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Professional paper

TEMPORAL AND SPATIAL ANALYSIS OF EARTHQUAKE IN STOLAC ON APRIL 22ND, 2022

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SUMMARY

The territory of Bosnia and Herzegovina represents a seismically relatively active zone, given that it is under the influence of the convergent movement of the African plate towards the Eurasian plate. Evidence of the seismicity of Bosnia and Herzegovina is the earthquakes recorded in the earthquake catalogs. The strongest earthquake recorded on the territory of Bosnia and Herzegovina in the 21st century is the earthquake that occurred in Stolac on April 22, 2022. The area of Stolac is characterized by numerous normal, oblique and overturned folds as well as reverse faults. The reverse faulting is the cause of the earthquake that occurred, which was proven by the analysis of the focal mechanism of the earthquake. Based on the GIS software of the National Institute of Geophysics and Volcanology of Italy for earthquake dislocations, the maximum possible earthquake magnitude was determined, which for the Stolac area is 7 degrees on the Richter scale. In view of this, it is necessary to design, build and reconstruct buildings so that they are resistant to earthquakes.

Keywords: earthquake, seismicity, beachball diagrams, hazard

1. INTRODUCTION

The temporal and spatial analysis of the earthquake in Stolac was performed on the basis of data taken from the archives of the Seismological Station at the Geophysical Department of the Faculty of Science, University of Zagreb, the Federal Hydrometeorological Institute of Bosnia and Herzegovina and the Euro-Mediterranean Seismological Center (EMSC). The earthquake in Stolac occurred on April 22 at 23:07 local time, magnitude Mw = 5.7 by Richter scale. According to the data of the seismological services, the earthquake was rated with intensity at the epicenter VIII° EMS and is described as a devastating earthquake [1]. The earthquake was felt throughout Bosnia and Herzegovina, Croatia, Montenegro, Albania, Italy, Kosovo, North Macedonia, Slovenia and Serbia. This earthquake was the strongest in Bosnia and Herzegovina since the one that hit Banja Luka in 1969. The earthquake caused casualty in the village Kukavac near Stolac, while major material damage was recorded in the area of Stolac, Čapljina, Mostar and surrounding villages.

2. CAUSES OF THE EARTHQUAKE IN THE AREA OF BOSNIA AND HERZEGOVINA

The area of Bosnia and Herzegovina is seismically and tectonically active due to the convergent movement of the African (Nubian) plate towards the Eurasian plate. The speed of movement is estimated at around 9-10 mm/year. based on GPS measurements (Figure 1). Approximately half of this convergent movement is consumed in active subduction zones along the Hellenic and Calabrian arcs, while the remaining part is transferred northward to the relatively stable part of the Adriatic microplate in the Ionian and Adriatic seas,

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from where it is transferred to the surrounding mountain ranges of the Apennines, the Alps and the Dinarides, and partly in the Pannonian Basin in Croatia and Hungary [1].

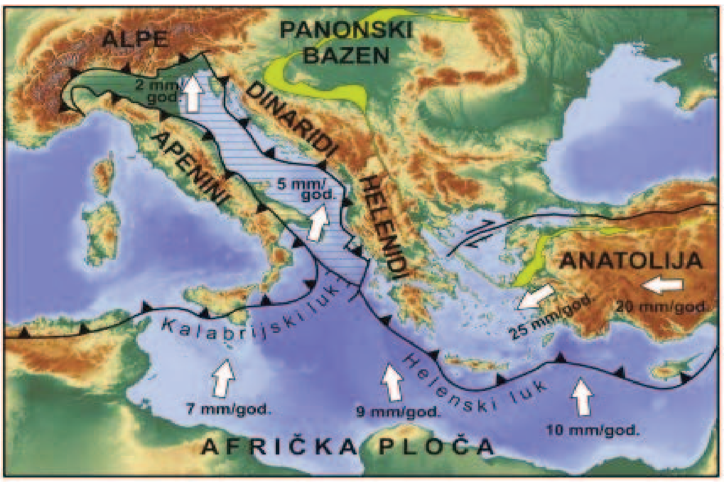

Figure 1. Geodynamic sketch of the eastern Mediterranean area and the speed of convergent movements of the African (Nubian), Anatolian and Adriatic microplates towards the Eurasian plate (tectonic boundaries taken from Handy et al., 2019 and Reilinger et al., 2006; GPS displacement vectors taken from McClusky et al., 2000 and Weber et al., 2010; Sava subduction zone, taken from Schmid et al., 2020 (marked in green)

The movement of the Adriatic microplate towards the Eurasian plate is at an estimated speed of 0.5 to 4.5 mm/year. Part is transferred by translation towards the north and simultaneous rotation in the direction opposite to the movement of the hands of the clock around the axis whose pole is located in the western Alps (Figure 2).

