St. James's Church (Mali Vrh) consequences Petrinja earthquake. Photographer: Janezdrilc. Source: https://commons.wikimedia.org/wiki/File:St._James%27s_Church_(Mali_Vrh)_09.jpg (Wikimedia Commons)

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Branko Kordić
Croatian Geological Survey, Croatia, bkordic@hgi-cgs.hr

Stéphane Baize *
French Nuclear Safety and Radiation Protection Authority, France, stephane.baize@asnr.fr

Josipa Maslač Soldo
Croatian Geological Survey, Croatia, jmaslac@hgi-cgs.hr

ENVIRONMENTAL IMPACT ASSESSMENT AND SEISMIC HAZARD ANALYSIS: PETRINJA 2020 EXPERIENCE

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* corresponding author

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Croatian Geological Survey, Croatia, bkordic@hgi-cgs.hr

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French Nuclear Safety and Radiation Protection Authority, France, stephane.baize@asnr.fr

Josipa Maslač Soldo
Croatian Geological Survey, Croatia, jmaslac@hgi-cgs.hr

ENVIRONMENTAL IMPACT ASSESSMENT AND SEISMIC HAZARD ANALYSIS: PETRINJA 2020 EXPERIENCE

ABSTRACT

On December 29, 2020, a shallow magnitude 6.2 earthquake struck northern Croatia near Petrinja. This earthquake was preceded by a strong foreshock with a magnitude of 5. In response to the Petrinja earthquake, a team of European geologists and engineers from Croatia, Slovenia, France, Italy, and Greece was promptly mobilized to conduct a thorough assessment of the environmental impact of the earthquake. Their observations in the Petrinja area revealed surface deformation, tectonic breaks along the earthquake source at the surface, liquefaction features in the fluvial plains of the Kupa, Glina, and Sava rivers, and slope failures caused by strong motion. However, with the analysis of geodetic data, the team concluded that the field measurements largely underestimated the total coseismic deformation at the surface: a large part has been distributed and diffused off the main fault. Liquefaction extended over nearly 600 km^2 around the epicenter, with the typology of liquefaction features including sand blows, lateral spreading phenomenon spreads along the road and river embankments, and sand ejecta of different grain sizes and matrices. After a series of investigations along the 2020 earthquake causative fault, we documented several paleo-ruptures during the Holocene and evidenced a cumulative strike-slip fault displacement all along the Petrinja Pokupsko Fault (PPF), including a few of those segments which did not rupture in 2020. Based on the Croatian experience of the last three years, we stress that further detailed studies, including neotectonics, paleoseismological and geophysical investigations, could bring new relevant information on the seismic activity and seismic hazards in the regional fault zone, the southern continuation of the PPF, along the related fault zone that stretches towards Kostajnica.

Keywords: *earthquake, investigation, field survey, seismic hazard.*

1. INTRODUCTION

The ML 6.2 Petrinja earthquake that occurred on 29 December 2020 is one of the largest continental earthquakes in central Europe since the ML 6.5 earthquake in Central Italy in 2016 and the ML 6.4 Durres earthquake in Albania on 26 November 2019, both in the Central Mediterranean area. The characteristics of this earthquake closely resemble those of the 1969 earthquake in Banja Luka, which had a mainshock of magnitude 6.4, preceded by a strong foreshock with a magnitude of 6.0. The series of earthquakes that occurred in the Petrinja area in 2020, as well as the earthquake near Zagreb nine months earlier, resulted in the loss of human lives and significant damage to infrastructure and buildings. The material damage is enormous and will take years to repair.

