rocks tear off and crumble.
12.	Totally catastrophic	Everything that is built by human hands collapses to the ground. Changes in the relief. Lakes backfilled. Changes in riverbeds.

TYPES OF EARTHQUAKES

In terms of their origin, there are three types of earthquakes: tectonic (accounting for 90% of all earthquakes that occur annually), volcanic (7%), and collapse (3%).

Tectonic earthquakes are the most common and can be the most destructive. They are caused by tectonic movements in the lithosphere along fault cracks and at the boundaries of tectonic plates and affect vast areas (Ros Kozarić, 2020). They are caused by stresses in the Earth’s crust and occur when stresses exceed the limit of elasticity of matter (Humski et al., 2021). There is a sudden release of accumulated energy, i.e., part of the potential energy is converted into kinetic energy of elastic vibrations that cause earthquakes (Obradović and Šarko 2021).

Volcanic earthquakes are caused by the movement of magma toward the surface of the Earth and have a local effect because only a small part of the total energy is converted into the mechanical energy of seismic waves (Humski et al., 2021). In addition to volcanic eruptions, volcanic earthquakes also occur after volcanic eruptions, and they are usually very strong (Obradović and Šarko, 2021).

Collapse earthquakes are caused by the impact of collapsed vaults and sidewalls in underground cavities (Pevec, 2021). They occur during the destruction of cavities in the Earth's crust formed by the work of water on soluble rocks[5] (Humski et al., 2021). They are very rare, and their hypocenters are very close to the surface of the Earth. Their released energy is low, as is their strength (Pevec, 2001).

SIGNIFICANT EARTHQUAKES IN CROATIA

Contemporary knowledge about earthquakes in Croatia during the past is based on various historical sources whose poor preservation, limitations, and selectivity (recording primarily large earthquakes of devastating consequences) should be taken into account.

Seismology began to develop in Croatia after the great earthquake in Zagreb in 1880, when the Earthquake Committee was established at the Yugoslav Academy of Sciences and Arts (today's Croatian Academy of Sciences and Arts). The accelerated development of seismology in Croatia should be assigned to Andrija Mohorovičić, who has gained an international reputation in the study of earthquakes and is rightly considered the founder of modern seismology in Croatia. It was Mohorovičić who founded the Zagreb seismological station in 1906, which still plays a key role in the Croatian territory (Herak, 1990). Basic data on known earthquakes in today's territory of Croatia are stored in the Croatian Earthquake Catalog (Hearak and Markušić, 1996).

The first known earthquake of catastrophic proportions, recorded within today's borders of Croatia, occurred in the 4th century (361), when the town of Cissa on the island of Pag was destroyed[6]. This earthquake was of an intensity of approximately X on the MCS scale, similar to the subsequent great earthquake that occurred in 1667 in the area of southern Dalmatia and about which there are several historical sources (Nola et al., 2013). Namely, on April 6, 1667, most likely at 8:45 a.m., Dubrovnik and its surroundings were struck by a devastating earthquake that was felt as far as the Gulf of Genoa, the western Adriatic coast (and in Venice), through Albania all the way to Smyrna (Asia Minor) and Istanbul. The earthquake significantly damaged parts of the city and surrounding areas (Gruž, Rijeka Dubrovačka, Mokošica, Rožat, the islands of Koločep and Lopud). The exact number of wounded and killed people is unknown and is estimated to be approximately 2200 people.

In the period from the 16th to the 20th centuries, as many as twenty strong earthquakes were recorded in the wider regional area of Zagreb, causing greater damage. There are only scarce descriptions of most of these earthquakes, so it is not possible to estimate either the magnitude of the earthquake or the position of the epicenter. The oldest documented earthquake in Zagreb occurred on March 26, 1502, when the tower of the church of St. Mark collapsed. The most important earthquake is the earthquake that occurred on November 9, 1880, at 7:33 a.m., with an intensity of approximately IX MCS and an epicenter in the Medvednica area (Humski et al., 2021). A large part of the city was destroyed, and two human lives were lost. According to records from that period, after the main earthquake, the ground in the Zagreb area occasionally shook during the following six months (Simović, 2000)[7].