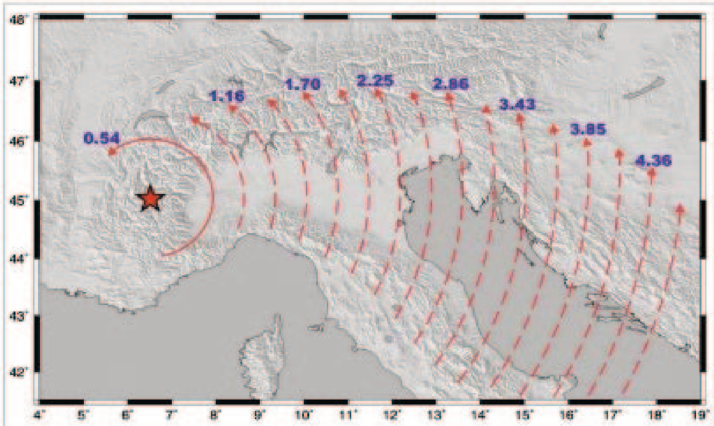

Figure 2. Schedule and speed of convergent movements (mm/year) in the stable part of the Adriatic microplate and in the surrounding mountain ranges calculated on the basis of GPS measurements (from Weber et al., 2010)

Accumulation of stresses in the rocks of the brittle part of the crust and on existing faults leads to tectonic tensions. With the increase of these tensions, the critical value of the shear resistance of rocks and existing faults is reached. By exceeding this critical value, there is a breakdown in rocks and faults and a sudden release of accumulated energy in the form of seismic waves that cause shaking on the surface [1]. That's how an earthquake occurs. Earthquakes in the territory of Bosnia and Herzegovina have been recorded and can be found in the historical archive and in the earthquake catalogs which are published by the Federal Hydrometeorological Institute of Bosnia and Herzegovina. A catalog of historical earthquakes (510 BC – 1900 AD) and earthquake catalogs for the 20th and 21st centuries are available to the public.

3. SEISMICITY OF THE TERRITORY OF BOSNIA AND HERZEGOVINA

The territory of Bosnia and Herzegovina belongs to a seismically relatively active zone. Seismotectonic active zones were formed due to the movement of segments of the Adriatic microplate. They differ in size and amount of movement and resistance of the Dinarid mass and are related to faults on the surface. In depth, the boundaries of the seismogenic zones are steeply inclined and curved due to the compressional regime of the Dinarides. Such zones are characterized by frequent earthquakes. The areas of thrust movement are related to the seismogenic zones of gentle dip. For the territory of Bosnia and Herzegovina, nine seismogenic zones have been identified. Each is characterized by the appearance of one or more dominant tectonic structures [5]:

1. Tuzla: left horizontal faults (direction of extension NE-SW), right horizontal faults (direction of extension NW-SE) and normal faults.
2. Žepče-Srebrenica: normal faults (NW-SE)
3. Banja Luka: normal faults (NW-SE) and horizontal faults (NE-SW and NW-SE)
4. Zenica-Sarajevo: normal faults (NW-SE)
5. Treskavica: normal faults and thrust fault
6. Mostar: left horizontal faults (NW-SE) and thrust fault
7. Livno-Tihaljina: thrust fault and normal faults
8. Neum-Trebinje: thrust fault and normal faults
9. Bihać: normal faults

