Geotechnical Reconnaissance and Engineering Effects of the December 29, 2020, M6.4 Petrinja, Croatia Earthquake, and Associated Seismic Sequence

Chapter 2: Tectonic Setting

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2. Tectonic Setting

2.1 Introduction

On December 29, 2020, at approximately 12:20 pm CET (11:20 am UTC) an earthquake of magnitude 6.4 M_W (6.2 M_L) occurred in central Croatia. U.S. Geological Survey (USGS 2020b) located the hypocenter at a depth of 10 km, approximately at 45.422° N and 16.255°E while the Croatian Seismological Survey of the University of Zagreb located the hypocenter at 45.4002N and 16.2187E, 3 km southwest of Petrinja and 12 km southwest of Sisak, at a depth of 11.5km. (Croatian Seismological Survey 2020) The information suggests that a rupture occurred within the central portion of the shallow Pokupsko–Petrinja strike-slip fault in the transition zone of the Adria Microplate and Eurasian plate. The maximum intensity of the earthquake was VIII (severe) on Modified Mercalli Intensity (MMI) scale and VIII (heavily damaging) to IX (destructive) on European Macro-seismic Scale (EMS). The earthquake was preceded by several foreshocks, the strongest of which had a magnitude of 5.2 $M_{W,}$ and followed by series of aftershocks, the strongest of which had a magnitude of 4.9 M_W ((Croatian Seismological Survey 2021; USGS 2020b; Markušić et al 2021).

While Petrinja was the most affected city, severe damage also occurred in Sisak, Dvor, Glina, Topusko, Strašnik, Majska Poljana, Gora etc. Damage also occurred in Zagreb and Zaprešić, located approximately 50 km and 60 km, respectively, to the north northwest of the epicenter. The earthquake caused seven fatalities, 26 persons were injured, and several hundred people had to be displaced (Pušić et al., 2021). The earthquake was felt throughout Croatia and in large parts of Slovenia, Austria, Bosnia and Herzegovina, Serbia, Hungary, Slovakia and Italy, and some parts of Montenegro, Germany, and the Czech Republic.

2.2 Regional Tectonic Setting

Croatia is located in a highly active Alpine–Mediterranean seismic region. While the convergent boundary region between the African and Eurasian plates primarily governs the tectonics of the Circum-Mediterranean, the tectonics of Croatia is controlled by the Adria Microplate – Eurasian Plate collision at the rate of 3.5–5 mm/yr that resulted in the formation of the Alps, Dinarides, Albanides, and Helenides (**Figure 2.1**).

Figure 2.1 Tectonic plates in Alpine–Mediterranean region (after Handy et al., 2015).

The complexity of this region is reflected in microplates and regional-scale structures that promote tectonic motions along the regional scale crustal faults (**Figure 2.2**). The collision between Adriatic and Eurasian plates presently remains the subject of many investigations (D'Agostino et al., 2008; Schmid et al., 2008; Ustaszewski et al., 2010; Ivančić et al 2018).

