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Earthquakes of Bosnia and Herzegovina from 2022 to 2023 recorded on the Bosnian Adria Array temporary network

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Abstract

As part of the Adria Array initiative, the seismic network in Bosnia and Herzegovina was augmented with 20 additional broadband stations between June 2022 and December 2024. In this study, we describe the characteristics and deployment of this temporary network, highlighting its impact on seismic catalog quality, including a lowered detection threshold to approximately magnitude 1.0. Beyond improving event detection, we provide a comprehensive seismic catalog from June 2022 to December 2023 that demonstrates enhanced constraints on location and magnitude for larger earthquakes. Additionally, we discuss the critical role of open data sharing in this seismically active region, emphasizing its importance for accurate seismicity monitoring and reliable seismic hazard assessment.

Keywords: Adria Array; Bosnia and Herzegovina; Seismic Catalog; Dense Arrays

1. Introduction

The region surrounding the Adriatic Sea, the northernmost arm of the Mediterranean, is a tectonically active belt extending from Sicily and the Apennines to the Alps, the Dinarides, and the Hellenides. In this region, the tectonic stresses are primarily driven by the subducting Adria plate, which is colliding with adjacent lithospheric units (e.g. Faccenna et al., 2014; Schmitz et al., 2020; van Hinsbergen et al., 2020). As a result, this densely populated region is highly susceptible to geohazards, such as earthquakes, tsunamis, landslides, and volcanic activity.

To improve the understanding of the seismotectonics of this Adriatic region and address the significant gaps in station coverage, the Adria Array Initiative was launched (Kolinsky et al., submitted), following the European AlpArray project (Hétenyi et al., 2018). Between 2022 and 2025, this multinational effort established a regional seismic network comprising 1058 permanent and 447 temporary broadband stations from 23 mobile pools (Kolínský et al., submitted). This unprecedented seismic coverage extends from the Massif Central in the west to the Carpathians in the east, and from the Alps in the north to the Calabrian Arc and mainland Greece in the south, providing a comprehensive and simultaneous data set, despite the region's complex geopolitical landscape.

Bosnia and Herzegovina (BiH), located at the crossroads of the Balkans, plays a central role in the region's seismic monitoring efforts. The country is divided into two political entities: Republika Srpska, with its capital in Banja Luka, and the Federation of Bosnia and Herzegovina, with Sarajevo as its capital. Each entity operates its own seismological service, responsible for monitoring seismic activity within its territory. Before the AdriaArray initiative, BiH had only a limited seismic network, consisting of 2 broadband stations, with just five stations transmitting real-time data in 2022 (Fig. 1). Please note that station TREB is a short-period sensor. During the AlpArray project and complementary experiments, three broadband stations were deployed in the north-western part of BiH from 2016-2018 (Molinari et al., 2016) and four broadband stations in the southern part from 2016-2017 (Molinari et al., 2018).

Between June 2022 and December 2024, the Swiss Seismological Service at ETH Zurich deployed 20 additional broadband seismometers across BiH to improve regional seismic monitoring. However, by the beginning of 2025, the Bosnian network had unfortunately shrunk back to its original size. In spring 2025, four stations were installed in the northern Una-Sana canton to monitor potential induced seismicity related to the planned radioactive waste repository on Mount Trgovska Gora, located in Croatia, along the border area with BiH. Such projects highlight the need for an adequate seismic hazard assessment.

This paper provides an overview of the seismotectonic context of BiH, describes the temporary seismic network established within the AdriaArray initiative, and presents an initial seismic catalog, focusing on the two largest seismic events recorded during the monitoring period. Finally, we discuss the minimum seismic network requirements needed to ensure effective long-term seismic monitoring in the region.

2. Seismotectonics and Seismic Hazard in Bosnia and Herzegovina

The Dinarides, the major tectonic unit across the Balkans, dominate the geological structures in BiH. These mountains are oriented in a northwest-southeast direction, with BiH located centrally within the range. For much of geological history, this area was submerged beneath the Tethys Sea until the onset of the Alpine orogeny, which began around 250 million years ago during the Upper Permian period. The Dinarides stretch across BiH, forming a natural divide between the Adriatic Sea to the southwest and the Pannonian Basin to the northeast (Mulić et al., 2006). This geologically complex region has been shaped by a variety of tectonic, sedimentary, and erosional processes over time, contributing to its diverse landscape and seismic activity.

As a result, BiH consists of several major paleogeographic-tectono-stratigraphic units, each differing in composition, structure, origin, and seismic hazard (Fig. 1, Hrvatović, 2006). These geotectonic units, extending from southwest to northeast, include: Carbonate platform of the Dinarides (1), Bosnian flysch zone (2), Ophiolite zone (3), Sava-Vardara zone (4), Neogene and Quaternary sediments formed mostly during the Pannonian basin extension, are found all over BiH (yellow). Since 1895, 22 seismic events with recorded magnitudes exceeding 5.0 have been observed in BiH and the adjacent regions (Table 1, Trkulja, 2010, Jozinović, 2018). Hrvatović (2006) identified nine seismogenic zones (Fig. 2a), which largely correspond to these stratigraphic units. Notably, the southern part of the carbonate platform (Outer Dinarides) has experienced significant seismic activity, with various events ranging from magnitude 5.0 to 6.0. The most destructive earthquake, with a Richter magnitude of 6.6, struck Banja Luka in 1969 (Ustaszewski et al., 2014). Many of these earthquakes have shallow focal depths, resulting in strong soil amplification (Bulajić et al., 2013; Markušić et al., 2019). Historical earthquake maps indicate that major events tend to occur within the boundaries of the seismogenic zones (Omerbashich and Sijaric, 2006).