This 2020 earthquake cannot be claimed as a “surprise”: the historic Croatian earthquake occurred on 8 October 1909 very close to Petrinja (20 km to the northwest), and it is known as the Pokupsko or Kupa Valley earthquake [1,2]. Both earthquakes present focal mechanisms consistent with the activation of an NW-SE right-lateral fault, which belongs to the fault system that runs along the southwestern margin of the Pannonian basin. After the 2020 Petrinja event, HGI (Croatian Geological Survey), in collaboration with a European team of geologists and engineers from France, Italy, Slovenia, and Greece, conducted a detailed survey of the environmental effects on the surface after the Mw 6.4 earthquake near Petrinja in December 2020. Despite field challenges (rain, snow, COVID-19, minefields), more than 700 observation points were collected on an area of 625 km^2 [3] and then analyzed in the office and laboratories. Field research was conducted using an existing geological map at a scale of 1:100,000, a 1:5,000 topographic map, historical aerial photogrammetric data provided by the Croatian State Geodetic Administration, and InSAR interferograms derived from Sentinel-1 satellite observations. An Unmanned Aerial System (UAS) was used during the fieldwork to document surface evidence. Airborne Laser Scanning (ALS) measurements were also conducted to generate high-resolution Digital Terrain Models (DTMs). These DTMs provided a foundation for on-site research and further investigation within a Geographic Information System (GIS) environment. An office spatial analysis was then conducted for a specific location in preparation for upcoming paleoseismological research. Following this analysis, the identified sites underwent further examination through the implementation of Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) geophysical profiles.

The Petrinja earthquake took place nine months after a magnitude 5.5 earthquake hit the City of Zagreb on March 22, 2020—Zagreb's strongest instrumentally recorded seismic event since Andrija Mohorovičić established the first seismograph in 1908. In contrast with the 2020 Petrinja earthquake, this event shows reverse kinematics along an ENE-WSW blind fault [4]. Seismic activity in the Zagreb region is well-documented, indicating high seismic hazard [5]. The earthquake caused extensive damage to residential buildings, especially those built in the first half of the 20th century [4]. Unfortunately, in addition to material damage, the earthquakes that occurred in 2020 in the areas of Zagreb and Petrinja also claimed human lives and had lasting consequences on people's lives, which was further worsened by the quarantine due to COVID-19 [6]. In contrast with the 2020 Petrinja earthquake, this event shows reverse kinematics along an ENE-WSW blind fault [5].

Basili [7] used at least partly the available information on those historical and instrumental earthquakes, as well as geological data, to define the main crustal earthquake sources of the region (Figure 1). Besides the ENE-WSW striking, south-dipping and left-reverse source beneath Zagreb, a 75 km-long NW-SE dextral source crosses almost the entire north-central territory of Croatia and terminates at Kostajnica. In the south, a series of NW-SE dextral sources are aligned, running beneath Banja Luka and Sarajevo.

This depiction of sources aims to represent the seismic hazard associated with major geologic features, supported by first-order evidence, for a calculation at the continental scale. However, it is a drastic simplification of the tectonic "reality". For instance, it does not match either the actual segmentation of the PPF or its real dip, as shown by the recent studies performed by the EU-Group [8,9]. To properly describe the earthquake sources, especially in order to further evaluate the hazards at the site-specific level, we claim that a proper analysis and interpretation of active faults and related effects is of primary importance. Because there is evidence that the NW-SE faults running across Croatia (under study) have a continuation in the northern part of Bosnia and Herzegovina, we emphasize that cooperation between the so-called EU group and the scientists from Bosnia and Herzegovina is paramount.