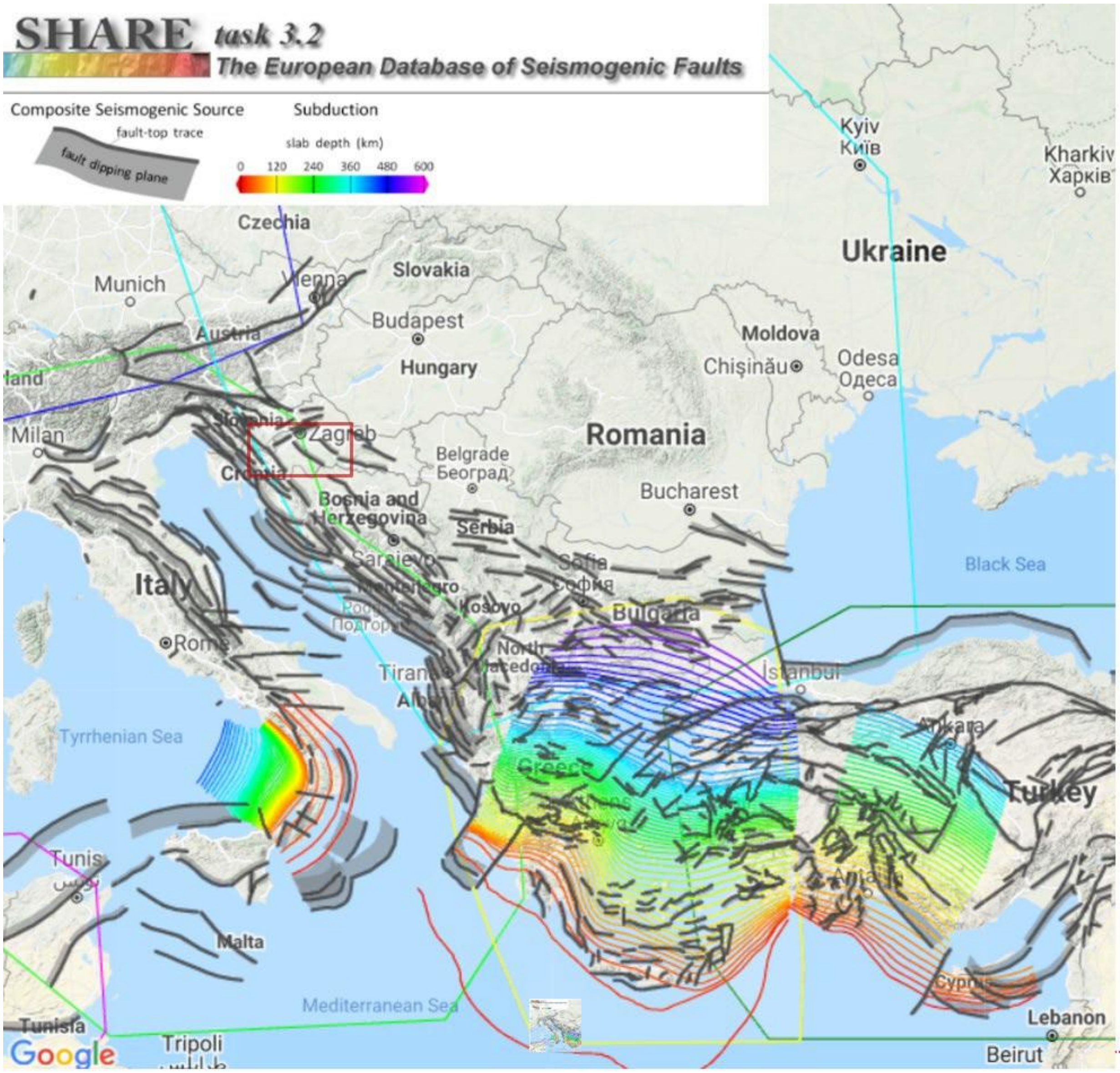


Figure 2.2 Section of the map of the seismogenic faults in Europe (Basili et al., 2013). Red frame show area shown in Figure 2.9.

The major tectonic units that govern the seismicity of Croatia (**Figure 2.3**) are the Pannonian Basin to the north, the Eastern Alps, the Dinarides, and Adria Microplate–Eurasian Plate transition zone (Schmidt et al. 2008). The interaction between these tectonic units controls the earthquakes in the upper crust that are distributed along active faults in the region (Stanko et al. 2020). While most of the recent earthquakes occurred in the coastal area due to the ongoing collision between Adria Microplate and the Eurasian Plate in the domain of the Dinarides, the seismicity of the Pannonian Basin to the north is characterized by far-field stress transfer, i.e., intra-plate events. The seismogenic faults in the SE part of the coastal area (Dalmatia) are predominately reverse faults, striking along the coastline, i.e., perpendicularly to the average tectonic stress direction. More to the NW along the coast, transpression and strike-slip are the dominant regimes. The seismicity of the Pannonian Basin is characterized by rare occurrences of strong events, whereby the tectonic motions range from reverse (e.g., Zagreb area), to pure strike-slip (e.g., Petrinja area).

