

# Seismological Network in Hungary: Insights from the AdriaArray Operational Period

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## Abstract

The Hungarian National Seismological Network has experienced significant advancements in its monitoring capabilities due to the increasing density of seismic stations across the country, leading to improved earthquake detection and localization. This paper presents an analysis of the noise characteristics, detection capabilities, and seismic events registered by the Hungarian National Seismological Network, utilizing data from both permanent and temporary stations, including those from international projects such as AlpArray, PACASE, and AdriaArray. The noise characteristics of the network were analyzed through probabilistic power spectral densities, highlighting the diverse noise conditions across Hungary. The stations were grouped based on their installation dates and geographical locations, revealing significant differences in noise levels due to geological conditions, anthropogenic influences, and seasonal variations. Noise conditions at high frequencies, crucial for detecting low-magnitude local earthquakes, were particularly influenced by both geological factors and human activity. The study also investigated the horizontal-to-vertical spectral ratios and found correlations between sediment thickness, resonance frequencies, and noise levels at different stations. The paper assesses the detection capability of the seismic network, focusing on its ability to identify earthquakes of varying magnitudes. We estimated the maximum background noise displacement, providing insights into the detection thresholds of the network. The results showed that the network is capable of detecting events as small as magnitude  $M_L = 0.5$  during the night in northern Hungary and events larger than  $M_L = 1.25$  throughout the country during all day. A case study of the Szarvas cluster in 2023, a notable seismic swarm demonstrates the network's ability to accurately localize earthquake sequences using advanced localization algorithms. This event highlighted the enhanced seismic monitoring capability of the expanded network and its ability to capture small local seismic events that were previously undetectable. The paper concludes with an overview of ongoing research and future developments, including studies on the crust and mantle structure of the Pannonian Basin and wider region, advancements in seismic hazard mapping, and the role of the AdriaArray stations in refining earthquake localization. The continuous development of the Hungarian National Seismological Network and its integration into international cooperations are expected to further enhance high quality seismological structural research and contribute to a more detailed understanding of regional seismicity.

Keywords: Seismic network; Seismic noise; Spectral ratios; Seismicity; Pannonian Basin

## 1. Introduction

The Adriatic Plate and its active margins regularly generate earthquakes up to magnitude 7, so it is a perfect place to study geohazards caused by geodynamic processes. To identify the drivers of the underlying deformation, we have to better understand the seismicity of the region, the subsurface structure of the crust and lithosphere, the plate configuration including slabs and plate boundaries, and the properties of active fault systems and of the acting stress field. We also need to investigate the overall geological evolution of the region, and how the transitions occur between different topographic and geological domains, such as the Alps, the Pannonian Basin, the Carpathians, the Dinarides, the Eastern European Craton, the Balkans, and the Aegean.

Hungary and Pannonian Basin, located in Central Europe, is an extensional continental back-arc basin surrounded by major orogens, including the Alps, Carpathians, and Dinarides. It provides an exceptional natural laboratory for studying the interactions between deep Earth processes and surface tectonics. The basin was formed during the Miocene under an extensional tectonic regime (Tari et al., 2023), and has undergone significant evolution due to tectonic processes associated with the retreating subduction of the Carpathian slab (Royden et al., 1982). The Pannonian Basin has experienced significant tectonic inversion from the late Miocene to the present, attributed to the convergence and rotation of the Adria block towards the European plate (Horváth and Cloetingh, 1996; Bada et al., 2007). This process is accompanied by enhanced differential vertical movements, with dextral strike-slip zones dominating the southern basin and sinistral strike-slip zones in the central and northern parts (Fodor et al., 2005; Ruzsáczay-Rüdiger et al., 2020). This retreat resulted in lithospheric thinning, magmatism, and crustal extension. Extension ceased around 9 Ma, followed by compressional tectonics and neotectonic activity (Horváth and Cloetingh, 1996). The tectonic activity of the basin is well-documented by high-resolution geophysical data, including seismic tomography, receiver function, magnetotellurics, well data, and reflection seismic profiles (Balázs et al., 2017; Koroknai et al., 2020; Kalmár et al., 2021; 2023; Timkó et al., 2024; Rubóczki et al., 2024).

The Pannonian Basin is characterized by a complex geological history, previous geophysical research focusing its sedimentary infill (Balázs et al., 2016), thermal evolution (Lenkey, 1999), fault geometries (Tari et al., 1999), active tectonics (Porkoláb et al., 2023; 2025) and internal crustal structure (Kalmár et al., 2021; Kalmár and Balázs, 2025). The basin is the hottest region in continental Europe, with a high geothermal energy potential (Horváth et al., 2006; Békési et al., 2018). Crustal thinning and subsidence were accompanied by the accumulation of up to 7-8 km thick sedimentary successions in the main Pannonian depocenters (Horváth et al., 2015; Balázs et al., 2016). The geological evolution of the Pannonian Basin is a result of dynamic processes of extension, lithospheric thinning, tectonic inversion, and ongoing neotectonic activity. This region remains a key focus for geophysical studies, offering critical insights into the broader processes of continental deformation and lithospheric dynamics in the Mediterranean and Central European regions (Horváth et al., 2006; Matenco and Radivojević, 2012).

Based on the above, it has been shown that data acquired by dense, regional seismic networks provide crucial information on seismically active faults as well as on the structure and deformation of the lithosphere. However, the Adriatic Plate, and especially its eastern margin have not yet been covered by a homogeneous seismic network. During the last decades, several regional temporary arrays were realized in Europe, targeting specific tectonic features. The largest one among them was the AlpArray Seismic Network (AASN), which was deployed in the frame of the AlpArray program (Hetényi et al., 2018). The overall goal of AlpArray was to study the orogenic process and the structure of the crust and upper mantle in the greater Alpine region using seismological and other geophysical methods.

Then in 2019, 13 institutions from seven countries (Austria, Czech Republic, Germany, Hungary, Poland, Slovakia and Switzerland) launched a cooperative project called the Pannonian-Carpathian-Alpine Seismic Experiment (PACASE, 2019-2022; Schlömer et al., 2024; network code ZJ; Hetényi et al., 2019). The PACASE network was designed to cover the Western Carpathians and the Pannonian Basin and to overlap spatially with stations of the AASN which continued to operate in the Eastern Alps and in the Bohemian Massif (Schlömer et al., 2024).

Meanwhile, a new large-scale cooperative European program took shape. AdriaArray (Kolínský et al., 2025), the largest passive seismic experiment (more than 1400 broadband stations) that has been performed in Europe so far, is based on intense cooperation between local network operators, mobile pool operators, field teams, ORFEUS (Observatories & Research Facilities for European Seismology), EPOS (Europe Plate Observing System), and interested research groups. Altogether, more than 60 institutions are participating in the AdriaArray experiment and are forming the AdriaArray Seismology Group founded in 2022. At the same time, the PACASE project ended and the PACASE seismic network was transferred into the AdriaArray network. The AdriaArray network is a seismic

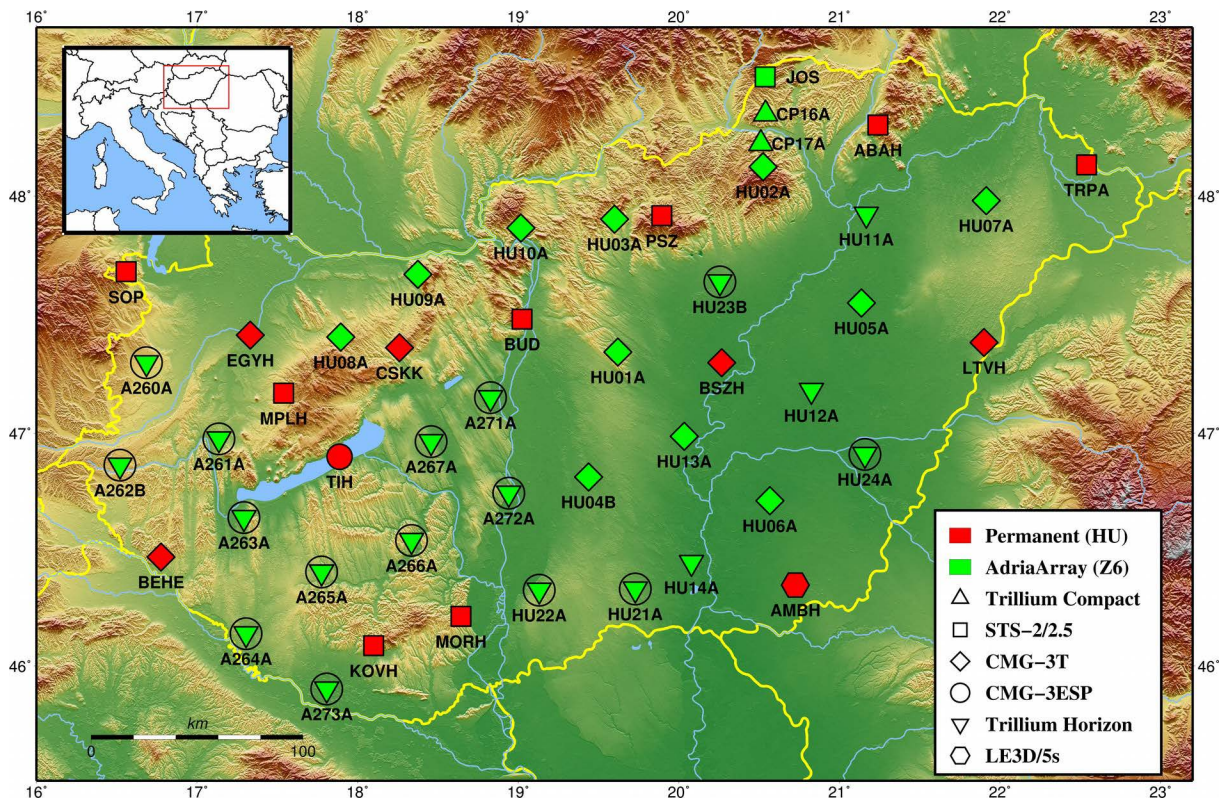
broadband array that covers the entire Adriatic plate in south-eastern Europe and joins newly deployed temporary and existing permanent stations all over the entire Adriatic plate. The average station spacing is about 50 km. The AdriaArray project addresses fundamental questions related to the geodynamics, deformation and stress field of the Adriatic plate in south-eastern Europe, and it will lead to a significant improvement of our understanding of the geodynamic causes of plate deformation and associated geohazards.

In this study we present the characteristics and instrumentation of the Hungarian National Seismological Network (HNSN) part of the AdriaArray experiment and describe the site selection criteria and process. We estimate the quality of the stations by calculating probability power spectral densities (PPSD) to ensure that the stations meet the quality requirements of the AdriaArray project. Then we discuss the detection ability of the network and illustrate how important it is in the localization of local events. We also summarize ongoing research projects and scientific results achieved using the AlpArray, PACASE and AdriaArray network data.