Based on a probabilistic seismic hazard assessment that included over 13,000 national and regional seismic events with magnitudes greater than 3.5, were compiled seismic hazard maps for BiH (Fig. 2b) (Džidić, 2019; Ademović et al., 2021). The map indicates that the probability for high ground accelerations are concentrated in the Livno-Tihaljina (VII), Neum-Trebinje (VIII), and central Mostar (VI), Zenica-Sarajevo (IV) seismogenic zones (compare with Fig. 2a). However, their resolution remains limited due to the lack of detailed mapping of local fault structures, which requires a comprehensive earthquake catalog. Consequentely, it is not surprising that the M4.0 Sarajevo earthquake from February 19^{th}, 2024, occurred in an area previously classified as having only moderate seismic hazard (Fig. 2b).

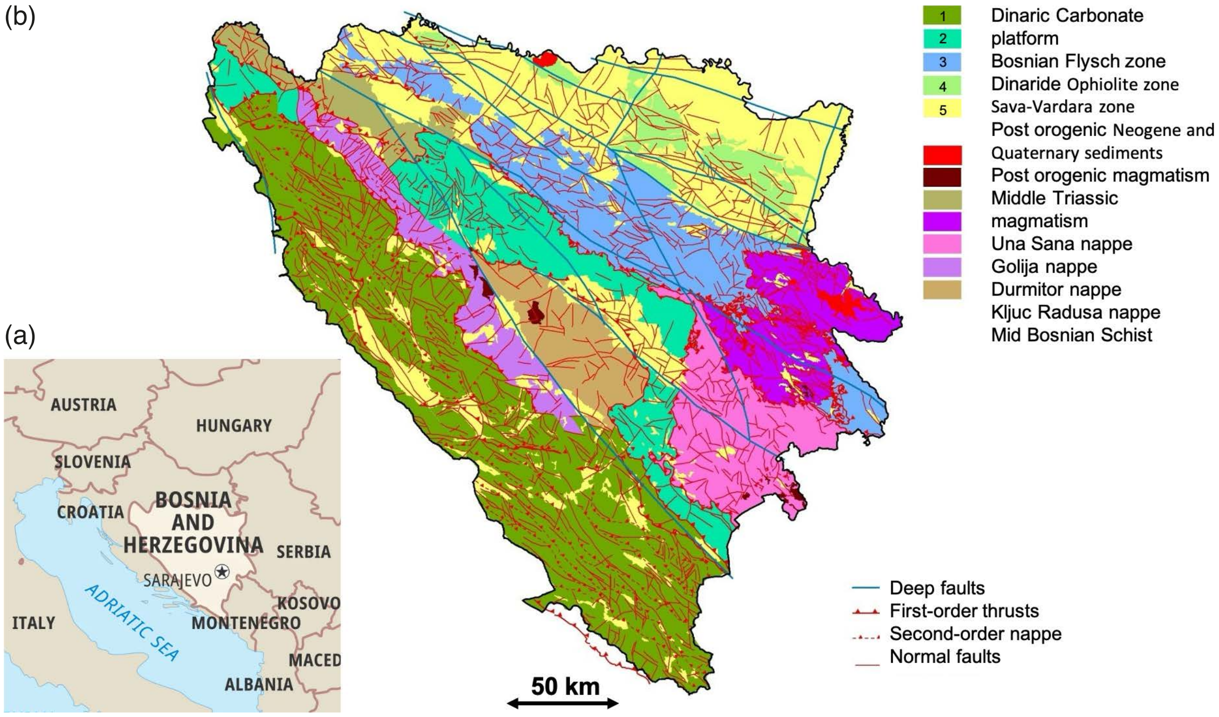

Figure 1. (a) BiH situated in the Western Balkan peninsula. (b) Geotectonic map of BiH (modified from Hrvatović, 2006), showing mapped fault structures. The numbers indicate the 5 geotectonic units discussed in the text. The light blue lines delineate the seismogenic zones that are also discussed in Fig. 2.