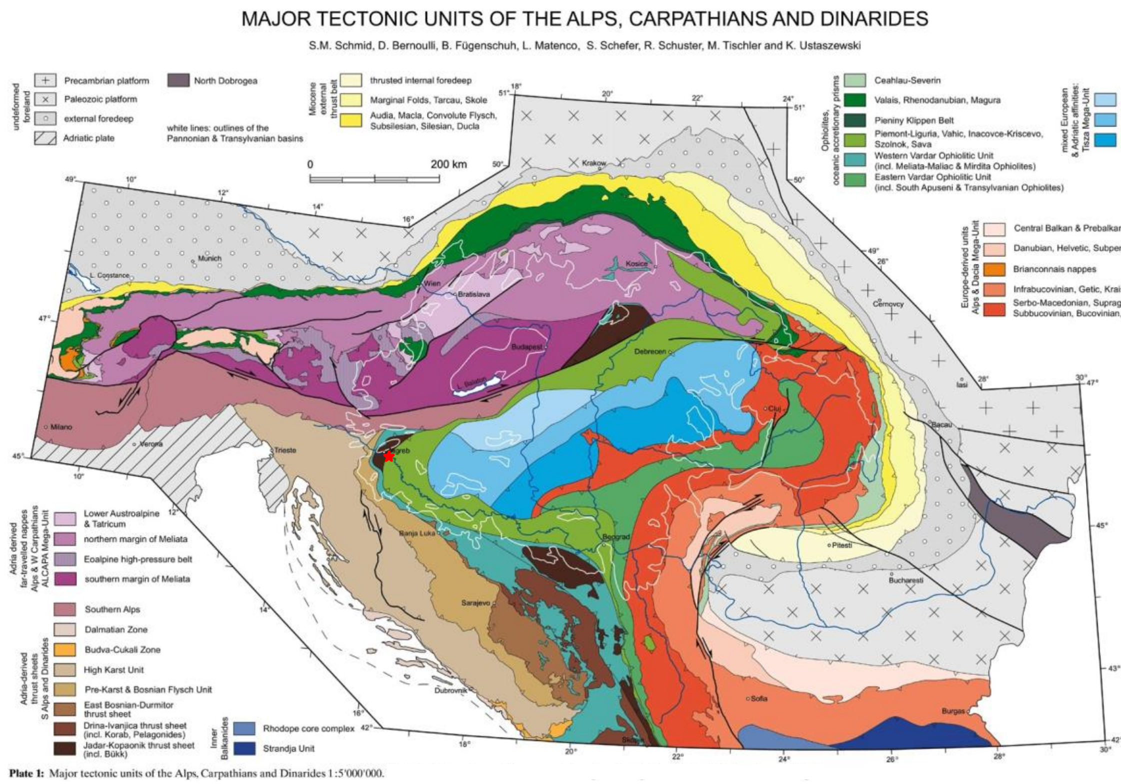


Figure 2.3 Location of Croatia concerning major surrounding tectonic units, also showing the epicenter (red star) of the Petrinja earthquake (adapted from Schmid et al., 2008).

2.3 Historical Seismicity of Croatia

The Croatian Earthquake Catalog (CEC, first described by Herak et al., 1996 and updated until the end of 2019) now lists over 120,000 earthquakes in Croatia and the neighboring regions. Its completeness threshold is estimated below M_L = 1.8 for the last decade, and over 10,000 earthquakes are added each year. The seismicity of the wider Zagreb area is directly linked to four seismic zones, including Zagreb, Novo Mesto–Krško, Karlovac–Metlika, and Pokupsko–Petrinja (**Figure 2.4**). The strongest seismic events in Zagreb epicentral area are related to the fault system of Medvednica Mountain, located north of the city of Zagreb. The earthquake, which occurred in Zagreb on November 9, 1880, also known as the “Great Zagreb earthquake, heavily damaged about 30% of the buildings, and nearly every house in Zagreb sustained some damage (Torbar 1882; Hantken von Prudnik, 1882; Herak and Herak, 2006). This was the first Croatian earthquake whose characteristics were determined through macro-seismic investigations and analyses. Next, the three strongest earthquakes in the Pannonian Basin, including the Zagreb and Pokupsko–Petrinja zones, which occurred in 20th and so far in the 21st century, are briefly described.