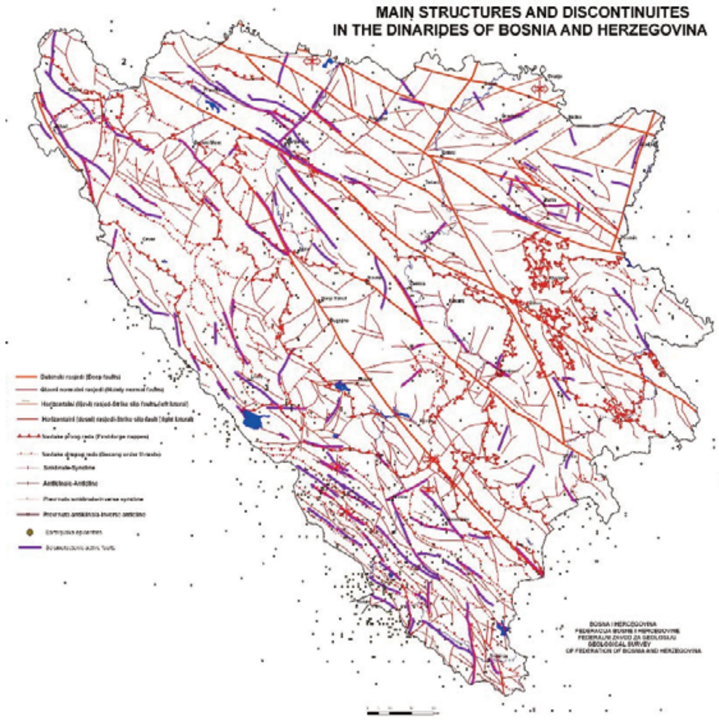

Figure 3. Main structures and discontinuities in the Dinarides of Bosnia and Herzegovina (Hrvatović, 2000)

Since 1900 (since earthquakes have been recorded instrumentally in this area), 1,084 earthquakes have been recorded whose magnitude was over 3.0 on the Richter scale or intensity greater than V° on the Mercalli scale. Numerous earthquakes with a magnitude over 5.0 on the Richter scale were also recorded. These are earthquakes that caused material damage or human casualties. In addition to natural earthquakes, which are a frequent occurrence, human caused earthquakes also occur in the region as a result of the construction of hydroaccumulation-dams, which were registered at the Bočac, Grabovica, Grančarevo, Rama and other dams.

3.1 FORECASTING SEISMIC ACTIVITY

To forecast seismic events for any territory, including Bosnia and Herzegovina, instrumental data from earthquake catalogs are used together with the application of mathematical-physical models of seismicity. In addition to the catalog of earthquakes, earthquake hazard maps for different return periods are created for the forecasting of seismicity or earthquake hazard for the territory of Bosnia and Herzegovina. Seismic hazard or earthquake hazard represents the potentially devastating effects of an earthquake (such as ground shaking, soil liquefaction, landslides, etc.) at the observed location. It is expressed by the statistical probability of exceeding the selected parameter in a given period. For the parameter that describes the earthquake action, the expected horizontal acceleration of the ground (ag, expressed in units of the acceleration of the Earth's gravity (1 g = 9.81 m/s^2), is simply associated with the forces acting on the building during the earthquake), and in different earthquake intensity scales are most often used in the public (the already mentioned MCS and Richter scale, with energy measurement at the focal point. Earthquake hazard maps for Bosnia and Herzegovina are an integral part of the National Supplement to Eurocode-8 of the Institute for Standardization of Bosnia and Herzegovina. The maps were made for different return periods, of 95 and 475 years (Figure 4).