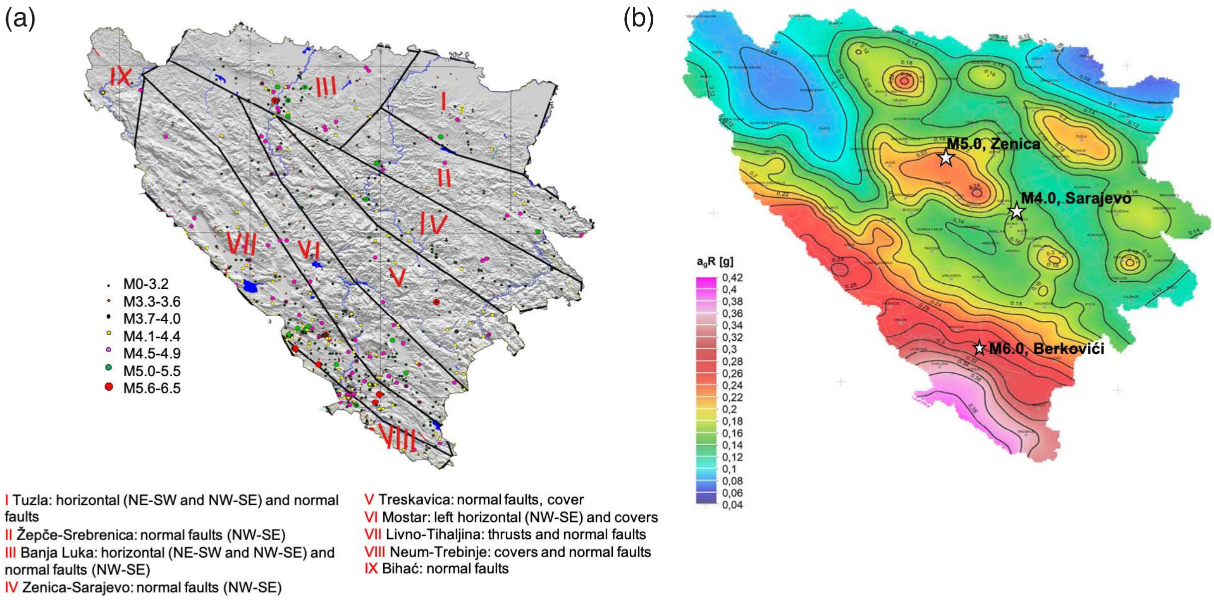

Figure 2. (a) Nine seismogenic zones (I-IX) across BiH (modified from Hrvatović, 2006). (b) Seismic hazard distribution in BiH (modified from Džidić (2019)). Stars mark the epicenters of key earthquakes discussed in the text; the April 22nd, 2022 M6.0 Berkovići earthquake, the December 30th, 2023, M5.0 Zenica earthquake and the February 19th, 2024, M4.0 Sarajevo earthquake.

Table 1. Historical earthquakes above M5 since 1985 (Trkulja, 2010, Jozinović, 2018). The earthquake near Berkovići in 2022 can also be found in the literature as Stolac earthquake (Ćatić, 2022). For the Berkovići and Zenica events, we report the ESMC moment magnitudes Mw and the local magnitudes ML.

Date	Location	Magnitude
1895-04-07	Petrovac	5.0
1907-08-01	Počitelj	5.7
1908-12-25	Vlasenica	5.3
1916-02-12	Bihać	5.0
1923-02-06	Jajce	5.0
1927-02-14	Ljubinje	6.0
1940-12-17	Derventa	5.1
1950-08-31	Drugovići	5.7
1962-06-11	Treskavica	6.0
1969-10-27	Banja Luka	6.6
1970-08-25	Gacko	5.0
1974-10-29	Lukavac	5.0
1979-05-15	Montenegro – Adriatic sea	6.9
1981-04-08	Sanski Most	5.0
1981-08-13	Banja Luka	5.3
1984-05-13	Hutovo blato	5.4
1990-04-03	Grude	5.1
1990-11-27	Livno	5.1
1996-02-17	Bihać Region	5.6
1996-09-05	Slano (Croatia)	6.0
2019-11-23	Herzegovina region Nevesinje	5.4
2022-04-22	Berkovići	M5.7 (ESMC), M_L6.0
2023-12-30	Zenica	M4.7 (ESMC), M_L5.0

3. Bosnian AdriaArray temporary seismic network

The Swiss Seismological Service (SED) at ETH Zurich provided 20 STS2 broadband instruments with Taurus digitizers to densify the seismic network in BiH, reaching an average station spacing of about 50 km. The first eight stations were installed by a single team in June 2022, mainly in the southern region. The remaining 12 stations were deployed in July 2022 by two teams. Site selection was conducted by both BiH seismological services, prioritizing installations within buildings, where power was readily available. However, real-time data transmission via cellular network posed a challenge due to the fragmented coverage provided by multiple operators. Additionally, long-term contracts were not feasible, requiring monthly payment installments. This aspect did not affect the quality of data transmission but caused substantial extra work for the network operators.

The stations transmitted continuous seismic data at 200 Hz sampling rate to the Swiss EIDA node (https://www.orfeus-eu.org/data/eida/nodes/ETHZ/), from which BiH seismological services accessed the data in real-time. These data were integrated into the local SeisComP systems, enabling real-time earthquake monitoring. The temporary seismic network is identified by Y5 FSDN code and is referenced in Obermann et al. (2022). In Fig. 3, we show the Y5 temporary network alongside the permanent stations available to BiH services for earthquake monitoring as of late 2024.

