DOI: https://doi.org/10.14256/JCE.4445.2025

Građevinar 5/2026

Primljen / Received: 30.10.2025.
Ispravljen / Corrected: 3.5.2026.
Prihvaćen / Accepted: 7.5.2026.
Dostupno online / Available online: 10.6.2026.

Monitoring seismic activity following 2020 Petrinja earthquake

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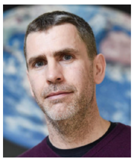

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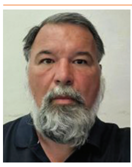

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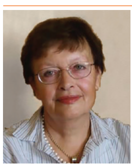

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Original research paper

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Monitoring seismic activity following 2020 Petrinja earthquake

The series of earthquakes in the Petrinja area began on Monday, 28 December 2020, at 6:28 a.m. local time (CET), with an earthquake of magnitude M_L = 5.1 (M_W = 4.9), which was felt across most of central Croatia. Its epicentre was southwest of Petrinja, near Strašnik village. This was soon followed by earthquakes of local magnitude 4.6, 7:49 a.m. and magnitude 3.8 at 7:51 a.m. in the same epicentral area, as well as a series of weaker earthquakes. Unfortunately, these relatively strong earthquakes proved to be just foreshocks, as an even stronger earthquake of local magnitude 6.2 (M_W = 6.4) occurred the next day, 29 December 2020, at 12:19 p.m., also with an epicentre near Strašnik. The cornerstone of this study is the vast amount of seismological data collected. We used both manual and advanced machine learning techniques to analyse the newly collected dataset. This resulted in a substantially expanded seismic catalogue with over 50,000 events. Seismicity analysis confirms that the largest events align with the primary dextral strike-slip Petrinja Fault; however, the aftershock pattern evolved, revealing that stress redistribution activated numerous secondary faults, leading to a complex spatial and temporal distribution of seismicity. The findings provide a detailed seismological record and crucial insights into the tectonic processes of this intraplate region.

Key words:
Petrinja, earthquake, aftershock, seismic network, machine learning

Izvorni znanstveni rad

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Praćenje seizmičke aktivnosti nakon potresa u Petrinji 2020. godine

Niz potresa na području Petrinje započeo je u ponedjeljak 28. prosinca 2020. u 6:28 po lokalnome vremenu (CET) potresom magnitude M_L = 5,1 (M_W = 4,9), koji se osjetio na većemu dijelu središnje Hrvatske. Epicentar se nalazio jugozapadno od Petrinje, u blizini sela Strašnika. Ubrzo su uslijedili potresi lokalne magnitude 4,6 u 7.49 te magnitude 3,8 u 7:51 u istome epicentralnom području, kao i niz slabijih potresa. Nažalost, ti relativno snažni potresi pokazali su se tek prethodnim potresima, jer je već sljedećeg dana, 29. prosinca 2020. u 12:19, zabilježen još jači potres lokalne magnitude 6,2 (M_W = 6,4), također s epicentrom u blizini Strašnika. Temelj ove studije čini velika količina prikupljenih seizmoloških podataka. Za analizu novoprikupljenog skupa podataka korišteni su klasični postupci analize te napredne metode strojnog učenja. Time je dobiven znatno proširen seizmički katalog s više od 50.000 potresa. Analiza seizmičnosti potvrđuje da su najveći potresi usklađeni s glavnim desnim Petrinjskim rasjedom, s pomakom po pružanju, no evolucija naknadnih potresa pokazala je da je preraspodjela naprezanja aktivirala brojne sekundarne rasjede, što je dovelo do složene prostorne i vremenske raspodjele seizmičnosti. Rezultati pružaju detaljan seizmološki uvid u procese u tome žarišnom području unutar tektonske ploče.

Ključne riječi:
Petrinja, potres, naknadni potresi, seizmička mreža, strojno učenje

1. Introduction

The Petrinja earthquake (M_w = 6.4; M_L = 6.2) on 29 December 2020 was one of the most important earthquakes that occurred in Croatia over the last several centuries. The mainshock was preceded by a strong foreshock (M_w = 4.9; M_L = 5.0) that occurred one day earlier, whereas the largest aftershock (M_w = 4.7; M_L = 4.9) was recorded on 6 January 2021. The seismicity of the area and detailed analyses of the famous Kupa Valley earthquake are presented in, for example, u [1, 2].

According to [1], the mainshock caused extensive destruction in the epicentral area. Shaking was felt throughout Croatia and Slovenia, as well as across much of Bosnia and Herzegovina, Serbia, Hungary, Italy, Austria, and Slovakia, with seven fatalities reported. Ground shaking triggered numerous secondary effects, including liquefaction, mud boils, sand volcanoes, landslides, and more than 100 sinkholes near the village of Mečenčani, southeast of the epicentre (Figure 1). Further details on the impact, damage and related effects are provided in, for example, [3-9]. This large intraplate strike-slip event drew considerable attention from the international seismological community. A preliminary analysis of early observations was provided by [10], whereas numerous subsequent studies focused on characterising the seismic source (e.g. [11-16]). The Coulomb stress changes following the main rupture were examined by [1, 14, 15, 17]. Several studies have analysed InSAR satellite data to interpret surface deformation (e.g. [14, 15, 18, 19]). A detailed spatio-temporal analysis of the Petrinja earthquake sequence during its first six months, including the relocation of more than 13,800 events using source-specific station corrections, evaluation of epistemic location uncertainty, computation of focal mechanisms, and assessment of competing finite-fault models, was presented by [1]. In this study, we provide a brief overview of the region's tectonics and describe the rapid deployment of seismic instruments following the Petrinja mainshock. Furthermore, we present an overview of the seismicity in the Petrinja epicentral area from 2020 to 2024. For seismicity monitoring, we employ two types of earthquake detection in seismograms: manual and machine learning (ML) approaches. The overall aim of this study is to outline the seismological work conducted in the five years following the Petrinja earthquake.