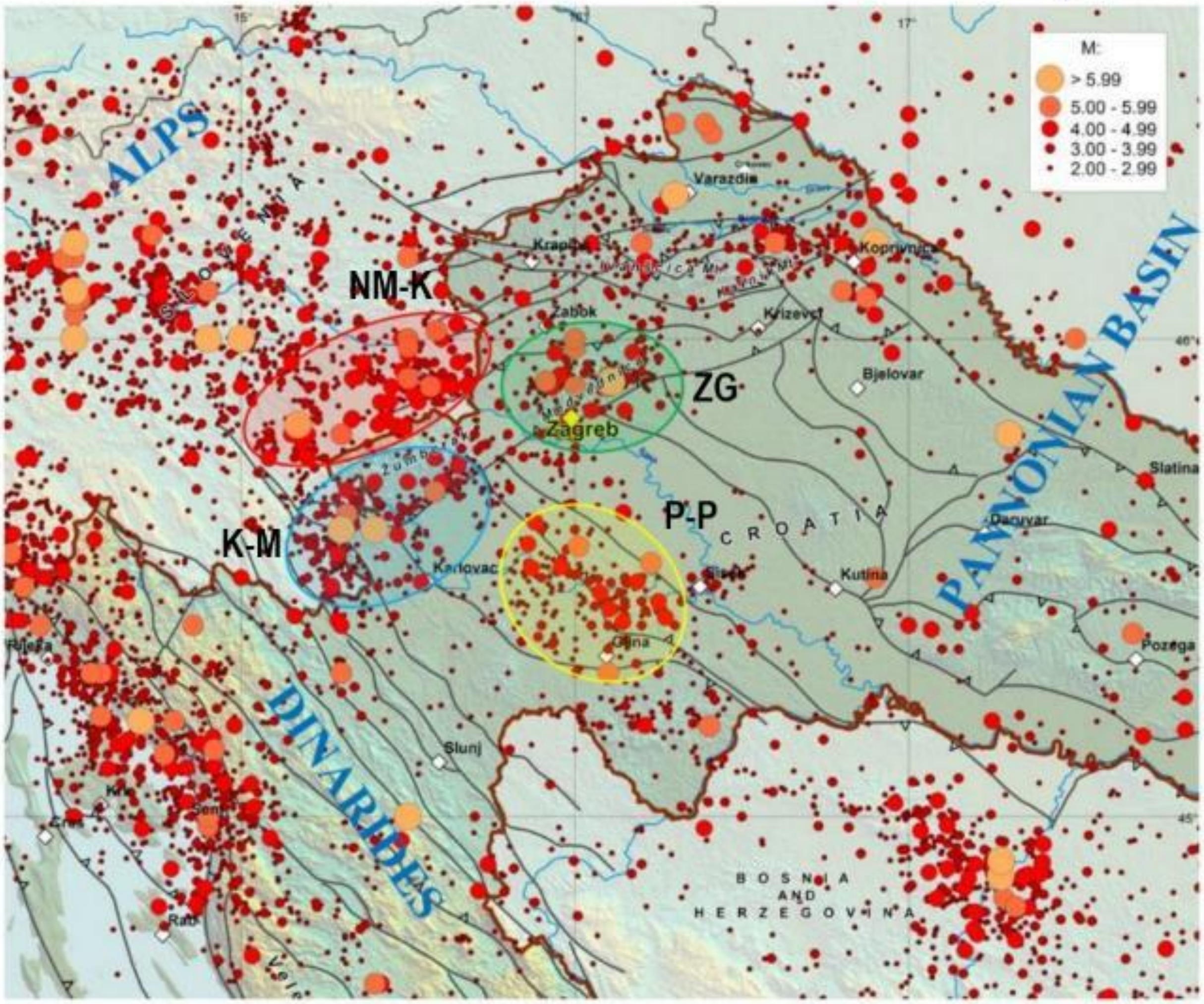


Figure 2.4 Spatial distribution of earthquake locations in the investigated area (373BC–2019, according to the Croatian Earthquake Catalogue (CEC), the updated version first described in Herak et al. 1996. Seismic zones are marked as: ZG (Zagreb) – green, NM-K (Novo Mesto–Krško) – red, K-M (Karlovac–Metlika) – blue, and P-P (Pokupsko–Petrinja) – yellow. Faults are marked with black lines (Ivančić et al., 2006, Ivančić et al., 2018), (adapted from Stanko et al., 2020).

<u>October 8, 1909 Earthquake</u>

On October 8, 1909, an earthquake occurred in Pokuplje ($M_S = 5.8$), with the epicenter located about 29 km south of Zagreb (Herak and Herak, 2010). This is the strongest known earthquake that occurred in Pokupsko–Petrinja zone before December 29, 2020. A number of seismographs, which were installed in Europe before this earthquake, provided invaluable data for Andrija Mohorovičić, a Croatian geophysicist. Based on the recorded seismograms, he determined that seismic waves reflect and refract upon striking a boundary between different materials in the Earth's interior, and longitudinal and transverse elastic waves propagate through rocks with different velocities. Mohorovičić concluded that the properties of rocks within the Earth must abruptly change at a depth of about 54 km, at the discontinuity, which separates the Earth's crust from its mantle, and is now known as the Mohorovičić discontinuity or simply the Moho. It is presently known that the thickness of the crust is 5–9 km below the ocean floor and 25–70 km below the continents.

Subsequent studies of the Earth's interior confirmed the existence of the discontinuity under all continents and oceans. Mohorovičić's theories were visionary at the time and were fully understood much later based on detailed observations of the effects of earthquakes on buildings and locating earthquake epicenters. The Kupa valley earthquake is cited in seismological literature predominantly in the context of the discovery of the Moho. Thus, the earthquake that occurred in Pokuplje on October 8, 1909, has been instrumental in geophysics for more than 100 years, and it has potentially a significant impact on the understanding of the December 29, 2020, Petrinja earthquake. More about Mohorovičić's contributions to seismology may be found by consulting translations into English of the original papers (Mohorovičić, 1910a,b; 1992; 2009), or in Herak and Herak (2007, 2010).

March 22, 2020 Earthquake

At approximately 6:24 am CET (5:24 am UTC) on March 22, 2020, an earthquake of magnitude 5.3 M_W with the hypocenter at a depth of 10 km struck Zagreb (**Figure 2.5**) (USGS 2020a). According to the Croatian Seismological Survey of the University of Zagreb (2020a), the earthquake had a magnitude of 5.5 M_L, and its epicenter was located 7 km north of the city in the northern suburbs of Zagreb. USGS ShakeMap depicted in Figure 2.5 (USGS 2020b) estimates PGA in the range of 0.2 g, which, along with the intensity of VII (MMI) is consistent with the observed levels of damage. The earthquake was felt throughout Croatia, in Slovenia, Bosnia and Herzegovina, Hungary and Serbia.

The focal mechanism of the earthquake was reverse faulting on a west-southwest–east-northeast trending fault (Tomljenović, 2020). Herak (2020) found that the rupture plane had a strike of 75° and dip angle of 45° to the south-southeast while USGS (USGS 2020b) reported a strike of 74°, but dip angle of 51°. According to Herak (2020), the axis of maximum tectonic pressure (P) was horizontal (with a plunge angle of 0° in the NNW–SSE direction), while the axis of maximum tension (T) was almost vertical with a plunge angle of 86°. The moment tensor solution for the March 22, 2020 earthquake (USGS 2020a) is shown in **Figure 2.6**.