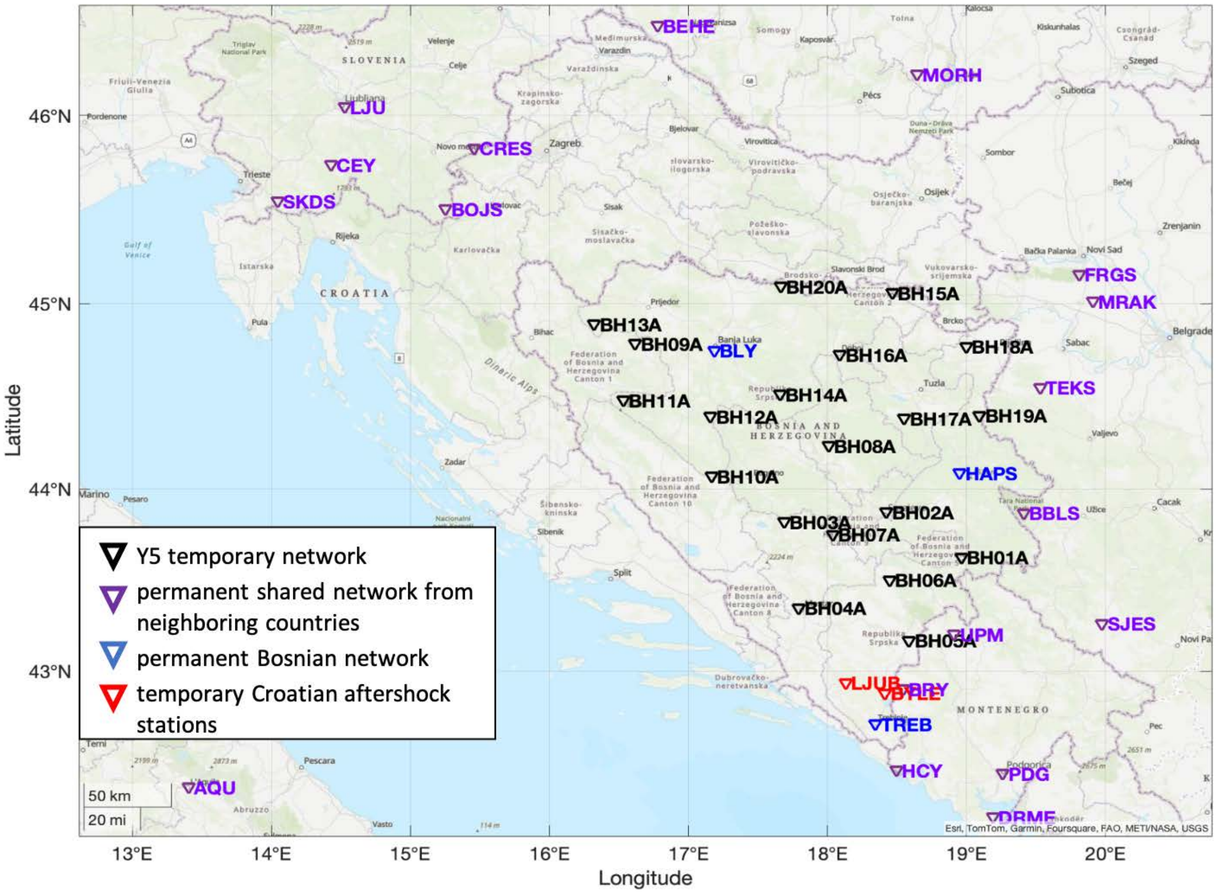

Figure 3. Adria Array Y5 temporary seismic network in BiH (black), shown alongside with the permanent stations from Banja Luka (blue), two temporary stations from Croatia (red) to monitor the Berkovići sequence and shared stations from neighboring countries (violet) used for earthquake location.

3.1 Fieldwork Preparation

Before field operations began, a comprehensive logistical plan was developed to ensure the efficient deployment of the seismic stations. Key considerations included evaluating potential local station sites, estimating material requirements, and the aligning of resources with the vehicle loading capacity. Coordination with site owners was also essential, requiring agreements on suitable dates for station setup. Additionally, road conditions were assessed to determine whether off-road vehicles were necessary in order to access to certain site locations. A critical preparatory step also involved the configuration and testing of 20 Taurus digitizers alongside STS-2 broadband seismic sensors. Simultaneously, 20 mobile routers were pre-configured, with assigned IP addresses and full system testing to ensure functionality. Customs documentation and shipping logistics were arranged in advance to facilitate the smooth transportation of the equipment.

For fieldwork deployment, pre-configured station setups were packed along with supplementary construction materials for potential seismic vault installations. Spare materials, extension cables, GPS/LTE and power cables were also prepared to ensure flexibility in the field. One logistical challenge encountered was the need to purchase prepaid SIM cards locally, since mobile operators could not be predetermined. This required configuring the access point name (APN) of the routers on site, causing minor delays. Furthermore, certain stations, accessible only by off-road vehicles, had to be rescheduled, but overall, this had minimal impact on the overall timeline. Weather conditions, an unpredictable factor, also had the potential to delay field operations. Fortunately, clear and hot weather allowed for the fieldwork to proceed without major disruptions.

Most stations were installed in state-owned buildings or areas, which facilitated relatively straightforward installations. The main technical challenge involved routing antenna cables out of buildings, particularly from basements or tunnels with limited access. Nonetheless, station security was not a concern, as the selected locations provided adequate protection.

3.2 Installation and operational details for each station

In Fig. 4, we show an exemplary installation site, BH04A, along with a power spectral density plot (PSD) of the vertical component. Site conditions and PSDs for all stations are shown in the Appendix, Figs. A1-A20. In the Appendix, we also provide in Table A1 the code name, coordinates, and operational period for each station.

Overall, the noise characteristics of the seismic stations were very good, approaching the U.S. Geological Survey (USGS) low noise model (Peterson, 1993). However, stations BH03A, BH06A, BH13A and BH14A that were placed on sediments, exhibit higher noise levels. Stations near masts, such as BH11A, BH15A and BH20A, showed periodic long-period deterioration, likely due to wind effects. The most problematic station was BH19A, which suffered connectivity issues despite the cell tower being clearly visible and accessible to the mobile antenna. Replacing the antenna and the router did not resolve the situation, resulting in minimal data availability during the operational period.