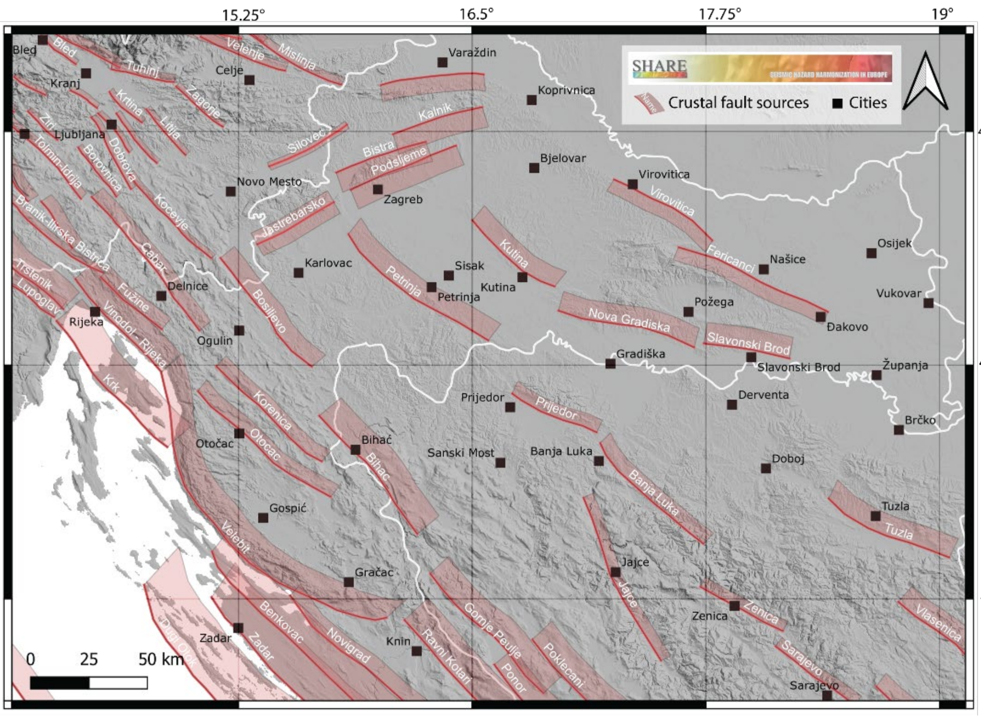

Figure 1. Map of seismic sources from SHARE European Earthquake Catalogue; shaded relief map produced from Copernicus 25 m Digital Elevation Model; WGS84 coordinate system

2. METHODOLOGY

Significant crustal earthquakes with a magnitude greater than six often lead to noticeable immediate effects, such as surface faulting, uplift, and subsidence, which are directly associated with the seismic rupture occurring deep underground. These effects are reliable indicators of the earthquake's location, magnitude, and movement. Secondary effects, including ground failure and liquefaction, are influenced by the extent and pattern of the earthquake ground motion, along with specific geological and geomorphic conditions. The primary and secondary coseismic effects noticed during a major modern earthquake like the Petrinja one, which had directly threatened the structural integrity of buildings and infrastructure in 2020, are expected to reproduce during future earthquakes of similar characteristics. In hazard assessment, modelers need to understand whether larger events could be possible, and hazard calculation requires an estimation of the recurrence of such events. The classical approach to do so is to extend the recordings of modern events to ancient times, as far as they were generated within the same seismotectonic and stress contexts.

Acquiring geodetic velocity fields is recommended to complete the understanding of the regional seismotectonic and fault behaviour. This can be done through GNSS data sets or interseismic analysis of InSAR data. Thanks to this, we can estimate potential rigid or semi-rigid blocks, zones of deformation accommodation (typically fault zones), and relative motions (rate of displacement per year).

2.1. SEISMOTECTONIC AND GEOLOGICAL BACKGROUND

Central Croatia is a seismically active region with a dense population and several active fault systems, many of which have yet to be fully characterized in terms of their seismic activity. The PPF is currently the only fault that has been partially studied and documented, mainly due to its identification as the main source of the 2020 Petrinja Earthquake [7]. Regionally, this fault is situated at the boundary between the southwestern margin of the Pannonian Basin system and the Internal Dinarides [10]. The complex Cenozoic tectonics in this region are related to the slow convergence of the Adriatic microplate and the Eurasian plate [11, 12], initiated by the obduction of ophiolites on the eastern margin of the Adriatic microplate. Throughout the Oligocene–Miocene, the Adriatic microplate shifted northward, while the European plate retreated eastward, resulting in the lateral extrusion of the Eastern Alps and Tisza tectonic blocks [13]. These pivotal tectonic events have been the primary drivers of the current structural configuration, which has undergone various changes in tectonic regimes during the evolution of the Pannonian Basin System [14]. Miocene extension enabled the Pannonian Basin system to open through the formation of NW-SE-oriented normal faults, which were later inverted during the Pliocene-Quaternary compressional phase.