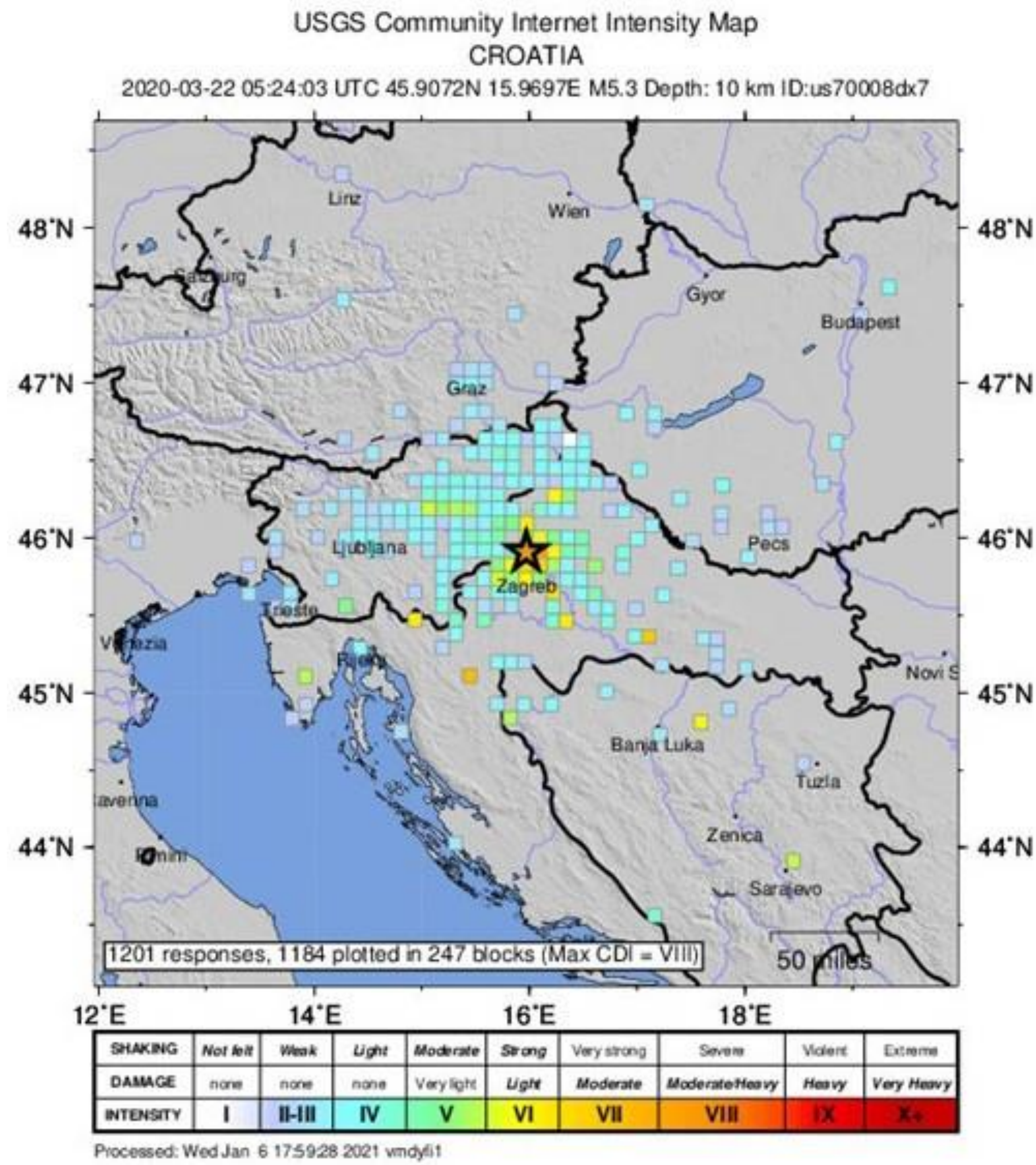


Figure 2.5 Intensity map estimated from ShakeMap of March 22, 2020 earthquake (source: USGS 2020a).

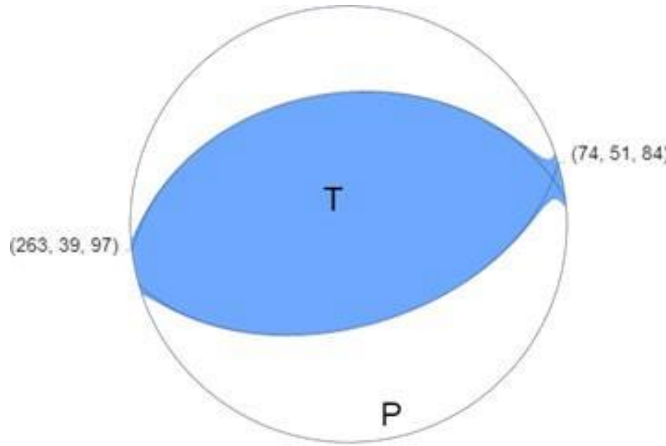


Figure 2.6 Moment tensor solution for the March 22, 2020 earthquake (source: USGS 2020a).