2. Tectonics and geology

The Central Croatia region, together with the Petrinja area, lies within the transition zone between the Internal Dinarides and SW Pannonian Basin structural units. This area has been subjected to multiple tectonic phases since the Late Jurassic, resulting in a complex geological and geodynamic setting. The present-day Adria–Europe shortening is predominantly accommodated within the External Dinarides and partly transmitted to the Internal Dinarides and the Dinarides–Pannonian basin transition area [20]. The active NNE-SSW compression within the study area is evidenced by earthquake focal mechanism solutions [21] and predicted by geodynamic modelling. Throughout the Late Cretaceous – Early Palaeogene, the broader Petrinja area formed part of the Sava realm of the Neotethys Ocean and was subjected to the ongoing subduction of remnant oceanic crust beneath European-derived tectonic units. At that time, the Sava oceanic realm was closed along the Sava Suture Zone (SSZ) [22, 23]. Regional compression-related tectonic uplift, folding, and imbrication of older units and associated syn-orogenic deposits were active in the region until the Mid-Eocene [20, 22]. Concurrently, thrusting propagated SW towards the Adriatic foreland and led to the onset of the nappe stack and formation of the Oligocene to Mid-Eocene External Dinarides fold-thrust belt and foreland basin. In the northern Internal Dinarides, a turnover from Late Cretaceous to Mid-Eocene compression to Early Miocene extension occurred along the SSZ, leading to the formation of the Sava Depression, that is, the south-westernmost basin of the Miocene Pannonian back-arc basin system [22]. The Sava Depression began to open during the Early Miocene (c. 18 Ma). This Early Miocene extensional detachment also led to the exhumation of the Internal Dinarides and the SSZ units in its footwall, in the form of core complexes (inselbergs in the present-day morphology).

The opening of regional- and local-scale Miocene basins was accompanied by the deposition of syn- to post-tectonic sedimentary units, which are presently partly exposed along the Sava Depression margins. In the Sava Depression, the Early Miocene syn-rift phase presumably lasted until the Middle Miocene (c. 13.5 Ma; [24]). It was subsequently followed by a post-rift, regionally widespread thermal subsidence phase, which is known to have started across the Pannonian basin system during the late Middle Miocene. Within the sedimentary fill across the Pannonian basin system, this phase is commonly recognized by the substantial thickness of Upper Miocene (Pannonian) sediments (c. 11.6-4.5 Ma) and an almost complete absence of contemporaneous extensional faulting in the central and northwestern parts of the Sava Depression (e.g. [24]).

The termination of the thermal subsidence phase and onset of the successive shortening phase were not uniform across the Pannonian basin system, either spatially or temporally. In the northwestern and central parts of the Sava Depression, this shortening started by the end of the Miocene or during the Early Pliocene c. 6 Ma; [22, 24]).It was driven partly by the The epicentral area of the Petrinja 2020–2021 earthquake series extends for approximately 20 km in a NW-SE direction, at a distance of approximately 7 km to the SW of the town of Petrinja (Figure 1). It corresponds to the Hrastovica Hill, the most prominent morphological structure in the vicinity of Petrinja, whose highest peak, Cepeliš, reaches 415 m a.s.l. According to surface geological data [27], this structure is

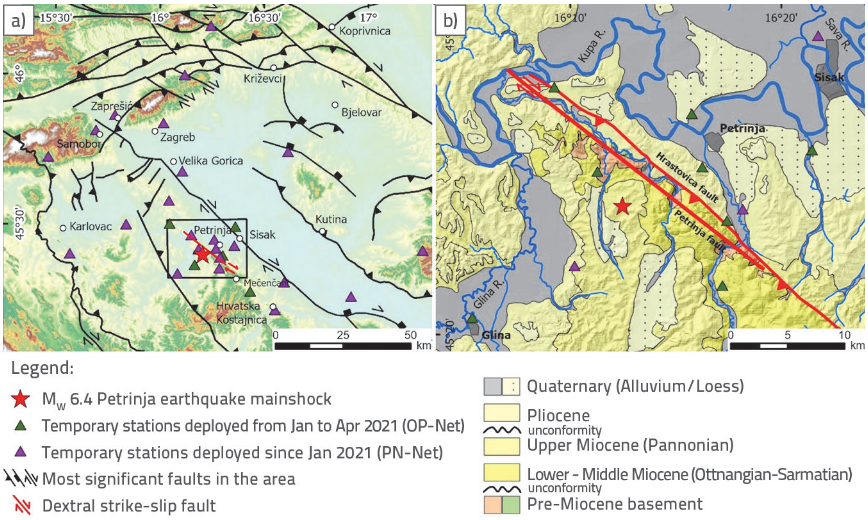

Figure 1. Fault traces are compiled from [20, 23, 25]; simplified geological map of wider Petrinja epicentral area, based on the Basic Geological Map, sheets Sisak [27] and Bosanski Novi [28]

an asymmetric anticline characterised by gently SW-dipping and steeply NE-dipping limb, the latter bounded by a NW-SE striking fault (Figure 1.b). Although the throw on this fault is presumed to be normal [27], a reverse sense of slip was observed during the 1909 earthquake and in the 2020 aftershocks. This raises the question of whether part of the c. 300 m relief represents the thrust component accumulated over several seismic cycles [21]. Locally, along its NE-dipping limb and hinge, this anticline is composed of Upper Cretaceous to Eocene rocks (basalts and pelagic limestones). These are unconformably covered by a concordant succession of Middle to Upper Miocene and Pliocene sediments, which are largely exposed along the SW-dipping limb of the anticline (Figure 1.b). The youngest sediments in the study area are Quaternary gravels, sands, silts, and clays deposited in the Kupa River floodplain and along its tributaries, locally associated with loess deposits mostly preserved in valleys but also found at higher altitudes close to the top of Hrastovica Hill.

Owing to the strength of the earthquake and the specific geological setting, in the aftermath of shaking in the wider epicentral area, a large number of secondary earthquake effects, that is, cosmic deformations on the surface, such as liquefaction, cracks, landslides, and sinkholes, were observed (e.g. [3, 29-31]).

3. Seismic networks

When a strong earthquake occurs, it is crucial for the seismological community to respond rapidly by deploying a dense network of temporary monitoring instruments throughout the broader epicentral region. This setup is essential for detecting even the weakest tremors, many of which would otherwise go undetected. The ability to accurately locate small earthquakes is vital for understanding the size and extent of the activated seismic fault(s). The accurate determination of seismic event depth is one of the most challenging aspects of earthquake analysis, as it is often the least precise and most uncertain parameter. This can be mitigated by enhancing the density and sensitivity of the seismic network, with special focus on the deployment of stations close to the main epicentral area. Moreover, as the highest number of aftershocks occur immediately following a mainshock, prompt installation of instruments in the affected areas is essential to ensure adequate recording of these events.

At the onset of the Petrinja earthquake sequence, the seismic network around the Kupa River was relatively sparse; the two nearest stations to the mainshock were located 32 and 36 km away (blue triangles in Figure 2).