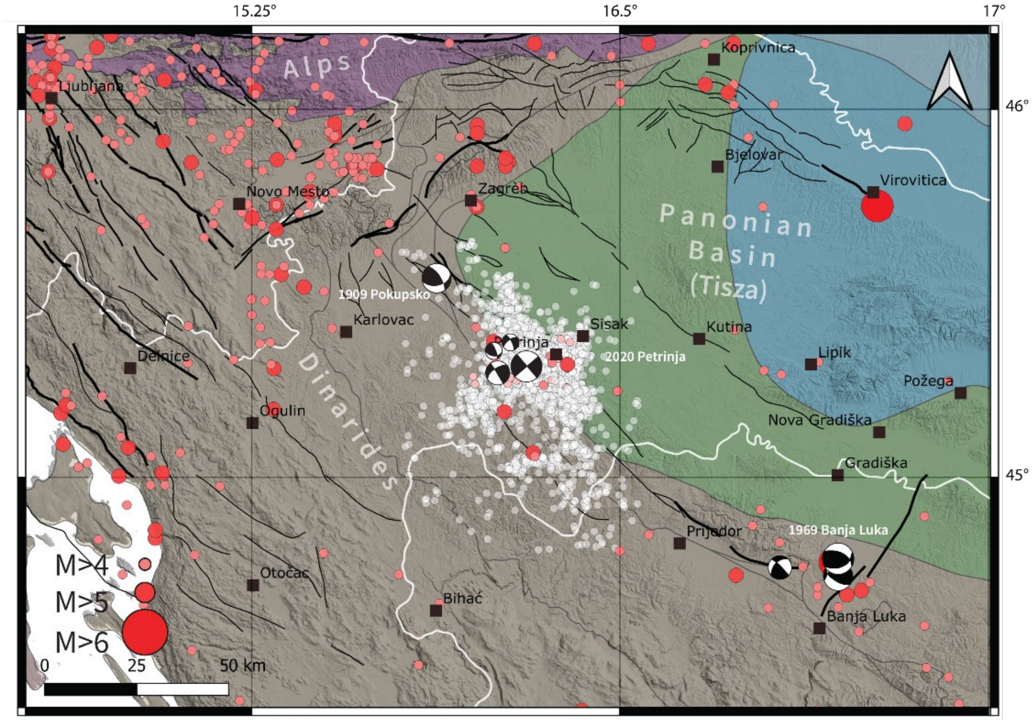

Figure 2. An overview of seismicity with the highlighted Petrinja earthquake series [1,15] combined with a European database of epicenters larger than M>4 on a 25 m hillshade colored according to the main tectonic units- Alps, Dinarides and Pannonian Basin; depicting active and potentially active faults (modified after [8]); WGS84 coordinate system

The present compressional/transpressional phase of the Croatian part of the Pannonian Basin is confirmed by geodetic measurements [9, 16] and a multitude of earthquake focal mechanisms, which are consistent with dextral kinematics of the NW-SE PPF. The seismic events of the Petrinja series [15] confirm the kinematics of the NW-SE striking dextral PPF. The southern segment of the PPF system extends towards the East Bosnian–Durmitor thrust in Bosnia and Herzegovina, while the northern segment continues through the Vukomeričke gorice, where the historic Pokupsko earthquake of 1909 (M > 5.8) was recorded [2]. This event provided crucial insights into the Moho layer and was instrumental in reconstructing the seismic kinematics, demonstrating the dextral-transpressive activation of the northern segment.

The northern part of Vukomeričke Gorice is less pronounced geomorphologically and is covered by younger Pliocene and Quaternary deposits, whereas the main part of the system is characterized by the uplift of Hrastovica Hills, constituted of Neogene deposits: this is along this latter section that the 2020 surface rupture occurred [17,18]. The tectonic uplift of Hrastovica is confirmed by borehole data and seismic profile analysis [8]. The post-earthquake survey has shown that the majority of the ruptures are located within Badenian (Middle Miocene) limestones and Pleistocene and Holocene unconsolidated sediments. Further paleoseismological research focuses specifically on these youngest sediments, where the most recent potential deformations caused by paleoseismic events are likely to be preserved.