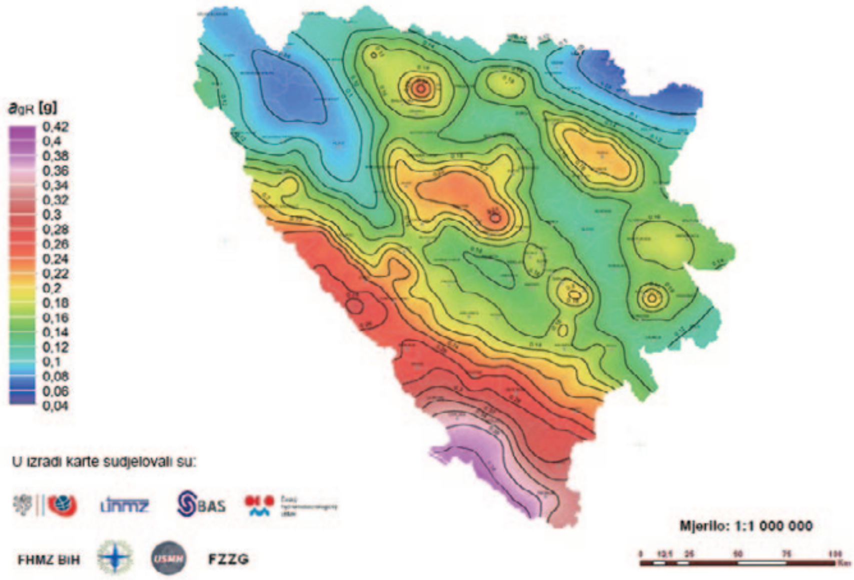

Figure 4. Earthquake hazard map for the territory of Bosnia and Herzegovina for the return period of 475 years (Institute for Standardization of Bosnia and Herzegovina)

According to this map, Bosnia and Herzegovina represents a very seismic active area. The earthquakes hazard is located in the area of Herzegovina, such as Neum, Trebinje, Nevesinje, Mostar, Posušje, Tomislavgrad and Livno. The hazard is also located in the area of Zenica, Bugojno and Banja Luka.

4. GEOLOGICAL SETTING OF STOLAC AREA

In the wider area of Stolac, rocks of Cretaceous, Paleogene and Neogene age were deposited [8].

4.1 TERRAIN EVOLUTION

When comes to evolution of the terrain, there are three distinct periods; continuous sedimentation during the Cretaceous, then very variable sedimentation conditions as a result of orogenic movements in the Paleogene, and lacustrine sedimentation during the Neogene. In the Lower Cretaceous, uniform sediments were formed in larger areas, consisted of limestone and subordinate layers of dolomite and dolomitic limestone. At the end of the Senonian, the sedimentation caused by the Laramide orogenic movements is interrupted. Mechanical-chemical wear occurs. This is when the first deposition of material and the formation of bauxite of Old Paleogene age, which are represented in the area of Stolac, actually begin. Sedimentation again covers larger areas at the beginning of the Late Paleocene. It is particularly prominent at the end of the Paleocene and in the Early Eocene, when alveolin-nummulite limestones are deposited directly on partially eroded deposits of the Late Cretaceous.

In the Middle Eocene, new tectonic movements lead to a break in the sedimentation of alveolin-nummulite limestones as terrestrial phase is formed during which the bauxite deposits are created again. After this terrestrial phase, in the Eocene there is transgression and the deposition of thick clastic deposits of the Eocene. After the deposition of clastic sediments, orogenic movements occur, which left the strongest traces on the Cretaceous and Paleogene sediments. During this orogenic phase, all the main tectonic structures in this area were created. After orogenic movements, freshwater Neogene sediments were discordantly deposited. These deposits were also covered by tectonic movements and were brought to different heights. During the older Quaternary, deposits of limnoglacial material were deposited in Mostarsko polje as a result of the melting of the ice from Velež, Čvrsnica and Prenje. Huge amounts of water and erosion in the younger Quaternary have led to the current appearance of the terrain [8].

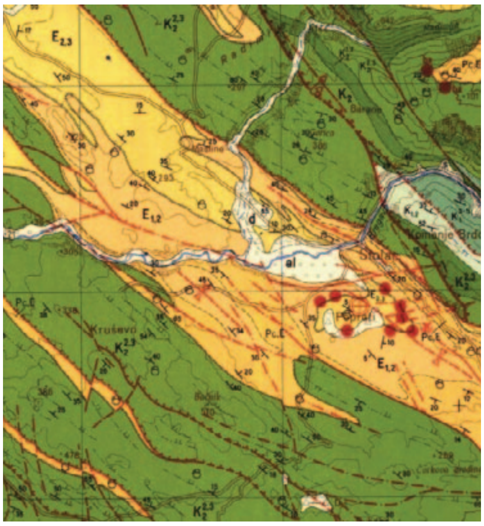

Figure 5. Geological map of the wider area of Stolac (section of the basic geological map, sheet Metković, Rajić & Papeš, 1975)