Figure 4. BH04A is installed in the Meteorological Observatory Mostar. The sensor is located in the basement, in the northeast corner of a two-storey office building. The basement is unused. The sensor is placed directly on the concrete floor of the building in a dense urban area.

4. Seismic Catalog

4.1 Event Detection and Location

In BiH, seismic catalogues are routinely computed by the Republic Hydrometeorological Institute of Republic of Srpska in Banja Luka. To improve the location accuracy, data is exchanged in real time with the neighboring countries (Serbia, Croatia, Montenegro, Slovenia, Italy), specifically from the stations marked in violet in Fig. 3. Catalogs are automatically created with SeisComp (Helmholtz-Centre Potsdam – GFZ German Research Centre for Geosciences and gempa GmbH, 2008) and manually revised using Seismic Handler (Stammler, 1993). One of the main challenges of automated catalogs is the limited number of permanent stations in BiH, which increases the detection threshold and results in less accurate locations and magnitude estimations. While large events are also detected by the stations in neighboring countries, the lower detection threshold relying on national stations is approximately M1.8. During the Adria Array temporary deployment, the increased number of detected phases significantly improved the sensitivity to smaller earthquakes, allowing the detection of events as small as M1, as we will see in the following sections.

4.2 Seismicity in BiH

In Fig. 5, we display the events from the seismic catalogs a) recorded prior to the AdriaArray network from January 2021 to May 2022, and in b) during the Adria Array temporary installations from June 2022 to December 2023. Noticeable still in 2023 is the aftershock sequence of the April 22nd, 2022 Berkovići earthquake with magnitude of 6.0 in the South (Fig. 5a), a region where the Adriatic microplate subducts beneath the Dinarids. The remaining seismicity is mainly spread along a NW-SE line, corresponding to the deep-reaching Sarajevo fault, which extends across BiH for more than 300 km. This central segment of the fault has episodically experienced moderately strong earthquakes (Papeš, 1988). During the AdriaArray project, the largest earthquake was registered in the Zenica area on December 30th, 2023, with a local magnitude of 5.0 (Fig. 5). In the Appendix Fig. A21, we show that the sparse permanent Bosnian stations cannot capture small magnitude events (ML $\leq$ 1.3) throughout central BiH.

In Fig. 6, we compare the magnitudes of cataloged events before and after Adria Array deployment, including the effects of network densification. A significant increase of smaller events is evident, thanks to the improved network coverage. We also observe a general shift towards lower magnitudes, related to a more accurate magnitude

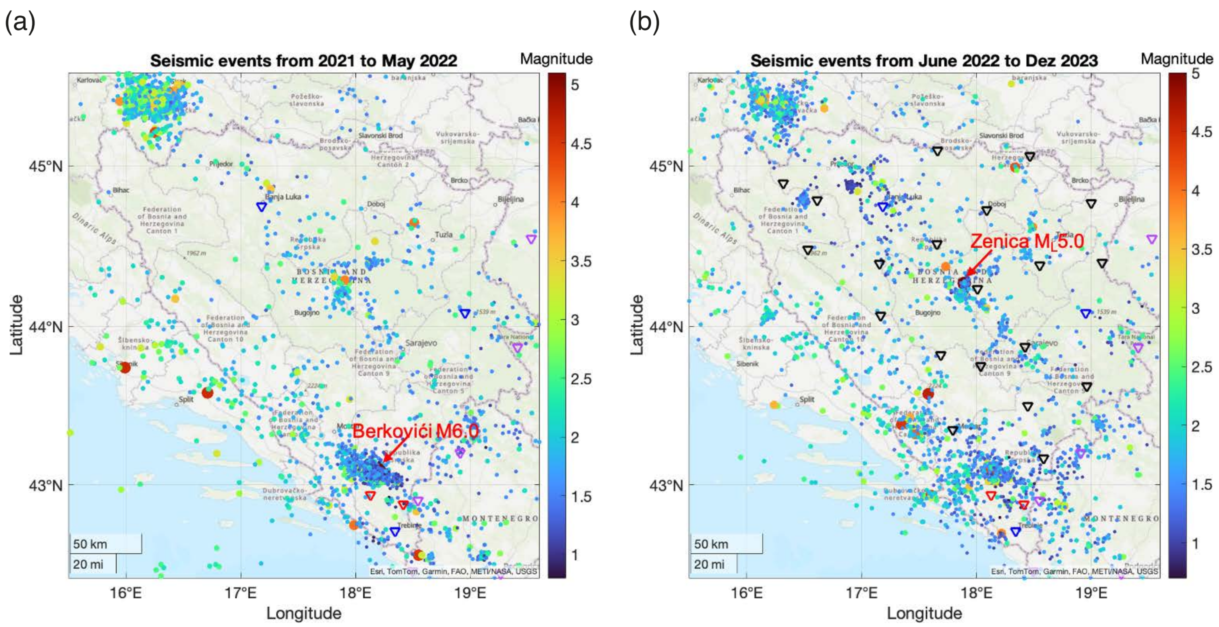

Figure 5. Seismicity in BiH and the neighboring regions (a) from January 2021 to May 2022 and (b) from June 2022 to December 2023.

estimation in a denser network, as also pointed out in Section 4.2. Overall, we detected 3100 events in both periods, respectively, with a significant number related to the Berkovići sequence.