December 29, 2020 Earthquake

On December 29, 2020, at 12:20 pm (ETC), an earthquake of magnitude of $M_w = 6.4$ occurred near Petrinja, Croatia (**Figure 2.7**) (USGS 2020b). This is one of the two strongest earthquakes instrumentally recorded in Croatia. The earthquake was felt across Croatia and in neighboring countries. The earthquake was preceded by two sizeable foreshocks having magnitudes of 4.7 and 5.2 on December 28, 2020 (USGS 2020b). While most of the aftershocks have occurred within the Petrinja Fault zones, some of them occurred within the nearby Jastrebarsko and North Medvednica Fault. Nevertheless, due to the proximity of the Jastrebarsko and North Medvednica faults to the epicenter of the March 22, 2020, Zagreb earthquake, the aftershocks that occurred along these faults can be associated with the Zagreb earthquake.

Based on geological maps, field data, field prospecting, and available seismological and preliminary satellite data, the December 29, 2020 earthquake activated the fault system in the wider Sisak, Petrinja, and Glina area. The main fault is highlighted in **Figures 2.8** and **2.9**. The fault consists of multiple segments with strike-slip movement.

A large amount of released energy during the movement of fault blocks caused the ruptures in the rock to manifest on the surface of the terrain along with ground shaking. The various coseismic features resulting from the earthquake were open surface cracks, , fluid spills, gravitational slides, sand boils induced by liquefaction in Kupa and Sava river valleys, opening of cover-collapse sinkholes, deformation on the surface of the terrain, and deformation of the linear infrastructural objects.

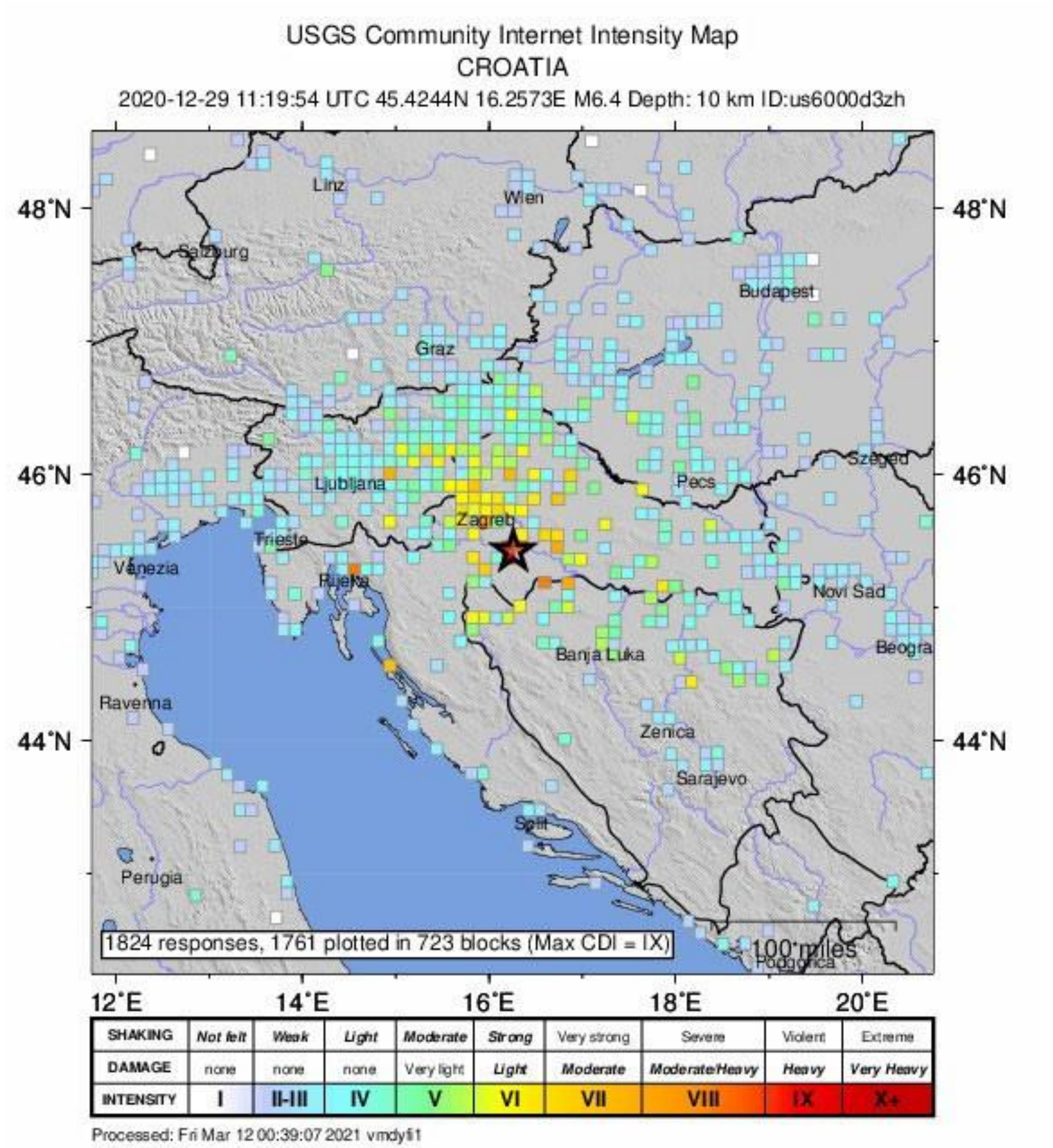


Figure 2.7 Intensity map estimated from ShakeMap of December 29, 2020 earthquake (USGS 2020).