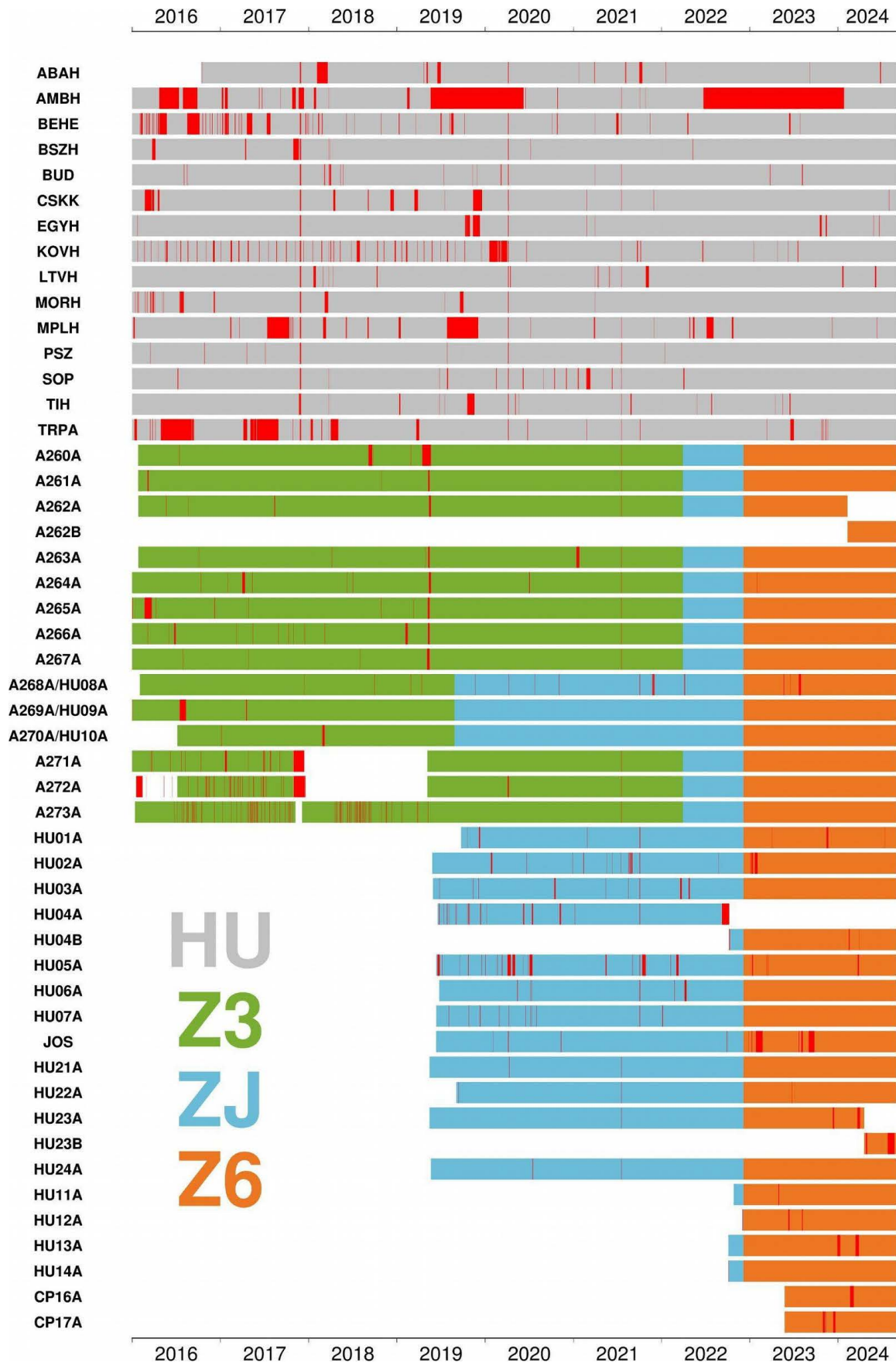
## 2. Evolution of the network

In 2024, the Kövesligethy Radó Seismological Observatory (KRSO) operated 47 seismological stations in the territory of Hungary (Fig. 1). Fifteen of them constitute the permanent stations of the HNSN, the others operate in the framework of AdriaArray. Fifteen of the temporary AdriaArray stations are operated by the KRSO, 15 are co-operated by KRSO and DSEBRA (Schlömer et al., 2025) and 2 of them are the part of West Carpathian Seismic Profile (Soni et al., 2025). The evolution of the network (since 2016), the operating time of the stations and the data availability can be seen in Fig. 2.

Although the history of seismological stations in Hungary goes back to the beginning of the 20<sup>th</sup> century, here we focus only the past 8 years, when the current distribution of permanent and temporary stations evolved. The latest permanent station (ABAH) was installed in 2016, the same year that AASN began to operate.



**Figure 1.** The HNSN in 2024. Symbols refer to the type of seismometer, red color: permanent station of the HNSN (network code HU; note that PSZ is co-operated by KRSO and GEOFON, it is available also with HU and GE network code), green: temporary stations of AdriaArray (Z6 network code). The temporary DSEBRA stations are indicated by a circle around the symbol. The inset map shows the location of Hungary within the territory of AdriaArray project.



**Figure 2.** Evolution of the network in Hungary and data availability from 2016 until 2024. The operational time of a station is marked by a continuous coloured band, colours indicate the corresponding network code (AlpArray: Z3, PACASE: ZJ, AdriaArray: Z6, Hungarian permanent: HU).

## Hungarian Seismological Network: AdriaArray operational period

Within the framework of the AlpArray project, 14 temporary stations were deployed in the western part of Hungary, 11 of them were operated by the KRSO, 3 (A271A, A272A, A273A) were equipped by the Swiss AlpArray SINERGIA program and co-operated with ETH Zürich (Gráczer et al., 2018; Molinari et al., 2016). All the AlpArray temporary stations had the FDSN network code Z3 (doi:10.12686/ALPARRAY/Z3\_2015).

In 2019, the dense network expanded to cover the entire territory of Hungary in the framework of PACASE project (Schlömer et al., 2024). KRSO dismantled 8 AlpArray stations (A260A-A267A) and installed the instruments at 8 new sites in the eastern part of Hungary (stations: HU01A-HU07A and JOS). The DSEBRA consortium (Deutsches Seismologisches Breitband Array – German Seismological Broadband Array consists of 100 uniform mobile broadband seismological stations and was acquired in 2017 to initially contribute to the backbone network of the European AlpArray initiative and later to join other European and international projects, Schlömet et al., 2024) provided the equipment for 15 stations in Hungary. 12 of them replaced the dismantled AlpArray stations formerly equipped by KRSO or ETH Zürich and 4 were installed in 4 new sites in the eastern part of Hungary (stations HU21A-HU24A). The three former AlpArray stations of KRSO (A268A, A269A and A270A) were renamed to HU08A, HU09A and HU10A, respectively. All the new stations had the ZJ network code of the PACASE network (doi:10.7914/SN/ZJ\_2019), except the former AlpArray stations replaced by DSEBRA, which kept the original Z3 AlpArray network code (Fig. 2) until the embargo of AlpArray data (March 31, 2022).

In 2022, the PACASE seismic network was transferred into the newly established AdriaArray network. Within this framework, KRSO installed 4 new stations in Hungary (HU11A-HU14A) to fill the gaps in the existing network in the central part of the Great Hungarian Plain. In this way, the average distance between a station and its 6 neighboring sites is 50 km. All the temporary stations in Hungary gained the new Z6 network code (Schlömet et al., 2022b, doi:10.7914/2cat-tq59) in December 2022.

During the operational time of the temporary stations, 3 of them (HU04A, HU23A, A262A) were moved to a different nearby site due to changes in ownership and/or changes in building usage. The last character in the name of these stations changed according to the naming convention (Fig. 2).

In 2023, two additional stations (CP16 and CP17) were installed in the northern part of Hungary as part of a dense seismological profile of the Western Carpathians. Details about these stations can be found in Soni et al. (2025).

### 3. Installation and instrumentation

Station deployment was always preceded by multiple noise level measurements to identify the best possible site. During the site selection process, contradictory aspects must be taken into account. On the one hand, the site should be far away from all sources of any anthropogenic seismic noise, on the other hand, electricity, safe placement and accessibility in all seasons are needed. Taking these aspects into account we looked for objects located in the countryside or on the edge of the settlement: cellars, weekend houses, hunting lodges, funeral homes. In the area of the Great Hungarian Plain, where seismic noise level is high due to thick sediments (~between 1 and 6 km) and unfavorable soil conditions, it is more difficult to find a suitable location. The electricity required to operate the instruments outside the settlements is usually only available on larger livestock farms or inhabited houses. Noise measurements lasting several days were carried out in the possible places and the final location was chosen by comparing the noise spectra.

Two examples of station configuration can be seen in Fig. 3. For thermal insulation, seismometers were covered by a bucket, filled with polystyrene packing foam peanuts. Orientation of sensors are checked by gyrocompass at all stations, except the two moved stations (A262B and HU23B) in 2024. In every case GPS timing is applied. All of the stations are online using 4G mobile or wired internet connections. The data of permanent stations are archived at GEOFON EIDA node, while the data of AdriaArray temporary stations are stored at LMU EIDA node.

The network consists of broadband seismometers, except one permanent station (AMBH) which is equipped temporarily by a short period instrument. Type of sensors are shown on the station map (Fig. 1). DSEBRA stations are equipped with Nanometrics Trillium Horizon 120 seismometers and Nanometric Centaur digitizer/datalogger (Schlömer et al., 2022a). In case of the temporary stations equipped by KRSO, three types of seismometers are used: the majority (11) are equipped with Güralp 3T 120s, 3 stations with Nanometrics Trillium Horizon 120 and one station with Streckeisen STS-2. All these temporary stations are equipped with Güralp DB24SEAM data acquisition units.



**Figure 3.** Two examples of installed temporary stations. (a) HU01A is installed in a cellar, the seismometer is placed on a granite slab, covered by a bucket filled with polystyrene packing foam peanuts. (b) HU06A sensor was placed on the concrete floor of an unused building.

### 4. Site characteristics of the stations

Gráczner et al. (2018) described the location, housing type and geological conditions of all permanent and temporary AlpArray stations, here we introduce the stations that have been deployed since then.

#### *HU01A – Pánd*

Pánd is a village in the central part of Hungary, at the southern end of Gödöllő-Monor hills. The pre-Cenozoic basement is 1.5 km deep and Upper-Pleistocene loess can be found on the surface. The station is located outside the village, in the territory of a social home. The seismometer is placed in a 20 m long cellar on a granite slab.

#### *HU02A – Bükkszentlélek*

The station is located in the northern part of the Bükk Mountains (North Hungarian Range). The sensor was put on the concrete floor in a cellar of a tourist park at 760 m altitude. Permian limestone can be found on the surface.

#### *HU03A – Ecseg*

Ecseg is a village at the foot of Cserhát Mountains. The pre-Cenozoic basement is at a depth of approximately 3.9-4 km, Cretaceous clay marl and Middle-Miocene limestone can be found on the surface. HU03A was deployed in a cellar on the edge of the village. The seismometer is placed on a granite slab.

#### *HU04A and HU04B – Ágasegyháza*

The stations are located in the Duna-Tisza Interfluve. The surface is covered by Holocene sand and the pre-Cenozoic basement is 0.45 km deep. HU04A was located in a pit next to an unused building. The sensor was put on a granite slab. In 2022, due to change of ownership, the station had to be moved. The new location is 3 km far from the original. HU04B was deployed in a stand-alone cellar of a weekend house. Sensor was put on a tiled floor.