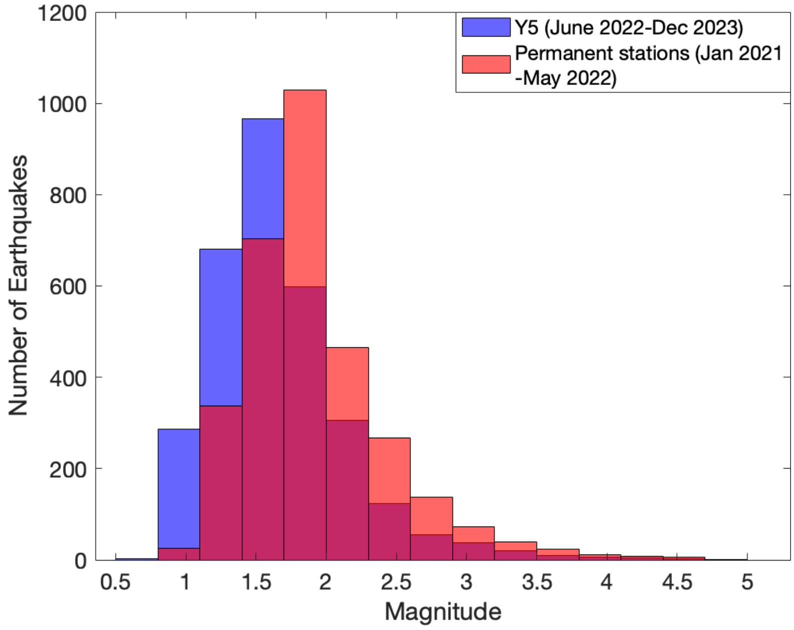

Figure 6. Histogram of earthquake magnitudes recorded for 1.5 years respectively. The histograms computed for earthquakes recorded on the permanent network from January 2021 to May 2022 are plotted in red, overlapping the blue histograms from the June 2022 to December 2023 events, detected on the Y5 temporary network. The Y5 network results in a notable improvement in low magnitude detections.

4.3 Largest-Magnitude events

In the following section, we take a closer look at two of the largest events that occurred during the AdriaArray deployment: the December 30th, 2023 ML 5.0 north Zenica earthquake and the February 1st, 2024 ML 4.0 northeast Sarajevo earthquake. Both events took place in seismogenic zones of high probability (Fig. 2). The seismic hazard in these areas, as highlighted by Omerbashich and Sijarić (2006), is related to the longest deep-seated fault of BiH that exceeds 300 km in length and reaches the Moho at a depth of 35-40 km (Stipčević et al., 2020).

4.3.1 Zenica Earthquake

On December 30th, 2023, at 20:43 UTC (21:43 local time), an event that the EMSC recorded with a magnitude of 4.7, struck BiH with the epicenter near Zenica. Significant tremors were felt throughout the broader region of BiH (Fig. 7).

17 stations from the Y5 network recorded this event. The closest station, BH08A, approximately 11 km from the epicenter, showed clear waveform clipping. A total of 17 Pg phase arrivals and 11 Sg phase arrivals were picked (Fig. 8), covering an epicentral distance from 11 km to 140 km. The local magnitude (ML) was manually determined by selecting waveforms with clear earthquake signals, resulting in an ML of 5.0. This higher value, compared to the M4.7 reported by EMSC, is likely due to EMSC not incorporating the AdriaArray stations in their calculations.

Further analysis revealed that at least 10 well-distributed stations across BiH were required to precisely locate this event and adequately determine its magnitude. This finding provides a strong indication for the minimum station density required to achieve proper earthquake monitoring in BiH.

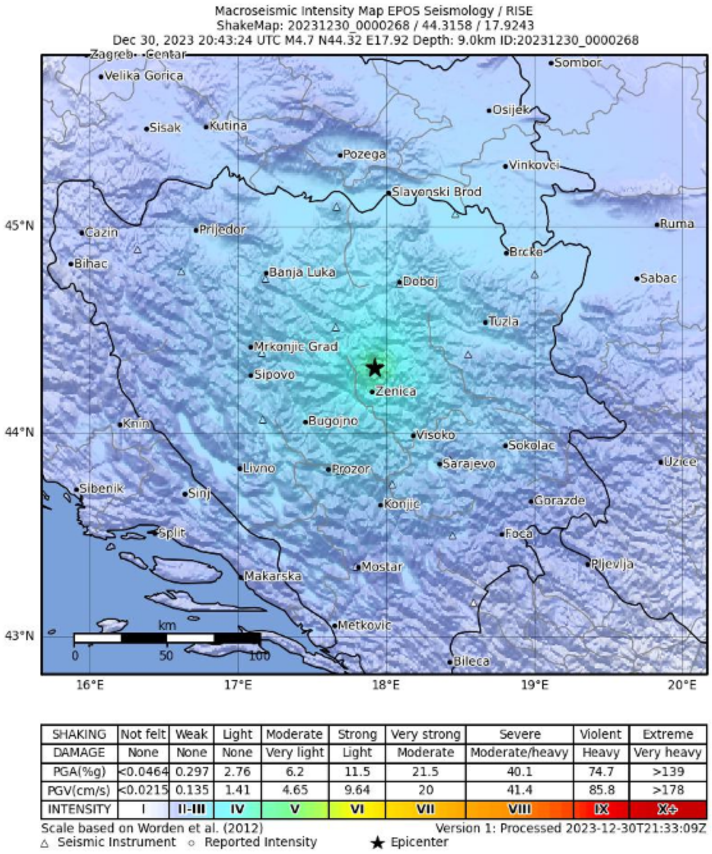

Figure 7. Macroseismic intensity ShakeMap of the December 30th, 2023, M4.7 (ML5.0) Zenica event (from ShakeMapEU, event ID ID:20231230_0000268).