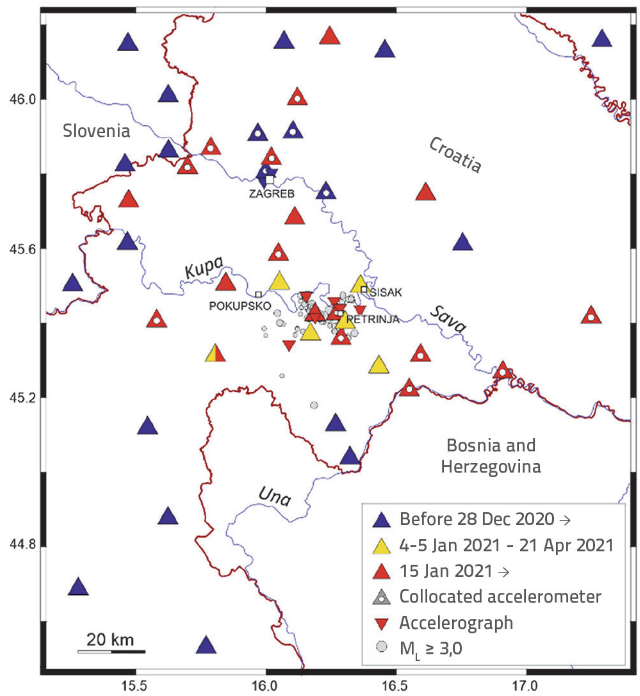

Figure 2. Seismic stations in the greater vicinity of the Petrinja earthquake epicentral area after installation of the OP-Net (yellow triangles) and PN-Net (red triangles, broad-band stations). Blue triangles represent broad-band stations operating within the Croatian CR-Network, the temporary Zagreb network, and stations from the Slovene (SL) and Hungarian (HU) networks. Small, inverted triangles denote strong-motion instruments. White circles within symbols indicate stations with collocated accelerometers. Modified after [1]

Fortunately, on 4–5 January 2021, a temporary six-station network (OP-Net; yellow triangles in Figure 2) was deployed in the epicentral area through collaboration between the National Institute of Oceanography and Applied Geophysics–OGS (Italy) and Department of Geophysics, Faculty of Science, University of Zagreb-despite the travel restrictions imposed by the COVID-19 pandemic. Shortly thereafter, by mid-January 2021, the installation of the Petrinja Network (PN-Net; red symbols in Figure 2) commenced, using newly acquired instruments by the Croatian Seismological Survey (see section 3.2 here and [1] for details). In the following section, we briefly describe the deployment of instruments and other field operations in the aftermath of the Petrinja mainshock and early phase of the aftershock sequence.

3.1. Rapid instrument deployment (OP-Net)

Because of the series of earthquakes in Zagreb that began on 22 March 2020 with M_w = 5.3 (M_L = 5.5) mainshock and the establishment of a monitoring network, Croatian seismologists were left with no free instruments to set up in the Banovina area following the late 2020 Petrinja earthquake. To address this challenge, seismologists from the Department of Geophysics, Faculty of Science, University of Zagreb quickly sought collaboration with their colleagues at the National Institute of Oceanography and Applied Geophysics (OGS, Italy). Through this partnership, the OGS generously provided six seismographs, each equipped with an integrated accelerometer, for rapid installation in the epicentral area. This collaboration was critical in ensuring that the necessary instrumentation was deployed as quickly as possible to monitor the ongoing seismic activity.

On 4–5 January 2021, only six days following the mainshock and amid restrictions imposed by the COVID-19 pandemic, five of these instruments were installed at key locations in the Banovina region at Hotnja, Sisak, Taborište, Novo Selo Glinsko, and Mečenčani (Figure 2, [32]). The placement of the two instruments at the locations in Sisak and Taborište is shown in Figures 3.a and 3.b. Additionally, one broadband seismometer from the Croatian seismic pool was installed at Petrova Gora on 4 January. The strategic placement and rapid deployment of this temporary seismic network augmented the permanent seismic network in the area, thereby improving azimuthal coverage and providing additional near-field observations. This was particularly important, as it helped reduce the uncertainty and instability often associated with the determination of earthquake location, especially focal depth (see Figure 4). With this improved coverage, even smaller earthquakes could be located more reliably, providing valuable data on the ongoing seismic activity in the region. The five short-period instruments from OP-Net were operating until mid-April 2021, when they were removed and returned to Italy.

This collaboration not only contributed to a better understanding of the seismic behaviour of the Banovina area but also highlighted the importance of international cooperation in the field of seismology. By quickly deploying a temporary network of high-quality seismic stations, the team was able to obtain crucial near-field data that was essential for monitoring aftershock activity and future seismic hazard assessments in the region.

Figure 3. Examples of installed temporary stations: a) Temporary stations in Sisak; b) and Taborište equipped with a short period instrument (seismograph with integrated accelerometer *Lunitek Sentinel-Geo*) from rapid deployment of the OP-Net; c) Temporary station in Petrinja cemetery of the Petrinja-Net with collocated seismometer *Kinemetrics MBB*-2 (grey insulation box) and accelerometer *Kinemetrics ETNA2* (under green insulation box); d) accelerometer in insulation box shown at close in

3.2. Petrinja temporary seismic network (PN-Net)

Following the initial deployment of the six seismic stations from OP-Net, the Croatian Seismological Survey at the Department of Geophysics, Faculty of Science, University of Zagreb, received a substantial financial donation from the Government of the Republic of Croatia (through the Ministry of Science and Education) for the procurement of a complete set of seismological instruments for seismic monitoring. Within a very short time, 20 modern seismometers with corresponding digitisers and data storage units, as well as 20 accelerometers with all the necessary auxiliary equipment, were acquired. The instruments were purchased and delivered promptly to

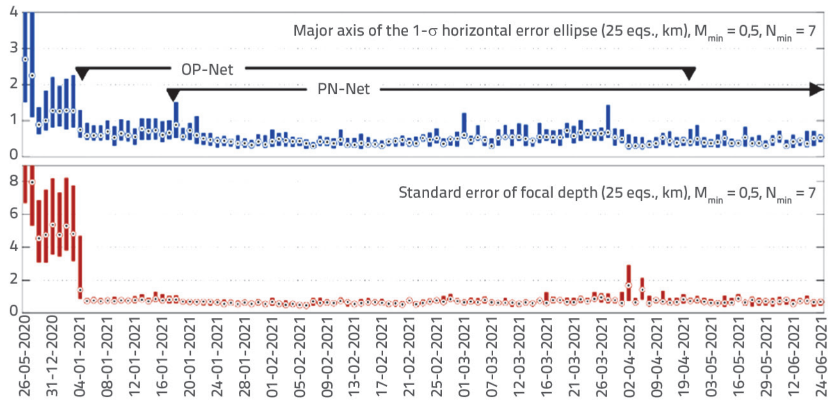

Figure 4. Temporal evolution of the 1-σ confidence radii for hypocentral locations, evaluated in non-overlapping moving windows of 25 consecutive events over the first six months of the Petrinja earthquake sequence. Only earthquakes with local magnitudes $M_L \geq 0.5$ and located with at least seven phase onset times were considered. Circled dots mark the medians, while bars indicate the 25th–75th percentile range. The periods of operation of temporary networks are shown in the top subplot.

enable the rapid commencement of instrumental recording of aftershocks that were occurring in the Petrinja fault area. The equipment was swiftly tested and configured, and the first instruments were deployed in the field only weeks after the mainshock.