4.2 TECTONICS

From a geotectonic point of view, the analysed terrains belong to the high karst thrust fault. In this area, four tectonic units are prominent, which are pulled on top of each other from the northeast to the southwest. Those tectonic units are: Svitava-Ljubuški, Stolac-Čitluk, Blagaj and Velež tectonic units. The Stolac-Čitluk tectonic unit covers the stretch from Rasno in the northwest to Ranča hill in the southeast. The northern border of this tectonic unit is formed by a dislocation that stretches from the southeastern edge of Mostarsko Blato through Žitomislić and Hodovo to Stolac. In the northwestern part of the area, along this dislocation, chondrodonta limestones are overlain by rudist limestones. In the area of Hodovo, this dislocation is covered by freshwater Neogene sediments. Moving towards the southeast, it can be seen on Radimlja, Bregava and Komanje hill near Stolac, where Albian-Cenomanian and chondrodonta limestones and dolomites are overlain by rudist limestones and partly Paleogene sediments. From a tectonic point of view, this unit is characterized by numerous normal, oblique and overturned folds as well as reverse faults. The Klobuk thrust fault out the most, whose forehead stretches from Klobuk on the western border of the analysed area through Ljubuški, Čapljina and Svitava on the southeast side of the area. South of Stolac, a reverse fault was identified. Northwest of this fault, there is a Tertiary syncline. In the bottom of the syncline consisted of alveolinic-nummulitic limestones and classites. In the limbs of syncline are Liburnian layers. Numerous deposits of bauxite occur on the border of Cretaceous and Paleogene limestones, as well as on the border of alveolin-nummulite limestones and Eocene clastites. It is also worth mentioning the reverse fault along which the rudist limestones were pushed onto the clastic deposits of the Eocene. It is visible on the ground and can be followed from Dubrava to Stolac and further to the southeast [8].

5. EARTHQUAKE IN STOLAC

The series of earthquakes in Stolac began with an earthquake that occurred on April 22, 2022 at 23:07 local time (SEV) at a depth of 10 km. The earthquake had a local magnitude of ML=5.7 and moment magnitude of Mw=6.1. The epicenter of the earthquake was in Strupići. Figure 6 shows a preliminary map of the epicenters of recorded earthquakes that occurred until April 24, 2022 at 1:00 p.m. (SEV). Note: all data are presented according to moment magnitude (Mw). In the period from April 22 at 11:07 p.m. to April 24, 2022 at 1:00 p.m., about a hundred earthquakes with a moment magnitude greater than 2.0 were recorded.

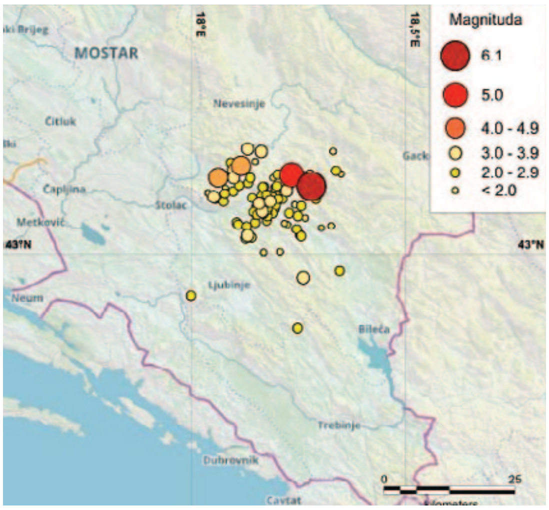

Figure 6. Map of epicenters of the earthquake near Stolac during from April 22, 2022 at 11:07 p.m. to April 24, 2022 at 1:00 p.m. according to the moment magnitude (Archive of the Seismological Station at the Geophysical Department of the Faculty of Science, University of Zagreb).

Table 1 shows the number of earthquakes by magnitude (M>3.0), and Figure 7 shows the temporal distribution of magnitudes of earthquakes with a magnitude greater than 1.9.

Table 1. Earthquakes of moment magnitude greater than 3.0 (Archives of the Seismological Station at the Geophysical Department of the Faculty of Science, University of Zagreb).