#### *HU05A – Hortobágy*

Hortobágy is in the central part of the Great Hungarian Plain. The settlement lies on 1.9 km thick sediments and the surface is covered by Holocene clay. The station is deployed in the Hortobágy Wild Animal Park of the Hortobágy National Park. Since the buildings are in continuous usage, the equipment is placed in a wooden box about 50 m from the houses. A concrete plinth was made for the sensor and additional thermal insulation was applied.

#### *HU06A – Eperjes*

Eperjes lies on the south-eastern part of the Great Hungarian Plain. The station is installed on the concrete floor of an unused small building on the edge of the village. The pre-Cenozoic basement is located at a depth of about 3 km and the surface is covered by Upper-Pleistocene loess.

#### *HU07A – Apagy*

The station is located about 2 km far from the village Apagy, in the northeastern part of the Great Hungarian Plain. It is deployed in an unused stable, which belongs to a hotel 200 m away. The pre-Cenozoic basement is about 2.6-2.7 km deep and the surface is covered by Holocene sand and fluvial silt. The seismometer is put on the concrete floor.

#### *HU11A – Újtikos*

HU11a is deployed in an unused one-storey house on the edge of Újtikos, a village in the northern part of Great Hungarian Plain. The sensor is placed on a tiled floor. Lower- and Upper-Pleistocene siltstone is present on the surface.

#### *HU12A – Kisújszállás*

Kisújszállás lies in the central part of the Great Hungarian Plain. The station can be found about 6 km from the inhabited areas, in a rarely used small building next to a crop storage. Holocene siltstone is exposed at the surface, and the sensor was put on the concrete floor.

#### *HU13A – Tiszakécske*

HU13A was deployed outside the residential area of Tiszakécske, in an uninhabited farm building. The seismometer was placed on a tiled floor. The surface layer consists of Upper-Pleistocene sand.

*HU14A – Dóc*

Dóc is a village in the southern part of Hungary, in the vicinity of Tisza river. The station was deployed outside the residential area, in an uninhabited farm building. Upper-Pleistocene sand can be found at the surface level and the sensor was placed on a tiled floor.

*HU21A – Pusztamérgecs*

The station was deployed in an occasionally used farm building, outside the residential area of Pusztamérgecs in southern Hungary. The settlement lies on 2.2 km thick sediments with Holocene sand on the surface. The sensor was placed on the concrete floor.

*HU22A – Érsekhalma*

Station HU22A is located in a relatively shallow, 1.2 km deep sedimentary basin filled with Cenozoic sediments and the surface is covered by Holocene sand. The instruments deployed in an outbuilding of a forestry house, on a concrete floor.

*HU23A and HU23B – Bernáthegecs*

Bernáthegecs is located in the northern part of the Great Hungarian Plains. The basement depth exceeds 3.1 km and the area is covered by Holocene sand. The stations were installed in the vineyard outside the centre of the village. Both stations were deployed in a cellar and the sensor was placed on a tiled floor. HU23A had to be dismantled in 2024 due to change of ownership, HU23B was installed about 0.5 km far from the first site.

*HU24A – Bélmegyer*

Bélmegyer lies on a 3.7 km thick sedimentary cover sequence in the eastern part of the Great Hungarian Plain, Holocene clay is on the surface. The station is deployed in the cellar of an unused hunting lodge. The building is located 4 km from the village and 1 km from an agricultural farm. Seismometer was placed on a granite slab.

*JOS – Jósvalő*

The station is deployed 2 km far from Jósvalő village, near Hungary's northern border, within the Aggtelek Karst region of the North Hungarian Range. It is positioned at an elevation of 288 meters, where Middle- and Upper-Triassic limestone is exposed on the surface. The first seismological station was installed here in 1970, in a basement built for this purpose. It closed in 1986 but re-opened in 2019 as a member of the PACASE network. The station kept his old name JOS. KRSO plans to operate this station as a permanent station after the AdriaArray initiative.

## **5. Noise characteristics of the stations**

### **5.1 Noise conditions**

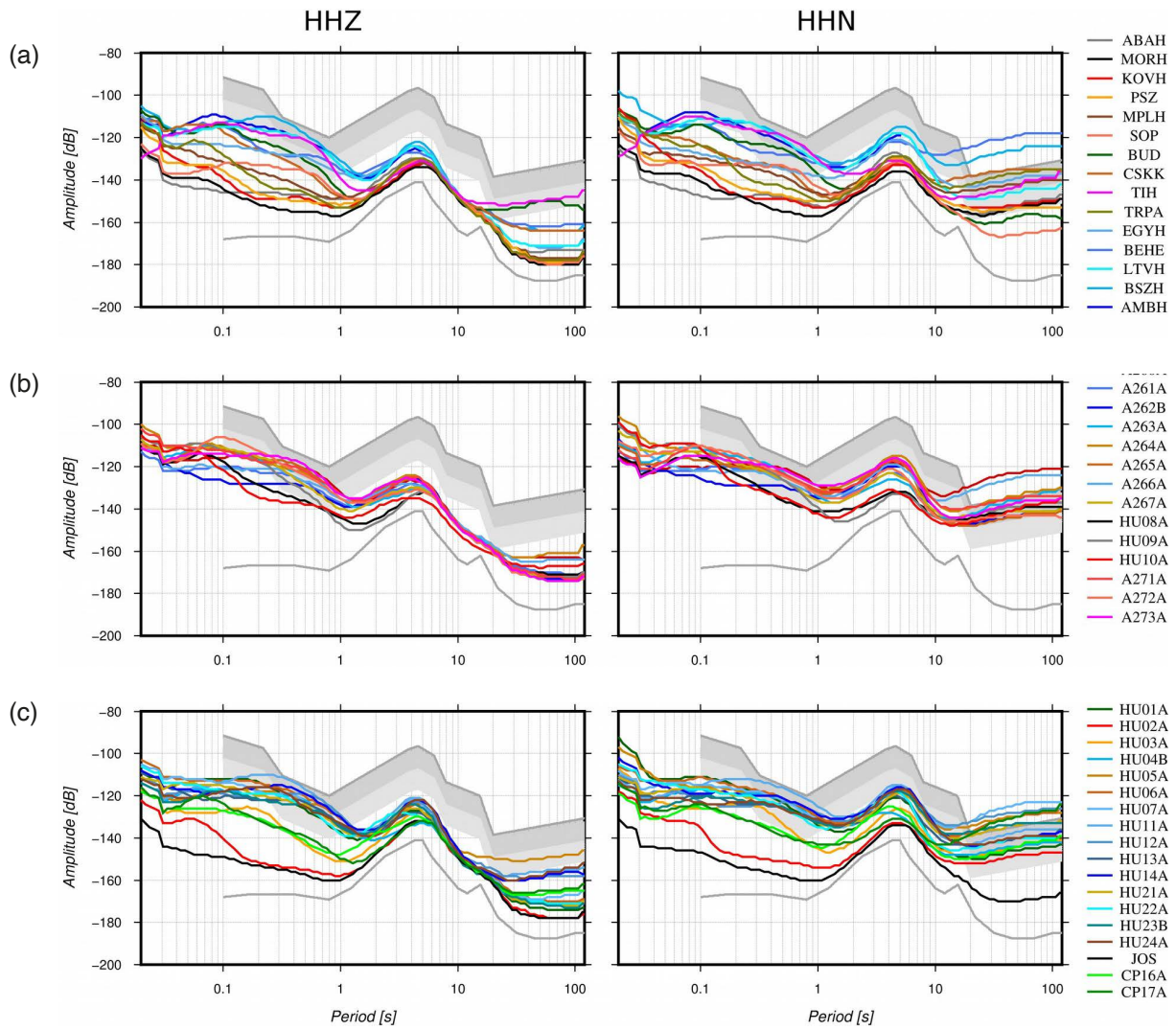
Probabilistic power spectral densities (PPSD; McNamara and Buland, 2004) were computed for the stations in Hungary using all the available data in 2024. The time window was chosen for presenting noise characteristics of the operating stations with the current instrumentation.

The median curves of the PPSDs can be seen in Fig. 4. For better visibility of the individual curves the results are shown in three groups: the permanent stations, former AlpArray stations installed in 2015 and 2016 and the third group consisting of the stations installed in 2019 and 2022 as PACASE or AdriaArray stations. Vertical and horizontal (north) components are shown, together with the curves of the New High Noise Model (NHNM) and the New Low Noise Model (NLNM) (Peterson, 1993).

Noise conditions at short period (<1 s) are crucial in detecting low-magnitude local earthquakes. This is also the typical frequency range (around and higher than 1 Hz) of anthropogenic seismic noise. First, the noise conditions of the vertical component are analyzed.

The curves of the permanent stations vary widely in the presented frequency range, which indicates the different geological conditions of the sites (Gráczer et al., 2018). The temporary stations in the western part of the country (former AlpArray stations) are more uniform lying in a narrower noise level range. In the case of the third station group, again great variation can be observed. The correlation between the noise level and

## Hungarian Seismological Network: AdriaArray operational period



**Figure 4.** Median curves of PPSDs, based on all available data in 2024 for vertical (HHZ) and one horizontal (north, HHN) component. (a) Permanent stations, (b) temporary stations installed during AlpArray, (c) temporary stations installed during AdriaArray. Curves of the NHHM and NLNM are shown (grey lines). Dark grey zone: NHHM-10 dB range, light gray zone: NHHM-20 dB range.

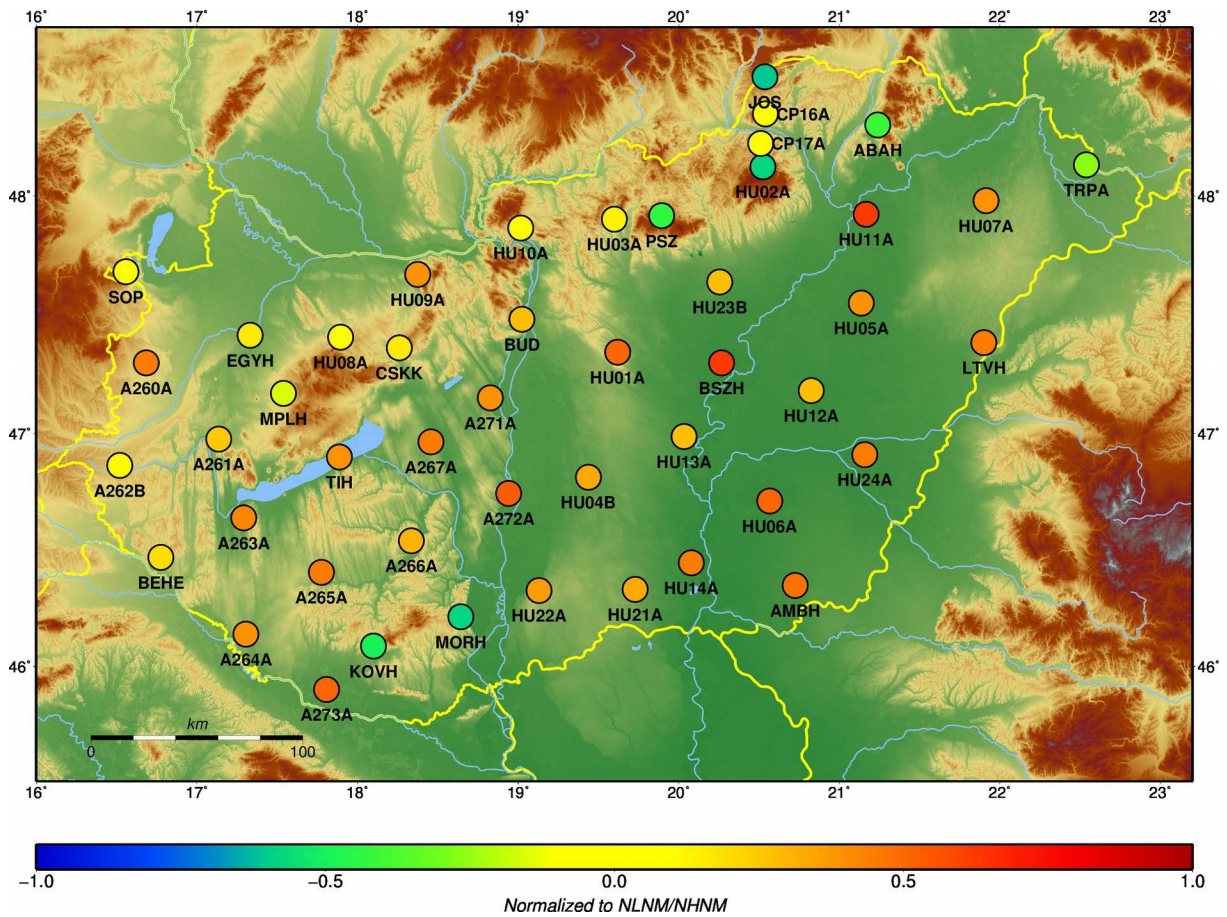
the geographical, geological conditions can be seen in Fig. 5. Here the values of the median PPSDs at 5 Hz were normalized between the corresponding values of NHHM (1) and NLNM (-1). Thus orange-red colours indicate values closer to NHHM and green-blue colours closer to NLNM.