At the end of the 19th century, on July 2, 1898, at 5:17 a.m., a strong earthquake occurred in the area of the Sinj Field. It was most strongly felt in rural settlements, from which the population had already left their homes at that time of day due to work on agricultural estates. Nevertheless, three adult women and three children were killed (according to the then sources), and some houses were completely demolished or significantly damaged: approximately ten thousand people were left homeless. Some wells ran out of water, while a new spring appeared in the settlement of Vedrine. More than 120

[5] Collapse earthquakes are typical of karst areas of the world, including Croatia.

[6] The city was located near the present settlement of Caska, on the northwestern coast of the Pag Bay.

[7] During the great earthquake, the writer August Šenoa was found in Zagreb. It was on this occasion, participating in the renovation during the autumn and winter days, that Šenoa became seriously ill and did not recover until his death the following year.

aftershocks were recorded in the first week after the earthquake (https://www.pmf.unizg.hr/geof/popularizacija_geofizike/crtice_iz_povijesti).

A strong earthquake of the VIII MCS occurred on December 17, 1905, with an epicenter in the Medvednica area causing considerable damage in Zagreb, but this time without human casualties. In the following month, on January 2, 1906, there was another earthquake with an epicenter on Medvednica of intensity VIII on the MCS scale; this time, great damage was also recorded without human casualties. In 1909, on October 8, there was an earthquake of intensity VII–IX on the MCS scale with an epicenter in the valley of the Kupa River. It was also felt in Zagreb (numerous chimneys collapsed and the walls of buildings cracked[8]) (Simović, 2000).

In Kvarner, the Vinodol area has experienced several very strong earthquakes, including one from March 12, 1916 (at 4:23 am), with an intensity of VIII MCS and a magnitude of 5.8 degrees. The epicenter was located approximately ten kilometers east of Novi Vinodolski. This strong earthquake was followed by a series of weaker aftershocks. On July 14, 1916, at 21:27, there was a very strong earthquake of an intensity VII MCS with a magnitude of 5.4 and an epicenter 12 km northwest of the previous earthquake. Significant material damage to houses and infrastructure (water pipes and roads) was recorded, and the earthquake was felt throughout the Kvarner region in Istria, Karlovac, Zagreb, and neighboring Slovenia.

Between 1922 and 1924, Baranja was the most seismically active part of Croatia, with earthquakes of intensity VII-VIII in the MCS (Humski et al., 2021).

On January 7, 1962, an earthquake with a magnitude of 5.9 on the Richter scale was recorded at 11:03 a.m. in the area of Makarska. There was cracking of the coast in Makarska at a length of approximately 700 m, and a large number of facilities were damaged. In the following period from January 7 to 22, seismographs in Zagreb recorded as many as 58 earthquakes with epicenters in the wider Makarska area, and damage to facilities was also reported in the areas of Imotski, Ploče, and Čapljina and in the coastal zone all the way to Dubrovnik with the islands of Lastovo, Korčula, Hvar, and the Pelješac Peninsula. The greatest damage was caused in the zone south of Makarska, and the earthquake also involved one human victim. As early as January 11 at 6:05 a.m., the Makarska coast was shaken by another strong earthquake of magnitude 6.1, which claimed another human life (Hrstić, 2012).

On September 5, 1996, an earthquake of magnitude IX struck Ston. Houses in the old town from the 14th century were severely damaged, and extensive damage was also recorded in the neighboring Dubrovnik littoral area. The main earthquake was followed by a series of aftershocks that lasted more than two years (https://www.pmf.unizg.hr/geof/popularizacija_geofizike/crtice_iz_povijesti).

On early Sunday morning March 22, 2020, Zagreb was hit by the strongest earthquake in the past 140 years, with a magnitude of 5.5 Richter. It was found that the hypocenter was located seven kilometers north of the center of Zagreb in the settlement of Markuševac at a depth of ten kilometers. After the main shock woke the inhabitants of Zagreb at 6:24 a.m., only half an hour later, at 7:01 a.m., did a new earthquake with a magnitude of 5.0 Richter followed. In the following 24 hours, 57 earthquakes stronger than 2.0 Richter were recorded in the city of Zagreb. The Seismological Service announced that by June 1, as many as 613 earthquakes with a magnitude above 1.3 Richter were recorded, along with 1037 earthquakes with a magnitude lower than 1.3 (Humski et al., 2021). Although an earthquake with a magnitude of 5.5 Richter falls into the category of moderate earthquakes, data on the assessment of damage to buildings show how devastating the earthquake was. The greatest damage was in the city quarters of Maksimir, Gornja Dubrava, Gornji grad, Medveščak, and Donji grad. The northern parts of the city of Zagreb suffered the most damage, while the southern and western quarters suffered significantly less damage. Considering that the epicenter of the first, strongest earthquake was near the settlement of Markuševec, such results are expected[9]. In addition to residential buildings, many public buildings of older construction were also damaged by the earthquake: the Rebro Clinical Hospital Center, the Clinic for Women's Diseases and Births in Petrova Street, the Clinic for Traumatology in