In the initial phase, the instruments were installed in the immediate epicentral area, in the town of Petrinja and villages of Brest Pokupski, Hrastovica, Mošćenica, Hrvatski Čuntić, Gora, and Novi Farkašić. In the subsequent phase, temporary seismological stations were installed in the broader epicentral zone at five locations (Pobrđani (Sunja), Jasenovac, Lasinja, Omanovac, and Čazma) to obtain data from a wider geographical distribution relative to the earthquake epicentres. Several instruments were deployed in the wider Zagreb area (Marija Bistrica, Samobor, Žumberak, Ladvenjak, etc.) to monitor the Zagreb earthquake aftershock sequence that started on 22 March 2020, which was still ongoing. In the following months, continuous field inspections of the mobile seismological network were carried out to collect data and verify operational performance. Hundreds of gigabytes of valuable seismological data were collected during this period. Subsequent activities included the acquisition of new data servers, followed by the establishment of a direct real-time data transmission link from all temporary field stations to the operational centre in Zagreb.

3.3. Overall performance of temporary seismic networks

The operation of OP-Net and later PN-Net had a profound impact on the accuracy of aftershock locations. As shown in Figure 4, the establishment of OP-Net improved the confidence of epicentral determinations by roughly 50%, while the average focal-depth uncertainty decreased from about ±5 km to less than ±1 km. The location confidence was further improved after the deployment of PN-Net.

4. Seismicity monitoring following the mainshock

As discussed in the previous section, rapid and robust response to a strong earthquake is crucial, necessitating the swift deployment of a dense, temporary seismic network across the activated fault zone. This enhancement is vital for detecting even the weakest aftershocks and is the primary strategy for improving the accuracy of earthquake location, particularly the challenging task of determining focal depth. The resulting high-resolution data are essential for elucidating the complex tectonics of the sequence. For the Petrinja earthquake, this enhanced monitoring was critical for mapping the spatial distribution of seismicity across the region. While the largest events were clearly associated with the main seismogenic structure-the right-lateral Petrinja Fault-the confident location of thousands of aftershocks revealed that many smaller tremors occurred along several secondary faults activated by stress redistribution. Consequently, the rapid deployment of the OP-Net and, subsequently, the PN-Net was fundamental to capturing this detailed fault geometry and understanding the full extent of the activated zone.

Here, we present two complementary analyses, both based on the rich seismic dataset collected over several years following the Petrinja mainshock. First, we present comprehensive results from the manual analysis of the collected seismograms encompassing permanent and temporary seismic networks. In the second part, we present the results from the automatic analysis using the deep neural network earthquake-signal detector, highlighting the advantages and disadvantages of using this approach compared to manual analysis.

4.1. Petrinja earthquake series – manual catalogue

In this section, we present the results of the manual analysis of seismic records collected between 28 December 2020 and 31 December 2024. During this period, 19,570 earthquakes were located in the wider Petrinja epicentral area (Figure 5). Locations for the first six months of activity are taken from the catalogue as reported in [1], while those for the subsequent period (July 2021–December 2024) are from the Croatian Earthquake Catalogue (CEC) ([33]; latest revision in 2025). The largest events are clearly associated with the main seismogenic structure, the right-lateral Petrinja Fault (red line in Figure 5, top). However, the spatial distribution of seismicity indicates that many aftershocks also occurred along several secondary faults activated by stress redistribution following the mainshock (see also [1]). These include sources between Sisak and Petrinja,