4.3.2 Sarajevo Earthquake

On February 19th, 2024, at 08:22 UTC (09:22 local time), a magnitude 4.0 earthquake struck BiH 15 km northeast of Sarajevo, at a shallow depth of 10 km. Despite strong shaking, no damage was reported, and no shakemap was produced by EPOS, the European seismic hazard platform.

The event was clearly recorded by ten of the Y5 stations within 100 km (Fig. 9). We picked 8 Pg phases and 7 Sg phases, estimating a ML of 4.0. All picks were of high-quality and we tested that also the exclusion of individual stations during magnitude computation produced consistent results.

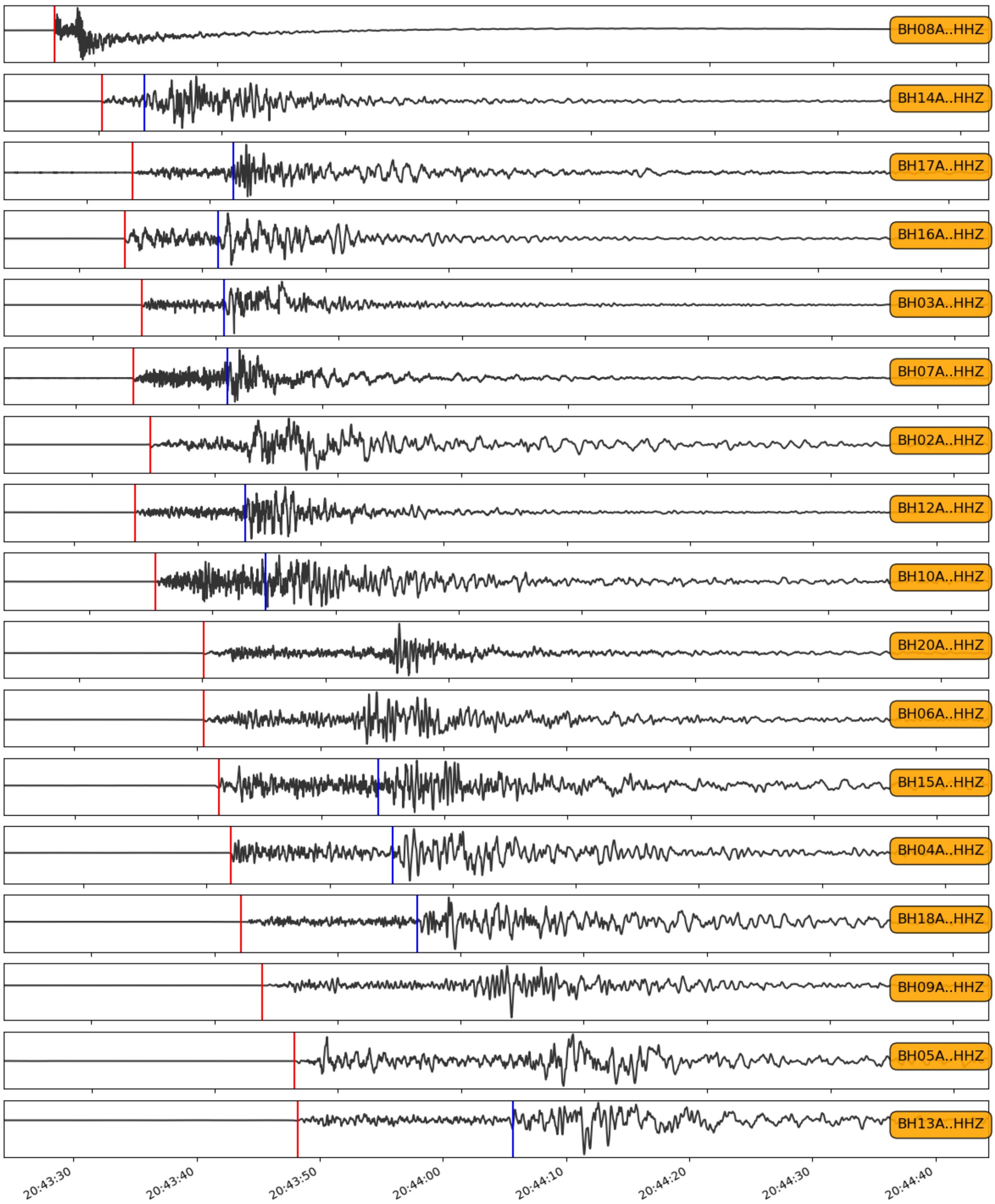

Figure 8. Waveforms of the December 30th, 2023, ML 5.0 Zenica earthquake as recorded by the Y5 network. Red vertical lines denote manually picked Pg arrivals, while the blue vertical lines mark manually picked Sg arrivals.