The best noise conditions in this frequency range can be observed at MORH, KOVH, PSZ, HU02A, JOS, ABAH, TRPA. These stations are installed on hard rock and also the effect of human activity is moderate. Higher noise level but still under the NHHM-20 dB line can be found at SOP, MPLH, HU08A, CSKK, HU10A, HU03A, CP16A, CP17A. The median PPSD curves of the remaining stations are above the NHHM-20 dB level, typically approaching the NHHM curve in the Great Hungarian Plain areas, but none of them exceeds it.

In the short period range (<1 s) the median curves of the horizontal components are very similar to the vertical ones.

In the next period range (2-10 s) oceanic microseisms dominate. Median curves are beneath the NHHM-20 dB line at all stations. In case of vertical components, below 6 s, the noise level is correlated with geological conditions (rock or sediment), above 6 s, the median curves are in a very narrow range with no significant variations.

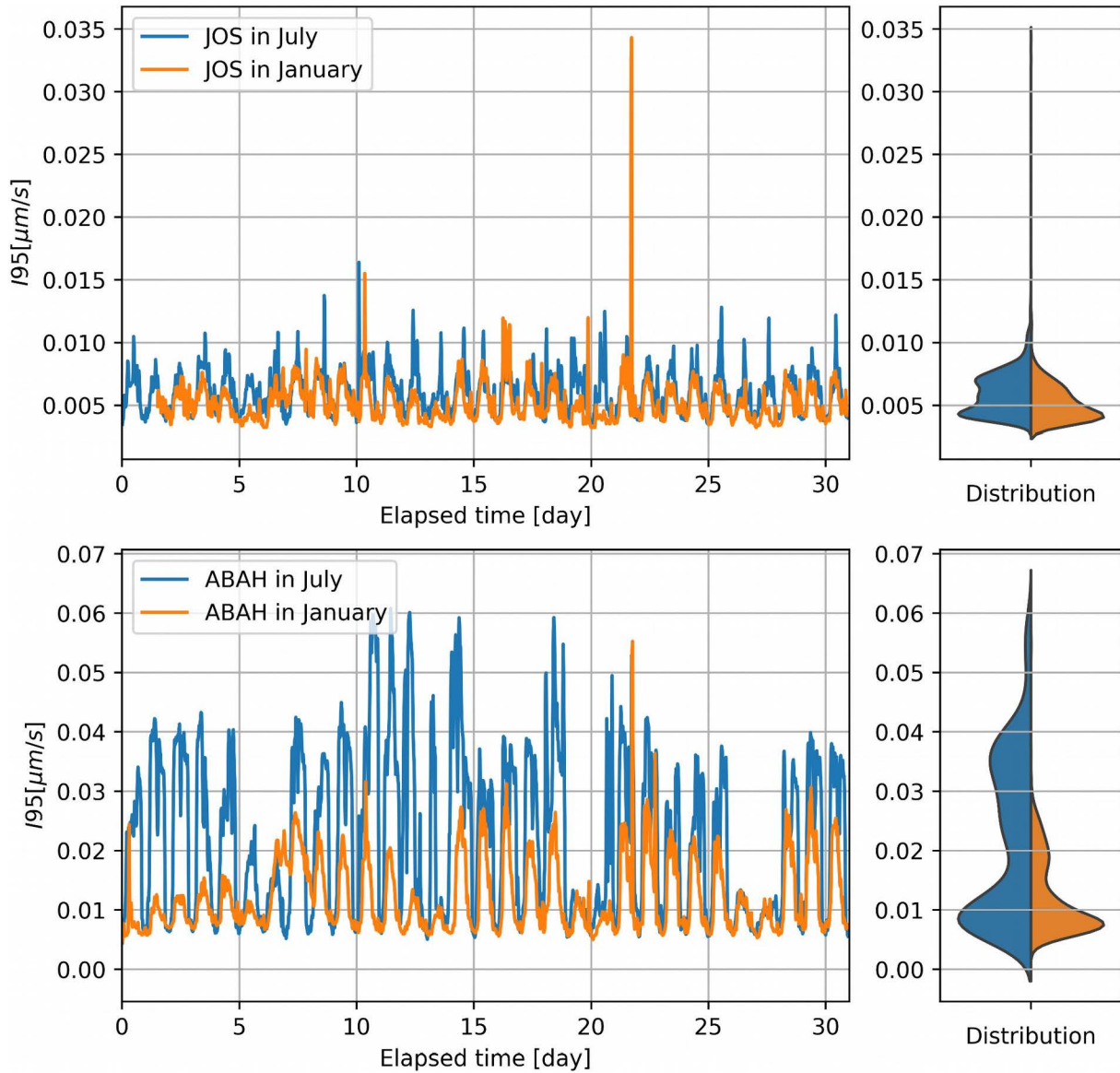
In the microseism range (1-10 s), the noise level of horizontal components increases in areas covered by thick sediments. This will be further analyzed in the next section (5.2).



**Figure 5.** Normalized values of the median PPSDs at 5Hz. Orange-red colours represent values closer to the NHNM, while green-blue colours indicate values closer to NLNM.

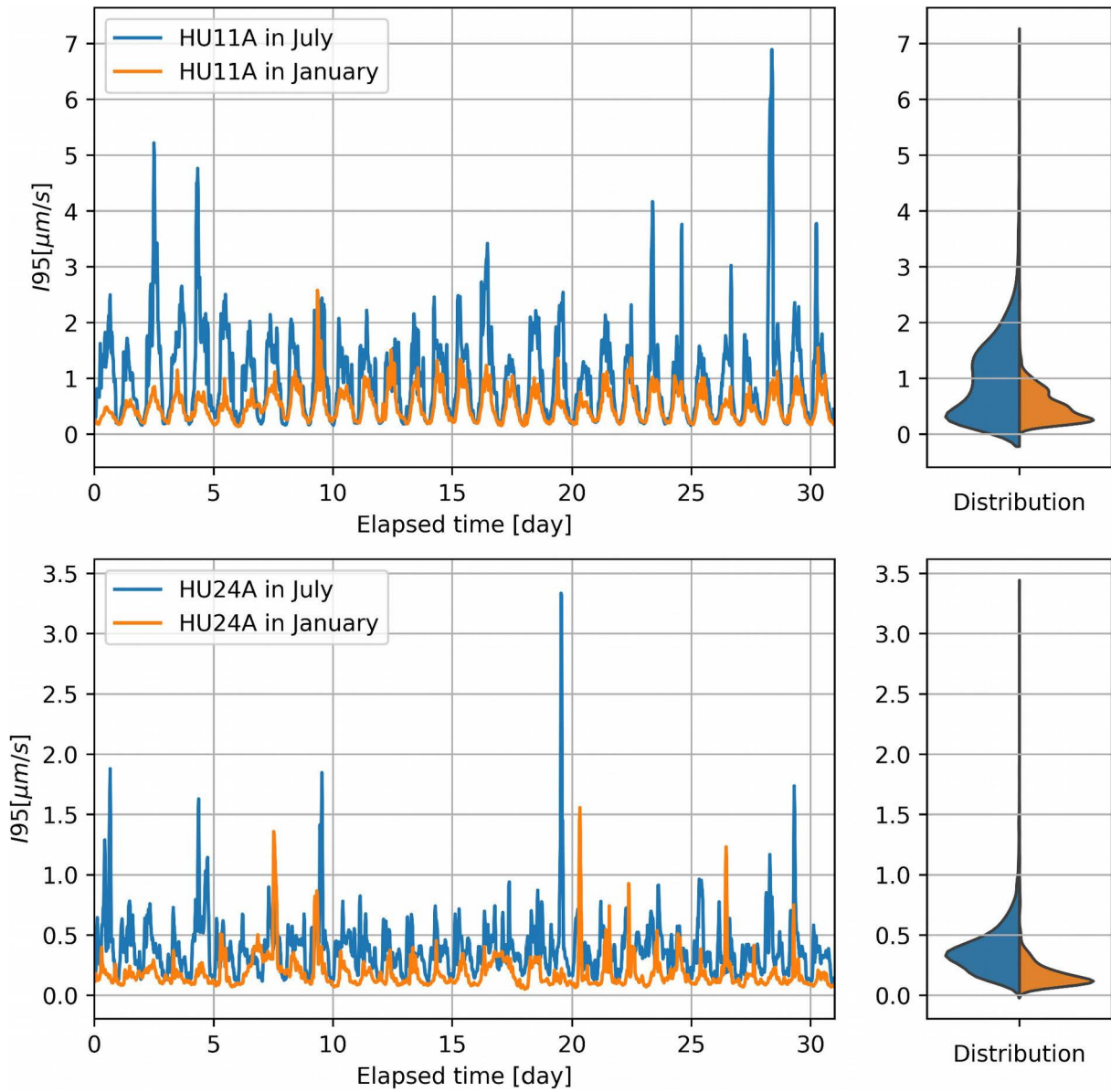
At long period ( $>20$  s), only the curves of three stations (BUD, TIH, HU05A) exceed the NHNM-20dB line at the HHZ component. In this range, the noise level of the horizontal component strongly depends not only on geological conditions but on the circumstances of the installation and applied insulation. Majority of the median curves can be found between the NHNM and NHHM-20 dB lines. Only the stations installed on hard rock in closed tunnels or cellars (e.g. JOS, SOP, BUD) have lower noise levels. During the AlpArray, two permanent (BEHE, BSZH) and three temporary (A260A, A262A and A266A) had worse noise conditions than the NHNM (Gráczer et al., 2018). The relocation of A262A resulted in decreased long-period horizontal component noise level as well. Four of the AdriaArray stations (HU05A, HU06A, HU07A, HU12A) have median curves above NHNM. In these cases, the applied insulation of the sensor is probably insufficient.