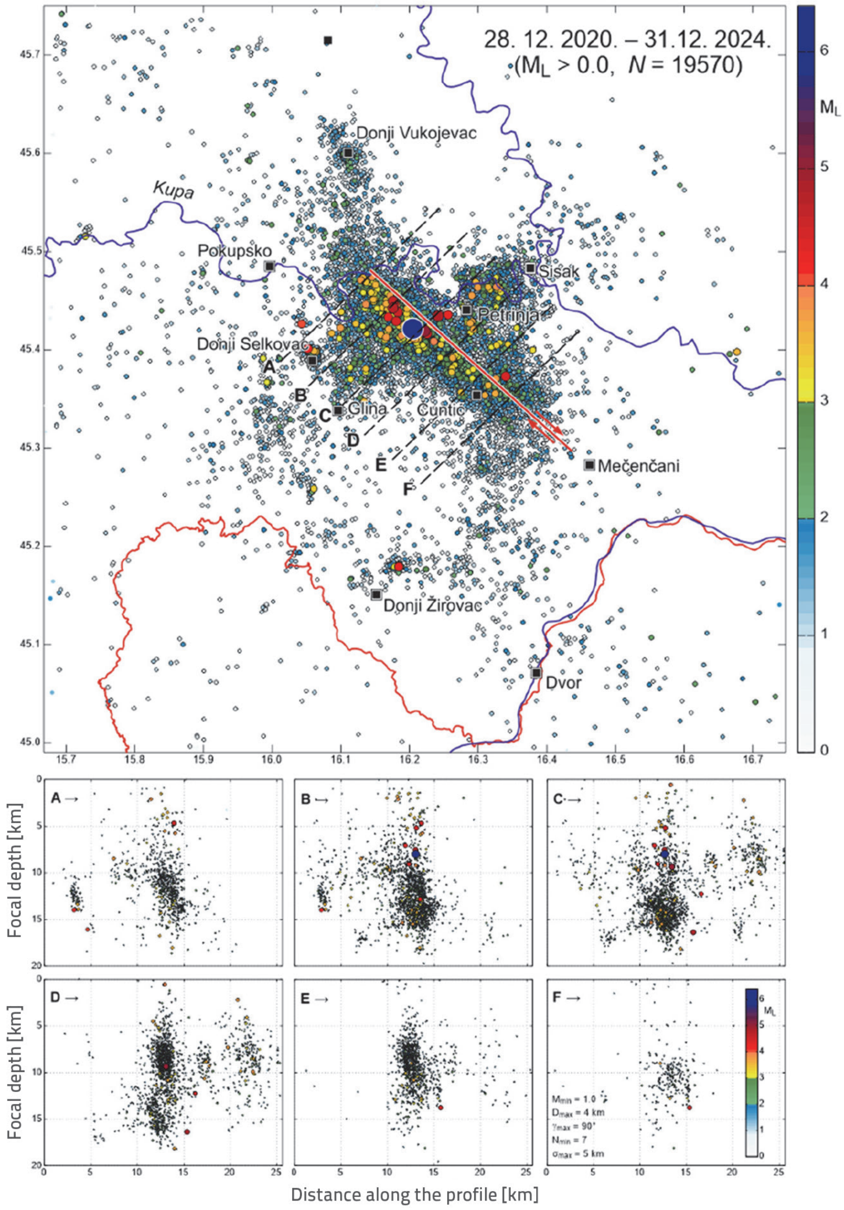

Figure 5. Top: Epicentres of all 19,570 earthquakes with magnitude M_L > 0.0 of the Petrinja sequence (2020–2024). Symbol sizes and colour scale with magnitude. The red straight line shows the simplified surface trace of the Petrinja Fault, and arrows show relative movement of the blocks. Black dashed lines indicate the traces of cross-sections A–F. Bottom: Cross-sections A–F showing vertical profiles of earthquake hypocentres that satisfy the conditions specified in subplot F (minimum magnitude M_{min} = 1.0; maximum distance from the profile D_{max} = 4 km; maximum station azimuthal gap, γ_{max} = 1.0; minimal number of phases used for locations N_{min} = 7; maximum allowed standard error of the hypocentre, σ_{max} = 5 km).

near village Donji Vukojevac, to the northeast and west of Glina, around Donji Selkovac and Donji Žirovac, and to the west of Mečenčani.

Insight into the hypocentral distribution is provided by six cross-sections (A–F) shown in the lower part of Figure 5, which include only reliably located earthquakes that meet the criteria specified in the figure caption. Most hypocentres are concentrated between depths of 5 and 15 km. The profiles delineate several activated faults, all sub-vertical or steeply dipping towards the northeast. Profile D further suggests the presence of a structural discontinuity or detachment within the Petrinja Fault zone at a depth of approximately 11 km. A more detailed analysis of these features lies beyond the scope of this study.

The temporal evolution of the Petrinja earthquake sequence is illustrated in Figure 6. During the first four days (28–31 December 2020), seismicity was almost entirely confined to the Petrinja Fault, which ruptured over a length of approximately 20 km, extending south-westward from the Kupa River towards Čuntić. Notably, several off-Petrinja Fault sources were already active in this early phase, including areas northeast of Petrinja, east of Velika Solina, and near Donji Žirovac-about 25 km from the Petrinja Fault. Most of the activity (approximately 65% of all located events) occurred in 2021. During this period, aftershocks propagated across the Kupa River, delineating a diffuse, approximately N–S-trending fault zone characterised primarily by low-magnitude events, mostly south of Donji Vukojevac. Concurrently, activity along the southeastern segment of the Petrinja Fault intensified, extending towards the village of Mečenčani and thereby increasing the total length of the activated fault segment to more than 30 km. The strongest activity in 2021, aside from that directly along the Petrinja Fault, occurred between Sisak and Petrinja, with additional aftershocks of M_L ≥ 4.0 near Velika Solina and Donji Žirovac.

Between 2022 and 2024, earthquake activity gradually declined along the north-western part of the aftershock zone and in the Sisak–Petrinja area, while most events persisted in the south-eastern portion of the zone, east and northwest of Čuntić (clusters A and B, Figure 6). During 2022, the initially linear alignment of aftershock epicentres along the Petrinja Fault evolved into a pattern concave towards the northeast. This change reflects continuing activity within a narrow band between Glina and Donji Vukojevac, as well as in the cluster marked B in Figure 6, situated predominantly within the north-eastern block of the Petrinja Fault zone. This contrasts with the

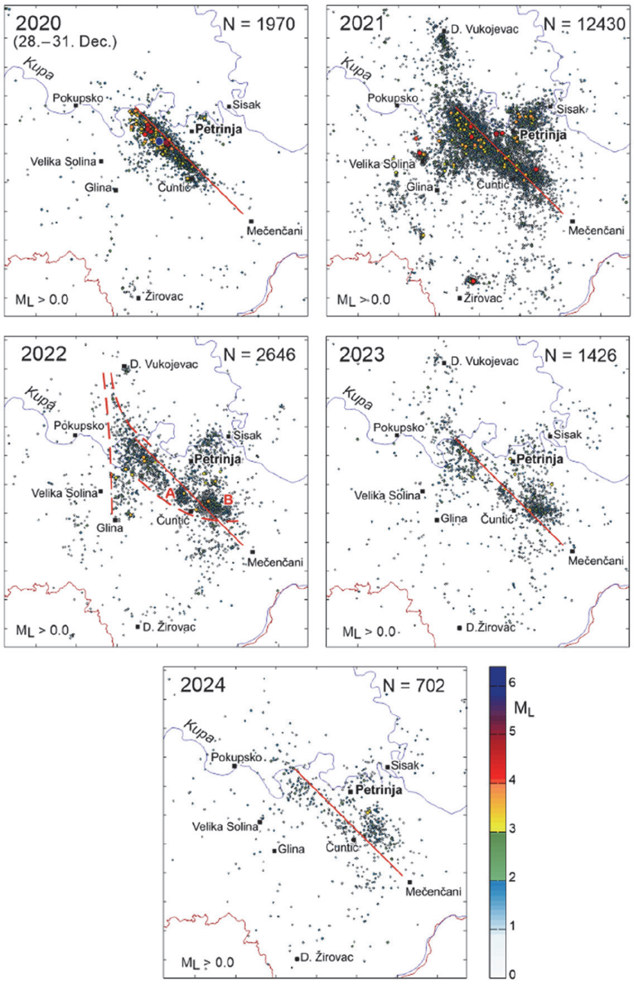

Figure 6. Epicentres of the earthquakes from the Petrinja sequence by year of occurrence (2020–2024). Total number of located events with M_L > 0.0 within each subplot is shown in the upper-right corner. Full red line marks the simplified trace of the Petrinja Fault. Dashed lines indicate observed trends

main Petrinja Fault activity (e.g. cluster A and the north-western segment), where most hypocentres are in the south-western block.