Magnitude	Date
3.4	28.08.2022
3.2	30.08.2022
3.8	01.09.2022

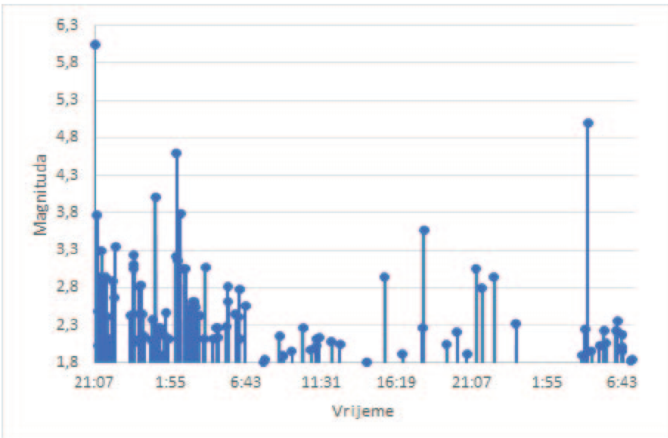

Figure 7. Temporal distribution of magnitudes of earthquakes with moment magnitude greater than 1.9 (Archives of the Seismological Station at the Geophysical Department of the Faculty of Science, University of Zagreb).

The area of Stolac is a very seismically active area. Strong earthquakes often occur, such as the series of earthquakes from August 28 to September 1, the strength of which is shown in table 2:

Table 2. Recorded earthquakes in the Stolac area in the period from August 28 to September 1, 2022. (Archives of the Seismological Station at the Geophysical Department of the Faculty of Science, University of Zagreb).

Magnitude	Date
3.4	28.08.2022
3.2	30.08.2022
3.8	01.09.2022

6. FOCAL MECHANISM OF THE EARTHQUAKE IN STOLAC 22.APRIL 2022. YEAR, MW=5.7

The analysis of the focal mechanism of the earthquake (or fault plane solutions, FPS) is based on the character of the first occurrences of P-waves that are read on the seismogram of the recorded earthquake at a certain seismological station. Since FPS diagrams resemble beachballs, they are also called "beachball diagrams". This type of diagram is needed in order to determine the type of fault that caused the earthquake, once the location and magnitude of the earthquake are known (Figure 8).The diagram shows two planes perpendicular to each other (so-called nodal planes). One of the nodal planes shows the fault on which the earthquake occurred, from whose first occurrences of P-waves the beachball diagram is constructed. In order to find out which of the two nodal planes shows the seismogenic fault, it is necessary to collect and analyze additional seismotectonic data.

Two perpendicular nodal planes in space enclose four quadrants that differ from each other in color. Opposite quadrants are usually colored black or white. The quadrants marked in black represent the tension or dilatation quadrants where the first occurrences of P-waves were recorded. They represent the displacement of material particles by the movements of P-waves "from" the focal point of the earthquake. While the white-marked quadrants represent the compression quadrants where the first P-wave tension occurrences were recorded. Here the movement of material particles are "towards" the focus of the earthquake [10].

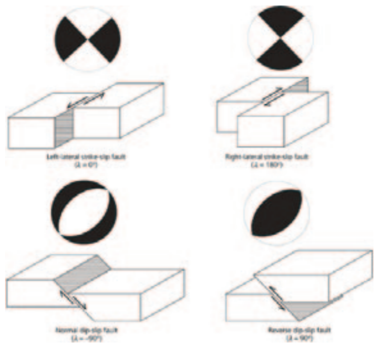

Figure 8. Focal mechanisms of earthquakes for basic types of fault geometry (Stein & Wysession, 2003)

The seismological stations located in the black quadrants recorded the first occurrences of P-waves, which are marked on the seismogram by an upward curve jump. In the white quadrants are located the stations that recorded the first arrivals of P-waves with a downward jump of the curve. To calculate the focal mechanism, seismologists use data from seismograms from as many seismological stations as possible. For the earthquake that occurred in Stolac on 22 nd April, 2022, magnitude 5.7 on the Richter scale, the focal mechanisms of the earthquake from different sources were determined (Figure 9), namely: GCMT – Global Centroid Moment-Tensor, GFZ – Geo Forschungs Zentrum Potsdam, INGV – Instituto Nazionale di Geofisica e Vulcanologia, IPGP – Institut de Physiquedu Globe de Paris, OCA – Observatoire de la Côte d'Azur, USGS – United States Geological Survey. [11]

Based on these data, it is concluded that the type of causative fault in the area of Stolac is a reverse type of fault.