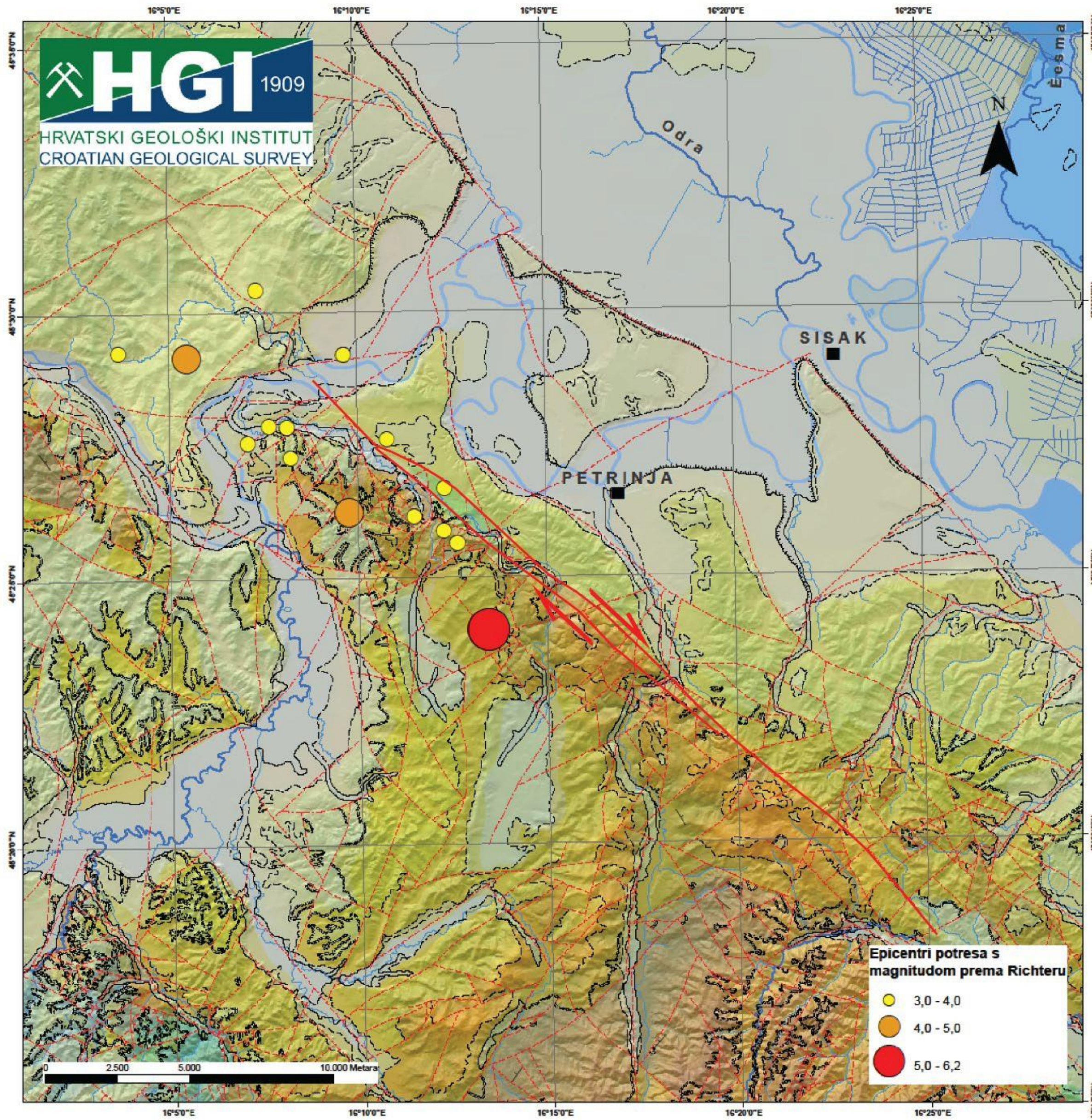
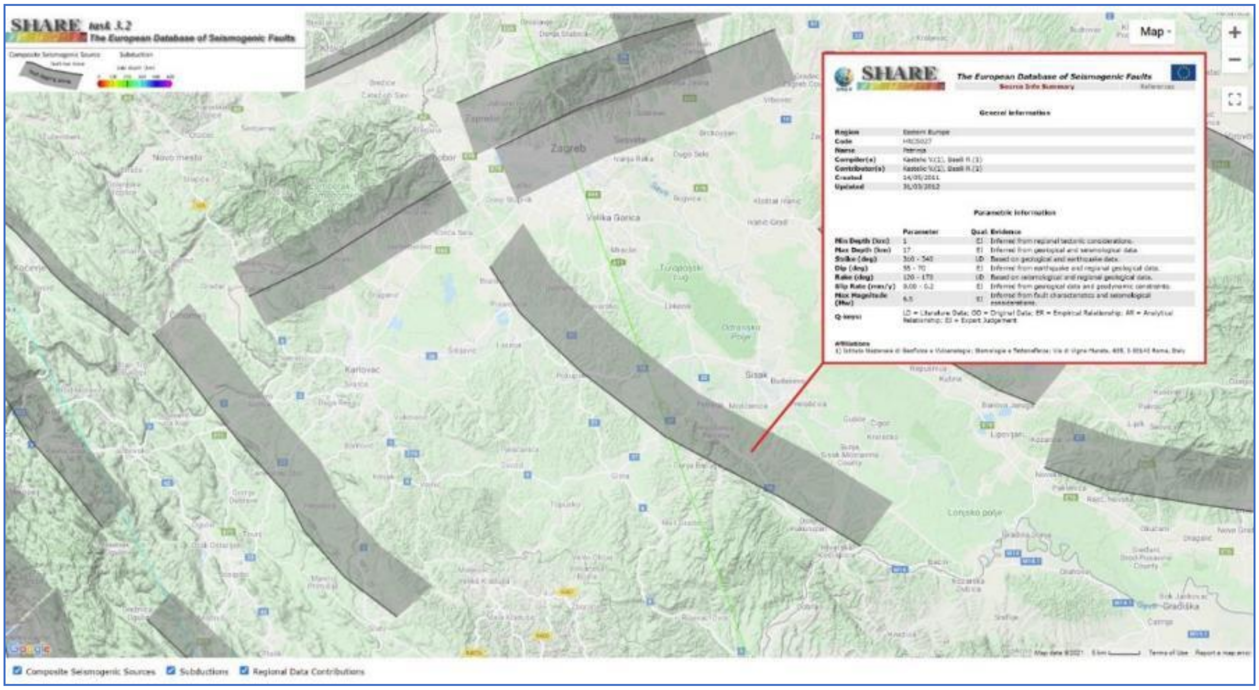