The catalogue for the Petrinja earthquake sequence is found to be complete for $M_L \geq 1.0$ (see Figure 7.a) starting from 30 December 2020, that is, approximately 13 hours after the mainshock to avoid the initial period when numerous small aftershocks were obscured by frequent larger events. The Gutenberg-Richter parameter b = 0.96 is slightly higher than b = 0.91 reported by [1] for the first six months and $M_L \geq 1.2$. The parameters in the modified Omori law, which describe the decay rate of aftershock occurrence, remained stable throughout the sequence-the coefficients derived for the four-year period (Figure 7.b) are nearly identical to those obtained by [1] for the initial six months. This suggests that aftershock activity will continue to decrease gradually over the coming years, with seismicity unlikely to return to approximately pre-2020 levels before around 2038.

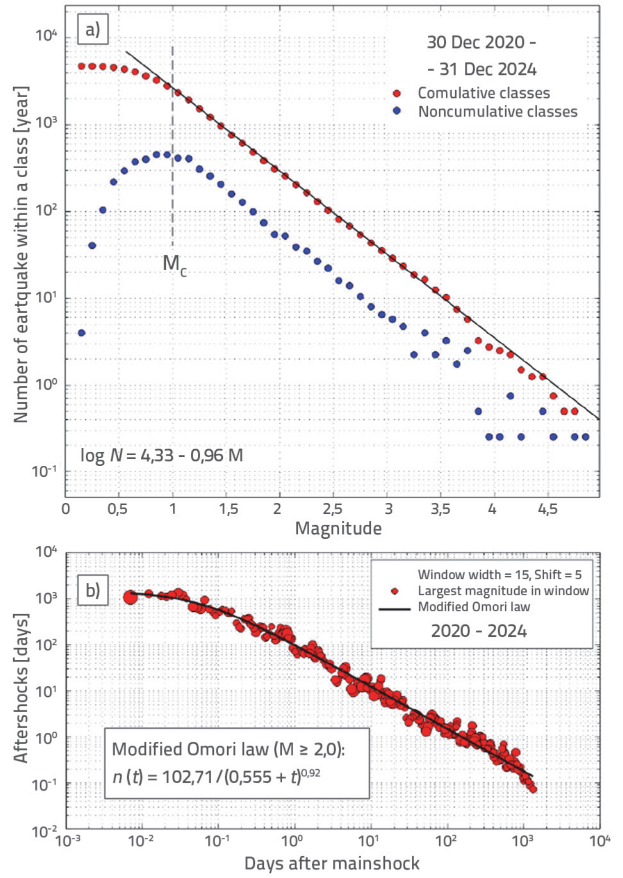

Figure 7. a) Frequency-magnitude distribution for the Petrinja sequence (2020–2024), excluding the mainshock; b) Modified Omori law showing the temporal variation in aftershock activity rates ($M_L \geq 2.0$) for the Petrinja sequence (2020–2024)

4.2. Automatic earthquake detection and location

The densification of seismic networks, such as that presented in this study, has resulted in a substantial increase in data volume and, consequently, in the time required for manual analysis of the collected data. In recent years, ML methods have emerged as efficient and reliable alternatives to traditional data processing approaches [34-36]. There are several reasons for this, most notably the speed of data analysis: a full day of continuous data can now be processed within minutes, which is particularly beneficial for smaller or underfunded institutions where manual analysis of long seismic sequences would be exceedingly time-consuming. Additionally, ML methods allow for improved and uniform accuracy, as well as the ability to quantify uncertainty in phase picks. Moreover, ML enables the detection of smaller-magnitude events and improves the identification of arrivals on noisier seismograms.

Here, the workflow and initial results from processing nearly two years of seismic data via ML are presented, covering the period from the onset of earthquake sequence to the end of November 2022 [37]. Continuous waveform data from the Croatian Seismograph Network (CR), OP-Net, and PN-Net seismic networks were analysed using the deep neural network earthquake signal detector EQTransformer [36],

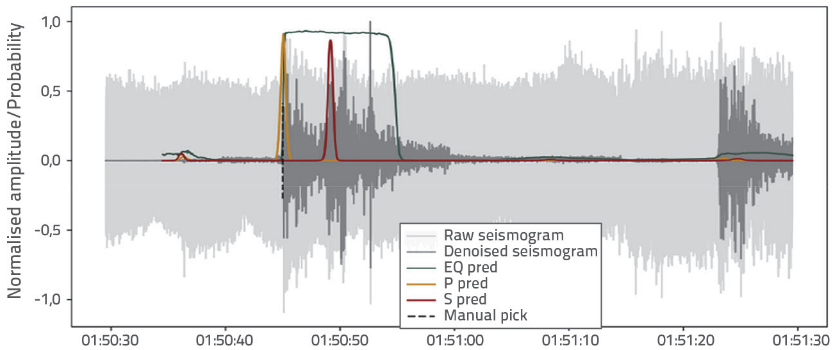

Figure 8. Example of EQTransformer detection and phase picking on a noisy seismogram from station PN03 (OP-Net). The plot shows the raw (grey) and denoised (black) seismograms, EQTransformer earthquake detection probability (green), P-phase (yellow) probability, and S-phase (red) probability, together with the manual pick (black dashed line). The event occurred on 20 January 2021 at 01:50:38 UTC and is considered a newly identified event, as it is not included in the Croatian Earthquake Catalogue

trained on the INSTANCE database [38], for detecting earthquakes and picking P- and S-phases. The detected picks were associated, and initial event locations were obtained using the PyOcto associator [39]. These preliminary locations were subsequently refined using the NonLinLoc algorithm [40], by applying source-specific station travel-time corrections [41] to improve location accuracy. Additionally, the probability output of the EQTransformer for each pick was used so that picks with higher probabilities were assigned smaller pick-time uncertainties during event location.