[8] It was by studying this earthquake that Andrija Mohorovičić identified the discontinuity which bears his name.

[9] It should be stressed that the northern part of the city is full of buildings from the 19th and the first half of the 20th century, many of which do not have structures that can withstand stronger earthquakes, unlike the buildings that were built in the second half of the 20th and the beginning of the 21st century in other parts of the city.

Draškovićeva Street, the Sisters of Milosrdnice Clinical Hospital, the Zagreb Cathedral, the Basilica of the Heart of Jesus in Palmotićeva Street, the Building of the Croatian Academy of Sciences and Arts, the Main Building of the Faculty of Law, the Museum of Arts and Crafts, the Archaeological Museum, and the Building of the Croatian National Theatre (Humski et al., 2021).

On December 29, 2020, at 12:19 pm, an earthquake of magnitude 6.4 Richter hit Sisak-Moslavina County. The epicenter was 3 km southwest of Petrinja. Apart from Croatia, the earthquake was also felt in parts of Bosnia and Herzegovina, Austria, Montenegro, Italy, the Czech Republic, Hungary, Slovenia, Romania, Slovakia, Serbia, and Germany (Humski et al., 2021). The field analysis identified ground displacement caused by the earthquake: the largest displacement was established in the area of Petrinja, with a mean displacement of 45 cm in the southeast, while the mean displacement for Glina was 10 cm in the northwest and 10 cm in the east for the area of Sisak. There was also a height shift of 10 cm in Glina. Massive material damage was recorded in the areas of Petrinja, Glina, and Sisak. There are as many as 38 000 damaged residential buildings (Ros Kozarić, 2020), and the reason for such a large number lies in the fact that most of the buildings were built of unreinforced walls and bricks that eventually lost their properties (Humski et al., 2021). The earthquake also claimed seven human lives, and the ground continued to shake.

It is important to emphasize that the earthquakes in Banovina and Zagreb, although occurring in the same year in a relatively small area, are not directly related because the two areas are not located in the same fault zones. According to one interpretation, the cause of the earthquake in Banovina was the activation of two perpendicular vertical faults. Namely, in the zone of contact between the Dinarides and the Pannonian Basin, a fault in the northwest–southeast direction passes through Pokuplje, and the length of the fault rupture is 25 km. The earthquake occurred on the fault, but the cause of the earthquake was far from Petrinja. Namely, the abovementioned Adriatic microplate dives beneath the Eurasian lithospheric plate and thus causes all tectonic movements in countries with access to the Adriatic Sea. The consequence of this is the faulting that led to the cracking of rocks and thus to the release of a large amount of energy (Ros Kozarić, 2020). However, the second interpretation is based on most other studies that show that this is a single fault system with a prevailing right horizontal displacement that led to the occurrence of earthquakes. These faults at the time of the earthquake in Banovina occurred within the zone of the main displacement of the already active Petrinja fault zone. The whole mechanism is a consequence of the movement of the Adriatic microplate toward the Eurasian tectonic plate (Bočić, 2021).

SEISMIC ACTIVITY IN CROATIA

The territory of the Republic of Croatia is located in the part of the Mediterranean that is tectonically and seismically active due to the movement of the African Plate toward the Eurasian Plate. Their contact occurs in the Mediterranean Sea. Precisely because of their collision, mountains in southern, southeastern, and central Europe formed. Volcanoes located on the west coast of Italy are also the result of this same collision (Humski et al., 2021). At the points of contact between these two plates, there are smaller tectonic plates, one of which is the Adriatic microplate, which some scientists consider to be independent of the African and Eurasian plates. At this point, the exact dimensions of the Adriatic microplate are not fully known. It may encompass the Adriatic Basin, the northwestern part of the Ionian Sea and the lowlands of the Po River, while there are theories that it also includes the Alpine, Dinaric, and Apennine mountains. (Oluić, 2015). On the other hand, it is known that the Adriatic microplate is moving, so on both sides, there is material that is under great tension, which is why an occasional release of energy occurs in the form of earthquakes (Handy et al., 2019; Herak et al., 2016).