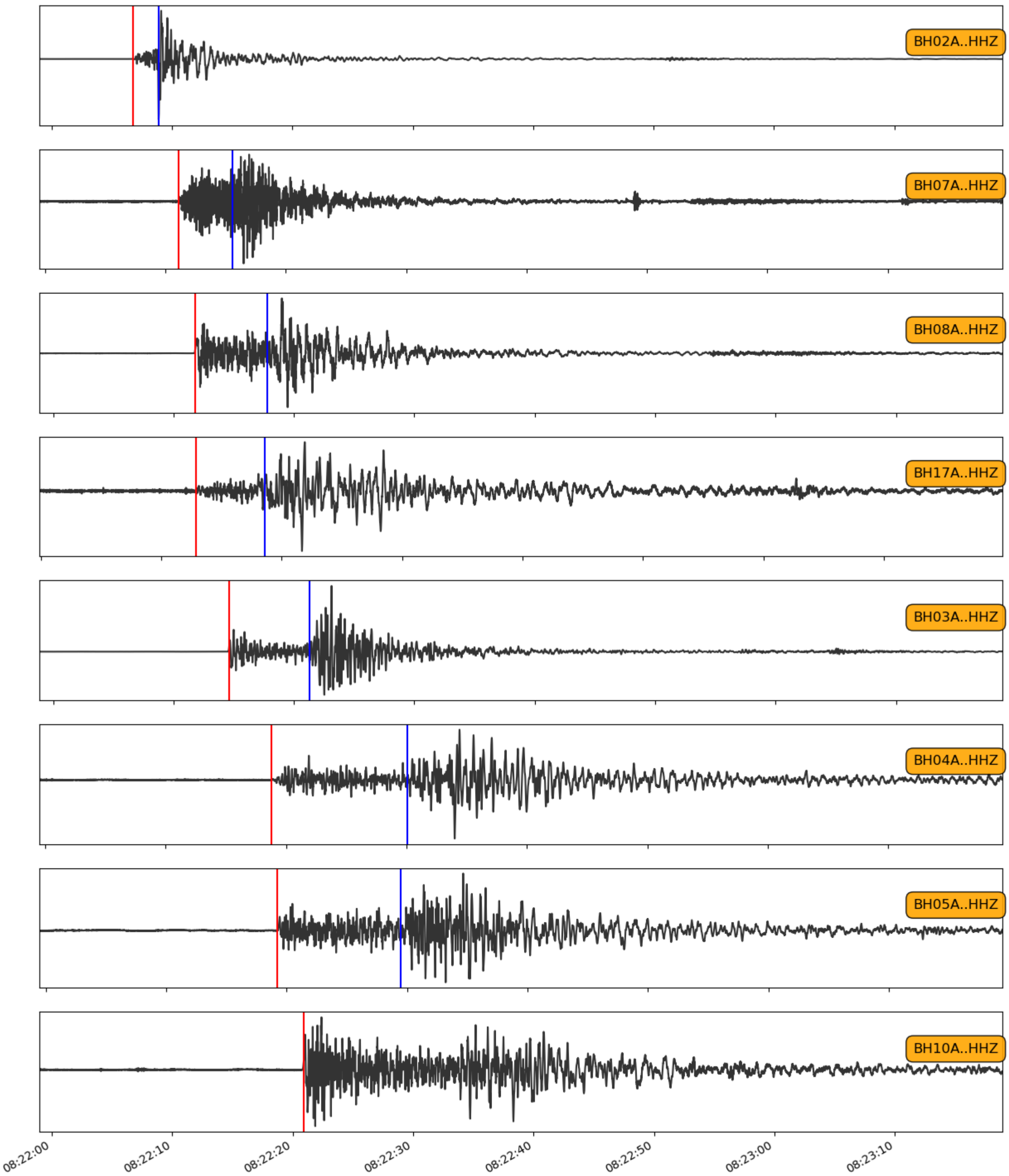

Figure 9. Waveforms of the February 19th, 2024 ML 4.0 Sarajevo earthquake recorded by the Y5 network. Red vertical lines denote manually picked Pg arrivals, while the blue vertical lines mark manually picked Sg arrivals.

5. Outlook

With the dismantling of the Y5 network, the number of seismic stations in BiH has significantly decreased, returning to its initial levels. However, the Hydrometeorological Institute of Federation of Bosnia and Herzegovina has installed 4 seismic stations, in the northern Una-Sana canton at the beginning of 2025. These stations will monitor potential induced seismicity related to the planned radioactive waste repository on Mount Trgovska Gora, located along the border area with BiH. Data will be streamed in real-time to the Italian EIDA node (Danecek et al., 2021).

Open seismic data exchange between the Balkan countries is essential for effective monitoring of this highly active seismic zone. As BiH is geographically central to the region, it plays a pivotal role in fostering cross-border data sharing. Expanding the seismic network would not only greatly enhance the monitoring capabilities within BiH but also benefit the neighboring countries.

To accurately assess seismic hazard and delineate faults with high resolution, BiH requires a well-distributed seismic network capable of significantly lowering the detection threshold. At a minimum, 10 strategically placed stations are necessary to achieve these objectives.

Data availability statement. The seismic catalogs from January 2021 to June 2022 and June 2022 to December 2023 are accessible at the ETH research collection under Obermann (2025). The seismic data, with metadata, is collected and available under the International Federation of Digital Seismograph Networks (FDSN) network code Y5 (Obermann et al., 2022).

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