Figure 2.8 Excerpt from a geological map of a wider epicentral area: the fault (fault zone), which is preliminarily considered to be the cause of the main Petrinja earthquake and the series of weaker earthquakes, is marked in red. Prepared by Pavle Ferić on the geologic map by Pikija 1987 (Vukovski 2021)



SHARE

The European Database of Seismogenic Faults

Source Info Summary | References

General information

Region	Eastern Europe
Code	HRCS027
Name	Petrinja
Compiler(s)	Kastelic V.(1), Basili R.(1)
Contributor(s)	Kastelic V.(1), Basili R.(1)
Created	14/05/2011
Updated	31/03/2012

Parametric information

	Parameter	**Qual.**	**Evidence**
Min Depth (km)	1	EJ	Inferred from regional tectonic considerations.
Max Depth (km)	17	EJ	Inferred from geological and seismological data.
Strike (deg)	310 - 340	LD	Based on geological and earthquake data.
Dip (deg)	55 - 70	EJ	Inferred from earthquake and regional geological data.
Rake (deg)	120 - 170	LD	Based on seismological and regional geological data.
Slip Rate (mm/y)	0.08 - 0.2	EJ	Inferred from geological data and geodynamic constraints.
Max Magnitude (Mw)	6.5	EJ	Inferred from fault characteristics and seismological considerations.
Q-keys:	LD = Literature Data; OD = Original Data; ER = Empirical Relationship; AR = Analytical Relationship; EJ = Expert Judgement		

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Figure 2.9 Basic characteristics of the Petrinja Fault shown in The European Database of Seismogenic Faults (Basilli, et al 2013)

The moment tensor of December 29, 2020, Petrinja earthquake is shown in **Figure 2.10**. It indicates a strike-strip fault focal mechanism. One nodal plane corresponds to left-lateral movement with a slight thrust component on a fault striking in the NE–SW direction. The other nodal plane indicates right-lateral movement on a fault striking NW–SE and dipping sub vertically to the southwest. It is because NW–SE direction of the Petrinja fault that Fault Plane 2 is likely defining the causative fault.

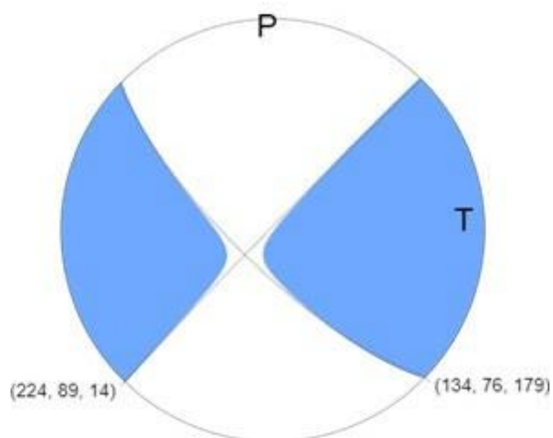

Figure 2.10 Moment tensor solution for the December 29, 2020 earthquake (source: USGS 2020b).

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