The initial EQTransformer analysis, with a detection threshold of 0.05 for P- and S-phases, resulted in a total of 8,953,730 seismic phases detected, comprising 6,588,039 P-phases and 2,365,691 S-phases. This large number of detected phases is to be expected, as the probability thresholds for P- and S-phases were set low. For the seismic phase association process, we varied the requirements based on the network density: for the first eight days of the sequence, that is, prior to installation of the first temporary network OP-Net, we required a minimum of five phases per event, and after 4 January 2021, we increased this requirement to a minimum of seven phases per event. After applying these association criteria, we obtained 943,844 valid picks (53% of P- and 47% of S-phases). This resulted in a seismic catalogue of 50,305 events located within the study area (15.7°–16.8° E, 44.8°–45.8° N). Of these, 34,141 events (68%) occurred by the end of June 2021, an additional 9930 events by the end of 2021, and 6,234 events by the end of the study period.

To ensure that the resulting catalogue represents real earthquakes, it was verified against CEC ([33]; latest revision in 2025) for the same study period. Events were classified as 'matched' if their origin times differed by less than two seconds from those in CEC. For events without a corresponding match in the manual catalogue, additional quality criteria were applied: an azimuthal gap smaller than 150°, at least ten associated seismic phases, and a semi-major axis of the confidence ellipsoid (as estimated by NonLinLoc) smaller than 20 km.

An example of such an event and the manner in which the EQTransformer detection and phase picking operate, is shown for station PN03 from the OP-Net network (Figure 8). The two-minute seismogram corresponds to an event with an origin time of 20 January 2021 at 01:50:38 UTC, classified as newly identified since it is absent from the Croatian Earthquake Catalogue (but present in another manual dataset with only a P-phase pick). Despite the high noise level, EQTransformer successfully detected the event and identified both P and S arrivals with peak probabilities of 0.93 and 0.87, respectively. For comparison, the denoised seismogram obtained using the deep neural network denoising/decomposition method [42] is also displayed, illustrating the underlying signal structure and the ability of the model to extract useful information from noisy data by default.

A comparison with CEC shows that 86% of its events have been successfully matched. Of the 50,305 events in the new ML catalogue and 22,386 events in CEC, 19,225 are common to both, whereas 3,161 CEC events are not detected. The analysis also identifies 31,080 new events, of which 9,184 meet the above quality criteria and are considered high-probability detections (Figure 9). The new events are concentrated near the Petrinja fault system and are consistent with the aftershock distribution of the 2020 M_w = 6.4 Petrinja earthquake. The vertical cross-sections indicate that most events are confined to the upper 15 km of the crust, with pronounced clustering at depths of 5–10 km. These depths are, on average, a

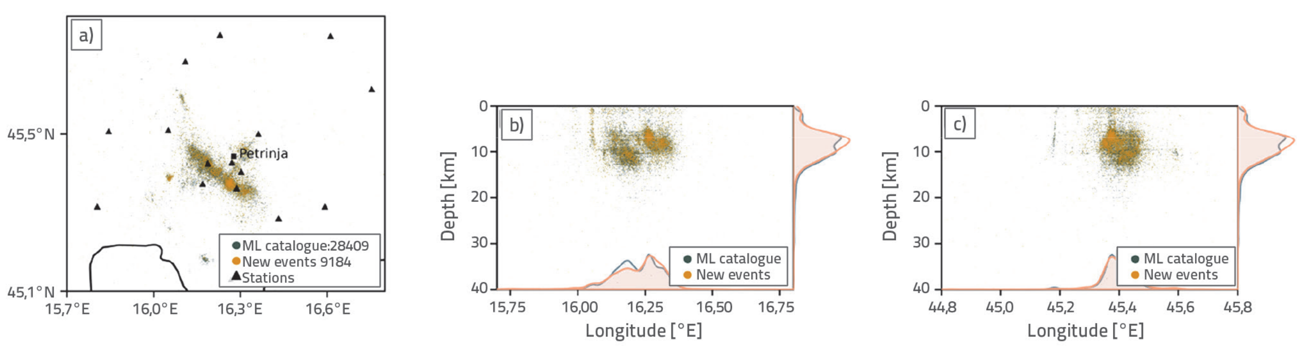

Figure 9. a) Map view of the 28,409 seismic events in our machine learning catalogue, with newly identified high-probability events highlighted in orange. Vertical cross-sections showing the depth distributions of events in the ML catalogue against longitude: b) and latitude; c), for those matching our criteria, with newly identified events highlighted

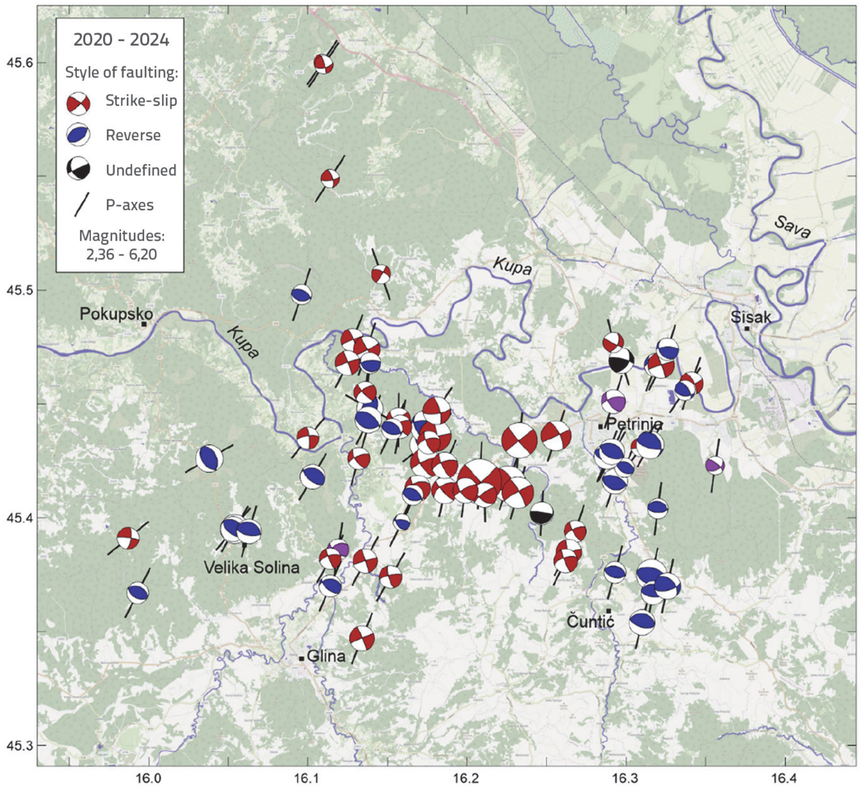

Figure 10. Focal mechanism solutions (FMS) for 2020–2024 from the CroFMS catalogue [21]. The solutions are shown as lower-hemisphere stereographic projection. The colour of the compressional quadrants denotes the style of faulting (see the legend). Short black lines indicate the orientation of the P-axes. The size of each beach-ball scales with magnitude, as shown in the legend. Only solutions of quality ≥ 2 are included.

few kilometres shallower than those in the manual catalogue, a trend also noted in previous ML studies [42].