2.2. GEODETIC ANALYSIS OF THE PETRINJA EARTHQUAKE USING GNSS AND INSAR DATA

The importance of geodesy has grown with advancements in technology and spatial data collection methods. After the 2020 Petrinja earthquake, we acquired unique geodetic datasets through field investigation. The deformation pattern of such events is often challenging to capture using terrestrial geodesy due to the constraints of monitoring resources. Following this event, we could take advantage of the data from a dense near-field network of numerous geodetic benchmarks. However, a multidisciplinary approach is required to calculate position corrections based on the geodynamics of the research area. This allowed for the accurate evaluation of the slip distribution causing the earthquake [9].

Before the Petrinja earthquake sequence, benchmarks were established for cadastral and engineering purposes (2003–2020). They were remeasured just after the sequence (8 January 2021–13 March 2021) using a GNSS receiver and Croatian Positioning System (CROPOS), an online service for precise positioning. The geodetic benchmark kinematic measurements are accurate at the centimetre level, while the deformation values are at the level of a few decimetres. The largest displacement values resulting from the seismic activity were observed near the Petrinja centre, with a magnitude of 75 cm in the ESE direction. Sisak experienced planar displacements of approximately 7 cm to the east, while in Glina, the displacements were noted at around 6 cm in the NW direction. Notably, the most significant NW displacements, measuring 65 cm, were recorded in Strašnik, near the epicentre. This rich dataset allowed for the reconstruction of a dense displacement field related to the sequence and was therefore used to assess better the displacement field recorded after the event on 29 December 2020 and inform about the slip distribution on the earthquake source [8,9].

Rapid re-measurement of preexisting civilian networks provides unique coseismic constraints in the near field, particularly useful where InSAR may experience decorrelation [9]. The Sentinel-1 constellation captured surface deformation thanks to pre-earthquake (18 December 2020) and post-earthquake (4 January 2021) SAR images. The GNSS and Sentinel-1 SAR images show that the movements related to the 2020 earthquake are consistent with a right-lateral motion along the NW–SE striking PPF zone, covering approximately 10-15 km. The initial analysis of the line-of-sight displacement from the earthquake's InSAR signal clearly indicated that surface rupture may have occurred, which partly guided our field survey.

The coseismic InSAR signal is somewhat obscured in the anticipated area of the ground breaks. The low coherence observed in the near-field fault area could be attributed to the presence of vegetation, water, soft-sediment deformation, or even liquefaction. However, the detection of post-seismic deformation was possible to document, relying on the analysis of a set of ascending and descending InSAR time series data from December 30, 2020, to January 28, 2021. The observed ground deformation patterns, both during (coseismic) and after (post-seismic) the seismic event, align with a significant right-lateral and NW–SE oriented surface fault trace, fitting to the surface breaks checked in the field [8].

Figure 3: Geodetic benchmark post-seismic observation with GNSS receiver. Photo by authors.

2.3. INSIGHTS FROM THE PALEOSEISMOLOGICAL STUDIES ON THE 2020 PETRINJA EARTHQUAKE"

Paleoseismology is a robust methodology for studying past earthquake activity at a specific fault or region (see [19] for a comprehensive overview). It provides valuable information to the understanding of the active tectonics still at work and yields critical data to hazard modelers. Paleoseismology performed directly on the fault is a primary source of information because it directly provides data on the earthquake source. The common bias of this approach is the poor completeness of stratigraphic information (and then we can miss events), which can be compensated for in extensive and well-dated sedimentary records like lakes [20]. However, these methods are not always available close to a fault, and they tend to provide inadequate constraints on the spatial parameters (i.e. lacustrine layers record near-field and far-field earthquakes). When the coseismic effects are found in the stratigraphy of recent deposits and soils on a fault, this represents evidence for the occurrence of an earthquake in the past along this structure. This evidence can then be characterized in terms of age, location and size. The repetition of large surface-rupturing earthquakes on the same fault leaves a cumulative, permanent signature in the landscape that defines an active fault. Therefore, even though they may not have produced earthquakes in modern times, the active faults are visible and mappable at the surface through the morphological signature of past earthquakes, and a level of hazard can be associated. This signature is specific and recognizable in the morphology and contains information on their behaviour: deciphering this information documents the seismic hazard of a region. For instance, a careful geomorphological analysis of the PPF allowed the identification of right-lateral offsets of river channels and terraces that cross perpendicularly to the fault, corresponding to the cumulative effect of similar right-lateral faulting events in the past millennia [21].