Diurnal and seasonal variations are also noticeable in the short period frequency range. To demonstrate these effects we calculated the I95 value (e.g., Groos and Ritter, 2009; Schlömer et al., 2022a; 2024) at some typical stations. The response of the instruments were removed from the raw waveforms and after applying a taper, bandpass filtering in the 1-20 Hz range was performed. Then, in each 1-hour-long window, shifted by 30 minutes, the 95<sup>th</sup> percentile of the amplitude distribution was calculated. The calculations were carried out for one summer (July) and one winter (January) month (Figs. 6 and 7) of 2024. Station JOS can be characterized by the best noise conditions, both diurnal and seasonal variations are insignificant in the high-frequency range (Fig. 6a). ABAH is also among the better stations, but strong variations can be observed. Although the I95 values are similar during the nights in January and in July, the daily peaks are considerably higher in the summer, which can be explained by increased human activity. In the case of stations in the Great Hungarian Plain with much worse noise conditions, the increased human (mainly agricultural) activity in the summer is also spectacular (Fig. 7). Also note the one magnitude difference on the y axis between the two figures (Figs. 6 and 7), which clearly shows the difference between stations installed on hard rock (JOS) and thick sediment (HU11A).

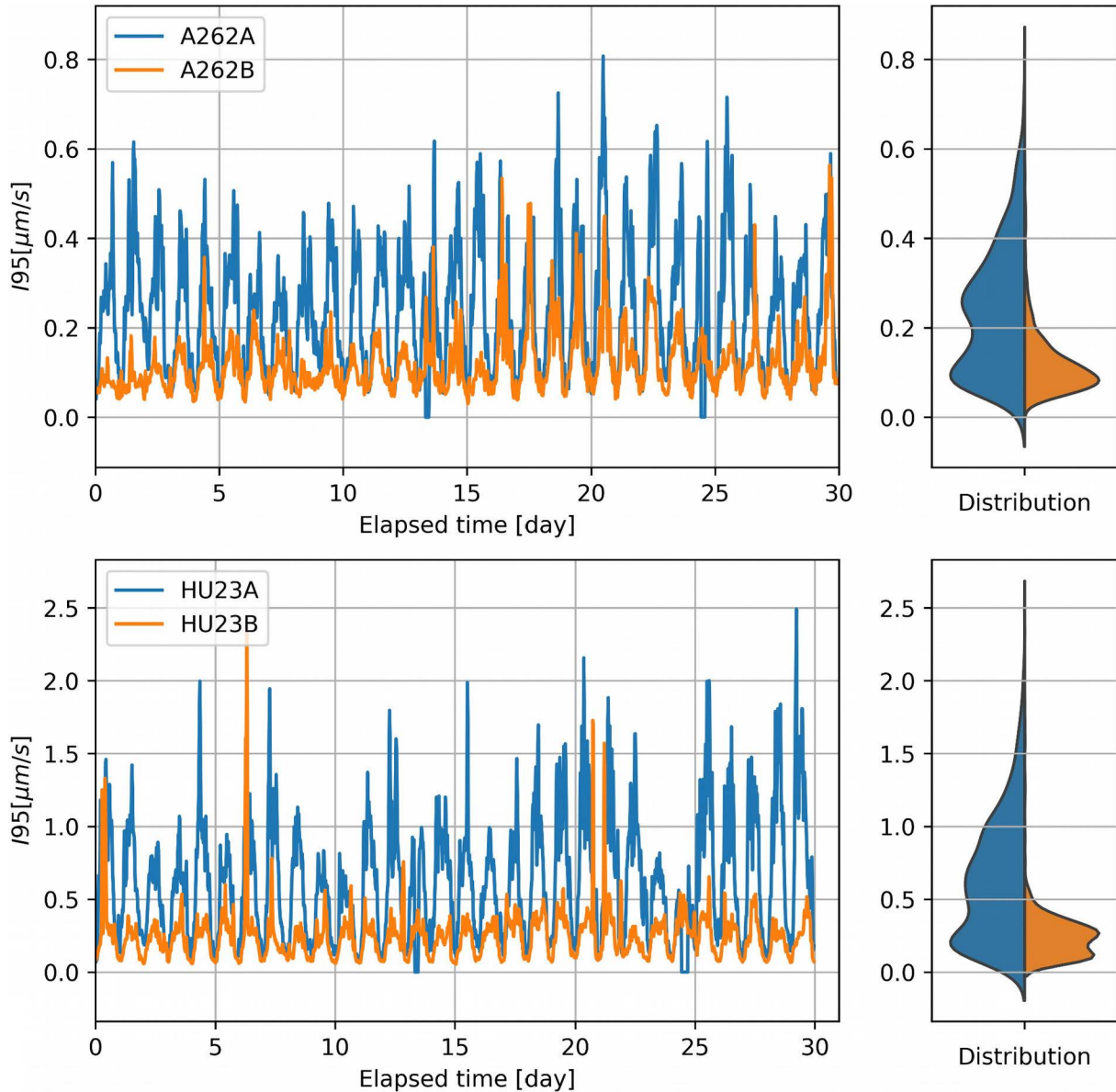


**Figure 6.** I95 values (left) and violin plots (right) calculated in the 1-20 Hz frequency band for one summer month (July) and one winter month (January) at stations JOS and ABAH. These stations are deployed on hard rock, characterized by good noise conditions. Diurnal and seasonal variations can be explained by the human activity near the site.

Further examples of I95 values can be seen in Fig. 8. Here the data of one summer month are shown in case of the relocated stations. In both cases, stations moved about 500 meters. In Szaknyér (A262A and B), the seismometer was installed on the ground floor of a two-story belfry originally. Because of the reconstruction of the building, it was moved to the funeral home at the edge of the settlement. Although this is a very small village, daytime human activity increased the seismic noise level. In Bernáthegy (HU23A and B), both locations were in cellars of weekend houses. Higher noise level at the first site can be explained by the more frequent and intense gardening activity.



**Figure 7.** I95 values (left) and violin plots (right) calculated in the 1-20 Hz frequency band for one summer month (July) and one winter month (January) at stations HU11A and HU24A. These stations are deployed on thick sediment.



**Figure 8.** Comparison of I95 values of the relocated stations. One month (June) data from 2023 (A262A, HU23A) and from 2024 (A262B, HU23B) are shown.

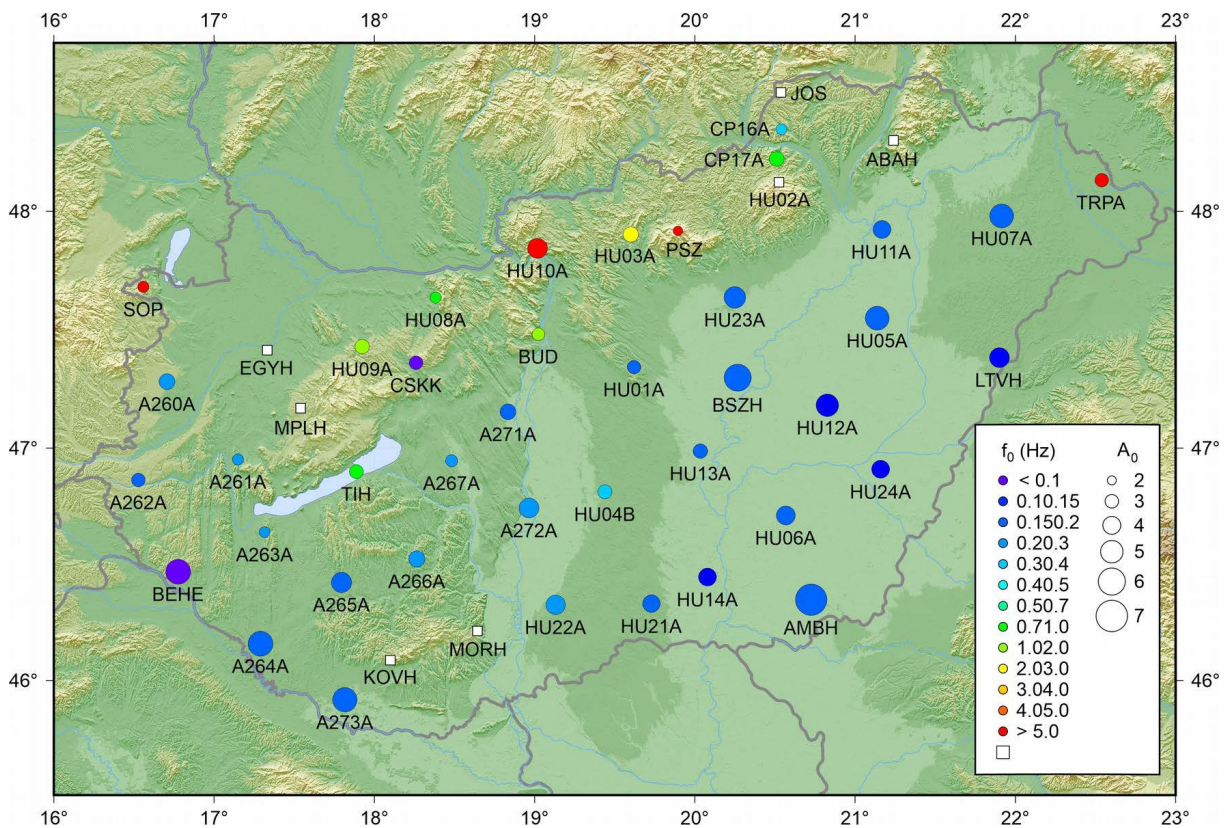
## 5.2 Horizontal-to-vertical spectral ratios

Gráczner et al. (2018) investigated the difference in average noise levels between the horizontal and vertical components for the AlpArray stations in Hungary, while Schlömer et al. (2024) investigated this difference for the entire PACASE network. In the high frequency range, especially at a period of 0.2 s they found insignificant noise differences between the vertical and horizontal components. At the higher frequencies, between 1-10 Hz, the similar noise levels of the HHZ and HHN components are also clearly visible in Fig. 4. Gráczner et al. (2018) also studied disparities in the longer period range, below  $T = 1$  s. They analysed the period range of 1 to 10 seconds and identified a noise difference of more than 10 dB between the horizontal and vertical components of the stations located on the deep sediments of the inner part of the Pannonian Basin (Great Hungarian Plain, Drava Basin, Little Hungarian Plain). In contrast, this difference was less than 5 dB at stations located in hard rock. Schlömer et al. (2024) compared the average PPSD values of the vertical with the north and east components in the range of the microseism at 6 s and showed that stations in Hungary (and some in south-eastern Poland, south-eastern Germany close to the Danube, and a few stations in Austria and Slovakia) have much higher noise levels on the horizontal components

than on the vertical component. They also concluded that the increased noise level in the horizontal component reflects the local geology namely that these stations are located in sedimentary basins.