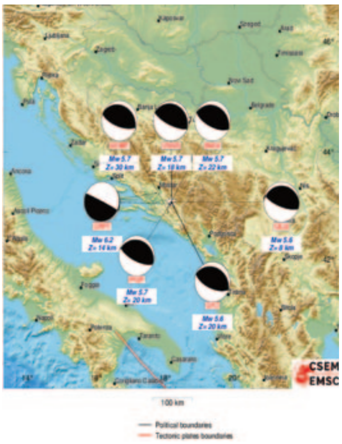

Figure 9. Focal mechanism of earthquakes from different sources (EMSC, 2022).

7. EFFECTS OF THE EARTHQUAKE

In the village of Kukavac near Stolac, one woman died as a result of injuries sustained when a rock fell on a house, while several people were injured. The earthquake caused damage to buildings throughout Stolac, Čapljina and Mostar. So far, the municipality of Stolac has received 463 reports of material damage from the recent earthquake. Coal production was interrupted in the "Sretno" pit in Breza. Due to the sudden release of pressure in the pit premises, several miners were slightly injured, and four of them requested medical assistance. Also, railway traffic from Podgorica to the northern part of Montenegro, on the Belgrade - Bar line, was interrupted.

After the earthquake in Stolac on April 22, 2022, the Euro-Mediterranean Seismological Center [11] received reports from witnesses about the ground shaking through its "I felt this earthquake" application (Figure 10).

Figure 10. Locations of citizen reports and estimated intensities reported through the "I felt this earthquake" application of the Euro-Mediterranean Seismological Center (EMSC, 2022)

8. EARTHQUAKE AREA OF STOLAC AND EARTHQUAKED HAZARD

So far, the strongest earthquake on the territory of Bosnia and Herzegovina in the 21st century was measured in Stolac on April 22, 2022. Based on data from the earthquake catalog of Bosnia and Herzegovina, the area of Stolac is extremely seismically active.Based on the GIS software of the National Institute of Geophysics and Volcanology of Italy for seismic faulting, the area of Stolac is covered by the Metković seismogenic zone, marked with the HRCS009 code (Figure 11). The orange polygon in the picture indicates a seismogenic source. Seismogenic faults can be expected within this area, which can cause an earthquake of the maximum expected magnitude of 7.

Figure 11. Seismogenic source or seismogenic zone HRCS009.
The orange polygon indicates the spatial position of that seismogenic source.

The entire area of Stolac municipality is an area that can be threatened. An earthquake is a phenomenon that affects large areas and can be felt kilometers from the epicenter. Therefore, the entire municipality is threatened by this natural phenomenon. The conditions for the construction of buildings in the function of protection from earthquake hazard, as well as other conditions for the organization of the settlement and construction, need to be regulated at the municipal level. Aseismic planning should be carried out in accordance with existing seismic maps. The planning, construction and reconstruction of buildings must be carried out in such a way that they are resistant to earthquakes, and seismic, geomechanical and geophysical research must be carried out for their location. [12].

9. CONCLUSION

Analyzing data of earthquakes in Stolac, which occurred before and after the devastating earthquake on April 22, 2022. year, the conclusion is that the area of Stolac is very seismically active. Earth tremors can be expected in this area, which can affect the life of the population. Due to the established lithological composition, the greatest danger is rockfall, which was precisely the main cause of casualty in the devastating earthquake of 2022. The main seismogenic source for the main and most earthquakes in this area is reverse faulting, which was also confirmed by solutions of the focal mechanism. Although devastating earthquakes have been recorded on the territory of Bosnia and Herzegovina in the past, the population is still not aware of the seismic danger, which is the hazard that Bosnia and Herzegovina faces. Earthquakes, such as those in Stolac in April of 2022.year, are proof that the territory of Bosnia and Herzegovina is located in a seismically active area. Precisely because of the potential devastating earthquakes that can be expected, it is necessary to implement protection measures, first of all, education of the population throughout Bosnia and Herzegovina (especially in seismically dangerous areas) and the planning, construction and reconstruction of buildings that should withstand the maximum expected earthquake magnitude.

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