The Petrinja earthquake effects gave us important information potentially helpful to decipher the fault behaviour from geological, geomorphological and paleoseismological information: the significant proportion of off-fault deformation determined with spaceborne and terrestrial geodetic observations leads us to a crucial methodological statement. Thus, to be complete, we must account for deformation accommodated over a wide zone (at the several hundred meters scale) when analyzing geomorphological and paleoseismological information. The first trenches dug between 2021 and 2023 confirmed this off-fault distribution of deformation [22]. This means that, in the future, in order to get a more complete assessment, we should, for instance, trench parallel and branching segments or consider long piercing lines crossing the fault zone in geomorphological analyses.

The NW-SE PPF is today the best-known active fault due to the occurrence of the 2020 earthquake. Several months later, a series of new actions were engaged, particularly concerning earthquake geology and the tectonic morphology of that fault bearing the 2020 surface ruptures. However, very little is known about the other NW-SE potential active faults that stretch north and south to Slovenia and Bosnia and Herzegovina, their relationships with NE-SW contractional faults, such as the one that caused the March 2020 earthquake below Zagreb, the capital city of Croatia. Considering the similarities between all these areas in terms of fault characteristics and local geology, the warning expressed in the previous paragraph on the methodological aspect is applicable to Bosnia and Herzegovina. Our suggestion is, in parallel to the studies in Croatia, to reconstruct the seismic history of the NW-SE PPF by mapping and defining its long-term seismic history. A similar project is engaged in Bosnia and Herzegovina on the faults running beneath/close to Banja Luka and Sarajevo.

Paleoseismological studies provide specific parameters that are essential for the evaluation of seismic hazards. Among these parameters, the slip rate of a fault is particularly significant and can be assessed using trench information and geomorphological analysis. Analyzing the stratigraphic signals present in trenches is crucial for establishing a timeline of surface-rupturing earthquakes, especially when the sediments affected and unaffected by faulting contain datable material. Under favorable conditions, it is possible to estimate the displacement that occurs during faulting events, which is closely related to the magnitude of those events. To further our understanding, we have engaged in or are preparing to engage in the following actions in Croatia:

- A comprehensive geomorphological study of the fault zone was conducted using a high-resolution LiDAR-based Digital Terrain Model (DTM) with a one-meter resolution. This analysis focuses on the area affected by the 2020 earthquake (see Figure 4). It has been possible to identify and locate the potential active fault segments surrounding the 2020 Petrinja earthquake surface rupture [21]. The fault pattern appears distributed over hundreds of meters to kilometers around the Hrastovica Hills front and is coupled with an active fold to the north. We could identify relevant sites that show a long-term displacement (on the order of tens of meters) of morphological features. Sampling campaigns have been conducted to date alluvial terraces using cosmogenic isotopes and radiocarbon (14C). This process has allowed us to establish slip rate values for each parallel fault segment. After a precise fault mapping based on geomorphology, surface geophysics is usually performed before trenching. This has been done in the past two years following the 2020 earthquake, with a series of GPR, ERT, and seismic surveys have been done to locate the further paleoseismological trenches [22,23] successfully. We can also envisage using GPR (or ERT), these geophysical techniques, to map piercing lines buried linear features that cross fault zones because the main component of faulting is to estimate the lateral component of displacement and then calculate their displacement and rate of displacement if they can be dated. The deformation zone width is large, so one strategy to overcome this limiting factor could be to trace a channel edge (for instance) and try to map it across the fault zone. Such an approach in Bosnia and Herzegovina will probably require the acquisition of a spatial dataset for high-resolution DTM.