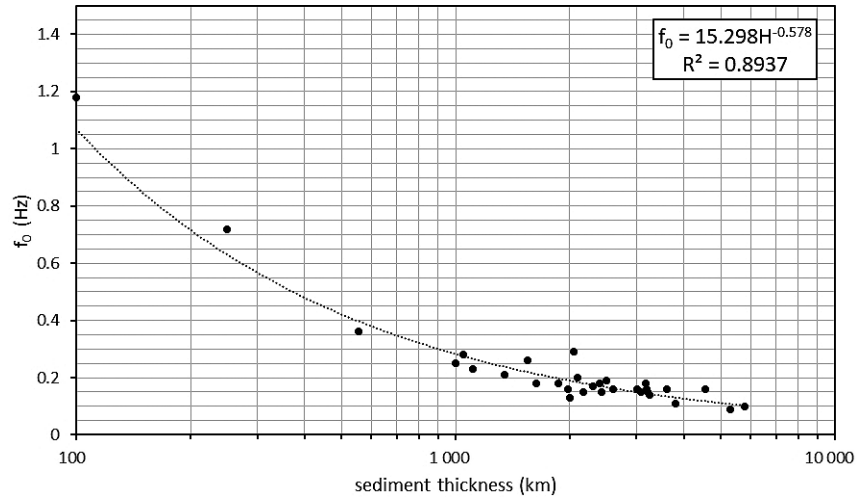
To study how these differences are affected by the dominant frequencies of the sites, we computed the horizontal-to-vertical spectral ratios (HVSr, Nakamura 2000) from 20 s to 20 Hz for all of the stations. In order to minimize the effects of coherent and transient noise sources, we used 3 hours long noise records of a warm, windless summer night (23.08.2024) for the calculations. The data processing included baseline correction, calculating amplitude spectra in 100-second windows, determining the horizontal component as the geometric average of the NS and EW components, determining HVSr in each window, calculating the average and standard deviations, studying temporal stability, and examining the reliability of the curves according to the SESAME project (Site Effects Assessment using Ambient Excitations) criteria (Atakan et al., 2004). The project focused on developing and standardising the HVSr technique, which included guidelines for data acquisition, processing and interpretation. Key reliability criteria for HVSr curves were defined, including the minimum number of windows used, consistency between mean and median curves, clear and stable peaks across different time windows, and low standard deviation of HVSr in the frequency band around the peak.

The frequencies and amplitudes of the resonance peaks that could be read from the curves are shown in Fig. 9. The map clearly shows (in blue) the stations that are located on sediment. Upon examination of the resonance frequencies, a strong correlation between frequency values and sediment thickness was observed (Fig. 10). At stations located on thick sediments of the Pannonian Basin (1-6 km), the fundamental resonance frequencies fall within the range of 0.1-0.3 Hz, that is approximately in the 3-10 s period range. These findings align with those of Gráczner et al. (2018) and Schlömer et al. (2024), who observed that in case of sedimentary stations the average noise level is higher for longer periods on the horizontal components than on the vertical. However, this amplification effect is not limited to the noise level but also manifests in the long-period components of the incoming earthquake waves. In the case of thin sediment thicknesses of a few tens of meters, the resonance peaks are observed to shift towards frequencies exceeding 1 Hz. In the case of stations located on hard rock, either no resonance is observed



**Figure 9.** Resonance frequencies and amplitudes of the resonance peaks at the permanent stations of the HNSN and temporal stations of the AdriaArray network. The colour of the circles indicates the resonance frequency, and their diameter shows the amplitude of the resonance peak. White squares mark the sites with no resonant peaks.

at all, or weathered layers near the surface cause a lower amplitude peak in the HVSR curve with frequencies greater than 4-5 Hz. However, in addition to the general observations, some exceptions were identified. Despite the EGYH permanent station being situated on sedimentary rock and the underlying bedrock being located at a depth of between 2 and 2.5 km, no discernible resonance peak is visible on the HVSR curve. A further exception is the BUD station. It is located in a tunnel on the side of a hill in Triassic dolomite. The HVSR observed at this site shows a directivity in dip direction that also coincides with the main noise sources in the capital, and is therefore largely anthropogenic in origin.



**Figure 10.** Correlation between sediment thickness and resonance frequencies determined for stations located on sediments.

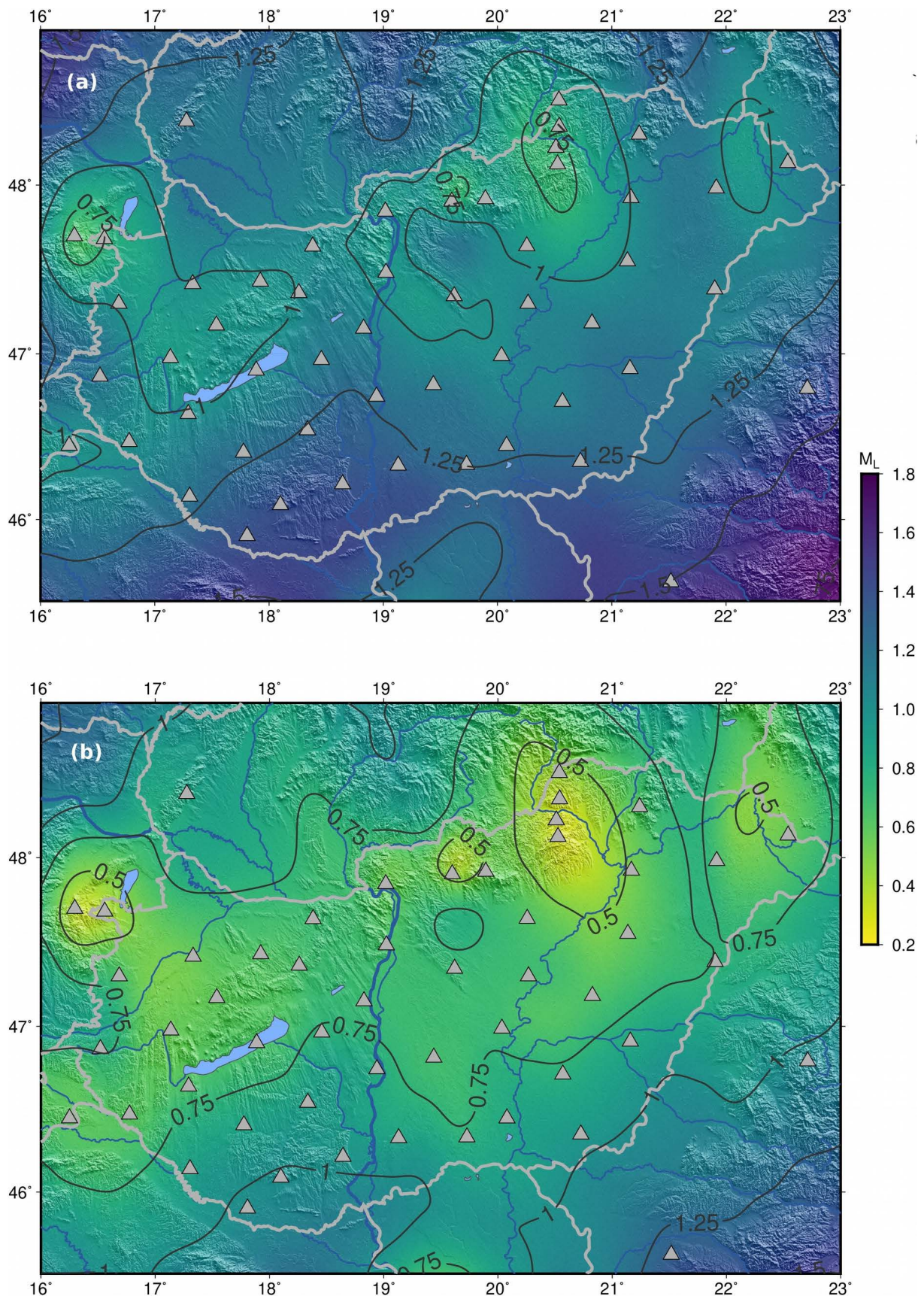
### 5.3 Detection capability of the network

Data of the temporary stations are also integrated in the daily work in the observatory. Identifying and locating seismic events in Hungary and its surroundings are based on data of all stations in Hungary and permanent stations from the neighboring countries.

The event detection capability of the network has been estimated using the SN-CAST method of Möllhoff et al. (2019). SN-CAST is an open source Python program, which can be used to calculate the geographical distribution of detection capability basing on stations coordinates and noise amplitudes. First, hypocentral distances between each stations and the point of a grid covering the network territory are calculated. Then, for each station, the maximum ground displacement amplitude is calculated by applying the equation of the local magnitude scale for a range of magnitude values. And as the last step, the smallest magnitude is found by applying the conditions which describe how many stations have to detect the event and what should be the signal to noise ratio (the ratio between event amplitude and background noise amplitude).

We have assumed that we could determine the magnitude of an earthquake if at least 4 stations have recorded it with a maximum event amplitude at least 3 times of the background noise amplitude. Since the event detection capability of the seismic network highly depends on the background noise level, we have estimated the maximum background noise displacement at 5 Hz based on power spectrum densities. The 90 percentile was chosen to calculate the worst-case scenario. All available data of 2024 were used. As noise levels differ significantly during day and night, we have constructed two maps showing the varying detection capabilities of the network (Fig. 11).

Detection capability of the network is sufficient to identify earthquakes above  $M_L = 1.25$  in Hungary regardless of the time of day. It is even possible to detect  $M_L = 0.5$  events in northern Hungary at night.

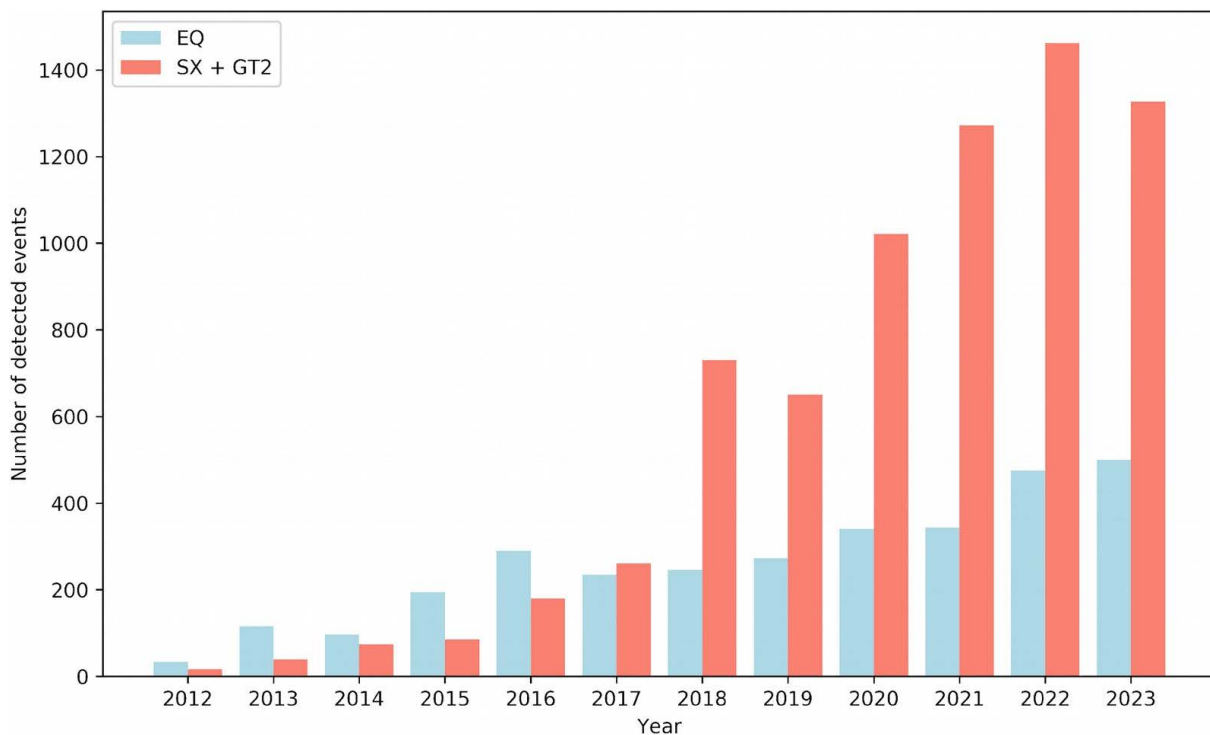


**Figure 11.** Detection capability of the network during day (a) and night (b). The maps show the minimal magnitude of the detectable earthquake, if we assume 5 km focal depth and assume that we can detect an earthquake if at least 4 stations have recorded it with a maximum amplitude at least 3 times of the background noise level.