Our results indicate that the ML workflow reproduces most manually identified events while substantially (over 50%) expanding the catalogue.

5. Focal mechanisms

This section provides a brief report on the available first-motion polarity focal mechanism solutions for the Petrinja epicentral area, collected until the end of 2024, as reported in the CroFMS catalogue [21]. The aim is to give an overview of the complex faulting associated with the Petrinja fault zone after the 2020 Petrinja earthquake.

As noted by [1], the largest events along the Petrinja Fault show predominantly strike-slip faulting (Figure 10). However, almost the same number of aftershocks occurred on reverse faults, most notably near Velika Solina, and in the clusters north-east of Čuntić and south-east of Petrinja. In their study, [1] demonstrated that the distribution of strike-slip and reverse faulting is consistent with the Coulomb failure stress change caused by the mainshock rupture.

The P-axes trend, mostly in the SSW-NNE direction, is comparable with the strike of the maximal horizontal stress (S_{Hmax}) in this area [21]. It is interesting to note that the P-axis of the mainshock strikes almost N–S, which implies an average clockwise rotation of the P-axis in the aftershock sequence of approximately 16° [1].

6. Discussion and conclusion

The comprehensive analysis of the Petrinja earthquake sequence from 2020 to 2024, supported by both manual and advanced ML techniques, provides a significantly enhanced view of the seismic and tectonic processes active in this crucial transition zone between the Internal Dinarides and the SW Pannonian Basin.

A critical element of this work was the rapid and collaborative deployment of temporary seismic networks, specifically the Italian-Croatian OP-Net and subsequent PN-Net. These deployments augmented the sparse permanent network, leading to significant improvements in the number of stations and data quality. The enhanced network density was instrumental in reducing the uncertainty of hypocentral locations, particularly focal depth, which is essential for accurate fault-plane mapping (Figure 4).

It is unfortunate that the earthquake struck an area that had not been adequately monitored, largely due to funding limitations in previous years. In particular, the absence of strong-motion instruments (accelerographs) meant that a unique opportunity to collect ground-acceleration data in the near-field of a large strike-slip earthquake was lost. Such data would have been the most valuable addition to the database of strong-motion records in Croatia. However, the deployment of the OP-Net (comprising both geophones and accelerographs), and later PN-Net, enabled the recording of acceleration during the strongest aftershock on 6 January 2021, as well as during all subsequent significant events.

The ability to swiftly deploy instruments enabled the capture of the highest-intensity aftershock period immediately following the mainshock. Furthermore, the immense data volume was efficiently processed using ML techniques, which substantially expanded the earthquake catalogue by over 50%, successfully detecting thousands of low-magnitude events missed by manual analysis and thereby validating the use of advanced methods in post-seismic monitoring.

The detailed analysis of nearly 20,000 manually located and over 50,000 ML-detected events (Figures 5 and 9) confirms that the largest earthquakes occurred along the right-lateral Petrinja fault, an active structure in the complex transition zone between the Dinarides and the Pannonian Basin. However, the seismicity distribution evolved over time, showing a complex pattern in which stress redistribution after the main rupture activated numerous secondary faults extending beyond the main fault trace. While activity has generally decayed following the Modified Omori Law (Figure 7.b), which predicts a gradual return to background levels around 2038, clusters of activity have persisted in the south-eastern areas.

An investigation into the focal mechanism solutions (CroFMS catalogue) revealed a complex interplay of faulting styles (Figure 10). While the major events show the expected strike-slip faulting, a substantial number of aftershocks exhibit reverse faulting in specific clusters. This heterogeneous pattern is consistent with the change in the Coulomb failure stress caused by the mainshock, which validates current models of static stress triggering. Additionally, the study highlights an important observation: the P-axes of the aftershocks, which align with the regional maximal horizontal stress (S_{Hmax}), exhibit a noticeable clockwise rotation relative to the mainshock's P-axis. This rotation provides vital constraints on the local stress field and its variations.

In conclusion, the five years of intense monitoring following the Petrinja earthquake have yielded a remarkably detailed and robust understanding of this significant intraplate strike-slip event. The successful collaboration and rapid deployment of the seismic networks, complemented by a powerful ML workflow, have created a uniquely rich dataset. This dataset not only defines the primary and secondary faults activated by the event but also provides compelling evidence that the heterogeneous aftershock faulting is a direct, predictable consequence of stress redistribution. The insights gained into the geometry and kinematics of the Petrinja fault system, aftershock productivity, and short-term variability of tectonic stress are important for refining seismic hazard models. These findings enable a more reliable characterisation of the main seismogenic faults, including their recurrence parameters, maximum expected magnitudes, and typical focal mechanisms. This, in turn, provides a stronger foundation for deterministic modelling of realistic earthquake scenarios in the Banovina area, thus supporting the development of long-term earthquake risk mitigation strategies in Central Croatia.

Acknowledgements

The Croatian Seismological Survey at the Department of Geophysics, Faculty of Science, University of Zagreb acknowledges financial donation from the Government of the Republic of Croatia (through the Ministry of Science and Education) for the procurement of a complete set of seismological instruments for seismic monitoring: 20 modern seismometers and 20 accelerometers with all the necessary auxiliary equipment. Seismologists from the Andrija Mohorovičić Geophysical Institute at the Department of Geophysics, Faculty of Science, University of Zagreb acknowledge the help of colleagues from the National Institute of Oceanography and Applied Geophysics (OGS, Italy) and their generous provision of six seismographs with integrated accelerometer for rapid deployment. The stations of the permanent Croatian network and those from the mobile pool (PN-Net) were managed by the Croatian Seismological Survey, Department of Geophysics, Faculty of Science, University of Zagreb. Automatic earthquake detection and location was performed within the project 'Investigation of seismically vulnerable areas in Croatia and seismic ground motion assessment – CRONOS' funded by the Norwegian Grants (Norwegian Financial Mechanism 2014-2021, grant 04-UBS-U-0002/22-90). The temporary stations of the OP-Net were managed by seismologists from the Andrija Mohorovičić Geophysical Institute, Department of Geophysics, Faculty of Science, University of Zagreb. We thank all our colleagues who helped with station deployment and maintenance, as well as seismograms and data analyses.

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