Earthquakes recorded in the Adriatic Sea also confirmed this seismic activity. The causes of these changes should be investigated precisely in terms of the movement of the Adriatic microplate toward the north, i.e., the Eurasian plate. Also important is its simultaneous counterclockwise rotation around a point in the Western Alps at a rate of 0.5 to 4.5 mm/year, which is why the western Adriatic coast is gradually approaching the Eastern Adriatic. Although there is no consensus among scientists on the dynamics of Adriatic microplate movements, all studies indicate that these movements are intensive (Oluić, 2015). The subduction of the Adriatic microplate beneath the Eurasian Plate is most intense in the Dinarides. Subduction results in fracturing just below the Dinarides, which has a further dramatic effect on the southern part of the Adriatic microplate while directing subduction to the area of the junction of the Dinarides and the Hellenids (i.e., the Pind-Šar Highlands). This long-term process began at the Eocene–Oligocene transition[10] (Handy et al., 2019).

The earthquakes that occur within the Adriatic microplate indicate the complexity of its structure. The greatest amount of seismic activity was registered in the 1930s (magnitude 5.6 – 5with magnitudes of 5.6–5.9 Richter) and 1980s (magnitude 5.0 – 5.3). Meanwhile, in 1962, an earthquake with a magnitude of 6.1 was recorded in the underwater world near Makarska. There was a new series of earthquakes in 2003 near the island of Jabuka: 150 minor earthquakes preceded the main one, followed by more than 4600 aftershocks (Console et al., 1993; Herak et al., 2005).

In Croatia and its neighboring countries, there are several seismotectonic zones. Skoko and Prelogović divided Croatia into five seismotectonic zones: the southern and western edge of the Pannonian Plain, the interior, the elevated parts of the Dinarides and the Adriatic area (Skoko and Prelogović 1989). On the other hand, Markušić and Herak divided the territory of Croatia, together with the surrounding areas, into as many as 17 zones (*Figure 5*): (1) Montenegro – Northwest Albania, (2) Dubrovnik, (3) Ston – Metković, (4) South Adriatic, (5) Dalmatia, (6) Dinara, (7) Zadar, (8) Vinodol, (9) Rijeka, (10) Bela Krajina, (11) Zagreb, (12) Pokuplje, (13) Varaždin, (14) Podravina, (15) Baranja, (16) Dilj gora, and (17) Banja Luka (Markušić and Herak 1999).

Each of these 17 zones is marked by a certain degree of seismic activity and faults, i.e., fault systems that have regional dimensions and therefore also extend to areas belonging to neighboring countries. This situation is most pronounced in narrowed coastal areas in Dalmatia, where earthquakes occur along faults that extend to the territories of neighboring Montenegro, Bosnia and Herzegovina, which also have devastating consequences for the Croatian territory. The situation is similar in the areas of northern Kvarner and Gorski Kotar, as well as in the Podravina and Pokuplje-Banovina zones. Along certain faults, which have been confirmed in these areas, there are occasional earthquakes that have serious consequences in Croatia. Zone number 1 (Montenegro – northwestern Albania) stands out, where earthquakes with an intensity of as much as IX to the X MCS occur along the faults in the Skadar area. Faults in zone 9 (Rijeka) are primarily in the area of neighboring Slovenia, and earthquakes are recorded along these zones, reaching an intensity of IX to the X MCS in the Croatian area. In zone 10 (Bela Krajina), earthquakes of up to IX MCS most often occur along the fault that extends from Bihać to Črnomelj in Slovenia. The Banja Luka fault in zone 17 is fully extended in northwestern Bosnia, and due to earthquakes reaching the VIII MCS, it can have significant repercussions in the border parts of Croatia, primarily in Banovina and Pokuplje.