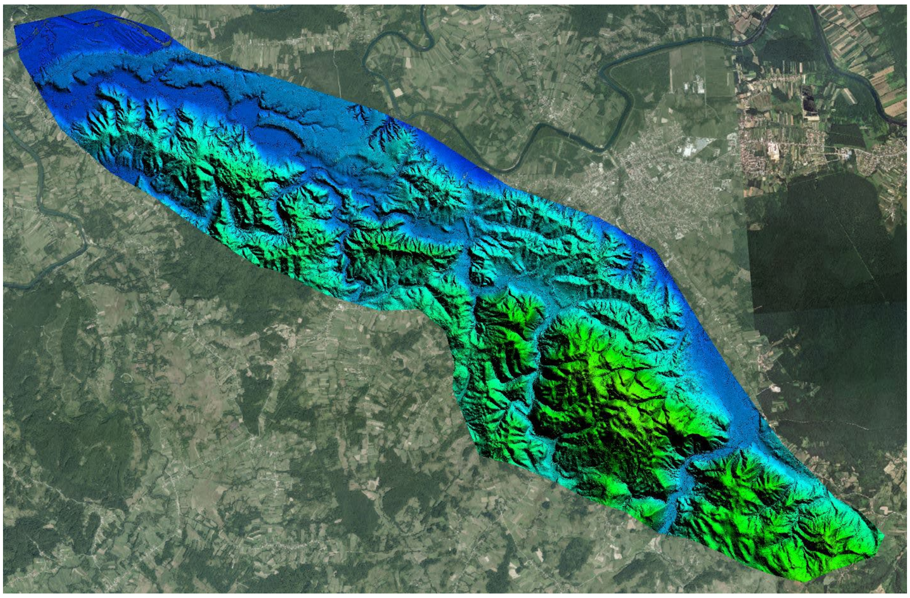

Figure 4: Orthophoto overlayed with high-resolution lidar-based DTM of the research area

- Paleoseismological trenching studies were initiated for the first time in Croatia to investigate the structure of the PPF and recognize its past activity. The first trench walls revealed the style of deformation at shallow depth, composed of faulting and warping in a wide zone that occurs persistently in coincidence with the morphologic fault scarp and 2020 ruptures at the surface. The permanent signature in the trenches' exposures suggests cumulative coseismic deformation, with a series of events during the Holocene and possibly with Roman-age and historical ones. However, we still need to work on the datasets of four trench sites to formulate a coherent calendar of events.

Figure 5: The first-ever trench excavated in Croatia, in Hrastovica, along the PPF that ruptured during the 2020 Petrinja earthquake. The central section shows white material (fine sands) corresponding to uplifted Pliocene-Miocene within the Holocene soils and sediments during successive coseismic offsets. Photo by authors.

Figure 6: Detail of a trench wall dug across the northernmost section of the 2020 Petrinja surface rupture in Medurace. The section shows that a series of fault strands displaces the whitish to yellowish sands at the bottom (probably Pliocene to Miocene in age), together with overlying pebbles and silts (probably Pleistocene to Holocene) during successive faulting events. The height of the wall is ~2 meters. Photo by authors.

3. CONCLUSION

The 2020 Petrinja earthquake is one of the most significant inland earthquakes of this decade. Although it is tragic, a unique opportunity has been created to survey and document new datasets and information about the earthquake and its manifestation on the earth's surface. Following the earthquake, the staff of the Croatian Geological Institute formed field groups. Soon after, teams from other EU institutions arrived at the site. This extensive and rapid mobilization of field earth scientists enabled regional field geologists and specialists in the geological impact of earthquakes to collaborate. We conducted a detailed examination of the primary surface evidence in the field, thoroughly documented our findings, and collected evidence that is often compromised due to the involvement of other services.

Geodetic benchmarks established for trigonometric and control networks play a crucial role in providing valuable information about fault sources and complementing satellite methods. This method is relatively cost-effective compared to the resources needed to maintain permanent stations. Therefore, it's essential to prioritize their installation, maintenance, and proper documentation.

Surface evidence is related to the main event, as the aftershocks were not intense enough to cause superficial deformations. Based on field observations, processing and analysis of earthquake environmental effects, we have characterized the fault as NW-SE oriented right-lateral strike-slip. Future research will investigate structures to the north and south. In addition, paleoseismological research and geophysical field surveys will be conducted at the sites (markers).