## 6. Hungarian National Seismological Bulletin and Network Development

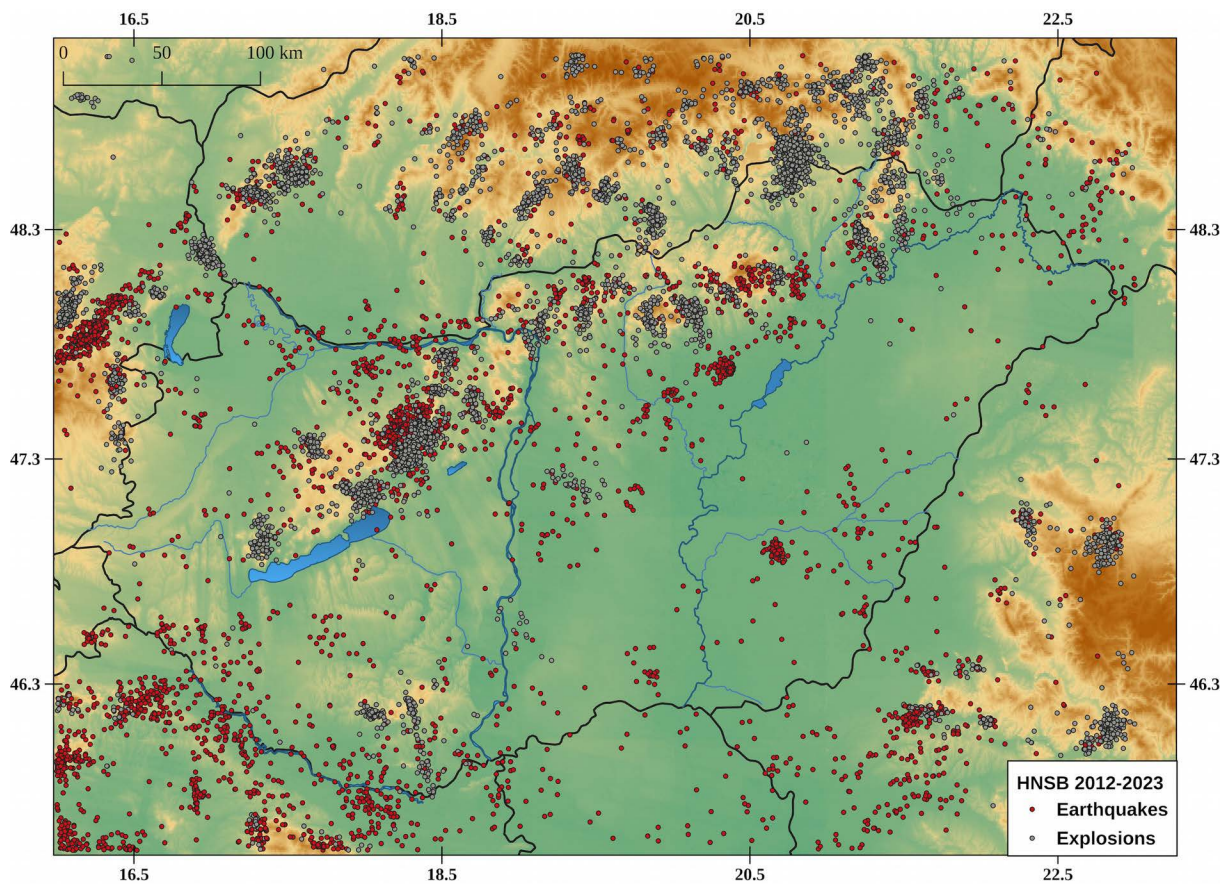
Since 2016, the increasing density of seismic stations in Hungary has led to improve detection capabilities and greater precision in earthquake localization. This enhanced monitoring network (AlpArray, PACASE and AdriaArray) provides a comprehensive perspective on seismic activity in Hungary, distinguishing between anthropogenic seismic events and natural earthquakes from 1996 to 2023. By integrating advanced methodologies and expanding the seismic infrastructure, recent efforts have significantly increased both the volume of detected events and the accuracy of their localization.

Accurate determination of earthquake locations and magnitudes is essential for understanding tectonic processes, delineating active fault zones, and conducting hazard assessments. Earthquake locations were determined using the Hypo71 program until 2014, then the entire catalog was revised using the iLoc software (Bondár and McLaughlin, 2009), which enabled more advanced localization capabilities. Utilizing the 3D RSTT velocity model (Myers et al., 2010), which accounts for both depth variations and horizontal directional changes, significantly improved the accuracy of seismic event localization in Hungary. This methodological shift has enabled the compilation of a unified, precise catalog of seismic events, the Hungarian National Seismological Bulletin (HNSB), with adjusted hypocenters that minimize location uncertainties. Not all detected events are included in the HNSB database due to a quality control process. In general, events with a secondary azimuthal gap greater than  $340^\circ$  (although a few exceptions may be considered) or those with large error ellipse major axes, which indicate high uncertainty, are excluded from the database. Only events that contain a sufficient number of reliable phases, ensuring accurate and robust location determination, are retained. The revised catalog, spanning from 1996 to 2023, features a uniform methodology applied to all events, ensuring consistent updates and enhancements to the dataset every year. The number of registered events in the HNSB ( $45.5^\circ$ - $49^\circ$ N;  $16^\circ$ - $23^\circ$ E) shows an annual increase (Fig. 12), with a particularly dramatic rise observed from 2016 onwards.



**Figure 12.** Annual count of anthropogenic seismic events (SX + GT2) and earthquakes (EQ) recorded in the HNSB from 2012 to 2023.

In the dataset significant number of anthropogenic seismic events (mostly quarry blasts) can be found. The quarry blasts confirmed by the mine operators are GT2 events (Ground Truth events with epicentre location accuracy of 2 km, Bondár et al., 2004). The unconfirmed quarry blast and other explosions are signed as SX (suspected explosion).



**Figure 13.** Recorded seismic events (explosions and earthquakes) in the HNSB from 2012 to 2023.

The dataset reveals a notable increase in anthropogenic seismic events (GT and SX combined) from 2012 to 2023. While the years from 2012 to 2016 show a relatively small number of recorded events, a marked rise begins in 2017. By the end of 2023, the national digital catalog had verified more than 1500 GT2 quarry blast events (Bondár et al., 2004), which provide essential data for multiple event location algorithms.

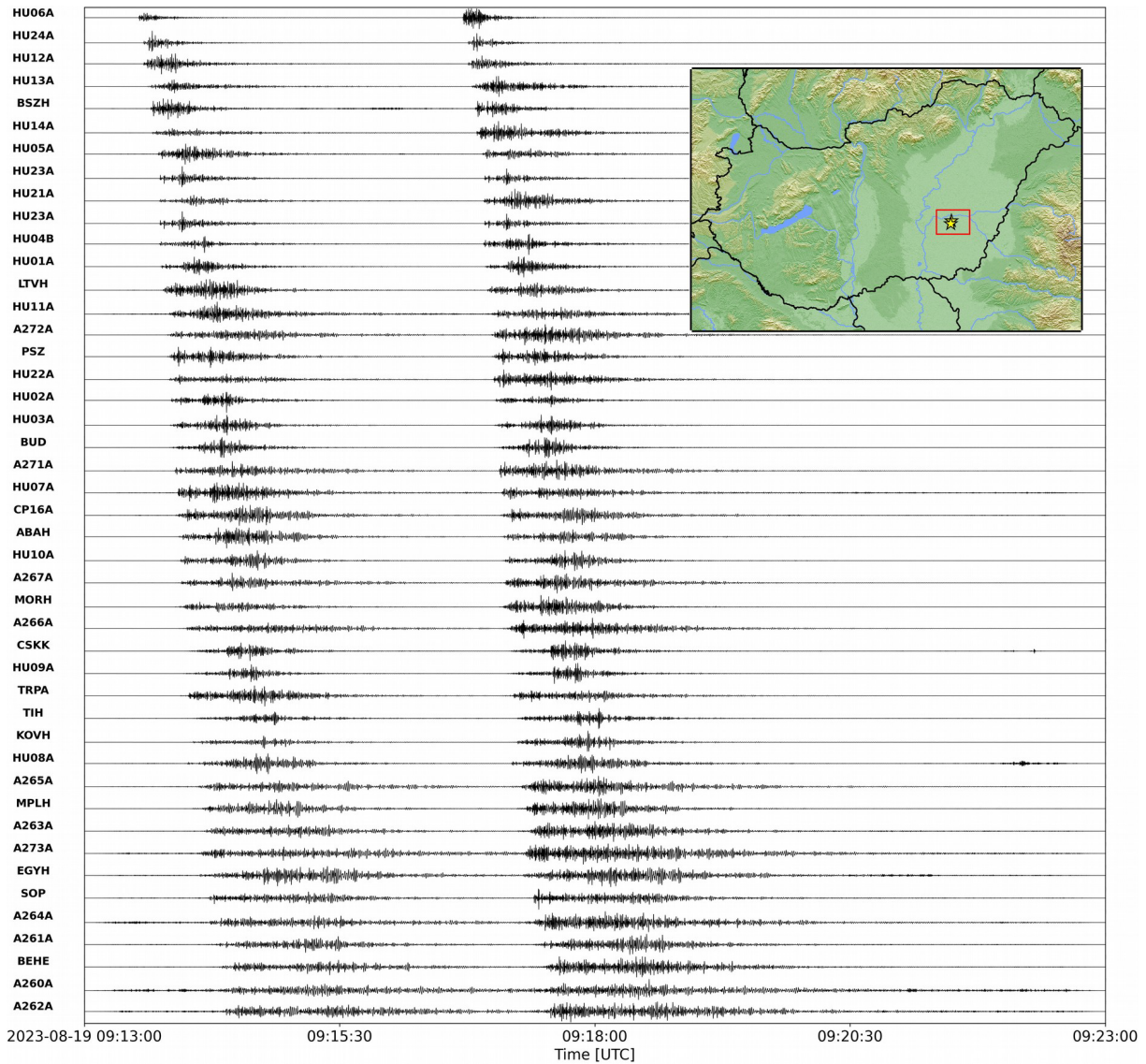
In contrast, natural earthquakes, represented as EQ events in the dataset, exhibit a fluctuating but overall increasing trend. Despite inherent annual variability, the data show a sharp rise in recorded events from 2016 onward, peaking at 500 events in 2023. This increase does not imply a higher frequency of natural seismic occurrences but rather reflects the benefits of the improved station network, which has progressively lower detection thresholds, enabling the capture of smaller, previously undetectable tremors.