Given the depth of the hypocenter, all earthquakes in Croatia are shallow earthquakes. Divergent, convergent, and horizontal shifts in our area occur over a long period of time. The plates are still moving, and thus, the activity of certain fault lines occurs; however, other fault lines remain inactive (Humski et al., 2021).

However, several zones of greater seismic activity can be singled out. One of them is located in the coastal part from the Slovenian-Croatian border to the area south of Dubrovnik. The second zone extends from the Slovenian border west of Karlovac through Žumberak and Medvednica to Bilogora. The zone from Pokuplje to northwestern Bosnia (Banja Luka) is also seismically active. The seismic areas of the Slavonian mountains (Psunj, Papuk, Krndija, and Dilj) are less active.

The weakest are the seismically active central and eastern parts of Croatia, although in 1884, an earthquake was recorded in the vicinity of Đakovo and in 1964 in the area of western Slavonia. The northwestern part of Croatia can be considered seismically moderately active with rare occurrences of stronger earthquakes, while southern Dalmatia is the seismically most endangered part of Croatia. The tectonically active area also includes Medvednica and the wider surroundings of the Zagreb (Humski et al., 2021).

The State Administration for Protection and Rescue of the Republic of Croatia estimates that there is a high risk of earthquakes of level VIII and IX MCS on 36.42% of the area of the Croatian territory where almost two-thirds of the Croatian population lives (2.7 million people according to the 2021 census). On the other hand, the risk of an earthquake of level VII MCS exists in more than half of the national territory (56.22%), which is home to just over a third of the population (1.5 million) (Nola et al., 2013).

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[10] These are geological epochs that, together with the Paleocene, form the Paleogene geological period, which began 65 million years ago and ended 23 million years ago. The Oligocene represents the last part of the Paleogene.

The Zagreb urban region is the area with the highest population density in Croatia, and due to its predominantly dense construction, catastrophic consequences in the event of devastating earthquakes are possible. Therefore, tectonic activity in the Zagreb area has been especially monitored. According to current knowledge, the tectonic activity in the Zagreb area is influenced by regional structural movements. Within this region, the Adriatic microplate plays a very important role, causing strong compression in the zone of the Alps and the northern part of the Dinarides. This activity is significantly felt along the Zagreb fault, which intersects the city of Zagreb. The Zagreb fault consists of a number of smaller faults, such as the fault on the line Kerestinec – Ilica – Maksimir – Sesvete and the one in the zone Podsused – Markuševac – Kašina – Zelina. The most seismically active part of the Zagreb fault is in the Medvednica area, between Markuševac and Moravče, with a length of approximately 20 km (Gusić et al., 2016).