A paleoseismological investigation needs significant experience to be efficient and to provide relevant information, which could be shared by our team during future cooperation with regional scientists. The collected datasets and pieces of information will be organized into a unique database, which will be permanently stored for current and future generations of researchers.

4. ACKNOWLEDGEMENTS

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AUTHORS' BIOGRAPHIES

Branko Kordić

Dr. Branko Kordić is a Research Associate at the Croatian Geological Survey (HGI-CGS). His work specializes in satellite geodesy, hydrography, remote sensing, and geodynamics, utilizing modern geodetic techniques for the collection of spatial data. He utilizes methods such as LiDAR, InSAR, GNSS, and UAS, which are crucial for gathering and analyzing information about the surface effects of earthquakes. Currently, he is working on research that focuses on assessing the seismic impacts of recent earthquakes through advanced geodetic methods.

Stéphane Baize

Stéphane Baize is a senior geologist specializing in earthquake geology (geomorphology and trenching), Quaternary geology and seismic hazard assessment. He is affiliated with the Nuclear Safety Agency in France, where he works in the Seismic Hazard Division. His professional activities and scientific interests focus on studying active faults, paleoseismology, and surface rupture surveys to contribute to seismic hazard studies. He has been involved in various research projects in France and around the world, including in the Balkans and Italy, South America and New Zealand, among others.

Josipa Maslač Soldo

Josipa Maslač Soldo is a young scientist, a research assistant at the Croatian Geological Institute, and a PhD student at the Faculty of Mining, Geology, and Petroleum Engineering at the University of Zagreb. Her research focuses on active faults in central Croatia and coseismic phenomena. She applies expertise in tectonic geomorphology and seismotectonics, as well as applied geophysics, to investigate active fault segments, thereby contributing to the geological understanding necessary for a more effective assessment of seismic hazards.

ПРОЦЈЕНА УТИЦАЈА НА ЖИВОТНУ СРЕДИНУ И АНАЛИЗА СЕИЗМИЧКОГ ХАЗАРДА: ИСКУСТВО ИЗ ПЕТРИЊЕ (2020.)

Сажетак: Дана 29. децембра 2020. године, сјеверну Хрватску у близини Петриње погодио је плитак земљотрес магнитуде 6,2. Овом земљотресу претходио је снажан потрес магнитуде 5. Убрзо након тога, тим европских геолога и инжењера из Хрватске, Словеније, Француске, Италије и Грчке био је мобилисан ради спровођења свеобухватне процјене утицаја земљотреса на животну средину. Њихова запажања у подручју Петриње открила су површинске деформације, тектонске пукотине при површини дуж сеизмичког жаришта, појаве ликвефакције у алувијалним равницама ријека Купе, Глине и Саве, као и урушавања косина изазвана јаким помјерањем. Ипак, анализом геодетских података тим је закључио да теренска мјерења знатно потцјењују укупну косеизмичку деформацију на површини: велики дио деформације био је распрострањен и расут изван главног расједа. Ликвефакција се проширила на готово 600 km² око епицентра, а забиљежене појаве укључују пјешчане ерупције, латерална ширења дуж путева и ријечних насипа, те избацивање пијеска различитих величина и састава. Након низа истраживања дуж расједа који је проузроковао земљотрес 2020. године, документовано је више палеорасједа током Холоцена и утврђено је кумулативно хоризонтално помјерање дуж цијелог расједа Петриња–Покупско, укључујући и сегменте који се нису помјерили 2020. године. На основу хрватског искуства из протекле три године, наглашавамо потребу за даљим детаљним истраживањима, укључујући неотектонска, палеосеизмолошка и геофизичка испитивања, која би могла пружити нова значајна сазнања о сеизмичкој активности и сеизмичким хазардима у зони регионалног расједа, односно јужном наставку расједа Петриња–Покупско, дуж повезане расједне зоне која се протеже према Костајници.

Кључне ријечи: *земљотрес, истраживање, теренска мјерења, сеизмички хазарди*