Consequently, the catalog now contains a filtered, high-quality set of events that reliably represent the seismicity of the wider Pannonian region (Fig. 13).

In conclusion, the analysis of Hungary's seismic activity dataset from 1996 to 2023 emphasizes the profound impact of anthropogenic factors and network development on seismic event detection. The rise in detected anthropogenic seismic events (SX and GT) and earthquakes (EQ) is attributed to the capabilities of the expanded monitoring network. The revised HNSB catalog serves as a foundational resource for ongoing seismic hazard assessment and geological research, offering critical insights into the interplay between human activity, network development, and natural seismicity in the region.

### 6.1 Case study: Szarvas cluster 2023

In the summer of 2023, a unique seismic swarm began in southeast Hungary. On August 19, two significant earthquakes ( $M_L = 4.0$  and  $M_L = 4.1$ ) occurred in the area around Szarvas and Csabacsüd (Fig. 14), followed by additional seismic events. The investigation of this earthquake cluster is of paramount importance, as 13 events in the sequence were widely felt by the population, with questionnaires collected from a 100 km radius.

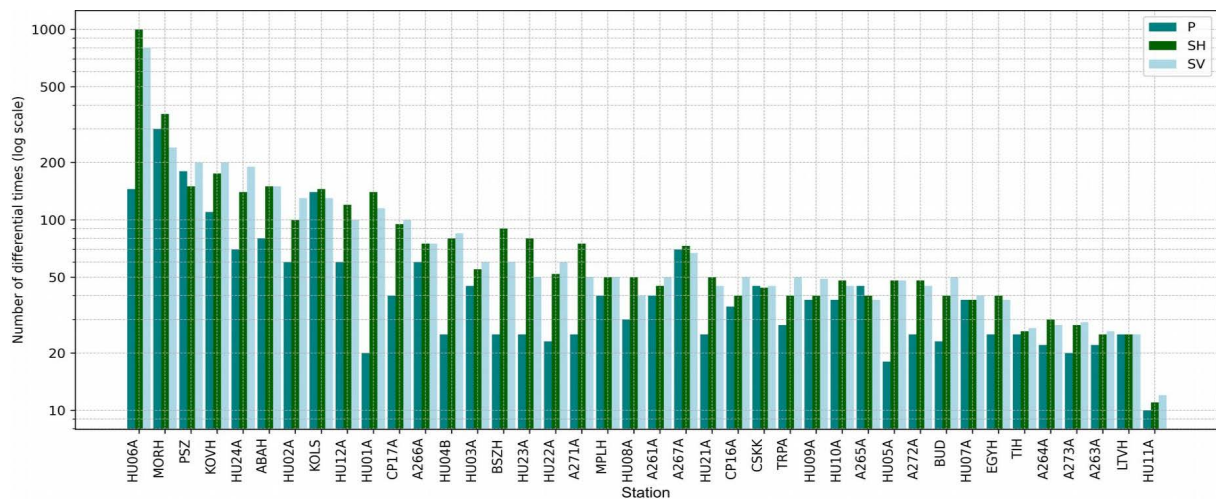


**Figure 14.** Seismograms of the two ( $M_L = 4.0$  and  $M_L = 4.1$ ) earthquakes occurred near Szarvas on August 19, 2023. The inset map shows the locations of the two events (yellow stars) and the red rectangle indicates the area shown in Fig. 16.

By September 8, a total of 109 earthquakes had been identified, with 73 recorded on the first day. On August 20, a reduced number of events (20) were registered, including another earthquake of  $M_L = 4.1$ . The subsequent days saw a significant decrease in seismic activity, but on September 8, another tremor perceptible to the public occurred ( $M_L = 3.2$ ). The magnitudes of the recorded earthquakes in this time period ranged from 0.8 to 4.1, highlighting the ability to detect even the smallest seismic events, such as the  $M_L = 0.8$  tremor. The majority of the recorded events fell within the 1.5 to 3.0 magnitude range, indicating that most seismic activity remained within moderate levels.

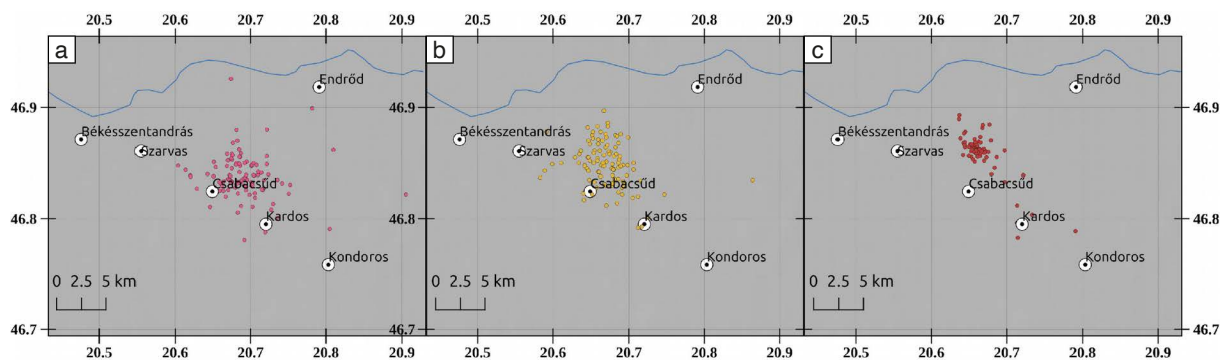
Given that several earthquakes of nearly identical magnitude occurred, with two striking in quick succession, it is challenging to definitively identify the main shock – in this context, we can refer to this phenomenon as an earthquake swarm.

In accordance with established procedures, we recalculated the initial hypocenters determined using SeisComp software (Helmholtz Centre Potsdam, 2008) with the iLoc location algorithm and prepared the data for hypoDD analysis, which is the routine multi-event localization software for small local event clusters. Figure 15 illustrates the station-wise distribution of differential times obtained through waveform correlation. The majority of SV and P correlations were recorded by the nearest temporary station associated with the AdriaArray project (HU06A), followed by high-quality permanent stations (MORH, PSZ, LTVH).



**Figure 15.** Quantity of differential time data extracted for the Szarvas earthquake cluster, categorized by station and component.

Figure 16 presents the various stages of cluster relocation. The Seiscomp solutions tend to disperse the events within the cluster, with epicenters even visible near Endrőd. The iLoc algorithm (Fig. 16b) effectively managed these events, significantly modifying the depth estimates, lowering the average focal depth from the initial 15-20 km to around 10 km. Ultimately, the hypoDD solutions (Fig. 16c), utilizing cross-correlation data, successfully consolidated the cluster, locating its center between Szarvas and Csabacsúd, which aligns well with the responses and reports from the local population. It is noteworthy that hypoDD discarded events that did not correlate strongly enough with the dataset during the iterations, resulting in 80 successful locations out of a total of 102 events.



**Figure 16.** Map views of the Szarvas earthquake cluster: Seiscomp (a), iLoc (b), and hypoDD (c).

## 7. First studies and ongoing research

The first significant completed study resulted in a homogeneously processed and quality-controlled P-to-S receiver function dataset, which was migrated in 3D spherical coordinates. This dataset provided the foundation for a Moho map of the Central and Eastern European region (Michailos et al., 2023). Another key study, utilizing data from the PACASE and AdriaArray networks, focused on mapping the lithosphere-asthenosphere boundary in the Pannonian Basin and surrounding regions through the analysis of S-to-P converted waves (Kalmár et al., 2023). These studies are vital for advancing our understanding of the subsurface structure in these regions.

Since the completion of these studies, additional data has become available, leading to three ongoing P-to-S receiver function studies focusing on the crust. These studies include investigations of the Bohemian Massif and its surroundings (Kampfóvá Exnerová et al., 2024), the Western Carpathians and Pieniny Klippen Belt (Soni et al., 2024),

and the Western Carpathians and the Polish region (Środa et al., 2024). As the Pannonian Basin lies on the edge of all three areas, the data collected from this region will also be processed.

In addition, a comprehensive P-to-S receiver function study is underway to investigate the mantle transition zone, using all data from AlpArray, PACASE, and AdriaArray in the Central and Eastern European region (Kalmár et al., 2025). Using the above seismological data and results, further complex seismological and geophysical studies have already been prepared for the area (e.g. Csatlós and Süle, 2024; Kalmár and Balázs, 2025). The first study calibrated the local magnitude scale in Hungary and the second work investigated the residual topographic conditions of the Pannonian Basin.

The AdriaArray stations also play a crucial role in earthquake (re)localization, particularly in the Pannonian Basin, contributing to more accurate determinations of earthquake hypocenters and epicenters (Wéber et al., 2025).

Lastly, efforts are being made in Hungary to develop a new seismic hazard map, as the last map was created nearly 20 years ago (Tóth et al., 2006). The AdriaArray stations are contributing significantly by providing a more detailed understanding of attenuation equations, the accuracy of active structures, and the designation of source zones, which will enhance the precision of the new seismic hazard map.

## 8. Conclusions

The advancements in HNSN and the integration of international collaborations, such as AlpArray, PACASE, and AdriaArray, have significantly enhanced the detection, analysis, and understanding of seismic activity across the Alps-Carpathian-Pannonian-Dinarides region. The expansion of the network, both in terms of density and geographic distribution, has lowered detection thresholds and improved the precision of earthquake localization, as evidenced by the revised HNSB catalog.

The comprehensive noise characteristic analysis conducted in this study reveals the critical influence of geological conditions and human activities on station performance, emphasizing the need for optimal site selection and insulation techniques. The correlation between noise levels and sediment thickness, as well as the observed resonance peaks in the HVSR analysis, underscores the importance of incorporating local geological properties into seismic network development.

The case study of the Szarvas earthquake swarm illustrates the practical applications of the enhanced network and advanced localization algorithms, demonstrating how improved instrumentation and data processing techniques contribute to better understanding seismic phenomena and mitigating risks associated with natural and anthropogenic seismic events.

Moreover, the integration of these advancements into broader research initiatives, including studies on the crust-mantle structure and velocities, local magnitude scale, seismic hazard assessment, and implementation to complex geophysical study, positions Hungary as a significant contributor to regional and global seismological research. Ongoing efforts to develop an updated seismic hazard map reflect the commitment to leveraging these technological and methodological improvements for the safety and resilience of the region.

This study highlights the collaborative nature and scientific significance of the HNSN within the AdriaArray framework. The insights gained will not only improve our understanding of regional geodynamics and seismicity but also provide a foundation for addressing geohazards and guiding future research endeavors in our country and south-eastern Europe.

**Data availability statement.** Waveform data from Hungarian AdriaArray stations are available through ORFEUS EIDA. The rolling embargo allows this data to be publicly available two years after its acquisition. Data from all AdriaArray temporary stations are, however, immediately available for seismological observatories with monitoring and alerting duties within the AdriaArray region. Waveform data of the permanent stations are available from the GEOFON EIDA node for the public. The yearly published Hungarian National Seismological Bulletin is available here: <http://www.seismology.hu/index.php/en/seismicity/earthquake-bulletins>.

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