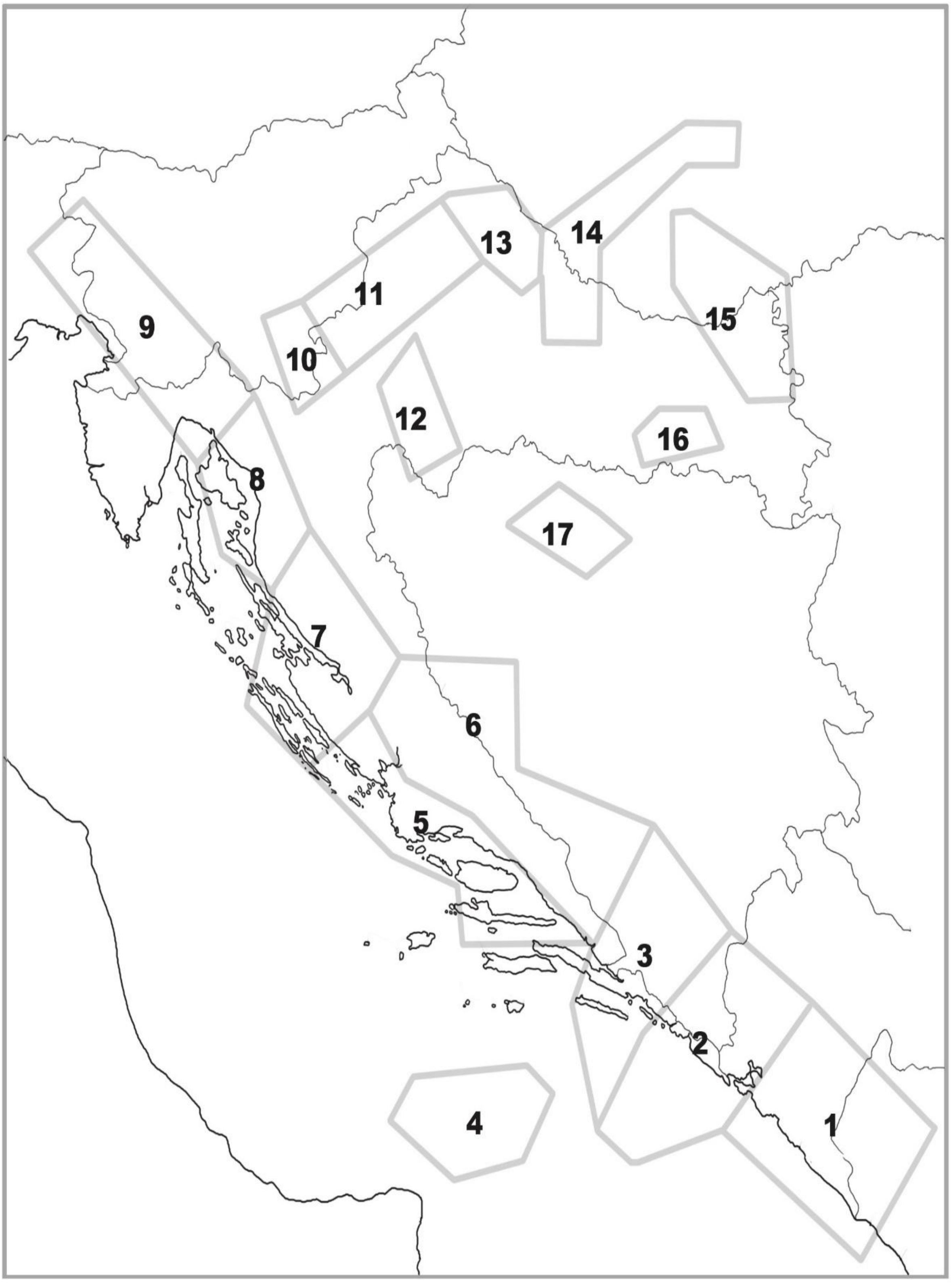

Figure 5. Seismic zones in Croatia and surrounding areas (source: Markušić and Herak, 1999)

CONCLUSION

The main causes of the earthquake mechanism are the movements of tectonic plates that form the lithosphere, i.e., the Earth's upper layer, due to the convection flow of matter in the Earth's mantle. At the points of contact of tectonic plates, boundaries are formed at which, because of tectonic movements, a large amount of energy is released. This energy manifests on the surface of the Earth in the form of an earthquake. Earthquakes can also occur inside plates as a result of the injection of magma into their weakened parts.

The Republic of Croatia is located in an area that is tectonically and seismically active due to the movement of the African plate and the Adriatic microplate toward the Eurasian tectonic plate. Although seismology cannot predict the moment when an earthquake will occur, seismically active zones on Earth are known. Croatia is located in one of the active zones, so in the future, strong earthquakes can be expected in the territory of the Republic of Croatia, precisely because of the continuous movement of the African Plate and the Adriatic microplate in the north direction. Given the depth of the hypocenter, all previous earthquakes in Croatia are classified as shallow earthquakes, which means that the part of Europe in which we live is spared of earthquakes of extreme strength and devastation. However, the entire territory of Croatia is not seismically equally active: the greatest amount of seismic activity is recorded in the western Dinaric belt (with the exception of Istria) and in the Adriatic seabed, and the least amount is recorded in the eastern plain part of the country. These are mostly tectonic earthquakes, and in karst areas, there are also weak collapse earthquakes.

Croatia is located in a seismically extremely active area, i.e., at the junction of the African and Eurasian tectonic plates, where the Adriatic microplate is active. Therefore, earthquakes are not rare and unknown phenomena in most national territories. For this reason, at the primary school level, students should be acquainted with the causes and mechanism of earthquake origin in Croatia and neighboring countries and be offered a chronological overview of the most destructive earthquakes in the past. Therefore, it is necessary to maintain a broader approach to the analysis of basic concepts about the structure and composition of the Earth and global plate tectonics.

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